welcome to the
European Microkelvin Collaboration

CAPACITIES

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:

September, 2011

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

Period covered: from 1.10.2010 to 31.3.2012

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):

  ☐ 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[3].

  ☐ 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/)
- 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.

Matti Krusius

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

Matti Krusius

Date: 6/6/2012

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

[3] 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 carried out in the FP7 Capacities Specific Programme "Research Infrastructures". Its goal is to promote the sub-millikelvin temperatures as a new frontier of research, by providing access to and developing applications in the ultra-low temperature regime. The work is divided in four Networking Activities (NAs), four Joint Research Activities (JRAs) and four Transnational Access Activities (TAs). The project brings together three leading European ultra-low temperature laboratories at Aalto University (Helsinki), CNRS (Grenoble), and Lancaster University, to create "a European laboratory without walls" which offers microkelvin expertize and facilities to external users. Associated with the three core institutions are eight European laboratories and one cryogenic business, 12 partner organizations in total. The objectives and results of these activities during the second 18-month project period will be described below in this second Periodic Project Report.

The quest to study properties of materials 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 much of the technology is known which is required to perform measurements at temperatures below a few tens of millikelvin where the conventional regime of the ^{3}He-^{4}He dilution refrigerator ends. However, often enough expertize is missing and the use of the ultra-low temperatures is prevented by a high threshold in practice. The goal of Microkelvin is to facilitate this step. In particular, research in nanosciences, materials physics, particle physics, cosmology, and instrumentation 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 12 partners to integrate the European microkelvin infrastructure and to make better use of our combined expertise which we believe to represent the leading edge of this discipline 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 the progress in these endeavours, 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)
Project Manager: Katariina Toivonen (email: katariina@neuro.hut.fi)
Project WEB-officer Matti Laakso (email: matti.laakso@aalto.fi)

Progress of the Microkelvin Collaboration

Microkelvin promotes new alternatives in physics research through the use of ultra-low temperatures and by providing access to research infrastructure which makes this possible. To achieve this goal, three 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. Examples from the past 18-month period are the "Microkelvin Workshop and User Meeting" of 2011 (Fig. 1) and 2012 (Fig. 2), which both were organized by the NA3 activity leader Peter Skyba in Smolenice Castle near Bratislava. The NA4 activities involve the founding 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 at first hand in the three institutions for up to three months. The visits are carefully discussed and planned in advance, to provide the visitor the maximum gain from his stay. In total, access was provided to 26 users from 22 different user groups for 22 user months. The users came from 14 different EU or associated countries. Over the past 3-year period the total of the delivered user months amounts to 70 % of the minimum total user months foreseen.
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 Attacking fundamental physics questions with microkelvin condensed-matter experiments
JRA4 Novel methods and devices for ultra-low-temperature measurements

Fig. 1. Participants of the 2011 Microkelvin Workshop and User Meeting in Smolenice Castle of the Slovak Academy of Sciences, 14 – 18 March, 2011.

JRA1: In this work packge MICROKELVIN is developing new concepts for efficient refrigeration and simultaneously building up refrigeration capacity in the collaborating laboratories. For instance, electronic sensors and devices have proven difficult to cool to the lowest dilution refrigerator temperatures of order 10 mK and have never yet been reliably cooled to the sub-mK regime. A new scheme has been devised where the electrical leads to the sensor are individually carefully filtered and thermalized to the different cooling stages of the dilution refrigerator and finally are also actively cooled below the mixing chamber, each with its own nuclear coolant. This approach is expected to yield in the nearest future a new record for cooling conduction electrons in planar on-chip micro-fabricated devices. The highlight so far without nuclear cooling provisions has been to reach a temperature of 7.5 mK with these techniques in a Coulomb blockade thermometer consisting of a metallic superconducting tunnel junction array.

Another goal is to combine adiabatic nuclear demagnetization cooling with pulse-tube-cooler precooled ^3He-^4He dilution refrigeration. Currently our industrial partner ***Bluefors*** is selling approximately 20 units annually of such automated dry dilution refrigerators. This is roughly one third of the world production. The combination of a cryogen-free and fully automated refrigeration apparatus with nuclear cooling, and all behind "push-button operation", will make the sub-mK regime both practical and more appealing for nanosciences. Several of such refrigeration installations have been now commissioned from BlueFors and are in the construction phase. Owing to delays, for instance in the delivery of dry superconducting high-field magnets (which are not fabricated by BlueFors), the first two are currently behind schedule, but running tests are expected to start soon. Of central interest are measurements of the cooling properties and the heat leak to the nuclear cooling stage from the mechanical vibrations transmitted by the pulse tube cooler.

Fig. 2. Participants of the 2012 Microkelvin Workshop and User Meeting in Smolenice Castle of the Slovak Academy of Sciences, 18 – 24 March, 2012.

In parallel, a further concerted effort calls for the construction of a large-scale low-heat leak nuclear refrigeration installation of more traditional make up, but with ambitious technical specifications. This apparatus is designed to provide an efficient environment for the μK-temperature cooling of nano-structured samples and devices, using the most advanced filtering and thermalization techniques.

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 promise to make microcooler operation 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. During the past 18-month period these have involved the turbulent flow of quantized vortex lines in the zero-temperature limit of superfluid ^{3}He-B, the Bose-Einstein condensation of magnons or spin-wave excitations in a magnetic trap formed by the order parameter texture in ^{3}He-B, the identification of BCS pairing states of superfluid ^{3}He in a nano-fabricated restricted geometry between two smooth parallel plates with different separations, and the development of new detectors suitable for the measurement of charge-neutral elastic scattering events with utmost sensitivity, as needed for dark-matter detection, for instance. A celebrated new result from the study of elastic collisions in liquid ^{3}He at intermediate energies is the identification of a roton-like excitation branch in the 2-dimensional Fermi-liquid state of ^{3}He with neutron diffraction techniques.

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 demands 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.

Microkelvin had a slow start initially owing to the fact that the EU project grant became available only four months after the starting date. Nevertheless, ¾ of the deadlines had been achieved at the first 18-month review point. At the present second review point of 36 months more than ⅔ of the deadlines have been achieved in time. The remaining ones are delayed for various practical reasons, but are all in a state of active progress. We anticipate that by the end of the four-year grant period or shortly after most, if not all, of the goals will have been met. Microkelvin is well on its track! The individual deadlines and the level of their achievement are reviewed below, with reference to the work plan of ANNEX I (according to the version in the amendment request from September 2011).

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

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 second 18 month project period from 1 October, 2010 to 31 March, 2012.

NA2

Name of the activity (work package): **Coordination of transnational access**
Reporting Period: **from 1.10.2010 to 31.3.2012**
Activity leader: **Matti Krusius (AALTO)**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead benefici-ary	Estimated person months	Nature	Dissemi-nation level	Delivery date
D1	User meetings (Proceedings)	NA2	Aalto CNRS ULANC	2	R	PU	13,37 (24,48) **achieved**

Expected milestones on the reporting period

List and schedule of milestones					
Milestone number	**Milestone name**	**WPs no's**	**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. However, the total of delivered access months is only ⅔ of the target value. To improve our chances to reach the set goals, Microkelvin has applied for a 6-month extension of the grant period from 31 March to 30 September in 2013 (without increase in overall funding).

Task: Coordination of Access

In NA2 the Microkelvin Collaboration coordinates the access to the three access giving sites. The goal is a minimum of 81 facility months of total access during four years. This should be distributed among 45 user groups and their 60 different users. The table below lists the access provided up to March 31, 2012. The total amounts to 41.2 facility months which corresponds to 68 % of the target value of 60.7 months for a period of 36 months. The number of different User Groups and their different users amounts to roughly one half of the target values.

In-house ultra-low temperature measurements require careful planning, lengthy construction work, and often several preliminary cool downs before all aspects of the measurement function in the desired manner. Therefore many of the different access-receiving projects tend to continue over several visits and the total access time per project has been approaching the 3-month limit permitted for each User Group. In addition, much of the work is continued between visits at the home institutions of both the User Groups and the personnel of the access-providing laboratory. Many of the collaborative efforts have also evolved from in-house projects at the access-giving site, which have been recast as collaborations, where the User Group provides some additional special expertize. The bonus from such extended cooperation cannot be underestimated and the large amount of work invested in these collaborations has paid off in the form a number of joint publications, as listed below.

List of access provided

	First 18-month period			Second 18-month period			3-year total	4-year goal
Site	Months	User groups	Users	Months	User groups	Users	Months	
AALTO	13.1	8	9	10.9	11	12	24.0	$\geq$ 27
CNRS	3.6	4	6	8.3	6	6	12.0	$\geq$ 27
ULANC	2.0	2	3	3.3	5	8	5.3	$\geq$ 27
18-mo total	18.8	14	18	22.5	22	26		
3-year total	41.3	23	38					
4-year goal	81	45	60					

Task: Meetings of the Selection Panel

The planning of the collaborative projects, which seek access, is supervised and approved by the Selection Panel. The discussions are carried out primarily by email. Typically the applications for access have been widely discussed and carefully planned before they reach the Selection Panel. Thus they require little interference from the Selection Panel members and projects are rarely turned down. The approved applications for visits to the access sites 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 second 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:

- Kick-Off Meeting April 3, 2009
- User Meeting, October 16, 2010, with 18-month Periodic Review Report
- User Meeting, March 17, 2011
- User Meeting, March 21, 2012, with 36-month Periodic Review Report

Task: User Meetings

The User Meetings are listed above. Related meetings and workshops on selected topics have been listed 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 next final workshop and user meeting with proceedings will be organized either in Lancaster or in Helsinki in 2013.

User sessions, where invited Users present in the form of a 30 min talk the results from their work at the access laboratory, have been arranged at all User Meetings. Special training sessions, to introduce new techniques, have been organized for new users at two User Meetings.

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 at its workshops, see programme of User Meeting March 18 – 24, 2012 on page

http://ltl.tkk.fi/wiki/Events/Microkelvin_2012/Program

and in the joint publications listed below which have resulted from the work based on the access programme.

Deviations from work plan The access provided in facility months is only 2/3 of the target value.

Use of resources follows otherwise the original plans.

Publications on joint work between Users and personnel at access sites from 1.10.2010 to 31.3.2012

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*", preprint on arxiv: cond-mat/1111.197.
2. S. Gasparinetti, F. Deon, G. Biasiol, L. Sorba, F. Beltram, and 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).
3. 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, and D.R. Leadley, *Strain dependence of electron-phonon energy loss rate in many-valley semiconductors,* Applied Physics Letters **98**, 182103 (2011).
4. J.P. Pekola, V.F. Maisi, S. Kafanov, N. Chekurov, A. Kemppinen, Yu.A. Pashkin, O.-P. Saira, M. Möttönen, and J.S. Tsai, *Environment-Assisted Tunneling as an Origin of the Dynes Density of States,* Phys. Rev. Lett. **105**, 026803 (2010).
5. 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).
6. M. Meschke, J. T. Peltonen, J. P. Pekola, and F. Giazotto, *Tunnel Spectroscopy of a Proximity Josephson Junction*, Physical Review B **84**, 214514 (2011).
7. 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).
8. H. Q. Nguyen, L. M. A. Pascal, Z. H. Peng, O. Buisson, B. Gilles, C. Winkelmann, Hervé Courtois, *Etching suspended superconducting hybrid junctions from a multilayer*, arXiv:1111.3541v1 (2011).

9. N. Vercruyssen, T.G.H. Verhagen, M.G. Flokstra, J.P. Pekola, and T.M. Klapwijk, *Evanescent states and non-equilibrium in driven superconducting nanowires*, submitted to Phys. Rev. B.

10. 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 $T \longrightarrow 0$: Decoupling from the reference frame,* Phys. Rev. Lett. **107**, 135302 (2011).

11. 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 ^{3}He-B,* Phys. Rev. Lett. **105**, 125301 (2010).

12. 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 and P. Williams, *A New Device for Studying Low or Zero Frequency Mechanical Motion at Very Low Temperatures,* Journal of Low Temperature Physics **165**, 114-131 (2011).

13. J.J. Hosio, V.B. Eltsov, R. de Graaf, M. Krusius, J. Mäkinen, and D. Schmoranzer, *Propagation of thermal excitations in a cluster of vortices in superfluid 3He-B,* Phys. Rev. B **84**, 224501 (2011).

14. P.M. Walmsley, V.B. Eltsov, P.J. Heikkinen, J.J. Hosio, R. Hänninen, and M. Krusius*, Turbulent vortex flow responses at the AB interface in rotating superfluid 3He-B,* Phys. Rev. B **84**, 184532 (2011).

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

16. S. Autti, Yu.M. Bunkov, V.B. Eltsov, P.J. Heikkinen, J.J. Hosio, P. Hunger, M. Krusius, and 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).

17. S. Holt and P. Skyba, *Electrometric DC I/V converter with wide bandwidth*, Rev. Sci. Instr. in print (2012).

18. *Observation of zero-sound at atomic wave-vectors in a monolayer of liquid ^{3}He*, H. Godfrin, M. Meschke, H.-J. Lauter, H.M. Böhm, E. Krotscheck, M. Panholzer, J. Low Temp. Phys. **158**, 147-154 (2010).

20. *Reemergence of the collective mode in ^{3}He and electron layers*, H.M. Böhm, R. Holler, E. Krotscheck, M. Panholzer, H. Godfrin, M. Meschke, H. J. Lauter, International Journal of Modern Physics B (IJMPB) Volume: **24**, Issues: 25-26 (2010) pp. 4889-4900 DOI: 10.1142/S0217979210057079.

21. *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, and M. Panholzer, Journal of Physics: Conference Series **340**, 012078 (2012).

22. *Observation of a roton collective mode in a two-dimensional Fermi liquid*, Henri Godfrin, Matthias Meschke, Hans-Jochem Lauter, Ahmad Sultan, Helga M. Böhm, Eckhard Krotscheck, and Martin Panholzer, Nature **483**, 576–579 (29 March 2012), doi:10.1038/nature10919.

NA3 Report

Name of the activity: **Knowledge and technology transfer**
Reporting Period: **from 1.10.2010 to 31.3.2012**
Activity leader: **Peter Skyba**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead benefici-ary	Estimated person months	Nature	Dissemi-nation level	Delivery date
D2	LT-X workshops (18, 28, 40, 44) and Industrial meeting (32) with reports	NA3	All partners		R	PU	18, 28, 32, 40, 44

Expected milestones on the reporting period: None

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 second Dissemination Committee meeting took place during the Microkelvin General Assembly in Smolenice, March 2011. The third meeting was held in March 2012, during the 2012 Microkelvin General Assembly. This completes the work foreseen in the Deliverables. However, additional GA meetings will be held in August 2012 in the context of the QFS2012 Conference in Lancaster and the final GA is planned for March 2013, when the Microkelvin grant programme finishes.

During these meetings, the Dissemination Committee examines the dissemination activities undertaken during the previous period, and issues recommendations for the following period. The main activities concern organizing special low temperature sessions at international meetings, lectures for the general public, and arranging Cryocourses and Cryoconferences for students and young researchers, which provide training in low temperature physics and techniques.

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 dissemination actions pointing towards different scientific communities, to industrial partners, and to the general public.

The Microkelvin web page www.microkelvin.eu is an active tool, open to external and internal users, where publications, technical reference material, information about Microkelvin and related scientific events (see below) are continuously updated.

The Microkelvin workshops constitute an important channel for dissemination; they are open to external participants, and the Users of the Microkelvin facilities are invited to present their results at these meetings.

Task 2. Dissemination of low temperature technology

Dissemination of low temperature technology and low temperature “know-how” between partners and users is realised as part of the Transnational Access (TA) Programme. Altogether 44 projects were accepted within TA1, TA2, and TA3 activities, since Microkelvin started. In addition, the Joint Research Activities are an outstanding example of low temperature “know-how” dissemination. Task 2 is running continuously.

The CryoTools data base is evolving continuously, since technical material is continuously collected.

Fig. 1. *14th International Workshop on Low Temperature Detectors (LTD-14).*

Three LT-X workshops were realised during this reporting period (see list and details below) on the following areas: methods, particle detectors, and nanoscience.

During this reporting period, we invited a group of leading industrial partners to join a cryogenics consortium, with the objective to improve training and dissemination. Cryosupport, Thales Cryogenics, Magnicon Gmbh, Oxford Instruments Nanotechnology Tools Ltd, and Air Liquide Advanced Technologies presently participate in the consortium. The Proposal (see below) constitutes an additional and important milestone within the present Task. The formal Industrial Meeting had to be postponed by a few months, given the schedule of the Marie Curie ITN proposal.

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

Task 3. Networking with other scientific communities

Microkelvin networking activities have been proceeding as planned. The events have been listed on the Microkelvin web pages at www.microkelvin.eu in the "Events" folder. The following meetings and workshops have been organized:

Reporting Period 01/10/2010-31/03/2012	Date	Year	Place	Country	Activity	Microkelvin reference
JRA4 Meeting in Heidelberg	Nov 5	2010	Heidelberg	Germany	JRA4	LT-Methods and devices I
Microkelvin general assembly and user meeting 2011	March 14-18	2011	Smolenice	Slovakia	NA-TA-JRA	GA &Users Meeting II
14th International Workshop on Low Temperature Detectors (LTD-14)	August 1-5	2011	Heidelberg	Germany	NA	LT-particle detectors I
Cryocourse 2011	Sep 18-27	2011	Grenoble	France	NA2	Training session I
Nanophysics at Low Temperature @ CMMP11 Symposium	Dec13-15	2011	Manchester	UK	NA	LT-Nano III
Microkelvin general assembly and user meeting 2012	March 18-24	2012	Smolenice	Slovakia	NA-TA-JRA	GA &Users Meeting III

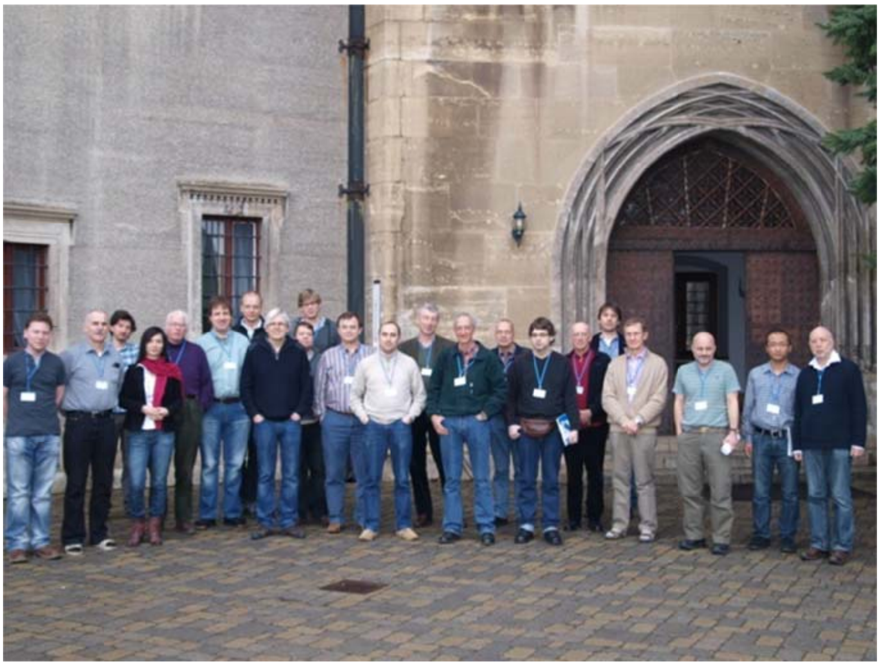

Fig. 2. *Microkelvin 2011 GA & Users meeting, Smolenice*

Microkelvin 2011 GA & Users meeting, Smolenice, 14 – 18 March, 2011
Institute of Experimental Physics, SAS Kosice, Slovakia
Number of participants: 26

14th International Workshop on Low Temperature Detectors (LTD-14)
Heidelberg, Germany, 1-5/08/2011
Number of participants: 305
Proceedings with 160 articles in 4 issues: JLTP **167,** coming out May/June 2012

MicrokelvinJRA4 Meeting in Heidelberg
Kirchhoff-Institut fürPhysik, Heidelberg University, Germany, 5/11/2011.
Number of participants: 15

Nanophysics at Low Temperature @ CMMP11 Symposium
Manchester, UK, December 12-15, 2011
Number of participants: 357

Cryocourse 2011: European Advanced Cryogenics Course
Grenoble and Chichilianne, France, September 18-27, 2011
Number of participants: 44 students and 23 teachers

***Fig. 3**. European Advanced Cryogenics Course 2011*

Task 4. Industry - research network

A European proposal for an Integrated Training Network (FRP7 ProposalCryocourse) was established by the Consortium described above, and submitted to the Marie Curie Initial Training Networks (ITN) Call: FP7-PEOPLE-2012-ITN in January 2012. Cryosupport, Thales Cryogenics, Magnicon Gmbh, Oxford Instruments Nanotechnology Tools Ltd, and Air Liquide Advanced Technologies, as well as our partner Bluefors are presently participating in this Industry-Research network.

Task 5. Dissemination to public audiences

Results from the work achieved within the Microkelvin Collaboration have been presented in a number of workshops, meetings and conferences as invited plenary talks, contributed talks, and posters. Below we list some examples of invited talks**:**

Jukka Pekola*: Coupling of electrical circuits to photon, phonon and electron environments,* The 7th Rencontres de Moriond on Quantum Mesoscopic Physics*,* 13.-20.3.2011, La Thuile, Italy, http://www-moriond2011-mesophysics.cea.fr/

Jukka Pekola*: Coupling of an electric circuit to environment and statistics of generated heat in driven single-electron transitions*, Thermodynamics: Can macro learn from nano? 23.-25.5.2011, Lund, Sweden, http://homepages.ulb.ac.be/~mesposit/org-site-test/welcome.html

Jukka Pekola: *Real-time observation of discrete Andreev tunneling events - influence on a single-electron turnstile and electron coolers*, LT26, Beijing, 2011

Jukka Pekola: *Residual quasiparticles, Andreev current and photon-assisted tunneling in Coulomb blockaded normal-superconductor junctions*, Superconducting hybrids: from conventional to exotic, 7.-10.9.2011, Villard de Lans, France http://inac.cea.fr/Pisp/julia.meyer/workshop2011.html

Jukka Pekola: *Fluctuation relations in driven single-electron transitions: theory and preliminary experiments*, 24th Marian Smoluchowski symposium on statistical physics, 17.-22.9.2011, Zakopane, Poland, http://th-www.if.uj.edu.pl/zfs/smoluchowski/

J. Pekola, *Work, heat and fluctuation relations in single-electron transport,* Kapitza seminar*,* 22.12.2011, Kapitza Intitute for Physical Problems, Moscow, Russia

Eddy Collin: *Microkelvin JRA4 in Grenoble*, Microkelvin JRA4 meeting, Heidelberg, 05/11/2010.

Eddy Collin: *Micro and Nano mechanics at ultra-low temperature*, France-Japan Collaboration Workshop, RIKEN Low Temperature Laboratory, 17/01/2011, Tokyo, Japan.

Eddy Collin: *Micro/nano mechanics at very low temperatures*, Topical Meeting on Nanomechanics, 23 June 2011, Institut Néel, CNRS-Grenoble, France

Eddy Collin: *MEMS and NEMS probes for low temperature physics: a nonlinear issue*, OMNT meeting on Nanomechanics, 4-5 July 2011, Toulouse (France).

Eddy Collin: *Low temperature nanomechanical probes: from linear to nonlinear regimes*, The 26th international conference on low temperature physics (LT26), Beijing, China, 10-17 August, 2011.

Eddy Collin: *Micro/nano mechanics at low temperatures: a nonlinear issue*, CMMP11 conference, 13 - 15 December 2011, Manchester, UK

Henri Godfrin: *Zero-sound collective mode observed in two-dimensional liquid 3He using inelastic neutron scattering*, 23rd General Conference of the Condensed Matter Division of the European Physical Society, Warsaw, Poland, 30/08-3/09, 2010

Henri Godfrin: *Two-dimensional Fermi liquids sustain surprising roton-like plasmons beyond the particle-hole band*, 5th European Conference on Neutron Scattering (ECNS2011), Prague, Czech Republic, July 17-22, 2011

Henri Godfrin: *Fermi liquid 3He: topology and elementary excitations*, Topological Materials, Institut Laue Langevin, Grenoble, 26-28 October 2011

Henri Godfrin: *Observation of a roton-like collective mode in a Fermi liquid beyond the particle-hole band using inelastic neutron scattering*, International Conference on Recent Progress in Many-Body Theories, Bariloche, Patagonia, Argentina, Nov. 28 to Dec. 2 2011

Topological superfluids confined in a regular nano-scale geometry, J. Saunders, R.G. Bennett, L.V. Levitin, A.J. Casey, B. Cowan, J.M. Parpia, D. Drung & Th. Schürig, German Physical Society Spring Meeting, Berlin, March 2011

Surface of a p-wave superfluid: NMR studies of superfluid 3He in sub-micron thick slabs, L.V. Levitin, R.G. Bennett, A.J. Casey, J. Saunders, J.M.Parpia, D. Drung & Th. Schürig, Strongly Correlated Electron Systems 2011, Cambridge, Aug 30- Sep 3, 2011

Superfluid 3He in confined nanoscale geometries and the quest for majorana fermions, J. Saunders Advanced Working Group: Experimental probes for topological materials, RHUL, Feb 2011

Topological Insulators and Superconductors, J. Saunders, Kavli Institute for Theoretical Physics, Santa Barbara

Superfluid 3He confined in controlled nanofabricated geometries, J. Saunders, ERC Symposium Quantum Puzzle, Vienna, June 22, 2011

Quantum transport on mesoscopic 3He films, P. Sharma, R.G. Bennett, A. Corcoles, J.M. Parpia, B.P. Cowan, A.J. Casey, J. Saunders, European Microkelvin Workshop, Smolenice, March 2011

Experiments on superfluid 3He in controlled nanofabricated geometries: model system for topological quantum matter, J. Saunders, Inaugural Scientific Meeting of Topological Protection and Non-Equilibrium States in Strongly Correlated Electron Systems (TOPNES), Nov 22-23 2011

Experiments on superfluid 3He in controlled nanofabricated geometries: model system for topological quantum matter, L.V. Levitin, R.G. Bennett, A.J. Casey, J. Saunders, J.M. Parpia, D. Drung & Th. Schürig Topological Insulators and Superconductors, Kavli Institute for Theoretical Physics, Santa Barbara Sep 19-Dec 16, 2011

Microkelvin JRA4 in RHUL, A.J. Casey, Microkelvin JRA4 meeting, Heidelberg, Nov 5 2010

Superfluid phases of 3He confined in a slab, L.V. Levitin, R.G. Bennett, A.J. Casey, B. Cowan, J. Saunders, J.M.Parpia, E Surovtsev, 26th International Conference on Low Temperature Physics, Beijing, August 2011

Superfluid 3He in confined nanoscale geometries and the quest for majorana fermions, J. Saunders, Advanced Working Group: Experimental probes for topological materials, RHUL, Feb 2011

Microkelvin JRA4 in RHUL, A.J. Casey, Microkelvin JRA4 meeting, Heidelberg, Nov 5, 2010

Invited talks by John Saunders on the above the results at the following meetings. **2012**: German Physical Society Spring Meeting, Berlin (JS). **2011**: Topological Insulators and Superconductors, Kavli Institute for Theoretical Physics, Santa Barbara (JS). Inaugural Meeting of TOPNES, St Andrews (JS). International Conference on Low Temperature Physics (LT26), Beijing (LVL). Strongly Correlated Electron Systems, Cambridge (JS). ERC Symposium Quantum Puzzle, Vienna (JS). Advanced Working Group on Experimental Probes for Topological Materials, RHUL (JS)

Talks given by S. Fisher, R.P. Haley, G.R. Pickett, and V. Tsepelin:

Invited Talk on *Direct measurement of energy dissipation from decaying Quantum Turbulence in 3He-B at ultralow temperatures*, Grenoble, France, 2-6 August 2010

Topological Materials, Invited Talk on *"Experiments on Quantum Turbulence in superfluid 3He at very low temperatures"*, Grenoble, France, 26-28 October 2011

European Advanced Cryogenics Course 2011, Cryo-users meeting on 7 Sep 2011

Workshop on Classical and Quantum Turbulence, Invited Talk on *"Experiments on homogeneous quantum turbulence in 3He: what do we really know, and what can we hope to do in the future?"* Abu Dhabi, United Arab Emirates, 2-5 May 2011

LT26, Invited Talk on *"Experiments on Quantum Turbulence in Superfluid 3He-B at very low temperatures"* Beijing, China, 10-17 August 2011

P. Skyba, Microkelvin Workshop 2011, *On the spin dynamics of the Q-ball resonance in Superfluid 3He-B,* Smolenice, Slovakia, March, 2011,

P. Skyba, Seminar in the Department of Physics of the Slovak Technical University, *Symmetry breaking in Physical Systems and in Superfluid 3He-B,* Bratislava, Slovakia, October, 14th, 2011

P. Skyba, LT26, Invited Talk, *Anomalous spin relaxation and quasiparticle damping in superfluid 3He-B at* $T \rightarrow 0$, Beijing, China, 10-17 August 2011

Invited talks by Christian Enss:

Investigation of the dephasing of tunneling systems in glasses using two-pulse polarization echo experiments, Keynote Lecture: 26th International Conference on Low Temperature Physics LT26, 13 August 2011, Beijing, China

Metallic Magnetic Calorimeters: New Developments and Applications, High Energy Physics Seminar: 22 August 2011 Seoul National University, South Korea

Metallic Magnetic Calorimeters: New Developments and Applications, Seminar: 20 August 2011 Korea Research Institute of Standards and Science, Daejeon South Korea

Non-equilibrium quantum systems - glasses at ultra-low temperatures, Physics Colloquium, 2 March 2011, Tulane University New Orleans, USA

Novel Ways in Particle Detection: Micro-Calorimetry at Low Temperatures, Physics Colloquium, 3 June 2011, Universität Karlsruhe

Non-equilibrium quantum systems - glasses at ultra-low temperatures, QFS2010: International Symposium on Quantum Fluids and Solids, 1. – 7. August, 2010 , Grenoble, France

Nuclear Spins Reveal the Microscopic Nature of Tunneling Systems in Glasses, Spring Meeting German Physical Society, 21 – 26 March 2010, Regensburg

Glasses at Ultra-low Temperatures: Interplay of Atomic Tunneling Systems and Nuclear Magnetic Moments, International Congress on Glass, 20. – 25. September 2010, Salvador, Brasilien

Metallic Magnetic Calorimeters: New developments and applications, 21st International Conference on the Application of Accelerators in Research and Industry, 8 – 13 August 2010, Ft. Worth, USA

Ultra-Cold Glasses and their Mysteries International Symposium: From Superfluid 3He to Glasses, Honouring D. Osheroff, 24 October 2010, Stanford, USA

Tunneling Systems in Glasses at Ultralow Temperatures, KITP Conference: Out-of-Equilibrium Quantum Systems, 23 – 27 August 2010, Santa Barbara, USA

Gläser bei ultratiefen Temperaturen - Kernmomente lüften das Geheimnis der Tunnelsysteme in amorphen Festkörpern, Physics Colloquium, 9 November 2009, LMU München

Neue Wege in der Teilchendetektion – Kalorimetrie bei tiefen Temperaturen, Physics Colloquium, 2 December 2009, Universität Tübingen

Gläser bei ultratiefen Temperaturen - Kernmomente lüften das Geheimnis der Tunnelsysteme in amorphen Festkörpern, Physics Colloquium, 8 December 2009, Universität Bayreuth

Thomas Schurig, *State-of-the-art superconducting quantum interference devices for electrical and magnetic measurements at low and very low temperatures,* Seminaire Daniel Dautreppe de la Societé Francaise de Physique, Grenoble, Nov 21-25, 2011

Public lectures and other dissemination Activities in Basel

February 2012 Basel Science Times, Pod-Cast interview with D. Zumbuhl, *Low temperature physics and quantum computation.*

November 2011 Lab tour for "Young Physicists Form" Switzerland.

October 2011 Lecture for Nanoscience I students, Uni Basel, *“Nanotechnologie fuer den Quantenrechner der Zukunft”*

March 2011 Gymnaisum Leonhard, Basel, *“Nanotechnologie fuer den Quantenrechner der Zukunft”,* two lectures for high-school students

November 2010 Lecture for Nanoscience I students, Uni Basel, *“Nanotechnologie fuer den Quantenrechner der Zukunft”*

November 2010 Freie Akademische Gesellschaft Basel, *“Auf dem Weg zum Quantencomputer”*

Public lectures in Lancaster: Two lectures for the public at Cafe Scientifique: Cockermouth on 17 Jan 2012, and Pendle on 6th June, 2011

Institute of Experimental Physics, SAS: February 24th, 2011 Cosmology in a droplet of superfluid helium, public talk (see web page: www.hodinavedy.sk).

Advertisement of public lecture

Photographs illustrating Researcher’s night in Kosice. Public presentations at the Hypernova store in Kosice: exhibitions, including low temperature physics – from 13:00 to 21:00 – more than 7000 visitors

Highlights

- Three scientific workshops, one training course and many management meetings 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
- Advertisement and dissemination of Microkelvin activities for public audiences during "open days", public lectures, visits and lectures in various schools, etc.
- We plan to organize two additional network meetings: one at Lancaster, UK, as a part of QFS 2012 conference, and the second, closing workshop in Helsinki in March 2013.

Reports

- Proceedings of the International Symposium on Quantum Fluids and Solids, Grenoble, France, August 2-7, 2010, two issues of Journal of Low Temperature Physics volume **162**, N°3/4 and N°5/6 (2011).
- 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).

Deviations from work plan – none

Use of resources – use of resources follows the work plan

NA4 Report

Name of the activity: **Strengthening European low temperature research**
Reporting Period: **from 1.10.2010 to 31.3.2012**
Activity leader: **Henri Godfrin (CNRS)**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead bene-ficiary	Estimated person months	Nature	Dissemination level	Delivery date
D2	Report on the European Cryogenic Society and Third Countries Network	NA4	CNRS	1	R	PU	36 **achieved**
D3	Ultralow temperatures forecast report	NA4	ULANC	1	R	PU	36 **partially achieved**

Milestones on the reporting period - None

Summary

This networking activity aims to strengthen the European low temperature research, in co-ordination with 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)

The Low Temperature Section formed within the European Physical Society during the first reporting period has been operating satisfactorily since then, contributing to the coordination of the low temperature community, and participating actively in the activities of the Condensed Matter Division of the European Physical Society. In collaboration with Microkelvin, the LT section has established, in particular, a list of researchers, engineers, institutions and industrial partners in Europe.

Four reports have been produced by the LT section during this period, attached to the present document as a single Annex ("2010-2011 Annual Reports of the LT section"). This document constitutes the deliverable associated to Task 1.

The LT section had regular meetings, held during the Microkelvin General Assemblies, since all its members but one, belong to the Microkelvin collaboration.

The chair of the Section participated in the CMD-EPS Board Meetings. These were held in Warsaw (September 18, 2009; April 16, 2010; August 30, 2010), and London (April 15 and September 30, 2011). The next meeting will take place in Edinburgh on April 27th. 2012.

Deliverable 2: Report on the European Cryogenic Society
(Low temperature Section of the European Physical Society) **achieved**

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

The "European - Third Countries Microkelvin Collaboration Network" has been created, with the objective to foster the collaboration in low temperature physics between European laboratories and high level laboratories abroad. The collaboration network, which we call EU-3C-Microkelvin, is administrated by the Microkelvin networking activities. During this second 18-month period several distinguished researchers have been invited to participate in Microkelvin activities.

- The "14th International Workshop on Low Temperature Detectors" (LTD-14), organized in Heidelberg (August 1-5, 2011), included two "Microkelvin Third Countries distinguished guests" from USA, Prof. Alexander Burin (Tulane University) and Prof. George Seidel (Brown University).
- The Symposium "Nanophysics at Low Temperature", organised by John Saunders on behalf of the Low Temperature Group of the IoP, and the European Microkelvin Consortium, included as Microkelvin Third Countries guest Prof. J.M.Parpia, Cornell University.
- For "Cryocourse 2011" (advanced European Cryogenics course), Microkelvin provided support to 12 bright students from Third countries (Argentina, Brazil, Ukraine, Russia, as well as one Nepalese and one Syrian students making a PhD in the USA. This action contributes to the dissemination of European science and technology and aims at attracting the best students to European universities and laboratories.

The recently created EU-3C-Microkelvin network is contributing significantly to the visibility of European science. The main activities are described above and in the previous report; a more detailed report including statistics is in progress.

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

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

The Microkelvin collaboration is interested in the creation of an official structure, a "Laboratoire Européen Associé", consisting of the Microkelvin Group at the Institut Néel in Grenoble, the Low Temperature Laboratory of the Aalto University, and the Microkelvin Laboratory of the Lancaster University. No progress along this line, however, has been made in this reporting period: Microkelvin activities had other priorities. No milestone is due at this point.

Task 4. Forecast report (ULANC and all partners)

This action is in progress. A comprehensive list of laboratories and available instrumentation has been compiled.

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

Highlights

An international conference (LTD 14), a European Conference (Nanophysics at Low Temperature), and a European School (Advanced Cryogenics Course: "Cryocourse") have been organized by Microkelvin during this period.

High level scientists from American universities and students from several countries participated in European scientific events organized by the third countries network of the Microkelvin Collaboration.

Reports

The “2010-2011 Annual Reports of the LT section” are attached as an Annex to this Report.

Deviations from work plan

– results exceed the initial programme

Use of resources

– the use of resources follows the planned programme

JRA1 Report

Name of the activity (work package): **Opening the microkelvin regime to nanoscience**
Reporting Period: **from 1.10.2010 to 31.3.2012**
Activity leader: **George Pickett**

Table of expected milestones on the reporting period

List and schedule of milestones					
Milestone number	**Milestone name**	**WPs no's**	**Lead beneficiary**	**Delivery date From Annex I**	**Comments**
M2	High conductivity cooled links to nanocircuits designed and tested	JRA1, Task 1	ULANC	30	**achieved**
M3	Nanocircuits stage installed in an access refrigerator	JRA1, Task 1	ULANC	36	**achieved**
M4	Phonon temperature on nanoscale silicon membrane measured	JRA1, Task 3	ULANC	36	**in progress**
M6	Compact microkelvin refrigerator at CNRS (BASEL) ready for access service	JRA 1, Task 2	CNRS (AALTO)	24 (36)	**in progress**
M8	Dilution refrigerator built, installed and tested	JRA 1, Task 3	ULANC	24	**achieved**
M9	Nuclear stage tested and running in dilution refrigerator	JRA 1, Task 3	ULANC	30	**in progress**

Table of expected milestones on the reporting period

List and schedule of deliverables							
Del. no.	**Deliverable name**	**WP no.**	**Lead beneficiary**	**Estimated person months**	**Nature**	**Dissemination level**	**Delivery date**
D3	Prototype of compact nuclear cooling refrigerator for access service at BASEL (Task 2)	JRA1	BASEL	20	P	PU	36 **in progress**
D4	Next-generation microkelvin facility for access service at ULANC (Task 3)	JRA1	ULANC	30	P	PU	36 **in progress**

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

Task 1. New facilitating technology for nanoscience at microkelvin temperatures

The objective of this task is the improvement in the cooling of nanosamples by increasing the thermal contact between the sample electron system and the refrigerant, and by reducing the external heat leak. The majority of this task has been carried by BASEL, ULANC and the access partner Ludwig Maximilian University, München.

