PROJECT PERIODIC REPORT

Grant Agreement number: 228464

Project acronym: MICROKELVIN

Project title: EUROPEAN MICROKELVIN COLLABORATION

Funding Scheme: Capacities Specific Programme, Research Infrastructures, FP7

Date of latest version of Annex I against which the assessment will be made: 10.4.2013

Periodic report: 1st ☐ 2nd ☐ 3rd X 4th ☐

Period covered: from 1.4.2012 to 30.9.2013

Name, title and organisation of the scientific representative of the project's coordinator[1]:

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement .

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate) [1]:

  ☐ has fully achieved its objectives and technical goals for the period;

  X has achieved most of its objectives and technical goals for the period with relatively minor deviations.

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.

- The public website, is up to date http://www.microkelvin.eu/index.php
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Matti Krusius ....

Matti Krusius

Date: ...30........./ ....11......../ 2013

For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism.

Acknowledgement

The Microkelvin Collaboration wishes to thank our EU appointed Project Officer Maria Douka for her forthcoming support and advice in running the programme and correcting problems during the grant period.

[1] If either of these boxes below is ticked, the report should reflect these and any remedial actions taken.

3.1 Publishable summary

Concept of the Microkelvin Collaboration

European Microkelvin Collaboration — MICROKELVIN — is an EU-funded Integrating Activity project of the FP7 Capacities Specific Programme "Research Infrastructures". It promotes sub-millikelvin temperatures as a new frontier of research, by providing access to and developing applications in the ultra-low temperature regime. The grant is divided in four Networking Activities (NAs), four Joint Research Activities (JRAs) and four Transnational Access Activities (TAs). The project brings together 12 leading European partner organizations, of which three core institutions offer expertize and facilities to external users, and one is a cryogenic business developing and manufacturing very low temperature research equipment. The results from the third 18-month project period will be described below in this third and final Microkelvin Periodic Project Report.

The quest to study materials and new physical systems at ever lower temperatures has for two centuries led to the discovery of a multitude of new phenomena and concepts in physics and beyond. Today we find that many of the technical resources have been developed how to reach and measure microkelvin temperatures or to perform studies in this regime. However, in practice often enough the expertise is missing and the use of the ultra-low temperatures is prevented by a high starting threshold. The goal of the Microkelvin Collaboration is to facilitate this step, by creating “a European laboratory without walls” which offers education, counselling, facilities and instrumentation to European researchers. For this end, further technical development of practical user-friendly refrigeration and measurement methods is also of importance.

Research in nanosciences, materials physics, particle physics, cosmology, or instrumentation are examples which could draw immediate benefit from extending experimental work to the low millikelvin and microkelvin regimes. For instance, in nanoscience a central aim is to reach the regime where quantum phenomena govern the behaviour of the system. Experiments in this quantum engineering regime make it possible to discover new phenomena, new materials properties, and allow us to develop novel quantum devices with much improved sensitivity and resolution. We are in urgent need of such innovations, as conventional microcircuits are running up against the physical limits of further miniaturization. While quantum behaviour can be observed in very small samples at relatively high temperatures, it becomes much more apparent as the temperature is lowered. The lack of expertise in microkelvin techniques has hitherto been a deterrent against performing nanoscience experiments at the very lowest temperatures.

Objectives of the Microkelvin Collaboration

The Microkelvin Collaboration is a bottom-up approach of leading European low-temperature laboratories to create and manage an integrated research infrastructure and to make better use of the combined European expertise which we believe to represent the leading edge of ultra-low-temperature physics on the global scale. Among its objectives are

- To integrate and upgrade the leading microkelvin facilities in Europe.
- To assemble a critical mass for effective work on large scale issues and provide access to a wider range of European users.
- To create new capability by exploiting the combined microkelvin capacity of these facilities for new areas of physics, especially nanophysics.
- To enhance the capacities of the access-giving facilities.

- To network the members of the low temperature and related research communities, the scientists with cryo-engineers and the end-users with access providers, to facilitate cross-disciplinary sharing of knowledge.
- To disseminate the expertise of the core institutes to the wider community by the development of compact user-friendly refrigerators for microkelvin research in efficient infrastructure environments.
- To foster the development of the next generation of refrigerators and instrumentation for ultralow temperature measurements and to help in their commercialization.
- To develop strategies and tools for the long-term build-up of a virtual European Ultralow Temperature Laboratory without walls.

Microkelvin maintains a website http://www.microkelvin.eu which summarizes progress, by listing the events organized by the Collaboration, its publications in scientific journals, and the official documentation monitoring the results. Its management office in Aalto University includes the following personnel:

Project Coordinator: Matti Krusius (email: mkrusius@neuro.hut.fi or matti.krusius@aalto.fi)
Project Manager: Katariina Toivonen (email: katariina.toivonen@aalto.fi)
Project WEB-officer: Jonne Koski (email: jonne.koski@aalto.fi)
Project Secretary: Mari Kaarni (email: mari.kaarni@aalto.fi)

Progress of the Microkelvin Collaboration

Microkelvin promotes new alternatives in physics research through the use of ultra-low temperatures. To achieve this goal, three main routes are followed:

1) Microkelvin disseminates information to the low temperature community at large through its ***Networking Activities NA3*** ("knowledge and technology transfer") and ***NA4*** ("strengthening European low temperature research"). The former activity maintains a data base on microkelvin physics and techniques which is available in the public domain on the internet. A second important task is the organizing of meetings and workshops. Most important have been three one-week workshops which have included reports of all Microkelvin research activities and the periodic review of the grant programme in 18-month intervals. The NA4 activities involve the founding and running of a "European Cryogenic Society" which has been accomplished in the form of a Low Temperature Section created within the Condensed Matter Division of the European Physical Society. A second example is the effort to enhance connections to high-level research in third countries outside the EU regime.

2) Microkelvin provides access to its three core laboratories through the ***Transnational Access Activity*** packages ***TA1 – TA3***. These packages carry the provisions for researchers to perform experiments and for students to learn working procedures in the three access institutions. In total for one visitor, the visiting time can amount up to three months. The visits are carefully discussed and planned in advance, and finally approved by the Selection Committee, to provide the visitor the maximum gain from his/her stay. In total, access was provided to 72 users for 81 months. The users came from 14 different EU or associated countries. In spite of a slow start, the access activity achieved all the goals foreseen in the original Microkelvin plan outlined in Annex I.

3) Microkelvin also involves new research to develop the experimental tools needed at the very lowest temperature. This work is contained in four work packages, the ***Joint Research Activities JRA1 – JRA4***. The four work packages contain the following tasks:

JRA1 Opening the microkelvin temperature regime to nanoscience (with ex-chip techniques)
JRA2 Development of ultra-low-temperature on-chip nanorefrigerators and thermometry
JRA3 Fundamental physics questions with microkelvin condensed-matter experiments
JRA4 Novel methods and devices for ultra-low-temperature measurements

JRA1: Microkelvin is both upgrading refrigeration capacity in its collaborating laboratories and developing new concepts for efficient refrigeration and thermometry. For instance, the construction of a new large-scale low-heat leak nuclear refrigeration installation has been in progress during the grant period in Lancaster University. This apparatus has ambitious technical specifications and is designed to provide an efficient environment for the refrigeration of nano-structured samples and devices to sub-millikelvin temperatures by means of the most advanced filtering and thermalization techniques.

The cooling of electronic sensors and devices has proven difficult even to the lowest dilution refrigerator temperatures of order 10 mK and has generally not been possible to the sub-mK regime. A new scheme has been devised in the University of Basel where the electrical leads to the sensor are individually carefully filtered and thermalized to the different cooling stages of the dilution refrigerator. With this approach the group has cooled Coulomb blockade thermometers consisting of a metallic superconducting tunnel junction array to about 5 mK. This Microkelvin achievement represents probably the lowest verifiable on-chip electron temperature so far. By including active cooling of the sensor leads, each with its own nuclear coolant, it is expected that much lower temperatures are quite realistic for conduction electrons in planar on-chip micro-fabricated devices.

Another advance is development of adiabatic nuclear demagnetization cooling in a pulse-tube-cooler precooled ^{3}He-^{4}He dilution refrigerator. Currently our industrial partner ***Bluefors*** is selling approximately 30 units annually of such automated dry dilution refrigerators. This is about one third of the world production. The combination of a cryogen-free fully automated refrigeration apparatus with nuclear cooling, all behind “push-button operation”, will make this approach practical for in-house sub-millikelvin operation in nanoscience laboratories. The apparatus and measurements performed with it can conveniently be operated remotely over the internet, which increases control and reliability of all procedures. Several of such refrigeration installations have been commissioned from BlueFors and are now coming into operation. Of central interest are measurements of their cooling properties and heat leaks to the nuclear cooling stage from the mechanical vibrations transmitted by the pulse tube cooler. Presumably in the next few years we will see more and more deliveries of such refrigeration systems, providing sub-mK temperatures at less than 0.5 MEuros.

JRA2: The goal is to use nanofabrication to develop on-chip refrigeration and thermometry. Both superconducting tunnel junction and quantum dot structures have been developed for cooling. For instance, in tunnel junction cooling in a superconcuctor –insulator – normal metal – insulator – superconductor tunnel structure (S-I-N-I-S structure) a thermal current appears while an electrical current is directed through the tunnel barrier. Two approaches have been pursued to improve the cooling effect at lower temperatures, since the optimum efficiency is achieved at about 0.4 T_c: either by reducing the superconducting gap with a small applied magnetic field or by selecting a superconductor with a lower T_c and smaller gap value. Both techniques have now been demonstrated to work and the low-temperature limit of these devices has dropped down to 30 mK. Further reduction of temperature is expected, for instance with multistage cooling schemes, so that ultimately microcooler operation could become feasible down to the 10 mK range.

JRA3: This work package aims to answer selected fundamental physics questions by means of sub-mK measurements. A number of first-time discoveries have been made. The study of the dynamics of quantized vortex lines in superfluid ^{3}He-B in the $T \longrightarrow 0$ limit has provided new understanding about the interplay of laminar and turbulent flow and their respective dissipation mechanisms. The phenomenon of Bose-Einstein condensation of magnons or spin-wave excitations has been clarified and developed to a practical research method for measuring the order parameter texture in ^{3}He-B. Spin relaxation in these resonance modes, both in the homogeneous mode at intermediate temperatures and the inhomogeneous magnetically trapped very-low-temperature mode, has proven particularly sensitive to the presence and properties of vortex cores. Another new development is the identification of BCS pairing states of superfluid ^{3}He in a nano-fabricated restricted planar geometry between two smooth parallel plates with different separations using SQUID-based NMR measurement.

Owing to their inherent nature some of the fundamental questions which were planned to be investigated within JRA3 have turned out less interesting or less feasible than originally anticipated and have been replaced by other more promising tasks. An example is a dark-matter detector where the target material is superfluid ^{3}He-B at 100 μK. Owing to difficulties with financing and collapsing roofs in the underground laboratory, this effort was put on a hold and instead its preliminary studies were expanded, namely the development of mechanical microresonators and measurements of the excitation spectrum of the ^{3}He Fermi liquid. The latter effort lead to a remarkable discovery of a long-lived roton-like plasmon mode, a collective mode in the density of two-dimensional ^{3}He liquid.

JRA4: Of vital importance for research in the sub-mK range is the development of new techniques for thermometry and sample characterization, particularly in the case of nano-size samples. Low noise and high sensitivity dictate the use of SQUID amplifiers which need to be coupled to micron-size sensors, often in a contactless measuring setup. The viability of this approach has been demonstrated in measurements of dielectric polarization echoes, thermal conductivity, and heat capacity of glassy materials down to 7 mK. Another demonstration of high sensitivity is the measurement of resistive current noise in a piece of copper, using inductive readout and calibration against a ^{195}Pt NMR thermometer down to 200 μK. These measurements would not have been possible without the development work invested in SQUID-based preamplifiers. A further frontier is our work on high-frequency SQUID amplifiers which are currently needed for quantum engineering experiments at the quantum limit of sensitivity.

Future of the Microkelvin Collaboration

Traditionally physics at ultralow temperatures has required elaborate large-scale infrastructure which cannot be bought, but is home-built, and is therefore difficult both to acquire and maintain by a single academic research unit of usual size. Nevertheless, over the past few decades several groups in Europe have established large-scale cryogenic facilities that are unique on the worldwide scale. Today these laboratories are leading much of the research in quantum fluids and solids, as well as in materials and nanosciences at ultra-low temperatures. Their collaboration within the Microkelvin programme has been working on two frontiers: (1) to upgrade the existing large-scale infrastructure which caters for the most demanding special research tasks and (2) to further the development and usage of more specialized equipment.

If we accept the preferences expressed by nanophysics researchers, for instance, then the evolution in microkelvin technology ought to develop the same way as we have seen computing changing during the past fifty years: from large main-frame equipment to diversified small-scale almost table-top apparatus which can be dedicated to specific tasks. Materials and nanophysics labs prefer to collect small-scale apparatus, ranging from sample fabrication and characterization to measurement and analysis, with affordable unit cost. In this environment the role of the European Microkelvin Collaboration becomes ever more important: it is to provide expertise, education, services, and new research in the development of refrigeration and measurement techniques. This development can be viewed as partial outsourcing of a research discipline, whereby European materials and nanophysics laboratories obtain research expertise and resources from a continent-wide Microkelvin Collaboration.

A further major mission of the Microkelvin grant programme is to extend the working regime in nanophysics towards lower temperatures. Lower temperatures can be predicted to lead to easily certifiable benefits. So far experiments in nanoelectronics or nanomechanics have not been cooled to sub-millikelvin temperatures. Microkelvin has helped to fix attention to this goal and today many different approaches are being developed to make this possible.

To consolidate this activity after the finish of the Microkelvin grant, the Collaboration aims to formally establish a European Ultra-Low-Temperature Laboratory, a distributed infrastructure with complementary instrumentation and the following goals: to give European research open access to its facilities and to operate as a flexible coordinated superstructure with the aim to help European research to make use of low temperatures. To support this activity, the Collaboration will be submitting a new grant application within future EU grant programmes which cater for the development of research infrastructure (see Appendices).

3.2 Core of the report for the period: Project objectives, work progress and achievements, project management

3.2.1 Project objectives for the period

This is the third and final Periodic Project Report at 54 months. A review with one external referee was conducted at 18 months (by prof. Konstantin Arutyunov from the University of Jyväskylä, Finland). The second review meeting at 36 months and the third at 54 months were organized internally with no external referees, owing to funding shortages at the EU Project Office. The EU appointed Microkelvin Project Officer Maria Douka has been supervising all review meetings.

Owing to delays in the Microkelvin trans-national access programme, the grant period was extended by an additional 6 months from 31 March to 30 September, 2013. This extension was granted without changes in the overall Microkelvin budget. In addition several internal transfers of funding between different budget items have been approved by the EU Project Office.

In the joint research activity packages work has been progressing as outlined in Annex I, except for changes in two tasks within the JRA3 work package. These changes were approved in Microkelvin Amendment No. 2. The goals and deadlines are defined in terms of milestones and deliverables which are listed below in the context of each separate work package. They have been copied from Annex I, using the version which was approved for Microkelvin Amendment No. 3 (from April 10, 2013). All these documents are publicly available on the Microkelvin web site in the address http://www.microkelvin.eu/documentation.php

3.2.2 Work progress and achievements during the period

An overview of progress in the networking packages NA2 – NA4 and in the joint research activities JRA1 – JRA4 is outlined below, covering the third 18 month project period from 1 April, 2012 to 30 September, 2013.

NA2

Name of the activity: **Coordination of transnational access**
Reporting Period: **last periodic review period from 1.4.2012 to 30.9.2013**
Activity leader: **Matti Krusius (AALTO)**

Table of expected deliverables

List and schedule of deliverables								
Del. no.	**Deliverable name**	**WP no.**	**Lead beneficiaries**	**Estimated person months**	**Nature**	**Dissemination level**	**Delivery date**	**Comments**
D1	User Meetings (Proceedings)	NA2	AALTO CNRS ULANC	2	R	PU	13, 37 (24, 48)	**achieved**
D2	Training sessions for Users	NA2	AALTO CNRS ULANC	1	O	PU	13, 37	**achieved**

Table of expected milestones

List and schedule of milestones					
Milestone number	**Milestone name**	**WP no.**	**Lead beneficiary**	**Delivery date From Annex I**	**Comments**
M2	Meetings of the Selection Panel in person (by email)	NA2	Aalto	1,13,37 (6,12,18…)	achieved

Summary

Microkelvin management and coordination have been running as planned. The total of delivered access months is at the target value, after the project period was extended by 6 months, and half of the Lancaster access volume was transferred to Aalto (in amendment No. 3 of April 10, 2013).

Task 1: Meetings of the Selection Panel

The planning of the collaborative projects, which seek access, is supervised and approved by the Selection Panel. These discussions are carried out by email: acceptance is asked for each individual application. Typically a visitor application has been carefully discussed and planned between the access provider and the visiting research group before it reaches the Selection Panel. Thus it generally requires little interference from the Selection Panel members and projects are rarely turned down. The applications which have been approved by the Selection Panel plus the reports from the completed visits are listed on the Microkelvin web site on page http://www.microkelvin.eu/project-activities-transnational.php

The reports from the visits during the third 18-month period have been reproduced in Sec. 3.2.3. The Selection Panel has met in person to discuss principles and procedures at the following occasions (see page http://www.microkelvin.eu/microkelvin-events.php):

- April 3, 2009, during the Microkelvin Kick-Off Meeting in Aalto University
- August 1, 2010, during the 2010 International Conference on Quantum Fluids and Solids QFS 2010 in Grenoble
- October 16, 2010, during the 2010 Workshop, User Meeting & Review in Aalto University, when the 18-month Periodic Review Report was prepared
- March 17, 2011, during the 2011 Workshop & User Meeting in Smolenice Castle of the Slovak Academy of Sciences
- March 21, 2012, during the 2012 Workshop, User Meeting & Review in Smolenice Castle, when the 36-month Periodic Review Report was prepared
- August 17, 2012, in the context of the Meeting of the Microkelvin General Assembly during the International Conference of Quantum Fluids and Solids – QFS2012 in Lancaster University
- September 13, 2013, during the 2013 Workshop, User Meeting & Review in Sannäs Manor House, Finland, when the 54-month Periodic Review Report was prepared

Task 2: User Meetings

User Sessions have been organized at all annual Microkelvin Workshops:

- 2010 Workshop, User Meeting & Review, October 14-17, 2010, in Aalto University http://ltl.tkk.fi/wiki/Events/Microkelvin_2010

- 2011 Workshop & User Meeting, March 14-18, 2011, in Smolenice Castle of the Slovak Academy of Sciences, organized by Dr. Peter Skyba (NA3 activity leader), http://www.saske.sk/UEF/OFNT/Microkelvin2011/
- 2012 Workshop, User Meeting & Review, March 18-24, 2012, in Smolenice Castle of the Slovak Academy of Sciences, http://ltl.tkk.fi/wiki/Events/Microkelvin_2012/Program
- 2013 Workshop, User Meeting & Review, September 9-13, 2013, in Sannäs Manor House 60 km east of the Helsinki airport, http://ltl.tkk.fi/wiki/Events/Microkelvin_2013/Program

The detailed programmes of these events are available on the respective workshop web sites. Related meetings and workshops where Microkelvin activities have been discussed or presented are listed below under work package NA3 (Knowledge and technology transfer).

Scientific proceedings from Microkelvin Workshops have been published from the

- Workshop on *Vortices, Superfluid Dynamics, and Quantum Turbulence,* 11-16 April, 2010, in Journal of Low Temperature Physics (Springer) 161, No. 5/6 (2010). The programme of the workshop is on page http://ltl.tkk.fi/wiki/Events/Vortices_2010
- Proceedings are planned from the final 2013 Microkelvin Workshop (see list above) which will be published in Journal of Low Temperature Physics. These proceedings will summarize and review the main results from Microkelvin work.
- Microkelvin has contributed to the contents and preparation of the following conference proceedings:
  - Proceedings of the International Quantum Fluids and Solids Conference QFS 2010 in Grenoble, 1-7 Aug, 2010; published in Journal of Low Temperature Physics (volume 162, numbers 3/4 and 5/6 in 2011), the editors were *Henri Godfrin* and Horst Meyer
  - Proceedings of the International Conference on Low Temperature Detectors LTD 14 in Heidelberg, 1-5 Aug, 2011; published in Journal of Low Temperature Physics (volume 167, issue ¾ in 2012), the editors were L. Gastaldo, *Andreas Fleischmann*, and *Christian Enss*
  - Proceedings of the International Quantum Fluids and Solids Conference QFS 2012 in Lancaster, 15-21 Aug, 2012; published in Journal of Low Temperature Physics (volume 171, issues 3/4 and 5/6 in 2013), the editor was prof. *Shaun Fisher*

Training sessions, to introduce new specialized techniques, have been organized for Users and Workshop participants at the following meetings:

- Microkelvin Kick-off-Meeting, April 2-3, 2009, in Aalto University. The programme of the meeting is on page http://www.microkelvin.eu/microkelvin-events.php
- 2010 Microkelvin Workshop, User Meeting & Review, October 14-17, 2010, in Aalto University http://ltl.tkk.fi/wiki/Events/Vortices_2010

Task 3: Coordination of Access

In NA2 Microkelvin Collaboration coordinates the access of visiting scientists to three access giving laboratories where the visitors are provided the necessary provisions to complete their research projects. This activity is summarized in two tables below: the first table lists the planned access according to Annex I and the second the actual access provided by the end of September, 2013. A total of 80.8 months of access was provided which approximately equals the original goal of a minimum of 81 facility months. The number of User Groups and different Users turned out to be larger than originally anticipated. Our experience from this activity can be summarized in the following way:

- Any collaborative research project at the access site requires detailed advance planning.

- In fact, it thereby becomes a common project between the host group at the access laboratory and the visitors.
- Since both the host and visitor groups bring supplementing expertize to the project, results are obtained faster and have better quality.
- Many of the access collaborations have evolved from in-house projects at the access-giving site, where the User Group then provides some additional special expertize. The benefits from such cowork have been a major success for the Microkelvin Collaboration and its Users.
- In most cases the final product is one or several joint research publications.

Summary of expected transnational access provision [Annex I from April 10, 2013]

Participant number	*Organisation short name*	*Short name of infrastructure*	*Installation*			*Operator country code*	*Unit of access*	*Estimated unit cost (€)*	*Min. quantity of access to be provided*	*Access costs charged to the GA*	*Estimated number of users*	*Estimated number of projects*
			number	*Short name*	*Estimated costs*							
1	AALTO	LTL	1	Cryohall 1	2667346	FI	Facility-month	10259	27	276995	18	14
1	AALTO	LTL	2	AALTO Micronova	6256691	FI	Hour	150.17	100	15017	5	5
1	AALTO	LTL	1	Cryohall 2	1341780	FI	Facility-month	8945.20	13.5	120760	9	7
2	CNRS	CNRS	1	CNRS MICROKELVIN	2393590	FR	Facility-month	9206.12	27	248565	18	14
3	ULANC	MicroKLab	1	MicroKLab	1341780	UK	Facility-month	8945.20	13.5	120760	9	7

Summary of actually provided transnational access

Institute	*Installation*	*Unit*	*Access to be provided*	*Estimated number of users*	*Estimated number of projects*	*Access provided*	*Actual number of users*	*Actual number of groups*
AALTO	Cryohall	mo	40.5	27	21	40.8	32	28
AALTO	Micronova	h	100	5	5	100	3	3
CNRS	CNRS Microkelvin	mo	27	18	14	28.1	22	17
ULANC	MicroKLab	mo	13.5	9	7	12.0	18	8
In total	-	mo	81.0	-	-	80.8	72	53

- The larger number of groups and visitors than originally expected shows that many visits tend to be short and often enough consist of a few separate visits to the access site. These are used for planning, analysis, and reporting, while the actual measurements are often predominantly performed by the personnel of the host laboratory. Commitments at home with teaching and administrative duties effectively cut down the time which the visitors can spend at the access site for measurements.

- The total access time of a visitor group was limited to 3 months. It was originally expected that this restriction would become a major obstacle since most experimental low-temperature research tasks are time consuming. However, it turned out that perhaps only 10 % or less of the projects needed to ask the EU Project Officer for permission to exceed the 3-month limit.
- The access program has collected high approval from both the host and visitor groups.

A detailed report of the visits within the access programme during the third (and last) 18-month grant period is displayed in Sec. 3.2.3 – "Project management during the grant period". Similar reports from the earlier review periods can be found in their respective periodic review reports. These reports are also available on the internet on page

http://www.microkelvin.eu/project-activities-transnational.php

Milestone 2: Meetings of the Selection panel **achieved**

Deliverable 1: User meetings **achieved**

Deliverable 2: Training sessions for new users at User Meetings **achieved**

Highlights

The vibrancy of the Microkelvin concept is demonstrated by the progress reported at its workshops and by the joint publications listed below which have resulted from the joint work within the access programme. The access programme has reached the targeted volume.

Deviations from work plan: During the four and a half grant years, two amendments to Annex I were approved with operational changes to the grant programme. In addition a few smaller changes in the magnitudes of different budgetary items were acknowledged by the EU Project Office. If we include and accept these changes, then progress in all activities has been as planned.

Use of resources: In amendment #3 half of the ULANC TA funding was transferred to AALTO and simultaneously the total grant period was extended by 6 months. The visitor programme follows otherwise the original plans.

Publications on joint research between Users and Microkelvin Access Personnel during the 54-month grant period from 1.4.2009 to 30.9.2013 (with explicit acknowledgement to EU grant 228464 Microkelvin)

JRA2: Ultra low temperature nanorefrigerator

1. H.Q. Nguyen, T. Aref, V.J. Kauppila, M. Meschke, C.B. Winkelmann, H. Courtois, J.P. Pekola, *Trapping hot quasi-particles in a high-power electronic cooler,* New J. Phys. **15**, 085013 (2013)
2. V.J. Kauppila, H.Q. Nguyen, T.T. Heikkilä, *Non-equilibrium and proximity effects in superconductor-normal metal junctions*, Phys. Rev. B **88**, 075428 (2013)

JRA3: Attacking fundamental physics questions by microkelvin condensed-matter experiments

1. H.M. Böhm, R. Holler, E. Krotscheck, M. Panholzer, H. Godfrin, M. Meschke, H. J. Lauter, *Reemergence of the collective mode in 3He and electron layers*, Int. J. Mod. Phys. B (IJMPB) **24**, 4889-4900, Issues: 25-26 (2010); DOI: 10.1142/S0217979210057079
2. H. Godfrin, M. Meschke, H.-J. Lauter, H.M. Böhm, E. Krotscheck, M. Panholzer, *Observation of Zero-Sound at Atomic Wave-Vectors in a Monolayer of Liquid 3He,* J. Low Temp. Phys. **158**, 147 (2010) [URL]

3. D.I. Bradley, S.N. Fisher, A.M. Guenault, R.P. Haley, N. Mulders, G.R. Pickett, D. Potts, P. Skyba, J. Smith, V. Tsepelin, R.C.V. Whitehead, *Magnetic Phase Transition in a Nanonetwork of Solid 3He in Aerogel,* Phys. Rev. Lett. **105**, 125303 (2010) [URL]

4. V.B. Eltsov, R. de Graaf, P.J. Heikkinen, J.J. Hosio, R. Hänninen, M. Krusius, V.S. L'vov, *Stability and dissipation of laminar vortex flow in superfluid 3He-B*, Phys. Rev. Lett. **105**, 125301 (2010) [URL]

5. J.J. Hosio, V.B. Eltsov, R. de Graaf, P.J. Heikkinen, R. Hänninen, M. Krusius, V.S. L'vov, G.E. Volovik, *Superfluid vortex front at T -> 0: Decoupling from the reference frame,* Phys. Rev. Lett. **107**, 135302 (2011) [URL]

6. D.I. Bradley, M. Clovecko, M.J. Fear, S.N. Fisher, A.M. Guénault, R.P. Haley, C.R. Lawson, G.R. Pickett, R. Schanen, V. Tsepelin, P. Williams, *A new device for studying low or zero frequency mechanical motion at very low temperatures,* J. Low Temp. Phys. **165**, 114-131 (2011)

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JRA4: Novel devices and methods for ultra low temperature experiments

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NA3 Report

Name of the activity: **Knowledge and technology transfer**
Reporting Period: **from 1.4.2012 to 30.9.2013**
Activity leader: **Peter Skyba (SAS)**

Table of expected deliverables during the grant period

Del. no.	Deliverable name	WP no.	Lead beneficiary	Estimated person months	Nature	Dissemination level	Delivery date
D1	Opening of the CryoTools data base (6) and E-mail lists of laboratories and industries (8)	NA3	CNRS	2	O	PU	6, 8 **achieved**
D2	LT-X workshops (18, 28, 40, 44) and Industrial meeting (32) with reports	NA3	All partners		R	PU	18,28,32, 40, 44 **achieved**

Table of expected milestones during the grant period

Milestone no.	Milestone name	WP no.	Lead beneficiary	Delivery date From Annex I	Comments
M1	Meetings of Dissemination Committee	NA3	CNRS	1, 13, 37	Web-site news **achieved**

Summary

The purpose of this activity is to disseminate the results of the Microkelvin work among the partners of the network, to the scientific community at large, and to popularize our achievements to public audiences.

Meetings of Dissemination Committee

The third Meeting of Dissemination Committee was held in March 2012 as a part of Microkelvin General Assembly meeting during the Microkelvin 2012 workshop organized in Smolenice 2012. The final (fourth) meeting of the Dissemination Committee was in September 2013 during the final Microkelvin workshop in Sannäs, Finland. This completes the work foreseen in the Deliverables.

During these meetings the Dissemination Committee examined the dissemination activities undertaken during the preceding project period and issued recommendations for the upcoming new period. The main activities were concerned with Microkelvin participation in international workshops and conferences, delivering lectures to the general public, organizing schools and conferences for students and young researchers, and providing training in low temperature physics and techniques by means of a series of Cryocourses.

Milestone 1: Meetings of the Dissemination Committee (1, 13, 37) **achieved and exceeded**

Task 1. Dissemination of the network results

Task 1 is running continuously, with several parallel routes of dissemination to different scientific communities, to industrial partners, and to the general public. Most prominent is our extensive list of scientific publications in various world leading scientific journals. The collaboration members have presented their results as invited plenary talks, as contributed talks and posters. There is also a rich list of outreach activities provided by the Microkelvin partners (see below). The organizing of conferences, workshops, and schools was regarded as utmost important, irrespectively whether these were arranged by Microkelvin alone or through its participation as a partner. Four Microkelvin workshops were organized which were open to external participants and to which users of the Microkelvin access facilities were invited to present their results.

The Microkelvin web page www.microkelvin.eu is an active tool, open to external and internal users, where publications, technical reference material, scientific events, and information about all Microkelvin activities and their progress is continuously updated.

Task 2. Dissemination of low temperature technology

The most far-reaching dissemination activity was the transfer of low temperature "know-how" and services to the European research community by means of the Transnational Access (TA) Program. More than 50 scientific projects were accepted by the Selection Panel and completed by more than 70 individual visitors to the access laboratories in Aalto University, Institut Néel of CNRS-Grenoble, and Lancaster University. Also the Joint Research Activities of the Microkelvin programme are outstanding examples of how to enhance the usefulness and availability of low temperature techniques and services for the physics community at large. The results were discussed in altogether 17 scientific events which Microkelvin helped to organize during the grant period, as listed on web page www.microkelvin.eu under "Events".

Task 3. Networking with other scientific communities

Microkelvin organized or participated in the organizing of the following events:

ReportingPeriod 01/04/2012 - 30/09/2013	Date	Year	Place	Country	Activity	Microkelvin reference
QFS 2012	15.8.-21.8.2012	2012	Lancaster	UK	NA-TA-JRA	LT-workshop, GA Meeting
Cryocourse 2012	2.9.-13.9.2012	2012	Heidelberg	Germany	NA2	Training session I
Workshop on Physics and Metrology at Low Temperatures	13.12.-14.12.2012	2012	Berlin	Germany	NA	LT-detectors, LT-Nano
EPS-CMD24 Conference	3.9.-7.9.2012	2012	Edinburgh	FUK	NA	LT-workshop
Cryocourse 2013	25.8.-3.9.2013	2013	Grenoble	France	NA2	Training session II
QFS 2013	30.7.2013-6.8.2013	2013	Matsue	Japan	NA	LT - workshop
Microkelvin general assembly, user and review meeting 2013	9.9.-13.9.2013	2013	Sannäs	Finland	NA-TA-JRA	GA & Users Meeting

Microkelvin was also involved in the organization of the International Symposium on Quantum Fluids and Solids QFS 2013 in Matsue, Japan, 30.7. – 6.8.2013. In addition, it has participated in the planning for the Ultra-Low Temperature Conference ULT 2014 in Bariloche, Argentina (August 16th-August 19th, 2014). This meeting is a satellite of the International Conference on Low Temperature Physics LT 27 in Buenos Aires, Argentina.

List of conferences, workshops and cryo-schools (which Microkelvin organized or where it contributed to the organization) with relevant web pages

- Microkelvin 2013 Workshop, Users' Meeting and Final Review, 9.-13.9.2013, Sannäs Manor House, Finland (web page: https://ltl.tkk.fi/wiki/Events/Microkelvin_2013)

Participants of the 2013 Microkelvin Workshop in front of Sannäs Manor House

- Cryocourse 2013: Advanced Cryogenic Course, 25.8.-3.9.2013, CNRS Grenoble, Grenoble, France (web page: http://cryocourse2013.grenoble.cnrs.fr/)
- Workshop on Physics and Metrology at Low Temperatures, 13.-14.12.2012, Physikalisch-Technishe Bundesanstalt, Berlin, Germany (web page: http://www.ptb.de/cms/fachabteilungen/abt7/physics-and-metrology-at-low-temperature.html)
- Cryocourse 2012: Eurpoean Advanced Cryogenic Course, 2.-13.9.2012, Ruprecht-Karls Universität, Heildelberg, Germany (web page: http://www.kip.uni-heidelberg.de/cryocourse2012/)
- EPS-CMD24 Conference, 3.-7.9.2012, Edinburgh, UK (web page: http://www.cmd-24.org/home)

- QFS 2012: International Symposium on Quantum Fluids and Solids, 15.-21.8.2012, Lancaster University, UK (web page: http://www.physics.lancs.ac.uk/QFS2012/)

Participants and lecturers of the 2013 Cryoschool in August in Chichilianne

Participants and lecturers of the 2012 Cryoschool in September in Heidelberg

Deliverable 2:	LT-X workshops (18,28,40,44)	**achieved and exceeded**
	Industrial meeting (32) with reports	**achieved**

Participants of QFS 2012 Conference in Lancaster, Aug 2012

Examples of invited talks presented by Microkelvin partners

Invited talks at **QFS 2012**, Lancaster University, Lancaster
(web page: http://www.physics.lancs.ac.uk/QFS2012/programme.html)

Andrew Casey: Superfluid ^{3}He confined in nanofluidic cells
Mika Sillanpää: Circuit QED with a hybrid of micromechanical resonator and transmon qubit
Pertti Hakonen: Towards microwave optomechanics with graphene mechanical resonators
Vladimir Eltsov: Self trapping and relaxation of magnon condensates in superfluid 3He-B
Eddy Collin: Nonlinear dynamics in nanomechanical resonators
Risto Hänninen: Kelvin-wave spectrum of a pinned vortex
Victor Efimov: Free decay of acoustic turbulent energy cascades in superfluid 4He

Invited talks at **QFS 2013**, Matsue, Japan (web page: http://qfs2013.riken.jp/program.shtml)

J. Saunders: Topological superfluids contained in nanoscale slab geometries
V. Eltsov: Experimental signatures of vortex core structures in superfluid 3He
P. J. Heikkinen: Gravity waves on the surface of topological superfluid 3He-B
Yu. M. Bunkov: Direct observation of a Majorana quasiparticle heat capacity in 3He
M. Defoort: Energy dissipation in nano-electro-mechanical devices at mK temperatures
V. Tsepelin: The turbulent drag in superfluids
R. Hänninen: Dissipation enhancement from a single reconnection event in superfluid helium
G.E. Volovik: Higgs bosons in particle physics and in condensed matter

Other invited/contributed talks presented by Microkelvin partners during the reporting period

AALTO

Invited talks presented by P.J. Hakonen:

- Towards optomechanics with graphene mechanical resonators, Materials Research Society Spring Meeting 2012, San Francisco, USA, April 9-13, 2012.
- Electromechanical parametric effects, Workshop on Noise and Nonlinearities in Mechanical Resonators, Barcelona, Spain, May 28 - June 1, 2012.

- Introduction to quantum amplifiers: basics and practicalities, Workshop on Noise and Nonlinearities in Mechanical Resonators, Barcelona, Spain, May 28 - June 1, 2012.
- Towards microwave optomechanics with graphene mechanical resonators, Quantum Fluids and Solids 2012, Lancaster, UK, Aug. 15-21, 2012.
- Hybrid circuit cavity quantum electrodynamics with a micromechanical resonator, Superconducting nanohybrids SNh-2012, San Sebastian, Donostia International Physics Center, Spain, Sept. 3-7, 2012.
- Microwave Amplification with Nanomechanical Resonators, International Solid-State Circuits Conference, San Francisco, USA, March 17-21, 2013.
- Electrical cavities with micromechanical resonators: optomechanics at microwaves, Conference on Nanomaterials and their application in biology and medicine, Poznan, Poland, June 16-19, 2013.
- Hybrid circuit cavity quantum electrodynamics with a micromechanical resonator, Workshop on Frontier between atomic and solid state physics, Paris, France, July 17-19, 2013.

Basel

- D. Zumbuhl: Semiconductor Spins in quantum transport experiments, 2nd NCCR QSIT Student School and 3rd NCCR QSIT General Meeting, school presentation, 28.1.-1.2.2013.
- D. Zumbuhl: Evidence for nuclear spin order in GaAs quantum wires at ultra-low temperatures Conference of the EPS Condensed Matter Division, Edinburgh, UK, September 2012.
- D. Zumbuhl: Intrinsic charge fluctuations and nuclear spin order in GaAs nanostructures, Seminar July 2012, University of Groningen, Netherlands.
- D. Zumbuhl: Intrinsic charge fluctuations and nuclear spin order in GaAs nanostructures, International summer school and conference "Scuola Enrico Fermi", June 2012, Varenna, Italy.
- D. Zumbuhl: Evidence for helical nuclear order in GaAs quantum wires, European Microkelvin Meeting, March 2012, Smolenice, Slovakia.

CNRS Grenoble

- H. Godfrin: Fermi Liquid 3He: the point of view of the experimentalist, Future Prospects in Many Particle Theory Workshop (FPMPT), June 25 - 27, 2012, Johannes Keppler University, Linz, Austria. (Invited talk)
- H. Godfrin: Fluides quantiques et Tres Basses Températures au CRTBT, 50 ans du Polygone CNRS de Grenoble - Journée "Histoire du CRTBT" Campus CNRS de Grenoble, 9 Avril 2013 (Invited talk)
- H. Godfrin: Modes collectifs des liquides de Fermi fortement corrélés : 3He -2D, Congres Général de la Société Française de Physique, Marseille, 1-3 Juillet 2012 (Invited talk)
- H. Godfrin: Experimental evidence for flat bands in strongly interacting 2D liquid 3He, Workshop on Flat bands Design Topology and Correlations March 6-9 2013, Dresden (Invited talk)
- D. Schmoranzer, M. Defoort, S. Dufresnes, E. Collin, H. Godfrin, L. Skrbek, Transition to turbulence in 4He due to mechanical oscillators, ETC14, European Turbulence Conference, Lyon, 1-4 September 2013 (Oral presentation)
- A. Sultan, H. Godfrin, B. Fak, J. Ollivier, H.-J. Lauter, T. Lichtenegger, E. Krotscheck, C.E. Campbell, Elementary excitations measured in liquid 4He confronted with Many-Body Theory International Conference on Neutron Scattering, 8-12 July 2013 Edinburgh (oral presentation)
- H. Godfrin, A. Sultan, B. Fak, H.-J. Lauter, J. Ollivier, M. Meschke The dynamics of correlated fermion and boson many-body systems unveiled by neutron scattering studies in quantum fluids MICROKELVIN 2013 Workshop, Sannäs, Finland, Sept. 9-13, 2013 (oral presentation

PTB

- Th. Schurig: Characterization of magnetic materials in the micro- and nanoscale utilizing SQUIDs, BITs 2nd Annual World Congress of Advanced Materials WCAM 2013, Suzhou, China, June 6, 2013.
- Th. Schurig: State-of-the-art Superconducting Quantum Interference Devices (SQUIDs) for quantum metrology, talk at the National Metrology Institute of the Peoples Republic of China, Bejing, June 9, 2013.

RHUL

- L.V. Levitin, Quantum Fluids and Superconductivity Meeting, Institute of Physics, London, July 2013
- L.V. Levitin, R.G. Bennett, A.J. Casey, B. Cowan, J. Saunders, J.M. Parpia, D. Drung & Th. Schurig, E. Surovtsev: Topological superfluids confined in a nanoscale slab geometry, APS, March Meeting, Baltimore, 2013
- J. Saunders: Topological superfluids confined in nanoscale slab geometries, Physics and Metrology at very low temperatures, PTB, Berlin, Dec 2012
- Aya Shibahara: Recent advances in fast precision noise thermometry in the mK regime, Physics and metrology at very low temperatures, PTB, Berlin, Dec 2012

SAS

- P. Skyba: Analogues of black holes event horizons in superfluid phases of 3He, 20th Conference of Slovak Physicists, Bratislava, 2.-5. 9. 2013, invited talk http://kf.elf.stuba.sk/~20konferencia/KSF_plenar_13
- P. Skyba et al.: Spin-wave analogue of event horizon in superfluid 3He-B, MICROKELVIN 2013 Workshop, Sannäs, Finland, Sept. 9-13, 2013

Task 4. Industry - research networking

World-wide much of the industry dealing with very low temperature technology is based in Europe. For instance, most commercial refrigerators capable of cooling below 0.1 K are produced in Europe. One of these companies is BlueFors, a Microkelvin partner. Thus a most important function of Microkelvin is the education of students and researchers in cryogenics and low temperature physics, to provide trained manpower for this industry. A steady stream of researchers with Ph.D. degrees educated at our institutes has been maintaining the industry.

More direct involvement with the cryogenic industry represent the different meetings and exhibitions in which the Microkelvin partners have participated. IEP-SAS in Kosice took part in arranging a Creative Factor – a technically and scientifically oriented school in creative form under the auspices of the U.S. Steel company in Kosice, http://www.steelpark.sk/index_en.php. This was as a result of a long-term cooperation of the U.S. Steel company and the Institute of Experimental Physics (of the Slovak Academy of Sciences) in Kosice. Here the institute provided the scientific expertise, planned the exhibitions, and presented them to the public as part of the Creative Factory.

In Finland, the transfer of Microkelvin technologies to industry has been strengthened by the funding agency TEKES in terms of the FinCryo project. Two new types of cryogen-free refrigerators have been developed for industrial collaborations within the FinCryo project: a refrigerator with reduced electromagnetic noise and mechanical vibrations for ultra-sensitive applications (to be operated in LTL) and a refrigerator aimed for magnetic field, optical, THz and X-ray measurements (installed for operation at the State Research Centre VTT). An insert for 'on-the-fly' exchange of samples has been developed for both systems.

An essential part of the FinCryo project is concerned with the development of cryogenic measuring equipment, including micro- and nanoscale devices such as temperature sensors, as well as signal amplifiers operating at cryogenic temperatures. TEKES funding has been instrumental in improving the technology especially in two areas, namely by boosting the development work of ultra low noise dry mK cryostats (eg. Bluefors Ltd. in collaboration with Aalto) and of Coulomb-blockade thermometers with a minimum temperature below 10 mK (eg. Aivon Ltd. in collaboration with VTT and Aalto). Thanks to these contributions within the FinCryo project, the process of turning Microkelvin technologies into viable commercial products has experienced a speed up.

- ***Patent:*** H. Seppä, J. Hassel, P. Hakonen, and P. Lähteenmäki, Low noise amplifier, Patent WO2012FI50244.

Task 5. Dissemination to public audiences - Outreach activities

AALTO

Eleven groups of high school students have been given guided tours through the laboratory. Some of the visiting classes have been from schools far away from the Helsinki region. Many visits have included a lecture on low temperature physics and the laboratory's research interests, a tour to the research facilities, and low temperature demonstrations. The demonstrations have utilized liquid nitrogen and have included, among other things, high-Tc superconductors.

Ten groups of university students from all over Finland have visited the laboratory. They also have been introduced to the research of the laboratory and the facilities, as well as shown low temperature demonstrations.

Two visits by the Millennium Youth Camp in Finland have been organized. Each visit included approximately 50 participants. The Millennium Youth Camp is an international event intended for technologically oriented young people. In 2012 and 2013, their program included a visit to the LTL where they were introduced to the research, facilities, and were shown demonstrations with high-Tc superconductors and liquid nitrogen (on 2012-06-14 and 2013-06-13).

State officials from the Ministry of Education and Culture wanted to have a demonstration of infra-intensive research and visited the Low Temperature Laboratory (on 2013-06-05).

The LTL arranged an Open doors -day for the families of Aalto employees and students. About 30 Aalto students and their family members visited the laboratory, where the visit included demonstrations with high-Tc superconductors and liquid nitrogen (on 2012-10-20).

Approximately 20 members of the Ursa Astronomical Association (amateur astronomy) visited the LTL. Of special interest here were the cosmological connections of superfluids in rotation (on 2012-04-18).

Seminar in honor of the 70th birthday of Matti Krusius included 50 participants. This public event highlighted the achievements of one eminent person in Finnish low temperature physics (on 2012-10-25).

Department of Philosophy, University of Bucharest, 3 July 2013, Bucharest, Romania, Sorin Paraoanu gave a talk "Much ado about nothing - the concept of vacuum in physics and philosophy".

"Let there be light", interview of Sorin Paraoanu by Zeeya Merali, podcast Foundational Questions Institute, March 6, 2013.

Pertti Hakonen gave an invited plenary talk to the researchers of Nokia NRC on the history of the Low Temperature Laboratory and its various European large scale projects, "From Big Bang and human brain to Flagship projects", NOKIA NRC Days 2013, Espoo, Finland. (on 2013-04-10 and 2013-04-11).

Lancaster

Recently (July 2013), we performed interviews and demonstrations on superfluids for the "The One Show", broadcast on prime-time TV in the UK. We also provide demonstrations and tours for more than 1000 visitors per year, work experience for schools, and we give talks at local schools.

Engagement with the public and MPs: Our state-of-the-art laboratory is a focus for school visits to showcase world-class research. Our laboratory hosted visits by MPs H. Dawson, G. Smith, and I. Gibson.

RHUL

J. Saunders: Superfluids and other Quantum Object: Quantum Mechanics of Large Systems, Institute of Physics Teachers Conference, RHUL, March 2013.

March 2013: As part of the Royal Holloway Science Festival Week, Andrew Casey ran a low temperature zone in the physics department where he delivered three lectures and sets of demonstrations hourly .

- Resistance is Futile: The Rise of Superconductors
- Fun with Liquid Nitrogen
- How cold is space

This event was attended by 2500 people of all ages from the local community.

2008-2012: every March low temperature physics demonstrations were delivered by Andrew Casey as part of an annual Royal Holloway Science Open day, with a typical attendance of around 3000 people.

Annual Lecture as part of a Physics Taster Day to around one hundred 16-18 year olds about low temperature physics, given by Andrew Casey during 2008-2013.

Annual Institute of Physics Course "Low Temperature Techniques", November 2011 and 2012, hosted at RHUL, organised by Andrew Casey with lectures by Andrew Casey and Jan Nyeki. November 2008-2010 hosted at University of Nottingham, lecture "Temperature: Measurement and Control" given by Andrew Casey. 40-50 attendees per year, a mix of new PhD students and people from Cryogenics Industry.

March 2011, The Big Bang Fair: UK Young Scientists and Engineers Fair, ExCel centre in London. Andrew Casey and Aya Shibahara ran low temperature physics demonstrations on a RHUL stand in conjugation with the Institute of Physics. The three day event was attended by 125,000 people, mainly school children from 5-18 years old.

Basel

Outreach activities provided by D. Zumbuhl et al.:

- TecDay am Gymnasium Willisau, Luzern, organisiert durch die Schweizerische Akademie der Wissenschaften. Modul: ``Der Quantencomputer - Superrechner der Zukunft?'', February 2013.
- TecLive am Gymnasium Baeumlihof, Basel, organisiert durch die Schweizerische Akademie der Wissenschaften. Modul: ``Der Quantencomputer - Superrechner der Zukunft?'', October 2012.
- Lecture for Nanoscience I students, Uni Basel, ``Nanotechnologie fur den Quantenrechner der Zukunft'', October 2012.
- Tele Basel, evening news *7vor7*, interview ``Kältesensation'', Aug 7, 2012.
- Uni Basel *UniNews*: ``Unerwartete Kühleffekte rücken Quantencomputer näher'', Aug 27, 2012.

- TecDay@GymOberwil, Wissenschaft? Technik? Ja klar!, organisiert durch die Schweizerische Akademie der Wissenschaften. Modul: ``Der Quantencomputer - Superrechner der Zukunft?", May 2012.
- Mustermesse Basel, ``Nanotechnologie für den Quantencomputer der Zukunft", April 2012.
- Basel Science Times, Pod-Cast Interview: ``Low temperature physics and quantum computation", February 2012.

CNRS-Grenoble

- CNRS hosts every year the event "Fete de la science", open to the general public. Visits to laboratories are organized for young people at the secondary studies level. The tour includes general talks, questions and also didactical demonstrations on low temperature physics and techniques, as this topic is well represented in the Grenoble area both in research and industry.

"Fete de la science" in Grenoble.

- A special date was celebrated by CNRS in April 2013: the 50th anniversary of the creation of the Grenoble Campus and the Low Temperature Research Centre ("CRTBT"). This was an excellent opportunity to invite the general public to enjoy general talks about Low Temperatures. The history of the centre was illustrated by Denis Guhtleben, a historian, in a comprehensive dissertation "50 ans du Polygone CNRS de Grenoble- Histoire du CRTBT", and by several conferences, including the talk by H. Godfrin : Fluides quantiques et Tres Basses Températures au CRTBT. The exhibition was attended by two French Ministers (Mme Genevieve Fioraso, Ministre de l'Enseignement supérieur et de la recherche ainsi que Mme Marylise Lebranchu, Ministre de la réforme de l'État, de la decentralization et de la fonction publique).

Physics experiments for kids at the Researcher's Night in Kosice

IEP SAS Kosice

- P. Skyba: Svet pri absolutnej nule, Bratislavska vedecká cukráreň. 19.2.2013. Popular lecture for gymnasium students (around 250 participants). http://www.vedatechnika.sk/SK/VEDAASPOLOCNOST/NCPVAT/Stranky/bratislavska-vedecka-cukraren.aspx.
- Public presentations in the Researcher's night 27.9.2012, Hypernova store, Kosice, Slovakia; various exhibitions, including low temperature physics – from 13:00 to 21:00 with more than 7000 visitors (http://www.sovva.sk/noc-vyskumnikov/2012/program/kosice.html).

Public low-temperature physics demonstrations in Heidelberg

Physics Show by Christian Enss and Angela Halfar

Christian Enss and Angela Halfar perform low-temperature physics demonstrations in Heidelberg

Heidelberg

- A two-hour Physics Show by Christian Enss and Angela Halfar presented on December 16, 2012. Public audience 500 people, show related to Microkelvin.
- Three scientific workshops, two training courses were organized during the reporting period.
- Dissemination of the low temperature "know-how" through the TA activities, as well as many invited and contributed lectures.

Highlights

- Three scientific workshops and two training courses were organized during the reporting period.
- Dissemination of low temperature "know-how" through the TA activities, as well as a slate of invited and contributed lectures.
- Advertisement and dissemination of Microkelvin activities to public audiences during "open days", public lectures, visits and lectures in schools and industrial events.
- Two small-size spin-off companies were established (Lancaster, Leiden).

Reports

- Proceedings of the International Symposium on Quantum Fluids and Solids, Lancaster, United Kingdom, August 2-7, 2010, two issues of Journal of Low Temperature Physics volume **171**, N°3/4 and N°5/6 (2013).
- Proceedings of the International Conference on Low Temperature Detectors LTD14, Heidelberg, Germany, July , 2011, two issues of Journal of Low Temperature Physics volume **167**, N°3/4 and N°5/6 (2012).
- Proceedings of the Microkelvin 2013 Workshop as a special issue of Journal of Low Temperature Physics under the title "Ultra-low temperatures and nanophysics – ULTN2013", to be published in the first half of 2014.

Deviations from work plan – none

Use of resources – follows the work plan

NA4 Report

Name of the activity: **Strengthening European low temperature research**
Reporting Period: **from 1.4.2012 to 30.9.2013**
Activity leader: **Henri Godfrin (CNRS)**

Table of expected deliverables during the grant period

Del. no.	Deliverable name	WP no.	Lead beneficiary	Estimated person months	Nature	Dissemination level	Delivery date
D1	Invitations to leading scientists and young researchers of Third Countries to MICROKELVIN meetings	NA4	CNRS		O	PU	12 **achieved**
D2	Report on European Cryogenic Society and Third Countries Network	NA4	CNRS	1	R	PU	36 **achieved**
D3	Ultralow temperature forecast report	NA4	ULANC	1	R	PU	36 **achieved this report**

Milestones during the grant period

Milestone number	Milestone name	WPs no's	Lead beneficiary	Delivery date	Comments
M1	Meeting for the creation of ECS	NA4	CNRS	10	Web-site news **achieved**
M2	Formal creation of Third-Countries Associated Low Temperature Network	NA4	CNRS	10	Web-site news **achieved**
M3	Statutes of Distributed European Microkelvin Laboratory	NA4	ULANC	48	Report **achieved**

Summary

The goal of this networking activity is to strengthen the European low temperature community, in coordination with other national and international organizations, to fight against fragmentation, to improve European visibility at the international level, and to forecast future trends in low temperature research.

Task 1. "Towards a European Cryogenics Society" (CNRS and all partners)

Microkelvin has taken the key steps to strengthen European research at low temperatures, by re-establishing a Low Temperature Section within the Condensed Matter Division of the European Physical Society. The section was formed during the first 18-month reporting period and has been very active since then. It has convened regularly: in Edinburgh on April 27, 2012, during the Edinburgh EPS-CMD24 Conference 3-7/9/2012 (in liaison with the Superconductivity and Magnetism sections), and during various Microkelvin events since almost all of its members come from the Microkelvin partner institutions. The LT Section reports regularly to the European Physical Society; a summary of its activities is annually presented at the meetings of the Board of the Condensed Matter Division.

Microkelvin and the LT Section have jointly maintained and updated a list of researchers, companies, and institutions working at low temperatures. This information is available on the Microkelvin web site (http://www.microkelvin.eu/) and on the LT section site (http://lts-cmd-eps.grenoble.cnrs.fr/). During the last months of the Microkelvin project, a discussion evolved about strengthening ties with the cryoengineering community, either as an integral part of the LT Section activities or by forming a new section working in liaison with the LT Section. A meeting about this issue was organised in Twente on October 18, with the participation of scientific and industrial partners and the support of Microkelvin.

These are examples of activities which would not have come about without Microkelvin help. The strengthening of the dispersed European low temperature community has been a long-standing challenge which has not been addressed owing to lack of resources and a responsible body. Here Microkelvin has stepped in to create cohesion among the scientific and technical partners, as well as the European cryo-related industry.

Deliverable 2: Report on the European Cryogenic Society **achieved**

The June 2013 report of the LT section is included as Appendix 6 at the end of this review report.

Task 2. Third Countries Network (CNRS and all partners)

Microkelvin has supported connections to Third Countries by

- inviting renowned scientists from non-EU countries to European events, with the objective to disseminate new research in science at the international level,
- inviting young researchers from non-EU countries to training sessions, with the objective to provide them with a better knowledge of EU science at an early stage of their careers and to attract the best students to European universities and laboratories

The main Microkelvin events participating in these actions during this reporting period were:

- **QFS2012: International Symposium on Quantum Fluids and Solids,** 15-21/8/2012 Lancaster University, Lancaster, UK; organised by S.N. Fisher and G.R. Pickett, supported the participation of third countries researchers: India 4, Korea 3, Moldova 2, Morocco 1, Russia 6, Ukraine 7, USA 4.
- **MICROKELVIN 2013 Workshop,** Helsinki 8-13/9/2013, organised by M. Krusius, invited Professor Kimitoshi Kono, head of the RIKEN laboratory in Japan.
- **Cryocourse 2012**, organised in Heidelberg by C. Enss, invited 6 students from Third countries (China, Colombia, Japan, Russia, Ukraine).
- **Cryocourse 2013**, organised in Grenoble by H. Godfrin, invited 6 students from Third countries (Argentina, Colombia, Russia, Ukraine, Tunisia, USA).

Deliverable 2: Report on Third Countries Network **achieved**

This report on the activities of the Third Countries Network constitutes the last deliverable belonging to Task 2.

Task 3. Virtual European ULT Laboratory (AALTO, CNRS, ULANC, and all partners)

Microkelvin collaboration has been exploring possible ways of creating a legal entity, covering a Virtual European ULT Laboratory, established by the leading European low temperature laboratories with interests in developing the µK regime. Official contacts were made with eg. the CNRS authorities to create a "Laboratoire Européen Associé" with Aalto and ULANC as partners, but without success. Finding a single legal framework for a distributed facility with more than two laboratories is still a difficulty – the instruments of creating a large scale facility at the EU level beyond bilateral agreements are presently beyond our reach. In spite of the obvious interest for ultralow temperature facilities to join forces, it looks like this will not be possible without a legal instrument directly established by the EU.

MICROKELVIN has worked in practice as a well-coordinated facility, as demonstrated by its Transnational Access programme and its Joint Research activities, which all having achieved their goals. This has motivated the preparation of a scientific case for Horizon 2020 to incorporate ultralow temperatures as a European infrastructure (see Appendices 1 and 2), and a Memorandum of Understanding of the partners on the statutes of a distributed European Microkelvin Laboratory (see Appendix 3). The latter document concludes the last milestone (M3) of Task 3.

Task 4. Forecast report (ULANC and all partners)

MICROKELVIN lists as its partner institutions most of the European laboratories in the field of ultra-low temperatures. It provides an ideal forum to discuss and prepare a foresight study about future research directions and their requirements on infrastructure. Consequently, we have produced a current snapshot of a forward view of the field and its implications. Several novel research directions are pursued in condensed matter physics which very clearly benefit if they are taken to lower temperatures. In addition, our view of the future promises innovations in sensitive high-resolution measuring instrumentation and in refrigeration, which all will act as drivers pushing the development of new methods and concepts at low temperatures. We hope that the forecast report will be an important help in outlining the future needs on the European low-temperature infrastructure. The "Road Map" has been prepared by ULANC with input from all other MICROKELVIN partner institutions (see Appendix 7 of this Review Report).

Deliverable 3: Ultralow temperatures forecast report **achieved**

Highlights

An international conference (QFS 2012), a European conference (EPS-CMD 2012), a Microkelvin workshop and two European Schools (Advanced Cryogenics Course: Cryocourse 2012 Heidelberg and Cryocourse 2013 Grenoble) have been organized by Microkelvin during this period.

High level scientists and students from Third Countries participated in European scientific events organized by the Third Countries network of the Microkelvin Collaboration.

Gender issues: Female participation in Cryocourse 2013 reached 15 from 34 students, demonstrating the result of a continuous effort to incorporate female students at the level of initial training.

Reports – "2012 Annual Report of the LT section"
– "Road map for ultra-low temperature physics"
are attached as annexes to this Periodic Review Report.

Deviations from work plan – no deviations, our results exceed the original goals

Use of resources – follows the planned programme

JRA1 Report

Name of the activity: **Opening the microkelvin regime to nanoscience**
Reporting Period: **last 18 months from 1.4.2012 to 30.9.2013 + entire grant period**
Activity leader: **George Pickett (ULANC)**

Table of expected milestones during the entire grant period

List and schedule of milestones					
Milestone number	**Milestone name**	**WP no.**	**Lead beneficiary**	**Delivery date**	**Comments**
M1	Advanced filtering and isolation system designed and built	JRA1, Task 1	ULANC	18	**Achieved (Basel)**
M2	High conductivity cooled links to nanocircuits designed and tested	JRA1, Task 1	ULANC	30	**Achieved (Basel)**
M3	Nanocircuit stage installed in an access refrigerator	JRA1, Task 1	ULANC	36	**Achieved (Basel) [1]**
M4	Phonon temperature on nanoscale silicon membrane measured	JRA1, Task 1	ULANC	36	**Achieved (CNRS)$**
M5	Pulsed-tube based dilution refrigerator and conventional (miniature nuclear) stage ready for integration at CNRS (AALTO)	JRA1, Task 2	CNRS (AALTO)	12 (18)	In progress* [2]
M6	The compact microkelvin refrigerator at CNRS (AALTO) ready for access service	JRA1, Task 2	CNRS (AAL-TO)	24 (36)	In progress*
M7	Complete the vibration isolation platform	JRA1, Task 3	ULANC	6	**Achieved (ULANC)**
M8	Dilution refrigerator built, installed and tested	JRA1, Task 3	ULANC	24	**Achieved (ULANC)**
M9	Nuclear stage tested and running in dilution refrigerator	JRA1, Task 3	ULANC	30	**Achieved (Basel, ULANC#)**

$See section on thermometry at the end of JRA4 Task 3.

*The CNRS pulse-tube-precooled dilution refrigerator is providing access to 20 mK. Lower temperatures are not yet offered, but are under preparation. The AALTO refrigerator was transferred to BASEL where the complete system including nuclear cooling is undergoing final testing. The delay was caused by the very late delivery of the superconducting liquid-helium-free magnet system. Meanwhile a third liquid-helium-free refrigeration system with hyperfine-field-enhanced nuclear cooling of $PrNi_5$ was completed in RHUL [2]. A fourth dry refrigerator with a traditional copper nuclear cooling stage was started in AALTO and is currently being tested for its cooling properties.

#The ULANC refrigerator is used for access services down to 3 mK. Lower temperatures will be offered in the coming months.

[1] A.C. Clark, K.K. Schwarzwälder, T. Bandi, D. Maradan, D.M. Zumbühl, Method for cooling nanostructures to microkelvin temperatures, Rev. Sci. Inst., to be published (preprint arXiv: http://arxiv.org/abs/1005.4972).

[2] G. Batey, A. Casey, M. Cuthbert, A. Matthews, J. Saunders, A. Shibahara, A μK cryogen-free experimental plat-form with integrated noise thermometry, to be published (preprint: http://arxiv-web3.library.cornell.edu/abs/1307.7049.

Table of expected deliverables during the entire grant period

List and schedule of deliverables							
Del. no.	**Deliverable name**	**WP no.**	**Lead beneficiary**	**Estimated person months**	**Nature**	**Dissemination level**	**Delivery date**
D1	Prototype of nanocircuit stage for access service at ULANC (Task 1)	JRA1	ULANC	16	P	PU	36 **Achieved in BASEL/ULANC**
D2	Prototype of compact nuclear cooling refrigerator for access service at CNRS (Task 2)	JRA1	CNRS	18	P	PU	24 **Providing access to 20 mK**
D3	Prototype of compact nuclear cooling refrigerator for access service at AALTO (Task 2)	JRA1	AALTO	20	P	PU	36 **Achieved in RHUL/BASEL/ AALTO at 54 mo**
D4	Next-generation microkelvin facility for access service at ULANC (Task 3)	JRA1	ULANC	30	P	PU	36 **Providing access to 3 mK at 54 mo**

Summary of objectives

- To improve the infrastructure at the access-giving facilities at AALTO, CNRS, and ULANC
- To open the microkelvin temperature regime to nanoscience experiments
- To transfer novel microkelvin technology and good practices to new low temperature laboratories

REPORT on the whole grant period 1.4. 2009 to 30.9. 2013

Task 1. New facilitating technology for nanoscience at microkelvin temperatures

The greater part of work in Task 1 has been carried out in Basel. Here the technology was created for the achievement of the later goals and was largely completed in the early part of the Microkelvin project. The primary goal of the Basel activities was to develop nuclear-cooling platforms for the refrigeration of nanocircuitry to μK temperatures, first in a conventional dilution refrigerator with a liquid-helium bath (JRA1, Task 3), and later in a cryogen-free pulse-tube-precooled dilution refrigerator (JRA1, Task 2). To achieve these goals Basel worked closely with Lancaster, Aalto, and BlueFors. In addition several new technologies needed to reach μK temperatures in nanosamples were developed by Basel in JRA1, in JRA2 (filtering and thermalizing), and in JRA4 (Coulomb blockade and/or quantum dot thermometry).

Basel's main contribution was the development of a novel nuclear cooling system in which the leads themselves form the nuclear refrigerant, thus minimising the usual problem of the main heat leak to the sample coming along the electrical leads. In the Basel design the refrigerant not only intercepts the heat leak and the electrical noise coming along the leads but is also in excellent contact to the nanosample when the main cooling channel is also via the leads. This means that each of the electrical leads connected to the nanosample has its own, individual nuclear adiabatic demagnetization stage, which implies of order 10 to 20 nuclear demagnetization stages in total operating in parallel. The Basel group initially demonstrated that these multiple nuclear cooling stages can be cooled to below 1 mK.

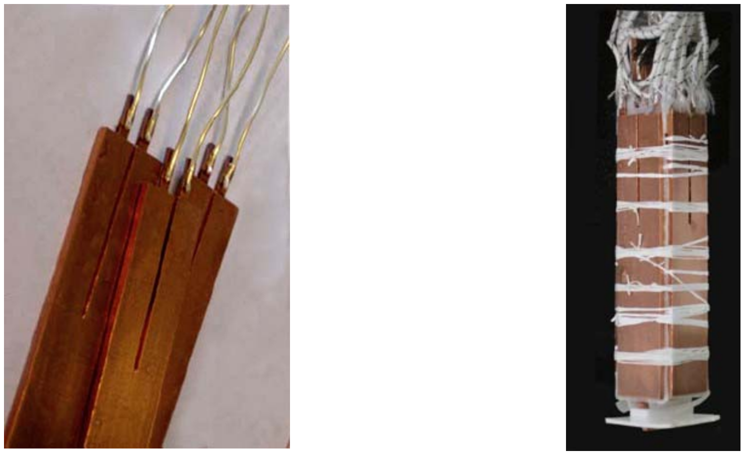


Fig. 1. *The BASEL refrigeration system for incoming leads which reaches 1 mK.* ***Left****; the individual Cu plates for each incoming lead and* **right**; *the full set of leads bundled and thermally isolated around the central sacrificial plate.*

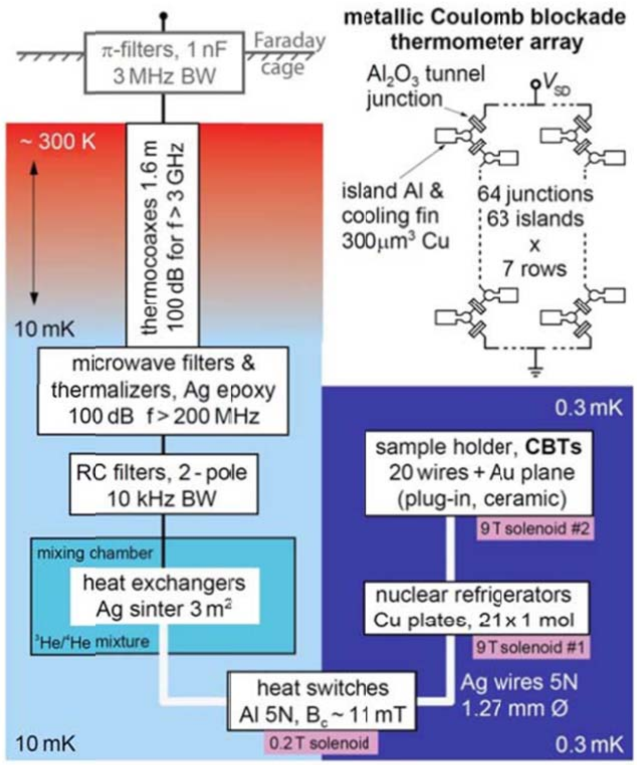


Fig. 2. *Schematic of the Basel nuclear cooling system.The leads to the nanocircuit are individually filtered, thermalized, and actively cooled with an integrated nuclear cooling stage.*

The leads are also comprehensively filtered to exclude electrical interference from room temperature. A schematic view of the nuclear cooling stages and filter configuration is shown in Fig. 2. Several stages of thermalization and filtering are provided on each sample wire. After pi-filters, each lead passes through a home-built Ag-epoxy microwave filter, followed by a discrete RC filter. Each wire then feeds into an Ag-sinter in the mixing chamber (MC), emerging as a massive high conductivity Ag wire. After Al heat-switches with fused joints, each lead traverses a separate Cu nuclear refrigerant (NR) via spot-welded contacts, terminating in an easily exchangeable chip holder plugged into Au-plated pins spot welded to the Ag wires. Therefore, excellent thermal contact of less than 50 μΩ is provided between the bonding pads and the parallel array of Cu mini nuclear cooling plates. This excellent thermal contact is in place while electrical isolation of all wires from each other and from ground is maintained, which is a requisite for nanoelectronic measurements. In testing the performance of this system, the copper refrigerant pieces cool to around 185 μK. This part of the project more than fulfils the requirements of Milestones 1, 2 and 3.

Within Task 1 the ULANC effort is in the context of the development of the new machine of Task 3. In other words how to transfer the Basel experience to ULANC. We have had to learn a complete new way of electrical shielding with such a "wet" machine (i.e. with a liquid He bath). Going through the stages in sequence, the cryostat is contained in a tinned–steel plate shielded room. For unavoidable engineering reasons this shielding is grounded to the steel structure of the building. Therefore there we provide an electrical break in all the external pumping lines as they enter the shielded room. Once inside the shielded room there is a further break in all lines between the room and the cryostat. This is the greatest level of electrical isolation which is possible in this system. The design of the external cryostat filter system has been undertaken by the access partner LMU, München. The circuit connections to the low temperature enclosure have been designed in consultation with LMU using specialist miniature coax. The low-temperature shielded thermometers are designed and installed, along with the shielded input boxes for the refrigerator heater circuits immersed in the still liquid. A further important aspect of the shielded lead system is accessibility of any experimental access user, with transferable connections at helium temperatures based on miniature connectors. Making such a "transferable" system has taken time to investigate, design, instal, and test.

Task 1 has been completed very successfully. This is critical as the knowledge so gained has been a necessary prerequisite for the success of the following JRA1 tasks.

Task 2: Compact microkelvin refrigerator

The aim of this Task is the design, production and general provision of a cryogen-free dilution refrigerator with associated nuclear cooling stage, to open the μK regime to all users, independent of whether they have the necessary infrastructure for producing refrigerants in their home laboratories. This task is a community service in the sense of making this temperature regime available to everybody.

The project boiled down to two stages, first, the design and construction of a cryogen-free (dry) dilution refrigerator and secondly, furnishing this with a high magnetic field system and a nuclear cooling stage. The basic concept of the dilution refrigerator and the nuclear cooling stage are adapted from the conventional cryogen-based (wet) cryostats. The difficulties are threefold: first, in designing the cryostat to minimize the deleterious effect of the inherent vibration from the pulsed coolers being transmitted to the dilution refrigerator; secondly, installing the experimental leads and tubing, since there is no helium bath to precool them, and finally and even harder, installing a high-field superconducting solenoid for demagnetizing the nuclear stage, along with its high-current leads to room temperature and all this in vacuum.

There have been some changes in the way this Task has developed within the Collaboration. Originally it was envisaged that two machines would be built, one in AALTO and one in CNRS. The AALTO dry dilution refrigerator was being developed in Helsinki through the spin-off company BlueFors. Since BASEL were developing the nuclear stages in TASK 1, it was agreed that the AALTO machine, when completed and tested by AALTO/BlueFors with the superconducting solenoid installed, would be transferred to BASEL for the addition of the nuclear stage and final commissioning.

The BASEL and CNRS machines have had difficulties, mostly owing to excessive delays with equipment deliveries. In the interim two other consortium members have also started building dry machines so we now have four machines running or undergoing test runs. We report on each one separately below.

We should underline two highlights. The first dry dilution refrigerator built at AALTO was a great success and enabled the two founders to start their own cryogenics company, BlueFors, which is now producing dry machines, approximately 25 units per year with a turnover approaching €M 10. The ULANC group has also spawned a small specialized company, Lancaster Cryogenics, for producing principally specialized dilution refrigerator components (which has produced among other things the heat exchangers for the CNRS machine, see below).

1) The CNRS Machine

As part of the Microkelvin collaboration, CNRS has been developing a new dry cryostat enabling sub-mK temperatures, devoted to "quick nanophysics" experiments. The idea is to couple a small powerful dilution machine with a small (but powerful) nuclear demagnetization stage. To assist in this project, the sintered heat exchanger stack and an aluminum heat switch have been provided by ULANC. The superconducting solenoid coils, thermal grounds, high current leads as well as the cryostat itself, have been developed in Grenoble.

The cryostat reaches typically 20 mK without the sintered silver heat exchangers. The high-Tc superconducting leads can provide a current of 60 amps to the still heat shield to which a small demagnetization magnet of about 4 T is thermally fixed. The cryostat is fully equipped with electrical lines, thermometers and amplifiers. A PTB SQUID amplifier for nanomechanics experiments is provided within a joint project Grenoble-Berlin-London.

Fig. 3. *The CNRS dry dilution refrigerator with ULANC heat exchangers.*

This refrigerator has been designed and built specifically for nanophysics experiments. It has everything necessary installed, including generous experimental space which allows great latitude for filters and other low temperature equipment. The machine is easy and quick to run, cooling from room temperature to 20 mK in about 24 hours. Opening and closing the cryostat takes about one hour.

Currently this refrigerator is undergoing final testing after earlier difficulties with magnet leads and the sintered heat exchanger stack. It now offers access down to 20 mK and accessibility to sub-millikelvin temperatures is expected soon, after the installation and testing of the sintered heat exchangers and the nuclear stage have been completed.

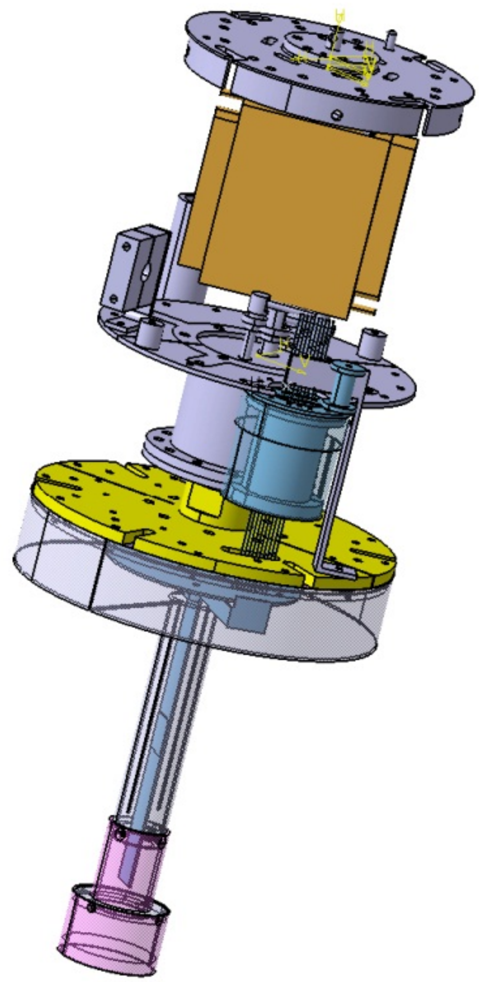
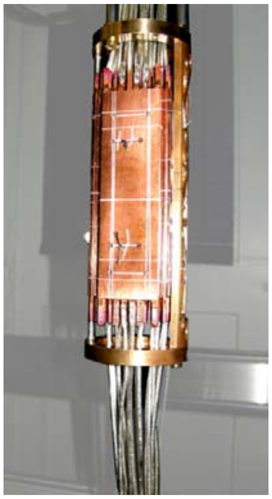


Fig.4. *The configuration of the CNRS dilution refrigerator and nuclear cooling stage.*

2) The BlueFors/BASEL Machine

The Bluefors/BASEL machine has been held up by the slow provision of the dry high field and very complex superconducting solenoid system. As pointed out in the last report, the dilution refrigerator for this cryostat was completed long ago and tested at the Bluefors plant by the BASEL group with a faultless performance, a base temperature of 7 mK, and the appropriate cooling power.

Further progress was delayed owing to the late delivery of the double magnet system ordered from Scientific Magnetics. The company had seriously underestimated the challenge of providing this very complex unit of two large-bore 9 Tesla magnets with compensation coils. Final delivery was two years late. During that wait the group continued the development of the nuclear stage and the associated electronics. When the magnet system was finally delivered, rapid progress has been made. The refrigeration system is currently being tested with the nuclear stage installed and is expected to reach nuclear cooling temperatures imminently.



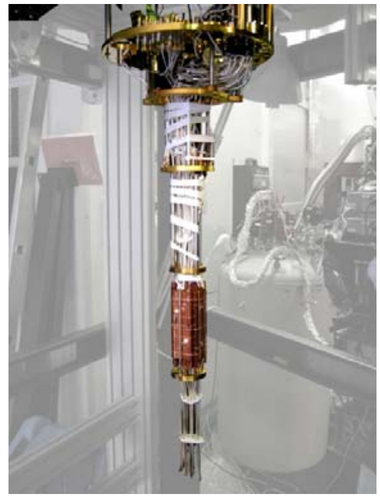
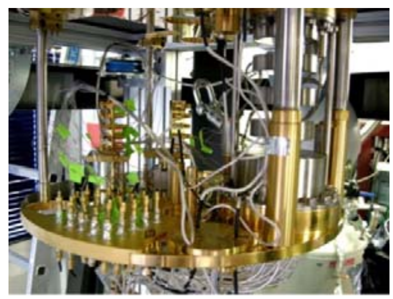


Fig.5. *The BASEL nuclear cooling stage* ***(left)*** *and in situ below the dilution refrigerator* ***(right)***.



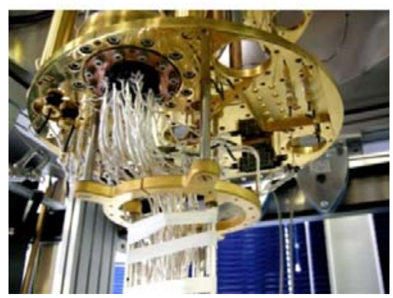


Fig. 6. *The large-diameter experimental space of the BASEL refrigerator is characteristic of "dry" cryostats in general:mixing chamber flange seen from the top* ***(upper figure)*** *and from below* ***(lower figure****) with the insulated silver conductors to the individual copper nuclear cooling plates, as seen in Fig. 5 on the right.*

While the above two machines have been under development, two other members of the consortium have also produced dry dilution refrigerator systems with nuclear stages attached.

3) The RHUL Machine

The RHUL group opted to develop a dry dilution refrigerator system coupled with a hyperfine-field-enhanced nuclear demagnetization stage. This approach has a large cooling capacity, large specific heat in the demagnetized state at low or zero magnetic field, requires less demanding conditions for precooling and is thus more forgiving with respect to possible shortcomings of the pulse-tube-cooled precooling system, for instance with respect to heat leaks from vibrations. By now the concept has performed extremely well with temperatures reaching 0.6 mK, as recorded with a noise thermometer as sensor.

The dilution refrigerator unit is an Oxford Instruments Triton 200 with a cooling power in excess of 200 μW at 100 mK, and a base temperature below 10 mK. The nuclear stage consists of 128 g of the inter-metallic compound $PrNi_5$ in the form of nine 6 mm diameter × 50 mm long rods, pre-tinned with 99.99 % cadmium. Each rod is connected to the upper and lower experimental plates with 1 mm diameter copper wire with a residual resistance ratio 1000. One wire per rod connects to the upper plate to the precooling contact and eight wires per rod to the lower sample plate. This cooling stage was adapted from a former pre-existing stage which had been used at Cornell University in a "wet" setup. The upper thermal contact plate was connected to the mixing chamber through a superconducting aluminium heat switch (provided by ULANC). The switch had six 1 mm diameter silver wires bonded to either end, which in turn were diffusion bonded to copper blocks with mechanical connections to the upper experimental plate and the mixing chamber. This link was particularly long, 30 cm, to mitigate the effects of the non-optimal stray field. Nertheless, it was possible to precool the stage to below 20 mK in a 6.2 T field within 24 hours.

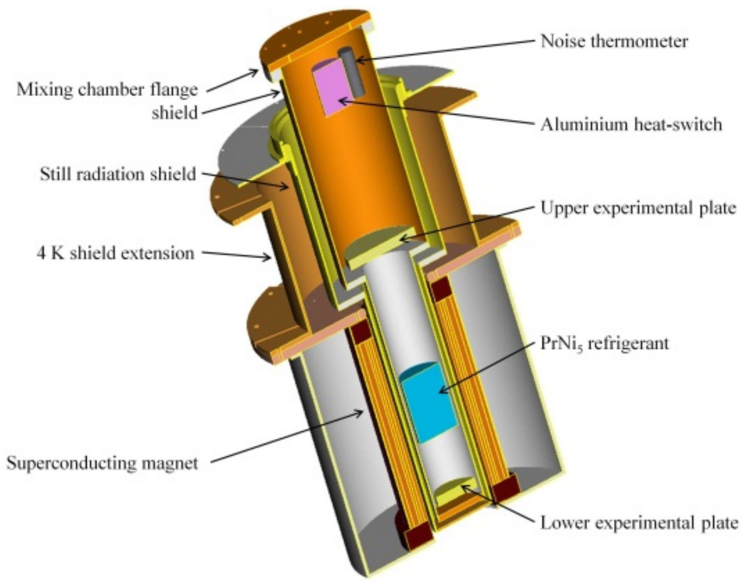


Fig. 7. *A cross-section view of the layout of the RHUL demagnetisation stage below the mixing chamber.*

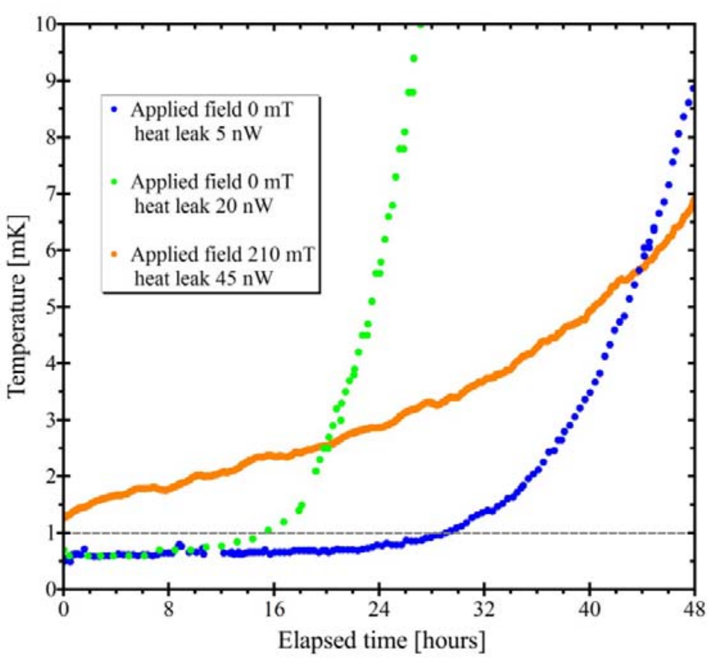


Fig. 8. *Warm-up curves of the nuclear cooling stage after demagnetization to different final fields.*

Thermometry was provided by a current-sensing noise thermometer. A minimum temperature of 600 μK was achieved at the lower experimental platform when the demagnetization was continued to zero final field [3]. In this situation the external heat leak of 5 nW heated the nuclear stage to 1 mK in 16 hours, as seen in Fig. 8. A heat leak of this magnitude is quite comparable to traditional nuclear cooling cryostats and shows that mechanical vibrations from the pulse tube cooler can be avoided to such extent that they are not detrimental. The performance of the noise thermometer is shown below over a temperature range covering four orders of magnitude.

