2024 European School on Magnetism

Oxford Instruments

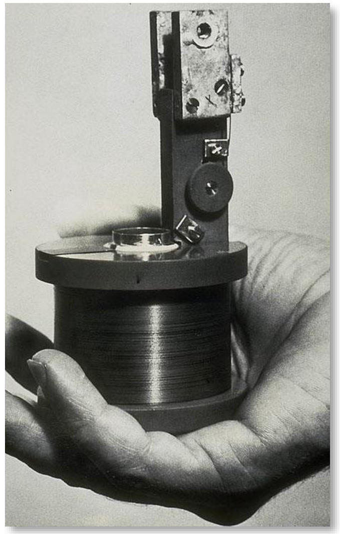
A Career in Superconducting Magnets

Steven Ball

Senior Development Engineer

Agenda

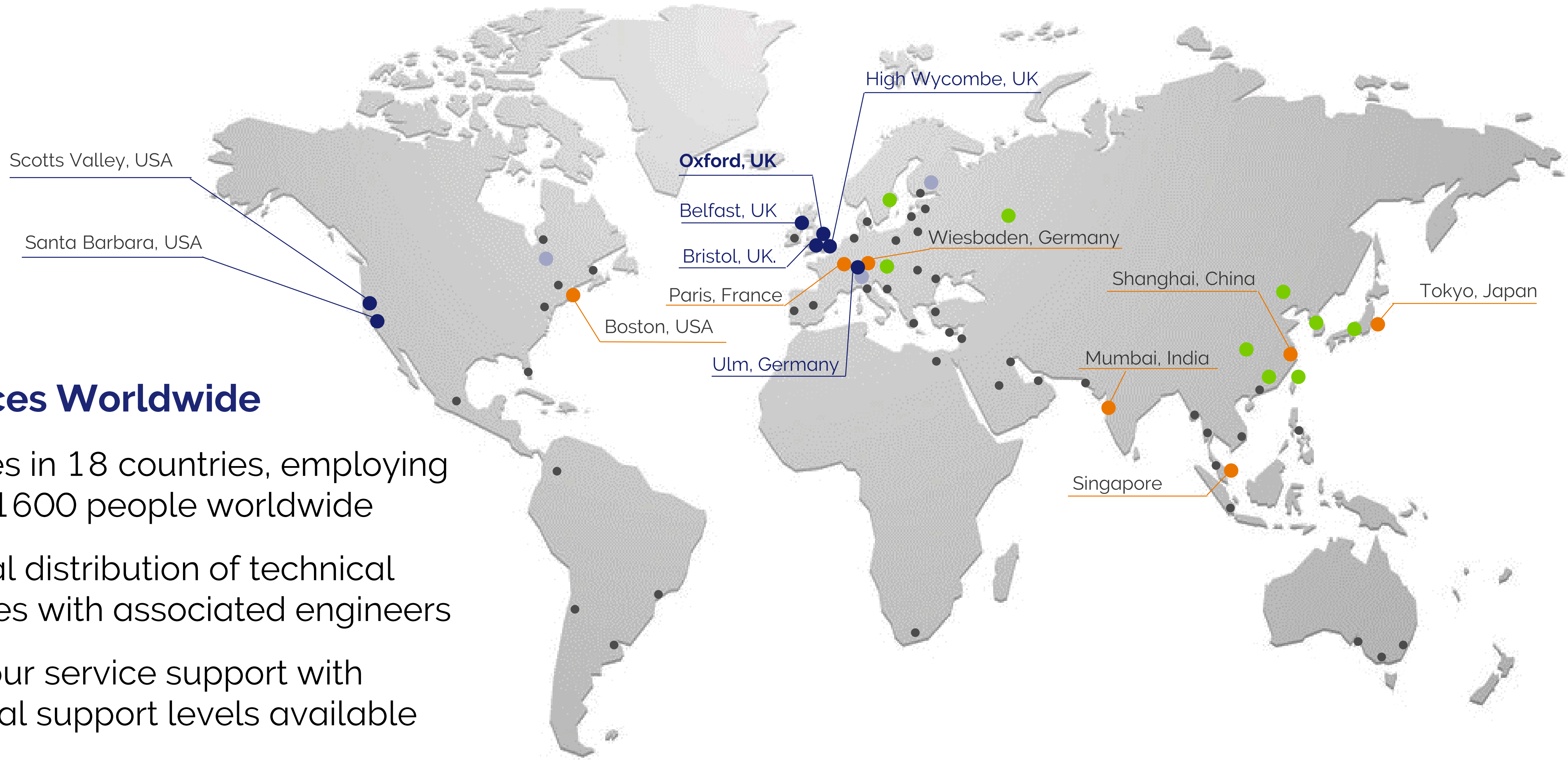
- Introduction to Oxford Instruments
- Superconducting magnets at Oxford Instruments
- A Career in Superconducting Magnets



