Cryogenics at Oxford Instruments

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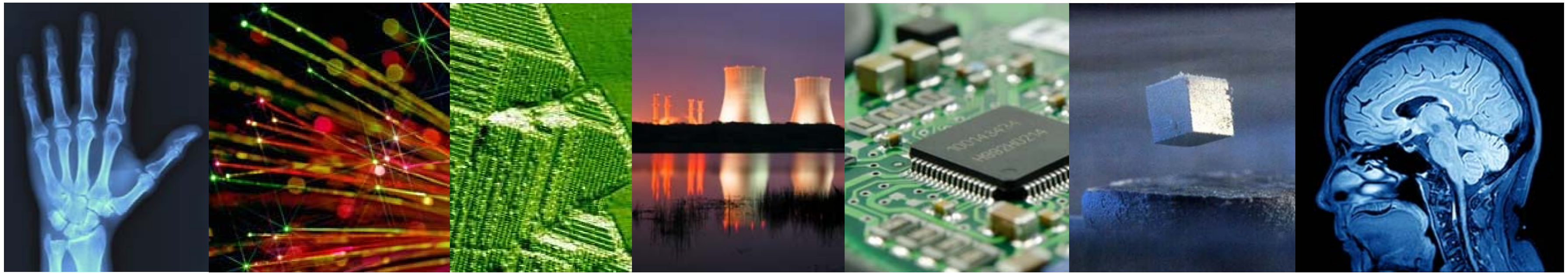
Introduction

Quantum and Nanoscience technologies impacting us in different ways

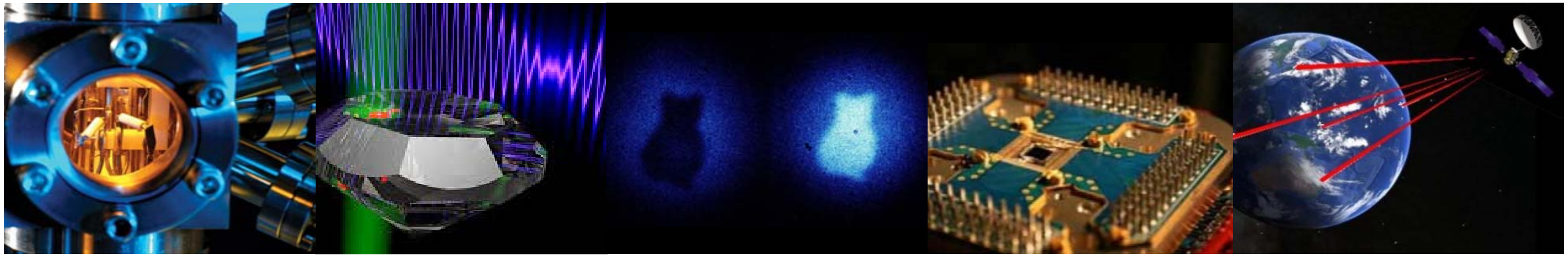
Quantum 1.0



X-Rays | Lasers | SPM | Nuclear Power | Electronics & Computing | Superfluids & mK temperatures | Superconductivity & MRI

*Much of the technology we now take for granted with underpinning theoretical description using quantum physics we now label **Quantum 1.0.** This technology typically relies on two fundamental characteristics of quantum mechanics **coherence** and **localisation***

Quantum 2.0

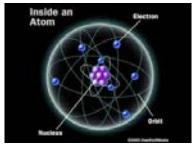


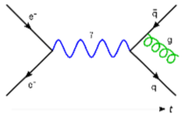
Clocks & Timing | Sensors & Metrology | Imaging | Computation & Simulation | Communications & Encryption

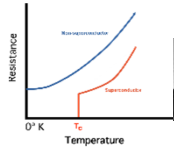
*There is a new technology revolution underway further exploiting the fundamental properties of quantum physics which will impact us we now label **Quantum 2.0.** This technology relies on two fundamental characteristics of quantum mechanics **superposition** & **entanglement***

Brief history of Quantum and Superconductivity

OXFORD INSTRUMENTS







1911
Onnes (and Holst) discover superconductivity in mercury. Onnes 1913

1925
Quantum Mechanics (Schrödinger, Heisenberg, Pauli, Dirac)

1928
The Quantum Theory of an electron in a solid: Band Structure (Bloch, Peierls, Brillouin, Van Vleck)

1928
The Quantum Theory of an electron in a solid: Magnetism (Pauli, Landau, Heisenberg, Bethe)

1950
Development of Quantum Field Theory (Feynman, etc)

1950
Ginzburg-Landau: phenomenological theory of superconductors

1957
Theory of superconductivity (B.C.S)

1970 -Oxford Instruments delivers world's first MRI system

1981 Feymman 1st to talk about Quantum Computing

Oxford Instruments delivered:

- Over 10,000 magnets
- > 800 Ultra Low Temperature systems
- > 3000 cryogenic systems

1962
First commercial superconducting magnet (Oxford Instruments)

1958
Josephson Effect of electron tunnelling in superconductors

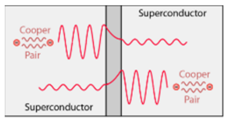
1980
The Integer Quantum Hall Effect

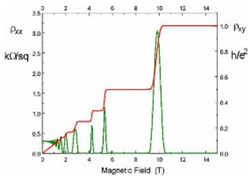
1982 First
The Fractional Quantum Hall Effect

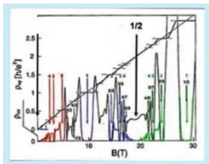
1986
Discovery of High Temperature Superconductivity

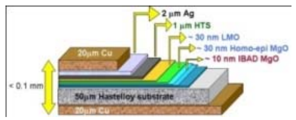
2003
Single Graphene sheets discovered
(2D materials)

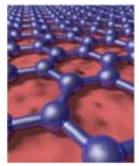
2017
32 Tesla All Superconducting magnet for research







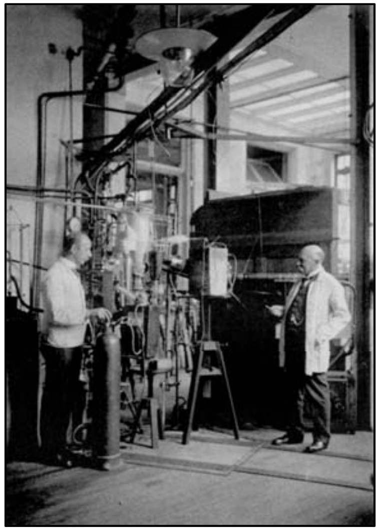




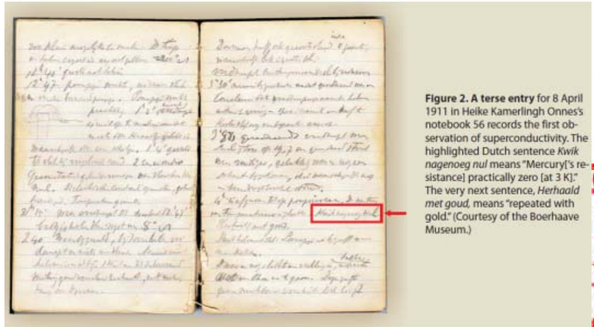
Discovery *by accident !*

Heike Kamerlingh Onnes (1853-1926)

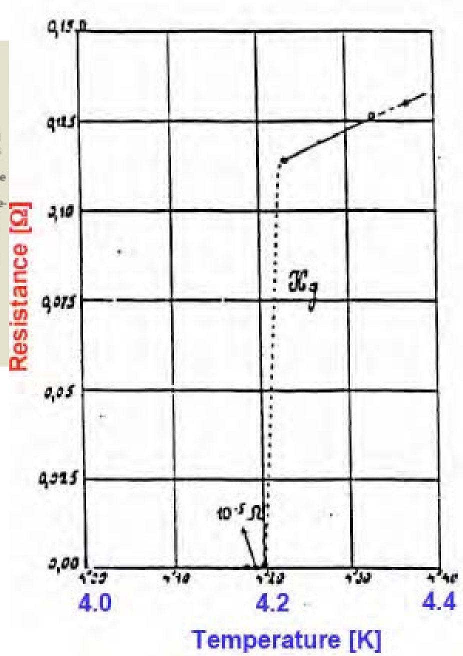
"Door meten tot weten"
("Through measurement to knowledge")



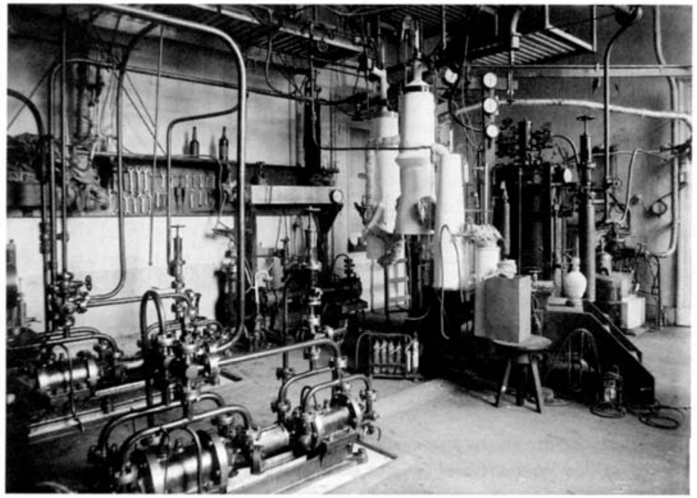
1908 Kamerlingh Onnes Liquefies Helium



8 April 1911
"The Resistance of Mercury at helium temperatures"
0.034 Ω at 13.9 K, 0.0013 Ω at 4.3K and less than **0.0001 Ω at 3K**



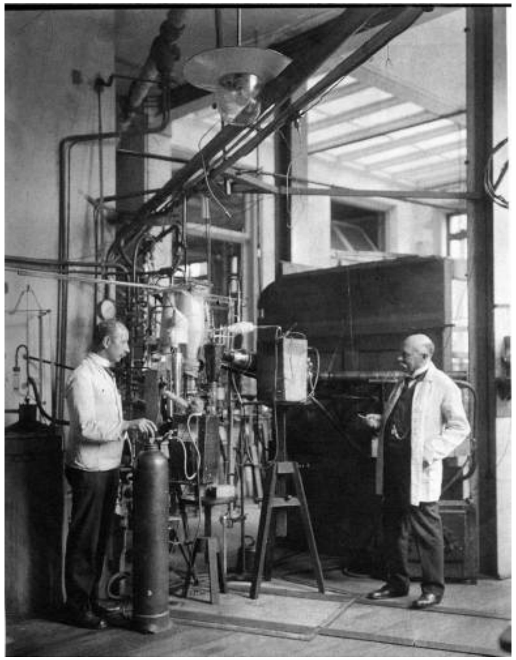
1892 James Dewar Invents 'Dewar Flask'

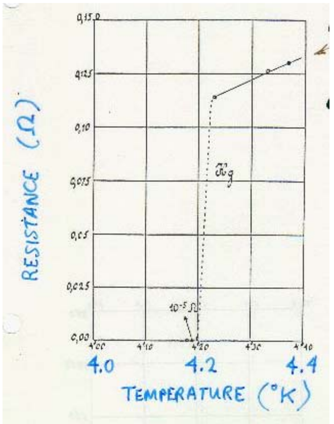


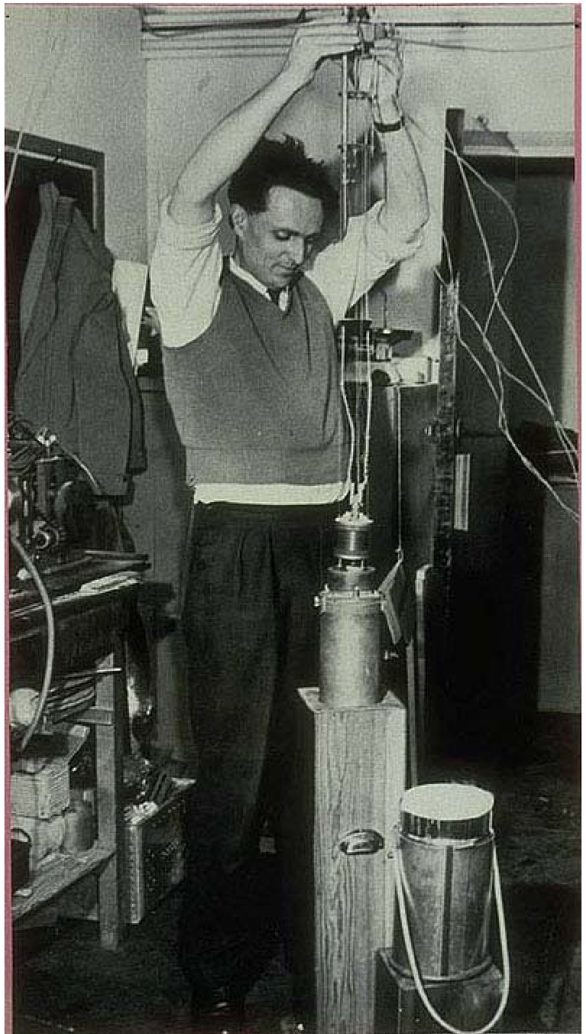
October 1911 (Reported in November 1911)
"On the sudden change in the rate at which the resistance of mercury disappears"

OI Born in "quantum 1.0" 1959

- Low temperature physics has been reliant on liquid cryogens for over 100 years
- Liquefaction of Helium in 1908 was quickly followed by the discovery of superconductivity in pure mercury
- In 1962 Sir Martin Wood – founder of Oxford Instruments - made the world's 1st commercial superconducting coil

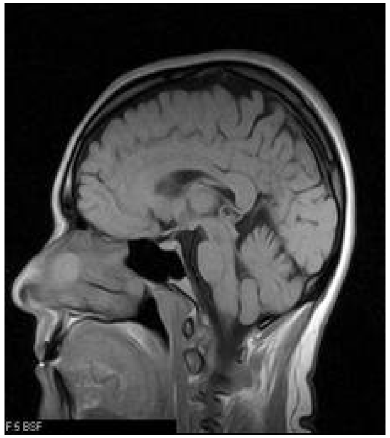




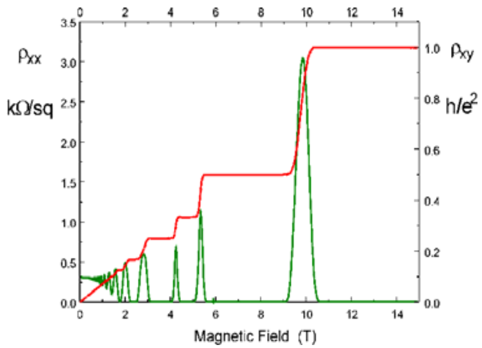

Martin Wood testing the first superconducting magnet at the Clarendon Laboratory. 1962.

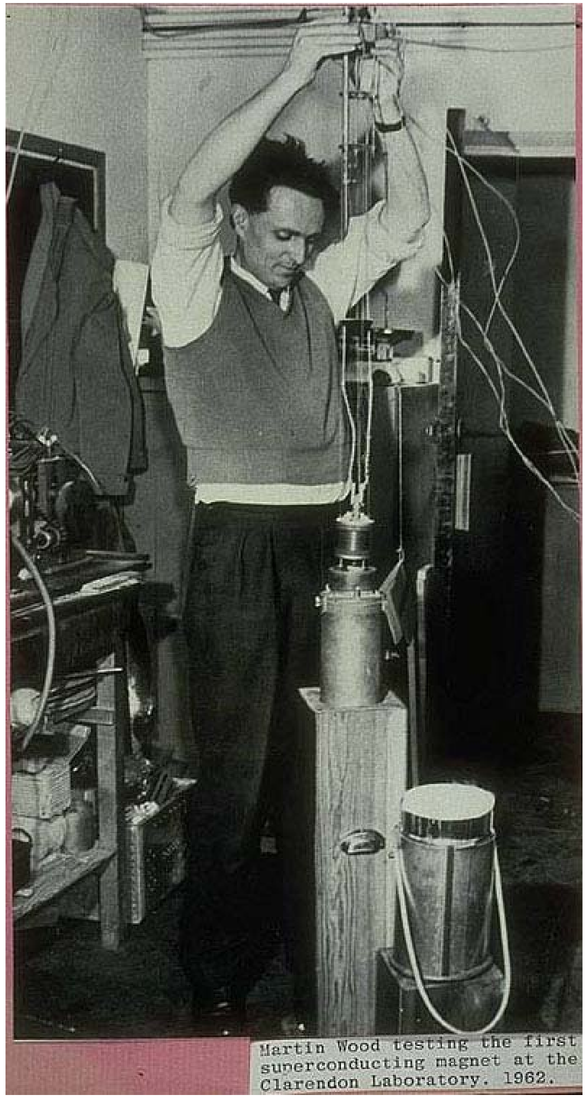
OI Born in “quantum 1.0” 1959

Foundation in future vision and innovative thinking



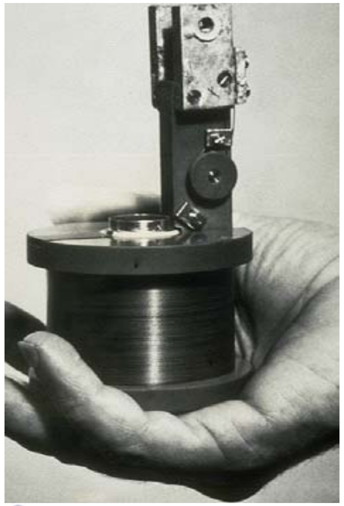
- Superconductivity has become an extensive technology across medicine, engineering and science
- In 1966 with Heinz London and Henry Hall, Sir Martin made the world’s first commercial dilution refrigerator
- Dilution refrigerators generate temperatures down to a few mK. In these extreme conditions we can observe new physics

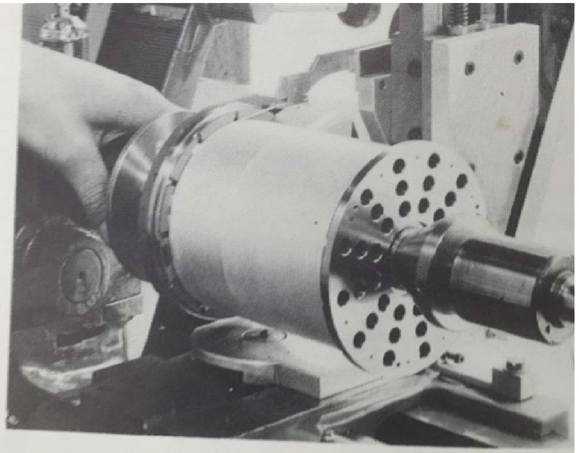




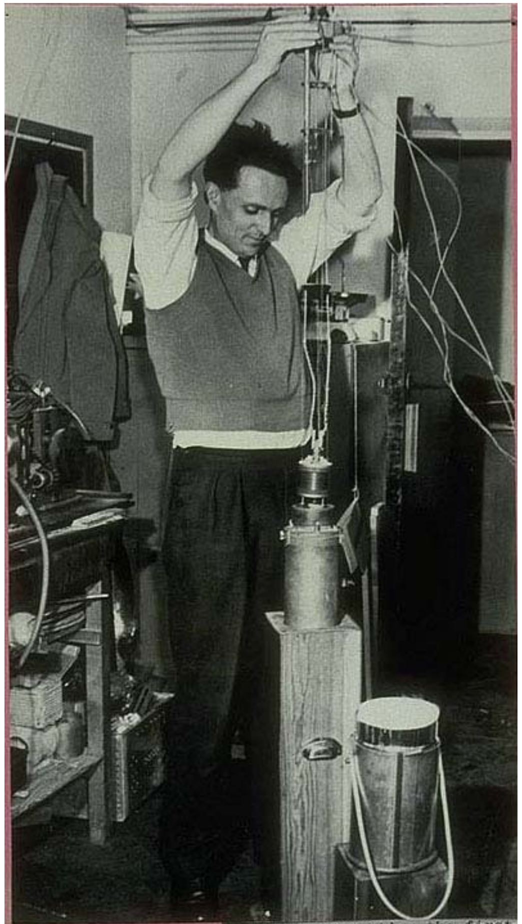
Humble beginnings …
in Superconducting magnet technology – 4 Tesla

- Breakthrough in superconductivity with the discovery of new materials for winding high field magnets – Niobium Zirconium and Niobium Tin
- Oxford Instruments develops the world's first superconducting magnet
- Receives the Queen's Award for Technical Innovation for developing the 10T magnet and dilution refrigerator





The winding of an early 10 Tesla magnet



Martin Wood testing the first superconducting magnet at the Clarendon Laboratory. 1962.

