50 years of dilution refrigeration

Continuous innovation of ultra low temperature research tools

Graham Batey
Oxford Instruments

In the beginning – 1960s

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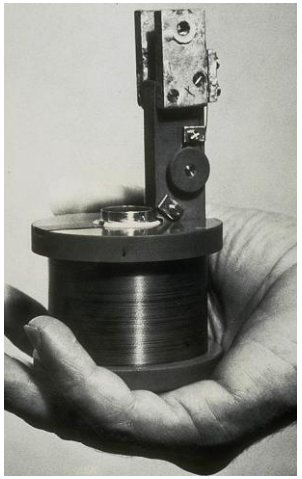
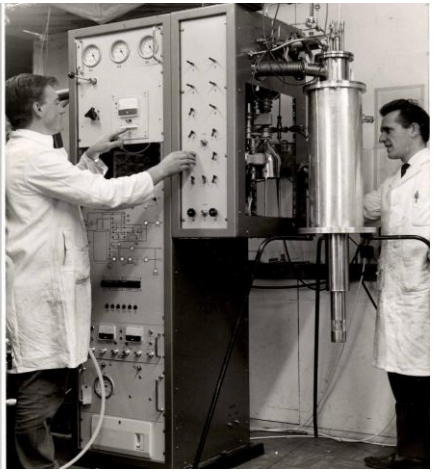
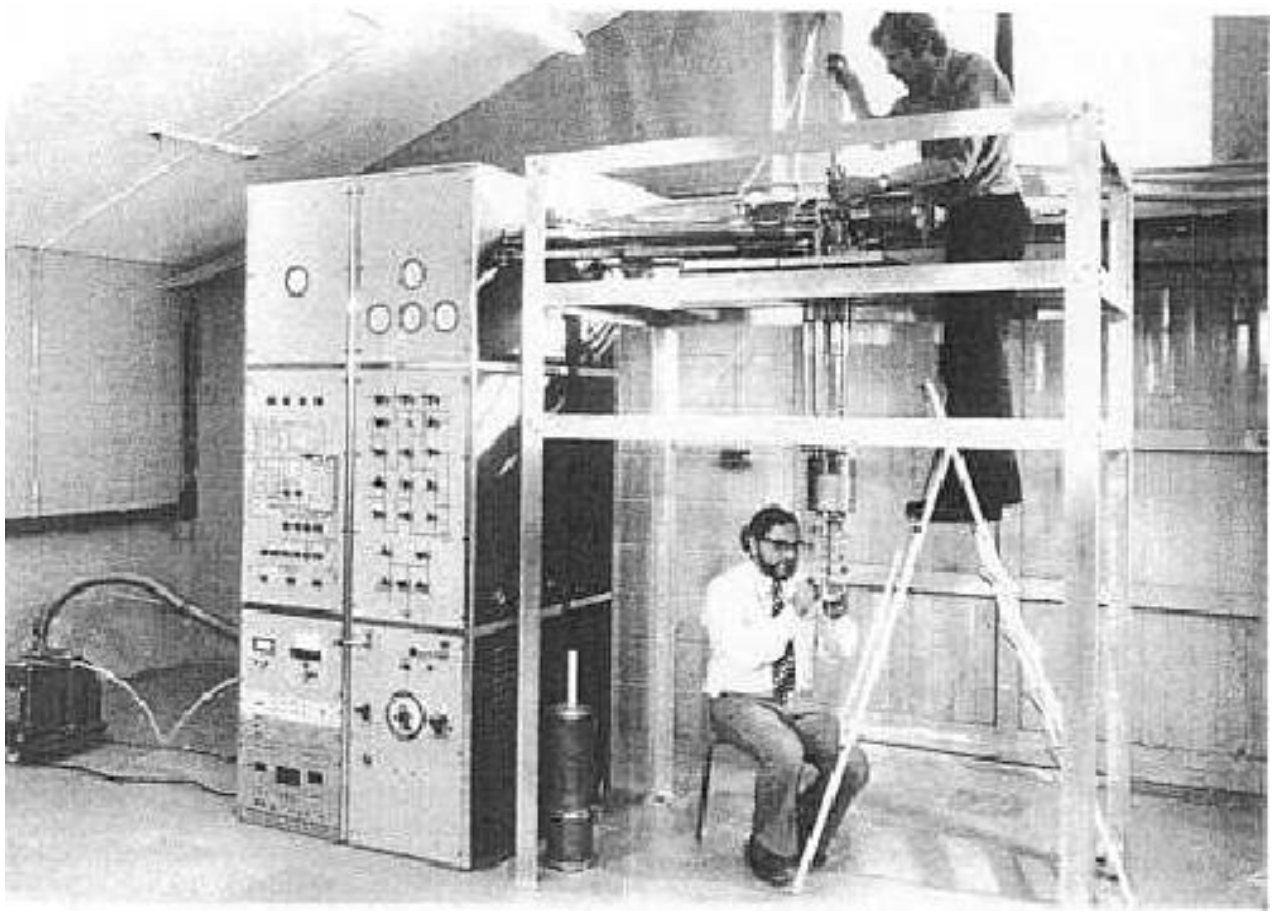
Sir Martin Wood and first dilution refrigerator achieved 67 mK





1970s

Copper heat exchanger dilution unit.



Low temperature experiments performed on large scale custom projects.

Silver heat exchangers heat exchangers introduced on Oxford Instruments' systems in 1976.