Introduction to Oxford Instruments

Founded in 1959 by Sir Martin and Lady Audrey Wood as the first commercial spin-out from Oxford University

Global Footprint



● BU head offices / Manufacturing ● Regional Hub ● Sales/ Service Office ● Development Sites ● Channel Partners

28 Offices Worldwide

- Offices in 18 countries, employing over 1600 people worldwide
- Global distribution of technical centres with associated engineers
- 24 hour service support with several support levels available

Our solutions. Your results.

Enabling a greener, healthier and more connected advanced society.

Advanced Materials

- Boosting understanding of material performance
- Supporting development of new materials
- Enabling sustainable manufacturing

Energy and Environment

- Enabling development of next-generation batteries
- Supporting transition from fossil fuels
- Facilitating food and water safety
- Helping prevent pollution

Healthcare and Life Science

- Accelerating improved treatments & vaccines
- Aiding development of personalised medicine & therapies
- Reduced development timelines & costs

Quantum Technology

- Supporting evolving commercial market
- Facilitating progress across a range of sectors, including pharma, logistics and finance

Semiconductors and IT

- Enabling faster and more sophisticated devices & computers
- Facilitating growing bandwidth demand
- Supporting surging data use & universal connectivity

Research and Fundamental Science

- Enabling world-class research and innovation by leading universities
- Facilitating breakthroughs in astronomy and space research

Business units

Advanced Technologies

NanoScience

Dilution refrigerator and superconducting magnet systems for quantum technology research

Plasma Technology

Etch and deposition processing equipment and solutions

X-Ray Technology

X-ray tubes and X-ray sources for analytical, medical imaging and industry NDT

Imaging and Analysis

NanoAnalysis

Tools for SEM, TEM and FIB to characterise and manipulate samples at the nanometre scale

Andor

Scientific cameras, microscopy systems and spectrographs for academia and industry

Asylum Research

Atomic force microscopes (AFM)

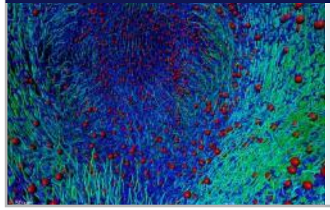
Magnetic Resonance

Benchtop NMR spectrometers and analysers for research and quality control

WITec

Confocal Raman imaging microscopes for chemical and structural characterisation

Imaris

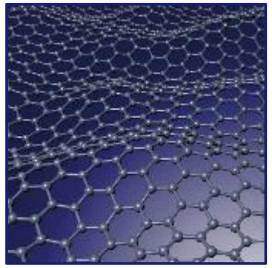


Microscopy image analysis software

Oxford Instruments NanoScience

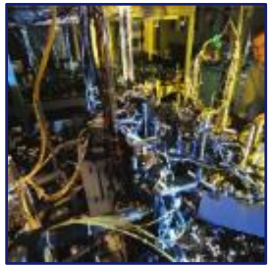
- *We design, supply and support market-leading research tools that enable* **quantum technologies**, **quantum materials discovery**, *and* **device development** *in the physical sciences*
- *Our tools support research down to the atomic scale through creation of high performance, cryogen free, low temperature and magnetic environments – with ever-increasing levels of experimental and measurement readiness*