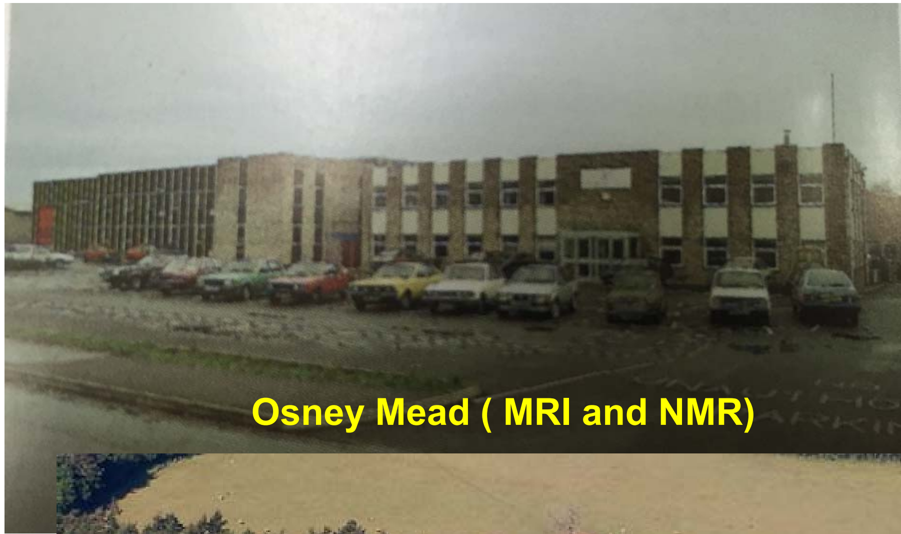
Humble beginnings …

in ultra Low Temperature 1st commercial 200mK fridge

The first commercial dilution refrigerator developed in collaboration with Fritz London at Osney Mead

the 200mK base temp proved dilution cooling beyond known 3He temperatures

Different locations in Oxford area



Our History

1959 → 1960s → 1970s → 1980s → 1990s → 2000s → Today

1959

Founded by Sir Martin and Lady Audrey Wood, Oxford Instruments is the first commercial spinout from Oxford University

1960s

Oxford Instruments develops the world's first superconducting magnet - 1962

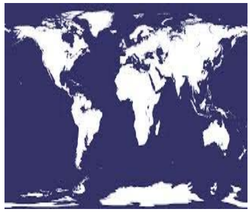
1970s

Oxford Instruments delivers world's first MRI system

1980s

Floated on London Stock Exchange

1990s

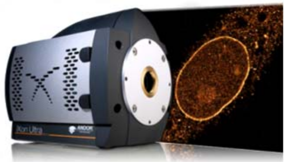


The Group expands its global presence opening offices in Japan and China

2000s

Continuing the heritage of innovative technologies, the Group develops unique cryogen free and silicon drift detector technologies

Today



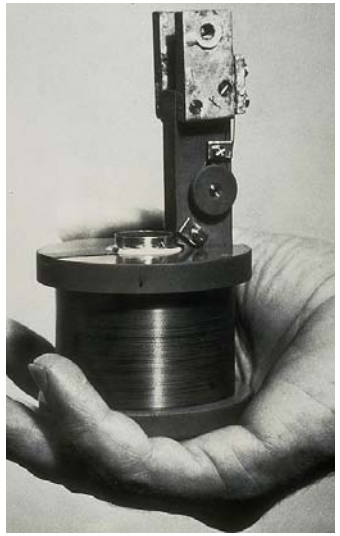
The Group focuses on the opportunities for Nanotechnology arising from the ongoing convergence of the sciences, achieving growth organically and through acquisition

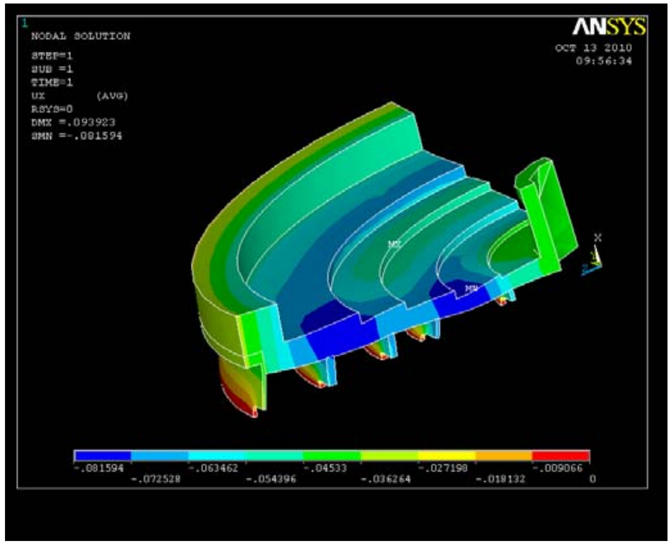
NanoScience Overview

Our core technologies

- Superconducting magnet design and manufacture
- Cryogenics
- Ultra-low temperature design and manufacture
- Instrumentation & measurements

- Realised by:
  - Cryogenic system integration
  - “Wet” (liquid helium) to “dry” (Cryofree®) technology shift
  - Project management
  - Design for manufacture
  - System integration

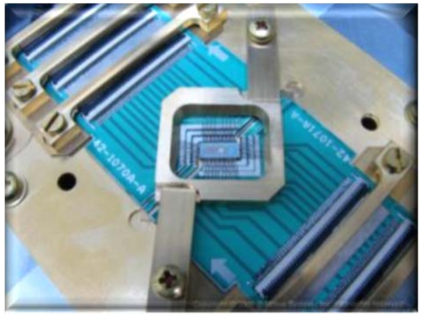


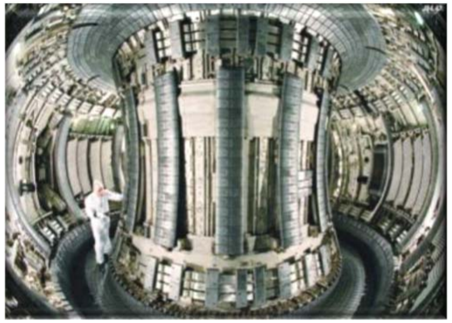


Our Markets - Diverse End Markets with growing demand for “better” (time, quality, accurate) measurement/fabrication

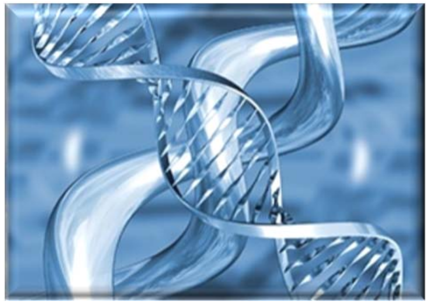
Quantum Computing

Image courtesy of D-Wave Systems Inc



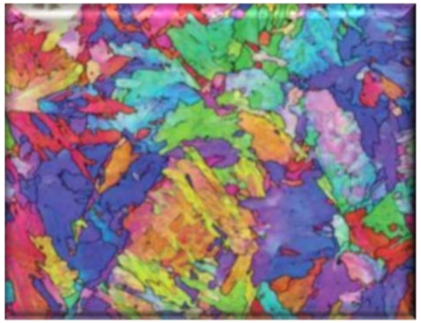


Energy Generation



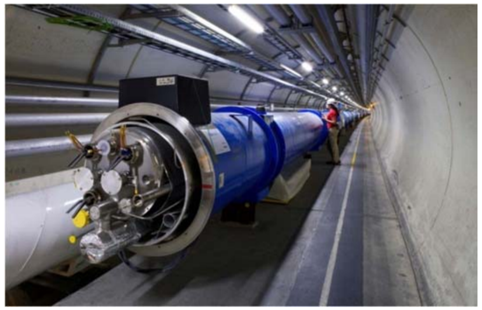
Life Sciences

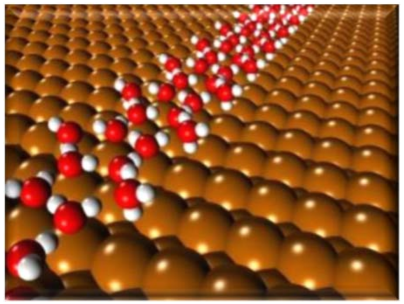
Health Care



Materials Discovery/ Characterisation

Semiconductor Research





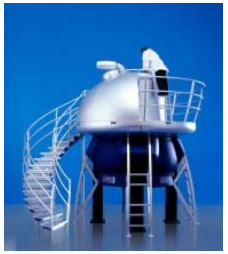
HEP/Particle Discoveries

LHC magnet (Courtesy of CERN)

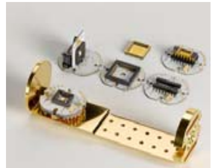
Nanotechnology/ Mesoscience

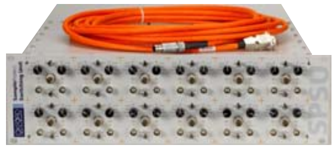
Primary technology components required for QT and NanoScience

- Superconducting magnets



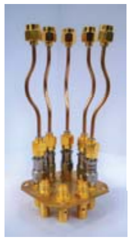
- Cryogenic platforms

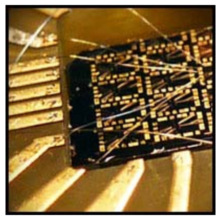


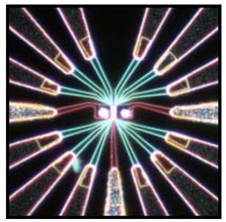


- Sample management

- Instrumentation

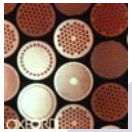






Timeline of Innovations in Superconducting and cryogenic applications !

1911!

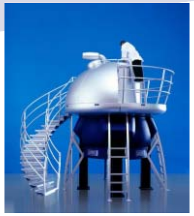


1960 -1970
Applications

Research Magnets
ULT (200mK)
LF NMR
Physics Magnets
HEP

1980- 2000
Volume Production

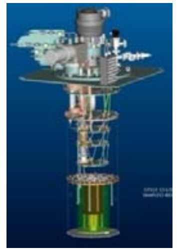
MRI
HTS (1986)
Split Pair
ULT (10 mK)

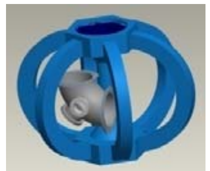


2000 -2013
HF 20T

HF Magnets
- Solenoids
- NMR

Energy Applications
Transport
Large Scale
Special Projects
Cryofree®





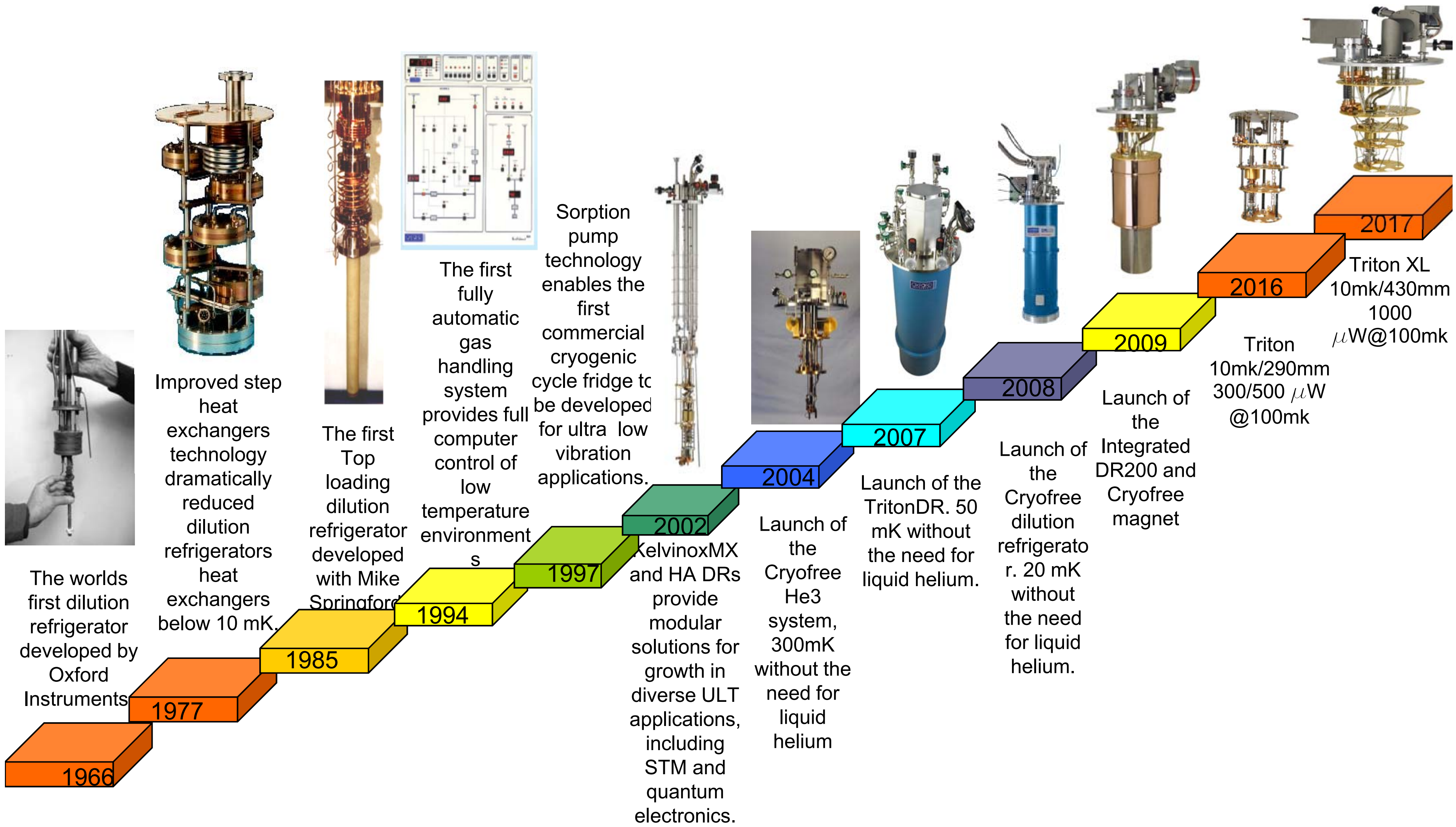
2016 -
New Frontiers

HF Research Magnets >23T
- Solenoids
- Cryofree®
- Split pair
- Vector rotate
- HTS

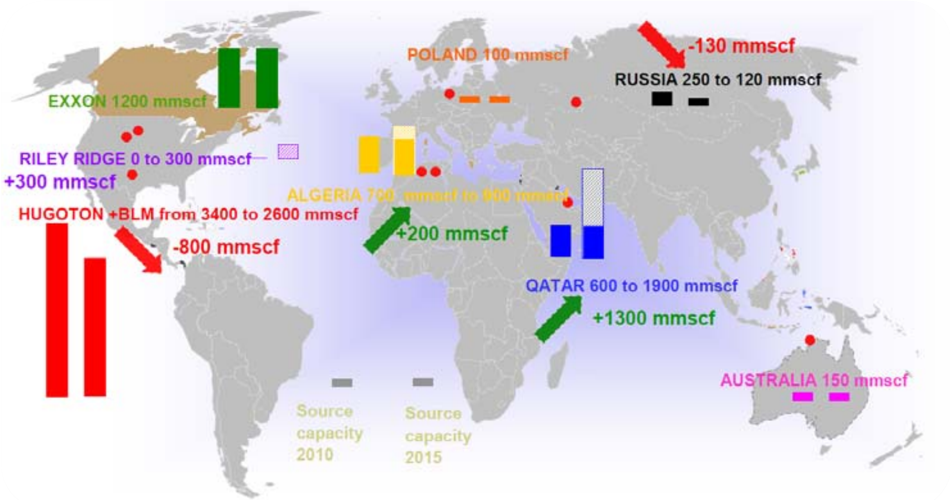
>20K

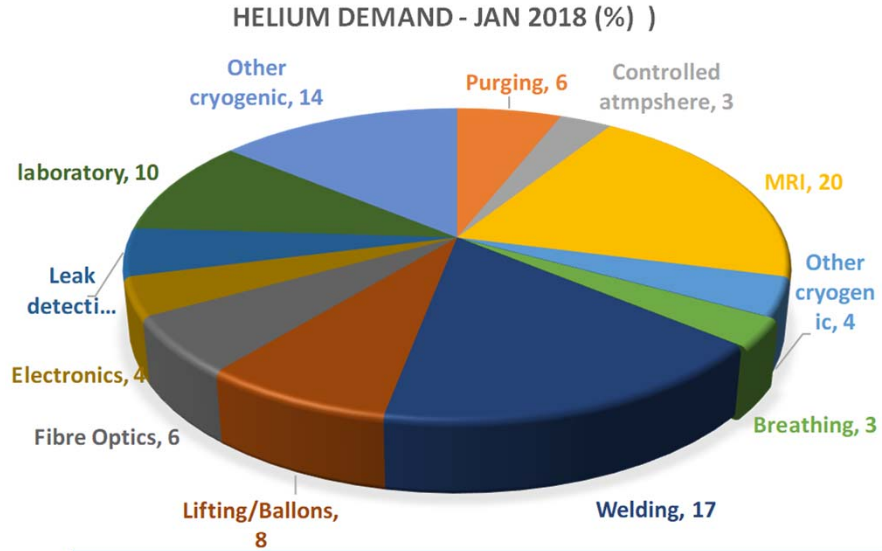
53 years of innovation at low temperatures