1980s – Top loading into vacuum and liquid systems

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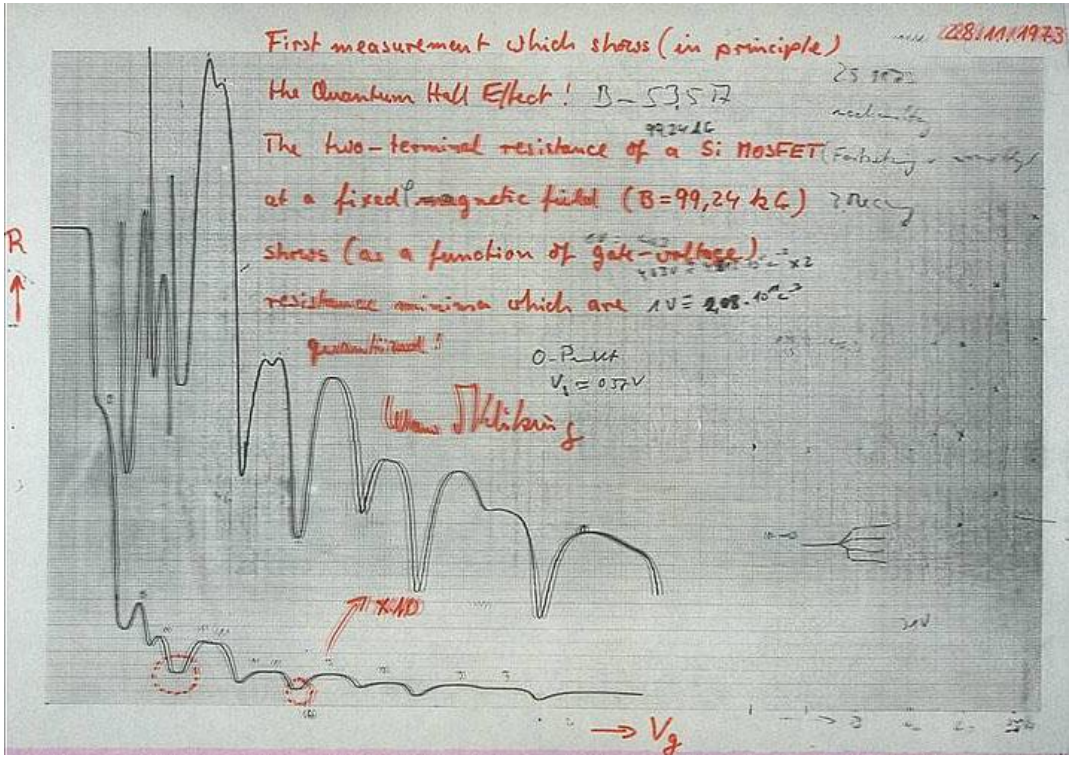
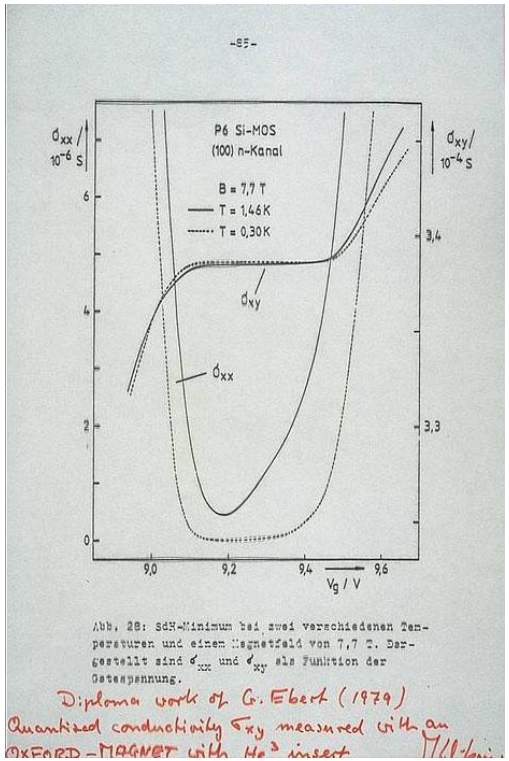
Top loading into the mixing chamber

Top loading into vacuum sample holder

1980s – Top loading into the mixing chamber





In 1985, the Nobel Prize was awarded to Professor Klaus von Klitzing ‘for the discovery of the quantized Hall effect”. He worked on Oxford Instruments’ helium-3 system and subsequently continued taking more data using an Oxford TLM dilution refrigerator and 21.5 T magnet.

1980s – Rotating dilution refrigerators to study vortices in helium

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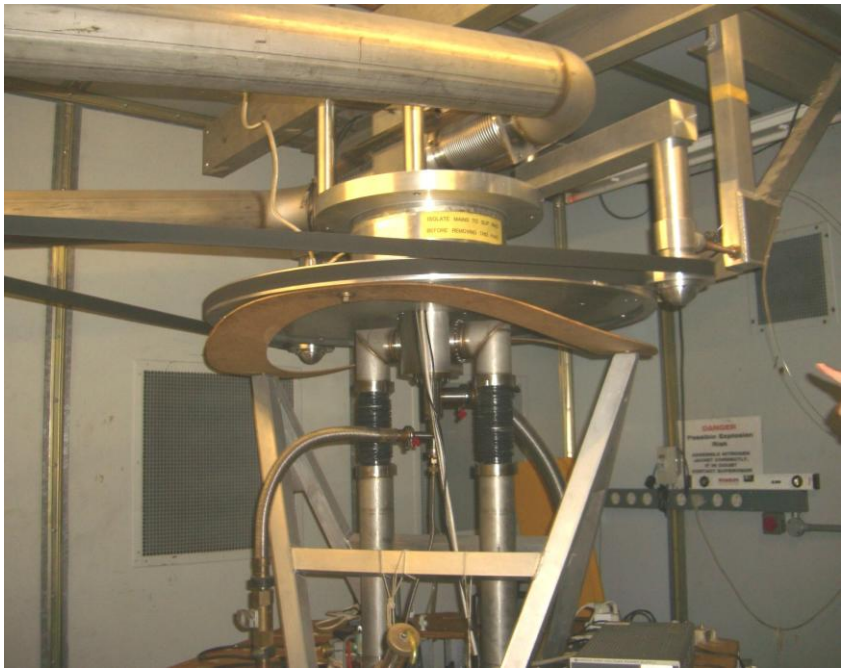
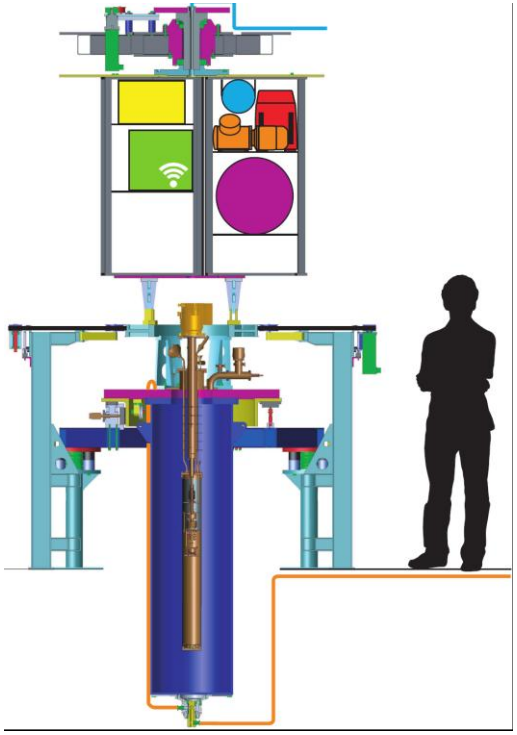
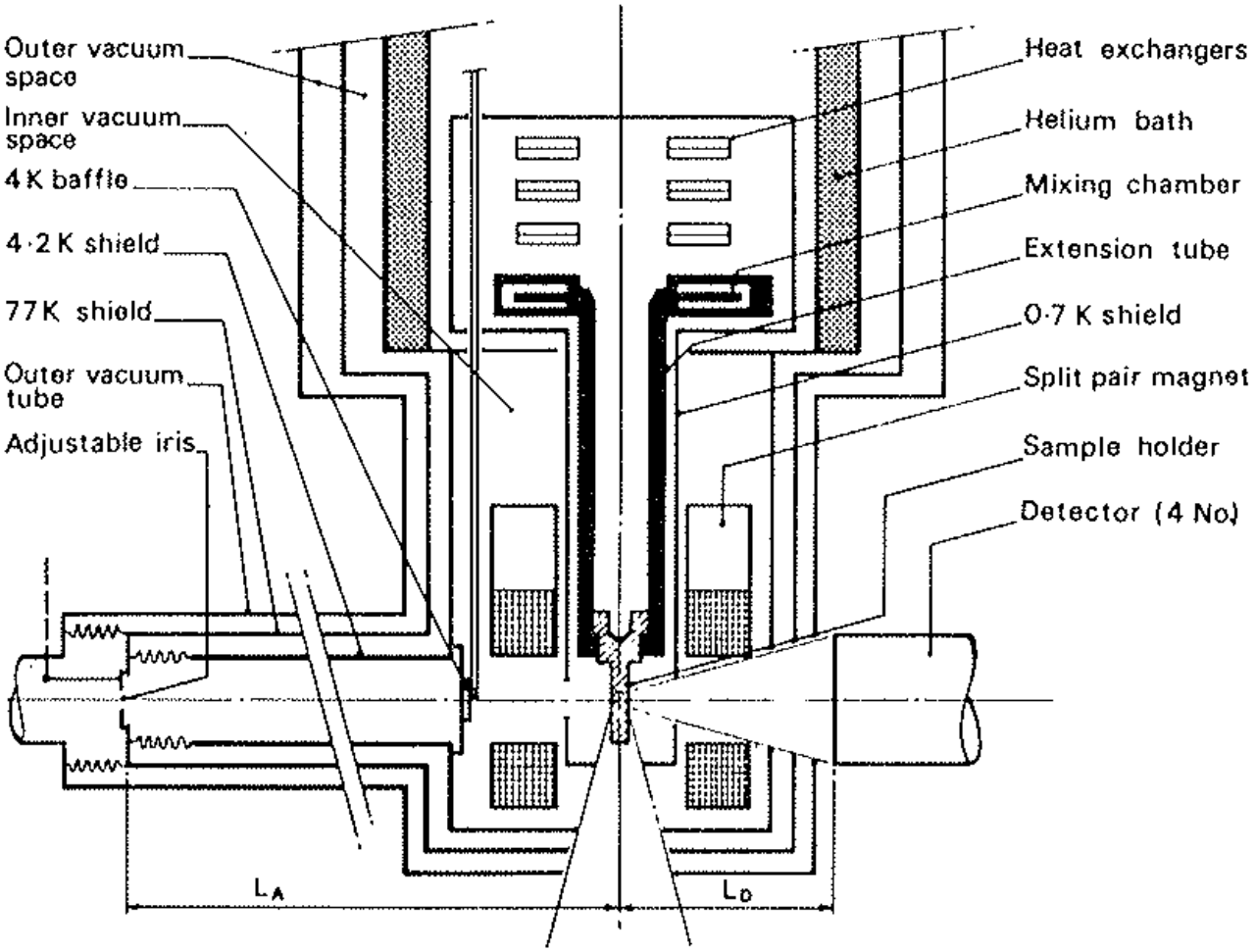