Quantum technologies



2D materials

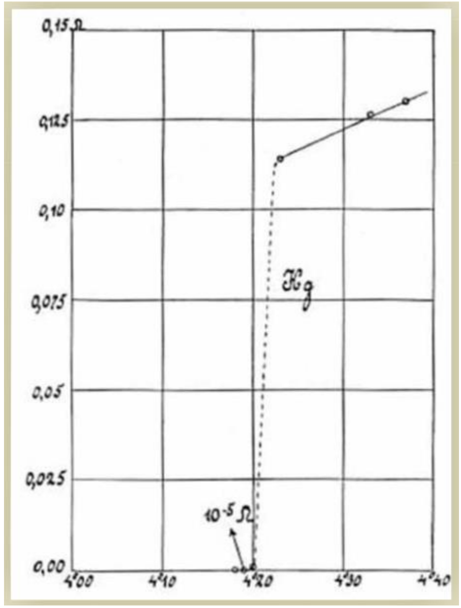
Condensed matter physics



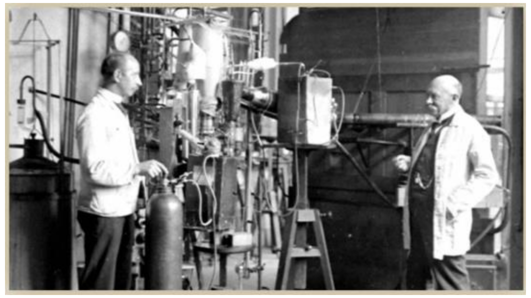
National research infrastructures

Superconducting magnets at Oxford Instruments

Superconductivity