These results demonstrate amply that the pulse-tube-precooled dilution refrigerator is an adequate platform for nuclear cooling. In view of all other technical and practical advantages resulting from the absence of a liquid helium bath, it is now evident that this type of cryostat design will be the way of future. Straightforward improvements to the design of the RHUL prototype are planned and are expected to lead to further enhancements in the performance. Next this cryostat will be used for studies of strongly correlated electron states in nanodevices with applications in quantum computing. This work evolved in collaboration with Oxford Insturments Nanosciecnce who supplied the 8T dry magnet and modified heat shields and vacuum cans to accommodate the additional length. The Company recognizes the importance of a cryogen-free sub-mK platform and will be providing custom built magnet systems and matching funds with RHUL to support a PhD student in further developing this technology.

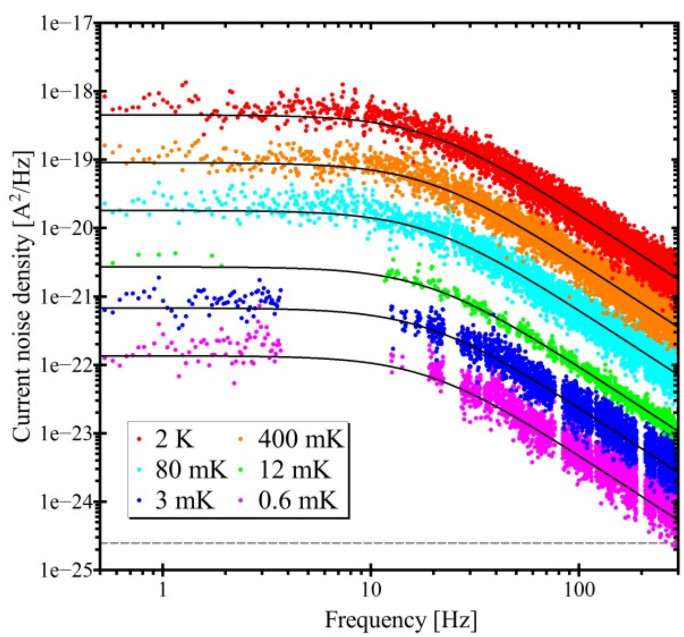


Fig. 9. *Current noise spectra from the 0.24 mΩ noise thermometer at different temperatures from 2 K down to 0.6 mK.*

4) The AALTO Machine

The Aalto dry demagnetization cryostat is based on the Bluefors pulse-tube-cooler-precooled dilution refrigerator with a 7mK base temperature and a 400 μW cooling power at 100 mK. It is equipped with a compensated 9 T dry superconducting magnet for demagnetization cooling. The 5 kg copper nuclear stage is of "Helsinki design" which means that it has a flange on top (outside of the main magnet windings) and a cylinder (inside the magnet bore) made from a single copper bar. The bar was sliced in the milling machine to 1 mm thick plates, to reduce heating from eddy currents in changing magnetic fields. Aterwards it was annealed in 0.5 μbar oxygen pressure close below its melting temperature, to remove hydrogen and to oxydize magnetic impurities in the copper.

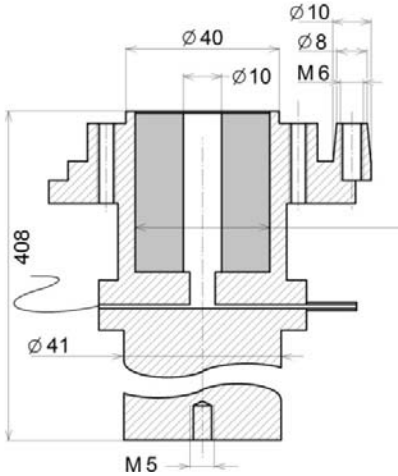


Fig.9. *Top and bottom of the Aalto nuclear cooling stage with a cylindrical open experimental liquid 3He volume within a heat exchange sinter in the centre of the copper bar.*

Fig. 10. *Slitted and heat-treated nuclear cooling stage (turned upside down) before mounting in the cryostat.*

Two different types of thermometry are used in the test measurements. Initially the main thermometer is an oscillating fork immersed in the liquid ^{3}He sample inside the experimental volume on the nuclear stage. In the normal state (above 1 mK) the damping of the fork increases on cooling and scales with the viscosity of helium as $1/T^2$. Below the superfluid transition the damping rapidly decreases, and in the ballistic regime, where the central frequency of the resonance is constant, it scales with the BCS exponent $e^{-\Delta/T}$. The intrinsic damping of the fork at low temperatures is 50 mHz, meaning that the Q-factor is about 1 000 000, which allows the fork to be sensitive to quasiparticles down to ~ 0.15 mK. Later a noise thermometer, provided by Joern Beyer from PTB-Berlin, will be installed as a second thermometer.

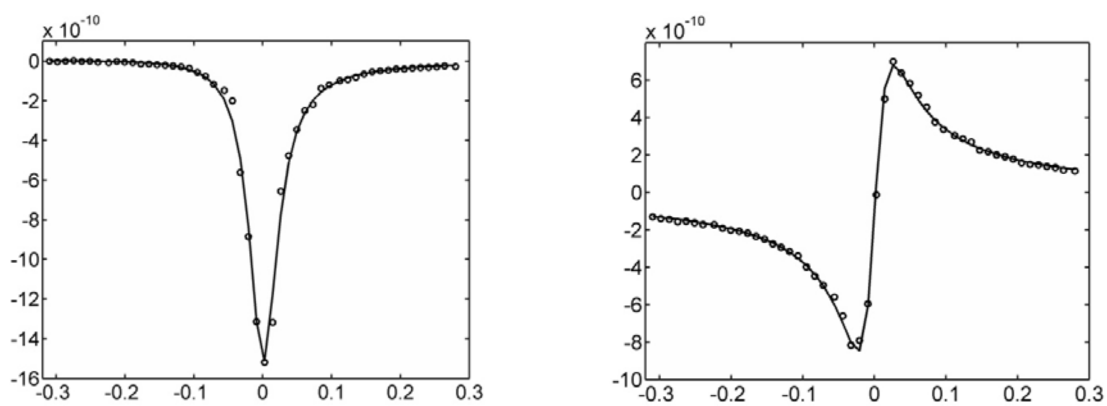


Fig. 11. *Resonance absorption* ***(left)*** *and dispersion* ***(right)*** *of the vibrating fork in vacuum at a temperature of 0.1 K.*

An important part of the nuclear demagnetization system is the heat switch, which conducts heat from the nuclear stage to the mixing chamber during precooling in a magnetic field in the normal state, but becomes a very poor heat conductor during the adiabatic demagnetization of the nuclear stage in zero magnetic field in the superconducting state. Here the heat switch consists of 7 aluminium strips diffusion-welded to two massive copper pieces. There is a superconducting solenoid attached to the upper copper part of the switch to turn the aluminium strips to the normal (conducting) state during precooling. In order to maintain the aluminium in the superconducting state while in the fringe field of the demagnetization magnet, there is a cylindrical niobium shield around its drive solenoid.

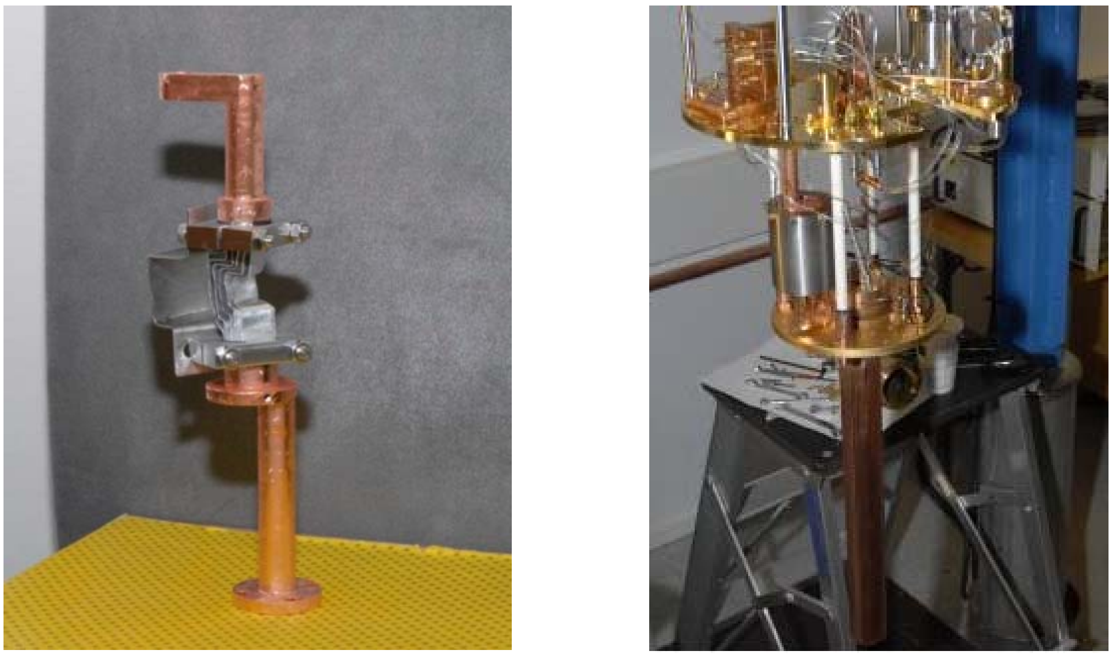


Fig. 12. *Aluminum heat switch and the copper conductors to which it is diffusion welded* ***(left)****; heat switch mounted on the nuclear stage and assembled inside the Nb-shielded superconducting solenoid* ***(right)****.*

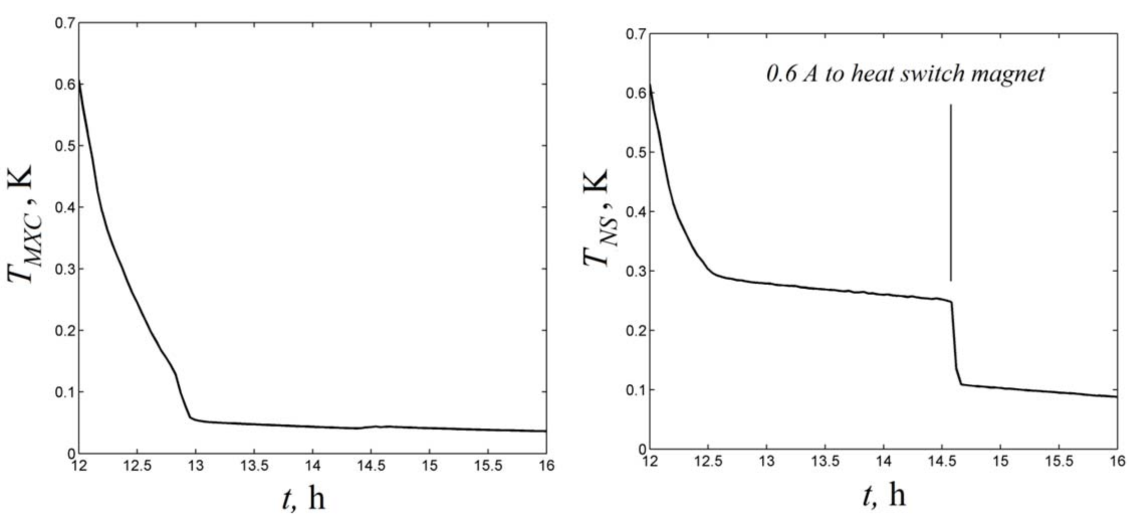


Fig. 13. *Heat switch performance during cool-down of the precooler: temperature of the calibrated mixing chamber resistance thermometer* ***(left)*** *and of the calibrated noise thermometer on the nuclear stage* ***(right)****, plotted on a common time axis (in hours). At ~14.6 h the heat switch is closed which causes the nuclear stage to cool rapidly.*

As seen in Fig. 13 on the left, the mixing chamber cools down rapidly when the heat switch is superconducting. Below 0.2 K the cool down rate increases as the switch becomes less and less conductive. On the right we see that at this point the temperature of the nuclear stage settles to an almost horizontal line. When the solenoid of the heat switch is charged with a current of 0.6 A, the switch becomes normal and conducting. Now the nuclear stage cools rapidly (right) while the mixing chamber shows a small bump in its temperature vs time plot (left).

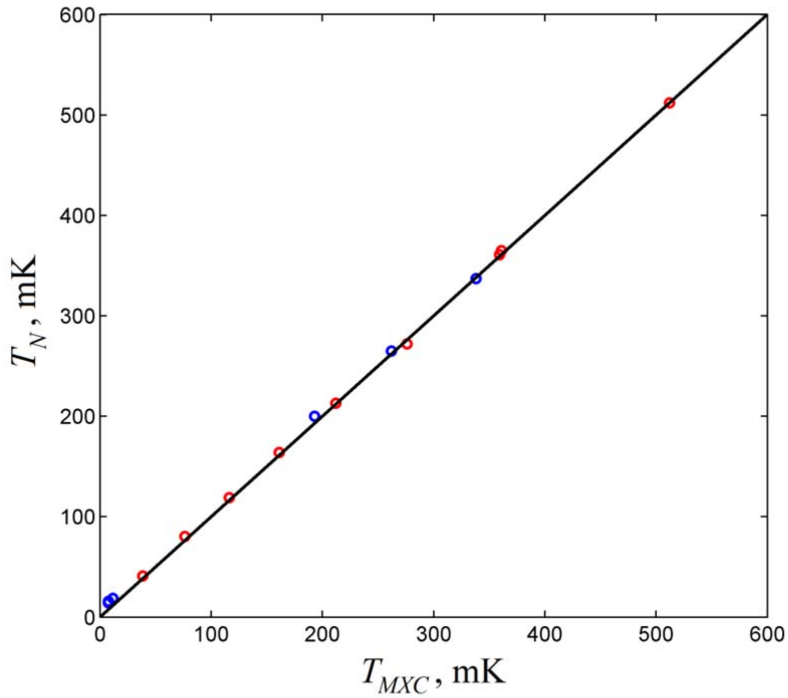


Fig. 14. *Noise temperature of the nuclear stage as a function of the mixing chamber temperature. Red data points have been measured during (stepwise) increasing temperature and blue during decreasing temperature. At the lowest temperatures in the graph, a temperature difference builds up across the heat switch, ΔT ~ 1/T, caused by the vibrational heat leak to the nuclear stage.*

For the first cool-down measurements the nuclear stage was equipped with a noise thermometer from PTB-Berlin. Its calibration was fixed at 512 mK and its reading was scaled as the square of the noise voltage. The calibration result is shown in Fig. 14. The heat leak in 8T field was estimated from the additional load to the mixing chamber and was found to be about 1 μW. Owing to this large heat leak the starting temperature for demagnetization was only about 40 mK. The temperature jump across the heat switch at 40 mK suggests that the thermal resistance of the switch is about $3 \cdot 10^4$ K/W. This value is somewhat high and is probably due to poor mechanical contact between the switch and the mixing chamber plate which relies on four M4 mm copper screws.

During demagnetization the nuclear stage cooled to 1.2 mK, as seen in Fig. 15. The heat leak in the final field of 100 mT was measured to be 37 nW, while at 25 mT it was 4 nW, and in zero field 2 nW. This proves that the vibrational heat leak is a serious impediment in pulse-tube-precooled nuclear cooling. Its reduction to more acceptable levels requires additional isolation from vibrations, their damping, and elimination of relative motion than present in a typical nuclear cooling setup and in the standard version of a BlueFors dilution refrigerator. Further improvement of this nuclear cooling approach is thus expected only after i) reducing the heat leak in high field due to vibrations produced by the pulse tube cooler and ii) after improving the mechanical connection of the heat switch to the mixing chamber plate and to the nuclear stage. These shortcomings now prevent achieving sufficiently low precooling temperatures for the demagnetization process.

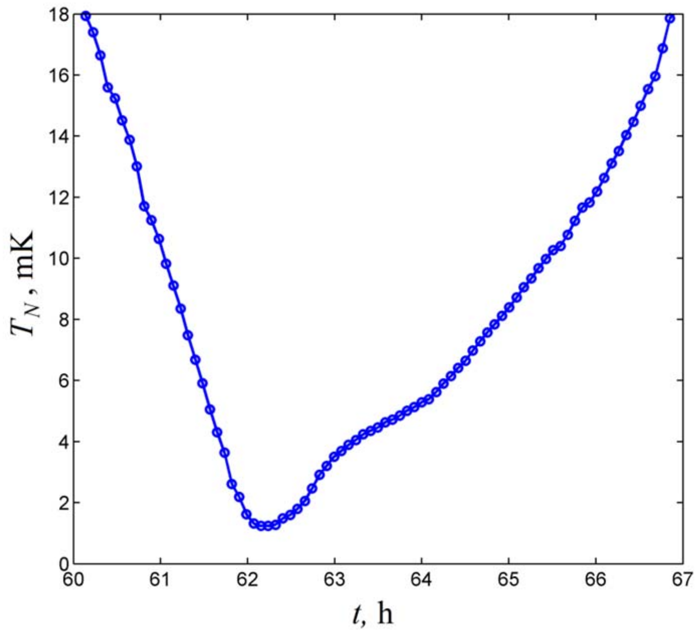


Fig. 15. *Noise temperature during demagnetization from 8 T to 25 mT, starting from a precooling temperature of 40 mK. Zero time corresponds to the beginning of precooling in high field.*

Milestones M5 and M6, which concern Task 2, are late, but further progress is imminent. By the end of the current year the Collaboration will have four liquid-helium-free nuclear cooling installations running which all have been constructed for access-type of community work. This type of refrigerator design can be predicted to replace all other more conventional approaches in the next coming years, with the exception of a few special situations where a pulse-tube-precooler is not applicable, *eg.* because of high demands on a vibration-free low-heat-leak measuring platform, as is the case in Task 3.

Task 3: The next generation microkelvin facility

The aim of this task is the construction of an entirely new advanced μK refrigerator facility intended exclusively for condensed-matter and nanoscale experiments at mK and μK temperatures sited at ULANC. By pooling our combined knowledge resources, primarily developed in Task 1, the plan is to make this the most advanced sub-μK facility for nanokelvin studies. The project progressed by first 1) building a 50 tonne vibration-isolation platform along with the external gas-handling system and infrastructure as the site for the facility. Next 2) the advanced dilution refrigerator was completed and 3) in parallel the nuclear cooling stage was prepared. Finally 4) the Microkelvin grant plan called for this system to be ready for access use before the grant period had run out.

The vibration-isolation infrastructure, including a building extension, a 5 m × 5m × 5m concrete foundation (with dewar pit) and the 50-tonne levitated cryostat block was finished on time to accomplish Milestone M7. We then had a hiatus because the dewar delivery was delayed by a year by the slow progress of the manufacturer. Since the dewars from this source have been excellent in the past, we were not keen to turn to another supplier midstream. That meant, however, that milestones M8 and M9 were delayed. Since then we have made up for this lost time. When the dewar arrived, we made an initial test of the machine by running the dilution refrigerator with just the concentric tube heat exchanger in place. This is a necessary bench-mark test: this configuration achieved a temperature of 13.1 mK which is the best performance we are aware of for a dilution refrigerator running with a tubular heat exchanger alone. A good performance at this stage is a prerequisite for the successful operation of the rest of the machine.

The sintered heat exchanger stack, which provides the low-temperature cooling performance of the dilution refrigerator, consists of 15 individual heat exchangers arranged in two columns with a vertical exchanger joining the two (Fig. 10 left). The final column of 6 exchangers is arranged in a parallel configuration (Fig. 10 right). The final tubes into the mixing chamber have large diameter, designed to yield a final temperature of ~ 1.6 mK: the dilute tube is 16 mm and the concentrated tubes are 8 mm in diameter. This is a bold step to take at a time when the price of 3He gas is in steep incline. The 20 cm of concentrated tubing to connect these exchangers to the mixing chamber have a volume of 10 cm^3 and require 10 litres of 3He. At current price level that has a value of roughly €10,000, just for the final connecting tubes. This level of investment in the working fluid of the refrigerator is going to militate against the construction of similar machines in the future. In the present design, the whole refrigerator of still, heat exchangers, and mixing chamber requires about 105 litres of ^3He, which approximates at current prices to a total investment of 0.2 M€. If we had not already had the gas in stock, we would not have been able to afford to buy it in.

Currently the new dilution refrigerator achieves 2.8 mK. With further optimisation of the ^3He charge - we do not want to use more than necessary - we expect to reach the design temperature. The machine is thus eminently useable with its present performance and satisfies Milestone M8, albeit somewhat delayed owing to supplier problems. Milestone M9, the refrigerator running with a working nuclear stage, has been by-passed to save time for access use at low-mK temperatures. The nuclear stage, making use of the experience gained in BASEL within Task 1, will be added when the experiment described below has proceeded to a stage where lower temperatures are required.

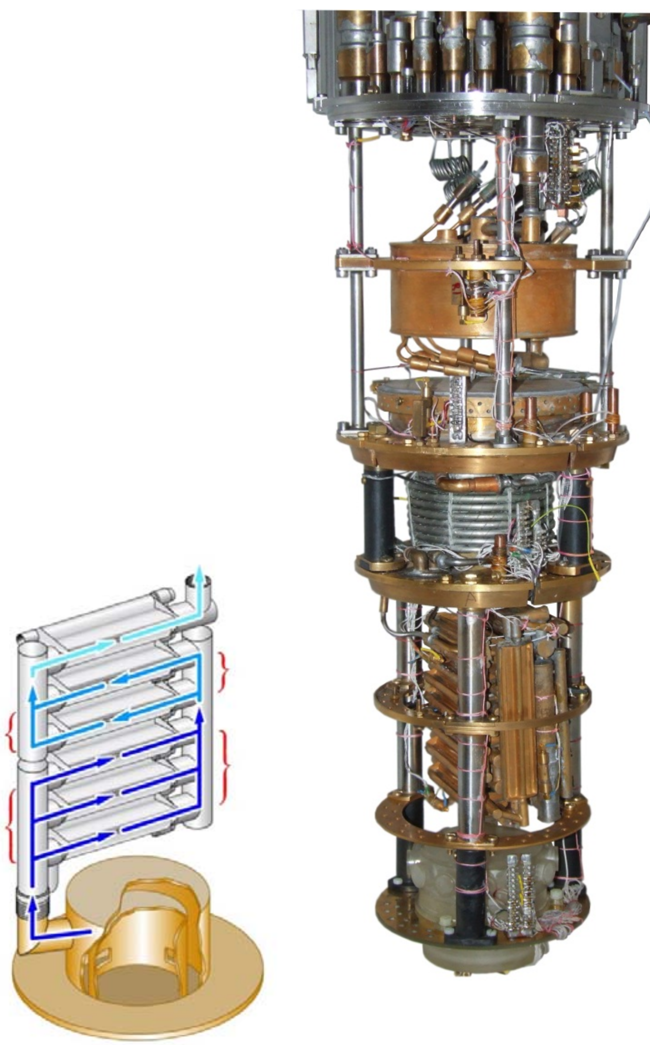


Fig. 16. *The Next-Generation Microkelvin Facility dilution refrigerator* ***(right)*** *and the path of the parallel heat exchanger flow in one heat exchanger stack* ***(left)****.*

Access experiments on the next generation facility

GaAs-based gated quantum dot devices: Ultra-low-temperature properties and thermometry in mesoscopic structures

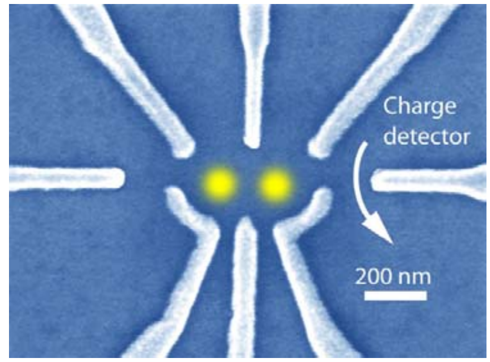


Fig. 17. *The double quantum dot configuration developed by the Ludwig group from Ludwig Maximilian's University.*

The dilution refrigerator in the new ULANC facility is used by the Stefan Ludwig group from the Ludwig Maximilians University in Munich to provide the lowest possible electron temperatures for GaAs-based gated quantum dot devices. The primary scientific and technological objective of this collaborative project is to investigate nanoelectronic circuits in a hitherto unrivalled range of low temperatures. This will allow us to reach lower energy scales and to go well beyond the present state-of-the-art to investigate collective and phase sensitive quantum phenomena. One of our main efforts will be to study coherent dynamics and entanglement in semiconductor-based quantum information circuits at ultralow temperatures. The possible effects to study include: mesoscopic interferometry; quantum Hall phases; the Kondo effect in coupled quantum dots; the 0.7 anomaly in quantum point contacts; and the hyperfine interaction between confined electrons and nuclear spins. In the current Munich experiment, we are looking at qubits localised on a laterally-defined double quantum dot in a two-dimensional electron system embedded in a GaAs/AlGaAs heterostructure. For qubit applications, spin qubits would benefit if we could reach a regime where nuclear spins become magnetically ordered, thus greatly increasing the qubit coherence times, when the disruptive effect of nuclear spin flips is removed.

"Zero Noise" Input Leads: Perhaps the most serious obstacle to cooling electronic devices is the effect of heat generated by the noise transmitted through electrical leads. To address this problem, sophisticated wiring/filter protocols and designs developed by Stefan Ludwig's group are being implemented. The München group has developed high quality low temperature measurement instruments and techniques for nanostructured devices which they produce in-house. By combining the new techniques and the equipment from our two laboratories, we are now performing the first ultralow temperature measurements on devices that have been fabricated and initially characterized in Munich. The first device is a mesoscopic sample that probes quantum Hall and double quantum dot nanostructures (Fig. 11). This will give us at least two ways of measuring (and then comparing) the electron temperature for the same 2DEG electron bath.

A second current User of the new facility is Oxford Instruments for whom we are testing low noise lead harnesses (manufactured by Oxford) to ascertain what level of noise is passed down the leads to μK temperatures.

Conclusions

The JRA1 activity can be seen as the fundamental core of the MICROKELVIN project: to develop techniques and platforms for making the μK temperature range accessible to nanoscience. One should point out that the activities proposed here at the outset of the grant are somewhat different from usual infrastructure programmes. This is not a project which provides European researchers in a particular area access to high-level expensive "centres-of-excellence" experimentation. It is rather one where the high-level facilities do not exist, and it is the job of

MICROKELVIN, and especially of JRA1, to ensure that the capability to provide μK access for nanoscience is developed and provided as an integral part of the project.

In that sense, JRA1 represents a development stage, not a mature operation. Thus the report above does not list a large number of publications but rather points to lots of new μK instrumentation which would not otherwise have become available. It is salutary to note the actual numbers. We are reporting on the building and running of five new advanced cryostats, among the best in the world, developed by this programme. It is also worth reporting that the level of cooperation shown in achieving this between the various contributing groups has been outstanding. The BASEL dilution refrigerator has been developed by BlueFors using expertise from AALTO. The BASEL nuclear cooling stage has been developed with help and advice from ULANC. The nuclear stage of the ULANC new microkelvin facility builds on this experience from BASEL. The CNRS machine has a heat exchanger stack manufactured by Lancaster Cryogenics with ULANC experience. The RHUL machine also uses a Lancaster Cryogenics (ULANC) heat switch. These are just a few examples of this cross fertilization and the culmination in achievements which would not have materialized without the collaboration and resources provided by MICROKELVIN. It is reflected across all aspects of the MICROKELVIN collaboration. For us this represents a new way of working, since we have been educated to working in our own individual laboratories. Nevertheless, all consortium members, who have contributed to the JRA1 programme, now feel that they have benefited from the new collaborative aspects facilitated by this project.

The future

The MICROKELVIN programme introduced new concepts for refrigeration, with the particular goal of extending nanophysics into the low-mK and sub-mK ranges. Although lower temperatures have been achieved and clear gains from working at lower temperatures have been demonstrated, μK temperatures are not yet available in nanophysics. To achieve this, our effort has to be continued.

The JRA1 programme has left us with five new machines which have, or are close to having, microkelvin capability for the study of nanoscience and nano-device physics. The new cooling concepts with automated remotely handled operation and measurement have proven their advantages in practice. Access recipients are already working on these machines and this activity will continue after the formal MICRO-KELVIN umbrella comes to an end. To make full use of this advanced and world-leading infrastructure we need to look ahead and invest in the future. Only this way will we capitalise on our efforts over the past four and a half grant years.

Highlights

- The success of the BASEL filtering, thermal anchoring and multiple-nuclear-cooling approach for the refrigeration of nanocircuits (Task 1). While sub-millikelvin conduction electron temperatures have not yet been demonstrated, the working range has been dropping far below 20 mK during the MICROKELVIN grant period.
- We note the exceptional trajectory of the BlueFors company. The company's prototype machine was built while the MICROKELVIN grant application was prepared. Now this startup has developed into a 10 MEuro per annum company, selling dry machines all over the world and massively fulfilling MICROKELVIN's 6th Objective: "To disseminate the expertise of the core institutes to the wider community by the development of compact, user-friendly, refrigerators for microkelvin research in low-infrastructure environments".

- Boosted by the demand for expertize and new technical solutions in the mK and μK temperature ranges, a new spin-off company Lancaster Cryogenics was started during the MICROKELVIN grant period.
- The concept of nuclear cooling in a dry liquid-helium-free setup, as originally predicted by MICROKELVIN, has been demonstrated a practical working solution and is expected to conquer the market during the next years (Task 2).
- The Lancaster large-scale cooling facility for condensed-matter experiments offers currently a dilution-refrigerator-cooled platform at 2.8 mK which is expected to drop in the μK range when the nuclear refrigeration stage is added (Task 3).

Reports:

[1] L. Casparis, M. Meschke, D. Maradan, A.C. Clark, C. Scheller, K.K. Schwarzwälder, J.P. Pekola, and D.M. Zumbühl, *Metallic Coulomb Blockade Thermometry down to 10 mK and below*, Rev. Sci. Instr. **83**, 083903 (2012).

[2] A.C. Clark, K.K. Schwarzwälder, T. Bandi, D. Maradan, D.M. Zumbühl, *Method for cooling nanostructures to microkelvin temperatures,* Rev. Sci. Inst. **81**, 103904 (2010).

[3] G. Batey, A. Casey, M.N. Cuthbert, A.J. Matthews, J. Saunders, A. Shibahara, *A microkelvin cryogen-free experimental platform with integrated noise thermometry,* preprint arXiv: 1307.7049 (2013).

Deviations from work plan

- The JRA1 work plan has proven essential for the development of refrigeration and thermometry in the low-mK and sub-mK temperature ranges. This work will continue after the Microkelvin grant period.
- All milestones and deliverables of JRA1 have been actively pursued. In some cases the deadlines have been late, owing to different practical difficulties, but they have now been achieved or will be achieved in the nearest future, since this progress is of utmost importance.

Use of resources during the third 18-month reporting period 1.4.2012 – 30.9.2013 has progressed as planned.

JRA2 Report

Name of activity: **Ultralow temperature nanorefrigerator**
Reporting Period: **last reporting period from 1.4.2012 to 30.9.2013 + final report**
Activity leader: **Jukka Pekola (AALTO)**

Summary of objectives

- Thermalizing and filtering electrons in nanodevices
- To develop an electronic nano-refrigerator for sub-10 mK electronic temperatures
- To develop an electronic microrefrigerator for cooling galvanically isolated nanosamples

Summary of results

The work in JRA2 followed the work plan closely. The objectives and achievements have been mainly technological in nature. Sub-10 mK electronic temperatures in a tunnel junction device was one of the central goals. This has been achieved and demonstrated with detailed measurements. A second major goal was to develop a platform capable of cooling various nanocomponents from 300 mK down to 50 mK and below. Significant progress in this mission was made and many central limitations were investigated and overcome. To fully achieve the goal of 50 mK temperatures, more work remains to be done in future efforts.

Table of deliverables during the grant period

Del. no.	Deliverable name	WP no.	Lead beneficiary	Estimated person months	Nature	Dissemination level	Delivery date
D1	Analysis of the combined ex-chip and on-chip filter performance (Task1)	JRA2	AALTO	6	R	PU	18 **achieved**
D2	Demonstration of sub-10 mK electronic bath temperature of a nano-electronic tunnel junction device achieved by the developed filtering strategy (Task 1)	JRA2	CNRS	24	R	PU	30 **achieved**
D3	Analysis of sub-10 mK nano-cooling techniques including (i) traditional N-I-S cooler with low T_c, (ii) quantum dot cooler (Task 2)	JRA2	AALTO	6	R	PU	24 **achieved**
D4	Demonstration of sub-10 mK nano-cooling with a N-I-S junction (Task 2)	JRA2	CNRS	24	R	PU	48 **achieved**
D5	Demonstration of cooling of a dielectric platform from 300 mK to about 50 mK (Task 3)	JRA2	AALTO	26	R	PU	36 **Partly achieved**
D6	Demonstration of cooling-based improved sensitivity of a quantum detector (Task 3)	JRA2	RHUL	9	R	PU	48 **achieved**

Table of milestones during the grant period

Milestone number	Milestone name	WP no.	Lead beneficiary	Delivery date	Comments
M1	Choice of the thermalization strategy	JRA2, Task 1	BASEL	12	Tests completed*
M2	Choice of the ex-chip filtering technique	JRA2, Task 1	BASEL	18	Tests completed*
M3	Choice of the superconducting material with a lower T_C	JRA2, Task 2	CNRS	24	Tests completed*
M4	Precise definition of the QD cooler geometry and materials	JRA2, Task 2	SNS	24	Tests completed*
M5	Design of membrane patterning and microcoolers	JRA2, Task 3	AALTO	18	Report*
M6	Delivery of the first membranes to the end users	JRA2, Task 3	AALTO	36	Prototype running flawlessly*

*Milestone was achieved and alrady reported in earlier Periodic Review Reports

Task 1. Thermalizing electrons in nanorefrigerators (AALTO, CNRS, BASEL)

Nongalvanic quantum dot thermometry: theoretical analysis

The realization of a nongalvanic quantum dot (QD) thermometer for 2 dimensional electron gases (2DEGs) with negligible thermal load has been proposed theoretically. This device consists of a QD coupled to the 2DEG reservoir of our interest. Discrete electronic energy levels on the QD allow for the inspection of the energy distribution function in the electron domain providing a precise characterization of its electronic temperature. Yet, the trick is to accomplish such inspection by means of an additional quantum point contact (QPC) capacitively coupled to the QD (see scheme in Fig. 1a). As shown in Fig. 2b, for a given QD working point the QPC current strongly depends on the electronic temperature. Our calculations reveal that the nongalvanic thermometer configuration enables to assess the electronic temperature of a 2DEG domain down to the microkelvin range minimizing the amount of thermal energy delivered. Interestingly, this thermometer is absolute in the sense that its operation does not depend on a calibration by means of other thermometers. As we have shown, temperature and gate voltage are related by a simple combination of fundamental constants and the lever arm of the dot, which can be determined experimentally from a measurement of the QD charging energy and the cross-capacitance between the gate and the QD.

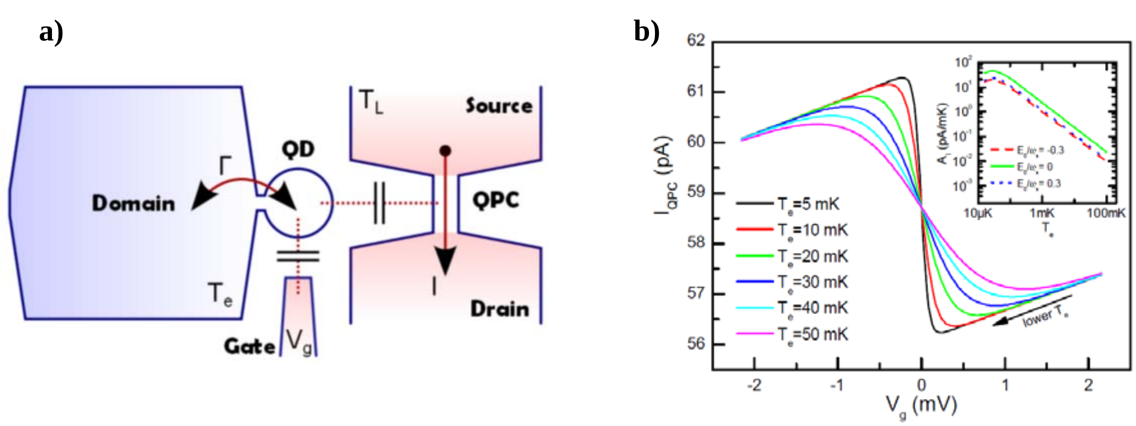


Fig. 1: *a) Scheme of the non-galvanic thermometer. The read out is performed in a nongalvanic fashion thanks to a QPC placed nearby. b) QPC current versus gate voltage for different values of the domain temperature. Inset: current gain versus temperature for three different QPC working points.*

Nongalvanic quantum dot thermometry: experimental realization

The abovementioned nongalvanic QD thermometer has been successfully realized experimentally. The device (Fig. 2) was fabricated from a GaAs/AlGaAs heterostructure hosting a 100-nm-deep 2DEG of 1.87×10^{11} cm^{-2} density and 1.26×10^{6} cm/Vs mobility. A mesa structure was first defined by optical lithography and wet-etching in a H3PO4 – H2O2 solution. The 2DEG was then contacted by means of annealed Au/Ge/Ni ohmic contacts. Finally, surface split gates were patterned by e-beam lithography and Al deposition.

We have demonstrated experimentally the performance of the nongalvanic QD thermometer and compared it to the simple galvanic QD thermometer configuration. Our data reveal how the former fulfills by far the virtues of the latter even in the regime in which electronic transport does not take place through the 2DEG itself therefore minimizing the energy dissipated into it. The nongalvanic QD thermometer is, on the other hand, an absolute thermometer whose response depends only on structural parameters which are easily measurable, as we have shown.

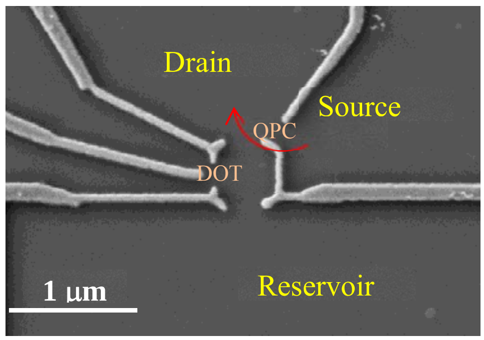


Fig. 2: *SEM image of one of the devices fabricated on GaAs/AlGaAs. Aluminum gates defined by e-lithography define the quantum dot and the quantum point contact.*

Phase-coherent heat transport in superconducting structures

Manipulation of heat currents in mesoscopic circuits is a young field of research. The role of dissipative phenomena at the nanoscale and the benefits that can be derived from them are starting to become understood. New developments have been forthcoming, starting from cooling applications and fine temperature tuning in cryogenic detectors, or superconducting circuits for quantum computing, and ending with the emergence of caloritronic circuits. Towards this end, a magnetic flux-controllable superconducting heat interferometer has been theoretically conceived and subsequently realized experimentally. This device is schematized in Fig. 4a whereas some experimental data are shown in Fig. 4b. As seen there, the electronic temperature of a metallic electrode connected to the heat interferometer varies periodically with the magnetic flux threading the ring.

This achievement served to show, on the one hand, how quantum coherence between two weak-linked superconducting condensates extends also to dissipative observables such as the heat current. On the other, this device might constitute the building block for the implementation of superconducting hybrid coherent caloritronic circuits like, for instance, thermal modulators, heat transistors and splitters, etc. Among them we have proposed the realization of a fully balanced thermal modulator (Fig. 4a) which can lead to *magnetic flux-controlled* thermal Josephson transistors and phase-tunable thermal rectifiers, i.e., structures allowing high heat conduction along one direction but suppressed thermal transport upon temperature bias reversal (Fig. 4b).

According to our theoretical estimations, the latter can provide remarkable heat rectification coefficients as large as ~ 800%.

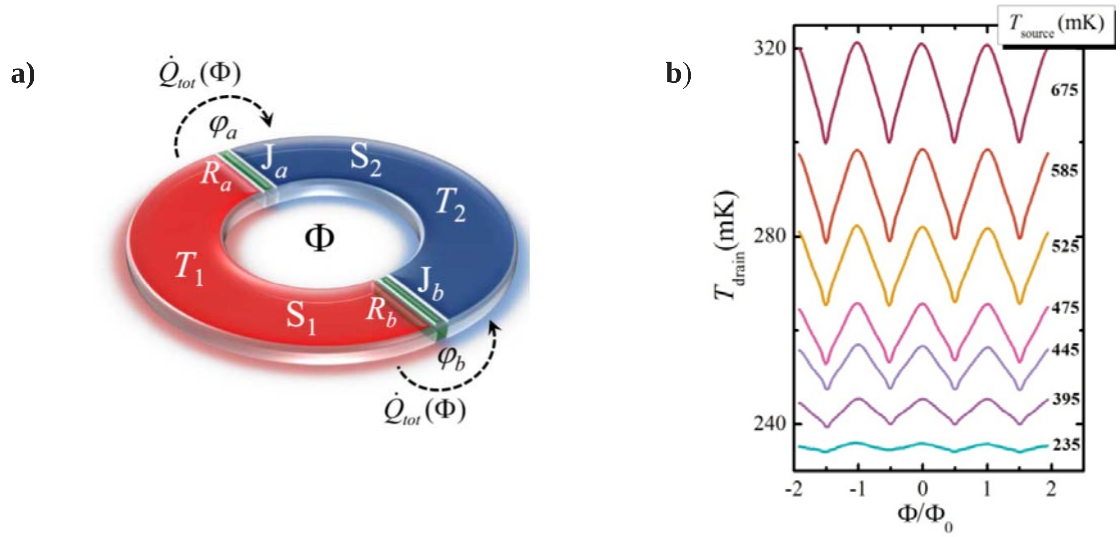


Fig. 3: *a) Heat modulator scheme. The device consists of a superconducting ring interrupted by two Josephson junctions. The heat flux flowing through it depends on the phase difference across the junctions and, hence, on the magnetic flux treading the loop. b) Flux-periodic electronic temperature of a metallic electrode connected to the hot branch of the heat modulator.*

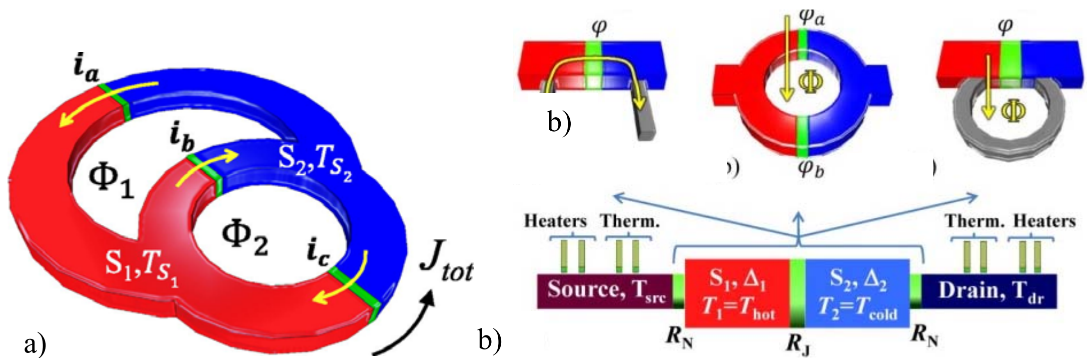


Fig. 4: *a) Scheme of the fully balanced thermal modulator. b) Three proposed ways of phase bias for a thermal rectifier and scheme of the device operation.*

Task 2. Microkelvin nanocooler (AALTO, CNRS, SNS)

Demonstration of sub-10 mK nanocooling with a N-I-S junction (Deliverable D4)

Demonstrating sub-10 mK temperatures in mesoscopic structures requires besides the cooling technique (in this case the N-I-S solid state cooler that was described in the 36-month periodic review report) reliable thermometry. N-I-S junctions themselves turn out not to be suitable close to or below 10 mK for a number of reasons. Mainly, they affect via the probing current the electron distribution within the island, typically even cooling can be observed due to the probe current. Reducing the probe current further typically reaches soon the limit of the leakage current through the junction which is on the one hand temperature independent and on the other hand overheats the electron system in the tiny island.

We employ an alternative temperature sensing method: the temperature dependent supercurrent through a normal metal island that is in close contact to a superconductor. This technique has both the advantage of being non dissipative (until the moment where the critical current is exceeded) and to be very sensitive towards the low temperature end (the critical current rises exponentially with falling temperature). In addition, it is straightforward to tune the useful temperature range of the S-N-S thermometer with the length of the island.

Fig. 5 shows a realization of the latest generation of these devices: the length of the normal metal island is adapted for the lowest temperature range, its volume is minimized to reach lower temperatures with less cooling power (note the width of 60 nm) and an optimized cooler geometry with an increased junction area having a typical tunnel junction resistance of 10 to 100 kOhm. These relatively opaque junctions allow on the on hand a sufficient cooling power and on the other hand do not dump an excessive amount of heat into the superconducting electrodes, so that the quasiparticle traps are efficient enough (task 3).

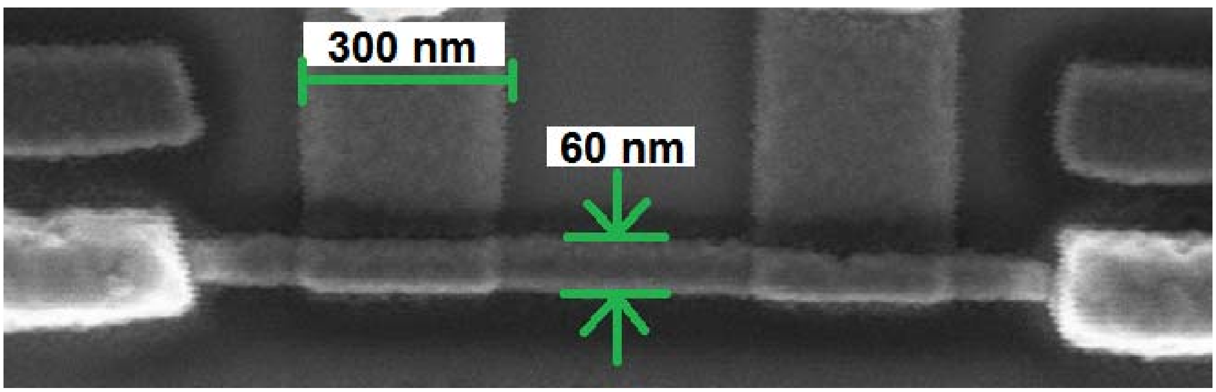


Fig. 5*: Top: electron micrograph view of the cooler: visible in the middle is a 60x20x1200 nm*^{3} *copper island. It continues underneeth the two side electrodes (100 nm thick superconductor) for an additional 100 nm forming two clean S-N contacts. The two 300 nm wide Aluminium-Aluminiumoxide (S-I-N) tunnel junctions are attached to the island about halfway between the middle and the clean contacts.*

We report here noticeable progress in the readout performance of the S-N-S thermometer. An enhanced experimental setup employing programmable floating current sources enables a precise measurement of the critical current with unprecedented accuracy and speed. (Fig. 6 left). The S-I-N-I-S junctions play here two roles at a time: once, the applied cooling current cools the electronic system within the normal metal island. Then, we use the resulting voltage across the same junctions as detector for the state of the S-N-S junction: the temperature rises sharply when the S-N-S junction switches to the normal state as joule heating sets in. This setup allows fast probing of the S-N-S thermometer with a frequency on the order of a few tens of Hertz. What is more, the resulting accuracy in relative temperature sensitivity reaches values of 100 µK due to the steepness of the transition.

Fig. 6 (left) depicts a set of cooling curves for three different S-I-N-I-S currents: as an example (arrows), a cooling current of 150 pA cools the electronic system in the normal metal island from a base temperature of 160 mK down to 80 mK. Starting from 100 mK a temperature is reached that lies well below the lowest bath temperature and typically comes close to 10 mK. A more precice temperature determination at this low temperature end with sufficient accuracy remains a challenge: the determination of the characteristic parameter (Thouless energy) of the S-N-S junction requires a measurement of the critical current over about one decade of temperatures, where the influence of the S-I-N-I-S cooler is negligible (In the example above from 160 mK up to almost 1K). This is still out of range as the critical current vanishes too rapidly on the high temperature side and as the cooling sets in already at moderately low temperatures even with smallest cooling currents, because the island has such a small volume.

This setup has due to its sensitivity potential for other studies like shot noise in the temperature caused by the injection of charge carriers through the junction, fluctuations of the temperature itself, and the study of the intrinsic properties of the S-N-S junction.

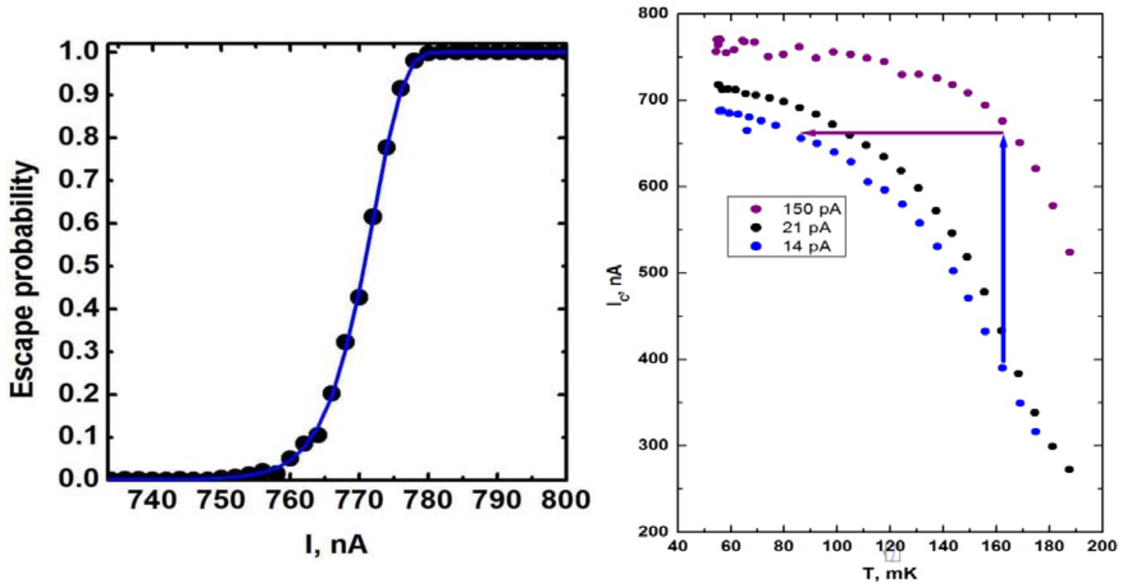


***Fig. 6**: **(Left)** Escape probability of the S-N-S junction at a base temperature of 60 mK and a bias current through the S-I-N-I-S junction of 150 pA. Each point of the escape histogram is measured applying 400 current pulses and counting the number of escapes to the normal state. **(Right)** Resulting temperature dependent measurement of the critical current for the S-N-S junction for different cooler currents. The blue vertical arrow is a guide to the eye indicating the increase in the measured critical current, the violet horizontal arrow shows in turn the corresponding decrease in temperature of the electron system (see text).*

Task 3: Development of a 100 mK robust, electronically-cooled platform based on a 300 mK ^{3}He bath (AALTO, CNRS, RHUL, DELFT)

Cooling a bulk object on a dielectric platform requires large cooling power, in the nW range in the sub-K regime. To achieve this goal, we need to improve the performance of the SINIS coolers. For nanoscale coolers it has been demonstrated that an Al based device works well below 300 mK. However, they have small cooling power and are not capable of cooling external loads. A more powerful cooler (larger junction area) requires a higher current and generates a large number of quasiparticles on the back side of the cooler. Thus it becomes important to thermalize the hot superconducting electrodes.

To continue our work from last year at Aalto and CNRS, we have improved the performance of the large area, high power SINIS cooler based on the fabrication technique in Ref. [17]. We thermalize the superconducting electrode (Al) by attaching a normal metal (called quasiparticle drain) through a fine tuned tunnel barrier. There is an optimum value of the drain barrier that stops the inverse proximity effect while the superconducting electrode can still be thermalized well. Without the quasiparticle drain, the cooler cools from 300 mK to 240 mK (red curves in Fig. 7). With the quasiparticle drain, the cooler cools to 200 mK (green). With a fine tuned drain barrier, the cooler reaches 150 mK (black). We provide a thermal model that accounts for the role of the drain barrier. The details are described in the section "Thermal Model" in Ref [34].

With a good quasiparticle drain and drain barrier, we increase the thickness of the cooler barrier (the barrier between Al and Cu – the cooled normal island). Generating a smaller number of quasiparticle from a smaller current, the cooler works better at low temperatures. It reaches 30 mK from 150 mK (bath temperature), or 50 mK from 200 mK (black curve). Note that 30 mK is about 0.03% of the superconducting gap in Al. We are working on a publication for this significant result.

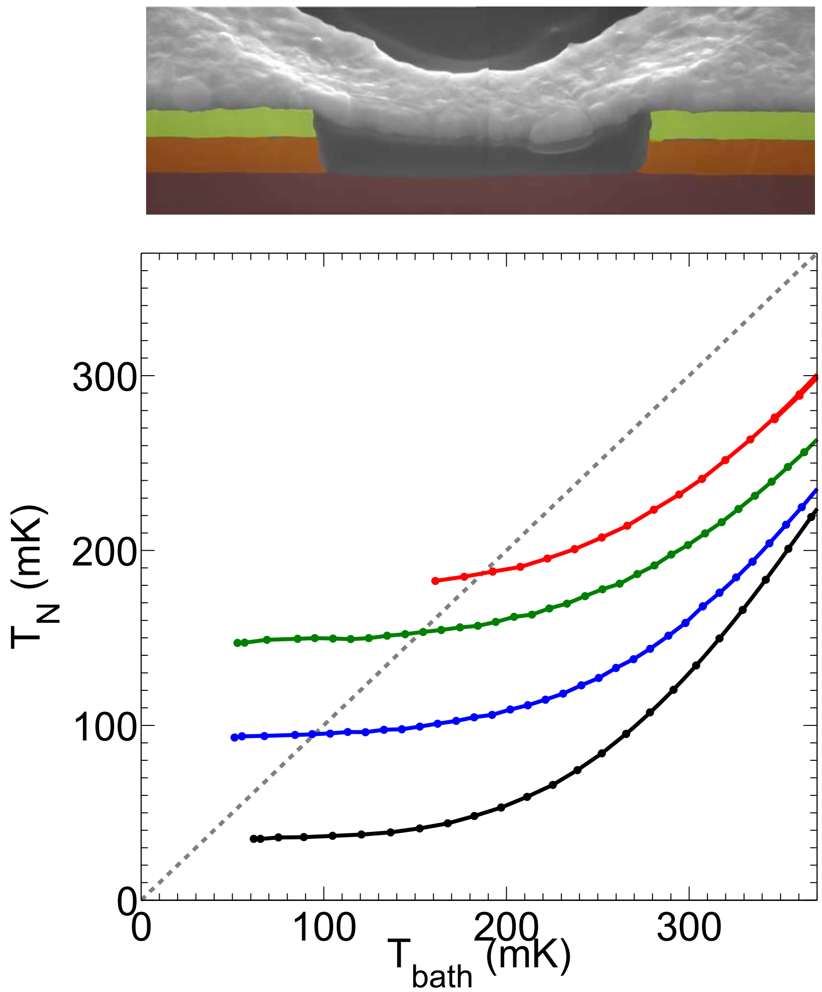


Fig. 7: (Top) *Side view of the cooler in an electron micrograph: top layer 100 nm of Cu, middle layer 200 nm of Al as superconducting electrode, bottom layer 200 nm of AlMn as quasiparticle normal metal drain. The two insulating tunnel barriers are invisible.* ***(Bottom)*** *Cooling performance of different coolers: all coolers have the same junction area (500 µm^2) and are fabricated according to identical recipes. Red curve no AlMn drain; green with AlMn but thick drain barrier; blue with AlMn and fine tuned drain barrier – these 3 coolers have the same cooler barrier ~ 500 Ωµm^2; black fine tuned drain barrier and thick cooler barrier ~ 2500 Ωµm^2. Note that these coolers have at least 500 pW cooling power at 300 mK.*

Based on this powerful cooler, we have developed two types of platforms:

(i) **Dielectric platform**: 100 nm low stress SiN membrane. With 4 nW cooling power from 4 coolers at the corners, the platform reaches 200 mK from 300 mK without perforating the membrane. Note that while the dielectric platform performs at the state of art result, we don't need to perforate it. This is a worthwhile result since it provides a robust platform for other applications. Attempts toward better performance are slow due to low yield when working with the membrane and owing to trouble with thermalizing the on-chip hot phonons at the backside of the cooler.

(ii) **Copper platform**: taking advantage of the suspended normal island by means of new fabrication techniques, we extend the Cu island and turn it into a platform for other applications. Our initial result shows that the Cu island cooled only 10 mK. This limitation apparently comes from the bad sample quality (the island seems to touch the substrate). Futher studies are planned in the near future.

To reach 100 mK or less from 300 mK on a platform is a challenging task. The phonons of the cooled region need to be well isolated from the bath. For this a low stress SiN membrane is an excellent choice. However, it is so fragile that the fabrication yield is very low, especially when multiple lithography is required. Moreover, our knowledge about 2D phonons is limited at low temperatures. This shortcoming reduces our choice of solutions. However, in any case with the new powerful cooler we expect to reach lower temperatures in the near future with an unperforated platform.

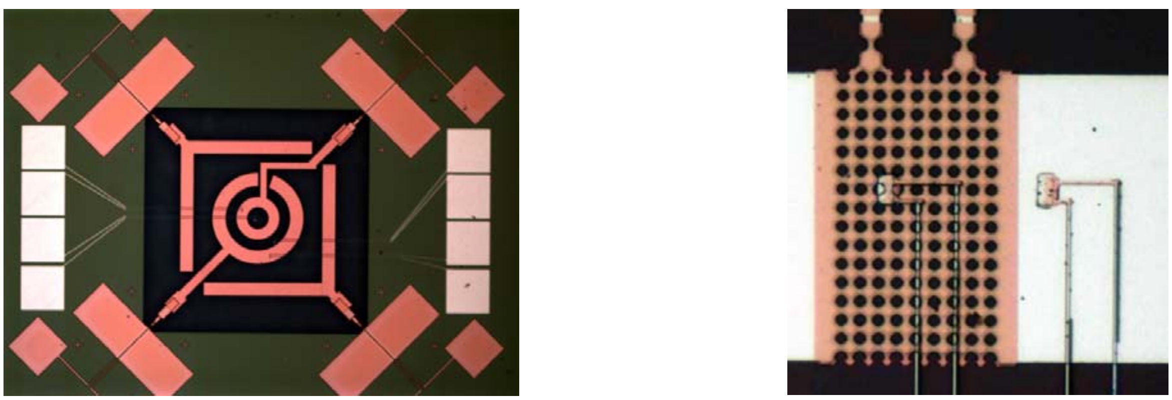


Fig. 8. ***(Left)*** *The dielectric platform: four big coolers at the corners provide 4nW of cooling power to the membrane. Without perforations in the SiN membrane the platform reaches 200 mK from 300 mK.* ***(Right)*** *The copper membrane with phonon thermometers on top.*

We have investigated quantum detectors manufactured on membranes and on bulk wafers. Based on very small Al/AlOx SIS Josephson junctions the switching properties of these junctions have been measured as a function of temperature, time, and a number of other parameters. Very small junctions are naturally underdamped and their properties are complex, nevertheless they form in principle the basis of both a novel thermometric method that is suitable for the testing of an electronic nano-cooler and simultaneously provide an opportunity for the exploration of new physics in a regime that is hitherto fairly unexplored. New and successful measurement techniques have been developed but the measurements have met with some technical challenges. Using very small SIS junctions on a membrane we have developed a fast, reliable, and sensitive pulsed switching current measurement scheme in the range of tens of nA. Fig. 9 shows cumulative probability curves for switching events measured in a heavily underdamped very small Josephson junction. The blue and red curves show the situation before and after identifying and eliminating sub-critical currents circulating in the junction. Of particular note is the fact that the theoretical probability distribution curve fits the data well in both cases, albeit with different fit parameters, and demonstrates the difficulty of identifying measurement problems in this regime.

Fig. 10 shows the autocorrelation function and Fourier transform derived from a time series of switching current data in the same junction. These clearly show the presence of sub-critical currents at 50 Hz (and its harmonics) and also at 8 Hz circulating in the junction. The identification and elimination of these nano and pico-amp currents will allow these junctions to be developed as a powerful thermometric technique for electronic nano-coolers and other situations where space and simplicity of fabrication is of importance. To this end we have developed a well controlled cryogenic RF low pass filter. These SIS Josephson devices, when viewed from a different perspective, are also known as superconducting phase qubits which may be manipulated with the introduction of an RF antenna.

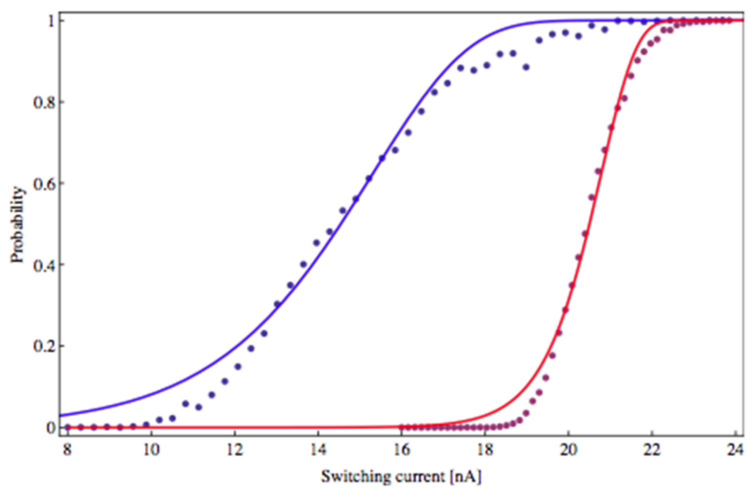


***Fig. 9**. Cumulative probability distribution curves for the critical current switching of an Aluminium/Aluminium Oxide/Aluminium Josephson junction in the heavily underdamped regime on a 100 nm membrane. The blue (red) dots show the distribution measured before (after) the identification and correction of a measurement problem that introduced unwanted subcritical ac currents into the junction. The corresponding solid curves show the fits to the theoretical expression demonstrating that a reasonable fit may be achieved in both circumstances.*

Deliverable 5: Demonstration of cooling a dielectric platform from 300 mK to about 50 mK (36 months) **partly achieved**

Deliverable 6: Demonstration of cooling-based improved sensitivity of a quantum detector (48 months) **achieved**

Milestone 6: Delivery of the first membranes to the end users (36 months) **achieved**

Highlights:

- Excellent trapping of quasiparticles in the large area SINIS cooler. The Al based device cools to 30 mK at 1 nW power per device.
- A heat interferometer based on Josephson junctions has been successfully realized.

Use of resources:

AALTO: A part-time senior researcher's salary has been paid from the Microkelvin grant and a postdoctoral fellow at Aalto has been funded by Microkelvin from July 2011 onward.

BASEL: Since August 2009, a senior scientist is partly funded by Microkelvin for JRA2 activities. From October 2009 until May 2010, a postdoctoral fellow was funded by Microkelvin, including for work in JRA2. From Jan 2011 until September 2012, a PhD student is partly funded by Microkelvin, including for JRA2 work.

CNRS: A postdoctoral researcher has been employed for the MicroKelvin project for working for JRA2 from April 1st to June 30th, 2010.

SNS: A postdoctoral fellow (M.J. Martinez-Perez) working at NEST for JRA2 was funded by Microkelvin from 1st April 2011 to 31st March 2013.

RHUL: A postdoctoral researcher at RHUL is employed on a part time basis for this project between 1 March 2012 and 30 September 2013, equivalent to 9 months of full time.

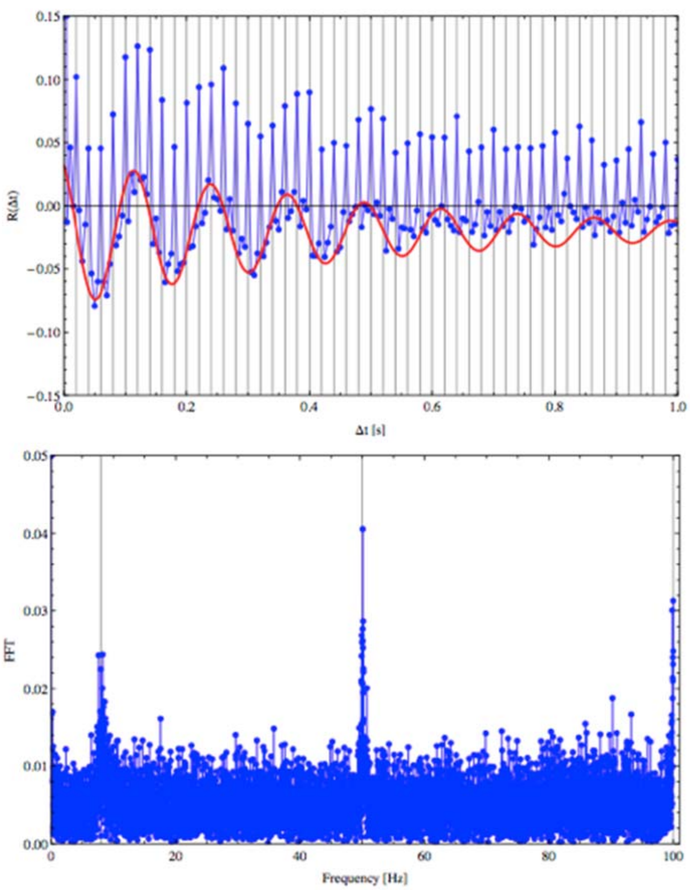


***Fig. 10**. **(Top)** The autocorrelation function calculated from a time series of switching current data of a small SIS junction in the underdamped regime. The plot shows clearly the presence of contributions (at 50Hz and 8Hz) to the subcritical current present in the junction. **(Bottom)** The corresponding Fourier transform.*

List of publications of JRA2 (over the first, second, and third 18-month reporting period)

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9. J. T. Peltonen, J. T. Muhonen, M. Meschke, N. B. Kopnin, and J. P. Pekola, *Magnetic-field-induced stabilization of nonequilibrium superconductivity in a normal-metal/insulator/superconductor junction,* Phys. Rev. B **84**, 220502(R) (2011).
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11. M. Meschke, J. T. Peltonen, J. P. Pekola, and F. Giazotto, *Tunnel Spectroscopy of a Proximity Josephson Junction,* Phys. Rev. B **84**, 214514 (2011).
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13. N. Vercruyssen, R. Barends, T. M. Klapwijk, J. T. Muhonen, M. Meschke, and J. P. Pekola, *Substrate-dependent quasiparticle recombination time in superconducting resonators,* Appl. Phys. Lett. **99**, 062509 (2011).
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JRA3 Report

Name of work package: **Attacking fundamental physics questions with microkelvin condensed-matter experiments**
Reporting Period: **Last 18-month period from 1.4.2012 to 30.9.2013**
Activity leader: **Henri Godfrin**

Table of expected deliverables during the grant period

Del. no.	Deliverable name	WP no.	Lead beneficiary	Estimated person months	Nature	Dissemination level	Delivery date
D1	Report on microfabricated silicon vibrating wires tested in superfluid 3He at 100 µK	JRA3	CNRS	3	R	PU	48 **achieved**
D2	Publication on vortex creation in superfluid 3He	JRA3	ULANC	20	R	PU	24, 36 **achieved**
D3	Publication on 2D defects	JRA3	ULANC	18	R	PU	36 **achieved**
D4	Report on a quantum model of a hydrodynamic Black Hole analogue	JRA3	AALTO	12	R	PU	48 **achieved**
D5	Publication on Q-balls in superfluid ^{3}He and their spin relaxation properties	JRA3	CNRS	9	R	PU	48 **achieved**
D6	Report on state-of-the-art particle detector with superfluid ^{3}He as target material	JRA3	CNRS	8	R	PU	48 **achieved**
D7	Report on the determination of the excitation spectrum in liquid ^{3}He	JRA3	CNRS	8	R	PU	48 **achieved**

Table of expected milestones during the grant period

Milestone number	Milestone name	WPs no's	Lead beneficiary	Delivery date From Annex I	Comments
M1	Determination of the energy released by a vortex tangle with known line density	JRA3, Task 1	ULANC	12	Test completed **achieved**
M2	Measurement of the dissipation when a vortex tangle is established	JRA3, Task 1	ULANC	24	Report **achieved**
M3	A precise determination of the effect of pressure on vortex creation via the dynamics of the second-order phase transition	JRA3, Task 1	ULANC	30	Report **achieved**
M4	Identification of the topological defects left after brane (phase boundary) annihilation	JRA3, Task 2	ULANC	24	Report **achieved**
M5	Observation of several "cosmological defects" obtained in a microkelvin multi-cell detector	JRA3, Task 2	ULANC	30	Test completed **achieved**
M6	Development of a Black-Hole analogue in a rotating system with an A-B boundary	JRA3, Task 3	AALTO	48	Report **achieved**
M7	Test of the Unruh effect from rapid motion of a phase boundary	JRA3, Task 3	AALTO	36	Test completed **achieved**
M8	Test of the percolation theory of the A-B transition	JRA3, Task 3	AALTO	36	Test completed **achieved**

M9	Observation of the interaction between two independent precessing Q-balls	JRA3, Task 4	CNRS	30	Report **achieved**
M10	Creation of excited modes of a "Q-ball" under radial squeezing by rotation	JRA3, Task 4	CNRS	36	Test completed **achieved**
M11	Realization of microkelvin thermometry based on "Q-ball" behaviour	JRA3, Task 4	CNRS	42	Report **achieved**
M12	Measurement of enhancement in the Q-ball spin relaxation rate from surfaces and vortices	JRA3, Task 4	AALTO ULANC	42	Report **achieved**
M13	Microfabricated silicon vibrating wires tested in superfluid ^{3}He below 100 μK in laboratory conditions	JRA3, Task 5	CNRS	42	Report **achieved**
M14	Neutron scattering measurement of ^{3}He excitation spectrum at intermediate energies	JRA3, Task 5	CNRS	42	Report **achieved**

Summary

The work package JRA3 provides the testing ground for the concepts, methods, and instrumentation developed within the various other Microkelvin activities. The goal is to solve some of the most fundamental problems, which can only be tackeled at the very lowest temperatures, by making use of the concerted expertise of the Microkelvin Collaboration. The list for such possibilities is long; here the questions to be studied are concerned with quantum field theory, cosmology, gravitation, particle detection, and very general aspects of condensed matter.

Task 1: Investigating quantum vortices as model cosmic strings (ULANC, AALTO, CNRS)

Aalto measurements: The question of dissipation mechanisms in the dynamics of quantum fluids remains central at temperatures close to absolute zero. While it is now well established that quantum turbulence provides finite energy dissipation, our recent findings demonstrate that momentum exchange with boundaries in a low-temperature superfluid is not affected by the turbulence effects and the superfluid behaves as an almost ideal fluid with respect to drag, Fig.1 [1]. This results in a new class of phenomena in superfluid hydrodynamics, which we call decoupling phenomena [2].

We can clarify the origin for the difference in energy dissipation compared to momentum exchange with the normal component with the numerically calculated simple model system in Fig. 2, which illustrates the situation in turbulent dynamics [4]. Here two vortex rings have been placed in a configuration where they move and reconnect in the presence of mutual friction damping. The damping leads to a continuous decrease of the total energy and momentum of the system. After reconnection Kelvin waves appear on the remaining single loop. The oscillating motion causes substantial extra energy dissipation, while the rate of momentum change is essentially not affected by the reconnection event. The explanation is that the direction of the mutual friction force alternates in the two half-periods of the oscillation. Thus momentum transfer to the normal component cancels out. Simultaneously the direction of the vortex velocity is also alternating, but it remains opposite to the mutual friction force. Thus the work done by mutual friction in the two half-periods of the oscillation adds up. Since reconnections and the fluctuating vortex motion are the characteristic features of quantum-turbulent flows, this conclusion is likely to apply to quantum turbulence in general.

Such dual behavior often makes interpretation of experiments on quantum turbulence difficult and calls for studies of simpler types of flow. For this reason, we have studied dissipation processes in the Kelvin-wave turbulence on individual vortex lines. Kelvin waves are helical distortions of vortices. The cascading of energy towards small scales owing to the non-linear interaction of Kelvin waves is thought to be an essential ingredient of quantum-turbulent flows at low temperatures. However, a generally accepted physical picture of this phenomenon does not exist, in particular owing to difficulties in demonstrating the Kelvin-wave cascade experimentally or in the numerical simulations.

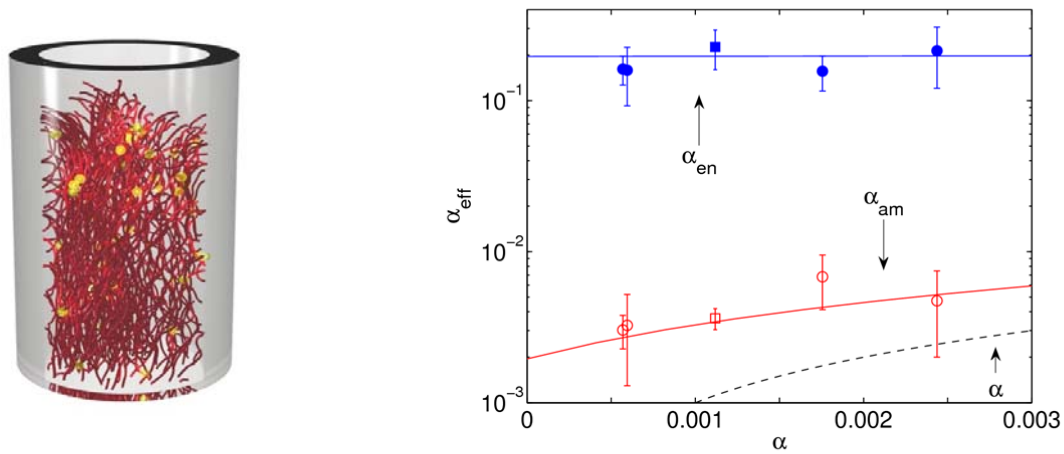


Fig. 1. *Measurements of quantum turbulence in the propagating vortex front. (Left) A snapshot from numerical calculations of vortex expansion in the rotating cylinder at* $0.27T_c$*. In the region of the front the vortices terminate at the cylindrical side wall. Turbulence is sustained by vortex reconnections which are highlighted with yellow dots. The front moves upward with velocity* V_f *into the vortex-free region and simultaneously precesses in the azimuthal direction [2]. (Right) Effective friction parameters in the front motion for energy dissipation* α_{en} *and momentum transfer (drag)* α_{am} *as a function of the temperature-dependent mutual friction parameter* α *measured in laminar motion [3]. The symbols represent direct measurements of* V_f *and of azimuthal precession while the solid lines represent an indirect determination using the* Ω*-dependence of* V_f*. The data were measured at 0.5 bar (circles) and 29 bar pressures (squares). Comparing* α_{en} *and* α_{am} *to* α *(dashed line) one concludes that turbulence in the front significantly enhances the energy dissipation while the drag is barely affected.*

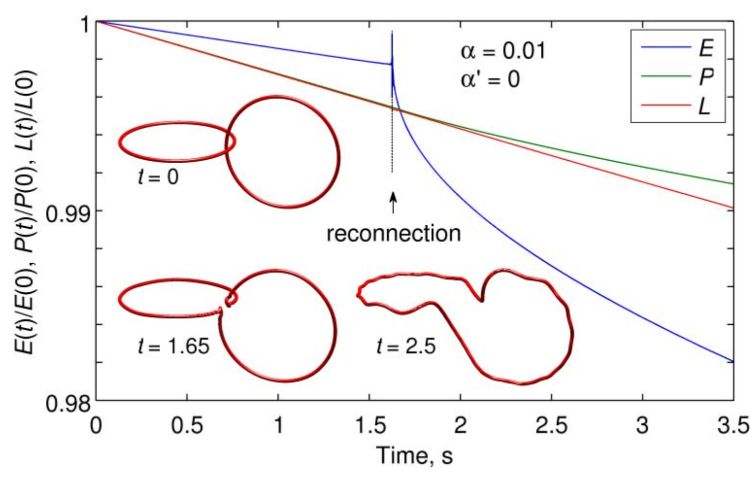


Fig. 2. *Numerical calculation of two reconnecting vortex rings. Two rings with a radius of 1 mm are placed initially at a distance of 1.9 mm between their centers, with their planes perpendicular to each other (as depicted in the inset t = 0). The reconnection happens at t = 1.62 s. The plot shows the calculated time dependences of the total kinetic energy E(t), momentum P(t), and angular momentum L(t), normalized to their respective values at t = 0. The calculation demonstrates quite different behavior in energy and momentum loss after the reconnection event. No externally applied flow is present.*

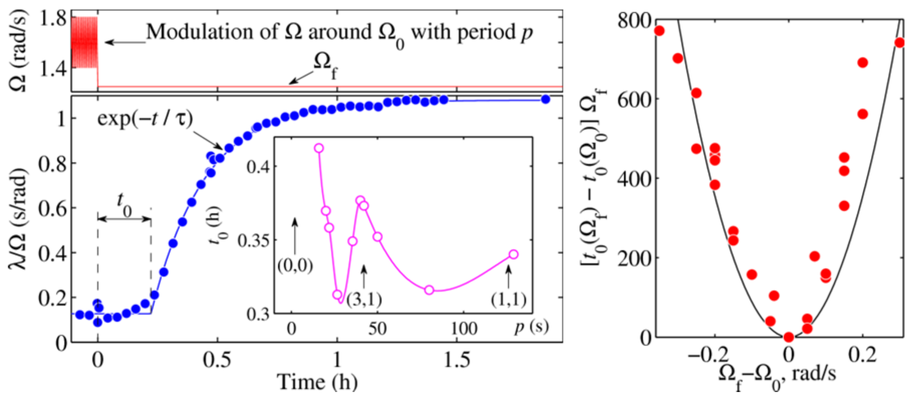


Fig. 3. (Left) *Measurement of turbulent dissipation created in periodic modulation of the rotation velocity of the* ^{3}*He-B sample. The top panel on the left shows the time dependence of the rotation velocity. In the bottom panel the values of the vortex parameter λ are plotted. It describes the vortex polarization. The recovery of λ, after the modulation has been stopped, consists of two parts: from the first part of the duration* t_0*, where the vortex polarization remains low and turbulence persists, while during the second part Kelvin waves on vortex lines decay and the polarization is restored with a relaxation time τ. In the inset the non-monotonic dependence of* t_0 *on the modulation period p demonstrates the presence of inertial-wave resonances, marked with arrows.* ***(Right)*** *The nearly parabolic dependence of* t_0 *on the shift of the rotation velocity after the modulation has been stopped allows us to calibrate the turbulent energy dissipation rate from the known free energy difference between rotations at* Ω_f *and* Ω_0*.*

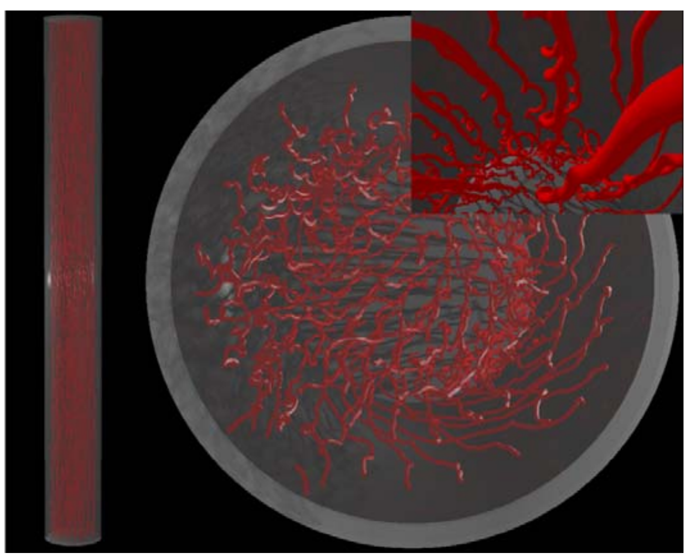


Fig. 4. *Helical Kelvin waves appearing on top of the vortex array at 0.20* T_c *in superfluid* ^{3}*He-B. These numerical calculations employing Biot-Savart integration along all vortex-filaments are conducted in a cylinder with radius 1 mm and length 20 mm, which is tilted by 2º with respect to the rotation axis. The initial configuration is a steady state vortex array at a rotation velocity of 1 rad/s. This figure illustrates the Kelvin waves which form on the vortices 50 seconds after we started to modulate the rotation velocity between 0.8 and 1.2 rad/s with a rate of 0.030 rads/s*^{2}*.* ***(Right)*** *Side view of cylinder with the line vortices and* ***(left)*** *view from the top.*

In our experiment (Fig. 3) we first create an equilibrium array of rectilinear vortex lines in steady-state rotation and then apply periodic modulation to the rotation velocity around some average velocity Ω_0. The goal is to excite Kelvin waves on vortex lines, as demonstrated by simulations in Fig. 4. The deflection of vortices from the rotation axis, i.e. the reduction in their polarization along the rotation axis, is observed as a change in the NMR spectrum. From the spectrum we extract the time dependence of the parameter λ, which describes the contribution of the vortices to the textural energy. As the vortex polarization decreases, λ also decreases. When this change has saturated, we stop the modulation and change the rotation velocity to a new value Ω_f, to build a reservoir of the global flow energy, $\Delta F = \pi\rho_s R^4(\Omega_f - \Omega_0)^2/4$. Then we measure the duration t_0 of the period in the subsequent relaxation, while the turbulence persists, the polarization of vortex lines remains low and the known amount of energy ΔF is dissipated. This allows us to determine the turbulent dissipation rate and rescale it to one vortex line in the cluster. By measuring this rate as a function of temperature and pressure, we hope to separate the contributions to the energy dissipation from the Kelvin-wave cascade and from the microscopic dissipation mechanism.

We have also observed that the energy stored in the global flow at the beginning of the relaxation, and thus the time t_0, has a non-monotonic dependence on the period of modulation of the rotation velocity (insert in Fig. 3). The peaks in this plot can be identified as inertial-wave modes of our rotating cylinder. In superfluids inertial waves were previously reported in ^{4}He [5], and our observation is the first demonstration of such waves in ^{3}He-B.

ULANC measurements: We have undertaken a series of experiments to study the creation of quantum vortices at low temperatures, in both ^{3}He-B and ^{4}He superfluids. It is interesting to compare the behavior in the two systems since they represent very different superfluids: superfluid ^{4}He is a simple Bose condensate whilst superfluid ^{3}He-B is an exotic condensate of Cooper pairs combing spin and orbital superfluidity with the usual mass superfluidity. Furthermore, the coherence length, which defines the size of the vortex core, differs immensely in the two superfluids: the coherence length is approximately the interatomic spacing, 0.1 nm, in superfluid ^{4}He and can be as large as 60 nm in superfluid ^{3}He-B, depending on the pressure.

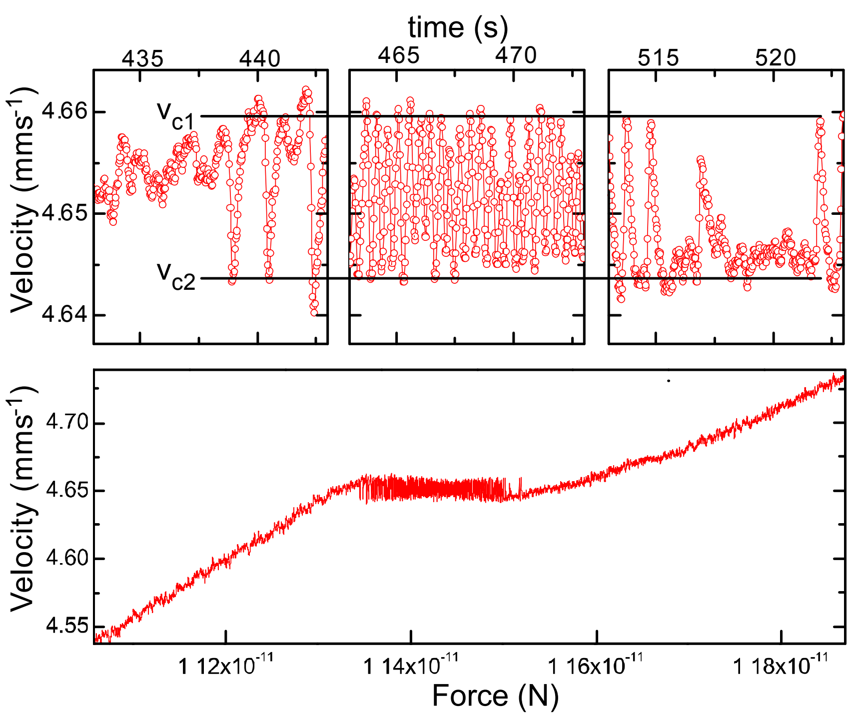


Fig. 5. *Periodic production of single vortex loops by a vibrating wire resonator in superfluid ^{3}He-B in the zero temperature limit.*

Measurements on vibrating wires show that turbulence in superfluid ^{3}He-B is generated above some critical velocity which is identical to the critical velocity for pair-breaking. This suggests an intrinsic mechanism of vortex production. However, we have also found evidence that some vortex production can also occur at lower velocities. The response of a vibrating wire at low driving forces shows some very interesting features. An example is shown in Fig. 5. Here the wire velocity is found to oscillate in time at a particular range of driving forces. The oscillations occur between two critical velocities v_{c1} and v_{c2}.This indicates a periodic emission of vortex rings. We believe the mechanism is due to a remnant vortex pinned to some surface feature, such as a spec of dust, on the wire. Under certain conditions, the alternating flow will excited a Kelvin wave resonance on the vortex, and the vortex will grow and twist, eventually reconnecting to form a vortex loop. Once a loop is emitted, the process repeats indefinitely. The process is very efficient at generating single vortex loops.