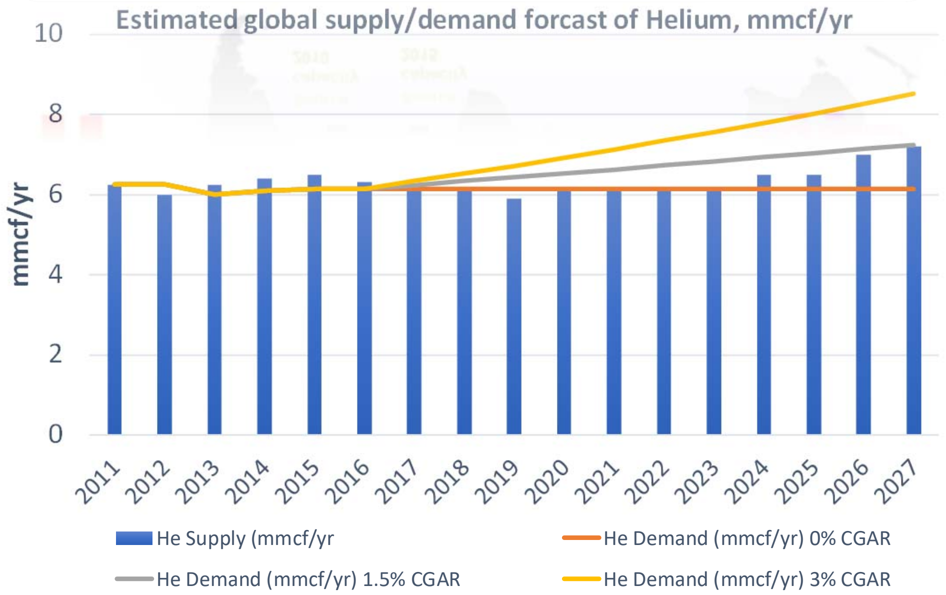
OXFORD INSTRUMENTS

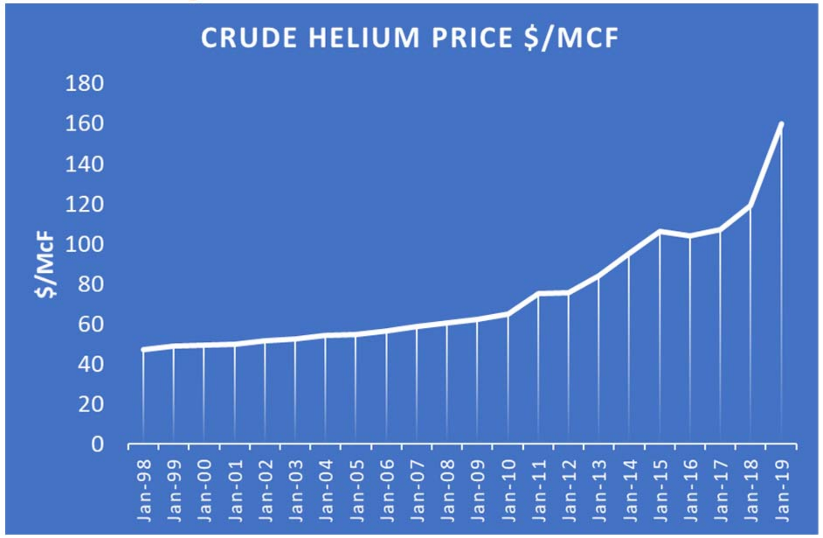


Major and Global Helium shortage
… Need new thinking on cryogenics (Oct 2019)









Superconducting magnet applications are very diverse

OXFORD INSTRUMENTS

Superconducting (SC) Applications

Research & Medical Magnets
- Medical/LS - MRI, NMR , Proton Bean Therapy
- Basic Sc Res/Physical sciences RM(LTS)
- HEP- Beamlines/Accelerates/ Detectors (LTS)
- Fusion – LTS & HTS
  - UHF >25T (LTS+HTS)
  - 5T-20T >20K (HTS)
  - Bench Top Applications (LTS+HTS)
    - 0.5-5T >20K-77K

Industrial applications
- Non-destructive Testing
- Inductive Heaters
- Magnetic separation
- Crystal Growth

Power & Energy Applications
- Fault Current Limiters (FCL)
- Transmission Cables
- SC Magnet Energy Storage
- Generators (Wind/Utility)
- Motors
- Transformers
- Synchronous Condensers

Microelectronics
- **Quantum Computing**
- Faster Computers
- Power Electronics

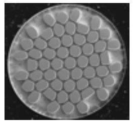
Communications
- Satellite channels
- Wireless devices
- Antennae

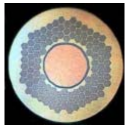
Defence & Security
- Detectors/Sensors
- Rail gun
- Degaussing cables

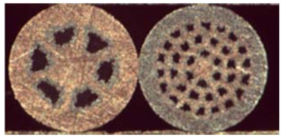
Transportation
- Electric planes
- Maglev
- Ships
- Rocket propulsion

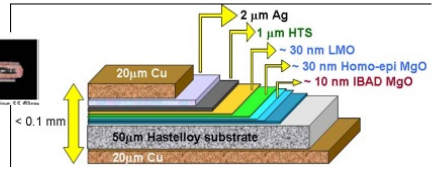
Practical Superconductors for Industrial Applications

NbTi LTS	Nb_3Sn LTS	MgB_2 MTS	Bi-2212/Bi-2223 HTS	YBCO HTS
Tc = 9.8 K Bmax (4.2K) 9.5T (2.2K) 11.5T	Tc = 18.1 K Bmax (4.2K) 20T (2.2K) 23.5T	Tc=39K Bmax (4k) 10T-20T ?	Tc = 90-110K Bmax is > 40T @4.2K; 8T @20K 4T @65K	Tc = 90-135K Bmax is > 40T @4.2K 12T @20K 8T @65K







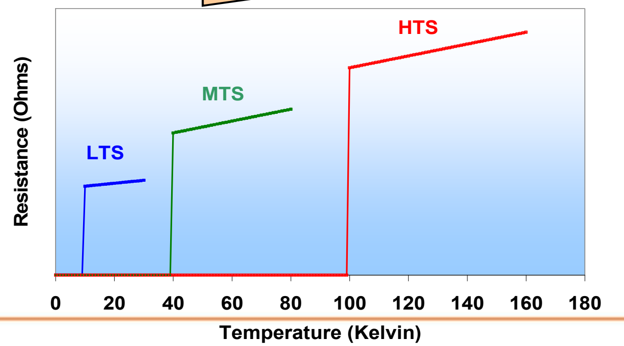


Difficulty of use

Cost of use

Critical Current Performance

LTS: Low Temperature Superconductors (10-20K)
MTS: Medium Temperature Superconductors (20-40K)
HTS: High Temperature Superconductors (90-130K)
Tc: Critical temperature
Bmax: Maximum Field Flux



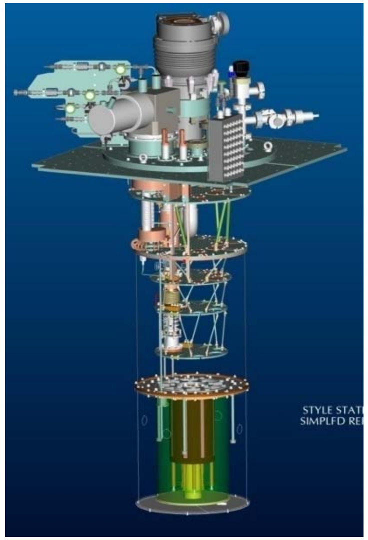
Typical Superconducting magnets <23 T

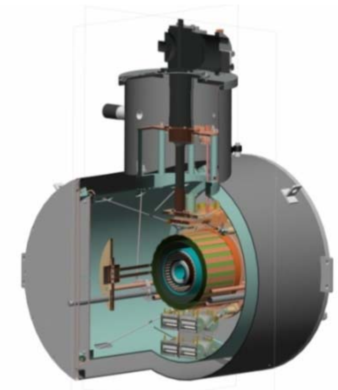
- **New compact HF products**
  (Nanotechnology, quantum technology, condensed matter, material research, RM, beam lines, etc…)
  - Solenoid magnets up to 20 T and, with HTS insert coils, 22.5 T at 4.2K (24T @2.2K)
  - Split pair magnets
  - Vector rotate magnets
  - Integrated with ULT- **sample environment solution**

- **Specific properties for applications**
  - High homogeneity, high stability
  - Cancellation, modulation, gradient coils
  - Active shielding

- **Cooling technologies**
  - Liquid helium ('wet') - **22T**
  - Recondensing - **20T**
  - Cryofree® - **18T**
    - 'Stand alone' cryofree magnets
    - Cryofree magnets with shared cooling



NanoScience Products

Cryogenics

- A range of 1.5K and 4K cryostats
- Optical access
- Integrated superconducting magnets

Ultra Low Temperature

- Temperatures 5 mK
- More than 300 *Cryofree* Triton systems installed
- A full range of integrated magnets
- Integrated wiring for "measurement ready"
- Environments for QIP applications

Superconducting Magnets

- Wet magnet up to 22T
- *Cryofree* Teslatron ^{PT} magnets up to 18T
- Custom magnets for a wide range of applications
- Vector rotate magnets

Instrumentation

- Mercury Electronics
- Cryogenic temperature control
- Magnet Power supplies
- Development kit software
- Sample Protect
- Measurement Probes

Superconducting magnets for NS Research and Industry

OXFORD INSTRUMENTS

Cryofree

Wet

3-400 K

1.5-300 K

< 10 mK

2-4KmK

7 T

8-18 T

Up to 16 T

Up to 22.5 T

Optics

Optics/RF

New materials and Science

Why Cryogenics

Superconducting need Cryogenics (Wet and dry)

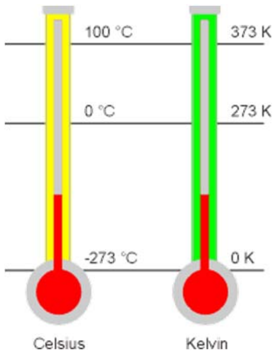
- Cryogenics – science of production and effects of very low temperatures
  - Limit to lowest temp—absolute zero (0K)
  - Cryogenic region → below 120K (-153ºC)
  - Cryogenic Liquids → super-freezing permanent gases to liquid states, ex: oxygen, nitrogen, hydrogen, and helium
    - Liquid Nitrogen: most easily available
    - Liquid Helium: lowest temp. <2.17K

  - For Cryogen free need Cryo-coolers Types:
  - Joule-Thomson
  - Brayton
  - Stirling
  - Pulse Tube
  - Gifford-McMahon

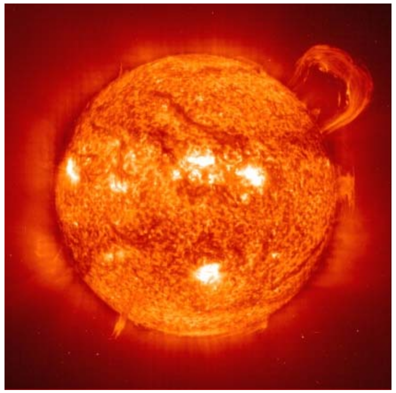
- Two stage pulse tube coolers to provide the cold environment for dilution refrigerators.
- Typically ~ 1 W cooling power @ 4.2 K
  ~ 40 W cooling power at 45 K
- Removes the need for liquid cryogens.

CRYOMECH

Cryogen free technologies ➡ new ultra low temperature (ULT) dilution fridge (10mk)

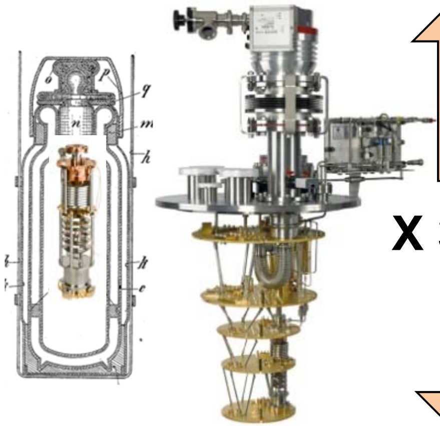


Sun~ 6,000 K



X 20

Room temp ~ 300K



X 30,000

D/R system~10mk

- Quantum behaviour require very low temperature to manage noise
- Space is only 2.7K
- Man can only beat nature at 'Ultra low temperatures' (ULT)

Lowest achieved in the world at OI Tubney
3.3 mK
Cryofree

What do we mean by ‘wet’ & ‘dry’ Dilution refrigerators ?

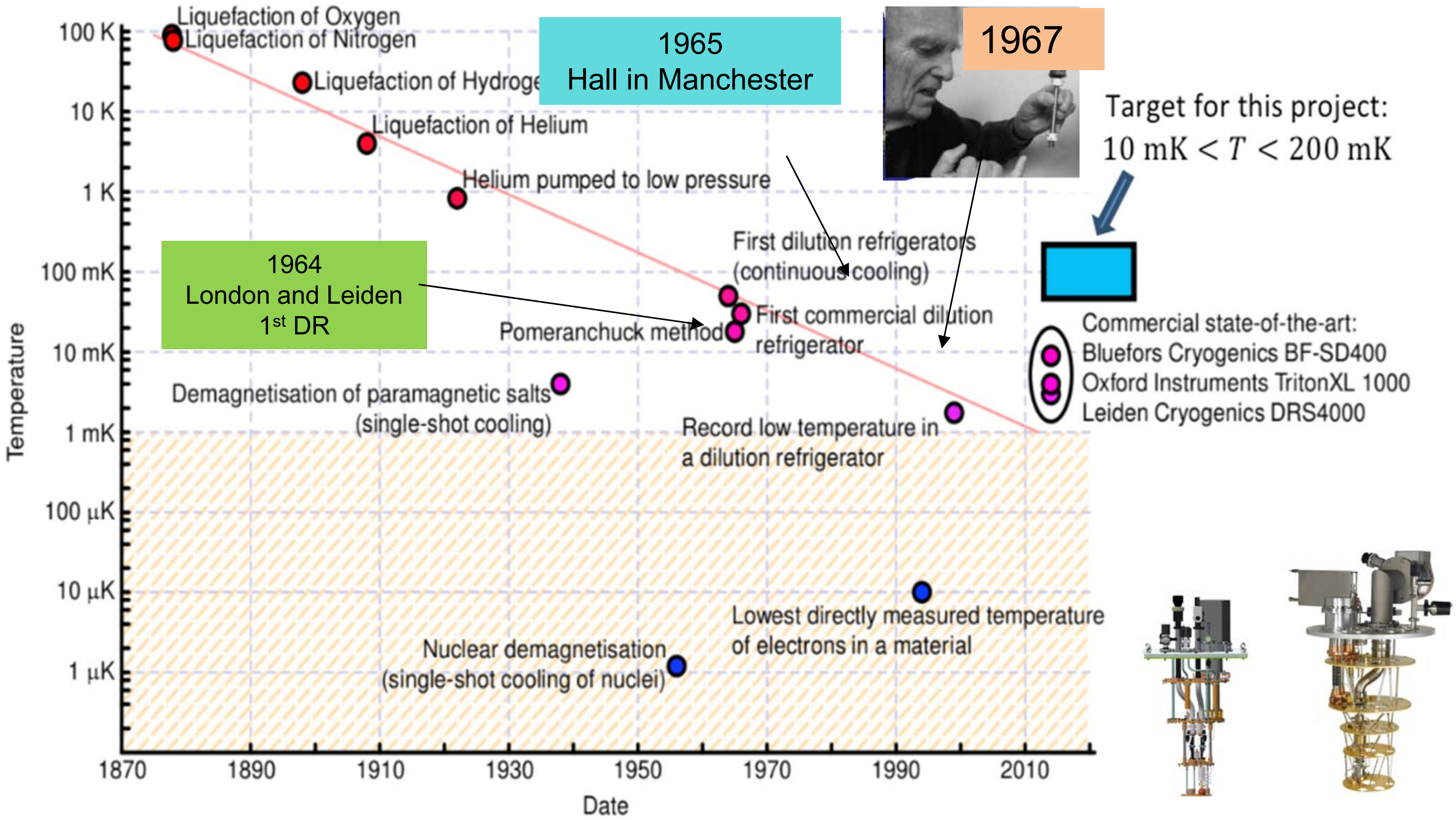
Wet systems use liquid helium

Dry systems use pulse tube cooler

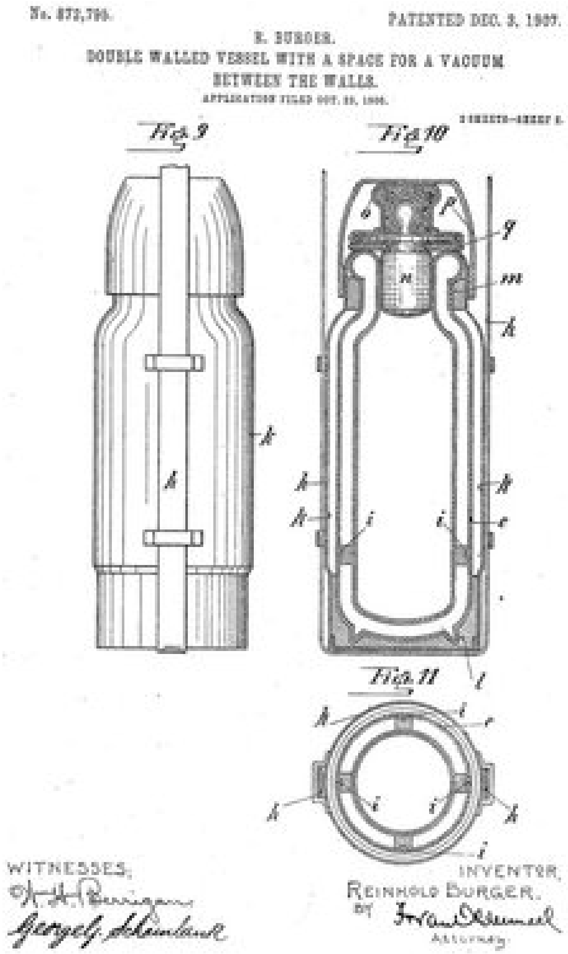
- All dilution refrigerators rely on a stable ~4K cold surrounding.
    - Until recently this has meant a liquid helium bath (boiling point of 4.2K at atmospheric pressure).
- Nowadays it is more common to use a pulse-tube cooler
    - greatly simplifies operation
- Dry systems (no liquid helium) avoid capital expenditure of ~£1M for liquefier, helium gas recovery system & liquid handling facilities
- ’Wet’ dilution refrigerators (using liquid helium) now account for only ~10% of all systems sold and are mainly only used when extremely low vibrations are required.
- A two-stage pulse-tube cooler provides typically 50W of cooling power at 70K on its first stage and 1W at 4K on its second stage. The electrical power consumption is typically 9kW.