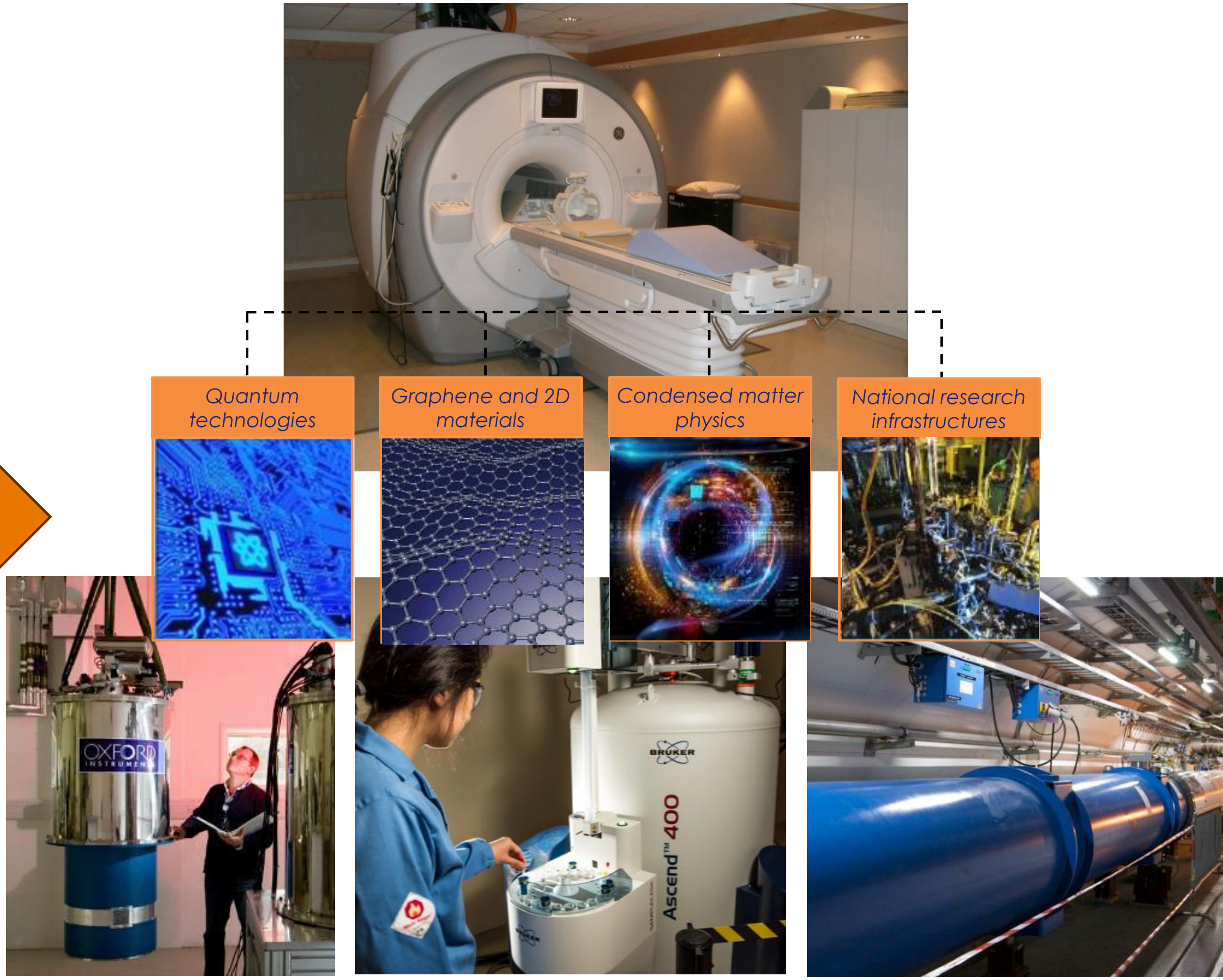
1911
Discovery of Superconductivity



1960s
Early commercial exploitation.

In 1962 Sir Martin:
Bought 1 lb of NbZr wire,
Computer designed the magnet,
Hand wound it himself,
Powered it with his car battery & a rheostat,
Achieved 4 Tesla!