Rotating cryostat Henry Hall et al 1988

Rotating cryostat Paul Walmsley et al 2013

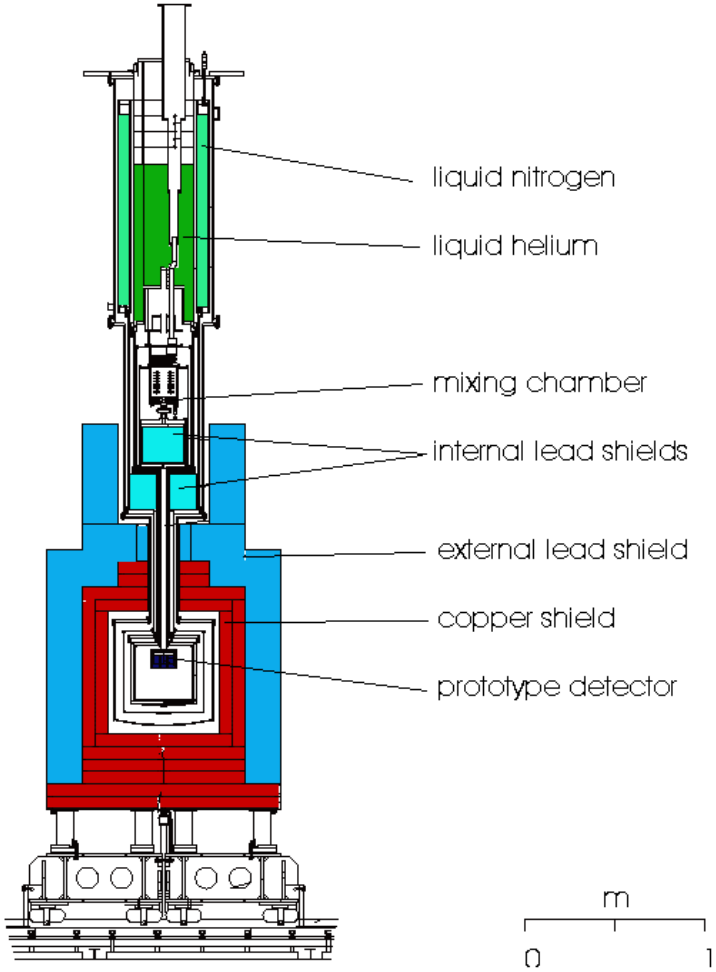
1980's – Side access system for beam line experiments



Published Hyperfine interactions vol. 43 – Schouten.

1990's – Dilution refrigerators for dark matter experiments

Special DR's for detectors – published JLTP vol. 39 Batey.



1990s – Plastic dilution refrigerators for pulsed magnets

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30 mk / 50 Tesla

1990s – Dilution refrigerators for gravity wave detectors

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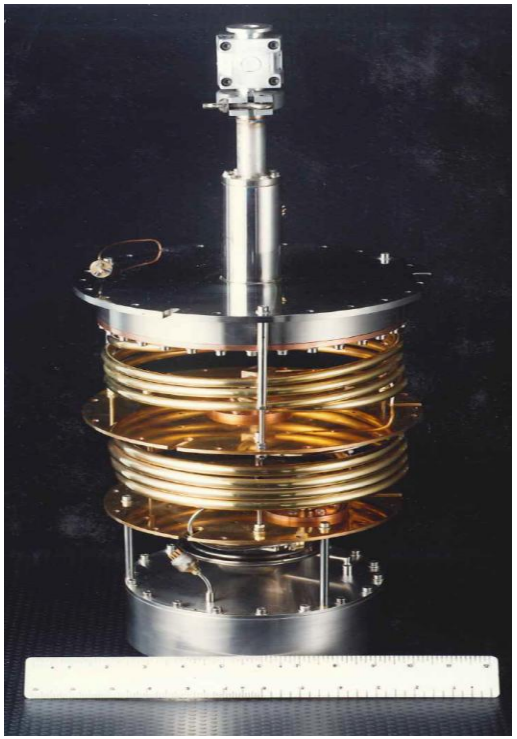
3 tonne aluminium bar, T<100 mk,
D/R in collaboration with T. Niinikoski.



High power dilution unit,
coiled copper sinter exchangers.