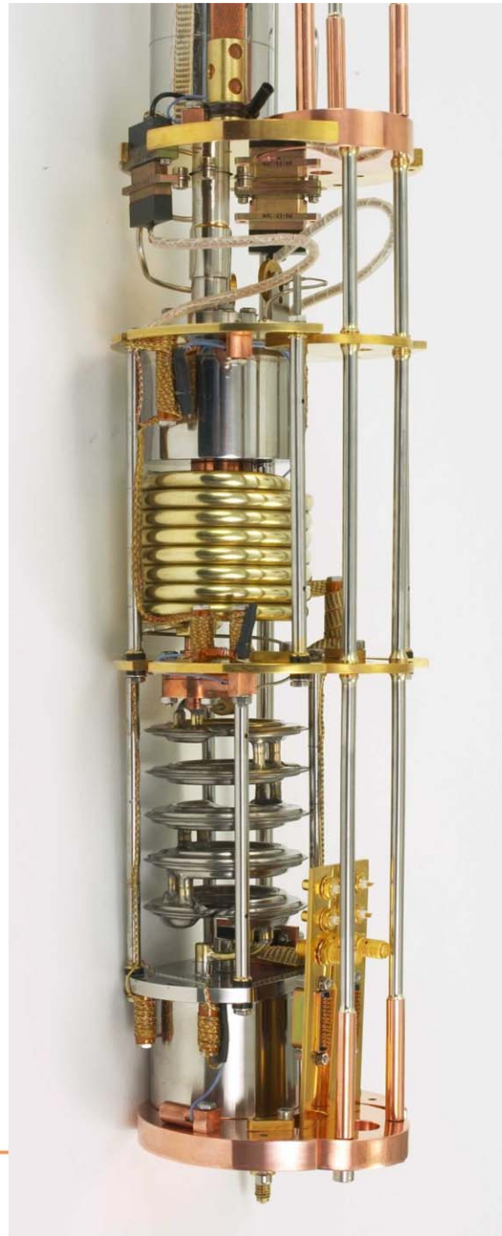
Cryofree Ultra low temperature Environment for Quantum technologies

"Moore's Law" for low temperatures



The Cryofree Revolution

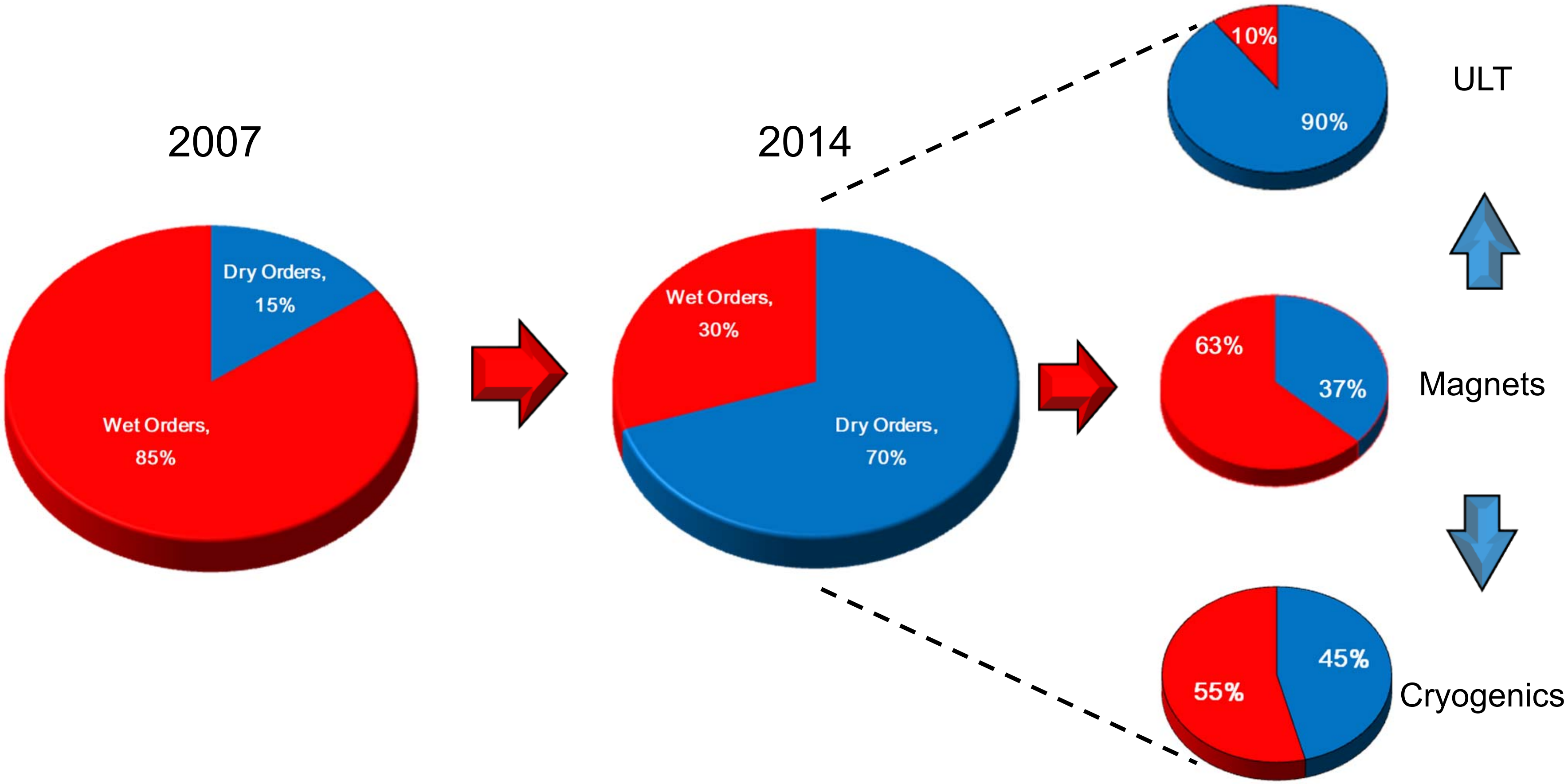




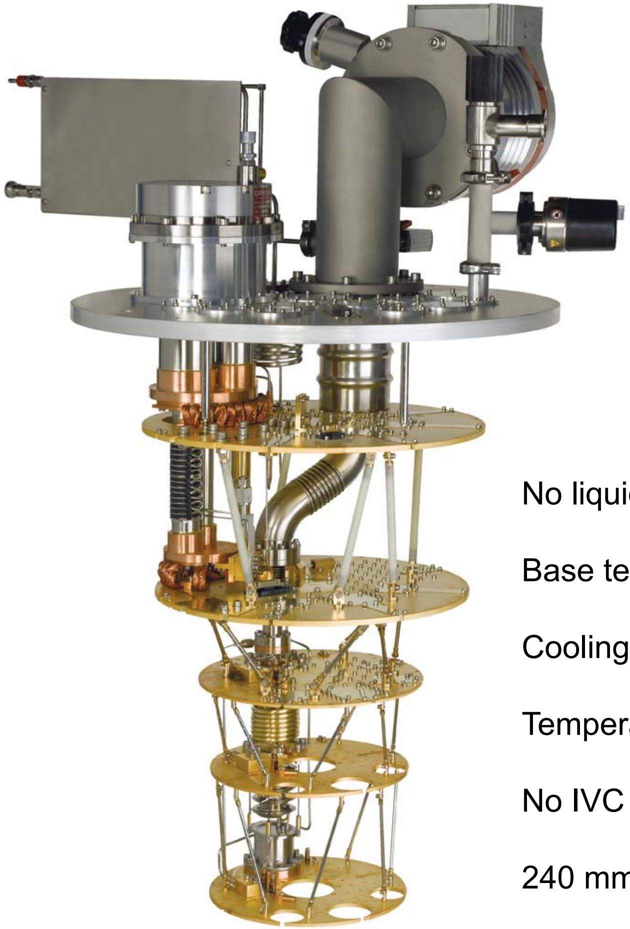
- Cryogenic liquids are costly, difficult to handle, pose safety concerns, and require support infrastructure
- To limit the liquid rate of boiling the cryostat must be tall and have a narrow neck into the liquid
- This narrow neck limits the sample environment available
  - Sample space
  - Magnetic field
  - Experimental services

The Cryofree Revolution

The critical element of our strategy over the past few years has been transitioning the business from ‘wet’ to ‘dry’



Integration with super conducting magnets



- Developed 1960's
- Continuous operation
- Temperature ~5-10mk

No liquid cryogens

Base temperature <10 mK

Cooling power 400 uW at 100 mK

Temperature control possible > 30 K

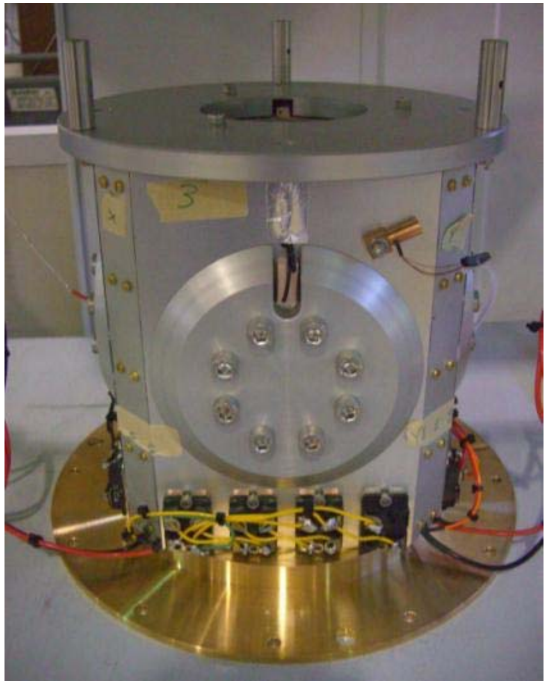
No IVC (only room temperature o-ring)

240 mm diameter mixing chamber plate

Open structure for easy experimental access

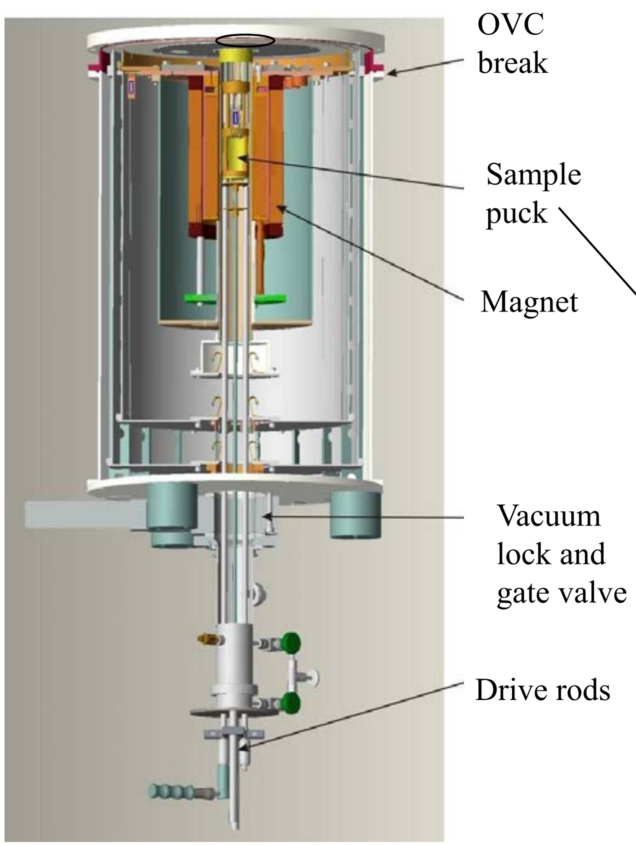
Fully automated cool down from room temperature in < 24 hours

Integrated B/T 10mK & 3 axis magnets



Sample management in ULT systems

‘Bottom load’ sample holder into cryostat



‘Top load’ sample holder into cryostat

Cryofree products (1.5-4.2 K)

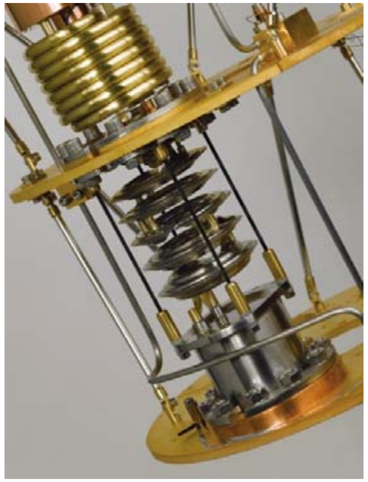
Low temperature/magnet integrated systems (1.5K – 4.2 K)

- Wide-ranging, flexible and upgradable systems
  - Range of magnetic field, typically 8-18 T
  - Variable temperature inserts down to 1.5 K
  - Additional ultra-low temperature inserts
  - Introducing measurement capability
  - A “Swiss Army knife” tool for multiple applications

Cryofree products (5mK-1.5K)

Ultra-low temperature/magnet integrated systems 5 mK -1.5 K)

- World-leading **Triton** Cryofree® dilution refrigerator systems
  - New opportunities via Cryofree technology – large sample spaces at < 10 mK
  - Ease-of-use and experimental throughput focus via sample loading innovation
  - Complete magnet integration
  - Key enabler in QIP research and device development



Custom products

Custom-engineered systems

- Application-centric system design
  - Neutron and X-ray scattering, XMCD, particle and ion traps, nuclear demagnetisation, …
  - Multiple cryogenic solutions including Cryofree®
- Close customer collaboration in system definition

Re-condensing

Why re-condensing ?

Recondensing – helium + refrigerator (PTR)

- Nitrogen pre-cool allows faster system set up
- Liquid helium, so stable, essentially isothermal environment
- Positive pressure maintained via PID control
  - protect against air ingress
- Helium provides system "ride through", against power outages etc.
  - maintains experimental environment/preventing system warm up
- Excess condensation capacity
  - allows condensing of helium flows for example through variable temperature inserts, dilution refrigerators etc.
- Allows trade off between cryogen consumption and speed of operation ie faster magnet sweeps and rapid sample cool down (often significant criteria where beam time is expensive and set up times need to be minimised)

diamond

Diamond Light Source Ltd
Diamond House
Harwell Science & Innovation Campus

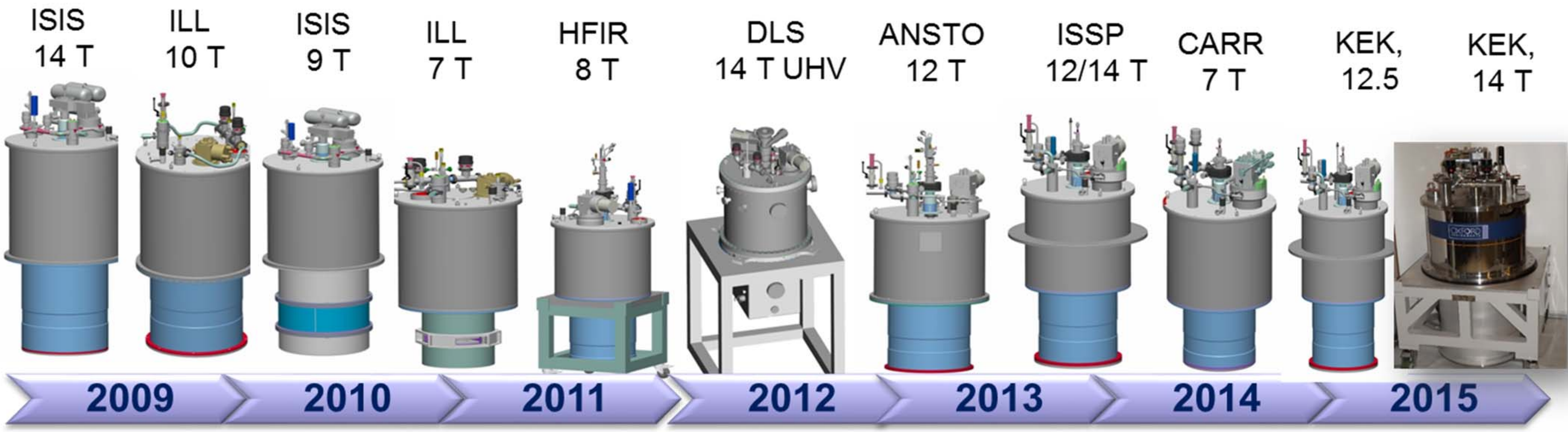
("Operation of superconducting magnet with dilution refrigerator insert in zero boil-off regime", Cryogenics 50 (2010) 666-669)