The goal of the Basel activities within JRA1 is to open the microkelvin temperature regime to nanostructured samples – first in a conventional dilution refrigerator precooled nuclear stage setup (JRA1, Task 1), and later on a compact, cryofree dilution refrigerator platform (JRA1, Task 2). To achieve these goals, Basel is collaborating closely with Lancaster, Helsinki, and Bluefors. Several new technologies needed to reach microkelvin temperatures in nanosamples are being developed by Basel in JRA1 as well as in JRA2 (filtering and thermalizing) and JRA4 (quantum dot thermometer).

We employ a novel scheme for cooling electronic nanostructures into the microkelvin regime by thermalizing each sample wire directly to its own nuclear refrigerator (NR) (Clark et al, RSI 2010). In this scheme, the sample cools efficiently through the highly conducting wires via electronic heat conduction, bypassing the phonon degree of freedom since it becomes inefficient for cooling at low *T*. A prototype of this refrigerator presented in Clark et al. has been significantly improved in a 2nd generation system, briefly outlined below and in the figure. A network of 21 parallel NRs is mounted on a rigid tripod intended to minimize vibrational heating. Two separate 9T magnets allow independent control of the NR and sample magnetic field.

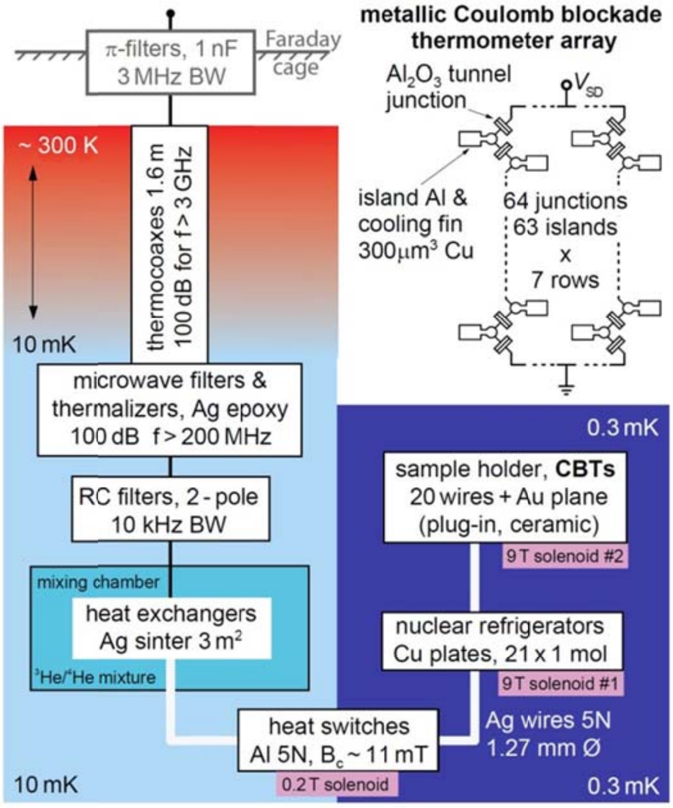

Fig. 1. Schematic of the Basel nuclear cooling system.

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 NR via spot-welded contacts, terminating in an easily-exchangeable chip-holder plugged into Au-plated pins which are spot welded to the Ag wires. Therefore, excellent thermal contact <50 mOhm is provided between the bonding pads and the parallel network of 21 Cu pieces – the microkelvin bath and heart of the nuclear refrigerator – while maintaining electrical isolation of all wires from each other and from ground, as required for nanoelectronic measurements.

The performance of the NR network is evaluated in a series of demagnetization runs and subsequent warm-up curves with power applied on heaters mounted on some of the NRs. The time the nuclear spin system needs to warm up depends on the applied power and on the nuclear spin heat capacity, which depends on material constants, temperature and magnetic field. This allows us to determine both the temperature T_{Cu} of the Cu-NRs after demagnetization as well as a small field-offset. For each demagnetization run, the NRs are precooled to ~ 12 mK in a B_i = 9 T magnetic field and then demagnetized to temperatures as low as T_f ~ (185 +/- 25) μK after the field has been slowly ramped down to B_f ~ 90 mT, giving efficiencies $T_i/T_f : B_i/B_f$ ~ 60%. Reruns showed excellent repeatability. We have therefore cooled a network of 21 Cu pieces to (185 +/- 25) μK on an advanced nuclear stage aimed at cooling nanosamples to microkelvin temperatures. This work is further described in a preprint Casparis et al., cond-mat/1111.1972.

The ULANC effort in Task 1 is related to the developments in Task 3 below and the developments are made in the context of the new machine of Task 3. 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 (Fig. 2). For engineering reasons this shielding is grounded to the steel structure of the building. Therefore there is 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 filters have been designed. 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. High frequency filters are still under construction, based on consultation with BASEL and LMU. The shielded lead system is designed to allow the cryostat to be accessible to any experimental access user, with transferable connections at helium temperatures based on miniature connectors, which has taken time to investigate, design, install and test.

Milestones

M2: High conductivity cooled links to nanocircuits designed and tested (30 mo) **achieved**

M3: Nanocircuit stage installed in an access refrigerator (36 mo) **achieved**

M4: Measurement of phonon temperature of nanoscale silicon membrane (36 mo) **?**

Highlights

- Cooled a network of 21 Cu pieces to (185 +/- 25) μK on an advanced nuclear stage aimed at cooling nanosamples to microkelvin temperatures.
- Further improved, 3rd generation Basel advanced nuclear stage has been planned and built, and is ready for installing in the Bluefors compact cryo-free dilution refrigerator

Reports:

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*", preprint on arxiv*:* cond-mat/1111.197.

Deviations from work plan

None, only delay owing to late delivery of magnet installation.

Use of resources

BASEL, Since August 2009, a senior scientist is partly funded by Microkelvin, for JRA1 activities. From October 2009 until May 2010, a postdoctoral fellow was funded by Microkelvin, including for work in JRA1. Since Jan 2011, a PhD student is partly funded by Microkelvin, including for JRA1 work.

Task 2. **Compact microkelvin refrigerator**

The objective of this task is to devise the most compact and easy-to-use microkelvin refrigerator for cooling nanosamples, exploiting existing knowledge in the consortium and the results of Task 1, with the intention of making the milli- and microkelvin expertise available to any laboratory worldwide independently of any existing cryogenic infrastructure.

The intention was that two cryogen-free machines were to be built. The first was to be built for AALTO, with BlueFors providing the dilution refrigerator, and AALTO the nuclear stage, and a second was to be built at CNRS. In the event, a decision was made to transfer the AALTO machine to BASEL for the installation of a BASEL nuclear stage which was the most developed at the time. Both these machines have experienced difficulties, owing to the high technical specification demanded. However, at dilution refrigerator level the dissemination to other laboratories has been a large success as outlined below.

The BlueFors/BASEL machine. The dilution refrigerator for this cryostat was completed long ago and tested at the Bluefors plant by the BASEL group. See figures below. This machine performed faultlessly with a base temperature of 7 mK and a cooling power according to the design specification.

Before this machine can be shipped to Basel it needs to be fitted with the double magnet system (from Scientific Magnetics). Unfortunately the company has seriously underestimated their difficulties of providing this unit, it is already 15 months late and not expected (at the best) for another two months. Further progress on this nuclear refrigeration machine awaits the delivery of the magnet combination.

However, in parallel, BASEL has continued with the design of the nuclear stage. A further improved, 3rd generation Basel advanced nuclear stage has been designed and built (based upon the 2nd generation stage described above), and is ready and waiting for installation in the cryostat when it arrives with the magnet installed.

The CNRS machine. The CNRS compact cryogen-free dilution refrigerator, installed during the previous reporting period, has been equipped with electrical wiring, necessary for measurements and access to the facility. This includes normal and superconducting wires for the operation and control of the refrigerator (carbon and RuO_2 thermometers, heaters) and similar wires for the measurement of low-level signals. Coulomb Blockade thermometers and CMN thermometers have been used during this period to calibrate the refrigerator thermometers. Coaxial lines for high frequency measurements for the very low temperatures have been installed (Fig. 3).

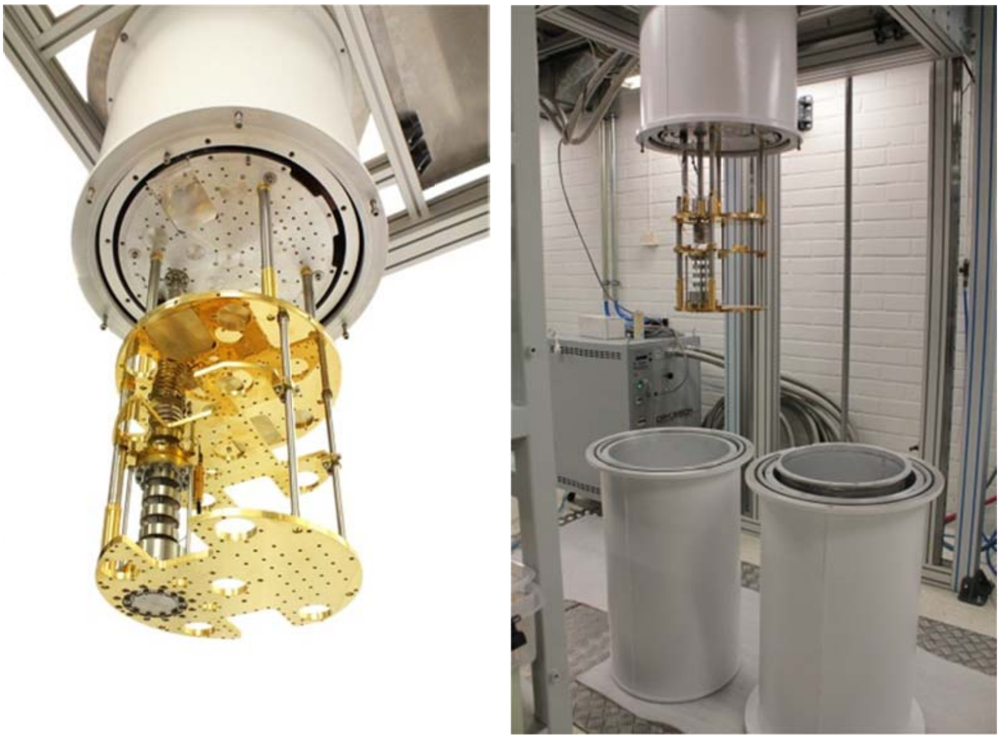

Fig. 2. Two views of the BlueFors dilution refrigerator, ready and waiting for the superconducting magnet system.

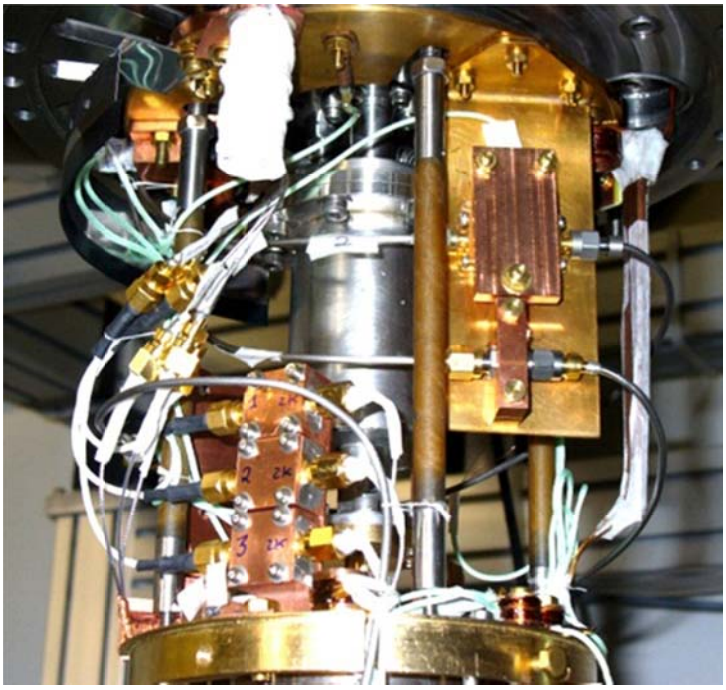

Fig. 3. The CNRS compact dilution refrigerator wiring, including high frequency coaxial lines and thermal grounds.

Fig. 4. The CNRS compact dilution refrigerator magnet.

Regarding the high current leads and superconducting magnets, two Nb-Ti superconducting magnets have been designed and tested. The CNRS design places the coil inside the Inner Vacuum Can (IVC), thus allowing a considerable reduction of the coil's size and energy. The price to pay for this ambitious design is that the superconducting coils are thermally anchored on the still radiation shield, under conditions of high vacuum. The high current leads must be brought through the IVC using leak-tight feed-throughs. While the system was previously tested with success in a conventional dilution refrigerator, our tests in the cryogen-free system revealed the major difficulty that heat cannot be extracted efficiently at the level of the insulation (Stycast 2850 FT) of the feed-throughs, resulting in a transition to the normal state of the Nb-Ti superconducting leads. The design has been changed, and testing of the new system is in progress.

The coils require high currents, on the order of 50 to 70 Amps. The current leads from the upper part of the cryostat at room temperature, to the first stage of the pulse-tube cryocooler have been made and tested. The selected material (brass) avoids the thermal escape effect, ensuring stable behaviour. From the first to the second stage (from 60 to 4 Kelvin), we use high-temperature superconductors to minimize the heat delivered to the second stage. Two types of leads were tested. The initial high-Tc silver-coated ribbons (YBCO CryoBlock2 HTS Wire) were moderately successful, but were found unsuitable owing to the fragility of the wire and the degradation of the contacts upon thermal cycling. We moved then to massive YBCO bars, as shown in the Figure below.

We are presently testing these lines with high currents, as a necessary step before the installation of the coils and the nuclear stage. The compact refrigerator is presently used for access service with a lower temperature range limited to 20 mK, and should be able to operate at sub-millikelvin temperatures as soon as the high current lines problems are solved. A user's proposal (SQUID amplifiers for NEMS at very low temperatures) is presently finalized.

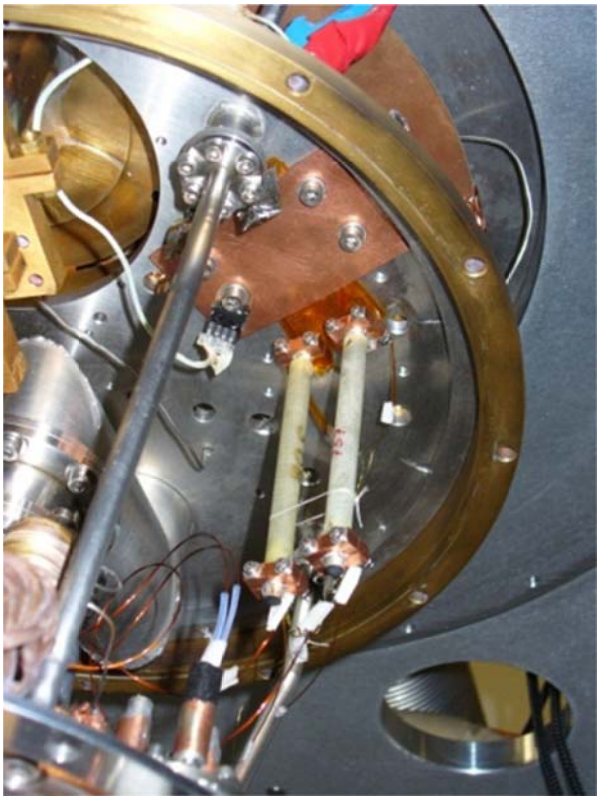

Fig. 5. High-Tc current leads for the superconducting magnets

As a postscript to the report on Task 2, we would like to emphasize again that the intention of this task was specifically the building of the two machines, but in general the opening of the milli- and microkelvin regimes to laboratories without refrigerant infrastructure. The SME developed in Helsinki, Bluefors, as part of this objective, as of today, has running in the field 25 cryo-free dilution refrigerators and has an order book for 40 more, which is prodigious progress for a new company in a niche field when we estimate that the world production of dilution refrigerators is only about 100 units per year.

Milestones

M6: The compact microkelvin refrigerator at CNRS (BASEL) ready for access service (24/36 mo)

Partially achieved (access service available at CNRS for temperatures *T* > 20 mK)

Highlights

The great success of our partner SME **Bluefors** in having 25 cryogen-free dilution refrigerator systems running around the world and with orders for 40 more.

Task 3. Next-generation μK facility

The aim of this task is the building of an advanced conventional nuclear cooling facility specifically designed for nanoscience and quantum coherence measurements at microkelvin temperatures.

In this context **ULANC** has the world leading expertise to build such a machine, holding the current world record for a continuously running dilution refrigerator (1.75 mK). The detailed aim of the task was to build a further machine with a similar performance but modified for the study of nanoscience at microkelvin temperatures. As envisaged from the outset, this machine has been built with ULANC expertise, laboratory space and finance with considerable input from SAS and Basel, and also with much input from the group of Stefan Ludwig at the Quantum Transport Group of Ludwig-Maximilian University, who will shortly have access to the machine when commissioning is complete.

Nobody has attempted to build such a combination before of large advanced dilution refrigerator with nuclear cooling, embedded in an extremely low noise environment. Our collaboration and consultations with the groups who specialize in low-noise environments convinced us that our original idea to build the nuclear refrigerator first and then introduce the nanoscale experiments as bolt-on additions is a little simplistic. We are therefore building in the low noise experimental access equipment as we go along. This parallel development compensates for the delay caused by the slow provision of the very large dewar (3m by 1m diameter) which took the company nine months longer to deliver than promised. This allowed us to begin designing and installing the low noise leads and filtering systems without waiting for final commissioning.

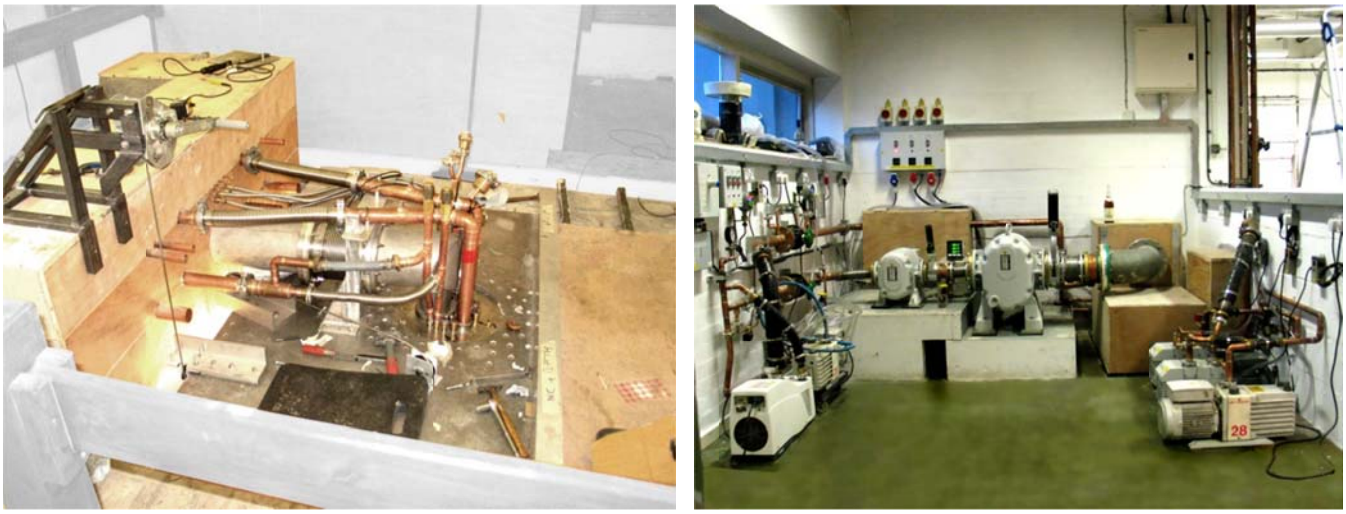

Fig. 6. The top of the 3x3x3m 50 tonne vibration-isolation block, and large double roots pump system (isolated from the shielded room behind).

For filters we are using a combination of technologies as developed by BASEL and by LMU. LMU are currently constructing the filter boxes to sit on the top of the cryostat to deliver all leads to the inside of the cryostat experimental volume. This turns out to be particularly demanding as it means that every electrical component in the inner vacuum space (for example resistance thermometers for routine diagnostics) must be completely electrically shielded and connected by miniature connectors to microcoax, which complicates the inner design considerably.

The project is a major one and just about at the limit of what can be achieved in a university rather than in a national facility, requiring a new building extension and considerable reinforcement of foundations and all mounted on a > 50 tonne concrete, lead and stainless steel mounting. As this report is being written the dilution refrigerator is being commissioned. While the extra complication of the noise isolation, which was more complicated than foreseen, and the slow delivery of the dewar, which was out of our control, the experimental design being carried out in parallel and with customers waiting for access, we expect this machine to be available for access not much later than envisaged at the outset.

Once we reach this stage, we foresee that interest in using this machine will be very high. (It is an interesting thought that though this project has cost MICROKELVIN almost nothing the integration of many European laboratories in the project has allowed us to take advantage of a much wider range of expertise than would otherwise have been the case.)

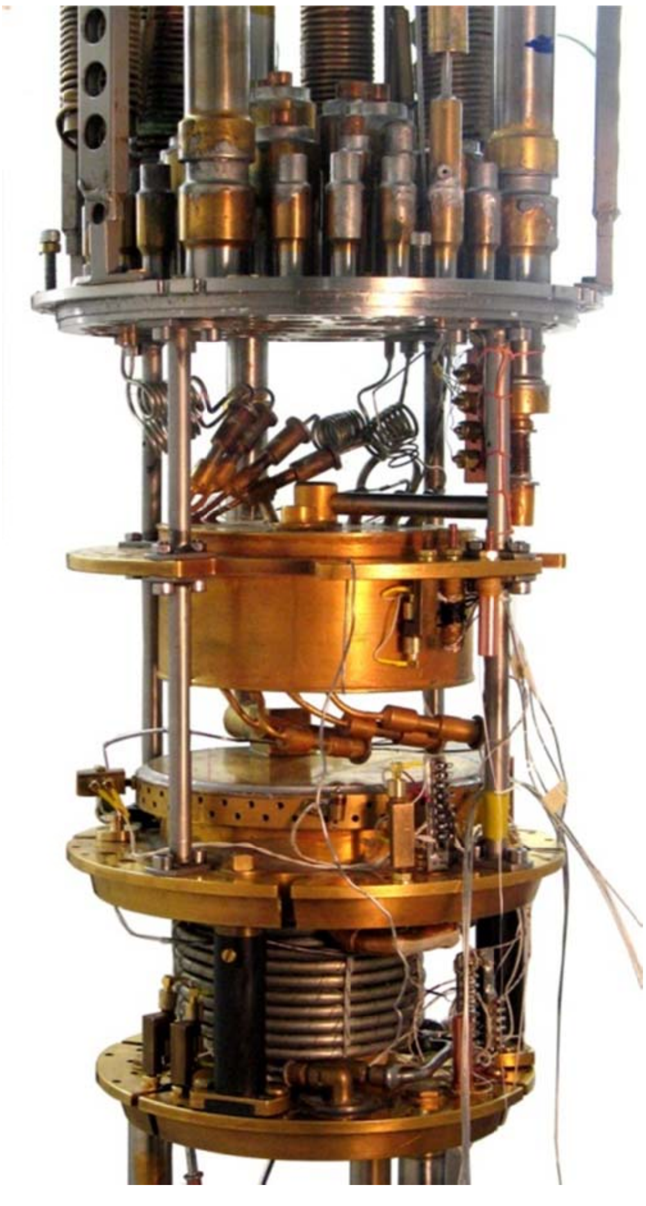

Fig. 7. The upper part of the dilution refrigerator showing the large 4 Kelvin space for filters and the three layers of the very large spiral heat exchanger (7 m long).

Regarding the scientific outcomes, since this task is very much in a building mode there are no publications as yet, but since it is a unique facility they will certainly follow. However, as a result of the interest generated by our building this new machine, and requests for specialized components which only we can produce, this task has led to the creation of a new company, Lancaster Cryogenics, which will provide niche ultralow temperature components for commercial sale. (The first commission is the design and partial production for a prototype dilution refrigerator for the Variable Energy Cyclotron Centre of the Indian Department of Atomic Energy.) Thus we have a further SME born directly from the MICROKELVIN experience.

Milestones

M8: Dilution refrigerator built, installed and tested (24 mo)
In progress, delayed owing to late delivery of dewar

M9: Nuclear stage, tested and running in the dilution refrigerator (30 mo)
In progress, delayed owing to late delivery of dewar

Highlights Founding of the new spin-off company Lancaster Cryogenics

Deviations from work plan Rearrangements in construction, to compensate for late dewar delivery

Use of resources Follows the original plans

Deliverables

Task 1

D1: Prototype of nanocircuit stage for access service at ULANC (36 mo)
Prototype completed in Basel. Access soon available in ULANC

Task 2:

D2: Prototype of compact nuclear cooling refrigerator for access service at CNRS (24)
Delayed owing to problems with magnet leads in vacuum

D3: Prototype of compact nuclear cooling refrigerator for access service in Basel (36)
Delayed, machine waiting magnet delivery

Task 3:

D4: Next-generation microkelvin facility for access service at ULANC (36)
Delayed by late delivery of dewar, but access soon available in ULANC

JRA2

Name of work package: **Ultralow temperature nanorefrigerator**
Reporting Period: **from 1.10.2010 to 31.3.2012**
Activity leader: **Jukka Pekola**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead bene-ficiary	Estimated person months	Nature	Dissemination level	Delivery date
D2	Demonstration of sub-10 mK electronic bath temperature of a nanoelectronic tunnel junction device achieved by the developed filtering strategy	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, (ii) quantum dot cooler (task 2)	JRA2	Aalto	6	R	PU	24 **partially achieved**
D5	Demonstration of cooling a dielectric platform from 300 mK to about 50 mK (task 3)	JRA2	Aalto	26	R	PU	36 **in progress**

List and schedule of milestones

Milestone number	Milestone name	WPs no's	Lead bene-ficiary	Delivery date From Annex I	Comments
M3	Choice of the superconducting material with a lower Tc	JRA2, Task 2	CNRS	24	**achieved**
M4	Precise definition of the QD cooler geometry and materials	JRA2, Task 2	SNS	24	**achieved**
M6	Delivery of the first membranes to the end users	JRA2, Task 3	AALTO	36	**achieved**

Summary

Introduction: Work on JRA2 was started in March 2010. Collaboration within JRA2 is maintained with mutual visits and common experiments: Giovanna Tancredi from RHUL spent time at LTL of Aalto University, to fabricate Josephson junction samples on the dielectric platforms; Coulomb blockade thermometers fabricated at AALTO were investigated in BASEL (L. Casparis et al. [14]). DELFT has investigated kinetic inductance detectors implemented on the cooler membranes provided by the AALTO group. These results are now published (N. Vercruyssen et al. [13]). A post-doc (Hung Nguyen) was hired to work on JRA2 projects; he spent his first year at CNRS to develop a new technique for producing tunnel junctions with large cooling power (H. Nguyen et al. [15]), and now moved to AALTO to continue this work. The work within JRA2 is discussed in more detail below.

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

(AALTO, BASEL)

Using a recently developed demagnetization refrigerator in Basel, intended for microkelvin experiments, we have investigated metallic Coulomb blockade thermometers (CBTs). The sensors with various tunnel-junction resistances R_j were fabricated at AALTO. The refrigerator cools as low as (185 +/- 25) μK (newer result achieved after manuscript was written) while the CBTs reach about 10 mK, limited by weak electron-phonon coupling for the high-R_j sensor and a residual heat leak of 40 aW. For lower-R_j junctions, we find for the first time a deviation from the electron-phonon cooling mechanism at the lowest temperatures, entering a more efficient cooling regime, though these CBTs appear to be more susceptible to environmental heating due to the stronger coupling in low-R_j sensors. For a 134 kOhm CBT sensor mounted on a conventional dilution refrigerator (base temperature ~ 5 mK) with further improved filtering and heat sinking, the lowest temperature measured was 7.5 +/- 0.2 mK (see Fig. 1), a factor of two lower compared to previous publications. Finally, we discuss possible improvements for cooling nanosamples far below 10 mK.

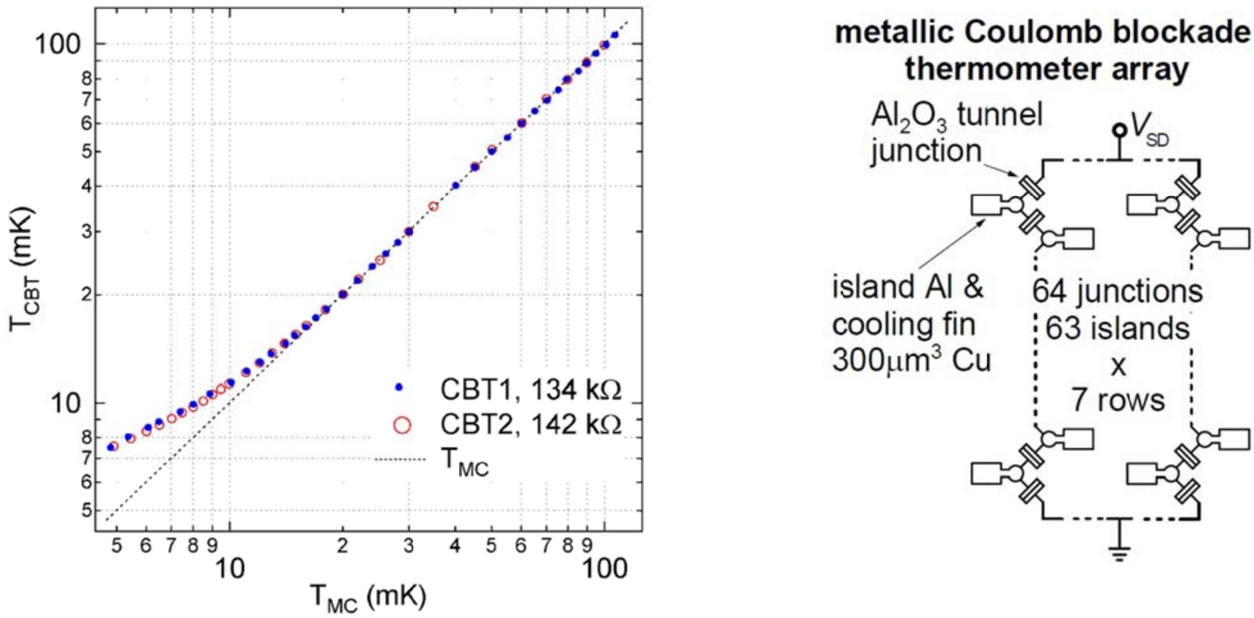

Fig. 1. **(left panel)** *CBT sensor temperature T_{CBT} as a function of the mixing chamber temperature T_{MC} of a dilution refrigerator, for two different CBT sensors as labeled. As a guide for the eye, the dashed line indicates complete equilibration $T_{CBT} = T_{MC}$.* **(right panel)** *CBT sensor device layout (devices fabricated by M. Meschke and J. Pekola (AALTO) were measured in BASEL). The devices employed consist of 7 parallel rows each comprising 64 Al_2O_3 junctions in series with large volume V = 300 (micro m)^3 Cu cooling fins. The device is measured in a small magnetic field, to suppress the Al superconductivity.*

Deliverable D2:	Demonstration of sub-10 mK electronic bath temperature of a nanoelectronic tunnel junction device with the developed filtering strategy (30 months)	**achieved**

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

(AALTO, CNRS)

Superconductors with a lower T_C are required to enhance the efficiency of superconducting coolers at very low temperatures. We followed during the reported period two main directions to investigate this topic: a) by reducing the superconducting gap by applying external magnetic fields and b) by making use of new production approaches to fabricate coolers with superconducting titanium electrodes having a lower T_C.

We found that the main effect of a small magnetic field is to enhance relaxation processes in the superconductor, thus stabilizing superconductivity in non-equilibrium conditions and consequently reducing overheating of the device. (J. T. Peltonen et al. [9]). In a tunnel junction cooler, applying a field of the order of 100 μT leads to significantly improved cooling of the N island, see Fig. 2. These findings are attributed to faster quasi particle relaxation within the superconducting electrodes as a result of enhanced quasi particle relaxation. This occurs through regions with a locally suppressed energy gap due to magnetic vortices in the superconducting leads at some distance from the junction. We show that designing the geometry of the superconducting electrodes with respect to an optimized vortex distribution close to the cooling junction but not within the junction area itself leads to a noticeable enhancement of the cooling performance of the coolers.

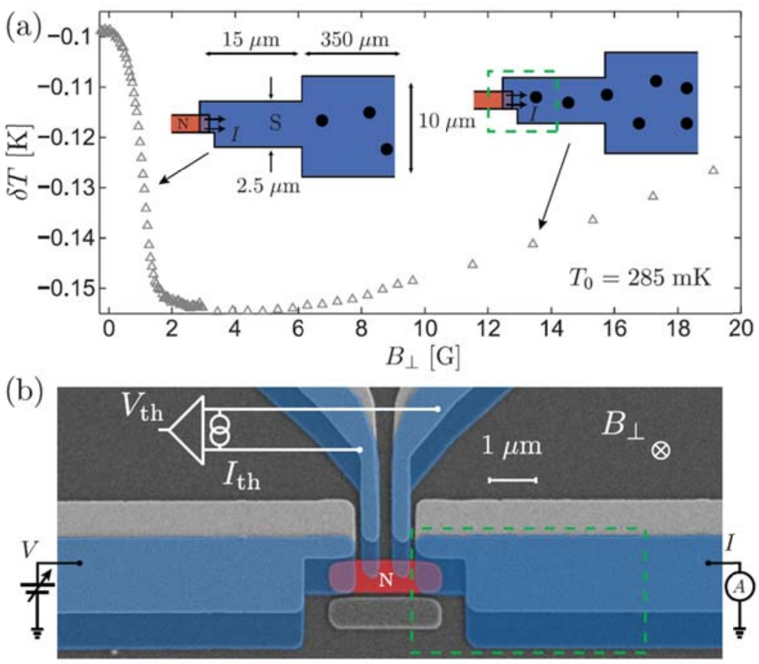

Fig. 2. **(a)** *Maximum temperature drop δT in an optimally biased SINIS cooler in a perpendicular magnetic field $B_\perp$, at a bath temperature T_0 = 285 mK. The sketches show the S electrode geometry and qualitative vortex configurations at $B_\perp$ = 2 G and at a value of $B_\perp$ beyond the optimum point. The area inside the dashed green rectangle corresponds to that in the micrograph below.* **(b)** *Scanning electron micrograph of a typical structure, together with the measurement scheme (see text for details). A Cu island (red, marked as N) in the middle is contacted to four superconducting Al electrodes (blue/dark) via Al oxide tunnel barriers for thermometry and temperature control (from Ref. [9]).*

The fabrication process of coolers with a low T_C superconductor is realized using two approaches:

1. We have developed a method to fabricate large-area superconducting hybrid tunnel junctions with a suspended central normal metal part (H. Nguyen et al. [15]), see Fig. 3. The samples are fabricated by combining photo-lithography and chemical etching of a superconductor - insulator - normal metal multilayer based on Al and Cu. The process involves few fabrication steps, is reliable, and produces extremely high-quality tunnel junctions. As fabrication starts with preparing the multilayer, the wafer can be baked in ultra-high vacuum environment, which is an essential ingredient for obtaining pinhole-free NIS junctions. Deposition can be made at high temperature, which enables epitaxial growth of Al and a high oxide quality. Significant electronic cooling has been demonstrated recently. This opens the way to use materials like titanium as superconducting material.

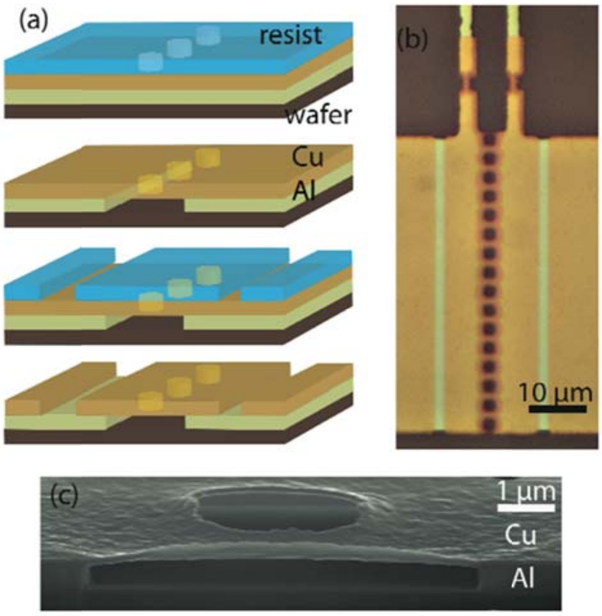

***Fig. 3**. **(a)** From top: Al/AlOx/Cu multilayer, on which a photoresist is patterned with contact pads and holes. Cu and Al are successively etched, leaving a suspended membrane of Cu along the line of adjacent holes. A second lithography and etch define the Cu central island. **(b)** Optical microscope image showing regions by decreasing brightness: bare Al, Cu on Al, suspended Cu and substrate. On the top, two thermometer junctions are added. **(c)** Scanning electron micrograph of a sample cut using Focused Ion Beam showing the Cu layer suspended over the holes region. The thickness of Al and Cu is 400 nm and 100 nm, respectively (from Ref. [15]).*

2. We have developed a novel fabrication process making tunnel junctions out of aluminium that stays in the normal state due to the proximity effect (J.V. Koski et al. [12]): the junctions are fabricated with a technique that enables the use of high-quality aluminum oxide tunnel barriers with normal metal electrodes at low temperatures also in zero magnetic field. The inverse proximity effect is applied to diminish the superconductivity of an aluminum dot through a clean lateral contact to a normal metal electrode. To demonstrate the effectiveness of this method, fully normal-state single electron transistors and normal metal-insulator-superconductor junctions, applying proximized Al junctions, were fabricated. This technique is compatible with titanium as a superconducting material.

Milestone 3: Choice of the superconducting material with a lower T_C (24 months) **achieved**

A nanocooler for cooling in the microkelvin temperature range has been designed and fabricated (see Fig. 4). The device consists of a 10 × 10 μm^2 electronic microdomain defined on a semiconductor heterostructure of a GaAs/AlGaAs two dimensional electron gas (2DEG). The cooling is achieved, on one hand, by means of two Quantum Dots (QDs). The use of QDs enables us to tune in-situ the energy of the electrons leaving the central domain therefore maximizing the cooling efficiency for each temperature range. These QD are fabricated by conventional e-beam lithography and thermal evaporation of Ti/Au leads that allow for the application of a gating voltage that depletes the regions below from charge carriers. On the other hand, a non-galvanic thermometer has also been implemented in the structure in order to probe the electronic temperature in a non-invasive way. The latter consists of a QD directly coupled to the electronic domain, the read out of which is performed through a Quantum Point Contact (QPC). The strong nonlinear density of states of the QD is exploited to determine the energy distribution of the reservoir providing therefore an efficient read out of the electronic temperature. By using a QPC capacitively coupled to the QD it is possible to measure experimentally the average electronic occupation of the latter without leading to current flow through it. According to our theoretical calculations, the use of a non-galvanic thermometer will enable probing experimentally the temperature of the electronic microdomain, in principle, well below 1 mK.