1990s – User facilities around the world

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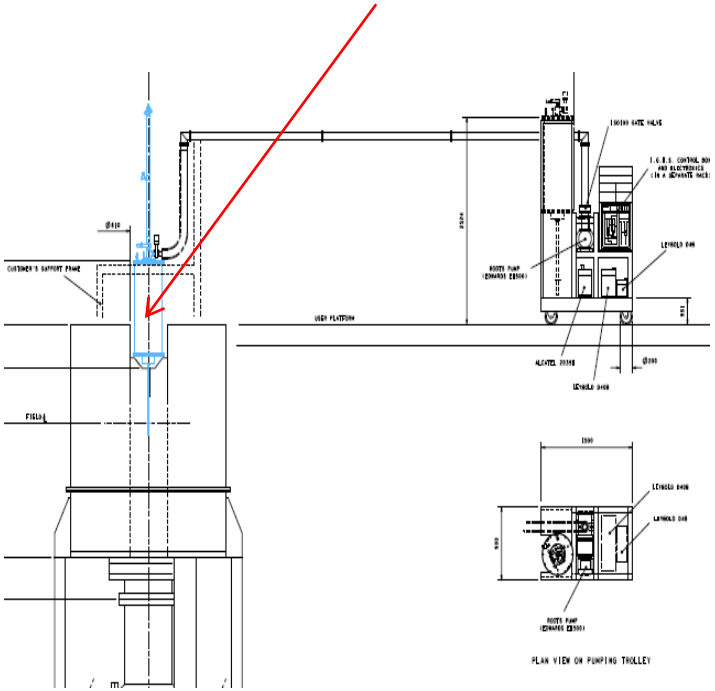
NHFML – 30 mK Dilution fridge in 45 T hybrid



45 T Hybrid Magnet
Base temp. @ 0 T = 17 mK
Base temp. @ 45 T = 30 mK

1990's – Ultra low temperature technology becomes a standard product

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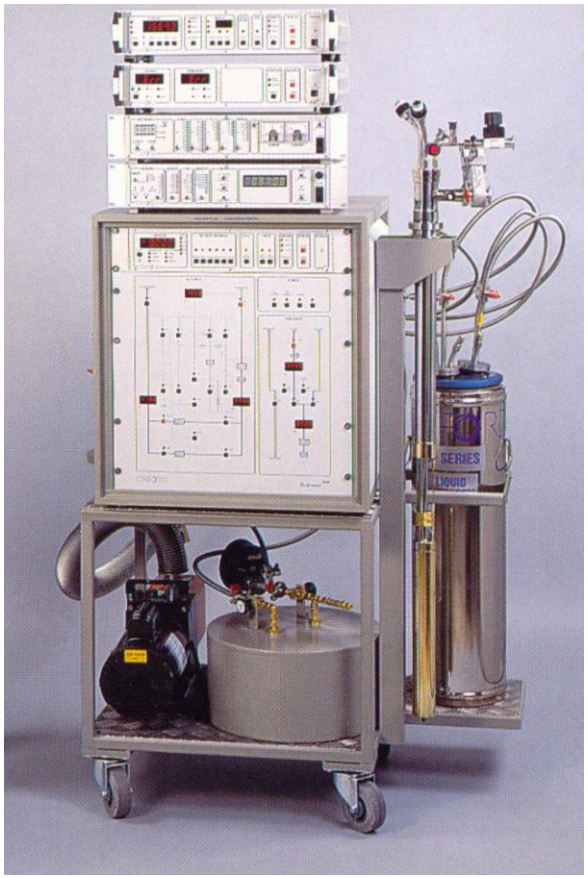
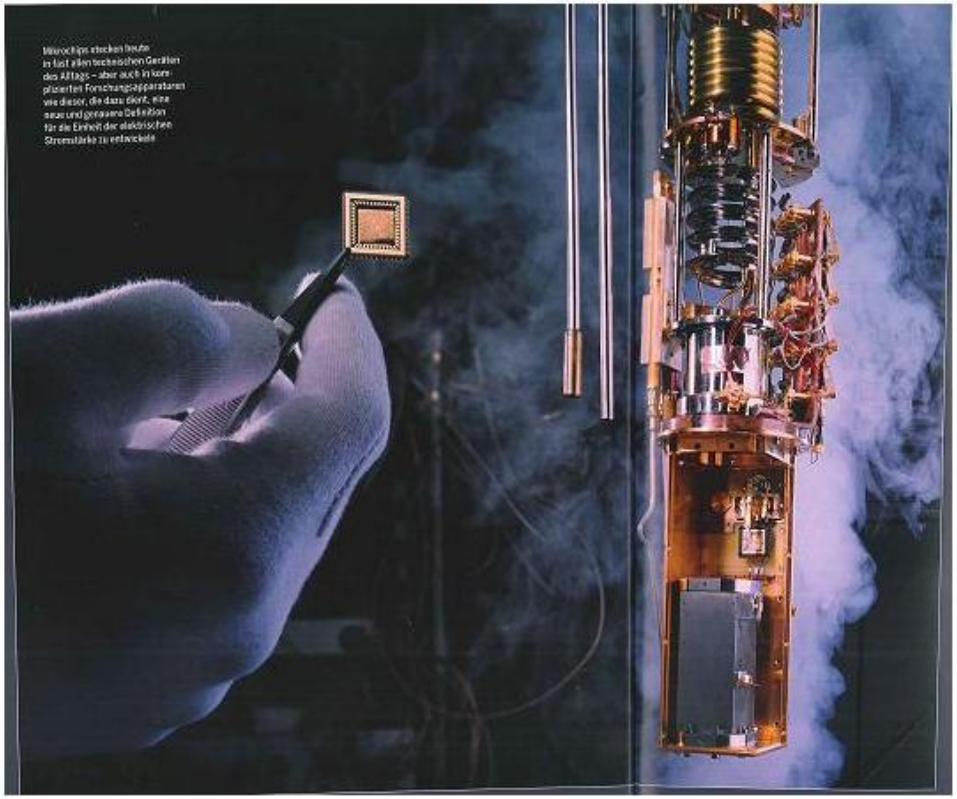


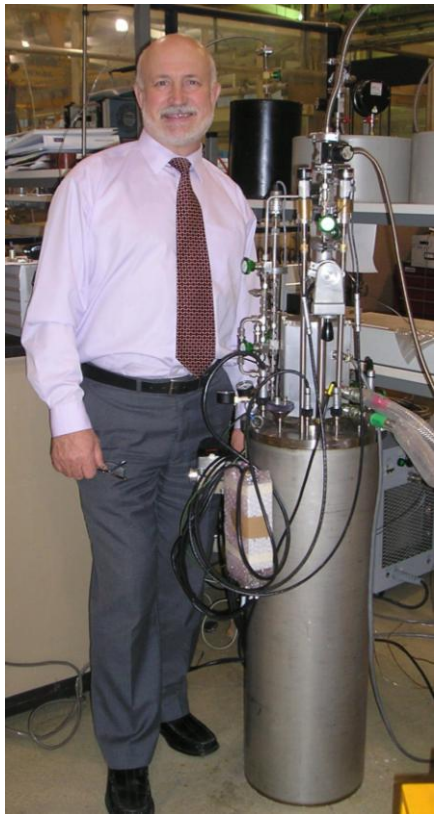
Development of standard Kelvinox® range of dilution refrigerators and magnet systems.

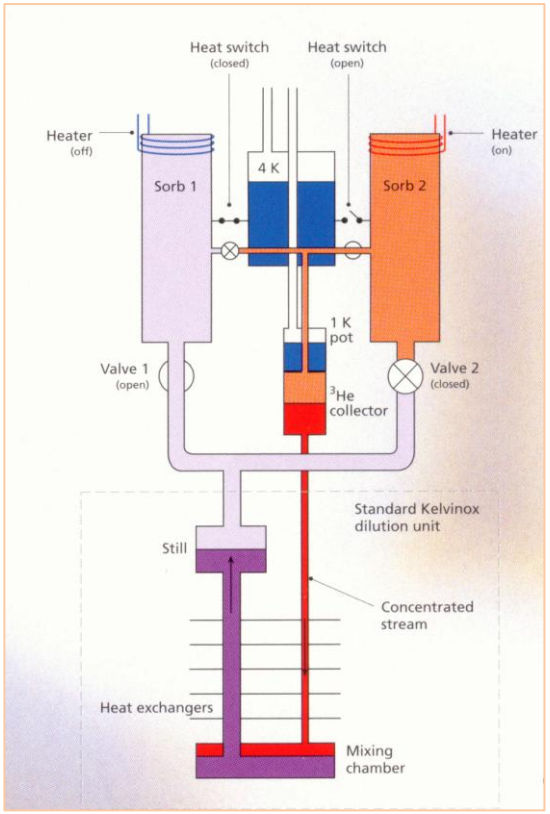
1990's – Development of electronic devices using Kelvinox range of dilution refrigerators



Development of electronic devices using standard Kelvinox range of dilution refrigerators and magnet systems.