Applications today



Quantum technologies

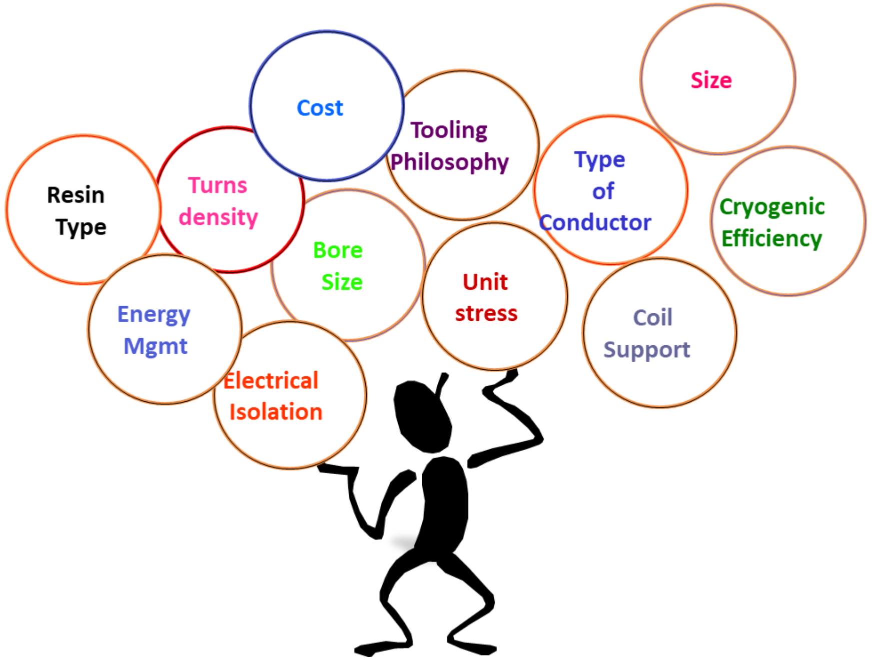
Graphene and 2D materials

Condensed matter physics

National research infrastructures

Factors in magnet design

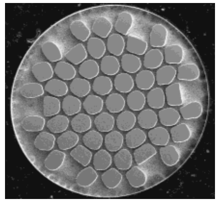
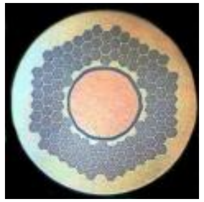
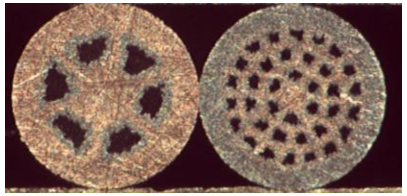
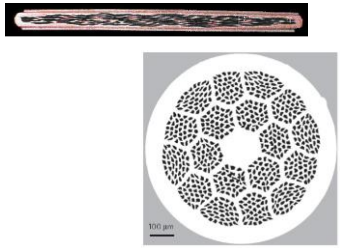
- Central field
- Solenoid or split pair?
- Bore size
- Split
- Ramp rate
- Homogeneity
- Stability
- Cooling – liquid helium or ‘dry’?

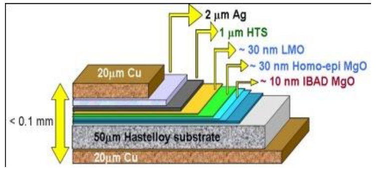


- Conductor choice
- Stress/strain
- Quench
- AC loss

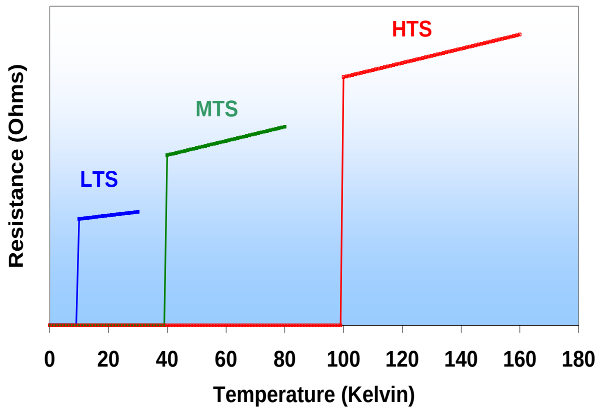
Current practical superconductors for magnets

NbTi LTS	Nb_3Sn LTS	MgB_2 MTS	Bi-2212/Bi-2223 HTS	ReBCO HTS
Tc = 9.8 K	Tc = 18.1 K	Tc=39 K	Tc = 90-110 K	Tc = 90-135 K
Max. field at 4.2 K				
9.5 T	**20 T**	**5 - 10 T**	**> 40 T**	**> 40 T**