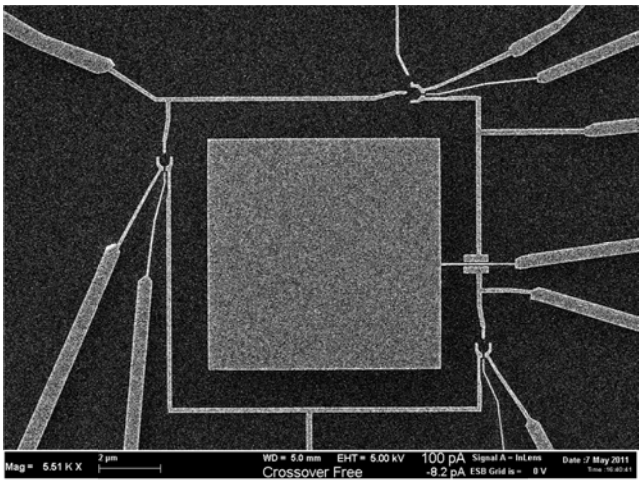

Fig. 4. *Scanning electron micrograph image of a prototype QD nanocooler defined on a GaAs/AlGaAs two-dimensional electron gas. The two QDs at the left and the right in the image are used to cool the central microdomain, whereas an additional QD or a QPC (see top of the figure) are used to measure the electronic temperature. The central square gate is used to control the charge density level in the microdomain, i.e. to tune the efficiency of the cooling process as well as the strength of the electron-phonon interaction in the 2DEG.*

Milestone 4: Precise definition of the QD cooler geometry and materials (24 months) **achieved**

(i) traditional N-I-S cooler with low T_C

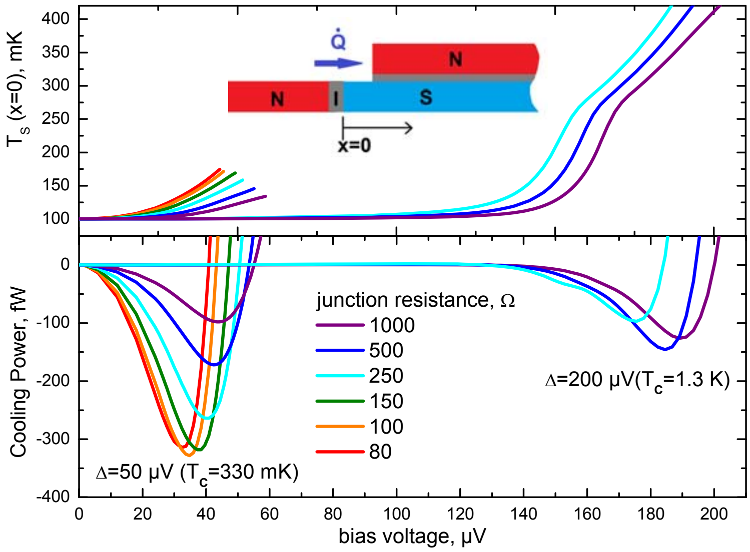

Fig. 5. **(bottom panel)** *Cooling power of a NIS cooler as a function of applied voltage bias. The cooling power for two different superconductor gap parameter values (50 μV and 200 μV) are plotted for a range of tunnel resistances. The results plotted here take the overheating of the superconductor into account.* **(top panel)** *Overheating of the superconductor used for a NIS cooler at position x=0 (at the tunnel junction). The inset shows the thermal model: the cooled island (left (N)) separated by a tunnel junction (I) from the superconductor (S). The cooler junction is separated by a tunnel junction from the quasiparticle trap (top (N)), starting close (1μm) to the tunnel junction.*

We describe here a model of electronic coolers that takes overheating effects into account. The performance of a NIS cooler degrades drastically towards low temperatures if operated far below the temperature with optimum efficiency of about $0.4T/T_C$ (~500 mK for aluminium). Consequently, increasing overheating effects suppresses the performance of such a device as shown in Fig. 5 (gap of 200 μV) when operated at 100 mK: the superconductor overheats when the cooling power is increased with transparent junctions instead of benefitting from the enhanced cooling power. Our thermal model assumes as the exclusive relaxation channel the tunneling of quasi particles from the superconductor to the quasi particle trap. The latter is assumed to be connected via a tunnel junction (to avoid the inverse proximity effect) with a resistance of 1 kOhm/μm^2. In addition, the heat conduction along the superconductor with a cross section of 30 nm x 2000 nm is modeled. For details of the thermal model see J.T. Muhonen et al. [16]. In comparison, a SIN cooler using a smaller gap superconductor (gap of 50 μV, optimum efficiency at about 120 mK) will operate here at a higher efficiency, deposit less heat to the superconductor and can produce a higher cooling power at this low operating temperature. Cooling a 1μm^3 copper island to about 10 mK from 100 mK requires a cooling power on the order of 20 fW, a realistic value for the described cooler with two junctions and assuming a cooling power proportional to $T^{3/2}$.

(ii) quantum dot cooler

As a first approach, a Quantum Dot (QD) was implemented and tested to probe the electronic temperature on the microdomain (see Fig. 6 (a)). This method was based on the analysis of the Coulomb-Blockade shape of the QD peaks. The validity of this technique was demonstrated in a test of an electronic microdomain in which the electronic temperature could be controlled by means of a Quantum Point Contact (QPC) that enabled the application of a heating current. Although it works at intermediate temperatures, this thermometry scheme leads unavoidably in excess heat dissipation on the electronic reservoir. For this reason, our next generation of quantum dot nanocoolers will include a non-galvanic thermometer that delivers much less energy into the microdomain. The latter is based on the use of a QPC to read out the QD occupation as schematically depicted in Fig. 6 (b).

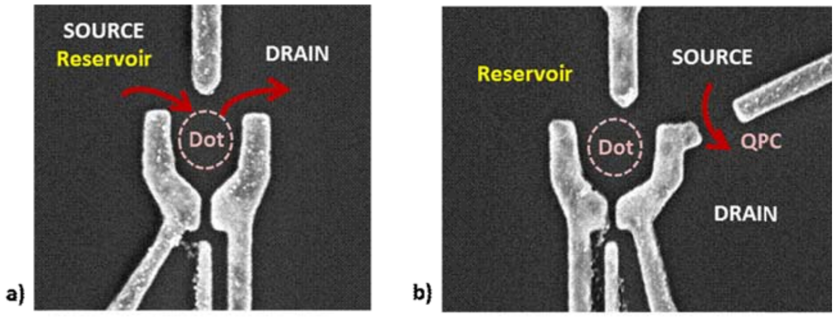

Fig. 6. **(a)** *QD thermometer implementation.* **(b)** *Non-galvanic thermometer implementation.*

Deliverable 3: Analysis of sub-10 mK nano-cooling techniques including
(i) traditional N-I-S cooler with low Tc,
(ii) quantum dot cooler (24 months) **partly achieved**

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

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

This milestone was achieved already at the end of the last 18-month reporting period and the results have been published by now (N. Vercruyssen et al. [13]). This proves that the membrane coolers are sufficiently robust and that the cooler survives additional process steps necessary for the realization of the end-user devices on top of the membrane.

Cooling a dielectric platform from 300 mK to about 50 mK

At AALTO we have designed optimized membrane coolers based on 2D computer simulations with known materials and heat relaxation parameters. We have implemented such coolers on commercial silicon nitride membranes (1 mm x 1 mm area, 100 nm thickness). The thermal characteristics have been measured. They prove to be similar to those reported in the literature in the past. Successful first cool downs have been performed, although the cooling performance was still far inferior as compared to predictions. The current understanding is that mainly the backflow of heat from the non-equilibrium superconducting secondary side of the cooler affects negatively the cooling performance. The encouraging results of enhanced cooler junction performance in the presence of magnetic vortices (J.T. Peltonen et al. [9]) will help to reduce the backflow of heat.

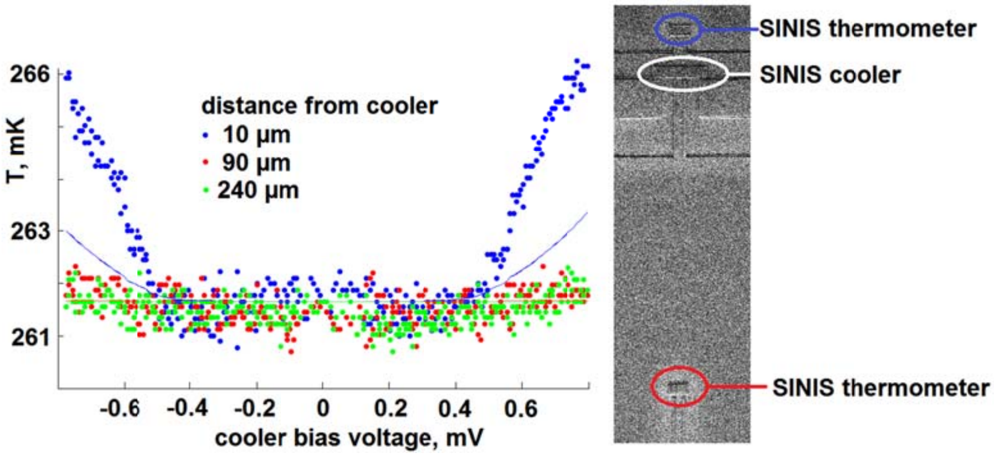

Fig. 7. **(left panel)** *Measured phonon temperature rise during the operation of the cooler. The lines are simple theory estimates assuming a point heat source of power I^2R and a Debye model for the silicon. This model underestimates the actual measured temperature change. A clear overheating of the phonon system is observed close to the cooler (10 μm distance), corresponding to an increase to almost 300 mK at the point of optimal cooling according to the rough model at a distance of 500 nm from the cooler. This would limit the cooling efficiency to about 60-70% of the ideal value.* **(right panel)** *SEM image showing the position of the SINIS cooler and the thermometers.*

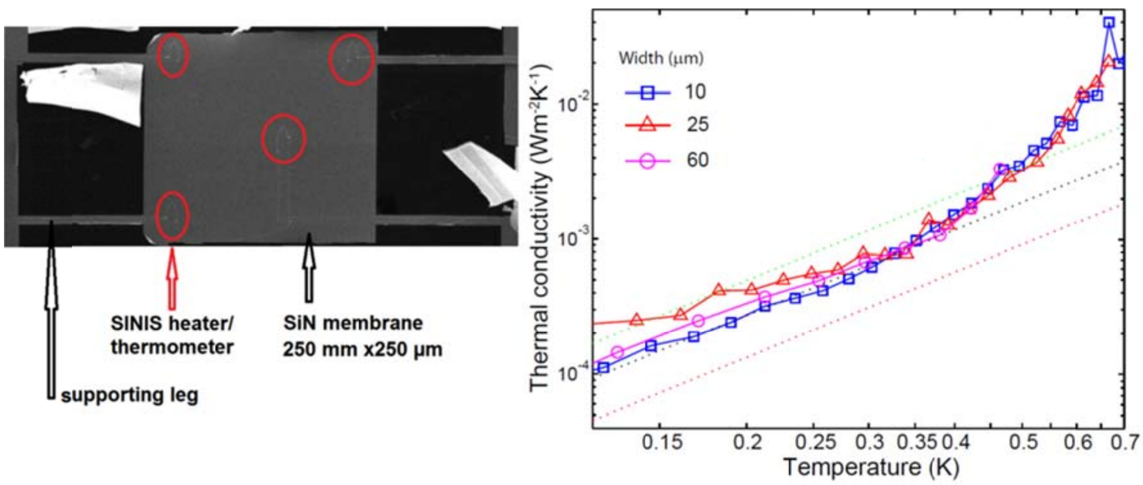

Fig. 8. **(left panel)** *Perforated SiN membrane with four SINIS structures for thermometry and heating. The windows are individually cut into the membrane with a Focused Ion Beam (FIB) allowing flexibility in the sample design. All leads to the NIS structures are fabricated from pure aluminium to avoid parallel heat flow.* **(right panel)** *Results of thermal conductivity measurements vs temperature. The measured thermal conductivity for three different leg widths is mutually consistent and within the expected range of the earlier measurements on full membranes (dotted lines). The increase of conductivity above 0.4 K can be attributed to the improving electronic thermal conductivity of the superconducting leads. By perforation we expect to achieve a reduction of the total heat load to the membrane by a factor 4 (leg width 60μm) to 25 (leg width 10 μm).*

In addition, we included as a further step the perforating of the membrane, as shown in Fig. 8, to reduce the backflow of heat. The ultimate goal is indeed to reach about 50 mK, by combining large area junctions and perforated membranes.

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

Further activity:

At RHUL, SIS Josephson Junction devices are to be fabricated on top of the electronically cooled platform provided by Aalto. In the early devices we wished to avoid spinning resist material on top of existing refrigeration devices and so the JJs were designed such that they could be built in the same lithography and evaporation process as the refrigeration circuitry. The first samples were successfully fabricated at Aalto University by G. Tancredi by this method.

In a further development we studied the deposition of metallic films on the reverse side of the SiN membrane. For some applications it is desirable to have a Cu backplane, and a special sample-holder and mask arrangement were designed to facilitate this. The aim of this electrically isolated backplane was to reduce the temperature gradient present in the cold fingers and membrane and to give an extra shunt capacitance to the JJ devices (via the membrane dielectric). The additional capacitance was designed to modify the escape rate of JJ's to be sensitive to temperature in the regime of interest. Fully fabricated membrane refrigerators with SIN thermometers have recently been delivered to RHUL for initial testing on the new dilution refrigerator, at temperatures below those available at AALTO. New samples with JJ's both on the SiN membrane and Si chip with and without the backplane will soon be built at RHUL and tested down to 10 mK. Further visits to AALTO for fabrication may be useful.

Highlights:

- *Demonstration of significantly improved cooling performance in small magnetic fields due to enhanced quasi particle relaxation by vortices in the superconductor*
- *Fabrication of large-area and defect-free tunnel junctions for cooling has been demonstrated*
- *7.5 mK electron temperature has been achieved in metallic CBTs*

List of publications of JRA2 (the first and the second report, months 1-18 and 18-36)

JRA2: Ultra low temperature nanorefrigerator

23. S. Gasparinetti, F. Deon, G. Biasiol, L. Sorba, F. Beltram, and 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).

24. 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, and D.R. Leadley, *Strain dependence of electron-phonon energy loss rate in many-valley semiconductors,* Applied Physics Letters **98**, 182103 (2011).

25. J.T. Peltonen, P. Virtanen, M. Meschke, J.V. Koski, T.T. Heikkilä, and J.P. Pekola, *Thermal conductance by the inverse proximity effect in a superconductor,* Phys. Rev. Lett. **105**, 097004 (2010).

26. J.P. Pekola, V.F. Maisi, S. Kafanov, N. Chekurov, A. Kemppinen, Yu.A. Pashkin, O.-P. Saira, M. Möttönen, and J.S. Tsai, *Environment-Assisted Tunneling as an Origin of the Dynes Density of States,* Phys. Rev. Lett. **105**, 026803 (2010).

27. F. Dahlem, P. Achatz, O.A. Williams, D. Araujo, E. Bustarret, and H. Courtois, *Spatially Correlated Microstructure and Superconductivity in Polycrystalline Boron-Doped Diamond*, Phys. Rev. B **82**, 033306 (2010).

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Use of resources:

AALTO: A part-time senior researcher salary has been paid from the Microkelvin project and a postdoctoral fellow working at Aalto for JRA2 is funded by Microkelvin from July 2011 on.

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, for work which includes JRA2 activities. Since Jan 2011, a PhD student is partly funded by Microkelvin, for work which includes JRA2 activities.

CNRS: From 1 April, 2010 to 31 August, 2011, a postdoctoral fellow working at CNRS has been funded by Microkelvin, for JRA2 work.

SNS: Microkelvin funding was used partly for liquid helium. Since 2011 a postdoctoral fellow is fully funded from the Microkelvin project for work in JRA2.

DELFT: Since July 2011 a post-doctoral fellow working at TU Delft is funded by Microkelvin, for work in JRA2 (10 months). Otherwise Microkelvin funding was used for liquid helium, and consumables.

JRA3 Report

Name of work package: **Attacking fundamental physics questions by microkelvin condensed-matter experiments**
Reporting Period: **from 1.10.2010 to 31.3.2012**
Activity leader: **Henri Godfrin**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead benefi-ciary	Estimated person months	Nature	Dissemi-nation level	Delivery date
D2	Publication on vortex creation and dissipation in superfluid 3He	JRA3	ULANC	20	R	PU	24,36 **achieved**
D3	Publication on 2D defects	JRA3	ULANC	18	R	PU	36 **work in progress**

Expected milestones on the reporting period

Milestone number	Milestone name	WPs no's	Lead benefi-ciary	Delivery date From Annex I	Comments
M2	Measurement of the dissipation in quantum turbulence and when a vortex state is created	JRA3, Task 1	AALTO	24	**achieved**
M3	A precise determination of the effect of pressure on vortex creation via the dynamics of the second-order phase transition	JRA3, Task 3	ULANC	30	**achieved**
M4	Identification of the topological defects left after brane annihilation	JRA3, Task 2	ULANC	24	**work in progress**
M5	Observation of several "cosmological defects" obtained in a microkelvin multi-cell detector	JRA3 Task 2	ULANC	30	**work in progress**
M7	Test of the Unruh effect from rapid motion of a phase boundary	JRA 3, Task3	AALTO	36	**work in progress**
M8	Test of the percolation theory of the A-B transition	JRA3, Task 3	AALTO	36	**achieved**
M9	Observation of the interaction between two independent precessing Q-balls	JRA3, Task 4	CNRS	30	**work in progress**
M10	Creation of excited modes of a "Q-ball" under radial squeezing by rotation	JRA3, Task 4	CNRS	36	**achieved**
M11	Realization of microkelvin thermometry based on "Q-ball" behaviour	JRA3, Task 4	ULANC	42	**Achieved in advance**
M12	Observation of enhancement in the Q-ball spin relaxation rate owing to surfaces and vortex cores	JRA3, Task 4	ULANC	42	**Achieved in advance**
M14	Neutron scattering measurement of 3He excitation spectrum at intermediate energies	JRA3, Task 5	CNRS	42	**Achieved in advance**

Summary

The goal of the JRA3 work package is to make use of the combined expertise of the Microkelvin Collaboration and to provide a concerted effort towards solving some of the fundamental physics problems which can be attacked with ultra-low-temperature techniques. Simultaneously work is devoted to the development of new microkelvin methods for studying problems in cosmology, gravitation, quantum fields, and particle detection. This report is answering to the demands of the amended Annex I from September 2011.

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

Introduction: The dynamics of quantized vortices in the $T \longrightarrow 0$ limit has been one of the forefronts of the ultra-low temperature physics of recent years. This work concerns both the Fermi superfluid ^{3}He-B, for which sub-millikelvin temperatures are needed, and the Bose superfluid ^{4}He-II, for which dilution-refrigerator temperatures suffice. For ^{3}He-B various measuring methods have been developed, while for ^{4}He-II other and fewer measuring means have so far been utilized. If the interaction of vortices with solid surfaces enters in the picture, then the results for ^{4}He-II have often proven less amenable to theoretical interpretation, owing to a vortex core radius of atomic size. Thus experiments with a small number of vortices are often easier to interpret if they are performed with ^{3}He-B, while both superfluids provide supplementary results when a large collection of vortices is studied, as might be the case in studies of homogeneous and isotropic turbulence. However, the newly found dissipation in turbulent vortex motion in the $T \longrightarrow 0$ limit is expected to arise owing to very different mechanisms in the Fermi ^{3}He-B and in the Bose ^{4}He-II superfluids.

The mechanisms for zero temperature vortex dissipation can be studied in superfluids, but typically not in superconductors. Three different types of studies have been conducted so far at the lowest temperatures: 1) The free decay of vortex tangles created with vibrating grids or wires has been monitored in ^{3}He-B by the Lancaster group. Here the time dependence of the decay has been recorded with vibrating wire detectors by observing either Andreev reflection from the tangle [1] or the amount of heat emerging from the decay [2]. 2) The axial expansion of vortices has been monitored with NMR techniques in a rotating cylinder of ^{3}He-B by the Aalto group. Here both the velocity of the turbulent vortex front [3] and the heating from the motion [4] has been measured. 3) The free decay of vortex tangles created in a sudden stop of the rotation of a cubic box of ^{4}He-II has been studied in the University of Manchester (outside the Microkelvin Programme) [5]. Here ion transmission techniques have been used.

When the conventional damping in vortex motion, mutual friction dissipation, approaches zero one might expect that quantum fluids become ideal text-book-like systems with truly dissipation-less flow, as the name superfluid suggests and as is the case for vortex-free superflow. It has by now been established that turbulent vortex flow displays significant temperature independent dissipation in the zero temperature limit, both in ^{3}He-B and ^{4}He-II. In contrast, laminar vortex flow does not display a temperature independent contribution of similar magnitude down to below 0.2 T_c [6]. Because of this difference it appears that reconnections among vortices are needed to bring about the zero-temperature dissipation. A central goal of current research is to understand the mechanism which gives rise to this new source of dissipation, especially in a fermion superfluid like ^{3}He-B. This is an open problem of wider inference, which deals with the motion of topological defects in quantum fields at absolute zero.

During the first 18-month Project Period the dissipation from turbulent vortex flow was measured in ^{3}He-B at the lowest temperatures. The dissipation was determined in the form of heating, which caused a measurable temperature rise in a closed volume, or in other words an increase in the density of ballistic quasiparticle excitations. This was accomplished in two measurements of different configuration, which were also performed with different techniques [2,4]. Thus they constitute convincing direct proof that turbulent vortex motion generates heat in ^{3}He-B also at the very lowest temperatures and that a new dissipation mechanism exists in coherent fermion systems at absolute zero by which turbulent vortex motion generates quasiparticle excitations. In a similar way, one might anticipate a collection of interacting cosmic strings to dissipate energy by generating gravitons. In the case of ^{3}He-B, the first theoretical suggestions on the possible mechanisms have now been presented [7]. During the second 18-month Project Period one of our central goals has been to characterize further the new source of dissipation, in order to learn whether it can be associated with quasiparticle states in the vortex core, as has been suggested [7].

ULANC measurements: The energy dissipated by decaying vortices is measured using a blackbody radiator device shown in Fig. 1. The energy is dissipated in the form of quasiparticle excitations. These thermalise within the radiator volume and are detected by a vibtrating wire resonator (VWR), as they slowly exit the radiator via the radiator orifice. The device is calibrated by using a second VWR as a heater that can apply a known amount of heat power. The blackbody radiator technique is extremely sensitive and can easily resolve the small energy released by the freely decaying turbulence.

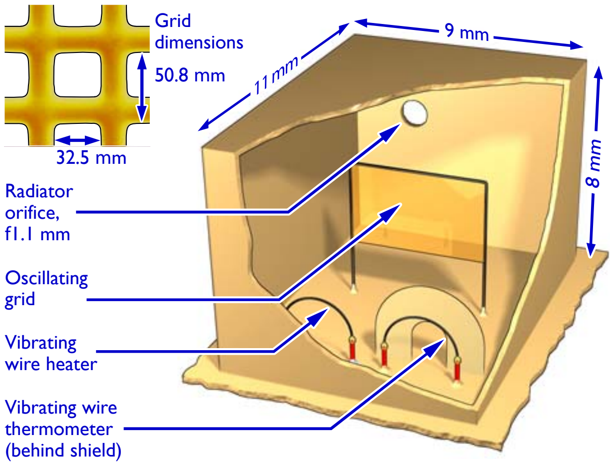


Fig. 1. The blackbody radiator used to measure the energy dissipated by freely decaying turbulence at ultralow temperatures.

The experiment produced the first direct measurement of the energy dissipated by *any* form of freely decaying turbulence. This is an important measurement as it allows a very direct comparison with the standard model for decaying classical turbulence. Furthermore, the experiment is performed at ultralow temperatures. This allows us to study pure quantum turbulence in the absence of any normal fluid component.

The measured energy dissipation at late times in the decay, and for moderately large initial vortex line densities, was in remarkable agreement with the expectations of the standard model for classical turbulence, Fig. 2. At lower line densities there was some evidence for a different regime of decay, consistent with that expected for a random tangle of vortex lines. This work was published in June 2011 [2].

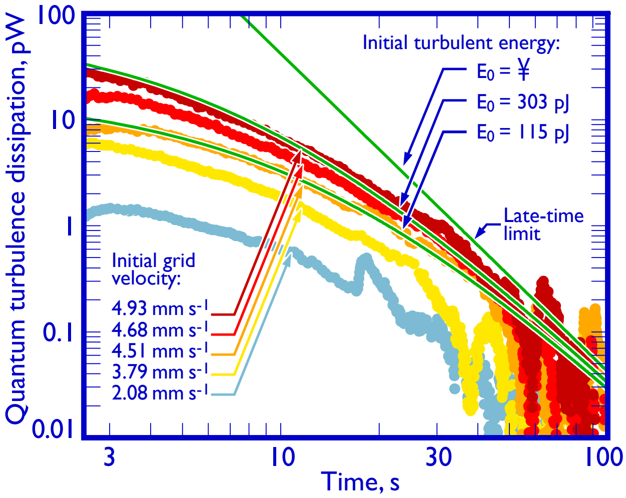


Fig. 2. The measured energy dissipated by freely decaying pure quantum turbulence. Solid lines show the excellent agreement with the standard model for classical turbulence.

The experiment raises several interesting questions concerning the conditions required for a classical-like turbulent tangle to form. We are currently addressing this by performing more systematic experiments over a wider range of conditions. To facilitate this, we have made changes to the radiator design to improve the energy resolution – we hope to improve this by at least two orders of magnitude. Also, the geometry of the radiator has been improved to achieve more homogeneous turbulence.

The current experiments incorporate a new type of grid device, Fig. 3, to generate the turbulence, which should provide better control of the initial vortex configuration and thus allow us to further investigate the generation mechanisms of quantum turbulence. The position/motion of the device is controlled by an applied current whilst the position can be very accurately measured using two pick-up coils located above the grid. By applying appropriate current ramps, the device can be manipulated with great control. For instance, it can be swept once through the measurement volume, or it can be oscillated back and forth with an arbitrary amplitude and frequency. The development of the device, described in a dedicated publication [8], was facilitated by Trans-National Activity within the Microkelvin project.

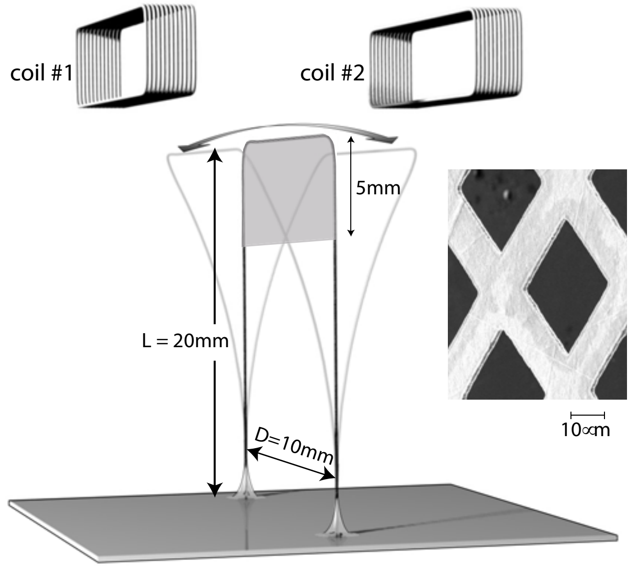


Fig. 3. The new floppy grid device.

In parallel to our quantum turbulence work in ^{3}He-B, we have also been continuing complimentary studies of turbulence in superfluid 4He at much higher temperatures [9]. In order to better understand quantum effects, it is important to compare quantum turbulent behavior in the two different superfluids (^{4}He and ^{3}He-B), and with classical turbulent behavior which can be probed in normal fluid ^{4}He. In Ref. [9] we made the surprising discovery that turbulence in the superfluid does not always develop fully, depending on the cooling history.

AALTO measurements: The steady-state axial propagation velocity of vortices along a long circular tube has been studied as a function of temperature T while the tube is rotating around its axis at different constant angular velocities Ω (Fig. 4). The work is performed with a rotating nuclear demagnetization refrigerator and NMR techniques. Initially, a ^{3}He-B sample is prepared which is as free of remanent vortices as possible. It is cooled in the non-rotating state to the desired temperature below 0.4 T_c. Next the cryostat is accelerated rapidly (at 0.03 rad/s^2) to the desired steady rotation velocity Ω. During the acceleration vortices are formed on the sintered heat exchanger surface and start to propagate axially along the sample tube with a well-defined front, while they simultaneously precess azimuthally with respect to the walls of the tube. The moment when the front passes through the lower end of the bottom coil is noted. This happens when Ω has already reached its final steady-state value. From the time difference, when the front moves from the bottom to the top coil, its velocity V_f is derived. To be successful, this measurement requires that the critical velocity of vortex formation is less than ΩR everywhere on the cylindrical wall, so that other competing vortex formation is not started during the propagation.

Below 0.4 T_c the propagating vortex configuration consists of a turbulent front and a twisted vortex cluster behind it. These precess at different azimuthal velocities. Owing to this difference in precession, reconnections are concentrated in the front where the vortices flare out towards the lateral tube wall. The axial velocity of the vortex front V_f depends on mutual friction $\alpha(T)$, on the number of expanding vortices $N(T,\Omega)$, and in particular on the properties of the front itself. Above 0.4 T_c in the laminar flow regime the axial front velocity follows roughly the velocity of the end point of a single-vortex on the cylindrical wall, when this vortex expands in the rotating vortex-free counterflow flow: $V_f \approx \alpha(T)\, \Omega R$. Towards low temperatures the front velocity slows down, as the mutual-friction dissipation decreases and ultimately vanishes in the ballistic regime as $\alpha(T) \propto \exp(-\Delta/T)$. However, with decreasing mutual friction turbulence is expected to become more prevalent and to concentrate in the front. As a result, the slow-down does not follow a monotonic exponential dependence but, as seen in Fig. 5, the reduced front velocity $V_f / \Omega R$ displays a shoulder at about 0.3 T_c and a plateau below about 0.2 T_c.

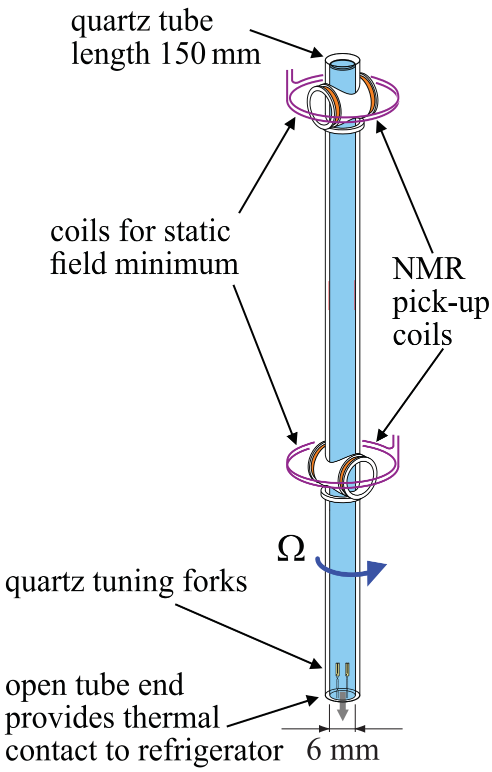


Fig. 4. Measuring setup in the rotating cryostat. The superfluid ^{3}He sample is contained in a circular quartz tube of 6 mm diameter. Two NMR receiver coils are located around the top section of the tube and are used to time the velocity of the vortex front propagating from the bottom to the top coil. The lower section of the tube below the NMR probes houses two quartz tuning fork oscillators which are used for temperature measurement. The open bottom end of the tube provides the thermal conduit to the sintered heat exchanger on the nuclear cooling stage.

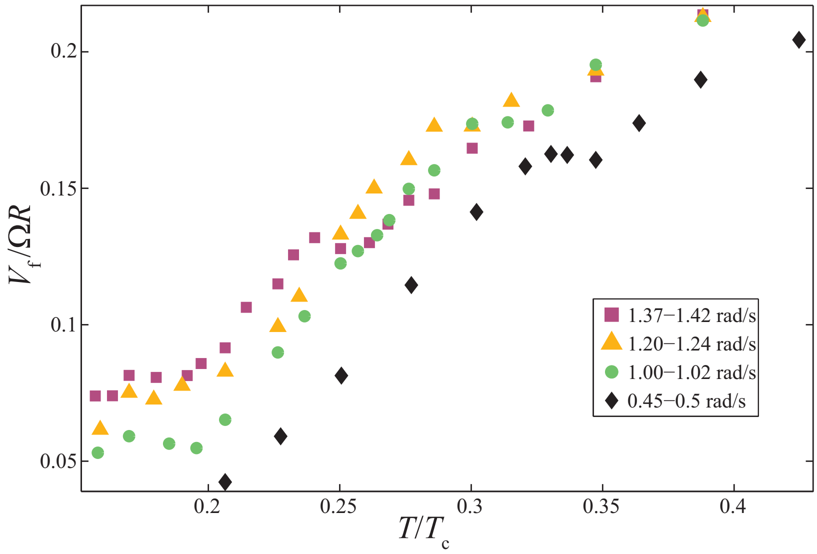
In earlier work [3], the shoulder was associated with a bottleneck in the energy transfer rate along the turbulent energy cascade: The kinetic energy is pumped into the vortex flow at large length scales of order R and is then transferred to smaller scales, by breaking up large eddies comprised of bundles with many parallel vortex lines into smaller ones, until at the cross-over scale comparable to the inter-vortex distance ℓ the energy is channeled to Kelvin wave excitations propagating on a single vortex.

The existence of a bottleneck in the energy transfer at the scale $\sim \ell$ has since then been questioned. The Kelvin wave cascade at length scales below ℓ distributes the energy via nonlinear interactions to ever smaller scales. The final limit is the length scale of the vortex core, the superfluid coherence length $\xi \sim \hbar\, v_F/(k_B\, T_c) \sim 70$ nm (at 0.5 bar liquid ^{3}He pressure). With decreasing mutual friction the cascade ultimately reaches down to this scale and couples to the quasiparticle excitations in the vortex core. These become overheated and then leak into the bulk volume. In Ref. [3] the low-temperature plateau was associated with this type of dissipation source.

The new results in Fig. 5 are more detailed, extend to a lower temperature of 0.14 T_c, and reveal in their Ω range (0.4 – 1.4 rad/s) a dependence of the normalized front velocity $V_f / \Omega R$ on Ω, or on the number of vortex lines propagating along the cylinder. At 0.14 T_c, the $T \to 0$ plateau of the front velocity turns out to be approximately two orders of magnitude above the simple extrapolation with only mutual-friction damping, assuming the number of vortices to remain at the equilibrium rotation value: $N = N_{eq}(\Omega) \approx \pi\, R^2\, 2\Omega/\kappa$. Thus the difference is appreciable. However, with decreasing temperature the number of propagating vortices was observed to drop more and more below the equilibrium value N_{eq}. This was inferred from the thermal measurements of Ref. [4], from the associated numerical simulation calculations, and from the observation that a slow laminar spin up followed after the front propagation had been completed, which increased N to N_{eq}. The reduction in the number of vortices N during the front propagation was explained to result from a compromise between mutual friction, which dominates above 0.3 T_c, and vortex line tension, which becomes increasingly more important at lower temperatures. We now need a consistent explanation of these mechanisms, to paint the complete picture of the $T \to 0$ dynamics in connection with the turbulent vortex front propagation.

Vortex propagation in a rotating cylinder constitutes a particular form of structured motion, which can be studied in a rotating cryostat. The motion is spatially separated in turbulent and laminar regions, with vortices highly polarized along the axis of rotation. This is in many respects the opposite of a homogeneous vortex tangle. However, like tangle formation, front motion is a process which is typical for superfluids if the conditions are suitable. It is amenable to comparison with numerical vortex filament calculations and, since it forms under the influence of competing interactions, several new types of structural and motional phenomena can be examined in this context.

Fig. 5. Front velocity $V_f(T,\Omega)$. The data display two plateaus as a function of temperature: 1) the plateau at about 0.3 T_c is associated with a bottleneck in the energy transfer rate from the large hydrodynamic length scales of the Kolmogorov cascade to the short length scales of the single-vortex Kelvin wave cascade [3]. The low temperature plateau represents the limiting dissipation in the $T \longrightarrow 0$ limit.



CNRS measurements: A precise determination has been completed of the effect of pressure on vortex formation via the dynamics of the second-order phase transition, known as the Kibble-Zurek mechanism. The data are presently analysed in the framework of theoretical models. Leggett proposed in his Baked Alaska scenario that nucleation of ^{3}He-B in ^{3}He-A is triggered by a cosmic particle, depositing enough energy to locally heat the liquid to the normal phase. If the subsequent cooling is then fast enough, there exists a finite probability that this region ends up as a bubble of B-phase within the A-phase bath. If the bubble exceeds a critical radius of order 1 μm, the surface energy will not be sufficient to let it disappear again and it can serve as a nucleation centre. Leggett advances the idea that a front of quasiparticles leaves ballistically (and not difusively) the centre of the hot spot. This normal phase shell of temperature $T > T_c$ then acts as an isolation between the B and the A phases, and thus gives the B-phase bubble enough time to grow above the critical radius.

An alternative model, called Aurore de Venise, is proposed by Bunkov and Timofeevskaya [10]. While Leggett considers that only one phase nucleates at the place of incidence, and the energy is distributed amongst a few quasiparticles which then leave the centre ballistically, this scenario proposes a more hydrodynamic picture, in which a whole region is heated above T_c. The rapid cooling then gives place to a number of different causally disconnected phases. The point of this model is that arbitrarily, both phases, A and B, can nucleate at different places. The probability to nucleate in either phase is not determined by the difference in free energies of the two states as one might intuitively suggest. Bunkov and Timofeevskaya calculate instead the 18-dimensional energy profile and claim that the probability is determined by the asymmetry of the profile near the high symmetry state. In other words, it does not matter, which state has a lower energy, important is the probability of its formation. And this probability depends on pressure. In the experiment, as seen in Fig 6, a discontinuity in vortex formation was observed at about 17 bar, which well corresponds to the theoretical prediction.

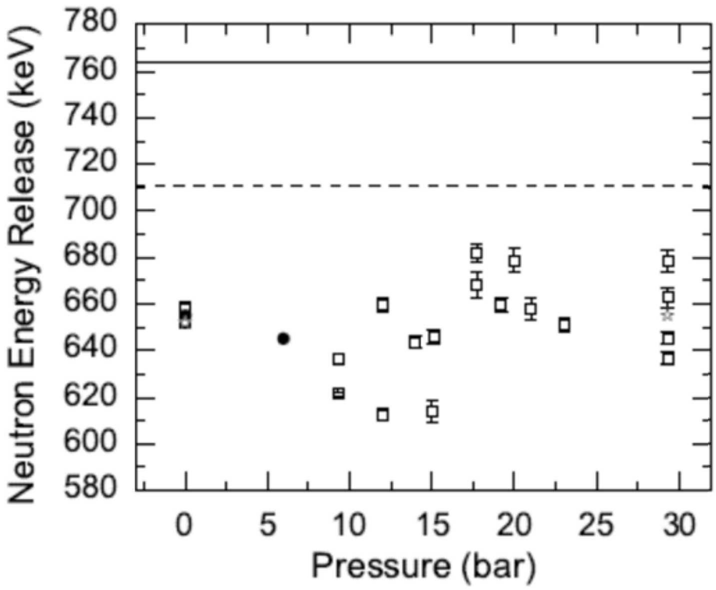


Fig. 6. *Pressure dependence of the heat release from a neutron absorption event in ^{3}He-B. The solid line corresponds to the total energy of 764 keV deposited by a neutron capture event. The dashed line corresponds to the energy after correcting for the scintillated energy loss [11].*

Further analysis of the "Big Bang" experiments in ultra-cold superfluid ^{3}He show that the probability of vortex formation corresponds quantitatively to the equations of the Kibble – Zurek theory of cosmic string formation. Indeed, the numerical calculations systematically show the fudge factor of order of magnitude, the only about 10% of vortices survived after a fast cooling through the phase transition. It might be that the computer simulations do not take into account some important components. It might also be that vortex formation in superfluid ^{3}He-B involves some kind of instability, which enlarges the vortex tangle owing to the huge inhomogeneity in the thermal background. These possibilities have been considered during the visits of A. Golov and V. Lvov to Grenoble. The result from the new data analysis and the associated calculations in a manuscript with the title "Dynamics of vortex creation in A and B phases at different pressures" is under preparation.

