PROJECT PERIODIC REPORT

Grant Agreement number: 228464

Project acronym: MICROKELVIN

Project title: European Microkelvin Collaboration

Funding Scheme: Capacities Specific Programme, Research Infrastructures

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

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

Period covered: from 1.4. 2009 to 30.9. 2010

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

Mikko Paalanen (in his absence completed by Matti Krusius, professor)

Director

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Project website[2] address: www.microkelvin.eu

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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[1]

I, as scientific representative of the coordinator[1] 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[4].

- The public website is up to date (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 6) 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 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator[1]: Mikko Paalanen
In his absence: Matti Krusius

Date: 29/10/ 2010

Signature of scientific representative of the Coordinator[1]: ....
Matti Krusius

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

3.1 Publishable summary

European Microkelvin Collaboration — MICROKELVIN — is an EU-funded Integrating Activity project carried out in the FP7 Capacities Specific Programme "Research Infrastructures". It is a bottom-up approach of 12 partners to provide access to and develop applications in the ultra-low temperature regime.

Research at the frontier near absolute zero has long been a powerhouse of new ideas in physics and beyond. The principal objective of MICROKELVIN is the opening of the milli- and microkelvin temperature regime to nanoscience, condensed matter physics, particle physics, cosmology, and instrumentation. The project will bring together three leading European ultra-low temperature laboratories at Aalto University (Helsinki), CNRS (Grenoble), and Lancaster University, to create "a unified laboratory without walls" offering microkelvin facilities to external users. Associated with the three core institutions are eight European laboratories and one cryogenic business.

A central aim of nanoscience experiments is to reach the regime where quantum phenomena begin to govern the behaviour of the system. This will make it possible to discover new phenomena, new materials properties, and it will allow us to develop completely novel devices. 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 expense of microkelvin facilities and the undeveloped state of the relevant laboratory techniques has hitherto been a deterrent against performing nanoscience experiments in this temperature regime.

The main objectives of MICROKELVIN 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 cryoengineers 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 low infrastructure environments.
- To foster the development of the next generation of refrigerators and instruments for ultralow temperature measurements.
- To develop strategies and tools for the long-term buildup of a virtual European Ultralow Temperature Laboratory.

The work of the MICROKELVIN Collaboration is divided in 4 Networking Activities (NAs), 4 Joint Research Activities (JRAs) and 4 Transnational Access Activities (TAs). The main objectives and results of these activities during the first 18-month project period will be described below.

During the first reporting period, in the **Networking Activities NA1 - NA4,** MICROKELVIN has designed its logo (Fig. 1), opened its web-site (www.microkelvin.eu) and management office. It has also consolidated its management structure by selecting the members of the General Assembly, Advisory Board, Management Committee, Dissemination Committee and the Selection Panel for Transnational Access Activities. The General Assembly has held two face-to-face meeting in connection of the Kick-off Meeting (Fig. 2) and the 18-month review meeting (Fig. 3), and one email meeting.

welcome to the
European Microkelvin Collaboration

Fig.1. Logo of MICROKELVIN Collaboration (www.microkelvin.eu)

Fig. 2. Participants of the Kick-off Meeting, April 2-3, 2009.

The contact information of the personnel in the Management Office is:

Project Coordinator:	Mikko Paalanen (email: paalanen@neuro.hut.fi)
Temporary replacement:	Matti Krusius (email: mkrusius@neuro.hut.fi)
Project Manager:	Katariina Toivonen (email: katariina@neuro.hut.fi)
Project WEB-officer	Matti Laakso (email: matti.laakso@boojum.hut.fi)

Fig. 3. Participants of the Review and User Meeting, Oct 14-16, 2010.

The main work load in the MICROKELVIN programme is contained in four work packages, the **Joint Research Activities JRA1 – JRA4.** These contain the following tasks:

JRA1 Opening the microkelvin temperature regime to nanoscience (ex-chip techniques)
JRA2 Development of ultralow 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

JRA1: MICROKELVIN is developing new concepts of refrigeration and simultaneously building up refrigeration capacity in the collaborating laboratories. One of the primary goals is to combine adiabatic nuclear demagnetization cooling with a fully automated pulse-tube cooler precooled ^{3}He-^{4}He dilution refrigerator, to provide a cryogen-free refrigeration apparatus for sub-mK work. The technical part of this effort is projected to be completed in the early months of 2011. At this point running tests will be started to measure the cooling properties of and the heat leak to the nuclear cooling stage. A second concerted effort is the construction of a large-scale low-heat leak installation of nulear refrigeration for the investigation of nano-structured samples and devices to μK temperatures. Parallel to this construction work development and test measurements have been progressing to thermalize and cool nanodevices with ex-chip methods to sub-mK temperatures. The highlight of this work during the first 18 months has been to reach a temperature of 11 mK in a Coulomb blockade thermometer consisting of a metallic/superconducting tunnel junction.

JRA2: The goal is to use nanofabrication for constructing microrefrigerators, which can be used to cool nanosamples on the same chip to ultralow temperatures. Microrefrigeration uses the thermal current accompanying an electrical current through a tunnel barrier. The cooling power is small but well-suited to cooling on-chip nano-size samples. They have been shown to cool electrons from 300 mK to 50 mK and other nano-size samples from 300 mK to 200 mK. These numbers are still far from the low temperature records of conventional refrigerators, which are 6 μK for bulk 3-dimensional electron samples and 4 mK for 2-dimensional electron gas in GaAs/AlGaAs heterostructures. During the first 18-month project period we have experimented with new ex-chip cooling strategies and developed new concepts in device design and fabrication. With these improved techniques a GaAs quantum dot Coulomb blockade thermometer could be used to measure temperatures down to 18 mK.

JRA3: Here the partners will jointly develop new ways to answer selected fundamental physics questions by means of sub-mK measurements. The selection and the plans of these experiments were drafted before the start of the contract period, but they are still unique in the international low temperature community. This work package lists 16 publications or preprints as a direct result from the work related to the problems and goals within this activity. A number of new first time ever discoveries have been made, for instance the first measurements of the heating generated by quantum turbulence in superfluid ^{3}He-B using two different complementary techniques and the first measurement of the superfluid ^{3}He BCS pairing states in nano-fabricated restricted geometries, in this first example case between two smooth parallel plates of 600 nm separation.

JRA4: In low temperature work, next to refrigeration, thermometry is the second vital feature. Like refrigeration, temperature measurement is also not a routine operation for nano-size samples. Studies of nanosamples are delicate because noise, thermal currents, and the excitation of the measuring probes easily drive them out of equilibrium. The main task in JRA4 is to develop novel high-sensitivity measuring methods, such as contact-less measurement for the characterization of different properties of small samples or measurement of micron-size sample volumes. A further objective is to develop thermometry in the low-mK and sub-mK temperature regimes. One of the highlights from the first project period is the first contactless measurement with sensitive SQUID-based detection of thermal conductivity of metallic glass down to 5 mK. This experiment will be next continued to lower temperatures in a newly installed nuclear demagnetization refrigerator.

With these integrated activities, MICROKELVIN promotes new research possibilities for European academic institutions in low temperature physics. To achieve this goal, an additional important task is to disseminate information to the low temperature community at large. The results from our work are published in scientific journals. MICROKELVIN also provides access to its three core institutions for researchers to conduct measurements and for students to learn working procedures at first hand. The visits are supported from the MICROKELVIN contract and are organized as **Transnational Access Activities (TA1 – TA3).** Such visits are generally less than three months in duration and are carefully discussed and planned in advance, to provide a visitor the maximum gain from his stay. During the first 18-month project period MICROKELVIN received 18 applications. All access applications were accepted by the Selection Panel. In total, access was provided to 13 users in 14 different projects for 17 user months. The users came from 8 different EU- or associated countries. The delivered user months are 20 % of the minimum total user months foreseen for the 4-year contract period.

The Collaboration had a slow start owing to the fact that the MICROKELVIN grant became available only four months after the starting date. Therefore we envisage that the numbers from the first project period do not yet reflect properly the volume of the MICROKELVIN activities.

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

The immediate project objectives for the first period are:

- Setting up a transparent effective management of MICROKELVIN Collaboration
- To advertise the access giving facilities and ensure their optimal use
- First steps towards effective dissemination of the network results
- First steps towards improving the infrastructure at the Access-giving Facilities and opening the microkelvin temperature regime to nanoscience experiments
- First steps towards pooling the low temperature expertise of the access-giving facilities in the study of wider problems in fundamental physics, in particular in the use of condensed-matter analogues in the understanding of problems in other areas of physics
- First steps towards the development of novel low temperature measurement techniques based on, for instance, contactless measuring methods, SQUID-amplifiers and Coulomb blockade devices

3.2.2 Work progress and achievements during the period

An overview of the progress in the networking packages NA3 – NA4 and in the different joint research activities JRA1 – JRA4 is outlined below, covering the first 18 months.

welcome to the European Microkelvin Collaboration

CAPACITIES

NA3 Report #2

Name of the activity (work package): **Knowledge and technology transfer**
Reporting Period: **from 1.4.2009 to 30.9.2010**
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**
D1	Opening of the CryoTools data base (6) and E-mail lists of laboratories and industries (8)	NA3	CNRS	2	O	PU	6, 8 **partially delivered**

D2	LT-X workshops (18, 28, 40, 44) and Industrial meeting (32) with reports	NA3	All partners		R	PU	18, 28, 32, 40, 44 **delivered**

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**
M1	Meetings of Dissemination Committee	NA3	CNRS	1, 13, 37	**achieved**

Summary

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

Meetings of Dissemination Committee

The Microkelvin Collaboration was started with a 'kick-off' meeting on April 3, 2009, where the Dissemination Committee was established in the first meeting of the General Assembly. The first meeting of the Dissemination Committee followed immediately afterwards. The strategy for its activity and a plan of actions were discussed. The second meeting of the dissemination committee was organized October 15, 2010. Thereby all work included in milestone M1 can be considered to have been fulfilled.

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

Task 1. Dissemination of the network results

The Microkelvin web page is in operation now for external and internal users. Microkelvin partners present their results on the Intranet web and on the official web page of Microkelvin (see www.microkelvin.eu folder Publications). Results are also presented and discussed in detail in workshops and meetings which have been organized by the Microkelvin Collaboration or with Microkelvin as a partner in the organization (see below). These meetings are open also to external participants. Usually some speakers are invited from outside the Collaboration to describe closely related work or other new developments. Task 1 is running continuously.

Task 2. Dissemination of low temperature technology

Dissemination of low temperature technology and low temperature "know-how" between partners and users is realised as a part of the Transnational Access (TA) Programme. Altogether 18 project were accepted within TA1, TA2 and TA3 activities, since Microkelvin started. In particular, the efforts to open the μK temperature regime to the study of nano-structured samples (Task 1 in JRA1, with access provided especially via TA3) and to combine pulse-tube precooled dilution refrigeration with adiabatic nuclear demagnetization cooling (Task 2 in JRA1, with access provided by especially through TA1 and TA2) are outstanding examples of low temperature "know-how" dissemination. Task 2 is running continuously.

Work on establishing a CryoTools data base has been started. The organization and the working strategy have been fixed and material for the data base is continuously collected. An example is the text book "Experimental principles and methods below 1 K" by O.V. Lounasmaa which has been made available in pdf form on the Microkelvin web site (after permission from the Elsevier Publishing House and the Lounasmaa family).

Deliverable 1: Opening of CryoTools data base and e-mail list of laboratories and industries (8 mo) **partially delivered**

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:

1) *Microkelvin Kick-off meeting*, 3 April, 2009, Espoo

2) *Physics and Metrology at Very Low Temperatures,*
PTB Berlin, Germany (Helmholtz Zentrum Berlin), 10 December, 2009

3) International Workshop on *Vortices, Superfluid Dynamics, and Quantum Turbulence,*
Lammi Biological Station, Helsinki University, Lammi, Finland, 11-16 April, 2010
workshop of 4 ½ days with 75 participants
Proceedings of this meeting are published in *Journal of Low Temperature Physics* (Springer) **161**, No. 5/6 (2010)

4) *Microkelvin JRA2 Kick-off Meeting*,
in connection with the International Workshop on *Physics of Micro and Nano-Scale Systems,*
Ystad, Sweden, 20-24 June, 2010

5) The *International Symposium on Quantum Fluids and Solids*, QFS2010, 1-7 August, 2010, Grenoble, was organised by the Microkelvin core laboratory CNRS in Grenoble. Microkelvin organized the participation of a number of scientists in the conference: 6 from Russia, 8 from Ukraine, 2 from India, one from Brazil, and one from Argentina. In addition Microkelvin participated in organizing the participation of the Nobel Prize winner Wolfgang Ketterle (MIT, USA) in the conference.

6) *Microkelvin Review and User Meeting*, 14 – 16 October, 2010, Espoo
Two-day meeting with 25 participants from outside the AU host institution

To achieve better efficiency in the management of the Microkelvin Collaboration two management meetings were organized on financial procedures and one on general organizational questions:

7) *Microkelvin Workshop on the Management of EU integrating activities*, 14-15 May, 2009, Espoo

8) *Lancaster Workshop on the Management of FP7 Projects*, 30 November, 2009, Lancaster

9) E-mail meeting of the General Assembly, on the vote about where to place a Microkelvin sponsored cryogen-free dilution refrigerator, to be ordered from Bluefors, 20 Oct, 2009

10) *Microkelvin Management Meeting*, in connection of QFS 2010 Conference, 1 Aug, 2010, Grenoble

Two workshops are currently in preparation:

11) A Microkelvin workshop on JRA4 activities and technology transfer will be organized by C. Enss. The meeting will take place Nov 5, 2010, at the Kirchhoff-Institut für Physik, Universität Heidelberg, http://www.kip.uni-heidelberg.de/index.php?lang=en

12) A Microkelvin workshop will be organized by P. Skyba in the spring of 2011 in Slovakia. The topics will be decided during the next few months

Deliverable 2: LT workshop for all partners with proceedings (18 mo) **delivered**

Task 4. Industry - research network

A plan of action was set up to contact individual industrial partners on the national level, to be performed by each partner of the Microkelvin Collaboration with the aim to create an E-mail list of interested industrial companies and organizations. The list is not yet complete, but much of the information has already been collected. Task 4 is performed continuously.

Task 5. Dissemination to public audiences

Results 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 *invited talks*:

S. N. Fisher et al.
Experiments on Quantum Vortices in Superfluid 3He-B in the $T \rightarrow 0$ limit,
QFS 2010, Grenoble, France

V. B. Eltsov et al.
Dissipation in Vortex Dynamics in Superfluid 3He-B at Low Temperatures,
QFS 2010, Grenoble, France

R. P. Haley et al.
Branes, strings, and boojums; defects in 3He and the Cosmos,
QFS 2010, Grenoble, France

G.E. Volovik,
Bose-Einstein condensation of non-equilibrium particles, quasiparticles of 3He, and beyond,
QFS 2010, Grenoble, France

P. Skyba et al.
Bose-Einstein condensation of magnons in superfluid 3He-B and symmetry breaking fields,
QFS 2010, Grenoble, France

C. Enss et al.
Non-equilibrium quantum systems – glasses at ultra-low temperatures,
QFS 2010, Grenoble, France

A. Casey et al.
NMR measurements of the Deformed Superfluid 3He-B Confined in a Single 0.6 Micron Slab,
QFS 2010, Grenoble, France.

P. Skyba et al.
Bose-Einstein condensation of Magnons in Superfluid 3He.
18. Conference of Slovak Physicists, Banská Bystrica, 6-9 September, 2010

E. Krotschek et al.
Two-dimensional 3He: a crucial system for understanding fermion dynamics,

QFS 2010, Grenoble, France

H. Godfrin
Observation of a roton-like collective mode in a Fermi liquid beyond the particle-hole band using inelastic neutron scattering
JDN18, Rencontres Rossat-Mignod, Rémuzat, France, 8 – 10 June 2010

H. Godfrin
Elementary excitations in liquid 3He in two and three dimensions,
Workshop on "Structural and dynamic properties of QFS studied by neutron and X-ray scattering", Institut Laue-Langevin, Grenoble, 7 August, 2010

H. Godfrin
L'Helium-3 liquide bidimensionnel: un liquide de Fermi fait pour intriguer les physiciens!
Collège de France, Paris, 26 April, 2010

S.N. Fisher: PSM2010, International Symposium on Physics of New Quantum Phases in Superclean Materials, invited talk on *"Experiments on a pure superfluid condensate: 3He at ultralow temperatures",* Yokohama, Japan, 9-12 March, 2010

A. Kirste et al.: *Development of a SQUID Susceptometer for Application at Ultralow Temperatures,* talk at Conference on "Kryoelektronische Bauelemente 2009", Oberhof, Germany, October 4-6, 2009.

D. Drung et al.: *Investigation of low-frequency excess flux noise in dc SQUIDs at mK temperatures,* talk at ASC 2010, Washington, 1-6 Aug, 2010; also submitted to IEEE Trans. Superconductivity

M. Meschke, et al.: *Comparison of Coulomb Blockade Thermometers with the International Temperature Scale PLTS-2000,* to be published in Int. J. Thermophys. 2010

Th. Schurig: *SQUIDs – Kalte Spürnasen für kleinste Magnetfelder;* public talk on Open Day „Helmholtz' Erben" at PTB Berlin, 25 September, 2010

The Low Temperature Laboratory in Kosice participated in the Researcher's Night in Europe, a European-wide project supported by European Commission, taking place on 24 September, 2010, in Kosice: www.sovva.sk/noc-vyskumnika-2010/kosice.html (in Slovak)

P. Skyba
One of the Coldest Places in the Universe
public lecture on Researcher's Night, 24 September, 2010, Kosice

Traditional ways of dissemination to public audience are Open days, which all partners regularly provide according to the schedule of their own organization.

Highlights

- The Microkelvin web page (http://www.microkelvin.eu) is in full operation for external and internal users, providing up to date information about projects, events, publications, etc.
- Four scientific workshops and many management meetings were organized during the reporting period
- Work on the CryoTools data base together with E-mail lists of laboratories and industries is in progress

- Dissemination of the low temperature “know-how” through the TA activities, many invited and contributed talks and public lectures, etc.

Reports

- Proceedings of the International Workshop on *Vortices, Superfluid Dynamics, and Quantum Turbulence,* Lammi, Finland, 11-16 April, 2010*,* in *Journal of Low Temperature Physics* (Springer) **161**, No. 5/6 (2010)

Deviations from work plan

- *The second meeting of the Dissemination Committee was postponed (owing to the late start in the distribution of contract funds), but this had little effect on the NA3 activities in the long run.*

Use of resources

- *Use of resources follows the work plan.*

NA4 Report #2

Name of the activity (work package): **Strengthening European low temperature research**
Reporting Period: **from 1.4.2009 to 30.9.2010**
Activity leader: **Henri Godfrin**

Table of expected deliverables on the reporting period

Del. no.	Deliverable name	WP no.	Lead beneficiary	Estimated person months	Nature	Dissemination level	Delivery date
D1	Invitations to leading scientists and young researchers of Third Countries to MICROKELVIN meetings	NA4	CNRS		O	PU	12 **achieved**

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**
M1	Meeting for the creation of ECS	NA4	CNRS	10	**achieved**
M2	Formal creation of Third-Countries Associated Low Temperature Network	NA4	CNRS	10	**achieved**

Summary

This networking activity aims "to strengthen the European low temperature research, in coordination with national (Institut Français du Froid, *etc.*) and international (International Institute of Refrigeration, IUPAP-C5, *etc.*) 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)

Considerable effort has been invested in creating a formal organizational structure among European physicists and engineers in low temperature physics and cryogenics. In the end this was achieved by forming a Low Temperature Section within the European Physical Society. This plan was initiated and drafted by the Microkelvin Collaboration and was then accepted by the EPS Condensed Matter Division on 18 September, 2009. In January, 2010, it was also approved by the EPS Board. A copy of the Statutes of this Section comes attached. The initial measures (see below) describe the responsibilities of the Microkelvin Collaboration in the organization of the new EPS Section.

The members of the board of the EPS LT Section are:

Henri Godfrin	Chairman Institut Néel, CNRS/UJF, BP 166, 38042 Grenoble cedex 09, France henri.godfrin@grenoble.cnrs.fr
Tjerk Oosterkamp	Leiden Institute of Physics, Leiden University, P.O. Box 9504 NL 2300 RA Leiden, Netherlands oosterkamp@physics.leidenuniv.nl
Mikko Paalanen	Aalto University, P.O. BOX 15100, 00076 AALTO, Finland paalanen@neuro.hut.fi
George Pickett	Lancaster University, Department of Physics Lancaster. LA1 4YW, UK g.pickett@lancaster.ac.uk
Wilfried Schoepe	Secretary Fachbereich Physik, Universität Regensburg, D-93040 Regensburg wilfried.schoepe@physik.uni-regensburg.de
Thomas Schurig	Department of Cryo- and Vacuum Physics, Physikalisch-Technische Bundesanstalt, Abbestrasse 2-12, D-10587 Berlin, Germany Thomas.Schurig@ptb.de

Except for W. Schoepe (professor emeritus), all are representatives of the Microkelvin partner institutions. This is not surprising, given that Microkelvin is the driving force in extablishing this new European professional platform.

Milestone 1: Meeting for the creation of the European Cryogenic Society (10) **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 first 18-month period many distinguished researchers have been invited to participate in Microkelvin activities.

- The workshop on "Vortices, Superfluid Dynamics, and Quantum Turbulence" in April at Lammi, which was paid to 70 % by MicroKelvin Networking activities, included one participant from Third World Countries, namely professor Menouar Hanafi from the University of Oran, Algeria.
- The Conference QFS2010, organized by CNRS in Grenoble, included as Microkelvin guests the Nobel Prize winner Wolfgang Ketterle (German, presently in the USA), Victor Efimov,

Murat Tagirov, Ilya Polishchuck, Lev Melnikovsky, Luiza Kondaurova, Sergey Nemirovskii from Russia, Tatiana Antsygina, Konstantin Chishko, Nina Krainyukova, Konstyantyn Nemchenko, Marina Poltavskaya, Grygorii Sheshin, Anatolii Karasevskii and Andrij Rovenchak from Ukraine, Vanderlei Bagnato from Brazil, Susana Hernandez from Argentina, plus Gulshan Malik and Lalit Kumar Saini from India.

This EU-3C-Microkelvin network is thus in operation and contributing to the visibility of European science.

Milestone 2: Formal creation of Third Countries Associated Low Temperature Network (10) **achieved**

Deliverable 1: Invitation of scientist and young researchers of Third Countries to Microkelvin meetings (12) **delivered**

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

Preliminary actions have been started towards the creation of a Euro-Laboratory of low temperatures. The CNRS "Institut de Physique" (Physics department of CNRS on the national level) has expressed interest as a first step, to create an official structure, a "Laboratoire Européen Associé", consisting of the Microkelvin team at the Institut Néel in Grenoble and a second group in Paris, the Low Temperature Laboratory of the Aalto University, and the Microkelvin Laboratory of the Lancaster University.

Task 4. Forecast report (ULANC and all partners)

This action is in progress, considering that the milestone (report) is due towards the end of the Project. A list of laboratories and available instrumentation has been initiated.

Highlights

- *Creation of the EPS Low Temperature Section*
- *Participation of the Nobel Prize winner Wolfgang Ketterle to a Microkelvin event*

Reports:

- *statutes of the LT section of EPS*
- *newsletters have been posted on the Microkelvin Web site*

Deviations from work plan

- *none - results have been achieved ahead of schedule*

Use of resources

- *the use of resources follows the planned programme*

Statutes of the Low Temperature Section of EPS Condensed Matter Division

Article 1 – Scope

The Low Temperature Section of the Condensed Matter Division (hereafter "the Section") represents and provides a forum for European scientists interested in the physics of condensed matter in the very low temperature limit.