Split pair magnets for Neutron scattering studies

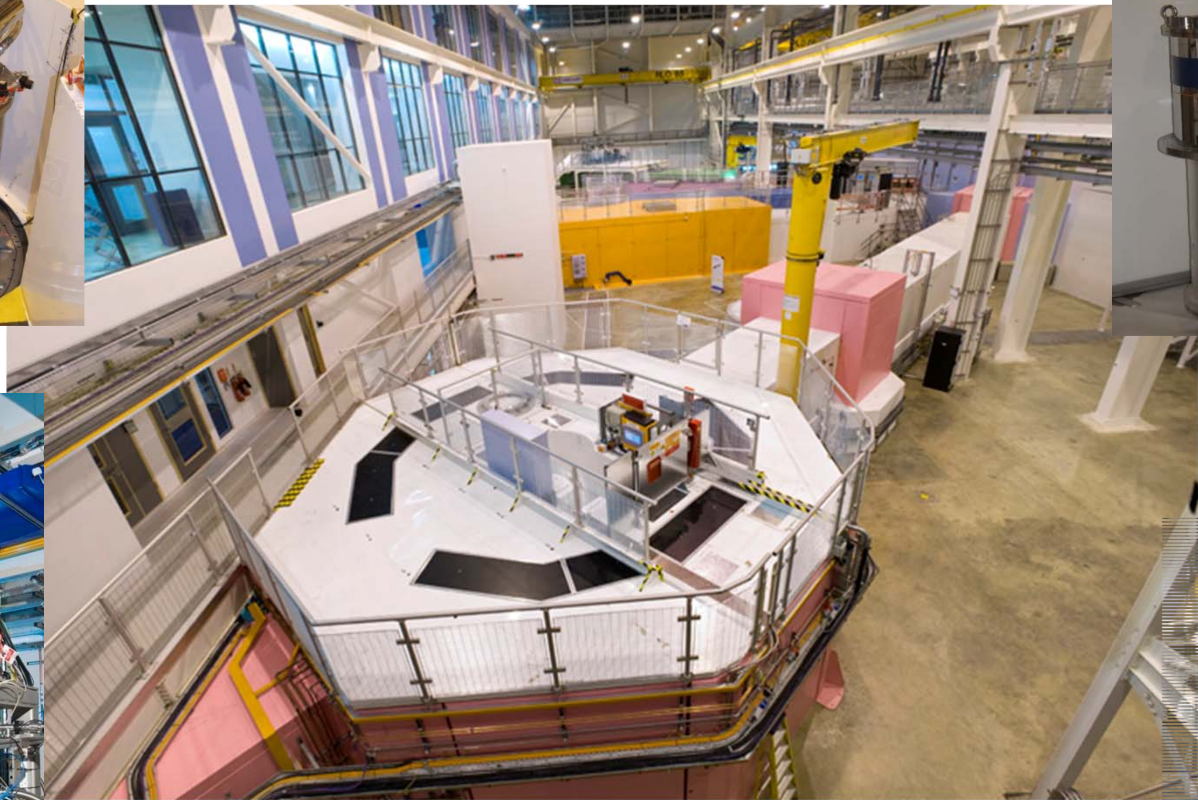
Takashi Kamiyama, KEK Institute, Japan

- Split pair for Neutron scattering studies
  - 14 T symmetric mode
  - 11.5 T in asymmetric mode
  - Re-condensing system

Central magnetic field homogeneity	**< 1.05% on 20 mm x15 mm symmetric mode (< 1.85% in asymmetric mode**
Temporal stability in the persistent mode	< 1x 10^{-4} relative hr^{-1}
Maximum sweep rate	0.25 Tesla min^{-1}



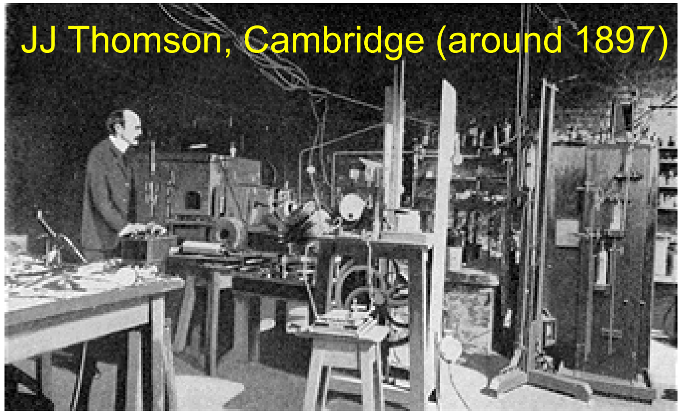
Summary– Re condensing beamline systems

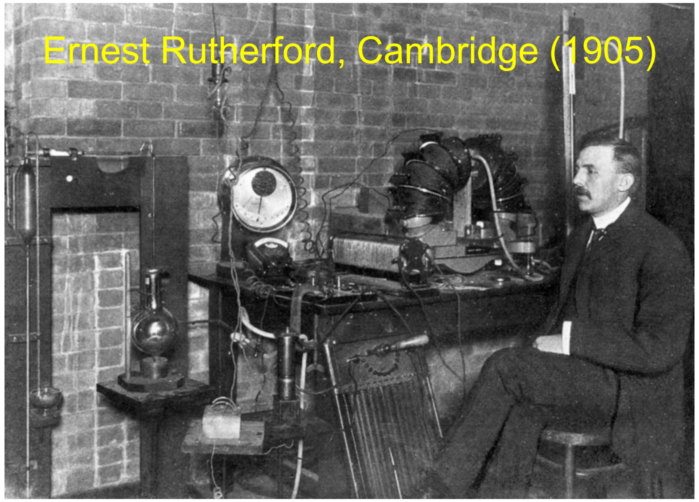


Enabling cost effective, low (and high!) temperature, high access, high magnetic field beam line environments

New thinking about customers needs

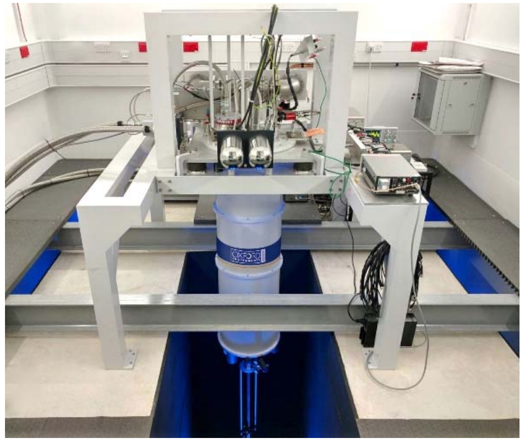
New thinking about the lab environment & tools


JJ Thomson, Cambridge (around 1897)


Ernest Rutherford, Cambridge (1905)

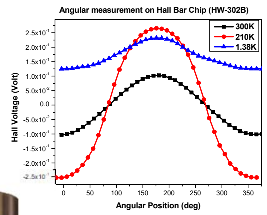
Neil’s Bohr Inst – Copenhagen Univ (2015)

Lancaster Univ IsoLab (2017)



Solutions for nanoscale research – for research

TeslatronPT measurement and upgrade paths (8T-18T)



Electrical measurement probes

< 300 mK with Heliox®VT

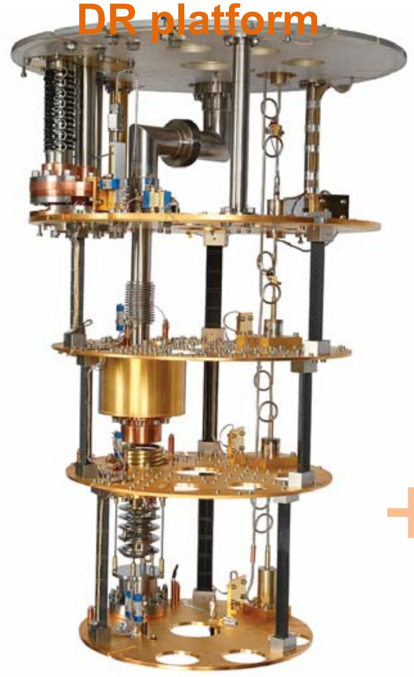
Standard sample rods

< 25 mK with Kelvinox®JT

- Range of magnet/sample space **(8T -18T** options)
- Variable temperature insert
  - **1.5 to 300 K**
  - **30 mm or 50 mm** sample space

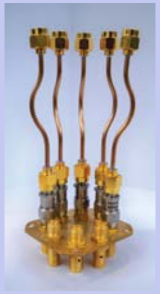
Selected low temperature applications

DR platform

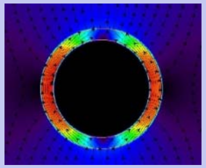


- **Mixing Chamber**
  - **150mm**
  - **290 mm**
  - **450 mm**

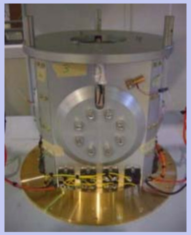
Experimental options



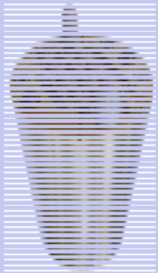
RF wiring



Mu-metal shielding



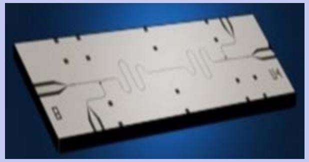
Integrated Magnet



Sample loading

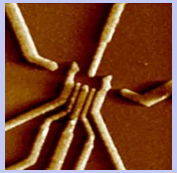
\+ =

Superconducting quantum computing



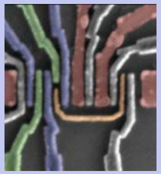
- Large sample space
- High cooling power
- Magnetic shielding

Quantum Hall effects



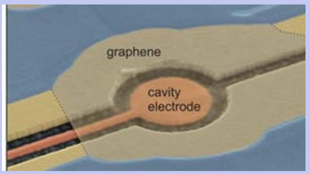
- High-field solenoid magnet
- Low eddy-current holder
- High-temperature control

Spin qubits and toplogical QC



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

Quantum opto-mechanics

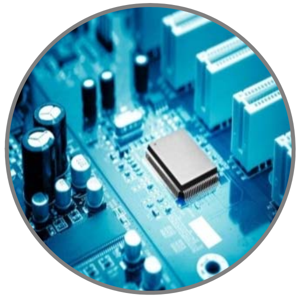


- Ultra-low vibrations
- Fast cool-down
- Low-noise wiring

Quantum Technologies

Quantum technologies impact society

- Arguably the most defining technologies of the twentieth century were underpinned by our understanding of quantum mechanics.



  - **The semiconductor** and the **laser** have become under-pinning ‘platform’ technologies that have enabled innumerable systems and products that have changed our lives.

  - The next generation of twenty-first century ‘quantum technologies’ will exploit and harness our understanding and control of subtle quantum mechanical effects, enabling brand new capabilities and leading to
    - Next manufacturing revolution at the nanoscale

UK Quantum Technology Landscape

Quantum timing & Atomic clocks

<5 yrs)

- Precision timing
- Ultra precise clocks
- Chip scale devices

Quantum Comms

(>5 yrs)

- Quantum networks
- Miniature handheld Quantum Key distribution(QKD) systems
- Point-multipoint and peer to peer QKD systems
- Repeaters
- Transmission systems

Quantum Sensing

(>5 yrs)

- Electromagnetic sensors
- Gravity sensing
- Quantum nanotechnology for Healthcare and environmental sensing
- Cold atom systems for metrology and navigation
- SQUIDS as sensitive magnetometers

Quantum Computing

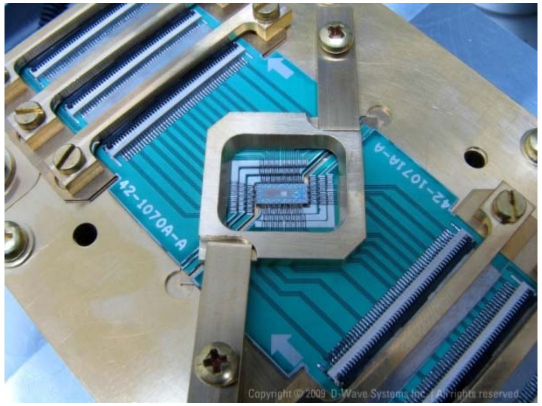
(>10 yrs)

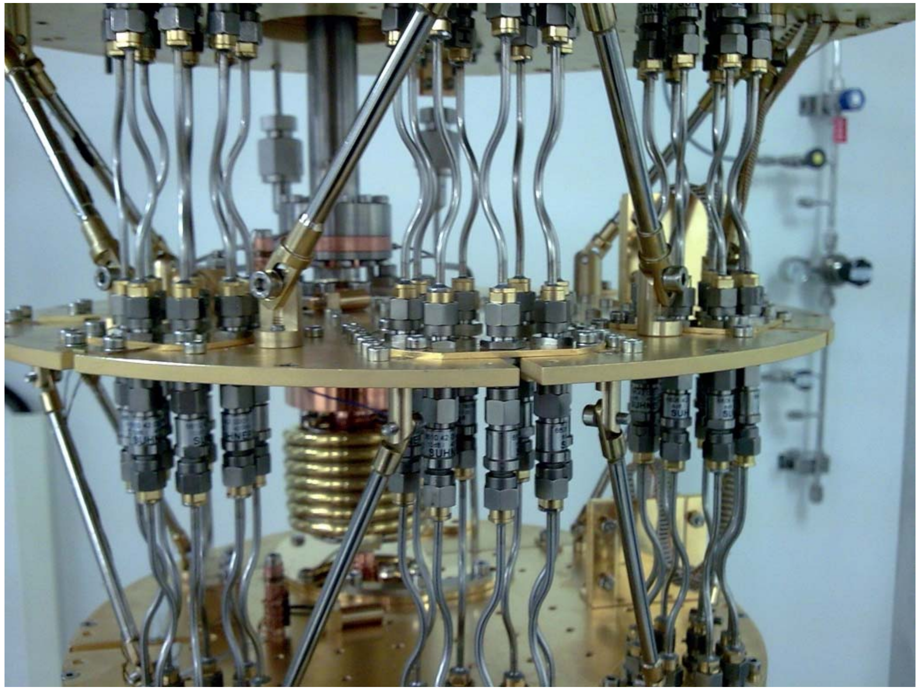
- Quantum computing
- Quantum information processing
- Quantum materials

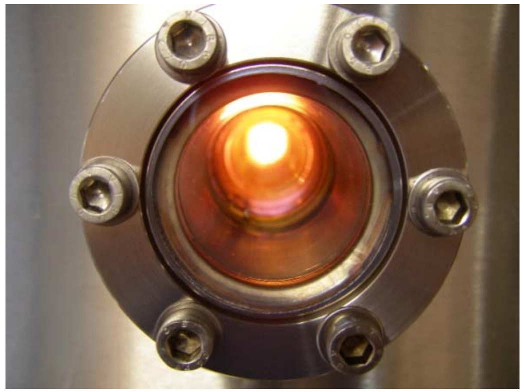
Quantum Computing

Superconducting Qubits

Yasunobu Nakamura, University of Tokyo





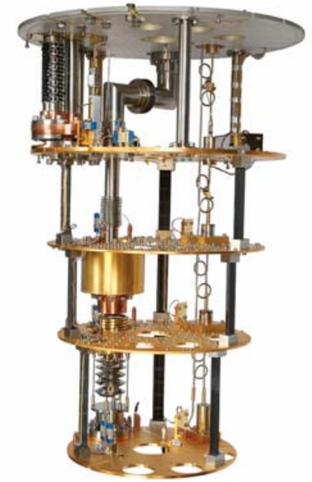


- Freedom from cryogens and freedom on sample volume has revolutionised low temperature applications
- Quantum Computing and security applications are growing rapidly
- New users are developing low temperature capability without the need for liquid cryogen infrastructure
- New applications characterising devices instead of materials

Configured environments for Quantum

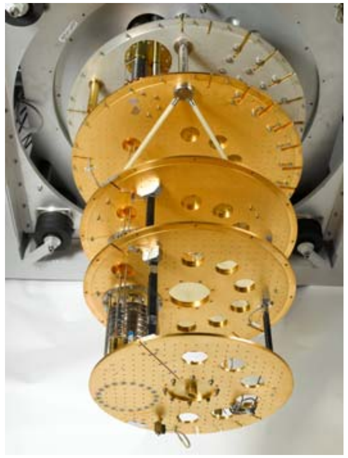
- Open access cooling platform
- High cooling capacity – 4K & mK
- Large payload > 10^5 cc
- High RF line-count
- Integrated magnets
- Rapid sample exchange

Triton: 290 mm @ < 10 mK –
Qubit Developments

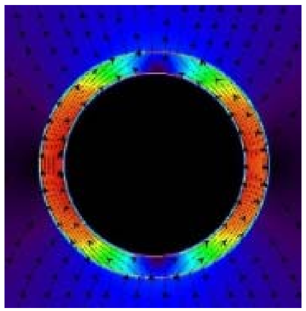


- < 10mK base temp
- > 12 µW @ 20 mK
- 500 µW @ 100 mK

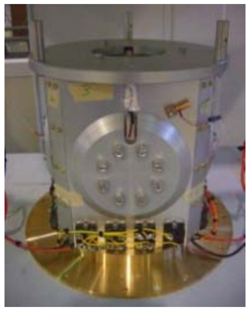
Triton XL: 430 mm @ < 5 mK
Qubit Scale up



- < 5mK base temp
- > 25 µW @ 20 mK
- 1000 µW @ 100



Mu-metal shielding



Integrated Magnets

Rapid sample exchange

High power cooling capacity

Integrated Optics

High density RF line-count

Cryogenic systems for QT & NS

- Q sensors <1 K (e.g. magnetic sensing for MRI, MEG, Geosurveys, environmental)
- New devices such as SQUIPTs, HyQUID offer Nb SQUID performance (or better) with lower noise, power dissipation.
- 2D materauls charecteristaion