We have studied how this process interacts with surrounding vortices generated from a neighbouring vibrating wire resonator, Fig. 6. The neighbouring wire generates vortices above its pair-breaking critical velocity of around 9 mm/s. The wire has no effect on the vortex loop generation below this velocity. However, at a slightly higher velocity, there is a very dramatic effect on the feature associated with loop generation as shown in the figure. The oscillations grow enormously, indicating that a far greater vortex production rate, due to the presence of vortices generated by the second wire. It is likely that the remnant vortex reconnects to vortices generated by the neighbouring wire, becoming part of a larger network of vortices which can grow more efficiently in the oscillating flow field.

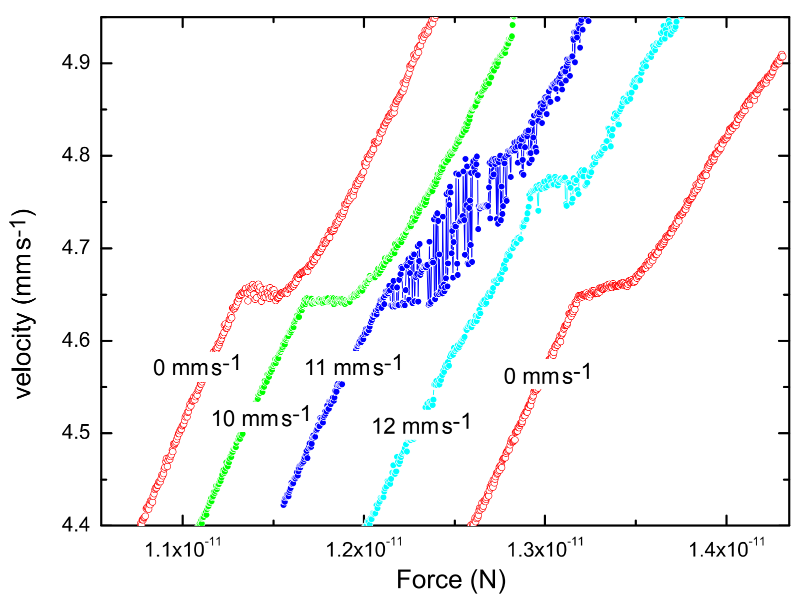
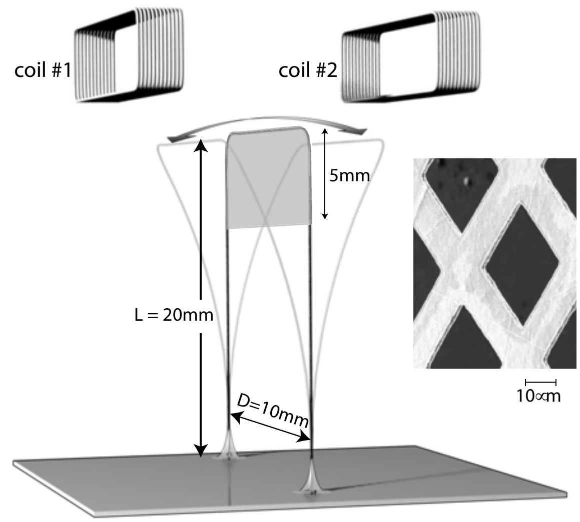


Fig. 6. *The velocity – force response of a vibrating wire showing a plateau feature associated with periodic vortex loop generation. The different curves show how the feature is modified by driving a near-by resonator to various velocities as indicated. The near-by resonator produces turbulence at the higher velocities which has a dramatic effect on the loop generation process.*

In superfluid ^{4}He we have studied turbulence from a vibrating grid. Turbulence from a towed grid is particularly interesting as it is believed to be very homogeneous and isotropic, and therefore a good system for comparing with theoretical models of turbulence. However, it is difficult to produce a towed grid device which operates in a superfluid in the *T=0* limit. It is much easier to produce a vibrating grid. An important question then is how the grid turbulence is affected by the oscillation frequency. We have addressed this question using the floppy wire techniques, which we developed earlier within the microkelvin framework.

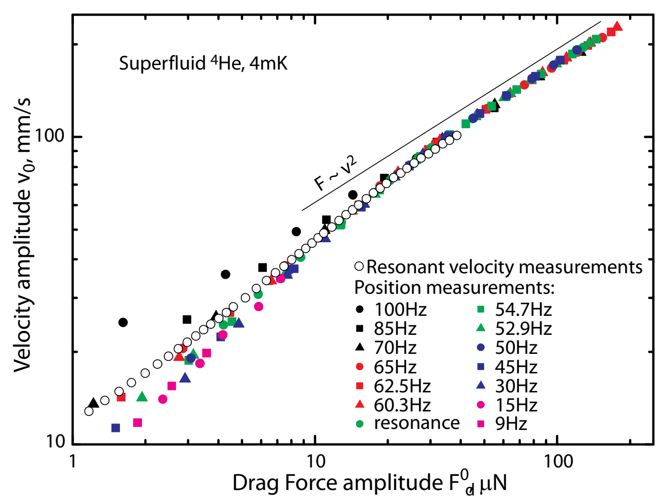
Fig. 7. The floppy grid device used to study the frequency dependence of grid turbulence in superfluid ^{4}He.



The device is shown in Fig. 7. A high frequency probe current is superimposed on the drive current. This induces a voltage on near-by pick-up coils, as shown in Fig. 7, depending on the position of the grid. This allows us to measure the position and hence the velocity of the grid. The technique can be used to measure the grid motion at arbitrary frequencies. We have used this technique to measure the turbulent drag on the grid moving through superfluid ^{4}He in the zero temperature limit.

The results are shown in Fig. 8 where we plot the velocity-force response of the floppy grid device for various frequencies and for high velocities where the response is dominated by the drag force from the quantum turbulence produced by the grid motion. The data collapse accurately onto a single curve showing that the turbulent drag at low temperatures is independent of frequency. This is a very significant result, as it suggests that a vibrating grid can be a useful tool to generate homogeneous quantum turbulence in the $T=0$ limit.

Fig. 8. The velocity – force response of the floppy grid device in superfluid ^{4}He over a wide range of frequencies. The results show that the turbulent drag is frequency independent.



We have also studied a floppy wire device in superfluid ^{3}He-B at low temperatures, revealing some unexpected behaviour. Similar to other vibrating wires, we find that the floppy wire generates quantum turbulence with a critical velocity which is very close to the critical velocity for pair breaking. However, in the case of the floppy wire, the effects of the vortices are immediately seen on the velocity-force response of the wire: the vortices self-screen the wire from surrounding quasiparticles which results in a dramatic drop in the thermal damping and a consequent rise in the velocity. This allows us to measure the surrounding turbulence from the foppy wire's own response, shown in Fig. 9. Usually the turbulence can only be observed using remote sensors, since the dissipation from pair-breaking dominates the response. This implies that pair breaking is lower for the floppy wire, presumably due to its lower resonant frequency. The frequency dependence of pair breaking is an interesting topic for future research.

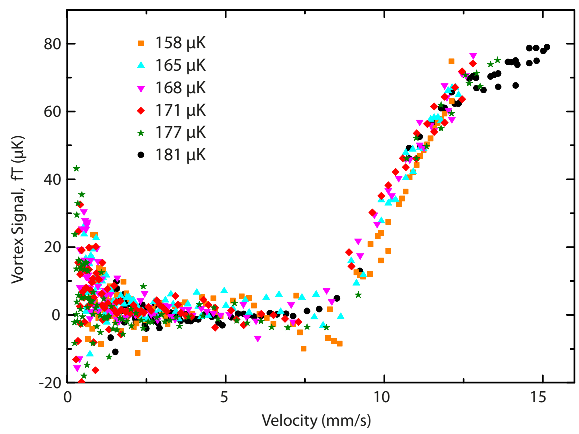


***Fig. 9**. Self- screening of quasiparticles due to turbulence generated by a floppy wire resonator in superfluid ^{3}He-B at low temperatures.*

We have also been developing custom made tuning forks for studying turbulence in superfluids at low temperatures. Tuning forks are commercially available and have low intrinsic losses. However, to increase their sensitivity for work at very low temperatures, it is necessary to use forks with a very small prong thickness. For this purpose, we have investigated custom made forks with prong thicknesses as low as 50 μm. This is the smallest size which can be manufactured using standard techniques. We have varied the length of the prongs to give a wide range of frequencies for studying superfluid properties at low temperatures.

We have studied the response of the forks in normal and superfluid ^{4}He. The response of several tuning forks at low velocities is shown in Fig. 10 as a function of their resonant frequency. At low frequencies, the response is well described by hydrodynamic drag due to the fluid viscosity. At higher frequencies the damping rises much more steeply and is dominated by the emission of acoustic sound. We have developed quantitative models which give a good description of this process.

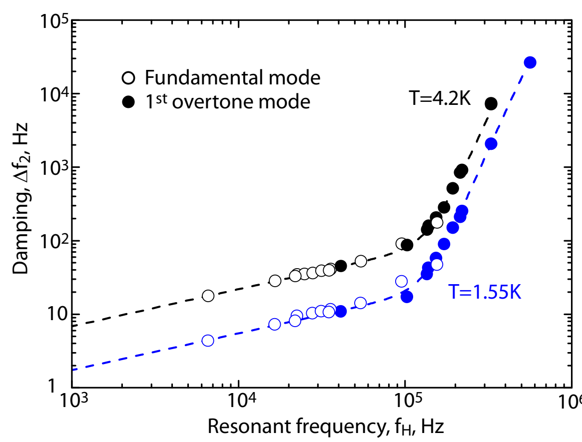


***Fig. 10.** The frequency dependence of the damping of a tuning fork in superfluid ^{4}He, showing the cross-over from hydrodynamic drag at low frequencies to acoustic drag at high frequencies .*

After characterising drag at low velocities, we have measured the drag due to quantum turbulence in superfluid ^{4}He over a wide frequency range. We find that the critical velocity for quantum turbulence varies as the square root of the resonant frequency, Fig. 11. This dependence can be understood from dynamic scaling arguments.

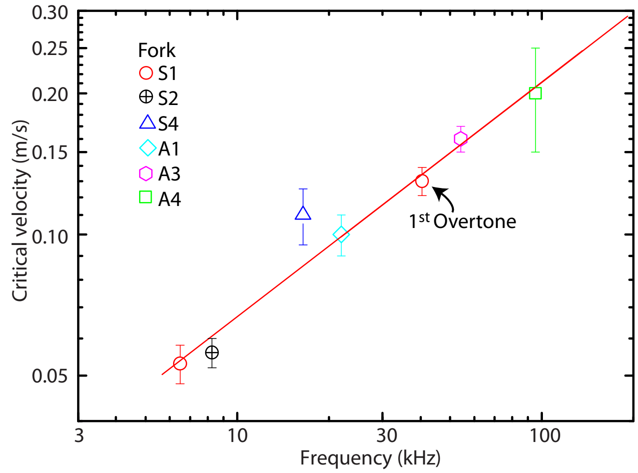


Fig. 11. *The critical velocity for turbulence generated with tuning forks in superfluid ^{4}He in the zero temperature limit, versus the resonant frequency. The data are consistent with a square-root frequency dependence.*

We find that the turbulent drag, when plotted against the velocity scaled by the critical velocity, has only a weak frequency dependence, shown in Fig. 12. This work is currently being prepared for publication.

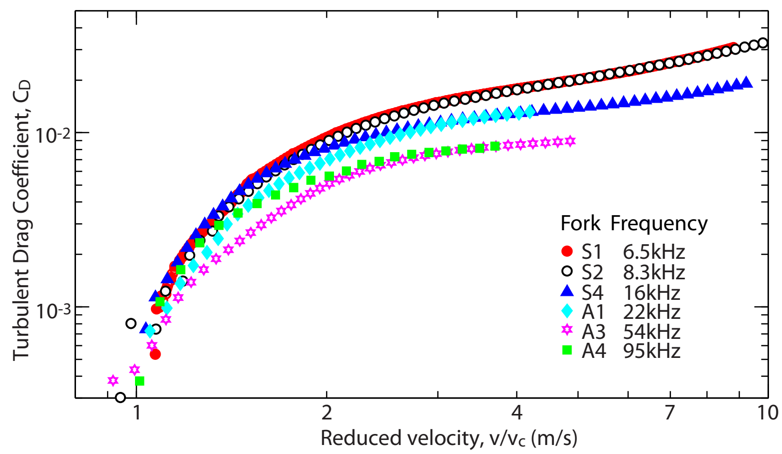


Fig. 12. *The turbulent drag of tuning forks versus the velocity scaled by the critical velocity, for various frequencies.*

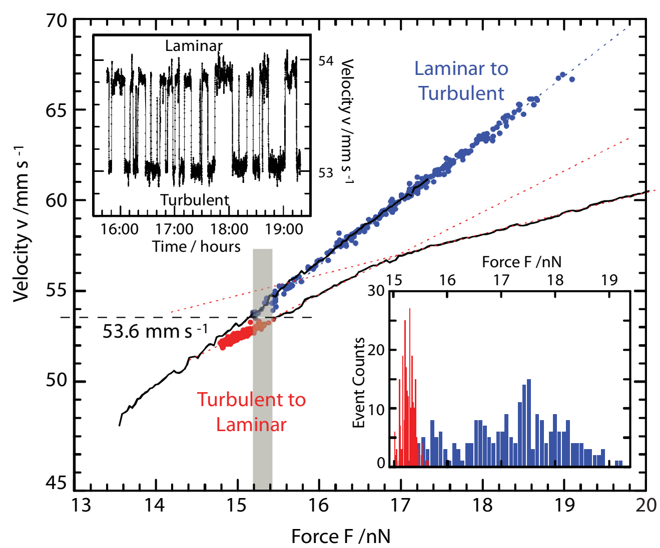


Fig. 13. *The velocity-vs-force response of a tuning fork in superfluid ^{4}He around the transition from pure potential flow to turbulence. The inset shows the intermittent switching. The points indicate different transitions for many different sweeps.*

We have also made a detailed study of the transition to turbulence for a tuning fork in superfluid ^{4}He at very low temperatures. The transition is shown in Fig. 13. On increasing the driving force, the velocity drops discontinuously when turbulence is nucleated. On subsequently decreasing the driving force the velocity steps upwards when the turbulence ceases. This produces hysteresis around the transition as shown in Fig. 13. Similar behaviour is observed for vibrating wires and vibrating spheres in superfluid ^{4}He.

The transitions occur at different points for each drive sweep. The points indicate the locations of the transitions for many different sweeps. Also, for some range of driving forces, indicated in the figure, spontaneous switching is observed between the pure potential flow and turbulent states, as shown in the inset. A statistical analysis (to be published) shows that the switching process is purely random, resulting in exponential distributions of the lifetimes for any given state.

Other Topics

The tuning forks, developed for the turbulence studies above, are versatile devices which can be used for a range of applications. In particular we have shown that they make convenient thermometers in normal liquid ^{3}He. Their use as thermometers relies on the knowledge of the fluid viscosity.

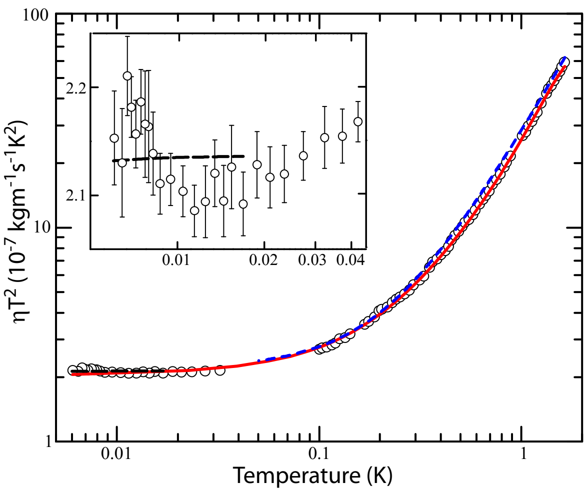


Fig. 14. *The viscosity of normal liquid ^{3}He inferred from tuning fork measurements over a wide temperature range.*

In Fig. 14 we show our measurements of the viscosity of normal ^{3}He, using a tuning fork. This serves as a calibration of the tuning fork thermometer. This makes a particularly convenient thermometer as it measures the fluid properties directly, thus avoiding problems with thermal boundary resistance, and it is easy to measure over a very wide temperature range. Unlike vibrating wire resonators, it does not require a magnetic field.

We have also been developing tuning forks to study solid ^{4}He. This is particularly interesting in light of the recent controversy concerning supersolid-like properties at low temperatures and exotic plasticity effects. Motion in the solid requires a large driving force and the resulting velocities are very small. So to measure this, we have developed a lithium niobate tuning fork which has much stronger piezoelectric properties than quartz which is normally used for tuning forks.

We have succeeded in observing the tuning fork response in solid ^{4}He over a wide range of temperatures, as shown in Fig 15. The tuning fork displays a large temperature dependent frequency shift and damping in hcp solid ^{4}He. At the lowest temperatures the tuning fork resonance in hcp 4He suddenly splits into several narrow resonances. We believe that these are resonances excited in the bulk solid, determined by the geometry of the container. The fork response is also sensitive to the hcp-bcc phase transition, shown in Fig. 16. This technique offers a valuable alternative to torsional oscillators for probing the exotic properties of solid helium in the low temperature limit.

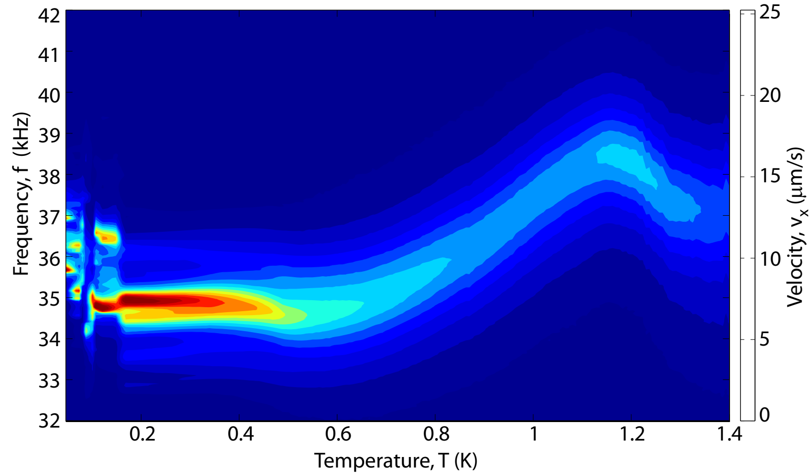


Fig. 15. *The response of a tuning fork in the hcp phase of solid 4He.*

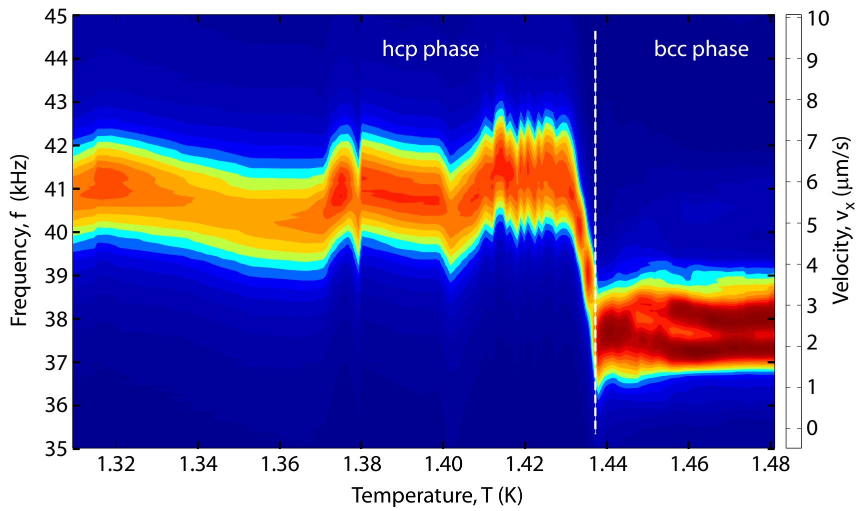


Fig. 16. *The response of a tuning fork at the hcp-bcc transition in solid 4He.*

We have also applied the floppy wire technique to study solid ^{4}He. Since the floppy wire technique measures the position of the wire, it is particularly well suited to measuring very low velocities. Furthermore, the device can be used in a high magnetic field which allows us to apply large driving forces, needed to move the wire through the solid. The cell and the device used for this work are shown in Fig. 17.

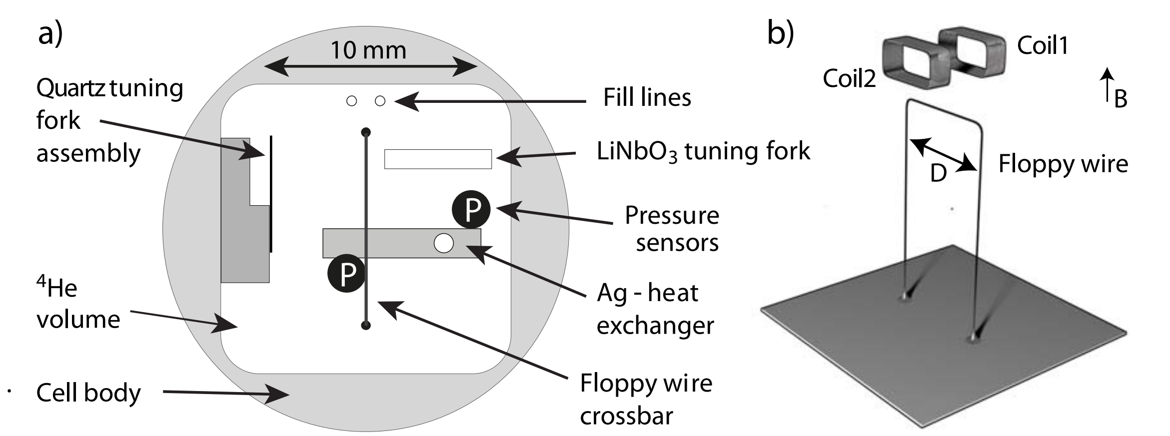


Fig.17. *The floppy wire device and cell used to study solid ^{4}He.*

At relatively low driving forces, we observe very slow motion of the floppy wire. In this case the wire moves as vacancies diffuse from the back to the front of the wire. These measurements, to be published, allow us to study the temperature dependence of the concentration of vacancies. This is particularly important as zero-point vacancies are predicted to give a mechanism for supersolidity at low temperatures.

At higher driving forces we see unexpected behaviour. In the hcp phase we see step-like motion, shown in Fig. 18. During a step, the wire velocity is very large, up to 1 mm/s. The abrupt motion of the wire separated by long intervals of time is reminiscent of the `stick-slip' mechanism of friction. We speculate that the wire may `stick' to complex networks of tangled dislocations in the solid. After some time, conditions prevail that allow the wire to cut through the tangle. There must be some stochastic mechanism which triggers this. The extremely high velocities observed during each slip suggest that the solid in the immediate vicinity of the wire must become extremely mobile, possibly fluid-like.

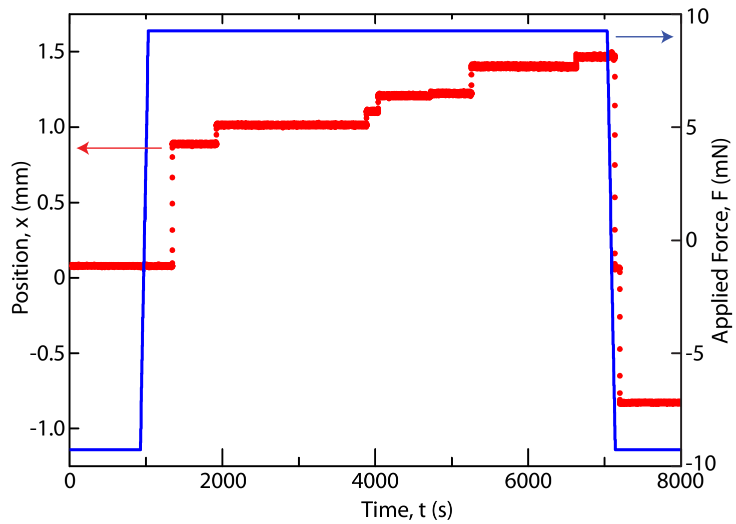


Fig.18. *Step-like response of the floppy wire in the hcp phase.*

We find very different response in the bcc phase. Here, there is no step-like motion, the wire moves smoothly in response to an applied force, the response is very non-linear and time dependent for large driving forces. The largest velocities observed are of order 1 μm/s. Remarkably, in the bcc phase the wire is not stationary after a large applied force is switched off. Instead, it relaxes very slowly towards some new equilibrium position. In one measurement we found that the velocity slows over a couple of days, reaching a near constant value of around 0.4 nm/s. The response gives a very clear demonstration of viscoelastic properties. When a large driving force is applied, the wire moves in the direction of the force, storing up elastic energy in the surrounding solid. When the force is removed, the elastic energy relaxes and the wire moves back towards where it came from. The very long time scales involved show that the motion is extremely dissipative and viscous-like. We note that viscoelastic effects have been considered recently on theoretical grounds in an attempt to explain the anomalous mechanical behaviour observed at low temperatures.

References to JRA3 Task 1:

[1] J.J. Hosio, V.B. Eltsov, P.J. Heikkinen, R. Hänninen, M. Krusius, V.S. L'vov, *Energy and angular-momentum balance in wall-bounded quantum turbulence at very low temperatures*, Nature Comm. **4**, 1614 (2013).

[2] J.J. Hosio, V.B. Eltsov, R. de Graaf, P.J. Heikkinen, R. Hänninen, M. Krusius, V.S. L'vov, and G. E. Volovik, *Superfluid vortex front at T→0: Decoupling from the reference frame*, Phys. Rev. Lett. **107**, 135302 (2011).

[3] J.J. Hosio, V.B. Eltsov, M. Krusius, J. Mäkinen, *Quasiparticle-scattering measurements of laminar and turbulent vortex flow in the spin-down of superfluid 3He-B*, Phys. Rev. B **85**, 224526 (2012).

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[1] J.J. Hosio, V.B. Eltsov, P.J. Heikkinen, R. Hänninen, M. Krusius, V.S. L'vov, *Energy and angular-momentum balance in wall-bounded quantum turbulence at very low temperatures*, Nature Comm. **4**, 1614 (2013).

[2] J.J. Hosio, V.B. Eltsov, M. Krusius, *Thermal detection of turbulent and laminar dissipation in vortex front motion*, J. Low Temp. Phys. **171**, 473 (2013).

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[5] R. Hänninen, *Dissipation enhancement from a single vortex reconnection in superfluid helium*, Phys. Rev. B **88**, 054511 (2013).

[6] *Crossover from hydrodynamic to acoustic drag on quartz tuning forks in normal and superfluid 4He,* D.I. Bradley, M. Clovecko, S.N. Fisher, D. Garg, E. Guise, R.P. Haley, O. Kolosov, G.R. Pickett, V. Tsepelin, D. Schmoranzer, L. Skrbek, Phys. Rev. B **85**, 014501 (2012). DOI: 10.1103/PhysRevB.85.014501

[7] *Turbulent drag on a low-frequency vibrating grid in superfluid 4He at very low temperatures,* D.I. Bradley, S.N. Fisher, A.M. Guénault, R.P. Haley, Mukesh Kumar, C.R. Lawson, Roch Schanen, P.V.E. McClintock, Lydia Munday, G.R. Pickett, Malcolm Poole, V. Tsepelin, Paul Williams, Phys. Rev.B **85**, 224533 (2012). DOI: 10.1103/PhysRevB.85.224533

[8] *Thermometry in Normal Liquid 3He Using a Quartz Tuning Fork Viscometer,* D.I. Bradley, M. Clovecko, S.N. Fisher, D. Garg, A.M. Guénault. E. Guise, R.P. Haley, G.R. Pickett, M. Poole, V. Tsepelin, J. Low Temp. Phys. **171**, 750-756 (2013).

[9] *The Onset of Vortex Production by a VibratingWire in Superfluid 3He-B,* D.I. Bradley, S.N. Fisher, A. Ganshin, A.M. Guénault, R.P. Haley, M.J. Jackson, G.R. Pickett, V. Tsepelin, J. Low Temp. Phys. **171**, 582-588 (2013).

[10] *Anomalous damping of a low frequency vibrating wire in superfluid 3He-B due to vortex shielding,* D.I. Bradley, M.J. Fear, S.N. Fisher, A.M. Guénault, R.P. Haley, C.R. Lawson, G.R. Pickett, R. Schanen, V. Tsepelin, J. Low Temp. Phys. to be published.

[11] *Response of a mechanical oscillator in solid 4He,* S.L. Ahlstrom, D.I. Bradley, M. Clovecko, S.N. Fisher, A.M. Guénault, E.A. Guise, R.P. Haley, O. Kolosov, M. Kumar, P.V.E. McClintock, G.R. Pickett, E. Polturak, M. Poole, I. Todoshchenko, V. Tsepelin, A.J. Woods, J. Low Temp. Phys. to be published.

[12] *Plastic properties of solid 4He probed by a moving wire: viscoelastic and stochastic behavior under high stress,* S.L. Ahlstrom, D.I. Bradley, M. Clovecko, S.N. Fisher, A.M. Guénault, E.A. Guise, R.P. Haley, M. Kumar, P.V.E. McClintock, G.R. Pickett, E. Polturak, M. Poole, I. Todoshchenko, V. Tsepelin, A.J. Woods, J. Low Temp. Phys. to be published.

[13] *Hysteresis, switching and anomalous behaviour of a quartz tuning fork in superfluid 4He,* D.I. Bradley, M.J. Fear, S.N. Fisher, A.M. Guénault, R.P. Haley, C.R. Lawson, G.R. Pickett, R. Schanen, V. Tsepelin, L.A. Wheatland, J. Low Temp. Phys. to be published.

Task 2: Investigating condensate-condensate phase boundaries as analogue branes (ULANC, CNRS, RHUL)

RHUL measurements: *Topological superfluidity of ^{3}He and SQUID NMR studies of a single nano-confined slab* The influence of confinement has been studied on the order parameter of superfluid ^{3}He in nano-structured geometries. This has involved the development of techniques to confine liquid ^{3}He within nanofabricated cavities of well-defined and characterised geometry, to cool the samples into the μK regime, and to characterise the samples with a NMR spectrometer of exquisite sensitivity. The sensitive SQUID NMR method was developed in close collaboration with PTB.

This work opens the possibility to study superfluid ^{3}He films of well-defined morphology for the first time. Experiments on a 700 nm cavity reveal the profound influence of confinement on the phase diagram [1]. Of particular relevance to this Task, this work provides experimental evidence for the stabilisation of the interface between A and B phases, and offers a new route for the control and manipulation of the A-B (brane) using confinement rather than magnetic field as the control parameter. Thus direct characterisation becomes possible with NMR of the defects which arise from controlled brane-antibrane annihilation events.

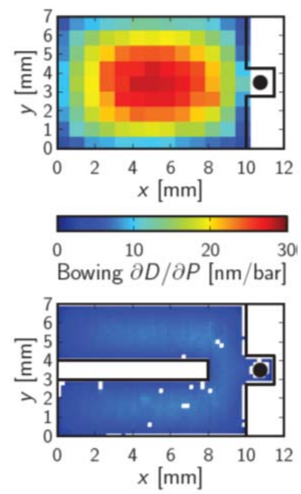

Fig. 1. *Comparison between the bowing as a function of pressure observed in the unsupported and supported silicon glass cells with 3 mm thick walls.*

A further discovery was that under confinement in a slab-like cavity inequivalent B-phase vacua could be stabilised in the same sample. This gives rise to a new topological domain wall between the two B-phase states [2]. We have clarified the pinning mechanism of this domain wall. This gives rise to the prospect of controlled fusion of such domain walls. This is of particular interest as the line, where the domain wall meets the cavity surface, is predicted to host Majorana fermions, whose gapless nature is protected against the application of a symmetry breaking magnetic field [Volovik. JETP Lett. **91**, 201 (2010)]. The experiments have characterised the planar distortion of the B-phase order parameter approaching the cavity walls; the measured distortion is consistent with the predictions of quasiclassical theory [2]. Quasiclassical theory also self-consistently determines the spectrum of Andreev surface bound states, identified as Majorana fermions. Within the consortium theoretical input from Volovik has played a crucial role in the interpretation of these experiments.

We have also prepared a cavity with height 1050 nm to search for the “striped” phase. This is a predicted superfluid phase with spatially modulated order parameter [Vorontsov and Sauls, Phys. Rev. Lett. **98,** 045301 (2007)]. The stability of this putative phase derives from the fact that in a cavity one of the “cosmic domain-walls” predicted by Volovik [Phys. Rev. **B37**, 9298 (1988)] may be energetically stable. We believe that the optimal conditions for observing this phase are at zero pressure (as close as possible to the weak coupling limit) and specular scattering. Based on previous work [1] the 1050 nm cell is the smallest stabilising the B-phase at zero pressure. It has been designed with significantly smaller pressure dependent bowing than the previous 700 nm cavity. The cavity profile has been determined using the optical technique described in the 36-month report; we achieve a precision of ± 2 nm over a pixel area 0.3 mm × 0.3 mm. To achieve fully specular surface scattering of quasiparticles we note that based on our own work and the prior work of other groups there is strong evidence that coating the surfaces *in situ* with a superfluid ^{4}He film will give close to the specular limit. We have fabricated a reliable cold valve, thermally anchored at a temperature of < 20 mK, which is superleak tight in order to stabilise the film.

This research opens the path to a new direction of research on superfluids in which confinement is used as the new control parameter. This should reveal a series of distinct physical phenomena of broad significance to the study of topological quantum matter. This includes possible new superfluid ground states, including the predicted striped phase, and Majorana surface bound states at the surface of the planar-distorted B-phase. New phases are also expected as the confinement is increased, in periodically structured confinement or in the presence of flow. In the reporting period we have fabricated silicon cavities with 100, 200 and 300 nm height (in collaboration with Jeevak Parpia at Cornell, using the Cornell Nanofabrication Facility and commercial facilities in the UK).

The techniques described in JRA4, using detection of NMR signals with microcoils coupled to a SQUID amplifier, will enable local probes in such geometries, the imaging of topological defects (domain walls and vortices), of relics from "collisions" between such defects, as well as providing local probes of Majorana surface excitations.

References to JRA3 Task 2:

[1] L.V. Levitin, R.G. Bennett, A. Casey, B. Cowan, J. Saunders, D. Drung, Th. Schurig, J.M. Parpia, *Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry,* Science **340**, 841 (2013).

[2] L.V. Levitin, R.G. Bennett, E.V. Surovtsev, J.M. Parpia, B. Cowan, A. Casey, J. Saunders, *Surface-induced order parameter distortion in topological superfluid 3He-B measured by non-linear NMR*, submitted to Phys. Rev. Lett.

[3] A. Shibahara, A. Casey, C.P. Lusher, J. Saunders, C. Assman, Th. Schurig, D. Drung, *Demonstration of nuclear magnetic resonance signals using microcoils coupled to low inductance superconducting quantum interference devices*, to be submitted to Appl. Phys. Lett.

[4] S. Dimov, R.G. Bennett, A. Corcoles, L.V. Levitin, R. Ilic, S.S. Verbridge, J. Saunders, A. Casey, J.M. Parpia, *Anodically bonded submicron microfluidic chambers,* Rev. Sci. Inst. **81**, 1 (2010).

Task 3: Horizons, ergo-regions, and rotating black holes (AALTO, CNRS)

SAS measurements: *Spin-wave analogue of event horizon in superfluid ^{3}He-B* - We have developed a theoretical model and performed the first experiments in the zero temperature limit studying black/white hole analogues, making use of a purely physical system based on the spin superfluidity of superfluid ^{3}He-B. The surface spin precession waves propagating on the background of the spin flow between two Bose-Einstein condensates of magnons in the form of homogeneously precessing domains were used as an experimental tool for simulating the properties of the black/white hole event horizon.

The concept of the experiment is simple. The experimental cell consists of two NMR towers connected by a channel. With continuous wave (cw) NMR techniques we a generate homogeneously precessing domain (HPD) in each tower and adjust the phase of precession in one domain relative to the second one. The difference in the phase of spin precession between the HPDs establishes a spatial gradient in the precession along the channel. This gradient results in the generation of a spin current flowing between the domains through the channel. By controlled subtle perturbation of one domain, the source domain, the resulting spin wave can be sent up-stream or downstream towards to the other domain, the detection domain. The velocity of the spin flow u and the group velocity of the spin wave c can be expressed as

$$u = \frac{5c_L^2 - c_T^2}{2\omega_{rf}} \nabla\alpha_{rf}, \qquad c^2 = \frac{(5c_L^2 + 3c_T^2)}{4\omega_{rf}} g\nabla BL.$$

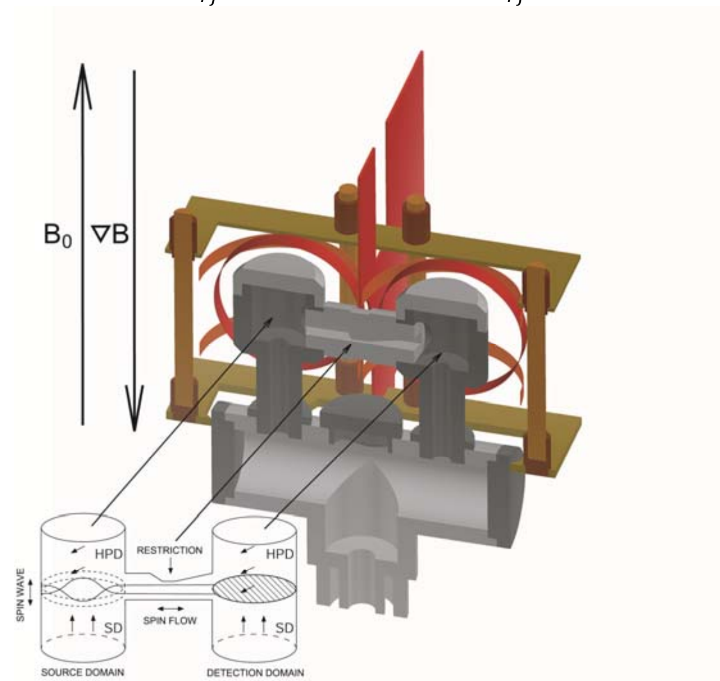

Fig. 1. *3D cross-section of the experimental cell arrangement and a schematic of the concept of the experiment.*

Here c_L and c_T denote spin velocities with respect to the field orientation, ω_{rf} is the angular frequency of the rf-field, g is the gyromagnetic ratio, L is the length of the HPD and *grad B* and *grad* α_{rf} are the field and phase gradients, respectively. One can show that the long spin-precession waves travelling along the surface of a thin layer of precessing and flowing spins are governed by the same equation as a scalar field in (2+1)-dimensional curved space-time. Thus, these disturbances (waves) experience the background as an effective space-time with the effective metric

$$ds^2 = c^2[-c^2dt^2 + (dx + udt)^2 + dy^2].$$

As implied by the above equation, "an event horizon" for the long spin-precession waves is formed where and when u^2 equals c^2.

The experiment was performed in a cell filled with helium-3 at a pressure of 3bar. The position of the domain wall was adjusted into the connecting channel and spin-precession waves were excited by 8 pulses at an appropriate frequency. The low frequency response from both HPDs (source and detection domain) for a particular value of the phase difference $\Delta\alpha_{rf}$ (i.e. the velocity of the spin flow) was extracted from the rf-signal by a technique based on the application of a rf-detector and a low frequency filter. Next, the signal was captured and stored with a digital oscilloscope for the data analysis.

Fig. 2 shows FFT spectra of the free decay signals for the source (upper) and detection (lower) domains. There are a few remarkable features which characterize their inter-dependences. Firstly, there are relatively strong signals detected in the source domain with an exception of a deep minimum in the region of $\Delta\alpha_{rf}$ corresponding to ~ 10^0. Secondly, weak signals are observed in the detection domain in the range of negative values of $\Delta\alpha_{rf}$ up to 10^0, above which a strong signal was measured. Thirdly, no signals within the experimental resolution were detected in the detection domain for values of $\Delta\alpha_{rf} > 20^0$.

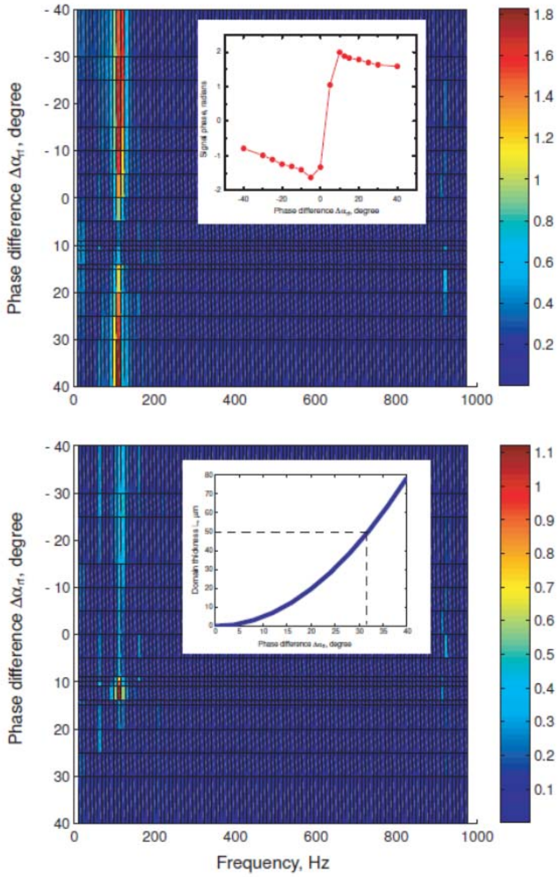

Fig. 2. *FFT spectra of free decay signals.*

For the negative values of $\Delta\alpha_{rf}$, the spin current flows from the source domain toward to the detection domain. Therefore, the excited surface spin waves are dragged by this flow to the detection domain, where they are detected, but with lower amplitude due to spin diffusion - the main process of the energy dissipation. The deep signal minimum in the source domain and corresponding maximum in the detection domain for $\Delta\alpha_{rf} \sim 10^0$ - 15^0 is due to zero spin flow between domains and this also leads to a resonance match. In fact, the source and detection domains represent two mutually connected resonance cavities, which are almost perfectly matched for zero spin flow. Therefore, when the surface spin waves are excited at this condition in the source domain, all the energy is transferred to and absorbed by the detection domain at once. For $\Delta\alpha_{rf} > 10^0$ the direction of the spin flow is reversed, i.e. the spin current flows toward the source domain and emitted surface spin waves propagate against this flow. The upper inset to Fig. 2 shows how the phase of the free decay signals in the source domain depends on $\Delta\alpha_{rf}$. There is an obvious gradual phase shift by ~ 180^0, when the direction of the spin flow is reversed back to the source domain. As one can see in the figure, there are no signals detected in the detection domain for $\Delta\alpha_{rf}$ above 20^0. Might this perhaps be an indication for the presence of a white hole horizon somewhere in the channel?

The bottom inset of Fig. 2 shows the coupled values of $\Delta\alpha_{rf}$ and L when they satisfy the event horizon condition (u^2 equals c^2). Here we have assumed that *grad* α_{rf} is localized and concentrated on the sharpest restriction in the channel, i.e. on a length of 0.5 mm. As it follows from the calculations, there is theoretical confirmation that the above mentioned experimental conditions (marked by dashed lines in the bottom inset) satisfy the criteria for the formation of the white horizon within the channel. Thus surface spin-precession waves sent from the source domain towards this horizon are blocked there, and never reach the detection domain. Details can be found in [1].

Our theoretical model and experimental data justify the claim that the spin precession waves propagating on the background of the spin flow between the two HPDs possess all physical features needed to elucidate the physics associated with the presence of the horizons, e.g. for searching for the emission of Hawking radiation in future measurements.

References to JRA3 Task 3:

[1] M. Kupka, P. Skyba, *Spin-wave analogue of event horizon in superfluid 3He-B*, submitted to Phys. Rev. Lett. (2013)

Task 4: Q-balls in superfluid ^{3}He (CNRS, ULANC, AALTO, SAS, RHUL)

Aalto measurements: In ^{3}He-B at temperatures below $0.2T_c$ Bose-Einstein condensates of magnon quasiparticles can be formed in a magnetic trap created in an external magnetic field by the inhomogeneous texture of the ^{3}He-B order parameter. Condensation is manifested by long-living coherent NMR signals. Unlike the condensates of cold atoms, magnon condensates in ^{3}He-B are able to modify their trapping potential since the order-parameter texture depends on the magnon density [1]. This property makes the magnon condensate analogous to a so-called Q-ball, which is a soliton of self-localized charge in the scalar field with attractive interaction [2]. In our experiments (Fig. 1) we have observed that the condensate with a large enough number of magnons moves from the pre-existing trap to another location forming a new potential trap. The new trap exists only while the condensate is localized inside it and thus displays the soliton nature of a ``true'' Q-ball.

The experimental signatures of this behavior are seen in Fig. 1. These include the observation of the precession frequency below the minimum possible for the condensate localized on the sample axis (middle panel) and the non-monotonous change of the signal amplitude with time (right panel). These effects can be explained using the fact that the axial pinch coil produces not only a field minimum in the axial direction, but also a small maximum in the radial direction [3]. In this geometry magnons can modify the texture in such a way that the axial symmetry of the system breaks and a non-central position of the condensate is energetically favored. We also observe this self-localization in the shifted minimum in numerical simulations (Fig. 2).

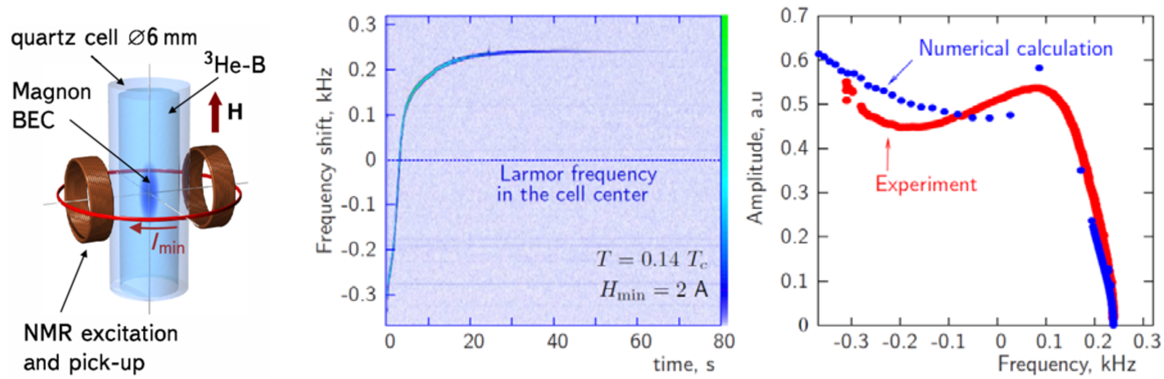

***Fig.1. (Left)** Experimental setup for the investigation of magnon condensation. The cylindrical sample boundary orients the order-parameter texture in such a way that a minimum of the spin-orbit interaction energy is created at the axis. The pinch coil with the current I_{min} creates a field in the opposite direction to the main polarizing NMR field **H.** This Zeeman minimum provides the trapping of magnons in the axial direction. **(Middle)** Time-dependent Fourier spectra of the signal from the NMR coil after a large number of magnons are pumped to the trap at time t = 0 show a peak with a gradually increasing frequency produced by coherent precession of the magnon condensate. **(Right)** The amplitude of the peak from the plot in the middle panel shows non-monotonous behaviour with time which is explained by the Q-ball model.*

Magnon condensates can be used as sensitive probes of the properties of superfluid ^{3}He at the lowest temperatures. In particular, we used the condensates to observe for the first time gravity waves on the free surface of ^{3}He-B [4]. The frequency of the coherent precession of the condensate is determined by the profile of the trapping potential, which depends on the geometry of the sample. When surface waves modify the geometry, the frequency of the precession changes, which is detected in the experiment, Fig. 3 (left). While the basic properties of the surface waves, like their frequencies, are found to follow the textbook, the dissipation-related properties at temperatures close to absolute zero turned out to be unexpected. We continue these investigations to determine whether the dissipation effects are connected to Majorana fermions, which are expected to cover the surfaces of a topological superfluid.

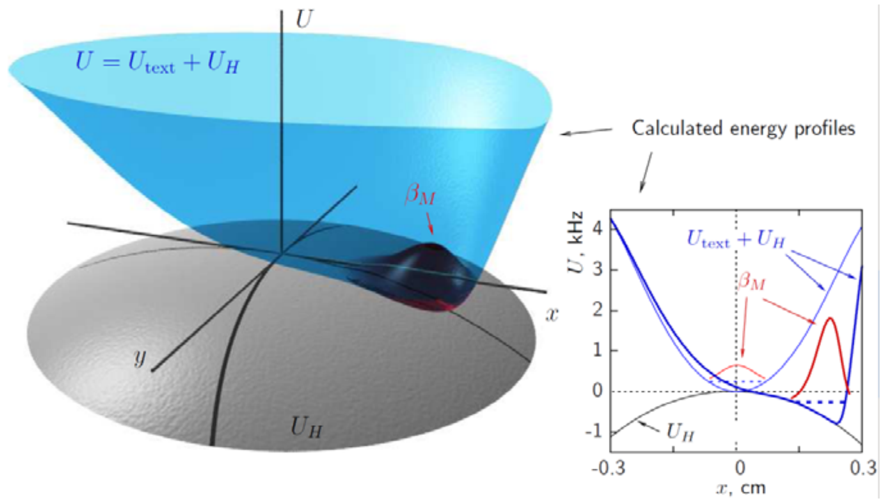

Fig. 2. *Numerical calculations on the relocation of the magnon condensate from the on-axis trap at small magnon number to a self-produced off-axis trap at large number of magnons. The radial dependence of the magnetic trapping potential U_H has a maximum at the sample axis. The magnon density is shown with the tipping angle of magnetization β_M. At small β_M the textural potential U_{text} exceeds U_H and provides trapping of magnons at the sample axis (thin lines on the plot on the right). At large β_M the textural potential is reduced to zero in the region of the condensate and thus the total energy decreases when the condensate shifts to an off-axis position (plot on the left and thick lines on the right plot).*

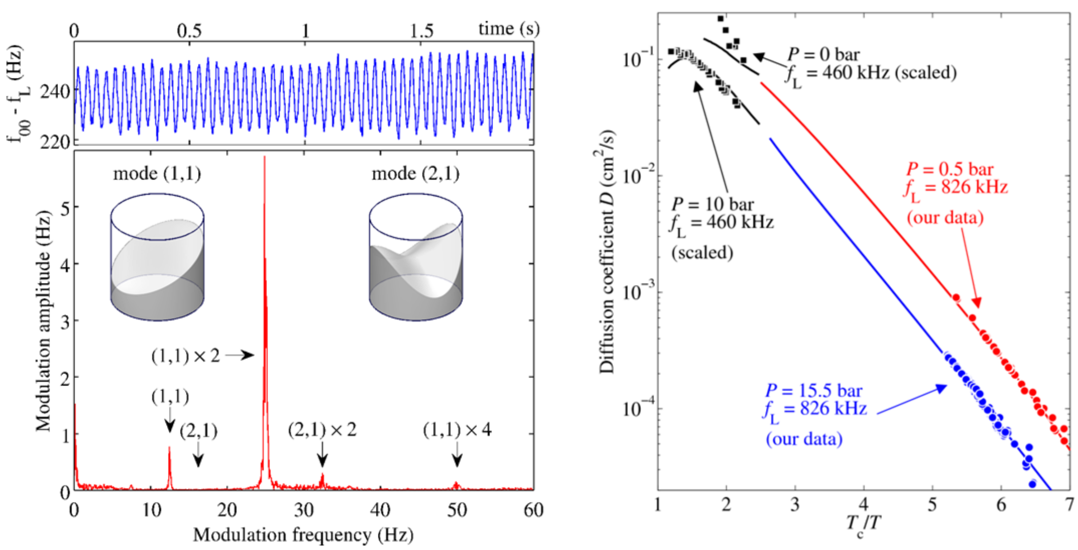

Fig. 3. (Left) *Frequency modulation of the magnetization precession of the magnon BEC, bordering to the free surface of ^{3}He-B, owing to surface waves. The upper record monitors the measurement of the precession frequency and the lower plot shows its Fourier transform. The signal is recorded at 0.15 T_c. The peaks in the lower plot correspond to the two surface modes, cartooned in the insets, and their harmonics (marked with ×n signs).* ***(Right)*** *Spin diffusion coefficient D vs T, as determined from the relaxation of magnon condensates (symbols). Our measurements are at $T < 0.2\ T_c$. Measurements from Ref. [5] at $T > 0.4\ T_c$ are rescaled to account for the difference in the Larmor frequency f_L, as D is inversely proportional to f_L at these temperatures. The lines are theoretical predictions from Ref. [6] without fitting parameters.*

Another important application of magnon condensates is the measurement of the relaxation of their spin precession. For the condensate localized in bulk ^{3}He-B, the temperature dependence of the relaxation is determined by the spin diffusion in the normal component [7]. In Aalto measurements using the spectroscopy of magnon levels in the trap the trapping potential can be precisely determined and thus the diffusion coefficient D can be extracted from the relaxation data [3], Fig. 3 (right). The results are in perfect agreement with the theoretical model. This means that such condensates (or Q balls) can be used as a sensitive thermometer working down to the lowest temperatures attainable in ^{3}He-B. Unlike popular thermometers using vibrating wires and forks, Q balls allow contactless determination of the temperature.

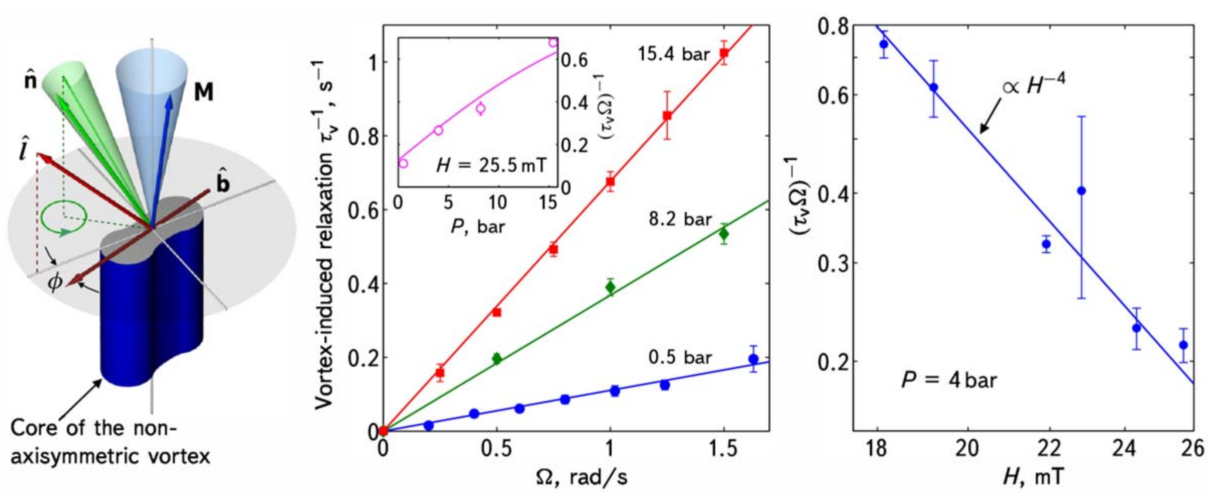

Fig. 4. *Vortex-core-induced relaxation of magnon condensates.* ***(Left)*** *The precessing magnetization* ***M*** *of the condensate causes the order-parameter axis vector* ***n*** *to precess, which couples to the anisotropy vector of the vortex core* ***b*** *via spin-orbit interaction. As a result the direction of* ***b*** *oscillates around the preferred direction set by the orbital anisotropy axis* ***l****. The oscillations of the non-axisymmetric core cause the excitation of the core-bound fermions which leads eventually to energy dissipation****. (Middle)*** *The dependence of the vortex-induced relaxation rate (symbols) on the rotation velocity (main panel) and pressure (insert) follow the theory predictions (lines). Here the theoretical lines have been scaled vertically to match the experimental points. The linear dependence on Ω comes from the vortex density while the increase of the relaxation with pressure is explained by the increase of the spin-orbit coupling which drives the core oscillations.* ***(Right)*** *Dependence of the relaxation on the magnetic field H also follows the prediction. The rapid decrease of the relaxation with decreasing H follows from the decrease of the force which pins the direction of* ***b*** *to* ***l****.*

In the rotating cryostat at Aalto the magnon condensates have been put in contact with the cores of quantized vortices in ^{3}He-B. It is found that vortex cores introduce magnetic relaxation which is approximately temperature-independent. Measurements of the relaxation as a function of pressure and magnetic field (Fig. 4) allow us to conclude that this relaxation is caused by vortex-core-bound fermion states, when the twisting motion of the non-axisymmetric vortex cores provides the coupling between the bound fermions and the magnon condensate. The core-bound fermions were predicted by Caroli, de Gennes and Matricon more than 50 years ago, however the 'minigap' energy spectrum of such states has never been directly observed. Measurements in ^{3}He-B may now provide a unique possibility to observe this spectrum, since the quasiparticle life time, estimated from the measurement of the mutual friction, becomes sufficiently long at the lowest temperatures, so that transitions between the individual quasiparticle levels in the core should be separated in the frequency domain.

Observation of the interaction between two independent precessing Q-balls

Aalto measurements: The long-lived coherent spin precession of ^{3}He-B at low temperatures around 0.2 T_c, while being a manifestation of Bose-Einstein condensation of spin-wave excitations or magnons in an experimentally controlled magnetic trap, can be used to study interactions between two independent boson condensates. By selective rf pumping the trap can be populated with a ground-state condensate or one at any of the excited energy levels. In the latter case the ground state is simultaneously populated by relaxation from the exited level, whereby a system of two coexisting condensates is formed. In Fig. 5 two coexisting Q balls are monitored. One is the ground state Q-ball and the second one is one of the excited Q-ball states. This unique experiment demonstrates the great potential of magnon BEC for testing problems of general physics nature.

Our measurements of the decay from the excited state (2,0) show faster relaxation than in the ground state. However, the measured relaxation time is in both cases much longer than the dephasing time of the linear NMR response (which is about 10 ms in the same conditions). The long life time of free precession is a prominent experimental signature of these coherent condensate states in general. In practice coherent precession in an excited state is accompanied by coherent precession in the ground state, but these two are independent phenomena: their relaxation time scales are quite different and, moreover, when pumping at the ground-state frequency, only the ground-state becomes occupied. In contrast, when the excited state is pumped, also the groundstate becomes populated via relaxation.

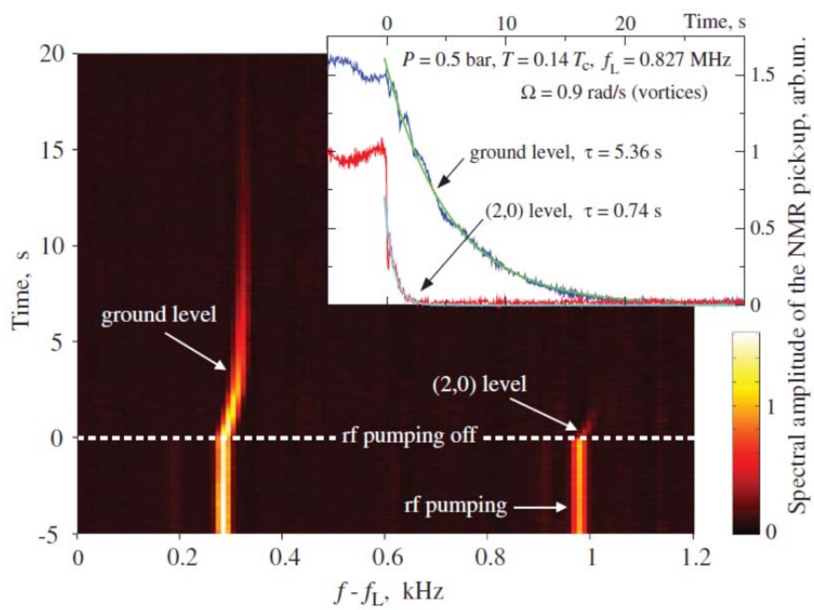

Fig. 5. *Decay of the magnon condensate, after rf pumping is switched off at t = 0. The amplitude of the Fourier transform of the signal from the NMR pick-up coil is shown in the main panel. Magnons are pumped to the (2, 0) level at t < 0, but the ground state is simultaneously populated owing to the decay of magnons from the excited state. At t > 0 both states decay and the frequency of precession increases as the trap responds to the decreasing magnon population. The inset shows the amplitudes of the two peaks and fits to exponential decay with time constant τ. The measurements have been performed at 0.14T_c in equilibrium rotation at 0.9 rad/s.*

BEC of magnons in superfluid 3He-B and symmetry breaking field

SAS measurements: States with a coherent precession of magnetization like a homogeneously precessing domain (HPD) or a persistently precessing domain, created in the superfluid

3He-B represent the macroscopic examples of the Bose-Einstein condensates of magnons. Once the magnons form one of these states, this many-magnon coherent quantum state is described by a "single-magnon wave function" (or an order parameter). A suitable external perturbation may cause the condensate to oscillate around the state of coherent precession, which demonstrates collective rigidity of the condensate against scattering a single magnon out of it. The states corresponding to free coherent precession of the magnetization are degenerate in the phase of precession, so there exist oscillations around such a state with a gapless dispersion relation, known as the Goldstone modes.

We show both experimental and theoretical results of the study of the spin density oscillations superposed on a homogeneously precessing domain in superfluid 3He-B in the presence of a high-frequency excitation field B_{RF}. We show that the presence of this field lifts the degeneracy of the precessing state with respect to the phase of precession, that is it violates the symmetry of the magnon condensate and the former Goldstone modes become non-Goldstone ones, as they acquire an energy gap in their spectrum. For example, the dispersion relation for the collective mode of order *n* has the form:

$$\omega^2 = \frac{3\Omega_B^2}{8\Omega_B^2 + 3\omega_{RF}^2}\left[\frac{4}{\sqrt{15}}\omega_{RF} g B_{RF} + \frac{1}{3}\left(5c_L^2 + 3c_T^2\right)\left(\frac{\xi_{m,i}}{R}\right)^2 + \frac{2}{3}\left(5c_T^2 - c_L^2\right)\left[\frac{(2n+1)\frac{\pi}{2}}{L}\right]^2\right],$$

where *R* and *L* correspond to the radius and the length of the HPD, respectively, $\xi_{m,i}$ are the roots of the Bessel equation, ω_{RF} is the Larmor angular frequency and the rest of the parameters represent the physical properties of superfluid ^{3}He-B. The presence of the "energy gap" as a result of the symmetry breaking field B_{RF} is obvious.

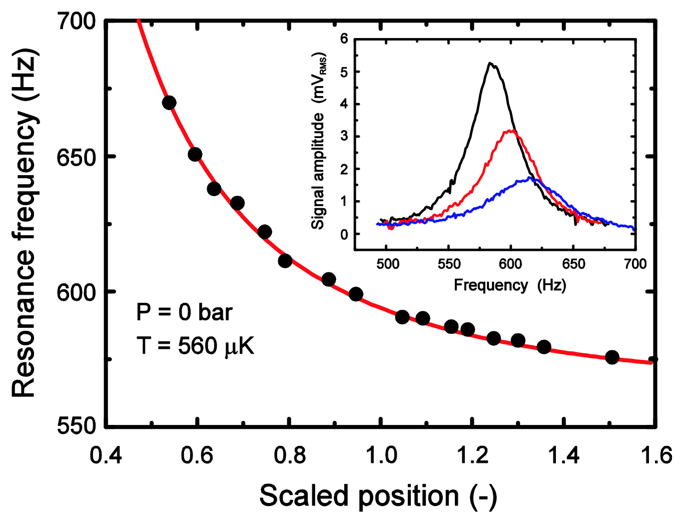

Fig. 6. *Resonance frequency of the HPD torsion mode as a function of the normalized length of the coherent domain. The* ***inset*** *displays the resonance characteristics for three different domain lengths.*

Fig. 6 shows an example of the experimental data, the resonance frequencies of the torsion oscillation mode as a function of the HPD length scaled by the cell length. The line has been fit to experimental data using the above equation. The inset to the figure presents the resonance characteristics of the excited torsion modes measured at three different lengths of the HPD. As the HPD becomes shorter the resonance frequency increases. However, simultaneously the oscillation mode becomes more dissipative reducing thus the amplitude of its oscillations. There are two main processes of energy dissipation: (i) spin diffusion and (ii) the Leggett-Takagi mechanism. The dissipation rate from spin diffusion depends on the HPD length as $1/L^2$, while the one via the Leggett-Takagi mechanism is linear with HPD length L. Therefore, the dissipation by spin diffusion dominates when the length of the HPD becomes shorter. Details can be found in Ref. [8].

Q-balls in superfluid ^{3}He and their spin relaxation properties

In Ref. [9] measurements were presented on Q balls or Persistently Precessing Domains (PPD), as they were called in that case, when excited by pulsed NMR at temperatures down to below $0.12T_C$. Reproducible PPDs were obtained in a field minimum, which could be manipulated and adjusted with an applied field gradient. When located far from the end wall of the NMR chamber, the PPDs were long lived, with lifetimes exceeding 1000 seconds at the lowest temperatures.

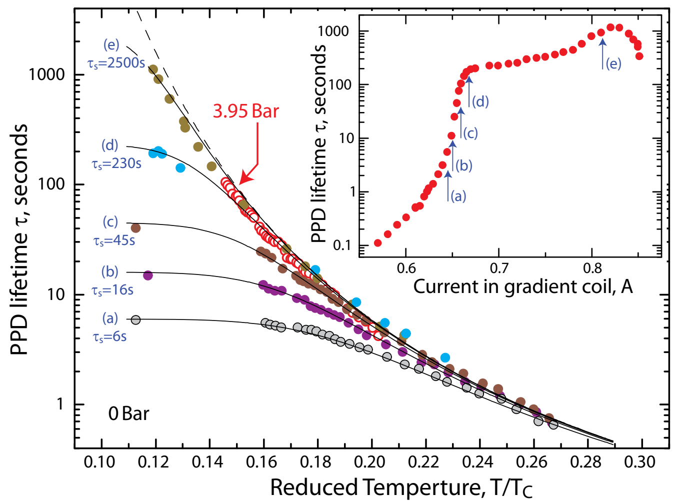

Fig. 7. Q-ball life time as a function of reduced temperature and in the ***inset*** *with the condensate in different positions in the sample cylinder.*

We compared the properties of the PPD with spin wave modes excited in the potential well generated by a field minimum combined with a flare-out orbital texture. The linear spin wave theory gives reasonable estimates for the size and the frequency shift of the PPD at late times, towards the end of its decay. However, the theory is clearly inadequate to describe the detailed time-dependent amplitude and frequency shift during the early decay. We have also presented calculations for the relaxation times for the linear spin wave modes due to the Leggett-Takagi and spin diffusion mechanisms. The Leggett-Takagi mechanism is found to be entirely redundant for these modes. Our estimates of the relaxation due to spin diffusion have a very similar magnitude to our measurements but with a slightly different temperature dependence.

As the PPD is moved towards the end wall of the cylinder an additional surface relaxation mechanism dominates at the lowest temperatures and the lifetimes are dramatically shortened. The additional relaxation does not significantly affect the amplitude of the PPD as a function of its frequency shift. This suggests that the amplitude - frequency response is an intrinsic property of the PPD. The surface relaxation time can be crudely estimated from general arguments, but it will be interesting to study the surface relaxation mechanism in more detail, especially in light of recent work on Majorana fermions at the free surface of 3He-B which may have interesting magnetic properties. Examples of our experimental data are shown in Fig. 7. The measured PPD life time at low temperatures displays both a bulk and a surface dissipation mechanism. The inset shows the life time with the Q ball at varying positions in the cylinder, which we manipulate by changing the magnetic field profile. Details can be found in Ref. 9.

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[1] S. Autti, Yu.M. Bunkov, V.B. Eltsov, P.J. Heikkinen, J.J. Hosio, P. Hunger, M. Krusius, G.E. Volovik, *Self-Trapping of Magnon Bose-Einstein Condensates in the Ground State and on Excited Levels: From Harmonic to Box Confinement*, Phys. Rev. Lett. **108**, 145303 (2012).

[2] Yu.M. Bunkov, G. E. Volovik, *Magnon Condensation into a Q Ball in 3He-B*, Phys. Rev. Lett. **98**, 265302 (2007).

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Microkelvin publications from the third 18-month period related to JRA3 Task 4:

[1] S. Autti, V.B. Eltsov, G.E. Volovik, *Bose analogs of MIT bag model of hadrons in coherent precession*, Pis'ma v ZhETF **95**, 611 (2012), [JETP Lett. **95**, 544 (2012)].

[2] Yu. M. Bunkov, E. M. Alakshin, R. R. Gazizulin, A.V. Klochkov, V.V. Kuzmin, V.S. L'vov, M.S. Tagirov, High Tc spin superfluidity in antiferromagnets, Phys. Rev. Lett. **108**, 177002 (2012).

[3] E.M. Alakshin, Yu.M. Bunkov, R.R. Gazizulin, A.V. Klochkov, V.V.Kuzmin, T.R. Safin, M.S. Tagirov, *Atomic type magnon Bose-Einstein condensation in antiferromagnet,* J. Phys.: Conference Series 400 032001 (2012)

[4] Yu.M. Bunkov, *Direct observation of Majorana quasiparticle heat capacity in superfluid 3He-B,* to be published, J. Low Temp. Phys. (2014)

[5] M.S. Tagirov, E.M. Alakshin, Yu.M. Bunkov, R.R. Gazizulin, S.A. Zhurkov, L.I. Isaenko, A.V. Klochkov, A.M. Sabitova, T.R. Safin, K.R. Safiullin, *Magnon BEC in antiferromagnets with Suhl-Nakamura interaction*, to be published, J. Low Temp. Phys. (2014)

[6] Yury Bunkov, The multi-Universe transition in superfluid 3He, J. Phys.: Cond. Matter **25** (2013)

[7] Yuri Bunkov, Andrei Golov, Victor L'vov, Anna Pomyalov, Itamar Procaccia, Evolution of neutron-Initiated micro-Big-Bang in superfluid 3He-B", Phys. Rev . B, submitted.

Task 5: ULTIMA-Plus: Dark matter search with ultra-low temperature detectors (CNRS, ULANC, HEID)

The development of ultralow temperature detectors for the search of dark matter is one of the main motivations of JRA3. This activity is concerned with probes and sensors which involve superfluid ^{3}He liquids, used both as refrigerant and sensing material, and also with new solid state sensors.

Heidelberg measurements: In Heidelberg, the focus has been on the development and realization of a novel multiplexing scheme suitable for magnetic calorimeters and improving the single pixel performance [1,2,3,4]. The schematic of the microwave SQUID multiplexer based dissipationsless, non-hysteretic rf-SQUIDs is shown in Fig. 1.

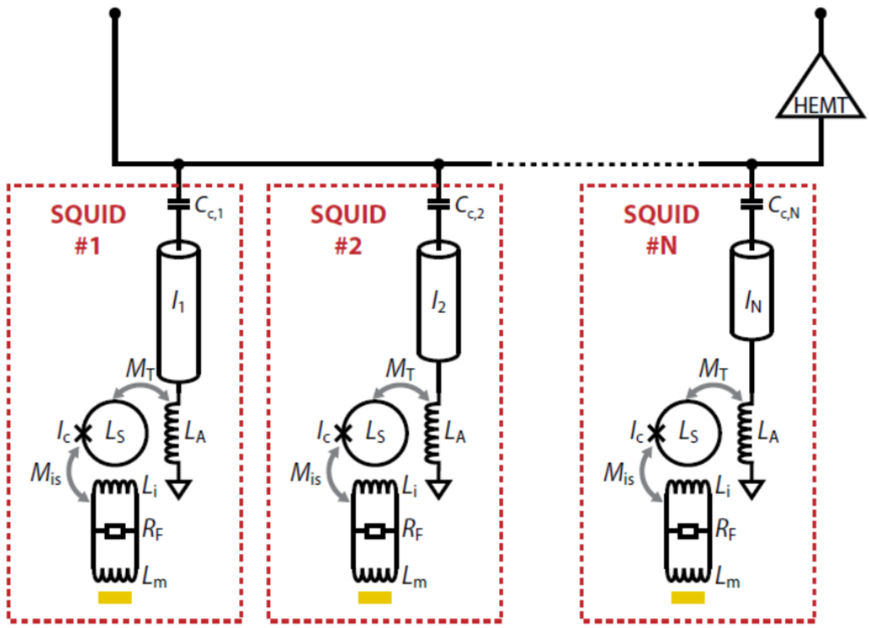


***Fig. 1.** Schematic of a rf-SQUID based microwave SQUID multiplexer.*

The microwave SQUID multiplexer is a frequency-domain multiplexing technique in which each detector is inductively coupled to a non-hysteretic, un-shunted rf-SQUID consisting of a closed superconducting loop with inductance L_s that is interrupted by a single Josephson junction with critical current I_c. For $\beta_L \equiv 2\pi L_s I_c/\Phi_0 < 1$ with $\Phi_0 = 2.07 \times 10^{-15} Vs$ being the magnetic flux quantum, the SQUID is non-hysteretic and behaves purely reactively, i.e. it can be modelled as a non-linear inductor whose value depends on the magnetic flux Φ threading the SQUID. For readout, the SQUID is inductively coupled to a load inductor terminating in a high quality superconducting $\lambda/4$ GHz transmission line resonator that is capacitively coupled to a transmission line. Since the load inductor is screened by the SQUID, its self-inductance depends on the magnetic flux Φ threading the SQUID, thus leading to a magnetic flux dependence of the resonance frequency of the associated resonator. For this reason, the circuit's resonance frequency gets shifted as the detector signal changes. To measure this frequency shift standard homodyne or heterodyne detection technique can be used. Due to the capacitive coupling scheme, many resonators, each having a unique resonance frequency, can be coupled to a common transmission line. This allows for the simultaneous probing of many SQUIDs by injecting a microwave frequency comb and continuously monitoring the amplitude and phase of each carrier signal.

In order to realize such a microwave SQUID multiplexer Heidelberg has developed a fabrication processes for non-hysteretic, un-shunted rf-SQUID and high quality superconducting $\lambda/4$

GHz transmission line resonators. The fabrication process for Josephson Junctions (JJ) of the rf-SQUIDs is sketched in Fig. X2 (left) and starts with an in situ deposition of a Nb/Al–AlO_x/Nb trilayer on a thermally oxidized Si substrate.

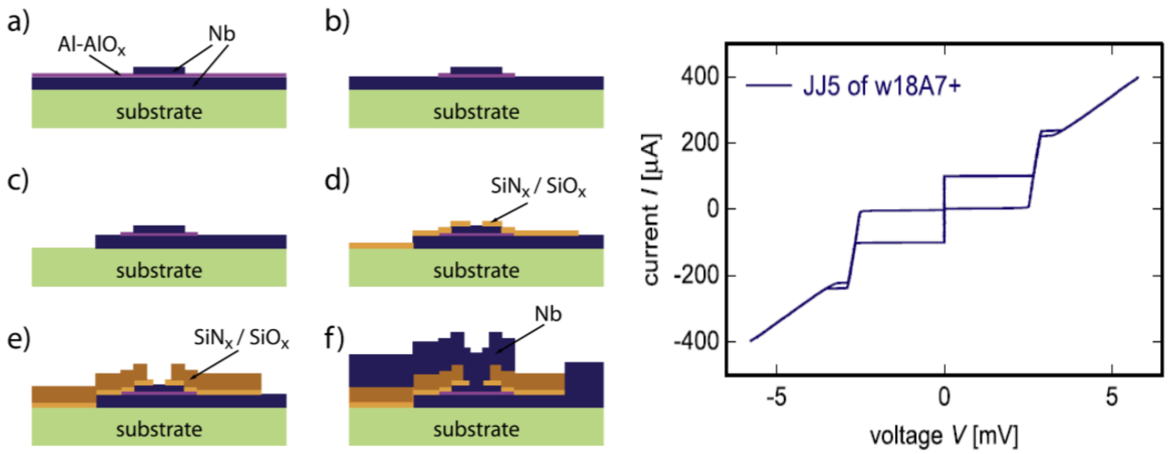


Fig. 2. *(**Left**) Schematic overview of different steps of the JJ fabrication process. (a) After patterning and ICP-RIE of the counter-electrode. (b) After patterning and wet-chemical etching of the Al layer. (c) After patterning and ICP-RIE of the base electrode. (d) After deposition of the first insulation layer. (e) After deposition of the second insulation layer. (f) After deposition of the final Nb wiring layer. (**Right**) I–V-characteristic of a square JJ with a design side length of l = 4.56 μm and a critical current density of j_c ~ 500 Acm^{-2} measured at 4.2 K.*

Fig. 2 (right) shows a representative I–V-curve of a JJ that was produced with the depicted fabrication process. It can be seen that excess currents do not occur and that the subgap leakage is low. For this specific example, the characteristic voltage V_m is 37 mV and indicates together with a resistance ratio $R_{subgap} = R_n$ of 28 the high quality of this JJ [1].

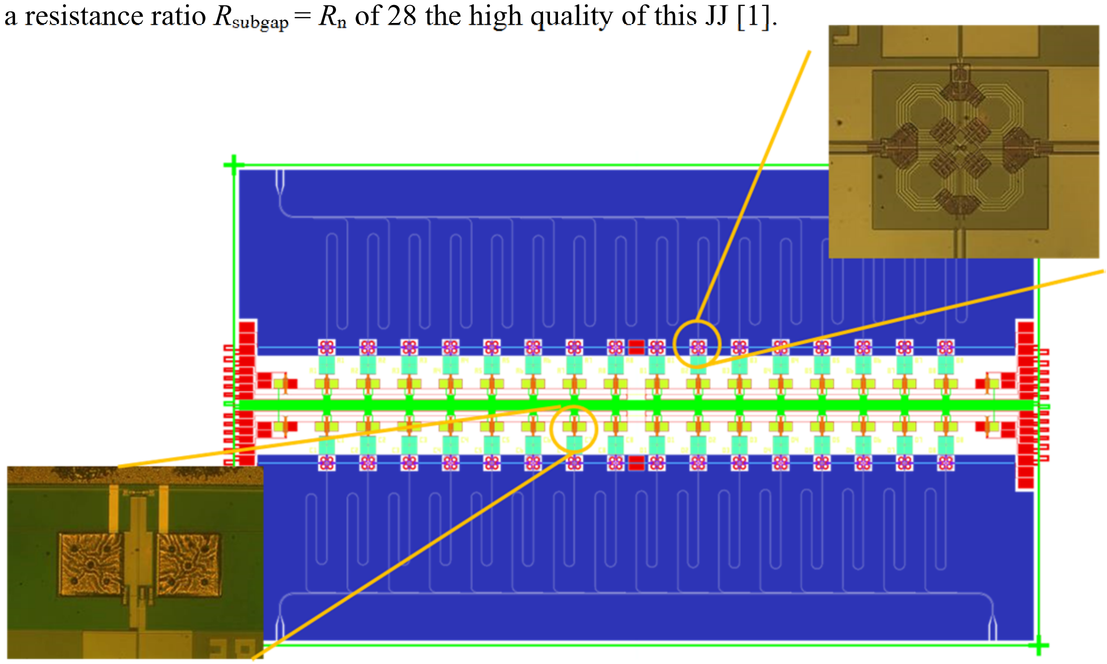


Fig. 3. *Layout of a 32 × 2 pixel magnetic calorimeter array with superconducting λ/4 GHz transmission line resonators and rf-SQUIDs (center). Photographs of a magnetic calorimeter with two pixels (left) and an rf-SQUID (right) on the actually fabricated detector chip.*

Recently, a fully functional two-dimensional magnetic calorimeter array (32 × 2 pixels) was fabricated in Heidelberg with integrated microwave SQUID multiplexer. In Fig. 3 we show a schematic of the layout together with photos of the magnetic calorimeter and of one of the rf-SQUIDs on the fabricated chip.

The performance of this magnetic calorimeter array has not yet been characterised in detail, but several of the individual components have been tested and showed the expected properties. In particular, this array is foreseen to demonstrate the suitability of the microwave SQUID multiplexing scheme and to act as a first small-scale electron capture experiment on ^{163}Ho to determine the neutrino mass [2,3,4].

In terms of single pixel performance there has been significant progress. With a new generation of sandwich-type magnetic calorimeters an unmatched energy resolution of 1.6 eV at 6 keV has been obtained. A spectrum of a ^{55}Mn source taken with this detector is shown in Fig. 4.

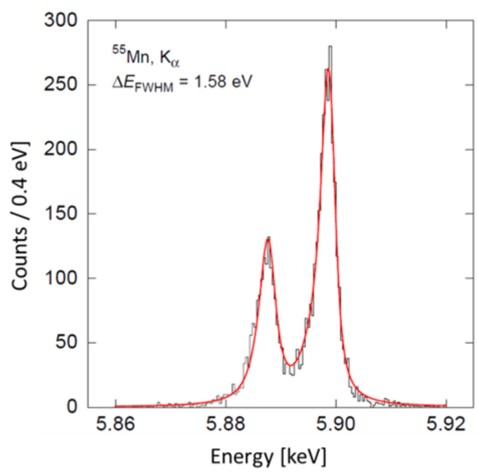


Fig. 4. *^{55}Mn Kα line acquired with the prototype sandwich detector (histogram), natural line shape convolved with a Gaussian of E_{FWHM} = 1.58 eV (solid red line).*

CNRS-Grenoble measurements: Ultra-low temperature ^{3}He probes

The Grenoble group has developed micro and nano-mechanical devices (MEMS and NEMS) for superfluid ^{3}He research. The aim is twofold:

- Replacement of existing technology (the well-known vibrating wires) with better probes, of similar sizes.
- Fabrication of new devices, which cannot be made with conventional techniques, such as small and complex matrix designs for detector arrays (e.g. for particle/radiation measurements in astronomy).

The second point is a straightforward consequence of the versatility of microfabrication. The difficulty lies in fact in the compatibility between ultra-low temperature cooling techniques and silicon-based devices. The main questions are whether these silicon devices will cool down to microkelvin temperatures and will they indeed be better than the standard devices? The first answers have now been obtained through a Lancaster-Grenoble collaboration, with a Microkelvin Transnational Access experiment, which was performed in Lancaster.

A Grenoble device similar to the one in Fig. 5 was placed in a Lancaster-type demagnetization cell. The cryostat was then cooled down to the lowest achievable temperature, and the interaction between the mechanical device and superfluid ^{3}He was recorded. The main information retrieved from these measurements is the viscous damping, which we compare to the one measured with a standard vibrating wire in Fig. 6.