Article 2 - Tasks

In accordance with the Statutes of the Condensed Matter Division, the tasks of the Section are, *inter alia*:

- to support the Condensed Matter Division in carrying out the tasks specified by Article 2 of the Condensed Matter Division Statutes, within the field of Low Temperature physics;

- to promote the support and co-ordination of research activities in condensed matter and related fields, requiring very low temperatures;

- to facilitate contacts with and between its members, in particular through the organisation and co-ordination of meetings, workshops, schools, etc.;

- to facilitate the realisation in Europe of international conferences in the field of low temperature;

- to help in the training of young researchers and in the development of their abilities in ways which may facilitate their professional future life;

- to co-operate with other sections of the Condensed Matter Division, sections of other Divisions, and European organisations or enterprises, in any common field of interest;

- to offer expertise and advice to other bodies of the European Physical Society, and to other European institutions and enterprises, in the field of condensed matter at low temperature;

- to promote the public understanding and appreciation of low temperature physics.

Article 3 - Membership

Membership of the Section is open to any member of the Condensed Matter Division interested in the field of Condensed Matter at low temperature, in agreement with Article 7 of the Statutes of the Condensed Matter Division. Members are accepted upon personal application. Non-members of the European Physical Society, the Condensed Matter Division, or its Low Temperature Section, may participate in the scientific activities of the Section, about which they receive information upon request.

Article 4 - Structure

The Section consists of Members interested more particularly in the low temperature aspects of Condensed Matter. The business of the Section is carried out by the Section Committee, in accordance with Article 7 of the Statutes of the Condensed Matter Division. The Section may organise groups covering specific areas of low temperatures, or responsible for specific tasks.

Article 5 - Section Committee

In accordance with Article 7 of the Statutes of the Condensed Matter Division, the Section will elect a Committee of six amongst its members; the Committee will contain a Chairperson, a Secretary and other officers; the Chairperson or the Secretary will represent the Section on the Divisional Board. The Chairperson is appointed by the Committee and the Secretary is elected among the Section members. The normal term of election is 4 years; no one will normally serve on the Committee for more that two successive terms.
The Committee normally contains 2 members from large low temperature laboratories, 3 members from small research groups, and at least 1 member related to technical or industrial research.

Article 5 - Elections

Elections to replace 3 retiring elected Committee members will be held every two years, either by mail or during a General Assembly of the Condensed Matter Division. Only members of the Section are electors or eligible in the election of Committee members. In preparing the list of nominees, the Committee will consult the Section members.

Article 6 - Meetings

At appropriate time intervals, the Section will organise in Europe a Conference on Low Temperature Physics, and support related activities, such as European specialised workshops and schools.

Article 7 - General Assembly

A general Assembly of the Section will be held every 4 years, preferably during a General Conference of the Condensed Matter Division.

Article 8 – The Statutes

The Statutes of the Section may be revised by a 2/3 majority of the Committee.

Annex 1 - Initial measures

1) The present Provisional Statutes are submitted to the Condensed Matter Division of the European Physical Society by the European low temperature collaboration MICROKELVIN, with the objective of achieving sustainable networking of the European low temperature community.

2) A provisional Committee will be formed; a list of 6 members nominated by the MICROKELVIN collaboration will be submitted to the Condensed Matter Division Board for approval. The provisional Committee members will be members of the European Physical Society and its Condensed Matter Division.

3) The provisional Committee will consult the Condensed Matter Division members and the European Low Temperature Community, establish a list of scientists active in the field, foster the adhesion of new members to the Low Temperature Section, and organize the

election of the Committee within 2 years after the approval of the Provisional Statutes by the Board.

During the transition period, the business of the Low Temperature Section will be carried out in liaison with the Board of the Condensed Matter Division.

JRA1 Report #1

Name of the activity (work package): **Opening the microkelvin regime to nanoscience**
Reporting Period: **from 1.4. 2009 to 30.9. 2010**
Activity leader: **George Pickett**

**Table of expected deliverables on the reporting period - ** *None*

Table of expected milestones on the reporting period

List and schedule of milestones					
Milestone number	**Milestone name**	**WPs no's**	**Lead benefici ary**	**Delivery date From Annex I**	**Comments**
M1	Advanced filtering and isolation system designed and built	JRA1, Task 1	ULANC	18	**achieved**
M5	Pulsed-tube based dilution refrigerator and nuclear cooling stage ready for integration at CNRS/AU	JRA1, Task 2	CNRS AU	12 18	**partially achieved/exceeded** **partially achieved/exceeded**
M7	Complete the vibration isolation platform	JRA1, Task 3	ULANC	6	**achieved**

Summary

The goal of the JRA1 work package is to open the microkelvin temperature regime to nanoscience experiments by introducing new filtering and thermalization metods and by improving existing refrigeration practices. In particular, cryogen-free dilution refrigeration with pulse-tube precooling and fully automated operation is combined with adiabatic nuclear demagnetization cooling for the first time. The new refrigeration apparatus is constructed to improve simultaneously the infrastructure at the three access-giving facilities (AU, CNRS, and ULANC).

Task 1. New facilitating technology for nanoscience at microkelvin temperatures (ULANC, BASEL, SAS, AU, and CNRS)

The goal of the Basel activities within JRA1 is to open the microkelvin temperature regime to nanostructured samples; first in a nuclear cooling stage precooled by a conventional dilution refrigerator (JRA1, Task 1), and later in a compact, cryogen-free 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). Below is a summary of the progress made over the past several months.

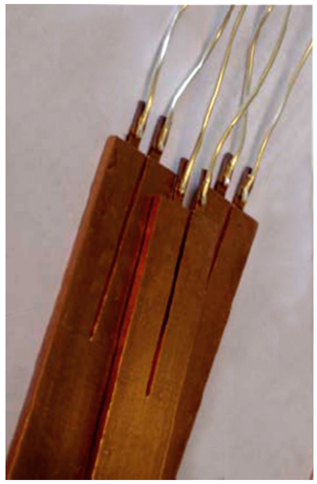


Fig. 1. The BASEL input lead refrigerant system which reaches 1 mK. ***Left****; the individual Cu plates for each incoming lead and* ***right****; the full set of leads bundled and thermally isolated around the central sacrificial plate.*

The primary strategy pursued to obtain microkelvin temperatures in nanosamples (for example GaAs 2D-electron gases, quantum dots, graphene and carbon nanotube samples, in fact any nanosamples with electrical leads) is to cool each of the electrical leads connected to the nanosample with its own, individual small nuclear adiabatic demagnetization stage, requiring about 12 - 16 nuclear demagnetization stages to operate in parallel. Over the past several months, we have designed, built, completed and are now testing and improving a prototype incorporating this strategy, installed on a conventional dilution refrigerator setup. The main components (for each electrical lead) are:

- thermocoax and silver epoxy microwave filters and thermalizers (JRA2),
- sintered silver heat exchangers in mixing chamber with leak-tight feedhroughs (JRA2),
- superconducting Al-Ag heat switch,
- high conductivity (RRR ~ 1,000, annealed) Ag leads, ~1 mm diameter,
- high conductivity Cu pieces (RRR ~ 300, annealed), about 20 x 2 x 80 mm,
- high conductivity spot-welded joints between all connections below the mixing chamber,
- stycast 2850 sample holder, allowing Au wirebonds from the incoming Ag leads to the sample.

Further, the setup requires the following components (not on each lead, only one installed):

- CMN thermometer thermally coupled to mixing chamber,
- LCMN thermometer on one of the Cu pieces,
- Pt NMR thermometer coupled to one of the Cu pieces,
- Coulomb Blockade GaAs quantum dot thermometer (JRA4).

A significant amount of work went into the development and assembly of all these components. We have recently demonstrated the cooling of the Cu pieces in parallel to 1 mK, starting from 13 mK, which is about to appear in a publication [1]. We are now working to achieve sub-mK temperatures, first in the Cu pieces themselves (next 6-12 months), and then in a quantum dot (or other on-chip) thermometer (12-24 months) or other nanostructured sample.

The Microkelvin consortium has recently decided to assign Basel and Bluefors the task of designing, constructing, and testing a compact, cryogen-free dilution refrigerator to serve as a platform for a nuclear demagnetization stage aimed at cooling nanosamples to microkelvin temperatures. We are currently designing, together with Bluefors, the dilution refrigerator. Several aspects of the design of the refrigerator as well as the rather complicated two-stage high-field superconducting magnet now have a complete design and construction of the instrument has begun. We expect completion of the refrigerator system in the first few months of 2011. We will use our experience from building this type of demagnetization stage on the design of a large conventional dilution refrigerator (Task 3), and will work towards minimizing the vibrations caused by the pulsed tube.

Milestone 1 : Advanced filtering and isolation system designed and built (18 mo) **achieved**

Task 2. **Compact microkelvin refrigerator**
(CNRS, AU, ULANC, RHUL, BASEL, BLUEFORS, and UL**)**

This task aims to make low millikelvin and microkelvin experiments accessible to any laboratory whether it has the infrastructure for dealing with liquid nitrogen and helium refrigerants or not. To this aim, we are developing a common concept for nuclear adiabatic demagnetization cooling in an apparatus with a pulse-tube precooled dilution refrigerator, using principally the experience of CNRS, AU, and BlueFors. Two parallel designs of the cryogen-free dilution refrigerator have been constructed within JRA1, one in Grenoble (CNRS) and one in Helsinki (BlueFors, AU). These are similar in principle, but in their practical details they experiment with different approaches.

Compact μK-refrigerator in Grenoble (CNRS)

In Grenoble, progress is as follows:

A pulse-tube based dilution unit has been built, fully installed (including pumping systems, anti-vibration isolation, measuring electronics, and digital data collection) and tested (leak testing, cooling tests). The refrigerator reaches 25 mK with a simple counterflow heat exchanger at a flow rate of 150 micromoles/sec. With a silver sinter heat exchanger stack it will reach 8.5 mK. Its operation is stable, reproducible, and the refrigerator maintains the base temperature for weeks without oscillating and without any frozen gas plugs in the low-temperature recirculation tubing. Several cool-downs have been performed with exactly the same results. Cooling power measurements have been performed; the results agree with the expected performance.

The milestone to run a demonstration nuclear stage in the machine by 12 months has been overtaken by the excellent progress of the BASEL group in getting their cooled-lead nuclear stage running sooner than expected. This will allow both cryogen free machines to incorporate such advanced nuclear stages sooner by skipping the demonstration stage.

Milestone 5 : Pulse-tube precooled dilution refrigerator and miniature nuclear cooling stage (12 mo) **partially achieved/ exceeded**

The pulse-tube precooled dilution refrigerator is completed and tested, with a minimum temperature of 25 mK. Sintered silver heat exchangers will now be added to this refrigerator, to reduce its minimum temperature and to improve its cooling power below 100 mK. The construction of the nuclear cooling stage is starting.

Fig. 2. The Grenoble cryogen-free ^{3}He-^{4}He dilution refrigerator.

Compact μK refrigerator in Helsinki (BlueFors, AU)

BlueFors has been working on the design of the cryogen-free dilution refrigerator with an integrated superconducting magnet system consisting of an 9 Tesla magnet for adiabatic demagnetization cooling and a second independent 9 Tesla magnet for the sample space. Originally the plan called for a standard 50 mm bore 9 Tesla demagnetization magnet. However, it was later agreed that besides cooling nanosamples to millikelvin temperatures it would be advantageous to be able to simultaneously apply a magnetic field (of order 9 Tesla) in the sample space. This implied a much more complicated magnet with a double set of current leads. Currently the magnet design is ready and the integration/interfacing with the cryogen-free dilution refrigerator system is under design.

BlueFors has developed and tested easily demountable high-temperature superconductor (HTS) current leads for the integrated magnet system. The copper section of the current leads between room temperature and the 60 K flange must be capable of carrying ca. 5.5 W of heat which must be transferred to the 60 K flange while maintaining electrical isolation. This has been achieved with a Kapton heat exchanger. The HTS leads between the 60 K and 4 K flanges must remain at below 64 K under all operating conditions. The lead itself and its demountable contact must be able to transfer ca. 0.2 W of heat from the 4 K flange, while maintaining electrical insulation. This has also been achieved using a Kapton heat exchanger.

The control and gas handling system of the cryostat has been assembled. Various details of the experimental flanges (mounting patterns etc.) and the layout of the mixing chamber with a central access port are being decided and designed. We anticipate that the pulse-tube precooled dilution refrigerator (with reinforced support structures) will become operational in late 2010 or early 2011.

As with the CNRS machine, the milestone to run a demonstration nuclear stage in the machine by 12 months has been overtaken by the excellent progress of the BASEL group in getting their cooled-lead nuclear stage running sooner than expected. As noted above, BlueFors will supply a machine directly to BASEL as part of the MICROKELVIN collaboration which will then have the advanced BASEL stage incorporated sooner by skipping the demonstration stage.

Fig. 2. The BlueFors sub-10 mK dilution unit

The HTS current lead assembly has been tested up to 120 A, while the magnets have been designed for operating currents around 50 A. Most of the cryostat design has been finished. However, it turns out that the double magnet system will be heavy, about 80 kg. This is much more than the earlier anticipated 30 kg of a single 9 Tesla magnet. Therefore we are currently working on a sturdier cryostat support system that can safely hold the additional mass without increasing the heat leak to unacceptable values.

Since vibration isolation is most important in this application, BlueFors has further developed the mechanical isolation of the pulse tube cooler. Besides decoupling using copper braiding at the two low-temperature stages of the pulse-tube cooler, a spring-loaded bellows system has also been developed during JRA1 for mounting the pulse-tube cooler head. This additional damping decouples the cooler at the room temperature top flange from the rest of the system.

Milestone 5 : Construction of pulse-tube based dilution refrigerator and nuclear cooling stage ready at CNRS/BlueFors (12/18 mo) **partially achieved/ exceeded**

Completion of the mechanical construction of the cryostat system was delayed by the higher specification demands for the magnet system. The 18-month milestone will be fulfilled a few months late.

Task 3. Next-generation μK facility
(ULANC, SAS, AU, CNRS, BASEL, RHUL**)**

Using the combined knowledge and expertise generated in Tasks 1 and 2, an entirely new advanced μK refrigerator facility intended exclusively for condensed-matter and nanoscale experiments at mK- and μK temperatures is being designed and built at ULANC in a purpose-built 90

m^2 laboratory hall with 7 m clearance and a 3 m dewar pit dedicated to this project, supported by ~ 500 kEuros from the UK Science Research Investment Fund and from ULANC. This is a very large facility, approaching the largest size equipment which can be housed in a usually-sized physics department. The experimental hall and the 3 m deep pit are already completed.

The first task was to build a sophisticated vibration-isolation system to reduce vibrational heating. The floor of the experimental hall is isolated from the rest of the building with a gap filled with flexible material. The first task was the construction of the 50 ton concrete/lead block floating on air springs to isolate the cryostat from ground-borne vibrations. This is very effective and in any case sits on the already isolated floor. The completion of this major structure and its supporting air springs marks the first milestone (M7) at six months which was achieved. This part of the task was completed using ULANC's own expertise.

The next task is to build the large dilution refrigerator and associated external control and gas-handling systems. These are currently under construction. The massive 2x2 m top plate of the cryostat has been made. Other cryostat components are being machined; the liquid helium dewar is being purchased. This is the point where we are also beginning to see input from our other partners, specifically BASEL and SAS. The cryostat and the pumping system are conventional, if large, but the sophisticated part of the machine is the cold dilution-refrigerator unit itself. The construction of the heat exchangers has had input from SAS where the techniques have been further developed, after an initial technology transfer to Slovakia.

It is at this stage that ULANC will begin calling on the experience from Task 1 (and most specifically from BASEL) for details of the electrical isolation and filtering of leads to be installed in the refrigerator. We will rely on the Task 1 experience even more when we come to the design and construction of the nuclear cooling stage in the near future.

Milestone 7 :	Complete the vibration isolation platform (6 mo)	**achieved**
Milestone 8:	Dilution refrigerator built, installed and tested (24 mo)	**well in progress**

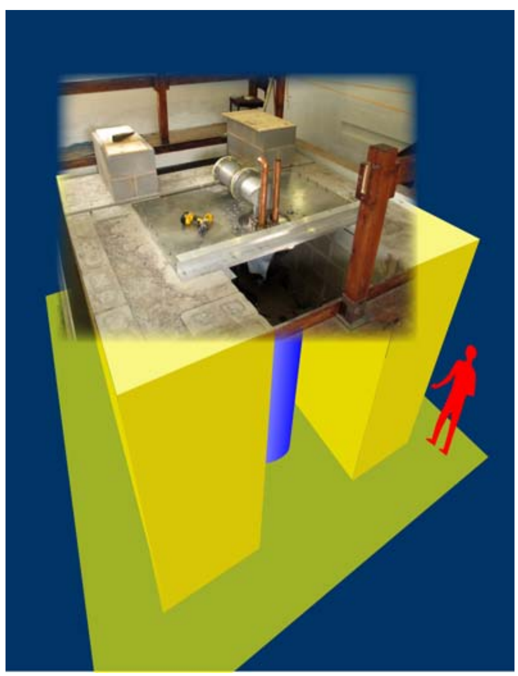


Fig. 3. The ULANC 50-tonne concrete/lead vibration isolation platform with dilution refrigerator just beginning installation.

Highlights

1. This period of the Work Plan for JRA1 is very much time of building and equipment development; highlights will come when the equipment is put to work. However, we can mention the very rapid progress of BASEL in Task 1, in achieving 1 millikelvin performance in a massively multiple nuclear stage. A publication [1] is currently in press (and will be of great value to Tasks 2 and 3).
2. We should note the commercial success of the BlueFors company whose prototype built under the auspices of MICROKELVIN, has now led to a commercial line with 10 sales already this year. In the current financial climate that is an excellent performance for a new company.

Publications

[1] *Method for Cooling Nanostructures to Microkelvin Temperatures,*
A.C.Clark, K.K. Schwarzwälder, T. Bandi, D. Maradan, D.M. Zumbühl,
Rev. Sci. Inst., to be published (preprint arXive: http://arxiv.org/abs/1005.4972).

Deviations from work plan - No changes in work plan.

Use of resources - No major changes in use of resources.

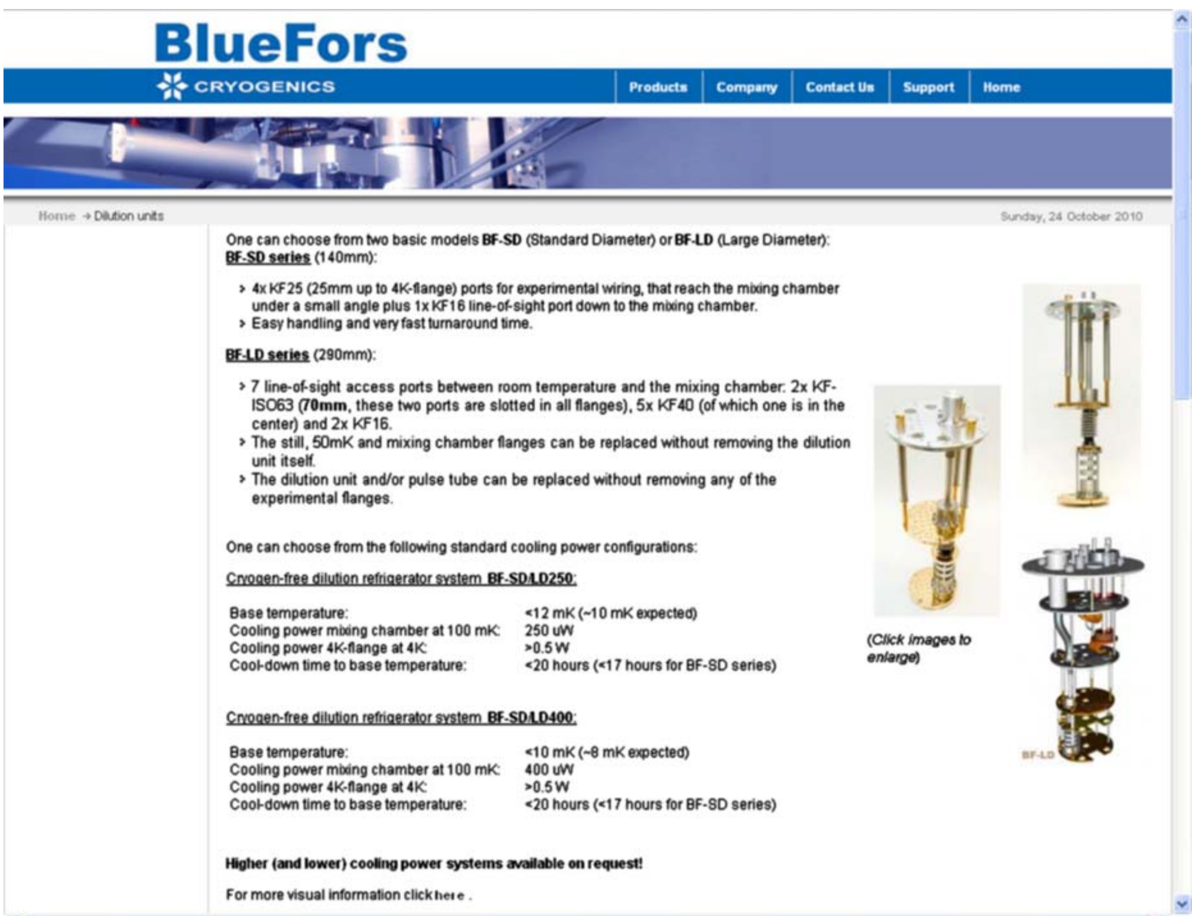


Fig. 4. The BlueFors webpage outlining their range of commercially available dilution refrigerators.

welcome to the European Microkelvin Collaboration

CAPACITIES

JRA2 Report #2

Name of the activity (work package): **Ultralow temperature nanorefrigerator**
Reporting Period: **from 1.4. 2009 to 30.9. 2010**
Activity leader: **Jukka Pekola**

Table of expected deliverables on the reporting period

D1	Analysis of the combined ex-chip and on-chip filter performance	JRA2 Task 1	AU	6	R	PU	18 **delivered***

*ex-chip filtering explained in Ref. [1] and on-chip filtering in Ref. [2].

Expected milestones on the reporting period

M1	Choice of thermalization strategy	JRA2, Task 1	BASEL	12	**achieved** tests completed
M2	Choice of ex-chip filtering technique	JRA2, Task 1	BASEL	18	**achieved** tests completed
M5	Design of membrane patterning and of microcoolers, based on calculations	JRA2, Task 3	AU	18	**achieved** design realized, Fig. 5

Summary

Introduction

The work package JRA2 started in March 2010 as a successor to the European "Nano-Fridge" project funded through the NanoSciERA call. The first meeting of the partners was organized June 24, 2010, in Ystad, Sweden, in connection with the international Workshop on the Physics of Micro- and Nano-Scale Systems. Collaboration within JRA2 is maintained with mutual visits and common experiments: Giovanna Tancredi from RHUL spent time at LTL of the Aalto University (AU), to fabricate Josephson junction samples on the membrane coolers; Coulomb blockade thermometers fabricated at Aalto are now investigated in the BASEL laboratory, and DELFT has investigated kinetic inductance detectors implemented on the cooler membranes provided by the AU group. A post-doc (Hung Nguyen) has been hired for two years to work on JRA2 projects; he spends his first year at CNRS and will then come for the second year to AU. The work within JRA2 is discussed in more detail below.

Task 1: Thermalizing electrons in nanorefrigerators (AU, CNRS, BASEL)

At AU we have investigated and developed on-chip filtering for nanodevices. Using small NIS tunnel junctions we could associate the sub-gap current with the quality of the filtering. In fact, we could develop a theoretical model which explains the experimental data and which is equivalent to ascribing a finite density of states (in the Dynes model) into the BCS density of states. We have found out that capacitive on-chip filtering, formed by a ground plane separated from the devices by an ALD-grown oxide layer, is very effective in filtering high-frequency noise [2]. In ongoing experiments we now test the influence of an on-chip RC transmission line as a filter. Typically, more than 40 dB suppression of high frequency (> 50 GHz) noise can be achieved by such on-chip filtering. We expect that combining on-chip filtering with ex-chip filtering (BASEL) can lead to excellent performance and very low electronic temperatures.