4 K

1.5 K

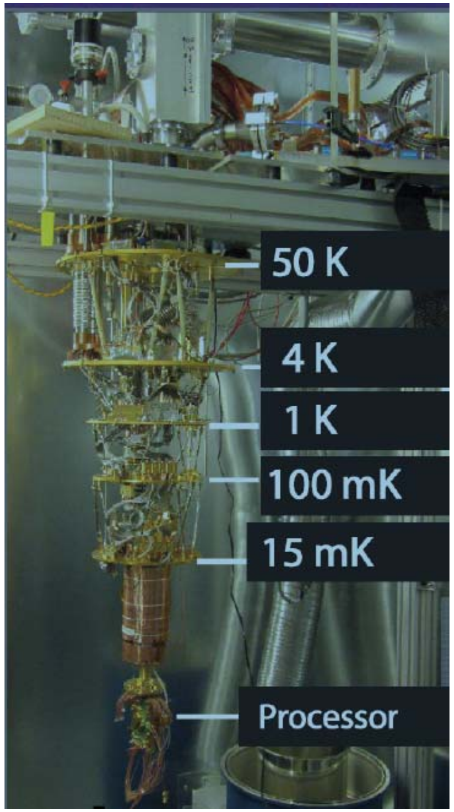
5 mk
290 mm

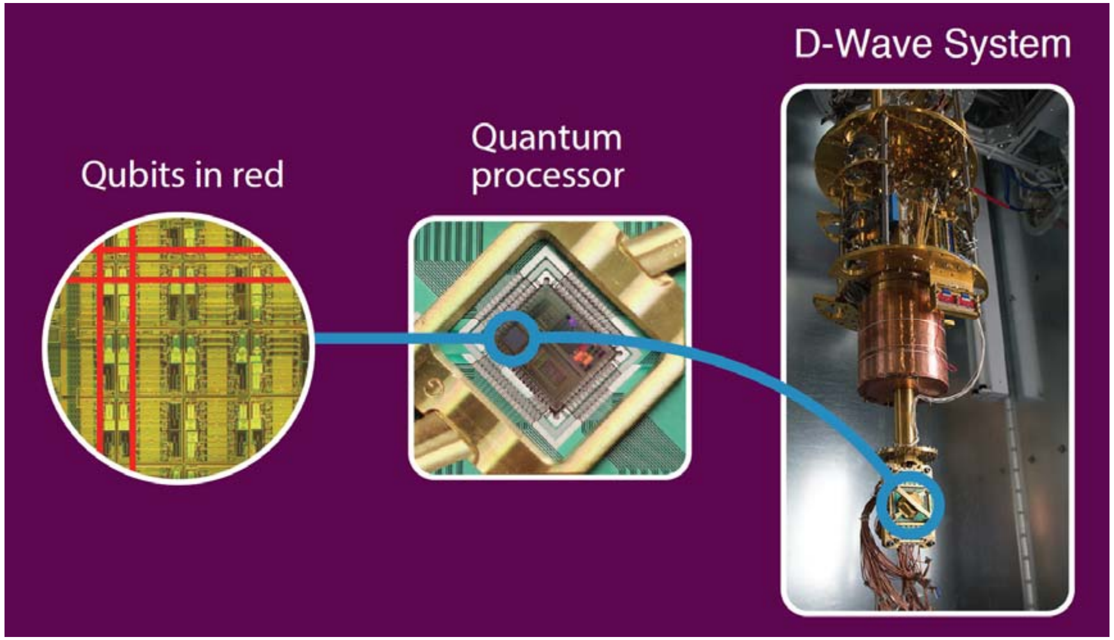
5 mK
440 mm

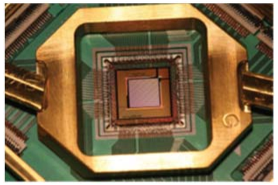
5 mK
550 mm

D-Wave Quantum Computers
Founded 1999 – 1st QC company

- The D-Wave 2X system implements a *quantum annealing* algorithm,
  - solves problems by searching for the global minimum of a function
  - relevant in many high value problems such as
    - minimizing error in a voice recognition system,
    - controlling risk in a financial portfolio,
    - or reducing energy loss in an electrical grid.
- D-Wave systems are being used, for example, by
  - Lockheed Martin, Google, NASA, and the University of Southern California.





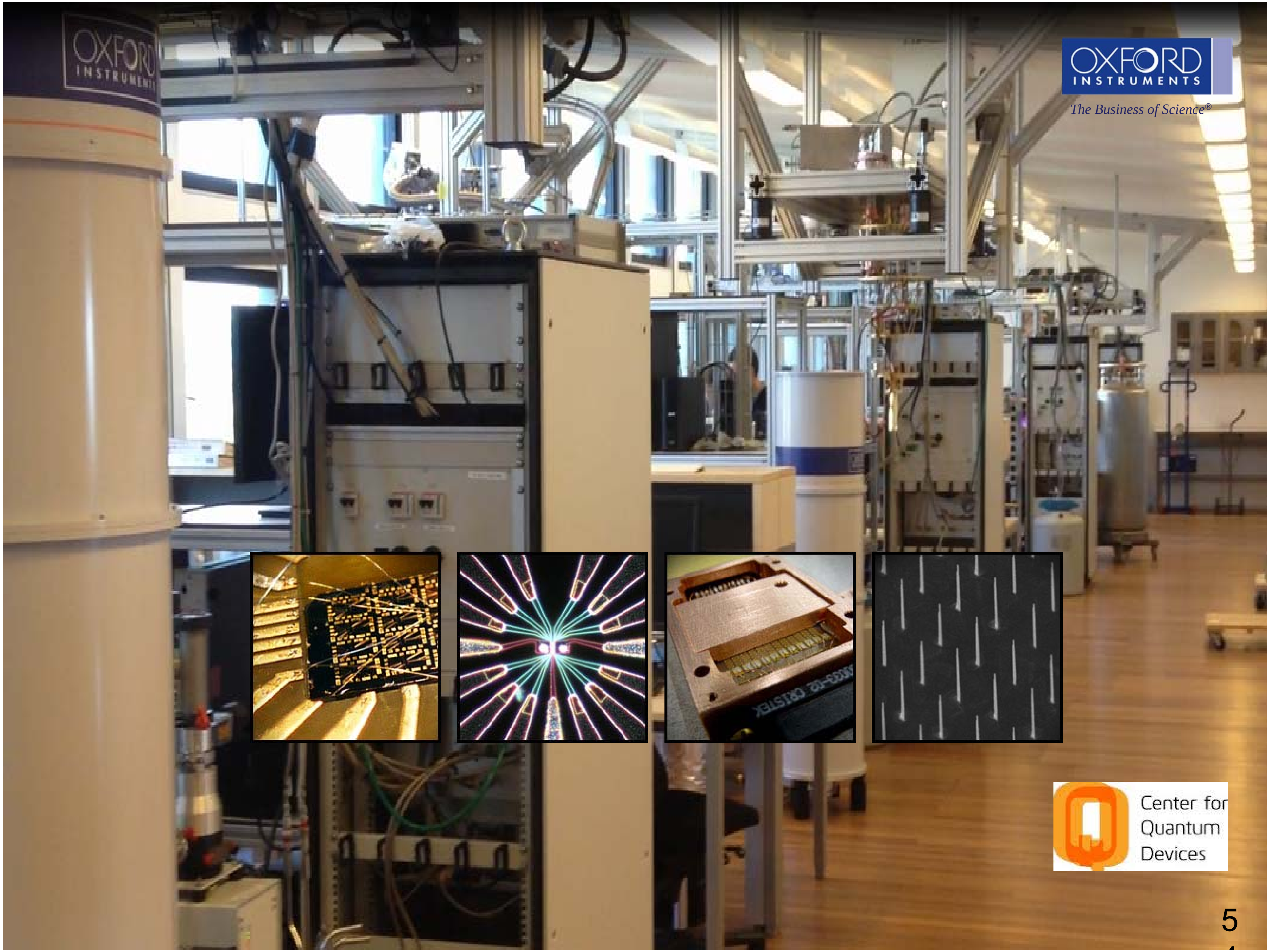


With 1000 qubits, the D-Wave 2X system can search through 2^{1000} possible solutions

Quantum computing research labs today

Courtesy of D-Wave systems Inc

The combination of Cryofree® technology and the intense interest in quantum information processing bring a new level of multi-system laboratories (Niels Bohr Institute), and the first commercial quantum computers

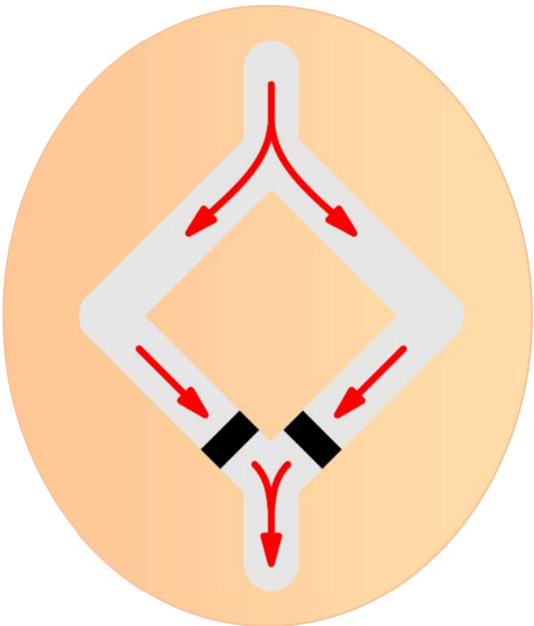

OXFORD INSTRUMENTS
The Business of Science®
Center for Quantum Devices

Quantum Sensors & Metrology

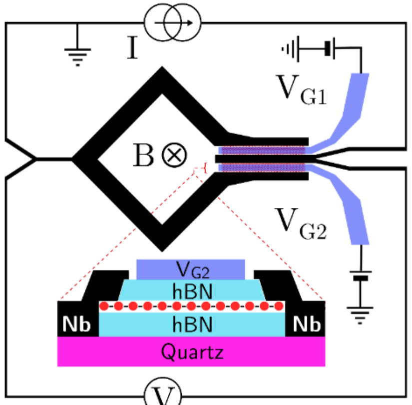
Cryofree Ultra low temperature Environment for Quantum Sensors - MEG

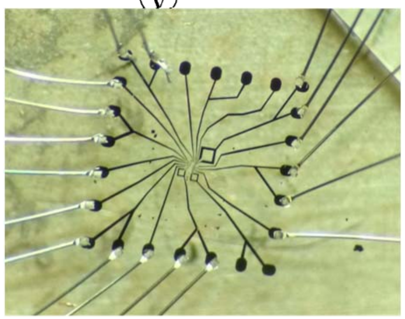
Sensor challenge: exploit new platform of 100 mk to outperform traditional magnetometers

Graphene-based tunable SQUIDs
APL: 10.1063/1.4981904

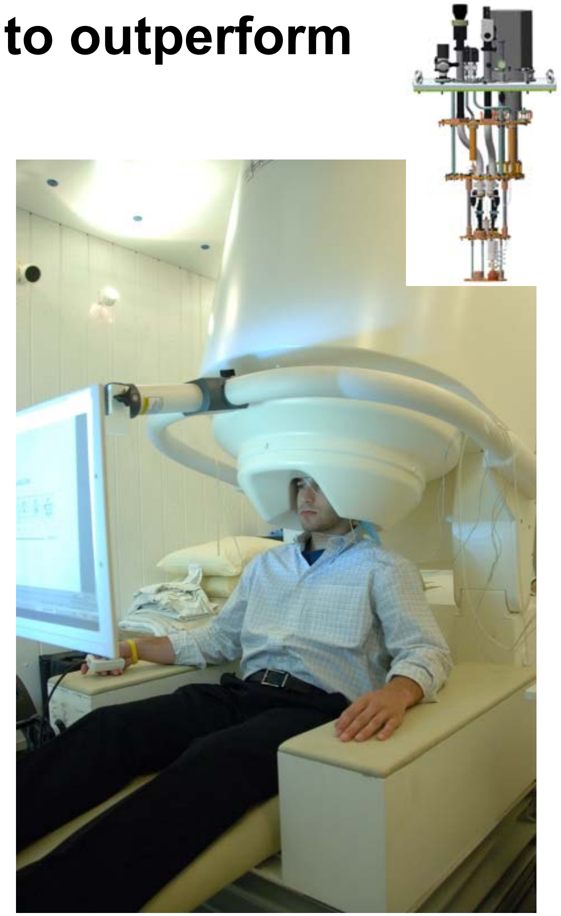


SQUID @4k





G-SQUID @100mk



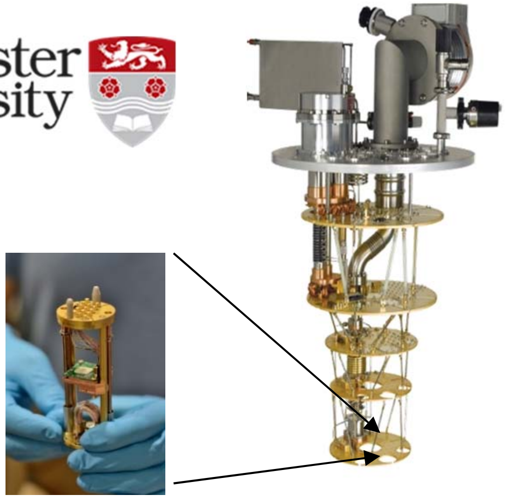
Sensors for medical imaging
Magnetoencephalography (MEG) scanners:

CUE-QS –
InnovateUK collaboration grant - Lancaster Univ.

Cryofree ultra low temperature environment for quantum sensor: CUE-QS

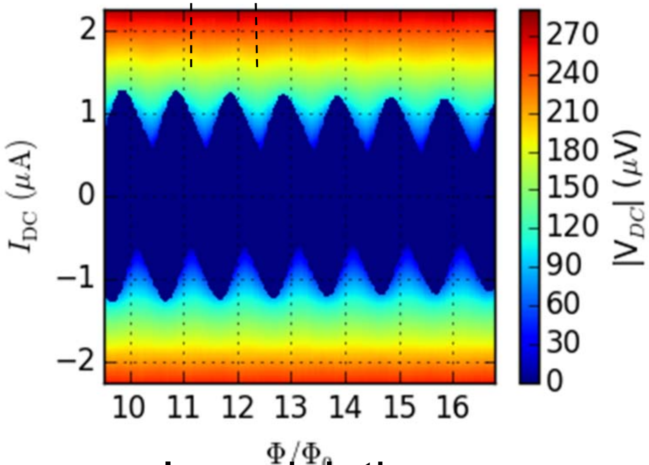
R. Haley, Y. Pashkin, J. Prance, M. Thomson

1. **Concept designs for 100 mK platform**
2. **Demonstrated Graphene (SQUID) sensor**
   - Square loop ~ 12.5 μm x 12.5 μm
   - Gated SGS Josephson junctions - monolayer graphene



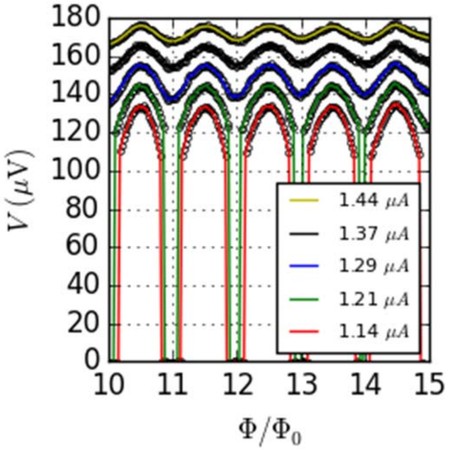
3. **Studied flux modulation of I_c and voltage**

9 μT ~ 230 μm², actual 212 μm²

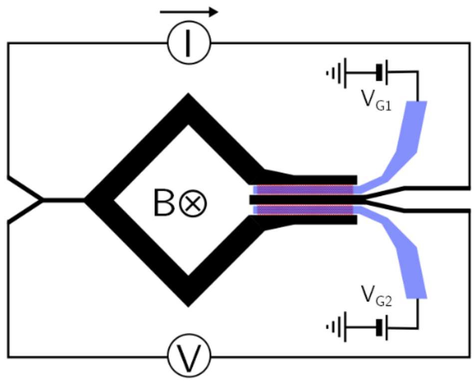


I_c modulation

20 mK



Voltage modulation

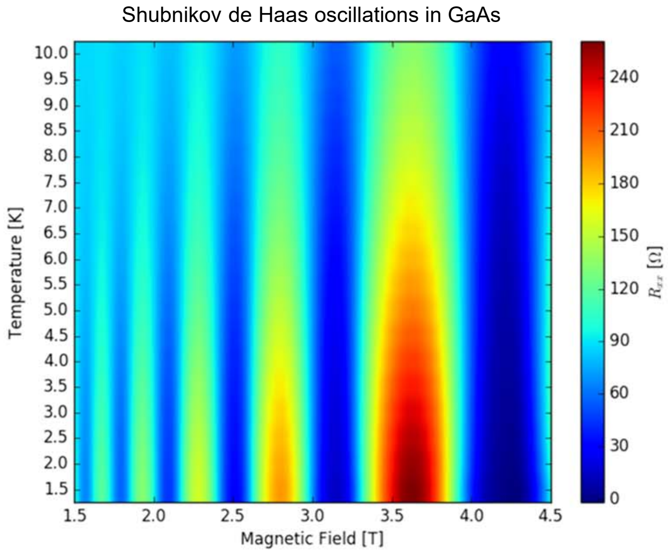


InnovateUK Grant

2D Materials - Quantum Transport

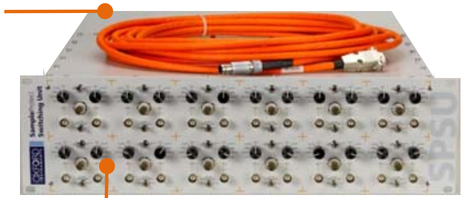
Multi-channel high speed measurement instrumentation

Magnetic field & temperature measurement & control

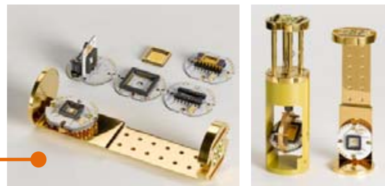


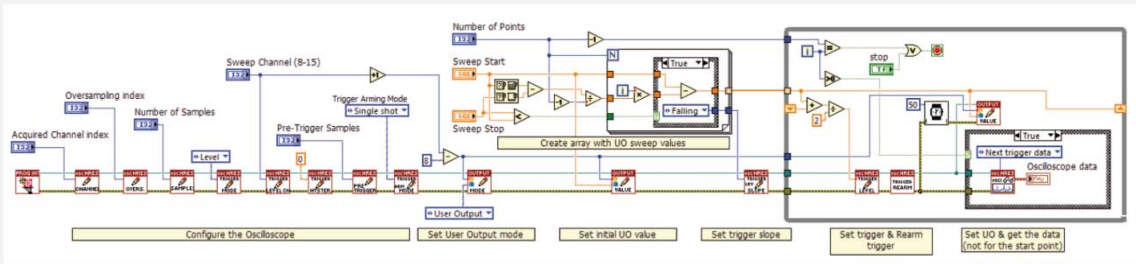
Low noise signal cabling

Device protection through bias & ground control

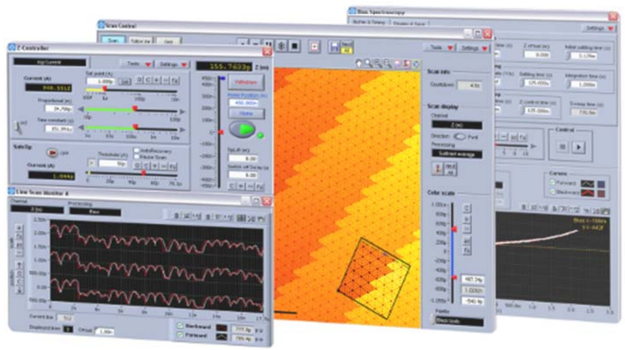


Rapid device exchange, manipulation & rotation





Data flow: Example of a measurement routine programmed with the programming interface. The routine controls a measurement by setting a gate voltage, triggering the HR oscilloscope, acquiring and storing a trace, before moving to the next gate voltage.