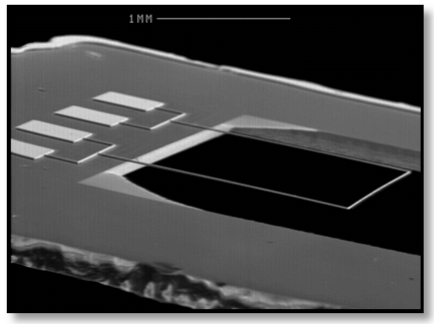


Fig. 5. *MEMS device for ^{3}He experiments*

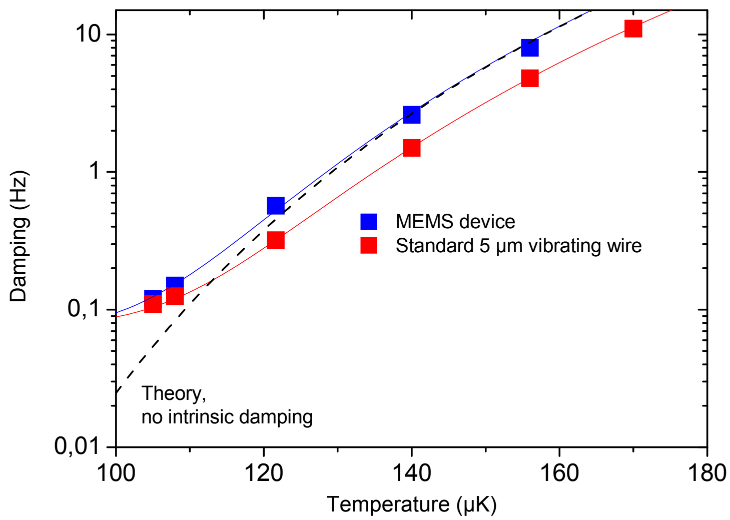


Fig. 6. *Comparison of measured damping of MEMs and standard superconducting wire resonators in superfluid ^{3}He.*

The result is clear: MEMS structures do cool down and their measured sensitivity is the same as that of a standard vibrating wire (in this temperature range where the quasi-particle density falls off exponentially with temperature, as shown by the dashed line). Furthermore, the MEMS curve lies about a factor of two above the vibrating wire, proving its higher sensitivity to the quasiparticle density. A lot of room is still available for optimization, since this particular structure is about t = 10 µm thick, while the sensitivity factor goes as $1/t$. In principle, for devices of same dimensions, the MEMS should be about 4 times more sensitive. And still smaller structures can of course be made.

MEMS devices can thus indeed be thought of as ultimate thermometers in superfluid ^{3}He. As such, they are the obvious tools for bolometry and particle detection in this medium. The limiting factor will finally, as for standard wires, be the intrinsic damping of the device. At 4.2 K, their mechanical properties are far better than those of a conventional vibrating wire. However, in Fig. 6 one can see that both probes seem to saturate at around the same value of 0.1 Hz, which is at least an order of magnitude higher than the expected intrinsic damping of the MEMS. The reason for this is still an open and needs further experiments.

Elementary excitation spectrum of liquid ^{3}He

CNRS-Grenoble measurements: Outstanding experimental results were obtained during the previous period using inelastic neutron scattering to investigate the elementary excitations of two-dimensional (2D) ^{3}He (films one-atom thick) at very low temperatures [5]. The data showing for the first time the existence of a roton collective excitation mode in a Fermi liquid at high wave-vectors, together with calculations specially developed in the framework of a microscopic many-body dynamical theory (University of Linz), were published in the journal "Nature" in March 2012.

During this reporting period we obtained additional beam time May 9 – 15, 2013, on the instrument IN5, which can be adjusted to gain resolution in the region of interest. The data cover 2D liquid ^{3}He, but also extend to higher densities, in the 4/7 spin-liquid phase. We are currently analysing the data.

Using a different theoretical technique (Quantum Monte Carlo), Nava and collaborators calculated very recently the ***dynamic structure factor*** for ^{3}He in two dimensions (M. Nava, D. E. Galli, S. Moroni, and E. Vitali, Phys. Rev. B **87**, 144506, 2013). These results are in excellent agreement with the experimental data, in spite of the particularly elaborate nature of the measurements and calculations. A new collaboration with the Italian group will be started, to explore 2D ^{3}He at different densities.

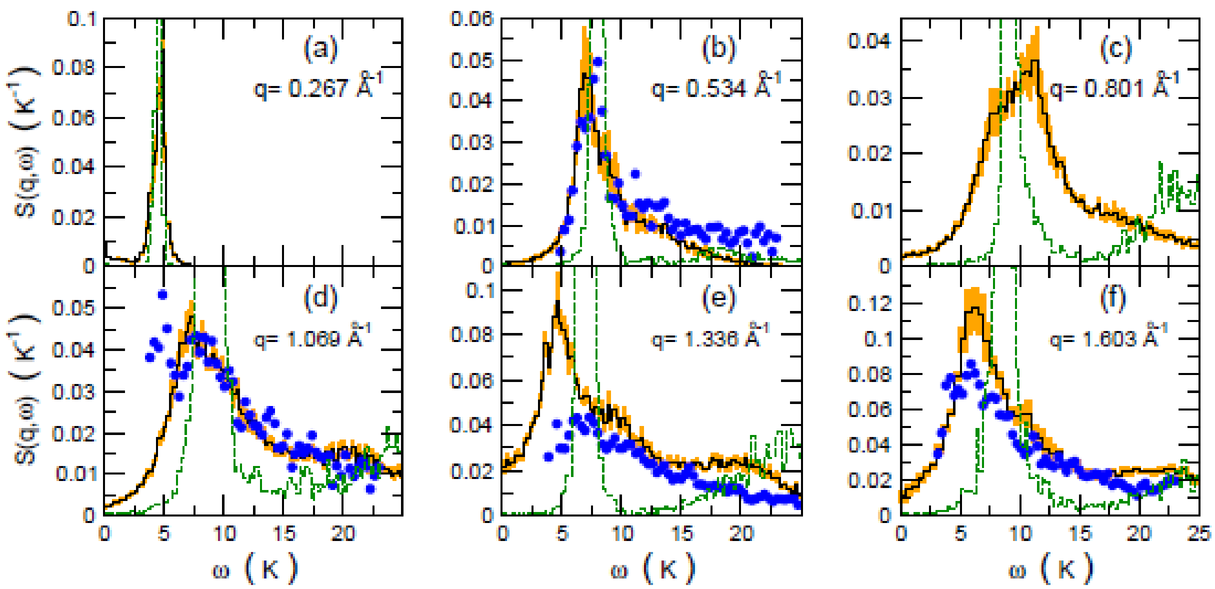


Fig. 7. *Comparison between our experimental data on 2D liquid 3He and the Quantum Monte Carlo calculations of Nava et al. calculated for the densities and wave-vectors used in the experiment (Yellow curve: Quantum Monte-Carlo; Blue dots: experiment; Dotted line: mass 3 bosons*

The static properties can be obtained by integration of the dynamic structure factor over the energy [6]. Given the absence of elastic contributions in a quantum fluid, and the accumulation of the background signal precisely around zero energy, we could obtain the first measurement of the static structure factor of 2D ^{3}He. Good agreement is found between the static structure factor deduced from the experiment and theoretical models, Quantum Monte Carlo simulations and Dynamical Many Body Theory (DMBT). A preliminary paper has been published [7]. Work is in progress to analyse new experimental data at higher energies, while the theory groups (Linz and Barcelona) are developing the theoretical understanding. Our results on 2D ^{3}He have been selected by the Institut Laue-Langevin (ILL) as a “highlight“ and had substantial coverage in the general media.

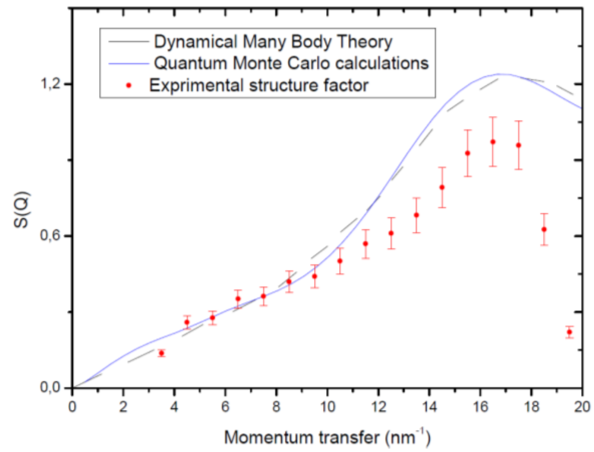


Fig. 8. *First experimental results for the structure factor of 2D ^{3}He. The difference with theory at high wave-vectors is due to a finite energy cut-off in the experiment. New data at higher energy will allow a more detailed quantitative comparison in this region.*

The lowest-lying excitation mode of a quantum fluid only accounts for a fraction of the spectral weight. Higher energy excitations, often described as “multiparticle excitations”, exist above the photon-roton mode. We have investigated these modes in liquid ^{4}He on the IN5 time-of-flight spectrometer of the ILL, in a large energy and wave-vector range. The measurements were performed at very low temperatures (in a dilution refrigerator, $T < 100$ mK), for several pressures between the saturated vapour pressure and the solidification pressure. The data are currently being analysed, but it is already clear that excellent agreement is found with the dynamical many-body theory. For interacting bosons, the present challenge is a quantitative ab-initio description, and multi-excitations allow stringent tests on the theories, well beyond the simple phonon-roton spectrum description.

References to JRA3 Task 5:

[1] *Characterization of the reliability and uniformity of an anodization-free fabrication process for high-quality Nb/Al–AlOx/Nb Josephson junctions,* S.Kempf, A. Ferring, A. Fleischmann, L. Gastaldo, C. Enss, Supercond. Sci. Technol. **26**, 065012/1-10 (2013)

[2] *Characterization of low temperature metallic magnetic calorimeters having gold absorbers with implanted 163Ho ions,* L. Gastaldo, PC.-O. Ranitzsch, F. von Seggern, J.-P. Porst, S. Schäfer, C. Pies, S. Kempf, T. Wolf, A. Fleischmann, C. Enss, A. Herlert, K. Johnston, Nucl. Inst. Meth. A **711**, 150-159 (2013)

[3] *Multiplexed readout of MMC detector arrays using non-hysteretic rf-SQUIDs*, S. Kempf, M. Wegner, L. Gastaldo, A. Fleischmann, C. Enss, submitted to J. Low Temp. Phys. (2013)

[4] *The electron capture 163Ho experiment ECHo,* L. Gastaldo, K. Blaum, A. Doerr, C. E. Düllmann, K. Eberhardt, S. Eliseev, C. Enss, A. Fäßler, A. Fleischmann, S. Kempf, M. Krivoruchenko, S. Lahiri, M.Maiti, Yu. N. Novikov, P. C.-O. Ranitzsch, F. Simkovic, Z. Szusc, M. Wegner, submitted to J. Low Temp. Phys. (2013)

[5] *Observation of a roton collective mode in a two-dimensional Fermi liquid,* Henri Godfrin, Matthias Meschke, Hans-Jochen Lauter, Ahmad Sultan, Helga M. Böhm, Eckhard Krotscheck, Martin Panholzer, Nature **483**, 576–579 (2012), doi:10.1038/nature10919

[6] *Static structure factor of two-dimensional liquid ^{3}He adsorbed on graphite*, A. Sultan, M. Meschke, H.-J. Lauter, H. Godfrin, J. of Low Temp. Phys. 169, 367-376 (2012); DOI: 10.1007/s10909-012-0649-9

[7] *Two-dimensional Fermi liquids sustain surprising roton-like plasmons beyond the particle-hole band,* A. Sultan, H. Godfrin, M. Meschke, H.-J. Lauter, H. Schober, H. Böhm, R. Holler, E. Krotscheck, M. Panholzer, J. Phys.: Conf. Series **340**, 012078 (2012) - Proceedings of the 5th European Conference on Neutron Scattering

Highlights

- First measurements of the thermal dissipation from turbulent vortex motion in ^{3}He-B in the $T \to 0$ limit.
- Development of new measurement techniques for the $T \to 0$ limit in ^{3}He-B: `floppy wire' drive for generating flow over a range of frequencies, quartz tuning fork arrays, microfabricated silicon resonators, Q-ball NMR mode, and SQUID-amplifier-based NMR of nano-dimensioned ^{3}He samples.
- New interpretation of low-temperature coherent NMR precession in the Q-ball mode and systematic measurements of its relaxation.
- First NMR measurements of ^{3}He pairing states between accurately parallel plates with sub-micron separation.
- Observation of a roton-like collective mode branch in 2-dimensional ^{3}He Fermi liquid.

Deviations from work plan

No significant deviations from the work programme in Annex I (after 2nd amendment, as approved 13 March, 2012).

Use of resources

Follows the grant plan in Annex I (after 2nd amendment, as approved 13 March, 2012).

JRA4 Report

Work package: **Novel methods and devices for ultra-low temperature measurements**
Reporting Period: **last 18-month period from 1.4.2012 to 30.9.2013**
Activity leader: **Christian Enss**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead bene-ficiary	Estimated person months	Nature	Dissemi-nation level	Delivery date
D2	Report on the performance of high resolution µSQUID scanning magnetometer	JRA4	CNRS	16	R	PU	48 **delivered**
D8	Report on 10 mK GaAs quantum dot thermometer (Task 3)	JRA4	BASEL	10	R	PU	12, 24 (36,48) **delivered**

Expected milestones on the reporting period

Mile-stone no.	Milestone name	WP no.	Lead beneficiary	Delivery date	Comments
M2	Realization of a high resolution µSQUID scanning magnetometer	JRA4, Task 1	CNRS	42	**achieved**
M5	NMR at frequencies up to 100 MHz with wide bandwidth SQUID amplifiers	JRA4, Task 2	RHUL	42	**achieved**
M10	New temperature scale for ultralow temperatures	JRA4, Task 3	PTB	42	**achieved**

Objectives

The goal is to develop novel methods for high-sensitivity low-noise measurement at µK temperatures. Contactless measurement techniques with SQUID amplifiers at the quantum limit are central. Sub-mK thermometry and minituarization of samples and sensors are additional important drivers.

Task 1: Contactless measurement of thermal dielectric, magnetic and acoustic properties (HEID, CNRS, AALTO, PTB, UL)

In this 18-month reporting period Heidelberg (HEID) has further refined the techniques of polarization echo measurements. This method is the basis of investigating the de-coherence of two-level systems (TLS) and the specific heat of amorphous solids at ultralow temperatures. During the previous 18 month period it was already reported that for the first time the specific heat of a dielectric glass was measured using this technique. Recently, detailed studies of the de-coherence and relaxation behavior of the optical glass BK7 has been carried out that led to a thorough understanding of the decay mechanism and the discovery of a de-coherence free subset of TLS [3,4]. Two different pulse sequences have been used in these experiments, which are shown schematically in Fig. 1.

Owing to vast improvements in the stability and sensitivity of the setup it became possible to detect polarization echoes after a decay of five orders of magnitude in both two pulse and three pulse echo experiments. This allowed us for the first time to study the behavior up to delay times t_{12} and t_{23} of a millisecond or more. Comparing the experimental data to the expectations from spectral diffusion, a decay mode that is believed to govern the de-coherence of TLS in amorphous solids, it could be shown that at long delay times the decay becomes much weaker than predicted theoretically. Figs. 2 and 3 show the experimental results for both two and three pulse echoes.

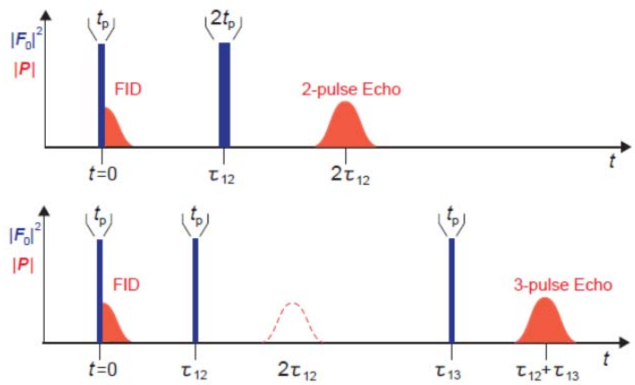
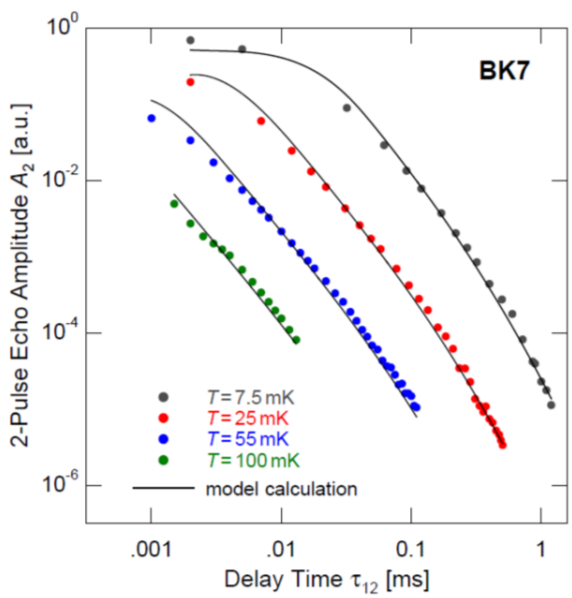


Fig. 1: *Pulse sequences of two (**top**) and three (**bottom**) pulse echoes. The variable F_0 denotes the electric field strength of the excitation pulses, P the detected polarisation and FID the free induction decays.*



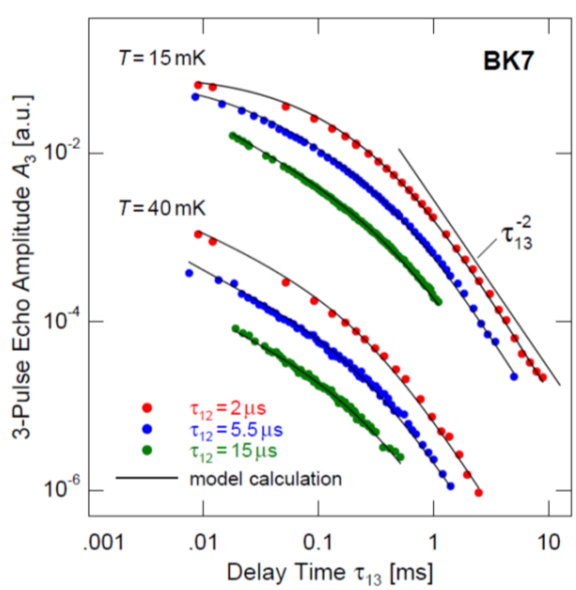


Fig. 2: *Amplitude of two pulse echoes generated at a frequency of about 1 GHz in BK7 as a function of the delay time τ_{12} at different temperatures. The lines represent theoretical fits described in [3,4].*

Fig. 3: *Amplitude of three pulse echoes generated at a frequency of about 1 GHz in BK7 as a function of the delay time τ_{13} for three different delay times τ_{12} at 15 mK and 40 mK. The lines represent theoretical fits described in [3,4].*

A detailed analysis of the data showed that this discrepancy can be overcome by introducing a particular distribution of TLS deformation potentials. In collaboration with the theory group of A. Burin from Tulane University a quantitative description of the data for all temperatures and delay times was worked out. Without going into details it should be pointed out that the different sets of data for two and three pulse sequences have been fitted with an expanded theory of spectral diffusion using the same parameter values. All parameters used in the calculations have reasonable values and agree with other experiments. The quality of the fit can be seen by the solid lines in Figs. 2 and 3.

A second focus in Heidelberg was the thermal conductivity of different bulk metallic glasses. As discussed in the previous 36-month periodic report, a new contact free method was used to determine the thermal conductivity of such pure conductors at ultra-low temperatures. Within the present 18-month reporting period several bulk metallic glasses have been investigated using this new technique. Fig. 4 shows the results for two superconducting bulk metallic glasses, which have transition temperatures of 665 and 1085 mK, as clearly indicated by a kink in the thermal conductivity. The measurements have been carried out over five orders of magnitude in temperature showing a very similar behavior for both metallic glasses. There are, however, subtle differences, which are not understood at this point. Theoretical work is going on right now to obtain at least a semi-quantitative picture of these new results.

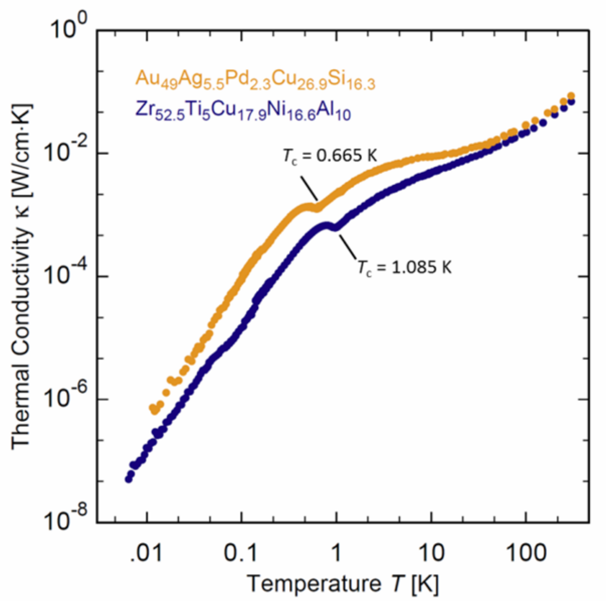


Fig. 4. *Thermal conductivity of two superconducting bulk metallic glasses as a function of temperature [5].*

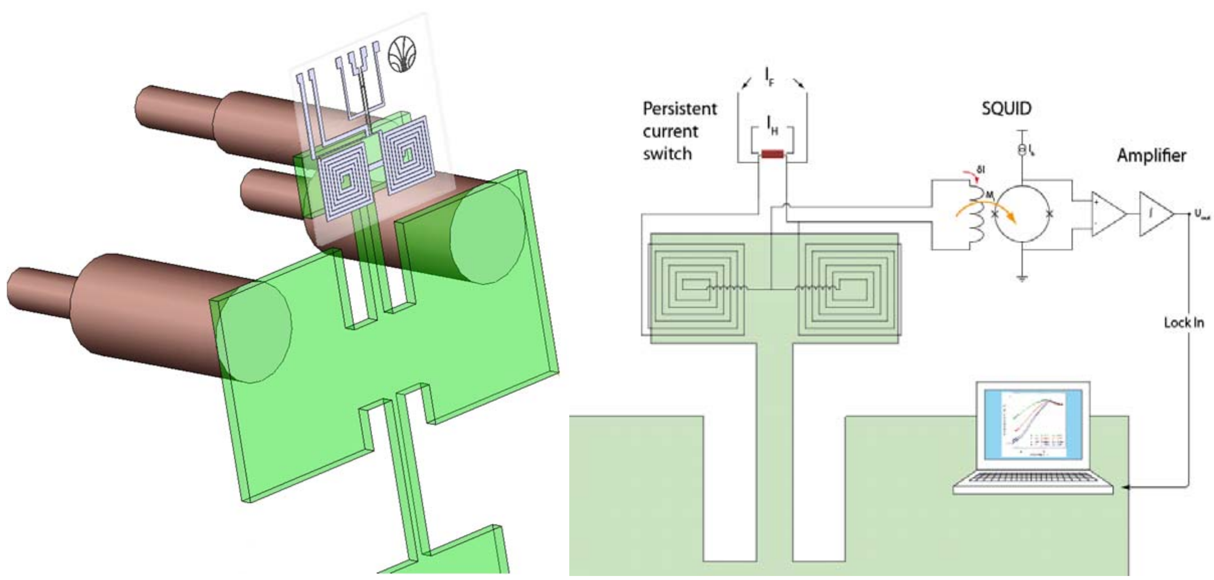


Fig. 5. *Schematic of the inductive detection principle. In light green the glass paddle oscillator is shown which is on one side coated with a thin superconducting film.* ***(left)*** *Geometry of the setup indicating the position of the meandering coil and the electrodes for capacitive drive and the displacement detection.* ***(right)*** *Paddle oscillator with meandering coil and a scheme of the readout electronics.*

In addition, a new contact free inductive method has been developed in Heidelberg to measure the elastic susceptibility of amorphous solids at low temperatures. It is based on the detection of the magnetic flux distribution produced by a current running in a meandering coil that is part of a superconducting flux transformer hocked to a sensitive dc-SQUID. The change of the flux distribution is caused by the motion of an elastic paddle oscillator coated with a superconducting film relative to the meandering coil. The detection principle is visualized in Fig. 5.

With this new technique a vast improvement in the resolution of both sound velocity and sound absorption measurements have been obtained. As an example data taken with this method of the superconducting bulk metallic glass $Zr_{55}Cu_{30}Al_{10}Ni_5$ are shown in Fig. 6. The quality of the data in terms of signal to noise is very high and is unmatched by previous techniques. This allows operating the oscillator at extremely small drive voltage thus limiting at the lowest temperatures effects caused by heating and non-linearity. One striking aspect of the new measurements is that the data obtained by evaluating single resonance curves at a particular temperature are in excellent agreement with the data measured monitoring the resonance frequency and amplitude continuously while cooling and warming.

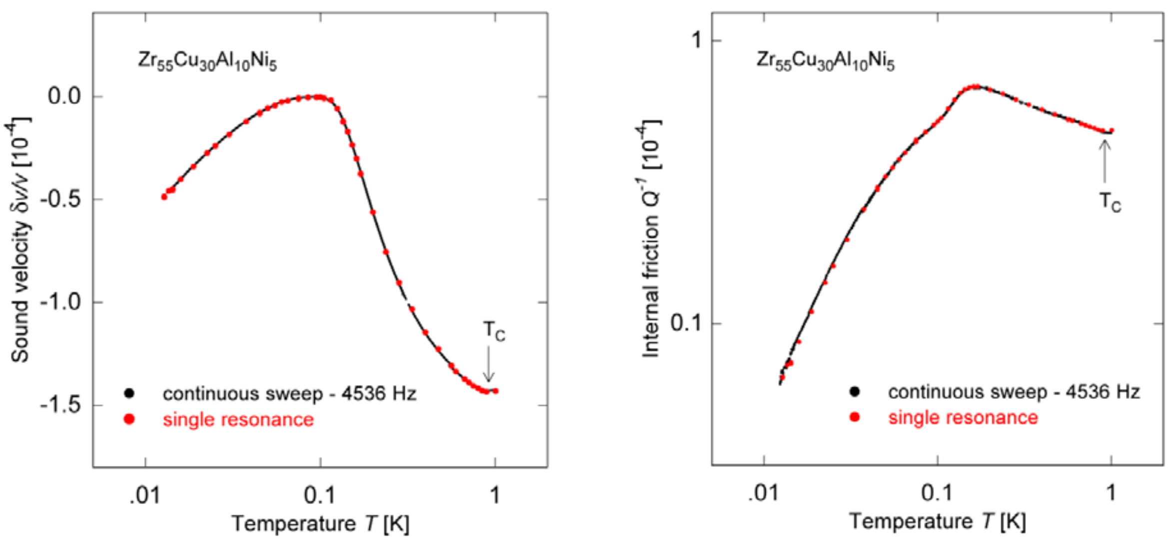


Fig. 6. *Sound velocity (**left**) and internal friction (**right**) of the bulk metallic glass $Zr_{55}Cu_{30}Al_{10}Ni_5$ as a function of temperature at 4.536 kHz.*

Nano-Mechanical Oscillators

CNRS-Grenoble continued to develop new micro and nano-mechanical devices for low temperature studies. One part of the work has been focusing on the measuring schemes, with the goal to develop new measurement possibilities. After having studied (nonlinear) parametric amplification, a new highly sensitive technique which transduces displacement into a frequency measurement has been developed [6].

This is presented in Fig. 7. For different drive amplitudes, one can reconstruct the resonance line shape, up to highly nonlinear drives. The lines in the graph are theoretical calculations without free parameters.

Characterizing and understanding these devices has been a most active research activity at CNRS. After having demonstrated how to experimentally calibrate in-situ these devices, they have produced analytic mathematical tools enabling to describe any of their resonance modes

[7]. These calculations have been compared to experimental findings and to numerical simulations. A higher-order mode is for instance shown in Fig. 8.

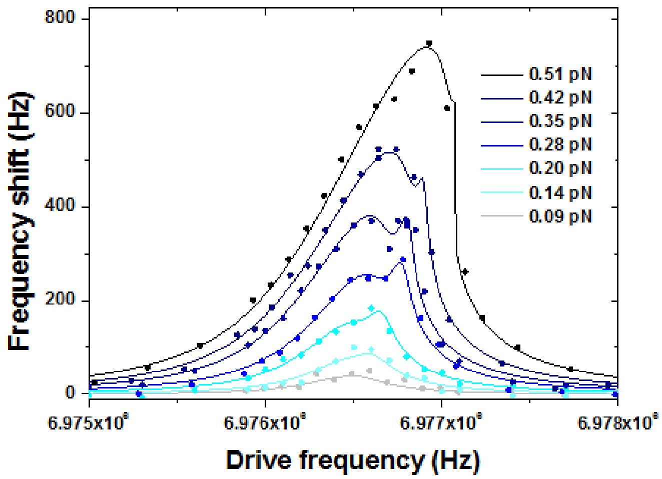


Fig. 7. *Resonance curve of a nano-mechanical oscillator measured at different drive amplitudes.*

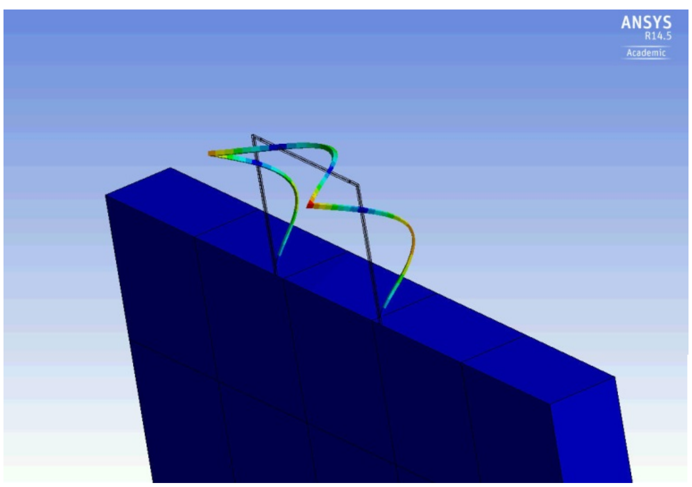


Fig. 8. *Numerical simulation of a higher order resonance mode in a MEMS oscillator.*

CNRS has also developed different types of devices from different materials. Part of the work has been focusing on understanding the properties of these materials, down to the lowest temperatures [8,9,10]. The studied properties have been e.g. the thermal conductance, specific heat, elasticity, and mechanical nonlinearities. Particular attention has been paid to the issue of mechanical dissipation in these devices, for two reasons: first, to understand the fundamental mechanisms behind friction (which is still a debated issue in the literature), and secondly, to produce the best possible devices [11].

One of the main results from this work is presented in Fig 9. The effect from the superconducting metallic coatings of our devices (here aluminum) was studied. The striking discovery was that mechanical dissipation was much lower in the superconducting state, proving the importance of (normal) electrons as the underlying mechanism. Quality factors of about a million are reached in these devices around 20 mK.

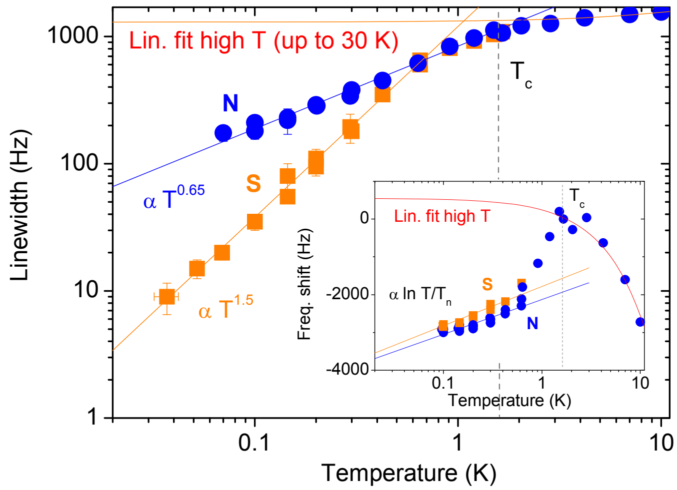


Fig. 9. *Dissipation in a NEMS for both normal and superconducting metal down to low temperatures.*

SAS-Kosice introduced a novel design of a micro-mechanical resonator based on Sn-whiskers and obtained preliminary vacuum measurements at ~ 20 mK [13]. The performed SAED analysis and experimentally observed phase transitions to the superconducting state at a temperature of ~ 3 K confirmed the β-phase of Sn-whiskers. The holder for a Sn-whisker was designed and successfully used.

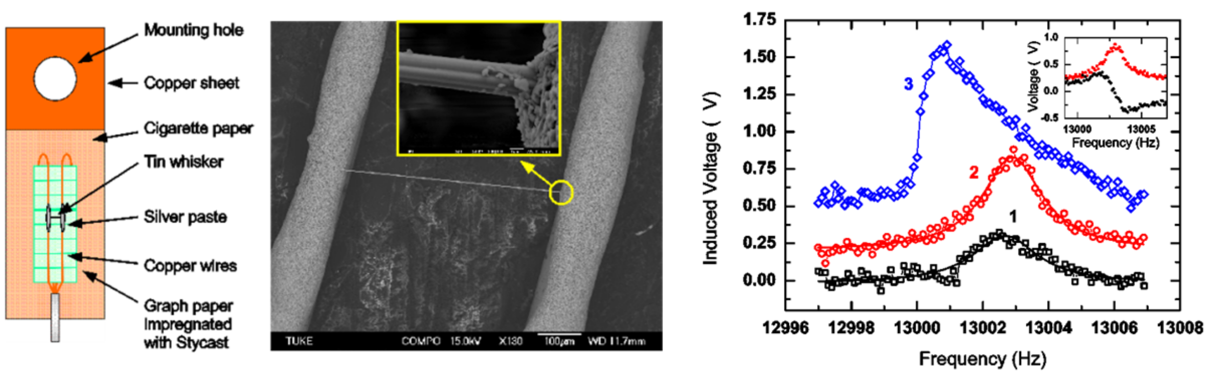


Fig. 10. *Scheme of the whisker holder* ***(left)****, SEM picture of Sn-whisker with connection details* ***(center)*** *and resonance characteristics of a Sn-whisker at different drive voltages* ***(right)****. The insert shows the real and imaginary part of the elastic compliance at medium drive voltage [13].*

However, the non-zero residual resistance of the whiskers at temperatures below the superconducting transition caused by the contact resistance of the silver conductive epoxy needs to be addressed by different new design of the holder. The measured resonant characteristics proved that Sn-whiskers can be used as mechanical resonators. The relatively low quality factor *Q* ~5000 was explained by the resistance of the Sn-whisker while it is in the normal state. Unfortunately, an unexpected problem emerged during the experiment when whiskers tended to break. The reason is still unclear. An explanation based on the allotropic transformation of β to α-phase tin could not be confirmed by subsequent SAED analysis conducted on samples after the refrigerator warm up. Fig. 10 shows a whisker holder, a SEM picture of a Sn-whisker with connection details, and its resonance characteristics.

AALTO has demonstrated how to achieve a large capacitive coupling energy of up to 2π MHz/nm for metallic beam resonators at tens of MHz. Focused ion beam (FIB) cutting was used to produce uniform slits down to 10 nm, separating patterned resonators from their gate electrodes in suspended aluminum films. The mechanical properties of Al were excellent after the

FIB cutting and a quality factor of Q ~ 3×10^5 for a 67 MHz resonator at a temperature of 25 mK was recorded. Between 0.2 K and 2 K the dissipation was found to be linearly proportional to temperature.

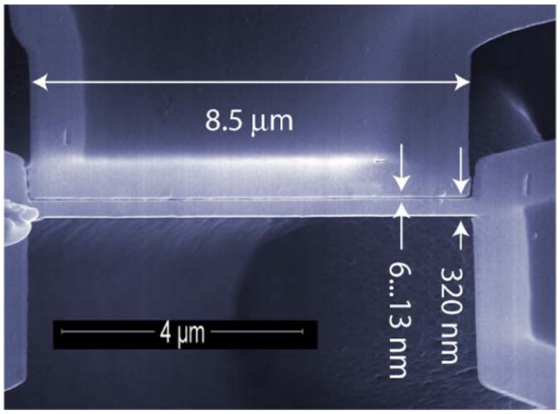


Fig. 11. *Al beam (320 nm wide) produced by focused ion beam cutting of a 100 nm thick Al film on a SiO_2 substrate.*

Nano-SQUID microscope

A tuning fork based nano-SQUID microscope which combines both topographic and magnetic contrast was built and runs successfully at CNRS-Grenoble (achieving M2). The microscope is operated within a table top dilution refrigerator with T_{min} < 200 mK. The first results were obtained imaging the coexistence of ferromagnetism (T_{Curie} = 3.5 K) and superconductivity (T_{sc} = 0.4 K) in URhGe [14,15,16]. Subsequently the evolution of the superfluid density was studied in pnictide superconductors by imaging individual vortices in $Ba(Fe_{1-x}Ni_x)_2As_2$ single crystals of varying Ni doping x: 2.6, 2.9, 4.2, and 6.5 % Ni were studied [17,18], spanning the under-, optimally- and the over-doped regions of the composition T_c-phase diagram.

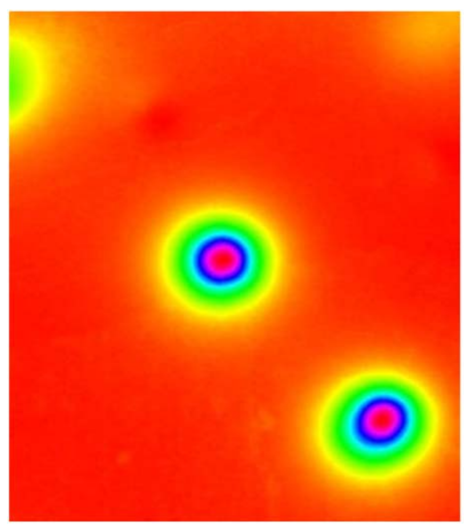


Fig. 12. *Photo (**left**) of the low temperature nano-SQUID microscope. Nano-SQUID microcope image (**right**) of vortices in $Ba(Fe_{0.935}Ni_{0.065})_2As_2$ taken at 0.7 K. The size of the image is 17.5µm x 21.25µm.*

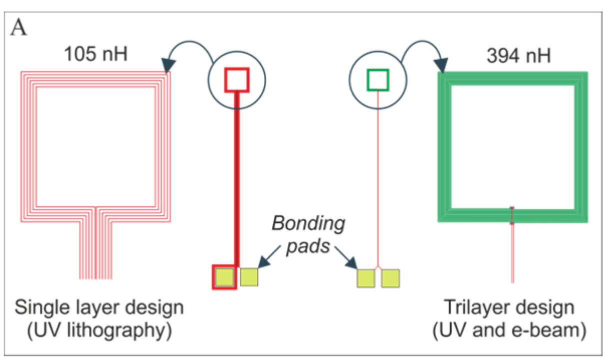
Magnetometers, microsusceptometers, and read-out SQUIDs

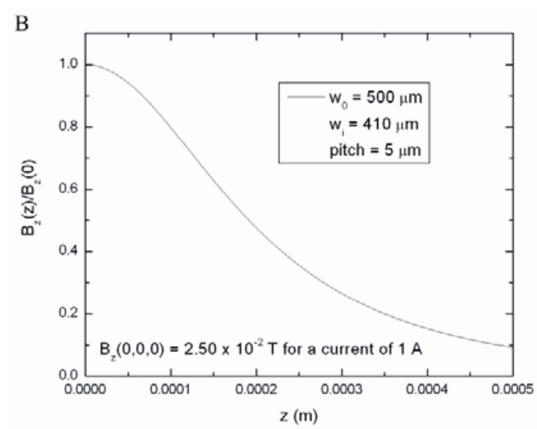
For the detection of magnetic fields of small sources or samples, small integrated magnetometers have been developed and fabricated at PTB-Berlin. Two SQUID current sensors (XL116T and XXL116T) with high input inductances (1.1 µH and 1.8 µH), designed for operation at mK temperatures, were selected and characterized. They were then provided to CNRS in March 2012, after mounting the chips on appropriate chip carriers, which fit the requirements of the CNRS experiments.

Based on the existing microsusceptometers with 30 µm pick-up loops, modifications have been made on these devices in order to improve the magnetic coupling (filling factor) to small particles with dimensions smaller than a micrometer. This modification required an additional FIB etching step of the completely processed device on the SQUID loop. The result is an additionally created nanoloop, which is in series with the 30 µm loops. In a demonstration of this technique, the nanoloop had an inner diameter of about 450 nm and a line width of about 250 nm. Details of the device and its application are given in [26].

Task 2a: SQUID amplifiers for microkelvin measurements (RHUL, HEID, AALTO, CNRS, ULANC, PTB)

Studies of superfluid ^{3}He in nanoscale confinement [21,22], which rely on high sensitivity NMR spectrometers developed by RHUL and PTB, are reported under JRA3. In addition the SQUID NMR method has been applied to a number of other fundamental studies of physics in systems of low dimensionality and on the nanoscale [23, 24].





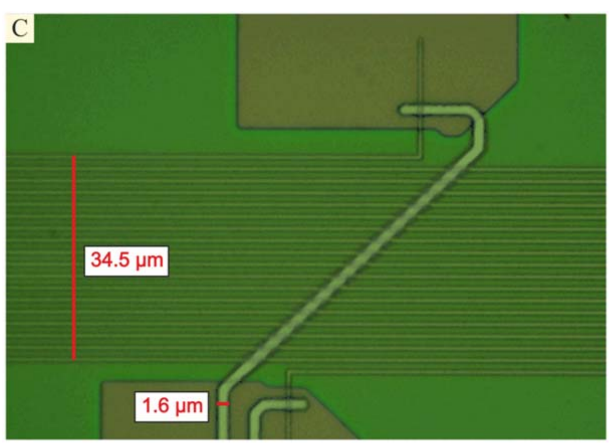


Fig. 13. ***A)*** *Schematic of the two microcoil designs,* ***B)*** *calculated axial field profile of the single layer coil as a function of distance,* ***C)*** *close up of the crossover section of the trilayer coil. The thicker lines join the two ends of the coil, which is patterned afterwards using e-beam lithography.*

An important objective (M4) was to develop the capability to detect locally the NMR response from superfluid ^{3}He samples, confined in a nanofluidic cavity. This was motivated initially by the need to image topological defects, and more recently by the upsurge of interest in topological superfluidity, Majorana surface bound states, and Majorana states bound to vortices. It required the development of microcoils, coupled to the input coil of a SQUID, to locally pick-up an NMR signal from a small volume (typically 10^4 μm^3). Such microcoils should also prove to be of wide applicability in non-contact measurements on nanoscale samples, where environmental considerations dictate that sample and pick-up coil should be remotely located relative to the SQUID.

Initial work for deliverable D3 has been extended and improved and now adds to milestone M4. At RHUL the NMR response from ^{3}He gas at 4K using an improved microcoil design has been observed. This approach provides now a stringent test of the sensitivity needed for modern superfluid ^{3}He measurement [25].

Both coil designs, shown schematically in Fig. 13A, have an outer square loop size of 500 μm x 500 μm ending in two bonding pads 3.5 mm away. The single layer design consists of a 10 turn pickup coil with a 2.5 μm line-width, 5 μm pitch, and internal loop size 410 μm x 410 μm.

The coil is made using only UV lithography and is relatively simple to pattern. The constraint that lines may not cross over, results in the pickup coil having an inductance of 105 nH with significant stray inductance in the bonding pads, such that the total inductance at the bonding pads is approximately 400 nH. The calculated field for unit current in the pickup coil, which determines the sensitivity of the coil by the principle of reciprocity, is shown in Fig. 13B. This profile determines the depth of the sample that will be assayed by the coil.

The recent trilayer design uses both UV and e-beam lithography and so crossovers of the patterned lines become possible. Fig. 13C shows a close up of the crossover region explaining how the two ends of the coil are joined to the lines leading to the output pads. With e-beam lithography, a line-width of between 600 and 800 nm is obtained, with a 2 μm pitch. The pickup coil has 18 turns, an internal loop size of 432 μm x 432 μm, and an increased inductance of 394 nH. With minimal stray inductance, the total inductance at the bonding pads remains at ~ 400 nH.

The NMR setup is shown schematically in Fig. 14. We couple the microcoils to a SQUID via a tuned input circuit configuration. The optimum total input inductance is $L_T = \alpha_i^2 Q L_i$. It is made up of the sum of the pickup coil inductance, the SQUID input coil inductance and any additional stray inductance. The single layer microcoil structure is simple to fabricate, but has significant stray inductance. The stray inductance is much smaller in the trilayer design, allowing more turns to be fabricated on the coil and resulting in a greater signal-to-noise ratio (SNR).

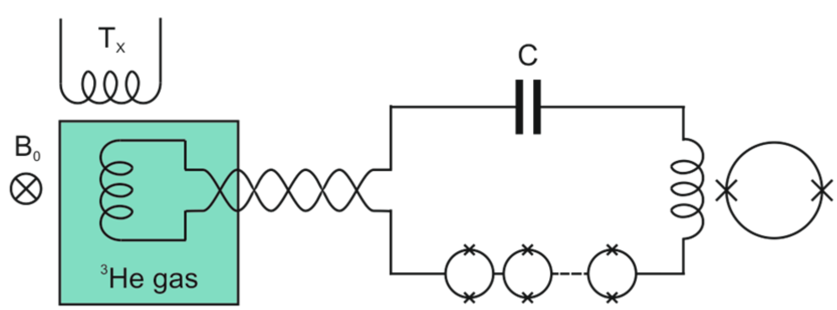


Fig. 14. *Schematic of tuned NMR setup. The top surface of the microcoil is exposed to the ^{3}He gas sample. All elements are at 4.2 K. The arrangement is housed in a superconducting Nb enclosure to shield from extraneous noise.*

In this work RHUL chose $Q \sim 30$. In this case the low inductance XS116 SQUIDs fabricated at PTB most closely match the optimum condition, with $L_s = 85$ pH. These SQUIDs have a 4 turn input coil with $L_i = 29$ nH, including the inductance of the integrated Q-spoiler, with a coupling constant $\alpha_i^2 = 0.5$. The microcoil is connected via a NbTi twisted pair to a remote SQUID approximately 20 cm away, in series with a low loss 47.5 nF capacitor. The connection to the microcoil was made through aluminium wire bonds to copper solder pads, providing the resistive element needed for the required Q. From the measured 4.2 K noise peak, shown in Fig. 15, and the known capacitance, the total inductances of the microcoil input circuits, derived from the measured resonance frequencies, are L_T = 617 nH and 614 nH, for the single and trilayer coils respectively. This is close enough to the optimum value not to degrade the signal to noise ratio of the spectrometer. The two coils were designed such that the total inductance would be the same and so that a direct comparison in performance could be made.

The microcoil was sealed inside a sample chamber made from Stycast 1266 into which ^{3}He gas, at a pressure of 1 bar, was added as a test sample. Thus the ^{3}He gas is in direct contact with the microcoil, which will be sensitive to a region of the sample of depth approximately equal to the coil diameter.

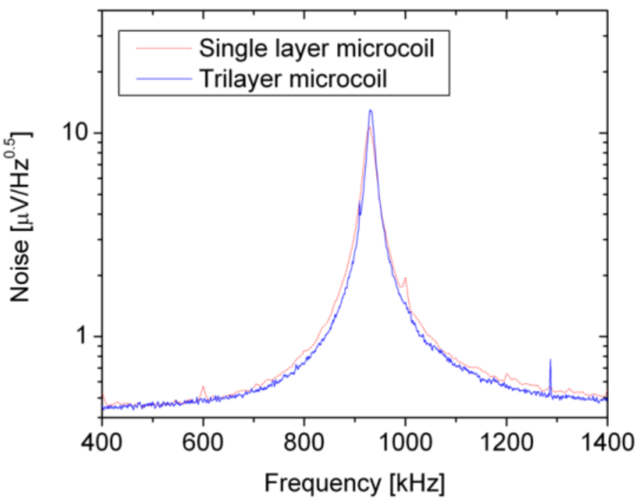


Fig. 15. *Noise peaks for both designs of microcoil, showing the total inductance remains constant as expected at 617 nH and 614 nH for the single layer microcoil and trilayer microcoil respectively.*

Fig. 16 shows a direct comparison between signals observed with both the single and trilayer microcoils. These signals are Fourier transforms, FFTs, of the average of 500 time domain free induction decays following the application of a 90° tipping pulse. Fits to the FFTs give a spin-spin relaxation time in the applied magnetic field, T_2* of order 2.5 ms. The comparison shows clearly the improvement obtained using the trilayer coil.

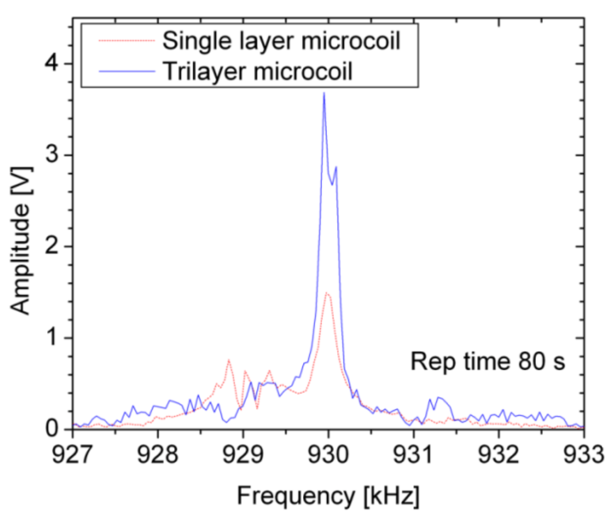


Fig. 16. *NMR signals from ^{3}He gas with an 80 s repetition rate, comparing the signal size of a 90 degree pulse for the two microcoil designs. Each trace consists of 500 averages.*

The final test was to exclude helium from a region up to 100 microns from the coil, to mimic the effect of the wall necessary in the confined nanofluidic superfluid experiment. This was achieved by fixing a 100 micron thick Kapton spacer over the coil with Corning vacuum grease. The observed reduction in signal was consistent with the predicted estimate of 20%. On this basis we predict an achievable SNR ~ 15 for a 1 micron thick slab of superfluid helium, confined 100 microns above the surface of the coil at 1 mK.

Task 2b: High frequency SQUID amplifiers at the quantum limit (UL, PTB, RHUL, HEID, AALTO)

The wide bandwidth (400 MHz) dc SQUID amplifier, developed at PTB, was reported in the previous 36-month periodic report as deliverable D4. In the current reporting period such a device has been installed on a cryogen-free dilution refrigerator at RHUL. It was used to measure nuclear quadrupole resonance (NQR) signals from ^{35}Cl in sodium chlorate, achieving milestone M5 [27].

For the sensitive detection of small, high frequency signals, a detector and amplifier with high linearity and high system slew rate at high signal frequencies is required. The f_1 (unity-gain frequency) of today's fastest commercial SQUID electronics is limited to about 6 MHz in FLL for a 1 m cable length between the SQUID and the electronics. However, even at this bandwidth, the SQUID response is already non-linear. To achieve a reasonable reduction of the non-linear distortion, the maximum signal frequency should be kept sufficiently below f_1 (below about 1/10th). High frequency flux-locked-loop (FLL) operation >> 10 MHz can only be achieved with the FLL electronics operated in the vicinity of the SQUID in order to reduce loop delay. This has been successfully demonstrated using FLL electronics built with semiconductor devices operated at 4.2 K. However, practical applications are limited because the dissipated power of those electronics is on the order of mW. To overcome this obstacle for practical use, a technique called Output Current Feedback (OCF) has been developed at PTB-Berlin.

A figure of merit for system linearity is the total harmonic distortion (THD) of the output signal for an applied sinusoidal input signal. This THD can be strongly reduced by negative feedback. The amplified SQUID voltage can be fed back negatively into the SQUID, which lowers the flux amplitude and so reduces THD. A SQUID with OCF realises this and effectively enables on-chip FLL with a much higher bandwidth in the 100 MHz range. The schematic of a two-stage SQUID with OCF is shown in Fig. 17.

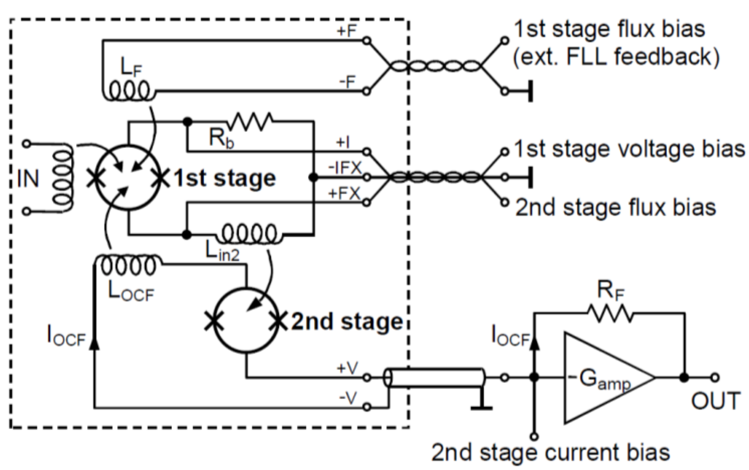


Fig. 17. *Two stage SQUID with OCF. Components inside the dashed box are at cryogenic temperatures.*

The OCF SQUID

The SQUID, which we used, was a C638-J45 OCF SQUID of type Z3040. This circuit consists of an input stage that is a 3×10-SQUID series-parallel array with two identical, magnetically decoupled signal coils, one for the input and the other for OCF (Fig. 17). The input coil inductance is 14 nH. The output stage is a 40-SQUID series array, the output current of which flows into the 50 Ω input resistance of the room temperature amplifier. This current is passed through the OCF coil to realize negative feedback. Thus, the two stage SQUID is operated in permanent FLL mode with the output of the second stage as a feedback to the first stage

For operating the SQUID sensor, a low noise wide-bandwidth amplifier (LNAM) is used in conjunction with a set of slightly modified XXF-1 electronics. The modifications provide a power supply for the wide bandwidth amplifier, as well as supplying the SQUID bias currents. The SQUID used here (as opposed to the Z30440 type in the previous 36-month Periodic Review Report) gives faster response, enabling a wider bandwidth by sacrificing in the linearity. This means it is better suited for smaller signals at higher frequencies.

Experimental setup on a cryogen free dilution fridge

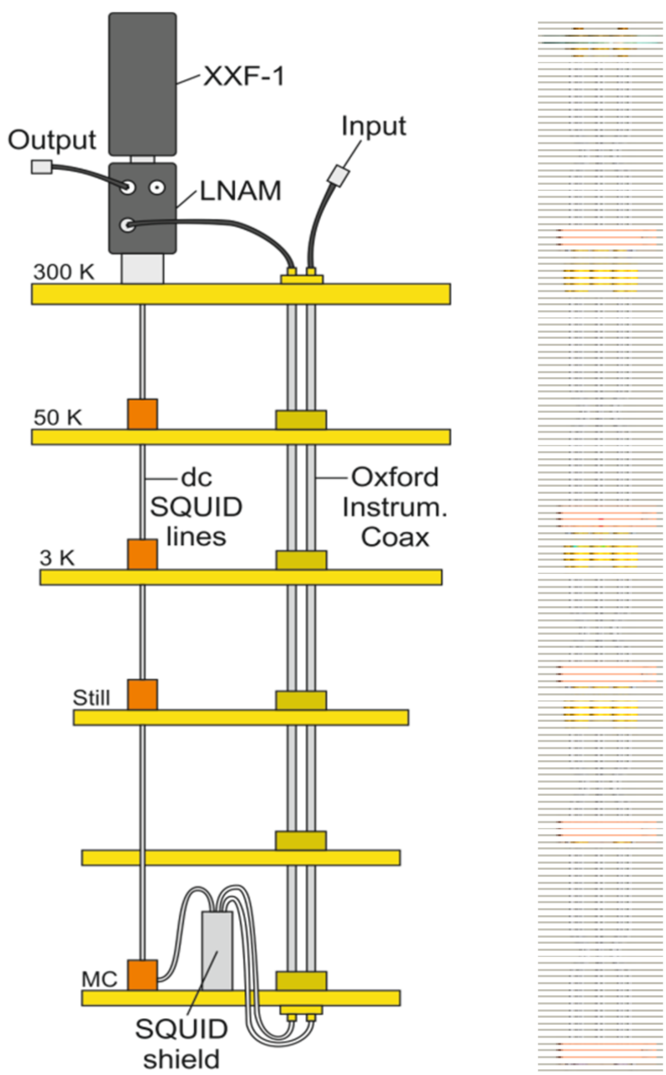


Fig. 18. *Schematics of the high frequency SQUID in the cryogen-free dilution refrigerator at RHUL,* ***left****. Details of the coaxial probe,* ***right****, which can contain up to eight coaxial cables and incorporates attenuators heat sunk at each plate of the dilution refrigerator.*

In the previous Review Report we reported the characterisation of these devices at 4.2 K measured with a simple dipper probe. During the current reporting period the high frequency SQUID was successfully installed on the mixing chamber of a cryogen-free dilution refrigerator at RHUL, Fig. 18. The 5 dc SQUID bias lines run as twisted pairs from room temperature to the mixing chamber, with heat sinking junction boxes at the 50 K, 3 K, still, and mixing chamber plates. There is a superconducting break in the lines between the 3 K and mixing chamber plates, to reduce heat leaks to the mixing chamber. From the mixing chamber junction box to the SQUID, the twisted 5 pairs of lines are made of copper wire. High frequency filtering is achieved with a 30 Ω resistor in parallel with a 680 nH inductor in series with each line. These filters and the SQUID are both housed in a superconducting Nb shield heat sunk to the mixing chamber.

The coupling of high frequency signals in and out of the SQUID, with simultaneous elimination of high frequency cross talk, was achieved using a standard design coaxial insert to the mixing chamber, with heat sinking of the outer ground at each plate. The two lines used in this work consist of a series of coaxial cables heat sunk through bulkhead SMA feedthroughs at each plate. The coaxial cables have BeCu centre conductor and outer shield down to the 3 K plate, then continue to the mixing chamber with NbTi inner and outer conductors. From the SMA connectors at the mixing chamber, flexible coax lines made from CuAg inner and outer conductors with Teflon insulation were used to connect to the SQUID output solder pads and the input coil. The SQUID output signal was further amplified with a low noise amplifier module (LNAM) developed at PTB.

Characterisation of SQUID and amplifier

Initially the input coax was coupled to the input coil of the SQUID for chracterisation purposes. The transfer function of the SQUID using a 100 kHz signal into the input coil is shown by the red line in Fig. 15. From this, we can determine the mutual inductance between the input coil and the first stage SQUID, $1/M_{\text{in}} = 22.79\ \mu\text{A}/\Phi_0$. For small signal amplitudes in the input coil, the transfer function is linear over approximately 0.5 Φ_0, as shown by the blue line in Fig. 19. The mutual inductance between the first stage SQUID and the OCF coil was also measured for the $I = 250\ \mu\text{A}$ bias position used in these experiments reported. This was $1/M_{\text{OCF}} = 12.66\ \mu\text{A}/\Phi_0$.

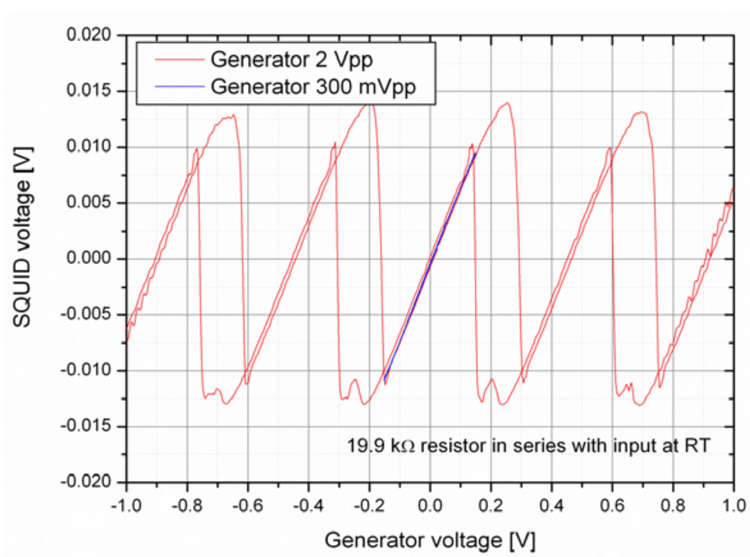


Fig. 19. *Transfer function for the OCF SQUID C638-J45 through a 19.9 kΩ resistor in series with the input coil at room temperature.*

The response of the setup as a function of frequency for small excitations was measured and demonstrated a 3 dB bandwidth of approximately 400 MHz with this SQUID. Thus signals up to ~ 40 MHz should be reliably captured without distortion. We demonstrated the absence of significant cross-talk and established that the recovery time after pulses was 100 ns.

Nuclear Quadrupole Resonance (NQR) experiment

Following the successful characterisation of the OCF SQUID on the RHUL dilution fridge, an experiment was carried out in order to observe NQR from a sample of sodium chlorate crystals. Pulsed NQR could be carried out without the complication of installing a high homogeneity NMR magnet, yet pulse sequences (with their inherent complications) were still required in order to measure the NQR lines, providing a rigorous test of this new regime for NMR/NQR using SQUID detection, achieving milestone M5.

Experiments were performed on a 172 mg powder sample packed into a cylindrical sample space 5 mm diameter and 5 mm long. The coil set was designed in broadband configuration for the input circuit. For Cl in $NaClO_3$ $\omega_0 / 2\pi$ = 30.632 MHz for ^{35}Cl and is 24.144 MHz for ^{37}Cl at low temperatures. Fig. 20 shows the NQR resonance from ^{35}Cl, at three different mixing chamber temperatures, qualitatively confirming the expected behaviour. Further checks to confirm the genuine nature of this signal, by varying the tippling pulse angle and frequency, were positive. We note that, for technical reasons to be addressed in future work, the present signals were obtained using extremely small tipping pulses ($\sim 10^{-3}$ radians). There is therefore the potential for orders of magnitude improvement in signal-to-noise ratio (SNR). A broadband NMR system has the advantage that NMR parameters, e.g. T_1, can be measured conveniently and directly over many orders of magnitude in frequency, giving important information on spin dynamics.

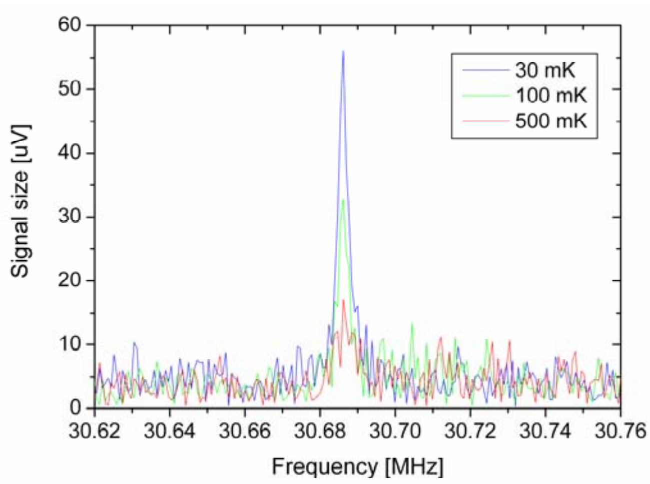
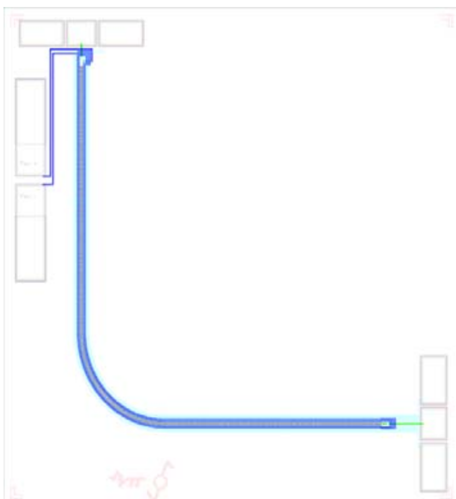


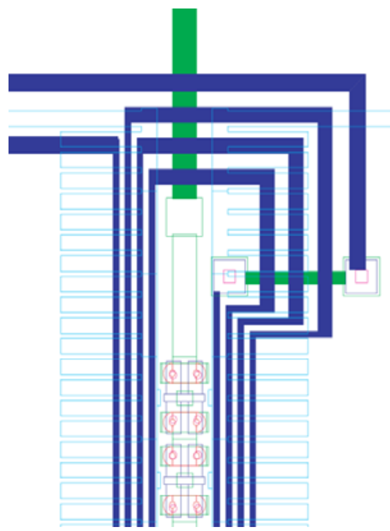
Fig. 20. *NQR signals from sodium chlorate as a function of temperature.*

Degenerate parametric amplifier

Parametric amplifiers provide an opportunity to construct low-noise, narrow-band phase-sensitive amplifiers whose working band can be tuned over a relatively large frequency range. Their operation typically relies on a tunable (nonlinear) reactive element and, in the absence of dissipation, they can function without any added noise except the extra contribution governed by the quantum mechanical principles. This enables such devices to be used as ultimate amplifiers, down-converters, or generators of squeezed states. Effectively parametric amplifiers are mixers with gain, *i.e.* they transfer energy from one frequency (pump) to another (signal). When pumping at twice the operating frequency, one obtains phase-sensitive amplifiers, degenerate parametric amplifiers (DPA), which can also be employed to squeeze noise below the standard quantum limit.

AALTO has developed degenerate parametric amplifiers based on Josephson junction (JJ) metamaterials. A device composed of 250 SQUID loops connected in series to form the signal line of a superconducting coplanar waveguide (CPW) has been designed and measured. The CPW was used in a cavity configuration to create a resonance for parametric amplification with enhanced dynamic range owing to the large number of SQUIDs. The overall layout of our amplifier circuits is displayed in Fig. 21a. The total length of the device is 4 mm, which corresponds to a cavity mode of ~ 6 GHz when the inductance of the SQUID loops corresponds to L = 15 pH. Fig. 21b reveals a few details of the sample construction. Ground strips of the coplanar line was constructed in a special way in order to guarantee good flux coupling from the modulation coil (marked in solid blue) to the SQUID loops. The optical image in Fig. 21c indicates that the manufactured SQUID loops are quite symmetric which facilitated a well-defined modulation of the array.





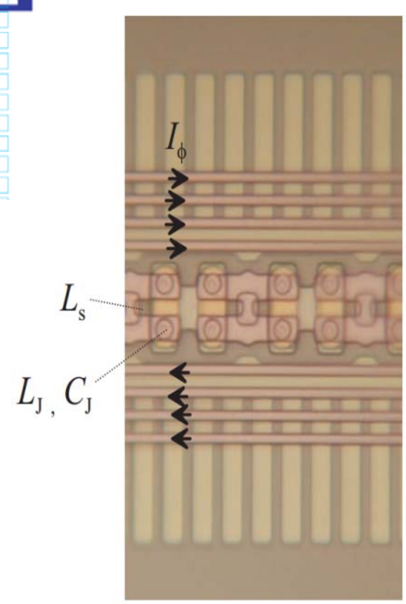


***Fig. 21. a)** Autocad drawing of the designed metamaterial parametric amplifier. The metamaterial resonator is a 4-mm-long coplanar waveguide with 250 embedded SQUIDs, with each junction having a critical current of ~10 µA. The modulation of the flux through the SQUIDs is realized through a lithographically fabricated spiral coil on top of the metamaterial. **b)** Close up of the upper end of the sample shown in Fig. 21a. Junctions are visible as red circles while the dark blue strip illustrates the modulation flux coil on a separate lithography layer. **c)** Optical image of the sample. The Nb-device was fabricated using the standard photolithography (contact hole) process at VTT.*

Our measurements were carried out in the vicinity of the resonant frequency f_r = 5.4 GHz with the pump at 10.8 GHz. The resonant frequency could be tuned in well-defined way between 4.6 - 6 GHz as indicated in Fig. 22. As a compromise between modulation strength and stability issues, we chose to operate our DPA at 5.4 GHz. The power dissipation of these devices was below 10 pW but, nevertheless, it turned out that dissipation in the sample was one of the limiting factors for their performance. At the time of writing, the actual source of the dissipation is unclear: it could be oxides of the niobium material, Al_2O_3 in the barriers, or the surrounding Si_3N_4 insulator.

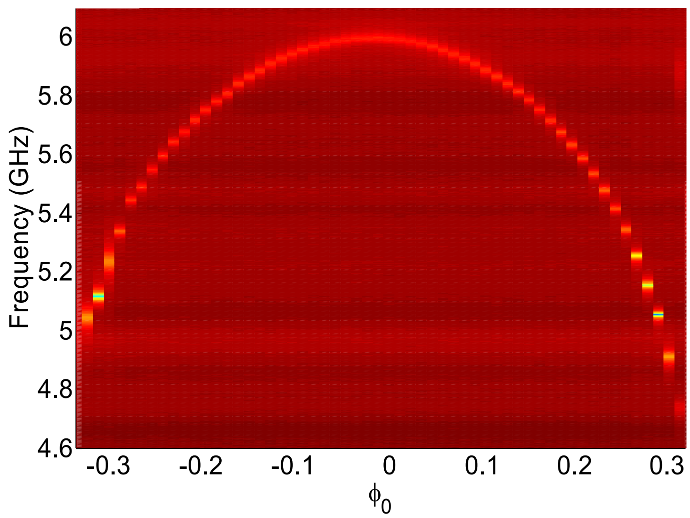


Fig. 22. *Tunability of the resonant frequency of the metamaterial as a function of phase over the JJs.*

In an amplifier system operating at 5 GHz, the quantum noise power per unit band is on the order of 100 mK and a good parametric amplifier shouldn't contribute to noise temperature much more than that. With a power gain of G = 20 dB, the DPA would require a post amplifier with a noise temperature T_N well below 4 K in order to fully utilize the performance of the parametric amplifier. Our measurements were done in a microwave setup where the system noise temperature was about 4 K. Hence, the output noise of the measurement system was not fully governed by our DPA and we had to deduce the noise temperature from the increase of S/N ratio when having the DPA ON vs. OFF. Such comparison at G = 22 dB is displayed in Fig. 23a, which yields $T_N = 0.4 \pm 0.2$K, deduced from the observed 9.8 dB increase in the S/N ratio.

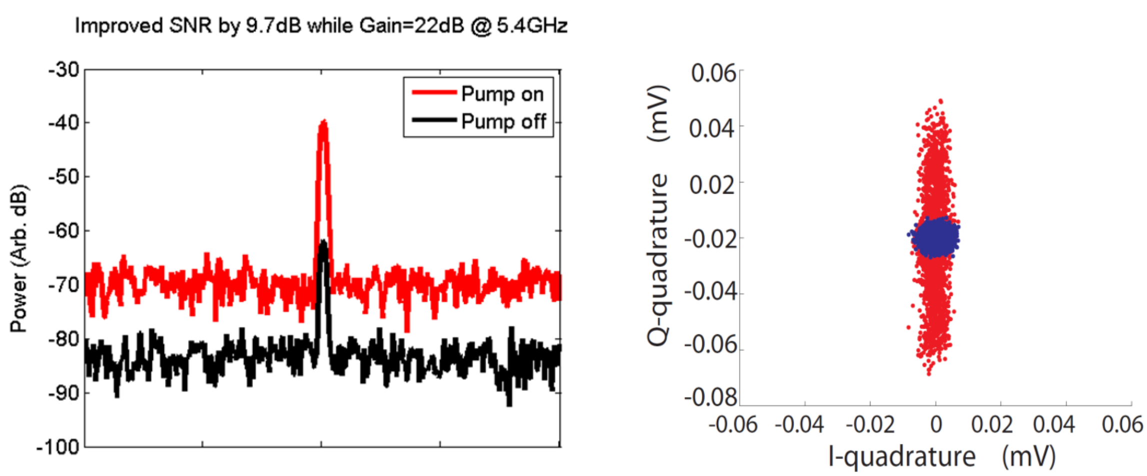


Fig. 23. ***a)*** *Signal-to-noise ratio measurements were used to infer the added noise power per unit band to be on the order of 0.4 ± 0.2 K.* ***b)*** *IQ-plot of amplified quantum noise at G = 10 dB (**red**) and without pumping (**blue**). Phase dependent gain is seen in the elongation of the red noise ellipse. Small squeezing is observable in the I-quadrature as the blue circle diameter exceeds the minor axis of the ellipse.*

The properties of our DPA depended on the pump power. The noise temperature was not smallest at the largest gain and a clear increase with pumping power was observed. This is due to dissipation in the SQUID loop array in the pumped cavity: the source of dissipation is heated, which leads to increased noise. The gain of the DPA is displayed in Fig. 24a at a few values of the pumping power. The band width of amplification *BW* goes down with the pump power, and the *G* x BW product amounts to approximately 1 GHz at high gain. Fig. 24b displays the measured dependence of the DPA gain on the phase angle between the pump and the amplified signal. The phase periodicity equals 180^o as is characteristic to degenerate parametric amplifiers. The out-of-phase component in this trace indicates clear deamplification.

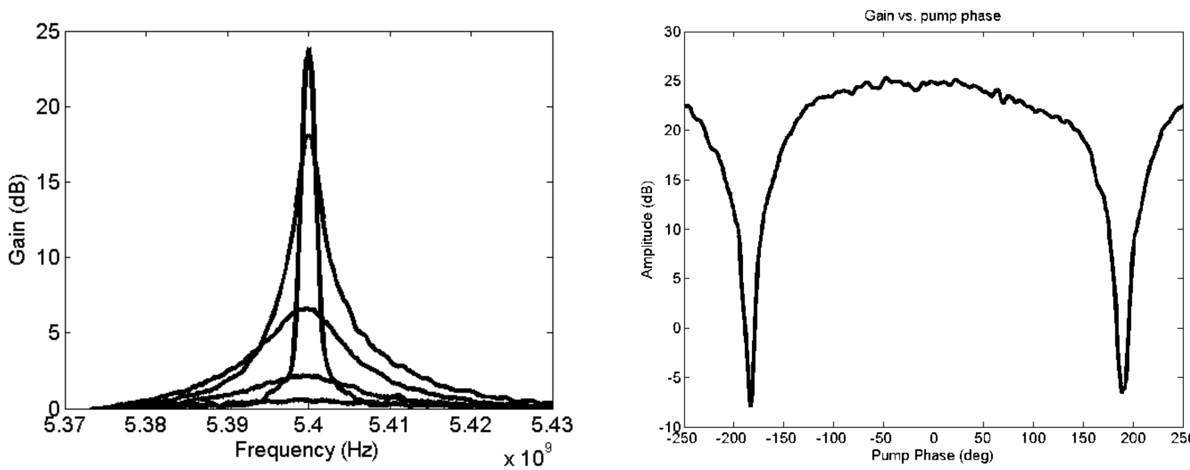


Fig. 24. ***a)*** *Gain of the DPA near the cavity resonance frequency at 5.4 GHz, measured at 5 levels of pump power*. ***b)*** *Dependence of the DPA gain on the phase angle between the pump and the amplified signal.*

Single Josephson Junction Amplifier (SJA)

Quantum limited amplifiers can also be based on negative resistance that is found on certain semiconductor devices, like Gunn tunnel diodes (i.e. Esaki diodes). AALTO employed the negative differential resistance of a Josephson junction (JJ) for constructing a novel amplifier in this class of devices. Our device, approaching the quantum limit of noise ($T_q = \hbar\omega/2k_B$) at 2.9 GHz, has been created using a selectively shunted, single Josephson junction where gain is obtained at the weakly shunted frequencies. Unshunted junctions have previously been analyzed and demonstrated to work in SQUID circuits at low frequencies. AALTO now developed analogous concepts for high frequency operation. The developed device differs markedly from previous implementations of unshunted Josephson devices because of the deliberately designed frequency-dependent impedance environment. An important part in the operation is played by noise compression, which improves the noise characteristics of the device and forces one to go beyond linear regime in the analysis of its operation.

Unshunted junctions are attractive as low-noise devices since they minimize fluctuations by avoiding unnecessary dissipation in the junction environment. In voltage-biased operation, these devices can be considered as mixers between the signal frequency and the Josephson frequency.

The fundamental macroscopic principle of our single junction amplifier is that the intrinsic resistance of a JJ is negative over sufficiently long time scales. This is usually hidden in weakly damped JJs since the negative-resistance branch is unstable. On the other hand, for strongly damped junctions, the total dynamic resistance is positive, as the experimental trace in Fig. 25a demonstrates.

The negative resistance can be calculated from the current-voltage *IV* characteristics $v_b = \sqrt{i_b^2 - 1}$ for a Josephson junction with negligible capacitance. The dynamic resistance for the junction itself $R_d = R/(di_{JJ}/dv_b)$ becomes $\sqrt{v_b^2+1}\Big/\left(v_b - \sqrt{v_b^2+1}\right)R$ which is negative at all bias voltages; here v_b and i_b are scaled voltage and current (by RI_C and I_C, respectively) and di_{JJ} denotes the current through the Josephson junction. To utilise the negative resistance of a JJ for amplification (see Fig. 25b for the reflection amplifier principle), stable operation has to be maintained by adequate damping at all frequencies (see Fig. 25c).

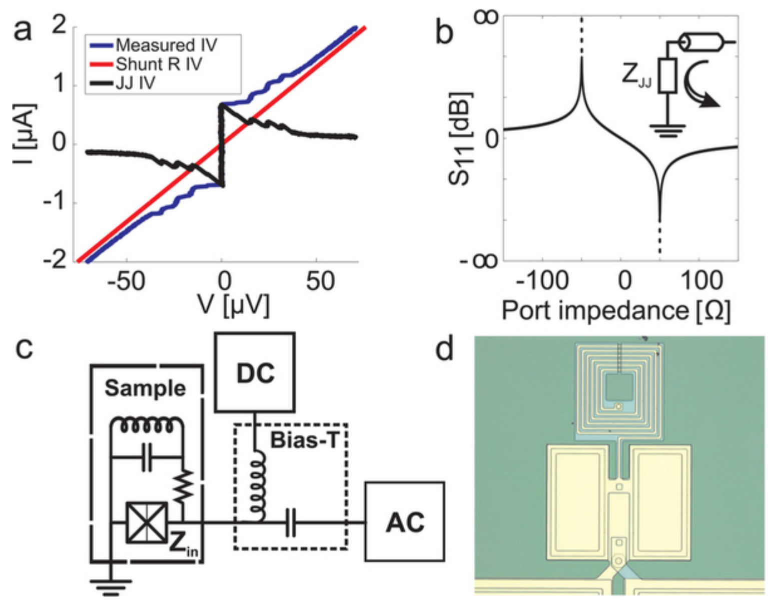


***Fig. 25.** **a)** Typical IV-curve of a SJA (in blue); red and black curves indicate the division of I into shunt and junction currents, respectively. **b)** Reflection (scattering) amplitude S_{11} in a Z = 50 Ω system as a function of the load impedance Z_{JJ}. **c)** Principal scheme of the SJA operation. **d)** Optical image of a SJA; the size of the image is approximately 270 µm × 230 µm.*

The frequency-dependent damping is set in such a way that the external shunt damps the low and high frequency dynamics, which ensures both stable DC bias and overdamped Josephson dynamics. The stabilization in the stop band is provided by the postamplification circuit. The shunt circuit and the postamplification circuit together guarantee the stability of the device by generating a wide-band resistive environment for the JJ. Operated as a reflection amplifier, the power gain $|S_{11}(\omega)|^2 = |\Gamma(\omega)|^2$ is determined by the reflection coefficient:

$$\Gamma(\omega) = (Z_{in}(\omega) - Z_0)/(Z_{in}(\omega) + Z_0)$$

Fig. 25d displays an optical image of our reflection amplifier manufactured at VTT. The experimental setup is illustrated in Fig. 26.

At low bias currents, the magnitude of the dynamic resistance $|R_d|$ is smaller than the environmental impedance in parallel to it, making the total damping impedance of the LC resonator in the shunt circuit negative. This leads to either spontaneous oscillations or saturation. The oscillations are highly nonlinear, which is manifested as higher harmonics in the spectra. The saturation shows up as vanishing response. As $|R_d|$ increases at higher bias points, the system is stabilized and the harmonics disappear since the device operates then as a linear amplifier.

The maximum measured gain of the SJA was found to be 28.3 ± 0.2 dB at input power P_{in} = −160 dBm (see Fig. 27a). The −1 dB compression point for P_{in} was found to be around −134 dBm; this indicates a dynamic range of 70 dB as the input noise corresponds to −204 dBm. Our measurements yield 1 MHz for the −3 dB. Based on signal-to-noise ratio improvements, we find the input-referred noise power added by the amplifier T_N = 220 ± 70 mK which corresponds roughly to 3.2 T_q.

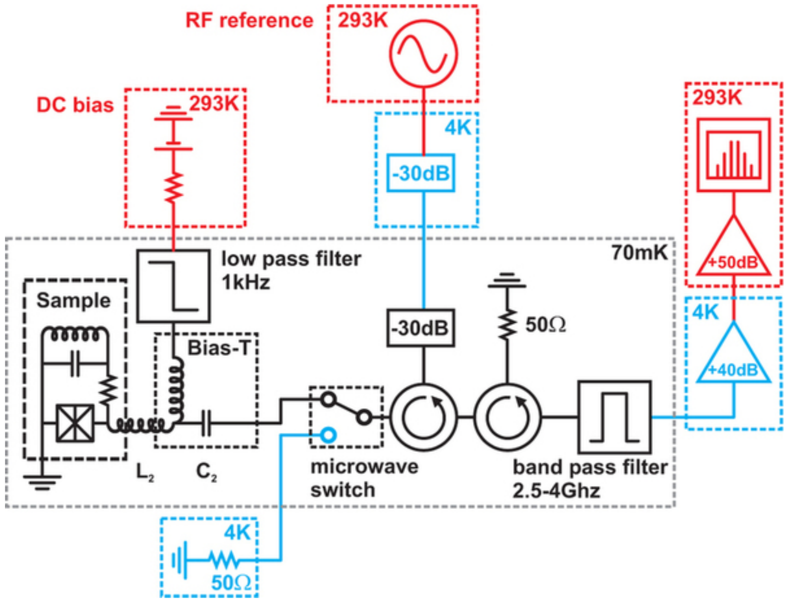


Fig. 26. The essential components of the SJA were located at 70 mK (indicated by the dashed black box). 60 dB of attenuation was employed to thermalize the incoming rf signal cable and two circulators eliminated the back action noise from the preamplifier. Using a source at 70 mK, the S/N ratio after the HEMT amplifier was improved by 17.2 ± 0.2 dB. Since the direct noise from the shunt is cut off from the Josephson junction by the bandstop filter and only the down-mixed noise is present, the noise characteristics of our SJA are excellent. The absence of direct noise is one of the basic differences when comparing SJAs with traditional microwave SQUID amplifiers.

The compression mechanism for noise is crucial for the high bias operation of the SJA. The operation with noise compression can be viewed as self-organization of the system. Microscopic degrees of freedom give rise to a macroscopic order which can be parametrized to describe the behavior of the system. In our device, the macroscopic ordering is dictated by the integrated noise over the amplified bandwidth. This parameter governs the macroscopic characteristics of the device (e.g I_C). The significance of self-organization is seen in the difference between the green and blue curves in Fig. 27b.

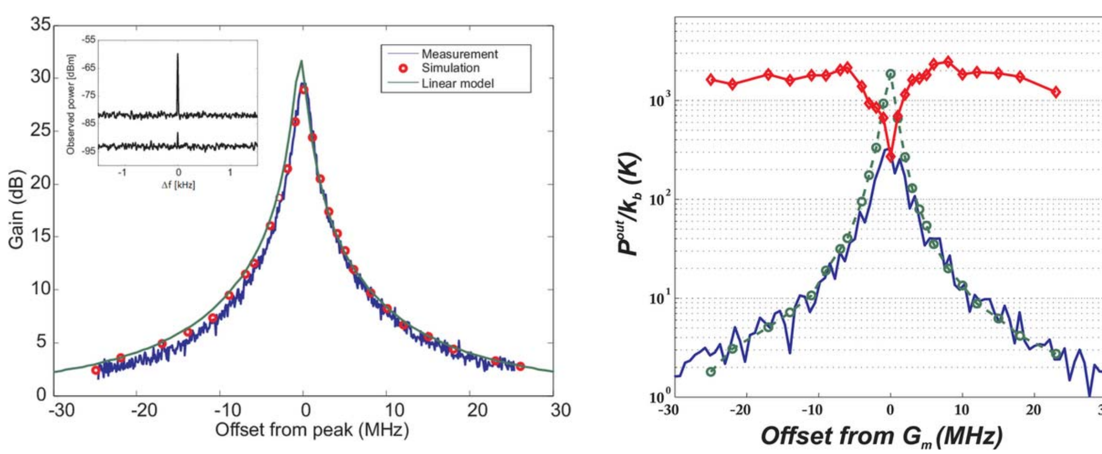


Fig. 27. ***a)*** *Gain of the SJA vs frequency at the optimal point of operation (blue, noisy trace).* ***b)*** *The effective output noise temperature (red trace, right scale) is lowered by compression at high gain as seen in the simulated noise power (left scale, denoted by solid blue line) when compared with the product of the simulated gain (G – 1) and the uncompressed down-mixed noise at 2.4 K (green curve).*

Task 3 Ultra-low temperature thermometers (RHUL, UL, HEID, PTB, AALTO, CNRS, BASEL)

Temperature is a fundamental parameter for low-temperature experiments. For traceable thermometry, i.e. for thermometry which is referenced to the international system of units SI and in this way comparable, the experimenter has to rely on the international temperatures scales ITS-90 and PLTS-2000. These scales reflect the metrological knowledge of more than 20 and 10 years ago, respectively. Currently, there are a number of activities under way to determine precisely the Boltzmann constant in order to base the definition of the Kelvin on a fundamental constant instead of materials' properties. Besides the awaited redefinition of the Kelvin the *mise en pratique* for the definition of the Kelvin has been created to enable a more flexible approach for traceable thermometry. In future, also direct measurements of temperature by primary methods will be allowed for the realization and dissemination of the Kelvin in accordance with the SI. This is a fundamental change of the practice of temperature measurement which takes into account recent technical advances in temperature metrology and also allows to bypass the international temperature scales when reasonable. Moreover, the need of establishing a new international temperature scale extending from the lowest to the highest temperatures is reduced on short time scale. This applies also to the low-temperature region.