1990's – Continuously circulating sorbtion pumped fridge for fractional quantum hall effect measurements





Published JLTP, vol. 13 Mikheev & Batey.

1990s – Ultra low temperature technology super fluid helium3 Nobel Prize

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The Nobel Prize in Physics 1996
David M. Lee, Douglas D. Osheroff, Robert C. Richardson

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The Nobel Prize in Physics 1996

David M. Lee
Prize share: 1/3

Douglas D. Osheroff
Prize share: 1/3

Robert C. Richardson
Prize share: 1/3

The Nobel Prize in Physics 1996 was awarded jointly to David M. Lee, Douglas D. Osheroff and Robert C. Richardson *"for their discovery of superfluidity in helium-3"*.

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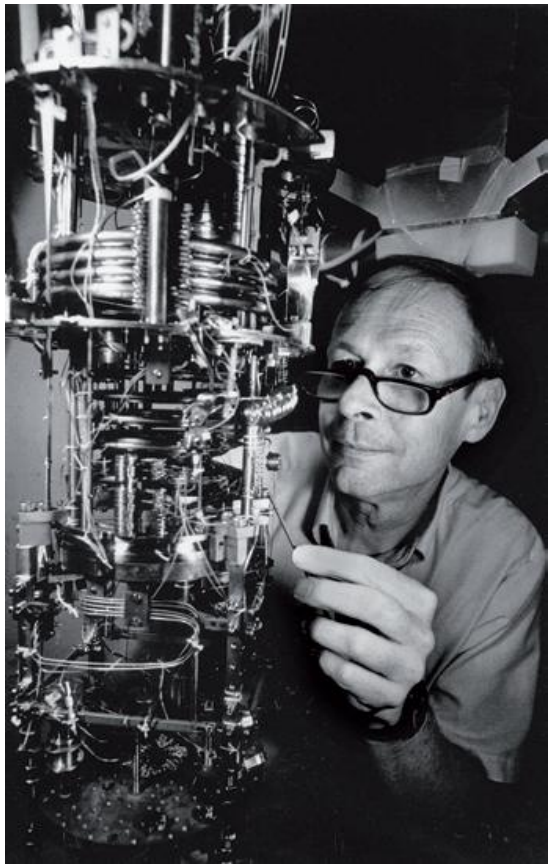
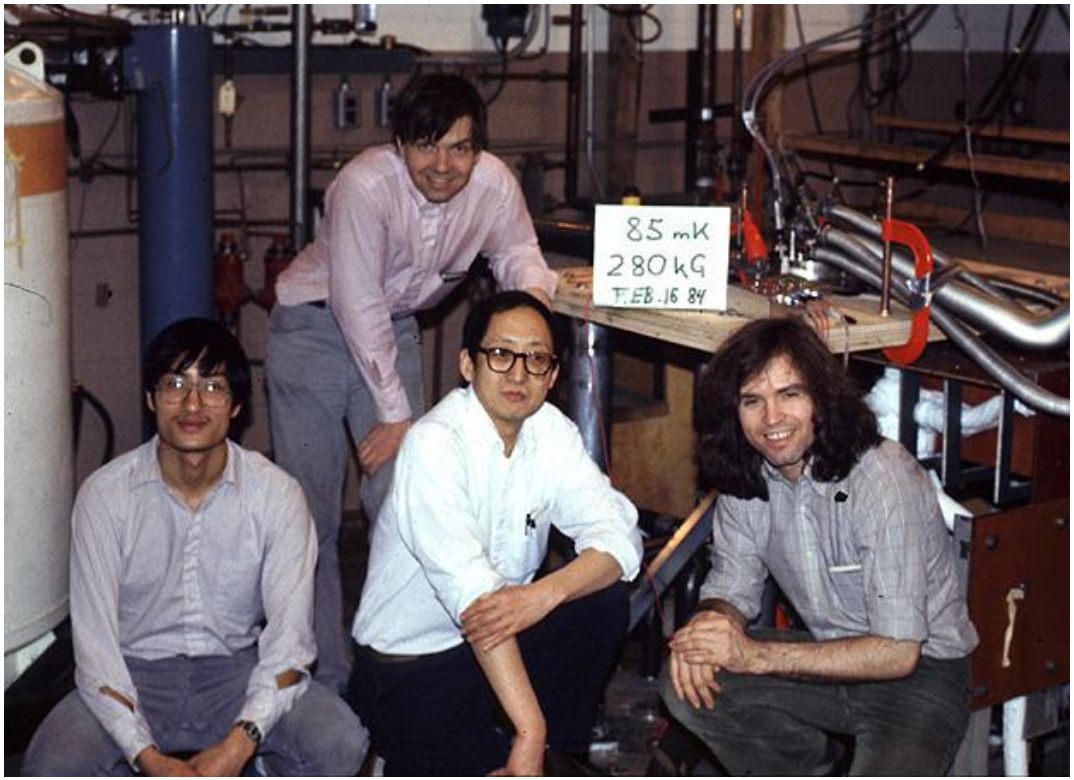


Bob Richardson with Oxford fridge

1990s – Dilution refrigerators used for fractional quantum Hall effect winning Noble Prize



The Nobel Prize in Physics 1998
Robert B. Laughlin, Horst L. Störmer, Daniel C. Tsui

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The Nobel Prize in Physics 1998

Robert B. Laughlin
Prize share: 1/3

Horst L. Störmer
Prize share: 1/3

Daniel C. Tsui
Prize share: 1/3

The Nobel Prize in Physics 1998 was awarded jointly to Robert B. Laughlin, Horst L. Störmer and Daniel C. Tsui *"for their discovery of a new form of quantum fluid with fractionally charged excitations".*