Quantum Standard Measurements

Quantum resistance measurements

Graphene for Standard Measurements and 2D Materials characterisations

OI: Ziad Melhem, Rod Bateman, Roman VIZNICHENKO
NPL: JT Jansen, A Tzalenchuk, S Rozhko ,
NGI: V Falko

- *InnovateUK Grant*
- *Graphene Flagship Grant (EU) - ongoing*

Cryofree enabling Smart science to applications

Smart science (Wet systems)

Technology demonstration (Cryofree systems)

1980 Discovery of QHE

2003 QHE as an electrical resistance standard

2010 Noble prize for Graphene

2011 NPL confirmed universality of QHE in 2D

2015 NPL demonstrate Q Metrology

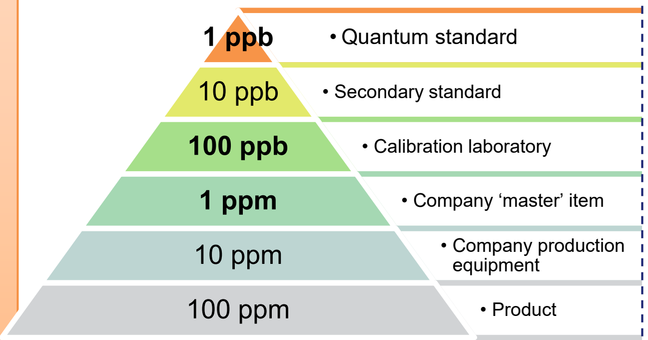
2017 OI+NPL+Chlamers+_UoM – demonstrate industrial feasibility of QHR

2019 OI+NPL + **Prototype** for TTQHR for Q Resistance standard

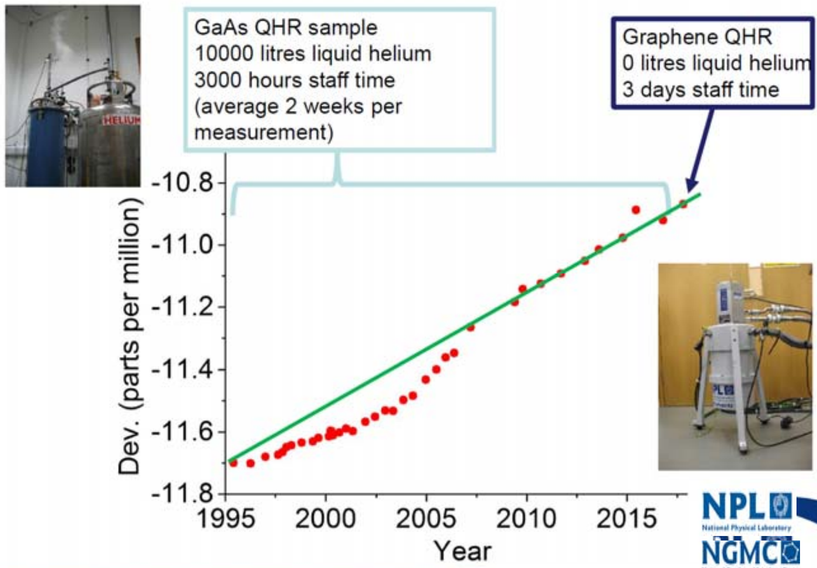
The primary standard for resistance is based on the quantum Hall effect (QHE)

- Existing platforms use liquid Helium sub 1 Kelvin and require high field > 14 Tesla.
  - Expensive- *National facilities*
  - Large footprint
  - Require extensive additional services to operate.
- Setup ideal for research

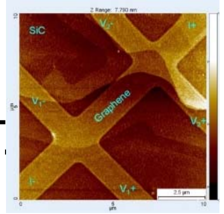
- Moving primary metrology from the metrology labs closer to the factory floor.
- Shorter traceability chain



23 years of resistance traceability: The history of one artefact resistor



Solution: Graphene enabled platform for QHE measurements (Std R & 2D characterisation !)

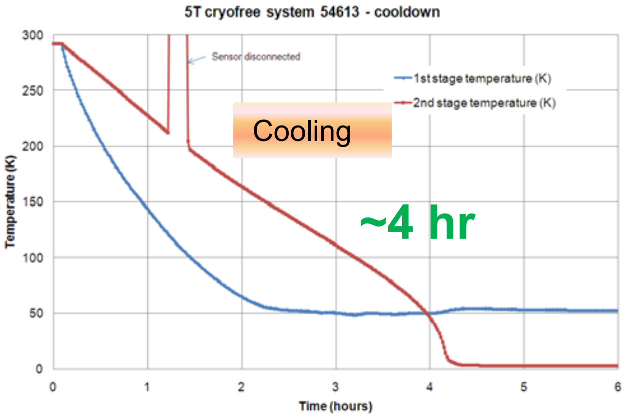


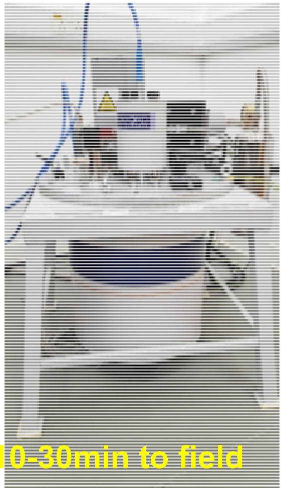
- A cryogen-free QHE system based on graphene,
- Compact/Turnkey cryogen-free environment which operates at 4k and 5T.
- Characterise the measurement system in an industrial environment.
- Magneto transport testing to determine the breakdown current at the factory

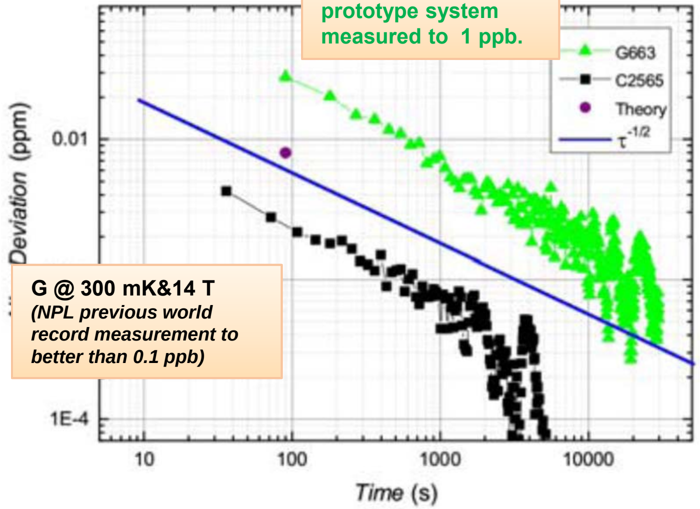
Current

Future

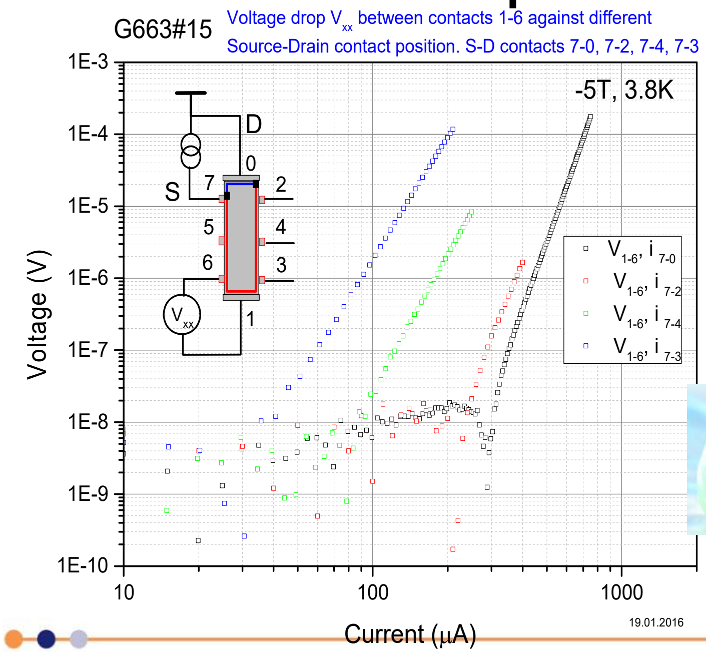
Results from a 5T Cryofree SC Magnet for table top Quantum Hall System at NPL

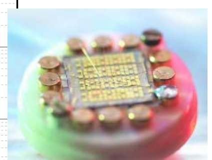




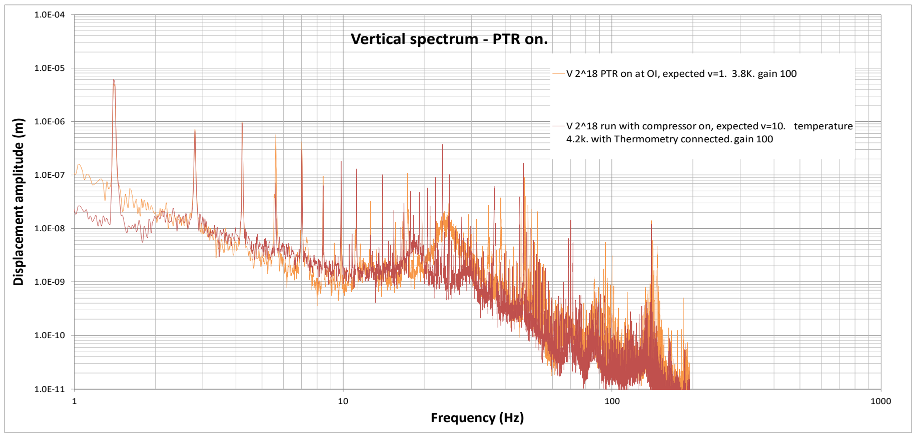


Breakdown current optimisation





PTR on, cold – vertical displacement spectrum



Spectrum dominated by PTR fundamental at 1.4Hz

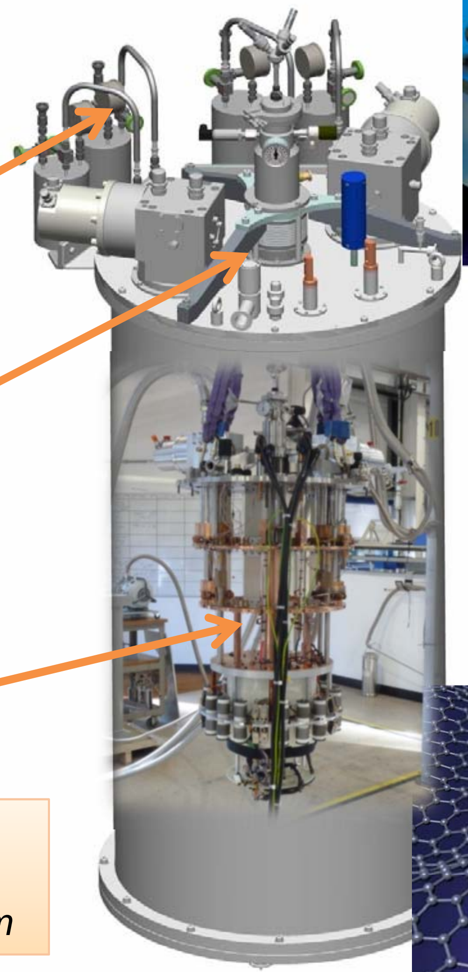
Science and industrial Applications

Graphene and & 2D materials Teslatron®PT now with HF options

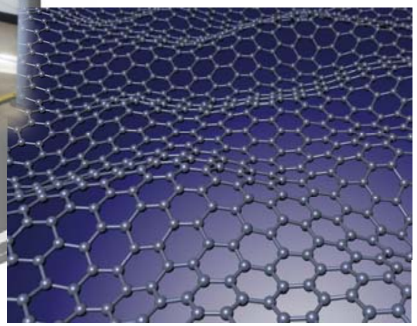
- 18 Tesla system developed, optimised, tested and installed at University of Manchester

(Understanding the Quantum Hall Effect in Graphene shed light on its unique structure and properties)

- Fast cool-down **(32 hrs)**
  - Patented "heat pipe" technology
- Low vibrations
  - Using Cu braids at critical links
- Fast magnet running- **(66 min)**
  - Advanced SC wire selection
  - Magnet construction optimised
  - Power supply optimised



in the lab of Prof Sir Kostya Novoselov
•Winner of Oxford prize 2007
•Noble prize winner for 2010 for Graphene with Geim

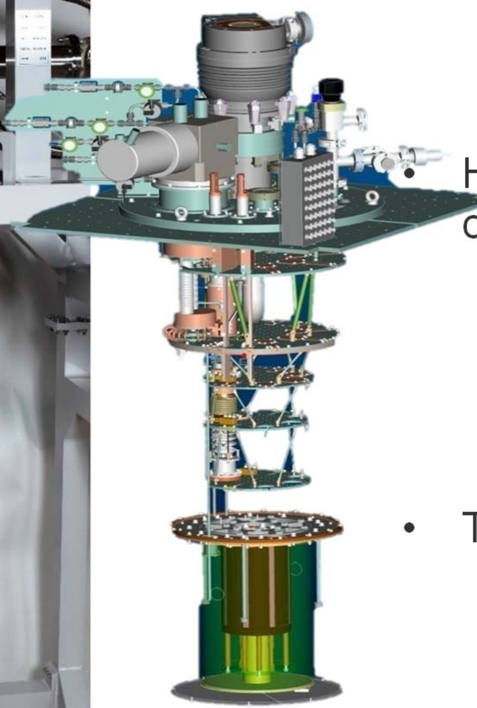


Graphene and Low- dim materials

New cooling platform the Triton XL400/XL1000 with 16T intergrated magnet

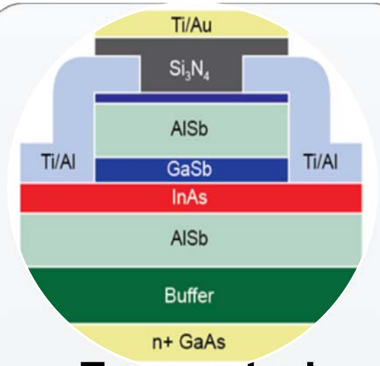
Prof Aveek Bid, INDIAN INSTITUTE OF SCIENCE BANGALORE- research on Graphene and other low-dim materials

Triton XL 400 with an integrated **16T** bottom loading

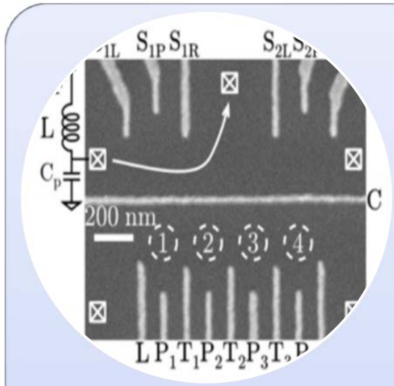


- A Triton XL 400 with
  - An integrated 16T magnet
  - Bottom sample loading.
- Highest field cryofree magnet ever integrated on a cryofree dilution fridge.
  - Achieved <6mK on the mixing chamber.
  - Samples can be cooled to <10mK in less than 8 hrs 14 high-frequency (up to 40GHz) connections plus 50 DC connections.
- The system is used for:
  - Quantum Hall Effect in novel materials - **Graphene** and 2DEG at oxide interfaces
  - Conductance fluctuations in low dimensional systems - metal nanowires and quantum dots
  - Mesoscopic Physics - charge and statistics in the fractional Quantum Hall regime
  - Other materials research

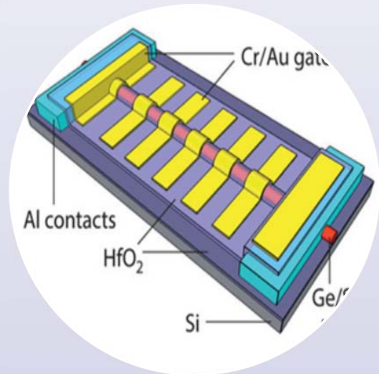
Spin qubits & topological insulators
Integrated 3-axis 90mm bore 6/1/1 magnet



Topological quantum computing is based on the unique properties of Majorana fermions**.** **Leo Kouwenhoven's** group in **Delft – Holland** study *edge-mode superconductivity in InAs/GaSb quantum wells*



Tarucha's group at **RIKEN,** Japan work on AlGaAs/GaAs **quantum dots**. They demonstrated control and read-out of 4 tunnel coupled quantum dots – *scalable solid state spin qubit architecture.*

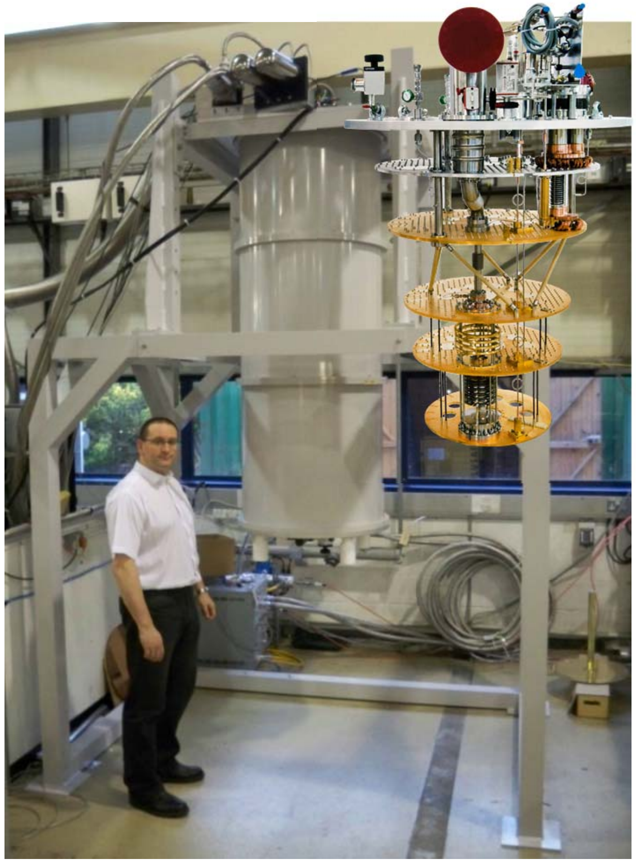


Charlie Marcus's - Niels Bohr Institute in Copenhagen study **quantum dot spin-qubits using Ge/Si nanowires**. This material benefits from zero nuclear spin which reduces the spin-orbit coupling and *improve decoherence time.*