Milestone 2	Measurement of the dissipation in quantum turbulence and when a vortex state is established (24 months) Justification: Refs. [2] and [4]	**achieved**
Milestone 3	A precise determination of the effect of pressure on vortex formation via the dynamics of the second-order phase transition (30 months) Justfcation: Ref. [11] and to be published	**achieved**
Deliverable 2	Publication on vortex creation and dissipation in superfluid ^{3}He (24 & 36 months) Justification: Refs. [2] and [4]	**achieved**

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[12] J.J. Hosio, V.B. Eltsov, R. de Graaf, M. Krusius, J. Mäkinen, and D. Schmoranzer, *Propagation of thermal excitations in a cluster of vortices in superfluid 3He-B,* Phys. Rev. B **84**, 224501 (2011).

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[16] D.I. Bradley, P. Crookston, M.J. Fear, S.N. Fisher, G. Foulds, D. Garg, A.M. Guénault, E. Guise, R.P. Haley, O. Kolosov, G.R. Pickett, R. Schanen, and V. Tsepelin, *Measuring the prong velocity of quartz tuning forks used to probe quantum fluids,* Journal of Low Temperature Physics **161**, 536-547 (2010).

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

[18] J.J. Hosio, V.B. Eltsov, M. Krusius, and J. Mäkinen, Quasiparticle scattering measurements of laminar and turbulent spin-down of superfluid 3He-B, Phys. Rev. B submitted (2012).

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

ULANC measurements: The AB interface in superfluid helium-3 is a highly ordered structure separating two very different quantum condensates. In the terminology of cosmic branes, it plays the role of a 2-brane that is embedded in a 3-brane comprising the underlying quantum vacuum states of the A and B phase condensates. It is interesting to investigate what happens when 2-branes collide, as analogous processes in cosmology may have instigated inflation, a crucial ingredient to our current understanding of the early Universe.

The first experiments to study brane collisions were performed at Lancaster [1]. We used quasiparticle detection methods to discover that colliding AB branes produced topological defects. This is analogous to the creation of cosmological defects in the inflationary epoch of the Universe.

The first experiments were quite limited since it was not possible to probe the collision region directly with the quasiparticle sensors (vibrating wire resonators) that were available at that time. Since then we have focussed our efforts on building a new experimental stage to investigate AB branes. We have solved the sensor problem by developing a new technique that uses high Q-factor quartz tuning forks that are insensitive to the magnetic field. We have advanced new techniques to measure the velocity amplitude of the forks [2], analysed their interaction with ^{3}He-B [3], and investigated their sound emission properties [4]. The latter is an interesting topic in its own right, but one that is also critical to fully understand the response of the forks in superfluids at ultra-low temperatures.

We also had to remodel the cryostat rig so that it can house and cool the newer, much larger experiments, and cope with the large increase in circuitry associated with the tuning forks. This has been a major undertaking, and we have run the cell and cryostat build concurrently with the detector development.

A schematic of the new experimental stage is shown in Fig. 1. The AB cell is situated in the lower tailpiece section and 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 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 passage of the AB interface is inferred from the behaviour of the array of vibrating quartz tuning fork resonators that project into the superfluid from the sidewalls of the cylinder. These are extremely demanding experiments, requiring a combination of extreme low temperature, exquisite control of shaped magnetic fields, and simultaneous control and read-out of more than a dozen measurement devices.

In the first run of the new cell the cooling performance was quite poor and it only reached a minimum temperature of order of 200 μK. However, this was sufficient to characterise the properties of the experimental tailpiece and the tuning forks in superfluid ^{3}He-B.

In addition, the cell incorporates a new `floppy wire' device which we are developing to investigate pair-breaking and vortex production over a broad range of low frequencies. During the first run, we also developed the measurement techniques required to operate this new probe [5].

After the first run, we opened up the stage and discovered small leaks in the inner cell. These were repaired, and the cell is currently being run a second time. The cell performance has been much enhanced, now reaching temperatures of order 100 μK. We are currently investigating the interaction of the tuning forks with the AB brane itself. It is important that we fully understand the properties of these branes before we start to look at the after-effects of colliding them together. We have discovered that the interaction of the forks with the interface is reproducible, and that it depends on the relative orientation of the fork and interface (Fig. 2). The forks are also found to be very sensitive to the textural configuration of both the A and B order parameters which are influenced by the brane that separates them. These experiments also allow us to investigate field-induced nucleation of the A phase from the B phase and the field-induced distortion of the B phase order parameter which will be critical in helping to identify the defects which are created by brane collisions.

In parallel with this experimental work, we are collaborating with M. Arrayas to investigate whether the AB brane is susceptible to any instability as it moves. This could be important in the context of colliding branes since any instability could have a large influence on defect creation.

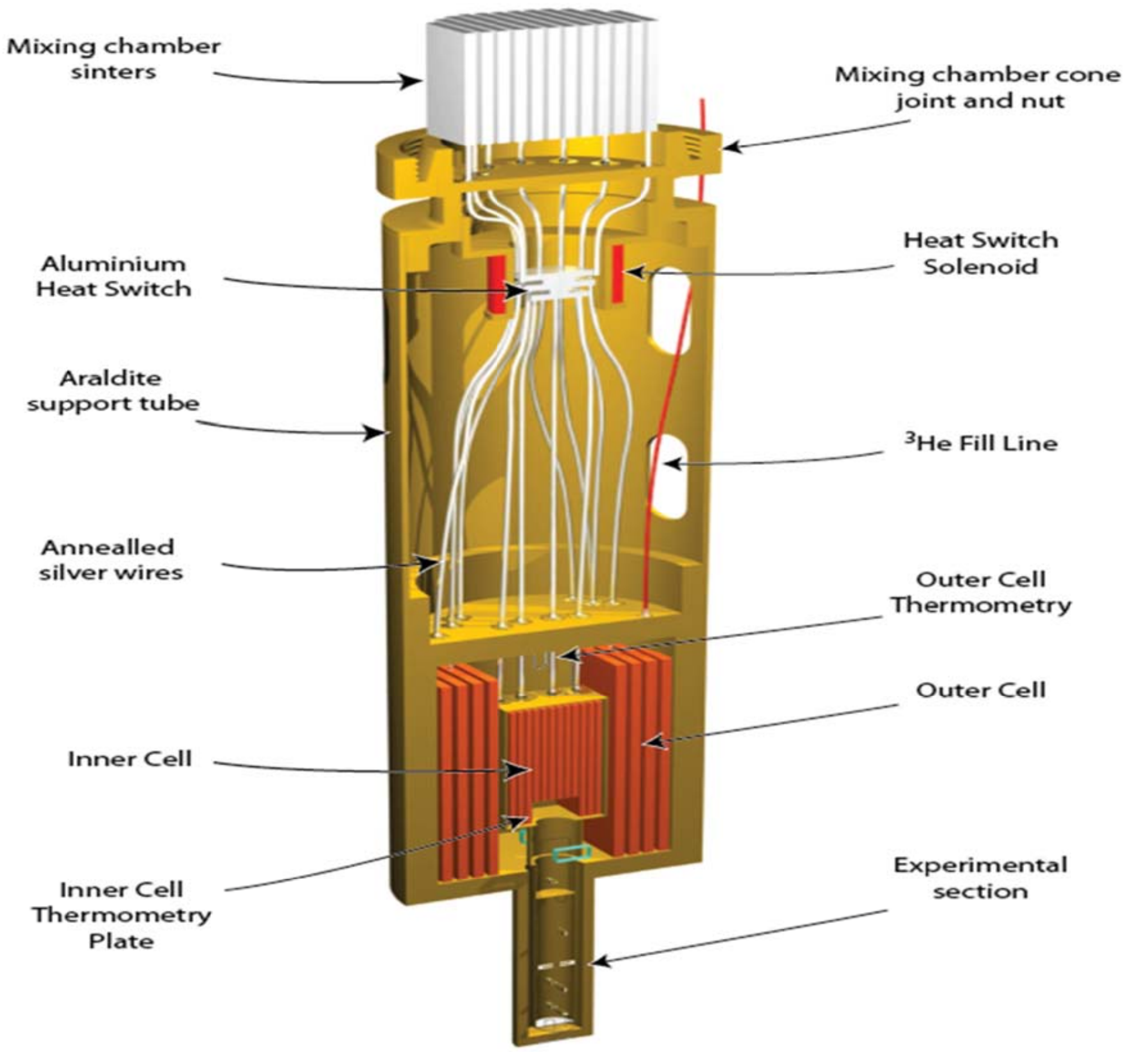
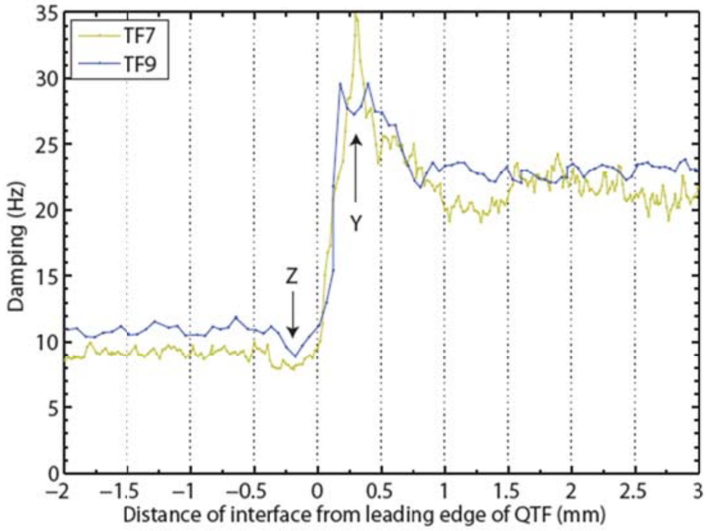
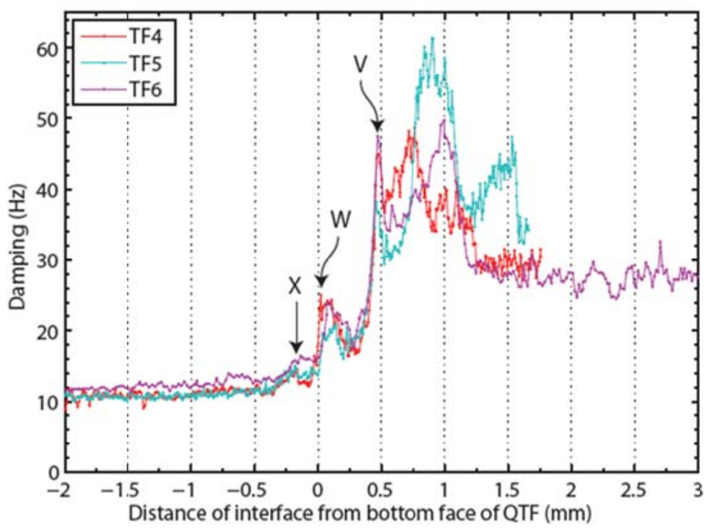


Fig. 1. The new stage to investigate AB branes.



(a) Tines oscillate in plane of interface.



(b) Tines oscillate perpendicular to interface.

Fig. 2. Interaction of quartz tuning forks with AB branes for two different orientations.

RHUL measurements with SQUID NMR of a single nano-confined slab of ^{3}He: We are studying the influence of confinement in nano-structured geometries on the order parameter of superfluid ^{3}He. Results from confinement in a 635 nm slab fabricated at Cornell, which has been studied using the sensitive SQUID NMR method developed at Royal Holloway, were discussed in the 18 month report. In these cavities we have experimental evidence for the stabilisation of the interface between the A and B phases and also the interface between inequivalent B-phase vacua, as predicted by Volovik [Phys.Rev. B**37**, 9298 (1988)], and analogous to cosmic domain walls. In a generalisation of this phenomenon, a superfluid state with spatially modulated order parameter has been predicted to exist [Vorontsov and Sauls, Phys.Rev.Lett. 98, 045301 (2007)], but has not yet been observed.

Since that time we have developed a method to fully characterize the cavity height profile. Measurements of cavity height at low temperatures are required since this is the key control parameter. These measurements were performed using a small cryostat with optical access at room temperature, 77K and below 7K. Spectral analysis was performed on a reflected collimated white light beam of diameter 0.3mm. We achieve a precision of ±2nm over a pixel area 0.3 mm × 0.3 mm. We observe some bowing of the cavity arising from differential thermal contraction between the glass and silicon. Measurements of the pressure dependence of the cavity height reveal that this is temperature independent with a coefficient 28 nm/bar at the centre of the cavity. These measurements agree with the cavity height profile determined at room temperature by a different method, using optical interferometry of laser light, in a refinement of the method described in a previous publication [Rev. Sci. Inst. **81**, 1 (2010)]. One paper describing the first NMR measurements on superfluid ^{3}He confined in such a fully-engineered nano-fluidic geometry is about to be submitted [6]. Two further papers are in preparation.

As discussed in the 18 month report, the work so far paves the way for future experiments in which confinement is used as the new control parameter. This should reveal a series of distinct physical phenomena. First new superfluid ground states are expected: possible stability of a superfluid ground state with spatially modulated order parameter (striped phase); quasi-two dimensional A phase, a gapped p+ip state; superfluid-insulator transition. Secondly the surface bound excitations, first discussed by Andreev, are predicted to have a Majorana character. In addition the B-phase supports "cosmic-like domain walls" predicted by Volovik. Experiments in controlled restricted geometries provide one avenue to investigate these phenomena, which are of broad significance to the study of topological quantum matter.

Experiments to study superfluid ^{3}He within a cavity of height 100 nm are in an advanced state of preparation. We have also prepared a cavity with height 1050 nm to search for the "striped" phase. This work requires us to achieve fully specular surface scattering of quasiparticles. 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 achieve close to the specular limit. To stabilize the film requires a reliable cold valve, thermally anchored at a temperature of less than 20 mK, which is superleak tight. We have fabricated such a valve and it is in the final stages of testing. Finally the techniques described in JRA4 will be applied as local probes in such geometries.

CNRS measurements: Experiments conducted at CNRS in multi-cell Lancaster-type "black body radiator" configuration (see Task 1), using a vibrating wire resonator at temperatures on the order of 100 μK, revealed the presence of a new type of defect in superfluid ^{3}He-B, which strongly suppresses the motion of the vibrating wire. We have investigated the characteristics of the defect, by applying different forces to the vibrating wire, and also varying the temperature up to the normal phase of 3He. The results will be reported in a publication with the title "Mechanical response of vibrating wire on a "cosmological defect" in superfluid 3He-B" by Yu. Bunkov, J. Elbs, H. Godfrin, A. Golov, E. Collin, P. Hunger, and C. Winkelman (presently under preparation).

Milestone 4: Identification of the topological defects left after brane annihilation (24 months) **partly achieved**
Justification: The defects have not yet been identified, but several important developments have been made while developing the techniques required for this measurement.

Milestone 5: Observation of several "cosmological defects" in a microkelvin multi-cell detector (30 months) **partly achieved**

Publications related to JRA3 Task 2:

[1] D.I. Bradley, S.N. Fisher, A.M. Guénault, R.P. Haley, J. Kopu, H. Martin, G.R. Pickett, J.E. Roberts and V. Tsepelin, *Relic topological defects from brane annihilation simulated in superfluid 3He,* Nature Physics **4**, 46-49 (2008).

[2] D.I. Bradley, P. Crookston, M.J. Fear, S.N. Fisher, G. Foulds, D. Garg, A.M. Guénault, E. Guise, R.P. Haley, O. Kolosov, G.R. Pickett, R. Schanen, V. Tsepelin, *Measuring the Prong Velocity of Quartz Tuning Forks Used to Probe Quantum Fluid,* Journal of Low Temperature Physics **16**1, 536-547 (2010).

[3] D.I. Bradley, P. Crookston, S.N. Fisher, A. Ganshin A.M. Guénault, E. Guise, R.P. Haley, M.J. Jackson, G.R. Pickett, R. Schanen, V. Tsepelin, *The damping of a quartz tuning fork in superfluid 3He-B at low temperatures*, Journal of Low Temperature Physics **157**, 476-501 (2009).

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

[5] 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 and P. Williams, *A new device for studying low or zero frequency mechanical motion at very low temperatures,* Journal of Low Temperature Physics **165**, 114-131 (2011).

[6] *Topological superfluids confined in a regular nano-scale slab geometry*, L.V. Levitin, R.G. Bennett, A.J. Casey, B.P. Cowan, J. Saunders, D. Drung, Th. Schürig, J.M. Parpia, to be submitted to Nature.

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

The physics of black holes can be studied with hydrodynamic analogue models. Quantum models, particularly with a Fermi superfluid like ^{3}He-B in the zero temperature limit, would model additional properties. This is an important goal in Task 3. However, to make the outcome from such studies more informative, it was decided at **Aalto** that more work was in order to shed light on the creation and motion of vortices in the zero temperature limit, before attempting a quantum model of black holes. A second consideration was to speed up the Q-ball studies in Task 4, since these measurements promise to provide new and more sensitive NMR techniques for monitoring vortices. These changes were introduced as an amendment request to Annex I in September 2011. In the updated Annex I Milestone M6 and Deliverable D4 on the back-hole analogue are due in month 48.

ULANC measurements: The generation of new particles from the quantum vacuum in accelerating motion is known as the Unruh effect. The goal is to search for this effect in superfluid ^{3}He in the Lancaster experiment (Task 2). In the apparatus of Fig. 1 a layer of A phase in a magnetic field can be supercooled below the thermodynamic A → B transition at H_{AB} (T,P), owing to the surface tension of the AB interface. While slowly sweeping down the temperature T in constant magnetic field H, the A phase layer thickness is reduced and ultimately somewhat below the critical value, $H < H_{AB}$ (T,P), a hole of B phase opens up in the center of the cylinder across the A-phase layer. After that the torus-shaped A-phase ring shrinks and annihilates on the cylinder wall in rapid supercooled motion. It is this final rapid motion of the AB interface which might give rise to quasiparticle generation via the Unruh effect in the ballistic temperature regime. This suggestion can be tested by monitoring the signal from the quartz tuning fork arrays.

CNRS measurements: The goal of this Task is to provide a test of the percolation theory of the A ⟶ B transition in superfluid ^{3}He under the conditions where the Kibble - Zurek mechanism is applicable (Task 2). The probability of the A-B transition in bulk superfluid ^{3}He strongly depends on pressure and temperature. It can also be triggered by cosmic rays [P. Schiffer, D.D. Osheroff, and A.J. Leggett, in Progress in Low Temperature Physics, Vol. **14**, editor W.P. Halperin, Elsevier, Amsterdam, 1995]. The explanation of the experimental data with the theory of A.J. Leggett called the Baked-Alaska model, produces a relatively poor fit. In contrast, the fit in with the theory of Bunkov and Timofeevskaya is more satisfactory. It can be considered as the percolation of about 50 droplets of B phase inside the A phase, which is a physically acceptable result. A new manuscript is under preparation.

Milestone 7: Test of the Unruh effect from rapid motion of a phase boundary (36 months) **work in progress**

Milestone 8: Test of the percolation theory of the A-B transition (36 months) **partiallyachieved**

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

Introduction: Coherently precessing nuclear spin resonance modes in superfluid ^{3}He have gained in importance since the start of the Microkelvin Collaboration, mainly for the following reasons:

1) Coherently precessing NMR modes can be described as condensates formed from bosonic magnon or spin-wave excitations [1]. These condensates are formed in an externally controlled rf pump field and, depending on the pump frequency, the condensation can take place in the ground state or on the excited levels of a magnetic trap where the trapping potential is partly provided by the externally controllable order-parameter texture of the bulk superfluid ^{3}He-B state. The magnon population in the trapped state grows nonlinearly when the difference in the frequencies of the pump field and the trapped eigenstate is swept down. This is the equivalent of reducing the chemical potential for the trapped state. Via the backaction of the increasing magnon population on the order parameter texture, the texture is flattened and becomes finally homogeneous. By this mechanism the trapping potential is observed to change from harmonic to box-like. The phenomenon is called self-trapping of the magnon population [2].

2) The description in terms of Bose-Einstein condensation makes use of the powerful tools which have been developed for the condensates formed from gaseous cold atom clouds. In Annex I of the Microkelvin grant proposal the low-temperature coherent condensate in ^{3}He-B was called a Q-ball. This name refers to the self-trapping property of the condensate, which has been analyzed in quantitative terms in Ref. [2]. In particle physics self-trapping or spatial localization is used to describe particle formation: a hadron can be understood to be the result from Q-ball formation, from the repulsive interaction of quarks with the surrounding pionic field, as described by the MIT bag model. The increased understanding of the low-temperature coherent NMR mode in ^{3}He-B in terms of magnon condensation in a potential well formed by the order parameter texture with a long textural healing length [2] has provided a much needed novel tool for exploring the $T \to 0$ limit.

3) A number of applications exist currently for which the coherently precessing mode can be used. One of them is to find the Josephson coupling between two spatially separated magnon condensates. Another is the current search for quasiparticle states with a zero-energy crossing in their spectrum, the Majorana fermions [3]. ^{3}He-B is the best example of a fully gapped topological insulator. One of its outstanding properties is the existence of quasiparticle states on surfaces and in vortex cores with a linear energy spectrum $E(\mathbf{k})$ and a state at zero energy. The experimental signature of this spectrum would be a power-law dependence on temperature for the thermal properties, instead of the usual exponential dependence $e^{-\Delta/(k_B T)}$ of the bulk properties. Different experimental proposals to explore the existence and properties of Majorana fermions

in ^{3}He-B were discussed at length in the Microkelvin 18-month Review Meeting 14 – 16 Oct, 2010.

ULANC measurements: We have continued to probe the properties of a Q ball in superfluid ^{3}He-B at ultra-low temperatures. In the Lancaster literature it is called a Persistent Precessing Domain (PPD). The experimental cell was designed to allow us to excite two independent Q balls simultaneously and to try to investigate the interaction between the two as they are brought into close proximity. This is a demanding experiment which requires accurate control and manipulation of the magnetic field profile with two field minima along the cell axis. We have succeeded in cooling the cell to very low temperatures with the necessary superconducting field coils. We have also succeeded in generating two independent Q balls simultaneously in the same experimental chamber.

However, the spatial manipulation of two simultaneous Q balls during their free decay is proving to be difficult. Further work is required to develop the experimental techniques required for this. In parallel, we have been investigating the nature of the Q ball and in particular, we have studied possible dissipation mechanisms at very low temperatures. The bulk dissipation mechanism is found to be extremely temperature dependent, being roughly proportional to the density of thermal quasiparticle excitations, shown in Fig. 1. In addition we find an extra surface dissipation mechanism that is quite insensitive to the pressure, and which sets it suddenly as the Q ball is moved close to the horizontal end wall of the experimental chamber, shown by the data in the inset to Fig. 1.

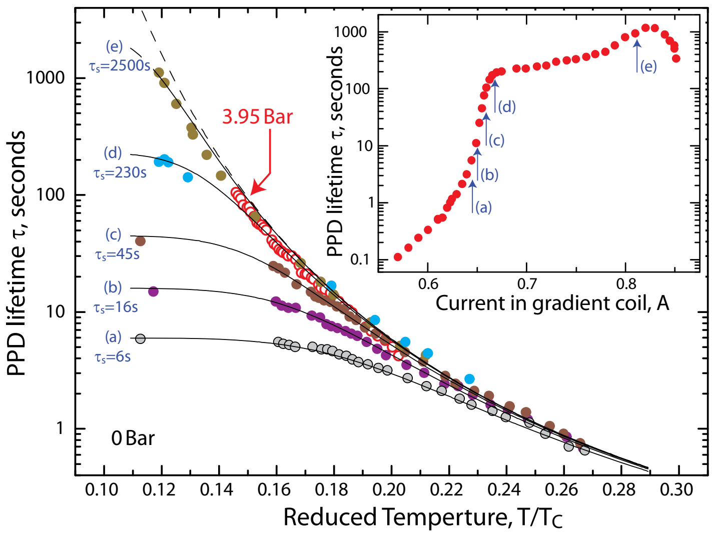


Fig. 1. Q-ball lifetime at low temperatures, revealing bulk and surface dissipation mechanisms. The inset shows the lifetime at varying positions in the cell, which we manipulate by changing the magnetic field profile.

AALTO measurements: Q ball or magnon condensate formation has been studied both in the ground state as well as on the excited levels of the magnetic trap shown schematically in Fig. 2. The self-trapping property is observed both in the ground state as well as on the excited levels. Josephson oscillations in the populations of an excited state relative to the ground state have been searched for, but have so far not been identified. By manipulating the coupling between these populations via the "flare-out" order parameter texture it is hoped that the oscillations will be eventually revealed.

Fig. 2. *Coherently precessing low-temperature NMR mode in* ^{3}*He-B. The order parameter field and trapping potential for the magnon condensate are shown in the sample cylinder (see Fig. 4 of JRA3 Task 1) . The magnetic trap is formed by the "flare-out" texture of the orbital anisotropy axis* **L** *(thin lines) in a shallow minimum of the vertical magnetic field* **H** *(right). The field minimum is produced with a few turns of pinch-coil windings around the NMR pick-up coil, as shown in Fig. 2. The arrows represent the magnetization* **M** *which precesses coherently with constant phase angle in the magnon condensate droplet (dark blue), in spite of the inhomogeneity in the texture and in the magnetic field.*

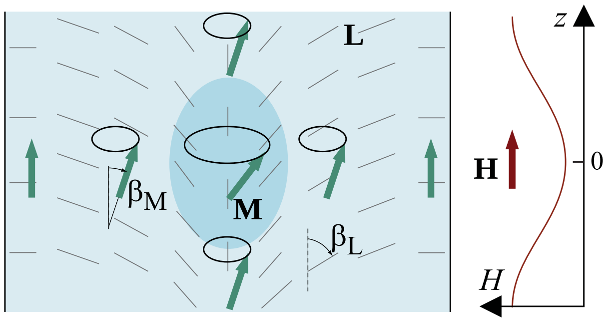
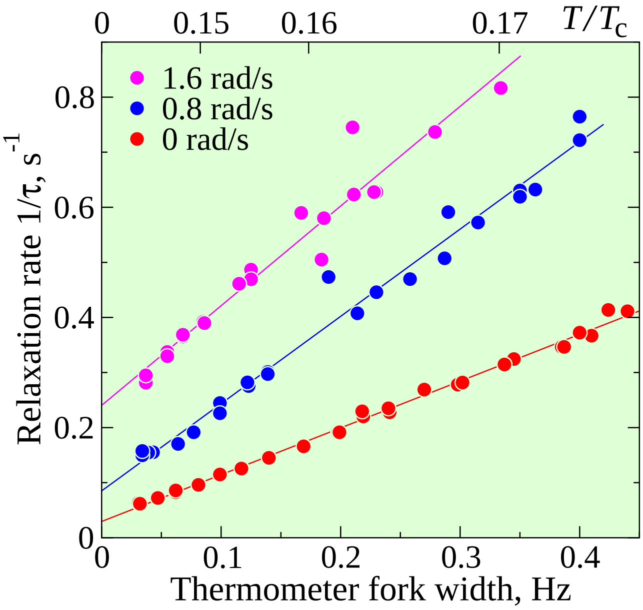


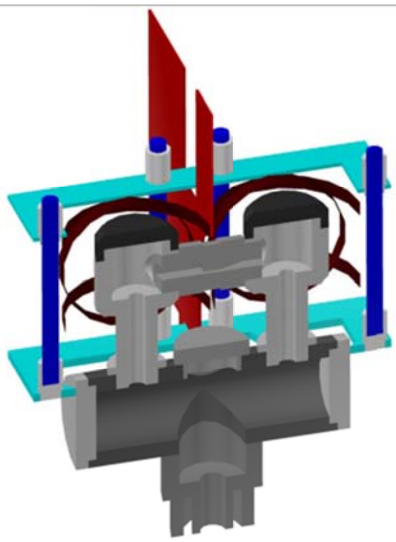
Fig. 3. *Measurements of the relaxation rate of the ground-state condensate at zero rotation and at two rotation velocities with the equilibrium array of rectilinear vortex lines. The measurement is performed in continuous-wave NMR conditions, by switching off the rf pumping and recording the slow decay in the magnon population as a function of time in the absence of the pump field. A large enhancement in relaxation with increasing vortex number is seen to result. The relaxation also depends on the trapping potential; here a smaller contribution from this source has not been subtracted. The temperature on the horizontal axis is determined from the frequency width of the resonance in the quartz tuning fork oscillator which is measured by scanning the frequency of its current drive. This width is proportional to the quasiparticle density in the bulk volume. Thus the relaxation rate is directly proportional to the quasiparticle density, but displays a finite intercept at zero temperature.*



One of the proposals to search for a signature from Majorana fermions is to measure the rate of free decay of the Q-ball NMR signal. Using the rotating cryostat, one can test the influence of different rotating states on the relaxation rate. By studying the population decay of the trapped magnon condensate as a function of the vortex density, one might then be able to separate between bulk relaxation and the contribution from vortices. In the radial direction the confinement in the magnon trap (Fig. 2) is provided by the shallow gradient in the deviation of the order parameter axis from the axial orientation in the centre of the cylinder. This can be changed and controlled with rotation, by arranging to have vortex-free rotation or the equilibrium density of vortices at different rotation velocities Ω, for instance. In a long cylinder the axial confinement can be provided by a minimum in the axially oriented NMR polarization field, as created with a small pinch coil, for instance. Another means of providing axial confinement is to have the NMR pick-up coil close to the end plate of the cylinder where the position of the condensate bubble will be stabilized by the distortion in the flare-out texture [3]. In this arrangement instead of an end plate there can also be the free liquid surface. Thus the relaxation can be probed and compared in a number of different situations, in order to identify a possible Majorana contribution. However, since all such changes also change the order parameter texture and thereby the trapping potential, the one has to be able to separate out the direct influence from the change in the profile of the order parameter field.

In Fig. 3 an example is shown of the relaxation rate as a function of temperature from extensive measurements at different vortex densities, with rectilinear vortex lines crossing the condensate bubble. This example demonstrates that relaxation is indeed a sensitive probe: with increasing density of vortex lines ($\propto 2\Omega/\kappa$) the slope of the lines in Fig. 3 increases linearly with Ω. Similar large enhancement in the relaxation rate follows when the free liquid surface is brought close to the NMR detector coil. A common feature is a finite zero-temperature intercept, as seen in Fig. 3. The Q-ball measurement in contact with the free surface proves to probe sensitively also waves and excitations on the free surface since they modulate the order parameter texture and thereby couple directly to the coherently precessing NMR mode. The relaxation measurements are ongoing and their interpretation is in progress.

SAS measurements: Two interacting Bose-Einstein condensates of magnons have been studied in superfluid ^{3}He-B. The condensates are in the coherently precessing state known as the Homogeneously Precessing Domain (HPD). The HPD state is a bulk condensate, with coherently precessing magnetization over the entire volume of the domain, which forms at temperatures above about 0.4 T_c. For this measurement an experimental cell was designed and fabricated with two NMR towers connected with a channel (see Fig. 4). Each of the towers had a separate set of rf and longitudinal coils serving for the generation and perturbation of the HPD, respectively.



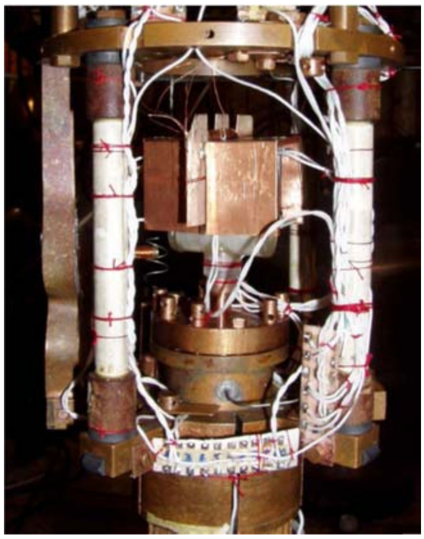


Fig. 4. *Schematic cross-section of the experimental cell for the investigation of two interacting magnon condensates in the HPD state (left). The actual apparatus mounted on the top of the nuclear stage is shown on the right.*

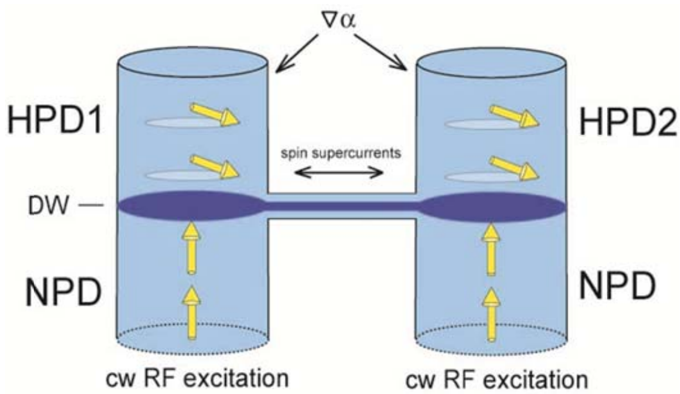


Fig. 5. *Schematic illustration of the experiment.*

When two HPD's were excited and generated simultaneously in both towers, the position of the domain wall (DW), which separates coherently precessing spins (*i.e.* the condensate of magnons) from the non-precessing ones, was placed in the connecting channel (Fig. 5). By means of a short current pulse applied to one of the longitudinal coils (e.g. HPD1), oscillations of the domain wall were excited and subsequently these oscillations (spin waves) were transmitted via the channel to the second precessing domain (HPD2).

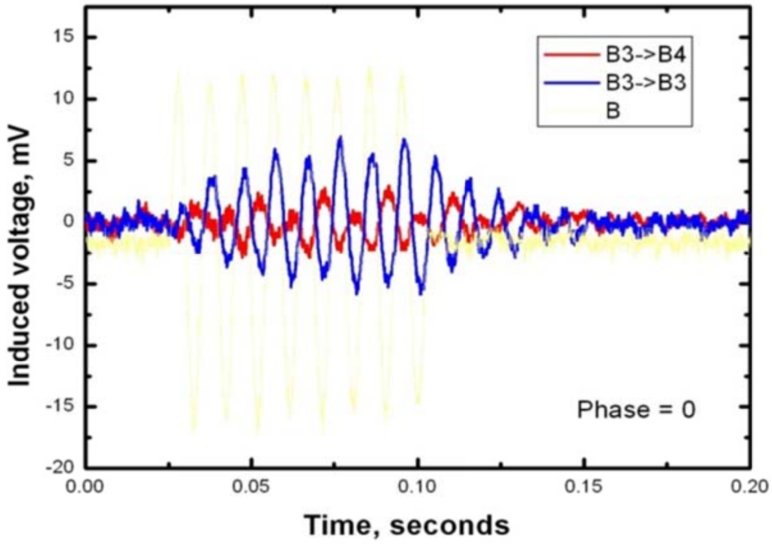


Fig. 6. *Measured signals from the spin waves: emitted wave (blue), received wave (red), excitation signal from generator (yellow).*

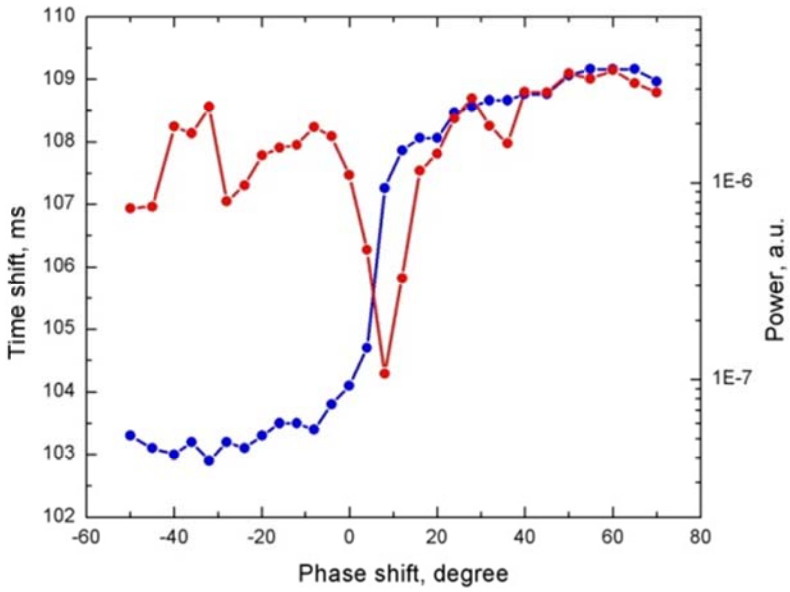


Fig. 7. *Time shift or phase delay (blue) and transmitted power as a function of the phase difference between rf excitation signals used for HPD's generation.*

Both the emitted and received spin waves were measured simultaneously with respect to their dependence on the magnitude of spin flow, which was controlled and adjusted via the phase of one of the rf-excitation signals used for the HPD generation of the two domains. Examples of the measured signals are presented in Fig. 6. Fig. 7 shows the measured dependences of the time shift or phase delay (blue) and the transmitted power (red) on the phase difference between the two rf excitation signals. The results can be partially interpreted in the framework of the theory developed by W. Unruh and R. Schuetzhold: *Gravity wave analogue of black holes* [Phys. Rev. D **66**, 044019 (2002)]. However, the physical picture is more complicated and work on the physical interpretation of the observed phenomena is in progress.

The difficulty with the interpretation of the data lies in that the presence of the rf field used for the HPD excitation removes the degeneracy in the phase of the precessing spins, *i.e.* it breaks the symmetry, due to which an energy gap appears in the excitation spectrum. We have developed a complex theoretical model of the collective oscillation modes (torsion and surface modes) of the homogeneously precessing domain. We show that the application of the rf field B_{RF} indeed violates the symmetry of the precessing spins, due to which the excitation spectrum acquires an energy gap. 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. A manuscript describing the model presented above has been sent to Physical Review B [5].

In a related experiment on the magnetic properties of superfluid ^{3}He-B we observed anomalous damping of piezoelectric tuning fork resonators immersed in the ^{3}He-B bath at temperatures below 200 μK (Fig. 8). Surprisingly, this damping depended on the magnitude of the applied magnetic field and exhibited a maximum at the field, which corresponds to the Larmor resonance condition. Preliminary results were published in Ref. [6].