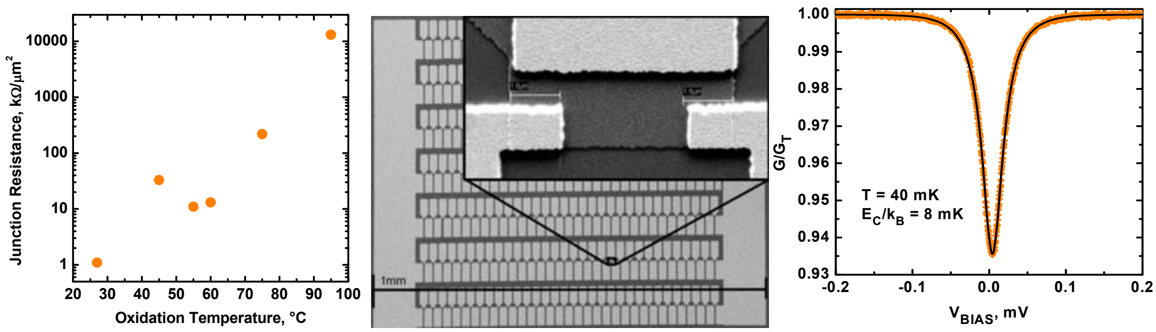


Fig. 1. A CBT sensor for low temperatures: ***(left)*** *Al-Ox junction resistance as a function of oxidation temperature using 100 mbar of oxygen for 30 minutes.* ***(middle)*** *SEM image of one CBT sensor with 7 parallel arrays of 64 junctions in series with attached cooling fins. The detail view shows two 1.6 µm x 1.2 µm junctions formed between the oxidized bottom layer (50 nm aluminium, dark gray) and the top layer (50 nm aluminium plus 300 nm copper).* ***(right)*** *Measurement of one sensor at 40 mK, which gives a charging energy of 8 mK.*

Coulomb blockade thermometers fabricated at AU have been measured in the filtered set-up of the BASEL group recently (see below). The sensor design is adapted for the temperature range below 10 mK using increased junction areas of about 2 µm² with a charging energy below 10 mK and sufficient cooling areas made out of thick copper. We used elevated temperatures while oxidising the tunnel barrier sufficiently heavily to get junction resistances of about 20 kΩ (Fig. 1). A high sensor resistance is important to limit Joule heating from the applied bias voltage.

The goal of the Basel activity in JRA2 (Task 1) is to develop and employ a strategy for thermalizing and filtering the electrical leads connected to nanostructured samples, with the aim of achieving microkelvin temperatures in nanosamples in a novel demagnetization refrigerator. Over the past months, we have developed a multi stage filtering and thermalizing strategy and started building and testing various filters and thermalizers, described below in more detail [1].

The first filtering stage consists of about 1.5 m of **thermocoaxial cable** mounted from room temperature down to the mixing chamber, heat sunk (outer conductor clamped / soldered) at several interim temperatures. Using our spectrum analyzer, we have characterized the attenuation properties of this type of cable from 10 MHz up to 50 GHz, finding an attenuation of more than 120 dB (the network analyzer noise floor) from frequencies above about 5 GHz up to 50 GHz. Thermocoaxial cables are known to give very high attenuations > 200 dB above ~10 GHz, until the frequency becomes so high that the wavelength is comparable with the diameter of the cable (~THz). At such frequencies the attenuation is reduced to about 130 dB.

As a second stage, to attenuate also lower frequencies down to a few MHz, we have developed, built, and tested **miniature silver-epoxy microwave filters**. A filter is fixed to each individual electrical lead (which allows rapid exchange of the filter element in case of damage) with easy to use MCX connectors. The filters come is the form of a cylinder of about 5 mm diameter and 25 mm length, with a MCX connector fixed to both ends. Starting from an initial filter design by G. Frossati (Leiden), these filters were further improved by a) using (conducting) silver epoxy, by b) heat sinking each filter to the mixing chamber using high conductivity copper braids, and by c) adding ~ 5 nF discoidal capacitors on both sides of the filter coil to further reduce the bandwidth. We make the filters by winding several meters of wire onto a premade silver epoxy former rod, while carefully employing some tricks to minimize stray capacitances between the windings of the wire. The measured attenuation reaches the noise floor at about 150 MHz (no capacitors) and at about 20 MHz (with capacitors), remaining below the noise floor in both cases up to 50 GHz. Cool-down tests to LN (77 K) and LHe temperatures (4.2K) were performed, indicating no significant degradation of filter attenuation performance. Should even lower cut-off frequencies be required, we are prepared to add another conventional discrete filter stage. Since several meters of insulated wire are embedded in the conducting silver epoxy which is cooled to the mixing chamber temperature, these filters act at the same time as quite effective thermalizers.

To further improve thermal contact, each wire connecting to the nanosample enters and leaves the (plastic) mixing chamber through a superleak-tight Stycast 2850 epoxy seal and is attached to a **sintered silver heat exchanger located in the 3He/4He mixture**. With the help from Lancaster, we have built and tested a silver sintering press. Using a home built BET equipment for surface area measurement, we have measured silver sinter surface areas of about 2 m^2/g of silver powder. These large surface areas are intended to overcome the significant Kapitza resistance between the 3He/4He mixture and the sintered silver. We are now in the process of evaluating the entire filtering and thermalization setup with measurements at low mK temperatures.

Recent measurements with a GaAs quantum dot Coulomb blockade thermometer (Fig. 2) (JRA4) and ongoing experiments with metallic/superconducting Coulomb blockade thermometers (in collaboration with Helsinki) indicate that our filtering strategy works well: 18 mK electron temperatures were measured with the GaAs quantum dot thermometer, while more recent tests with the CBT reached 11.5 mK (publications in preparation).

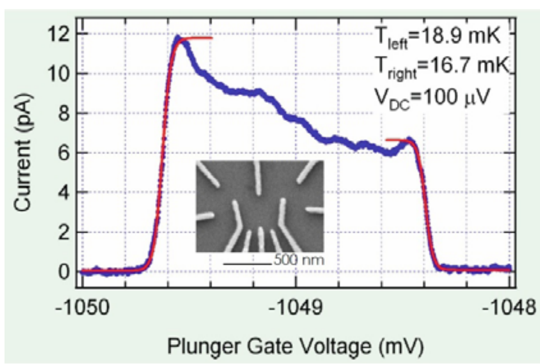


Fig. 2. Low temperature data of a GaAs CBT, with a SEM micrograph of a co-fabricated device.

Deliverable 1: Analysis of combined ex-chip and on-chip filter performance (18 mo) **delivered**

Milestone 1: Choice of the thermalization strategy
(sintered heat exchangers in mixing chamber) (12 mo) **achieved**

Milestone 2: Choice of the ex-chip filtering technique (18 mo) **achieved**

Both thermalization of electrical leads and ex-chip noise filtering have advanced well beyond the design milestones M1 and M2.

Task 2: Microkelvin nanocooler
(AU, CNRS, SNS)

The goal of the NEST activity in JRA2 (Task 2) is to develop an electron refrigerator based on quantum dots (QDs). This system will allow us, in suitable conditions, to cool an electron gas reservoir down to the µK regime starting from around 10 mK. Over the past months we have grown two-dimensional electron gas samples (2DEGs) based on the GaAs/AlGaAs materials system, and optimized the structure in terms of charge density as well as mobility. The optimized 2DEG was then used for the implementation of both quantum dots and the prototype cooler consisting of thermometers and refrigerators. In the following we will describe in some detail this work.

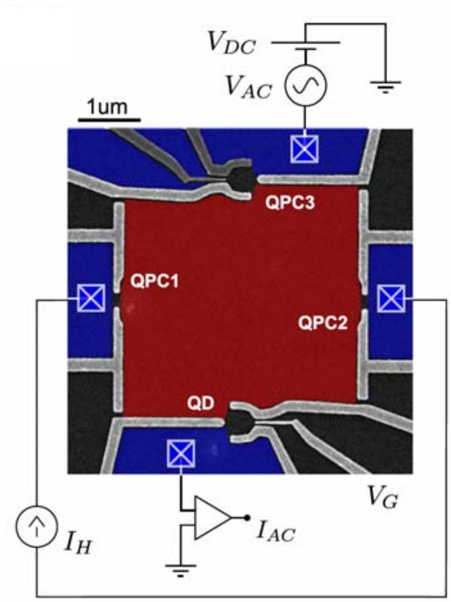


Fig. 3. The investigated semiconductor structure.

The semiconductor heterostructure consists of a GaAs/AlGaAs 2DEG grown with MBE methods. The 2DEG is confined 100 nm below the surface, and is characterized by a charge density $n_s = 2.26\times10^{11}$ cm^{-2} and mobility $\mu = 3.3\times10^6$ cm^2/Vs. Aluminum Schottky gates were patterned on the heterostructure with e-beam lithography, thermal evaporation, and subsequent lift-off in order to define a 16 µm^2 electronic domain which is connected to the outer portions of the 2DEG through two QDs and two quantum point contacts. All these structures are defined through electrostatic confinement by applying a negative voltage to the surface gates. The characterization of the entire system was carried out down to 250 mK in a ^{3}He refrigerator.

In the first stage of this activity we developed a method to accurately determine the electron temperature in the microdomain. This method is based on the analysis of the Coulomb-blockade (CB) shape of the QD peaks. To this end a theoretical model was developed in order to describe the CB lineshape when a finite temperature bias is applied across the QD. The quantum point contacts are used to heat the 2DEG microdomain by driving a dc current, while one of the QDs is operated as a thermometer to determine the temperature of the heated reservoir [3]. As a known heating power is delivered to the microdomain, the conductance across the QD is probed and the steady-state temperature detected. The microdomain temperature is thus determined from the zero-bias conductance shape of the Coulomb-blockade peaks. This procedure has made it possible to characterize the QD thermometer and to optimize this thermometry scheme, which we will later use in the final refrigeration device.

In the second stage of the activity we investigated heat relaxation mechanisms in the 2DEG microdomain in order to understand the main thermal properties of the system [3]. These will be of crucial importance when assembling the final refrigeration device. We have measured the electron temperature in the microdomain as a function of the heating power for different values of resistance of the quantum point contacts. As the coupling to the surrounding 2DEG regions is reduced, we observe a crossover from a regime where excess heat is carried away by hot quasiparticle tunnelling through the quantum point contacts to one where power exchange with lattice phonons dominates. In particular, we have demonstrated that in our heterostructure at low temperatures the latter mechanism follows the T^5 power law expected for the **screened electron-acoustic phonon piezo-electric** interaction. The strength of the electron phonon interaction constant in our GaAs 2DEG was determined to be ~11 $fW\mu m^{-2}K^{-5}$. To summarize, the determination of the electron-phonon coupling constant in the heterostructure as well as the development of an accurate thermometry scheme for the electron gas constitute the basis for the final realization and optimization of the quantum-dot refrigerator.

At AU we have tested coolers with Ti (T_c = 0.4 K) as the superconductor. The issue here is the formation of a high quality tunnel barrier, which comes essentially for free if one uses the standard material Al (T_c = 1.2 K) as the superconductor. In the case of Ti, we combine it with a normal metal that can be oxidized. Junctions between Ti and AlMn have the desired transport characteristics, and with a relatively small concentration of Mn (about 1%), the AlMn alloy remains in the normal state down to the lowest temperatures. However, the heat transport characteristics are not yet satisfactory: more work is needed to demonstrate cooling in these junctions.

Thermal relaxation in the superconductor is a critical issue in the NIS cooler. We have found out an interesting effect: cooling is optimized in magnetic fields perpendicular to the film, when the field is just a few gauss. The enhancement in the cooling power can be as large as 100% as compared to zero magnetic field. At fields exceeding a few gauss the cooling performance becomes independent of the magnetic field, until at fields of few hundred gauss the performance deteriorates again due to suppression of the superconducting gap. We are analyzing this effect now theoretically.

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

At CNRS, we have developed superconducting micro-coolers with a large junction area (Fig. 4). The fabrication process is based on two-step UV lithography and etch of a superconductor - insulator - normal metal multilayer. We have succeeded in obtaining a first device with a tunnel resistance of 6 Ohm. The low temperature characterization [4] has demonstrated a modest cooling effect of a few mK starting from a bath temperature of 300 mK. The small cooling effect can be related to the presence of a resist on the device and substrate or to the presence of pinholes in the junction. These tests will soon be reproduced with new sets of device with no resist, or based on epitaxial multi-layers, or a varying interface transparency. This will pave the way towards the integration of large cooling power micro-coolers on a membrane supporting a quantum device.

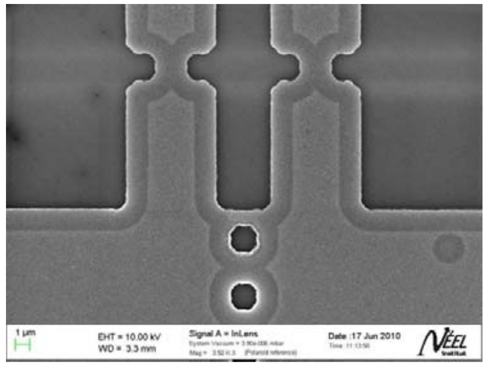


Fig. 4. Superconductor-Insulator-Normal metal multilayer patterned with UV lithography and ion beam etch to form a (horizontal) double tunnel junction cooler on which two additional junctions (on top) can be used as a thermometer The dark grey areas on the sample correspond to the Cu film freely hanging over the substrate, as the bottom Al layer has been overetched.

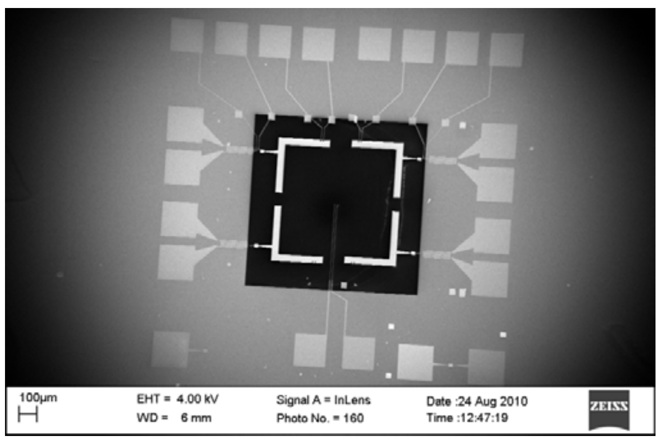


Fig. 5. SEM image of a membrane cooler. Cold fingers (made of Au) extend to the membrane from the cooling arrays (Al and Cu) located on the bulk of the chip. A SINIS thermometer is placed in the middle to measure the membrane temperature. Some extra diagnostics structures are placed at the top and bottom.

At AU we have designed an optimized membrane cooler 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) (Fig. 5). Thermal characteristics have been measured and they are similar to those reported in literature in the past. Successful first cooldowns have been performed although the cooling performance is still far inferior as compared to predictions. The current understanding is that the backflow of heat from the non-equilibrium superconducting secondary side of the cooler affects negatively the cooler performance.

Milestone 5: Design of membrane patterning and of microcoolers, based on heat and quasiparticle diffusion calculations (18 mo) **achieved**
The design was realized in Fig. 5 and also combined with a detector in Fig. 6, which is assigned as M6 at 24 months.

Application Groups (DELFT, RHUL)

DELFT and RHUL are the application groups. Their work has started. A post-doctoral researcher, Giovanna Tancredi from RHUL, has spent two months at AU preparing successfully superconducting tunnel junction samples on cooler membranes. These structures are planned to be tested at RHUL in 2011.

The goal of the Delft activities is to evaluate cooling of superconducting resonators using N-I-S nanorefrigeration (JRA2, D6). Through the kinetic inductance minimal changes of the superconducting condensate can be measured, as the resonators have high quality factors. Pair breaking processes can be detected in the form of irradiation or as thermal excitations. The aim is to integrate such a superconducting resonator with N-I-S coolers on a dielectric platform, to analyse the cooling performance and to characterize the thermal behaviour of the system.

For the fabrication of the superconducting resonators a 100 nm thick Al layer is sputter deposited on a 100 nm thick silicon-nitride membrane of 1x1 mm^2. The quarter-wave resonators are patterned by means of electron beam lithography (EBL) and a reactive ion chlorine etch. The NIS cooler arrays (Fig. 6) are fabricated at AU.

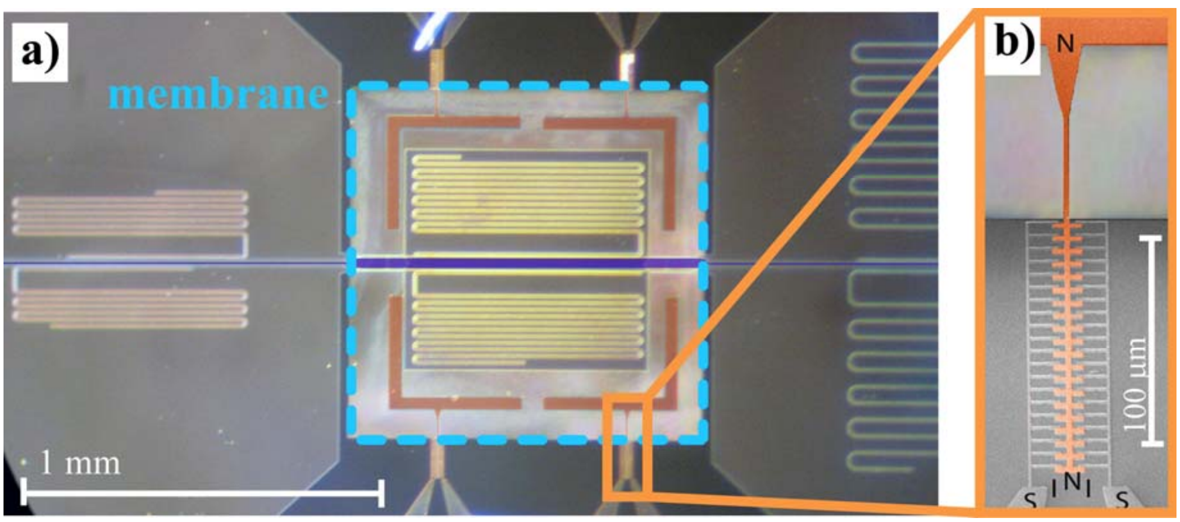


Fig. 6. Membrane equipped with two superconducting resonators. (a) Four L shaped cold fingers thermalize the membrane to cooler arrays, which are (b) on bulk silicon

The performance of the coolers is analyzed by measuring the temperature of the resonators versus the bias of the NIS coolers. We have measured unambiguous cooling of the resonator [5] at bath temperatures of 275, 312 and 350 mK, with a maximum cooling of 0.65 mK. Though the temperature difference is small, the effect on the resonator is clear. The sensitivity of the superconducting resonator as a thermometer appears to be as small as 5 microkelvin.

To quantify the thermal coupling to the environment we measured the relaxation time of the resonators on the dielectric membrane. Compared to relaxation times on bulk silicon they are an order of magnitude higher. The relaxation is no longer limited by the recombination of quasi-particles, but by the relaxation of the complete system. This means the resonators are well thermalized to the membrane.

Highlights

- Demonstration and modelling of the suppression of external noise with on-chip filtering
- Thermocoaxes tested and installed (filter)
- Miniature silver-epoxy filters built, tested and installed (filter and thermalizer)
- Sintered silver heat exchangers built, tested, and installed (mixing chamber, thermalizer)
- Cooled to 18 mK with GaAs quantum dot thermometer (publication in progress)
- Growth and characterization of low-density and high-mobility GaAs/AlGaAs two-dimensional electron gases
- Development of an accurate thermometry scheme based on QDs for the determination of the electron temperature in a 2DEG microdomain under out-of-equilibrium conditions
- Measurement of the electron-phonon coupling constant in GaAs/AlGaAs 2DEG
- Successful integration of different technologies (membrane, cooler, detector)
- Proof of cooling for a superconducting device on a membrane with N-I-S arrays
- Demonstration of the sensitivity of a superconducting resonator as thermometer
- Evaluation of the thermal coupling to the environment

Publications

[1] *Method for Cooling Nanostructures to Microkelvin Temperatures,*
A.C.Clark, K.K. Schwarzwälder, T. Bandi, D. Maradan, D.M. Zumbühl,
Rev. Sci. Inst., to be published (preprint arXive: http://arxiv.org/abs/1005.4972)

[2] *Environment-assisted tunneling as an origin of the Dynes density of states,*
J.P. Pekola, V.F. Maisi, S. Kafanov, N. Chekurov, A. Kemppinen, Yu.A. Pashkin, O.-P. Saira, M. Möttönen, and J.S. Tsai,
Phys. Rev. Lett. **105**, 026803 (2010)

[3] *Probing the local temperature of a 2DEG microdomain with a quantum dot: measurement of electron-phonon interaction,*
S. Gasparinetti, F. Deon, G. Biasiol, L. Sorba, F. Beltram, and F. Giazotto,
arXiv:1007.0172, submitted (2010)

[4] *Spatially correlated microstructure and superconductivity in polycrystalline boron-doped diamond,*
F. Dahlem, P. Achatz, O. A. Williams, D. Araujo, E. Bustarret, and H. Courtois, Phys. Rev. B **82**, 033306 (2010)

[5] *Electronic cooling of superconducting resonators,*
N. Vercruyssen, R. Barends, T. M. Klapwijk, J. Muhonen, M. Meschke, J. P. Pekola,
in preparation

Deviations from work plan

- no deviations

Use of resources

AU: A part-time senior researcher salary has been paid from the Microkelvin project. The participation of Microkelvin members in the Ystad workshop with the JRA2 kick-off meeting in June, 2010, was covered by the project.

BASEL: Since August 2009, a senior scientist is partly funded by Microkelvin, for JRA2 activities. Also since October 2009, a postdoctoral fellow is funded by Microkelvin, for work in JRA2.

CNRS: Since April 2010, a postdoctoral fellow working at CNRS is funded by Microkelvin, for work in JRA2.

SNS: Microkelvin funding was used partly for liquid helium. From the beginning of 2011 a postdoctoral fellow is planned to be fully funded from the Microkelvin project for work in JRA2.

DELFT: Microkelvin funding was used for liquid helium, clean room activities, and a PhD student.

welcome to the
European Microkelvin Collaboration
CAPACITIES

JRA3 Report #2

Name of the activity (work package): **Attacking fundamental physics questions by microkelvin condensed-matter experiments**
Reporting Period: **from 1.4. 2009 to 30.9. 2010**
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	Dissemination level	Delivery date
D1	Report on micro-fabricated silicon vibrating wires tested in superfluid 3He at 100 μK	JRA3 Task 5	CNRS	3	R	PU	12* **in progress**

* The early delivery date is now believed to be an accidental mistake (since it precedes milestone M12 at 30 months (Task 5 of JRA3) when the laboratory tests at 100 μK should be completed).

Expected milestones on the reporting period

Milestone number	Milestone name	WPs no's	Lead benefi-ciary	Delivery date From Annex I	Comments
M1	Determination of the energy released by a vortex tangle with known line density	JRA3, Task 1	ULANC	12	**achieved**
M2	Measurement of the dissipation when a vortex state is established	JRA3, Task 1	AU	24	**achieved**
M4	Identification of the topological defects left after brane annihilation	JRA3, Task 2	ULANC	24	measurements **in progress**
M6	Realization of Black-Hole analogue in rotating system with AB interface	JRA3, Task 3	AU	24	**delay discussed** change in plans
M9	Observation of the interaction between two independent precessing Q-balls	JRA3, Task 4	CNRS	30	**preliminary measurements done**
M12	Micro-fabricated silicon vibrating wires tested in 3He-B below 100 μK in above-ground laboratory	JRA3, Task 5	CNRS	30	**in preparation**

Summary

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

Introduction: The dynamics of quantized vortices in the low temperature limit is a topic which is attracting a great deal of interest. Of particular interest are the possible dissipation mechanisms of vortices in coherent quantum systems. Superfluids are model systems to study this. The knowledge gained may impact on the much broader topic of turbulence in general, as well as more exotic systems such as cosmic strings.

When the conventional mechanism for the damping of vortex motion, mutual friction dissipation, approaches zero one might expect that quantum fluids become ideal text-book-like systems with truly dissipationless flow, as the name superfluid would suggest. This is certainly the case for vortex free flow, and it is also true for laminar vortex flow [1], although it has not yet been firmly established whether laminar vortex flow can be generated experimentally in the zero temperature limit. In contrast, turbulent vortex flow has been found to display significant, temperature independent, dissipation in the zero temperature limit. This finding was made in superfluid ^{3}He-B by the ULANC and AU teams before the start of the Microkelvin Project. A central goal for current research is to understand the mechanism responsible for the turbulent dissipation.