Vector rotate magnets

Integrated cooling with magnet for spintronics - New platform the Triton XL1000

Ensslin 's group of nanophysics at ETH Zurich



Triton XL 1000 with cancelled 12T and bottom loading

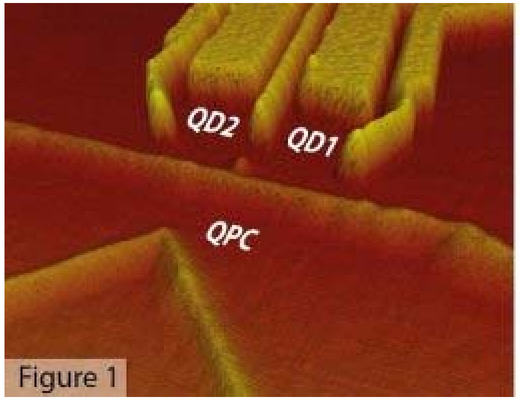


Figure 1

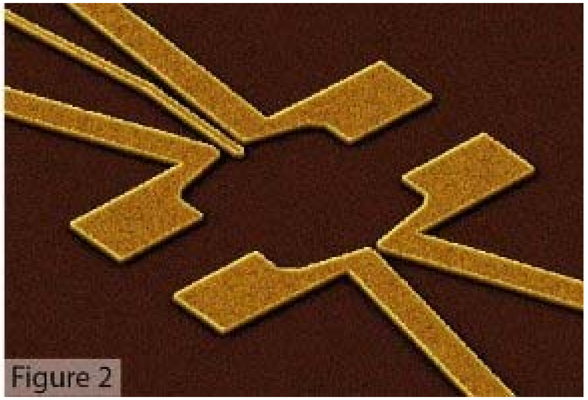


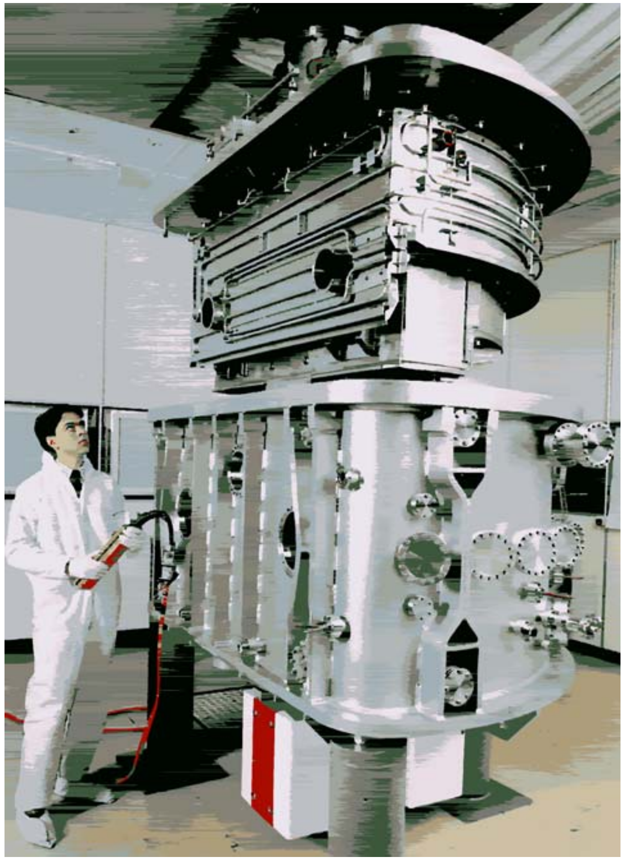
Figure 2

•Figure 1: typical set-up for studying single-electrons confined in quantum dots based on GaAs/AlGaAs heterostructures.

•These techniques are now being transferred to high mobility devices (Figure 2) for the study of fragile quantum states such as quasiparticles of the fractional quantum Hall effect.

> *•Control over these quasiparticles allows for the investigation of edge states, an important step towards the realization of a topological qubit*

Helios: compact synchrotron X-ray source for microchip lithography



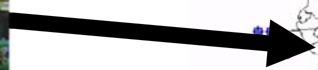
photos courtesy of OXFORD INSTRUMENTS

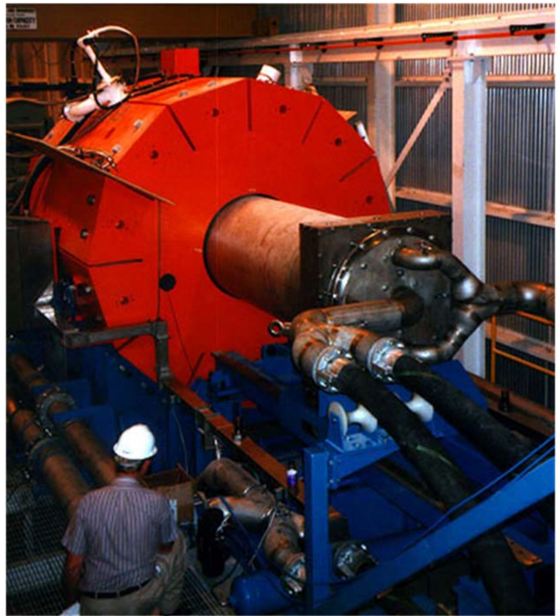
Industrial Magnets
Magnetic separation - Carpco

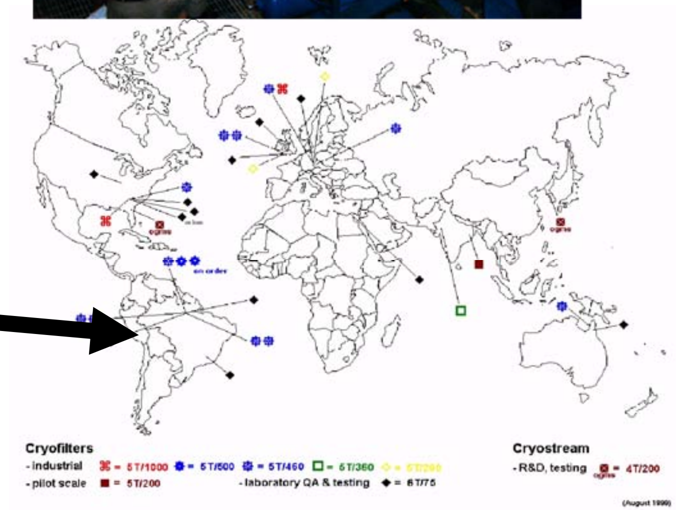
- High gradient magnetic separation (HGMS)
- Primarily for kaolin processing
  - removing weakly magnetic impurities to improve whiteness (and therefore economic value)
- **5 T** magnets, 360 mm to 1000 mm bore

operate at the mining source

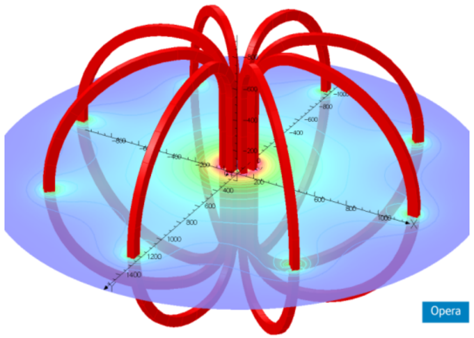
- Amazon rainforest, Brazil
- Queensland, Australia
- Cornwall, UK

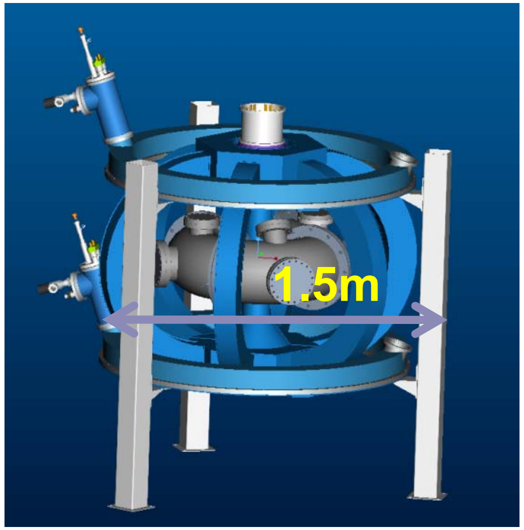




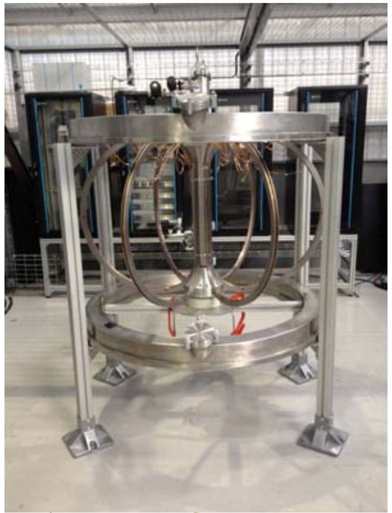


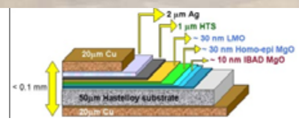
HTS Coil Technology Development– Start with Low Field !





R/a	25/12.5cm
B_t	0.4T
900m HTS	12mm YBCO





Courtesy of SuperPower Inc

PF coils tested to ~450A – Solo test
TF coils tested to ~450A - Solo test
TF coils tested to ~ 170A - system tests

MRI Superconducting magnets

MRI Magnets Development
Health Sector

- All using LTS Materials
- >4000/yr production
- >4 Billion Euro/yr market

1st MRI — AS 1.5T — AS 3T — 1.5T Small — 9.4T

1980 2011 — 1986 — 1989 — 1994 — 1997 — 2000 — 2001 — 2005 — 2019

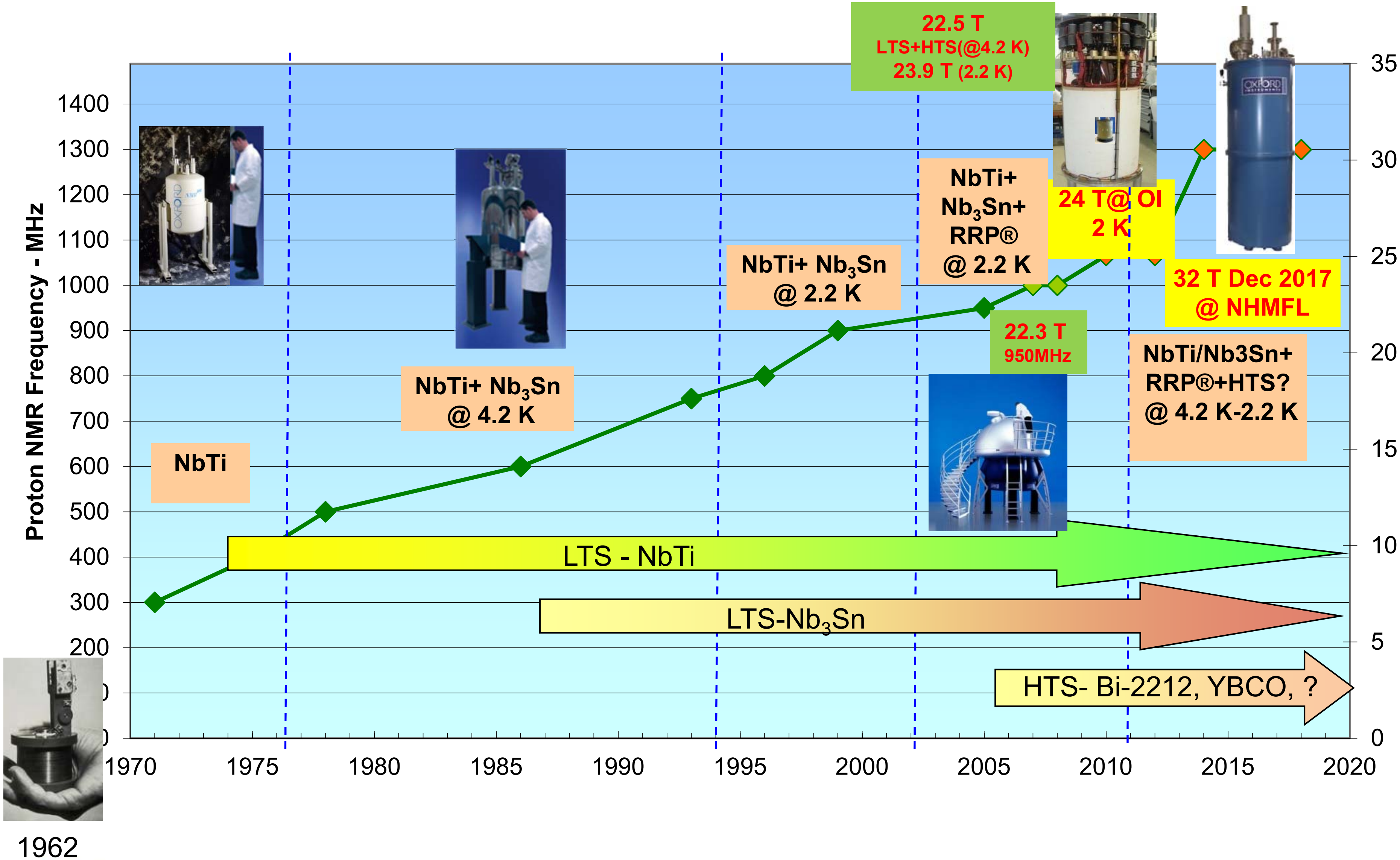
1st Active shield (AS) — 1st Open MRI Magnet — AS 4T — 7T — 11.7

Courtesy of Siemens

Courtesy of CEA

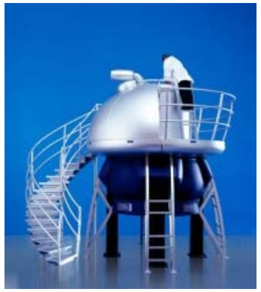
High Field Superconducting magnets

Timeline for Superconducting Magnet (Solenoids) Development

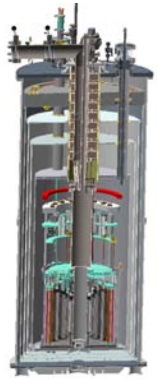


New class of COMPACT LTS outserts for HF applications >20 Tesla

22 T / 54 mm (NMR @ 2.2 K) [2000] → **15 T / 160 mm** (Driven @ 4.2 K) [2014] → **19 T / 150 mm** (Driven @ 4.2 K) [2015] → **15 T / 250 mm** (Driven @ 4.2 K) [2015] → 18 T / 150 mm (Persistence @ 4.2 K) [2017] → **12 T / 320 mm** (Persistence @ 4.2 K) [2018-2020] → 20T / 100 mm (Persistence @ 4.2K [2019-2021]





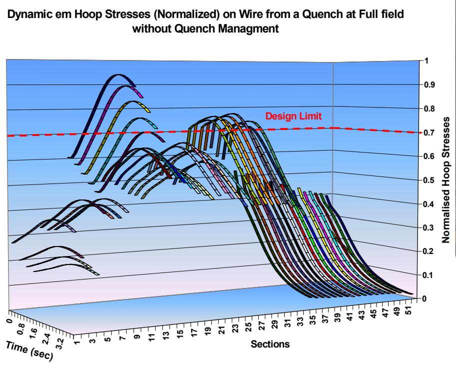



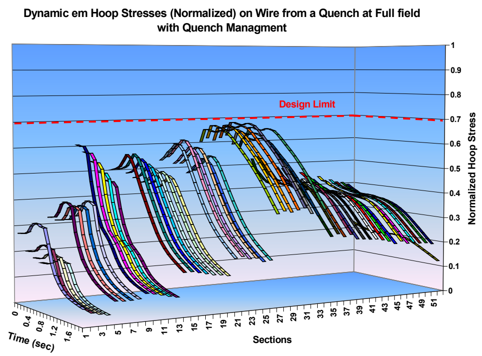
Mack Truck

8.6 Tonnes, 60 Mph

3.05 MJ

22.1T Magnet
5000 H
30 MJ





Key takeaway – Future HF magnets need to be compact …
Opportunities for NF to verify use of new materials and diagnostics

HTS & LTS for >25 T RM –
Collaboration with HLD-Dresden : 2017 - Active

HTS- Bi2212
Coil#1 fabrication

Coil#1 ready for test at Low B

Coil#1 ready for test at 19T/150

19 T ready for test

Summary

Summary

- **Cryofree**® systems are now the default offering for diverse applications across
  - Optics, electrical measurement and magnetic characterisation
    - except where exceptional B or T demands liquid helium
  - New class of Quantum and Nanotechnology applications
- Wide range of temperature and field is complemented by
  - Optical access
  - Sample wiring and handling
  - Dedicated instrumentation
- Time to first experiment and time between experiments is reduced via
  - Tool design
- We are increasing the measurement capabilities through strategic partnerships
  - with a focus on open and researcher-configurable measurement techniques

✓ Significant industries have grown from the low temperature physics community

Quantum Eco-system Engagement

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

QUANTUM COMMUNICATIONS HUB

QUANTIC

UK National Quantum Technology Hub in Sensors and Metrology

NQIT Networked Quantum Information Technologies

- Industrial partnerships
- Advisory Board memberships
- PhD Studentships
- Equipment prototyping
- Collaborative R&D

- Doctoral Training engagement

- Innovate UK, NGI & NPL project partners
  - Graphene Flagship
  - Graphene QHR Standards
  - Cryofree ULT Quantum Enhanced Sensors (CUEQS)

- IEEE Cryo-electronics IRDS partner
- EU Quantum Flagship
  - Quantum Microwave Communication & Sensing (QMiCS) – mK off chip teleportation

QMiCS QUANTUM FLAGSHIP