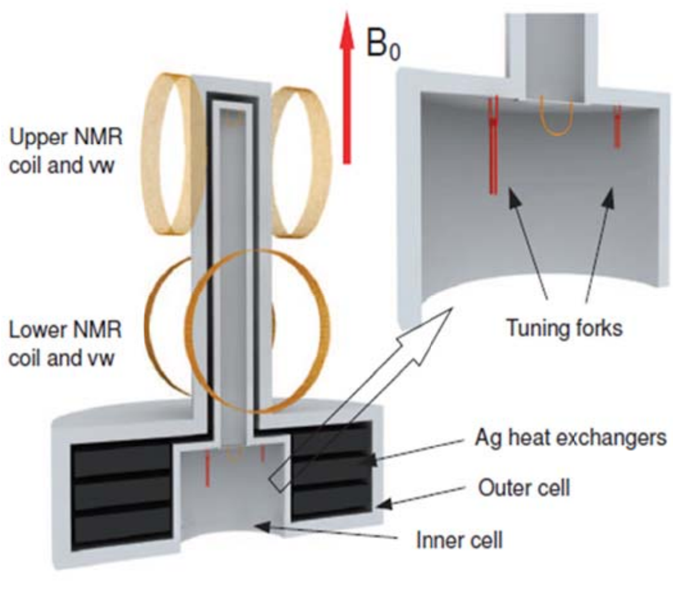


Fig. 8. *3-dimensional cross-section of the experimental cell.*

The observed phenomenon seems to be related to nuclear magnetic resonance excited by mechanical motion. The presence of a surface in superfluid ^{3}He-B breaks the symmetry of the superfluid condensate, by enforcing the formation of Cooper pairs with orbital momentum parallel (or anti-parallel) to the surface normal and suppressing all others.

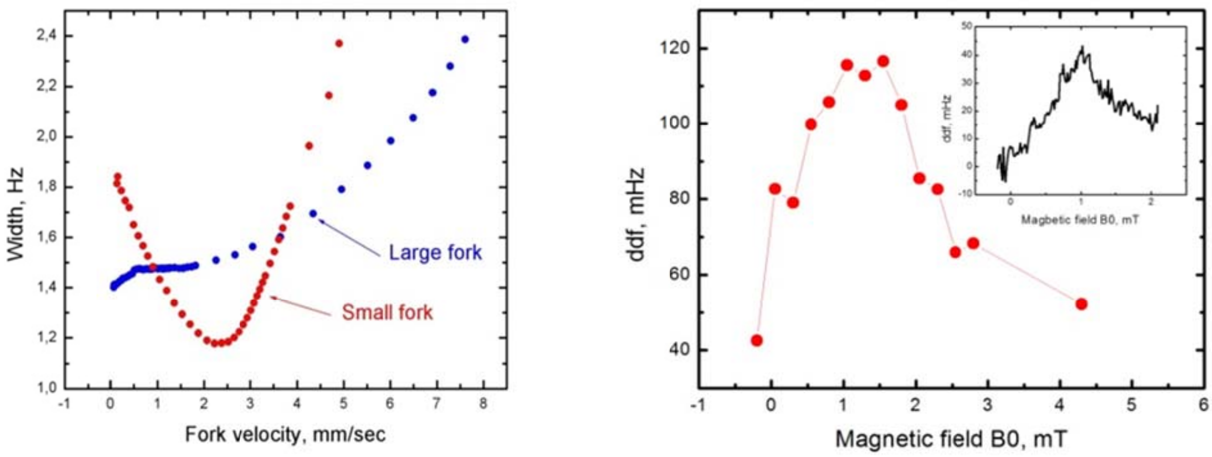


Fig. 9. *Resonance width or damping of the large and small tuning forks (left); dependence of the large fork damping on the applied magnetic field (right).*

The result is strong anisotropy near the surface, associated with the energy gap suppression over a distance of the order of the coherence length from the surface. The energy gap suppression changes the spectrum of the excitations and creates "space" for Andreev bound excitations, which are excitations with energy lower than the gap energy. Moreover, the surface of the tuning fork is covered with 2-3 layers of solid ^{3}He, which oscillate together with the resonator. Solid ^{3}He layers, with a huge magnetic moment at ultra-low temperatures [7], generate an alternating magnetic field oriented perpendicular to the static field, during the fork motion (Fig. 10).

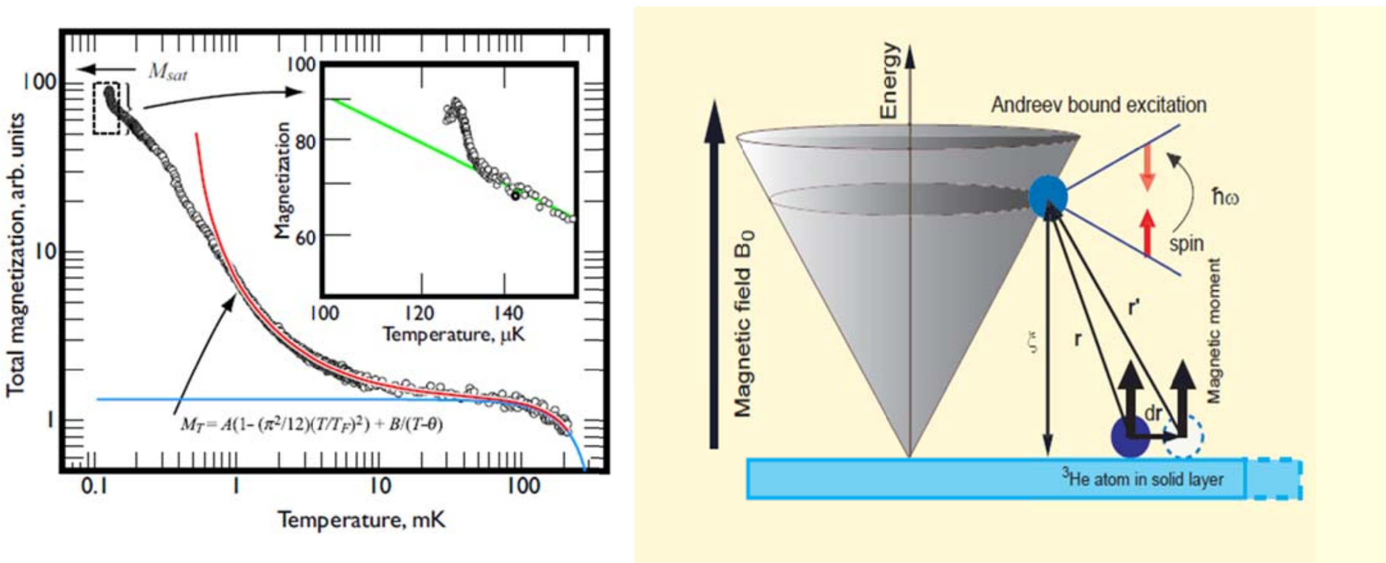


Fig. 10. (Left) *Total magnetization of the helium inside aerogel: at ultra-low temperatures the magnetization of the solid ^{3}He layers dominates [7].* ***(Right)*** *Schematic picture of the mechanism for the anomalous damping of a tuning fork.*

The alternating magnetic field (Fig. 10, on the right) acts on the spins of the Andreev bound states. When the Larmor resonance condition is satisfied, these spins are excited and they reverse their orientation and, being oriented opposite to the magnetic momenta of solid ^{3}He, a repulsive interaction between them is set up. The repulsive interaction is overcome by the tuning fork motion, but is paid by the additional energy taken from the excitation source. At the magnetic resonance condition the maximum number of spins are flipped and the maximum damping is observed. To prove this interpretation, additional measurements have to be performed.

The above measurements with tuning fork oscillators at extremly low damping and high Q value have to be performed with great care. The influence of the electrical measurement on the mechanical tuning fork oscillator properties at ultra-low temperatures was examined [8] and was shown to be an important consideration. A description of the novel I/V converter, which we recommend as suitable for tuning forks measurements, is presented in Ref. [9].

Milestone 9: Observation of the interaction between two independent precessing Q-balls (30 months)

work in progress

Explanation: Two independent precessing Q balls have been excited simultaneously in the same experimental cell, but prove to be difficult to manipulate in a controlled way. Further work is required to develop the techniques to manipulate two or more Q balls simultaneously in controlled manner.

Milestone 10: Creation of excited modes of a "Q-ball" under radial squeezing by rotation (36 months) **achieved**
Justification: Ref. [2]

Milestone 11: Realization of microkelvin thermometry based on "Q-ball" behaviour (42 months) **achieved in advance**

Milestone 12: Observation of enhancement in the Q-ball spin relaxation rate owing to surfaces and vortex cores (42 months) **achieved in advance**

References to JRA3 Task 4:

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

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[5] M. Kupka and P. Skyba, *BEC of magnons in superfluid 3He-B and symmetry breaking field*, submitted to Physical Review B, under review process, recommended for publication.

[6] M. Človečko, E. Gažo, M. Kupka, M. Skyba, and P. Skyba: *High quality tuning forks in Superfluid 3He-B below 200 uK,* J. Low Temp . Phys. **162**, 669-677 (2011).

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[8] P. Skyba, *Notes on measurement methods of mechanical resonator used in low temperature physics*, J. Low Temp. Phys. **160**, 219-239 (2010).

[9] S. Holt and P. Skyba, *DC I/V converter with wide bandwidth and selectable gain*, submitted to Reviews of Scientific Instruments, under review process, recommended for publication.

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

Introduction: The development of ultralow temperature detectors for the search of dark matter is one of the prime goals 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 new solid state sensors.

Heidelberg measurements: In Heidelberg (HEID), new generations of fully micro-fabricated magnetic calorimeters have been developed for applications ranging from x-ray spectroscopy [1] to beta detectors for neutrino mass measurements [2]. The first magnetic calorimeter linear arrays with 8 pixels have been successfully fabricated and characterised in details. For moderately hard x-rays up to about 20 keV the single pixel resolution of such a detector is 3 eV. For hard x-rays and gamma rays up to 200 keV with massive 200 μm thick Au absorbers for a large quantum efficiency a resolution of about 40 eV has been obtained. A picture of such an eight pixel linear array is shown in Fig. 1.

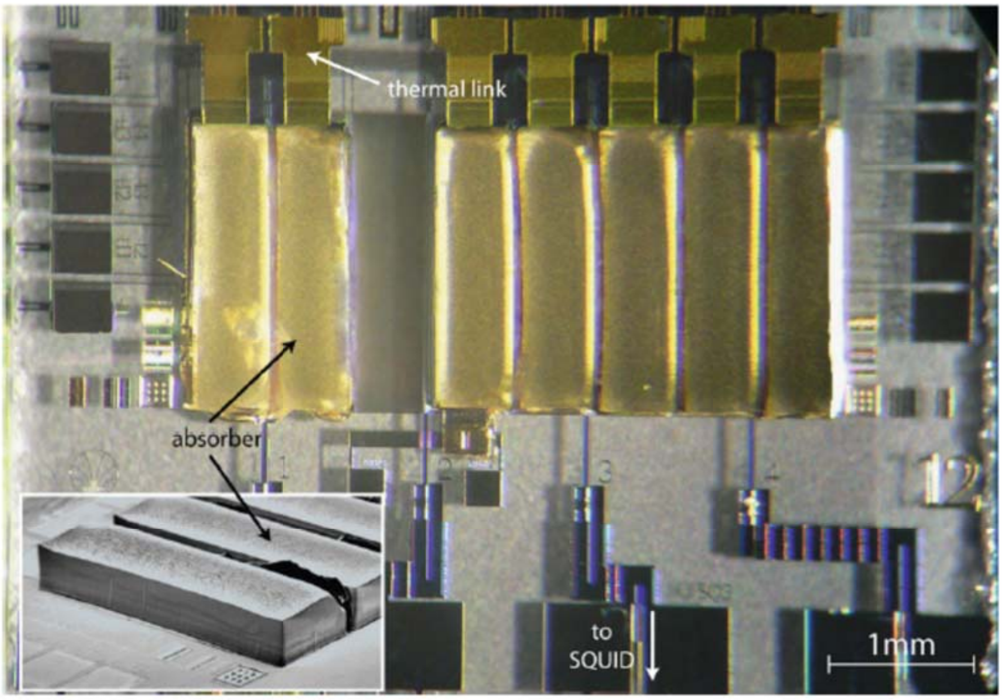

Fig. 1. *Optical and SEM picture of a magnetic calorimetery linear array for hard x-rays.*

The performance of this detector was tested in two runs in a dilution refrigerator. As readout a two stage dc SQUID from PTB was used together with XXF-1 electronics from Magnicon. Fig. 2

shows the expected stopping power of this detector calculated with PENELOPE and a test spectrum taken with a ^{55}Fe x-ray source.

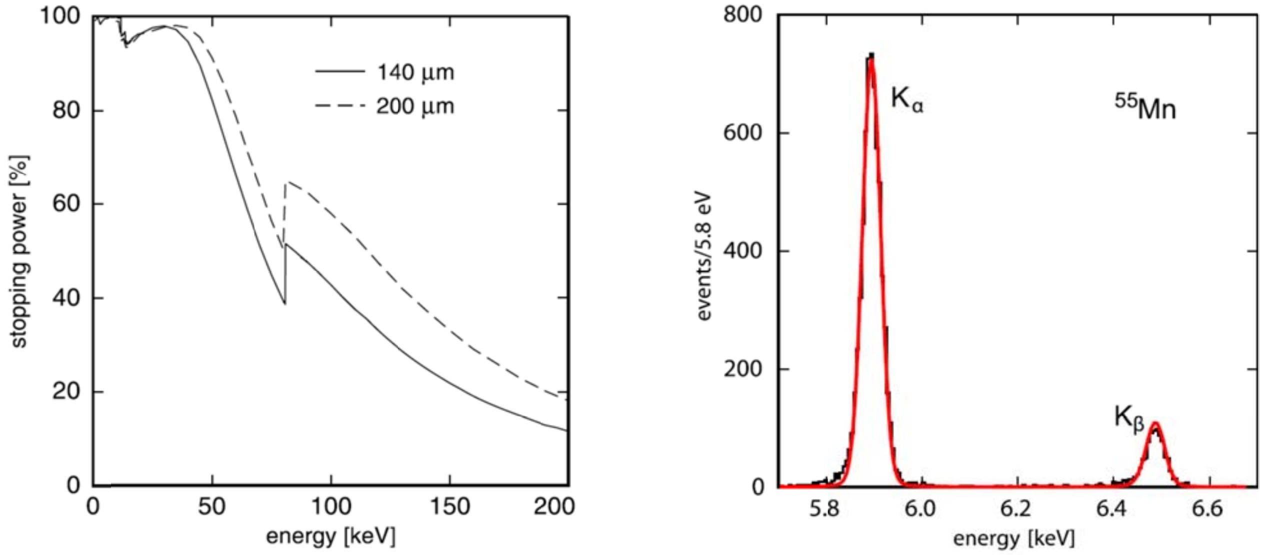

Fig. 2. *Expected stopping power of the max200 detector (left) and* ^{55}*Mn X-ray spectrum taken with this detector at 20 mK (right).*

Recently a new geometry of magnetic calorimeters has been developed [1]. The major difference from the previous geometry is a sandwich structure of the sensor coil system, were the Au:Er sensor material is deposited via sputtering on top of a Nb spiral and has on its top a superconducting ground plane, to enhance the flux sensitivity. The sketch of the detailed geometry and an SEM image of this detector are depicted in Fig. 3.

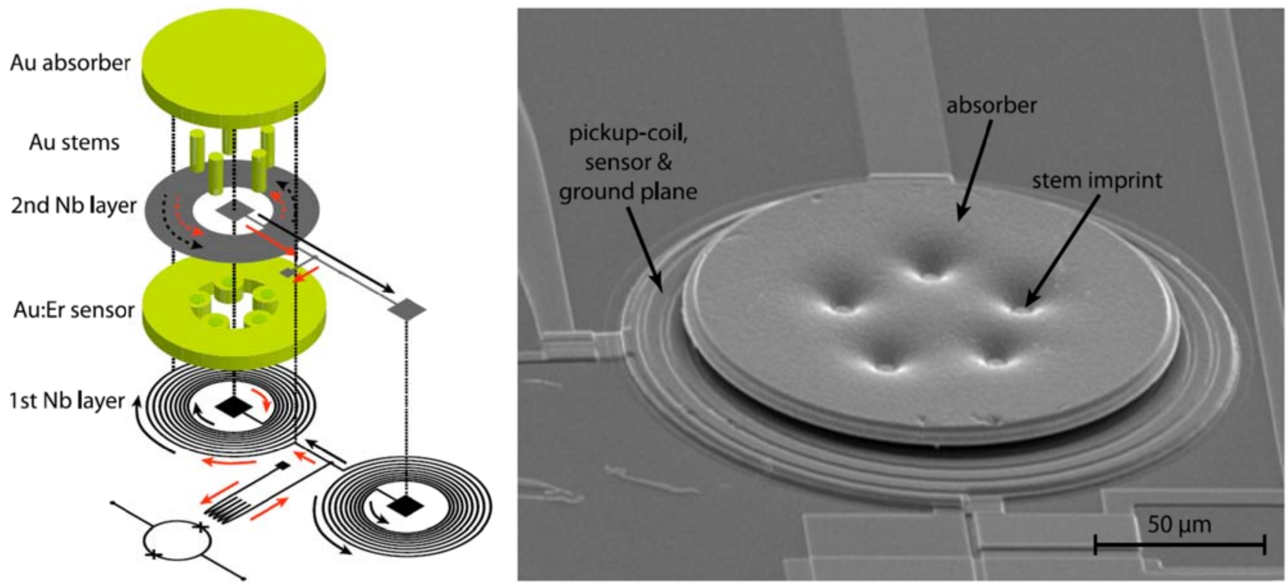

Fig. 3. *Exploded sketch and SEM picture of the sandwich type magnetic calorimeter.*

A first prototype detector has been fabricated and tested in adiabatic demagnetisation fridge. Again a two stage dc SQUID from PTB was used as a readout of this detectors along with the XXF-1 electronics from Magnicon. This new geometry of magnetic calorimeters proofed to be very capable in the first test measurements. Using a 55Fe source a resolution of 2 eV has been obtained, which is the best ever achieved energy resolution of a magnetic calorimeter at 6 keV. The performance of the detector is illustrated in Fig. XZ.

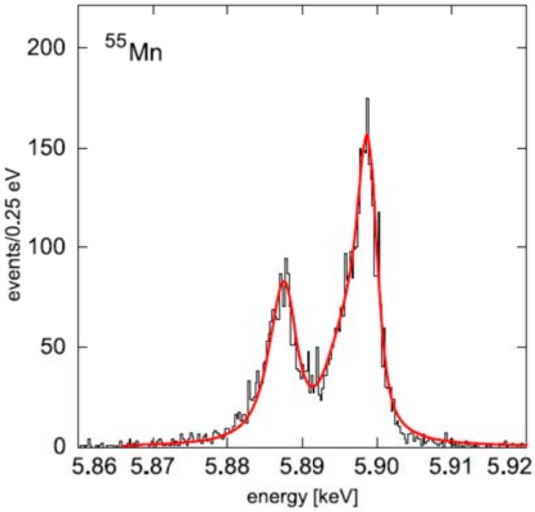

Fig. 4. *^{55}Mn Kα line, acquired with the prototype sandwich detector, histogram: natural line shape convolved with a Gaussian of E_{FWHM} = 2.0 eV (solid red line).*

Grenoble measurements: In Grenoble, a new generation of Vibrating Wires (micro-mechanical resonators) for low temperature physics has been developed and the corresponding lithographic masks have been made. The first steps involved preparation of the oscillators using micro-fabrication technologies such as optical lithography (UV, deep UV), laser lithography, selective wet etching, reactive ion etching, physical vapour deposition and related characterisation techniques (microscopy, interferometry, profilometry). During this time, new designs of micro-oscillators were also produced.

These structures, made at our Nanofab microfabrication facility, are similar in shape to those described in the previous report (goal-post shaped). However, we use now silicon nitride (Si_3N_4) instead of silicon, thus allowing a substantial reduction of the thickness of the devices with outstanding mechanical properties.

The electrical excitation of the VWR requires that the system is superconducting at low temperatures. For this purpose, we deposit onto the structure an aluminium coating. Two techniques were used: lift-off (sample 01-L) and etching (Sample 01-G). Several different goal-post oscillators were produced, which are available for future tests and measurements. An experimental setup for testing (resonance frequency and quality factor) the produced samples in cryogenic conditions was assembled and tested successfully.

These sensors will be a key element for our research within Microkelvin in general, in particular for the particle detection project ULTIMA. Their applications in the study of turbulence in superfluid ^{4}He and ^{3}He, motivated a Microkelvin proposal by D. Schmoranzer (Charles University, Prague). Their ultimate test, involving a dedicated experiment at ultralow-temperatures on the DN1 refrigerator, is foreseen for the last reporting period.

The effect of elastic collisions of neutrons on a liquid 3He detector is analogous to that expected for WIMPs (neutralinos). In order to gain a better understanding of the excitations created by neutrons impinging on a 3He target, we performed experiments at the ILL high flux reactor. Preliminary results presented in the previous report were obtained on a sample consisting of a single atomic layer of 3He. In a Fermi system, collective density fluctuations (known as ‘zero-sound’ in 3He, and ‘plasmons’ in charged systems) and incoherent particle–hole excitations are observed. At small wave vectors and energies, both types of excitation are described by Landau’s theory of Fermi liquids. At higher wave vectors, the collective mode enters the particle–hole band, where it is strongly damped.

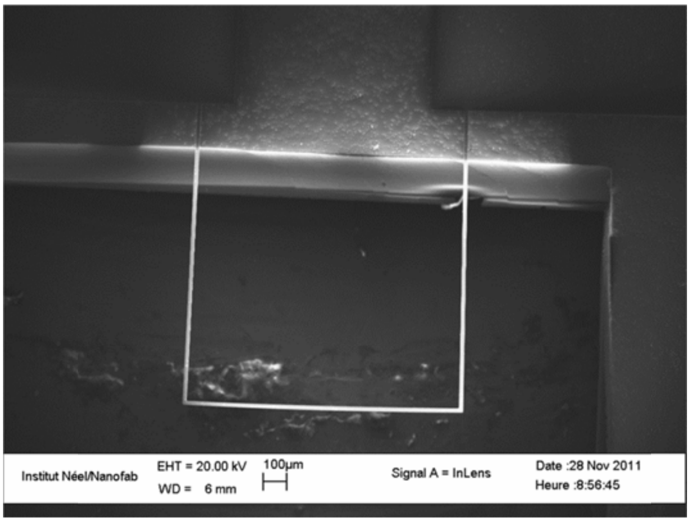

Fig. 5. *Microfabricated vibrating wire resonator. The length of the goal-post is 1.2 mm, the structure width is 20 µm, and the thickness on the order of 100 nm.*

The dynamics of Fermi liquids at high wave vectors was thus believed to be essentially incoherent. Our inelastic neutron scattering measurements reveal the existence of a roton-like excitation. We find that the collective density mode reappears as a well-defined excitation at momentum transfers larger than twice the Fermi momentum. We thus observe unexpected collective behaviour of a Fermi many-body system in the regime beyond the scope of Landau’s theory.

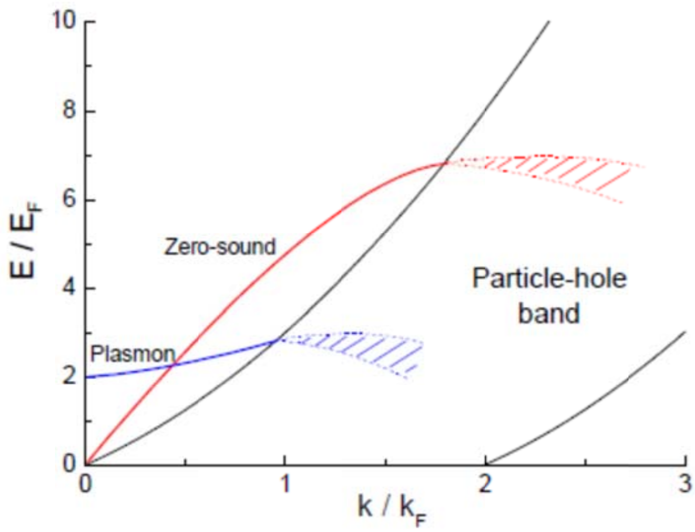

Fig.6. *Schematic representation of the elementary excitations of a Fermi liquid. The spectrum displays an incoherent particle-hole band, and collective modes (zero-sound in a neutral Fermi liquid, like ^{3}He, or plasmons in a charged system, like the conduction electrons of a metal).*

During the second 18-month period, the neutron data were analysed, and a detailed comparison was made with the theory. A very satisfactory interpretation of the measured spectra is obtained using a dynamic many-body theory, developed in Linz by E. Krotscheck et al.

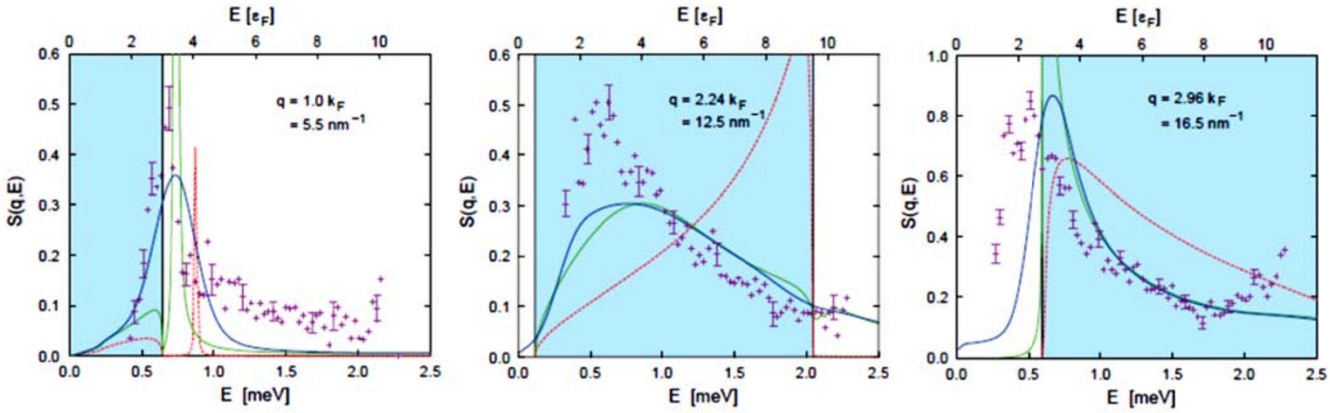

Fig.7. *Neutron spectra at selected wave vectors. The spectra correspond to wave-vectors 5.5, 12.5 and 16.5 nm^{-1}. Crosses represent the experimental data. The red dashed lines are the results of RPA calculations (slightly broadened to make delta-functions visible). The results from our dynamic many-body theory are shown as green lines; blue lines denote theoretical results folded with the experimental resolution. The light blue area depicts the particle-hole band.*

Our results [4] on the high wave vector dynamics of ^{3}He open a new research field in Fermi liquids. Generalizing Ruvalds' proposal of a superconducting pairing mechanism mediated by long-wavelength plasmons, our observation of a roton-like coherent mode characterized by a high density of states leads us to suggest a novel pairing mechanism, mediated by high-momentum density fluctuations. The consequences of the presence of plasmon collective modes at high wave vectors for the dynamics of electronic systems, including high-T_C superconductors, heavy fermions, metals and graphene, deserve exploration.

Milestone 14: Neutron scattering measurement of ^{3}He excitation spectrum at intermediate energies (month 42) **achieved in advance**

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[1] *Development of metallic magnetic calorimeters for high precision measurements of calorimetric ^{187}Re and ^{163}Ho spectra,* P. C.-O. Ranitzsch, J.-P. Porst, S. Kempf, C. Pies, S. Schäfer, D. Hengstler, A. Fleischmann, C. Enss, and L. Gastaldo, J. Low Temp. Phys. **167** (2012).

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[4] *Observation of a roton collective mode in a two-dimensional Fermi liquid*, H. Godfrin, M. Meschke, H-J. Lauter, A. Sultan, H.M. Böhm, E. Krotscheck, and M. Panholzer, Nature **483**, 576 (2012).

[5] *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, and M. Panholzer, Journal of Physics: Conference Series **340**, 012078 (2012).

Deliverable 2: Publication on vortex creation in superfluid 3He **achieved**

Deliverable 3: Publication on 2D defects **achieved**

Highlights

- First measurements of the thermal dissipation from turbulent vortex motion in ^{3}He-B in the $T \to 0$ limit [3,4].
- 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 [15].
- First NMR measurements of ^{3}He pairing states between accurately parallel plates with sub-micron separation [23].
- Observation of a roton-like collective mode branch in 2-dimensional ^{3}He Fermi liquid [18].

Publications

[1] D.I. Bradley, P. Crookston, M.J. Fear, S.N. Fisher, G. Foulds, D. Garg, A.M. Guénault, E. Guise, R.P. Haley, O. Kolosov, G.R. Pickett, R. Schanen, V. Tsepelin, *Measuring the Prong Velocity of Quartz Tuning Forks Used to Probe Quantum Fluids,* Journal of Low Temperature Physics **161**, 536 (2010).

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[5] M.A. Silaev, *Universal mechanism of dissipation in Fermi superfluids at ultra-low temperatures*, Phys. Rev. Lett. **108**, 045303 (2012); M.A. Silaev and G.E. Volovik, *Topological superfluid 3He-B: fermion zero modes on interfaces and in the vortex core,* J. Low Temp. Phys. **161**, 460 (2010).

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[16] C. Pies, S. Schäfer, S. Heuser, S. Kempf, A. Pabinger, J.-P. Porst, P. Ranitsch, N. Foerster, D. Hengstler, A. Kampkötter, T. Wolf, L. Gastaldo, A. Fleischmann, and C. Enss, *maXs: Microcalorimeter Arrays for High-Resolution X-Ray Spectroscopy at GSI/FAIR*, J. Low Temp. Phys. **167** (2012).

[17] P. C.-O. Ranitzsch, J.-P. Porst, S. Kempf, C. Pies, S. Schäfer, D. Hengstler, A. Fleischmann, C. Enss, and L. Gastaldo, *Development of Metallic Magnetic Calorimeters for High Precision Measurements of Calorimetric 187Re and 163Ho Spectra,* J. Low Temp. Phys. **167** (2012).

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[22] S. Holt and P. Skyba: *DC I/V converter with wide bandwidth and selectable gain*, submitted to Reviews of Scientific Instruments, under review process, recommended for publication.

[23] *Topological superfluids confined in a regular nano-scale slab geometry*, L.V. Levitin, R.G. Bennett, A.J. Casey, B.P. Cowan, J. Saunders, D. Drung, Th. Schürig, J.M. Parpia, to be submitted to Nature.

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Deviations from work plan

No significant deviations from the work programme (amended Annex I from Sep 2011)

Use of resources Follows the original grant plan

JRA4 Report

Work package: **Novel methods and devices for ultra-low temperature measurements**
Reporting Period: **from 1.10.2010 to 31.3.2012**
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
D1	Report on contactless decoherence and heat-capacity measurement method (Task 1)	JRA4	HEID	21	R	PU	18, 36 **delivered**
D3	Report on the performance of microcoils coupled to low inductance SQUIDs (Task 2)	JRA4	RHUL	18	R	PU	12, 24 **delivered**
D4	(Task 2)	JRA4	RHUL	15	R	PU	18, 36 **delivered**
D5	Report on current sensing noise thermometer for ultra low temperatures (Task 3)	JRA4	RHUL	15	R	PU	12, 24 **delivered**
D6	Report on ^{195}Pt-NMR thermometer for ultra low temperatures (Task 3)	JRA4	PTB	8	R	PU	18, 36 **delivered**
D7	Report on metrologically compatible CBT sensor (Task 3)	JRA4	AALTO	6	R	PU	12, 24 **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

Milestone number	Milestone name	WPs no's	Lead benefi-ciary	Delivery date from Annex I	Comments
M1	Contactless setup to investigate decoherence (specific heat) of solids	JRA4, Task 1	HEID	18 (36)	**achieved**
M4	Demonstration of NMR signals from 10 x 100 micron 3He samples	JRA4, Task 2	RHUL	36	**achieved**
M7	Design and testing to 200 uK of noise thermometer optimized for metrological measurements	JRA4, Task 3	RHUL	24	**achieved**
M8	Operation of GaAs quantum dot thermometer at 10 mK	JRA4, Task 3	BASEL	24	**achieved (~ 15 mK)**
M9	Design and test of a Pt-NMR thermometer down to temperatures of 10 uK	JRA4, Task 3	PTB	36	**achieved**

Summary

The goal is to develop novel methods for the investigation of nano-size samples and circuitry. These new approaches include contactless measuring schemes, low-noise SQUID pre-amplifier techniques coupled to micron-size sensors, and appropriate thermometry, which all works down to the μK temperature range.

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

In Heidelberg several important improvements have been realized and extended measurements with the newly developed techniques have been done during the past 18 months [1]. One major improvement concerns the time resolution of the dielectric echo measurements. This has an impact not only on the investigation of the dephasing of polarization echoes in glasses, but most importantly also on the contactless specific heat measurements. With the new setup the time resolution for recording echoes is better by an order of magnitude which allows the tracing of fast changes of the echo amplitude. In the previous setup, it was necessary to average several echoes before recording the echo data, because the recording speed was to slow to obtain enough single echoes to be averaged offline. Now single echoes can be recorded sufficiently fast, so that a much more sophisticated data analysis becomes possible. For example, individually echoes which are particularly noisy for some reason can be eliminated. With this improved setup detailed investigations of the specific heat of BK7 have been done.

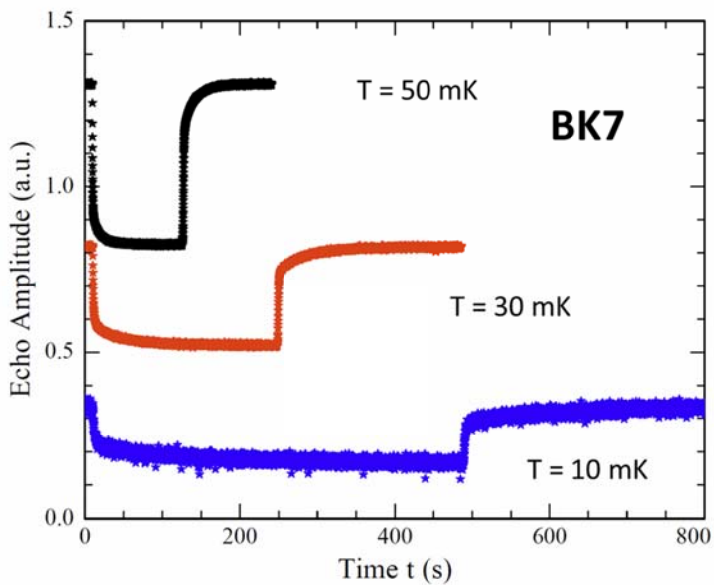

__Fig. 1:__ Amplitude of dielectric polarization echoes generated in BK7 as a function of time at three different temperatures.

Fig. 1 shows the time evolution of the echo amplitude for three different heat periods at three different temperatures. The change of the echo amplitude while heating the glass with photons from an LED can clearly be seen. The changes of the echo amplitude correspond to changes of the temperature of less than 10 % of the bath temperature in order to stay in the linear regime. From data traces like this we can derive the thermal conductance and the specific heat of the glass, as shown in Fig. 2 and 3. This shows that this new method is now well established. For the very first time the specific heat of a glass has been measured successfully down to about 7 mK.

Also decoherence measurements have been further improved. In particular, the setup has been modified to make possible investigations of so called T1 processes with dielectric rotary echoes. The progress of the decoherence measurements was reported at the LT26 International Low Temperature Conference in Beijing (August 2011) in the form of an invited talk by C. Enss.

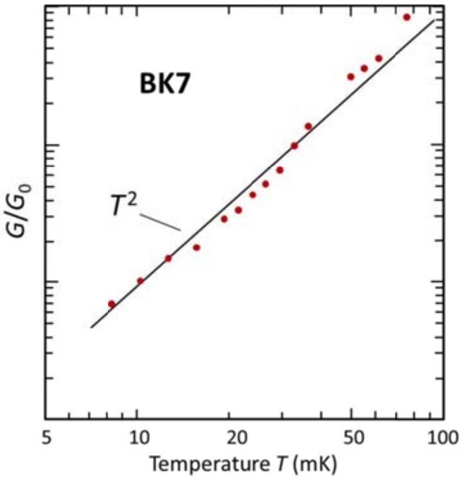

Fig. 2: *Normalized thermal conductance of BK7 as a function of temperature. The solid line is the expected variation for phonon tunneling.*

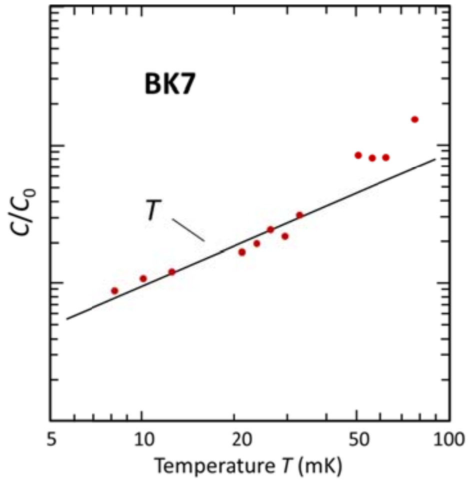

Fig. 3: *Normalized specific heat of BK7 as a function of temperature. The solid line is the expected temperature dependence according to the standard tunneling model for glasses.*

CNRS is developing new micro/nano mechanical devices for low temperature physics [2,3,4,5]. It has been demonstrated that these probes can be accurately calibrated, and that their dynamics can be understood from first principles. The setup for these measurements is shown in Fig. 4. Actuation and detection can be performed with both capacitive and magneto-motive schemes. The capacitive drive enables also the tuning of the devices, leading to new degrees of freedom. Using these new possibilities, parametric amplification could be demonstrated in goalpost devices.

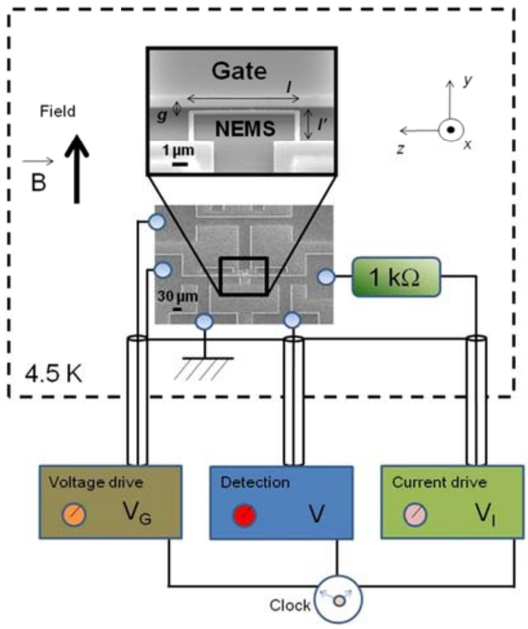

Fig. 4: *Sample and experimental setup. The device resonates at 7 MHz. We use a dual channel generator together with lock-in detection.*

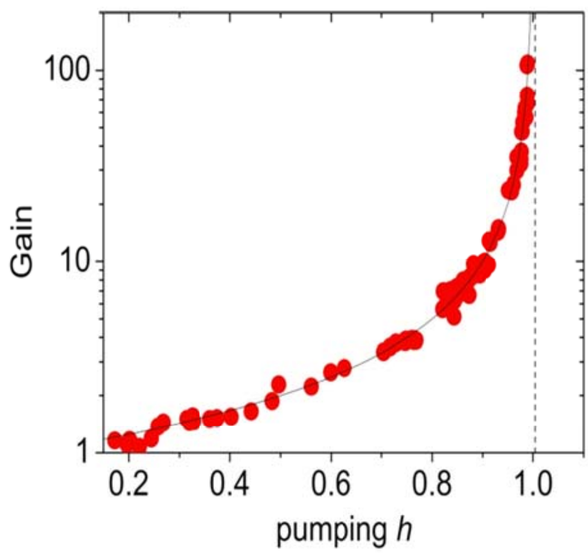

Fig. 6: *Gain measured as a function of the parametric pumping factor. The line is a theoretical fit and h=1 is the limit of the amplifying scheme.*

Parametric amplification is an extremely useful scheme applied in optics, electronics and also mechanics. It occurs when a mechanical parameter of an oscillator (like its spring constant) is modulated at twice the resonance frequency of the mode studied. In a recent paper we presented results obtained with a nano-mechanical device, where amplification of the drive force with gains up to a 100 has been achieved (Fig. 6). This is exceptional for an oscillator which is moving a substantial fraction of its thickness. A model has been developed to describe the limiting parameters of the scheme. It is applied to the study of the fine structure of friction mechanisms occurring in the coating films deposited on the nano-mechanical device. An unprecedented resolution of 0.5 % has been achieved.