In the turbulent flow of a viscous medium the kinetic energy must ultimately be dissipated as heat. In a Fermi superfluid such as ^{3}He-B at the very low temperatures, heat corresponds to thermal quasiparticle excitations. Hence, dissipation of vortices must result in the generation of quasiparticles out of the `vacuum state' of the superfluid condensate (in a similar way, cosmic strings must dissipate energy by generating other types of particles (gravitons) out of the vacuum). But the mechanisms responsible are not understood and experiments are needed to study this.

Our recent experiments address this. We have measured, for the first time, the energy dissipated by quantum turbulence in superfluid ^{3}He-B at very low temperatures. Experiments have been made by the ULANC and the AU teams, using very different techniques, which provide detailed quantitative measurements of the turbulent dissipation. In Lancaster the heating from the free decay of a vortex tangle has been measured as a function of time. The result can be compared directly with the standard model of decaying (classical) turbulence. In Helsinki the dissipation has been measured from steady state turbulence. It is generated when a vortex front moves axially in spiral motion along a rotating circular column, and thereby replaces vortex-free superfluid counterflow with the equilibrium vortex state. In this case, the measured heating can be compared directly to the kinetic energy of the vortex-free counterflow or the velocity of the turbulent front. The results from both of these measurements are currently being prepared for publication.

ULANC measurements: The experiments were performed using "black-body radiator" techniques to measure the dissipation (of order ~1 pW) produced by a decaying vortex tangle. The vortex tangle is generated with a vibrating grid or a vibrating wire inside a (black-body-radiator) box. The box has a pin hole through which it is in thermal contact with the bulk superfluid bath outside. The quasiparticle density in the box is determined as a function of time from the resonance frequency width of a vibrating wire resonator running at low excitation amplitude. It can be monitored after the motion of the generator has been stopped and the vortex tangle inside the box slowly decays. The results are compared to current theoretical predictions for classical turbulence of viscous fluids. In classical turbulence, energy is transferred from large to small length scales, via the so-called Richardson cascade, where the energy is finally dissipated by viscosity. This leads to a particular distribution of energy across the range of length scales, called the Kolmogorov spectrum. The results for both wire and grid generated turbulence agree quantitatively with the classical model, indicating that the same cascade mechanism and the same energy spectrum, at large length scales, must exist in quantum turbulence. This is quite remarkable given that there is no viscosity in a superfluid at these low temperatures.

These measurements are now planned to be extended to higher vortex densities and to more homogeneous quantum turbulence. To do this a new device has been developed for generating the turbulence, with the help of the transnational access activity. The device sweeps a grid (and other objects) through a superfluid at near-uniform velocities over distances of or order 10 mm. The device is versatile and can produce a wide range of velocities. Preliminary tests have been performed in superfluid ^{4}He in which velocities of up to 10 cm/s are achieved. Also a technique has been developed for accurately measuring the position and velocity of the device which allows to infer directly the drag force from the superfluid and hence the power dissipated into the fluid. Recently such a device has been installed in a Lancaster style nuclear cooling stage to measure the properties or near-uniform wire motion in superfluid ^{3}He-B. It will be used to investigate the pair-breaking critical velocity and dissipation for uniform motion, which may reveal analogies with quantum Hawking radiation and will probe Majorana surface states at the wire surface. Once the techniques have been sufficiently developed, one can apply them to sweep a grid uniformly through superfluid ^{3}He-B enclosed by a black-body radiator. This makes it possible to generate very intense homogenous turbulence to better study the energy dissipation processes and to further investigate the underlying process governing quantum turbulence.

AU measurements: These experiments are carried out in a rotating cryostat with the sample setup shown in Fig.1. The initial starting state is a long cylindrical sample which is rotated at constant velocity in the metastable vortex-free Landau (or Meissner) state. Here the superfluid component is not rotating while the normal component, the tenuous gas of quasiparticle excitations moving along ballistic flight paths, is locked to corotation with the container walls. Vortex formation is then locally triggered in a sudden burst. This starts a spirally precessing and axially propagating vortex motion along the cylinder [2]. In this way the cylinder is filled with the equilibrium number of vortices. The axially propagating vortex motion advances in the form of a front to which the turbulence is concentrated. Behind the front the motion becomes gradually laminar.

The distribution of counterflow and vortices is monitored with NMR techniques. In steady state motion the front velocity provides one measurement for the rate of dissipation. The velocity is determined from the measurement of the time it takes for the front to move from one detector coil to the other. A second measurement is obtained with the bolometer from the heating which is observed during the motion of the front and the subsequent laminar recovery [3]. The sensor for reading the quasiparticle density is a quartz tuning fork oscillator. A pair of them is used in the bolometer box through which the heat current from the vortex motion flows. One element is used as heater for calibration purposes, while the other is a temperature sensor. In this way the quasiparticle density in the bolometer box can be monitored as a function of time while the vortex front propagates and later while the helically twisted vortices unwind, and the vortex number and configuration adjust to that of the equilibrium vortex state at constant rotation.

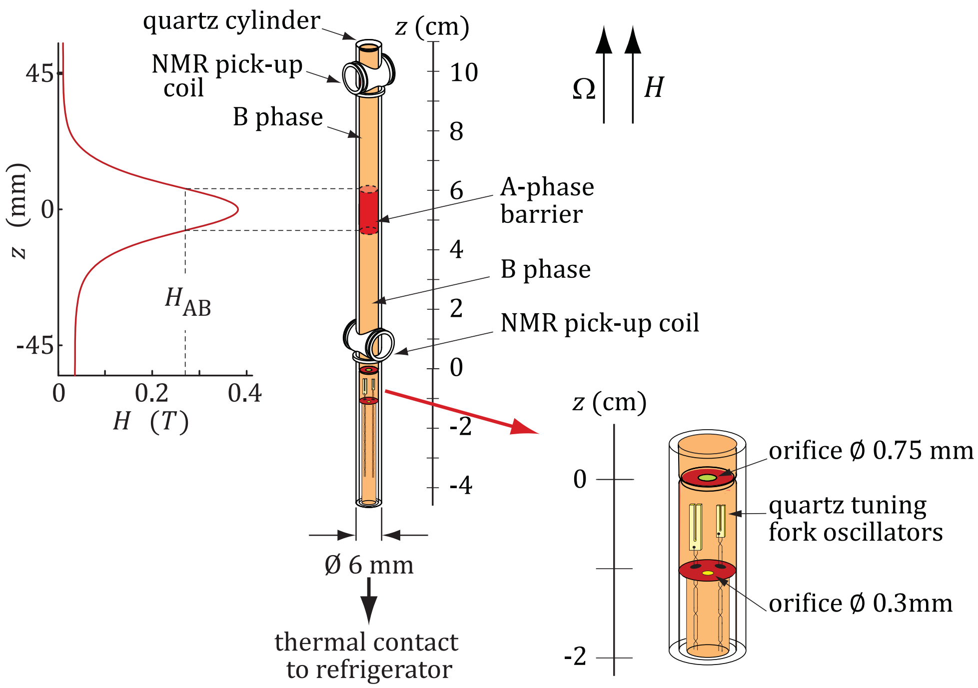


Fig. 1. Measuring setup in the AU experiments with a rotating cryostat. The top section above the upper orifice is the superfluid ^{3}He sample which is monitored with two independent NMR probes. The middle section between the two orifices is the bolometer box (shown in more detail on the right). The lower section below the lower orifice provides the thermal conduit to the sintered heat exchanger on the nuclear cooling stage. The diagramme on the left shows the axial distribution of the axially oriented magnetic fields. The magnetic field stabilized barrier layer of ^{3}He-A in the middle of the sample can be used to separate the sample in two independent shorter cylinders or for injecting seed vortices from the AB interface in vortex-free B-phase flow [2].

In the course of these measurements a new NMR technique [4] was studied which is more sensitive at temperatures below 0.2 T_c [5]. This method will be used next to measure the propagation velocity below 0.2 T_c over a longer distance of propagation than before, to improve the measuring accuracy. Also the cross section of the rotating column will be changed in the course of these measurements from circular to square. This will cause a change in the overall vortex flow properties of the container from laminar to turbulent.

General: The two measurements described above probe the dynamic properties of quantized vortices in the zero temperature limit, where mutual friction with the normal fluid (quasiparticles) is negligible. This is the appropriate limit for many other coherent quantum systems, such as large atom clouds of Bose-Einstein condensates, the interior of a rotating neutron star, and the elusive cosmic strings. In these systems, vortex flow is not influenced by bulk pinning, unlike the situation in most superconductors. Our two measurements of quasiparticle generation by vortex motion were performed with very different types of applied flow and measurement techniques. The results obtained are complementary and provide detailed information which can be compared to theoretical calculations and numerical simulations, to learn more about the intrinsic dissipation mechanisms of vortex motion.

Earlier Lancaster experiments on the generation and decay of a turbulent vortex tangle have been modelled with computer simulations in collaboration with the research group of Makoto Tsubota in Osaka City University. The earlier experiments were made by measuring the decay of the vortex line density, rather than the energy dissipation. Nevertheless, the simulations, published in Ref. [6], allow a direct comparison of several key properties of the generation and decay of turbulence. The simulations confirmed the previous interpretations of the experimental results and provide fresh insight into the dynamical mechanisms involved. Similarly, in Helsinki numerical calculations have been used to analyze the dynamics of the turbulent vortex front [3] and the response of the superfluid when rotation is suddenly stopped (spin-down) or when rotation is abruptly started (spin up) [1, 2]. These realistic simulations with advanced computing techniques provide a powerful tool for supplementing experiments and provide a very detailed picture of turbulent dynamics.

Milestone 1: Energy release from the decay of a vortex tangle (12 mo) **achieved**

Milestone 2: Dissipation from vortex motion in rotation spin up (24 mo) **achieved**
In both cases the final publication is under preparation

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

Introduction: The study of the superfluid phases, phase boundaries, and the various topological defects in the different phases of the ^{3}He superfluids is performed within this task. Traditionally this has been a physically most rewarding research area in superfluid ^{3}He work, owing to the rich possibilities of different novel structures within the orbital p-wave spin-triplet order parameter manifold plus the fact that there are practically no non-ideal features which would complicate this task. Two types of approaches are included within this task: (1) restricted nano-structured geometries at Royal Holloway – a regime which has so far not been investigated systematically anywhere – and (2) strongly non-equilibrium studies at Lancaster in the presence of configured inhomogeneous magnetic fields.

RHUL measurements: At Royal Holloway, superfluid ^{3}He confined in a restricted geometry, consisting of a 635 nm wide slab of liquid between two parallel plates, has been explored to test for the presence of new coherent pairing states. The silicon – glass parallel plate sample container with extreme smooth walls was fabricated at Cornell University and was studied using the sensitive SQUID NMR method developed at Royal Holloway [7]. The expected profound modification of the superfluid phase diagram, and the gap suppression due to confinement have been well characterised experimentally. This includes the *in situ* tuning of surface scattering from diffuse to specular surface scattering by ^{4}He pre-plating. The main results are as follows:

- T_c exhibits a pressure dependent suppression.
- The A phase is stabilized at all temperatures at zero pressure (providing evidence for strong coupling effects at $p = 0$ since the A phase and planar phase are degenerate in the weak coupling limit).
- The measured A-B transition deviates from weak coupling quasi-classical theory consistent with the effect of strong coupling corrections.
- Our estimate of the critical slab thickness below which the $T = 0$ ground state will be A phase at zero pressure is 900 nm.

- The influence of ^{4}He pre-plating, which provides a method of enhancing specular scattering *in situ* has been investigated. It slightly enhances the region of stability of the A phase, and significantly reduces T_c suppression.
- The influence of ^{4}He preplating on the A phase superfluid gap has been determined near T_c and in the low temperature limit; for diffuse walls the results are in good quantitative agreement with the gap suppression calculated by quasi-classical theory. We have shown that the gap suppression can be eliminated, consistent with specular walls, by ^{4}He preplating.

Above 4 bar we have investigated the B phase, which develops a strong planar distortion due to the walls which persists across the slab. It has proved possible to extensively characterize the spatial variation of the gap with NMR using small and large angle tipping pulses. In the B phase both a stable and a metastable state have been identified, with positive and negative shifts of the transverse NMR line, respectively. Although initially mysterious, discussion with G. Volovik (Helsinki partner) made clear that these originate from parallel and antiparallel alignments of the susceptibility anisotropy axis and the gap anisotropy axis (which only differ in energy because of the dipolar interaction). Support for this interpretation was provided by a series of studies involving magnetic field cycling. Our identification was confirmed by a non-linear NMR study which, following a generalisation of the standard theory of NMR response to inhomogeneous order parameters (in collaboration with Evgeny Surotsev, Kapitza Institute) has allowed the determination of two spatial averages of the order parameter matrix. These results can be compared to the predictions of quasi-classical theory. There was no evidence for the stability of the striped phase predicted theoretically. This strongly motivates a search for the striped phase at zero pressure, in a larger 1.2 to 1.5 μm wide slab.

Preliminary versions of some of these results have been published [8, 9], more complete accounts are now being prepared for submission. The present work paves the way for future experiments in a range of slab geometries with thickness in the range 0.8 to 1.5 μm, and controllable boundary scattering. 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. Experiments in controlled restricted geometries provide one avenue to investigate these phenomena, which are of generic significance.

ULANC measurements: We have built a new experimental setup dedicated to the study of A-B phase boundaries in superfluid ^{3}He at temperatures close to 0.10 T_c. The sample cell is formed as part of a Lancaster style nuclear cooling stage which can cool the superfluid to the lowest achievable temperatures, around 100 μK or less. The cell is much larger than previously used for these studies, requiring us to also upgrade the dilution refrigerator. The larger size allows us to incorporate more copper refrigerant to give longer cold-times at the lowest temperatures. Furthermore, it provides a larger experimental volume to allow more experimental devices and sensors. The added volume is particularly useful for studies of the phase boundaries, since it gives more versatility in manipulating the phase boundaries and their spatial profile. The new cell has several tuning forks and vibrating wire resonators which will operate in the vicinity of the phase boundaries, all encapsulated within a black-body radiator which will allow us to measure the dynamics of the phase boundaries. The increased sensitivity and spatial resolution should provide us with more detailed information on the defects created after brane (phase boundary) annihilation. The devices will also allow us to directly measure any vortex tangles generated by the annihilation. In addition, we will study thermal transport across the interface and phase nucleation phenomena. The new cell will also make it possible to study the interaction of quantum turbulence (vortex tangles) with phase boundaries. In this case, we can generate the turbulence with vibrating wire resonators or tuning forks.

The equipment has recently been installed on the refrigerator. Initial tests indicate that all the devices are working as planned, and the apparatus is currently being cooled. The first measurements at microkelvin temperatures will be made in the next few weeks. The first task will be the identification of the topological defects which are left behind in a sudden nonequilibrium event when two branes annihilate.

Milestone 4: Topological defects from brane annihilation (24) **exp running**

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

Simulation experiments on black hole dynamics are currently in progress in a few European laboratories with viscous fluids. To learn more about the quantum aspects it would be most useful to attempt measurements also with superfluids and other coherent quantum systems. We have a detailed plan how to do this with ^{3}He superfluids in the rotating cryostat.

The AU rotating cryostat has recently been used for quantum turbulence measurements (see Task 1 above). During the course of this work, where the thermal energy equivalent of the hydrodynamic kinetic energy was determined, residual heat leaks and the very-low-temperature operation of the cryostat have been substantially improved. These improvements have opened the temperature regime below 0.2 T_c for routine measurements. This is important for the black hole simulation experiments which will concentrate on the extreme low temperatures, in order to describe the pure quantum response.

The man power in this research group is 4 – 5 persons, on an average. This is not sufficient to run simultaneously black hole experiments and measurements on magnetic relaxation in Q-ball states (Task 4). The need for the latter work has become more urgent recently, owing to the interest in topological insulators and their surface states which have the Majorana character. Superfluid ^{3}He-B is one of the best candidates to search for Majorana surface states – if not the best. Magnetic relaxation in Q-ball states in different conditions under rotation are one possibility to investigate surface properties with great sensitivity in the $T \to 0$ limit. To answer to this demand, it has been suggested that the Q-ball measurements (M9 at month 30) should be moved forward in time and measurements on the black-hole dynamics (M6 at month 24) should be postponed to later. In parallel measurements would also be conducted on turbulent dissipation in the $T \to 0$ limit. Currently discussions are thus ongoing about the order in which these different projects should be carried out which are now crowding the work programme of the rotating cryostat.

Milestone 6: Realization of Black-Hole analogue experiment (24 mo) **in preparation**

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

Introduction: It has been known since the 1970ies that non-local coherent precessing nuclear magnetic resonance states exist in 3He superfluids even in the presence of inhomogeneous order parameter textures. These resonances have become increasingly popular recently after the recognition that such states can be discussed in terms of Bose-Einstein condensation of magnon excitations. This insight has made it possible to use the powerful techniques which have been developed for the study of Bose-Einstein condensation in cold atom clouds. For magnetic resonance studies currently the persistently ringing (ie. slowly relaxing) very low temperature coherent mode is of greatest current interest. This resonance mode is also characterized by the Q-ball property known from particle physics.

AU measurements: Q-balls of magnon Bose-Einstein condensates were studied with the participation of Grenoble researchers Yuriy Bunkov and Pierre Hunger [4, 5, and to be published]. The excited states of the trapped condensate were identified and investigated. They were found to be stable at low RF pumping levels at their eigenfrequency. It is possible to create any excited state by appropriately choosing the pumping frequency. The relaxation of the Q-balls was studied. It was found that the excited Q-balls live long enough to exhibit properties of coherent precession similar to those of the ground state Q-ball (Fig. 3). A better understanding of these phenomena should allow the use of Q-ball states for probing the vortex core structure in rotating superfluid ^{3}He-B [5]. This is planned to be done in the next near future.

CNRS measurements: Bose-Einstein condensates of magnons were investigated with superfluid ^{3}He in aerogel (a highly porous silica material). Here trapped magnon condensates with coherent precession can also be formed. The influence of the disorder introduced by the aerogel on the superfluid phase transition was studied. We established that the anisotropy of aerogel reorients the superfluid order parameter and makes new states of coherent precession possible in both the A and B phases, depending on the type of anisotropy [10].

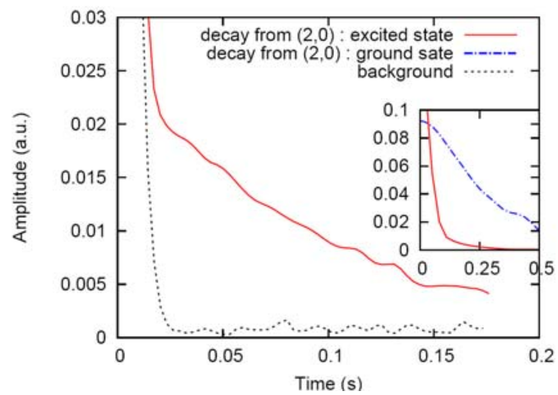


Fig. 2. Decay signals from Q-balls in their ground state (dashed blue line) and in their excited state (solid red line). In both cases the Q-balls precess freely on time scales longer than any incoherent precession signal.

ULANC measurements: We have cooled an experiment designed to study the interaction between two independent precessing Q-balls. We have cooled this setup to record low temperatures where the Q-balls precess freely and coherently for half an hour or more. Previously we found that these long-lived Q-balls are excited in a field minimum. So in the current experiment, we have a purpose-built superconducting magnet system which allows us to generate two field minima, which we can spatially manipulate and bring together, to allow us to study the interaction of Q-balls. The experiment is working well and we have successfully managed to excite and observe two long-lived Q-balls simultaneously. However, the experiments are proving to be demanding since it is difficult to manipulate multiple Q-balls: the Q-balls are found to be quite irreproducible and very sensitive to the external environment (magnetic noise) and are easily destroyed. Work on this is ongoing.

Milestone 9: Interactions between two independent Q balls (30) **exp running**

Milestone 10: Creation of excited modes of a Q ball under radial squeezing by rotation (36) preprint available [4] **achieved**

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

Introduction: The development and testing of new probes and sensors for quantum fluids' studies is a key element for our research within Microkelvin for all the different tasks within work package JRA3. This work includes studies of the phenomena which are observed when such probes are used in the ^{3}He liquids in different parameter regimes. This is especially important for the success of Task 5 where suitable probes have to developed for the use in dark-matter detectors under varying conditions.

SAS measurements: We have performed measurements on quartz tuning fork oscillators at the very lowest temperatures in ^{3}He-B. These tests revealed an unexpected phenomenon [11] which clearly demonstrates how urgently studies of mechanical vibrating elements need to be carried out at the lowest temperatures, if we want to use such probes efficiently for dark matter detection. The damping of the fork motion as a function of the fork velocity was measured at different values of magnetic field and is shown in Fig. 3. Quartz tuning forks have been found to be insensitive to magnetic fields at higher temperatures, but here an unexpected field dependence of the fork damping is measured for the first time.

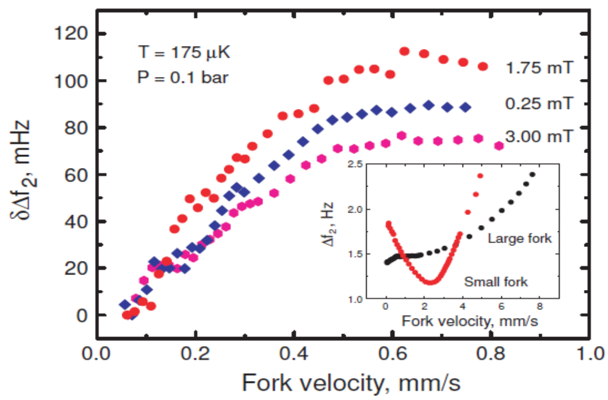


Fig. 3. Dependence of the mechanical resonator damping as a function of its velocity, measured at ultralow temperatures for various values of the magnetic field.

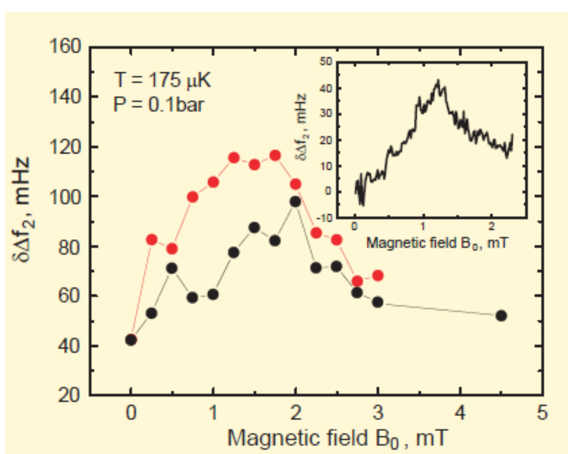


Fig. 4. Dependence of the change in damping, $\delta\Delta f_2$, as a function of magnetic field. The inset shows the same dependence measured at constant fork velocity during a slow sweep of the magnetic field.

The additional damping of the fork $\delta\Delta f_2$ as a function of the external magnetic field B_0 is shown in Fig. 4 for two different demagnetization cool-down runs. The measured dependences show a resonant feature: the presence of the maximum in absorption at a field of 1mT, which would correspond to the ^{3}He NMR resonance frequency 32.4 kHz. This happens to be the resonance frequency of the tuning fork. Surprisingly, we are thus lead to ask whether nuclear magnetic resonance absorption can be excited by the mechanical motion of the magnetic moments of the solid ^{3}He layer bound to the surface of the vibrating mechanical resonator. Obviously other interpretations are also possible and must be tested to explain this unusual observation.

ULANC measurements: A similar unexpected observation was made recently in Lancaster, also with a mechanical resonator. It had previously been shown in Grenoble that the heat capacity of the solid ^{3}He layers on a mechanical vibrator can reduce its sensitivity as a bolometric particle detector. Thanks to our increased sensitivity to surface effects, we discovered now a new magnetic phase transition in the solid ^{3}He layers which coat the nanometer sized strands of silica aerogel [12]. This was measured with a piece of aerogel fixed on a vibrating element, while recording the damping of the mechanical resonance at the lowest temperatures in a bath of ^{3}He-B. There has been much activity in recent years in studying liquid ^{3}He in silica aerogel at low temperatures. The aerogel is formed by a network of irregular strands of nm thick silica, spaced by a few tens of nm. The strand spacing is comparable to the coherence length of superfluid ^{3}He. When the aerogel is immersed in liquid ^{3}He it acts as an impurity, allowing the study of 'dirty' superfluidity. However, the strands are also coated with a few layers of solid ^{3}He. We realised that this can be utilised to cool the superfluid into a new record low temperature regime by performing direct nuclear adiabatic demagnetisation on the solid ^{3}He layer. During these measurements, we observed an interesting and unexpected phase transition in the nuclear spins. This opens up a new area of research into nuclear magnetic ordering in nanometer scale geometries.