Below 1 K the best approximation of thermodynamic temperature is actually given by the PLTS-2000 which can be realized with high accuracy. For its dissemination PTB provides a calibration service. During the project, the realization of the PLTS-2000 was also used for investigating and evaluating new thermometers as CBT, CSNT and MFFT. As one result, PTB has started a new calibration service for MFFTs in 2013. Now, MFFTs can be purchased from the company Magnicon with a calibration traceable to the PLTS-2000. But below the lower end of the PLTS-2000 at 0.9 mK no internationally agreed temperature scale exists at all. One of the main problems to be solved in developing a new ultra-low temperature scale below 1 mK is to select an appropriate carrier able to maintain the scale with sufficient accuracy and reproducibility. As a first step in this direction PTB has carried out Pt-NMR measurements down to microkelvin temperatures in a double demagnetization stage cryostat. In parallel the measurement system of the cryostat was modelled in a thermodynamically consistent way and the resulting estimates for the thermodynamic temperature were compared with the NMR measurements (achieving M10). The results obtained within the framework of this project are described below in Task 3b and the D6 report.

Further progress in this direction will require the investigation of Pt-NMR at ultra-low temperatures including a detailed material analysis of the Pt used as well as comparisons with other thermometric methods based on completely different working principles as for instance noise thermometers.

Task 3a: Noise thermometer (RHUL, UL, HEID, PTB, AALTO)

Noise thermometry at ultralow temperatures has two central challenges, which so far have prohibited a successful application of this technique below 200 µK. One is the inherently small noise signal at such low temperatures and the other the strongly temperature dependent electron-phonon decoupling. Both problems have recently been addressed in a rigorous way [28]. In Heidelberg (HEID) a new readout scheme, based on the method of cross correlation, has been introduced, that allows reducing the amplifier noise by at least one order of magnitude. A simplified diagram of this readout scheme is shown in Fig. 28. The magnetic Johnson noise of a piece of copper attached to the nuclear stage of demagnetization cryostat is read out by two dc-SQUIDs simultaneously via two superconducting flux transformers. After amplification and filtering at room temperatures the signals were digitized and a flux noise power spectrum was calculated applying a cross correlation method. The resulting spectrum obtained at different temperatures is shown in Fig. 29a. One can clearly see that the shape of the spectrum is independent of temperatures as it is expected for a noise source with a constant conductivity. At low frequencies one observed a flat white noise spectrum up to a certain frequency. This cut-off frequency is determined by the self-screening of the magnetic flux fluctuations in the metallic resistor.

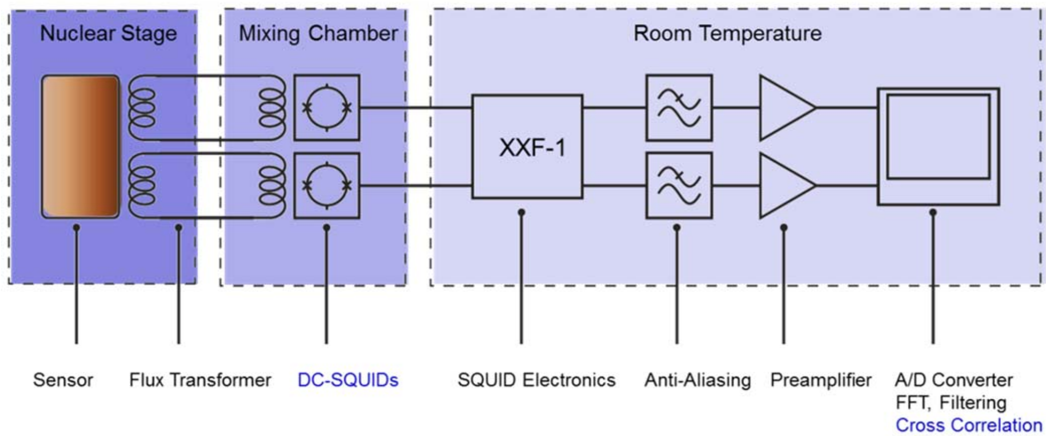


Fig. 28*: Simplified diagram of the noise thermometer setup.*

In order to address the second problem, a bulk piece of copper was used as a noise source instead of a thin film. The best compromise in terms of signal size and bandwidth requires an optimal value for the conductivity of the copper noise source. At the same time the level of magnetic impurities in the copper has to be extremely low in order to avoid a temperature dependent Kondo-type resistance. In order to reach an optimal conductivity heat treated highly purified copper (5N) was used and cold-worked to obtain an residual resistance ratio of about 28 corresponding to a cut-off frequency of about 100 Hz.

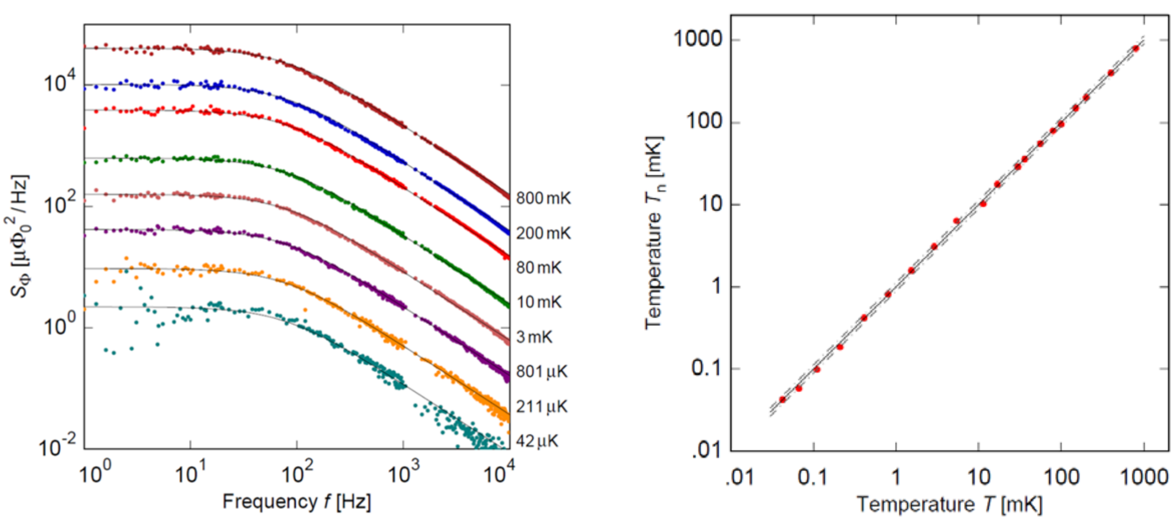


Fig. 29. ***a)*** *Noise spectra obtained using the cross-correlation technique with a subsequent Fourier transformation. By lowering the temperature, the white noise plateau gets smaller whereas the cutoff frequency remains unchanged, showing that the resistance and the self-inductance of the noise source is independent of temperature. The solid lines are guides for the eye [28].* ***b)*** *Noise temperature as a function of the temperature measured by Pt NMR (below 10 mK) and fix-point calibrated RuO thermometry (above 10 mK). The solid line shows the equality of noise and reference temperatures, and the dashed lines are parallel shifted by ± 5 % [28].*

The flux noise power spectrum shown in Fig. 29a is used to determine the temperature of the noise source, which was mounted in the field compensated region on a nuclear stage of a demagnetisation cryostat. For a one point calibration a superconducting fix point device used. The temperatures obtained with the noise thermometer are compared to the temperatures measured with a ^{195}Pt-thermometer (below 10 mK) and a calibrated RuO_2 thermometer (above 10 mK). The results are shown in Fig. 29b. The temperatures obtained with these three thermometers agree in the range between 42 µK and 800 mK very well. They differ at most by 5% in the entire temperature range of almost 5 orders of magnitude.

RHUL has focussed on the development of current sensing noise thermometers (CSNTs). A subset of this work meets milestone M7. RHUL has surpassed this noise thermometry objective in three ways. First the use of current sensing noise thermometry (CSNT) on a cryogen-free millikelvin refrigerator has been demonstrated [29], operating to below 1 mK. Secondly, an improvement in thermometer speed by more than two orders of magnitude, with temperature resolution of 1% achieved in a 0.1s measurement time has been achieved [30]. Thirdly work on a CSNT containing a superconducting fixed point device, demonstrates an integrated thermometer with no need for a single point calibration using external devices.

Fig. 30 shows a schematic diagram of a CSNT. This measures the thermal (Johnson) noise in a resistor to determine its temperature. Using a low T_c dc superconducting quantum interference device (SQUID) as the front end amplifier, the current sensing technique is a practical approach for measuring absolute temperature from 4.2 K down to sub mK temperatures. In this scheme, the SQUID can be located remotely from the sensor resistor, allowing the resistor to be placed in environments hostile to SQUID operation. The excellent sensitivity of the dc SQUIDs from PTB allows the use of sensor resistors with much larger resistance than used in the original RHUL work, thereby increasing the speed of the thermometer.

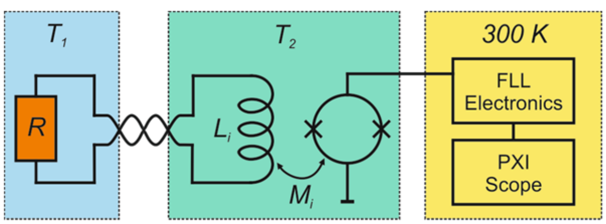


Fig. 30*. Schematic diagram of the current sensing noise thermometer. The dc SQUID amplifies the thermal noise current of the resistor with the output captured by a digitiser. T1 can be at a different temperature from T2, the temperature of the SQUID.*

The mean square noise current flowing in the SQUID input coil per unit bandwidth arising from the thermal noise in the resistor is then given by $\left\langle I_N^2 \right\rangle = \frac{4k_BT}{R}\left(\frac{1}{1+\omega^2\tau^2}\right)$. The time constant $\tau = L/R$, where the total inductance in the input circuit L includes the SQUID input coil inductance L_i and any additional stray inductances. By increasing the resistance, it is possible to increase the bandwidth of the noise spectrum. However, increasing R will reduce the noise power from the resistor at dc, which must be kept much larger than the SQUID noise. The SQUID is operated in flux-locked loop (FLL) mode where the gain depends only on fixed, known parameters. Thus, if the value of the resistive sensor and the SQUID gain can be measured, a current noise spectrum can be used to determine the absolute temperature.

Fast noise thermometer compatible with cryogenic cycle dilution refrigerator

There is a need for fast absolute thermometry at dilution refrigerator temperatures. By employing a relatively large sensor resistor we can both enhance speed and increase the noise bandwidth, conferring relative immunity to the hostile noise environment of a typical cryogenic cycle dilution refrigerator. Here we demonstrate the achievement of these objectives. In this work we use a PTB two-stage SQUID with an input coil inductance of $L_i = 1.05$ μH, operated at 100 mK. At this temperature, the white flux noise floor of the SQUID is 0.58 $\mu\Phi_0 Hz^{-1/2}$, equivalent to a coupled energy sensitivity, $\varepsilon_c = 5h$.

The 1.29 Ω sensor resistor, Fig. 31, was made of 50 μm diameter platinum tungsten wire (Pt92/W8). PtW was chosen as it has an only weakly temperature dependent resistivity as well as very small magnetoresistance.

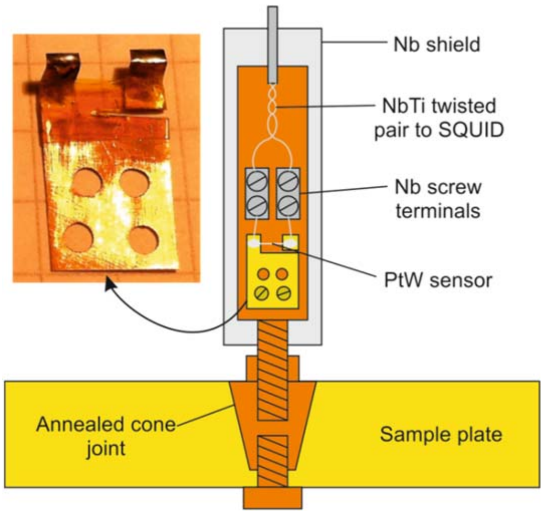


Fig. 31. *Schematic of the noise thermometer mounting onto the copper sample plate. The plate is thermally linked to the mixing chamber of the dilution refrigerator.*

Noise spectra from 4 K down to mixing chamber temperatures are shown in Fig. 32. Each trace consists of 100 averages, with a total acquisition time of 42 seconds.

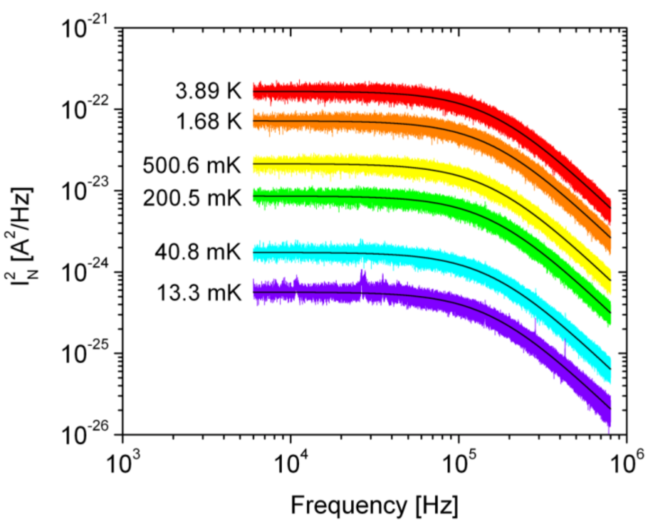


Fig. 32. *Current noise spectra from the PtW noise thermometer spanning temperatures from 4 K down to mixing chamber temperatures. Each trace consists of 100 averages of 0.42 s traces, taken at 2.5 MS/s, giving a total acquisition time of 42 s per trace. The fits to the expected depoendence are also shown.*

The current sensing noise thermometer was compared with a ^{3}He melting curve thermometer using the Provisional Low Temperature Scale, PLTS-2000. In addition a calibrated germanium thermometer was used above 50 mK. Fig. 33 shows excellent agreement to within 1 % down to 50 mK and to within 2 % down to 30 mK. Deviations at lower temperatures arise from a small residual heat leak through the superconducting lead which connects to the non-thermally /electrically grounded side of the sensor resistor. This is being addressed in our next generation of noise thermometers by improving the heat sinking of the wire. A somewhat smaller resistance will effectively eliminate this problem, subject to some compromise in speed.

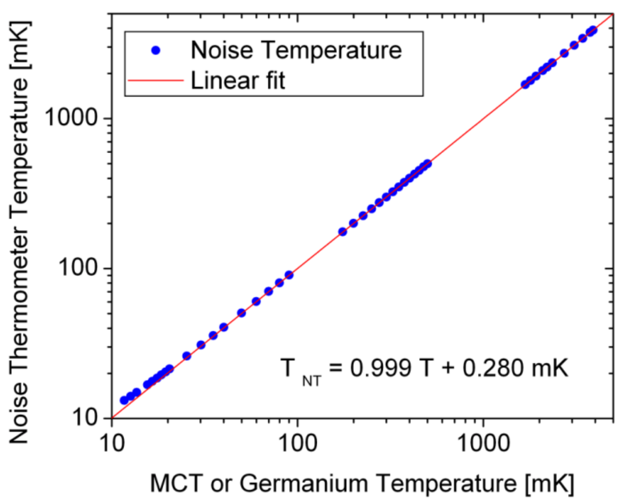


***Fig. 33**. Comparison of the temperature of the current sensing noise thermometer with that of various thermometers over a wide temperature range. The points shown include those from the noise spectra in Fig. 3. The linear fit to the high-temperature data is also shown.*

The precision of the thermometer was determined experimentally through a series of single shot noise traces taken consecutively. Around 1000 individual spectra were captured for accurate statistics. In a measurement time of 419 ms, a precision of 0.50 % was obtained. This precision was confirmed to be independent of temperature, by sampling at 1.5 K, 100 mK and at 13 mK. At the base temperature of the fridge, single shot noise measurements were taken repeatedly with a measurement time of 105 ms. The precision scaled in the expected way, with the noise thermometer achieving 1.15 % precision in this time. This is about two orders of magnitude faster than our previous noise thermometers, magnetic field fluctuation thermometers, and on-chip current sensing noise thermometers, which all achieved 1 % precision in about 10 s. The measured precision as a function of measurement time is shown in Fig. 34.

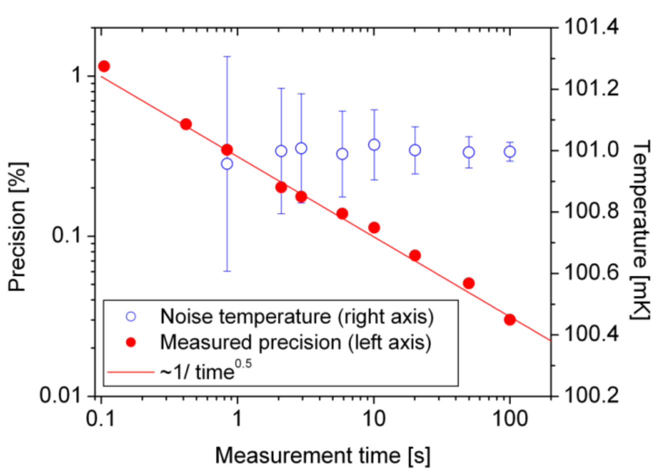


***Fig. 34**. Blue open circles (right axis): Noise thermometer temperature as a function of measurement time at a reference temperature of 100 mK. The error bars show the standard deviation from the mean temperature. Red closed circles (left axis): Precision as a function of measurement time, with a fitted line proportional to the inverse of the square of the measurement time. The two left-most points were taken at variousdifferent reference temperatures, illustrating the independence of the precision on temperature. Note that the precision is plotted on a log scale, whereas a linear scale is used for temperature.*

Noise thermometer optimised for ultra-low low temperature operation

A copper foil noise thermometer with a measured low temperature resistance of 0.20961 mΩ was made, with improved heat sinking of the leads (Fig. 35). In addition, we included an in-situ tantalum fixed point device (T_c = 4.45 K), with 12 turns of NbTi wire forming part of the superconducting flux transformer wound around a tantalum bobbin. The noise thermometer is mounted on a sample plate heat sunk to the nuclear stage, along with a melting curve thermometer (MCT) and a platinum NMR thermometer also mounted on the same plate. The SQUID used for reading out the noise thermometer is a C636 G23 XL SQUID from PTB with a noise floor of 5 x 10^{-13} A/Hz$^{0.5}$, well below the dc noise of the lowest temperature measured.

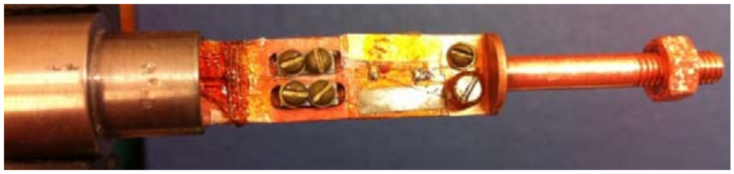


Fig. 35. *The low temperature copper noise thermometer construction. The noise resistor itself is in the top right underneath cigarette paper. The Nb foil heat sink can be seen below the noise thermometer. At the very bottom right of the holder, there is a tantalum fixed point device.*

The tantalum fixed point calibration was checked at the start of the run, Fig. 36, using a calibrated germanium thermometer. The superconducting transition gives rise to the expected jump in the total self-inductance of the flux transformer. This is clear proof of the concept that a well characterised superconductor with a narrow transition width can be used as an *in-situ* fixed point device. The noise thermometer was also calibrated against a melting curve thermometer mounted on the same plate. This calibration was used in the measurements at ultralow temperatures.

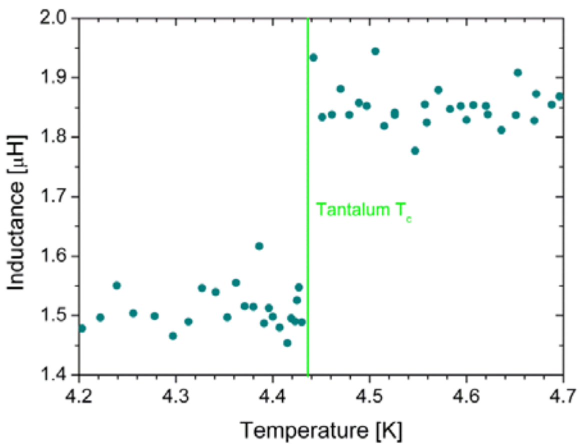


Fig. 36*. Inductance change seen when the noise thermometer cools through the superconducting transition of the tantalum fixed point device.*

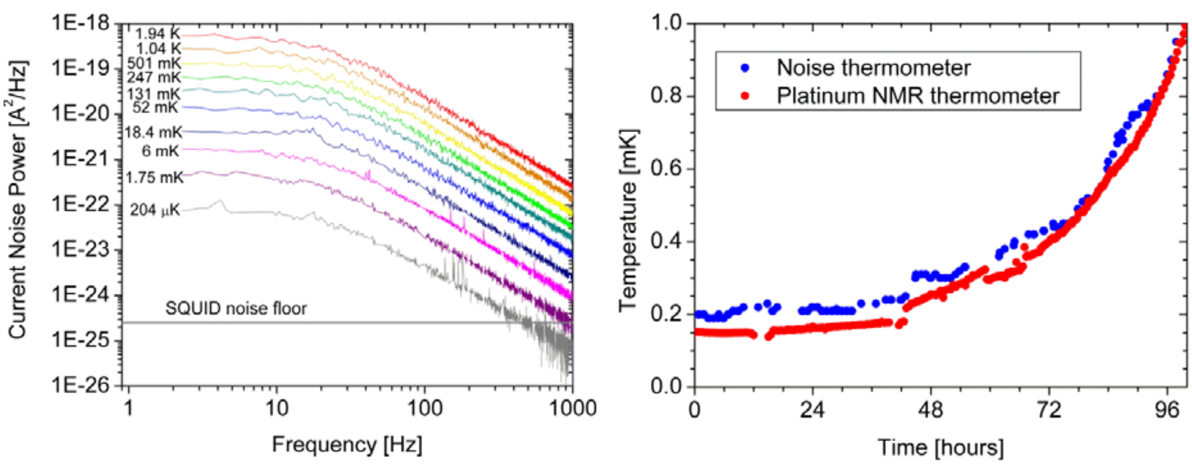


Fig. 37. ***(Left)*** *Noise traces for temperatures ranging from 2 K down to 200 µK. The SQUID noise floor is indicated.* ***(Right)*** *Noise thermometer temperature compared to platinum NMR temperature while the nuclear stage warms up from its base temperature.*

Fig. 37 (left) shows a selection of noise traces at different temperatures of the nuclear stage, showing temperatures down to 200 µK, after a nuclear demagnetization. Fig. 37 (right) shows the warm up of the nuclear stage to 1 mK, demonstrating reasonable agreement between the noise and platinum thermometers.

At PTB research on Task 3a has been continued with the goal to increase the measurement quality of the Magnetic Field Fluctuation Thermometer (MFFT). A setup and experimental procedures were developed to realise MFFT reference measurements at temperatures that are directly traceable to the PLTS-2000 scale [31]. The precise reference temperatures are realised by means of superconducting reference points. Furthermore, a methodology to determine the MFFT calibration parameters from the reference measurement as well as to obtain an estimate and uncertainty in a MFFT measurement of an unknown temperature was devised [32]. The calibration services for MFFTs mentioned above make use of the results of these activities.

Several cool-downs of PTBs old nuclear demagnetization refrigerator PTB MK2 were performed to investigate the operation of the commercially available Magnicon MFFT-1 thermometer down to temperatures of 1 mK and below. In the temperature range from 1.6 K down to the lower end of PLTS-2000, the deviations of the noise temperatures from the reference temperatures T_{90}/T_{2000} according to the international temperatures scales were found to be in the range of ±1 %, proving that the MFFT is applicable at ultra-low temperatures. In these experiments MFFT temperatures as low as 400 µK were measured. However, the lack of a reliable temperature reference below 902 µK did not allow accurate assessment of this temperature data. In order to further extent the MFFT range of operation towards lower temperatures, a modified MFFT design was developed. It uses a SQUID magnetometer with increased magnetic sensitivity and improved magnetic shielding. The noise temperature of this MFFT-2 design has been estimated to be as low as 5 µK. A MFFT-2 prototype is currently being manufactured. It will be provided to AALTO to be tested at temperatures down to ca. 300 µK.

Task 3b: Ultra low temperature ^{195}Pt NMR thermometer (PTB, AALTO)

During the first 3 years of the project, the Pt NMR thermometry experiments at PTB have been carried out in the µK refrigerator MKA3 with a single copper nuclear cooling stage. As described in the internal18/36 month report of Deliverable D6 "Report on ^{195}Pt-NMR thermometer for ultra-low temperatures", PTB has tested Pt-NMR thermometers down to 10 µK using a PLM4 system operating at a frequency of 250 kHz (Milestone 9). Within the last 18 month, a ^{195}Pt-NMR thermometer was mounted and investigated in more detail on the nuclear demagnetization stage of PTB's MKA3. It was be operated with a PLM5 system enabling operation at lower frequencies (125 kHz, 64.5 kHz). In particular, the effect of radiation damping and the influence of self-heating due to power dissipation have been examined.

To improve on the platinum NMR thermometry investigations at ultra-low temperature, the experimental platform of the MKA3 cryostat was upgraded. In addition to the copper nuclear cooling stage, a second platinum stage was included. Three bulk platinum thermometers were installed and tested on this double-stage nuclear demagnetisation setup, as shown in Fig. 38 below.

Two of these (Pt-NMR #1 and #2) are located in the field compensated regions of the superconducting magnets to measure the electronic temperature on top of the first and the second nuclear demagnetisation stages, respectively. In addition, a cylindrically shaped part of the platinum nuclear cooling stage (Pt-NMR#3) permits measurement of the nuclear spin temperature in the final magnetic field of the second stage. Both the nuclear spin and electronic temperatures can be derived by solving the thermodynamic field equations for given boundary and initial conditions of the nuclear demagnetisation process. The measured temperature agrees with the thermodynamic temperature calculated as a numerical solution of the thermodynamic field equations down to 10 µK within an uncertainty of 5%. A more detailed description is given in a supplement of the previous 36-month review report on the deliverable D6 "Report on ^{195}Pt-NMR thermometer for ultra-low temperatures".

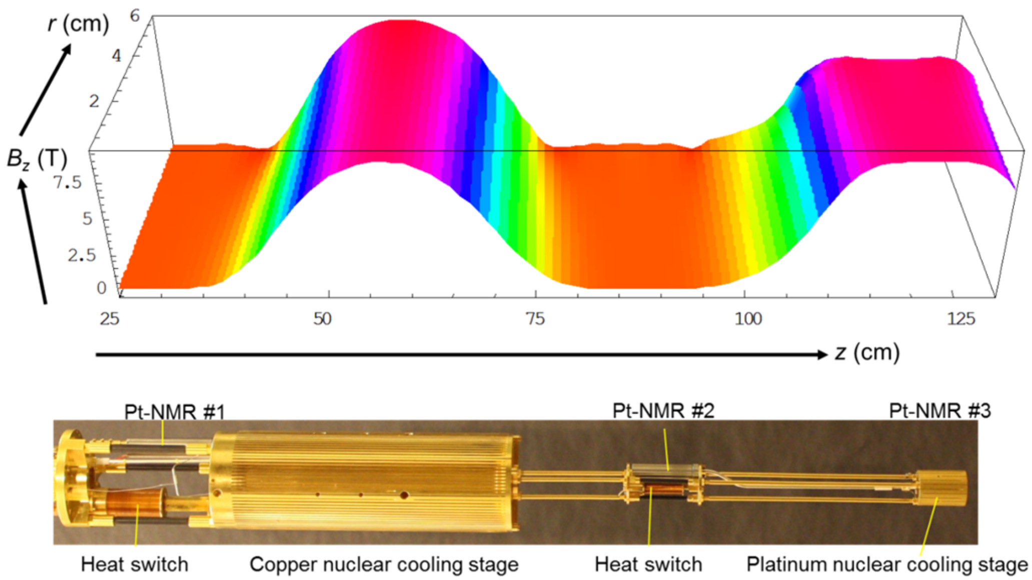


Fig. 38. *(**Top**) Magnetic field distribution in MKA3. (**Bottom**) Photo of the actual cryostat indicating the positions of the Pt-NMR thermometers.*

Task 3c: Coulomb blockade thermometer for nanosamples (AALTO, CNRS, BASEL)

Coulomb blockade thermometry (CBT) is based on detecting the non-linear conductance of a semiconductor quantum dot or of an array of tunnel junctions: the width of the conductance peak or dip around zero bias voltage is measured, and this width can be related directly to absolute temperature without calibration. We wish to develop Coulomb blockade thermometry for nano samples at the lowest possible temperatures, including both tunnel junction CBT sensors as well as GaAs quantum dot temperature sensors in semiconducting nanosamples. The goal of the Basel activity in JRA4 (Task 3c) is to demonstrate operation of a GaAs quantum dot as a Coulomb blockade thermometer in the temperature range from several hundred milli-Kelvin down to about 10 mK (prototype running after 24 months, Milestone 8). In a second stage, this thermometer will be used at even lower, sub-mK temperatures which we plan to achieve with a new type of demagnetization refrigerator currently under development by Basel/Lancaster in the JRA1 activities.

Previously, we have fabricated GaAs quantum dot thermometer devices based on charge sensing, and operated these down to 9.5 +/- 2 mK at the base temperature of the dilution unit (8.8 mK). During the course of these experiments we realized that the susceptibility of these devices to the electrical environment, i.e. voltage noise, makes it challenging to measure temperatures below 10 mK with our setup. As a consequence we decided to replace the ceramic chip carrier and sample socket with an Ag epoxy chip socket, which is conductive and thus provides a ground plane for additional shielding of the sample. In order to improve the noise environment, we also introduced a new filtering stage between the nuclear refrigerator and the sample. Possibly this will increase the thermal resistance between the Cu plate and the sample, but it provides a filtered Faraday cage around the sample at very low *T*. Albeit a considerable effort to reduce the ohmic contact resistance to our GaAs devices, typical values lie between 50 and 100 Ohms, which will dominate the thermal resistance between the nuclear refrigerator and the sample in any case.

With the new sample socket and chip carrier we measured a series of metallic Coulomb blockade thermometers which differed in junction resistance. We observed that the lowest temperature after demagnetization shows a clear dependence on junction resistance. For the measured devices the highest resistance leads to poorer thermalization, indicating that the Wiedemann-Franz mechanism contributes significantly to the cooling mechanism. The low resistance (15 kOhm per junction) CBT cools to a temperature of 5.2 +/- 0.2 mK after demagnetization. With a charging energy of 17 mK, this thermometer is already operated deep in the intermediate Coulomb blockade regime, where the device is not in true metallic CB anymore, making temperature measurement more difficult.

NbN thermometry on silicon membrane with μK sensitivity

CNRS measurements: In this work, phonon thermometry is investigated in a thin film of niobium nitride, to measure the phonon temperature of a suspended membrane. When this material is on the insulating side of the metal to insulator transition, the increase of resistance at low temperatures permits a measurement of temperature down to 20 mK with very high sensitivity. The lowest temperature variation that can be detected is around 2 μK at 50 mK. The limitations come from the voltage Johnson noise across the resistive thermometer and the preamplifier's intrinsic noise, which is below 2nV/SQRT(Hz).

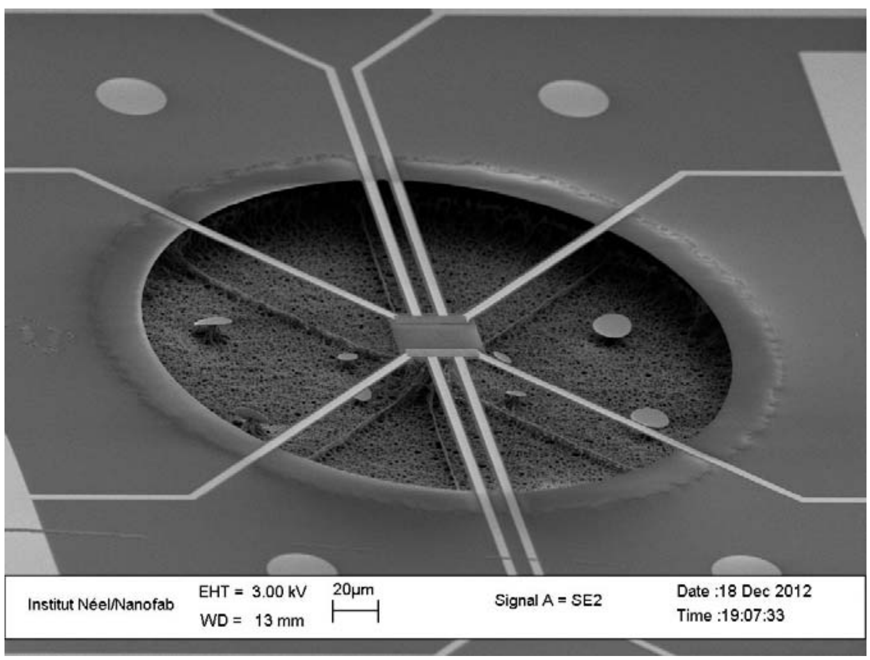


Fig. 39. *High sensitivity nanocalorimeter built on a 100 nm silicon nitride membrane, as developed at CNRS-Grenoble by O. Bourgeois, K. Lulla, T. Fournier, and T. Crozes. With this device the phonons in the membrane can be cooled to investigate phonon transport in a large temperature range at low temperatures, opening a new field of investigation, "nanophononics".*

The membrane is thermally isolated through suspended arms. The thermometer is connected using superconducting leads far from their phase transition providing high thermal isolation. The thermometer is then only thermalized through the membrane thermal bath. Measurements have been performed on a silicon membrane and a silicon nanowire below 1 K. As an illustration, below the R(T) characteristics of a NbN thermometer are depicted. This device was used to measure the phonon temperature of a silicon membrane from 1K down to 15 mK.

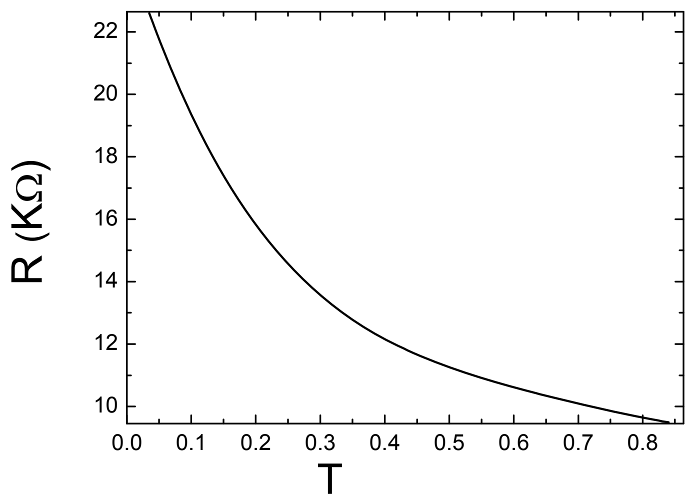


Fig. 39. *Resistance vs temperature characteristic of the NbN thermometer, with a sensitivity of 1 part in 10^4 at low mK temperatures.*

The temperature measurement of the phonon bath is listed as **milestone M4** in joint research activity JRA1 Task 1 as "***phonon temperature of nanoscale silicon membrane***". This goal has thus been well achieved, and the sensitivity of 10^{-4} is remarkable.

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Highlights

- First measurement of thermal conductivity of metallic glasses between 10 mK and 300 K.
- NMR signals from small volumes using two different microcoils, with ^{3}He gas as test sample. Measured signal-to-noise ratio (SNR) in good agreement with predictions. Similar microcoils will be used for imaging topological defects in superfluid ^{3}He confined in nanocavities.

- High bandwidth (400 MHz) SQUID amplifier has been operated on a cryogen-free dilution refrigerator, to observe NQR signals from ^{35}Cl in a powder sample of $NaClO_3$ at 30 MHz. This demonstrates the potential of making direct NMR measurements over a wide range of Larmor frequencies with an untuned spectrometer.
- Fast current sensing noise thermometers have been developed for dilution refrigerator temperatures, using large sensor resistors, benefiting from the ultrasensitive SQUID amplifiers developed at PTB. A precision of 1% in 0.1s was achieved, and compatibility with a cryogen-free dilution refrigerator was demonstrated
- A current sensing noise thermometer has been operated on a cryogen-free refrigerator with a demagnetization stage, which achieved 0.6 mK. This demonstrates the compatibility of cryogen-free dilution refrigeration with both nuclear refrigeration methods and noise thermometry for the first time.
- A current sensing noise thermometer, with a remote SQUID amplifier, has been operated in a conventional nuclear demagnetization refrigerator achieving temperatures below 200 µK.
- An inductive read out in a noise thermometer using a cross correlation technique has been operated below 50 µK surpassing Milestone M7.
- A series of fundamental studies of quantum fluids and solids on the nanoscale has been performed, using the SQUID NMR technique. This opens novel further opportunities to investigate two dimensional ferromagnetism, a one-dimensional fermion system, and topological superfluids under nanofluidic confinement, to name some of our future efforts.
- CBT operated down to 5.2 ± 0.2 mK surpassing Milestone M6.
- GaAs QD thermometer operated down to 9.5 +/- 2 mK.

Deviations from work plan

No deviations from workplan

Use of resources

The use of resources was as foreseen by the budget of JRA4

3.2.3 Project management during the period

Microkelvin management tasks and achievements

- The first amendment to Annex I concerned the change of name of one grant partner from Helsinki University of Technology to School of Science of Aalto University.
- The second amendment request to Annex I was submitted in September 2011 and was approved by the EU Project Office in December 2011. The requested changes concerned the name of the Coordinator [from Mikko Paalanen to Matti Krusius] and JRA3 [Task 3 – Horizons, ergo regions, and rotating black holes, and Task 5 – ULTIMA-Plus: Dark matter search with ultra-low temperature detectors].
- The third amendment asked for an extension of the grant period by 6 months and a transfer of half of the Lancaster University access volume to Aalto University. This amendment came into effect on April 10, 2013.

Microkelvin website

- The website has been continuously kept up to date on page http://www.microkelvin.eu/
- Microkelvin workshops and their programms are listed on pages http://ltl.tkk.fi/wiki/Events/Microkelvin_2013 and http://ltl.tkk.fi/wiki/Events

Microkelvin progress

- Microkelvin had a slow start initially owing to the fact that the EU project grant became available only four months after the starting date of April 1, 2009. Nevertheless, ¾ of the deadlines were achieved at the first 18-month review point.
- At the second review point of 36 months more than ⅔ of the deadlines were achieved in time. The remaining ones were delayed for various practical reasons, but were all in a state of active progress. We anticipated then that by the end of the four-year grant period or shortly after most, if not all, of the goals would be met. Microkelvin was deemed to be well on its track!
- Now at the final review point of 54 months this prediction proves to turn true: xx % of the deadlines has been achieved. The individual deadlines and the level of their achievement are reviewed in Section 3.2.2.

Transnational Access Activities

Transnational access promised for the entire grant period 1.4. 2009 – 31.3. 2013 [as reassigned between the providing sites in Amendment #3 of Annex I]

Participant number	*Organisation short name*	*Installation*		*Unit of access*	*Min. quantity of access to be provided*	*Estimated number of users*	*Estimated number of projects*
		Number	*Short name*				
1	AALTO	1	Cryohall	Facility-month	40.5	18	14
1	AALTO	2	AU Micronova	Hour	100	5	5
2	CNRS	1	CNRS MICROKELVIN	Facility-month	27	18	14
3	ULANC	1	MicroKLab	Facility-month	13.5	18	14
Altogether	-	-	-		81.0	-	-

Transnational access given in first 18-month review period from 1.4.2009 to 30.9.2010

Participant number	**Organisation short name**	**Installation**		**Unit of access**	**Transnational access provided**	**Number of groups**	**Number of users**
		Number	**Short name**				
1	AALTO	1	Cryohall	Facility-month	13.1	8	9
1	AALTO	2	AALTO Micronova	Hour	34.5	1	1
2	CNRS	1	CNRS MICROKELVIN	Facility-month	3.6	4	6
3	ULANC	1	MicroKLab	Facility-month	2.0	2	3

Transnational access given in second 18-month review period from 1.10.2010 to 31.3.2012

Participant number	**Organisation short name**	**Installation**		**Unit of access**	**Transnational access provided**	**Number of groups**	**Number of users**
		Number	**Short name**				
1	AALTO	1	Cryohall	Facility-month	10.9	11	12
1	AALTO	2	AALTO Micronova	Hour	66.5	2	2
2	CNRS	1	CNRS MICROKELVIN	Facility-month	8.3	6	6
3	ULANC	1	MicroKLab	Facility-month	3.3	5	8

Transnational access provided in the third periodic reporting period 1.4.2012 – 30.9.2013

Participant number	**Organisation short name**	**Installation**		**Unit of access**	**Transnational access provided**	**Number of groups**	**Number of users**
		Number	**Short name**				
1	AALTO	1	Cryohall	Facility-month	16.7	20	20
1	AALTO	2	AU Micronova	Hour	0	0	0
2	CNRS	1	CNRS MICROKELVIN	Facility-month	16.1	10	12
3	ULANC	1	MicroKLab	Facility-month	6.63	6	9

Transnational access provided in total over the grant period 1.4.2009 – 30.9.2013

Participant number	**Organisation short name**	**Installation**		**Unit of access**	**Transnational access provided**	**Number of different groups**	**Number of different users**
		Number	**Short name**				
1	AALTO	1	Cryohall	Facility-month	1223 days or 40.8 months	28	32
1	AALTO	2	AALTO Micronova	Hour	100	3	3
2	CNRS	1	CNRS MICROKELVIN	Facility-month	842 days or 28.1 months	17	22
3	ULANC	1	MicroKLab	Facility-month	359 days or 12.0 months	8	18
Altogether	-	-	-	Facility-month	2424 days or 80.8 months	49	65

Observations from the final 18-month reporting period

- Half of the trans-national access volume of Lancaster University was moved to Aalto University in Amendment No. 3 which was finally approved April 10, 2013. This transfer ensured a more effective use of the funding provided for access activities.
- The transnational access programme reached its targeted volume, as seen in the above tables.
- The number of different research groups and their individual members, who participated in the access programme, was much larger than anticipated in Annex I

Project meetings, dates, and venues

- Listed in Sec. 3.2.2 under NA2 and NA3 Task 3

Changes in the consortium

- Half of the total access time of 27 months originally assigned to the Microkelvin Laboratory of the Lancaster University was transferred to the Cryohall facility at Aalto University. The reassigned 13.5 access months was provided at the Cryohall facility at the same unit cost as originally budgeted for the Microkelvin Laboratory. Thus no changes occurred in the overall budget of the grant.
- Simultaneously the duration of the transnational access programme and the grant period was extended by 6 months until September 30, 2013. This extension also applied to networking activities, since the final review and user meeting had to be postponed, but not to joint research activities.
- These changes were the content of the third amendment to the grant agreement which was finally confirmed April 10, 2013.

Impact of deviations from the planned milestones and deliverables

- The demonstration of nuclear cooling in a pulse-tube-precooled cryogen-free dilution refrigerator in Basel was delayed because of delays in the delivery of dry superconducting magnet systems (by an external commercial supplier). A similar effort in CNRS, but with entirely homemade equipment, was also delayed because of the restructuring of the institute and the associated reduction in machining capacity of the in-house metal workshop.
- However, the construction work of two more setups was started in the meantime. Of the four installations now in the pipe line, one has successfully achieved its expected performance specifications and for two more the test runs with promising results are now in full swing.

Changes to the legal status of beneficiaries

- Change of name of one partner: from Low Temperature Laboratory to O.V. Lounasmaa Laboratory [Low Temperature Section] in the School of Science of Aalto University

Completed Microkelvin Transnational Access projects in the third reporting period 1.4.2012 – 30.9.2013

The reports from the Access Projects are publicly available on the web page
http://www.microkelvin.eu/project-activities-transnational.php

Title of the project	**Nonequilibrium transport through nanodevices** AALTO 21
User group leader	Iouri Galperine, professor
User	Iouri Galperine, professor
Home Institute	Department of Physics, University of Oslo
Host supervisor	Nikolai Kopnin, professor Lounasmaa Laboratory, Aalto University
Description of the work	The main objective is development of a theoretical framework for systematic studies of nonlinear stationary and time-dependent transport through hybrid devices consisting of normal and superconducting parts. This task requires understanding the interplay between Coulomb interaction (Coulomb blockade effects) and coherent phenomena related to the dynamics of the superconducting condensate. The latter requires full account of quantum dynamics in confined superconductors involving several specific features. Among the unusual non-equilibrium properties of hybrid systems are the so-called branch imbalance - asymmetry in populations of electron- and hole-like branches of the excitation spectrum, specific electro-neutral interface modes, non-traditional heat release and transport, etc. We plan to work out theoretical approaches allowing for the above-mentioned phenomena. During the 7-day visit of Iouri Galperine, we have arranged a meeting between experimentalists and theorists. Based on the results of this meeting, we have formulated the main problems and chosen the order in which they will be addressed in order to use our expertise in the best way. We have discussed leading approximations allowing obtaining concise results from the general theory of quantum transport. We have done our best to review and formulate the basic set of equations to be analyzed and solved, either analytically or numerically. We expect to move along this planned route.
Project achievements	This is the starting point of a new project, which we expect to be fruitful. The final results are still unclear at this stage.
Amount of access given	7 days (25.11.-1.12.2012)

Title of the project	**Studies of quantum turbulence in superfluid 3He under rotation** AALTO 22
User group leader	Carley Paulsen, senior researcher
User	Martin Jackson, post-doctoral researcher
Home Institute	Institut Néel, CNRS, Grenoble
Host supervisor	Vladimir Eltsov, senior researcher, Lounasmaa Laboratory, Aalto University
Description of the work	Superfluid 3He under rotation provides a unique environment for quantum turbulence studies. The main topic of this project is the influence of polarization of vortex lines, which can be affected by rota-

	tion, on the behaviour of quantum turbulence at very low temperatures. The ultimate goal is to understand how the polarization affects the turbulence build-up and decay as well as the processes of energy transfer and dissipation. Measurements of the coherent magnon states in a cylindrical sample of superfluid 3He-B during modulated rotation were made at temperatures between 0.15 and 0.2 mK. Modulation causes depolarization of vortex lines which was expressed and measured in terms of the frequency shifts of the magnon states. It was controlled by the duration and amplitude of the modulation. After stopping the modulation, the rotation velocity was changed to a new level and the decay of the vortex configuration to the equilibrium state was observed. It was found that the decay proceeds in 2 steps: First for a long time the vortex polarization remains low, indicating that global-scale turbulent flow is still present in the sample and only then polarization restores in a process which probably involves individual vortex lines and thus is relevant for the decay of Kelvin-wave turbulence. We measured these two decay times as a function of temperature, amplitude of the modulation, and of the final rotation velocity.
Project achievements	The main finding is that the first decay time is proportional to the global flow energy, stored in the system after oscillations have finished. The energy can be calculated from the difference of the average velocity during oscillations and the final velocity, provided that the oscillation frequency is not close to the inertial wave resonances and thus the energy of the inertial wave can be neglected. From the value of the hydrodynamic energy and the measured decay time we can find the decay rate of the polarized quantum turbulence at ultra-low temperatures. At these temperatures it is expected that the decay occurs via the Kelvin-wave cascade. Given that vortices in our experiment are strongly polarized we can assume that each of them acts individually in dissipation and thus dissipation due to the Kelvin-wave cascade on a single vortex can be measured for the first time. This is an important achievement since both theory and numerical calculation of vortex dynamics so far are incapable of giving a reliable prediction of this effect.
Amount of access given	32 days (16.7.-10.8.2012 and 12.11.-17.11.2012)

Title of the project	**Charge and heat transport in quantum dots coupled to superconducting leads** AALTO 23
User group leader	Professor Hervé Courtois
User	David van Zanten, M.Sc., graduate student
Home Institute	Institut Néel, CNRS, Grenoble
Host supervisor	Professor Jukka Pekola, Aalto University
Description of the work	The task was to analyse electron and heat transport through SINIS structures where the normal island is a weakly coupled quantum dot.

	This work was then compared to numerical calculations on SINIS structures where the normal island does not have a significant level spacing.
Project achievements	The main goal of this one week visit was to establish a close collaboration, to gain new understanding so that ultimately one could measure charge and heat transport through quantum dots coupled to superconducting leads. As a first step, a numerical model was realized to describe heat and current transport in the basic SINIS structure. This laid the foundations for including discrete energy levels in the dot (in the otherwise familiar picture of transport analysis based on a master equation approach) and for including in the rate equations the theoretical input on what is known about different relaxation mechanisms. This approach enables a comparison to experimental results obtained from metallic islands where the density of states is practically uniform. The experiment will ultimately measure directly the energy relaxation rates, which determine the degree of non-equilibrium in a dynamic situation. The discreteness of the energy levels may provide a way of faster operation of a single-electron turnstile, and suppression of its transfer errors. Results: (1) A collaborative project was started with plans for future experiments and modelling. (2) The first step with a numerical model to describe heat and current transport was completed.
Amount of access given	7 days (5.2.-11.2.2012)

Title of the project	**Biot-Savart tree-algorithm together with smooth wall boundary conditions at different geometries** AALTO 24
User group leader	Carlo Barenghi, professor
User	Andrew Baggaley, senior researcher, Ph.D.
Home Institute	School of Mathematics and Statistics, Newcastle University, UK
Host supervisor	Risto Hänninen, senior researcher, Ph.D. Lounasmaa Laboratory, Aalto University
Description of the work	With the help of the new and faster tree algorithm for vortex filament calculations, the primary task is to mimic and interpret various experiments, first in simple rotating cases where the results can be tested. Later more complex applications will be included, where the direct visualization of quantized vortices is typically difficult. Such experiments are, for example, the propagation of the vortex front in a rotating cylinder or the decay of a vortex tangle after a sudden stop of rotation. It is expected, that the results obtained help us to better understand quantum turbulence. We are most interested in the zero temperature limit, where energy dissipation should occur at length scales shorter than the inter-vortex distance. Therefore a faster code is needed, in order to cover a wider range of length scales with improved resolution. Within this vortex filament formulation we can then also

	search for improved methods to identify possible coherent structures and to probe the cascade of Kelvin waves on the vortex. The primary goal is to use the vortex filament model and combine two pre-existing numerical codes such that we can exploit the benefits from both programs. The tree-algorithm code by A. Baggaley, which is N*log(N) method (versus the standard N^2 method), allows a considerable speed-up and makes possible to use vortex line densities larger than before. So far this code is limited to periodic boundary conditions. Using the tree-algorithm as a basis, a new code will be implemented where experimentally feasible boundary conditions are taken into account. This will be done by using the code of R. Hänninen, where the geometry, i.e. a cube and a cylinder, are already implemented. During this first short visit our task is to discuss how to combine these two approaches so that a working code can ultimately be composed.
Project achievements	During the two-week visit a new computer code was established which uses the tree-algorithm and takes into account smooth solid boundaries. The code makes it possible to simulate quantum turbulence in cubical and cylindrical geometries using parameters that are close to experimental ones. The code still needs some testing and additions before it can be used to large scale simulations. The image field is currently calculated using image vortices. In most cases this is enough, e.g. the vortex front motion is well described using this approximation. Routines to calculate the energy spectrum have not been done yet. The implementation of these routines needs some rethinking since solid boundaries, especially in cylindrical geometry, complicate the Fourier presentation.
Amount of access given	15 days (28.4.-12.5.2012)

Title of the project	**Relaxation of magnon Bose-Einstein condensates in superfluid 3He-B** AALTO 25
User group leader	Yuriy Bunkov, professor
User	Yuriy Bunkov, professor
Home Institute	Institut Néel, CNRS, Grenoble, France
Host supervisor	Vladimir Eltsov, senior researcher Lounasmaa Laboratory, Aalto University
Description of the work	Long-lived coherent spin precession of 3He-B at the lowest temperatures below 0.2 Tc has been interpreted as Bose-Einstein condensation of magnon quasiparticles in the potential well formed by the order-parameter texture in the applied static magnetic field [1]. As the temperature decreases, the life time of such condensates rapidly increases to minutes. Using the rotating cryostat at the LTL we can bring the condensate in contact with quantized vortex lines or with the free surface of the 3He-B sample. The question we want to answer is whether vortex-core-bound or sur-

	face-bound fermionic states in 3He-B leave a signature in the relaxation properties of the magnon condensates. Interest in these states has significantly increased recently owing to the prediction that these fermionic states are at zero-energy possessing the Majorana character. [1] A. Autti, Yu.M. Bunkov, V.B. Eltsov, P.J. Heikkinen, J.J. Hosio, P. Hunger, M. Krusius, G.E. Volovik, *Self-trapping of magnon Bose-Einstein condensates in the ground state and on excited levels: from harmonic to box-like confinement*, Phys. Rev. Lett. **108**,145303 (2012).
Project achievements	The goal is to develop a model which describes the effect of the bulk quasiparticles on the relaxation time. This contribution can then be subtracted from the measured dependences. The final objective is to examine the additional relaxation which is caused by zero-energy states, to reveal the signatures of bound fermion states with Majorana character. The relaxation rate of magnon condensates depends on the exact profile of the trapping potential. Thus the work includes two stages: First, the trapping potential is determined. For this the spectroscopy of magnon levels in the trap is used and the appropriate potential, which produces the same level positions, is calculated for each of the relaxation measurements. Second, a numerical model of the relaxation, which includes spin diffusion and possibly other relaxation sources, is developed. The results from the calculations will then be compared to the measured temperature dependences of relaxation in different trap configurations which can be controlled by applying rotation. We expect to find good agreement between experiment and calculation at higher temperatures and a deviation at lower temperatures. In this deviation we will look for a contribution, which depends on temperature as a power-law, the smoking gun signature for bound states with a zero state in the energy spectrum. Measurements on spin relaxation of magnon condensates in various configurations have been performed in the rotating cryostat. A clear result has been obtained for the temperature dependence of the relaxation time associated with the bulk quasiparticles. Also the increase of the relaxation rate when a vortex cluster is put in contact with the magnon condensate has been observed. In contrast, the influence of the free liquid surfaces is found to be much weaker. The analysis and interpretation of the results is in progress. During this visit Yuriy Bunkov was also working together with Grigori Volovik on two major publication projects, a book chapter and secondly on a monograph. Both describe the different coherently precessing NMR states and magnon condensation in superfluid 3He. A publication will be prepared which explains the relaxation properties of the very-low-temperature magnon condensates in 3He-B.
Amount of access given	36 days (4.-18.4. and 10.-30.5.2012)

Title of the project	**Superconducting graphene resonators** AALTO 26
User group leader	Saverio Russo, professor
User	Daniel Cox, graduate student
Home Institute	Centre of Graphene Science, School of Physics, University of Exeter, UK
Host supervisor	Pertti Hakonen, professor Lounasmaa Laboratory, Aalto University
Description of the work	Graphene is a unique two-dimensional, gapless semiconductor: the conduction and valence bands touch in two inequivalent K points, the Dirac points, where the density of states vanishes. However, the conductivity at the Dirac point remains finite. Indeed, it has been theoretically shown by M. Katsnelson and J. Tworzydlo et al. in 2006 that, in perfect graphene, the conduction occurs only via evanescent waves at the Dirac point. Mechanical graphene resonators have been actively investigated during the last few years. We have adopted capacitive measurement methods for detection of nano-mechanical motion. Dissipation at high measurement frequencies is one of the unknown factors in employing these capacitive techniques for graphene resonators. One way to go around this problem is to employ proximity-induced superconductivity to reduce electrical losses. In this project we plan to develop superconducting graphene resonators and investigate their electrical and mechanical characteristics. This plan calls for the following list of work to be performed: 1. preparation and characterisation of monolayer graphene samples with superconducting contacts, 2. releasing the graphene sheets using an appropriate method, for example vapour-phase HF-etching, 3. characterization of the samples at DC at room temperature, 4. selection of good samples for low temperature measurements, 5. measurements in a dilution refrigerator, 6. obtain data on conductivity, supercurrents, and shot noise, 7. detect mechanical resonance using FM detection methods, 8. investigate coupling between mechanical motion and superconducting electrical transport, 9. compare FM detection to supercurrent resonance detection. Of the above work list, items 1-2 will be performed using Micronova facilities, while items 3-9 will be carried out at LTL of Aalto University.
Project achievements	Two sets of graphene samples were fabricated. One consisted of exfoliated sheets on traditional Si/SiO2 and contacted with superconducting aluminium leads and then etched with gas phase HF etching. The other set was exfoliated graphene on top of LOR resist, which negates the need to use HF etching, and instead allows the use of organic solvents and more exotic materials; aluminium contacts were also fabri-

	cated on these samples. So far only normal state conducting properties of these samples have been examined. Two experiments were performed – one looking at interference effects in graphene and the other concerned with high DC bias electron-phonon coupling – both of which require high quality suspended samples. To examine interference phenomena in our ballistic samples, conductance measurements were used to probe the electronic Fabry-Pérot resonances that arise from reflections at the sample edges and contacts. Shot noise measurements were successfully taken to validate the multimode nature of these interferences. Shot noise measurements were also employed for in-situ thermometry in graphene in order to probe the electron-phonon coupling. Here a high DC bias was applied, and AC conductance along with shot noise were measured simultaneously. Accordingly, the heating power vs. electronic temperature was obtained which could be analysed in terms of the coupling between acoustic phonons and electrons; strong indications for the dominance of double phonon processes were found.
Amount of access given	30 days (8.9.-8.10.2012)

Title of the project	**Dynamics and dissipation in vortex motion in the zero-temperature limit in rotating superfluid 3He-B** AALTO 27
User group leader	Victor L'vov, professor
User	Victor L'vov, professor
Home Institute	Weizmann Institute of Science, Rehovot, Israel
Host supervisor	Vladimir Eltsov, senior researcher Lounasmaa Laboratory, Aalto University
Description of the work	The dynamics of quantized vortices at the lowest temperatures is a central topic in the Microkelvin program (*Joint Research Activity package 3 Task 1 – Investigation of quantum vortices as model cosmic strings*). Measurements on superfluid vortex motion have been ongoing for several years in the rotating cryostat of the Low Temperature Laboratory of the Aalto University. Different processes have been studied, in particular the interplay of laminar and turbulent vortex flow. One of the main challenges is to understand the sources of dissipation in vortex motion in the limit $T \rightarrow 0$, which corresponds to the vacuum limit for quasiparticle excitations, i.e. the normal component. This is the regime in which bulk hydrodynamics is expected to break down since the density of the ballistic quasiparticle cloud will be too sparse to support a tight coupling between the superfluid and normal components via the mutual friction damping in vortex motion. The motion of cosmic strings could be expected to take place in this same regime today, if cosmic strings are found to exist. At higher temperatures mutual friction in the bulk volume provides the coupling of the superfluid vortices to the external reference frame,

	both with respect to energy and angular momentum transfer. Mutual friction arises from the scattering of normal excitations from a vortex which moves with respect to the reference frame provided by the normal fluid. With decreasing temperature mutual friction dissipation vanishes exponentially, as the density of normal excitations approaches zero. However, current measurements show that in turbulent vortex motion dissipation does not extrapolate to zero in the $T \rightarrow 0$ limit. What are these mechanisms which govern superfluid dynamics at the lowest temperatures? One of the processes which have been employed for such studies is the motion of a turbulent vortex front in a long rotating cylinder. Measurements of the azimuthally rotating and axially advancing front have been performed since 2005 in the rotating cryostat. The front divides the cylinder in two sections: Ahead of the front there is vortex-free rotating counterflow ($v_s = 0$, $v_n = \Omega R$), while behind the front there is a bundle of twisted vortices at some value Ω_s of solid-body-rotation density (vs $\approx \Omega_s R \leq \Omega R = v_n$). Turbulence concentrates in the front itself, where reconnections occur continuously at a steady rate while the front is moving. The first results [1] on the axial velocity of the front were obtained with NMR techniques and were interpreted assuming that the dissipation is primarily produced by the turbulent front motion. Subsequent thermal studies [2] of the axially moving transition from vortex-free counterflow to the rotating equilibrium vortex state (at constant rotation velocity Ω) showed that with decreasing temperature in the limit $T \rightarrow 0$ an increasing fraction of the total dissipation arises from the laminar part of the vortex flow. Although this result was opposite to what was generally expected, it is consistent with measurements of the spin-down response [3] of the equilibrium vortex state after a sudden stop of the rotation drive. **References:** [1] V.B. Eltsov, A.I. Golov, R. de Graaf, R. Hänninen, M. Krusius, V.S. L'vov, and R.E. Solntsev, *Quantum turbulence in a propagating superfluid vortex front;* Phys. Rev. Lett. **99**, 265301 (2007). [2] V.B. Eltsov, R. de Graaf, J.J. Hosio, P.J. Heikkinen, R. Hanninen, M. Krusius, V.S. L'vov, and G.E. Volovik, *Superfluid vortex front at T → 0: Decoupling from the reference frame*, Phys. Rev. Lett. **107**, 135302 (2011). [3] V.B. Eltsov, R. de Graaf, P.J. Heikkinen, J.J. Hosio, R. Hänninen, M. Krusius, and V.S. L'vov, *Stability and dissipation of laminar vortex flow in superfluid 3He-B*, Phys. Rev. Lett. **105**, 125301 (2010).
Project achievements	There are unresolved questions concerning the correct interpretation of different dynamic measurements at the lowest temperatures. If we want to make use of the helium superfluids as laboratory model systems of coherent quantum matter in the vacuum $T \rightarrow 0$ limit, the dynamics should be understood better. In superfluid turbulence the kinetic energy flows via the Richardson – Kolmogorov cascade to ever smaller length scales when the temperature is reduced. Finally, at the inter-vortex distance it has to be

	bridged from larger eddies consisting of bundled vortices to Kelvin waves propagating on single vortex lines. With further temperature reduction more and more of the dissipation occurs in the Kelvin wave cascade. New results are currently accumulated both in laboratory measurements as well as in high-resolution numerical calculations as a function of temperature, rotation velocity, and the radius of the rotating cylinder. Both sets of data appear to emphasize the importance of the Kelvin wave cascade. Comparing the results, we expect to construct an empirical model which provides a unified explanation. Hopefully this model will guide the way to a physical understanding of the Kelvin wave cascade and its dissipation. During his 3-week visit in the Low Temperature Laboratory, prof. L'vov discussed and analyzed results from vortex front measurements. He prepared a report which describes a phenomenological model and its fit to the experimental data when the superfluid component starts to lose increasingly its coupling to the rotating reference frame of the container walls with decreasing temperature. The model provides a perfect fit but unfortunately not all details about the basis for this model are currently known.
Amount of access given	24 days (11.8.-3.9.2012)

Title of the project	**Dynamics of quantized vortices in superfluids & superconductors** AALTO 28
User group leader	Edouard Sonin, professor
User	Edouard Sonin, professor
Home Institute	Racah Institute of Physics, Hebrew University, Jerusalem, Israel
Host supervisor	Matti Krusius, professor Lounasmaa Laboratory, Aalto University
Description of the work	The main purpose of the visit is to discuss theoretical and experimental problems in vortex dynamics and turbulence in superfluids in the zero-temperature limit, as needed and appropriate for the theoretical research project of prof. Sonin, in particular with regard to his plans to publish a monograph on these topics. In addition, he participated in discussions and in the analysis of measurements on the propagation velocity of the turbulent vortex front in superfluid 3He-B which are currently conducted in the Lounasmaa Laboratory.
Project achievements	During his 10-day visit prof. Sonin discussed with N. Kopnin and G. Volovik two problems of zero-temperature vortex dynamics and turbulence: (i) Symmetry of Kelvin-waves and the Kelvin-wave cascade, and (ii) the role of superfluid backflow on the vortex mass. Prof. Sonin gave a seminar talk titled "Symmetry of Kelvin-wave dynamics and the Kelvin-wave cascade in the T = 0 limit in superfluid turbulence". There were discussions with Matti Krusius and Vladimir Eltsov on the role of the angular momentum in the motion of the vortex front in their experiments. Ways to numerically detect power exponents in the Kelvin-wave cascade were discussed with Risto Hän-

	ninen. Sonin also received information on experimental research on suspended graphene in the Lounasmaa Laboratory. A number of issues concerning the views of Nikolai Kopnin and Gregory Volovik on the Kelvin-wave dynamics and on the problem of vortex mass at T = 0 were clarified. This was of great importance for the preparation of prof. Sonin's monograph, where he expects to discuss these concepts in two separate chapters. Unfortunately, a final consensus on these widely debated issues is still lacking, and more discussion and work is needed. A manuscript with the title "Transverse force on a vortex and vortex mass: effects of continuum and vortex-core quasiparticles" is in preparation by prof. Sonin. He expects to submit it to Phys. Rev. B for publication during the current year 2012.
Amount of access given	10 days (5.-14.9.2012)

Title of the project	**NMR relaxation of trapped magnon condensates in the rotating equilibrium vortex state** AALTO 29
User group leader	Peter Skyba, senior scientist
User	Peter Skyba, senior scientist
Home Institute	Inst. of Exp. Physics, Slovak Academy of Sciences, Kosice, Slovakia
Host supervisor	Vladimir Eltsov, senior researcher Lounasmaa Laboratory, Aalto University
Description of the work	The aim of the project is to study the mechanisms of energy dissipation in the magnon condensate in the presence of quantized vortices in rotating superfluid 3He-B in the ballistic temperature regime. The vortex core contains bound fermionic quaisparticles and it is assumed that they may have Majorana character. It is also expected, that these vortex-core-bound quasiparticles could affect energy dissipation in the coherently precessing NMR mode which represents condensation of magnons or spin-wave excitations to a coherent condensate state. In the rotating equilibrium vortex state this corresponds to the situation when rectilinear quantized vortex lines traverse the condensate in the configuration of a regular array. The task is to identify the mechanisms by which the vortices contribute to spin relaxation, i.e. whether it is possible to distinguish a separate contribution generated by vortices which can be subtracted from that caused by the quasiparticles which form the thermal background.
Project achievements	During my visit I took part in an ongoing experiment studying the interaction between the states with coherent Q-ball-like spin precession and quantized vortices in superfluid 3He-B at temperatures below 0.2 Tc. At these temperatures the density of quasiparticle excitations is so low, that they can be considered a very dilute gas with a mean free path which is determined, in principle, by the size of the experimental cell. The Q-ball state was generated by pulsed NMR techniques and its life time was determined from the free induction signal, i.e. from

	the time constant of exponential amplitude decay. The interaction of the Q-ball with vortices is manifested as an additional dissipation process that leads to the shortening of the Q-ball life time. However, it was found that the time constant of the Q-ball decay is a periodic function of the static applied magnetic field with a period corresponding to a frequency of 1.5 kHz. In the vortex-free state, i.e. when there are no quantized vortex lines pre-sent, the above mentioned periodicity vanishes. This periodicity is a sur-prising observation, and to elucidate its physical origin more measurements have to be performed. During my two-week visit I also gave a seminar on the properties of the coherent spin precession modes in superfluid 3He-B at higher temperatures around 0.5 Tc, with applications to studies of black-hole analogues. To summarize, we studied the interaction between Q-ball states with coherent spin precession and quantized vortices in superfluid 3He-B in the ballistic regime. We found that the presence of vortices enhances the dissipation rate in the Q-ball state. This is explained as increased quasiparticle scattering, since quantized vortices introduce additional scattering centres to quasiparticles, reducing their mean free path. However, the unexpected observation of the periodicity of the Q-ball dissipation rate with the applied static magnetic field remained unexplained and, to understand the physics behind this phenomenon, new studies are needed.
Amount of access given	17 days (4.10.-20.10.2012)

Title of the project	**Nonequilibrium transport through nanodevices** AALTO 30
User group leader	Iouri Galperine, professor
User	Iouri Galperine, professor
Home Institute	Department of Physics, University of Oslo
Host supervisor	Nikolai Kopnin, profesor
Description of the work	The main objective is the development of a theoretical framework for systematic studies of statistical thermodynamics of mesoscopic systems at low temperatures. This task requires understanding of the interplay between entropy, work and information balance in nanodevices under manipulation of bias and gate voltages. In particular, we suggest a novel protocol optimizing performance of a Maxwell's Demon device based on a single-elec-tron pump. We plan to work out different theoretical approaches allowing us to analyse thermodynamics in mesoscopic devices and optimize their performance. During the 13-day visit of Iouri Galperine, we have arranged a meeting between experimentalists and theorists. Based on the results of this meeting, we have formulated the main problems and chosen the order in which they will be addressed in order to use our expertise in

	the best way. We have discussed leading approximations which allow us to obtain concise results for the problem under consideration. We have formulated the basic set of equations, which we have solved for a minimal model. We expect to move along the planned route, and are now at an intermediate point of the project, which we expect to be fruitful.
Project achievements	We are preparing a publication, which will be finished in the next few months.
Amount of access given	13 days (27 May – 8 June, 2013)

Title of the project	**Fluctuations and work in driven open quantum systems: From theory to experiment** AALTO 31
User group leader	Joachim Ankerhold, professor
User	Vera Gramich, graduate student
Home Institute	Institute for Theoretical Physis, Condensed Matter Theory Group, University of Ulm
Host supervisor	Jukka Pekola, professor
Description of the work	The advent of new fabrication techniques as well as the ability to tailor quantum matter on ever smaller scales has been pushed towards new horizons in the last few decades and has lead to fascinating developments in low temperature and solid state physics. For condensed matter systems it turned out that superconducting devices are particularly important as they allow us to observe and analyse quantum phenomena on ever growing scales with unprecedented accuracy. In particular, the long experimental expertise in the PICO group of the O.V. Lounasmaa Laboratory combined with the theoretical know-how of J. Ankerhold and V. Gramich. has made a new approach possible on two such superconducting quantum circuits, namely the Cooper pair sluice and the SINIS turnstile. The objective of this project focuses on (i) the extension of an experimentally feasible detection of the Lamb shift (environmentally induced energy shift of the two lowest-lying energy levels) in a driven two-level system with a superconducting island (the Cooper pair sluice) and (ii) the study of switching experiments in a SNS junction below 300 mK, using the SINIS turnstile for thermometry (S=superconductor, N=normal metal, I=insulator). With respect to the first goal (i), a careful theoretical analysis and under-standing of the usually neglected Lamb shift terms was carried out using the Floquet-Born-Markov master equation approach which is convenient for describing periodically driven systems as is the case here. The study of the dynamics was supported by various numerical simulations and was then applied to a physical system – the Cooper pair pump. Here we focused on how realistic this proposal is for a measurement scheme of the Lamb shift in a broadband environment, if an existing set-up is used.

	Regarding the second issue (ii), the SNS-SINIS samples were designed and fabricated at the host institution, where we have been involved in the junction fabrication process using standard electron-beam lithography and three-angle shadow deposition in an UHV evaporator. Several transport measurements in He-3/He-4 dilution refrigerators were carried out.
Project achievements	(i): It turned out that the Lamb shift terms affect the dynamics significantly and become more and more important close to the degeneracies in the quasi-energy spectrum of the Floquet states. Even for a simple single fre-quency drive which serves as a toy model, just acting on experimental pa-rameters, we can increase the environmental affect. We think after many discussions with the experimentalists from the PICO group, that it is possi-ble to gain experimental access to these Lamb shift terms in a relatively easy manner. The logical consequence to ask for the definition of work performed in such a driven (open) quantum system is however still an open question which can be addressed to the Cooper pair sluice in future. (ii): After performing the switching experiments (from the superconductive state to the normal state) in the superconducting state, just before the switching occurs, a small overheating is observed due to a voltage drop across the junction. Here, the classical electron-phonon interaction was used to design a new measurement set-up because the order of magnitude for this rising voltage is nanovolts. This work is still an ongoing process: new samples are fabricated and data have to be treated and analysed more carefully.
Amount of access given	93 days (15/5 -15/8, 2013)

Title of the project	**Spin accumulation caused by triplet supercurrent** AALTO 32
User group leader	Dr. F. Sebastian Bergeret
User	Asier Ozaeta, graduate student
Home Institute	Centro de Fisica de Materiales, Universidad San Sebastian
Host supervisor	Dr. Tero Heikkilä, O.V. Lounasmaa Laboratory, Aalto University
Description of the work	The plan is to investigate the nonequilibrium properties of superconductor-ferromagnet-superconductor junctions with non-collinear magnetizations carrying a triplet supercurrent. In a spin-polarized magnet this triplet super-current also carries spin current, which will therefore induce spin accu-mulation inside the superconductor. From the combination of spin current and supercurrent we expect spin-thermoelectric effects that we will explore as well. These effects would be most pronounced at very low temperatures. We expect the Microkelvin low temperature groups, such as those in Pisa (Dr. Francesco Giazotto) and Delft (Prof. Teunis Klapwijk) to be capable of measuring these. As the project progressed, we discovered a simpler and much stronger spin-thermoelectric effect, taking place in a junction between a ferromagnet and a superconductor in the presence of a spin-splitting

	field. Also this effect should be measurable by some of the Microkelvin low temperature groups.
Project achievements	Our approach was based on using the quasiclassical theory and the tunnel Hamiltonian description of hybrid superconducting contacts, along with a recently formulated boundary condition applicable for such superconductor-ferromagnet junctions (F.S. Bergeret, A. Verso and A.F. Volkov, Phys. Rev. B 86, 214516 (2012)). We show that a huge thermoelectric effect can be observed by contacting a superconductor whose density of states is spin-split by a Zeeman field with a ferromagnet with a non-zero polarization (P). The resulting thermopower exceeds kB/e by a large factor, and the thermoelectric figure of merit ZT can far exceed unity, leading to heat engine efficiencies close to the Carnot limit. The thermopower diverges at low temperatures in the absence of limiting effects, yielding a figure of merit ZT=P^2 /(1-P^2) and heat engine efficiencies close to the theoretical upper bounds. We also show that spin-polarized currents can be generated in the superconductor by applying a temperature bias even in the case of zero polarization. Besides, we analyze the Hanle effect in a superconductor: this consists of the rotation of the injected spin in a magnetic field non-collinear with the injector. A manuscript “Huge thermoelectric effects in ferromagnet-superconductor junctions in the presence of a spin-splitting field” has been submitted to Physical Review Letters in July, 2013 [arXiv:1307.4672]. We also plan to submit a paper on the Hanle effect in a superconductor in the fall of 2013.
Amount of access given	92 days (1/3 – 31/5, 2013)

Title of the project	**Bose-Einstein condensate of magnons as a probe for vortex structures in 3He-B** AALTO 33
User group leader	John Saunders, professor
User	Lev Levitin, post-doctoral research assistant
Home Institute	Royal Holloway, University of London
Host supervisor	Vladimir Eltsov, senior researcher
Description of the work	Bose-Einstein condensates of magnon quasiparticles in magneto-textural traps in superfluid 3He-B provide a sensitive probe for the order-parameter texture and relaxation effects at temperatures below 0.3 Tc. Their applications to studies of quantized vortex lines and other topological defects in superfluid 3He are especially promising. The goal of this project was to extend such studies to complex vortex structures and to prepare for future more detailed research on the vortex-core-bound fermions.
Project achievements	The relaxation of a magnon condensate in superfluid 3He-B via interaction with a vortex array stabilised by rotation gives insight into the

	nature of vortex core excitations. The variation of the relaxation rate with time and magnetic field (or the frequency of coherent precession of the magnon conden-sate spin) was investigated. Technical improvements eliminated delays between measurements in a series of relaxation measurements and increased both the rate at which the measurements can be performed and the amount of data that can be collected within a single day. Thus the precision of the measurements of previously observed periodic magnetic field dependence of the relaxation rate was increased. The temporal dependence, which previously was believed to be noise, proved to be oscillations which probably are associated with rotation. The next step is to determine whether the temporal changes can be attributed to small shifts in the period of the magnetic field dependence. When the cryostat rotation velocity is changed abruptly, the relaxation rate ceases to depend on both field and time, but the dependence is recovered later, suggesting that the dependence is related to the presence of a regular vortex array, that undergoes rearrangement after speeding up or slowing down of the rotation.
Amount of access given	14 days (26 May – 8 June, 2013)

Title of the project	**Noise in quantum phase slip superconducting nanowires** AALTO 34
User group leader	Konstantin Arutyunov, professor
User	Konstantin Arutyunov, professor
Home Institute	Department of Physics, Jyväskylä University
Host supervisor	Pertti Hakonen, professor, Aalto University
Description of the work	The goal is to perform an experimental study of noise spectra from quantum fluctuations in nanoscale superconductors. This subject is of multidisciplinary nature, it requires state-of-the-art nanofabrication, advanced materials science, ultra-low temperatures and microwave techniques, as well as complex theoretical analysis. Shot noise contains information on electronic transport properties that cannot be obtained by simple conductance measurements. Given that a phase slip event is identical to tunneling, it is reasonable to assume that it should provide a certain contribution to the noise spectrum. To the best of our knowledge, a model describing excess noise in quantum-phase-slip (QPS) governed nanowires has not been introduced so far. The goal of the project is to demonstrate voltage noise due to quantum phase slips in narrow superconducting wires and study their dynamics both in the incoherent and coherent regimes. The objectives correspond to the long-term vision of developing this topic in superconductivity in general and in superconducting nanoelectronics in particular. The results will provide important understanding of the nature of quantum solids and of the very foundations of quantum coherent phenomena.

Project achievements	The JYU team fabricated nanostructures for the noise experiments: (i) 4-terminal nanostructure with an array of parallel superconducting nanowires in the regime of QPSs; and (ii) hybrid tunnel nanostructures comprising as a central electrode a superconducting loop in the regime of QPS. The first samples were fabricated using standard 'work horse' materials: Al and Ti. In order to enhance impedance matching, we employed 100 wires in parallel. The device geometries were tested in Jyväskylä before shipping the samples for noise measurements to the Low Temperature Laboratory (LTL). The samples were measured at 20 mK and voltage fluctuations in the superconducting state were compared with fluctuations in the normal state. Furthermore, noise in the biased regime was also investigated. The conductance measurements showed similar behaviour in the nanowires as observed in Jyväskylä. This means that the measurement setup at LTL works at sufficiently low external noise levels for detailed studies of phase slips. The voltage fluctuation measurements displayed distinct excess noise in the samples. The excess noise was related with resistance and bias voltage, i.e. with the rate of phase slips. The level of shot noise, however, was quite small, smaller than expected, which indicates that the theoretical understanding should be revised. Comparison with normal state noise demonstrated that the excess noise level is below the normal state shot noise. This is believed to be an indication that the noise is not fully white in the superconducting state. For future experiments, a wider bandwidth setup will be constructed that will allow the investigation of the frequency dependence of the excess noise. We also measured the temperature dependent contribution of thermal phase slips (close to the critical temperature Tc) and compared that with the quantum behavior well below Tc. This comparison was complicated by the spread of critical temperatures of the wires. It was concluded that for this part of the work, single wires would be needed for further experiments.
Amount of access given	24 days (10 – 20 June and 2 – 14 September, 2013)

Title of the project	**Cosmological analogue experiments on SQUID arrays** AALTO 35
User group leader	Ralf Schützhold, professor
User	Ralf Schützhold, professor
Home Institute	Universität Duisburg-Essen, Germany
Host supervisor	Sorin Paraoanu, senior scientist Lounasmaa Laboratory, Aalto University
Description of the work	The connection between gravitation and condensed matter physics has long been established through the seminal work of Unruh and others, and an intense experimental effort has been put since into real-

	izing experimentally various quantum-field effects in curved space-times in condensed matter systems. The field is sometimes called “analog gravity”. In particular, at the Microkelvin infrastructure of the O.V. Lounasmaa Laboratory there is a strong tradition in this field, often through the use of superfluid He. This expertise is both theoretical (represented by scientists such as G. Volovik) and experimental, in the ROTA group. For example, the Kibble-Zurek effect (the creation of vortices by an ultrafast quench) has been first observed in the ROTA group. In this project we aim at studying another condensed-mater system in which such effects can be realized, namely arrays of SQUIDs used as the signal line in a coplanar waveguide. These samples have been designed and fabricated recently at the host institution, and the aim of the project is to develop theoretical models for these devices.
Project achievements	We have analysed the problem of creating analogue cosmological effects such as the creation of particles by expansion or the Hawking radiation. We have focused on how realistic these proposals are for being implemented in our setup. It turns out that the Hawking radiation would be very difficult to realize. In the samples currently under design, we think, after discussing possible experimental problems, that the cosmological creation of particles is feasible.
Amount of access given	4 days (2 – 5 April, 2013)

Title of the project	**Instability of the AB interface in superfluid 3He at ultra-low temperatures** AALTO 36
User group leader	Richard P. Haley, reader, senior scientist
User	Richard P. Haley
Home Institute	Ultra-Low Temperature Physics Laboratory, Lancaster University
Host supervisor	Vladimir Eltsov, senior scientist
Description of the work	When the AB interface is stabilized using a magnetic field gradient and superflow is applied along it, then at a certain critical velocity of flow the interface becomes unstable. A corrugation instability similar to the Kelvin-Helmholtz instability develops and eventually vortices are released into the B phase. The development rate of the instability depends on the friction in the interface motion. At temperatures above 0.3 *T*c the development is so fast that it was not possible to measure the rate in previous experiments. The objective of this project is to attempt a measurement of the development rate at temperatures below 0.2 *T*c, where the dynamics should be slower. First we stabilized the AB interface in a cylindrical container filled with 3He using a magnetic field. We used NMR techniques to measure the decay time of a Bose-Einstein condensate of magnons in the B phase that was trapped between the AB interface and the closed end of the container. We used its decay time as a proxy for the density of

	quasiparticle excitations in the confined B phase. We then applied flow along the interface by rotating the container, and used the NMR measurement to infer the presence of vortices in the B phase, which was originally vortex-free. We also made a series of measurements where we started with only B phase in the container, and used the magnetic field to first introduce A phase and then to remove it. This sequence was sometimes repeated several times. We wanted to discover if the superfluid had any "memory" of the earlier presence of the A phase, perhaps due to topological defects being left behind after its sudden non-equlibrium removal, as had been seen in similar experiments at Lancaster. During this visit we found that the presence of the A phase affected the lifetime of the condensed magnons, and we wished to discover whether the annihilation of the A phase left any defects which also affected the lifetime.
Project achievements	We discovered that the presence of the AB interface reduced the lifetime of the magnon BEC in the B phase that was confined between the A phase and the closed end of the cylindrical container. We were able to explain this in terms of an increase in the density of quasiparticle excitations in the confined B phase owing to the AB interface providing a thermal resistance to the transport of these excitations. In a series of experiments, where we created and then annihilated the A phase, we were unable to determine experimentally whether this left behind any topological defects. If it did, their existence did not affect the NMR measurements and we were thus not sensitive to their possible existence. We also tried to ascertain whether the existence of defects would affect the critical velocity of the Kelvin-Helmholtz instability, but found that the critical velocity is reproducible within 10 %. We did the first measurements of the development rate of the AB instability by quickly changing the rotation velocity to be over-critical and back. It was found that at a temperature of 0.14 *Tc* and pressure of 4 bar the development time of the instability is of the order of 10 s, while previous theoretical estimates gave values of the order of hours. The reason for this discrepancy remains unclear.
Amount of access given	13 days (12 – 24 May, 2013)

Title of the project	**Study of graphene in superfluid 3He** AALTO 37
User group leader	Gil Jannes, Ph.D.
User	Gil Jannes, Ph.D.
Home Institute	Universidad Politecnica de Valencia - Nanophotonics Technology Center
Host supervisor	Grigori Volovik, professor
Description of the work	This project is devoted to the study of the topological properties of superfluid 3He and graphene which are common to both of these systems. The plan is to exploit experiments with graphene in the super-

	fluid 3He environment and to prepare for such efforts during this short 6-day visit. Both systems are topological materials. They contain topologically protected massless fermions: 2+1 Dirac fermions in graphene ; 3+1 Weyl fermions in bulk 3He-A ; 2+1 Majorana fermions on the surface of 3He-B ; 1+1 Majorana fermions in the cores of quantized 3He-B vortices. In both systems relativistic quantum fields and gravity emerge with all the related phenomena, such as the chiral anomaly, Hawking-Unruh effects, and Schwinger pair production in electric field. The combination of graphene and superfluid 3He makes it possible to study the interplay of these properties in these two topological materials plus the new effects, which emerge, when these materials are combined, Our possible experiments on graphene immersed in superfluid 3He may include the following: measurement of the spin Josephson effect in 3He-B due to the spin current through the graphene layer; the exploitation of oscillating graphene for the observation of Majorana fermions on the graphene 3He-B boundary in superfluid 3He-B; investigation of the properties of graphene in the superfluid environment at ultralow temperatures under different 3He-B conditions (in the presence of rotation, superflow, quantized vortices, external magnetic fields, magnon Bose-Einstein condensate, etc.) which are all unique in condensed matter physics.
Project achievements	We have discussed in particular that group of fundamental problems which are related to rotation and which can be studied combining the physics of graphene and the physics of the superfluid phases of 3He. These include: • Mach's principle applied to rotation. Mach's principle is one of the iconic principles underlying general relativity. Applied to rotation, it poses the question whether it makes sense to speak of an overall rotational motion of the universe, and whether a local observer would be able to detect such a hypothetic overall rotational motion. If matter and gravitation as we observe them emerge in the low-energy limit from the quantum vacuum, then Mach's principle (in the sense that an overall rotation of the universe is not detectable) can be correct. The key point is that one needs to take the quantum vacuum, and in particular the rotation of the vacuum, into account. This can be studied in superfluid and graphene, where the role of the quantum vacuum is played by the ground state of the system, and the role of matter is played by the excitations, the Majorana and Dirac fermions. The rotation is provided by the ROTA cryostat operating at sub-mK temperatures. • Mach's Closed time like curves. The existence of such curves in general relativity (GR) is a debated issue. The GR community poses the question, whether it is possible to simulate such hypothetical objects in condensed matter. The possible route is to use the effective metric simulated by different types of quantum vortices created in the superfluid phases of 3He under rotation, and to use the effective metric experienced by Dirac fermions in gra-

	phene for the simulation of Goedel's rotating Universe. In summary, the physics of graphene and of the superfluid phases of 3He have many common features. Both systems are topological materials where quasiparticles behave as relativistic Majorana or Dirac fermions, which experience effective gravity in terms of tetrad field and metric. This makes it possible to use graphene and superfluid 3He for the simulation of the rotating relativistic quantum vacuum.
Amount of access given	11 days (16 – 21, June, 2013 and 2 – 6 Sep, 2013)

Title of the project	**Studies of graphene and superfluid 3He** AALTO 38
User group leader	Mikhail Katsnelson, professor
User	Mikhail Katsnelson, professor
Home Institute	Radboud University of Nijmegen
Host supervisor	Grigori Volovik, professor
Description of the work	This project is devoted to the study of those properties which are common to both superfluid 3He and graphene. The plan is to exploit experiments with graphene in the superfluid 3He environment and to prepare for such efforts during this short 6-day visit. Both systems are topological materials. They contain topologically protected massless fermions: 2+1 Dirac fermions in graphene ; 3+1 Weyl fermions in bulk 3He-A ; 2+1 Majorana fermions on the surface of 3He-B ; 1+1 Majorana fermions in the cores of quantized 3He-B vortices. In both systems relativistic quantum fields and gravity emerge with all the related phenomena, such as chiral anomaly, Hawking-Unruh effects, and Schwinger pair production in electric field. The combination of graphene and superfluid 3He makes it possible to study the interplay of the two topological materials plus the new effects, which emerge, when these materials are combined, Experiments on graphene immersed in superfluid 3He may include the following: measurement of the spin Josephson effect in 3He-B due to the spin current through the graphene layer; the exploitation of oscillating graphene for the observation of Majorana fermions on the graphene 3He-B boundary in superfluid 3He-B; investigation of the properties of graphene in the superfluid environment at ultralow temperatures under different 3He-B conditions (in the presence of rotation, superflow, quantized vortices, external magnetic fields, magnon Bose-Einstein condensate, etc.) which are all unique in condensed matter physics.
Project achievements	We elaborated several different directions into which the experimental work can be directed. These include: - Theoretical and experimental investigation of possible exciton condensates of 3He atoms across a graphene sheet (in the absence of tunnelling of atoms through the sheet), when the broken symmetry is U(1) x U(1).