In a joint experiment with the partner PTB, UL has achieved a large improvement in the detection sensitivity of a mechanical resonator by directly coupling a cantilever with an attached magnetic particle to an optimized SQUID magnetometer. Leiden has demonstrated the cooling of the cantilever's fundamental mode to about 160 µK [6,7], by means of feedback-cooling and in combination with low displacement and force noise.

Milestone 1: Contactless setup to investigate decoherence (specific heat) of solids **achieved**

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

As reported in the 18-month Periodic Review Report, PTB has developed a new generation of SQUID sensor called C6 which includes current sensors compatible with high frequency operation in flux-locked loop (FLL) mode and low power dissipation for operation at low temperatures. Micro-sized SQUID gradiometers and micro-susceptometers are also included in this device family. During the reporting period, micro-susceptometers have been fabricated and characterized carefully. Fig. 7 shows a SEM photography of such a susceptometer (for comparison see Fig. 2.3 of the 18-month report representing the CAD design of the device). These susceptometers are test devices which are supplementary placed on SQUID current sensor chips. It is planned to make pure susceptometer chips available in the following generation C7 of the PTB SQUID family. For more detailed information see the "PTB internal report on micro-susceptometers ". In this report, data of the susceptometer balance, noise performance of single and two-stage operation, and a practical susceptibility measurement can be found. A micro-susceptometer with a 30 µm size pickup coil has been delivered to UL for read-out experiments of MEMS oscillators with magnetic particles placed on the beam.

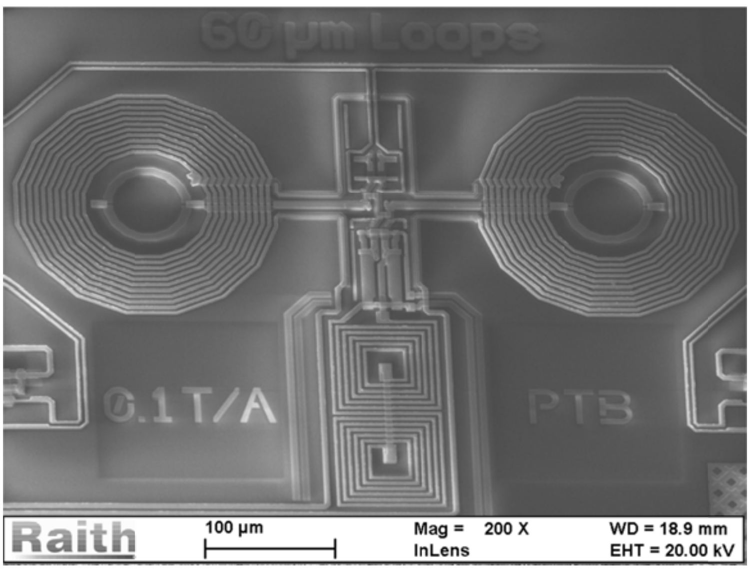

Fig. 7: *SEM image of a micro-susceptometer with integrated field coil. Versions with 30 µm and 60 µm pickup coils are available. The samples of the material under investigation have to be placed within one of the loops.*

For the detection of magnetic fields of small sources or samples, small integrated magnetometers have been fabricated. For magnetic readout experiments of MEMS oscillators 3 magnetometers with 30 µm pick up loops and 2 SQUID current sensor arrays for signal amplification have been provided to the partner UL.

Alexander Kirste from PTB has visited the CNRS group in Grenoble in May 2011. The aim of his visit was a discussion of possible SQUID read-out of MEMS oscillators. It seemed to be promising to use two-stage SQUID sensors with a high input inductance for the read-out of micro-resonators with an integrated superconducting loop operated in a magnetic field at mK-temperatures. It has been agreed that PTB will provide SQUID sensors for the CNRS experiments. A SQUID read-out electronics has been acquired by CNRS in autumn 2011. At the end of the reporting period, two SQUID current sensors (XL116T and XXL116T) with high input inductances (1,1 µH and 1,8 µH) intended for operation at mK temperatures have been selected and characterized and will be provided to CNRS by PTB in March 2012, after mounting the chips on appropriate chip carriers which fit the requirements of the CNRS experiments.

As expected, after renewing the equipment for SQUID fabrication in the time period November 2009 – December 2010, PTB has started fabrication runs in the beginning of 2011. The interrupted SQUID fabrication during this period has caused a delay in deliverable D4, a wideband SQUID for RHUL. Due to the new fabrication tools it was necessary to change and optimize several fabrication steps. In particular, patterning steps based on chemical etching have been replaced by plasma etching. The optimization procedure is not completed yet but stable fabrication of devices could be already achieved. A most critical point concerning the new etching steps is related to crossovers of plasma etched lines due to steep edges. Another problem which will be solved next year is related to Al etching steps. Currently, the definition of the Josephson junctions is still done using chemical etching because the fluorocarbon based plasma etching provided by the etching machine purchased in 2010 is not suited for Al/AlO_x patterning. In order to enable dry etching of the junctions utilizing chlorinated hydrocarbons, an additional etching tool will be acquired in 2013.

RHUL has supported the time consuming characterization of devices at PTB with a three-week visit of Aya Shibahara as guest scientist. This has been partly funded by PTB and by Microkelvin. As already reported, PTB has fabricated single layer micro-coils for the RHUL NMR experiments on confined ^{3}He samples. Following the first successful experiments at RHUL using these coils in combination with SQUID current sensors, experiments with a next generation of micro-coils have been planned. These next iteration micro-coils are based on a tri-layer technique patterned using a combination of photolithography and e-beam lithography. It turned out that using PTB’s new e-line system for coil manufacturing is not straightforward. The coil area is large compared to the line width which makes it necessary to use a so-called fixed-beam-moving-stage exposure mode of the system. Due to file conversion problems with the CAD programme and the e-line system, overexposure of particular areas of the coil design occurred. Meanwhile, this problem has been solved. A more serious problem is the high aspect ratio of line width and line thickness of the coil windings. In order to enable high critical currents in the superconducting coils, a thickness of the Nb lines of about 200 nm is required which needs a photoresist thickness of about 500 nm – 700 nm in the lift-off patterning process. When exposing the e-beam resist with this thickness, one is facing problems with the developed resist patterns, as shown in Fig. 8. In order to overcome this obstacle, a two-layer resist system consisting of a polymer layer covered with a thin (200 nm) e-beam resist will be used. Currently PTB is optimizing this patterning process.

A new direction in nano-sciences at ultralow temperatures is the study of quantum fluids confined within engineered and fully characterised nano-fluidic cavities. Nano-scale samples of quantum fluids provide clean model systems for addressing problems of fundamental significance and technological relevance.

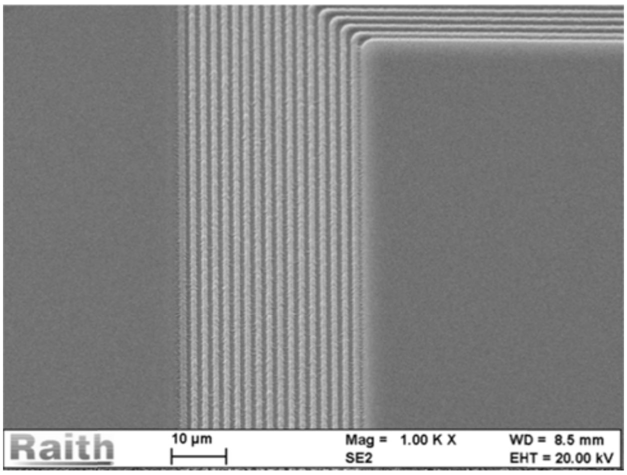

Fig. 8: *Problematic resist patterns occurring while using the thick e-beam resist for microcoil fabrication (REM).*

Research at RHUL on quantum transport in mesoscopic ^{3}He films [7] has provided new insight on the size dependence of the electrical resistance of metallic nano-scale interconnects. This is a key technological issue in semiconductor microelectronics, influencing both device speed and energy consumption. Reducing the impact of surface scattering on electrical transport in such interconnects is a key objective. A first principles understanding of this phenomenon is crucial, but so far lacking.

Our work addresses this problem with studies of the flow of a thin film of helium-three over a surface, using a high sensitivity torsional oscillator (Fig. 9). We find that the measurements are well described by an essentially parameter-free transport theory. The input to this theory is the power spectrum of the surface roughness, measured with an atomic-force microscope. Since scattering within the film is well understood we can unambiguously address the interplay of surface and intra-film scattering. [Studies of metallic films are complicated by grain boundary scattering].

According to the theory, a mesoscopic film of non-uniform thickness, arising from rough surfaces, can be mapped onto a film of uniform thickness. This mapping introduces an effective disorder within the film. Remarkably the disorder potential is fully determined by the measured surface roughness. The theory is clearly confirmed by our measurements of the effective transport relaxation time, which shows a distinct temperature dependence.

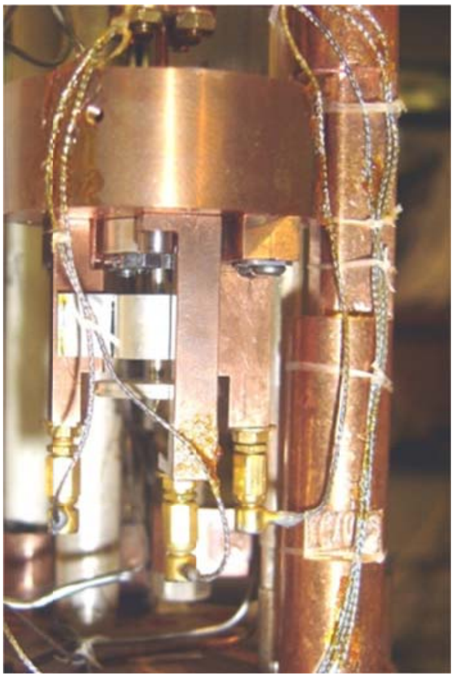

***Fig. 9**: Torsional oscillator for studies of superfluid ^{3}He mounted on the nuclear stage of the RHUL cryostat ND2.*

The results suggest strategies for engineering high quality metallic nano-scale interconnects in electronic devices, through a better understanding of the importance of lateral correlations in the plane of the film, as well as the vertical roughness scale.

As reported in the 18-month report, at RHUL we have developed SQUID NMR for the study of superfluid ^{3}He in a nano-fluidic chamber, in close collaboration with PTB. This research direction has been on-going since the first reporting period. It marries nanofabrication methods, high sensitivity NMR and ultralow temperatures to study the properties of confined superfluid ^{3}He in a regular and well characterised nano-scale geometry for the first time. In the first experimental cell the ^{3}He sample was confined within a slab geometry of thickness 635 nm. The cell is a novel design formed from anodically bonded glass and silicon, and results from a collaboration with Cornell University.

As discussed in the 18-month report, the success of the NMR experiment relies on the high sensitivity of the NMR detection system, developed at RHUL, based on a two stage DC SQUID amplifier, fabricated at PTB, with an energy sensitivity of 20 *h*. Crucially, over the reporting period we have developed optical interference techniques to characterise the cavity height profile. This was determined at room temperature by optical interferometry using green and blue laser light. However measurements of cavity height at low temperatures are required since this is the key control parameter. These measurements were performed using a small cryostat with optical access (Fig. 10) at room temperature, 77 K and < 7 K. Spectral analysis was performed on a reflected collimated white light beam of diameter 0.3 mm. We observe some bowing of the cavity arising from differential thermal contraction between the glass and silicon. Measurements of the pressure dependence of the cavity height reveal that this is temperature independent with a coefficient 28 nm/bar at the centre of the cavity. These measurements fully characterise the cavity height profile and representative data are shown in Fig. 11.

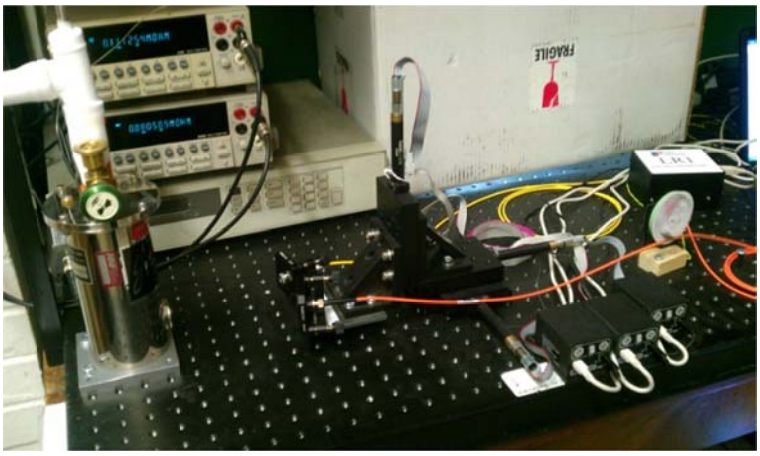

Fig. 10. *Optical cryostat for characterising the height profile of cavities at low temperatures.*

A paper has just been submitted on the topological superfluidity of ^{3}He under confinement in regular nano-scale cavities. Two further papers are in preparation. The work has been the subject of several invited talks.

A new slab cell with 100 nm cavity height has been fabricated using all silicon construction. It will be used to investigate the influence of increased confinement on the phase diagram of superfluid ^{3}He and the possibility of stabilizing new phases, It will also provide a further, more stringent, test of the sensitivity of the NMR technique. A further cell of spacing 1.2 μm has also been constructed and optically characterized. This will be used to continue the search for the predicted striped phase, with spatially modulated order parameter and to attempt to detect the presence of exotic surface bound states.

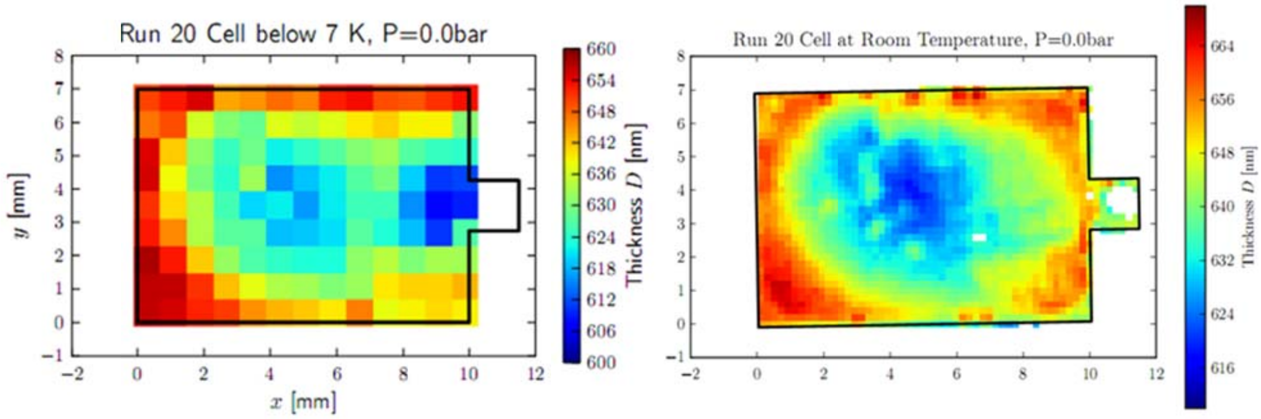

***Fig. 11**: Height distribution of nano-fluidic cavity measured at < 7 K and at room temperature.*

As part of Task 2a the partners RHUL and PTB have designed micro-coils to be coupled to low noise DC SQUIDs, for use as local probes in NMR experiments on confined ^{3}He. A detailed internal report was produced in month 15 and in month 36 [D3].

We have designed two micro-coils, both square of 500 μm outer length. The initial design (for UV-lithography) is simplest to fabricate and has 10 turns but a significant stray inductance, whereas the second design (UV- and e-beam lithography) has 18 turns and a lower stray inductance. Coils of the initial design have been fabricated by PTB and delivered to RHUL together with the 29 nH input inductance SQUIDs required to couple to the coils (Fig.12). Design calculations show that significant improvement in signal to noise ratio (SNR) can be obtained if the silicon wall of the ^{3}He cavity cells are be thinned down to 100 μm from the current thickness of 380 μm. With this thinner wall, a SNR of 15 should be possible in a single shot for a 1 μm thick film of ^{3}He. Calculations show that the second coil design should result in a further in SNR to 26 in a single shot.

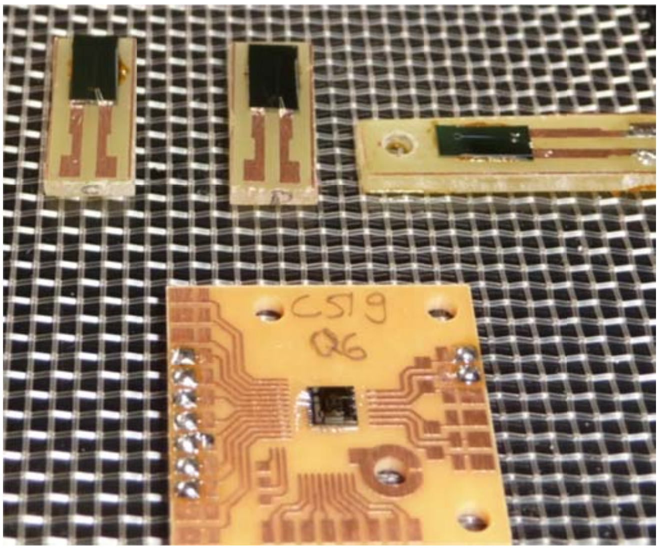

***Fig. 12**: 29 nH PTB SQUID and single layer design micro-coils delivered to RHUL.*

To test the initial micro-coil design SQUID NMR measurements were performed on a 1 bar sample of ^{3}He gas on a dipping probe at 4.2 K. The sample was in direct contact with the surface of the micro-coil. ^{3}He NMR signals were successfully observed with the expected signal to noise and are shown in the later sections.

The next step will be to obtain the e-beam multi-layer coil from PTB to confirm that the predicted improvement in SNR can be achieved. The coil can then be covered with 100-400 μm thick silicon to emulate viewing the helium through a wall.

The aim of the micro-coils is to serve as local NMR probes in the study of ^{3}He confined in nano-fluidic cavities. Integrating these coils into our nano-fluidic cells requires us to change our fabrication process from those cells used in meeting milestone three. Progress has been made in the fabrication of all silicon, direct wafer bonded, 100 nm deep cavities. This is described in section 4 of report D3.

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

As mentioned above, the SQUID sensor generation C6 includes current sensors which are compatible with high frequency operation in flux-locked loop (FLL) mode and operable at low temperatures. A bandwidth of about 10 MHz can be achieved with high input inductance current sensors without a significant decrease of noise performance but nevertheless, for upcoming NMR experiments a much higher bandwidth of SQUID amplifiers is required. During the reporting period, PTB was working on improving the bandwidth of SQUID amplifiers significantly to achieve deliverable.

After high-frequency operation of a SQUID series array with so-called on-chip current feedback (OCF) has been demonstrated by Dietmar Drung and coworkers (PTB) in 2008 [9], efforts have been spent to setup a system that can be used for practical NMR application. For this purpose, a special high-bandwidth amplifier has been developed for low-noise amplification of the SQUID output signal. For operating the SQUID sensor, a common XXF SQUID readout electronics can be used if some minor modifications have been made. This XXF electronics provides the SQUID bias currents and the supply power for the wide-band amplifier. The latter is housed in a so-called LNAM box placed between the dip stick with the SQUID and the XXF electronics as shown in Fig. 13. The SQUID is connected with the SQUID via a coaxial cable.

***Fig. 13**: Dip stick with high frequency SQUID read-out consisting of adapted XXF electronics (left box) and a LNAM box containing a low-noise wide-band amplifier.*

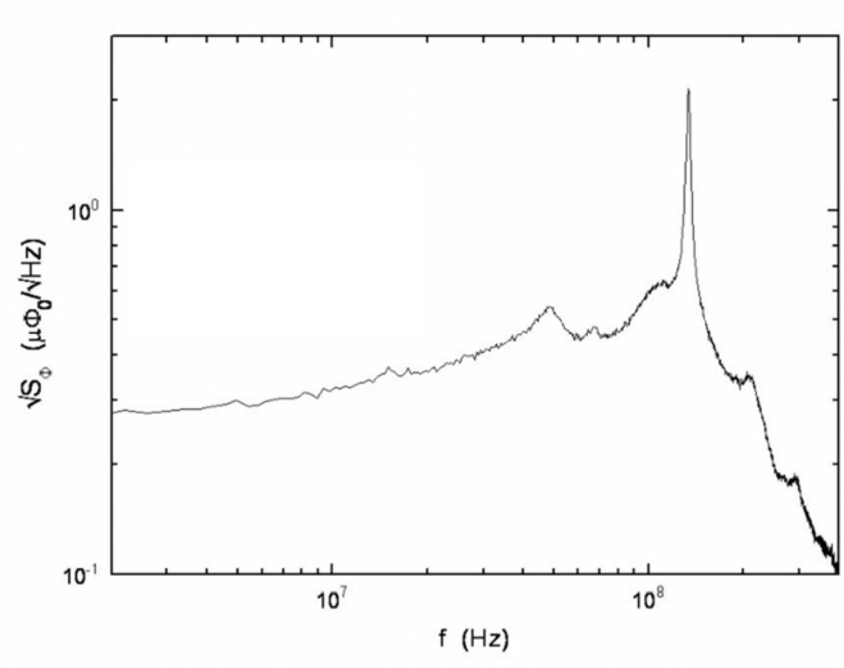

***Fig. 14**: Noise vs frequency characteristics of wide-bandwidth SQUID amplifier using OCF SQUID and low-noise room temperature amplifier.*

The characterization of this amplifier setup with an OCF SQUID device with a resonant circuit at the input has demonstrated the opportunity of large bandwidth operation of up to about 200 MHz. The noise vs frequency characteristics depicted in Fig. 13 shows a significant increase of noise in the region above 50 MHz with several peaks resulting from the coaxial cable. These effects are already described in [9]. As a result of these investigations, a concept has been worked out to change the LNAM box. Currently a new printed circuit board design with modifications of the amplifier is under development. It seems to be possible to achieve stable low-noise operation up to about 300 MHz after making these changes. The goal is to finish this work in June 2012. Meanwhile the setup described above which allows for very high bandwidth operation could be already used by Partner RHUL if required.

Milestone 4: Demonstration of NMR signals from 10 x 100 micron ^{3}He samples **achieved**

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

At RHUL research on Task 3a relates to the design, optimisation and operation of SQUID based current sensing noise thermometers over a wide temperature range. The activity has mainly involved a diversification of the ultra- low temperature platforms for the testing and optimisation of these thermometers under different experimental conditions. A new cryogen-free Triton 200 dilution refrigerator from Oxford Instruments has been installed and tested down to its base temperature. It was subsequently upgraded to incorporate a 5 T magnet. A Kelvinox 400 high access dilution refrigerator with additional 9 T – 9 T pair of magnets, supplied by Oxford Instruments, has been installed and tested. The magnet pair provides the sample field and the magnetic field for adiabatic nuclear demagnetisation of a copper stage. A copper nuclear stage for this set-up has been designed and constructed. Heat treatment was achieved through access to the Aalto low temperature facility. This will lead to a third copper nuclear adiabatic demagnetization cryostat at RHUL [ND3]. An upgrade of ND1 is also currently underway.

A current sensing noise thermometer optimised for operation down to 200 µK has been designed constructed and tested. It is mounted on the copper stage of the nuclear demagnetisation cryostat ND2. A ULT run will begin early 2012, and is currently awaiting the completion of a nano-fluidic superfluid helium NMR cell. Following these activities we anticipate that current sensing noise thermometers will be installed and attached to the nuclear stages of ND1, ND2 and ND3 at various stages during 2012. Software development for data acquisition has been completed, which allows wide bandwidth (MHz's) capture of noise spectra for FFT spectrum analysis from thermometers using PXI digitisers.

PTB is currently updating its cryogenic infrastructure. In this context, PTB has expressed its interest in the results of JRA1 task 2 and financial support from MICROKELVIN concerning the construction of a microkelvin cryostat based on a cryogen-free pulse-tube refrigerator. Due to formal constraints, PTB had to perform a Europe-wide bidding for the new cryostat. Finally, in 2011 PTB has bought from its own budget an Oxford instrument cryogen-free *Triton 400* system with an 8.5 T magnet. The fully-automated facility was installed and successfully tested. With the magnet fully energized a minimum temperature of about 6.4 mK was measured using a *Magnetic Field Fluctuation Thermometer* (MFFT). Now, the new system will be equipped with a ^{3}He melting pressure thermometer for the realization of the PLTS-2000. The new facility will allow to reduce the cost for calibration services at low temperatures which PTB provides. In future, the new cryostat also will be equipped with a nuclear demagnetization stage, to expand the available temperature range into the microkelvin region.

At PTB several cool-downs of the old nuclear demagnetization refrigerator MK2 were performed to investigate MFFTs down to temperatures of 1 mK and lower. In the temperature range from 1.6 K down to the lower end of the PLTS-2000 scale the deviations of the noise temperatures from 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 but, owing to the lack of a reliable temperature reference below 902 µK, no assessment of this temperature data could be carried out. The results were presented at LT26 in Beijing 2011 [11].

At Heidelberg (HEID) a current noise thermometer with inductive readout has been developed for use at ultra-low temperatures. In this setup the sensor is a copper piece directly attached to the copper stage of a nuclear demagnetization fridge and the inductive readout is done via a flux transformer hocked to a DC SQUID from PTB and mounted on the mixing chamber. This device has been tested in several runs and measured against a ^{195}Pt thermometer, also attached to the nuclear stage. This new device has clearly reached temperatures well below 200 µK without decoupling. Fig. 15 shows the temperature measured with the noise thermometer plotted against the temperature of the nuclear state. The lowest temperature in this run was about 88 µK.

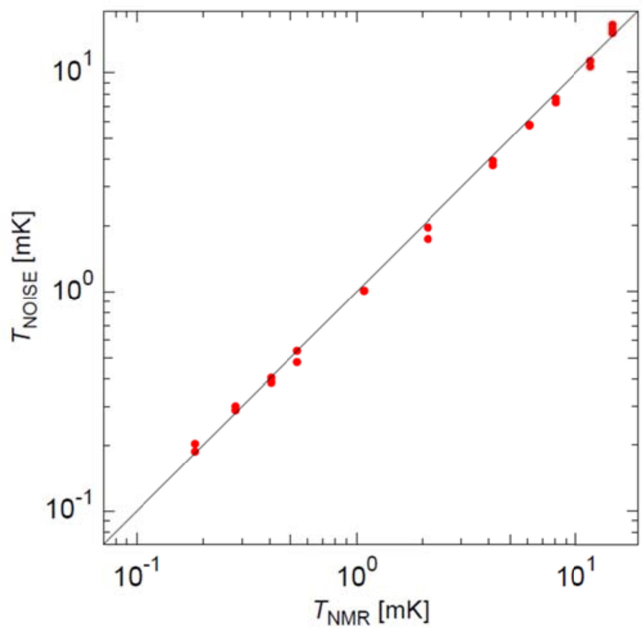

Fig. 15: *Temperature measured with a current noise thermometer as a function of the nuclear stage temperature.*

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

As already described in the 18-month Review Report, 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). Currently, a ^{195}Pt-NMR thermometer is mounted and investigated in more detail on the nuclear demagnetization stage of the PTB µK refrigerator MKA3. It will be operated with a PLM5 system enabling operation at lower frequencies (125 kHz and 64.5 kHz). In particular, the effect of radiation damping and the influence of self-heating due to power dissipation will be examined.

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

Comparison measurements of CBT and SJT thermometers prepared at AALTO with a high accuracy realization of the PLTS-2000 carried out at PTB (see JRA4 report #1, p. 58) are now published [10]. The results show good agreement between $T_{\mathrm{CBT/SJT}}$ and T_{2000} in the range from 0.65 K to 0.25 K. At lower temperature down to 0.008 K the increasing deviations of $T_{\mathrm{CBT/SJT}}$ from T_{2000} are described in detail by a model accounting for the thermal and electrical properties of the thermometers.

The goal of the Basel activity in JRA4 (Task 3c) is to demonstrate the operation of a GaAs quantum dot as a Coulomb blockade thermometer in the temperature range from several hundred mK down to about 10 mK (prototype running after 24 months, Milestone 8). Later 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, and operated these down to 15 +/- 2 mK, limited by tunnel-broadening that could not be further reduced. When this device was later warmed up to room temperature and inspected with an SEM, it became clear why the tunnel rates could not be further reduced: the nano-gates were severely damaged, by electric discharge during the chip-carrier loading process. We have since analyzed the chip-carrier loading issues, fabricated an improved grounding ring for loading and unloading.

The procedure is further complicated by the stringent requirements put forth on a microkelvin temperature compatible chip-holder. The process of diagnosing, improving and re-trying has taken many cool-downs over the past 18 months (though obviously some testing was done at room temperature using dummy nano-samples on GaAs without the very valuable 2D gas material). Currently we are again improving the system and have performed tests which indicated that the electrostatic problems are solved. We are now preparing for the next cool-down to run a GaAs dot thermometer.

The advanced Basel nuclear stage has otherwise made excellent progress, in collaboration with Lancaster and Bluefors, recently cooling to 185 +/- 25 microK on an improved 2nd generation system (JRA1). Further, in collaboration with Helsinki (Pekola), we have cooled a metallic CBT sensor to 7.5 +/- 0.2 mK, for the first time departing from the electron-phonon cooling regime at the lowest temperatures.

Milestone 7: Design and testing down to 200 µK of a noise thermometer optimized for metrological measurements **achieved**

Milestone 8: Operation of GaAs quantum dot thermometer at 10 mK **achieved** (down to 15 mK)

Milestone 9: Design and testing of a Pt-NMR thermometer down to 10 µK **achieved**

Highlights

- First ever specific heat measurement of an amorphous solid below 20 mK
- First ever thermal conductivity measurement on a metallic glass below 100 mK
- Parametric amplification: Best gain greater than 100 for a moving device! Detection limit: with only room temperature electronics, 1 fN
- High frequency SQUIDs width a bandwidth of up to 500 MHz
- First noise thermometer operated without thermal decoupling below 200 µK
- Metallic CBT cooled to a temperature of 7.5 mK

Publications

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[3] *Nonlinear parametric amplification in a tri-port nanoelectromechanical device*, E. Collin, T. Moutonet, J.-S. Heron, O. Bourgeois, Yu. M. Bunkov, H. Godfrin, Phys. Rev. B 84, 054108 (2011)

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[5] *In-situ comprehensive calibration of a tri-port nano-electro-mechanical device*, E. Collin, M. Defoort, T. Moutonet, J.-S Heron, O. Bourgeois, Yu. M. Bunkov, H. Godfrin, Submitted to Rev. Sci. Instrum. (01/2012).

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[11] *Noise thermometry at low temperatures: MFFT measurements between 1.6 K and 1 mK*, J. Engert, D. Heyer, J. Beyer and H.-J. Barthelmess, to be published in Journal of Physics: Conference Series

Deviations from work plan

The GaAs Coulomb Blockade Thermometers were cooled down to 15 mK instead of 10 mK. The reason was a batch of chips which was electrostatically damaged so that the devices worked only partially. This problem is now solved, a new generation of GaAs CBT's has been fabricated and will be measured soon.

Use of resources

The use of resources has proceeded as foreseen in the JRA4 budget.

3.2.3 Project management during the period

Microkelvin management tasks and achievements

- An 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 JRA3 [Task 3 – Horizons, ergo regions, and rotating black holes, and Task 5 – ULTIMA-Plus: Dark matter search with ultra-low temperature detectors]. This review report is following the amended Annex I.

Project website

- the website has been continuously kept up to date on page http://www.microkelvin.eu/

Transnational Access Activities

Transnational access promised 1.4. 2009 – 31.3. 2013

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

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

Problems during the reporting period

- transnational acces programme lags behind target by ⅓

Project meetings, dates and venues

- listed in Sec. 3.2.2 under NA3 Task 3

Changes in consortium

- change of coordinator: Microkelvin spokesman and coordinator professor Mikko Paalanen suffered a brain hemorrhage on September 24, 2010. Professor Matti Krusius has been replacing him since then and was officially instituted as coordinator in December, 2011.

Impact of deviations from the planned milestones and deliverables

- demonstration of nuclear cooling in cryogen-free dilution refrigerator is delayed because of delays in magnet delivery

Changes to the legal status of beneficiaries

- change of name of one partner: from Helsinki University of Technology to Aalto University

Completed Microkelvin Transnational Access projects from 1.10.2010 to 31.3.2012

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

Title of the project	**Microrefrigerator with enhanced cooling power** AALTO12-1
User group leader	Hervé Courtois, professor
User	Nguen Hung, post doctoral researcher
Home Institute	Institut Néel, CNRS, Grenoble
Host supervisor	Jukka Pekola, professor, Low Temperature Laboratory, Aalto University
Description of the work	This work is concerned with the development of a SINIS cooler platform with large junction area and a suspended normal metal part, fabricated with photolithography and over-etching techniques. The cooler should provide a large cooling power and will be implemented on a membrane for application purposes. This project is part of the JRA2 research activities of the Microkelvin Collaboration. Two sets of samples fabricated in Grenoble were measured in Helsinki. The junction area was 1500 nm square with RN~15 Ohm for each sample. The two sets of samples differed in the copper-etching process: one used ion beam etching, the other used wet etching with HNO_3. Cooler characteristics (IV measurements) and cooling of the samples were measured in a dilution refrigerator down to 50 mK. We also discussed the implications of the results and the future continuation of the present plan.
Project achievements	The measurements agree with those performed earlier in Grenoble in a ^3He refrigerator at 300 mK, which we conclude to confirm the reproducibility of the fabrication technique and the robustness of the samples. Our heat transport analysis suggests that the junction was overheated and its geometry needs to be optimized for better thermalization of the heat dissipation. Based on this measurement, we redesign the junction to have smaller width. Other possibilities, like introducing a quasiparticle trap placed directly under the junction area or a more transparent oxide layer between the quasiparticle trap and the overheated superconductor, are being discussed and might be implemented next.
Amount of access given	14 days

Title of the project	**Microrefrigerator with enhanced cooling power** AALTO12-2
User group leader	Jan Kolacek
User	Michal Sindler, graduate student, M.Sc.
Home Institute	Institute of Physics, Czech Academy of Sciences, Prague
Host supervisor	Jukka Pekola, Low Temperature Laboratory, Aalto University
Description of the work	Quantized charge pumping in superconducting circuits is a research topic which, on one side, deals with geometric phases and adiabatic evolution in quantum mechanics, and, on the other hand, possibly provides future tools in quantum metrology for the realization of the unit ampere. In the proposed project Cooper pairs are transported in fully superconducting circuits with small Josephson junctions by the help of gate voltages and magnetic fluxes. The ultimate goal of the project is to test and hopefully demonstrate the robustness of the adiabatic evolution in quantum Josephson circuits against various noise sources: the adiabatic manipulation would open an alternative way for quantum information processing in superconducting circuits. Recent theoretical efforts yield encouraging predictions in this respect. Michal Sindler took part in the fabrication and performed measurements of Cooper pair pumps ("sluices"), especially with focus on the improvement of the detector sensitivity: 1) The device was realized by means of an on-chip ground plane with the help of an atomic layer deposited (ALD) aluminum oxide film between the shunting structure and the detector junction. Using electron beam lithography and shadow angle evaporation, the Al/AlOx/Al Josephson junction was fabricated on the ALD oxide layers. The escape dynamics in the shunted Josephson junctions was studied experimentally below 0.5 K temperatures. In addition, using the ALD technique, on-chip RF coils in the pumping devices were successfully implemented. 2) The Josephson junction was studied with a shunted resistor mounted on the sample stage. The advantage of this technique is to improve the retrapping process in the junction dynamics, so the detector in the pumping system can respond much more quickly to an input current variation. The structures were fabricated in the MICRONOVA clean rooms and the test experiments were performed in a dilution refrigerator at LTL.
Project achievements	The main achievement of this project was to improve the detector sensitivity as well as on-chip RF coil performance in the Cooper pair pumping systems. By studying the escape dynamics of the Josephson junctions, it was demonstrated that the technique to add a large shunt capacitance using ALD processing in a Josephson junction is very reliable, to prevent the junction from entering phase diffusion. With the help of the ALD technique, coupling of the flux-input into SQUIDs was also enhanced by placing the input coils directly under the coils. This is important in order to avoid parasitic coupling in the circuit. Unfortunately,

	because of the limited time span of the visit at LTL, there was not enough time to apply these techniques to the pumping devices.
Amount of access given	92 days + 40 hours of Micronova clean room services

Title of the project	**Fabrication of nanoresonators for energy dissipation in superfluid 3He** AALTO13
User group leader	Vladimir Komanicky, Dr.
User	Vladimir Komanicky, Dr.
Home Institute	Safarik University, Kosice
Host supervisor	Jukka Pekola, Low Temperature Laboratory, Aalto University
Description of the work	**Fabrication of metallic bridges by electron beam lithography techniques** Free standing nanobridges from aluminum and gold were fabricated in the clean-room facility at Aalto University. 1. A positive resist layer consisting of a MMA/PMMA bylayer resist was spin coated on the silicon substrate. 2. The structures were drawn in GDSII format and a dose test was performed. 3. After development and metallization the correct dose was determined. 4. Structures with different lengths of the metallic beam were prepared by EBL, metallized and after lift-off step etched in a RIE plasma etcher. 5. The correct etching mixture and etching time were determined for freestanding metallic beams. **Testing of the physical properties of fabricated metallic bridges** The resistance of the bridges at room temperature and at 4K was determined by four probe measurements. The bridges exhibit the expected resistance values at room temperature and at 4K.
Project achievements	We were able to optimize the process for the fabrication of metallic resonators based on the suspended metallic beam. We have fabricated bridges of various lengths from aluminum and gold. Basic transport properties of the nanostructures were tested at room temperature and at 4K. The structures behave as expected and are pretty robust in terms of handling. Further measurements will be conducted in Kosice.
Amount of access given	12 days + 26.5 hours of Micronova clean room services