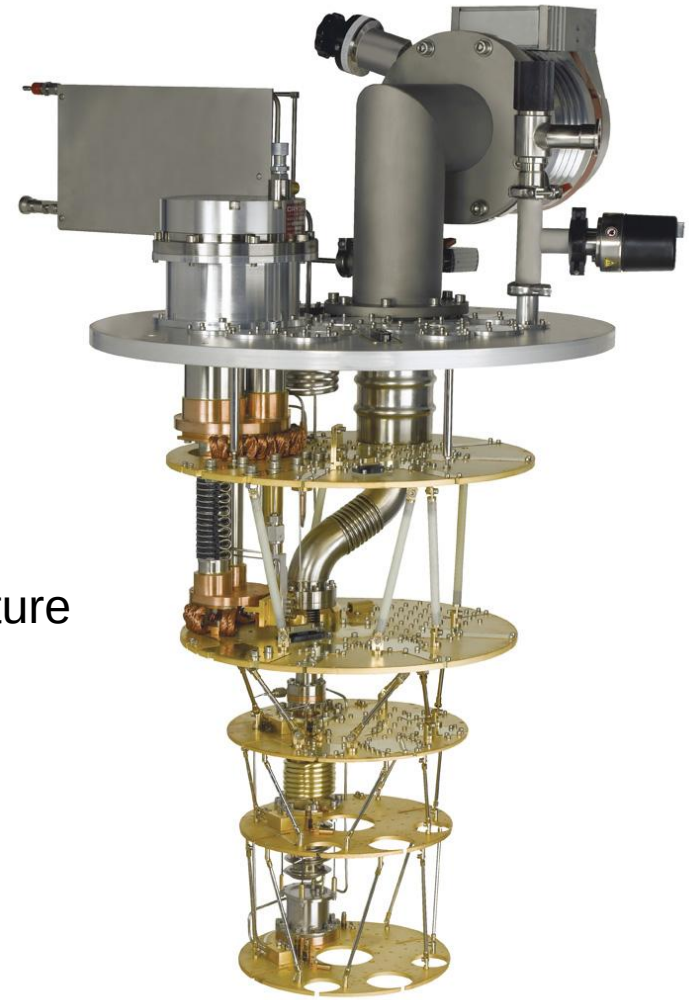
2000s – Cryofree® technology and the rise of quantum computing

OXFORD INSTRUMENTS
The Business of Science®

J-T condensation – as per Kurt Uhlig

- No liquid helium required
- Open structure for easy experimental access
- Very large experimental plates
- Fully automated cool down from room temperature

90% of market is now Cryofree and size of market has doubled using this technology!



2000s – Cryofree technology and the rise of quantum computing

OXFORD INSTRUMENTS
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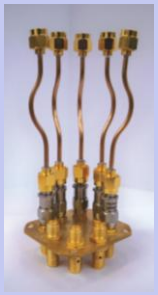
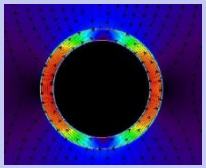
Triton DR platform

+

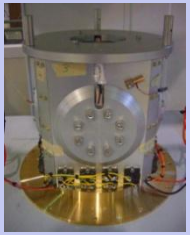
Experimental options



RF wiring



Mu-metal shielding

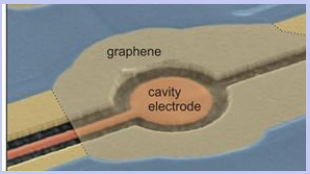


Integrated magnet

Sample loading

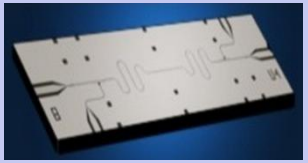
=

Quantum opto-mechanics



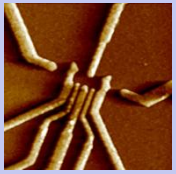
- Ultra low vibrations
- Fast cool down
- Low noise wiring

Superconducting quantum computing



- Large sample space
- High cooling power
- Magnetic shielding

Quantum hall effects



- High field solenoid magnet
- Low eddy current holder
- High temperature control

Spin qubits and toplogical QC

- 3-axis vector magnet
- Sample loading mechanism
- Low noise wiring

2000s – Cryofree technology and the rise of quantum computing

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The combination of **Cryofree®** technology and the intense interest in quantum information processing (QIP) bring a new level of multi-system laboratories, and the first commercial quantum computers (Niels Bohr Institute). 7 installed with 4 more to be delivered.

2000s – Cryofree technology and the rise of quantum computing

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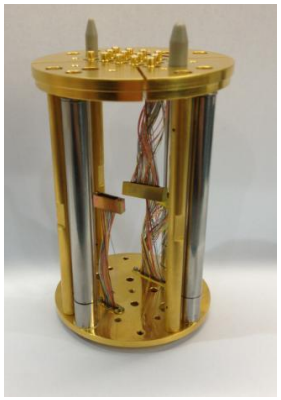
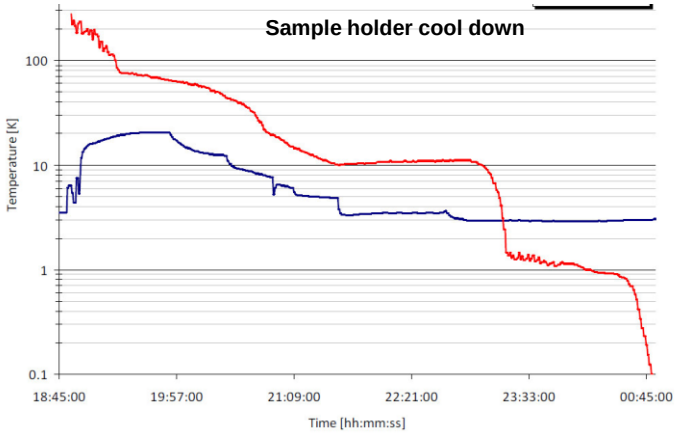
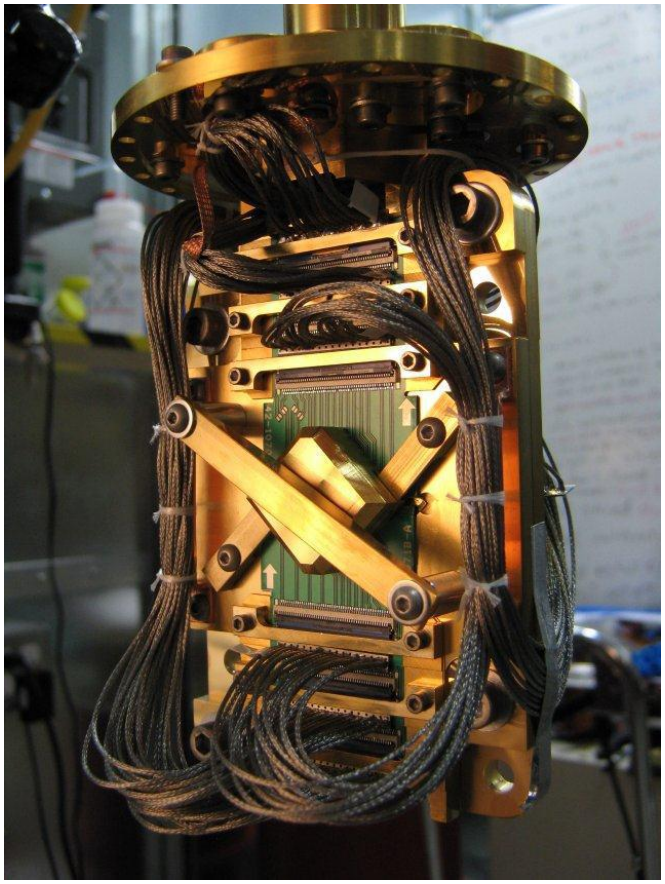
Rapid device prototyping using sample loaders ~ 8 hrs cooldown time

Building large experiments D-Wave processor ~ 240mm dia.