	- The study of 3He-B Majorana fermions on the graphene sheet and their interaction across the sheet. There should be present an interaction of the spins of Majorana fermions with magnetic impurities localized on the graphene sheet, as considered for edge states in topological insulators. This may give a measurable mass to Majorana fermions. The interaction between Majorana particles can be transmitted by ripples in the sheet, which play the same role as relativistic gravity (exchange by gravitons), as follows from the momentum space topology which predicts an effective gravity field in terms of the effective tetrad (zweibein). - Another possible channel for the interaction between Majorana fermions is direct spin-spin interaction and the interaction with Dirac fermions of graphene. - The study of spin currents across graphene using the magnon BEC in superfluid 3He-B. There can be different channels of coupling the spin degrees of freedom across the graphene sheet: the electronic subsystem of graphene (Dirac fermions); an adsorbed magnetic layer of solid 3He; magnons; ripplons; or the direct dipole interaction of 3He spins across the graphene sheet. - Oscillating graphene membrane, driven electrically or magnetically: One should study the renormalization of the membrane mass by the associated hydrodynamic mass of the superfluid. - Other studies of the 3He-B and 3He-A superfluids: modification of the ripplon spectrum due to the superfluid hydrodynamics, the contribution of Majorana fermions on the surface of 3He-B to the frequency shift and the dissipation, and the effect of orbital viscosity in 3He-A due to Majorana fermions in the bulk. - Dynamical Casimir effect: Membrane oscillations as a time dependent metric for Majorana fermions. This may lead to an analogue of pair creation in the expanding Universe. We shall compare this phenomenon with the current experiments of the decay of the magnon BEC owing to oscillations of the free surface. Possibly this may reveal a common mechanism for the creation of Majorana fermions by oscillating fields. - Study of heat currents across graphene, including the propagation of 3He quasiparticles across graphene. - Study of low dimensional magnetism of graphene, the effect of the dipole interaction on the magnetic long-range order; possible ferromagnetism of doped graphene at ultralow temperatures; electric dipole moments localized on graphene. To summarize, the physics of graphene and of the superfluid phases of 3He have many common features. Both systems are topological materials where quasiparticles behave as relativistic Majorana or Dirac fermions. We have identified the regimes where these features are overlapping. This will allow us to use graphene for the study of superfluid 3He, or vice versa, to use superfluid 3He for the study of graphene, while the combination of their topological effects can be used to study the physics of the topological quantum vacuum.

Amount of access given	7 days (11 – 17 Aug, 2013)

Title of the project	**Vortex waves in rotating superfluid 3He-B** AALTO 39
User group leader	Anna Pomyalov, Dr.
User	Anna Pomyalov, Dr.
Home Institute	Weizmann Institute of Science, Rehovot, Israel
Host supervisor	Vladimir Eltsov, senior researcher
Description of the work	Kelvin waves on vortex lines are believed to be an important component of quantum turbulence in superfluids at low temperatures. In particular, energy transfer over the Kelvin-wave cascade could be responsible for a finite rate of the energy dissipation in the zero-temperature limit. Up to date, however, the Kelvin-wave cascade has not been identified experimentally. We plan to study a type vortex motion, which is closely related to Kelvin waves on individual vortex lines: vortex waves on an array of vortices. Such a vortex array is produced by rotation of a long cylindrical 3He-B sample at temperatures below 0.3 Tc down to 0.15 Tc. Vortices are pinned at one end of the cylinder at a rough surface. The angular velocity of rotation is modulated to create vortex waves. Their build-up, propagation and relaxation is monitored using two nuclear magnetic resonance spectrometers at different heights in the cylinder and by Andreev scattering from vortex lines using quartz tuning forks. The ultimate goal is to study the role of vortex waves in the dissipation processes of superfluids in the zero-temperature limit. Earlier measurements have indicated that oscillations of the vortex cluster result in a frequency shift of the magnon condensate NMR mode, owing to a reduction in the polarization of vortices in the cluster when the vortex waves are created. After the modulation of the rotation velocity is stopped, the restoration of the polarization proceeds in two distinct phases with non-trivial temperature and pressure dependences of their relaxation times. The immediate objective is to understand the nature of these relaxation processes and to establish to what extent they are related to the global turbulence of the reconnecting vortex lines, to Kelvin-wave turbulence on individual vortices or to the damping of individual Kelvin waves.
Project achievements	During the visit to the Low Temperature Laboratory we performed a systematic analysis of the experimental data collected within the Microkelvin AALTO19 project and participated in new measurements on the rotating cryostat with the goal to clarify the role of inertial waves and of Kelvin waves in a two-step energy dissipation process. We managed to formulate a consistent explanation of the basic experimental results. In particular, from the rotation-velocity dependence of the parameters of the relaxation we concluded that the only reasonable way to rationalize the observations is to assume that the rate of energy dissipation in one vortex line is independent of the stored energy. This significantly limits possible

	candidates for the relaxation mechanisms. Our analysis of the experimental data allows us to formulate the crucial questions in future experiments, in particular, concerning the temperature and pressure dependences of the relaxation parameters. The new data will allow us to make a choice between the possible mechanisms of energy dissipation, to clarify the role of the Kelvin wave cascade and to formulate an adequate model of the relaxation of vortex waves based on the current understanding of Kelvin-waves. Some feasible routes for the numerical simulation of vortex dynamics were also formulated. These will become important to create the proper understanding about the relaxation of vortex waves. In addition, as a second project, we analysed experimental results on the interaction of gravity waves on the free surface of the superfluid with a trapped Bose-Einstein condensate bordering to the free surface. We suggest a simple Hamiltonian model of this interaction that presumable can rationalize the available experimental data. Based on the Hamiltonian model of the interactions of the surface waves with trapped magnons, as developed during the visit, we suggest some new measurements that will clarify the basic physics of this phenomenon. The relevant experiments are now in preparation.
Amount of access given	15 days (19 July – 2 Aug, 2013)

Title of the project	**Dissipation losses from Kelvin waves and the Kelvin-wave cascade** AALTO 40
User group leader	Edouard Sonin, professor
User	Edouard Sonin, professor
Home Institute	Racah Institute of Physics, Hebrew University
Host supervisor	Risto Hänninen, senior researcher
Description of the work	Current measurements display larger dissipation in helium superfluids from vortex motion in the zero temperature limit, $T \longrightarrow 0$, than what standard mutual friction theory predicts. These measurements also extrapolate to a finite value at $T = 0$ which is not possible if simple direct mutual friction damping is considered. One current assumption is that these observations might be ascribed to a Kelvin-wave cascade propagating on individual vortex lines. However, recent numerical calculations with the vortex filament method on a single vortex reconnection event between two inter-linked vortex rings at mutual friction values down to $\alpha \sim 10^{-3}$ show no evidence for the presence of the Kelvin-wave cascade: the increased dissipation after the reconnection is explained by direct mutual friction damping of Kelvin wave excitations, without any indication for nonlinear interactions connecting different Kelvin modes. We plan to discuss how measurements and vortex filament calculations can be further extended to search for the existence of the Kelvin wave cascade. The description of vortex motion in the very low temperature limit is

	one of the prime goals in the Microkelvin Joint Research Activities (JRA3 Task 1). This regime is also of central interest for drafting parts of the monograph on superfluid vortex dynamics which Edouard Sonin is working on. One of the tasks is to estimate numerically the energy flux from the Kelvin-wave cascade in different physical situations (or different Kelvin spectra) and to compare this flux with theoretical predictions and the direct dissipation from mutual friction. This comparison should reveal e.g. the importance of finite size effects (due to a finite resolution of the calculation) and, more generally, guide us to find the proper parameter values for the regimes where the Kelvin-wave cascade is at its strongest, such that it might become also experimentally observable.
Project achievements	We analysed together with Risto Hänninen different ways how to reveal unambiguously the presence of the Kelvin-wave cascade numerically. The main challenges were: (i) to pump the energy only to large length scales avoiding pumping into the inertial interval of scales; (ii) to avoid the damaging effect of the discreteness of the wave spectrum on the emergence of the Kelvin-wave cascade. The outcome of these discussions was that an unambiguous numerical simulation of the Kelvin-wave cascade is a serious problem, and plans to solve it were considered. Ou work is now in the planning stage, and the goal to reveal the cascade depends on the forthcoming simulations. In addition to the problem of the missing Kelvin wave cascade, there were thorough discussions of the controversial problem of the transverse force on the vortex with the theoreticians of the O.V. Lounasmaa Laboratory (Kopnin, Silaev, and Volovik). These discussions were stimulated by the talk presented by Edouard Sonin at the Laboratory seminar. A new interpretation of the semi-classical result for the transverse force was suggested, but full consensus on some conceptual issues was not reached.
Amount of access given	14 days (26 Aug – 8 Sep, 2013)

Title of the project	**SQUID-based NMR spectrometer for a rotating nuclear demagnetization cryostat (ROTA)** AALTO 41
User group leader	Joern Beyer, Dr.
User	Joern Beyer, Dr.
Home Institute	Physikalisch-Technische Bundesanstalt PTB - Berlin
Host supervisor	Vladislav Beyer, Dr.
Description of the work	The purpose of this project is to build and test a high-precision NMR spectrometer for the rotating nuclear demagnetization cryostat (known as the ROTA cryostat),which is used for measurements on rotating superfluid 3He. The spectrometer is based on a SQUID amplifier developed in PTB. The high signal sensitivity of this device will bring us the following advantages, compared to the current setup with

	a high Q LC resonator coupled to a liquid-helium-temperature MOSFET preamplifier : -- Larger NMR frequency range. It will become possible to work without a highly tuned resonant circuit at a fixed frequency, and thus it will become possible to perform measurements over a larger range of frequencies. This improvement will be useful for our current studies of energy dissipation in superfluid 3He-B in the presence of vortices, since measurements in a wide frequency range can provide information about the spectrum of quasiparticles bound to vortex cores. -- Possibility to use much smaller NMR signal coils and thus improve spatial resolution. This can be useful for building an NMR microscope which can resolve individual vortices and textural point defects. -- Overall better signal/noise ratio in all measurements.
Project achievements	The SQUID amplifier was tested at 4.2 K. A test setup was specially built for this purpose, based on the NMR measurement of 3He gas. The setup consists of a 40 mT NMR magnet, transmitter and receiver coils, and a sample container for the 3He gas. During the work we used the SQUID amplifier to measure the signal properties and noise sources in various experimental conditions. We achieved quite good amplifier performance in the absence of a constant magnetic field which is needed for the NMR signal. We found that there exists a difficulty in using the SQUID amplifier for NMR experiments, especially in CW mode, because of its high sensitivity to low-frequency noise which arises from noise and disturbances in the magnet current. For proper operation a good quality current supply as well as mechanical rigidity of the magnet windings is needed. We also learned a few important things about electrical and magnetic shielding and mechanical design of the device. The SQUID based NMR measurement will be used next for studying the relaxation properties of the low-temperature coherent trapped magnon modes as a function of frequency with a broad-band spectrometer.
Amount of access given	9 days (1 – 9 Sep, 2013)

Title of the project	**Soliton solutions within the vortex filament model using full Biot-Savart equation** AALTO 42
User group leader	Hayder Salman, Dr. Lecturer
User	Hayder Salman, Dr. Lecturer
Home Institute	Theoretical & computational fluid dynamics, School of Mathematics, University of East Anglia
Host supervisor	Risto Hänninen, senior researcher
Description of the work	One major part of the Microkelvin activities is concerned with the dy-

	namics of quantized vortices, especially in the zero temperature limit. In this limit the Kelvin wave cascade is expected to play an important role in energy dissipation. The Kelvin wave cascade is preceded by a self-reconnection driven regime in which localised large amplitude disturbances dominate the dynamics. For example, during a reconnection event, a vortex first becomes strongly distorted in the vicinity of the reconnection site. In that case, the deformation is rather described as a by-product of solitons interacting, or even breathers, as uncovered by the recent work of Hayder Salman. Both, solitons and breathers are localized disturbances with a well-defined propagation velocity. In classical fluid mechanics, solitons are much investigated objects. Within the vortex filament model, several soliton solutions have been found using the local induction appoximation (LIA). Our goal is to find exact soliton solutions numerically using the full Biot-Savart law. We plan to find the family of soliton solutions using the (non-local) full Biot-Savart equation within the vortex filament model. The solition solutions should be found for various energies and momenta associated with these large amplitude excitations. The results will be summarized and compared with the previously found (local) LIA solutions in scientific publications (e.g. Physics of Fluids). The main task is to modify the Biot-Savart algorithm to allow us to converge to soliton solutions with the vortex filament model. Formally this corresponds to finding the zeros of a vector-valued function of several variables. The solutions with the local induction approximation (LIA) can be used as an initial starting guess, which should help the convergence of the proposed algorithm.
Project achievements	We have made significant progress in formulating the functional that needs to be minimised to find the soliton solutions. In particular, we have identified two methods working with either extrinsic vortex position coordinates or intrinsic curvature/torsion coordinates. Since the codes available are easier to adapt for the minimising of the functional in extrinsic coordinates we have focused on this problem initially. This led to a number of challenges, in particular since the soliton we seek is moving relative to the vortex points. The intrinsic formulation does not suffer from this difficulty but requires substantial changes to be made to the codes we are using. We will, therefore, continue to pursue this other approach. We have also identified another problem involving the search for breathers in current simulations of superfluid turbulence. Dr. Salman has identified the signature of these new breather excitations and we aim to understand their role in superfluid turbulence.
Amount of access given	16 days (12 -27 Aug, 2013)

Title of the project	**Self-localization of magnon Bose-Einstein condensates** AALTO 43
User group leader	Yuriy Bunkov, professor

User	Yuriy Bunkov, professor
Home Institute	Institut Néel, CNRS, Grenoble
Host supervisor	Matti Krusius, professor
Description of the work	During the past years the phenomenon of "Spin Supercurrent" has been redressed in the language of Bose-Einstein condensation, which has created new understanding on how to explore these coherent resonance modes further. Recent experiments in Aalto University have been measuring the relaxation properties of the new low-temperature coherent magnon modes. The relaxation has been found to display strong dependence on the magnon density in the magnetic trap. Of particular interest are excited BEC states, which were originally observed for the first time in superfluid 3He-B. The spin relaxation time of the magnon condensate can be readily measured and displayed with available techniques both in the ground state and on the different excited levels. The purpose of my visit was to understand the enhanced relaxation at high magnon density, especially in the excited states. My goal is to explore whether the relaxation of the excited BEC states can be explained in part in terms of oscillations in the angle θ which fixes the minimization of the spin-orbit coupling in superfluid 3He-B. If this turns out to be the case, the result would mean a reworking of the current version of my monograph "Spin superfluidity and magnon Bose-Einstein condensation", which is in its final phases of writing and which describes the recent achievements in Q-ball physics within the Microkelvin project.
Project achievements	I have formulated the new explanation of the magnon-condensate relaxation as radiation of a new type of excitations, the θ waves. I plan to demonstrate with computer simulations the existence of this additional relaxation phenomenon. A research report on this effect is also in planning stages.
Amount of access given	6 days (4 – 9 Sep, 2013)

Title of the project	**Electronic cooling in hybrid tunnel junctions** CNRS 09
User group leader	Francesco Giazotto, senior scientist, Ph.D.
User	Maria Camarasa-Gomez, graduate student
Home Institute	NEST, University of Pisa, Italy
Host supervisor	Hervé Courtois, professor Institut Néel (CNRS) and Université J. Fourier, Grnoble, France
Description of the work	We investigate out-of-equilibrium effects in hybrid superconducting junctions in the weak-coupling (i.e. tunneling) regime. Transport through a Superconductor (S) - Insulator (I)- Normal metal (N) junction can lead to the cooling of the electrons in N. Our target is to understand in depth the charge and heat dynamics in such electronic micro-coolers for practical device applications (bolometry, etc.). We

	combine transport experiments with theoretical calculations of the expected performance. From a fundamental point of view, this will give us unprecedented insight into the thermal couplings at low temperatures between the different baths at quasi-equilibrium (electrons, phonons, substrate) in the different parts of a device. S-I-N-I-S microelectronic coolers have an optimum cooling power around $T = T$c/3, where Tc is the superconducting transition temperature of S. In order to bridge the gap from experimentally easily achieved temperatures around 1.7 K and desired electronic base temperatures well below 100 mK, cascade cooler systems, involving superconductors with different gap amplitudes, is required. The superconductor with the lower gap plays the role of N with respect to the larger gap superconductor here. As to the study of the technical feasibility of such a cascade coolers, we have developed a code that simulates both charge and heat dynamics in a cascade microelectronic cooler system. The main difficulty is the coupling between charge and heat dynamics: the electronic conductance depends on temperature (via the gap and the Fermi distributions), which in turn depends on the cooling power, which again depends on the conductance. The dynamics are therefore governed by coupled differential equations that can only be iteratively solved. The study was performed taking into account the different couplings between electron and phonon baths in the various parts of the device and the substrate, such as to provide a realistic simulation of a real device.
Project achievements	The first step consisted of verifying the stability and reliability of the code. We described simple cases, such as NIN, NIS or SIS junctions, in which we do not consider the electron-phonon coupling with the substrate. After this, we studied a more complex system in which we examined the effects of applying a bias in a cascade structure involving two superconductors. We found that, in a very general way, by putting in series two superconductors, we could indeed cool in principle the normal metal down to 0.3K, starting from a bath temperature of 1K. The main difficulties encountered concerned the slowness of the numerical convergence, which obliged us to change the coding language to python during the project. The conclusions of this theoretical work support the idea that cascade cooling is possible in principle and that Vanadium + Aluminium should be a good materials choice for the two superconductors.
Amount of access given	26 days (18/6 – 13/7, 2012)

Title of the project	**Adiabatic Demagnetization Stage** CNRS 10
User group leader	Jozef Kacmarcik, researcher
User	Jozef Kacmarcik, researcher

Home Institute	Department of Low Temperature Physics, Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia
Host supervisor	Henri Godfrin, professor Institut Néel, CNRS, Grenoble, France
Description of the work	The technical goals of this project were to design, construct, test and optimize small demagnetization stages with a paramagnetic salt coupled with standard PPMS sample pucks to cool down two samples from room temperature to typically 40 mK in less than to 2 hours. These modified pucks are intended for use in the Quantum Design PPMS (Physical Property Measurement System) device that is used both in the Néel Institute, CNRS - Grenoble, and in the Department of Low Temperature Physics, IEP - SAS in Kosice. The scientific objective of the project was to use these demagnetization stages for the experimental research of heavily-doped silicon and diamond down to 40 mK. The aim was to determine the critical temperature of doped superconducting samples and to modulate their superconducting properties by applying an external electric field using ionic liquids. This is expected to tune the carrier concentration at the surface (interface) of the doped epilayers.
Project achievements	The first experiments and tests were made with a prototype demagnetization stage where a sample holder with wires is fixed to one part of the stage, i.e. the samples have to be mounted directly on the stage. We prepared special cables for connecting external devices to the PPMS setup. First of all we calibrated a RuO2 thermometer down to the lowest temperatures. To do this, we used a Lakeshore resistance bridge as well as the PPMS internal electronics to read the resistance of the thermometer in order to avoid overheating of thermometer. Later, we needed to find a proper regime to reach the lowest temperature possible – to optimize the initial magnetic field at 2 K at the beginning of the demagnetization process and subsequently the rate of demagnetization. We found that a starting field of 4 Tesla and a demagnetization rate of 1 Tesla/min were optimal for cooling the stage down to 44 mK. In the next step we designed and prepared for construction the second generation of the demagnetization stage compatible with the Helium-3 Resistivity sample pucks for PPMS. This new design has the great advantage that a sample can be prepared for experiment on a sample-holder separate from the stage and can then later be attached onto the stage. In addition a sample mounted this way may also be directly used for experiments with the PPMS Helium-3 Refrigerator or with the PPMS Vertical Puck for measurements of magnetically anisotropic materials performed in magnetic fields. We succeeded to cool down the demagnetization stage from 2 K to 44 mK in four minutes and from room temperature in less than two hours. We performed transport measurements of heavily-doped silicon and diamond samples to determine their critical temperature of the superconducting transition. We also performed preliminary experiments on silicon and diamond samples in order to modulate the

	superconducting properties by applying an external electric field using ionic liquids expected to tune the carrier concentration at the surface (interface) of the doped epilayers. We could considerably increase the conductivity of the samples, but up to now no superconductivity was observed. We improved the design of the inner part of the salt box in the second generation demagnetization stage – instead of using copper we used silver wires to increase the contact area between the paramagnetic salt and the cold plate of the stage. Unfortunately difficulties to grow the salt in the box precluded the tests of this new demagnetization stage during the project duration. We will continue within the next weeks.
Amount of access given	32 days (14/5 – 15/6, 2012)

Title of the project	**Rapid thermometers for specific heat measurement in thermodynamic equilibrium** CNRS 11
User group leader	Sven Sahling, Privatdozent, Ph.D.
User	Sven Sahling, Privatdozent, Ph.D.
Home Institute	Institut für Physik, Technische Universität Dresden, Germany
Host supervisor	Gyorgy Remenyi, senior researcher Institut Néel, CNRS – Grenoble, France
Description of the work	1D spin chains and spin ladders exist in Sr12Cu24O41. At very low temperatures the heat capacity will be determined by the 1D chains with dimerized antiferromagnetic spins. The chains are cut into sequences of different length due to holes. At the ends of the sequences appear free spins. No magnetic ordering was observed of these free spins above 1K. The nature of the ground state of this system is unclear up to now (magnetic ordering or spin glass). In addition there exist in this material 1D spin and charge density waves, which also can give a time and magnetic field dependent contribution to the heat capacity. The corresponding spectrum of relaxation times can be determined by the investigation of thermal relaxation. The holes shift from the chains to the ladders after doping the sample with Ca. This gives the possibility to check the influence of the holes in the chains on the thermodynamic properties.
Project achievements	- Calibration of AuGe thermometers at very low temperatures. - Calibration of heat capacity measurement at low temperatures. - Development of experimental methods (hardware and software elaborated in Institut Néel) for long and short time thermal relaxation and heat capacity measurement. - Measurement of magnetization, heat capacity and thermal relaxation, the dependences on temperature, magnetic field, and time. **Results: Part 1 (February-March 2012) –** CNRS 11-1

	The heat capacity of a Sr14Cu24O41 single crystal was investigated at very low temperatures and magnetic fields up to 10 T and as a function of time between 1 ms and 104 s. The contributions to the heat capacity at low temperatures are complex. In addition to the phonon contribution we found a magnetic field independent quasi linear term, 2 Schottky terms, which are strongly time dependent and 4 Schottky-terms, which are time independent, but field dependent. For the two time and field dependent contributions the relaxation time spectrum was determined as a function of temperature and magnetic field. At least one of them is caused by the 1D CDWs. The other Schottky contributions are probably caused by free Cu spins on the 1D Cu chains. **Results: Part 2 (September 2012) –** CNRS 11-2 The heat capacity of a Sr2Ca12Cu24O41 single crystal was measured at very low temperatures and magnetic fields up to 10 T and as a function of time between 1 ms and 104 s. A strongly time and magnetic field dependent Schottky term was found, caused probably by the 1D charge density waves. All parameters are in good agreement with the corresponding term for Sr14Cu24O41. As expected, all other Schottky contributions disappear in the Ca doped sample. In addition the magnetization of the Sr2Ca12Cu24O41 crystal was measured. Magnetization steps were observed, as typical for frustrated magnetic systems. The analysis of all data is going on.
Amount of access given	34 days (1/9 – 4/10, 2012)

Title of the project	**Electron Transport Through Molecular Devices** CNRS 12
User group leader	Luis Hueso, senior researcher
User	Emanuel Masourakis, graduate student
Home Institute	Centre of Graphene Science, School of Physics, University of Exeter, UK
Host supervisor	Hervé Courtois, professor Institut Néel (CNRS) and Université J. Fourier, Grenoble, France
Description of the work	The project deals with the fabrication of single electron devices based on gold nano-particles. The first step is to control as best as possible the placement of a single nanoparticle within a sub-10 nm gap between two of the electrodes of the 3 terminal device. A desired deposition method should not alter the electrical characteristics of the device and especially the electrical coupling between the device terminals and the deposited nanoparticle. In addition, we aim to control the concentration of deposited nanoparticles as well as the exact cite to which they are attached. Finally, the deposition method must be easily reproducible.
Project achievements	The method involves the functionalization of the device surface with aminopropyltriethoxysilane (APTS) and the subsequent deposition of Au nanoparticles by submerging the entire device into solution. The

	silane end groups of APTS bond to and protonate the SiO2 substrate and Au device terminals, creating a layer of positive charge on the functionalized areas of the surface. The Au nanoparticles used are coated with a thin layer of tannic acid making them negatively charged. When the device is submerged into a solution of Au nanoparticles the protonated surface will attract the negatively charged nanoparticles. The protonation of the surface (and subsequently the amount of nanoparticles attracted to it) can be controlled by regulating the pH of the solution. The deposition of APTS was examined using two methods. Primarily a simple spin coating process was used to functionalize the surface. The second method involved a process by which Ar gas was flown through the APTS solution and then proceeded to the surface of the device, gradually creating a layer of APTS on the entire surface of the device. Finally, in an attempt to circumvent the use of APTS, we examined an electro-deposition method for attracting the nanoparticles to the surface. In this method, a voltage is applied across the two terminals of the device while it is submerged in the solution. The process causes the nanoparticles to be deposited on the two terminals and in the area between them. The spin coating method was the simplest to apply. The challenge with this method, however, lies in creating a sufficiently thin layer. A thick layer will cause the electrical coupling between the device terminals and the nano-particles to be too weak. Even though good functionalization was achieved, the coupling was such, that the method was finally discarded. The Ar gas method, although more complicated to control and reproduce, gave much thinner (better) layers. In addition functionalization seemed to occur more selectively, allowing the nanoparticles to be concentrated on the functionalized areas and be absent in non-functionalized areas. One of the main challenges consisted of preventing the polymerization of APTS on the substrate surface after deposition. This was attempted by regulating the parameters of the gaseous deposition. The electro-deposition method appeared to work quite well in attracting nanoparticles to a specific location. Unfortunately, in this method it seemed to be very hard to control the concentration of deposited nanoparticles.
Amount of access given	31 days (2/5 – 1/6, 2012)

Title of the project	**Magnetization and susceptibility measurements on spin liquids Ba3CuSb2O9 and (ET)2Cu2(CN)3** CNRS 13
User group leader	Sean Giblin, lecturer, Ph.D.
User	Sean Giblin, lecture, Ph.D.
Home Institute	School of Physics and Astronomy, University of Cardiff, UK
Host supervisor	Carley Paulsen, senior researcher Insitut Néel, CNRS – Grenoble, France

Description of the work	The aim of the project was to investigate the bulk magnetic properties of quantum spin liquids under applied magnetic field. The interpretation of muon (a local implanted probe) experiments suggests, when performed on Ba3CuSb2O9 and (ET)2Cu2(CN)3, the existence of a quantum critical point and that the system is driven into a bulk non-collinear antiferromagnet on the application of a small magnetic field. However an alternative prediction suggests a staggered magnetisation of the quantum spin liquid state. It is possible that the muons are perturbing the sample and the interpretation of the muon data does not easily allow the separation of these two scenarios. However, the observation of an induced moment in the bulk of the sample would confirm the existence of a quantum critical point. Moreover if observed, ac susceptibility can be used to probe the dynamics around the transition. The understanding of triangular lattices which are the simplest prototype of the frustrated lattice spin liquid should offer a base for interpreting the behaviour of the more complex kagome and hyperkagome spin liquids.
Project achievements	Sean Giblin came to Grenoble to perform the experiments, with the help of the CNRS staff (Carley Paulsen, Elsa Lhotel, and Martin Jackson). Four samples were measured, with three being measured in the low field magnetometer and one in the high field magnetometer. Measurements were performed between 80 mK and 1 K, importantly relaxation measurements were performed on the magnetometers out to many hours; to our knowledge this aspect of the instrumentation combined with the low trapped field at the sample is unique. The staff at CNRS facilitated all requests for help including the rewriting of code to allow the change of cooling rates to investigate new physics. All samples were investigated using both ac susceptibility and dc magnetometry. We demonstrated in Ba3CuSb2O9 that we saw no bulk magnetic order, using the same sample as previously used for other experiments. We did however use the remaining time to investigate other frustrated magnets including observing order in a frustrated single crystal for the first time and investigating the properties of cooling rates. Both of these results will have an impact on the field in general.
Amount of access given	26 days (3/10 – 28/10, 2012)

Title of the project	**Rapid thermometers for specific heat measurement in thermodynamic equilibrium** CNRS 14
User group leader	Sven Sahling, Privatdozent, Ph.D.
User	Sven Sahling, Privatdozent, Ph.D.
Home Institute	Institut für Physik, Technische Universität Dresden, Germany
Host supervisor	Gyorgy Remenyi, senior researcher Institut Néel, CNRS – Grenoble, France
Description of the work	- Investigation of the thermodynamic properties (heat capacity, ther-

	mal relaxation) of a high quality Fe_3O_4 single crystal at very low temperatures and high magnetic fields. - Determination of the relaxation time spectrum of low energy excitations.
Project achievements	- Calibration of AuGe thermometers at very low temperatures. - Calibration of heat capacity measurement at low temperatures. - Development of experimental methods (hardware and software elaborated in Institut Néel) for long and short time thermal relaxation. - The heat capacity, thermal relaxation and magnetization of Fe_3O_4 were investigated at very low temperatures and magnetic fields up to 10 T. Special thermometers and measuring techniques allowed us to measure the time dependence of the sample temperature after a short heat pulse (between 1 ms and 10000 s) even at very low temperatures and high magnetic fields. The experimental equipment (thermometers, software, and hardware) for the investigation of relaxation processes in solids at very low temperatures and high magnetic field was finished. Test measurements with gold demonstrate that we are able to register relaxation times between 1 ms and 10000 s. The heat capacity, thermal relaxation and magnetization of Fe3O4 were investigated at very low temperatures and magnetic fields up to 10 T. The broad relaxation time spectrum was determined as a function of temperature and magnetic field for zero field and magnetic field cooling with different cooling rates. The analysis of the heat capacity and magnetization data of Sr14-xCaxCu24O41 was finished for x = 0 and x = 12. The heat capacity is complex. For the Ca doped sample we found four contributions to the heat capacity, for the undoped sample even eight. A part of these contributions is strongly time dependent. The separation of the different contributions was possible due to the detailed measurements of the heat capacity at constant field as a function of temperature and at constant temperature as a function of magnetic field for short (30 ms) and long relaxation times. The relaxation time spectrum for the time dependent contributions was obtained as a function of temperature and magnetic field. It is expected that a part of these contributions depends on the direction of the magnetic field. This will be examined in the next experiments. One paper on the results has been completed and will be published next month.
Amount of access given	60 days (3/2 – 3/4, 2013) 31 days (12/8 – 11/9, 2013)

Title of the project	**Structure factor of two-dimensional 3He** CNRS 15

User group leader	Jordi Boronat, professor
User	Jordi Boronat, professor
Home Institute	Departament de Física I Enginyeria Nuclear, Universitat Politècnica de Catalunya, Barcelona, Spain
Host supervisor	Henri Godfrin, professor Institut Néel, CNRS – Grenoble, France
Description of the work	Our main goal is to get insight on the properties of 3He adsorbed on a carbon surface by a combined effort of theory and experiment. Recent activity in the experimental group of Prof. Godfrin in the Institut Néel-CNRS of Grenoble has allowed for the first time to measure elusive and long pursued magnitudes in low temperature physics: the static and dynamic structure factors of 3He in a nearly two-dimensional environment. The precision achieved makes possible to compare with accurate theoretical results derived from microscopic theory. Our goal with this project is to merge the new experimental data and many-body theory in order to better understand the properties of quasi-two-dimensional 3He, which is the best example of a strongly interacting Fermi fluid.
Project achievements	We have prepared the computation programs to carry out the quantum Monte Carlo calculation of the static structure factor of a 2D 3He film. We have checked that the data is numerically consistent using some bench-marks. The program is now in the position of starting to generate statistics to sample properly the data. The program will provide us with results of the total static structure factor and the up-up and up-down spin components. With these functions we can obtain results for both the density and spin structure factors. The calculations will be carried out during the next weeks within the density range relevant for the Grenoble experiments. On the other hand, we have started to analyse the experimental neutron scattering data and devised the right strategy for an accurate extraction of the static structure factor to be compared with the theoretical estimates. The quantum Monte Carlo programs have been checked and their con-sistency verified. The first benchmarks have been carried out and the results prove to be consistent. Now what remains is to accumulate sufficient statistics to reduce the noise to a reasonable level. The strategy for a right integration of the experimental data on the dynamic structure factor measured recently in Grenoble has been devised and the first results are already obtained. Corrections at higher energy have been also discussed and are going to be implemented in the next weeks.
Amount of access given	8 days (15/1 – 22/1, 2013)

Title of the project	**The electron glass in semiconductors** CNRS 16
User group leader	Aviad Frydman, professor

User	Aviad Frydman, professor
Home Institute	Condensed matter physics, experiment, Bar Ilan University, Israel
Host supervisor	Thierry Grenet, Dr.
Description of the work	The electrical conductivity in highly disordered electronic hopping systems, which are subject to strong electronic interactions, exhibits glassy phenomena such as slow relaxation to equilibrium, memory effects, and aging (as representative of an “electron glass”). So far electron glass properties have been seen only in highly disordered metals or metal-like materials exhibiting hopping transport and having charge carrier densities larger than $n = 10^{20}$ cm^{-3}. No clear signs for glassy effects were observed in semiconductors. It has been proposed that an electron glass requires a hopping system characterized by a large number of charge carriers within a localization length. A semiconductor has a relatively small charge carrier density. Hence, in order to fulfill the above requirement one would need a relatively high degree of doping, in order to increase the localization length, and very low temperatures so that transport in the semiconductor is dominated by the hopping conductivity. In this project, we explored the electron glass phenomena in semiconducting samples at ultra-low temperatures. Despite decades of research, many aspects of the electron glass are not understood. No statistical or thermodynamic theory of non-ergodic systems exists and therefore there is no full understanding of any glasses, even less so of the electron glass that may be a special case of a “quantum glass”. Hence the situation in semiconductors is very important. We trust that the information gained by exploring the electron glass in heavily doped semiconducting samples will provide useful information for a deeper understanding of the processes responsible for glassines in low dimensional electronic systems.
Project achievements	The first stage of the project was dedicated to identifying the correct semiconducting samples. We studied a number of different systems and chose 4 samples: 2 doped bulk silicon samples and 2 samples of 2D films of amorphous diamond. All these samples had carrier concentrations above 10^{18} cm^{-3} and measurable resistances at temperatures smaller than 0.5 K. We then studied the electron glass properties of all these samples at different temperatures down to the lowest temperature at which their resistance was measurable. For the silicon samples, a gate was added to explore the field effect. The results were compared to granular aluminum samples which had similar resistances. The Al samples were also measured within the framework of this project. We thus successfully studied the transport properties and the relaxation to equilibrium after quench cooling in 4 different semiconductor samples, two 3D doped Si and two 2D amorphous diamond films. The transport of the films exhibits hopping conductivity with properties similar to those of "classic" electron glasses. The relaxation properties, on the other hand, were very different. We were not able to measure any conductivity relaxation after a rapid cool-down in any

	of semiconducting samples within our measurement resolution. We were able to put an upper bound of $5*10^{-3}$ % on conductivity relaxation in semiconductors (if such exists). This is orders of magnitude smaller than the relaxation observed in dirty metals. For example, we measured a granular aluminium film having similar resistance at low temperatures and observed a conductance relaxation close to 10% 100000 seconds after the cool down. We are now measuring the field effect of the gate voltage on the silicon samples. So far we see no signs of a "memory dip" in the conductance versus gate voltage curve which is one of the fingerprints of electron glasses. We are in the process of performing the data analysis but even in the absence of that it is clear that our results show that semiconductors do not exhibit electron glass effects even in systems having very high carrier concentration – contrary to our expectations. This result is very significant to the understanding of the origin of such effects in disordered conductors and requires new ideas to explain the difference between amorphous Anderson insulators and doped semiconductors.
Amount of access given	92 days (28/3 – 28/6, 2013)

Title of the project	**Late-time dynamics of quantized vortices generated after absorption of a neutron in superfluid 3He-B** CNRS17
User group leader	Anna Pomyalov, Ph.D., senior researcher
User	Anna Pomyalov, Ph.D., senior researcher
Home Institute	Weizmann Institute of Science, Rehovot, Israel
Host supervisor	Yuriy Bunkov, professor
Description of the work	The objective is to improve our understanding of the processes occurring after rapid quench-cooling of a small heated bubble of liquid 3He within a bulk superfluid bath at very low temperatures. We propose to conduct a thorough analysis of experimental results on the number of metastable topological defects left in superfluid 3He-B after the absorption of one neutron and to elaborate a new ``inflationary" model that will account for the initial spreading and growth of the vortex tangle (and also extraction of long-lived individual vortex rings/loops) under the outward wind of thermal excitations immediately following the ``mini Big Bang". Comparison of the specific predictions of this modified model with various existing experimental observations should hopefully help to improve the quantitative interpretation of experiments with respect to the efficiency of the Kibble-Zurek mechanism for the generation of topological defects. At present there are major unresolved questions concerning the correct interpretation of the different dynamic measurements at the lowest temperatures. Clearly the dynamics should be understood better if we ever want to make use of the helium superfluids as laboratory

	model systems of coherent quantum matter in the vacuum $T \rightarrow 0$ limit. Dr. Pomyalov has studied extensively the decay of homogeneous and isotropic superfluid turbulence via the Richardson – Kolmogorov hydrodynamic energy cascade which ultimately at sufficiently low mutual friction dissipation and small length scales (comparable to the inter-vortex distance) couples to Kelvin waves propagating on single vortex lines. It is important to understand how these theories apply to the propagating temperature front when the heated bubble shrinks after the neutron absorption reaction. The new experimental data is expected to provide a better understanding about the consistency between measurement and calculation and hopefully ultimately about the mechanisms which control defect formation in the Kibble-Zurek process.
Project achievements	A detailed analysis of the experimental data from the DN1 cryostat of the Microkelvin facility in Grenoble was performed. The applicability of the "standard" Kibble-Zurek model of the nucleation of topological defects in homogeneous conditions was confirmed: the energy stored in the tangle of quantized vortex lines agrees well with the experimentally observed energy deficit. To rationalize the long life time of the energy deficit we reconsidered several new mechanisms in the tangle evolution and showed, for example, that vortex production by counterflow should be disregarded, while the emission of small vortex loops was found to be very important. Based on the new understanding achieved during this visit and the results obtained during previous visits of profs. V. L'vov and A. Golov, a manuscript with the title "Evolution of Neutron-Initiated Micro-Big-Bang in superfluid He-3B" by Y. Bunkov, A. Golov, V. Lvov, A. Pomyalov, and I. Procaccia was written and uploaded to the Los Alamos electronic archive: arXiv:1309.1005. This manuscript will be submitted to Phys. Rev. B shortly. The results provide a basis for further studies, in particular for analytical and numerical modeling.
Amount of access given	16 days (5 Aug – 20 Aug, 2013)

Title of the project	**Investigation of 2D and 3D frustrated magnets in the mK regime** CNRS 18
User group leader	Romain Sibille, Dr., senior researcher
Users	Dr. Romain Sibille and Dr. Michel Kenzelmann
Home Institute	Laboratory for Developments and Methods, Paul Scherrer Institute, Villigen, Switzerland
Host supervisor	Dr. Elsa Lhotel, Institut Néel, CNRS, Grenoble
Description of the work	This project is concerned with experimental investigations of highly frustrated magnetic systems by means of macroscopic magnetization and AC susceptibility measurements in the mK range. These materials are, first, pyrochlore insulators of general formula

	$A^{III}{}_2B_2O_7$ with A = Ce or Tb and B = Sn or Hf. In these compounds, the magnetic moments lie on a 3D lattice of corner-sharing tetrahedra leading to geometrical frustration. In such systems, the tendency of the magnetic moments to form long-range ordered ground states is inhibited due to magnetic frustration, thus resulting in novel short-range ordered alternatives such as spin glasses or spin liquids of which spin ice is an example. Second, $Co^{II}{}_5(OH)_2(C_4H_4O_4)_4$ is a metal-organic framework in which a 2D geometrically frustrated lattice of magnetic ions has a different topology compared with the most largely studied Kagome, triangular and star lattices. Despite its Weiss temperature of -50 K, no magnetic transition was observed down to 1.8 K. Its behaviour below this temperature is addressed.
Project achievements	Thanks to the exceptional capabilities of the SQUID magnetometers developed by C. Paulsen at Institut Neel – CNRS, and now jointly operated with E. Lhotel, we performed fine and detailed magnetic characterizations at very-low temperatures on three compounds. Data have been recorded for magnetization (up to 8 T, down to 75 mK) and AC susceptibility (same temperature range, with rare and fruitful access to very low frequencies for this technique). The data taking was primarily performed by Romain Sibille, but additional help was administered by Michel Kenzelmann. These important results will be completed in the next weeks/months by neutron scattering experiments at Paul Scherrer Institut - CH. We have investigated the magnetic behaviour of $Co^{II}{}_5(OH)_2(C_4H_4O_4)_4$ at very-low temperatures (transition temperature is 380 mK). A single-crystal specimen was used and allowed measuring the transition with the field applied along each of the crystallographic directions in this monoclinic material. These data will be of prime importance for the validation of the magnetic structure (neutron powder diffraction experiments planned in July 2013). The dynamics of the magnetism has been studied by recording AC susceptibility data for various frequencies and time-dependence of the magnetization. The low-temperature magnetic properties of the pyrochlore material $Tb_2Hf_2O_7$ were studied for the first time, to the best of our knowledge. We have observed an exotic behavior which is mainly characterized by a signal around 800 mK, with both magnetization and ac susceptibility techniques. The exact nature of this transition remains to be clarified by complementary techniques. We expect this work to amount to the following publications: - *'Magnetism in $M^{II}{}_5(OH)_2(C_4H_4O_4)_4$ compounds with 2D bowtie lattice'* (submission fall 2013) - *'Frustrated magnetism in $Tb_2Hf_2O_7$'* (submission beginning of 2014)
Amount of access given	25 days in total - Dr. Romain Sibille 26/5 – 15/6, 2013, for 21 days - Dr. Michel Kenzelmann 2/6 – 5/6, 2013, for 4 days

Title of the project	**Specific heat measurements of disordered films across the superconductor-insulator-transition** CNRS 19
User group leader	Aviad Frydman, professor
User	Shachaf Poran, M.Sc., graduate student
Home Institute	Condensed Matter, Bar-Ilan University, Ramat Gan, Israel
Host supervisor	Olivier Buisson, senior researcher
Description of the work	The interplay between disorder and superconductivity has intrigued physicists for decades. Experimentally it was found that superconductivity in 2D thin films can be destroyed by a sufficiently large degree of disorder. Once superconductivity is destroyed the sample undergoes a transition to an insulating state across a superconductor insulator transition (SIT), a fundamental manifestation of a quantum phase transition at T=0. Recently this field was revived due to the experimental observations of a number of dramatic features near the SIT such as simple activated temperature dependence of the resistance on the insulating phase, a large peak in the magneto-resistance and traces of superconductivity at temperatures above Tc and in the insulating phase. Current experiments, focused on transport and tunneling methods, seem to have reached saturation and new techniques are needed in order to shed light on the physics behind the superconducting transition in disordered films. In this respect, thermodynamic heat capacity measurements may provide important information towards solving some of the puzzles of the field. The plan is to study the heat capacity as a function of temperature of disordered ultra-thin lead films undergoing the SIT. These films can be produced by quench condensation at low temperature directly in the calorimeter. As the number of atomic layers increases, the Pb films encounter the insulator to superconducting transition. Depending on the substrate, we can produce and study either granular or uniform Pb films. Ultra-thin Pb films will thus be quench condensed in situ in the calorimeter directly on the membrane sensor. We use the facilities at the Néel Institute, especially a specific experimental probe for thin-film characterization as well as the nanofabrication facilities of NANOFAB. Quench condensation allows fabrication of granular lead films. The highly sensitive Cp measurement must be performed at very low temperature in order to follow the appearance of a peak versus temperature as the layer is grown in situ. The major advantage of this method is to be able to measure the Cp signature versus the thickness of the thin film without being obliged to open the system. All the Cp measurements have to be performed down to the lowest temperature of the cryostat. A characterization of the superconducting layer by regular resistive measurement is the first step. The second step is the actual measurement of heat capacity. The overheating during the evaporation of the materials in the quench condensation is estimated and measured with

	the thermometer on the membrane. Detection of signs for superconductivity in the insulating phase or at temperatures smaller than 1K (down to 0.3K) requires precise temperature control and monitoring.
Project achievements	Several technical issues with the measurement system were addressed and fixed at the beginning of the visit. The fabrication of the sensor was achieved using regular clean room facilities, especially the very thin membrane sensor. The heat capacity of several different samples of quench-condensed granular Pb films was measured and the results are currently being examined. Electrodes have been installed directly on the membrane allowing the concomitant measurement of the resistance of the evaporated sample as well as its heat capacity. Several specimens were used to measure the heat capacity of ultrathin granular Pb films. I was able to build several working membrane sensors. The heat capacity as well as the resistance of the sample was measured between 2 and 10 K. The insulator to superconducting transition was followed with the resistive measurement, and the heat capacity was measured from the insulating to the superconducting side. Measurements in magnetic field were also performed up to 2 Tesla.The data are currently analyzed in order to publish the techniques of heat capacity measurement in the evaporation chamber as well as the scientific results on the thermal signature of an insulator to superconducting transition.
Amount of access given	92 days (1 June – 31 Aug, 2013)

Title of the project	**Bose-Einstein condensation of quasiparticles and spin superfluidity** CNRS 20
User group leader	Grigori Volovik, professor
User	Grigori Volovik, professor
Home Institute	O.V. Lounasmaa Laboratory, Aalto University
Host supervisor	Yuriy Bunkov, professor
Description of the work	Spin superfluidity - superfluidity in the magnetic subsystem of condensed matter - is manifested as spontaneous phase-coherent precession of spins. The spin supercurrent is one more representative of superfluid currents known or discussed in other systems, such as the superfluid current of mass and atoms in superfluid 4He; the superfluid current of electric charge in superconductors; the superfluid current of hypercharge in the Standard Model of particle physics; the superfluid baryonic current and the current of chiral charge in quark matter; etc. Spin superfluidity can be described in terms of the Bose condensation of spin waves -- magnons. There are different phases of magnon superfluidity, including those in a magnetic trap. The latter states have features common to the objects in high-energy physics: Q-balls and hadrons (MIT bag model of hadron). The magnon superfluidity is also manifested by the spin current Josephson effect; by spin current vortices -- topological defects, which are analogs of a quantized vortex in

	superfluids, an Abrikosov vortex in superconductors, or a cosmic string in relativistic theories; by Goldstone modes, etc. The task is to write a book on magnon BEC and its analogues in other physical systems (condensed matter and particle physics). The book should present a clear and comprehensive description of the BEC of non-equilibrium quasiparticles. It is written for researchers working actively in magnetism, superfluidity and superconductivity, BEC, spintronics, as well as to specialists of high energy physics theory. The physics of spin supercurrents can perhaps find applications in spintronics. The book describes the new and rapidly developing field of Bose-Einstein condensation of excitations, mostly using as an example the BEC of spin excitations, or magnons. The main goal of the book is to provide a clear and comprehensive picture of the BEC of non-equilibrium quasiparticles. Magnon BEC is a rich phenomenon, with many different types of condensates (two types of magnon BEC in bulk 3He-B; magnon BEC in magnetic traps on the ground and excited levels; magnon BEC in 3He-A, etc.). The phenomenon of magnon BEC has been applied to studies on the properties of superfluid 3He, particularly about the different types of vortices and topological defects. It has also many parallels with relativistic quantum fields and cosmology. Magnon BEC in magnetic traps resembles a non-topological soliton, a droplet of the bosonic quantum field known as the Q-ball. The physics of spin supercurrents can find applications in spintronics. This multidisciplinary book will be addressed to researchers working actively in magnetism, superfluidity and superconductivity, BEC, spintronics, as well as to theorists of high energy physics. It is also aimed for graduate students of these disciplines.
Project achievements	Several chapters of the book have been written earlier. Two new Chapters were now introduced. One of them is devoted to the geometric forces related to spin and orbital momentum in general, with applications to spin superfluidity and to spintronics. One of the geometric forces is the spin-motive force, which is at the moment under extended discussion in spintronics, where it is a force acting on an electron by the magnetization. It was introduced for metallic ferromagnets, where it reflects the conversion of the magnetic energy of a ferromagnet into the electrical energy of the conduction electrons. The same spin-motive force exists in magnon BEC, where it converts the energy of the coherent precession of magnetization to a superfluid current. The orbital-motive force is operating in superfluid 3He-A, where there are two contributions to the orbital-motive force. One contribution comes from the chiral nature of this liquid. The second contribution originates from chiral Weyl fermions living in the vicinity of the topologically protected Weyl points, and is related to the phenomenon of chiral anomaly. The second new Chapter is devoted to the modern subject of spontaneous breaking of time translation symmetry, a hot topic originated by the Nobel-Prize-winner Wilczek. The coherent spin precession of a magnon condensate gives new insight to this problem, providing a

	demonstration of quasi off-diagonal long-range order. The above two Chapters of the book gave rise to two manuscripts: G.E. Volovik, Spin-motive force and orbital-motive force: from magnon BEC to chiral Weyl superfluids, arXiv:1308.6700 G.E. Volovik, On the broken time translation symmetry in macroscopic systems: precessing states and ODLRO, submitted to preprint arXiv
Amount of access given	14 days (18 – 31 Aug, 2013)

Title of the project	**Detailed study of quantum turbulence from vibrating objects in superfluid Helium-4** Lancs09
User group leader	Ladislav Skrbek, professor
User	David Schmoranzer, Ph.D.
Home Institute	Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
Host supervisor	Shaun Fisher, professor Microkelvin Laboratory, Lancaster University
Description of the work	There has been much interest in quantum turbulence in recent years. It is interesting in its own right, as well as for its many analogies with classical turbulence and other less accessible systems. The simplest way to generate turbulence at very low temperatures is by vibrating objects at sufficiently large amplitudes. This project was aimed at studying the generation of quantum turbulence from different objects in normal and superfluid 4He over the full range of accessible temperatures, and over a very wide range of oscillation frequencies. The experiments were to be performed on the advanced refrigerator at Lancaster, allowing measurements below 3 mK. The objective was to acquire detailed measurements over the full temperature range and to study the effects of the turbulence generated from the different devices over a broad range of frequencies. Substantial amounts of detailed data analysis and modeling will be required to interpret the experimental results. Experiments over the whole temperature range are needed to compare different regimes: in the zero temperature limit there is no normal fluid so the behaviour is governed by quantum vortices in the pure superfluid; at intermediate temperatures we have coupled normal and superfluid turbulence; at high temperatures we have pure classical turbulence in a normal liquid. A low frequency vibrating wire also allows us to study the behaviour in the zero frequency limit and various tuning forks allow us to study frequency dependent behaviour expected at higher frequencies, as well as the interplay between turbulence and acoustic emission.
Project achievements	We have made comprehensive measurements of the drag forces from quantum turbulence produced by a low frequency (~ 60 Hz) vibrating wire and several quartz tuning forks covering a wide range of frequencies from a few kHz up to more than 100 kHz. Measurements were made in superfluid 4He over the full range of accessible temperatures, from just below the superfluid transition temperature ~ 2.2 K down to

	temperatures of just a few mK. We have detailed measurements for how the turbulent drag changes going from classical turbulence in normal liquid Helium above 2.2 K, through the two fluid regime at intermediate temperatures, to the pure quantum turbulence at the lowest temperatures. Measurements have been made on the low frequency wire and several tuning forks from velocities of order 1 mm/s up to around 1 m/s. This allows us to extract the dissipative drag coefficient which is dominated by turbulence at the highest velocities. Simultaneously we have measured the shift in the resonant frequency as a function of velocity which, together with similar measurements in vacuum, allows us to extract the non-dissipative inertial drag force for the different types of turbulence. For the tuning forks at higher frequencies, we see additional drag at low velocities due to acoustic emission, which was investigated in a previous access project. The project has been very successful. It has produced the first detailed measurements of the drag forces from quantum turbulence on a low frequency vibrating wire, together with a detailed comparison of the turbulent drag from tuning forks over a very wide frequency range. At the highest frequencies the drag is dominated by acoustic emission at low velocities, so we have also been able to investigate the possible interplay between acoustic emission and quantum turbulence. The measurements will take a substantial effort to analyse and interpret. This is will be done over the coming weeks and months. It will be particularly interesting to study the transitions from classical to two-fluid to pure quantum turbulence. In addition, the low frequency wire can be driven over a broad range of (low) frequencies using `floppy wire' techniques which we developed in an earlier access project. This will allow us to study the frequency dependence of the turbulent drag from the same object (the drag may be sensitive to surface defects, so it is particularly valuable to study the same object at different frequencies). The classical fluid drag on a wire (which we can measure in normal liquid 4He) should show considerable frequency dependence at low and intermediate velocities. It will be interesting to discover whether there is a comparable dependence in the pure superfluid at the lowest temperatures and in the two-fluid regime at intermediate temperatures.
Amount of access given	15 days [28/05/12 to 11/06/12]

Title of the project	**The superfluid 3He AB interface; dynamics and instability modes** Lancs 10
User group leader	Manuel Arrayás, lecturer, Ph.D.
User	Manuel Arrayás, lecturer, Ph.D.
Home Institute	Universidad Rey Juan Carlos, Fuenlabrada, Madrid, Spain
Host supervisor	Richard Haley, reader, Ph.D. Microkelvin Laboratory, Lancaster University, UK
Description of the work	The primary objective of the project is to further understand the properties of the A-B interface 2-brane. In the experiments a shaped magnetic field is used to stabilise and manipulate the phase boundary between A and B. This exploits the influence of a magnetic field on the phase tran-

	sition between the two, with the B phase being stable up to a critical field of 340 mT, where-upon there is a first-order transition to the A phase. A first-order transition has an energy cost associated with the surface tension between the two phases. This must be taken into account when assessing the equilibrium shape of the interface within the magnetic field profile, as well as the differences in wetting energy between the two phases and the container walls. I have been developing numerical methods to find the equilibrium position for realistic field profiles and boundary conditions, to simulate the interface behaviour when subjected to perturbations, and to see how its properties may be modified by defects that can exist within it. My visit was planned to coincide with ongoing experiments where the Lancaster ULT planned to move the AB interface through an array of detectors and monitor its progress through the experimental cell; I was to participate in these experiments and help to interpret the results using my previously developed simulation tools. The experiment consists of a vertical cylinder of superfluid, 6 cm long and 1.2 cm in diameter. A superconducting solenoid provides a controllable magnetic field gradient, allowing for the stabilisation of the AB interface across the cylinder. Ramping the current in the solenoids then ramps the field gradient and moves the AB interface up and down in the cylinder, converting B phase to A phase and vice versa. The passage of the AB interface is inferred from the behaviour of vibrating quartz tuning fork resonators that project into the superfluid from the sidewalls of the cylinder. These resonators are sensitive to the density of broken Cooper pair quasi-particle excitations, and are thus used to detect any changes as the inter-face is moved through the cell. It was seen that the interaction of the resonators with the interface was reproducible. Furthermore the signal depended on the relative orientation of the fork and interface. New techniques were also developed to move the interface much more quickly through the cell, using temperature steps rather than magnetic field gradients. This was to investigate whether a fast-moving interface is more susceptible to instabilities. This remains an open question.
Project achievements	To explain the dissipation associated with the periodic motion of the inter-face, reported by Bartkoviak *et al.* at Lancaster, we have made further simulations using the model proposed by Legget and Yip (see for example "Helium-3", edited by W.P. Halperin and L.P. Pitaevskii, Chapter 8), with coefficients for dissipation and surface tension taken from the experiments. They turn out to be bigger than the predicted by the theory. We have made an analysis of the effect of the inertia, and found that for low drive frequencies, the effect is negligible. We have also studied the case of a pinned interface, vibrating as a membrane, and found behaviour similar to a damped harmonic oscillator driven periodically. Some preliminary results show that the inclusion of a frequency dependent damping coefficient as proposed in the theory will not be able to account for the extra dissipation observed. There is the possibility to make it velocity dependent, which remains to be tested. Also, the idea that at higher frequencies there is an extra relaxation mechanism increasing the dissipation, due to textural rearrangement at the interface, is being considered at present.

Amount of access given	36 days [21/08/2012-25/09/2012]

Title of the project	**Study of Plastic flow in solid Helium-4** Lancs 11
User group leader	Emil Polturak, professor
User	Emil Polturak, professor
Home Institute	Department of Physics, Technion-Israel Institute of Technology, Haifa, Israel
Host supervisor	Shaun Fisher, professor Microkelvin Laboratory, Lancaster University, UK
Description of the work	This project aimed to study plastic flow in solid Helium-4 over a broad range of temperatures, from around 1.5 K to well below 10 mK. In particular, the objective was to study the motion of a wire through the solid under an applied force. The device was developed in an earlier trans-national-access project. It was previously used to study quantum turbulence in superfluid 4He over a wide range of temperatures, from the superfluid transition temperature (~2K) to below 3mK. Here, we use the device (and the same cell) to study solid 4He. The experiments will be performed on the Lancaster Advanced Refrigerator. The project will investigate the plastic properties of solid helium, including plastic flow (creep) at low drive forces, the yield stress and the plastic response at higher driving forces. We are particularly interested in what happens at lower temperatures where there has been a great deal of recent interest in possible "super-solid" and/or "quantum plasticity" behaviour. Substantial amounts of data, analysis and modeling will be required to interpret the experiments. The project scientist has much experience in similar experiments at higher temperatures.
Project achievements	To study the plasticity of solid 4He we used a wire which was formed into a square loop. A sideways driving force on the wire arises from the Lorentz force exerted when a current is passed through the wire in a vertical magnetic field. The position of the wire was measured using two near-by pick-up coils. A high frequency (~30kHz) probe current was superimposed on the drive current. This induced voltages in two nearby coils. The magnitude of the voltage depends on the wire position. The position measurements were calibrated by measuring the elastic displacement of the wire in liquid 4He. In the solid phase at high temperatures the wire was found to move slowly and steadily through the solid. Here, the resultant plastic flow of the solid around the wire is thought to be facilitated by the diffusion of vacancies – an effect previously investigated by the project scientist at higher temperatures. We also found non-linear behaviour at higher driving forces, presumably due to the motion of defects. In addition we found some unexpected behaviour at higher driving forces. The wire was found to move in a stepwise fashion. The size of the steps in-creased with the driving force, and high velocities (of order 1 mm/s or more) occur at the step itself. Work is on-going to understand

	this behaviour, and we will extend the measurements to lower temperatures (so far, no steady motion has been observed at low mK temperatures). The project has revealed some very interesting results. For the first time we have observed slow steady motion of a wire through hcp solid 4He at temperatures below the bcc region of the phase diagram. At low driving forces the velocity is linear in the applied force, but becomes non-linear at higher forces (the velocity varies approximately as the 4th power of the force). These properties can probably be understood on the basis of vacancy diffusion as was investigated previously by the project scientist at higher temperatures. A quantitative comparison is on-going. At higher forces, unexpected behaviour is observed. The wire position changes in a step wise fashion, with increasing step size at larger driving forces. During the step the wire moves at high velocities (of order 1 mm/s or more). Further work is on-going to try to understand this. One difficulty is that the wire occasionally becomes normal which heats the cell and locally melts the solid, but there is no sign of the wire becoming normal during the steps.
Amount of access given	6 days [28/10/2012 - 02/11/2012]

Title of the project	**Quantum diffusion of vacancies in Helium-4 crystal** Lancs 12
User group leader	Igor Todoshchenko, senior researcher
User	Igor Todoshchenko, senior researcher
Home Institute	O.V. Lounasmaa Laboratory, Aalto University, Finland
Host supervisor	Shaun Fisher, professor Microkelvin Laboratory, Lancaster University, UK
Description of the work	This project is devoted to measurements on the plastic flow of helium-4 crystals at low temperatures with a range of driving forces. A metallic wire inserted into solid helium can move due to the flow of vacancies or interstitials in the surrounding stress field. The project objectives are to investigate plastic flow by studying the dynamic properties of the wire as a function of temperature, the quality of the crystal, and the applied force. The project will probe many interesting aspects, some of which are outlined below. We expect the plastic properties to change dramatically on varying the temperature and the crystal quality. In the bcc phase, defects can move quite easily along many 'easy' planes. In the hcp phase, defect motion is far more restricted. At high temperatures, vacancies are thermally activated. While at low enough temperatures, vacancies are predicted to delocalize with the formation of quasiparticles (vacancions). Vacancies have an activation energy of the order of 10 Kelvin, so that the equilibrium density of vacancies will rapidly fall with decreasing temperature below 1 Kelvin. However, non-equilibrium vacancies can be introduced in the solid by changing the density of the crystal at constant volume. Furthermore, at sufficiently large vacancy densities and at low enough temperatures, vacancies may Bose-condense into a single ground state. This system might then display superflow, mass flow without dissipa-

	tion, which should have a dramatic effect on the wire response.
Project achievements	We investigated the plastic flow with a superconducting wire in the shape of a rectangular loop. The wire was placed in a strong vertical magnetic field, and a DC current through the wire produces a transverse Lorentz force. A small AC current (approx. 30 kHz) is superimposed on the DC current to induce a voltage on nearby pick-up coils. The amplitude of the induced voltage depends on the position of the wire. The absolute position of the wire can be extracted after calibrating the response in liquid He or in vacuum. We were able to nucleate the He crystal by applying heat to the cell locally, or by simply pressurizing the cell slowly. Crystals were prepared in many different ways. Slow growth at almost constant temperature and pressure produces better quality crystals. Fast cooling or warming produces crystals with a lot of defects. We grew crystals of very poor quality by inducing a very rapid pressure and temperature change by briefly driving the wire normal with a large DC current. The measuring cell also contained two pressure sensors and a set of small tuning forks which were used to monitor the position and size of the crystal in the cell. We have made many measurements of the wire response in different crystals and over a wide range of temperatures. We measured the velocity of the wire as a function of driving force (stress) in various crystals of different qualities. The data are currently being analysed. Our preliminary findings indicate that below 1.4 K the mobility of the wire depends strongly on the crystal quality. Perfect crystals showed only very slow motion, consistent with thermally excited vacancies whose density decreases rapidly with decreasing temperature. In contrast, crystals of poor quality appeared to show much faster plastic flow. The results suggest that there are two channels of plasticity, one is generated by thermally-activated vacancies and another may be generated by disorder-activated vacancies. At high drives the velocity-stress relationship of the wire becomes nonlinear, possibly with cubic velocity dependence, probably due to the self-generation of vacancies by the moving wire. We have also observed fast jumps of the wire position with amplitudes as high as 0.5 mm. The velocity of the wire during such jumps was as fast as 1 mm/s. These jumps never happened with crystals of good quality. We speculate that the jumps might be associated with 'cloud bursts' of vacancies of very high density. Such cloud bursts might be ideal to investigate the possible Bose condensation of vacancions.
Amount of access given	12 days [06/11/2012 - 17/11/2012]

Title of the project	**Analysis of data on quantum diffusion in Helium-4 crystal** Lancs 13
User group leader	Igor Todoshchenko, senior researcher
User	Igor Todoshchenko, senior researcher
Home Institute	O.V. Lounasmaa Laboratory, Aalto University, Finland

Host supervisor	Shaun Fisher, professor
Description of the work	The project focuses on performing the final experiments and analysing our previous data obtained in Lancaster on the plastic flow of helium-4 crystals. The experiments involved a thin wire moving through bulk helium-4 crystals due to the Lorentz force applied to the wire. At low speeds, the velocity of the wire is proportional to the driving force (stress) and the motion of the wire is due to the diffusive flow of vacancies present in the solid. The driving force applied to the wire induces a stress field in the solid, and vacancies move from the regions of less dense solid behind the wire to the regions of more dense solid ahead of the wire. The wire mobility is thus proportional to the concentration of vacancies and to the mobility of a single vacancy. We have analyzed the dependence of the wire mobility on temperature and on the history of the crystal sample and found that the concentration of vacancies varies a lot from sample to sample. High quality crystals show a small concentration of vacancies while samples which were thermally cycled could have more than an order of magnitude larger concentration of vacancies. These additional vacancies may be induced by the stress in the solid due to the change in melting pressure. At higher drives, we find that stress-induced vacancies are created by the wire.
Project achievements	The data on the mobility of the wire at low stresses show a large scatter at temperatures below 1.5 K. We have paid special attention to be sure that the data has been taken in the linear regime and thus the scatter reflects real variability in the crystal quality which depends on the sample history. We have applied a model of diffusive motion of vacancies around the wire to show that the lower boundary of the mobility is due to thermally activated vacancies as expected for high quality crystals. In this model the diffusion coefficient of a single vacancy is proportional to the tunnelling frequency, or to the width of the energy band of vacancies. Samples with low mobility were freshly made and were measured at the same temperature at which they were grown. These good quality samples have only thermally activated vacancies. After changing the temperature of the sample the mobility of the wire becomes much larger indicating that the vacancy concentration may be increased by more than one order of magnitude. We suggest that additional vacancies appear due to stresses in solid when changing the melting pressure (temperature). Vacancies can also be created by the wire at high drives, which results in a cubic term in the velocity-stress dependence of the wire. We have shown that the flow of vacancies is responsible for the plastic motion of a wire through solid helium 4. The lowest observed values of the mobility of the wire are in good quality crystals and these agree well with a model based on the diffusion of thermally activated vacancies. By fitting the low mobility data we can infer the width of the energy band of vacancies. To our knowledge this is the first measurement of the band width of vacancies and the measured value is in the good agreement with theoretical expectations. The higher values of the wire mobility are attributed to the flow of vacancies created by the stresses in solid. Stresses in our samples have two origins. First is stress due to the change in melting pressure as the temperature is varied. Second is stress

	induced by the wire itself at high drives. We find that the concentration of additional vacancies in both cases is similar, about 10-3 for stresses close to the ultimate tensile stress of 10-20 mbar. We thus show that a finite concentration of vacancies can be introduced in bulk solid helium 4 by applying stress to the sample. This may be useful for future studies of the potential exotic behaviour at very low temperatures. For instance, the maximum observed concentration of the stress-induced vacancies corresponds to a Bose-condensation temperature of around 30 mK.
Amount of access given	9 days [25/03/2013-02/04/2013]

Title of the project	**The superfluid 3He AB interface; dynamics and instability modes** Lancs 14
User group leader	Manuel Arrayas, Ph.D., reader
User	Manuel Arrayas, Ph.D., reader
Home Institute	Universidad Rey Juan Carlos, Madrid
Host supervisor	Richard Haley, reader, University of Lancaster
Description of the work	Following the objectives of the previous visits, the primary goal was to elucidate the dynamical properties of the A-B interface 2-brane. The bound-ary between the A and B phases is controlled experimentally us-ing shaped magnetic fields. In previous work we first calculated the equilibrium profiles of the interface for various field and experimental cell configurations, as well as the shape of a B phase “bubble” that is completely surrounded by A phase. Turning to the dynamics, we have been attempting to account for the dissipation that has been measured for an oscillating interface, but the experimental result remains unex-plained so far. It seems that dissipation at low frequency and amplitude may be described well by a model due to Yip and Leggett, but it does not fit the behaviour of high frequency and high velocity measurements quantitatively, or even qualitatively. The main object-ive of this visit has been to test whether the anomalous drag can be linked to a lag in the textural realignment that must take place within the A and B order pa-rameters close to the interface as it moves. Understanding this “friction” is crucial for assessing the growth of the instability modes of a moving interface.
Project achievements	In the current experiments the superfluid AB interface is stabilised and moved using a controllable magnetic field gradient provided by a stack of superconducting solenoids placed outside the container vessel, which is a vertical cylinder 6 cm long and 1.2 cm in diameter. Ramping the current to the solenoids then ramps the field gradient and moves the AB interface up and down the cylinder, converting B phase to A phase and vice versa. The motion and properties of the interface are inferred from the behaviour of vibrating wire and quartz tuning fork resonators that project into the super-fluid from the top, bottom, and sidewalls of the cylinder. We have simulated the equilibrium interface profiles, and the quasi-equilibrium properties of an interface that is moved slowly through the cell and past the detectors. We have analysed measurements from a previous experimental cell, with a different solenoid stack, where it was possible to oscillate the interface. Towards the end of the visit we began considering the effect of orbital viscosity, and made or-

	der of magnitude calculations of its contribution to the dissipation process. In order to explain the dissipation associated with the periodic movement of the interface, measured at Lancaster, this time we started to consider an extra relaxation mechanism at the AB interface due to rearrangement of the order parameter textures on the B phase side. The idea is that the magnetic field produces a small axial distortion of the energy gap, so the quasiparticle distribution has to relax to equilibrium when the gap structure bends in the texture. Due to the finite quasiparticle scattering time, a net viscous force develops. We had a breakthough in finding a functional form for a frequency dependent damping coefficient that allowed us to make qualitative fits to the measured data for the first time. Quantitative estimations also appear to be of the right order of magnitude.
Amount of access given	25 days (11/6 – 5/7, 2013)

Title of the project	**Ultralow temperature properties and thermometry in mesoscopic structures** Lancs 15 – Florian Forster Lancs 16 – Stefan Ludwig
User group leader	Stefan Ludwig, professor
User 1	Florian Forster, graduate student
User 2	Stefan Ludwig, professor
Home Institute	Fakultät für Physik, Ludwig-Maximilians Universität, München
Host supervisor	Richard Haley, reader, Lancaster University
Description of the work	A major goal of the MICROKELVIN project is to develop technology to better enable the cooling of electronic devices and nanocircuits to temperatures below 1 mK. For this purpose a new EU Access Facility machine was recently built at Lancaster. A major obstacle to cooling electronic devices is heat generated by noise transmitted through electrical leads. To address this, sophisticated wiring/filter protocols and designs developed by Stefan Ludwig's group in Munich are being implemented in the new machine at Lancaster. The Ludwig group have also developed high quality low temperature measurement techniques for nanostructures which they produce in-house. This project aims to perform the first ultralow temperature measurements on nanostructures built in Munich. To achieve this, Stefan Ludwig and Florian Forster require several visits to the Lancaster Access Facility to further develop the necessary measurement techniques and thermometry and to perform the preliminary measurements. The primary scientific and technologic objective of this collaborative project is to investigate nanoelectronic circuits in a hitherto unrivalled range of ultralow temperatures. This will allow us to reach lower energy scales and go well beyond the present state-of-the-art to investigate collective and phase sensitive quantum phenomena such as: mesoscopic interferometry effects; quantum Hall phases; the Kondo effect in coupled quantum dots; the 0.7 anomaly in quantum point contacts; and the hyperfine interaction between confined electrons and many nuclear spins. One of our main efforts will be to study coherent dynamics and entan-

	glement in semiconductor-based quantum information circuits at ultralow temperatures. The combination of expertise in ultralow temperature physics in Lancaster and low temperature nanoelectronic measurements in Munich provides the framework for a successful collaboration. Nanostructures will be produced and initially characterised in Munich, while the final ultralow temperature measurements will be performed in Lancaster.
Project achievements	This visit of Stefan Ludwig and Florian Forster at Lancaster University was devoted to an exchange of skills and technology between Munich and Lancaster and intensive planning of the ongoing project. The goal of the visit was to boost the progress of the project in order to enable first measure-ments on semiconductor chips scheduled to start in mid August. Important aspects were the optimization of the wiring which will include a large number of customized electric filters and of the compatibility between the tech-nology developed in Munich with that being built for the dilution refrigerator in Lancaster. In detail we (i) planned and optimized the wiring, (ii) developed a concept for low-pass filters customized for the existing system and the planned experiments, (iii) developed a design for the first generation of sample holders, and (iv) developed a detailed schedule for the planned experiments. The points (i-iii) are now being pursued in Lancaster while Florian Forster is producing and testing the proper samples for the first experiments in Munich. These visits were important for the future development of the new Lancaster facility, constructed for studying nanoelectronic circuits at ultralow temperatures. We now implement the planned structures and activities. We expect to be able to present first experimental results on semiconductor nanostructures at ultra-low temperatures in the fall of this year.
Amount of access given	6 days in total (both visitors for the 3 days 24/4 – 26/4, 2013)

Title of the project	**Ultra-low temperature MEMS** Lancs 17
User group leader	Henri Godfrin, professor
User 1	Eddy Collin, Dr.
User 2	Martial Defoort, graduate student
User 3	Henri Godfrin, professor
Home Institute	Institut Néel, CNRS, Grenoble
Host supervisor	Shaun Fisher, professor
Description of the work	In this project we investigate micro-electro-mechanical devices (MEMS) at ultra-low temperatures. We want to measure their mechanical properties (dissipation and nonlinear characteristics) in vacuum and immersed in a bath of ultra-cold liquid ^{3}He, to learn about the interactions in the superfluid environment. The mechanical structures we want to study are goalpost-shaped silicon devices that mimic vibrating wires. Their properties have been well

	characterized down to 1 K in vacuum, but not lower. As far as mechanics are concerned, there are two issues: - A technical issue that aims to demonstrate that these devices are indeed good oscillators at very low temperatures, far below 1 K (i.e. high Q, small nonlinearities, easy to detect a signal). This is mandatory for the scientific issue that is concerned with the interaction between the MEMS and liquid ^{3}He. - A scientific issue that aims to understand the sources of dissipation and nonlinearity. The dissipation issue is a topical subject linked to the physics of glasses, and dissipation in nano-mechanical structures in general. A second scientific objective is to study the interaction between the MEMS and liquid ^{3}He. This has not been done before, and we hope to demonstrate an unprecedented resolution in the measurement of the fluid viscosity. In the superfluid at the lowest temperatures, this would lead to extreme resolution for thermometry and bolometry. Small size and high sensitivity should also prove useful in the study of quantum turbulence. High quality MEMS devices have been prepared and characterized in Grenoble. They are mounted in a ^{3}He cell on a demagnetization cryostat in Lancaster. Measurements of the mechanical properties are performed as a function of temperature and fluid parameters (pressure P and magnetic field B) using the standard magnetomotive (i.e. the vibrating wire) technique.
Project achievements	A MEMS sample from Grenoble was installed on a demagnetization cryostat in Lancaster. It has been placed in an experimental container filled with superfluid ^{3}He cooled down to 100 μK. The interactions of the MEMS with the surrounding bath of quantum excitations have been characterized. The device damping in ultra-cold superfluid ^{3}He has been measured. Following predictions, it has been found to be a sensitive and efficient quasi-particle detector, about 5 times more sensitive than a usual vibrating wire device. However, strong nonlinearities and a low pair-breaking velocity have been discovered, which require further investigation.
Amount of access given	17 days in total (Collin 17-22 June, 2013; Defoort 17-22 June, 2013; Godfrin 19-23 June, 2013)

Title of the project	**The superfluid 3He AB interface: friction and orbital viscosity** Lancs 18
User group leader	Manuel Arrayas, Dr. senior researcher
User	Manuel Arrayas, Dr. senior researcher
Home Institute	Low temperature plasma physics, Universidad Rey Juan Carlos, Madrid
Host supervisor	Richard Haley, reader
Description of the work	The analogies between the order parameter of superfluid helium-3 and those describing other fundamental systems allow us to use superfluid helium-3 as a model system to study a broad range of phenomena. For instance the symmetry-breaking phase transitions to the superfluid pro-

	vide a test-bed for studying transit-ions in the quantum vacuum state of the evolving early Universe. The order parameters of the superfluid A and B condensates are analogous to quantum vacuum states existing in 3 dimensions as a 3-brane. The highly ordered 2D interface between the A and B phases is then a 2-brane. Now experimental work is in progress to measure the properties of this interface, with a focus on its dynamical behaviour. Dr Arrayas is experienced in studying and simulating the dynamics of interfaces and has been assessing various instability modes. During his last visit we realised that friction on the moving interface must be important in impeding the growth of instabilities. This led us to examine the unexplained non-linear dissipation observed for an oscillating interface. The motion of the interface must induce changes in the local texture on either side of the interface. These changes will be damped by orbital viscosity. Our preliminary crude estimates indicated that this could be a dominant mechanism for the observed dissipation. Our primary objective is to include orbital viscosity in our model for the moving interface and use it to describe the subsequent dissipation. This is of crucial importance to understand the interface dynamics at low temperatures. We have measurements of the dissipation caused by an oscillating interface that we have been unable to explain, even qualitatively. We believe that orbital viscosity could offer a solution to this. We will first concentrate on using orbital viscosity to calculate the dissipation from a changing texture in the distorted B-phase. We will then apply this to simple model textures such as the flare-out texture on the B-phase side of the interface. The resulting dissipation will then feed back into the equation of motion governing the interface dynamics. In principle we can also study the effect on non-ideal textures and textural defects on either side of the interface. We can compare this with existing experimental data. We will also apply these ideas to calculate the velocity of a freely moving interface. This secondary objective is important as the free interface moves so fast in our experiments that we have only been able to put a lower limit on its speed owing to limitations in our measurement technique. Knowing the velocity impacts on assessing the stability of the moving interface and therefore on the likelihood of leaving topological textural defects in its wake.
Project achievements	In our experimental arrangement the texture of both the A and B phase order parameters is influenced by the interface, and bends by 90 degrees from its direction in bulk. As the interface moves, the texture of the surrounding A and B phases must bend and realign to accommodate it. Previous attempts by Leggett and Yip, and Kopnin, to model the friction on a moving interface did not include effects of the bending texture, and therefore ignored orbital viscosity, leading to estimates of dissipation that are much lower than what we measured experimentally. We have modelled the moving interface and the concomitant bending of the texture. We have applied ideas of orbital viscosity to calculate the subsequent dissipation, and hence the friction on the moving interface. We have compared the model calculations to the existing measurements of the anomalous drag on an oscillating interface. We have used this model to make estimates of the speed of a freely moving interface lim-

	ited by friction. In order to explain the dissipation associated with the periodic movement of the interface, as measured at Lancaster, this time we started to consider an extra relaxation mechanism at the AB interface due to the rearrangement of the order parameter texture on the B phase side. The idea is that the mag-netic field produces a small axial distortion of the energy gap, so that the quasiparticle distribution has to relax to equilibrium when the gap structure bends in the texture. Due to the finite quasiparticle scattering time, a net viscous force develops. We had a breakthough in finding a functional form for a frequency dependent damping coefficient that allowed us to make qualitative fits to the measured data for the first time. Quantitative estima-tions also appear to be of the right order of magnitude. At the moment, the relaxation time of quasiparticles to equilibrium needed to fit the experimental data is larger than the estimation from the time that a quasiparticle reaches the container wall. There is also a high frequency mechanism presented in the dissipation process that seems to be independ-ent of the orbital viscosity one. We have modelled it as an extra term, but its physical origin is under discussion.
Amount of access given	25 days (13 Aug – 6 Sep, 2013)