Title of the project	**Vortex front propagation and the axially moving transition from the vortex-free Landau state to the equilibrium vortex state** AALTO14
User group leader	Professor Victor L´vov
User	Professor Victor L´vov
Home Institute	Weizmann Institute of Science, Rehovot, Israel
Host supervisor	Matti Krusius, Low Temperature Laboratory, Aalto University
Description of the work	The dynamics of quantized vortices at the very lowest temperatures is a central topic in the Microkelvin programme (Joint Research Activity package 3 Task 1 – Investigation of quantum vortices as model cosmic strings). One of the challenges is to understand the sources of dissipation in vortex motion at the lowest temperatures, in the limit $T \rightarrow 0$. This is the regime in which the motion of cosmic strings could be expected to take place today, if they are found to exist. At higher temperatures dissipation is known to be caused by mutual friction. It arises from the scattering of normal excitations from a vortex which moves with respect to the reference frame provided by the normal fluid. Mutual friction dissipation vanishes as the density of normal excitations approaches zero at the lowest temperatures. However, currently it is believed that in turbulent vortex motion dissipation does not appear to extrapolate to zero in the limit $T \rightarrow 0$. Are there thus new mechanisms which govern superfluid dynamics at the lowest temperatures? One of the phenomena which have been employed for such studies is the motion of a vortex front axially along a long rotating cylinder. The front divides the cylinder in two regions: ahead of the front is vortex-free rotating counterflow and behind the front a twisted bundle of vortices. Measurements of the azimuthally precessing and axially advancing front have been performed in the rotating cryostat of the Low Temperature Laboratory with the fermion superfluid 3He-B using noninvasive NMR techniques. One of the tasks is to investigate the front propagation velocity $V_{\mathrm{f}}(\Omega,T)$ as a function of rotation velocity Ω and mutual friction dissipation $\alpha(T)$. The front velocity can be used as a measure of dissipation and can thus provide the key to the understanding of the dynamic properties of vortices at the lowest temperatures. New results are currently accumulated both in laboratory measurements as well as in high-resolution numerical calculations on the axial velocity and the azimuthal precession of the propagating vortex front as a function of temperature and rotation velocity. This data is expected to provide a better understanding of the consistency between measurement and calculation. Also the explanation for the unexpected dependences of the front velocity in different temperature regimes should emerge from these studies. The extrapolation of the data to $T \rightarrow 0$ should ultimately reveal the mechanisms which control the axially propagating transition from the vortex-free Landau state to the equilibrium vortex state at the lowest

	temperatures. Prof. L'vov 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 turbulence in the propagating vortex front. During his 1-month visit in the Low Temperature Laboratory prof. L'vov participated in the front velocity measurements and in the numerical calculations.
Project achievements	The front velocity measurements (similar to earlier thermal measurements) show that there is a characteristic temperature of 0.3 Tc where a transition occurs from the mutual-friction-dominated regime at high temperatures to the low-temperature regime where the decoupling of the superfluid from the reference frame of the normal component starts and vortex tension wins in importance. In this latter regime Vf (Ω,T) decreases more slowly than mutual friction $\alpha(T)$ an its extrapolation, when $T \to 0$, displays a non-zero intercept. The detailed properties of the front velocity in this regime are still under discussion. "Superfluid vortex front at $T \to 0$: Decoupling from the reference frame", J.J. Hosio, V.B. Eltsov, R. de Graaf, P.J. Heikkinen, R. Hänninen, M. Krusius, V.S. L'vov, and G.E. Volovik, Phys. Rev. Lett. **107**, 135302 (2011) [doi:10.1103/PhysRevLett.107.135302]. A follow-up publication with an explanation of the vortex front velocity as a function of rotation velocity and mutual friction dissipation is in preparation.
Amount of Access given	30 days

Title of the project	**Dynamics of quantized vortices in superfluids & superconductors** AALTO15
User group leader	Professor Edouard Sonin
User	Professor Edouard Sonin
Home Institute	Racah Institute of Physics, Hebrew University of Jerusalem
Host supervisor	Matti Krusius, Low Temperature Laboratory, Aalto University
Description of the work	Prof. Sonin has studied the axially propagating motion of vortices in a rotating column of superfluid He [1]. The central questions are the configuration of the propagating vortices and an analysis of the laminar dynamics at not too low temperatures (where the mutual friction dissipation $\alpha \sim 1$). The calculations start from an analysis of the axially expanding motion of a single vortex in a rotating and otherwise vortex-free cylinder. They then proceed to the case of many vortices which move along the cylinder as a precessing and propagating front followed by a uniformly twisted bundle of vortices. The calculations apply for laminar motion and are based on the balance of energy and of linear and angular momenta in stationary state propagation. The stability of this state has been examined. The results are compared to experimental and numerical work, which has been going on in the Low Temperature Laboratory of the Aalto University. An analytic theory of the axial vortex motion in rotation, which is consistent with experiment and numerical vortex filament calculation, would provide a much better understanding of the rich dynamics in the different regimes of mutual friction. It will provide important guidance for future research. The analysis is based on the equations of vortex dynamics in the two-fluid hydrodynamics of helium superfluids. Recent progress in experiment and numerical vortex filament calculations has guided the choices of selecting possible parameter ranges and approximations for working out useful solutions. **References:** [1] *"Equilibrium rotation of a vortex bundle terminating on a lateral wall"*, E.B. Sonin and S.K. Nemirovskii, Phys. Rev. B **84**, 054506 (2011).
Project achievements	The parameters of precessing vortex front propagation were derived for the first time from the basic hydrodynamic principles, the general two-fluid vortex dynamics equations. This allows checking previous qualitative estimations for the laminar regime. An analysis of the Ostermeier-Glaberson instability, arising from the axial currents generated by the twisted configuration of the vortex bundle behind the propagating vortex front, opens a way to discuss the transition from laminar vortex flow to turbulence, which is based on a more solid theoretical foundation than before. This is planned to be done in the future. A publication on this work has been submitted: *"Dynamics of twisted vortex bundles and laminar propagation of the vortex*

	front", E.B. Sonin, Phys. Rev. B, in print (2012).
Amount of Access given	30 days

Title of the project	**Shot noise on suspended graphene at mK temperatures** AALTO16
User group leader	Saverio Russo, professor, University of Exeter, UK
User	Daniel Cox, student
Home Institute	University of Exeter, UK
Host supervisor	Pertti Hakonen, Low Temperature Laboratory, Aalto University
Description of the work	**The goal of the project was:** 1. To investigate electrical transport in suspended graphene sheets, 2. To measure shot noise of ballistic graphene, 3. To verify basic models for electrical transport in graphene on the basis of shot noise and conductivity (I: evanescent modes, II: weak electron-phonon coupling), and 4. To investigate coupling of mechanical motion to electrical transport. **Preparatory phase at the University of Exeter:** 1. preparation and characterisation of monolayer/few layer graphene samples, 2. releasing the graphene sheets using an appropriate method, for example HF-etching 3. characterization of the samples at DC at room temperature 4. selection of good samples for low temperature measurements **Measurements at LTL:** 1. Measurements were performed in a dilution refrigerator with high frequency wiring and a cooled preamplifier. 2. The experiments concentrated on high-frequency conductivity and shot noise of graphene sheets 3 The results obtained were analysed using the current theoretical models for graphene. 4. Preliminary measurements on the coupling of mechanical modes and electrical transport were done.
Project achievements	At low bias voltage, we find that, in accordance with earlier experiments, the Fano factor (F=S/2e</>) measured at the charge neutrality point is close to $F = 1/3$, which is theoretically expected for graphene samples. At high bias, we observe that electron-phonon scattering is enhanced and this leads to inelastic electron relaxation that causes suppression of shot noise.

	According to diffusive theory, as long as the inelastic scattering length is longer than the elastic mean free path, there is a direct connection between the Fano factor and the temperature: T=F eV/2k. We have employed this dependence to obtain T(V) from the measured shot noise. As a consequence, we may estimate the conductivity $G(T(\text{V}))$ without optical phonon scattering using the measured or theoretical conductance $G(T)$. From the additional suppression of G, we can determine the electron scattering time from optical phonons. In suspended monolayers, we find that the Fano factor goes via a minimum around 1 V as a function of the bias voltage. Using diffusive theory, the voltage at the minimum can be related directly to the electron - optical phonon scattering, provided that this scattering is the dominant inelastic mechanism. The reason for the increasing shot noise at very large bias is that the ability of electron–phonon scattering to suppress noise starts to diminish as the maximum energy absorbed by one phonon is less than an eV, and, in principle, for very large V, F approaches 1/3 again.
Amount of access given	66 days

Title of the project	**Microkelvin experimental platform** AALTO17
User group leader	John Saunders, professor, Royal Holloway, University of London
User	Jan Nyeki
Home Institute	Royal Holloway College, University of London, Egham
Host supervisor	Juha Tuoriniemi, Low Temperature Laboratory, Aalto University
Description of the work	At the London Low Temperature Laboratory, RHUL, we are creating a facility to widen access of the scientific community to the microkelvin experimental temperature range, a key objective of the Mictokelvin Collaboration. Our aim is to provide access to external academic (UK, EU and international) and industrial users to the microkelvin temperatures (sub-dilution refrigerator base temperature) in magnetic fields up to 9T. This will contribute to the opening up of this temperature regime to new research users from a widened community, including nanophysics, semiconductor physics, strongly correlated materials, etc. This project is funded by a £0.8m infrastructure grant and involves a collaboration with Oxford Instruments. At Royal Holloway, using our cryogenic engineering expertise, we have designed and manufactured a new microkelvin experimental platform based on a copper demagnetization stage. In order to achieve an optimal performance of the system at very low temperatures, a special heat treatment of the copper parts is crucial. The copper demagnetisation stage itself is approx 500 mm long and weighed approx 5.5 kg. It was imperative to heat treat it in a vertical position in order to prevent deformation under its own weight at high temperatures. The microkelvin experimental plate was, on the other hand, heat treated while keeping the

	furnace in horizontal position. The Aalto Low Temperature Laboratory has the required infrastructure (a custom built quartz tube vacuum furnace) and local expertise from similar tasks carried out previously. The furnace is large enough to accommodate the parts and to perform the required heat treatment procedures. Two copper parts of the new microkelvin experimental platform were manufactured at Royal Holloway and heat treated at Aalto. The furnace at Aalto University had been working for more than a decade in horizontal position only. It has had an option to work in vertical position as well. However, a hardware upgrade was necessary. The project itself was divided into three phases: During my first visit a set of new radiation baffles, the support structure for heat treatment in vertical position and the loading mechanism for heavy objects were designed. All parts necessary for the furnace upgrade were manufactured at Aalto. During my second visit the experimental plate was annealed in horizontal position. After that the furnace was erected into vertical position and refurbished with the new support structure and radiation baffles. Several test runs were performed at high temperatures in order to clean the new structures and to tune parameters of the annealing process. The RRR of test samples was measured following each run. As the last step, the demagnetisation stage itself was loaded into the furnace and annealed. During the final visit the RRR of test samples from the last anneal of the nuclear cooling stage were measured. The demagnetisation stage was cleaned from unexpected surface residuum in the upper part. Both heat treated parts were transported back to Royal Holloway.
Project achievements	Two copper parts of the newly built microkelvin experimental platform were manufactured at Royal Holloway and heat treated at Aalto: a) The copper demagnetisation stage was annealed for 17 hours in vacuum immediately followed by a 10 hour long anneal in 1.5 mbar air atmosphere, both at 800 ^oC. The target Residual Resistivity Ratio for this process was RRR ~ 500. Measurements on test pieces returned RRR=545±100. b) The microkelvin experimental plate was annealed for 42 hours in vacuum immediately followed by 28 hour long anneal in 1.5 mbar air atmosphere, both at 850 ^oC. The target Residual Resistivity Ratio for this process was RRR > 1000. Measurements on test pieces returned RRR=3870±100. As part of the project the existing infrastructure at Aalto (a quartz tube vacuum furnace) was upgraded. This will be beneficial for other users in the future. This work supports the construction of a new ultralow temperature facility, and is expected to lead to publications within the time frame of the Microkelvin project.
Amount of access given	14 days

Title of the project	**Andreev Scattering of quasiparticles in superfluid 3He-B** AALTO18
User group leader	Carlo Barenghi, professor, Newcastle University, UK
User	Nugzar Suramlishvili, Dr.
Home Institute	Newcastle University
Host supervisor	Nikolai Kopnin, Low Temperature Laboratory, Aalto University
Description of the work	Further progress of our project at Newcastle University requires the development of numerical models based on a deeper understanding of the interactions between quasiparticles and quantized vortices in ^{3}He-B. During his visit, Dr Suramlishvili's first objective was to discuss with Professor Nikolai Kopnin and his colleagues within the Helium Theory Group the influence of vortex core states on the Andreev reflection of quasiparticles. It is hoped that incorporating the core structure and their bound states into our numerical model will make the calculations more realistic. The second objective is to apply our numerical method to the particular geometry corresponding to recent experiments, performed by Prof. Matti Krusius and his colleagues within the Rota Group, where the vortex structure is created by rotating the ^{3}He-B sample at constant angular velocity and the line density, orientation, and spatial extent of the vortices are well defined. This may help to interpret the existing experimental data and to create a better link between theory and future experiments. It is also hoped that these discussions will lead to a collaborative research between Newcastle and Aalto Universities. The Andreev reflection technique is based on the fact that the dispersion curve $E\ (p)$ of quasiparticles is tied to the reference frame of the superfluid, so that in a superfluid moving with a velocity v_S , the dispersion curve becomes $E\ (p\ ) + p \cdot v_S$, where p is the momentum. $E(p)$ plays the role of a Hamiltonian. The semi-classical Hamilton's equations describing the propagation of ballistic thermal excitations in the velocity field of a three dimensional configuration of quantized vortices are solved with a code, which is variable step and variable order implementation in Fortran programming language of the Numerical Differentiation Formulas and particularly efficient for solving stiff problems. The superfluid velocity is given by the Biot-Savart Law and is calculated by means of the vortex filament method using periodic boundary conditions. During the visit the following work was performed: 1) Seminar talk: *"Numerical simulations of the interaction between quasiparticles and three-dimensional vortex structures in ^{3}He-B"*. 2) We had useful discussions with Professors N. Kopnin and G. Volovik concerning the semi-classical method used in the numerical code. 3) We discussed the possible models of vortex core bound states with Professor N. Kopnin.

	4) We discussed the possible numerical models of past and future experiments with Dr. V. Eltsov and J. Hosio.
Project achievements	1) We received expert advice from Professor Kopnin and his colleagues concerning the vortex core structure and quasiparticle bound states in order to incorporate them in the numerical code. (The process of implementation of the corresponding part of the code is in progress). 2) We gained information on the design of the experiments in order to make the existing numerical model as close as possible to the real experimental conditions and to implement the code modelling the quasiparticle gas in the presence of rectilinear vortices. (The process of implementation of the code is in progress).
Amount of access given	14 days

Title of the project	**Vortex waves in rotating superfluid 3He-B** AALTO19
User group leader	Paul Walmsley, Dr.
User	Paul Walmsley, Dr.
Home Institute	Schuster Laboratory, University of Manchester, UK
Host supervisor	Vladimir Eltsov, Low Temperature Laboratory, Aalto University
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 along the Kelvin-wave cascade should make it possible to have a finite rate of energy dissipation in the zero-temperature limit. Up to date, however, Kelvin waves as well as the Kelvin-wave cascade have not really been probed experimentally in superfluids. Our goal was to study a type of vortex motion, which is closely related to Kelvin waves on individual vortex lines: vortex waves in an array of vortices, which is produced by rotation of a long cylindrical 3He-B sample at temperatures down to 0.15 T_c. The plan was to modulate the angular velocity of rotation to create vortex waves and to study their build-up, propagation, and relaxation using nuclear magnetic resonance techniques. The immediate goal was to understand the effect of the oscillations in a vortex cluster on the frequency shift of the magnon condensate NMR mode. This shift had been observed earlier in preliminary measurements. The goal was to establish, whether the shift is caused by the reduction in the polarization of vortices in the cluster when vortex waves are created.
Project achievements	New measurements were performed using NMR to probe the magnon states in a cylindrical sample of superfluid 3He-B during modulated rotation. The effects from varying the amplitude of modulation, the time that the modulation was switched on, or the temperature (between 0.15 to 0.18 Tc) were investigated in the presence of a steady DC component of rotation at 1.4 rad/s. The frequency shift of the magnon states versus time after both starting and stopping the modulation were also studied.

	In order to understand the observed behaviour, various textures of the order parameter and the corresponding frequency shifts of the magnon states were calculated numerically, including the effect from azimuthal and axial flow (resulting from various configurations of vortices). This was achieved by modifying existing computer codes. A simple fitting procedure was applied to the transients produced during relaxation after stopping the modulation, enabling comparisons between the various measurements to be made. The preliminary results from simulations produced in a separate but related project by Risto Hänninen were analysed and compared to the experimental observations. The hypothesis based upon the preliminary measurements, that the primary effect observed in the NMR magnon spectra is caused by the reduction in the polarization of the vortex array, has now been confirmed: the modulations produce highly polarized quantum turbulence. The calculations performed in the course of the project show that the measurement is not sensitive to the axial flow produced by the large-scale collective motion in the vortex array (the analogue of classical inertial waves). The transient signals produced by stopping the modulation proved to be particularly instructive. There appear to be two different processes occurring during this relaxation. The first is apparently due to the decay of the large-scale (long wavelength) vortex waves (inertial waves). The time scale for this process was dependent on the amplitude of modulation, temperature, and how long the modulations were switched on. There is little change in the experimental signal during this decay. The second process was characterized by the late-time exponential decay of the experimental signal with a time constant of ~300 seconds. This time scale is independent of the amplitude and duration of the modulation and thus appears to be related to the dissipation of Kelvin waves on individual vortex lines. The amplitude and duration of the modulation affects how much energy is stored in the long wavelength modes. After stopping the modulation, energy is fed from the long wavelength modes to the shorter wavelength Kelvin modes providing some evidence for the proposed Kelvin-wave-cascade scenario that is believed to occur in the decay of quantum turbulence.
Amount of access given	36 days

Title of the project	**Self trapping of magnon Bose-Einstein condensates** AALTO20
User group leader	Yuriy Bunkov, professor
User	Yuriy Bunkov, professor
Home Institute	Institute Neél, CNRS, Grenoble
Host supervisor	Matti Krusius, Low Temperature Laboratory, Aalto University
Description of the work	Long-lived coherent spin precession of 3He-B at the lowest temperatures around 0.2 Tc was discovered by Yuriy Bunkov while he was visiting the ultra-low temperature laboratory in the Lancaster University in

	the early nineties. Since then this coherent NMR mode has defied accurate description. During the past four years the phenomenon has been redressed in the language of Bose-Einstein condensation, which has created new understanding on how to explore the resonances further [see Yu.M. Bunkov and G.E. Volovik, Phys. Rev. Lett. **98**, 265302 (2007)]. An important new dimension has been found to be rotation, by which one can control and modify the order parameter texture. It forms the radial part of the trapping potential which confines the magnon condensate and ultimately gives the energy spectrum of the different condensate states. Such measurements were performed in the first half of 2010 during the visits of Yuriy Bunkov and his graduate student Pierre Hunger. Subsequently a manuscript was prepared on the results from these measurements and their interpretation [preprint: arXiv-1002.1674v1]. Since then it has been found that the long spin relaxation times of the magnon condensates in the ground state or on the different excited levels can be readily measured and displayed with the available techniques. The first measurements on the relaxation times have now been performed in the different rotating states, but this work should be continued further. Nevertheless, it is clearly seen that a regular equilibrium vortex array provides large additional spin relaxation, similar to what has been observed to happen at solid surfaces in measurements at the Lancaster University. However, for instance vortices in a dynamic state of tangled motion or the free liquid surface have not yet been probed. Such measurements would provide important missing information which is needed to identify the source of the new relaxation mechanism. The goal of the visit was to discuss the relaxation studies and to rework the current version of the manuscript “Self-localization of magnon Bose-Einstein condensates in the ground state and on excited levels: from harmonic to a box-like trapping potential” which was submitted to a journal for publication recently [preprint: arXiv-1002.1674v3].
Project achievements	The main results of this work are (i) a demonstration of self trapping of a Bose-Einstein condensate composed of quasiparticle excitations in an externally controllable trapping potential and (ii) non-ground-state condensate formation. Both phenomena are new properties of boson condensates which have been discussed theoretically in the context of ultracold atom condensates but have not been experimentally realized there.
Amount of access given	7 days

Title of the project	**Non-equilibrium transport through nanodevices** AALTO21
User group leader	Iouri Galperine, professor, University of Oslo
User	Iouri Galperine, professor, University of Oslo
Home Institute	University of Oslo
Host supervisor	Nikolai Kopnin, Low Temperature 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.
Project achievements	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. This is the starting point of a new project, which we expect to become fruitful, but it is hard to specify at this point a definite date for results.
Amount of access given	7 days

Title of the project	**Charge and heat transport in quantum dots coupled to superconducting leads** AALTO23
User group leader	Hervé Courtois
User	David van Zanten
Home Institute	Institut Néel, CNRS, Grenoble
Host supervisor	Jukka Pekola, Low Temperature Laboratory, Aalto University
Description of the work	Our goal is to analyze electron and heat transport through SINIS structures when the normal island is a weakly coupled quantum dot. The results will be compared to numerical calculations on SINIS structures where the normal island does not have a significant level spacing. During this first one week visit we plan to start a collaborative project for gaining 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 foundation 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 for faster operation of a single-electron turnstile, and suppression of its transfer errors.
Project achievements	A collaborative project was started with plans for future experiments and modeling. The first step, a numerical model to describe heat and current transport, was completed.
Amount of access given	5 days

Title of the project	**Specific heat signatures of a Kosterlitz-Thouless transition** CNRS05
User group leader	Professor Javier Rodriguez-Viejo, Universidad Autonoma de Barcelona
User	Manel Moline Ruiz, M.Sc. graduate student
Home Institute	Physics Department, Universidad Autonoma de Barcelona
Host supervisor	Henri Godfrin, professor, CNRS, Grenoble
Description of the work	We have performed heat capacity measurements on ultra-thin films of superconducting lead (Pb), quench condensed in situ in the calorimeter directly on the membrane sensor. We used the facilities of TA2-Grenoble, especially a specific experimental probe developed at the Institut Néel for these measurements, as well as the nanofabrication facilities of NANOFAB. The thermal evaporation of lead, silver, and eventually of magnetic materials in situ is planned, which all will be fully characterized at low temperatures. The calibration of the quartz crystal is crucial to control the thickness of the thin films accurately. The highly sensitive heat capacity measurement has to work at very low temperatures, in order to follow the temperature dependence of a heat capacity peak as the layer thickness is grown in situ. The major advantage of this method will be to be able to measure the Cp signature versus the thickness of the thin film without being obliged to open the measuring system. All the Cp measurements will be performed down to the lowest temperatures of the cryostat.
Project achievements	The crucibles have been installed in the low temperature probe. The quartz crystal has been calibrated from room temperature down to low temperatures. The calorimetric sensors (on a silicon membrane base) have been built at the Nanofab facility and very sensitive thermometers have been deposited for measurement. All the thermometer calibrations were completed. Evaporation of lead on a test sample has been done and a measurement of the evaporated film thickness has been performed a posteriori. A measurement of the heat capacity of a lead thin film has been carried out down

	to 0.5 K. The characterization of the heat capacity jump of thick films (50 nm) demonstrate that a clear phase transition will be observed even at very low thickness (below 0.5 nm). The signal to noise ratio is largely favourable. The first evaporations of lead at 4 K have been performed in the calorimeter. The calibration of the quartz crystal microbalance has been done. We demonstrated also the possibilities for successive evaporations of material in quench-condensation conditions in the calorimeter, without having to warm up the system. The helium leaks have been checked and repaired. Each of the crucibles had to be independently leak tested before being mounted on the probe. Now the system is operational at 1 K. The evaporation of a lead thin film has been done on a silicon membrane calorimetric sensor. The plan is to publish the measurement technique in the Reviews of Scientific Instruments during 2012.
Amount of access given	92 days

Title of the project	**Micro and nano sensors for probing quantum turbulence** CNRS06
User group leader	Ladislav Skrbek, professor, Charles University, Prague
User	David Schmoranzer, Dr.
Home Institute	Charles University, Prague
Host supervisor	Henri Godfrin, Institute Neél, CNRS, Grenoble
Description of the work	The aim is to develop and manufacture sensitive micro-oscillators for probing turbulence in cryogenic liquids, emphasizing usage in He superfluids at very low temperatures. Sensors in the form of wires, cantilevers, and spheres were proposed, with emphasis on goal-post oscillators developed in CNRS Grenoble. The manufactured devices will be characterized and are then going to be used to study quantum turbulence within a research project at the Charles University in Prague, as well as for future experiments performed on-site at CNRS Grenoble. One of the objectives of the project is also to provide the user with sufficient training in micro-fabrication technologies so that the work on the development of various micro-oscillators can continue after the visit is concluded. The first steps involved preparation of the oscillators using micro-fabrication technologies such as optical lithography (UV, deep UV), laser lithography, selective wet etching, reactive ion etching, physical vapour deposition, and related characterization techniques (microscopy, interferometry, profilometry). During this time, new designs of micro-oscillators were also produced and the corresponding lithographic masks were made. An experimental setup for testing the fabricated samples in cryogenic conditions was assembled and tested successfully. Several different

	goal- post oscillators were produced, which are available for future tests and measurements. Among the achievements we list: 1. Training in the fabrication of micro oscillators 2. New designs were proposed and masks were prepared 3. Cryogenic test setup was assembled and characterized Difficulties encountered during the visit: 1. Delicate manipulation of the samples during fabrication and installation in its measuring setup. 2. Long waiting times for some micro-fabrication procedures at the installation.
	The results will be published when measurements on the sensors have been performed at low and very low temperatures both in Prague and Grenoble.
Amount of access given	86 days

Title of the project	**Late-time dynamics of quantized vortices generated after absorption of a neutron in superfluid 3He-B** CNRS07-1
User group leader	Andrei Golov, professor, University of Manchester, UK
User	Andrei Golov, professor, University of Manchester, UK
Home Institute	University of Manchester, UK
Host supervisor	Yuriy Bunkov, professor, CNRS - Grenoble
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 behind in superfluid 3He-B after the absorption of one neutron. We elaborate a new ``inflationary" model that will account for the initial spreading and growth of the vortex tangle (and also the 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 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.
Project achievements	A thorough analysis of the experimental data from the DN1 cryostat of the Microkelvin facility has been performed. The applicability of the "standard" Kibble-Zurek model of the nucleation of topological defects in homogeneous conditions was reviewed. Various assumptions of the model have been critically checked. As a result, several new mechanisms leading to vortex production, multiplication, and conservation were suggested and discussed. Preliminary estimates of the rates and efficiencies of the different mechanisms have been made. These will provide a basis for further an-

	alytical and numerical modeling. In summary, the theoretical model of vortex formation in inhomogeneous temperature conditions was developed. The experimental data is consistent with this model. A manuscript with the title "Evolution of neutron-initiated Big-Bang in superfluid 3He-B", by Yu. Bunkov, A. Golov, V. Lvov, and Procaccia, is under preparation and is planned to be completed by the end of 2012.
Amount of access given	9 days

Title of the project	**Late-time dynamics of quantized vortices generated after absorption of a neutron in superfluid 3He-B** CNRS07-2
User group leader	Victor L'vov, professor, Weizmann Institute of Science, Rehovot
User	Victor L'vov, professor, Weizmann Institute of Science, Rehovot
Home Institute	Weizmann Institute of Science, Rehovot, Israel
Host supervisor	Yuriy Bunkov, professor, CNRS - Grenoble
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 behind in superfluid 3He-B after the absorption of one neutron. We elaborate a new ``inflationary" model that will account for the initial spreading and growth of the vortex tangle (and also the 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 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.
Project achievements	A thorough analysis of the experimental data from the DN1 cryostat of the Microkelvin facility has been performed. The applicability of the "standard" Kibble-Zurek model of the nucleation of topological defects in homogeneous conditions was reviewed. Various assumptions of the model have been critically checked. As a result, several new mechanisms leading to vortex production, multiplication, and conservation were suggested and discussed. Preliminary estimates of the rates and efficiencies of the different mechanisms have been made. These will provide a basis for further analytical and numerical modeling. In summary, the theoretical model of vortex formation in inhomogeneous temperature conditions was developed. The experimental data is consistent with this model. A manuscript with the title "Evolution of neutron-initiated Big-Bang in superfluid 3He-B", by Yu. Bunkov, A. Golov, V. Lvov, and Procaccia, is under preparation and is planned to be completed by the end of 2012.

Amount of access given	11 days

Title of the project	**Local magnetization measurements with a miniature array of Hall probes** CNRS08
User group leader	Dr. Zuzana Pribulova
User	Dr. Zuzana Pribulova
Home Institute	Department of Low Temperature Physics, Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia
Host supervisor	Henri Godfrin, Institute Neél, CNRS, Grenoble
Description of the work	The proposed project has two important scopes: a technical and a scientific one. The technical part is the transfer of knowledge and expertise in local magnetisation measurements using miniature Hall probes arrays for future use in an apparatus in Kosice as well as the testing of Hall probes in collaboration with an expert (Thierry Klein). The scientific goal of the project is the experimental study of iron based superconductors down to 0.3 K. The aim was to study the phase diagram temperature vs magnetic field and magnetic relaxation in iron based superconductors with a focus to study the first penetration field (related to the lower critical field H_{c1}) into the sample down to very low temperatures. The first experiments described below were made in a 3He cryostat at the Microkelvin facility, with the support of Dr. Klein. We completed the wiring and the installation of a sample holder – for both magnetization and specific heat measurements. Then we prepared all required connectors and shielded boxes for easy connection with the measurement devices. After we cooled the cryostat down we needed to find a proper regime for the helium circulation through several stages (cooling of the charcoal, 1K pot). When we reached the lowest temperature, we tested the Hall probes and subsequently started the measurements of the penetration field H_p. Using the Hall probe arrays from Bratislava we measured the magnetic field induced in the sample after we applied a well-defined field in the superconducting coil. From the response of the sample we could determine the penetration field. We performed the measurements in the temperature range starting from 0.75 K up to 3.2 K and magnetic fields up to 5000 Oe.
Project achievements	Even with the best settings, we could not reach temperatures lower than 0.75 K in the 3He pot. Moreover, the time available at the lowest temperature was short compared to the test run without a load. We suspect that a large heat link existed between the 1K-4He pot and the 0.3K-3He pot which was the reason. In the near future the sample holder will be changed to reduce heat input to the 3He pot. In spite of the technical difficulties we succeeded to measure the temperature dependence of the first penetration field of $SrPd_2Ge_2$ – a material which is isostructural to iron-based pnictides but lacks any magnetic ordering. From the measured dependence we will derive values of the

	lower critical field and the penetration depth of the material. Since the operation time of the 3He pot at its lowest temperature was short and we needed to regenerate the 3He charcoal pump often, the measurement became very time-consuming. For this reason we performed measurements using only one Hall probe. In the future we would like to continue the research of this material at lower temperatures and with several different Hall probes. Since we had very little measurement time, we could not test the Hall probes in details. However, the first test showed that they are very sensitive even at these low temperatures. On the other hand they seem to be sensitive to any kind of shock so that they have to be treated very carefully. Forthcoming additional tests are necessary to prove their reproducibility and overall performance.
Amount of Access given	17 days

Title of the project	**Rapid thermometers for specific heat measurement in thermodynamic equilibrium** CNRS11-1
User group leader	Sven Sahling, Dr. senior researcher Institut für Festkörperphysik, Technische Unversität, Dresden
User	Sven Sahling, TU Dresden
Home Institute	Institut für Festkörperphysik, Technische Unversität, Dresden
Host supervisor	Gyorgy Remenyi, Dr., Institut Néel, CNRS, Grenoble
Description of the work	The various contributions to the heat capacity of a $Sr_{14}Cu_{24}O_{41}$ single crystal 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.
Project achievements	The heat capacity of a $Sr_{14}Cu_{24}O_{41}$ single crystal was investigated in the temperature range between 50 mK and 20 K, in magnetic fields up to 10 T, and as a function of time between 1 ms and 10^4 s. At least one of the heat capacity components is caused by the 1D CDWs. The other Schottky-contributions are probably caused by free Cu-spins on the 1D Cu-chains. This will be probed in the next experiments in September by the investigation of $Sr_2Ca_{12}Cu_{24}O_{41}$, where the number of free Cu spins on the 1D Cu-chains is drasticly reduced. Publications are planned to follow the measurements which are performed at low and very low temperatures in Grenoble during the rest of 2012 or early 2013. A suitable publication medium is Phys. Rev. B**.**
Amount of access given	39 days

Title of the project	**Q-balls in superfluid 3He-B and magnetic relaxation in $T \longrightarrow 0$ limit** Lancaster03
User group leader	Peter Skyba, RNDr., CSc.
User	Peter Skyba, RNDr., CSc.
Home Institute	Institute of Experimental Physics, SAS
Host supervisor	Shaun Fisher, professor, Lancaster University
Description of the work	Our objective was to study the dissipation mechanisms in NMR which operate in the persistently precessing domain (PPD) at very low temperatures in 3He-B, and in particular to consider whether Andreev (Majorana) bound surface states may have any influence on the decay mechanisms. We reanalyzed existing experimental data and supplemented missing data by taking new measurements as required. On the basis of our findings, we hope to prepare a draft of an article on the low temperature properties of the PPD with emphasis on the magnetic relaxation mechanisms. Measurements of the properties of the PPD as a function of temperature were re-analyzed to provide extra details which were not previously considered. We have compared the results to current ideas on the nature of the PPD and we have analyzed the data to identify the possible dissipation mechanisms. We have also considered how the PPD might be influenced by current ideas on Andreev (Majorana) bound surface states in superfluid 3He-B. Based on the results of our analysis and using recent experimental and theoretical studies of precessing spin structures, we have built a better physical picture of the PPD based on the spin-wave scenario, although the exact understanding of the PPD remains a theoretical challenge. We were not able to perform any additional measurements as the experiment at Lancaster was interrupted due to a leak of the helium-3 system involving the experimental cell, but the existing data is sufficient for our current needs. A draft of the article is currently in preparation.
Project achievements	Based on the reanalysis of the data and recent theoretical work on spin wave modes in superfluid 3He-B we were able to form a better physical picture of the PPD and how it might be related to the spin wave modes observed at higher temperatures. The data analysis of the measurements on magnetic relaxation (PPD life time) clearly show the presence of an additional surface mechanism although neither the frequency of the PPD signal nor its frequency - amplitude dependences seem to be affected by this mechanism.
Amount of Access given	10 days

Title of the project	**Quantum turbulence generated and detected using a floppy wire** Lancs04

User group leader	Peter Skyba, professor, Institute of Experimental Physics, Slovak Academy of Sciences, Kosice
User	Marcel Clovecko, Dr., research associate
Home Institute	Institute of Experimental Physics, Slovak Academy of Sciences, Kosice
Host supervisor	Shaun Fisher, professor, Lancaster University
Description of the work	The goal of this project is to develop a new 'floppy wire' device, along with the associated measurement techniques and instrumentation, to study superfluid flow over a very broad range of temperature, velocity and frequency, to optimize the potential applications, and to maximize the sensitivity (and hence the information which can be obtained from experiments). A large device, with a grid mesh attached, will be constructed and tested in superfluid 4He to develop techniques to accurately measure the drag force on the moving device, for both transient and oscillatory motion. Superfluid 4He is an ideal medium for developing the technique and will also allow us to make a preliminary study of superfluid turbulence generation by the grid at high velocities. Using the unique cooling facilities at Lancaster, we then hope to apply the techniques to obtain some preliminary results in superfluid 3He-B at the lowest achievable temperatures. The project will also require some development of the measurement instrumentation (in particular, we need to develop a controllable current source which is needed to produce stable steady currents with superimposed high frequency probe currents, as was designed by Peter Skyba from the Kosice group).
Project achievements	A large 'floppy wire' device (25 mm wide and 39 mm tall) with a grid mesh (25 mm x 10 mm) was constructed, with a new brass holder to simplify the assembly of the 4He experimental probe. The device was cooled to temperatures of around 1.5 K in a 4He glass cryostat. With the newly designed experimental probe, we were able to directly see the grid and its motion at low temperatures, by looking through the inspection slits in the silver coating of the glass dewar. We made a video to give a more visual demonstration of the new technique. We measured the force versus velocity response, comparing the conventional ac measurements with our new dc measurement technique, to develop and optimize the new measurement and analysis techniques. Several experimental runs were made to collect data using a wide range of measurement parameters and conditions. This also provided us with some interesting preliminary measurements of the response of superfluid 4He to quasi-static flows. We also wrote a computer program to simulate the response of the device to help better develop and check our analysis and data taking software. A new controllable current source, designed and built at Lancaster, was tested and was used to take the later measurements. The 3He experiment, incorporating the earlier floppy wire device, was installed and the initial cooling commenced (unfortunately, owing to leaks, we were not able to take measurements of this during the project, but the system has since been cooled and the device works very well).

