Institution: Royal Holloway, University of London

Unit of Assessment: B9 Physics

Title of case study:
The London Low Temperature Laboratory: impact on ULT thermometry and cryogenic platforms

1. Summary of the impact

The London Low Temperature Laboratory (LLTL) led by Professor Saunders in the Department of Physics, has developed novel ultra-low temperature (ULT) platforms and instrumentation alongside its programme of fundamental research.

- The group's research has acted as a key driver for improvements in scientific instrumentation, refrigeration and thermometry, which have met critical market needs, including the capability to measure the absolute temperature in these extreme environments.
- It has led to a direct economic impact to industry through the development of new commercial scientific instrumentation products.
- Key partners in delivering impact are Oxford Instruments Nanoscience (OIN), the European National Measurement Institutes (NMIs), and the European Microkelvin Consortium.

2. Underpinning research

Saunders joined Royal Holloway in 1986, following the development of the UK's first nuclear refrigeration cryostat while a PhD student at the University of Sussex, and periods at Cornell University, and as a Royal Society University Research Fellow. His research group has carried out fundamental research into quantum fluids and solids at the ULT frontier, publishing over a hundred articles in peer-reviewed journals.

The technical demands of operating in these extreme conditions have led to the insights central to the impacts described in this case.

The production of **cryogenic platforms** to meet these demands was in collaboration with an industrial partner, OIN, who turned the proof-of-principle prototypes into commercial products. We describe research which led to three distinct commercial products:

- The earliest example of impact resulted from a collaboration (supported by a Royal Society Joint Project, 1988-93, and Kapitza Fellowship, 1994) with Prof. Mikheev at Royal Holloway. The concept of using activated charcoal as an internal pumping device in a dilution refrigerator, removing the need for external vacuum systems was successfully applied [1], achieving performance comparable with conventional dilution refrigerators. Mikheev joined OIN in 1994 where subsequent development led to the launch of a new product in 1997, the Kelvinox AST.
- In 1997, to meet the demands for a flexible platform for ULT experiments, compatible with the access required for using SQUID (superconducting quantum interference device) amplifiers, a large sample volume cryostat coupled to extensive access for wiring and services was designed jointly by Royal Holloway/OIN and built by OIN (EPSRC Joint Research Equipment Initiative grant [G1]) [4]. This ULT facility became the prototype of the high-access OIN Kelvinox 400HA cryostat, launched as a commercial product in 1998. The suitability of the facility for SQUID based experiments was demonstrated through the programme of work carried out in [G4].
- The advent of cryogen-free dilution refrigerators, a rapidly growing sector of turn-key low temperature platforms, has been of central importance to the field of new quantum technologies. Within the European Microkelvin consortium [G7] the LLTL has been promoting access to ULT for the nanoscience community. A Royal Holloway/OIN collaboration was the first to successfully combine nuclear demagnetisation with cryogen-free operation to reach sub-mK temperatures [6], launched commercially in July 2013.

A related strand of research, of crucial relevance to ULT research and its technological applications concerns **thermometry**. This has involved partnerships with OIN and with NMIs. An unsolved problem of crucial relevance in low temperature physics was the ability to accurately and conveniently measure the temperature, using a method traceable to international temperature scales. The Royal Holloway group were the first to demonstrate, on the ULT facility described previously, the practicality of a current-sensing noise thermometer (CSNT) [2,3] for operation from 4 K down to below 1 mK [patent P1]. The method exploits DC SQUIDs to detect Nyquist thermal noise in a sensor. The direct link to the Boltzmann constant, k_B, is of particular relevance to the NMIs, with whom we collaborate [4,5] in the dissemination of the Provisional Low Temperature Scale (PLTS-2000). Through the European Metrology Research Programme [G8] we are working to establish a new scale to resolve discrepancies within PLTS-2000. Following [2,3] we have developed an improved simple, practical and fast device, which measures temperature with 1% precision in less than a second. The technology is licensed to OIN, leading to the phasing out of the use of the Cobalt-60 Nuclear Orientation thermometer, to field test their cryostats. This thermometer relies on its natural radioactivity, resulting in extensive regulation for handling and transport, is slow and useful over only a limited temperature range.

The step-change in performance arising from the advances made through our research are transforming thermometry in this temperature range, by providing a thermometer which can cover the entire temperature range, from 4K into the microkelvin regime, with high precision, and without the need for calibration.

3. References to the research

Selected Peer-Reviewed Papers, **author at RHUL;** * denotes papers that best indicate quality.