Title of the project	**Ultralow temperature properties and thermometry in meso-scopic structures** Lancs 19
User group leader	Stefan Ludwig, professor
User	Florian Forster, graduate student
Home Institute	Nanophysics, Solid State Physics, Fakultät für Physik, Ludwig-Maximilians Universität
Host supervisor	George Pickett, professor
Description of the work	A major goal of the Microkelvin project is to develop technology to better enable the cooling of electronic devices and nanocircuits to temperatures below 1mK. For this purpose a new EU Access Facility machine was recently built at Lancaster. A major obstacle to cooling electronic devices is heat generated by noise transmitted through electrical leads. To address this, sophisticated wiring/filter protocols and designs developed by Stefan Ludwig's group in Munich are being implemented in the new machine at Lancaster. The Ludwig group has also developed high quality low temperature measurement techniques for nanostructures which they produce in-house. This project aims to perform the first ultralow temperature measurements on nanostructures built in Munich. To achieve this, Stefan Ludwig and Florian Forster require several visits to the Lancaster Access Facility to further develop the necessary measurement techniques and thermometry and to perform the preliminary measurements. The primary scientific and technological objective of this collaborative project is to investigate nanoelectronic circuits in a hitherto unrivalled range of ultralow temperatures. This will allow us to reach lower energy scales and go beyond the present state-of-the-art to investigate collec-

	tive and phase sensitive quantum phenomena such as: mesoscopic interferometry effects; quantum Hall phases; the Kondo effect in coupled quantum dots; the 0.7 anomaly in quantum point contacts; and the hyperfine interaction between confined electrons and many nuclear spins. One of our main efforts will be to study coherent dynamics and entanglement in semiconductor-based quantum information circuits at ultralow temperatures. The combination of expertise in ultralow temperature physics in Lancaster and low temperature nanoelectronic measurements in Munich provides the framework for a successful collaboration. Nanostructures are being produced and initially characterised in Munich, while the ultralow temperature measurements will be performed in Lancaster.
Project achievements	This extended visit was devoted to an exchange of skills and technology between Munich and Lancaster and included practical work of Florian Forster in the Ultra-Low-Temperature Laboratory of Lancaster University. The goal was to boost progress, to enable first measurements on semiconductor chips. Together with Jon Prance and Rich Haley, Florian produced low temperature filters, thermal couplings, and installed wires and filters in the refrigerator. This involved a great deal of technical work and test measurements. This practical work embedded in a local team turned out to be ideal for the exchange of skills and technology between Munich and Lancaster. In addition, he brought some of the specialist room temperature filtering and measurement devices that have been custom-built in Munich and are now integrated in the Lancaster set-up. The next step is to mount the device chips on a new bespoke chip holder that has been made at Lancaster. Then we will be ready for starting the investigation of nanoelectronic circuits at ultralow temperatures at the new Lancaster facility. This second visit of Florian Forster in Lancaster was an important step towards the development of the new Lancaster facility for the study of nano-electronic circuits at ultralow temperatures. Our initial goal to pursue the first experiments on ultra-cold nanostructures during this visit was not achieved due to technical delays in getting the dilution refrigerator to work. These difficulties are now being fixed and we are about to mount and cool the first mesoscopic sample. We expect to be able to present the first experimental results on semiconductor nanostructures at ultra-low temperatures by the end of this year.
Amount of access given	26 days (14 Aug – 8 Sep, 2013)

Title of the project	**Ultralow temperature properties and thermometry in mesoscopic structures** Lancs 20
User group leader	Stefan Ludwig, Ph.D., professor
User	Stefan Ludwig, Ph.D.
Home Institute	Fakultät für Physik, Ludwig-Maximilians Universität
Host supervisor	George Pickett, professor
Description of the work	A major goal of the Microkelvin project is to develop technology to better enable the cooling of electronic devices and nanocircuits to tem-

	peratures below 1mK. For this purpose a new EU Access Facility machine was recently built at Lancaster. A major obstacle to cooling electronic devices is heat generated by noise transmitted through electrical leads. To address this, sophisticated wiring/filter protocols and designs developed by Stefan Ludwig's group in Munich are being implemented in the new machine at Lancaster. The Ludwig group has also developed high quality low temperature measurement techniques for nanostructures which they produce in-house. This project aims to perform the first ultralow temperature measurements on nanostructures built in Munich. To achieve this, Stefan Ludwig and Florian Forster made several visits to the Lancaster Access Facility to develop the necessary measurement techniques and the thermometry and to perform preliminary measurements. The primary scientific and technological objective of this collaborative project is to investigate nanoelectronic circuits in a hitherto unrivalled range of ultralow temperatures. This will allow us to reach lower energy scales and go well beyond the present state-of-the-art to investigate collective and phase sensitive quantum phenomena such as: mesoscopic interferometry effects; quantum Hall phases; the Kondo effect in coupled quantum dots; the 0.7 anomaly in quantum point contacts; and the hyperfine interaction between confined electrons and many nuclear spins. One of our main efforts will be to study coherent dynamics and entanglement in semiconductor-based quantum information circuits at ultralow temperatures. The combination of expertise in ultralow temperature physics in Lancaster and low temperature nanoelectronic measurements in Munich provides the framework for a successful collaboration. Nanostructures are being produced and initially characterised in Munich, while the final ultralow temperature measurements will be performed in Lancaster.
Project achievements	The original aim of the visit was to foster ongoing measurements and to actively participate in the planning of future experiments, based on the first results. Due to unforseeable technical delays, the measurements of actual nanostructures had to be delayed and are not yet pursued. Stefan Ludwig decided to nevertheless visit Lancaster as planned in order to boost the ongoing project. During this visit we have installed cables and filters, which have been prepared by Florian Forster together with Jon Prance and Rich Haley, in the newly built dilution unit at the University of Lancaster. More importantly, we examined the status of the project components (refrigerator, sample holder, wiring, filters), corrected the ongoing work and arranged a number of discussions, including Stefan Ludwig, Florian Forster, Jon Prance, Ian Bradley, Rich Haley, and George Picket, in which we further developed our strategy to efficiently cool nanostructures to below 1mK and to accurately measure their temperature. Our first milestone will be to cool a mesoscopic device containing a Hall bar and a lateral double quantum dot to a few mK and measure this at low temperatures. The visit was thus important to further exchange skills and technology between Munich and Lancaster, another step towards the development

	of the new Lancaster facility for studying nanoelectronic circuits at ultralow temperatures. Our initial goal to pursue the first experiments on ultra-cold nanostructures during this visit was not achieved owing to technical delays in getting the dilution refrigerator to work. These difficulties are now being fixed and we are about to cool the first mesoscopic samples. Instead of pursuing the first measurements together during Stefan Ludwig's visit, we used his visit for an assessment of the ongoing work and to plan the experiments to come in much greater detail. We expect to be able to present the first experimental results on semiconductor nanostructures at ultra-low temperatures by the end of this year.
Amount of access given	6 days [16/9 – 21/9, 2013]

Title of the project	**Ultralow temperature properties and thermometry in mesoscopic structures** Lancs 21
User group leader	Stefan Ludwig, Ph.D., professor
User	Florian Forster, graduate student
Home Institute	Fakultät für Physik, Ludwig-Maximilians Universität
Host supervisor	George Pickett, professor
Description of the work	A major goal of the Microkelvin project is to develop technology to better enable the cooling of electronic devices and nanocircuits to temperatures below 1mK. For this purpose a new EU Access Facility machine was recently built at Lancaster. A major obstacle to cooling electronic devices is heat generated by noise transmitted through electrical leads. To address this, sophisticated wiring/filter protocols and designs developed by Stefan Ludwig’s group in Munich are being implemented in the new machine at Lancaster. The Ludwig group has also developed high quality low temperature measurement techniques for nanostructures which they produce in-house. This project aims to perform the first ultralow temperature measurements on nanostructures built in Munich. To achieve this, Stefan Ludwig and Florian Forster have made several visits to the Lancaster Access Facility to develop the necessary measurement techniques and thermometry and to perform the preliminary measurements. The primary scientific and technological objective of this collaborative project is to investigate nanoelectronic circuits in a hitherto unrivalled range of ultralow temperatures. This will allow us to reach lower energy scales and go beyond the present state-of-the-art to investigate collective and phase sensitive quantum phenomena such as: mesoscopic interferometry effects; quantum Hall phases; the Kondo effect in coupled quantum dots; the 0.7 anomaly in quantum point contacts; and the hyperfine interaction between confined electrons and many nuclear spins. One of our main efforts will be to study coherent dynamics and entanglement in semiconductor-based quantum information circuits at ultralow temperatures. The combination of expertise in ultralow temperature physics in Lancaster and low temperature nanoelectronic measurements in Munich provides the framework for a successful collaboration. Nanostructures are being produced and initially characterised in Mu-

	nich, while the ultralow temperature measurements will be performed in Lancaster.
Project achievements	This third visit of Florian Forster at Lancaster University was an extension of his second visit (the two visits were interrupted by one week of vacation). The technical description of the performed work is the same as for his second visit. During this third visit he completed the low temperature filters and thermal couplings for the refrigerator. The Hall bar and quantum dot samples are now ready to be bonded to the low temperature chip holder. Our initial goal to pursue first experiments on ultra-cold nanostructures during this visit was not achieved owing to technical delays in getting the dilution refrigerator to work. These difficulties are now being fixed so we are about to mount and cool the first mesoscopic sample. We expect to be able to present the first experimental results on semiconductor nanostructures at ultra-low tempera-tures by the end of this year.
Amount of access given	16 days [15/9 – 30/9, 2013]

3.3 Deliverables and milestones tables

Deliverables – Microkelvin – Annex I – amended version of Sep, 2011

Table of Deliverables

Del. no.	Deliverable name	WP no.	Lead beneficiary	Estimated person months	Nature	Dissemination level	Delivery date
D1	Opening and operation of Management Office	NA1	AALTO	10	O	PU	1 Delivered I
D2	Opening and maintaining of website	NA1	AALTO	4	O	PU and PP	1 Delivered I
D3	MICROKELVIN reports	NA1	AALTO	6	R	PU	20, 40, 56 Delivered I,II,III
D1	User Meetings (Proceedings)	NA2	AALTO CNRS ULANC	2	R	PU	13, 37 (24, 48) Delivered I,II,III
D2	Training sessions for users	NA2	AALTO CNRS ULANC	1	O	PU	13, 37 Delivered I,II
D1	Opening of the CryoTools data base (6) and E-mail lists of laboratories and industries (8)	NA3	CNRS	2	O	PU	6, 8 Delivered I
D2	LT-X workshops (18, 28, 40, 44) and Industrial meeting (32) with reports	NA3	All partners		R	PU	18, 28, 32, 40, 44 Delivered I,II,III
D1	Invitations to leading scientists and young researchers of Third Countries to MICROKELVIN meetings	NA4	CNRS		O	PU	12 Delivered I,II,III
D2	Report on European Cryogenic Society and Third Countries Network	NA4	CNRS	1	R	PU	36 Delivered II,III
D3	Ultralow temperature forecast report	NA4	ULANC	1	R	PU	36 Delivered III
D1	Prototype of nanocircuit stage for access service at ULANC (Task 1)	JRA1	ULANC	16	P	PU	36 Delivered III
D2	Prototype of compact nuclear cooling refrigerator for access service at CNRS (Task 2)	JRA1	CNRS	18	P	PU	24 Partly delivered III
D3	Prototype of compact nuclear cooling refrigerator for access service at AALTO (Task 2)	JRA1	AALTO	20	P	PU	36 Partly delivered III
D4	Next-generation microkelvin facility for access service at ULANC (Task 3)	JRA1	ULANC	30	P	PU	36 Partly delivered III
D1	Analysis of the combined ex-chip and on-chip filter performance (Task1)	JRA2	AALTO	6	R	PU	18 Delivered I
D2	Demonstration of sub-10 mK electronic bath temperature of a	JRA2	CNRS	24	R	PU	30 Delivered II

	nano-electronic tunnel junction device achieved by the developed filtering strategy (Task 1)						
D3	Analysis of sub-10 mK nano-cooling techniques including traditional N-I-S cooler with low T_c & quantum dot cooler (Task 2)	JRA2	AALTO	6	R	PU	24 Partly delivered II Delivered III
D4	Demonstration of sub-10 mK nanocooling with a N-I-S junction (Task 2)	JRA2	CNRS	24	R	PU	48 Partly delivered II Delivered III
D5	Demonstration of 300 mK to about 50 mK cooling of a dielectric platform (Task 3)	JRA2	AALTO	26	R	PU	36 Partly delivered II Partly delivered III
D6	Demonstration of cooling-based improved sensitivity of a quantum detector (Task 3)	JRA2	RHUL	9	R	PU	48 Partly delivered II Delivered III
D1	Report on microfabricated silicon vibrating wires tested in superfluid 3He at 100 μK	JRA3	CNRS	3	R	PU	48 Partly delivered II Delivered III
D2	Publication on vortex creation in superfluid 3He	JRA3	ULANC	20	R	PU	24, 36 Delivered II
D3	Publication on 2D defects	JRA3	ULANC	18	R	PU	36 Delivered III
D4	Report on a quantum model of a hydrodynamic Black Hole analogue	JRA3	AALTO	12	R	PU	48 Delivered III
D5	Publication on Q-balls in superfluid ^{3}He and their spin relaxation properties	JRA3	CNRS	9	R	PU	48 Delivered III
D6	Report on state-of-the-art particle detector with superfluid ^{3}He as target material	JRA3	CNRS	8	R	PU	48 Delivered III
D7	Report on the determination of the excitation spectrum in liquid ^{3}He	JRA3	CNRS	8	R	PU	48 Delivered III
D1	Report on the contactless decoherence and heat-capacity measurement method (Task 1)	JRA4	HEID	21	R	PU	18, 36
D2	Report on the performance of high resolution μSQUID scanning magnetometer (Task 1)	JRA4	CNRS	12	R	PU	48 Delivered III
D3	Report on the performance of microcoils coupled to low inductance SQUIDs (Task 2)	JRA4	RHUL	18	R	PU	12, 24 Delivered I,II
D4	Report on the performance of wide bandwidth SQUIDs (Task 2)	JRA4	RHUL	15	R	PU	18, 36 Delivered II
D5	Report on current sensing noise thermometer for ultra-low temperature (Task 3)	JRA4	RHUL	15	R	PU	12, 24 Delivered II

D6	Rep. on 195Pt-NMR thermometer for ultra low temperatures (Task 3)	JRA4	PTB	8	R	PU	18, 36 Delivered II
D7	Report on metrologically compatible CBT sensor (Task 3)	JRA4	AALTO	6	R	PU	12, 24 Delivered II
D8	Report on 10 mK (100 μK) GaAs quantum dot thermometer (Task 3)	JRA4	BASEL	10	R	PU	12, 24 Delivered I,II (36, 48) Delivered III

Explanations:

PU = Public
PP = Restricted to other programme participants (including the Commission Services).
RE = Restricted to a group specified by the consortium (including the Commission Services).
CO = Confidential, only for members of the consortium (including the Commission Services).
Make sure that you are using the correct following label when your project has classified deliverables.
EU restricted = Classified with the mention of the classification level restricted "EU Restricted"
EU confidential = Classified with the mention of the classification level confidential " EU Confidential "
EU secret = Classified with the mention of the classification level secret "EU Secret "

I = reported in 18-month Periodic Review Report (dated 29 Oct, 2010)
II = reportedin 36-month Periodic Review Report (dated 6 June, 2012)
III = reported in the present 54-month Periodic Review Report (dated 30 Nov, 2013)

Milestones – Microkelvin Annex I (version of Sep 2011)

Table of milestones

Milestone number	Milestone name	WPs no's	Lead benefi-ciary	Delivery date From Annex I	Comments
M1	MICROKELVIN kick-off meeting	NA1	AALTO	1	Web-site news Achieved I
M2	Management Committee email meetings	NA1	AALTO	1, 4, 8,..	Web-site news Achieved I, II, III
M3	General Assembly and Advisory Board meetings	NA1	AALTO	1, 12, 24, 36	Web-site news Achieved I, II, III
M4	Periodic project reviews	NA1	AALTO	18, 36, 54	Web-site news Achieved I, II, III
M1	Appointment of SP	NA2	AALTO	1	Web-site news Achieved I
M2	Meetings of Selection Panel (email meetings)	NA2	AALTO	1, 13, 37 (6, 12, 18…)	Web-site news Achieved I, II, III
M1	Meetings of Dissemination Committee	NA3	CNRS	1, 13, 37	Web-site news Achieved I, II, III
M1	Meeting for the creation of ECS	NA4	CNRS	10	Web-site news Achieved I
M2	Formal creation of Third-Countries Associated Low Temperature Network	NA4	CNRS	10	Web-site news Achieved III
M3	Statutes of Distributed European Microkelvin Laboratory	NA4	ULANC	48	Report Achieved III
M1	Advanced filtering and isolation system designed and built	JRA1, Task 1	ULANC	18	Prototype ready Achieved I, II, III
M2	High conductivity cooled links to nanocircuits designed and tested	JRA1, Task 1	ULANC	30	Prototype ready Achieved II
M3	Nanocircuit stage installed in an access refrigerator	JRA1, Task 1	ULANC	36	Prototype running flawlessly Achieved III
M4	Phonon temperature on nanoscale silicon membrane measured	JRA1, Task 1	ULANC	36	Demonstration Achieved III
M5	Pulsed-tube based dilution refrigerator and conventional (miniature nuclear) stage ready for integration at CNRS (AALTO)	JRA1, Task 2	CNRS (AALTO)	12 (18)	Prototypes running flawlessly Partly achieved III
M6	The compact microkelvin refrigerator at CNRS (AALTO) ready for access service	JRA1, Task 2	CNRS (AALTO)	24 (36)	Prototypes ready Partly achieved III
M7	Complete the vibration isolation platform	JRA1, Task 3	ULANC	6	Prototype ready Achieved I
M8	Dilution refrigerator built, installed and tested	JRA1, Task 3	ULANC	24	Prototype running flawlessly Partly achieved III
M9	Nuclear stage tested and running in dilution refrigerator	JRA1, Task 3	ULANC	30	Prototype running flawlessly In progress at 56 mo
M1	Choice of the thermalization strategy	JRA2, Task 1	BASEL	12	Tests completed Achieved I
M2	Choice of the ex-chip filtering technique	JRA2, Task 1	BASEL	18	Tests completed Achieved I
M3	Choice of the superconducting material with a lower T_C	JRA2, Task 2	CNRS	24	Tests completed Achieved II

M4	Precise definition of the QD cooler geometry and materials	JRA2, Task 2	SNS	24	Tests completed Achieved II
M5	Design of membrane patterning and microcoolers	JRA2, Task 3	AALTO	18	Report Achieved I
M6	Delivery of the first membranes to the end users	JRA2, Task 3	AALTO	36	Prototype running flawlessly Achieved II
M1	Determination of the energy released by a vortex tangle with known line density	JRA3, Task 1	ULANC	12	Test completed Achieved I
M2	Measurement of the dissipation when a vortex tangle is established	JRA3, Task 1	ULANC	24	Report Achieved I
M3	A precise determination of the effect of pressure on vortex creation via the dynamics of the second-order phase transition	JRA3, Task 1	ULANC	30	Report Achieved II
M4	Identification of the topological defects left after brane (phase boundary) annihilation	JRA3, Task 2	ULANC	24	Report In progress at 56 mo
M5	Observation of several "cosmological defects" obtained in a microkelvin multi-cell detector	JRA3, Task 2	ULANC	30	Test completed Achieved III
M6	Development of a Black-Hole analogue in a rotating system with an A-B boundary	JRA3, Task 3	AALTO	48	Report Achieved III
M7	Test of the Unruh effect from rapid motion of a phase boundary	JRA3, Task 3	AALTO	36	Test completed Achieved III
M8	Test of the percolation theory of the A-B transition	JRA3, Task 3	AALTO	36	Test completed Achieved III
M9	Observation of the interaction between two independent precessing Q-balls	JRA3, Task 4	CNRS	30	Report Achieved III
M10	Creation of excited modes of a "Q-ball" under radial squeezing by rotation	JRA3, Task 4	CNRS	36	Test completed Achieved III
M11	Realization of microkelvin thermometry based on "Q-ball" behaviour	JRA3, Task 4	CNRS	42	Report Achieved III
M12	Measurement of enhancement in the Q-ball spin relaxation rate from surfaces and vortices	JRA3, Task 4	AALTO ULANC	42	Report Achieved III
M13	Microfabricated silicon vibrating wires tested in superfluid ^{3}He below 100 μK in laboratory conditions	JRA3, Task 5	CNRS	42	Report Achieved III
M14	Neutron scattering measurement of ^{3}He excitation spectrum at intermediate energies	JRA3, Task 5	CNRS	42	Report Achieved III
M1	Contactless setup to investigate decoherence (specific heat) of solids	JRA4, Task 1	HEID	18 (36)	Prototype running flawlessly Achieved I, II
M2	Realization of a high resolution μSQUID scanning magnetometer	JTA4, Task 1	CNRS	42	Prototype running flawlessly Achieved II, III
M3	SQUID NMR detection of nano-scale 3He samples at sub-mK temperatures	JRA4, Task 2	RHUL	12	Prototype running flawlessly Achieved I, II, III
M4	Demonstration of NMR signals from 10 x 100 micron 3He samples	JRA4, Task 2	RHUL	36	Prototype running flawlessly Achieved III
M5	Demonstration of NMR at frequencies up to 100 MHz with wide bw SQUID amplifier	JRA4, Task 2	RHUL	42	Prototype running flawlessly Achieved III

M6	Realization and measurement of 10 mK CBT sensor	JRA4, Task 3	AALTO	15	Prototype running flawlessly Achieved I
M7	Design and testing to 200 μK of noise thermometer optimized for metrological measurements	JRA4, Task 3	RHUL	24	Prototype running flawlessly Achieved II, III
M8	Operation of GaAs quantum dot thermometer at 10 mK	JRA4, Task 3	BASEL	24	Prototype running flawlessly Achieved II, III
M9	Design and test of a ^{195}Pt-NMR thermometer down to temperatures of 10 μK	JRA4, Task 3	PTB	36	Prototype running flawlessly Achieved II
M10	New temperature scale for ultra low temperatures	JRA4, Task 3	PTB	42	Prototype running flawlessly Achieved II, III

Explanations:

I = reported in 18-month Periodic Review Report (dated 29 Oct, 2010)
II = reportedin 36-month Periodic Review Report (dated 6 June, 2012)
III = reported in the present 54-month Periodic Review Report (dated 30 Nov, 2013)

3.4 Publications

Cumulative list of all Microkelvin publications in scientific peer reviewed journals (with explicit acknowledgement to EU grant 228464 Microkelvin):

MICROKELVIN – CUMULATIVE PUBLICATION LIST

Publications carrying an explicit acknowledgement to Microkelvin grant #228464 under the EU FP7 framework of research infrastructure programmes

JRA1: Opening the microkelvin regime to nanoscience

1. A.C. Clark, K.K. Schwarzwälder, T. Bandi, D. Maradan, D. M. Zumbühl, *Method for cooling nanostructures to microkelvin temperatures,* Rev. Sci. Instrum. **81**, 103904 (2010) [URL]
2. L. Casparis, M. Meschke, D. Maradan, A.C. Clark, C. Scheller, K.K. Schwarzwälder, J.P. Pekola, D.M. Zumbühl, "*Metallic Coulomb Blockade Thermometry down to 10 mK and below*", Rev. Sci. Instr. **83**, 083903 (2012) <http://rsi.aip.org/resource/1/rsinak/v83/i8/p083903_s1>
3. H. Ftouni, C. Blanc, A. Sikora, J. Richard, M. Defoort, K. Lulla, E. Collin, O. Bourgeois, *Thermal conductivity measurement of suspended Si-N membranes from 10 K to 275 K using the 3w-Völklein method*, J. Phys. Conf. Series **365**, 012109 (2012)
4. G. Batey, A. Casey, M.N. Cuthbert, A.J. Matthews, J. Saunders, A. Shibahara, *A microkelvin cryogen-free experimental platform with integrated noise thermometry,* New J. Phys. **15**, 113034 (2013) [URL]; arXiv: 1307.7049 (2013)
5. C.P. Scheller, T.-M. Liu, G. Barak, A. Yacoby, L.N. Pfeiffer, K.W. West, D.M. Zumbühl, *Evidence for helical nuclear spin order in GaAs quantum wires*, preprint arXiv:1306.1940
6. F. Blondelle, E. Collin, H. Godfrin, *Electrical conductance of bolted copper joints for cryogenic applications*, J. Low Temp. Phys., Microkelvin Proceedings, submitted (2013)

JRA2: Ultra low temperature nanorefrigerator

1. S. Gasparinetti, F. Deon, G. Biasiol, L. Sorba, F. Beltram, F. Giazotto, *Probing the local temperature of a 2DEG microdomain with a quantum dot: measurement of electron-phonon interaction*, Phys. Rev. B **83**, 201306(R) (2011)
2. J.T. Muhonen, M.J. Prest, M. Prunnila, D. Gunnarsson, V.A. Shah, A. Dobbie, M. Myronov, R.J.H. Morris, T.E. Whall, E.H.C. Parker, D.R. Leadley, *Strain dependence of electron-phonon energy loss rate in many-valley semiconductors,* Appl. Phys. Lett. **98**, 182103 (2011)
3. J.T. Peltonen, P. Virtanen, M. Meschke, J.V. Koski, T.T. Heikkilä, J.P. Pekola, *Thermal Conductance by the Inverse Proximity Effect in a Superconductor,* Phys. Rev. Lett. **105**, 097004 (2010) [URL]
4. J.P. Pekola, V.F. Maisi, S. Kafanov, N. Chekurov, A. Kemppinen, Yu.A. Pashkin, O.-P. Saira, M. Möttönen, J.S. Tsai*, Environment-Assisted Tunneling as an Origin of the Dynes Density of States,* Phys. Rev. Lett. **105**, 026803 (2010) [URL]
5. F. Dahlem, P. Achatz, O.A. Williams, D. Araujo, E. Bustarret, H. Courtois, *Spatially Correlated Microstructure and Superconductivity in Polycrystalline Boron-Doped Diamond,* Phys. Rev. B **82**, 033306 (2010) [URL]
6. F. Dahlem, T. Kociniewski, C. Marcenat, A. Grockowiak, L. Pascal, P. Achatz, J. Boulmer, D. Debarre, T. Klein, E. Bustarret, H. Courtois, *Subkelvin tunneling spectroscopy showing Bardeen-Cooper-Schrieffer superconductivity in heavily boron-doped silicon epilayers,* Phys. Rev. B **82**, 140505 (2010) [URL]

7. R. Barends, N. Vercruyssen, A. Endo, P.J. de Visser, T. Zijlstra, T.M. Klapwijk, P. Diener, S.J.C. Yates, J.J.A. Baselmans, *Minimal resonator loss for circuit quantum electrodynamics,* Appl. Phys. Lett. **97**, 023508 (2010) [URL]

8. R. Barends, N. Vercruyssen, A. Endo, P.J. de Visser, T. Zijlstra, T.M. Klapwijk, J.J.A. Baselmans, *Reduced frequency noise in superconducting resonators,* Appl. Phys. Lett. **97**, 033507 (2010) [URL]

9. F. Dahlem, P. Achatz, O.A. Williams, D. Araujo, H. Courtois, E. Bustarret, *Nanocrystalline boron-doped diamond films, a mixture of BCS-like and non-BCS-like superconducting grains*, Physica Status Solidi (A) **207**, 2064 (2010)

10. J. T. Peltonen, J. T. Muhonen, M. Meschke, N. B. Kopnin, J. P. Pekola**,** *Magnetic-field-induced stabilization of nonequilibrium superconductivity in a normal-metal/insulator/superconductor junction***,** Phys. Rev. B **84**, 220502(R) (2011)

11. M.J. Prest, J.T. Muhonen, M. Prunnila, D. Gunnarsson, V A. Shah, J.S. Richardson-Bullock, A. Dobbie, M. Myronov, R.J.H. Morris, T.E. Whall, E.H.C. Parker, D.R. Leadley, *Strain enhanced electron cooling in a degenerately doped semiconductor,* Applied Physics Letters **99**, 251908 (2011)

12. M. Meschke, J. T. Peltonen, J. P. Pekola, F. Giazotto, *Tunnel Spectroscopy of a Proximity Josephson Junction,* Physical Review B **84**, 214514 (2011)

13. J. V. Koski, J. T. Peltonen, M. Meschke, J. P. Pekola, *Laterally proximized aluminum tunnel junctions*, Applied Physics Letters **98**, 203501 (2011)

14. N. Vercruyssen, R. Barends, T. M. Klapwijk, J. T. Muhonen, M. Meschke, and J. P. Pekola, *Substrate-dependent quasiparticle recombination time in superconducting resonators,* Appl. Phys. Lett. **99**, 062509 (2011)

15. H.Q. Nguyen, L.M.A. Pascal, Z.H. Peng, O. Buisson, B. Gilles, C.B. Winkelmann, H. Courtois, *Etching suspended superconducting hybrid junctions from a multilayer,* Appl. Phys. Lett. **100**, 252602 (2012), arXiv:1111.3541v1 (2011)

16. Juha T. Muhonen, Matthias Meschke, Jukka P. Pekola, *Micrometre-scale refrigerators,* Rep. Prog. Phys. **75**, 046501 (2012)

17. N. Vercruyssen, T.G.H. Verhagen, M.G. Flokstra, J.P. Pekola, T.M. Klapwijk, *Evanescent states and non-equilibrium in driven superconducting nanowires*, Phys. Rev. B **85**, 224503 (2012)

18. Sukumar Rajauria, L. M. A. Pascal, Ph. Gandit, F. W. J. Hekking, B. Pannetier, H. Courtois*, Efficiency of quasiparticle evacuation in superconducting devices,* Phys. Rev. B **85**, 020505(R) (2012)

19. E.F.C. Driessen, P.C.J.J. Coumou, R.R. Tromp, P.J. de Visser, T.M. Klapwijk, *Disordered TiN and NbTiN s-wave superconductors probed by microwave electrodynamics*, Phys. Rev. Lett. **109**, 107003 (2012), arXiv:1205.2463v1 [cond-mat.supr-con]

20. F. Deon, V. Pellegrini, F. Giazotto, G. Biasiol, L. Sorba, F. Beltram, *Proximity effect in a two-dimensional electron gas probed with a lateral quantum dot,* Phys. Rev. B **84**, 100506 (2011)

21. F. Giazotto, F. Taddei, *Hybrid superconducting quantum magnetometer,* Phys. Rev. B **84**, 214502 (2011)

22. F. Giazotto, M.J. Martinez-Perez, *The Josephson heat interferometer*, Nature **492**, 401 (2012), arXiv:1205.3353 <http://arxiv.org/abs/1205.3353>

23. F. Giazotto, M.J. Martinez-Perez, *Phase-controlled superconducting heat-flux quantum modulator,* Appl. Phys. Lett. **101**, 102601 (2012), arXiv:1205.2973 http://arxiv.org/abs/1205.2973

24. F. Giazotto, F.S. Bergeret, *Phase-tunable colossal magneto-heat resistance in ferromagnetic Josephson thermal valves*, Appl. Phys. Lett. **102**, 132603 (2013); (arXiv:1211.6570), http://arxiv.org/pdf/1211.6570.pdf

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26. M.J. Martinez-Perez, F. Giazotto, *Fully-balanced heat interferometer*, Appl. Phys. Lett. **102**, 092602 (2013); (arXiv:1210.7187) http://arxiv.org/pdf/1210.7187.pdf

27. H.S. Knowles, V.F. Maisi, J.P. Pekola, *Probing quasiparticle excitations in a hybrid single electron transistor,* Appl. Phys. Lett. **100**, 262601 (2012)

28. S. Gasparinetti, P. Solinas, Y. Yoon, J.P. Pekola, *Single Cooper-pair pumping in the adiabatic limit and beyond,* Phys. Rev. B **86**, 060502 (2012)

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4. Proceedings of the International Conference on Low Temperature Detectors LTD 14 in Heidelberg, 1-5 Aug, 2011; J. Low Temp. Phys. **167**, ¾ (2012), Editors L. Gastaldo, Andreas Fleischmann, and Christian Enss

5. Proceedings of the International Quantum Fluids and Solids Conference QFS 2012 in Lancaster, 15-21 Aug, 2012; J. Low Temp. Phys. **171**, 3/4 and 5/6 (2013), Editor Shaun Fisher

6. Microkelvin Proceedings, issue in J. Low Temp. Phys. under the title *"Ultra-low temperatures and nanophysics - ULTN 2013",* to appear in 2014, Editors Matti Krusius and Jukka Pekola

4 Appendices

1. Microkelvin General Assembly on Friday, 17 August, 2012, in Charles Carter building, Lancaster University, during QFS-2012 International Symposium on Quantum Fluids and Solids.
2. Microkelvin General Assembly on Thursday, 17 January, 2013, conducted as an e-mail meeting.
3. Microkelvin General Assembly on Thursday, 12 September, 2013, in Sannäs Convention Centre during the Microkelvin 2013 Workshop.
4. Report from June 2013 of the Low Temperature Section of the European Physical Society – Condensed Matter Division
5. Ultra-low temperature forecast report: Road Map to future European low temperature research
6. Consultation questionnaire of the EU Commission about the future need of European infrastructure programmes (October 2012).
7. EU Commission assessment and results of the consultation on the need of future European infrastructure programmes (March 2013).

European Microkelvin Collaboration

Microkelvin General Assembly

Meeting at the International Conference on Quantum Fluids and Solids – QFS2012
Friday, 17 August, 2012, at 20:30
lecture theatre in Charles Carter building (opposite the George Fox building)
Lancaster University

Members present at the meeting (in red absences**):**

George Pickett ULANC (Chair)
Shaun Fisher ULANC (invited)
Rob Blaauwgeers BLUEFORS
Christian Enss HEID
Francesco Giazotto SNS
Henri Godfrin CNRS
Teun Klapwijk DELFT
Matti Krusius AALTO (Coordinator)
Tjerk Oosterkamp UL
John Saunders RHUL
Thomas Schurig PTB
Peter Skyba SAS
Dominik Zumbuhl BASEL

Not represented: BLUEFORS, SNS, DELFT, UL, SAS, and BASEL

AGENDA

1. ***Amendment Request #3***. In order to secure time for finishing the planned Trans-National Access programme, a request for a 6-month extension of the grant period was submitted to the EU Project Office in June 2012. The extension comes with no additional funding. Approval has not been granted yet, a report about the current status is given (by Krusius).
2. ***Coordination budget***. Summary of the current status of the coordination budgets for organizing meetings and workshops: 1) at Aalto the coordination budget shows a deficit of 11 000 Euros (report: Krusius), 2) at CNRS-Grenoble (report: Godfrin) and 3) in Lancaster (report: Fisher) the budgets might still support modest new initiatives.
3. ***2012 PTB Workshop budget***. Report on the planned workshop and its budget (report: Schurig). How will the financing be organized (reports: Godfrin, Fisher)?
4. ***Future items in coordination budget.*** Are there further meetings or workshops for which Microkelvin funding should be reserved? Final Microkelvin User and Review Meeting in October 2013: dates, venue, organizer, budget, proceedings are to be decided (Krusius, Fisher)?
5. ***Deadlines in JRA.*** The proposed extension of the grant period does not affect the timetable for milestones and deliverables. Are we going to achieve these as foreseen (with roughly 80 % success rate as in all earlier cases)? In particular, what is the situation with respect to the construction of new refrigerators which are worked on in JRA1 and which should become available for general access within the Microkelvin consortium?

6. ***TNA services***. Summary of access months at the 3 access-giving sites: 1) at Aalto the target of 27 visitor months will be exceeded in September 2012 (Krusius), 2) at CNRS-Grenoble the planned total is at 15.5 months (Godfrin) and 3) in Lancaster at 5.8 months (Fisher). Discussion about actions to achieve the targeted visitor months and to maximize the use of the TNA funds during the remaining 13 months.
7. ***Management budget for the 6*-month extension in 2013.**
8. ***Promotion of Microkelvin concept for Horizons 2020***. Distribution of the Microkelvin promotion document (prepared by George Pickett). Reports about discussions with national representatives who are involved in the decision making for the EU Framework Horizons 2020. Discussion about further actions.
9. ***News from the EU Project Office***.
10. ***Collaborative projects with industrial partners***.
11. ***Any other business*.**
12. ***Closing of meeting*.**

Matti Krusius
Coordinator

George Pickett
Chairman

European Microkelvin Collaboration

Microkelvin General Assembly

Meeting at the International Conference on Quantum Fluids and Solids – QFS2012
Friday, 17 August, 2012, at 20:30
Charles Carter building, Lancaster University

Members present at the meeting (in red absences):

George Pickett ULANC (Chair)
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Matti Krusius AALTO (Coordinator)
Tjerk Oosterkamp UL
John Saunders RHUL
Thomas Schurig PTB
Peter Skyba SAS
Dominik Zumbuhl BASEL

Not represented: BLUEFORS, SNS, DELFT, UL, SAS, and BASEL

MINUTES OF GENERAL ASSEMBLY

1. ***Amendment Request #3***. The Request is currently processed at the EU Project Office, but because of vacations progress has been held up. We are proceeding with the assumption that a 6-month extension until the end of September 2013 will ultimately be granted, as indicated by the EU Project Officer. This will have the following implications:
   - visits within the TNA programmes can be hosted until end of September 2013
   - meetings within the coordination budget can be organized until end of September 2013
   - final Review and Users Meeting will be organized in September 2013
   - deadlines of the JRA work packages are not postponed; the RTD budgets reserved for these activities have to be closed at the end of March 2013.
2. ***Coordination budget***. The coordination budget of Aalto has been exceeded by 11 000 Euros, in Lancaster the coordination funds will be used up if the current plan of meetings is carried through, while in Grenoble an uncommitted reserve exists. The Lancaster budget will cover for the commitments to the QFS-2012 and EPS-CMD24 Conferences as well as for the final Review and Users Meeting in September 2013. At the time of the GA meeting the amount of uncommitted funds in the Grenoble budget is not accurately known.
3. ***2012 PTB Workshop***. The PTB workshop in December 2012 (see announcement in addenda) asks for travel and accommodation support for its Microkelvin participants. This money will come from the Grenoble budget.
4. ***Future items in coordination budget.*** No further commitments are imminent, but Microkelvin makes an effort to respond to new modest initiatives as needed. The final Review and Users Meeting will be paid from the Lancaster coordination budget. The Meeting will take place in

September 2013, unless a permission is granted to postpone it until later in October. This would be preferable to leave more time between the QFS2013 Conference Aug 1 – 6 and the Microkelvin Workshop. The venue will be either Helsinki or Lancaster. If additional reserves exist in the coordination budget, preference is given to topical meetings on each of the four JRA packages. These can be organized during late 2012 or early 2013 with 1 – 3 day duration.

5. ***Deadlines in JRA.*** The proposed extension of the grant period does not affect the timetable for milestones and deliverables. Can we expect to achieve these deadlines as foreseen, with roughly 80 % success rate as has been the case in our earlier Periodic Project Reviews? The construction of new refrigerators in JRA1, to be readied for general vsitor access within the Microkelvin consortium, is the most delicate case. This is because of delays in equipment deliveries from various sub-contractors (such as suppliers of liquid helium dewars or superconducting magnets). The general opinion was that we are still well on track, in spite of delays, and will be able to finish the construction work in time.
6. ***TNA services.*** Activity in the TNA programmes of both Grenoble and Lancaster will be stepped up. Permission will be requested from the EU Project Office to transfer part of the funding for TNA to Aalto so that visitor programmes there can be continued beyond September 2012.
7. ***Management budget for the 6-month extension in 2013.*** The budget for managing the Microkelvin collaboration will be exceeded if the request for the 6-month extension of the grant period is accepted. When this happens, the management deficit will be discussed with the EU Project Office, to locate a budget item from where a sum of order 30 000 Euros can be transferred for management.
8. ***Future of Microkelvin.*** The collaboration has started preparations for the time after the finish of the current grant period. A roadmap of the steps to be taken has been drafted by Professor Enss. The plan calls for establishing a joint European low temperature laboratory without walls which will continue working for the goals of the Microkelvin Project as much as possible in the absence of a common grant. The Collaboration will speak out for the need to acquire funding for the common cause and prepare applications for a new grant, to support the infrastructure and the services for European research in need of the lowest temperatures.
9. ***News from the EU Project Office***. No urgent matters needed to be discussed.
10. ***Collaborative projects with industrial partners***. A meeting with industrial partners is planned to be organized by Professor Godfrin in Paris in late 2012 or early 2013. A list of the companies and their invitations is in preparation.
11. ***Any other business.*** Because of the late hour and early start of the Conference programme next morning, no further topics were taken up.
12. ***Closing of meeting.***

Lancaster August 17, 2012

Matti Krusius
Coordinator

George Pickett
Chairman

Addenda:

1. **The case for the European Microkelvin network.** A statement promoting the need to continue support for maintaining the European research infrastructure and the further development of the microkelvin regime (draft by George Pickett).
2. **Towards a European Ultra-Low-Temperature Laboratory.** A roadmap for starting a Europe-wide collaboration between existing Low Temperature Laboratories (draft by Christian Enss).
3. Announcement of the workshop **"Physics and Metrology at Low Temperatures"** to be organized by the Physikalisch-Technische Bundesanstalt in Berlin 13 – 14 December, 2012.

THE CASE FOR THE EUROPEAN "MICROKELVIN" NETWORK

The ever-increasing complexity of current electronics is rapidly bringing us to the limit when typical component sizes finally reach atomic dimensions and no further miniaturization is possible. At that point we will need something entirely new.

Electronics based on coherent electron behaviour promises to provide the new way forward. In nanocircuits, the electrons can behave coherently over the circuit dimension and thus follow the quantum rules of wave motion rather than Ohm's law. This will open up a whole range of new devices based on quantum electronics.

The major difficulty standing in way of this advance is the achievement of the coherence needed. The electrons must be able to move through the circuit without scattering. But to achieve scattering lengths larger than the sample size, we need to minimise both impurity scattering and thermal scattering. The former demands extremely high purity materials which we already have the technology to produce. The latter, to limit *thermal* scattering, requires low temperatures. For this, even at the more easily accessible millikelvin temperatures, the circuits need to be of nanoscale.

This severe size restriction provides the motivation for exploiting the implicit imperative in nanoscience that there are enormous advantages to be gained by working at much lower microkelvin temperatures. Despite this clear demand, nanoscience in general is inhibited from advancing below the millikelvin temperature regime by a lack of appropriate expertise and facilities.

In Europe we *already* have the greatest concentration of microkelvin infrastructure and expertise in the world, developed by our quantum-fluids community. Over the last three years the MICROKELVIN network has been putting this existing infrastructure at the disposal of the wider nanoscience community, developing together new techniques to bring coherent structures into a completely new temperature regime. This is leading to the creation of a European microkelvin "laboratory without walls" to exploit this necessary work. The activity is also encouraging European commercial interest in the opportunities in this new emerging area which should give European technology a lead.

The UK has two microkelvin facilities intimately associated with this work, and both taking leading roles in the endeavour. (Replace with your own appropriate "national" comment to suit).

We are asking you, as a decision maker in influencing the programme of Horizons 2020, to be aware that this vitally important activity is continued by being included in the future road map.

The advance toward smaller sizes and lower temperatures is inevitable in the long term, but the European lead in the microkelvin field gives us now the opportunity to be first with this new development.

The infrastructure is now coming together. The need is manifest. We simply have to ensure that the opportunities continue in Europe.

Background Information

Research at the frontier near absolute zero has long been a powerhouse for generating ideas in physics and beyond, from concepts in particle physics to practical ultrasensitive devices for application in technology and medicine. One in four Nobel prizes over the last century has gone to a low-temperature physicist. In the same period the lowest accessible temperatures have fallen by 10 orders of magnitude (4 K to 100 pK) far exceeding the rate of miniaturization of microcircuits (Moore's law) over recent decades. Today some 250 (1000) low temperature research groups (researchers) in Europe work at sub-Kelvin temperatures. Ten major companies and 15 SME's have cryoengineering groups. Their total annual turnover is about 1 000 000 000 € and 50 000 000 €, respectively. There is a European need for around 100 low temperature scientist and cryoengineers per year.

While Europe is the current world leader in microkelvin physics, in terms of research workers, records held and research output, the effort is fragmented between universities and government laboratories and lacks the critical mass for high quality research and training programs. Industrial exploitation is also very low with no commercially available refrigerators able to reach the microkelvin regime. Only 20 laboratories worldwide can build their own microkelvin refrigerators with 12 located in Europe, almost all of which are involved in this action. Many current world low temperature records are held by partners of the MICROKELVIN collaboration.

Recently interest in the sub 10 mK regime has increased, with the emergence of two frontiers, nanoscale dimensions and microkelvin temperatures. Nanocircuits behave as quantum objects which can be incorporated *directly* into conventional electronic circuits, thus allowing engineering to tap directly this whole new range of quantum possibilities with clearly very great economic implications. To make full advantage of such systems we need to increase the coherence time of the nanocircuits. This obviously requires increased purity of the materials, improved architecture of the circuits, but also a large reduction in the influence of the surrounding thermal 'outside world'. Consequently, operation at lower temperatures has a great impact on this field.

In summary, more efficient research work in the microkelvin regime, although demanding, will open new opportunities. This demands a higher level of networking and integration of the European low-temperature community. The MICROKELVIN Collaboration is opening the microkelvin temperature regime to a wider range of scientists. It will counteract European fragmentation, bring nanoscience into the microkelvin arena, and stimulate industrial entry into the field.

Memorandum of Understanding

TOWARDS A EUROPEAN ULTRA-LOW-TEMPERATURE LABORATORY

Research at the frontier near absolute zero has long been a powerhouse of new ideas in physics and beyond. Physics at ultralow temperatures requires elaborate large-scale infrastructure that is difficult to build and maintain by a single academic research unit. Over the past two decades several groups in Europe have established large-scale cryogenic facilities that are unique on the worldwide scale. Today, several of these laboratories are leading the research in the fundamental physics of quantum fluids and solids, as well as in nano-science at ultra-low temperatures. In order to preserve and further develop these special complementary infrastructures we agree to establish a unified *European Ultralow Temperature Laboratory* **(EUTL).** As a first step towards this unified laboratory without walls, the *European Microkelvin Collaboration* has formed a close coalition among the leading European ultra-low temperature laboratories, with the purpose to develop together common infrastructures and to open up the microkelvin regime to nano-sciences. Within this Microkelvin Collaboration three of the twelve partner laboratories were chosen to provide trans-national access to external users of their facilities. In addition, front-line research in the form of joint projects have been carried out among the partner laboratories. As a further step, the Collaboration aims to formally establish EULT, as a distributed infrastructure with complementary instrumentation.

The European Ultralow Temperature Laboratory will have the following attributes:

- It gives European research wide open access to its unique facilities. A scientific board will steer the access policy and handle the applications.
- It will operate as a close and formal collaboration of the individual units without establishing an administrative superstructure above them. In this way high flexibility can be maintained by obtaining maximum synergy effects.
- The individual units of the unified laboratory work closely together to develop new instrumentation and cryogenic techniques. They collaborate in graduate student education and establish a flexible exchange program for scientists and students between the units.
- The units will carry out joint research projects and will have regular collaboration meetings. They will discuss and decide on a common research roadmap for microkelvin physics on a biannual basis.
- The members of the EUTL jointly administer the European funding to maintain and develop the infrastructure of the units, as well as for international access, scientific exchange and joint research projects.

The institutions signing this memorandum of understanding aim to establish The European Ultralow Temperature Laboratory by 2014 under the umbrella of the European Framework Programme HORIZON 2020.

Basel, Berlin, Grenoble, Heidelberg, Helsinki, Kosice, Lancaster, London, ...

Physics and Metrology at Low Temperatures

13-14 December 2012
Berlin

Physikalisch-Technische Bundesanstalt
www.ptb.de/berlin

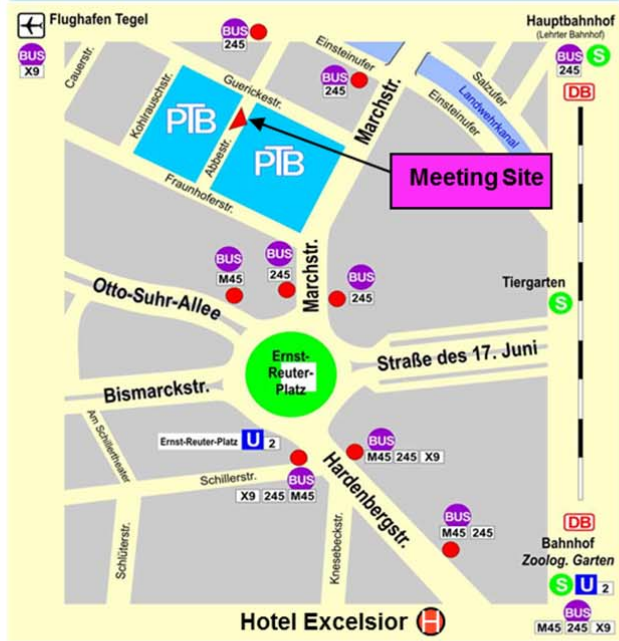
welcome to the
European Microkelvin Collaboration

CAPACITIES

PTB 125 Jahre genau

HELMHOLTZ ZENTRUM BERLIN
für Materialien und Energie

Access



By train: Berlin Main Station (Hauptbahnhof), take S-Bahn railway S5, S7 or S75 to Zoologischer Garten station. From there it is a 20-min. walk to PTB campus. Subway U2 (destination Ruhleben), buses 145 and 245, and express bus X9 connect to Ernst- Reuter-Platz.

By plane: Berlin-Tegel airport is connected to Ernst-Reuter-Platz and the train station Berlin Zoologischer Garten by express bus X9. The airport Berlin-Schönefeld is connected to the train station Berlin Zoologischer Garten by railway (Regionalexpress) and by the S-Bahn S9.

By car: The PTB campus is located in Berlin's "City West", close to the train station Berlin Zoologischer Garten and the Technical University.

Invitation

13 -14 December 2012
Physikalisch-Technische Bundesanstalt
Campus Berlin

Physics and Metrology at Low Temperatures

The Workshop

25 years ago, the Berlin low-temperature groups at the Physikalisch-Technische Bundesanstalt (PTB), the Hahn-Meitner Institute and the Freie Universität initiated the *Berlin Low-Temperature Colloquium* to strengthen their collaboration and to discuss new developments and trends in low-temperature physics and cryogenic techniques. Several workshops have been held in the framework of this colloquium bringing together experts from academic institutes, universities and industrial companies active in the fields of low-temperature physics and metrology.

Following the low-temperature physics and metrology symposia held by PTB and the Helmholtz Zentrum Berlin HZB (founded by merging the former Hahn-Meitner Institute and BESSY) in May 2007 and December 2009, this workshop is dedicated to this anniversary.

Meanwhile, the *European Microkelvin Collaboration*, a project funded by the European Commission which was introduced in the 2009 workshop by its coordinator Mikko Paalanen, is in its final stages and the workshop will give an opportunity to review and disseminate results obtained so far and to discuss the activities towards creating an integrated European virtual laboratory in microkelvin physics and technology.

This workshop is intended to initiate discussions and networking activities within the European low-temperature community and to identify future demands on low-temperature metrology.

Programme

Scope

- Cooling techniques
- Thermometry
- Sensors
- Quantum gases, fluids and solids
- Magnetism and properties of solids
- Quantum electron transport
- Superconductivity

Presentations

Presentations will be given as talks and posters. If you would like to give a presentation at the workshop, please submit a brief summary to margit.kleinsorge@ptb.de.

Deadline for contributions: 23 November 2012.

Exhibition

In conjunction with the workshop we invite companies concerned with the field of low-temperature technology to exhibit their product portfolio. Please contact the workshop office for more information.

Tentative Schedule

- Workshop starts on Thursday at noon
- Social gathering on Thursday evening
- Presentations continue on Friday
- For those interested in a lab tour and further
- discussions, PTB colleagues are available on Friday

The Venue

The workshop is organized by the Physikalisch-Technische Bundesanstalt (PTB), Germany's National Metrology Institute, and the Helmholtz Zentrum Berlin. It takes place at the historical PTB campus which is located within walking distance of the Kurfürstendamm, a well-known shopping street in central Berlin, and the station Zoologischer Garten, right in the heart of Berlin's “City West”.

---------------------------- Original Message ----------------------------

Subject: Microkelvin General Assembly. e-mail meeting
From: mkrusius@neuro.ltl.hut.fi
Date: Thu, January 17, 2013 2:14 pm
To: enss@kip.uni-heidelberg.de
henri.godfrin@grenoble.cnrs.fr
T.M.Klapwijk@tudelft.nl
J.Saunders@rhul.ac.uk
Thomas.Schurig@ptb.de
skyba@saske.sk
f.giazotto@sns.it
oosterkamp@physics.leidenuniv.nl
rob@BlueFors.com
g.pickett@lancaster.ac.uk
dominik.zumbuhl@unibas.ch
s.fisher@lancaster.ac.uk
Cc: Maria.Douka@ec.europa.eu

MICROKELVIN GENERAL ASSEMBLY
E-mail meeting
Thursday, 17 January, 2013

Members of General Assembly

George Pickett ULANC (Chair) <g.pickett@lancaster.ac.uk>
Rob Blaauwgeers BLUEFORS <rob@BlueFors.com>
Christian Enss HEID <enss@kip.uni-heidelberg.de>
Francesco Giazotto SNS <f.giazotto@sns.it>
Henri Godfrin CNRS <henri.godfrin@grenoble.cnrs.fr>
Teun Klapwijk DELFT <T.M.Klapwijk@tudelft.nl>
Matti Krusius AALTO (Coordinator) <mkrusius@neuro.hut.fi>
Tjerk Oosterkamp UL <oosterkamp@physics.leidenuniv.nl>
John Saunders RHUL <J.Saunders@rhul.ac.uk>
Thomas Schurig PTB <Thomas.Schurig@ptb.de>
Peter Skyba SAS <skyba@saske.sk>
Dominik Zumbuhl BASEL <dominik.zumbuhl@unibas.ch>

cc to Maria Douka (EU Project Officer) <Maria.Douka@ec.europa.eu>

Dear Members of the General Assembly,

In this e-mail session we ask for your opinion on the following proposal:

PROPOSED CHANGE IN MICROKELVIN GRANT PROGRAMME

In view of the large shortfall in completed access months at Lancaster University, 13.5 months of the remaining 20 months of unused access will be transferred to Aalto. In total, Lancaster will remain responsible for half of its original 27-month allocation and Aalto will become responsible for an additional 13.5 months.

APPROVE / DECLINE

Date:
Name:

Explanatory material:

The proposed change to the Microkelvin grant plan will be included in the third amendment if this proposal is approved by the General Assembly. The third amendment asks for a 6-month extension of the grant period and was submitted last June. Its processing at the EU Project Office was temporarily halted, until a decision on the new proposal has been formed.

The new proposal is put forward to make more efficient use of the Microkelvin trans-national access programme. Below are listed (1) the existing plans for future access visits at the Lancaster and Aalto Universities, and (2) brief justifications why part of the remaining Lancaster access resources should be made available at Aalto.

1) PLAN OF ACCESS PROGRAMME

LANCASTER PLAN FOR ACCESS (January 2013)

All visits listed below have been discussed, the application process has been started, but some lengths of stay have to be confirmed.

Stefan Lev (plus student) LMU, Munich Host: Richard Haley	1 week (plus 1 week)	new visitor(s) new project
Manuel Arrayas Universidad Rey Juan Carlos, Madrid Host: Richard Hale	6 weeks	unfinished project
Eddy Collin and/or Henri Godfrin CNRS, Grenoble Host: Shaun Fisher	2 weeks	new visitors new project
Rolf Haug Leibnitz University, Hannover Host: Viktor Tsepelin	6 weeks	new visitors new project
TOTAL	4 months	

AALTO PLAN FOR ACCESS (January 2013)

All of the visits listed below have been discussed and confirmed, but no firm commitments have been made.

Lev Levitin or Andrew Casey Royal Holloway College University of London Host: Vladimir Eltsov	2 weeks	new visitor new project
Alexander Kirste PTB, Berlin Host: Vladimir Eltsov	2 weeks	new visitor new project
Richar Haley Lancaster University Host: Vladimir Eltsov	2 weeks	new visitor new project
Laurent Boué Weizmann Institute, Rehovot Host: Risto Hänninen	2 weeks	new visitor new project
Hayder Salman University of East Anglia Host: Risto Hänninen	2 weeks	new visitor new project
Gil Jannes University of Madrid Host: Grigori Volovik	2 weeks	new visitor unfinished project
Mikhail Katsnelson Radboud University Nijmegen Host: Grigori Volovik	1 week	new visitor new project
Yuri Galperin University of Oslo Host: Nikolai Kopnin	2 weeks	1 week in 2011 unfinished work

Konstantin Arutyunov University of Jyvaskyla Host: Pertti Hakonen	2+2 weeks	new visitor new project
Vera Gramich Universität Ulm Host: Jukka Pekola	3 months	new visitor new project
Asier Ozaeta University of Basque Country Host: Tero Heikkilä	3 months	new visitor new project
TOTAL	11 months	

2) JUSTIFICATION

- Owing to a delayed start, there is unused Microkelvin access time at the University of Lancaster in the amount of 20 months.

- A second reason for the shortfall in access visits to Lancaster is an unforeseen delay in the construction and test programme of the new large-scale microkelvin refrigeration facility. This machine has received many inquiries for nano-device measurements from new users, but it is still undergoing finishing work and running test.

- Because of the limited time left until the end of the project period September 30, 2013, it would be advisable to transfer some of the unused access resources from Lancaster to Aalto, ie. from one of the access providing partners to another.

- The 27-month contingent of access time was used up at Aalto in October, 2012. Owing to a large number of in-house research groups and their heavy involvement in low temperature nanophysics, a need for further access time has appeared at Aalto. To satisfy these needs, a transfer of the unused access time to Aalto would be beneficial.

Matti Krusius
Coordinator, Microkelvin
ph. +358503442578 or +358505747078

Microkelvin General Assembly: motion approved

---------------------------- Original Message ----------------------------
Subject: Microkelvin General Assembly: motion approved
From: mkrusius@neuro.ltl.hut.fi
Date: Fri, January 18, 2013 3:52 pm
To: Maria.Douka@ec.europa.eu
Cc: g.pickett@lancaster.ac.uk
s.fisher@lancaster.ac.uk

Maria Douka, Programme Officer
Microkelvin Project Office
European Commission

Dear Maria,

The proposal to transfer half of the Lancaster Trans-National Access activity to Aalto has been approved by the Microkelvin General Assembly in an e-mail meeting. Ten of the 12 members have supported the motion. There were no notes of rejections.

The transfer of the Trans-National access activity from Lancaster to Aalto will be completed without changes to overall funding, deliverables, or milestones.

With regards
Matti Krusius
Microkelvin Coordinator

RESPONSES FROM GENERAL ASSEMBLY MEMBERS

---------------------------- Original Message ----------------------------
Subject: Microkelvin General Assembly. e-mail meeting - approve motion
From: "Matti Krusius" <mkrusius@neuro.hut.fi>
Date: Fri, January 18, 2013 2:47 pm
To: mkrusius@neuro.hut.fi

MICROKELVIN GENERAL ASSEMBLY
E-mail meeting
Thursday, 17 January, 2013

APPROVE

Date: 18 January, 2013
Name: Matti Krusius

---------------------------- Original Message ----------------------------
Subject: Re: Microkelvin General Assembly. e-mail meeting
From: "Teun Klapwijk - TNW" <T.M.Klapwijk@tudelft.nl>
Date: Fri, January 18, 2013 2:08 pm
To: "Thomas.Schurig@ptb.de" <Thomas.Schurig@ptb.de>
Cc: "Matti Krusius" <mkrusius@neuro.hut.fi>

Agreed,
Teun

---------------------------- Original Message ----------------------------
Subject: RE: Microkelvin General Assembly. e-mail meeting
From: "Saunders, J" <J.Saunders@rhul.ac.uk>
Date: Fri, January 18, 2013 12:39 pm
To: "'Matti Krusius'" <mkrusius@neuro.hut.fi>

Dear Matti
I support this proposal.
John

---------------------------- Original Message ----------------------------
Subject: Re: Microkelvin General Assembly. e-mail meeting
From: Thomas.Schurig@ptb.de
Date: Fri, January 18, 2013 12:35 pm
To: "Matti Krusius" <mkrusius@neuro.hut.fi>

Dear Matti

I support the proposal.

Approve

Jan 18, 2013

Thomas Schurig

****
Dr.sc.nat. Thomas Schurig
Department 7.2 Cryophysics and Spectrometry
Physikalisch-Technische Bundesanstalt
Abbestrasse 2-12
D-10587 Berlin
Office: +49 (0)30 34817290
Fax: +49 (0)30 34817684
****

---------------------------- Original Message ----------------------------
Subject: Re: Microkelvin General Assembly. e-mail meeting
From: "Rob Blaauwgeers" <rob@BlueFors.com>
Date: Fri, January 18, 2013 11:42 am
To: "Matti Krusius" <mkrusius@neuro.hut.fi>

APPROVE

Date: January 18, 2013
Name: Rob Blaauwgeers

--
Dr. Rob Blaauwgeers
BlueFors Cryogenics Oy Ltd
Helsinki, FINLAND

Phone/Fax: +358 (0)9 2245110
Mobile: +358 (0)40 8243181
Email: Rob@BlueFors.com

---------------------------- Original Message ----------------------------
Subject: Re: Microkelvin General Assembly. e-mail meeting
From: "Dominik Zumbuhl" <dominik.zumbuhl@unibas.ch>
Date: Fri, January 18, 2013 11:38 am
To: "Matti Krusius" <mkrusius@neuro.hut.fi>

Dear All

I agree with the proposed changes:

APPROVE
January 18, 2013Dominik Zumbuhl

best regards
Dominik

---------------------------- Original Message ----------------------------
Subject: Re: Microkelvin General Assembly. e-mail meeting
From: "Oosterkamp, T.H." <Oosterkamp@Physics.LeidenUniv.nl>
Date: Thu, January 17, 2013 5:57 pm
To: "Matti Krusius" <mkrusius@neuro.hut.fi>

I approve.
Greetings,
Tjerk Oosterkamp

Leiden University

---------------------------- Original Message ----------------------------
Subject: RE: Microkelvin General Assembly. e-mail meeting
From: "Henri Godfrin" <henri.godfrin@grenoble.cnrs.fr>
Date: Thu, January 17, 2013 3:36 pm
To: "'Matti Krusius'" <mkrusius@neuro.hut.fi>

Dear Matti,

I approve the proposal below.

APPROVE
Date: 17/01/2013
Name: Henri Godfrin

---------------------------- Original Message ----------------------------
Subject: RE: Microkelvin transnational access - from Maria Douka
From: "Fisher, Shaun" <s.fisher@lancaster.ac.uk>
Date: Thu, January 17, 2013 1:25 pm
To: "Matti Krusius" <mkrusius@neuro.hut.fi>
Cc: "Pickett, George" <g.pickett@lancaster.ac.uk>

Hi Matti,

Yes, we are happy with this.

Best wishes,
Shaun Fisher

European Microkelvin Collaboration

MICROKELVIN

General Assembly

Meeting at the 54-month Final Review of the Microkelvin Grant Programme
Thursday, 12 Sep, Sannäs Convention Centre, 21:30

Members present at the meeting:

George Pickett ULANC (Chair)
Rob Blaauwgeers BLUEFORS
Christian Enss HEID
Francesco Giazotto SNS
Henri Godfrin CNRS
Teun Klapwijk DELFT (represented by Nathan Vercruyssen)
Matti Krusius AALTO (Coordinator)
Tjerk Oosterkamp UL
John Saunders RHUL
Thomas Schurig PTB (represented by Joern Beyer)
Peter Skyba SAS
Dominik Zumbuhl BASEL

Not represented: BLUEFORS

Invited: Maria Douka (EU Project Officer)

AGENDA

1. ***54-month Review.*** Summary of achievements and deficiencies. Recommendations for the review to be conducted tomorrow.
2. ***Microkelvin finances.*** Summary of final fiscal situation at different partner institutions, JRA accounts, but in particular coordination accounts at Grenoble (Godfrin) and Lancaster (Fisher). Transfer from coordination to Aalto management.
3. ***Microkelvin future.*** Preparations for the next infrastructure call under Horizon 2020 in 2014. Visions of the trends in physics over the next five years – how can the low-temperature community help to achieve these? Formal decision on how many members are appointed to the working party who prepares the grant application and who are they? Guidelines for the working party.
4. ***Any other business.***
5. ***Closing of meeting.***

Matti Krusius
Coordinator

George Pickett
Chairman

European Microkelvin Collaboration

MICROKELVIN

General Assembly

Meeting at the 54-month Final Review of the Microkelvin Grant Programme
Thursday, 12 Sep, Sannäs Convention Centre, 21:30 – 23:15

Present at the meeting:

George Pickett ULANC (Chair)
Joern Beyer (replacing Thomas Schurig PTB)
Christian Enss HEID
Henri Godfrin CNRS
Matti Krusius AALTO (Coordinator)
John Saunders RHUL
Peter Skyba SAS
Tjerk Oosterkamp UL (arrived at about 22:30)
Dominik Zumbuhl BASEL

Invited: Shaun Fisher ULANC
Pertti Hakonen AALTO

MINUTES OF GENERAL ASSEMBLY

1. **54-month review.** The review was to be conducted on the following day, Friday 13 Sep. No external evaluators had been invited which was generally considered a regrettable shortcoming. The prevailing feeling was that the achievement level of milestones and deliverables would be close to maximum possible: no single major failed deadline was identified.

2. ***Microkelvin finances***. In view of the imminent ending of the Microkelvin grant period on Sep 30, all accounts should be prepared for close down. The management account at AALTO would be supplemented by a transfer of 15 kEuros from the coordination accounts at CNRS and ULANC. EU Project Officer Maria Douka had provided the permission to use JRA accounts until Sep 30. The Trans-National Access program had reached its targeted visitor months and its accounts were exhausted. The AALTO coordination account was exceeded already during the second 18-month grant period, while those at CNRS and ULANC were expected to show some small surplus after all bills from the Microkelvin Workshop 2013 had been paid.

   It was reminded that all Partners should take the final auditing of their finances and the closing of all Microkelvin accounts as a high-priority task since the payment of the final grant contributions was contingent upon a positive outcome.

3. ***Microkelvin future.*** It was unanimously concluded that preparations should start for a new grant application in view of the expected infrastructure call under Horizon 2020, to be opened in December – January and with a submission deadline in mid 2014. The concept of the Microkelvin Collaboration has proven successful and has been well accepted among the international low-temperature community at large. Based on the "EU consultation on possible topics for future activities for integrating and opening existing national research infrastructures" it had

been placed in the "List of topics with high potential and with merit for future Horizon 2020 actions for integrating and opening existing national research infrastructures" under "Engineering, materials sciences, and analytical facilities" as the "Collaboration of European laboratories to foster education, technology development, and research at ultra-low temperatures as a joint laboratory without walls". Our EU Project Officer recommended submission of the application in the first possible Horizon 2020 call.

The concept of the Microkelvin Collaboration had been worked out in 2008 – 2009 by Henri Godfrin, Mikko Paalanen, and George Pickett, who prepared the first Microkelvin grant application. Based on this experience, it was concluded that the most efficient working group for preparing a new application would be one with a small number of members so that responsibilities would not get diluted. To maintain balance in geographic distribution and seniority, it was proposed that the new task group should carry four members, two with earlier experience and two new comers with fresh ideas: Christian Enss, Henri Godfrin, Pertti Hakonen, and George Pickett. This motion was accepted. George Pickett agreed to start the work by calling the group to working order, but the group was left free hands to select a chairman for its later work.

The group was charged with the task to prepare the best possible winning application with no predetermined constraints on the form or structure of the new plan.

4. ***Any other business.*** No decisions on further matters were taken**.**
5. ***Closing of meeting.***

Matti Krusius
Coordinator

George Pickett
Chairman

ANNEX to NA4 report: LT Section report June 2013
European Physical Society – Condensed Matter Division
– Low Temperature Section

Name of Section: Low Temperature Section of the CMD
June 2013
Author: Henri Godfrin
Development of the Division/Group in 2012[4,5] The LT section worked during this period in the organisation of CMD24, as well as several low temperature conferences and courses.
List of Board members Henri Godfrin France — Institut Néel, CNRS/UJF BP 166 38042 Grenoble cedex 09, henri.godfrin@grenoble.cnrs.fr Tjerk Oosterkamp — Leiden Institute of Physics, Leiden University, P.O. Box 9504 NL 2300 RA Leiden, Netherlands oosterkamp@physics.leidenuniv.nl Mikko Paalanen — Aalto University, P.O. BOX 15100, 00076 AALTO, Finland paalanen@neuro.hut.fi George PickettLancaster University, Department of Physics Lancaster. LA1 4YW, U.K. g.pickett@lancaster.ac.uk Wilfried Schoepe — Universität Regensburg, D-93040 Regensburg, Germany wilfried.schoepe@physik.uni-regensburg.de Thomas Schurig — Department Cryo- and Vacuum Physics, Physikalisch-Technische Bundesanstalt, Abbestrasse 2-12, D-10587 Berlin, Germany Thomas.Schurig@ptb.de
Board Meetings The LT section had a board meeting in Smolenice, (Slovakia) March 23rd, 2012. The next section meeting will take place in Helsinki, September 2013.
Prizes The LT section is particularly glad that the EPS Europhysics prize distinguished members of our community: S Bramwell, C Castelnovo, S Grigera, R Moessner, S Sondhi, A Tennant.
Conferences and their statistics

[4] membership, chairpersons, co-option, sections, constitutional matters
[5] List of Board members as annex

The LT section organised several symposia during the European Physical Society - Condensed Matter Division EPS-CMD24 Conference, September 3-7th.2012, Edinburgh, UK (Low Temperature Physics sessions 1 to 5, including both LT section and superconductivity section topics). The sessions were particularly well attended (statistics are provided separately by the CMD24 organisers). The closing lecture of CMD24 was given by prof. Sebastien Balibar, a distinguished member of the Low Temperature community. The LT section promoted and participated in the organisation of the International Symposium on Quantum Fluids and Solids (QFS2012) in Lancaster, 15- 21 August 2012. The number of registered participants was 267. The LT section participated actively in the organisation of the European Advanced Cryogenics course "Cryocourse", Heidelberg, September 2-13, 2011 (38 students). http://www.kip.uni-heidelberg.de/cryocourse2012/ The next Cryocourse will take place in Grenoble, August 25- September 2, 2013. Other meetings promoted by the LT section: The Workshop on Physics and Metrology at Low Temperatures, December 13-14th 2012 at the Physikalisch-Technische Bundesanstalt, Berlin, Germany
Cooperation with other EPS Divisions/Groups Cooperation with the Superconductivity section chair for the organisation of several symposia at CMD24. A joint organisational meeting was held during the CMD Board meeting in Edinburgh on 27 April, 2012.
Cooperation with Divisions/Groups of national physical societies
Publication of conference presentations The 2 volumes of the proceedings of LTD14 have been published in the Journal of Low Temperature Physics, Vol. 167 Nos. 3/4 and 5/6 2012 The 2 volumes of the proceedings of QFS2012 (Lancaster) have been published in the Journal of Low Temperature Physics, Vol. 171 Nos. 3/4 and 5/6 2013.
Gender[6] Particular attention was placed in selecting women as participants of Cryocourse, the advanced Cryogenics course. As usual in our field, women were underrepresented (7/38 at the last Cryocourse), but the percentage is now substantial, and regularly increasing. At all the conferences organised and promoted by the LT section, care is taken to look first for possible female invited speakers.

[6] The policy of EPS is that women should be encouraged to join division and group Boards, to be well represented in conference programme committees and to be selected for invited talks at EPS conferences; scientific quality is, however, always the leading criterion.

Co-operations with China, Japan, Korea, South-America (any other) The next International Conference on Low Temperature Physics will take place in Buenos Aires, Argentina, in August 2014. The LT section of EPS is involved in the organisation (participation as co-chair of the Cryogenics section of LT27, and members of the Advisory Committees). The satellite on Ultra-low temperatures (Bariloche, Argentina, August 2014) is organised by the LT section Chair, and promoted by the LT section. These conferences will take place for the first time in South America. The LT section has strong collaborations with the USA, China, Japan, Russia, Ukraine, Brazil, Argentina, among others. We invited several researchers from these countries to attend Cryocourse and QFS2012, providing them with substantial financial support.
Special activities in 2012
Suggestions and recommendations The LT section will support any action tending to improve the efficiency of the EU system of contracts.
Any special recommendations
Any special communication
Work plan for 2013
Activities supporting the organisation of the international conference LT27 (see above). Organisation of the school "Cryocourse 2013" Participation in events organized by the EPS and the national Societies Section Meeting in Helsinki

Physics, Engineering and Nanoscience at Extreme Low Temperatures: A Roadmap

The MICROKELVIN Ultralow-Temperature Forecast Report

SEVENTH FRAMEWORK PROGRAMME

PHYSICS, ENGINEERING AND NANOSCIENCE AT EXTREME LOW TEMPERATURES: A ROADMAP

THE *MICROKELVIN* ULTRALOW TEMPERATURE FORECAST REPORT

G R Pickett
Lancaster University, UK (ULANC)

With valuable input from the following MICROKELVIN Consortium members:

Olivier Bourgeois, Centre National de la Recherche Scientifique, Grenoble, (CNRS)
Eddy Collin, Centre National de la Recherche Scientifique, Grenoble, (CNRS)
Hervé Courtois, Centre National de la Recherche Scientifique, Grenoble, (CNRS)
Christian Enss, Universität Heidelberg (HEID)
Francesco Giazotto, Scuola Normale Superiore di Pisa (SNS)
Henri Godfrin, Centre National de la Recherche Scientifique, Grenoble (CNRS)
Pertti Hakonen, Aalto University (AALTO)
Klaus Hasselbach, Centre National de la Recherche Scientifique, Grenoble, (CNRS)
Teun Klapwijk, Technische Universiteit Delft (DELFT)
Tjerk Oosterkamp, Universiteit Leiden (UL)
Jukka Pekola, Aalto University (AALTO)
John Saunders, Royal Holloway and Bedford New College (RHUL)
Thomas Schurig, Physikalisch-Technische Bun-desanstalt, Berlin (PTB)
Peter Skyba, Ustav Experimentalnej Fyziky Slovenskej Akademie Vied (SAS)
Dominik Zumbuhl, Universität Basel (BASEL)

To be published.

A ROAD MAP FOR ULTRALOW TEMPERATURE PHYSICS APPLICATIONS

THE *MICROKELVIN* ULTRALOW TEMPERATURE FORECAST REPORT

I CONTEXT

Since the FP7 MICROKELVIN Consortium numbers among its members a large and representative fraction of the European scientific community working in the field of ultralow temperatures, it provides an ideal forum for preparing an interdisciplinary foresight study into the needs of the subject over both the immediate and longer term futures. Consequently, in the following we have produced a current snapshot and a forward view of the field and its implications and needs. The document covers innovations in instrumentation and refrigeration, in methods, concepts, and equipment concerning the global development of low temperature physics and related research. We hope that this will provide a substantial component in informing future European needs for equipment and (access giving) infrastructure. The content of the following "Road Map" has been prepared with input from all the MICROKELVIN partner institutions.

II INTRODUCTION

The simplicities of the behaviour of materials at very low temperatures has been for decades a powerful driver for generating ideas, techniques and devices with applications spread over many areas of science and technology. The field is also one of the most dynamic of the frontier areas with the lowest attainable temperatures falling by 10 orders of magnitude (4 K to 100 pK) over the past century. This is significantly faster than Moore's law that loosely defines the miniaturization of conventional electronic components.

The field also supports a considerable body of industry and research capacity. We estimate that there are of the order of 300 research groups in Europe working at sub-one-Kelvin temperatures involving over 1000 researchers. Around 10 major companies and ~20 SME's have cryoengineering groups, with total annual turnovers in the region of €10^9 and €10^8, respectively.

At the time when MICROKELVIN was initiated we estimated a need for around 100 new low-temperature scientist and cryoengineers per year in Europe alone. Since that time we have had the global recession. Surprisingly that has not depressed industrial economic activity, for example in the production of dilution refrigerators, and output is probably 30% up on that before the crisis of 2008 onwards. Added to that, current signs are that the world economy is on the upturn which may well mean that this already buoyant activity will begin to increase even more rapidly in the immediate future, assuming that economic activity not only recovers but also compensates for the relatively depressed demand of the immediate past.

Currently Europe is the undisputed leader in microkelvin physics, in terms of research workers, records held and research output. The aim of MICROLKELVIN was to make a start in integrating this rather fragmented activity into a more coherent whole. Of the score or so laboratories with the capability to build their own microkelvin refrigerators, 12 are located in Europe, and almost all have participated in MICROKELVIN which has led to a great rationalization and cross-fertilization of the field in

Europe. The period of the MICROKELVIN activity has also coincided with an interesting point in the development of microkelvin capability. We have been able to cool materials into the regime of 1 to 5 μK for at least a decade, but these temperatures have rather been demonstrations of capability since the techniques needed to exploit them were lacking.

However, over the intervening period, our abilities and experience have increased (not least from the efforts of MICROKELVIN) and we can see the beginning of a considerable expansion of the exploitation of the microkelvin (and low-millikelvin) regime for the development of novel material functionality, in nanoscience, in quantum computing, and in metrology. This can be immediately illustrated from the simple fact that a large majority of dilution refrigerators currently being supplied are destined for work in the area of quantum computing and allied fields.

III THE SIGNIFICANCE OF ULTRALOW TEMPERATURES

The motivation for working at ultralow temperatures falls into three main areas (with considerable overlap).

First, since the temperatures are low, the associated thermal energies are small allowing us to study a large range of systems in the low-thermal noise limit, with the correspondingly large increase in our experimental “resolution”. This advantage applies to virtually all physical phenomena.

Secondly, an extension of this means that since the associated thermal energies are very small, systems which exhibit inherently low energy phenomena, completely masked by thermal noise at higher temperatures, can be investigated. There are many examples, but one relevant to MICROKELVIN is the incredibly delicate coherently precessing NMR behaviour seen in superfluid ^{3}He at sub-millikevin temperatures. These are perhaps the most delicate macroscopic structures ever accessed in condensed matter physics. These are new physical phenomena which can be studied no other way.

Finally, and perhaps most importantly, ultralow temperatures bring us into the regime where we can study systems in their coherent ground states. Coherent (or near-coherent) condensates are the defining signature of low-temperature physics, and are manifest in superconductors, superfluids, conduction electron clouds in metals of restricted size, cold dilute gases and many others. The behaviour of systems at or near their quantum mechanical ground state is likely to be providing the drivers of this field for decades to come. Of course, this is nothing new. It has been true for the last half century but the great difference is that currently we are making the transition from the basic investigation of these systems to industrial exploitation.

Superconductivity was the first such system to escape from the laboratory and now forms the basis of a considerable industry involved in providing, first and foremost, high magnetic fields with applications in purification, MRI imaging, magnetic confinement for fusion power and particle acceleration, but also specialized microwave filters and particle detectors. Coherent electron systems in both normal, superconducting and hybrid systems for quantum computing are likely to be the next to make the transition, the ultralow temperatures being necessary to suppress decoherence effects which interfere with the needed integrity of the qubit manipulation.

Coherent systems also feed into the techniques of metrology in numerous ways as coherent systems can give us physical standards of unimaginable accuracy and stability. The increasingly important "Quantum Metrology Triangle" which closes the loop *Frequency*-Single Charge Effect-*Current*-Quantum Hall Effect- *Voltage*-Josephson Effect- *Frequency* relies on coherence and low temperature to operate. Physical standards are the unsung forgotten heroes of science but without very high accuracy, which does not come for nothing, many of those common place services, which we take for granted today, would not be possible. The obvious example is the Global Positioning System which not only implies a precise knowledge of the position and time synchronization of the satellites but also has to take significant relativistic effects into account. (Velocity time dilatation slows the satellite clocks by around 7 μs per day, while the gravitational potential at satellite altitude speeds them up by 45 μs per day, leading (if uncorrected) to an accumulated error of >10 km per day.)

A further important point to emphasize here, not surprising in a frontier area, is the lack of agreed international standards in nanoscience. Also, when we discuss the microkelvin temperature regime, we should bear in mind that the current PLTS-2000 temperature scale is only defined down to 0.9 mK. Since we can cool solids to temperatures 200 times colder than that, the lack of a microkelvin-relevant scale is a considerable shortcoming.

IV SOCIETAL IMPLICATIONS

Low-temperature physics has had a large societal impact which is not always appreciated in the wider world. Superconductivity is one case as outlined above which has already had a game-changing impact on medicine by making possible the high magnetic fields necessary for magnetic resonance imaging which is finding its way into all major hospitals around the world, with an estimated 15,000 units in current use. Functional materials provide another important contribution to society in general.

Materials are more easily developed and characterised at low temperatures owing to the simplification that low temperatures bring to the behaviour of systems in general. The whole of the current information highway aspects of modern society rely on materials research from the past. Future research in the materials area can only increase this impact. Since every pocket mobile phone, now carried by a large fraction of the world population (extant mobile phone numbers approximately equal the world population in 2013) not to speak of smartphones and pads, rely on materials. It is hard to imagine a more pervasive technology. Clearly, the more complex computing and information transfer and manipulation, which is rapidly developing now, will also rely heavily on new materials and processes, including the very quantum-based systems, which are currently under intense development.

Standards are also becoming critical to advanced technologies which impact widely on everyday life. Now we are entering many technological fields where the effects of relativity even at modest velocities have to be taken into account, the accuracy of mensuration and the fundamental constants we rely on are becoming ever more critical. Mechanical nano-manipulation is also a current growing field which is likely to have major impacts in medicine, engineering and communications. Low temperature physics, and increasingly milli- and micro-kelvin physics have an ever increasing impact on all these fields and many others, encompassing all the aspirations of the EU Horizon 2020: Health, Food, Energy, Transport, Climate and Resources, and Secure Societies.

V EMERGING TOPICS FOR THE IMMEDIATE FUTURE

In the following we list those emerging future topics which have been highlighted by the members of MICROKELVIN as being of particular importance for development, taking into account all aspects of fundamental, applied and wider societal potential implications.

In §1 below, we begin with a consideration of the field we broadly denote as nanoelectronics. Encouragement the extension of this field to the millikelvin and sub-millikelvin regime has been central to the philosophy behind the MICROKELVIN project. Furthermore, judging by the numbers of workers associated with this field and the numbers of dilution refrigerators being supplied for it, this sector is certainly the most important which we are considering in this document.

We then consider in §2 Nanomechanical oscillators. We now have the capability to bring microscopic (visible) mechanical structures into the vibrational quantum limit. This is a new interesting field in its right. The phononic ground state is a very new idea. However, our ability to manipulate and excite small mechanical objects will bring enormous practical advances in the medical and metrological field.

In §3 we then consider quantum fluids and solids, which historically has provided the driving force in pushing groups to work in the sub-millikelvin regime. A very large part of our capability in this temperature region has been gained through efforts to push quantum fluid systems to lower and lower temperatures. Not only is this an important field in the physics of condensed matter but having been the main driving force to reaching lower temperatures means that this field embodies collectively a large fraction of the practical milli- and microkelvin expertise in Europe.

We next consider in §3 a portfolio of general physics problems with relevance to milli- and microkelvin temperatures, viz.; Quantum Phase Transitions, Nuclear Order, Phononic Crystals, Heavy Fermion Systems and Spin glasses and frustrated Spin systems.

We then look at the likely development of metrology and standards which are given an enormous boost in accuracy by the low temperature environment.

Finally we consider the impact of the rapid expansion of the sales and application cryogen-free dilution refrigerators which MICROKELVIN has played a large role in encouraging.

1 NANOELECTRONICS

By working at lower temperatures and smaller sizes we can access coherent electron circuitry which can provide entirely new functionality in computation and electronic manipulation. Indeed the pursuing of this goal has been one of the principal motivations for the MICROKELVIN project from the outset.

There are two beneficial factors encouraging us to work at lower temperatures. First, the coherence lengths of the carriers become longer at lower temperatures, since the disturbing effects of phonons, impurities and radiation are reduced. This means that we can achieve coherent behaviour in larger devices.

However, the most important factor in current preoccupations is the similar temporal effect of the dephasing time, which is critical for the operation of systems intended for quantum computing since the information storage and manipulation must obviously be carried out in a time short compared with the dephasing time. Dephasing times should fall with falling temperature, but most measurements appear to show a saturation at low temperatures for reasons unknown.

One serious problem in such systems is the disturbing effect of spin fluctuations in those nuclei which have a nuclear moment. Working at lower temperature, i.e. in the regime where nuclear spin-flips become suppressed (because of nuclear ordering) would be extremely beneficial.