T_c critical temperatures



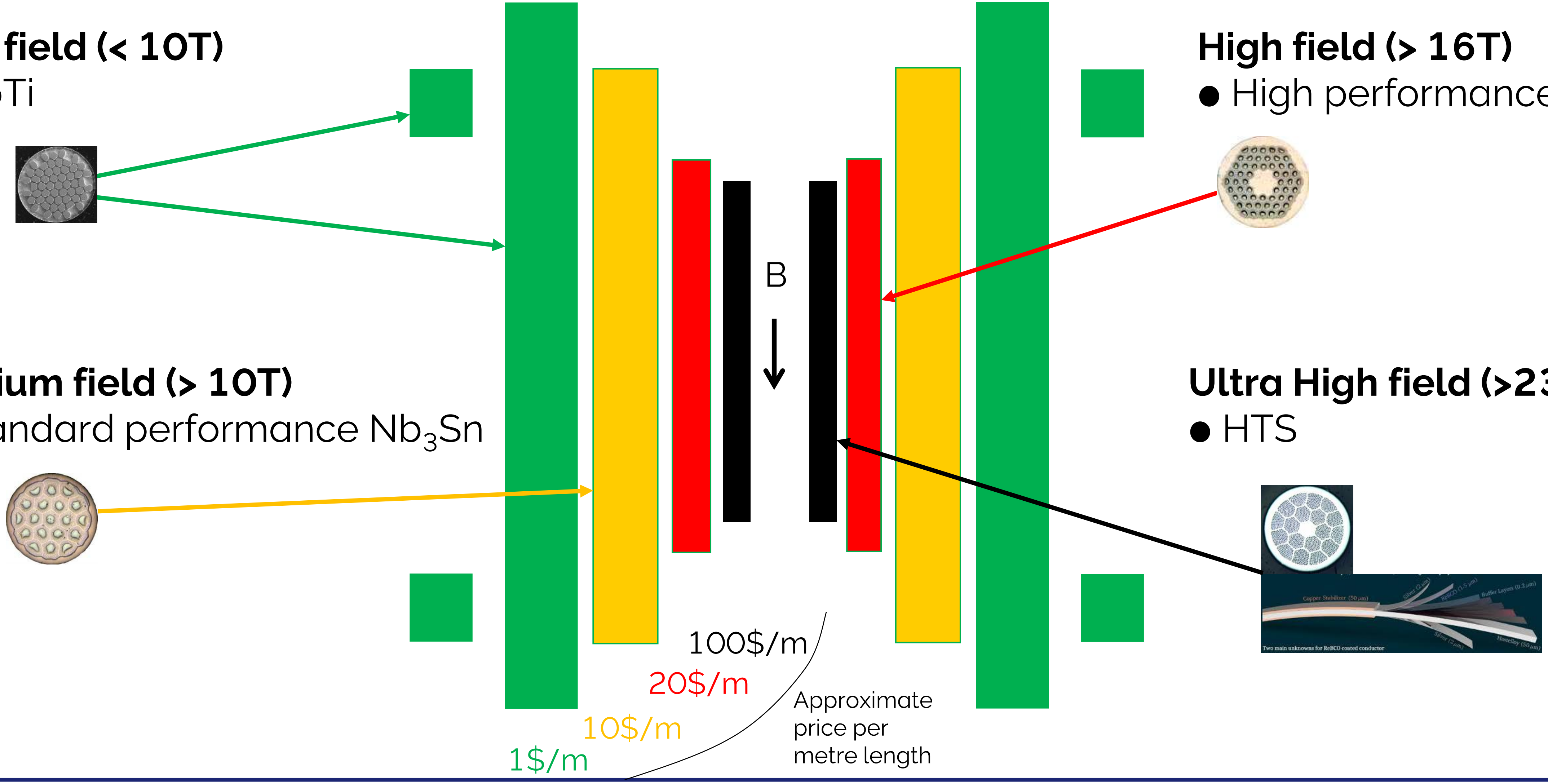
Critical Current Performance

Cost of use

Difficulty of use

LTS: Low Temperature Superconductors (T10-20K)
MTS: Medium Temperature Superconductors (20-40K)
HTS: High Temperature Superconductors (90-130K)