1) **1994** *Continuously operating cryogenic cycle dilution refrigerator* **P. Mohandas, B.P. Cowan, J. Saunders**, V.K. Chagovets, V.N. Lukashov, **V.A. Maidanov**, N.P. Mikhin, N.F. Omelaenko, E.Ya. Rudavskii and **V.A. Mikheev**, Physica B: Condensed Matter, Volumes 194-196, Part 1, 55-56 (1994).
2) ***2001** *Current sensing noise thermometry using a low T_c DC SQUID preamplifier.* **C.P. Lusher, J. Li, V.A Maidanov, M.E. Digby, H. Dyball, A. Casey, J Nyéki**, V.V. Dmitriev, **B.P. Cowan, J. Saunders**, Measurement Science & Technology, Vol. 12, No. 1, 115 (2001). Awarded **best paper** in Measurement Science and Technology 2001.
3) **2003** *Current-sensing noise thermometry from 4.2 K to below 1 mK using a DC SQUID preamplifier.* **A. Casey, B.P. Cowan, H. Dyball, J. Li, C.P. Lusher, V. Maidanov, J. Nyéki, J. Saunders, D. Shvarts**, Physica B, Vol. 329, 1556-1559 (2003).
4) **2003** *Nuclear magnetic resonance using DC SQUIDs with APF* **A. Casey, B. Cowan, M. Digby, H. Dyball, R. Körber, J. Li, C. Lusher, V. Maidanov, J. Nyéki, J. Saunders**, D. Drung, T. Schurig, Physica C: Superconductivity, Vol. 399, 93-97 (2003).
5) ***2003** *European Dissemination of the ultra-low temperature scale, PLTS-2000*, R Rusby, D Head, D Cousins, H Godfrin, YM Bunkov, R Rapp, F Gay, M Meschke, **CP Lusher, J Li, A Casey, D Shvarts, BP Cowan, J Saunders**, V Mikheev, J Pekola, K Gloos, P Hernandez, S Triqueneaux, M Groot, A Peruzzi, R Jochemsen, A Chinchure, E van Heumen, GE de Groot, W Bosch, F Mathu, J Flokstra, D Veldhuis, Y Hermier, L Pitre, A Verge, B Fellmuth, J Engert. Temperature: Its Measurement and Control in Science and Industry**:** AIP Conference Proceedings Vol. 684, 89-94 (2003).
6) ***2013** *A microkelvin cryogen-free experimental platform with integrated noise thermometry* G Batey, **A Casey**, M Cuthbert, A Matthews, **J Saunders, A Shibahara, arXiv:1307.7049v1,** to be published in New Journal of Physics.

Key Grants, referred to in text as [G#]

1) EPSRC Joint Research Equipment Initiative: *Ultra-low temperature facility for application of SQUID technology to noise thermometry and NMR* (1997-98) EPSRC GR/L24465/01; £62,247 with matching funds from industrial partner (Oxford Instruments). PI J. Saunders.
2) Royal Society Joint Project with PTB Berlin: *Application of SQUIDs to Nuclear Magnetic Resonance and Noise Thermometry* (April 1999- March 2001); £7,600.
3) Royal Society Study Visit from Russia for Dr V Maidanov (Jan - April 2000) £4,325.

4) EPSRC Instrument Development Call: *NMR Instrumentation using DC SQUIDs for experiments at ultra-low temperatures and on room temperature samples* (May 1999- April 2003) EPSRC GR/M51291; £545,597. J. Saunders, C.P. Lusher and B.P. Cowan. (*Final report ranking: outstanding*).
5) *Dissemination of the European Ultra-Low Temperature Scale* (Jan. 2000 – Dec. 2002) EU Framework V, 12 Partners, Contract G6RD-CT-1999-00119; €150,000 to Royal Holloway.
6) West Focus Project for Accessible Research Knowledge (PARK) Fund: *Ultra-Low Temperature Thermometry* (2009); £40,680. PI A. Casey.
7) European Commission FP7: *European Microkelvin Collaboration* (April 2009 – Sep 2013) grant no. 228464, Capacities Specific Programme, Research Infrastructures; €288,000 Royal Holloway share. J. Saunders (PI), P.J. Meeson.
8) European Metrology Research Programme (EMRP): *Implementing the new Kelvin* (June 2012 - 2015) grant JRP-s13 InK. Researcher Excellence Grant (Researcher Dr Aya Shibahara); €287,000.
9) *Application of SQUID NMR to the study of novel p-wave ^{3}He superfluids in regular confined geometries* (April 2005 – March 2008) EPSRC EP/C522877/1; £518,606. J. Saunders (PI), B.P. Cowan, C.P. Lusher, A. Casey; (underpinning grant).

Patents, referred to in text as [P#]

1) US Patent No. 6357912: Current Sensing Noise Thermometer 2002 (Royal Holloway, University of London and J. Li)

4. Details of the impact

The primary beneficiary of our impact is OIN, and through them to a wider community of scientists and industrial facilities that require ULT platforms and reliable, convenient thermometry. The CSNT has also had direct impact on the NMIs that maintain and disseminate the temperature scales.