CNRS measurements: To extend on such surface-layer studies, we have investigated in Grenoble, with the collaboration of Helsinki, with neutron scattering at very low temperatures the elementary excitations of a monolayer of liquid ^{3}He adsorbed on graphite. We observed for the first time the particle-hole excitations characterizing the Fermi liquid state of two-dimensional liquid ^{3}He [13]. We were also able to identify the highly interesting zero-sound collective mode above a particle-hole band [14]. Contrarily to bulk ^{3}He, at low wave-vectors this mode lies very close to the particle-hole band.

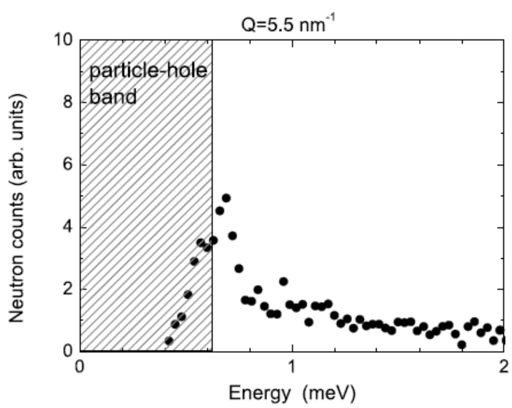


Fig. 5. Inelastic neutron scattering spectrum at a wave-vector of 5.5 nm^{-1}. Note the mode above the particle-hole band.

At intermediate wave vectors, the collective mode enters the particle-hole band, where it is strongly broadened by Landau damping. At high wave vectors, where the Landau theory is not applicable, the zero-sound collective mode reappears beyond the particle-hole band as a well defined excitation, with a dispersion relation quite similar to that of superfluid ^{4}He. This spectacular effect is observed for the first time in a Fermi liquid (including plasmon excitations in electronic systems).

Neutrons are used to simulate WIMPs, such as the neutralino, and provide an important test of the detector sensitivity and discrimination capacity. Zero and first sound excitations in liquid ^{3}He are of interest for particle detection: part of the detected energy is dissipated as sound, in a still unknown proportion, thus affecting the absolute energy measurements in bolometric studies. Related work (acoustic emission by quarz tuning forks in cryogenic fluids) will be conducted with a Czech laboratory in the framework of a TA2 facility project in the near future.

In Grenoble, we are also studying and developing MEMS (micro-mechanical) and NEMS (nano-mechanical) devices for low temperature physics [15]. The development of new probes and sensors for quantum fluids' studies is a key element for our research within Microkelvin in general, but in particular for the particle detection project ULTIMA-Plus. The micro-fabrication techniques available at the Microkelvin TA2 facility have enabled us to create novel structures with micro and nano dimensions, vibrating silicon resonators, which are similar to the conventional vibrating wire resonators made from superconducting wire, used by us in various Microkelvin projects as temperature sensing elements in bolometric detectors.

We have studied the non-linear dynamics of several MEMS devices at low temperatures (Fig. 1), and have proved that they can be used all the way from their linear to a highly non-linear regime [15]. A thorough theoretical analysis has allowed us to obtain analytical solutions, to explain the general behaviour of these resonators. We understand their dynamics in the whole dynamic range, including the inelasticity effects arising from the superconducting metal coatings [16]. The coatings are needed to actuate and read the resonators [preprint, submitted to Physical Review B].

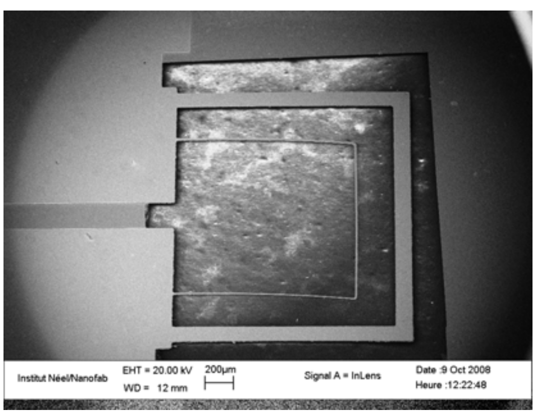


Fig. 3a Double MEMS device (vibrating wire resonator) for ULTIMA-Plus

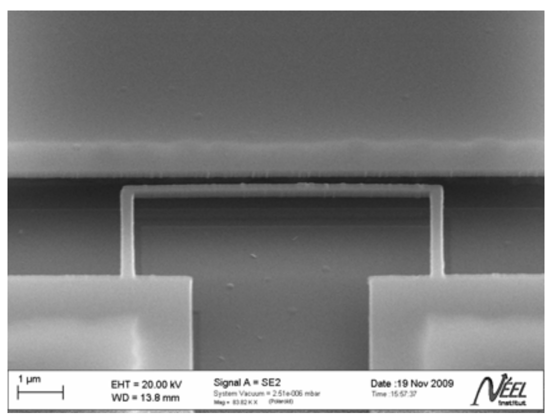


Fig. 3b NEMs device; note the very different scale than on the left.

The core developments within Task 5 (design, microfabrication, characterisation, and testing of MEM and NEM devices) are therefore well advanced. The objective set as Milestone M12 (testing the devices at 100 µK in ^{3}He-B) seems perfectly reachable and will be next carried out next in above-ground laboratory surroundings. The construction of the under-ground laboratory for the ULTIMA-Plus dark matter observatory will have to be postponed, owing to the unavailability of French financial support for operating the underground facilities at Canfranc. Instead, we are waiting for the construction of the extension to the Modane underground laboratory, which is planned to be completed during the next 2 – 3 years.

Milestone 9: Micro-fabricated silicon vibrating wires tested in ^{3}He-B below 100 μK in above-ground laboratory conditions (30) **experiment starting**

Deliverable 1: Report on micro-fabricated silicon vibrating wires tested in ^{3}He-B at 100 μK (12)
There must be an accidental mistake in the 12 mo delivery time – it should be more than the 30 months foreseen for M12 **expected later**

Highlights

- *Measurement of heat released in quantum turbulence*
- *Identification of the excited Q-ball eigenstates and their relaxation properties*
- *First observation of the interaction between two independent precessing Q-balls*
- *Observation of the zero-sound mode in two-dimensional Fermi liquid ^{3}He*
- *Observation of mechanically excited NMR*
- *Observation of a magnetic ordering phase transition in a nanonetwork of solid ^{3}He in aerogel*
- *Measurement and identification of superfluid ^{3}He phases in 635 μm wide parallel plate geometry*

Publications

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

[2] *Vortex formation and annihilation in rotating superfluid ^{3}He-B at low temperatures,*
V.B. Eltsov, R. de Graaf, P.J. Heikkinen, J.J. Hosio, R. Hänninen, and M. Krusius, J. Low Temp. Phys. **161**, No. 5/6, December issue (2010).

[3] *Generation of quasiparticle excitations by vortex motions in superfluid ^{3}He-B,*
V.B. Eltsov, R. de Graaf, P.J. Heikkinen, J.J. Hosio, R. Hänninen, M. Krusius, and V.S. L'vov, preprint (2010).

[4] *Non-ground-state Bose-Einstein condensates of magnons in superfluid ^{3}He-B,*
Yu.M. Bunkov, V.B. Eltsov, R. de Graaf, P.J. Heikkinen, J.J. Hosio, M. Krusius, and G.E. Volovik, preprint arXiv:1002.1674v1 [cond-mat.quant-gas].

[5] *Vortex core contribution to textural energy in ^{3}He-B below 0.4 T_c,*
V.B. Eltsov, R. de Graaf, M. Krusius, and D.E. Zmeev, J. Low Temp. Phys. **162**, No. 5/6, March (2011); preprint arXiv:1006.4108v1.

[6] *Generation, evolution, and decay of pure quantum turbulence: A full Biot-Savart simulation,*
S. Fujiyama, A. Mitani, M. Tsubota, D.I. Bradley, S.N. Fisher, A.M. Guenault, R.P. Haley, G.R. Pickett, and V. Tsepelin,
Phys. Rev. B (Rapid Communication) **81**, 180512 (2010).

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

[8] *Superfluid ^{3}He confined in a single 0.6 micron slab: A-phase transition between superfluid phases with hysteresis,*
Levitin, L.V., Bennett, R.G., Casey, A.J., Cowan, B., Parpia, J. and Saunders, J.
J. Low Temp. Phys. **158**, 159-162(2010).

[9] *Superfluid ^{3}He confined to a single 0.6 micron slab: Stability and properties of the A-like phase near the weak coupling limit,*
Bennett, R.G., Levitin, L.V., Casey, A., Cowan, B., Parpia, J. and Saunders, J.
J. Low Temp. Phys. **158**, 163-169 (2010).

[10] *Evidence for Magnon BEC in Superfluid ^{3}He-A,*
P. Hunger, Yu.M. Bunkov, E. Collin, and H. Godfrin,
J. Low Temp. Phys. **158**, 129-134 (2010).

[11] *Probing Andreev-Majorana bound states in superfluid ^{3}He -B using NMR excited by mechanical resonance,*
M. Človečko, E. Gažo, M. Kupka, M. Skyba, and P. Skyba,
submitted to Phys. Rev. Lett.

[12] *Magnetic phase transition in a nanonetwork of solid ^{3}He in Aerogel,*
D.I. Bradley, S.N. Fisher, A.M. Guénault, R.P. Haley, N. Mulders, G.R. Pickett, D. Potts, P. Skyba, J. Smith, V. Tsepelin, and R.C.V. Whitehead,
Phys. Rev. Lett. **105**, 125303, (2010).

[13] *Two-dimensional ^{3}He: A crucial system for understanding fermion dynamics,*
H.M. Böhm, E. Krotscheck, M. Panholzer, H. Godfrin, H. J. Lauter, and M. Meschke,
J. Low Temp. Phys. **158**, 194-200 (2010), DOI10.1007/s10909-009-0033-6.

[14] *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, and M. Panholzer,
J. Low Temp. Phys. **158**, 147-154 (2010).

[15] *Novel "vibrating wire like" NEMS and MEMS structures for low temperature physics,*
E. Collin, J. Kofler, J.-S. Héron, O. Bourgeois, Yu. M. Bunkov, and H. Godfrin,
J. Low Temp. Phys. **158**, 678-684 (2010).

[16] *Metallic coatings of microelectromechanical structures at low temperatures: Stress, elasticity, and nonlinear dissipation*,
E. Collin, J. Kofler, S. Lakhloufi, S. Pairis, Yu.M. Bunkov, and H. Godfrin,
J. Appl. Phys. **107**, 114905 (2010).

Additional publications prepared by Microkelvin visitors and/or related to JRA3 tasks:

[17] *Interaction of Kelvin waves and non-locality of the energy transfer in superfluids,*
J. Laurie, V.S. L'vov, S. Nazarenko, and O. Rudenko,
Phys. Rev. B **81**, 104526 (2010).

[18] *Spectrum of Kelvin-wave turbulence in superfluids,*
V.S. L'vov and S. Nazarenko,
Pis'ma v ZhETF **91**, 464-470 (2010); JETP Lett. **91**, 428-434 (2010).

[19] *Direct energy cascade in two-dimensional compressible quantum turbulence,*
R. Numasato, M. Tsubota, and V.S. L'vov,
Phys. Rev. A **81**, 063630 (2010).

[20] *Fermion zero modes at the boundary of superfluid 3He-B,*
G.E. Volovik,
Pis'ma ZhETF **90**, 440-442 (2009); JETP Lett. **90**, 398-401 (2009).

[21] *Osmotic pressure of matter and vacuum energy,*
G.E. Volovik,
Pis'ma ZhETF **90**, 659-662 (2009); JETP Lett. **90**, 595-598 (2009).

Deviations from work plan

- *Milestone 13 within Task 5 (operating a multicell prototype in an underground laboratory, month 42) has to be postponed. The financial support for the underground laboratory, expected from the French ANR, has not been granted. The operation will eventually be carried out towards the end of the Microkelvin contract, if sufficient funding and underground laboratory space become available. The program is scientifically highly interesting (the Ultima project had been approved by the Canfranc International Underground Laboratory). The delay in this last-stage sub-task does not affect other tasks.*

Use of resources

- *The use of resources follows the project plan, with some delay in the hiring of post-doctoral researchers. Academic low temperature physics is a small specialized discipline, where post-doctoral researchers are few and new recruitments require time. It is expected that suitable post-doctoral candidates can be located, as students pass their Ph.D. degrees. Also our post-doctoral positions have been widely announced which may bring further results.*
- *The above-ground development work for the ULTIMA dark matter detector, which will be performed in the Grenoble laboratory, will proceed as planned. The underground experiments have to be postponed, and may not become feasible during the contract period. We propose that the 6 man-months allocated to the underground work will be redistributed as follows: two man months to a more detailed study of the interaction of neutrons with the ^{3}He target within Task 5, and two man months each for increasing the support to CNRS activities in JRA1 and in JRA4.*

JRA4 Report #1

Name of the activity (work package): **Novel methods and devices for ultra low temperature measurements**
Reporting Period: **from 1.4. 2009 to 30.9.2010**
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	Report on the performance of wide bandwidth SQUIDs (Task 2)	JRA4	RHUL	15	R	PU	18, 36 **delayed see Task 2a**
D5	Report on current sensing noise thermometer for ultra low temperatures (Task 3)	JRA4	RHUL	15	R	PU	12, 24 **delivered**
D6	Report on 195Pt-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	AU	6	R	PU	12, 24 **delivered**
D8	Report on 10 mK GaAs quantum dot thermometer (Task 3)	JRA4	BASEL	10	R	PU	12, 24 **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**
M3	SQUID NMR detection of nano-scale ^{3}He samples at sub-mK temperatures	JRA4, Task 2	RHUL	12	**achieved**
M6	Realization and measurement of 10 mK CBT sensor	JRA4, Task 3	TKK	15	**partially 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, AU,PTB)

Development of new contactless measuring techniques in Heidelberg (HEID):

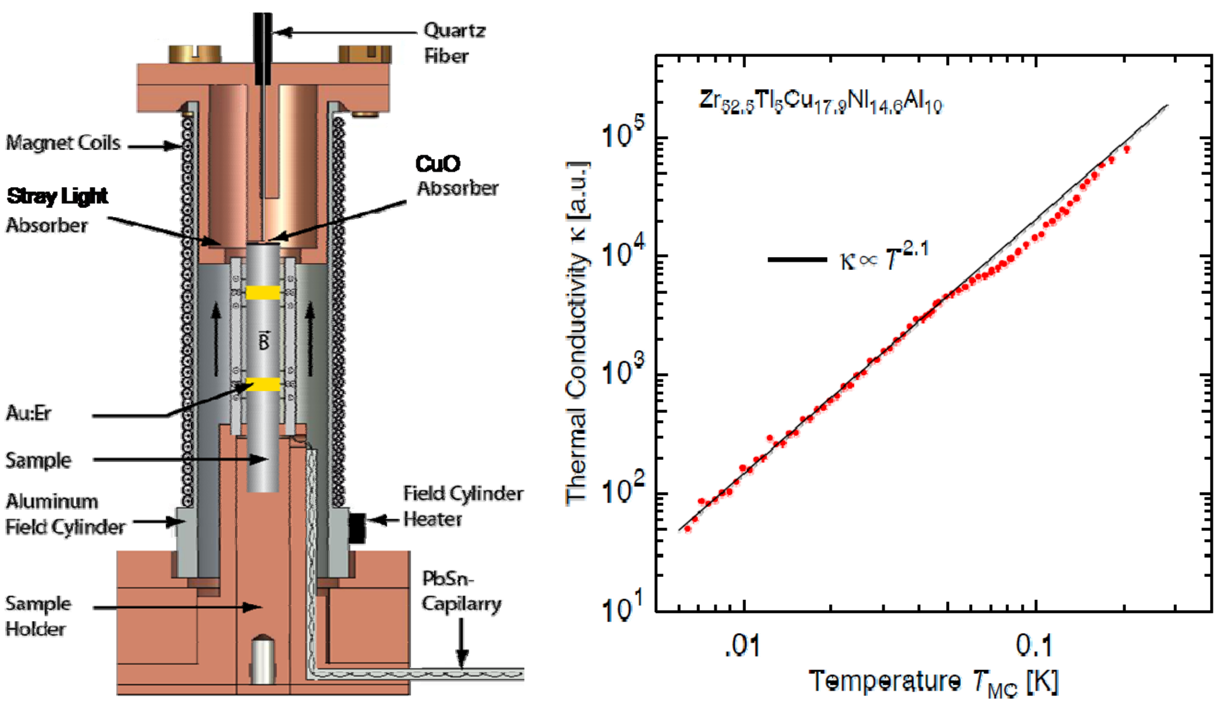


*Fig. 1.1: **(left)** Schematic of the new thermal conductivity setup for superconducting metallic glasses; **(right)** Thermal conductivity of a bulk metallic glass measured with this technique.*

- A dc-SQUID based new non-contact method for measuring the thermal conductivity of superconducting bulk metallic glasses was developed and successfully tested in measurements down to 6 mK (Fig. 1.1). These are the first measurements of the heat transport of metallic glasses at these temperatures [1]. To be able to go below 6 mK, a nuclear demagnetisation refrigerator has been modified and wired for such experiments. In a first cool-down the dilution unit of this cryostat was successfully tested.
- Using the same bulk metallic glasses, a torsional oscillator set-up for investigating the low frequency elastic properties of these materials at ultralow temperatures has been constructed. For detecting the displacement amplitude of the oscillator a novel DC SQUID readout has been designed and successfully tested.
- A new concept for measuring the specific heat of dielectric glasses using polarisation echoes has been developed and a prototype sample holder has been constructed and successfully tested at low temperatures. First data on an optical glass (BK7) have been taken.
- A new setup up for the measurement of the dephasing of dielectric polarisation echoes has been developed using an ultralow-noise low-temperature amplifier and cold filters, improving the sensitivity by roughly three orders of magnitude. With this set-up it became possible to investigate the decay of the dielectric polarisation echoes at very large delay times. Thus the distribution function could be tested in such parameter regions which have not been explored before. At temperatures of 50 mK the decay of the echo can be monitored at times exceeding 100 microseconds. As an example a measurement on BK7 is shown in figure 1.2.

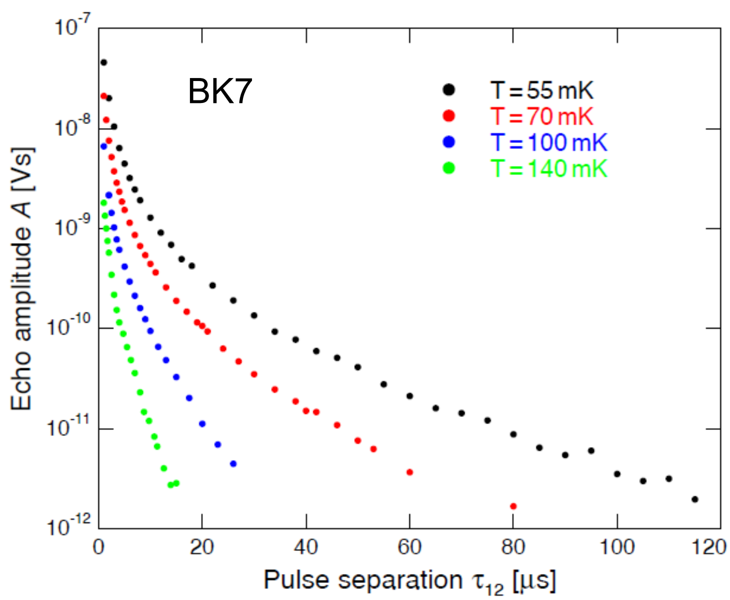


Fig. 1.2: Amplitude of polarisation echoes generated in BK7 as a function of the delay time for different temperatures.

In Grenoble (CNRS), the dynamics of MEMS (Micro Mechanical Systems) vibrating-wire-like silicon oscillators has been investigated at low temperatures. It was shown that, as function of the drive, these devices can be used from the linear regime all the way up to highly non-linear response. This has been concluded from a careful analysis of the dynamics over the whole range of excitation [2].

M1: Realization of contactless setup to investigate decoherence (18 mo) **achieved**

Realization of contactless setup to investigate specific heat (36 mo) **achieved**

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

While operating SQUIDs at very low temperatures, PTB has observed increasing noise at low frequencies. To address this issue of excess low-frequency noise at ultra-low temperatures, a series of test SQUIDs was measured both at 4.2 K in liquid helium and at 10 mK in a dilution refrigerator. A thorough analysis was performed of these new measurements, together with results obtained during the past four years from various other experiments [3]. Considering the large spread of the low-frequency noise data, there was no systematic dependence of the 4.2 K noise level on the fabrication parameters. However, the low-frequency noise increased strongly below about 1 K for wafers where the bottom Nb layer and the insulation layer were fabricated in a newly installed sputtering system (FHR), when compared to the fabrication in an old machine (Alcatel). From these results and other experiments with plasma treatment of Nb thin films it is assumed that highly energetic particles cause defects during the sputter deposition and the intermediate plasma etching steps. This problem is still under investigation. We will address it first experimentally by changing the technical parameters of the etching and deposition equipment.

PTB is renewing the equipment for SQUID fabrication in the time period November 2009 – December 2010. Among other things, a new mask aligner, a new profilometer which enables stress measurement of thin films, and an electron beam lithography system have been already installed in the cleanroom. Currently a plasma etching system is set up. The FHR sputtering system was changed with respect to the plasma energy in the etching and in the deposition chamber. Modern sputtering deposition systems are optimized for high deposition rates. Running the etching cathode or the sputter guns stable with low particle energies is not possible. The changes made will enable stable low energy operation in this system. Because of the serious reconstruction and renewal activities the SQUID fabrication was interrupted from November 2009 until October 2010. In October the first runs of single fabrication steps have been started. Micro coils for the Royal Holloway (RHUL) experiments have been manu-factured and delivered together with SQUID current sensors from earlier fabrication runs, but complete SQUID fabrication is expected in the beginning of 2011. This is the reason for the delayed deliverable D4 (RHUL) of wideband SQUIDs. After full resumption of the SQUID manufacture at PTB, novel SQUID devices will be made and delivered to RHUL.

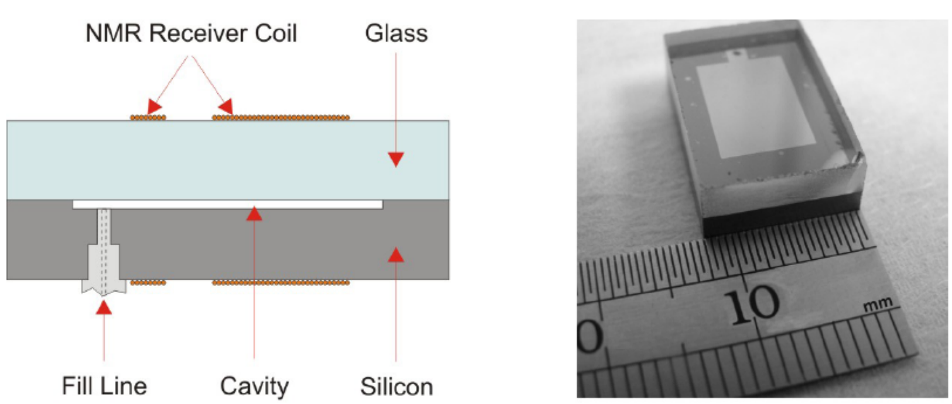


*Fig.2.1: **(Right)** Silicon/Glass nanofabricated cell for the confinement of superfluid ^{3}He. **(Left)** The schematic diagram of the sample setup shows the NMR receiver coil which forms part of the tuned input circuit of the SQUID based spectrometer.*

At Royal Holloway, SQUID NMR has been developed for measuring superfluid ^{3}He confined within a nanofluidic sample chamber. The ^{3}He sample was placed within a regular and well characterised parallel plate geometry of thickness 635 nm. The setup is of novel design, formed from anodically bonded glass and silicon, and results from collaboration with Cornell University [4]. The slab-like cell has 3 mm thick walls to allow pressure tuning of the sample (Fig. 2.1).