Contents lists available at ScienceDirect

Cryogenics

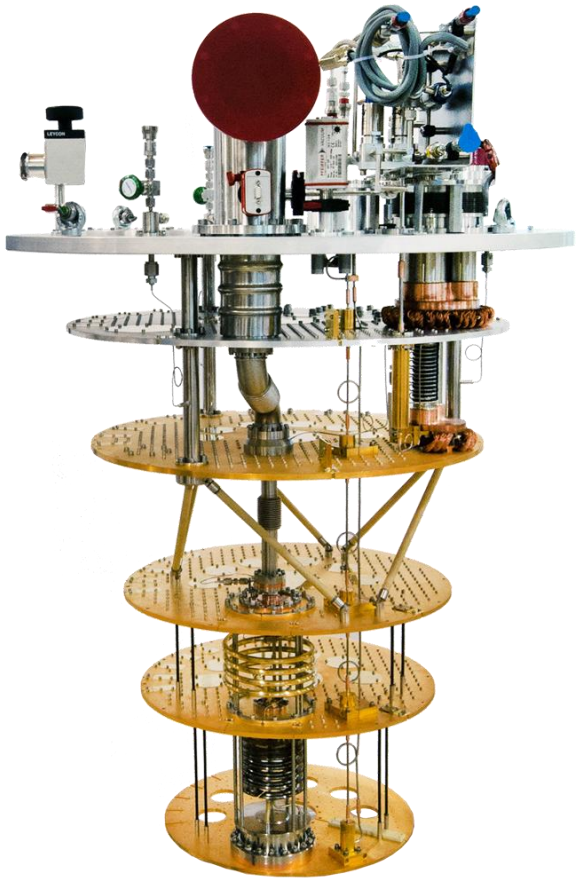
journal homepage: www.elsevier.com/locate/cryogenics

A rapid sample-exchange mechanism for cryogen-free dilution refrigerators compatible with multiple high-frequency signal connections

G. Batey, S. Chappell, M.N. Cuthbert, M. Erfani, A.J. Matthews *, G. Teleberg

Oxford Instruments Omicron NanoScience, Tubney Woods, Abingdon, Oxfordshire OX13 5QX, UK

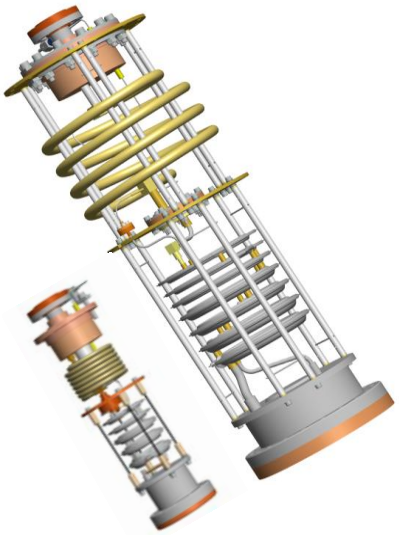
2010s – Large scale Cryofree dilution refrigerators



Mixing chamber
430 mm dia.

Coldest Cryofree dilution refrigerator in the world !

- 3.3 mK base temperature
- 25 µW of cooling power at 20 mK
- 1000 µW of cooling power at 100 mK



IOPscience
Journal of Physics: Conference Series

Journal of Physics, Conf series ***568*** *(2014) 032014*

A new ultra-low-temperature cryogen-free experimental platform

G Batey, A J Matthews and M Patton
Oxford Instruments Omicron NanoScience
Tubney Woods, Abingdon, Oxfordshire, UK, OX13 5QX
E-mail: Anthony.Matthews@oxinst.com

2010s – Small scale Cryofree dilution refrigerators

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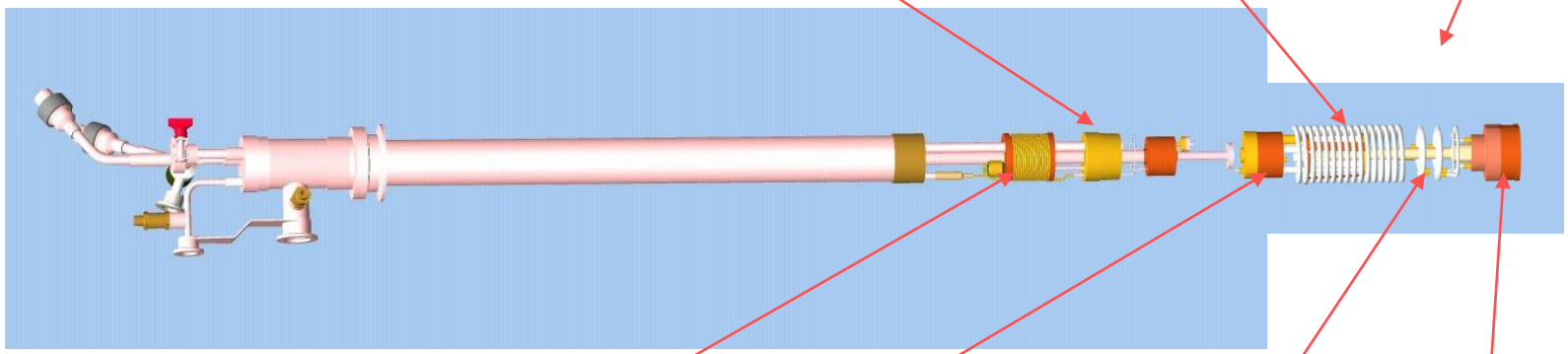
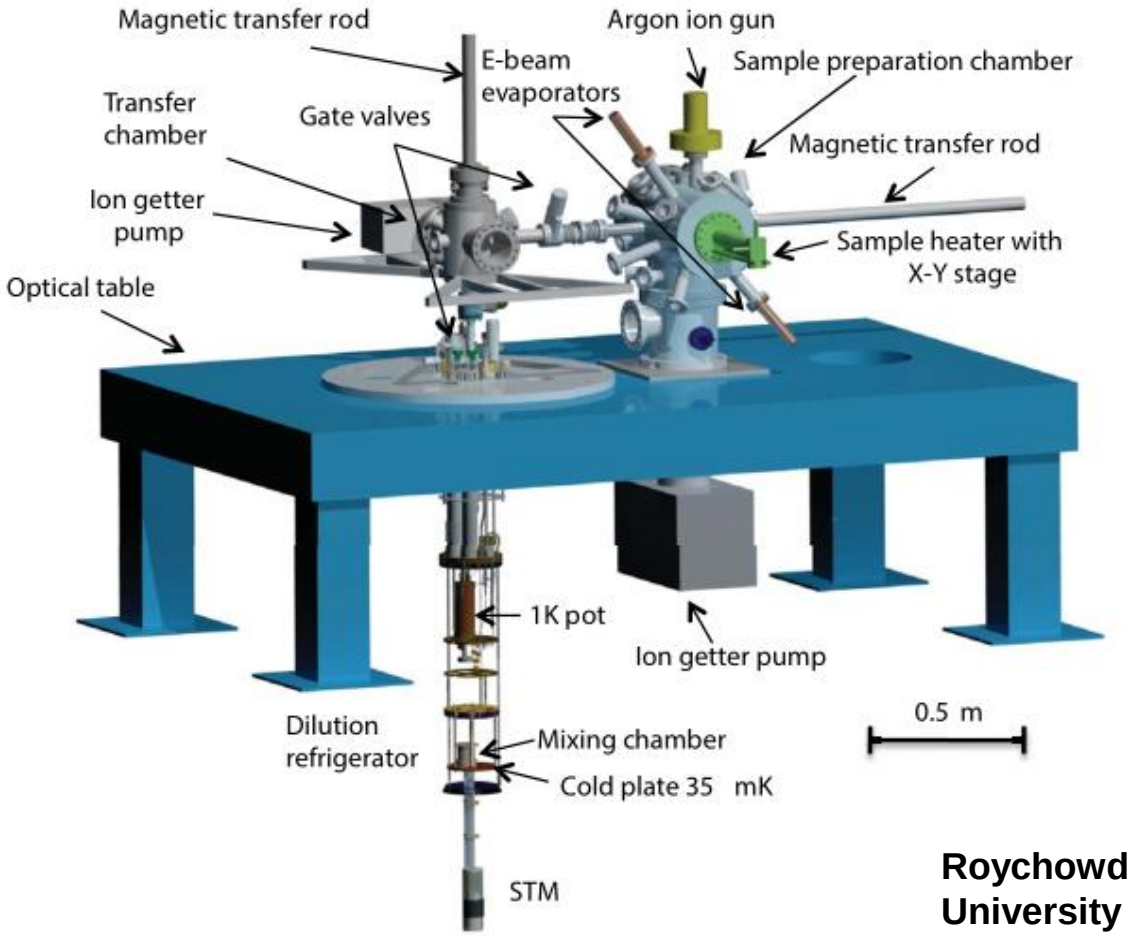
Outer diameter < 50 mm to suit 50 mm diameter 'wet' or 'dry' VTI