	In summary, we successfully made a large 'floppy wire' with an attached grid and associated measurement coils. We modified the experimental test probe and cooled the device to liquid Helium temperatures. We made various measurements in normal 4He at 4K and in superfluid 4He at 1.5K, and recorded some video pictures of the working device. We tested and used the new current source, which worked extremely well, producing a wide range of ac currents superimposed on a very steady dc current. We demonstrated that the technique allows a very accurate measurement of the position of loop with good time resolution. The dc measurements were compared with the wire's ac response, which we measured using conventional techniques, at its resonant frequency of 17 Hz. A program (using Matlab) was developed to simulate the device response. Very good agreement was obtained with the dc measurements with only one fitting parameter: the effective mass of the wire. The simulations were used to predict the result of the ac measurements. Preliminary results suggest that there is a clear difference between the dc and ac drag force in 4He. This suggests that there is a significant frequency dependence of the response. This will be studied in more detail in future experiments. Of particular interest is the frequency dependence of the turbulent drag at high velocities and the critical velocity for turbulence. Also in 3He-B we will measure the frequency dependence of the drag force at ultra-low temperatures to study surface states/Majorana fermions. We expect to publish preliminary results in the next few months.
Amount of access given	40 days

Title of the project	**Design of quartz tuning fork array for quantum turbulence research** Lancs05
User group leader	Professor Ladislav Skrbek
User	Professor Ladislav Skrbek
Home Institute	Faculty of Mathematics and Physics, Charles University in Prague, Czech Republic
Host supervisor	Shaun Fisher, professor, Lancaster University
Description of the work	Turbulence impacts on virtually every aspect of our everyday experiences, with enormous scientific and technological implications, but is still quite poorly understood. Superfluid 3He below 0.3 Tc provides a unique environment for studying the fundamental principles of turbulence. Quantum turbulence in a superfluid consists of a tangle of vortex lines. In superfluid 3He, vortices can be non-invasively probed by ambient thermal excitations using Andreev reflection. Following its discovery 10 years ago, a great deal of progress has been made in this system. We now hope to extend these studies with turbulence visualisation measurements. For this purpose, large numbers of sensors are essential. Quartz tuning forks are well suited for this since they have very low intrinsic dissipation, small size, and can be manufactured to tailored specifications. The ULT group at Lancaster has the necessary infrastructure

	and extensive expertise in studies of quantum turbulence in superfluid 3He, whilst the Prague group has vast experience with quartz tuning forks. In this project, professor Skrbek will utilize this expertise to investigate tuning fork arrays for low temperature applications, such as ULT turbulence visualisation techniques. The Lancaster ULT group has recently purchased some prototype arrays of custom-manufactured quartz tuning forks which cover a wide range of frequencies from 6 kHz to 160 kHz. Substantial progress has been made in developing the required measurement techniques to simultaneously drive and measure large numbers of forks in a single array. Such arrays are ideal for making a systematic study of the properties of tuning forks in quantum fluids, including sound emission. In this project, we investigated the detailed properties of the individual tuning forks in the arrays. We studied their current - voltage characteristics, resonant frequencies and their intrinsic low temperature dissipation / quality factors. In particular we looked at the frequency dependences of these quantities and compared measurements in vacuum and in liquid He to investigate the effects of sound emission. The tuning fork arrays were cooled to temperatures of around 1.5 K in a 4He glass cryostat. Our experiments showed that sound emission becomes the dominating damping mechanism at resonant frequencies above 100 kHz in liquid 4He. Comparison of the experimental data with the various theoretical models showed that a 3-dimensional model of sound emission described our data well.
Project achievements	We mounted tuning fork arrays on the experimental test probe and cooled the forks to liquid He temperatures. We made characterization measurements in vacuum at 4.2 K and various detailed measurements in normal 4He at 4 K and in superfluid 4He down to 1.5 K. We analyzed experimental results from damping measurements using a program written in Matlab. Experimental results on tuning fork damping at frequencies below 100 kHz are in very good agreement with hydrodynamic models. Experimental data at higher frequencies suggest that acoustic emission becomes the main damping mechanism and that the measured damping in helium can be described using a 3-dimensional sound emission model. Our results show that sound emission plays a significant role in the damping of the tuning forks in He and requires similar studies to be conducted in normal and superfluid 3He. Such studies will be carried out in the near future.
Amount of Access given	12 days

Title of the project	**Novel methods & devices for ultra-low-temperature measurement** Lancs06
User group leader	Dominik Zumbuhl, professor
Users	Lucas Casparis, M.Sc. graduate student Myrsini Lafkioti, M.Sc. graduate student

	Dario Maradan, M.Sc. graduate student
Home Institute	Department of Physics, University of Basel
Host supervisor	George Pickett, professor, Lancaster University, UK
Description of the work	The most fundamental and important role of the MICROKELVIN consortium is the opening of the microkelvin regime to nanoscience experiments. The BASEL group is one of the very few outside the access-offering institutions who are actively pursuing the nuclear cooling of nano-scale samples. The BASEL group have their own systems and are also taking delivery of a cryostat built within the consortium by BLUEFORS. The purpose of the current project is the technology transfer from the ULANC group to BASEL of the methods of operating large nuclear cooling systems and in particular the development of nuclear magnetic resonance thermometers. The project will allow the BASEL group, with its existing nuclear refrigerator and also with the new consortium-provided system, to capitalize on the experience of the ULANC group's long experience in operating large-scale nuclear cooling installations. The two principal outcomes of this project are first, the transfer of good practices concerned with running and managing the large refrigerators, especially with regard to thermometry and secondly, the construction of two state-of-the art platinum brush thermometers by the visitors under ULANC supervision for transfer and use in BASEL. The thermometers are constructed of 0.025 mm diameter bare 99.99% pure platinum wire. The wire will be wound on a former to form a bundle a cm or so long. The wires at one end will then be soldered together using molten silver as the solder medium. Neither platinum nor silver has a significant oxide layer when molten so this system has the advantage that no added flux is needed. The silver bead at the end of the thermometer will then be spot-welded to the silver support unit being brought from Basel. Once this weld is finished the wires are gently separated to avoid resistive contacts between them which can lead to eddy current heating when the bundle is being used as the working "fluid" for a pulsed NMR thermometer. Two such thermometers will be produced, using the Pt wire bundles manufactured in Lancaster and the NMR coil system, support and silver thermal contact pieces prepared in Basel.
Project achievements	The Platinum wire was successfully fabricated into two Platinum brushes and molten into the silver support structure, in order to allow a large as possible thermal conductance. The support structure and the platinum brushes were further welded together to allow placement in the BASEL Microkelvin system. During the whole visit we discussed at great length pulsed NMR thermometry, as well as microkelvin physics in general. In the meantime the last step of building a pick-up coil around the Pt brushes and assembly of the thermometer have been accomplished in Basel. The thermometer is now an essential part of the BASEL Microkelvin experiment. The device is now undergoing tests and will next be calibrated

	against other thermometers.
Amount of access given	12 days – all three users were visiting at the same time for 4 days

Title of the project	**Superfluid AB interface: analogue cosmological brane** Lancs07
User group leader	Manuel Arrayas, Dr. reader
User	Manuel Arrayas, Dr. reader
Home Institute	Universidad Rey Juan Carlos, Madrid
Host supervisor	Richard Haley, Dr., Lancaster University
Description of the work	The primary objective of the project is to provide further understanding on the properties of the A-B interface 2-brane. In the experiments a shaped magnetic field is used to stabilize and manipulate the phase boundary between the A and B phases. We exploit the influence of the magnetic field on the phase transition between the two phases, with the B phase being stable up to a critical field of 340 mT, whereupon there is a first-order transition to the A phase. A first-order transition is associated with a latent heat and a surface tension between the two phases. The surface tension must be taken into account when assessing the equilibrium shape of the interface in the presence of a magnetic field with spatial distribution, as well as the differences in wetting energy between the two phases and the container walls. We have developed numerical methods to find the equilibrium interface position for realistic magnetic field profiles and boundary conditions, to simulate the interface behaviour when subjected to perturbations, and to see how its properties might be modified by defects that can exist within it. My visit was planned to coincide with on-going experiments where the AB interface is moved through an array of detectors, by which the motion is monitored. I participated in these measurements and helped 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 along the cylinder, allowing for the stabilization of the AB interface across the cylinder. Sweeping the current in the solenoid changes the field gradient and moves the AB interface up and down the cylinder, converting B phase to A phase and vice versa. The passage of the AB interface was inferred from the output of vibrating quartz tuning fork resonators that protrude into the superfluid from the sidewalls of the cylinder. These resonators are sensitive to the density of broken Cooper pair quasiparticle excitations, and are used to detect any changes as the interface 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 the interface. New techniques were developed to move the interface more quickly through the cylinder, using temperature steps rather than magnetic field gradients. This was undertaken to investigate whether a fast-moving interface is more sus-

	ceptible to instabilities. This remains an open question.
Project achievements	For the analysis we have used a dynamical effective model proposed by Leggett and Yip (see for example "He 3", edited by W.P Halperin and L. P Pitaevskii, Chapter 8). Initially, to calculate the equilibrium profile, the effective inertia term of the interface was neglected. Under that condition, the simulations suggest that the contact angle of the interface with the walls is not playing a fundamental role due to the dimensions of the interface at equilibrium. Also the slow movement of a perturbed interface has been simulated and preliminary results point to the damping of any transverse perturbation of the interface under cylindrical symmetry. A bubble equilibrium configuration also has been calculated. When the interface moves through the cylinder and while passing a fork, we observed hysteretic behaviour in the fork response. The contact angle could be important here, but this is an open question at the moment. It is not clear whether the dynamical model used in the simulations can answer questions like this. For a fast moving interface we have included now the inertia term. The linear approximation gives a driven Mathieu equation when the magnetic field is changed harmonically. It is a well-known fact that the Mathieu equation exhibits parametric resonance. There is some work in progress to explain a previous experiment by Bartkowiak et al.
Amount of access given	23 days

Title of the project	**Development of cable and filter protocols for nano-electronic device measurements at microkelvin temperatures** Lancs08
User group leader	
User	Daniel Harbusch, M.Sc., graduate student
Home Institute	Ludwig-Maximilians Universität, Munich
Host supervisor	George Pickett, professor, Lancaster University
Description of the work	The primary scientific and technologic objective of this access collaboration is to investigate nano-electronic circuits in a hitherto unrivalled range of ultralow temperatures. This will allow the Ludwig group (LMU Munich) to reach lower energy scales and investigate collective phenomena such as the Kondo effect in coupled quantum dots, the 0.7 anomaly in quantum point contacts or the hyperfine interaction between confined electrons and many nuclear spins in much greater detail compared to the current state-of-the-art. Future possibilities include the study of coherent dynamics in semiconductor-based qubits at ultralow temperatures. The combination of the expertise in ultralow temperature physics in Lancaster and in our low temperature nano-electronic measurements in Munich provides the framework for a successful collaboration. Nanostructures will be produced and initially characterized in Munich while the final ultralow temperature measurements will then be performed in Lancaster. The short term objective of this initial visit was to ensure that the Lancaster facility has the necessary equipment, cables and noise-filtering systems in place to

	facilitate the planned future experiments.
Project achievements	This visit was intended to lay the groundwork in Lancaster for designing and installing customized filters and cabling for our new measurements on the new Lancaster MICROKELVIN machine. Furthermore, it was also used to verify that nanodevices fabricated and tested in Munich can be easily transported to and installed on the Lancaster apparatus. We discussed cable and filter options at great length, and worked on new designs with the Lancaster group. The design discussions were very useful and also made us aware of other issues that would be involved in mounting new experiments on an access facility, for example the ancillary room-temperature electronics that will be required, how they will be provided, and how to achieve an extreme low-noise environment with shielding protocols that we have developed in Munich. The exchange of knowledge and expertise was very fruitful. Further achievements included agreement on exactly what specific cable and connectors would be purchased and used, and on the custom passive devices to be built by each party of the collaboration.
Amount of access given	2 days

3.3 Deliverables and milestones tables

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

Del. no.	Deliverable name	WP no.	Lead benefi-ciary	Estimated person months	Nature	Dissemina-tion level	Delivery date
D1	Opening and operation of Management Office	NA1	AALTO	10	O	PU	1 achieved
D2	Opening and maintaining of web-site	NA1	AALTO	4	O	PU and PP	1 achieved
D3	MICROKELVIN reports	NA1	AALTO	6	R	PU	20, 40, 50 achieved
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
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 partly achieved
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 in progress
D1	Prototype of nanocircuit stage for access service at ULANC (Task 1)	JRA1	ULANC	16	P	PU	36 in progress
D2	Prototype of compact nuclear cooling refrigerator for access service at CNRS (Task 2)	JRA1	CNRS	18	P	PU	24 in progress
D3	Prototype of compact nuclear cooling refrigerator for service in Basel (Task 2)	JRA1	AALTO	20	P	PU	36 in progress
D4	Next-generation microkelvin facility for access service at ULANC (Task 3)	JRA1	ULANC	30	P	PU	36 in progress
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 partially achieved
D4	Demonstration of sub-10 mK nanocooling with a N-I-S junction (Task 2)	JRA2	CNRS	24	R	PU	48 in progress
D5	Demonstration of 300 mK to about 50 mK cooling of a dielectric platform (Task 3)	JRA2	AALTO	26	R	PU	36 in progress
D6	Demonstration of cooling-based improved sensitivity of a quantum detector (Task 3)	JRA2	RHUL	9	R	PU	48 in progress
D1	Report on microfabricated silicon vibrating wires tested in superfluid 3He at 100 μK	JRA3	CNRS	3	R	PU	48 in progress
D2	Publication on vortex creation and dissipation in superfluid 3He	JRA3	ULANC	20	R	PU	24, 36 achieved
D3	Publication on 2D defects	JRA3	ULANC	18	R	PU	36 in progress
D4	Report on a quantum model of a hydrodynamic Black Hole analogue	JRA3	AALTO	12	R	PU	48 in progress
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 in progress
D7	Report on the determination of the excitation spectrum in liquid ^{3}He	JRA3	CNRS	8	R	PU	48 achieved
D1	Report on the contactless decoherence and heat-capacity measurement method (Task 1)	JRA4	HEID	21	R	PU	18, 36 achieved
D2	Report on the performance of high resolution μSQUID scanning magnetometer (Task 1)	JRA4	CNRS	12	R	PU	48 achieved
D3	Report on the performance of microcoils coupled to low inductance SQUIDs (Task 2)	JRA4	RHUL	18	R	PU	12, 24 achieved
D4	Report on the performance of wide bandwidth SQUIDs (Task 2)	JRA4	RHUL	15	R	PU	18, 36 achieved
D5	Report on current sensing noise thermometer for ultra-low temperature (Task 3)	JRA4	RHUL	15	R	PU	12, 24 achieved
D6	Rep. on 195Pt-NMR thermometer for ultra low temperatures (Task 3)	JRA4	PTB	8	R	PU	18, 36 achieved

D7	Report on metrologically compatible CBT sensor (Task 3)	JRA4	AALTO	6	R	PU	12, 24 achieved
D8	Report on 10 mK (100 µK) GaAs quantum dot thermometer (Task 3)	JRA4	BASEL	10	R	PU	12, 24 (36, 48) achieved

4 **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).

List of Milestones – Microkelvin – Annex I – amended version of Sep, 2011

Milestone number	Milestone name	WPs no's	Lead bene-ficiary	Deli-very date	Comments
M1	MICROKELVIN kick-off meeting	NA1	AALTO	1	Web-site news achieved
M2	Management Committee email meetings	NA1	AALTO	1, 4, 8,..	Web-site news achieved
M3	General Assembly and Advisory Board meetings	NA1	AALTO	1, 12, 24, 36	Web-site news achieved
M4	Periodic Project Reviews	NA1	AALTO	18, 36,48	Web-site news achieved
M1	Appointment of SP	NA2	AALTO	1	Web-site news achieved
M2	Meetings of Selection Panel (email meetings)	NA2	AALTO	1, 13, 37 (6, 12, 18…)	Web-site news achieved
M1	Meetings of Dissemination Committee	NA3	CNRS	1, 13, 37	Web-site news achieved
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 in progress
M3	Statutes of Distributed European Microkelvin Laboratory	NA4	ULANC	48	Report in progress
M1	Advanced filtering and isolation system designed and built	JRA1, Task 1	ULANC	18	Prototype ready achieved
M2	High conductivity cooled links to nanocircuits designed and tested	JRA1, Task 1	ULANC	30	Prototype ready achieved
M3	Nanocircuit stage installed in an access refrigerator	JRA1, Task 1	ULANC	36	Prototype running flawlessly in progress
M4	Phonon temperature on nanoscale silicon membrane measured	JRA1, Task 1	ULANC	36	Demonstrator
M5	Pulsed-tube based dilution refrigerator and conventional (miniature nuclear) stage ready for integration at CNRS (Basel)	JRA1, Task 2	CNRS (AALTO)	12 (18)	Prototypes running flawlessly in progress
M6	The compact microkelvin refrigerator at CNRS (Basel) ready for access service	JRA1, Task 2	CNRS (AALTO)	24 (36)	Prototypes ready in progress
M7	Complete the vibration isolation platform	JRA1, Task 3	ULANC	6	Prototype ready achieved
M8	Dilution refrigerator built, installed and tested	JRA1, Task 3	ULANC	24	Prototype running flawlessly achieved
M9	Nuclear stage tested and running in dilution refrigerator	JRA1, Task 3	ULANC	30	Prototype running flawlessly in progress
M1	Choice of the thermalization strategy	JRA2, Task 1	BASEL	12	Tests completed achieved
M2	Choice of the ex-chip filtering technique	JRA2, Task 1	BASEL	18	Tests completed achieved
M3	Choice of the superconducting material with a lower T_C	JRA2, Task 2	CNRS	24	Tests completed achieved
M4	Precise definition of the QD cooler geometry and materials	JRA2, Task 2	SNS	24	Tests completed achieved

M5	Design of membrane patterning and microcoolers	JRA2, Task 3	AALTO	18	Report achieved
M6	Delivery of the first membranes to the end users	JRA2, Task 3	AALTO	36	Prototype running flawlessly achieved
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	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 in progress
M5	Observation of several “cosmological defects” obtained in a microkelvin multi-cell detector	JRA3, Task 2	ULANC	30	Test completed in progress
M6	Development of a Black-Hole analogue in a rotating system with an A-B boundary	JRA3, Task 3	AALTO	48	Report
M7	Test of the Unruh effect from rapid motion of a phase boundary	JRA3, Task 3	AALTO	36	Test completed in progress
M8	Test of the percolation theory of the A-B transition	JRA3, Task 3	AALTO	36	Test completed partially achieved
M9	Observation of the interaction between two independent precessing Q-balls	JRA3, Task 4	CNRS	30	Report in progress
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 partially 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 in progress
M14	Neutron scattering measurement of ^{3}He excitation spectrum at intermediate energies	JRA3, Task 5	CNRS	42	Report achieved
M1	Contactless setup to investigate decoherence (specific heat) of solids	JRA4, Task 1	HEID	18 (36)	Prototype running flawlessly achieved
M2	Realization of a high resolution μSQUID scanning magnetometer	JTA4, Task 1	CNRS	42	Prototype running flawlessly achieved
M3	SQUID NMR detection of nano-scale 3He samples at sub-mK temperatures	JRA4, Task 2	RHUL	12	Prototype running flawlessly achieved
M4	Demonstration of NMR signals from 10 x 100 micron 3He samples	JRA4, Task 2	RHUL	36	Prototype running flawlessly in progress
M5	Demonstration of NMR at frequencies up to 100 MHz with wide band-width SQUID amplifier	JRA4, Task 2	RHUL	42	Prototype running flawlessly in progress
M6	Realization and measurement of 10 mK CBT sensor	JRA4, Task 3	AALTO	15	Prototype running flawlessly achieved
M7	Design and testing to 200 μK of noise thermometer optimized for metrological measurements	JRA4, Task 3	RHUL	24	Prototype running flawlessly achieved
M8	Operation of GaAs quantum dot thermometer at 10 mK	JRA4, Task 3	BASEL	24	Prototype running flawlessly achieved

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
M10	New temperature scale for ultra low temperatures	JRA4, Task 3	PTB	42	Prototype running flawlessly in progress

3.4 Explanation of the use of the resources

TABLE 3.4.1 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 1 FOR THE PERIOD 2 (AALTO)			
Work Package	Item description	Amount	Explanations
JRA 2	Personnel costs	160771,39	27,0 pm
NA 1	Personnel costs	50786,93	13,4 pm
TA 1	Access costs	111823,75	Access to AALTO Cryohall: 10,9 access months multiplied by the estimated unit cost in Annex I (10259,06 €/month)
TA 1	Travel costs	34754,83	Travel costs of access visitors
NA 1	Travel costs	590,67	Travel costs of the coordinator
	Travel costs	7851,25	MicroKelvin conferences
	Consumables	12435,81	Miscellaneous items for RTD
NA 2	Consumables	25359,9	User meeting and training session (months 19 and 24)
NA 1	Consumables	102,38	Management, miscellaneous
	Indirect costs	175591,90	Indirect costs
TA 1	Access costs	9991,00	Access to AALTO Micronova clean room. 66,5 access hours multiplied by the estimated unit cost in Annex I (150,17 €/h)
	Personnel costs	-1580,86	P1 adjustment: the 2010 coef-ficient was calculated based on 2010 data after closing accounts
	Indirect costs	-948,52	P1 indirect costs
	Access costs	5657,28	P1 access costs reported as agreed with Financial manager Ewa Kowalczyk
	TOTAL DIRECT COSTS	593187,71	

TABLE 3.4.2 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 2 FOR THE PERIOD 2 (CNRS)			
Work Package	Item description	Amount	Explanations
JRA1, 3, 4	Personnel costs	180676,02	42,41 pm
JRA3	Travel costs	2249,03	Presentation of JRA3 results at Int. Conf. Low Temp. Phys. LT26
JRA1, 4	Consumables	1760,50	O'rings for cryostat, AFM tips for nano-oscillators

NA	Personnels costs	14714,99	1,56 pm
NA	Subcontracting	21500,00	QFS2010 Conference: subcontracting of logistics (286 participants)
NA	Travel costs	28787,02	Travel and housing expenses of participants to Microkelvin Events: Microkelvin Workshop Smolenice 2011, Microkelvin Workshop Smolenice 2012, Microkelvin JRA4 Meeting 2010 Heidelberg, Microkelvin LT-X, LTD14 Heidelberg, Cryocourse 2011 Grenoble-Chichilianne.
TA2	Access to CNRS Facilties	77331,41	Access costs corresponding to 8,4 facility-months delivered
TA2	Travel costs users	7188,20	Travel and housing costs of access visitors
	Indirect costs	41225,46	Indirect costs
JRA3	Travel costs	1570,09	Adjustment P1/P2 / Presentation of Microkelvin JRA3 results at the Conference SFP-JMC12 and at the Kapitza Institute Colloquium (Moscow).
JRA3	Consumables	1304,82	O'rings, mechanical parts, fluid control parts for dil. refrigerator
NA	Travel costs	34227,31	Participants' travel and housing for Microkelvin meeting in Helsinki, EPS Low Temp. Section meeting in Warsaw, QFS2010 Conference in Grenoble, housing for Nobel Prize winner W. Ketterle and other Third Countries Network partners
TA2	Access to CNRS Facilties	270,00	Mistake RP1 (reverse number)
	Indirect costs	22261,34	Indirect costs
	TOTAL DIRECT COSTS	535066,19	

TABLE 3.4.3 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 3 FOR THE PERIOD 2 (ULANC)

Work Package	Item description	Amount	Explanations
JRA1, 3	Personnel costs	95980,66	19,6 pm
RTD	Consumables	7472,43	Miscellaneous for RTD
TA3	Travel costs	7165,66	Travel for access visits

TA3	Access Costs	25941,08	2,9 access months multiplied by the estimated unit cost in Annex I (8945,20€/month)
	Indirect costs	66371,25	Indirect costs
	Travel costs	62,70	Adjustment for P1 Transaction missed from claim 1
	Indirect costs	37,62	Adjustment for P1
	Access costs	-5098,76	Correction due to miscalculation of access days
	TOTAL DIRECT COSTS	197932,64	

TABLE 3.4.4 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 4 FOR THE PERIOD 2 (HEID)

Work Package	Item description	Amount	Explanations
JRA 3	Salary costs	8098,63	2,25 pm
JRA 4	Salary costs	75211,49	15 pm
	Coordination costs	9337,53	Consumables LTD 14 Conference Heidelberg 1.-5.8.2011
	Indirect costs	58970,71	Indirect costs
	TOTAL DIRECT COSTS	51618,36	

TABLE 3.4.5 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 5 FOR THE PERIOD 2 (RHUL)

Work Package	Item description	Amount	Explanations
JRA2	Personnel costs	3656,47	0.55 pm
JRA4	Personnel costs	75684,77	24,69 pm
JRA2, 4	Consumables	30449,56	Consumables and components
JRA2, 4	Travel	15842,13	Conference attendance
	Indirect costs	75379,76	Indirect costs
	TOTAL DIRECT COSTS	201012,69	

TABLE 3.4.6 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 6 FOR THE PERIOD 2 (SNS)

Work Package	Item description	Amount	Explanations
	Personnel costs	24229,53	14 pm
	Consumables	5463,00	Gas for Heliox-VL product
	Consumables	1655,00	GaAs mechanical wafer
	Consumables	523,96	Adhesive tape for cryogenics
	Consumables	220,00	Gold electrode, non-tarnish

			INFICON Crystals
	Consumables	739,62	Superconducting wire
	Consumables	645,00	Silicon wafers
	Consumables	6935,00	Liquid helium
	Consumables	1081,00	Intermetallic Crucible liner for e-beam evaporator
	Travel costs	462,87	Conference "Physique Quantique Mesoscopique"
	Travel costs	1243,16	Attendance "APS March Meeting 2012", Boston
	Indirect costs	25918,88	Indirect costs
	TOTAL DIRECT COSTS	69117,02	

TABLE 3.4.7 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 7 FOR THE PERIOD 2 (SAS)

Work Package	Item description	Amount	Explanations
JRA3	Consumables	3190,02	Conference LT26, Beijing, 2011
	Indirect costs	1914,01	Indirect costs
	TOTAL DIRECT COSTS	5104,03	

TABLE 3.4.8 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 8 FOR THE PERIOD 2 (BASEL)

Work Package	Item description	Amount	Explanations
JRA 1, 2, 4	Personnel costs	31235,44	11 pm
JRA 1	Personnel costs	17603,86	14 months part time
JRA 2	Personnel costs	7756,04	14 months part time
JRA 4	Personnel costs	10050,43	14 months part time
JRA 1, 2, 3	Personnel costs	3968,00	14 months part time
JRA 1, 2, 3	Personnel costs	1017,26	administrative staff, part time
JRA 1, 2, 4	Consumables	7691,48	Liquid Helium
JRA 1, 2, 4	Travel costs	977,49	Microkelvin Meetings
JRA 1, 2, 4	Consumables	643,23	Miscellaneous
	Indirect costs	48565,94	Indirect costs
	TOTAL DIRECT COSTS	129509,17	

TABLE 3.4.9 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 9 FOR THE PERIOD 2 (DELFT)

Work Package	Item description	Amount	Explanations

JRA 2	Personnel costs	44959,95	14 pm
JRA 2	Consumables	1580,46	Liquid Helium
JRA 2	Consumables	837,00	Cernox Sensor Calibrated
	Indirect costs	50771,76	Indirect costs
	TOTAL DIRECT COSTS	98149,17	

TABLE 3.4.10 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 10 FOR THE PERIOD 2 (BLUEFORS)

Work Package	Item description	Amount	Explanations
JRA1	Personnel costs	29409,79	8,42 pm
	Indirect costs	17645,87	Indirect costs
	TOTAL DIRECT COSTS	47055,66	

TABLE 3.4.11 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 11 FOR THE PERIOD 2 (UL)

Work Package	Item description	Amount	Explanations
JRA 1, 4	Personnel costs	29564,64	5,4 pm
JRA 1, 4	Travel costs	835,75	Miscellaneous
	Indirects costs	22619,72	Indirects costs
	Personnel costs	-1414,23	Adjustment P1 for salary side costs
	Indirects costs	-19888,34	Adjustment for P1 indirect costs
	TOTAL DIRECT COSTS	31717,54	

TABLE 3.4.12 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 12 FOR THE PERIOD 2 (PTB)

Work Package	Item description	Amount	Explanations
JRA 4	Personnel costs	17459,78	2,35 pm
	Indirect cost	24443,7	Indirect cost
	TOTAL DIRECT COSTS	41903,48	

3.5 Publications

Cumulative list of Microkelvin publications in scientific research journals [since April 2009, with acknowledgement to the Microkelvin grant # 228464]:

JRA1: Opening the microkelvin regime to nanoscience

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

Preprint

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*", preprint on arxiv: cond-mat/1111.197.

JRA2: Ultra low temperature nanorefrigerator

1. S. Gasparinetti, F. Deon, G. Biasiol, L. Sorba, F. Beltram, and 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, and D.R. Leadley, Strain control 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, and 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, and J.S. Tsai, Environment-Assisted Tunneling as an Origin of the Dynes Density of States, Phys. Rev. Lett. **105**, 026803 (2010) [URL]
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ADDENDA

1. Agenda of the General Assembly on March 21, 2012
2. Minutes of the General Assembly on March 21, 2012
3. Report of the Low Temperature Section of the Condensed Matter Division of the European Physical Society

European Microkelvin Collaboration

MICROKELVIN

General Assembly

Meeting at the 36-month Review of the Microkelvin Grant Programme
Wednesday, 21 March, Red Saloon, Smolenice Castle, 20:00 – 22:00

Members present at the meeting:

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

Not represented: BLUEFORS and SNS

AGENDA

1. ***36-month review***. Summary and impressions from today's review proceedings; are further actions needed beyond the regular plan?
2. ***Microkelvin finances***. Summary of present fiscal situation at different partner institutions. Special attention is needed to accelerate financial résumés for the 36-month review report.
3. ***Milestones & deliverables for the last 12 months***. Summaries on all JRA's. Discussion about actions needed: are the goals going to be achieved or is an amendment request required?
4. ***Funding of JRA's***. Are transfers of funds between partners needed to make maximal use of available resources during the final grant period?
5. ***TNA services***. Summary of access months at the 3 access-giving sites. Are targeted visitor months going to be achieved during the last year? Are transfers of funds between access-giving sites needed?
6. ***Upcoming networking projects and their budgets***. Final workshop and review meeting in March 2013. Other meetings of the Microkelvin Collaboration. Meetings with Microkelvin sponsorship. Societal outreach projects.
7. ***Proceedings***. Annex I calls for published proceedings from two Microkelvin User Meetings. Which meetings will support published proceedings?

8. ***Development projects with industrial partners***. Commercialization projects have been suggested, such as a high-frequency cabling package with thermal filters and anchors for nano-electronics measurements in a dilution refrigerator, or a ready-to-use Coulomb-blockade thermometer package down to 10 mK temperatures, or thermometry services for temperatures below 10 mK. Reports from BlueFors and John Saunders. Proposals and initiatives for the last year?
9. ***Amendment proposal***. Formal decision about a possible amendment proposal and its contents.
10. ***Balancing of the grant budget***. Formal decision about how to balance the Microkelvin budget during the remaining grant period. Approval for transfer of funds between partner organizations has to be sought from the EU Project Office.
11. ***Succession of the Microkelvin programme.*** Discussion of available possibilities, actions, and organization of work.
12. ***Any other business.***
13. ***Closing of meeting.***

Matti Krusius

Matti Krusius
Coordinator

G.R. Pickett

George Pickett
Chairman

European Microkelvin Collaboration

MICROKELVIN

General Assembly

Meeting at the 36-month Review of the Microkelvin Grant Programme
Wednesday, 21 March, Red Saloon, Smolenice Castle, 20:00 – 22:00

Present at the meeting:

George Pickett ULANC (Chair)
Joern Beyer (replacing Thomas Schurig PTB)
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John Saunders RHUL
Peter Skyba SAS
Andrea Vinante (replacing Tjerk Oosterkamp UL)
Dominik Zumbuhl BASEL

MINUTES OF GENERAL ASSEMBLY

1. **36-month review**. More than 70 % of the milestones and 80 % of the deliverables have been achieved at the 36-month deadline. The rest of the work is in good progress. No major deviations from the work plan have occurred, except for delays in equipment deliveries which have slowed down the construction of new refrigerators.

2. ***Microkelvin finances***. On the whole, the present financial state of the Microkelvin Collaboration follows the original plan. One request for a transfer of funds between partners has been made to the EU Project Office. This request concerned the transfer of 12 000 Euros from Aalto to Heidelberg for organizing the Low Temperature Detectors 2011 Conference in Heidelberg. The request was granted. A similar new request will be submitted to the EU Project Office to transfer close to 30 000 Euros from CNRS-Grenoble to SAS-Kosice for the board and lodging of the 88 participants of the Microkelvin 2012 Workshop in the Smolenice Castle.

   The trans-national access programme is lagging behind. Together the three access providing sites have hosted 41 months of visitor access, which is only half of the final 81-month target for the 4-year grant programme. Only Aalto with its 24 months of visitor time is approaching its 27-month target. The reason for the lag is partly the late start in the first payment of the Microkelvin grant money from Brussels (which should have occurred in April 2009 but actually happened in September 2009). The second reason is the unfamiliarity of both the CNRS and Lancaster laboratories with the difficulties in running their visitor programmes. To get the Microkelvin TNA programme finished at the targeted level appears challenging. The EU Project Officer notes that TNA is one of the three pillars in the Infrastructures Programme, a transfer of funds from TNA to JRA is not appropriate. However, to provide more opportunities to complete the TNA programme according to plans, the consortium may decide to ask for a 6-month extension. This request would be approved by the EU Project Office.

3. ***Milestones & deliverables for the last 12 months***. The meetings of all four JRA groups earlier during the day had concluded that the outlook for the final year looked promising: most likely the presently unfinished milestones and deliverables will be achieved and the new ones will be completed more or less according to plans.

4. ***Funding of JRA's***. The use of the grant money within the work packages of the JRA projects is proceeding according to the original plans. No transfers of funds between partners are needed during the final grant period.

5. ***TNA services***. As noted in #2, the Trans-National Access Programme has reached the half-way point, but to provide the remaining 40 months of access, a 6-month extension of the grant programme is advisable. A request for the extension will be made to the EU Project Office.

6. ***Upcoming networking projects and their budgets***. Several outreach projects are planned for the final year: **1)** The final User Workshop and Review Meeting of the Microkelvin Collaboration will be conducted in March or September of 2013, depending on the outcome of the 6-month extension request. This workshop will be organized in Helsinki or Lancaster. **2)** A meeting of the Microkelvin General Assembly will be organized during the QFS 2012 Conference in Lancaster in August. **3)** One or two sessions in a Microkelvin sponsored minisymposium are planned for the Meeting of the Condensed Matter Division of the European Physical Society in September 2012 in Edinburgh. **4)** A meeting with industrial liaisons is planned for next fall, possibly in Paris, to be organized by Henri Godfrin. A roadmap for the collaboration with our about 20 industrial partners is needed. It will become valuable when the continuation of the Microkelvin Collaboration becomes a timely issue under the Horizons 2020 framework (presumably in 2014, see #11).

7. ***Proceedings***. Annex I calls for published proceedings from two Microkelvin User Meetings. Proceedings will be prepared about the final User Meeting in 2013.

8. ***Development projects with industrial partners***. Commercialization projects have been suggested, such as a high-frequency cabling package with thermal filters and anchors for nano-electronics measurements in a dilution refrigerator, or a ready-to-use Coulomb-blockade thermometer package down to 10 mK temperatures, or thermometry services for temperatures below 10 mK. John Saunders reported that no new suggestions were received. This matter will be discussed in the meeting with industrial partners in the fall of 2012, to be organized by Henri Godfrin possibly in Paris. It was concluded that the present budget does not allow additional development work for commercial purposes and that therefore such plans will be postponed to a possible continuation of the Microkelvin concept under the Horizons 2020 framework.

9. ***Request for changes in the programme.*** **1)** A request will be submitted to the EU Project Office about granting a 6-month extension for the entire programme, from March 31 to September 30 in 2013 without any additional extra funding. **2)** In addition, permission is needed for transferring funds between partners, to pay the bill from the 2012 Workshop in Smolenice Castle. **3)** The Aalto administration notes that it had designed the entire programme to wind down on March 31, 2013. If the programme is continued for another 6 months, then the coordination budget at Aalto needs to be increased by 32 500 Euros. This can be done by a transfer of funds within the Microkelvin coordination budget.

In all the above cases it would be practical to avoid the regular route of an Amendment Proposal, since its processing might not be finished before the current closing deadline of 31 March 2013. Instead, these requests, which do not involve major budgetary changes, can perhaps be handled by the EU Project Office.

10. ***Balancing of the grant budget***. Current Microkelvin budgeting follows the original plans and, except for some smaller adjustments within the coordination budget, no major balancing is needed. With a six-month extension of the grant period the TNA programme has a chance to get completed at the targeted level.

11. ***Succession of the Microkelvin programme.*** Rumour has it that there may not be any more calls within the current FP7 framework where one could expect a continuation of the Microkelvin programme to fit in. However, the first calls within the new framework Horizons 2020 might make it possible to submit an application which is not too dissimilar from the present concept. It was decided that the chairman prepares a one-page expression of intent, to lobby for a bottom-up call in a programme for Infrastructures. This common statement of the Microkelvin Partners comes attached to these Minutes of the General Assembly. Horizons 2020 is expected to pay special attention to research excellence and to industrial leadership, particularly among small and medium-size enterprises. Both aspects are already important features of the current Microkelvin programme and will be further strengthened in the new application.

    The General Assembly unanimously supported a motion to draft a formal agreement for establishing a European Microkelvin Laboratory without walls which would include all present Partners with μK refrigeration access. The form and contents of this agreement will be discussed in the next General Assembly in August 2012 in Lancaster, after the Partners have had a chance to enquire about such an approach at their home institutions.

    The possibility to offer μK access to users from outside the EU countries was discussed. For instance, with the dismantling of many American low-temperature laboratories, facilities with μK temperatures are in short supply in the Americas, in particular for nanophysics measurements. Perhaps the American National Science Foundation could be interested to support such visits.

12. ***Any other business.*** The absence of the Advisory Board Members from the Review Meeting was discussed. It was decided that an effort should be undertaken to engage and activate the Members of the Advisory Board. The 36-month periodic review report will be sent to them with the polite request that the Collaboration would greatly appreciate their comments.

13. ***Closing of meeting.***

Smolenice March 23, 2012

Matti Krusius — Coordinator

George Pickett — Chairman

Addendum: Promotion for bottom-up calls in Framework Horizons 2020 (networking infrastructures)

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.

Low Temperature Section of the Condensed Matter Division

Annual report 2010: 2011/01
Author: Henri Godfrin

Development of the Division/Group in 2010[4] [5]	The creation of the new LT section was approved in October 2009. A Committee was formed. Statutes were sent to the EPS.
Board meetings	Board discussions have been regularly conducted by mail.
Conferences and their statistics	The LT section organised QFS2010, the International Conference on Quantum Fluids and Solids in August 2010, Grenoble, France; 287 participants.
Prizes	-
Cooperation with other EPS Divisions/Groups	Participation in the EPS-HEP2011 conference organisation, Grenoble July 2011.
Cooperation with Divisions/Groups of national physical societies	-
Publication of conference presentations	Proceedings of QFS2010 will be published in Journal of Low Temp. Phys. in March 2011 (2 volumes)
Gender[6]	QFS2010 was organised giving priority to women as speakers and supported participants, to attempt to improve the existing situation of substantial imbalance
Co-operations with China, Japan, Korea, South-America (any other)	Support was provided to participants of less favoured countries to attend QFS2010
Special activities in 2010	The list of potential new section members has been established. Participation in the organisation of LT26 and QFS 2012.
Suggestions and recommendations	
Any special communication	
Work plan for 2011	Consolidation of the LT section. Preparation of 2012 conferences.

[4] membership, chairpersons, co-option, sections, constitutional matters
[5] List of Board members as annex
[6] The policy of EPS is that women should be encourage 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.

Name of Section: Low Temperature Section of the CMD

Report: 2012/01

Author: Henri Godfrin

Development of the Division/Group in 2011[7,8]

The LT section worked during this period in the organisation of the section and the traditional events: low temperature conferences and courses.

List of Board members

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Board Meetings

The LT section had its board meeting in March 2011, in Smolenice (Slovakia).
The next section meeting will take place in Smolenice, in March 18-24, 2012.

Prizes

Conferences and their statistics

The LT section promoted the organisation of the International Conference on Low temperature Detectors (LTD14), Heidelberg (Germany) August 1-5, 2011. The number of participants was 303.
The LT section participated actively in the organisation of Cryocourse, the European Advanced Cryogenics course, Grenoble, September 18-27, 2011 (44 students).

[7] membership, chairpersons, co-option, sections, constitutional matters
[8] List of Board members as annex

The LT section promotes the organisation of the International Symposium on Quantum Fluids and Solids (QFS2012) in Lancaster, 15- 21 August 2012. The LT section promotes the organisation of Cryocourse, the European Advanced Cryogenics course in Heidelberg, September 2012.
Cooperation with other EPS Divisions/Groups Participation in the organisation of EPS-HEP2011 in Grenoble (July 21-27, 2011) (about 800 participants). The chairman of the LT section was a member of the Local Organising Committee.
Publication of conference presentations 2 volumes of the proceedings of QFS2012 have been published in the Journal of Low Temperature Physics Vol. 162, issues 3/4 and 5/6, February and March 2011). 2 volumes of the proceedings of LTD14 will be published in the Journal of Low Temperature Physics
Gender[9] particular attention was placed in selecting women as participants of Cryocourse. As usual in our field, few women were present, but the percentage is increasing regularly.
Co-operations with China, Japan, Korea, South-America (any other) 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 LTD14, providing them with substantial financial support.
Special activities in 2010 Conference LTD14 and Cryocourse (see above)
Suggestions and recommendations
Any special communication
Work plan for 2012 The international Conference on Quantum Fluids and Solids QFS2012 will be organised in Lancaster in August 2012. We will send mails for recruiting new EPS members in our community, and promoting affiliation to the LT section. Realisation of a Training Course (Cryocourse) in Heidelberg (September 2012).

[9] 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.