A NMR signal from this geometry is detected, despite the low filling factor, by SQUID NMR (Fig. 2.2). The success of the NMR experiment relies on the high sensitivity NMR system, developed at RHUL, based on a two stage DC SQUID amplifier, fabricated at PTB, with an energy sensitivity of 20h. The noise temperature of the amplifier was determined to be 5 mK. The properties of this instrumentation have been explored in a series of experiments, which determine the effect of confinement on the superfluid phase diagram, and quantify the influence of confinement on the superfluid order parameter. Preliminary reports have been published [5,6], two full papers are in preparation, and the work has been the subject of several invited talks. This work is the first study of superfluid ^{3}He in a nano-fabricated confined geometry, and achieves the aims of milestone M3 (12 months) in observing NMR signals from ^{3}He nanoscale samples at sub mK temperatures.

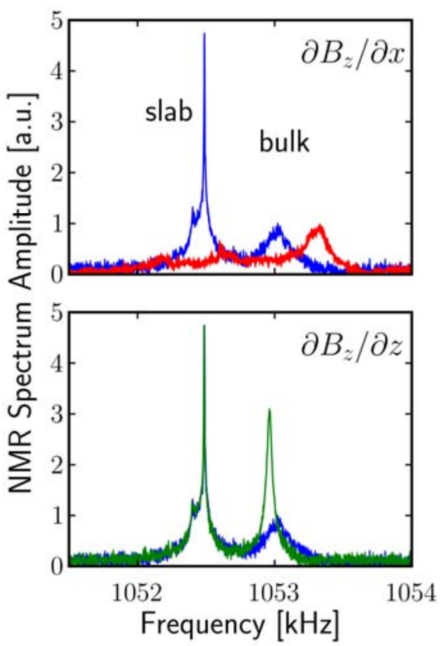


Fig. 2.2: NMR signals obtained using SQUID NMR for ^{3}He confined in a 635 nm high nanofabricated cavity. Employing field gradients, one can clearly identify the signal coming from the slab and an additional bulk signal coming from a volume at the entrance to the cell.

A new slab cell with narrower 150 nm spacing is being fabricated, and will provide a further, more stringent, test of the sensitivity of the NMR technique. The objective is to stabilise the predicted quasi-two-dimensional A-like phase, in which the gap nodes disappear as a result of quantum confinement. A further cell of spacing 1.2 μm is also under development 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. Development of more local probes is desirable in order to better characterise the possible striped phase, to detect the presence of exotic surface bound states, and to identify topological defects in the confined superfluid.

As part of Task 2a partners RHUL and PTB have designed microcoils to be coupled to low noise, low input coil inductance DC SQUIDs, for use as local probes in NMR experiments on confined ^{3}He. A detailed internal report (D3) on the design was produced in month 15. This included the initial design and the proposed next iteration, to be fabricated using a combination of photo-lithography and PTB's new e-line system (Fig. 2.3).

The single layer microcoils were fabricated at PTB and have undergone initial tests there. In this single layer 10 turn microcoil design significant inductance comes from the lead wires around the bond pad. Two coils were tested. They were connected using aluminium wire bonds (of resistance 20-30 mΩ) to a SQUID with a low input coil inductance. The coil inductance (including leads), was estimated from the roll-off in the noise spectrum to be 350 nH, close to the calculated value of around 400 nH. This is reasonable since the bond pad inside the bypass coil will lower the inductance. Both coil inductances agree with one another to better than 1%.

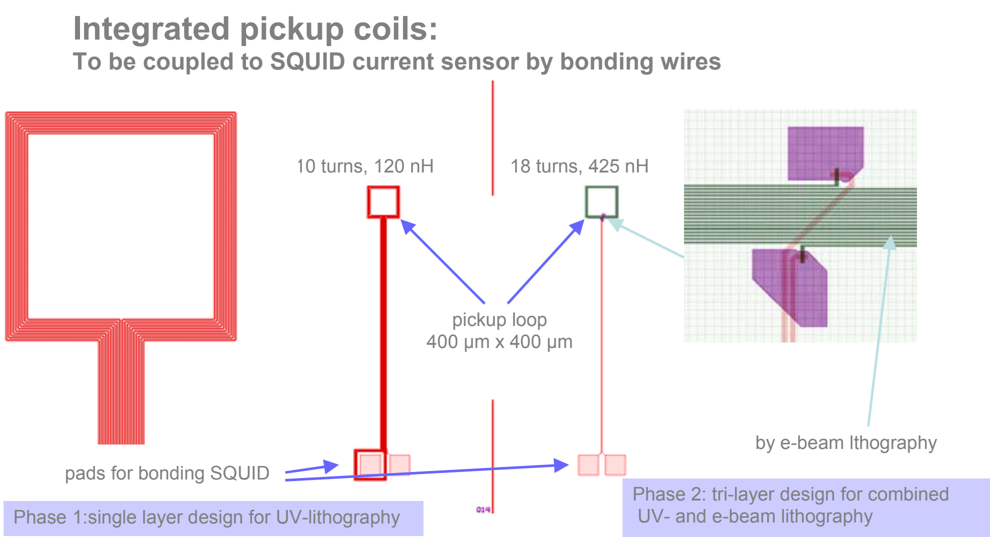


Fig. 2.3: PTB microcoils for use as local NMR receiver coils investigating the properties of confined superfluid ^{3}He.

These microcoils will ultimately be coupled to low noise DC SQUIDs, for use as local probes in NMR experiments on confined ^{3}He. The slabs will have a maximum thickness of 1 micron and the microcoils will probe an area of order 100 x 100 microns.

After the PTB tests the coils were delivered to RHUL in month 18 for testing in a SQUID NMR spectrometer. This represents a significant step towards achieving milestone M4 (month 36) of observing NMR signals from helium samples using microcoils.

M3: Demonstration of SQUID NMR detection of nanoscale ^{3}He samples at sub-mK temperatures (12 months) **achieved**

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

At PTB a new generation of SQUID wafers has been developed. This new design version is called PTB C6. The wafer contains devices 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 have been also developed. The first single-layer coils have been successfully tested using a SQUID with a low input inductance. These microcoils were connected to the SQUID with Al bond wires (20-30 mOhm).

At RHUL these devices will be next coupled to a NMR spectrometer for the study of ^{3}He in high magnetic fields, to investigate the A1 phase in a confined geometry. The plan is to perform these measurements in fields up to 3Tesla, which corresponds to a Larmor frequency of 100 MHz, beyond the bandwidth of the current NMR spectrometer. The next stage of this task involves therefore the development of the prototype control electronics for high frequency operation and the testing of this high bandwidth device. Thus the work for milestones M4 (36 mo) and M5 (42 mo) is well advanced.

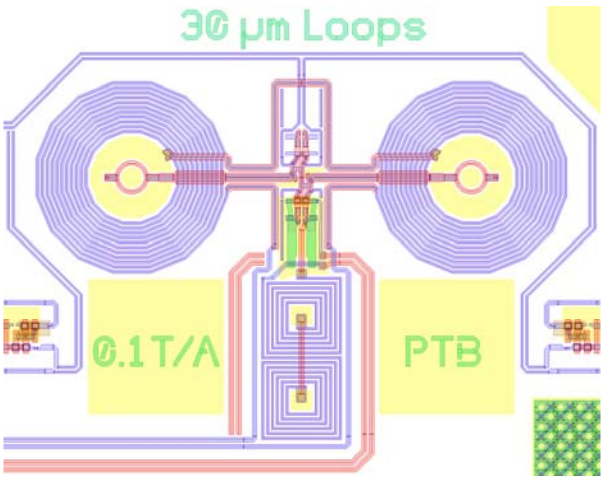


Fig. 2.3: Micro SQUID susceptometer with integrated field coil.

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

At RHUL we are developing current sensing noise thermometry using DC SQUIDs fabricated at PTB. The SQUIDs are mounted inside a new compact package (Fig. 3.1). We have demonstrated that no deterioration of amplifier noise results from the new package. Progress has been made with electronics and data acquisition, with the goal to improve the precision of temperature measurement for a given acquisition time, which was documented in an internal report D5. These initial tests at 4K showed the sensor to perform in modest magnetic fields, up to 400 mT, with no effect on the temperature measurement (Fig 3.2).

Two sensors based on this compact packaging were mounted on a cryogen-free Triton 200 dilution refrigerator at Oxford Instruments Nanoscience's facilty at Tubney Woods, Oxfordshire. These sensors have now been tested between 10 mK and 4K. Work on optimizing their performance in the presence of a pulse-tube cryocooler is ongoing, in collaboration with Oxford Instruments Nanoscience. Performance tests of sensors mounted on a cryogen-free cryostat in the presence of a large magnetic field are scheduled for Nov/Dec 2010. A third noise thermometer based on this design will be mounted on the RHUL nuclear demagnetization cryostat ND2 for sub-mK tests in early 2011, this will enable the sensor to be cooled to 200 μK in time for the 24 month report.

In Heidelberg a new version of a magnetic flux noise thermometer was installed in a dilution refrigerator and was successfully tested down to about 5 mK.

At PTB a new cryogen-free 3He/4He dilution refrigerator from Oxford Instruments has been installed and tested. This apparatus is intended for the investigation and development of new SQUID devices and noise thermometers.

Fig. 3.1: Compact niobium package for mounting the SQUID, to be used for RHUL current sensing noise thermometer.

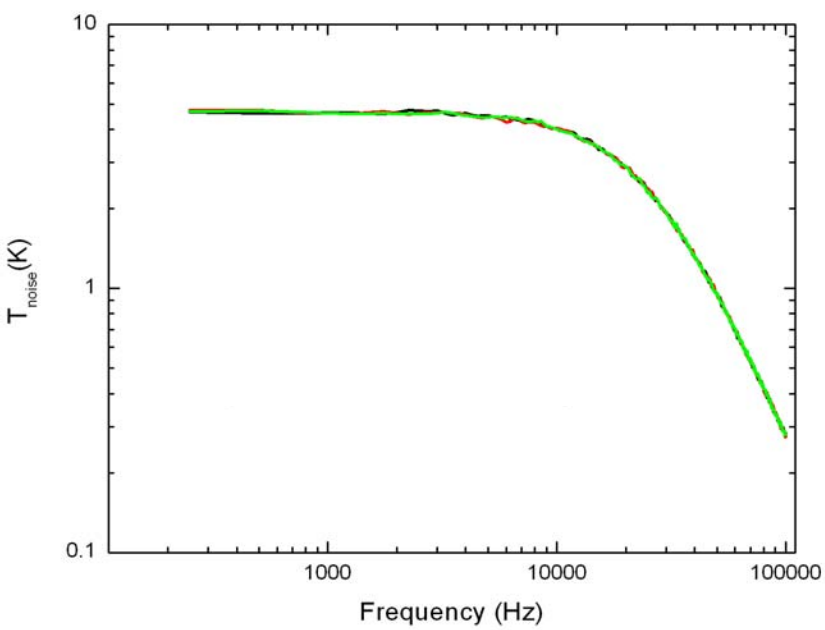


Fig. 3.2: Noise spectra at 4.2K, 0 mT Black, 50 mT Red, 400 mT Green.

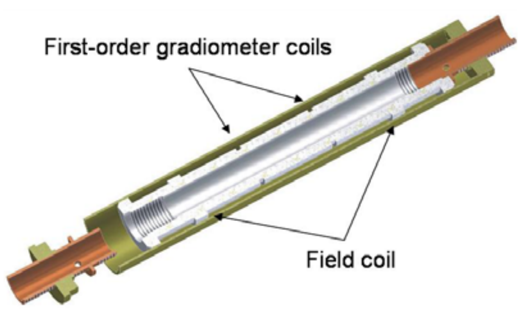
Task 3b: Ultra low temperature ^{195}Pt NMR thermometer (PTB, AU)

For reliable measurement of ultralow temperatures (T < 1 mK) pulsed ^{195}Pt NMR thermometry is currently the only established method. Two NMR thermometers with a usual Pt sample of natural ^{195}Pt abundance and an isotopically enriched sample have been set up and installed in the

PTB microkelvin refrigerator MKA3 (Fig. 3.3). The Pt samples are cylinders instead of the usually used Pt wire brushes which enables complete mathematical description of the device.

In order to back up this thermometry, a second, alternative thermometer based on SQUID susceptometry is being developed at PTB. This requires a SQUID susceptometer suitable for operation in the μK facility as well as ultra pure metallic sample materials from which the paramagnetic contribution of the nuclear spin system can be evaluated. The susceptometer setup consists of an axial first-order gradiometer as the primary coil, connected to a novel PTB SQUID current sensor. Alternatively, this setup can be used to measure the noise temperature of the sample. First experiments have been done at a temperature of 4.2 K (Figs. 3.4 and 3.5). Measurement and simulation are in good agreement. A signal-to-noise ratio of about 100 was achieved.

Fig. 3.3: Nuclear demagnetization stage of PTB μK refrigerator MKA3 with Rh reference point thermometer (I), ^{195}Pt NMR thermometer (II), and isotopically enriched ^{195}Pt NMR thermometer (III).



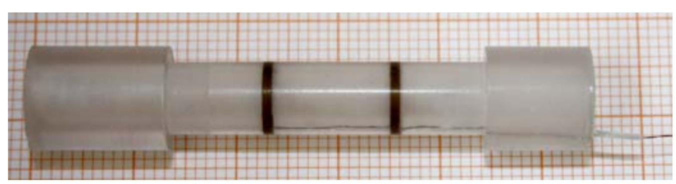


Fig. 3.4: Coil setup for the combined SQUID susceptometer and noise thermometer: ***(left)*** *schematic view and* ***(right)*** *photograph.*

A commercial SQUID magnetometer (Quantum Design MPMS XL) was used to characterize the magnetic and electrical properties of ultra pure samples (Pt, Cu), which are intended as thermometric sensing materials, by evaluating the magnetic contribution of the nuclear system. The contamination from magnetic impurities is derived from a fit of the magnetic susceptibility χ(1/T) to the

Brillouin function over a wide temperature range 1/T. The electrical conductivity σ(T) and the residual resistance ratio (RRR) are determined from a measurement of the ac susceptibility (f < 1 kHz).

A more detailed description of the NMR thermometry can be found in the internal report of Deliverable D6 “Report on ^{195}Pt-NMR thermometer for ultra low temperatures”.

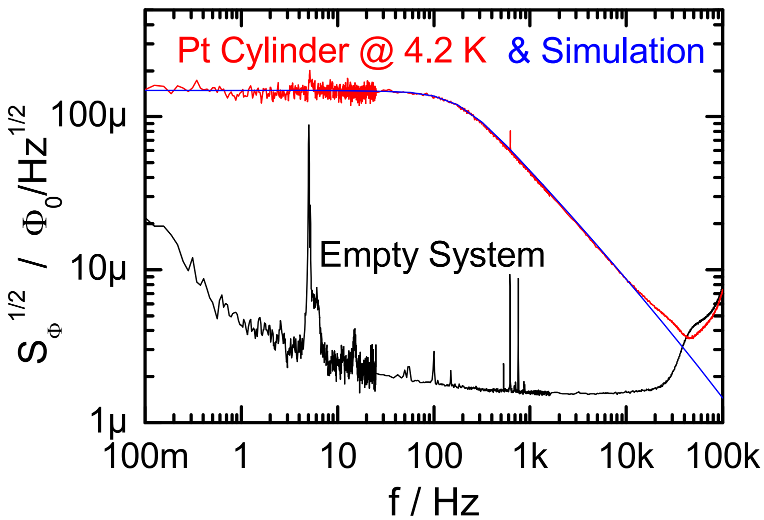


Fig. 3.5: Noise temperature measurement with SQUID susceptometer setup at 4.2 K and simulation.

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

The goal of the Basel activity is to demonstrate 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). In the second stage, this thermometer will be used at even lower sub-mK temperatures which we plan to achieve with a new type of demagnetization refrigerator currently under development by Basel / Lancaster in the JRA1 activities.

The first step is to fabricate suitable GaAs quantum dot devices for use as thermometers. This task we have completed, at least for the first generation of GaAs dot thermometers, over the past months using the Basel nano-fabrication cleanroom facilities, described in more detail below.

Starting from a high-stability, high-mobility wafer of 2D electron gas material formed at a heterointerface of AlGaAs and GaAs grown by collaborators at UCSB (Prof. Gossard), the group at BASEL has defined mesas using optical lithography and a GaAs wet-etch. Then, ohmic contact pads were defined with optical lithography and Pt/Ge/Au layers deposited in a lift-off process, which were subsequently annealed in a rapid thermal annealer. Some effort went into developing an appropriate ohmic contact recipe, which currently works satisfactorily, but could and maybe should still be improved further to achieve more reliably low contact resistances. The surface gates used to define the electrostatic potential that confines the electron(s) in the dot were patterned using electron beam lithography. Quite a bit of work went into developing and fine-tuning the quantum dot surface gate pattern with appropriate electron beam doses, requiring a resolution of about 30 nm. As the last step, the electron-beam features were connected electrically with bonding pads using a final optical lithography step with metallization lift-off.

The devices were then cleaved, wire-bonded and tested at 4 K in a dip-stick setup, indicating that several dots worked very well. In a subsequent cooldown in a dilution refrigerator setup, Coulomb blockade was observed in these devices, which is naturally a prerequisite for a Coulomb blockade thermometer. The number of electrons in the dots investigated could be reduced to zero.

Currently, the use of these devices as thermometers at low temperatures between 10 mK and 1 K is investigated. In particular, for the dot to work as a good thermometer, the tunneling rates Γ need to be adjustable to small enough values, satisfying $\hbar\Gamma < kT$ at all temperatures T of interest. Further, it is far from trivial to cool the electrons in these samples to temperatures well below 100 mK. Towards this end, strategies for high-frequency filtering and heat sinking all electrical wires connected to the sample are currently being developed by Basel in JRA1 and JRA2.

Recently, an electron temperature of 18 mK ± 3 mK has been achieved with the GaAs Coulomb blockade thermometer (Fig. 3.6) in a regular but heavily filtered dilution refrigerator steup, reaching good agreement with other thermometers for temperatures above 30 mK up to 1K (publication in preparation). Further, in a separate experiment (not described in the publication), a GaAs quantum dot thermometer was cooled down and measured in the Basel nuclear refrigerator network setup (JRA1) and cooled to 15 ± 2 mK, though it saturated at that temperature during a demagnetization run. We have investigated the reason for the saturation and have concluded that the GaAs dot was not sufficiently deep in the temperature broadened regime because of a too large tunneling rate through one of the barriers, resulting in a highly asymmetric tunneling rate configuration. This was caused by device fabrication issues with one of the gates that controlled the tunneling rate into the dot.

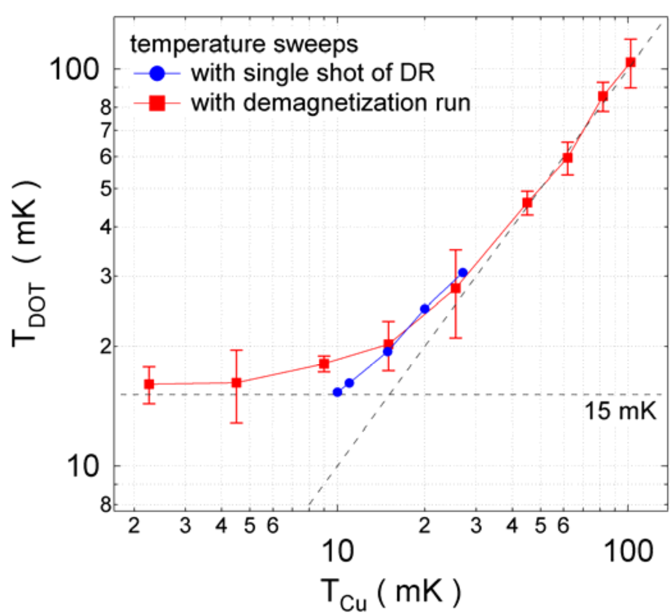


Fig. 3.6: Temperature measured with a GaAs quantum dot Coulomb blockade thermometer vs the temperature of the copper stage on which is was mounted.

In addition CBTs and single-junction thermometers (SJT) have been prepared at AU in the beginning of the summer 2010. Subsequently they were measured in joint experiments at PTB and the data were compared to a ^{3}He melting curve thermometer. Very good agreement between 0.25 K and 0.65 K was obtained. As a result of these measurements, the functional capability of both thermometers could be verified. Below 0.25 K significant heating of the sensor is observed. In this context an accurate evaluation of models describing the electrical and thermal properties of the thermometers (electron-phonon coupling) was carried out for the first time [7].

Most recently the tests of the CBT sensor were continued to lower temperatures in Basel with improved thermalization of the sensor leads (Fig. 3.7). The lowest recorded temperature was determined to be 11.5 mK with an uncertainty margin of ± 1 mK. These measurements are still being evaluated and new improvements are considered.

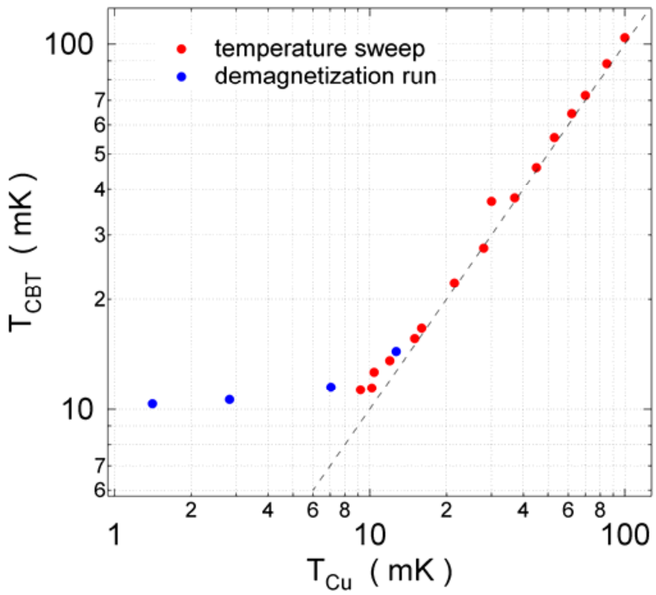


Fig. 3.7: Temperature measured with a single junction CBT vs the temperature of the nuclear stage on which the thermometer is mounted.

M6: Realization and measurement of 10 mK CBT sensor (15 mo) **achieved**

M7: Design and testing to 200 µK of a current-sensing noise thermometer for metrological measurements (24 mo) **in progress**

M8: Operation of Ga-As quantum-dot thermometer at 10 mK (24 mo) **in progress**

Highlights

- *First (non-contact) thermal conductivity experiment on metallic glasses below 100 mK Setup developed to measure the dephasing of dielectric polarisation echoes*
- *First study of superfluid ^{3}He in a nano-fabricated confined geometry*
- *GaAs quantum dot thermometer fabricated and operated from 15 mK up to 1K*

Publications

[1] *Thermal conductivity of superconducting bulk metallic glasses at very low temperatures,* D. Rothfuss, U. Kühn, A. Reiser, A. Fleischmann, and C. Enss, accepted for publication in CJP (2010)

[2] *Metallic coatings of microelectromechanical structures at low temperatures: Stress, elasticity, and nonlinear dissipation,* E. Collin, J. Kofler, S. Lakhloufi, S. Pairis, Yu. M. Bunkov, and H. Godfrin, J. Applied Physics 107, 114905 (2010)

[3] *Investigation of low-frequency excess flux noise in dc SQUIDs at mK temperatures,* D. Drung, J. Beyer, J.-H. Storm, M. Peters, and Th. Schurig,

submitted to IEEE Trans. Superconductivity

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

[5] *Superfluid He-3 confined in a single 0.6 micron slab: A-phase transition between superfluid phases with hysteresis,*
Levitin, L.V., Bennett, R.G., Casey, A.J., Cowan, B., Parpia, J. and Saunders, J.
J. Low Temp. Phys. **158**, 159-162 (2010)

[6] *Superfluid He-3 confined to a single 0.6 micron slab: Stability and properties of the A-like phase near the weak coupling limit,*
Bennett, R.G., Levitin, L.V., Casey, A., Cowan, B., Parpia, J. and Saunders, J.
J. of Low Temp Phys. **158**, 163-169 (2010)

[7] *Comparison of Coulomb blockade thermometers with the International Temperature Scale*
M. Meschke, J. Engert, D. Heyer, J. Pekola,
PLTS-2000; Int. J. Thermophys. (2010)

Deviations from work plan

- *no deviations*

Use of resources

- *There has been a delay in appointing a suitable candidate as postdoctoral researcher at RHUL, this post has now been filled by Lev Levitin, starting from October 2010. He has been working on projects related to the Microkelvin Programme as part of his EPSRC funded PhD.*

3.2.3 Project management during the period

During the first18-month reporting period the MICROKELVIN Collaboration established its management structure, held 6 management related meetings, opened its web-site, and launched its Networking, Joint Research, and Transnational Access Activities.