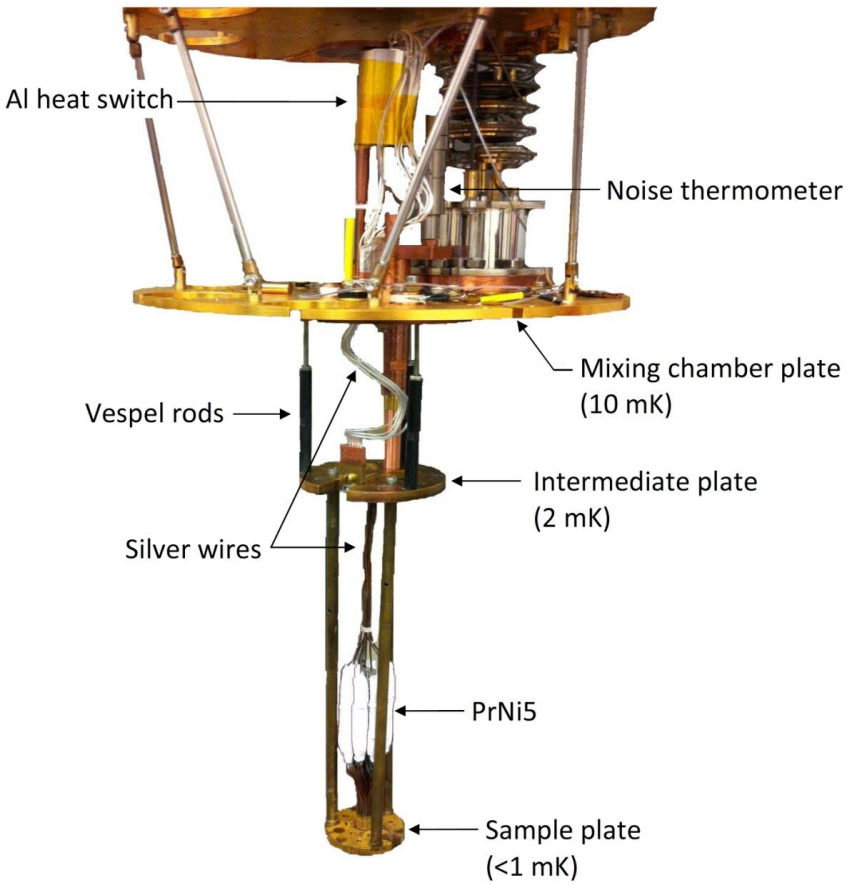
2010s – Dilution refrigerators and SPM

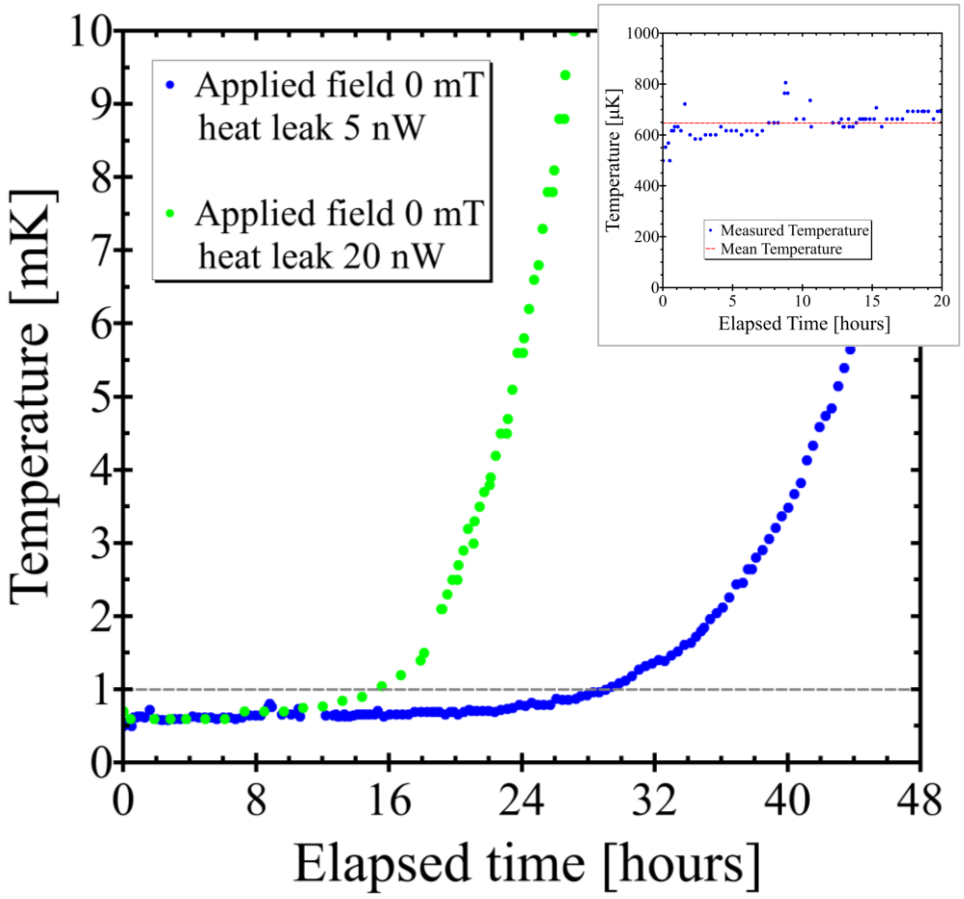


Roychowdbury et al
University of Maryland

FIG. 1. (Color Online) Overview of dual tip mK STM system. The dewar and radiation shields that surround the dilution refrigerator are not shown.

2010s and the future





Nuclear demagnetisation experiments on a **Triton** system achieve < 1 mK for 30 hours and a base temperature of 600 μK.

New Journal of Physics
The open access journal for physics

A microkelvin cryogen-free experimental platform with integrated noise thermometry

G Batey[1], A Casey[2,3], M N Cuthbert[1], A J Matthews[1,3], J Saunders[2] and A Shibahara[2]

What will the next 50 years bring?

The next 50 years of the dilution refrigerator story is expected to be equally exciting as there is likely to be a very high volume requirement in one of the following fields –

- Quantum Computing or Quantum communication?
- Milli Kelvin STM analytical system?
- Low temperature detectors for security screening?

Thank you