A strong program of collaboration and joint development with Oxford Instruments Nanoscience, has led to the creation of new innovative products. OIN is a global company that creates high performance cryogenic and cryogen-free environments for ultra-low temperature and high magnetic field applications in physics, chemistry and materials science. The importance of these products has been recognised through a *Queens Award to Industry 2010*, and the *IoP Gold Medal in Business and Innovation* (Dr Graham Batey, 2011). These products have contributed to OIN maintaining its leading world market share. The Technical Director of OIN states in a letter of support: “*By identifying key areas of collaboration and joint development it is clear that RHUL and OIN have been able to use a strong and fruitful partnership for the benefit of the wider scientific community by developing new products, the UK economy by providing employment and commerce and the local scientific community by providing training, collaboration and career development*.” This partnership was formalised through a 2010 Memorandum of Understanding (MoU) between Royal Holloway and OIN. OIN has invested in Royal Holloway through a £200k contribution to a £800k low temperature infrastructure upgrade in 2010. This consisted of a new nuclear demagnetisation cryostat for the study of semi-conductor samples at ULT and a cryogen-free dilution refrigerator which provided the platform for the first demonstration of nuclear cooling below 1 mK on a cryogen-free system. This activity is supported by a matched funding *Impact* PhD studentship.

The impact of the specific products developed is:

(1) The 1994 development of the cryogenic cycling fridge led directly to the 1997 product launch of the Kelvinox AST. OIN built and delivered over 15 such systems up until 2003, with a combined revenue of £1.3M. Most of these systems are still in use today.

(2) The Kelvinox 400HA was developed based upon the prototype produced through the EPSRC Joint Research Equipment Initiative [G1]. This product has been on sale since 1998 and plays an active part in OIN’s current portfolio with over 50 systems delivered, with a combined revenue of over £7M.

(3) Based on the prototype microkelvin cryogen-free experimental platform, OIN have launched in July 2013 the first such product, responding to demand from the Quantum Information Processing

community. OIN are projecting that this field will develop into a global market worth $1B by 2025.

Practical primary thermometry for ULT applications. The impact of the development of the Current Sensing Noise Thermometer comes through its influence on the policies of NMIs such as PTB (Berlin) and NPL (London) and changing the procedures of OIN.

Disseminating the PLTS-2000 scale, where noise thermometry plays a critical role, was achieved through the FP5 funded programme [G5] supported by a Royal Society Study visit [G3]. This emphasized discrepancies in PLTS-2000 [4,5], which are being addressed by the EMRP-funded programme JRP-s13 “Implementing the new Kelvin” [G8]. This EMRP project will arrive at a better determination of thermodynamic temperature.

Through the EMRP project and building on earlier research [2,3], and subsequent development partly funded by the West Focus PARK Fund [G6], in 2009 we developed a practical, fast and user friendly noise thermometer. This provides a practical route for disseminating thermodynamic temperatures to end users. The impact is to enable industrial suppliers of low temperature platforms to factory test the performance, to test on site as part of commissioning, and importantly to allow users/customers themselves to confirm continued operation. Our set-up was successfully tested on the OIN factory site at Tubney Woods, and future OIN cryogen-free systems will be delivered with a current sensing noise thermometer for onsite performance tests, replacing the Cobalt-60 thermometer currently used.

Via our collaboration with PTB [G2, G7 and G9] our work has stimulated the production of a related noise thermometer by Magnicon GmbH, a spin-off company of PTB. Their product, the MFFT-1 (magnetic field fluctuation thermometer), was launched in 2008 at ULT2008, “Frontiers of Low Temperature Physics”, a conference organised at Royal Holloway.

The long standing relationship with OIN has also helped supply their need for high quality postgraduate level staff. Royal Holloway students and staff who went on to work for Oxford Instruments: **Marcio Siqueira,** formerly of OIN, founder of Almax easyLab; **Vladimir Mikheev**, until recently a consultant engineer at OIN involved in development of cryogen-free dilution refrigerators; **Simon Kingsley**, now ULT engineer at OIN; **Junyun Li** of OIN China; **Hetal Patel,** development engineer at OI Molecular Biotools.

5. Sources to corroborate the impact

The work on the development and impact of OIN products can be confirmed by the Technical Director of OIN and, specifically for the Kelvinox 400HA, the OIN Consultant Engineer who collaborated on the project.
The influence on NMIs and temperature scales can be confirmed by the Head of Temperature Standards, National Physical Laboratory, (who is the coordinator of the EMRP project “*Implementing the new Kelvin*”) and the Director, Cryophysics and Spectrometry, Physikalisch-Technische Bundesanstalt Institut, EMRP project partner and European Microkelvin Consortium partner.
Supporting documents:

- MoU between Royal Holloway and Oxford Instruments, for collaborative research projects (2010), and current-sensing noise thermometry licensing agreement (2013);
- http://www.oxford-instruments.com/news/2013/october/new-groundbreaking-cryogen-free-micro-kelvin-refri
- Strategic Partnership Agreement between Royal Holloway and NPL, signed September 2011;
- Report to the European Commission: Development and Evaluation of the Current Sensing Noise Thermometer (June 2004);
- Final report, European Microkelvin Consortium (September 2013).