<u>Microkelvin management tasks and achievements</u>

The structure of the MICROKELVIN organization (see below) and the duties of its officials were presented in the Kick-off meeting on April 3, 2009.

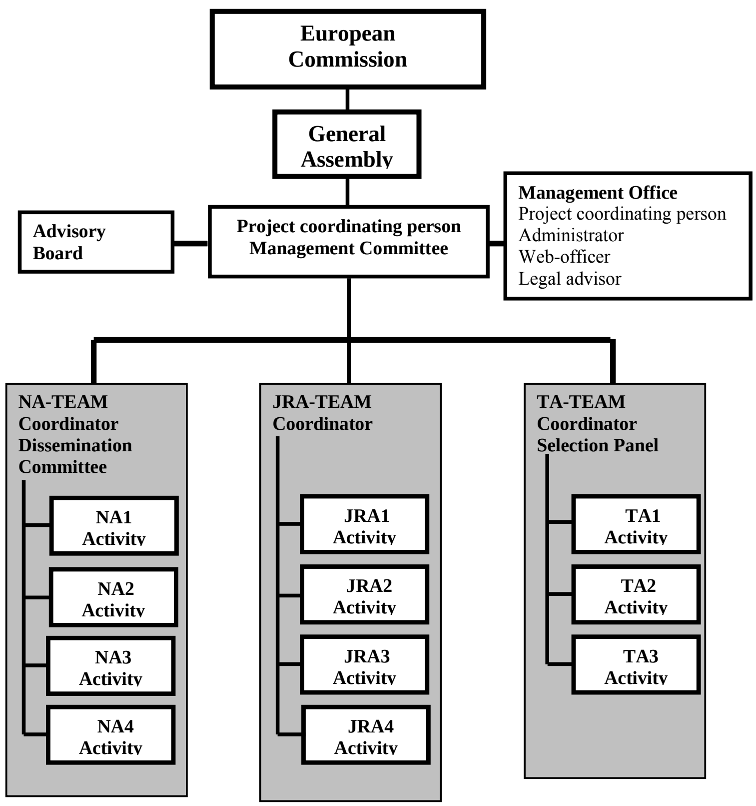


Table 1. Organizational scheme of MICROKELVIN collaboration

The 12 partners of MICROKELVIN have each one representative in the *<u>General Assembly:</u>*

George Pickett (chair)	Lancaster
Rob Blauuwgeers	BlueFors Cryogenics
Francesco Giazotto	SNS
Henri Godfrin	CNRS, Grenoble
Christian Enss	Heidelberg
Teun Klapwijk	Delft
Tjerk Oosterkamp	Leiden
Mikko Paalanen (secretary)	AU

John Saunders	Royal Holloway
Thomas Schurig	PTB, Berlin
Peter Skyba	SAS, Kocise
Dominik Zumbuhl	Basel

The General Assembly had its first meeting in connection of the Kick-off Meeting, electing/confirming the following officials:

Project Coordinating Person

Mikko Paalanen	Aalto University

Management Committee

Mikko Paalanen	Aalto University
Henri Godfrin	CNRS, Grenoble
George Pickett	Lancaster University

Management Office

Project coordinating person	Mikko Paalanen
Administrator:	Katariina Toivonen
WEB-officer:	Matti Laakso
Legal advisor:	Otaniemi Innovation Center

Scientific Advisory Board

Anne Davies	Cambridge University, UK
Giorgio Frossati	Leiden University, The Netherland
Andrei Geim	University of Manchester, UK
Kimitoshi Kono	Riken, Japan
Li Lu	Chinese Academy of Sciences, Beijing, China
Douglas Osheroff	Stanford University, USA
Klaus von Klitzing	Max Planck Institute, Stuttgart, Germany

Transnational Access Activities

TA-Team Coordinator:	Mikko Paalanen
TA1 Leader:	Mikko Paalanen
TA2 Leader:	Henri Godfrin
TA3 Leader:	George Pickett

Networking Activities

NA-Team Coordinator:	Henri Godfrin
NA1 Leader:	Mikko Paalanen
NA2 Leader:	Mikko Paalanen
NA3 Leader:	Peter Skyba (with Tjerk Oosterkamp, Dominik Zumbuhl and Rob Blauuwgeers)
NA4 Leader:	Henri Godfrin

Joint Research Activities

JRA-Team Coordinator:	George Pickett
JRA1 Leader:	George Pickett
JRA2 Leader:	Jukka Pekola
JRA3 Leader:	Henri Godfrin
JRA4 Leader:	Christian Enss

Problems during the reporting period and changes in the consortium

Microkelvin was officially started on April 1, 2009. However, due to various delays in finalizing and signing the Grant Agreement, the beneficiaries received the first distribution of EU-funding in August, 2009, i.e. over 4 months after the official starting date. This delay is reflected in the slow start of all project activities and in delays of deliverables. No changes have occurred in the structure of the consortium during the reporting period.

Project meetings, dates and venues (http://www.microkelvin.eu/microkelvin-events.php):

1. *Microkelvin Kick-off and General Assembly Meeting*
   Date: 3.4. 2009
   Place: Espoo, Finland

2. *EU Workshop on Management of EU-projects*
   Date: 14.-15.5.2009
   Place: Espoo, Finland

3. *Lancaster Workshop on Management of EU-projects*
   Date: 30.11. 2009
   Place: Lancaster, UK

4. Email Meeting of General Assembly
   Voting on the placement of a MICROKELVIN-sponsored cryogen-free dilution unit
   Date: 20.10. 2009

5. *JRA4 ProjectMeeting: Workshop on*
   Physics and Metrology at very low Temperatures
   Date: 10.12.2009
   Place: Berlin, Germany

6. *International Workshop on Vortices, Superfluid Dynamics, and Quantum Turbulence*
   Date: 11.-16.4.2010
   Place: Lammi, Finland

7. *JRA2 Kick-off Meeting*
   Date: 24.-25.6. 2010
   Place: Ystad, Sweden

8. *Microkelvin Management Meeting*
   Date: 1.8. 2010
   Place: CNRS, Grenoble, France

9. *Microkelvin Review and User Meeting,*
   Date: 14.-16.10.2010
   Place: Espoo, Finland

Altogether 8 management meetings were held (see above) during the reporting period. The General Assembly held two face-to-face meeting (#1 and #9) and one email meeting (#4). In two of the

Meetings (# 2&3) the finance officers of the three Transnational Access giving sites (AU, CNRS, Lancaster) were lectured about financial management of access giving infrastructures in FP7. Two other meetings (#s 5 and 7) were dedicated for launching Joint Research Activities 4 and 2. Two workshops are currently in preparation:

10. *Workshop on JRA4 activities and technology transfer*
    Date: 5.11.2010
    Place: Heidelberg, Germany

11. *Microkelvin workshop on all JRA activities*
    Date: March, 2011
    Place: Smolenice, Slovakia

Changes in the legal status of the beneficiaries

The legal status of the Coordinator of MICROKELVIN was changed on January 1, 2010, from a public university governed by the Ministry of Education to a private university governed by a foundation. At the same time the name of the coordinator changed from Helsinki University of Technology to Aalto University (AU).

Development of the Project website

The MICROKELVIN web-site www.microkelvin.eu was designed in collaboration with Showtime Studios, London, and opened on June 17, 2009. The web-site contains a public domain and an intranet domain for partners only. In the public domain one can find information about objectives, structure, joint research activities, networking activities, and transnational access activities. It also contains the applications and reports of accepted transnational access projects as well as publications produced within various activities.

Transnational Access Activities

Selection Panel:

The Selection Panel was elected by the General Assembly on April 3, 2009. The following scientists served in the Selection Panel during the reporting period:
Mikko Paalanen, Aalto University, Finland (chair)
Henri Godfrin, CNRS, Grenoble, France
George Pickett, Lancaster University, UK
John Saunders, Royal Holloway, University of London, UK
Peter Skyba, Slovakian Academy of Sciences, Kosicé, Slovakia
Jan Kees Maan, Radboud University Nijmegen, The Netherlands
Per Delsing, Chalmers University of Technology, Gothenburg, Sweden
Paul Leiderer, University of Konstanz, Germany
Rudolf Gross, Walther Meissner Institut fuer Tieftemperatur Forschung, Garching, Germany

Mikko Paalanen, Henri Godfrin and George Pickett are the local leaders of the three MICROKELVIN transnational access sites. John Saunders and Peter Skyba are MICROKELVIN partners. The four other members of the Selection Panel are not beneficiaries of Microkelvin.

During the reporting period the management office received 18 transnational access applications. The applications were sent to the members of the selection panel by email. Their acceptance was obtained also by email on average within two weeks. No applications were rejected. This reflects the careful planning and discussion of the visits before the applications were submitted. The selection criteria and approved applications can be found on the web-site http://www.microkelvin.eu/project-activities-transnational.php.

During the reporting period 14 transnational access projects were successfully completed in the three access giving facilities (see the table below and http://www.microkelvin.eu/project-activities-transnational.php).
The number of different users was 13 and they came from 8 different European or associated countries (Czech Republic 1, France 2, Israel 1, Poland 1, Slovakia 3, Sweden 1, The Netherlands 1, and United Kingdom 3).

Transnational access promised 1.4. 2009 – 31.3. 2013

Participant number	***Organisation short name***	***Installation***		***Unit of access***	***Min. quantity of access to be provided***	***Estimated number of users***	***Estimated number of projects***
		Number	***Short name***				
1	AU	1	Cryohall	Facility-month	27	18	14
1	AU	2	AU 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 1.4. 2009 -30.9. 2010

Participant number	***Organisation short name***	***Installation***		***Unit of access***	***Transnational access provided***	***Number of users***	***Number of projects***
		Number	***Short name***				
1	AU	1	Cryohall	Facility-month	13.13	9	8
1	AU	2	AU Micronova	Hour	34.5	1	1
2	CNRS	1	CNRS MICROKELVIN	Facility-month	3.63	6	4
3	ULANC	1	MicroKLab	Facility-month	2.03	3	2

Completed Microkelvin Transnational Access projects 1.4. 2009 – 30.9. 2010
http://www.microkelvin.eu/project-activities-transnational.php

Title of the project	Vortex motion and dissipation at very low temperatures in 3He-B TKK 01
User group leader	Ladislav Skrebk, professor
Users	David Schmoranzer, graduate student
Home Institute	Charles University, Prague, Czech Republic
Description of the work	David Schmoranzer participated in the development and installation of the quartz tuning fork measuring probes. He learned quickly the various tasks and became a vital dependable part of the entire effort. It is expected that he will be able to use this experience on quartz tuning fork oscillators in his thesis work. Owing to delays in the reconstruction of the rotating refrigerator installation, the work did not reach during his visit the stage where he would have had a chance to participate in the measurements of Andreev reflection. It is planned that David will participate a second time in this work in November – December 2009 for 2 – 4 weeks. At that point we expect that the experiment will be producing new physical information about dissipation in vortex motions in the $T \rightarrow 0$ limit.
Amount of access given	84 days

Title of the project	Design of mechanical cantilevers for a sub-mK experiment TKK 02
User group leader	Tjerk Oosterkamp, professor
Users	Tjerk Oosterkamp, professor
Home Institute	Leiden University, Leiden, The Netherlands
Description of the work	In Leiden we have developed a system by which to detect a cantilever with very good force sensitivity and position sensitivity that does not require optical detection. Instead it uses a SQUID to read out the change in flux in a nearby coil due to a magnetic particle that is attached to the cantilever. This cantilever may be applied in a range of situations, e.g. as a force sensor for Magnetic Resonance Force Microscopy, as a viscosity measuring device in mixtures of HO and He4, or possibly as a low temperature thermometer. The visit provided a chance to learn about experimental details and design a sub-mK experiment for the cantilevers employing a copper nuclear demagnetization stage. For this it was important that there were one or two discussion partners with the necessary expertise that were willing to help me out.
Amount of access given	9 days

Title of the project	Dissipation in vortex motion TKK 03
User group leader	Victor L`vov, professor
Users	Victor L`vov, professor
Home Institute	Weizmann Institute of Science, Rehevot, Israel
Description of the work	Both experimental and numerical studies indicate that the flow of vortices remains laminar in superfluid 3He-B up to superfluid Reynolds numbers $Re_S \sim 1000$ in a container with axial rotation symmetry. This is in contrast to the unstable rotational spin up and spin down of viscous fluids and of superfluid 4He.

	The reasons which reinforce the unusual stability of laminar flow are the rapidly decaying transients of the highly viscous normal component of 3He-B and the large superfluid vortex core radius of more than 10 nm, which reduces both surface pinning and vortex reconnections. We discussed the influence of finite amplitude perturbations on the stability of vortex flow in the limit of very low temperatures, when the superfluid Reynolds number tends to infinity.
Amount of access given	24 days

Title of the project	Magnetic Q ball TKK 04
User group leader	Yuriy Bunkov, professor
Users	Yuriy Bunkov, professor
Home Institute	Institute de Neél, CNRS, Grenoble, France
Description of the work	In our studies of magnetic Q ball states, which represent Bose-Einstein condensates of magnons in a magnetic trap formed by the order parameter texture, we have succeeded in identifying the ground state and a full series of axially and radially confined excited states. The energies of the excited levels can now be exactly determined and compared with the theoretical estimations. We have also experimented with the Q ball states to measure the superfluid density anisotropy from the influence of rotating vortex-free counterflow on the texture. Similarly the contribution of quantized vortices in the rotating equilibrium state to the order parameter texture can be determined from the influence which rotation exerts on the parameters describing the magnetic trap.
Amount of access given	31 days

Title of the project	Hybrid turnstile for single electrons AU 05
User group leader	Per Delsing, professor
Users	Martin Gustafsson, graduate student
Home Institute	Chalmers University of Technology, Gothenburg, Sweden
Description of the work	The SINIS turnstiles fabricated for this project did not suffer from excessive heating, like samples previously fabricated elsewhere have done. However, the sub-gap leakage current was instead unacceptably high, which led us to investigate the reasons for this in detail. These investigations showed evidence that the high sub-gap leakage is due to thermal noise coupling to the SINIS structure through the high-frequency pumping gate. The collaboration continues after this visit, with efforts to filter away the high-frequency noise, as well as to adjust the overall gate coupling to reach a good trade-off between leakage current and heating.
Amount of access given	25 days

Title of the project	Cross correlations in graphene AALTO 06
User group leader	Maciej Wiesner, senior researcher
Users	Maciej Wiesner, senior researcher
Home Institute	Adam Mickiewicz University, Poznán, Poland
Description of the work	This project investigates cross correlations of a current in a graphene sheet. One of the most informative parameters, in studying the quantum properties of

	a current in mesoscopic samples, is the shot noise (current fluctuations). The current fluctuations are characterized by the 2^{nd} order and higher moments of their probability distribution P. Experimentally, the mean of P is obtained by time averaging, i.e. by dc current. The second moment (the variance) of P, measures the amplitude of the current fluctuations. The third moment (the skewness) measures the asymmetry of the fluctuations. The existence of the third moment is related to the breaking of time reversal symmetry by the dc current. At zero bias, positive and negative current fluctuations are equivalent, so the third moment is equal to zero. Microwave signals will be used to calculate cross-correlation functions which are averaged to improve the signal-to-noise ratio. Values of a normalized cross-correlation function can vary between ±1. Usually one can relate the negative current-current correlation to charge carriers obeying the Pauli exclusion principle (fermions), whereas positive cross-correlation is attributed to bosons. However, two entangled electrons, forming a Cooper pair in the superconductor (the injecting contact), are emitted into different exit leads due to Coulomb repulsion, giving rise to positive cross-correlation. There are experiments showing successful Cooper pair splitting using a quantum wire divided into two quantum dots. Construction of the splitter using a monolayer graphene sheet is the main task of the project. To make an effective Cooper pair injector, the optimization of the transmissivity of the injecting contacts is of vital importance. With an optimized Cooper pair splitter the cross-correlation measurement will be carried out at mK temperatures in Otaniemi.
Amount of access given	92 days

Title of the project	Vortex motion and dissipation at very low temperature in 3He-B AALTO 07
User group leader	Vladislav Skrebk, professor
Users	David Schmoranzer, graduate student
Home Institute	Charles University, Prague, Czech Republic
Description of the work	This project is a continuation of the Andreev reflection measurements on a rectilinear array of quantized vortices – an experiment performed for the first time in a system with a well-defined geometry of quantized vortices, which is essential for comparison with theoretical calculations and numerical simulations. Another important benefit is the calibration of the thermal resistance of the orifice of the sample container (by both steady-state and dynamic methods) and of the residual heat leak to the container. These will become essential parameters for future *in situ* experiments on the dissipation from the propagation of a turbulent vortex front along the long rotating cylinder. A furher new result is a mathematical model, which helps to gain insight in the heat transport dynamics, but ultimately will have to be supplemented by a direct simulation of the quasiparticle motion through the sample volume. A couple of setbacks and delays were encountered. First, the belt broke which provides the rotation drive to the cryostat, causing a three day delay in the measurements. The first replacement belt turned out to be rough and reduced the stability of rotation. Secondly, the measurements on Andreev reflection turned out to depend on the stability of the heat leak to the sample container. Since it varies on a daily basis, extra noise is accumulated in the results unless the data points are essentially individually calibrated. Finally, the second quartz tuning fork oscillator suffered from unstable operation, owing to gradual mechanical break down. These difficulties did not prevent the completion of this project. The results can now be compared to simulation calculations and prepared for publication.
Amount of access given	31 days

Title of the project	Vortex motion and dissipation at very low temperatures in 3He-B AALTO 08
User group leader	Andrei Golov, professor
Users	Paul Walmsley, post-doctoral researcher
Home Institute	University of Manchester, Manchester, UK
Description of the work	The behaviour of ^{3}He-B in a cylindrical container following a sudden stop of rotation, known as spin down of the superfluid component to rest, was investigated at low temperatures ~ 0.2 Tc. Laminar flow of quantized vortices was found to remain stable down to below 0.2 Tc, with characteristic decay times of up to 5000 s, following the stop of rotation. When the AB interface was present, the decay was observed to be much faster and the counterflow peak in the NMR spectrum noticeably differed from that during the usual laminar response (which corresponds to a solid-body-like radial distributionof the azimthully circulating large-scale counterflow velocity). The NMR spectra were found to be consistent with a model where there were no vortices in the central region of the cylinder but instead they were concentrated in a twisted configuration in an outer shell close to the cylinder wall. This is because the mutual friction in the A-phase is orders of magnitude higher than in the B-phase. The rapid radial motion of the A-phase vortices to the cylinder wall, during the spin down, creates a vortex-free hollow in the B-phase at the AB interface. Differences in azimuthal vortex motion between the two phases results in the vortices in the B-phase becoming helically twisted around the cylinder axis. The inhomogeneous twist produces reconnections and turbulence among the vortices in the B phase, which results in a more rapid spin down. Subsequent spin ups were much slower compared to the case where there was no AB boundary present. This is explained by the almost complete absence of remanent vortices after the previous spin down experiment (in the presence of the AB interface).
Amount of access given	35 days

Title of the project	Surface waves at the solid-liquid interface of a 3He crystal in 3He superfluid AALTO 09
User group leader	Shaun Fisher, professor
Users	Viktor Tsepelin, lecturer
Home Institute	Lancaster University, Lancaster, UK
Description of the work	The sample container design has been finalized with detailed placement of the components inside the inner chamber. The manufacturing of the inner parts of the container (heat exchanges, thermometers, etc.) has been started. Vibrating resonators have been selected for the inner cell, tuning forks have been tested and are ready to be mounted in the container. Progress in this project has been reviewed regularly. Some of the heat links were found to be inadequate, as their residual resistance ratio (resistance at 300 K compared to that at 4.2 K) was too low. The purity of the metal of the heat links needs to be checked and possibly improved.
Amount of access given	7 days

Title of the project	Bose-Einstein condensate of magnons in rotating superfluid 3He AALTO 10
User group leader	Yuriy Bunkov, professor
Users	Pierre Hunger, graduate student
Home Institute	Instituté de Néél, CNRS, Grenoble, France
Description of the work	The low-temperature coherently precessing NMR mode in superfluid 3He-B can be understood as condensation of magnons in a magnetic trap formed by the order parameter texture. This non-local NMR precession mode has been investigated thoroughly recently, since it promises to provide a new sensitive tool for the study of the very low temperature regime. These measurements have been conducted with continuous-wave excitation, but relaxation losses can be studied by suddenly turning off the CW pumping. The slow decay of the free induction signal can then be recorded. Our analysis of the free decay signal shows that an excited state relaxes without pumping to the ground state. The process which leads to this transition is now under theoretical studies. New and important information about the properties of Bose-Einstein condensates in excited states was obtained. A similar experiment in atomic gases has not yet been done!
Amount of access given	32 days

Title of the project	Quasiparticle excitations generated by superfluid turbulence AALTO 11
User group leader	Victor L´vov, professor
Users	Victor L`vov, professor
Home Institute	The Weizmann Institute of Science, Rehevot, Israel
Description of the work	Dissipation from the motion of quantized vortices at the very lowest temperatures is of great current interest in the study of coherent quantum systems. At higher temperatures the source of dissipation is the damping in vortex motion known as 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. This mechanism of dissipation approaches zero in the zero temperature limit, when the cloud of normal excitations becomes rarefied. In a rotating cryostat one can explore the motion of vortices as a response to a change in the rotation velocity, and by comparing the results for different initial conditions. The unsettled question concerns the zero temperature limit: Is dissipation in vortex motion indeed approaching zero or are there new mechanisms which govern the superfluid dynamics and become measurable at the lowest temperatures? The MicroKelvin collaboration provides an opportunity to study these questions experimentally in the fermion superfluid 3He-B by means of a rotating cryostat. With this apparatus 3He-B is cooled to below 0.2 Tc in rotation which can be controlled to within ±1 circulation quantum. Measurements on the spin-up and spin-down responses of the superfluid component under varied conditions have shown that vortices respond instantaneously to changes in the rotation velocity down to very low densities of normal excitations, where their mean free path is much longer than the sample diameter. However, dissipation strongly depends on vortex polarization and on reconnections both in the bulk volume and on the surface of the container, *i.e.* on whether vortex flow is laminar or turbulent. Two different types of vortex motion have been studied at the lowest temperatures: the turbulent propagation of a precessing vortex front along the rotating column of superfluid where dissipation approaches a con-

	stant but finite value, and the laminar spin down or spin up of the superfluid component after an abrupt change of rotation velocity, where dissipation in the bulk volume is caused by mutual friction and thus vanishes, when $T \rightarrow 0$.
Amount of access given	24 days

Title of the project	Late-time dynamics of quantized vortices generated after absorption of a neutron in superfluid 3He-B CNRS 01
User group leader	Andrei Golov, professor
Users	Andrei Golov, professor
Home Institute	University of Manchester, Manchester, UK
Description of the work	Reworked plans were analyzed for new measurements on neutron irradiated superfluid 3He in the T –> 0 limit, where the dominating mechanism responsible for vortex formation is the Kibble-Zurek phenomenon. It was concluded that, without the rapid spreading of vortices nucleated within an initial localized hot spot in otherwise homogeneous bulk superfluid, it is unlikely that the vortex density will survive the time required for calorimetric measurements. Moreover, alternative inhomogeneous mechanisms of vortex nucleation and multiplication, working in parallel with the Kibble-Zurek mechanism and mainly caused by counterflow currents, are expected to be important. It was thus concluded that further analytical and especially numerical modelling is required for a better understanding of the processes involved. This analysis will lead to recommendations for the most appropriate conditions for our forthcoming experiments.
Amount of access given	42 days