In the longer term the increased spatial coherence of the carriers in devices at lower temperatures may be equally important. Working at lower temperatures with longer coherence lengths would allow the use of larger structures. A not-so-obvious benefit of this is the purity of the materials being used. The semi-conductor industry has developed over many decades smaller and smaller structures but the methods needed to produce these structures does not rather tend to produce poor quality materials. With larger structures we could contemplate ways of introducing components of high purity single-crystal conducting material with the possibilities of electropolishing the sufaces which should lead to even greater inelastic scattering lengths.

However, first we have to overcome the problems of cooling such circuits.

1.1 Cooling

1.1.1 "Brute Force Cooling" from a Bulk Cooling Stage

We begin by considering the cooling of nanoelectronic circuits, since this remains a stumbling block to the cooling these systems to milli- and microkelvin temperatures. A major part of the MICROKELVIN programme has involved the investigation of several alternatives.

Since the nanodevice technology currently is overwhelmingly an outgrowth of the "room temperature" semiconductor industry, with its extremely mature and comprehensive methods and techniques. That means that devices are largely built on semiconducting substrates. That is fine at room temperature where the poor electrical conductivity of these materials ensures an electronic "vacuum" substrate, but allied with a substantial bath of thermal phonons which can act as a medium for maintaining thermal equilibrium without interfering with the electronic processes being supported.

At low temperatures, this comfortable situation no longer holds. The phonons remain the primary mechanism for thermal transport, but since the density of the phonon gas falls roughly as T^3, at one millikelvin the density is only some 1 part in 10^{16} of the room temperature value. This is negligible by any standard and thus the typical semiconducting substrate material at low temperature is effectively a thermal vacuum.

That is the crux of the matter. If the circuits are built on a thermally dead material, how do we make thermal contact to them for cooling? The simple initial answer is that we must rely on the incoming electrical leads to provide not only the electrical inputs to the circuit under investigation but must also at the same time provide the thermal contact to effect the cooling. Wait! We have forgotten the possibility that we can simply immerse the circuits in say for example the liquid helium coolant in, for example, the dilution refrigerator and make direct contact with the primary cooler at least down to a few millikelvin. If only it were so easy. Unfortunately, the thermal contact between the device substrate surfaces and the liquid helium is also modulated by phonons. This provides immediately a mismatch problem. Since the acoustic characteristics of the helium and of the substrate are very different, the transmission probability across the interface is thus very small. Added to that the fact that number of phonons in the liquid is in any case tiny and in the substrate negligible, cooling by immersion does not happen.

Given that, at present, we have no practical alternative to relying on cooling via the leads, how do we then proceed? The paradox here is that the circuit to be cooling is of necessity thermally levitated between the weak connection to the cooling system and the influence of the outside world via leads and the surrounding environment. It is clear that the answer is better contact to the refrigerator and better isolation from the outside world.

One approach is to make the leads an integral part of the refrigerator as pioneered by MICROKELVIN. This has the effect of coupling the refrigerant directly to the specimens and also interposing a large cold thermal mass on the thermal route down the leads from room temperature to the specimen. This approach will no doubt lead to many similar approaches in the future. Even in this scenario the leads are still coupled and represent a direct electric link from room temperature directly to the circuit under test. This link could be broken or effectively broken by the use of amplifier units operating at the cold end of the cryostat which can shut out room temperature radiation down the leads by suitable impedance manipulation.

1.1.2 On-Chip Cooling

More targeted cooling is another route to this end. Cooling individual chip components by miniature direct "quantum dot refrigerators" and various superconducting hybrid systems may point the way forward. These systems tend to rely on the Peltier effect of pumping one Fermi fluid against another (as in fact does the dilution refrigerator) but with metallic systems having Fermi temperatures in the 104K regime there is little entropy left to play with at low temperatures.   Nevertheless careful work with current SINIS systems has pushed the lowest temperatures achievable on a cooled membrane to a few tens of millikelvin. While in the present form these systems are probably limited to the millikelvin range, on-chip cooling to these temperatures would be a boon to all ultralow temperature nanoscience workers.

Using such devices in a multistage configuration may well add another step down in temperature. This advance has not yet been investigated experimentally but a number of configurations are under consideration and this probably points the way to the future for this cooling method.

Alternative methods of on-chip cooling may also show promise. Various systems based on quantum dots or combinations of quantum dots have been proposed in the past but have not yet been realised. Another possibility is to use a single-electron transistor coupled to the mode which is to be cooled. The conclusion is that although the entropy available for such cooling systems is extremely limited, there are ingenious ways around this being proposed. The advantages are so clear that these avenues will definitely be followed in the future.

As a postscript to the above discussion, on-chip cooling has been developing in parallel with on-chip thermometry which is an obvious need if these systems are to be of practical use. Coulomb blockage thermometers are now operating down to ~5 mK.

It is unfortunate that both liquid ^{3}He and liquid ^{3}He/^{4}He solutions have such high viscosities; otherwise the "on chip" micro dilution refrigerator would be a real possibility. It is hard to see any way round this problem in the immediate future. However, microfluidics may help us in this context. The understanding of the dynamics of liquid flow through mesoscopic channels is in its infancy and is certainly throwing up non-intuitive results, so this possibility may not be totally ruled out. (The benefit here is that a dilution refrigerator works on the Peltier principle but with a working fluid with entropy content orders of magnitude higher than any electronic system.)

To state a target, what we really need is a reliable methodology for on-chip cooling of, for example, quantum dots into the 10 mK regime. That would provide a platform for reaching the microkelvin regime and also provide a real boost to nanoscience as it would sidestep the need for complex refrigeration equipment.

To sum up this section, the actual cooling of nano-electronic devices remains the principal problem in taking the subject into the microkelvin regime. Nevertheless new methods and ideas are coming up and we expect real progress in this area in the near future.

(As a footnote to this section, as it is more general, is the parallel need for other "on-chip" techniques, for lack of a better description. If we are to be able to cool system with "on-chip" spatial resolution we need other tools with similar properties, for example, thermometry with chip-size resolution, and also ways of controlling and probing thermal transport on the nanoscale, nanophononics.

1.2 Applications to Quantum Computation and Manipulation

In this section we consider the contributions that milli- and microkelvin temperatures can make to the advance of quantum computing and quantum manipulation. Given the current stage of development, this theme largely boils down to designing, understanding and devising methods for addressing various qubit designs, an important ingredient of which is the coherence time of the qubit states. It is of course critical to the operation of quantum systems that the coherence of the states survives for long enough to allow useful manipulation. Thus the qubit states need to be shielded from the disturbing effects of the rest of the lattice matrix and also from the disturbing effect of the incoherent motion of the nuclear spins within the qubit material.

One of the most promising designs proposed so far are systems based on single and multiple quantum dots. The dots can be prepared with well-defined energy levels (representing the |n> states of the qubit), but probably most importantly in the long term is the fact that they can be integrated into current electronic circuits. There are many designs of qubits being considered but the attraction of one which maps easily on to the very mature semiconductor electronics methodology is that it will save a lot of time in the short term.

Silicon is an attractive host material for realising qubits for several reasons. As pointed out above it is readily interfaced to conventional electronics but it is particularly suitable for contributing to long quantum coherence times. The electron spin lifetimes in semiconductors tends to be very long compared with the disturbed orbital motion which is more exposed to other lattice processes. The electron states thus decay via the coupling to the orbital motion (spin-lattice coupling. In silicon spin-orbit coupling is relatively weak, which is a bonus. Furthermore, in naturally occurring silicon only one nuclide (^{29}Si <5% abundant) has a spin (1/2). Moreover, this can be removed by enrichment leading to pure ^{28}Si which can be obtained commercially. All these factors lead to enhanced coherence times.

An added reason for taking measurements to ultralow temperatures is to avoid the decohering effect of random nuclear spin tumbling, by taking the system below the temperature at which the nuclear spins order thus depressing this added effect. Putting all these incremental factors together could enormously enhace the coherence of silicon-based systems.

As a postscript, nuclear spin based qubits in this material are also attracting interest.

2 NANOMECHANICAL OSCILLATORS

Condensed matter systems for quantum manipulation have hitherto been almost exclusively based on electronic ensembles with electronic states being the “working fluid”. This makes sense in that electronic systems can be immediately connected to external circuits and that there is a vast industry involved in making functional metallic and semiconducting structures for device use.

In recent years however interest has turned to nanomechanical oscillators, initially as a way of looking at mesoscopic systems in their vibrational quantum mechanical ground states. Once these systems can be cooled to temperatures comparable to the low level phonon energy splitting then we are reaching the quantum limit. In this regime we can also potentially prepare a oscillator in a superposition of states which is a fundamental step in making the bridge between quantum behavior in microscopic systems (which we know about) and to similar effects in the mesoscopic world.

Individual phonons in the oscillator can be coupled/entangled with excitations in other systems, e.g. by coupling to the photons in a resonant laser-excited cavity or to the states in an artificial atom/ quantum dot.

This is all fundamental physics but closely related to quantum computing as it implies the transfer of qubits to and from the oscillating system which can be used for storage and manipulation. However, the Nano resonators are indeed micromechanical objects which can carry out micromechanical measurements. For example by preparing the surfaced of the resonator we can attach macromolecules to it. This changes the oscillation frequency, meaning that they can be used as microbalances for large molecules. Such systems can simply be used as sensors in many applications but by also reacting the target molecules the oscillators can be used to follow chemical changes to molecules by keeping a record of the mass during a reaction. Thus these systems have great potential for sensor applications and applications especially in molecular biology and in medicine.

Systems can be constructed of a range of materials, for example, carbon nanotubes and probably also graphene. However, semiconductor systems are currently the most advanced given our ability to create complex shapes in these systems. Silicon or silicon nitride systems can be designed to order to select the mass, frequency, and can be created as wires, grids beams and many other geometries.

Devices with active units comparable in size to the superfluid ^{3}He coherence length can be used to probe new physics in this superfluid (see §3 below).

3 QUANTUM FLUIDS AND SOLIDS

At the very lowest temperatures the energy scales become comparable to the separation of the ground state from the lowest excited states and at this point we enter the regime where quantum mechanics begins to dominate the behaviour of the materials on a macroscopic scale. At this point the focus of the behavior becomes the coherent ground state with excitations as a perturbation whereas in classical systems the excitations dominate. Helium is unique in this context as the lightness of the atoms and the weakness of the interatomic forces (there is no chemistry in helium) means that both isotopes of helium remain liquids all the way to absolute zero as the zero-point energy needed to confine the atoms in an ordered solid lattice is too large to be provided by the weak interatomic forcers.

The consequence of that is that helium provides quantum-dominated behavior in all three states of matter, gas, liquid and solid.

The heavy isotope of helium ^{4}He is the easier to use as it undergoes a transition to superfluidity (or to the creation of a coherent liquid condensate) already at the high temperatures of 2Kelvin. However, the 4He atom is virtually inert, it is a Boson with even numbers of constituent particles and has no spin or angular momentum properties, no charge, no magnetic moment and is thus only labelled with a mass. The ^{3}He atom on the other hand has a nuclear spin of ½ and is a Fermion. Thus to form a coherent ground state it must form Cooper pairs which means that the pairs have angular moment and a nuclear spin as well as mass.

Since the preferred parity results in pairs with the spin vector $S = 1$, and the orbital momentum vector $L = 1$, the various combinations of spin and orbital quantum numbers also means that superfluid ^{3}He can exist in a number of distinct phases.

This complex structure results in a very rich spectrum of behaviours which mirror in particularly simple form many other aspects of physics, and thus the liquid provides an ideal model system for studies from phase transitions, phase boundaries, quantum turbulence and cosmology.

Particular topics in this area highlighted by the members of the consortium include the following:

3.1 Spin Superfluids

The nuclear spin of the Cooper pairs means that very inner structure of superfluid ^{3}He can be probed by NMR methods. Since the spin system of the liquid condensate is only weakly coupled to the properties we can consider it to be a separate "stand-alone" spin superfluid. This spin superfluid is coherent which means that when probed with NMR the whole liquid responds rather liquid a macro magnetic molecule, rather than independent nuclei as in the case of conventional NMR.

This behaviour means that once the magnetic system is driven into the coherent precession of the whole system the behaviour is very much protected from dissipation processes and we can create the most delicate precessing domains with lifetimes approaching an hour whereas conventional NMR precessions only live for milliseconds or less. The fact that the superfluid exists in several phases adds to the portfolio of behaviours which can be accessed.

The coherent precession of the magnetic part of the superfluid has long been analysed in terms of continuum behaviour. However, recently it has been recognized that this behaviour can be regarded as a Bose-Einstein condensation of the spin excitations, magnons, and thus the coherent precessing domains seen in the liquid add to the number of phenomena which can be considered Bose-Einstein condensates.

These delicate precessing structures are as mentioned above perhaps the most delicate macroscopic systems ever seen. They also allow us to study various coherent effects on a *very* macroscopic scale. The systems are coherent over millimeter sized domains and the spin superfluid has a coherence length in the fractions of a mm range. This means that one can put two precessing domains in contact via a millimeter sized channel and observe the Josephson effect at macroscopic sizes. Since it is a *magnetic spin* fluid which is involved the wavefunction "phase" or something very closely associated with the phase can be observed directly by a magnetic search coil around the channel. That allows us to get access to the very "guts" of the operation of the Josephson effect. These systems have many potential applications (see below) and are currently rather underestimated.

Applications

While these very delicate structures are limited to the millikelvin region they can provide a guide for looking at other phenomena. The Aalto University group has studied the interplay of vortex lattices with the precessing modes.

3.2 Two-Dimensional systems

Since helium can be deposited on a surface as a single layer, or multiple layers, we have access to another "quasi" phase of these quantum materials, that of the two-dimensional system. Since the lower layer is normally highly bound to the substrate we can study 2D quantum solids. Additional layers which are less strongly bound can be liquids. Thus we have access to two-dimensional quantum solids, quantum liquids and mixed systems. This again provides an ideal model system for looking at many other phenomena in the physics of two-dimensional systems. With patterned confinement the materials can be prepared with many different geometrical attributes.
Aspects of particular interest in this area at present are quantum phase transitions, where the transition takes place at zero temperature driven by quantum fluctuations rather than as for a conventional phase transition at finite temperature driven by thermal fluctuations. Two-dimensional systems can also behave as topological superfluids (as discussed above) in which we can study the newly "re-

discovered” possibilities of Majorana Fermions, topological excitations which are their own anti-particles.

The ^{3}He monolayer system also gives the possibility of further unconventional superfluid phases not accessible in the bulk liquid, and also the possibility of two-dimensional supersolids.
The magnetic properties of 2D systems are also of considerable interest, as magnetic interactions in two dimensions are inherently different from those in three dimensions. The influence of a substrate which can force a hexagonal lattice also allows the study of frustration in magnetic ordering in a very clear way.

Highly correlated two-dimensional systems display exotic phase transitions, as observed in 2D 3He as well as in High Tc materials. Exploring the nature of these transitions in helium has clear advantages. This is certainly the case for the identification of the fundamental physical phenomena responsible for the quantum dynamics observed in still mysterious areas of the phase diagram, where one observes pseudogap, non-fermi liquid, domain wall or charge density wave behavior.

Experiments on specifically designed and engineered systems, combining very low temperature NMR and heat capacity measurements with the power of microscopic neutron scattering, constitute a promising area of research, with impact in condensed matter physics and materials science. Understanding the properties of highly correlated fermions on a microscopic basis is one of the most important challenges of present fundamental and applied research.

APPLICATIONS

The “purity” of 2D superfluid systems provide ideal model “laboratories” for studying a wide range of physical problems associated with reduced dimensionality.

3.3 Topological Superfluids

Inside the depressed gap at the boundary of the ^{3}He superfluids bound states can exist. They can be Andreev bound states and are expected to exhibit the features of Majorana Fermions in which the particle is its own antiparticle. There has been much recent interest in Majorana Fermions in topological insulators and using the same language superfluid ^{3}He can be considered as a topological superfluid with analogous properties.

Applications

Topological defects and Majorana particles are a current hot topic, and the inherent chirality in the structure of the ^{3}He superfluids make this an ideal medium for studying such problems.

3.4 New Superfluids

At present we have two accessible examples of “dense” superfluids; superfluid ^{3}He and superfluid ^{4}He. “Accessible” is the operative word here, meaning that we can produce examples in the laboratory. Since the temperatures at which these liquids form is very low, they fall largely outside normal human experience and are thus regarded as unusual and exotic .

However, the superfluid state is not so unusual. It is assumed that the nucleon (proton and neutron) liquids inside neutron stars are superfluid. Since these km-sized objects have angular momenta corresponding to that of the parent pre-collapse star, the rotation speeds are mind-boggling. That means that the dynamics of the superfluid nucleon liquid is dominated by the dynamics of the necessarily dense array of quantized vortices necessary to support the high rotation. By analogy the nucleon dynamics in heavy nuclei may be treatable by the known superfluid methods. Superfluidity is perhaps not as rare as we think.

That said, there are several systems which are more immediately accessible. For example, one of the "holy grails" of superfluid studies has been the search for superfluidity in the ^{3}He component of a dilute solution of ^{3}He in superfluid ^{4}He. This system would be very interesting being a fully interpenetrating solution of one superfluid within another, in a dense system. (Interpenetrating systems have been studied in the ultra-dilute cold gas systems). This would demonstrate a number of entirely novel properties. The prognosis for the probable transition temperature of dilute ^{3}He in ^{4}He is certainly sub 10^{-6} K but the technology to reach these temperatures is constantly improving. Thus this state may well be achievable, but only in the very long term. Similar mixed systems can be set up in the dilute laser-cooled gases but the ^{3}He system would be the first dense interpenetrating system.

Superfluid ^{3}He itself is also a rich source of new sub-phases. The common A and B phases are well studied but there are many more which have not been studied because they are hard to create. Preliminary work has looked at these systems in unusual places, for example, very close to the superfluid-normal transition. This will continue. In this context one should also mention the possibility of higher order Cooper pairs with higher level angular momenta (beyond p-wave pairing) in analogy with the d-wave pairing observed in the majority of unconventional superconductors.

Finally, there must be superfluidity in the higher helium isotopes but the lifetimes are too short for current techniques to be applicable.

3.5 Analogues for Other Systems

3.5.1 Pure Quantum Turbulence

There is no "theory" of classical turbulence. We know that the Navier-Stokes equations are the relevant ones but they are too complex to solve in the general case. In the helium superfluids turbulence takes the form of an ensemble of similar singly quantized vortices. Thus larger turbulent structures can be "parsed" into simpler units providing an "atomic" theory of turbulence, which may well shed light on understanding the more complex classical case.

At finite temperatures this can be very complex with turbulence both in the normal fluid and also in the condensate. However, at temperatures approaching absolute zero the normal fluid fraction becomes negligible and the turbulence can be studied in the condensate alone. This is an expanding field with potentially large economic implications if the studies do indeed shed light on the classical behavior.

Applications

The principal application of these studies is the gaining of insight into an inherently simpler form of turbulence in the hope of throwing light on the classical turbulence problem. Classical turbulence is well understood at an engineering level but as stated above there is no general theory as the governing Navier-Stokes equations are too complex to solve in realistic situations. If pure quantum turbulence can achieve a better understanding of the classical problem this would have enormous economic implications as turbulence problems impact on all human activities from the small scale such as blood flow and micro-fluidics, via hydrodynamics, aeronautics, to the large scale, simulation of weather etc. The physics implications are even wider ranging from internal dynamics in nuclei to the behavior of galaxy clusters.

3.5.2 Cosmological Analogues

The wavefunctions of both superfluid 3He and 3He show similarities with the metric of the Universe. In the standard model it is assumed that after the big bang the fundamental forces (strong, weak and electromagnetic) successively differentiated themselves in a series of phase transitions which ultimately broke the symmetries SU(3)xSU(2)xU(1). The two expressions are not identical by any means but similar enough that the superfluid can be used for analogue laboratory cosmological experiments, for example, the genesis of cosmic strings.

Hitherto interest in this area has largely been in the area of cosmic string formation by the Kibble mechanism. Here, the Universe is presumed to have undergone several symmetry-breaking phase-transitions shortly after the Big Bang where the nucleating new broken-symmetry phase is nucleated in independent regions of space (with independent order parameters) and when these regions coalesce a “phase glass” of different order parameters is formed. The various regions anneal to form a continuous phase but not all the configurations can be annealed out and topological defects remain, in particular linear defects, or cosmic strings. Since these are high density objects they would have been instrumental in the clustering of galaxies and their creation and evolution is of importance. Superfluids and especially superfluid 3He can be made to undergo similar transitions via the Kibble- Żurek mechanism in fast cooling events leading to analogous linear defects, vortices.

More recently, the phase boundary between the 3HeA and B phases has been proposed as a model for cosmological branes and preliminary experiments on brane-annihilation have already been made.

Applications

Cosmological problems fall outside the normal process of experimental scientific investigation since the critical events have already occurred, cannot be repeated, and we can only retro-construct the processes involved from the current state of the Universe. Superfluid tabletop “cosmological” experiments provide insight into these otherwise inaccessible phenomena.

4 GENERAL TOPICS

4.1 Strongly Correlated Systems

Condensed matter physics has been lucky that the gas of strongly interacting conduction electrons in simple metals is describable in terms of an ensemble of independent “free” electrons with some adjustment of the parameters to take into account the interactions with other electrons. Thus the simple band structure of a simple metal can be generated by taking the ion core lattice and calculating the single-particle behaviour of an added electron, putting in the electron-electron interaction later as a perturbation. That has always been a serendipitous situation. Electrons are strongly interacting and in the first instance there is no reason whatsoever for us to believe that they should behave as almost free independent particles.

That however is not always the case. In the strongly-correlated systems the conduction electrons do indeed act as a single entity and are simply not amenable to the “standard” independent particle treatment. That has two consequences. First, calculating the behaviour is vastly more complex and currently, it is fair to say, not at all well understood. Secondly, the strong correlations mean that these systems show new physics. Since the electronic interactions are so strong all the apparent “single-electron” behaviours, e.g. electronic heat capacity, magneto-resistance, etc. are very much increased over their “conventional” material values. These materials thus have great potential as advanced materials. A particularly low-temperature behaviour of these materials is the quantum phase transition described below.

4.11 Quantum Phase Transitions

One range of phenomena which, by definition, are tied to ultralow temperatures is that of the quantum phase transitions. In a conventional “thermodynamic” phase transition the elements of the system have mutual interactions which tend to order them in some way. This ordering is opposed by the destabilising effect of temperature or put another way, by thermal fluctuations. At high temperatures these thermal fluctuations suppress the tendency to order, but at some sufficiently low temperature the fluctuations become so weak that the interactions are no longer suppressed and the system orders. This happens at the ordering temperature. There are interesting behaviours in the region of the transition with correlation lengths and correlation times diverging.
If we instead now look at similar behaviours at zero temperature, clearly thermal fluctuations cannot play a role, but the analogous effect of quantum fluctuations take their place. If there is some external parameter of the system, magnetic field for example, which determines the strength of the quantum fluctuations, then by changing the field and suppressing the quantum fluctuations, a transition can occur in analogy with the thermodynamic case where the thermal fluctuations are suppressed by falling temperatures. These behaviours are very much associated with strongly correlated systems.

4.2 Nuclear Ordering and Negative Temperatures

In non-magnetic metals there are three main thermal baths at low temperatures; the phonon system, the conduction electron system and the ensemble of nuclear spins. At millikelvin temperatures the number of phonons has become vanishing and we are left with just the conduction electrons and the nuclear spins. The conduction electrons come into thermal equilibrium with each other rapidly. The nuclear spin system is also able to equilibrate relatively rapidly since the spin-splitting on neighbouring nuclei is the same and there is a resonant transfer of magnetization between nuclei leading the nuclear system to rapid thermalization.

That said, the coupling between these two systems is very much worse. To transfer energy between the two systems there must be a mutual spin flip between a nuclear spin and an ambient electron spin with the same energy splitting. The number of electrons which can contribute to this process is limited by the Fermi statistics and falls linearly with temperature. That means that at low temperatures the "spin-lattice" relaxation time can be very long (of order hours).

That is the bane of nuclear cooling, as nuclear refrigerants must be cooled gently enough that the electron system can follow the nuclear temperature during and after demagnetization. Overcoming this poor thermal contact is a principal problem for this cooling method.

However, if we can cool the system to the μK regime the relaxation time becomes so long that the nuclear system becomes effectively isolated which allows us to make experiments on the nuclear spin system at temperatures spanning the nuclear ordering temperatures while paradoxically the surrounding atoms are at much higher temperatures. For example (in rhodium at AALTO) the current world low temperature record is ~ 100 pK for the nucei, while the surrounding lattice of electronic shells remains at 50 μK, almost six orders of magnitude warmer.

Once we have the nuclear system cold and isolated in this way, there are many interesting properties which can be looked at. Since the nuclear spin levels are finite in number (there is no continuum at high energies) then a reversal of the external field reverses the energies of the spin states. The ground state becomes the highest state and so forth. Since at these temperatures the reversal is made on a time scale much shorter than the thermal relaxation time the population of the states is conserved during the change. Thus the most populated state is now that with the highest energy. This is a *negative* temperature. Being able to access the whole temperature space from positive to negative opens up access to new physics in fundamental thermodynamics.

Finally, with an order nuclear system we can study the "back-reaction" of the nuclear order on the surrounding electronic system. This has implications in, for example, in superconductivity. Ferromagnetic ordering interferes with superconductivity. How is this manifest when a very weak superconductor (e.g. lithium T_c ~0.4 mK) is cooled past the nuclear ordering temperature? Does the superconductivity survive?

4.3 Spin glasses and frustrated Spin systems

Magnetic systems are useful for the study of complexity: simple, but competing interactions, lead to an unusual spin-disordered state, the spin-liquid phase. The density of states at low energies is particularly high, due to the existence of many possible spin arrangements of similar energy, while simple order (Ferromagnetic or Néel) is impeded. Geometrical frustration is well known in triangular, kagomé or pyrochlore lattices, whereas quantum frustration due to competing ring exchange (Dirac) processes is well established in 2D 3He and also in cuprates or spin ladders. Different types of spin liquids have been found, but little is known about the dynamics, the nature of the elementary excitations, or the influence of defects on the phase diagram. Very low temperature studies are needed in order to explore the low-lying energy states, which contain crucial information on the quantum ground state and the dynamics of these systems.

5 METROLOGY, STANDARDS and THERMOMETRY

5.1 Low temperature high-sensitivity instrumentation

The low-noise environment provided by milli- and microkelvin temperatures offers great advantages for high-precision metrology and standards determinations. That said, much of the relevany discussion here is covered in other parts of this report.

However, we can mention that the low power dissipation of a superconducting detector and a well-controlled back action make Scanning NanoSQUID microscopy a unique tool capable to image magnetic flux at lowest temperatures. Current challenges concern the increase in spatial resolution, which will be obtained in a) reducing the probe size to a few hundred nanometers and in b) scanning the NanoSQUID at several nanometers above the sample surface. These techniques can be used for examining, for example, the study of (ferromagnetic) superconductors, topological insulators and spin-ice systems.

Centers of development of SQUID microscopy are U. Stanford, Weizmann Institute and Grenoble.

Europe has a strong role to play due to the range of expertise available in Europe, from high resolution SQUIDs and SQUIDs amplifiers by PTB and the forefront novel nano-detectors developed in the research laboratories.

5.2 Extending the temperature scale from milli- to microkelvin temperatutes.

The current standard scale for defining temperature down to 0.9 mK, the PLTS-2000 scale, is very much provisional and much work is being done on that around the world. We need also to be thinking about its successor reach well into the microkelvin region, bearing in mind that stable temperatures can be reached with current techniques which are already three orders of magnitude lower that those covered by PLTS-2000.

VI THE FUTURE LABORATORY ENVIRONMENT (What We Are Going To Need)

In the substantial §V above we considered the emerging and continuing topics which we expect to drive the field forward. In the current section we wish to examine the future needs and ongoing developments of the infrastructure and laboratory environment.

The basic requirements for a very large fraction of the work described above can be summarized as follows (this particular division is chosen because of the differing infrastructures required):
a) A low-temperature environment, in general with a dilution refrigerator system to provide millikelvin temperatures and a nuclear cooling stage to produce microkelvin temperatures.
b) A low-energy physical environment, which means low electrical thermal and vibrational inputs.
c) Finally, the various specific requirements needed for individual experiments; for example, high magnetic fields, high pressures etc.

The Cold Environment: Dilution Refrigeration

We begin by considering the low-temperature aspects and specifically the dilution refrigerator which has become the workhorse device for reaching millikelvin temperaturtes.

Two factors immediately spring to mind. Given that micro-coolers are still very much on the horizon, milli- and microkelvin temperatures are going to have to rely on the dilution refrigerator as the workhorse cooling system for a long time to come. That said, it is a salutary fact that work on the further development of dilution refrigerators is limited at a tiny number of laboratories in Europe. Apart from the translation to dry systems, the basic dilution refrigerator configuration (and performance) has hardly changed in three decades. While we know how to run machines to the 2 mK region, all except one of the commercial suppliers cannot guarantee temperatures much below 10 mK.

There is a lot of scope for further work in this area.

Two possibilities are immediately obvious. First, it is a sign of the conservatism of the field that the standard dilution unit in the very constricted cylindrical format needed to fit in a narrow wet machine has simply been applied with essentially no change to the platforms. Dry platforms have masses of space. The dilution refrigerator could benefit from a redesign of the geometric configuration. Designing and manufacturing annular heat exchangers is a major problem. Let's us have some much simpler linear designs now that we are not limited by space.

Furthermore, with careful design it is possible to approach 10 mK with just a spiraled-tube tubular heat exchanger (13 – 15 mK anyway). We would benefit from some improvement to this part of the machine. With the current price of ^{3}He gas producing, good machines without the need for discrete sintered-silver heat exchangers would be an economic boon. (The latest [and for this reason probably the last] large Lancaster dilution refrigerator needs a charge of >100 litres of ^{3}He gas which at current prices (given current prices this translates to an investment of € 200,000 – 300,000.)

The period of the operation of the MICROKELVIN project has seen an enormous growth in the use of cryogen-free systems. The advantages of such machines are very obvious. First, they need no refrigerant liquefaction infrastructure. Secondly, since they are not limited in size by a helium dewar they can accommodate much greater experimental volumes. Finally, in general they are much faster to thermally cycle to room temperature and back.

The disadvantages are perhaps more subtle, but may be critical for the most exacting work. The prime disadvantage arises from the cryocooler refrigeration units. These rely on reciprocating piston systems which inevitably carry a vibrational cost. This can be fatal to delicate experiments, for example the various styles of scanning microprobe microscopes, force, tunneling and so forth. With vibration levels in the best wet and dry systems differing still by orders of magnitude that remains a problem. The second, and more subtle, disadvantage is the (anecdotal) feeling that dry machines are reluctant to operate for extended periods of time without blockage problems. This of course besets all dilution refrigerators but it seems that dry machines may be more prone.

What we need

We really need some active academic development in improving the vibrational isolation of dry machines. That would make them much more acceptable in demanding situations.

The Cold Environment: Nuclear Refrigeration

To proceed below the millikelvin regime, we need to add a nuclear demagnetization stage. Here the picture is a little clearer. Several laboratories have produced measured lattice temperatures in metallic samples below 10 mK (Lancaster University, Universität Bayreuth, and the Physikalisch-Technische Bundesanstalt, Berlin). There is plenty of entropy available in nuclear refrigerants and achieving the requisite low temperatures is not the problem.

Current thinking on nuclear refrigeration suggests the following recipe for a suitable nuclear working material. First, the nuclide used must obviously have a spin (or a fraction of the naturally occurring nuclides must have a spin). Secondly, the material must be a normal metal (because we need to couple the nuclei to the lattice for external refrigeration, which rules out non-conductors and superconductors). Thirdly, the nuclear spin must order in response to an external field. This rules out nuclei with a quadrupole moment which have a competing ordering process in the internal electric field gradient in the metal. (We can avoid this condition by only using cubic materials where by definition the internal field gradients are zero. However, this rules out alloys since the internal electric fields in random alloys can be very large). Also we must rule out magnetically ordered materials where the internal magnetic field is generally large compared with any external field which we can apply.

Applying these “rules” to our list of pure metals results in only a handful or suitable candidates. Serendipitously one good possibility is copper (both naturally-occurring isotopes have nuclear spin 3/2, with abundances ^{63}Cu: 69%, ^{65}Cu: 31%). Thus copper has become the working metal of preference, and we are very lucky that this material is already widely used as an engineering material, is available in very purity and does not need any complicated and expensive isotopic purification or other treatment. In short, we have a convenient material for use in nuclear refrigeration and by using it we can reach 10 μK with current techniques, with the promise of much lower final temperatures with lower starting temperatures (e.g. by using two stage demagnetization).

What we need:

We really do not need any immediate further work in this area. We can achieve very low temperatures in demagnetization systems with current knowledge. The difficulties come in the next section.

The Cold Environment: Making thermal contact.

While we know how to cool nuclear stages to the microkelvin regime, the difficulties come, in making thermal contact to the external specimen to be cooled. This is especially a problem when the sample may be something on the nanoscale. For a discussion of this problem see § V 1.1 above.

What we need:

We need a lot of development work in improving contact to nuclear refrigerants of experiments to be cooled. This need crosses the whole area of microkelvin studies from quantum fluids to nanoscience and device studies. This work will be central to moving the whole subject further. See again § V 1.1 above.

Highly-Isolated Laboratory

A relatively new feature in the field is the development of highly "quarantined" laboratories, where experiments can be while enjoying extreme levels of isolation from external disturbance. These facilities are designed for the most precise measurements that it is physically possible to make under conditions of ultralow temperatures and with as complete as possible isolation from ground-borne and air-borne vibration and from electromagnetic interference. In other words, these are laboratories for making experiments at the lowest attainable levels of interference from the outside world.

Our abilities to make very low temperature measurements in recent years have largely outstripped our capability in terms of isolated environments. We have been able to cool metallic samples into the few-microkelvin regime for many years but have not been able to do realistic experiments at these temperatures as our knowledge of shielding the isolated environment and dealing with disturbance coming down the leads from the outside world has not been sufficiently good. That situation is changing (with much input from MICROKELVIN).

We can now contemplate experiments at these extremes. That means that highly isolated laboratories custom-built for the purpose are now a practical proposition.

What we need:

Several laboratories of this type are currently planned or under construction. More work in this area would be valuable. This is a topic which tends to fall outside the normal academic discussion, with various groups in disparate areas building such facilities and of necessity reinventing the wheel. Some joined-up thinking here would be helpful. The advantage of such facilities is the fact that they are of general application, can be used for many extreme conditions experiments, and thus are not necessarily tied to a specific field or technique.

VIII FUTURE NEEDS: INFRASTRUCTURE TECHNIQUES – MANPOWER

Millikelvin Regime

We can get a rough handle on the increase in the volume of activity in the general area of this forecast report from the global sales of dilution refrigerators. We estimate that current dilution refrigerator production is in the region of 140 units per year, of which perhaps 40% are destined for European destinations. These machines are complex enough when a sophisticated experiment is added that we can suppose that for most effective use they should be under the control of a competent postdoc. Thus Europe alone looks to need an output of 60 competent millikelvin-trained postdocs to satisfy this need. The industry itself also needs trained personnel for thecproduction process but this rrepresents perhaps only a handful of new positions in any one year.

How well we are doing in fulfilling this need is not clear as it is not so easy to estimate the numbers produced in Europe but we would estimate that the leading MICROKELVIN laboratories produce perhaps 20 doctorate candidates per annum with dilution refrigerator experience. Other European laboratories perhaps produce a similar number with some millikelvin experience. Putting those together leaves a shortfall of some 20 of the manpower needed for manning the current levels of equipment investment.

Microkelvin Regime

In the case of the demands for researchers educated in the mircrokelvin regime it is much harder to estimate requirements. The microkelvin regime where workers require knowledge of nuclear refrigeration is only catered for by a handful of laboratories around Europe (virtually all MICROKELVIN members). Having said that, this activity is expected to increase in coming years and we can envisage a situation where between 10 and 20 post-doctural workers with microkelvin training will be required per annum in Europe over the next few years. That is pretty much in balance with the estimated output at the present but is likely to lag behind in the future.

IX ENVOI (Conclusion)

The microkelvin temperature regime is proving to be an increasingly important research area which is opening up many avenues of new ideas in physics, technology and especially in quantum technology. As the MICROKELVIN consortium has shown, a targeted attack on one front “the opening up of the microkelvin temperature range to nanoscience” can extend best practice around Europe and in this particular case along with the introduction of several new microkelvin installations now in place which otherwise would not have been built. There are other fields in the general “low-temperature” limit, especially in metrology and quantum technology which would benefit from a similar approach.

Paradoxically Europe is fortunate in having a rather fragmented research landscape, arising from the concentration on national facilities, when compared with say the US. This underlying “disadvantage” has been a major driver for the EU’s efforts to promote inter- rather than just intra-national collaborations with the result that, at least in the area of interest here, we have been able to do things with the flexibility provided by EU transnational actions which would not have been possible elsewhere. Furthermore, the health of the subject, as expressed in this Road Map, indicates that this is only the beginning of what is becoming a new of working, being pioneered here in Europe.

Consultation on possible topics for future activities
for integrating and opening existing national research infrastructures

Title	
	Title of the proposal
	Microkelvin – a collaboration of European laboratories to foster education, technology development, and research at ultra-low temperatures as a joint "laboratory without walls".

Contact person	
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	Krusius
	First name(s)
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	Organisation
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	Position in the organisation
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	Finland
	e-mail address
	mkrusius@neuro.hut.fi or matti.krusius@aalto.fi

Is your proposal representing your own personal view or are you	Organisation

responding on behalf of your organisation as a whole?	view

Description of the research infrastructures covered and the trans-national access and /or services provided

Indicate the type of research infrastructures to be covered by the proposed topic, and list the research infrastructures in Member States, Associated Countries and Third Countries, that would provide transnational access and/or services to researchers, with brief descriptions of the state-of-the-art equipment and services offered to users that make them rare or unique in Europe. Outline the specific areas of research and scientific communities normally served by the infrastructures, as well as new areas opening to users, if any. Indicate what would be the overall access modalities necessary to be developed. Text of maximum 4000 characters including spaces.

Type of infrastructure: We promote European integration in the field of ultralow-temperature (ULT) physics, with the goal of submitting a proposal for a European infrastructure, the "European Ultralow Temperature Laboratory", a distributed research infrastructure without walls. This proposal builds on the successful concept of the European Microkelvin Collaboration under FP-7.

Microkelvin: The current EU grant for ULT collaboration, which continues until September 2013, has encouraged and supported new research initiatives at ultralow temperatures, by providing access to refrigeration and measuring instrumentation which is not widely available in national institutions. It also provides education and training in low temperature physics and techniques for graduate students and has established a new forum for European cryogenic business to meet and discuss. The appearance of these new opportunities and the lively activity around them has gained Microkelvin great popularity in the European low temperature community. There is an urgent popular demand for a continuation of this effort.

Structure of collaboration: Within Microkelvin, trans-national access to research infrastructure is provided by three centralized laboratories located in different Member States. These have been selected to have the capability of reaching temperatures down to the microkelvin range, with a large assortment of different types of refrigeration installations. The second requirement is to provide the measuring equipment and expertise for covering a wide range of different important experimental techniques. This is achieved by including in the current Microkelvin programme altogether 12 Partners from 8 Member States. In a new plan we propose to widen our constituency of partners and access sites.

Services & clientele: The users of the ULT infrastructure are traditionally research groups in materials science and more recently in nanoscience. Microkelvin emphasizes the need to advance the range of accessible temperatures well below 10 millikelvin in nanosciences. Novel approaches are developed for cooling conduction electron systems to low millikelvin temperatures. For materials science research we plan to provide further possibilities by including higher magnetic fields and elevated pressures in our assortment of opportunities. A further goal is to develop more sensitive measuring systems – often making use of SQUID-based sensors – for measurements approaching the quantum limit. The turn-around time of our equipment is improved by promoting automatic computer-controlled routines, especially for the operation of refrigerators. Much of the current refrigeration technology is based on the use of liquid helium; its market price is now unstable and rapidly rising. To reduce the dependence on liquid helium, we invest in cryogen-free "dry" refrigeration technology. The development of these capabilities has improved the quality and service offered at our infrastuctures and has reduced the time needed for a typical experiment.

Trans-national access modalities: ULT measurements are complicated by the demands on vacuum tightness, low heat loading, and reduced signal levels. Thus typical visiting times at the access site tend to be 1 – 3 months in duration. Secondly, the large assortment of different equipment and working routines require that the visitor and the host team work closely together during the visit. To put this in perspective, the Microkelvin 36 month periodic review report lists 40 months of total visitor time spent at the three access sites which is divided among 23 user groups and their 38 individual visiting researchers. Most visits lead to joint publications between the user group and the host team. The 36-month report lists 22 joint published reports with many more in the pipe line (see web page http://www.microkelvin.eu/project-activities-transnational.php).

Scientific domains served by the research infrastructures

Select the scientific domain(s) served by the research infrastructures	Engineering, Material Sciences and Analytical Facilities Physical Sciences
Indicate the main scientific domain served	Physical Sciences

Key potential partners

Indicate a list of key potential partners. Text of maximum 3000 characters including spaces, with 1 line per potential partner (participant organisation name, country and contact person)

The current Microkelvin collaboration has 12 partners which are listed below:

1) **O.V. Lounasmaa Laboratory**, **Aalto University**, Finland, National Centre of Excellence, selected and supported by the Academy of Finland for 2012-16. Its research concentrates on nanoelectronics and ultra-low temperatures. The Laboratory has two record low-heat-leak ULT refrigerators, of which one is a rotating machine. A new “dry” sub-millikelvin refrigerator is in construction, prof. Matti Krusius

2) **Institut Néel**, **Centre National de la Recherche Scientifique**, Grenoble, France. The largest centre in Europe dedicated to low-temperature research, with three sub-millikelvin refrgerators, prof. Henri Godfrin

3) **Ultralow Temperature Group**, **Department of Physics, Lancaster University**, UK. Lancaster physics was rated top in the UK (in the most recent UK research assessment exercise, RAE2008). Its Microkelvin Group has the largest cluster of advanced nuclear cooling refrigerators in Europe for studies on materials and devices down to 100 microkelvin. A new refrigerator built during Microkelvin is dedicated to nanoscience studies. The group holds the world record for dilution refrigerators (1.75 mK), also for the nuclear cooling of metals (copper and platinum), as measured by an in-situ thermometer (6 microK), and for cooling liquid helium-3 (~80 microK), prof. George Pickett

4) **Ruprecht-Karls-Universitaet** Heidelberg, Germany, prof. Christian Enss

5) **Royal Holloway and Bedford New College**, University of London, UK, prof. John Saunders

6) **Scuola Normale Superiore di Pisa**, Italy, prof. Francesco Giazotto

7) **Institute of Experimental Physics, SAS, Kosice**, Centre of Low Temperature Physics, Centre of Excellence of the Slovak Academy of Sciences, Slovakia, Dr. Peter Skyba

8) **Universitaet Basel**, Switzerland, prof. Dominik Zumbuehl

9) **Technische Universiteit Delft**, The Netherlands, Prof. Teun Klapwijk

10) **BlueFors Cryogenics**, Helsinki, Finland, Dr. Rob Blaauwgeers

11) **Universiteit Leiden**, The Netherlands, prof. Tjerk Oosterkamp

12) **Physikalisch-Technische Bundesanstalt**, Berlin, Germany, Dr. Thomas Schurig

The present members will constitute the core of a new application in the next call for EU research infrastructures. Negotiations about partners and structure of the successor programme are ongoing. Access sites will be chosen to possess both the capability of achieving sub-millikelvin temperatures and of making available different physical measurement techniques so that these laboratories together carry expertise and equipment to serve as wide a range as possible of customer groups with different interests.

Scope and activities

Describe the overall objectives of the activity. Describe the benefit that the proposal would bring about in terms of integrated provision of infrastructure related services. When appropriate, describe how the network would integrate with the relevant e-Infrastructures. Text of maximum 2000 characters including spaces.
Outreach: Historically research in materials sciences has been driving the quest for lower temperatures. In Microkelvin, one of the principal objectives has been to reach out also to nanosciences. The ever-increasing complexity of electronics is rapidly bringing us to the limit when typical component sizes reach atomic dimensions and no further miniaturization is possible. At that point we need something new. Electronics based on coherent electron behaviour promises to provide a new way forward. In nanocircuits, the electrons can behave coherently over the circuit dimensions and thus follow the quantum rules of wave motion rather than Ohm's law. This will open up a whole range of new devices based on quantum electronics and this is where lower temperatures can help. For coherent transport, the electrons must be able to move through the circuit without scattering. To achieve scattering lengths larger than the sample size, we need to minimize both impurity scattering and thermal scattering. The former demands high purity materials. The latter, requires low temperatures. For this, even at the more easily accessible millikelvin temperatures, the circuits need to be of nanoscale. This size restriction provides the motivation for exploiting the advantages to be gained by working at much lower microkelvin temperatures. Despite this need, nanoscience is inhibited from advancing below the millikelvin temperature regime by a lack of expertise and facilities. In Europe we already have the greatest concentration of microkelvin infrastructure and expertise in the world, developed by our quantum-fluids community. Microkelvin has been putting this existing infrastructure at the disposal of the nanoscience community, developing together new techniques to bring coherent structures into a new temperature regime. This is leading to the creation of a European microkelvin "laboratory without walls" and is encouraging new European commercial interests.

Indicate the Networking Activities that could be foreseen to foster a culture of co-operation between the research infrastructures and scientific communities. Indicate the Joint Research Activities that could be foreseen to improve, in quality and/or quantity, the services provided by the infrastructures. Text of maximum 4000 characters including spaces.
The mix of different activities in the current Microkelvin grant, consisting of networking, trans-national access, and joint research tasks, has proven both practical and efficient: Networking activities have provided an incentive to start new services for the low-temperature community, while trans-national access services have invigorated the research field, by creating new initiatives and by bringing more researchers in the centre

of the action. Among these is our effort to bring both leading experts from high-level laboratories and researchers from developing countries to our Microkelvin and Microkelvin-related meetings. The four packages of Joint Research Activities have been instrumental in developing refrigeration and measuring techniques. In the absence of Microkelvin, they would not necessarily have been worked on, unless they happened to be essential stepping stones for progress within the agenda of some single research group. This is because physics at ultralow temperatures requires elaborate large-scale infrastructure in refrigeration and measuring instrumentation that is difficult to build and maintain in sufficient extent by individual academic research units.

Joint Research Activities: Two of the four Joint Research Activity packages develop cooling techniques, both with conventional approaches (JRA1) as well as by applying new "on-chip" nano-electronics methods (JRA2). High- sensitivity low-noise measurement, in some cases at the quantum limit, is a further important field of development (JRA4). Some results from these efforts are tested within the Collaboration in studies of fundamental physics questions in experiments at microkelvin temperatures (JRA3). These are condensed matter simulations of problems in the physics of atomic condensates, in cosmology, gravitation, or particle physics. All tasks in the different JRA packages are from the very frontier of ULT research and have been planned to provide input to other physics communities for their research. The 70 Microkelvin research publications listed in the 36-month Periodic Review Report characterize the extent of this work (see web page http://www.microkelvin.eu/documentation.php).

In nanoelectronics a major present obstacle is the cooling of conduction electrons to 10 mK and below. In JRA1 conduction electrons have now been cooled to lower temperatures than before, by improving thermal contact to the refrigerator, by reducing heat leaks from external sources, and by including active direct cooling of the electrons. Faster and more accessible refrigeration has been achieved with new "dry" pulse-tube-cooler operated 3He-4He dilution refrigerators which have been developed by our SME partner BlueFors and which then have been tested by our various partners. In Lancaster an advanced large-size low-heat-leak refrigeration installation has been constructed which is specifically designed to increase access for nanoscience and quantum coherence measurements in nanomechanics at microkelvin temperatures.

In JRA2 different novel approaches are developed to cool nanodevices with both ex-chip techniques, by improving thermal contact and electric filtering, and directly with on-chip nanocoolers. The goal is to generate for various types of thin-film sensors a platform which would cool from 0.3 K to 50 – 10 mK temperatures. Obviously success here would be of great value for instance in satellite-borne infrared astronomy. At present the goal is to demonstrate improved cooling with a thermometer integrated on the same chip or platform. Coulomb-blockade or GaAs quantum dot thermometers for this task are developed in JRA4, along with other thermometry down to the microkelvin regime. High-sensitivity SQUID amplifiers operating at different frequency regimes is a further frontier in the JRA4 development work.

Need for European integration

Explain why this proposed topic would require a European (rather than a national or local) approach. Describe how resources provided by EU would be mobilised. Indicate how account is taken of other national or international activities, and any resources that would complement an EU contribution. Text of maximum 3000 characters including spaces.

The need for integration: Traditionally, the development of refrigeration and measurement techniques at ultra-low temperatures has been the responsibility of small academic research groups. Their limited resources of manpower and funding have enforced narrow specialization of the research agenda. No single European country has been able to create a laboratory strong enough to cover all the demands on development and services which are now needed on the European scale. The same considerations apply to present needs of advancing research and education. Currently it is the Microkelvin Collaboration which provides a forum for discussing and funding coordination of research efforts, training, and access services on the inter-European arena. Now after three years of operation, we realize how this has created new opportunities, revitalized the field, and accelerated progress. This should be continued.

Workshops: To advance its inter-disciplinary goals, Microkelvin has organized annually its own one-week workshop of 50 – 80 participants. The programme is constructed around different topics of great current interest, with the aim to bring together both the ULT community and research groups in materials and nano-sciences which are particularly interested in pushing their efforts to lower temperatures. In addition, in special sessions Access Users have an opportunity to present their results to the workshop audience, to receive feedback and to discuss further new ideas. The workshop programme also includes training sessions for graduate students in various different aspects of ULT techniques.

Education: The ULT community has organized every second year a two-week lecture and training course in low-temperature physics and techniques for 30 – 50 European graduate students. It consists of series of lectures on different topics which have been delivered by professors and senior researchers, with the goal to familiarize senior students from different fields with low-temperature refrigeration and measurement. In the intervening years a cryo-conference has been taking place where graduate students lecture about their own research and discuss its results. Both types of training programmes have been extremely popular among the graduate students who have learnt to know both physics and their fellow students from all around Europe. These activities have been supported by the Marie Curie Training programme and now by the Microkelvin Collaboration.

Popularization: A popular effort within Microkelvin has been the popularization of physics in general as well as in the ultralow temperature regime. This has been carried out usually locally and annually by the individual Partners in the form of public lectures, exhibitions, and happenings.

Expected impact

Describe the expected impact of the proposed activities on the scientific communities, on the functioning of the research infrastructures, and on the development of the European Research Area (including balanced territorial development). Highlight the contribution to socio-economic impacts, including for promoting innovation and developing appropriate skills in Europe. Text of maximum 3000 characters including spaces.

Research at the frontier near absolute zero has long been a powerhouse for generating new ideas in physics and beyond, from concepts in particle physics to practical ultra-sensitive devices for application in technology and medicine. One in four Nobel prizes over the last century has gone to a low-temperature physicist. In the same period the lowest accessible temperatures have fallen by 10 orders of magnitude (from 4 K to 100 pK), far exceeding the rate of miniaturization of microcircuits (Moore's law) over recent decades. Today some 250 (1000) low temperature research groups (researchers) in Europe work at sub-Kelvin temperatures. Ten major companies and 15 SME's have cryoengineering groups. Their total annual turn¬over is about 1 000 000 000 € and 50 000 000 €, respectively. More than two thirds of the annual world production of refrigerators for reaching temperatures down to the 10 millikelvin range is produced in Europe (by BlueFors in Finland and Oxford Instruments in UK). There is a European need for around 100 low temperature scientist and cryo-engineers per year.

While Europe is the current world leader in microkelvin physics, in terms of research workers, records held and research output, the effort is fragmented between universities and government laboratories and often lacks the critical mass for high quality research and training programmes. No commercially available refrigerators exist which are able to reach the sub-millikelvin regime. Less than 20 laboratories worldwide can build their own microkelvin refrigerators, most of these are in Europe and are involved in the current Microkelvin Collaboration.

The interest in lower (sub 10 mK) temperatures has recently been boosted by the need to increase coherence in nanocircuits. This requires better purity of the materials, improved architecture of nanocircuits, but also a large reduction in the influence of the surrounding thermal 'outside world'. Thus more efficient research in the microkelvin regime, accomplished by means of networking and integration of the European low-temperature community, will help to respond to similar new needs and to open the microkelvin temperature regime to a wider range of scientists. Here the current Microkelvin trans-national access programme, which encourages visiting scientists to make use of existing ULT infrastructures and expertise, has greatly widened the circle of researchers who are familiar with experimental possibilities and techniques at ULT conditions. As a result, more measurements have been performed on fundamental physics problems, nanosciences are being introduced into the microkelvin arena, and new industrial entries into the field are going to be emerging.

Projects previously funded under FP7 and FP6

Only for those proposed topics that correspond to the follow-up of FP7 or FP6 funded Integrating Activities, please provide specific additional information on: the project(s) previously or currently funded and the level of funding; the main results and expected achievements of the funded project(s); the progress foreseen in the activities proposed beyond FP7. Text of maximum 4000 characters including spaces.

The total EU contribution to the Microkelvin grant (# 228464) is 4.2 M Euros. For the European ULT community this investment has proven its worth: There exists common agreement that an increased level of achievement has resulted from better inter-European planning and coordination of the research effort. We expect to continue the collaboration in any way possible. Since funding is necessary, the only route viable is through an EU- supported programme for research infrastructures.

The ULT community supports unanimously the existence of grants for infrastructures in the upcoming Horizons 2020 framework, with bottom-up possibilities for different communities to submit an application.

To develop a coherent approach which takes us beyond the current Microkelvin grant, which finishes in September 2013, the Microkelvin partners have agreed to establish a unified European Ultralow Temperature Laboratory (EUTL). As a first step towards such a laboratory with¬out walls, we have formed a close coalition among the leading European ultra-low temperature groups, with the purpose to develop together a common distributed infrastructure with complementary instrumentation. We expect important advances from our work, which will make the ULT regime more practical and attractive with our many new technical solutions. Lower temperatures introduce clear advantages in many types of measurements. This fact can be exploited by familiarizing a growing circle of Users at our Access Sites to simpler and more proficient ULT solutions. This is in stark contrast to the situation before Microkelvin. We hope that the new EU grant programme for supporting research infrastructures will make it possible to continue this development, to further extend our knowledge and use of the very lowest temperatures.

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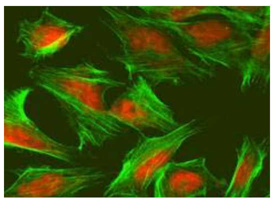
Consultation on possible topics for future activities for integrating and opening existing national research infrastructures

Assessment report






Research & Innovation

Consultation on possible topics for future activities for integrating and opening existing national research infrastructures

Assessment Report

February 2013

Research & Innovation

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1. INTRODUCTION

The European Commission organised a consultation for preparing future EU activities for integrating and opening national research infrastructures. The consultation was open from 15 July to 22 October 2012. It was advertised on the European Commission website and by e-mailing to a large public incl. Programme Committee Members, National Contact Points, European Strategy Forum for Research Infrastructures (ESFRI) delegates, coordinators of proposals and projects of the Seventh Framework Programme (FP7), Research Infrastructures operators, FP7 reviewers and evaluators.

The future EU activities for integrating and opening national research infrastructures correspond to the follow-up of the successful FP7 actions named "Integrating Activities", conditional to the approval of the European Commission proposal for the next Framework Programme for Research and Innovation, Horizon 2020, by the EU Parliament and Council. The aim of these activities is to provide a wider and more efficient access to, and use of, the research infrastructures existing in EU Member States, Associated Countries, and at international level when appropriate.

The consultation addressed stakeholders, i.e. operators of research infrastructures and user communities, in a bottom-up manner, in order to map possible future topics of Integrating Activities.

Research infrastructures are defined here as facilities, resources, systems and related services that are used by research communities to conduct top level research in their respective fields. This definition covers: major scientific equipment or sets of instruments, as well as knowledge-containing resources such as collections, archives and thematic data infrastructures, together with the associated human resources. Research infrastructures may be “single-sited”, “distributed”, or “virtual” (the service being provided electronically).

This report describes the results of the assessment of topics submitted within the consultation, which was carried out by independent experts. The individual assessment of the topics was carried out remotely and the consensus phase was carried out on the Commission's premises in Brussels from 19 to 22 February 2013.

2. RECEPTION OF TOPICS

Proposed topics were submitted using an online submission tool available on the official website of the European Commission public consultation and addressed the following scientific domains served by the research infrastructures:

- Biological and Medical Sciences
- Energy
- Environmental and Earth Sciences
- Mathematics and ICT
- Engineering, Material Sciences, and Analytical facilities
- Physical Sciences
- Social Sciences and Humanities

The Commission received 547 submissions representing 246 different potential topics. Some topics were indeed submitted more than once, sometimes by different stakeholders, and were identified by the Commission services as duplicates prior to the assessment. Table A below presents the number of received topics in response to this consultation, the number of duplicates, the number of topics finally assessed and the corresponding number of experts, who took part in the assessment by scientific domains.

Scientific domain	Total received	Duplicates	Assessed	No of experts involved
Biological and Medical Sciences (BMS)	104	32	72	11
Energy (ENER)	24	2	22	5
Environmental and Earth Sciences (ENV)	273	220	53	10
Mathematics and ICT (ICT)	14	3	11	5
Engineering, Material Sciences, and Analytical facilities(MAF)	52	8	44	7
Physical Sciences (PHY)	53	34	19	6
Social Sciences and Humanities (SSH)	27	2	25	6
Total	**547**	**301**	**246**	**50**

Table A: Number of topics: i) received, ii) duplicates iii) assessed iv) number of experts involved.

3. ASSESSMENT PROCEDURE

3.1. General

The assessment of topics was carried out with the assistance of 50 independent experts. In selecting experts, the primary objective was to ensure a high level of expertise and an appropriate range of competencies. Under these conditions, special attention was given to achieve an appropriate balance between academic and industrial expertise, a reasonable gender balance and a reasonable distribution of geographic origins. As a result, 20 out of the 50 experts (40%) were women and the 50 experts came from 21 different countries of which 18 Member States.

3.2. Assessment of topics

At the start of the assessment, all experts were briefed on the process and procedures as well as on the criteria and the objectives of the consultation under consideration. The confidentiality requirements of the whole process including verifications against conflicts of interests and the respective obligations of the experts were emphasised during the briefing.

The experts were split in 7 sub-groups corresponding to the scientific domains addressed in the consultation. They assessed and graded each topic assigned to their sub-group exclusively on the basis of the material received during the consultation. The individual assessment was carried out remotely. The experts then participated in a 1 to 3 days meeting, in Brussels, with the other members of their sub-group, in order to reach consensus about the assessment of each topic submitted. All consensus meetings were organised in Brussels during the period between 19 and 22 February 2013.

Individual assessment criteria

The individual assessment was based on common criteria for all topics to guarantee an impartial process. Those criteria were based on the objectives of the Integrating Activities and were detailed in the consultation, they addressed the level of:

1. Improvement of access to the research infrastructures concerned, by the researchers;
2. Integration effect on the research infrastructures concerned, at European level, and contribution to structuring the European Research Area;
3. Contribution for advancing science in Europe, enabling the development of new advanced technologies;
4. Contribution to harmonising and organising the flux of data collected or produced;
5. Contribution to increasing the potential for innovation and technology transfer of the related research infrastructures;
6. Contribution to developing appropriate skills specifically required for using or operating Research Infrastructures in Europe.

Final grading

The final assessment carried out during the consensus meeting consisted in grading each topic into one of four categories:

A – Topic with high potential for future Horizon 2020 Research Infrastructures actions for integration of and access to existing national research infrastructures;

B – Topic with merit but with some limitations that would need to be overcome;

C – Topic with low potential for future Horizon 2020 Research Infrastructures actions for integration of and access to existing national research infrastructures;

D– Topic outside the scope of the Horizon 2020 Research Infrastructures actions for integration of and access to existing national research infrastructures (e.g.: not addressing research infrastructures, or supporting the operation of ESFRI projects).

Consensus

During the consensus meeting, the experts of each subgroup:

- Agreed on the final grades of all topics;
- Made recommendation on possible clustering or combination of topics;
- Suggested a rewording of topics derived from merging or not enough clear with respect to the infrastructures or the scientific community addressed;
- Were invited to make remarks/suggestions on the conduct and scope of the consultation.

3.3. Assessment outcome

In each sub-group, one expert acted as rapporteur and delivered, with the support of the Commission services, a report reflecting the assessment of the topics by the sub-group.
The following table gives an overview of the topics, which have been assessed and graded by the subgroup:

Sub-group	Number of topics assessed	Final grading			
		A*	B*	C	D
BMS	72	16	19	9	27
ENER	22	6	6	4	4
ENV	53	23	8	6	12
ICT	11	3	3	2	2
MAF	44	10	15	12	7
PHY	19	6	6	2	4
SSH	25	9	5	2	8
Total	**246**	**73**	**62**	**37**	**64**

Table B: Assessment outcome
*: Some of the topics with high potential and with merit have been merged or clustered, as a consequence, the total number of topics graded can be different than the total number of topics assessed

Most of the topics graded "D" were topics, which were not addressing Research Infrastructures, or the objectives of the Integrating Activities, or were supporting the operation of Research Infrastructures identified by the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap, which would be covered by other activities supporting Research Infrastructures under Horizon 2020. It should be noted that a number of topics addressing the development, deployment and operation of e-infrastructures and which had high potential or were with merit in the scientific domains targeted by the consultation were considered without prejudging their future coverage under Horizon 2020.

4. TOPICS WITH HIGH POTENTIAL AND WITH MERIT FOR FUTURE HORIZON 2020 ACTIONS FOR INTEGRATING AND OPENING EXISTING NATIONAL RESEARCH INFRASTRUCTURES

Based on the consensus meetings, the recommended topics that have high potential and are with merit for future Horizon 2020 Research Infrastructures actions for integrating and opening existing national research infrastructures are given in Annex for all sub-groups. The topics, which are the result of a clustering by the sub-group are identified in the Annex by an acronym with a multiple reference.

5. Specific remarks

The following sections give observations and specific remarks made by the various sub-groups on the topics they assessed.

Biological and Medical Sciences:

The experts recognise the need for strong EU dedicated infrastructures providing tools and resources for analysing the enormous genomic / phenomic data available in animals (in particular livestock, including poultry and fish), plants and microorganisms. The experts consider- this as one of the top priorities. The availability of non-human data is likely to provide useful insights into data derived from humans. The link between bioinformatics and well-structured communities of researchers, with clear focus on biological objectives and usage of tools, is highly desirable. A good training and education programme within the infrastructure can help to link separate programmes. The initiatives should be coordinated by biological scientific communities together with e.g. EMBL-EBI, which should play a central role for maintenance and distribution of data. The links between genomics and phenomics should be emphasized. EU infrastructures should provide resources towards: i) dedicating computing time from EU based supercomputers (virtual cluster to optimize EU CPU time usage), and data storage; ii) developing user friendly tools for non bioinformatics skilled scientists; iii) loading of user own data to be analysed thanks to i) and ii); iv) developing of pipelines upon request, or implementing them whenever developed to make an available tool to a large community; v) training in the use of tools and data analysis.
It is suggested that for future calls on infrastructure, communities representing a broad diversity of interests in this field (animal / plant / microbe / human) should be considered as separate topics. The experts suggest not to merge the topics but to coordinate them to foster synergies and avoid potential duplication of functionality. The objective would be to achieve a comprehensive set of bioinformatics infrastructures covering different important areas.

Regarding the topic on "Large scale standardised image data acquisition and analysis in population imaging studies" and based on the number of other proposals on topics submitted within neuroimaging, the experts suggested merging topics on neuroimaging into a single topic focussing on the human brain similar to the US programme “Human Brain Mapping Effort”. The concept should be based on the various in vivo MRI, PET and EEG brain imaging technologies and integrate existing databases on human brain imaging data, including meta-data (such as demographics, disease, neuropsychology, biomarker measures, etc.) of large population and patient cohorts. A highly relevant example can be the aging and neurodegenerative disease area. The imaging data are cumbersome and expensive to acquire and thus, the required sample sizes to obtain sufficiently powered studies to arrive at solid conclusions need to be large. This is difficult to achieve in smaller sized studies. Brain imaging data already at European research centres provide a significant resource to European scientists, particularly if images are of high quality and can be pooled for meta-analysis. Emphasis should be also placed on training components and standardisation. The initiative could be coordinated within the scope of EATRIS (dealing with many other aspects than human brain imaging) and the Human Brain Project (HBP, dealing with building the human brain in a silicon substrate).

Additional comments from the experts:
- infrastructure topics in the field of Biological and Medical Sciences can be addressed through different approaches: i) technology/instrumentation (e.g. around a specific technology dealing with several diseases or scientific fields); and ii) thematically (e.g. organised around a disease or a specific scientific field across technologies). The balance between these two approaches should be a subject of consideration.
- the topic "Integration of open access literature with open data in the life sciences" could have a significant impact if expanded to a broader area beyond the life sciences field.
-nutrition is a growing important research area and we encourage the exploration of some of the ideas proposed in that area, which might be developed into an appropriate infrastructure project beneficial to nutrition research.
- although no specific proposals were submitted, some areas would benefit from bringing together relevant existing national infrastructures. These areas might include: i) Biomarkers; ii) Microbioma; iii) Structural bioinformatics online services; iv) Non communicable diseases and their determinants, e.g. metabolic syndrome.

Energy:

The experts recommended extending the "molten salt in concentrating solar power (CSP)" topic to tower receivers and solar generation of industrial process heat.

The experts of the sub-group suggested for consideration the following topics, which had not been submitted to the consultation:

- Advanced biofuels (possibly linked to sustainability of advanced biomass resources in the environmental panel)
- Bio-refining: combined production of bio-materials and energy
- Exploitation of unconventional gas resources
- Energy efficiency in buildings including the combination of heat and electrical power
- Geothermal heat pumps for heating and cooling
- Energy storage systems (other than batteries) for electricity generation
- Heat storage and transformation

Environmental and Earth Sciences:

The following topics:
- European Network of Atmospheric Observation Infrastructures;
- Infrastructure for European ocean observing system;
are overarching integrating activities.
Depending on the development of the individual integrating activities components, such topics could be open at the end of Horizon2020 or the need for a more appropriate coordinating initiative should be envisaged.

Mathematics and ICT:

The experts of the sub-group recognised that there were no topics submitted from the mathematics community, although there may be potential and interest in integrating research infrastructures.

The experts noticed that ICT05, being of an horizontal and enabling nature, could also be supported under the e-infrastructures activity line. The same applies to ICT07/08, provided that trans-national access to HPC centres is provided to individual users and small teams of researchers, following the access provision model used within Integrating Activities.

Engineering, Material Sciences, and Analytical facilities:

The experts noted that some of the topics were addressing strategic domains, but that their formulation had some limitation as it restricted artificially the area of research. The experts agreed that the topics with high potential could be regrouped along several broad areas such as:

- *Advanced nanofabrication*
- *Advances in micro – and nano electronic semiconductor technologies (More Moore) in collaboration with industry*: - Advances in semiconductor technologies for ICT; - Characterisation platform for Si-based technologies;
- *Frontier research for nano electronic applications (More than Moore):* - Advanced frontier research in the fabrication for Nano-Electronics; - Novel materials for nanotechnological applications;
- *Fabrication and characterization based on large scale bright sources:* - Advanced fine analysis and nano scale metrology based on large scale bright sources; - Advanced characterisation using bright sources of neutron beams; - Advanced characterisation using large scale light sources; etc.
- *Advanced characterisation and nanometrology*: - Based on laboratory scale facilities; - Based on solid state spectroscopy
- *Risk assessment in nanomaterials and nanotechnology*
- *Nanophotonics*: - Improvements of silicon nanophotonic applications and development of new approaches beyond silicon technology; - On-chip integration with nanoelectronic devices
- *Functional materials for special applications*: - Polymer nanomaterials for food packaging; - Ceramics for energy and environmental applications; - Development and treatment of materials using advanced technologies e.g. ion beam technology
- *Research on materials under extreme conditions*: - High pressure, ultra low temperature, high magnetic fields
- *Large scale testing facilities for engineering applications*: - Wind tunnels research facilities; - Test bench for electric vehicles; - Test infrastructures for construction and operation of underground facilities
- *Desalination of sea and river waters driven by conventional and renewable sources*

Physical Sciences:

The "European Virtual Observatory" topic has high potential for Horizon 2020 and is relevant to Research Infrastructure Activities under both 4.1.2 “Integrating and opening national RIs of pan-European interest”, and 4.1.3 “Development, deployment and operation of ICT based e-Infrastructures”.

Most of the proposals received did not address directly all the individual assessment criteria. The question arises whether the individual assessment criteria were made sufficiently clear in the call.

A small number of topics were thought to be too immature for inclusion at the time of this consultation. In addition it was noted that the European groups in some areas of astrophysics (e.g. X-rays, gamma rays, ultra-high energy cosmic rays) did not submit ideas in their domains. Taking these points into account, the experts of the sub-group recommend that it would be useful to refresh the set of topics and ideas half-way through Horizon 2020 to ensure that the Integrating Activity remains up to date. Exploring ways to reach communities working in areas of physics not represented in this set of proposals should be considered.

Social Sciences and Humanities:

A majority of proposals emanated from Humanities (about 60%), despite difficulties in classifying some highly multidisciplinary topics. The majority of the topics have been graded as high potential and with merit. Several topics could be linked to the activities of existing or upcoming Research Infrastructures established on the basis of the European Research Infrastructure Consortium (ERIC)[1].

[1] The Community legal framework for a European Research Infrastructure Consortium (ERIC) entered into force on 28 August 2009 (ref EC 723-2009)

Annex

List of topics with high potential and with merit for future Horizon 2020 actions for integrating and opening existing national research infrastructures

Biological and Medical Sciences:

Acronym	Topic title
BMS01	Integrated Disease and Phenotype Ontologies and Supporting Tools
BMS02	Molecular Profile Reference Databases for Cells and Tissues
BMS04	European infrastructure for genome research
BMS06/BMS07	European animal genomics and phenomics infrastructure
BMS08	An integrating activity for fish genome resources
BMS09	Trans-national infrastructure for plant genomic science
BMS12	European infrastructure for the design, synthesis and analysis of peptides.
BMS14	Protein Production Platform
BMS15	European proteomics research infrastructure
BMS16	European NMR infrastructures for Life Sciences
BMS17	Integrated network of research facilities for high-end cryo-electron microscopy applied to structural biology
BMS18	Transnational access and enhancement of integrated Biological Structure determination at synchrotron X-ray radiation facilities
BMS21	Bridging a critical gap in the integration of imaging and 3D structural data on scales from molecules to cells to samples
BMS27	Large scale standardised image data-acquisition and analysis in population imaging studies
BMS29	Integration of national non mammalian model animal facilities on the European level
BMS31	European Primate Network: Maintaining and Developing Best Practice, 3Rs, Staff Education and International Standards in Biological and Biomedical Research
BMS32	Cyber-infrastructure for farmed and companion livestock
BMS33	An integrated technology platform for high-throughput, multi-level phenotyping research to design robust farm animals for tomorrow
BMS34	Network of Animal Biological Resources Centers
BMS35	Aquaculture Infrastructures for Excellence in EU Fish Research
BMS36	European network of high containment animal facilities to improve control of livestock transboundary and zoonotic infectious diseases.
BMS38	European Seed Bank Research Infrastructure
BMS39	Forest tree genetic resources, a pan-European patrimony to be maintained and developed at the benefit of the scientific community
BMS42	European Nanomedicine Characterization Laboratory
BMS44	Research capacity for vector control
BMS45	Improved access of the scientific community to collections of non-pathogenic, pathogenic, emerging and clinical human/animal virus isolates (including fish and arthropods) up to biohazard risk group 4
BMS48	European infrastructure for vaccine development

BMS49	Facilities, resources and services for mining the nature and relevance of biocide resistance
BMS50	Pan-European resource for gene transfer vectors towards clinical application
BMS55	Platform for Biology of ageing research and healthy ageing multi-disciplinary biobanking approaches
BMS56	Interfacing hospitals and healthcare units data resources with BBMRI across Europe
BMS57	Strengthening the infrastructure for a European Cohort Consortium.
BMS62	Rare and Unusual Cancers Integrating Research Infrastructure
BMS63	Integrating leading research centres in rare diseases to ESFRI research infrastructures involved in discovery, preclinical and clinical development of innovative diagnostics and therapeutics: a new approach to the health care and development of treatments for rare disease patients
BMS71	Integration of open access literature with open data in the life sciences

Energy:

Acronym	Topic title
ENER08	Network of European Laboratories for Improving Performance and Reliability of PV Module and Systems
ENER05/ENER17	Creation of Hybrid Innovation in Renewable Energy: from Large scale Tank testing through Offshore Nurseries to Full Scale
ENER03	Development of Parabolic Trough Concentrating Solar Power technology used Molten Salts as the Heat Transfer Fluid
ENER06	Direct Normal Irradiance measurement and analysis network
ENER09	European Battery Test Integrated Network
ENER10/ENER04	European CCS Research Infrastructures
ENER11	European Infrastructure providing direct support to science and development on Hydrogen Technologies (complete-use-chain) towards an European Strategy for Sustainable, Competitive and Secure Energy
ENER13	European Network of Wind Energy Tunnels
ENER14/ENER01	European Smart Grids Research Infrastructure
ENER22	Network of test facilities for ICTs for energy efficiency
ENER19	Research Wind turbines for validation and verification of aerodynamics and loads
ENER20	Testing of wind turbines or electrical subsystems for grid integration at lab condition

Environmental and Earth Sciences:

Acronym	Topic title
ENV01	Infrastructures for Long-Term Ecosystem and Socio-ecological Research (terrestrial and aquatic environments in Europe).
ENV02	Infrastructures for hydrological/hydrobiological research (hydrological, hydrometeorological and hydrochemical aspects as well biological/ecological indicators).
ENV04	Aerosol, Clouds, and Trace gases Research Infrastructure (European ground-based stations for long term observations of aerosols, clouds and short lived gases).
ENV06	Arctic Research Icebreakers (High Arctic research vessels; long-term and interdisciplinary planning of icebreakers and ice-margin vessels at European and international level).
ENV11/ENV12	European Research Drilling Infrastructure (integrate with IODP, share technology with ICDP and link with EMS).
ENV14	Extended Integrated non-CO2 Greenhouse Gas Observing System (building on InGOS project, expand the spatial coverage and promote new instrumentation and techniques).
ENV15	European infrastructure network for research on crustal fluids (analogue experimental facilities as a supporting pillar to EPOS; liaising with ICDP).
ENV17	European Critical Zone Observatories: threats to soil and water.
ENV18	European Facilities for Airborne Research in Environmental and Geo-science (with development of a sustainable access scheme).
ENV19	Aquatic ecology mesocosms infrastructure (across Europe and in different ecosystems from sub-Arctic to Coastal Mediterranean).
ENV20/ENV30	Infrastructure for Forest Ecosystem and Forest Resources Research (incl. data on genetic and species diversity, effects of air pollution and mitigation and adaptation to climate change, bioeconomy).
ENV21	European Geological Data Infrastructure (link with EPOS; compliance with INSPIRE directive and support to open data sharing).
ENV22	European GNSS Infrastructure for Solid Earth, Atmosphere and Environmental Sciences (links to EPOS, to community science, social science and civil contingency-early warning).
ENV23/ENV28	European Network of Atmospheric Observation Infrastructures (integrating activities of ACTRIS, IAGOS, ICOS, InGOS and incl. Sun-Photometric network).
ENV24	Infrastructures for research on diadromous fish (long-term monitoring and experimental research on diadromous fish).
ENV25	European Network of Observatories and Research Infrastructures for Volcanology (incl. data sharing; linkage to EPOS, GNSS and early warning system).

ENV26	European Seed Bank Research Infrastructure (native plant genetic resources to improve seed collection, conservation and germination and to mitigate the effect of [genetic and] biodiversity loss).
ENV27	European Simulation Chambers for Atmospheric Studies.
ENV29	Fixed Point Open Ocean Observatories (from sea floor to the air-sea interface, including carbon fluxes).
ENV32	An Integrated European Glider Infrastructure for Research, ocean observation and management.
ENV33	European RI for geochemistry (better understanding of geochemical processes in the geosystem; state-of-the-art facilities for geochronology, environmental tracers, rare samples; data archiving).
ENV34	Infrastructure for environmental hydraulic research (best facilities to help solve climate change adaptation problems; harmonising and organising the flux of data).
ENV36	High Throughput Plant Phenotyping (from controlled conditions to instrumented fields in the context of global change).
ENV37	Infrastructure for European ocean observing system.
ENV38	InfraStructure for the European Network for Earth System modelling.
ENV39	Integrated Surface-Atmosphere exchange Network for Urban environments (urban biogeochemical research).
ENV40	Greenhouse Gas research and monitoring infrastructures (expand ICOS infrastructure in critical regions for understanding carbon and nitrogen cycle and ecosystems).
ENV42	International Network for Terrestrial Research and Monitoring in the Arctic
ENV43/ENV07	Integrated and sustained coastal observation network (expand from JERICO for a wider European and data coverage, in particular biological data and Mediterranean areas).
ENV50	Infrastructures for research on sustainable agriculture in a changing environment (from indoor controlled-condition facilities to farming field trials, up to more integrated platforms within experimental farms).
ENV51	Interdisciplinary infrastructure to facilitate broad access to natural history collections (building on SYNTHESYS, and including paleontological material; mechanisms to enable global availability of data).

Mathematics and ICT:

Acronym	Topic title
ICT01	Distributed, multidisciplinary European Infrastructure on Big Data and Social Data Mining
ICT02	A Research infrastructure for the Study of Archived Web materials.
ICT05	Infrastructure for Referencing and citation of research data and other scientific content
ICT06	Access to a Global Federated Data Infrastructure for Scientific Data from Physical and Analytical Facilities and integration with a Data Analysis Framework
ICT07/ICT08	Integrating activity for facilitating access to HPC centers
ICT09	Infrastructures for Information Visualization and Interaction Technologies

Engineering, Material Sciences, and Analytical facilities:

Acronym	Topic title
MAF03	Assessment of Si-based (and -compatible) technologies for ICT: from Device-to-System.
MAF05	Access to MEMS, Semiconductor and Packaging Infrastructure for SMEs, and University Researchers
MAF07	European Research Infrastructure for micro and nano-Photonics
MAF08	Flexible Research Infrastructure for Nano-Electronics
MAF09	European Research Infrastructure for application related multimaterial nano and micro fabrication and characterisation
MAF10	Development of innovative components in the fields of micro and nano electronic, MEMS/NEMS, photonics, magnetic and superconducting Nano devices, polymer MEMS, BioMEMS, spintronics, metal and ceramics micromachining
MAF11	Nanoscience Facilities with direct integration of fine analysis methods based on radiation sources
MAF13	European Open-Access Nanotechnology Program based on an Established and Successful Operations Model
MAF14	European Research Infrastructure for integrated nanorisk assessment and nanoregulation
MAF15	Prototyping and characterization of nanostructured materials and devices on a semi-industrial scale: from proof-of-principle to proof-of-prototype
MAF16	Infrastructure for Metrology for Characterization of Advanced Materials required by Key Enabling Technologies as Energy, Biotechnology and Nanotechnologies
MAF17	Implementation of a European analytical and metrology network
MAF19	European Open Access Facilities for the Development of Ceramics for Energy and Environmental Applications
MAF20	High-quality Research Infrastructures on Polymer Nanomaterials for innovative, sustainable and functional Food Packaging Applications
MAF21	Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy
MAF22	Free electron lasers - realising their potential for science and innovation
MAF25	Coordinated Access to Lightsources to Promote Standards and Optimization
MAF27	Solid State Nuclear Magnetic Resonance – Materials Science
MAF29	Materials e-service for technology Evolution
MAF30	Support of Public and Industrial Research using Ion Beam Technology
MAF31	European Facilities for High-Pressure Research

MAF32	High Magnetic Fields for Science
MAF34	Collaboration of European laboratories to foster education, technology development, and research at ultra-low temperatures as a joint “laboratory without walls”.
MAF36	European Strategic Wind tunnels Improved Research Potential
MAF44	Desalination of sea and river waters driven by conventional and renewable sources

Physical Sciences:

Acronym	Topic title
PHY01	Integration of research infrastructures for particle accelerator science and technology
PHY02	Advanced infrastructure for detector development for future High Energy physics projects at accelerators
PHY06	Advanced Radio Astronomy in Europe
PHY08/PHY09	European Gravitational Wave Infrastructures Integration (including atom interferometry techniques)
PHY10	European Laboratory Astrophysics
PHY11	European Virtual Observatory
PHY13	Integrated Activities for High Energy Astrophysics Domain
PHY15	Optical-Infrared Coordination Network for Astronomy
PHY16	European Network for Solar Physics
PHY17	European Nuclear Science and Applications Research
PHY18	European Planetary Science Network
PHY19	Integrating activity in the domain of underground science

Social Sciences and Humanities:

Acronym	Topic title
SSH01/SSH17	European RI for Restoration and Conservation of Cultural Heritage
SSH02	RI for the Study of Industrial and of Labour Heritage in contemporary society
SSH03	RI for the Study of Religions in Europe
SSH05	Contemporary European History: European Holocaust Research Infrastructure
SSH07	RI for the cost-benefit analysis in support for research on social and fiscal policy measures
SSH08	RI on European Historical Population Research
SSH10	RI for the European Rock Art Research Archives
SSH11	Generations and Gender: A cross-national longitudinal data infrastructure for research on social cohesion and social inclusion
SSH13	Research Infrastructure for Citizen Science Outreach and Crowd Sourcing in the Social Sciences and Humanities
SSH15	RI for studying the role of intangible investment for economic growth
SSH18	RI for the Scientific Study of Music in Europe (Connecting Industry, Research and Users through Music)
SSH19	RI for Elections Studies in Europe
SSH23	RI for the study of the cultural role of historical inscribed materials
SSH24	RI for the Study of Slavery and its Legacies.

MICROKELVIN: European Microkelvin Collaboration

It is an unfortunate truth that electronics has not had any innovations in close to a decade – a change is needed. Coherent electron circuitry could be this change. However, coherent electron circuitry needs larger electron scattering lengths and high levels of purity. Therefore there is a need to work at extremely low temperatures – milli- and microkelvin levels – to reduce thermal scattering. While there is strong demand for very low temperature facilities, there is a lack of expertise and infrastructure to have greater microkelvin experiments. As such, MICROKELVIN is working to integrate Europe's microkelvin facilities and place them at the disposal of the wider research community.

QUANTUM PHENOMENA ARE 'COOL'

A central aim of nanoscience experiments is to reach the regime where quantum phenomena begin to govern the behaviour of the system. This promises to allow new generations of properties and devices just as conventional microcircuits are running up against the physical limits of further miniaturisation. While quantum behaviour can be observed in very small samples at relatively high temperatures, it becomes much more apparent as the temperature is lowered.

The expense of microkelvin facilities has hitherto been a deterrent to conducting nanoscience experiments in this temperature realm. As such, the primary objective of the MICROKELVIN project is to open up existing European microkelvin facilities, developed for quantum fluids experiments, to allow experimental nanoscience to progress to this new temperature regime.

EXPANDING RESEARCHERS' ACCESS

A network of core and associated institutes will provide access, expertise and education for microkelvin nanoscience in Europe. As well as offering the low temperature facilities the consortium can also provide a microfabrication capability very closely positioned to the access facilities. It is envisaged that the access-giving facilities will yield a total of 20 months of visitor time per year for collaborating scientists.

MICROKELVIN's improved infrastructure will give the wider science community access to milli- and microkelvin facilities which will, in turn, foster the development of new techniques and materials to bring coherent structures into a completely new temperature regime.

The ultimate goal of the MICROKELVIN project is to create a virtual microkelvin 'laboratory without walls'. This will allow more researchers access to the information and data gathered at the consortium's facilities and advance research in electronics and quantum phenomena. Bringing together top researchers from across Europe will enable MICROKELVIN to pool existing research and knowledge and project it outwards by creating new stand-alone machines that can access the 'virtual laboratory' from anywhere. Such technology will increase commercial interest and benefit the field of microkelvin field as a whole.

SEVENTH FRAMEWORK PROGRAMME

EUROPEAN COMMISSION

Project acronym: MICROKELVIN

Funding scheme (FP7): Integrating Activities (IA)

EU financial contribution: €4.2 million
EU project officer: Maria Douka

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Completion date: 31 March 2013

Partners:
Helsinki University of Technology (FI)
Centre National de la Recherche Scientifique, Grenoble (FR)
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EUROPEAN COMMISSION