Title of the project	Quantum turbulence generated and detected using a floppy wire LANCASTER 01
User group leader	Peter Skyba, professor
Users	Marcel Clovecko, post-doctoral researcher
Home Institute	Institute of Experimental Physics, SAS, Kosicé, Slovakia
Description of the work	We successfully prepared new vibrating resonator devices, installed, and tested them in liquid helium. A wire with an attached grid was measured in normal and superfluid 4He. The measurements were compared with the wire's ac response which we measured in the same way as a conventional vibrating wire resonator (its resonant frequency was about 50 Hz). The wire position was successfully calibrated from the induced voltage as a function of DC current. To a good approximation, the deflection is directly proportional to the DC current so it is relatively simply to calibrate. We demonstrated that the technique provides a very accurate measurement of the position of the loop with good time resolution. Rather than stepping the DC current, we found that linear ramps worked much better, and allowed us to control the transient velocities over a wide range. Typical ramp times were in the range of 10 to 100 ms. We were able to determine the instantaneous velocity of the loop as a function of the instantaneous drive force. The wire has a relatively high Q factor so that damped oscillations were readily seen. We compared the behaviour with calculations based on a linear harmonic oscillator. More measurements have to be done to fully understand this behaviour. A floppy wire will be installed in a new cell for experiments in superfluid 3He. Our results were very useful in developing the design and measurement

	techniques. The device itself is quite versatile and may find many applications to other areas of quantum fluids and solids research.
Amount of access given	25 days

Title of the project	Novel type of heat exchangers for nuclear cooling refrigerators LANCASTER 02
User group leader	Peter Skyba, professor
Users	Slavomir Cabani and Emil Gazo, graduate students
Home Institute	Institute of Experimental Physics, SAS, Kosicé, Slovakia
Description of the work	The goal of this project was to transfer the techniques and knowledge concerning the design and manufacture of state-of-the-art discrete (step) heat exchangers between the laboratories in Lancaster and Kosice. We will directly apply the newly acquired knowledge and skills in the design and fabrication of much improved heat exchangers for our dilution refrigerators in Kosice. This will also be valuable for constructing new experimental cells and cooling stages used for superfluid 3He research at Kosice. We have also learnt at Lancaster valuable new techniques for building cooling machines with advanced vibration isolation techniques and how to measure and optimise the cooling performance of these refrigerators.
Amount of access given	36 days

Title of the project	Dynamic structure factor of 2-dimensional liquid 3He beyond the particle hole band CNRS 02
User group leader	Krotscheck, Eckhard, professor
Users	Panholzer, Martin, post-doctoral research associate
Home Institute	Johannes Kepler University of Linz, Austria
Description of the work	Two-dimensional 3He, a simple 2D Fermi liquid, displays a well defined collective mode at high wave-vectors. The observed density excitation is similar to the phonon-roton mode well known in 4He. This striking effect is well beyond the scope of Landau's theory of Fermi Liquids. It has been successfully described by the many-body "two-particle two-hole" theory developed by the Linz group. It was highly desirable to explore the dynamics of the system at elevated wave-vectors, to follow the newly discovered dispersion relation branch at high energies. The objective of the present experiment was to investigate the collective zero-sound mode of two-dimensional liquid 3He films at high wave-vectors and energies, at very low temperatures (less than 100 mK). The sample cell has been prepared at the TA2 facility. The characterization of the 3He samples on 4He preplated graphite was performed by adsorption isotherms (November 9-11). A complete neutron scattering experiment using the TA2 very low temperature facilities was then performed at the ILL reactor (Nov 12-17). A complete determination of the dynamic structure factor $S(q, \omega)$ of liquid 3He films of atomic thickness has been made at a neutron wavelength of 0.41 nm. The data obtained increase substantially the range where the zero sound mode is observed. The existence of a well defined collective excitation at elevated (k, ω) is confirmed by our data analysis, performed in Linz and Grenoble. Final results were obtained April 5-9, 2010, when the data analysis was concluded. Manuscripts were subsequently submitted to Journal of Low Temperature Physics for publication.
Amount of access given	15 days

Title of the project	Dynamic structure factor of 2-dimensional liquid 3He beyond the particle hole band CNRS 02
User group leader	Krotscheck, Eckhard, professor
Users	Krotscheck, Eckhard, professor
Home Institute	Johannes Kepler University of Linz, Austria
Description of the work	See above (Panholzer, Martin)
Amount of access given	5 days

Title of the project	Upgrade of pulse-tube cooled dilution refrigerator which is used for the optimization of particle detectors, operated in the Gran Sasso underground laboratory CNRS 03
User group leader	Giuliani, Andrea, professor
Users	Giuliani, Andrea, professor
Home Institute	University of Insubria, Como, Italy
Description of the work	Our team in Como is involved in the Project CUORE, investigating the neutrino-less Double Beta Decay of the isotope Te-130 in an experiment located in the Gran Sasso underground laboratory. For this purpose, very low temperature bolometers are used. Several key parameters influence the quality of the system: the minimum temperature, the consumption of cryogenic fluids, and the refrigerator cooling time. For this reason, we wanted to benefit from the latest improvements in very low temperature technology, through the Grenoble TA2 facility of the FRP7 Microkelvin Infrastructure. The work performed within this project consists of the design and construction of a new condensation stage on the pulse-tube cryocooler to reduce the mixture condensation time. This is now completed. The second part of the project, i.e. the development and construction of new heat exchangers to reduce the minimum temperature, is presently on-going, undertaken essentially by TA2 technical and scientific personnel. A second visit by the Como team will take place for the final tests of the equipment.
Amount of access given	7 days

Title of the project	Upgrade of pulse-tube cooled dilution refrigerator which is used for the optimization of particle detectors, operated in the Gran Sasso underground laboratory CNRS 03
User group leader	Giuliani, Andrea, professor
Users	Rusconi, Claudia, post-doctoral researcher
Home Institute	University of Insubria, Como, Italy
Description of the work	See above (Giuliani, Andrea)
Amount of access given	7 days

Title of the project	Nonlinear NMR in superfluid 3He in aerogel CNRS 04
User group leader	Golov, Andrei, professor
Users	Zmeev, Dmitri, post-doctoral research associate
Home Institute	Schuster Laboratory, University of Manchester, UK
Description of the work	The objective of this project is to investigate the properties of the non-linear NMR modes in superfluid 3He in aerogel under different conditions. In NMR experiments performed on the DN1 instrument of TA2, we investigated superfluid 3He in radially compressed aerogel samples. We used for this purpose high sensitivity, very low power, continuous-wave NMR instrumentation developed at the TA2 facility. New signals were observed close to Tc. Contrary to all know signals in superfluid 3He, these display a negative frequency shift. These observations are presently under theoretical investigation.
Amount of access given	33 days

3.3 Deliverables and milestones tables

Deliverables

TABLE 1. DELIVERABLES[5]									
Del. no.	Deliverable name	WP no.	Lead beneficiary	Nature	Dissemination level[4]	Delivery date from Annex I (proj month)	Delivered Yes/No	Actual / Forecast delivery date	Comments
D1	Opening and operation of Management Office	NA1	AU	O	PU	1	Yes	1	Delivered
D2	Opening and maintaining of web-site	NA1	AU	O	PU and PP	1	Yes	1	Delivered www.microkelvin.eu
D1	User Meeting	NA2	AU, CNRS ULANC	R	PU	13	No	19	Delivered Oct 14-16, 2010
D2	Training sessions for users	NA2	AU, CNRS ULANC	O	PU	13	No	19	Delivered Oct 16, 2010
D1	Opening of the Cryo-Tools data base (6) and E-mail lists of labora-tories and industries (8)	NA3	CNRS	O	PU	6, 8	Partially		Data base under construction
D2	LT-X workshops	NA3	All partners	R	PU	18	Yes		3 workshops

[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).

D1	Invitations to leading scientists and young researchers of Third Countries to MICROKELVIN meetings	NA4	CNRS	O	PU	12	Yes		See NA4 report
D1	Analysis of the combined ex-chip and on-chip filter performance (Task1)	JRA2	AU	R	PU	18	Yes		Report accepted for publication
D1	Report on micro-fabri-cated silicon vibrating wires tested in super-fluid 3He at 100 μK	JRA3	CNRS	R	PU	12	No - Mis-take in Annex I delivery date	30	See JRA3 report
D1	Report on contactless decoherence and heat capacity measurement method (Task 1)	JRA4	HEID	R	PU	18	Yes		Report accepted for publication
D3	Report on the perfor-mance of microcoils coupled to low induc-tance SQUIDs (Task 2)	JRA4	RHUL	R	PU	12	Yes		Report published Measurements of new coils in progress
D4	Report on the perfor-mance of wide band-width SQUIDs (Task 2)	JRA4	RHUL	R	PU	18	No		Delay owing to clean-room equipment upgrade
D5	Report on current sensing noise thermo-meter for ultra low temperature (Task 3)	JRA4	RHUL	R	PU	12	Yes		See JRA4 report
D6	Report on 195Pt-NMR thermometer for ultra low temperatures (Task 3)	JRA4	PTB	R	PU	18	Yes		See JRA4 report

D7	Report on metrology-cally compatible CBT sensor (Task 3)	JRA4	AU	R	PU	12	Yes		See JRA4 report
D8	Report on 10 mK (100 μK) GaAs quantum dot thermometer (Task 3)	JRA4	BASEL	R	PU	12	Yes		Preprint available about thermometry to 18 mK

Milestones

TABLE 2. MILESTONES							
Milestone no.	Milestone name	Work package no	Lead beneficiary	Delivery date from Annex I	Achieved Yes/No	Actual / Forecast achievement date	Comments
M1	Advanced filtering and isolation system designed and built	JRA1, Task 1	ULANC	18	Yes		Preprint available
M5	Pulsed-tube based dilution refrigerator and conventional (miniature nuclear) stage ready for integration at CNRS (AU)	JRA1, Task 2	CNRS (AU)	12 (18)	Partially	30 (25)	Dilution refrigerators working down to a minimum temperature of 20 mK (10 mK) - see JRA1 report
M7	Complete the vibration isolation platform	JRA1, Task 3	ULANC	6	Yes		
M1	Choice of the thermalization strategy	JRA2, Task 1	BASEL	12	Yes		
M2	Choice of the ex-chip filtering technique	JRA2, Task 1	BASEL	18	Yes		
M5	Design of membrane patterning and microcoolers	JRA2, Task 3	AU	18	Yes		
M1	Determination of the energy released by a vortex tangle with known line density	JRA3, Task 1	ULANC	12	Yes	18	Two publications in preparation (preprints available)

M1	Contactless setup to investigate decoherence of solids	JRA4, Task 1	HEID	18	Yes		Report accepted for publication
M3	SQUID NMR detection of nano-scale 3He samples at sub-mK temperatures	JRA4, Task 2	RHUL	12	Yes		3 publications
M6	Realization and measurement of 10 mK CBT sensor	JRA4, Task 3	AU	15	Yes		Thermometry down to 11.5 mK (see JRA4 report)
M1	MICROKELVIN kick-off meeting	NA1	AU	1	Yes		April 3, 2009
M2	Management Committee email meetings	NA1	AU	1, 4, 8.	Yes		
M3	General Assembly and Advisory Board meetings	NA1	AU	1, 12, 24, 36	Yes		
M4	Mid-term review	NA1	AU	30			
M1	Appointment of SP	NA2	AU	1	Yes		April 3, 2009
M2	Meetings of Selection Panel (email meetings)	NA2	AU	1, 13, 37 (6, 12, 18…)	Yes		Conducted by email to discuss each application
M1	Meetings of Dissemination Committee	NA3	CNRS	1, 13, 37	Yes		
M1	Meeting for the creation of ECS	NA4	CNRS	10	Yes		See NA4 report
M2	Formal creation of Third-Countries Associated Low Temperature Net-work	NA4	CNRS	10	Yes		See NA4 report

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 1 (AU)

Work Package	Item description	Amount	Explanations
JRA2	*Personnel Costs*	*40 385,52 €*	*Salary for post doc (13,6 person months)*
JRA3	*Personnel Costs*	*28 668,01 €*	*Salary for senior researcher (4 person months)*
NA1	*Personnel Costs*	*35 368,53 €*	*Salaries for Project coordinating person, administrator and web-site officer (5 person months)*
NA1, NA2	*Other direct costs*	*24 944,87 €*	*Kick-off 2009, Lammi workshop 2010*
TA1	*Other direct costs*	*30 649,43 €*	*Travel costs of MicroKelvin visitors*
TA1	*Access costs*	*146 094,00 €*	*Cryohall access costs*
NA1	*Subcontracting*	*4 202,17 €*	*Construction of MicroKelvin web-site*
NA1, JRA2	*Other direct costs*	*9 627,34 €*	*Miscellaneous*
	TOTAL DIRECT COSTS	*319 939,87 €*	

TABLE 3.4.2 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 2 FOR THE PERIOD 1 (CNRS)

Work Package	Item description	Amount	Explanations
JRA	*Personnel costs*	*87 284,23 €*	*12,27 M/M on JRA (1 post-doc 6 months, and CNRS researchers 6,25 months)*
JRA	*Consumables*	*1 934,99 €*	*Connectors, fine tubes, silver foil, small vacuum parts*
NA	*Personnel costs*	*9 156,09 €*	*0,79 M/M CNRS Coordination of Networking Activities.*
NA	*Travels costs*	*7 405,66 €*	*Travel & subsistence expenses of Microkelvin partners to attend Microkelvin meetings; Third countries Microkelvin network: partial support for Microkelvin meetings.*
TA2	*Support / Access to CNRS / Facilties users*	*37 418,34 €*	*Travel & subsistence expenses of TA2 users, and corresponding Access cost.*
	TOTAL DIRECT COSTS	*143 199,31 €*	

TABLE 3.4.3 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 3 FOR THE PERIOD 1 (ULANC)

Work Package	Item description	Amount	Explanations
JRA3 task 2	*Personnel costs*	*21 055,67 €*	*Post-doc salary for 5 months*
JRA1 task 3	*Personnel costs*	*14 596,05 €*	*Post-doc salary for 4 months*
TNA/JRA1	*Personnel costs*	*7 429,29 €*	*GRP costs*
TNA	*Personnel costs*	*2 880,87 €*	*SNF costs*
RTD	*Components/ consumables*	*15 432,40 €*	*Various items required for construction of new microkelvin facility JRA1 task 3*
Management	*Coordination/ networking*	*1 152,11 €*	*Travel and subsistence for training and information visit to TKK Helsinki (Y Fox & B Colman)*
TNA	*Access*	*10 877,18 €*	*Travel and subsistence for visitor access to facility*
	TOTAL DIRECT COSTS	*73 423,57 €*	

TABLE 3.4.4 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 4 FOR THE PERIOD 1 (HEID)

Work Package	Item description	Amount	Explanations
JRA3, JRA4	*Personnel costs*	*61 713,93 €*	*Salaries of 3 PhD students (summary 14 person-months) JRA3 1 person month, JRA4 13 person months*
	TOTAL DIRECT COSTS	*61 713,93 €*	

TABLE 3.4.5 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 5 FOR THE PERIOD 1 (RHUL)

Work Package	Item description	Amount	Explanations
JRA2	*Personnel Costs*	*4 702,68 €*	*Salary of Co-PI 0.72 months*
JRA4	*Personnel Costs*	*15 229,28 €*	*Salary of RA 2.4 months and PI 0.94 months*
JRA2/4	*Consumables*	*639,49 €*	
JRA2/4	*Travel*	*1 243,05 €*	
	TOTAL DIRECT COSTS	*21 814,50 €*	

TABLE 3.4.6 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 6 FOR THE PERIOD 1 (SNS)

Work Package	Item description	Amount	Explanations
	TOTAL DIRECT COSTS	*0 €*	

TABLE 3.4.7 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 7 FOR THE PERIOD 1 (SAS)

Work Package	Item description	Amount	Explanations
JRA3	*zal. cu 681/10 skyba france*	*531,00 €*	*QFS 2010 conference and GA meeting of Microkelvin, Grenoble, France*
	TOTAL DIRECT COSTS	*531,00 €*	

TABLE 3.4.8 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 8 FOR THE PERIOD 1 (BASEL)

Work Package	Item description	Amount	Explanations
JRA1, 2 & 4	*personnel costs*	*36 869,47 €*	*Salary of 1 post-doctoral fellow for 8 months*
JRA1	*personnel costs*	*20 188,52 €*	*Salary part time of 1 senior researcher for 14 months*
JRA2	*personnel costs*	*7 204,37 €*	*Salary part time of 1 senior researcher for 14 months*
JRA4	*personnel costs*	*10 338,47 €*	*Salary part time of 1 senior researcher for 14 months*
JRA1, 2 & 4	*Major cost: liquid He (consumables)*	*9 046,86 €*	*Liquid Helium cost for operation of dilution refrigerators*
JRA1, 2 & 4	*other direct cost*	*280,55 €*	*Salary of 1 post-doctoral fellow for 8 months*
	TOTAL DIRECT COSTS	*83 928,24 €*	

TABLE 3.4.9 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 9 FOR THE PERIOD 1 (DELFT)

Work Package	Item description	Amount	Explanations
JRA2	*Travel costs*	*812,50 €*	*Travel costs T. Klapwijk - Helsinki Kick-off meeting*
JRA2	*Consumables*	*1 731,43 €*	*Consumables - Helium*
	TOTAL DIRECT COSTS	*2 543,93 €*	

TABLE 3.4.10 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 10 FOR THE PERIOD 1 (BLUEFORS)

Work Package	Item description	Amount	Explanations
JRA1	*Personnel costs*	*26 221,53 €*	*Salary for three employees total of 6,82 pm*
	TOTAL DIRECT COSTS	*26 221,53 €*	

TABLE 3.4.11 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 11 FOR THE PERIOD 1 (UL)			
Work Package	Item description	Amount	Explanations
WP1&4/JRA 1&4	*Personnel costs*	*40 777,67 €*	*JRA1 600 hours ~ 4,73 pm and JRA 777hours ~ 5,13 pm*
WP4/ JRA4	*Personnel costs*	*31 775,61 €*	*888 hours ~5,83 pm*
WP4/JRA4	*science workstation*	*2 618,00 €*	*to take measurement data*
WP4/JRA4	*electronic components*	*198,97 €*	*to assess vibrations*
Wp1/JRA1	*travel to kick-off meeting*	*494,42 €*	*travel to kick-off meeting*
	TOTAL DIRECT COSTS	*75 864,67 €*	

TABLE 3.4.12 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY 12 FOR THE PERIOD 1 (PTB)			
Work Package	Item description	Amount	Explanations
JRA4	*Personnel costs*	*20483,25 €*	*Local project leader 3 pm* *Senior Researcher 0,9 pm*
	TOTAL DIRECT COSTS	*20483,25 €*	

Annex to 18-month Periodic Project Report

European Microkelvin Collaboration
MICROKELVIN

Review & User Meeting 14 – 16 Oct, 2012
General Assembly 15 Oct, at 14:30-15:00

Current General Assembly members present:

George Pickett, ULANC (Chair)
Christian Enss, HEID
Matti Krusius, AU (Acting Coordinator)
John Saunders, RHUL
Peter Skyba, SAS
Rob Blaauwgeers, BlueFors
Henri Godfrin, CNRS
Tjerk Oosterkamp, UL
Thomas Schurig, PTB
Dominik Zumbuhl, BASEL

DELFT and SNS, Pisa: not represented.

Venue: Lecture hall 161, Low Temperature Laboratory, Aalto University

AGENDA

1. **Membership matters.** Appointment of Acting Coordinator until Mikko's future rehabilitation becomes clearer.
   Are all present members of the General Assembly prepared to continue?

2. **Proposal to request an extension of MICROKELVIN for one further year.** Pros and cons.

3. **Suggestion to add new Task to JRA3.**
   Would this in any case fit into Task 2?

4. **Difficulties of Translating EU funding assumptions**.
   Here in Lancaster we have difficulties mapping the EU funding assumptions onto the university practice. Is this general?

5. **Review report matters.**

6. **Any other business.**

MINUTES OF THE GENERAL ASSEMBLY

1. Greetings and wishes of recovery were sent to the Coordinator of Microkelvin, **Mikko Paalanen,** who suffered a brain hemorrhage on Sep 24 and could not participate in the meeting. The greetings were sent in the form of a card.

2. Membership matters:

- All Members of the General Assembly agreed to continue their work.
- Matti Krusius was selected as acting Coordinator of Microkelvin during the absence of Mikko Paalanen.
- George Pickett was selected as chairman of the Selection Panel during the absence of Mikko Paalanen. Matti Krusius is replacing Mikko Paalanen as Selection Panel member.

3. **18 month review report:**

- Owing to the accident affecting the Canfranc Underground Laboratory and the recent plans for an extension of the French Modane Underground Laboratory, financial support expected from French sources to install and operate the ULTIMA equipment underground will only become available shortly before the completion of the Microkelvin contract. As a result, the underground experiments planned in Task 5 of JRA3 may not be feasible. Nevertheless, the above-ground development work for ULTIMA to be made in the Grenoble Laboratory will proceed as initially planned. The 6 man-months allocated to the underground work will be redistributed as follows; two man months to a more detailed study of the interaction of neutrons with the ^{3}He target within Task 5, and two man months each for increasing the support to CNRS activities in JRA1 and in JRA4.
- The decision was formed not to propose an extension to the four-year Project Period and not to include new amendments to the Project Tasks. This was recommended by the Project Officer and the Reviewer. They did not find it necessary that a new Task 6 is generated within JRA3. They also proposed that additional man months could be allocated to JRA2 and JRA4 (for those Tasks where the project is behind schedule) in the amount which was foreseen for the Dark Matter observatory. Such changes can be made by redistributing funds among the different JRAs and milestones inside the CNRS budget. CNRS can thus keep the present total budget frame and funds do not need to be transferred to other partners.
- In accordance with these recommendations, the decision was formed not to propose changes to the list of tasks in JRA3. Recent studies on the liquid ^{3}He phases at the very lowest temperatures performed by several Microkelvin partners within JRA3 have produced interesting new results, which are needed to achieve the next milestones. In the 18-month Periodic Project Report this work will be included within the existing tasks in the appropriate context.
- Also future concerted research on Majorana surface states will be included in JRA3 under the various existing Tasks. No new formulation of tasks or milestones will be performed.
- The total man power involved in reaching the different milestones and deliverables in the various tasks should be estimated more carefully in our Reports.

4. **Networking funds.** A number of consortium members have expressed the view that there should be a mechanism to facilitate intersite visits within the JRA activities. This is especially important since many of these activities concern the collaborative development of equipment and capability. Therefore, on the advice of the Project Officer, networking money will be allocated for visits among the partner laboratories to reinforce the JRA activity and associated knowledge transfer. This will not impact nega-

tively on existing Networking Activities: we have been able to organize 4 major events within NA, clearly achieving results beyond the expected target.

In practice, the NA funding will be redistributed by the NA coordinator (CNRS), after submission of a Microkelvin Proposal (form downloadable from the Microkelvin web site) and its approval by the Dissemination Committee to the partners in two possible ways:

a) For short visits involving a few researchers: reimbursement of expenses will be made by CNRS following the standard procedure.

b) Meetings involving many participants: CNRS will transfer the funds to the partner organizing the event, who will take care of the costs (travel, housing, subsistence), and will include them in his Microkelvin financial report to the EU.

5. A **Microkelvin workshop** will be organized by P. Skyba in the spring of 2011 in Slovakia. The topics will be decided during the next few months.

A **Microkelvin workshop** will be organized on JRA4 activities and technology transfer by C. Enss. The meeting will take place Nov 5, 2010, at the Kirchhoff-Institut für Physik, Universität Heidelberg,

http://www.kip.uni-heidelberg.de/index.php?lang=en

6. **Internal communication** on research matters and progress in the different tasks will be improved.

Otaniemi Oct 15, 2010

Matti Krusius
Meeting secretary

George Pickett
Chairman, General Assembly