Where each of the different superconductors are used



Low field (< 10T)
- NbTi

Medium field (> 10T)
- Standard performance Nb_3Sn

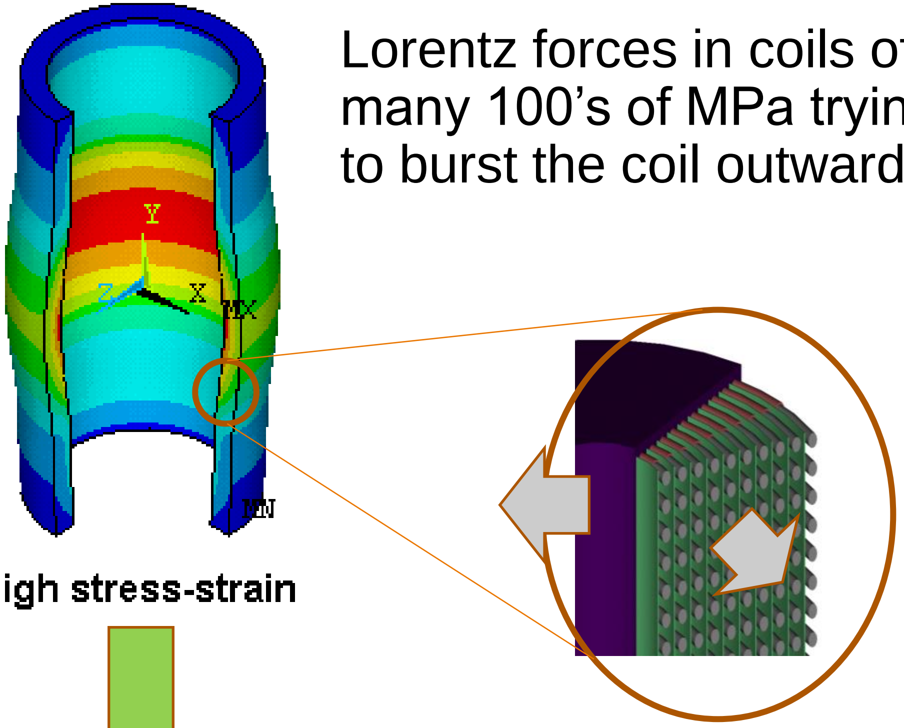
High field (> 16T)
- High performance Nb_3Sn

Ultra High field (>23 T)
- HTS

100$/m
20$/m
10$/m
1$/m

Approximate
price per
metre length

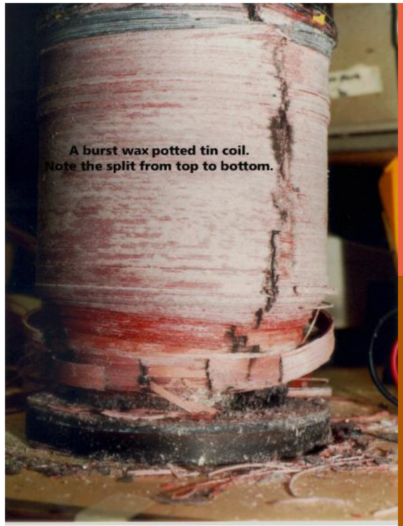
Electromechanical stress



Lorentz forces in coils of many 100’s of MPa trying to burst the coil outwards

High stress-strain

Nowadays we use high technology to ensure magnet integrity.


A burst wax potted tin coil.
Note the split from top to bottom.

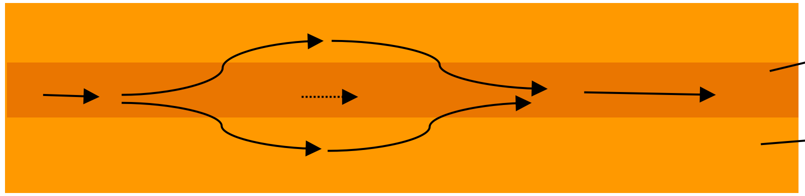
Some occasional magnet stress issues may have occurred in the early days

All this was way back in the last century though!

Complex fibre and resin composites

High tensile reinforcement materials

Superconducting quench

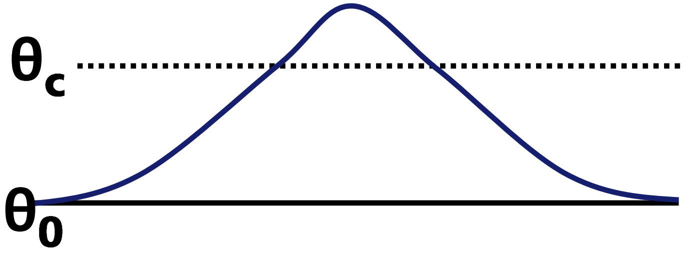


A single superconducting filament

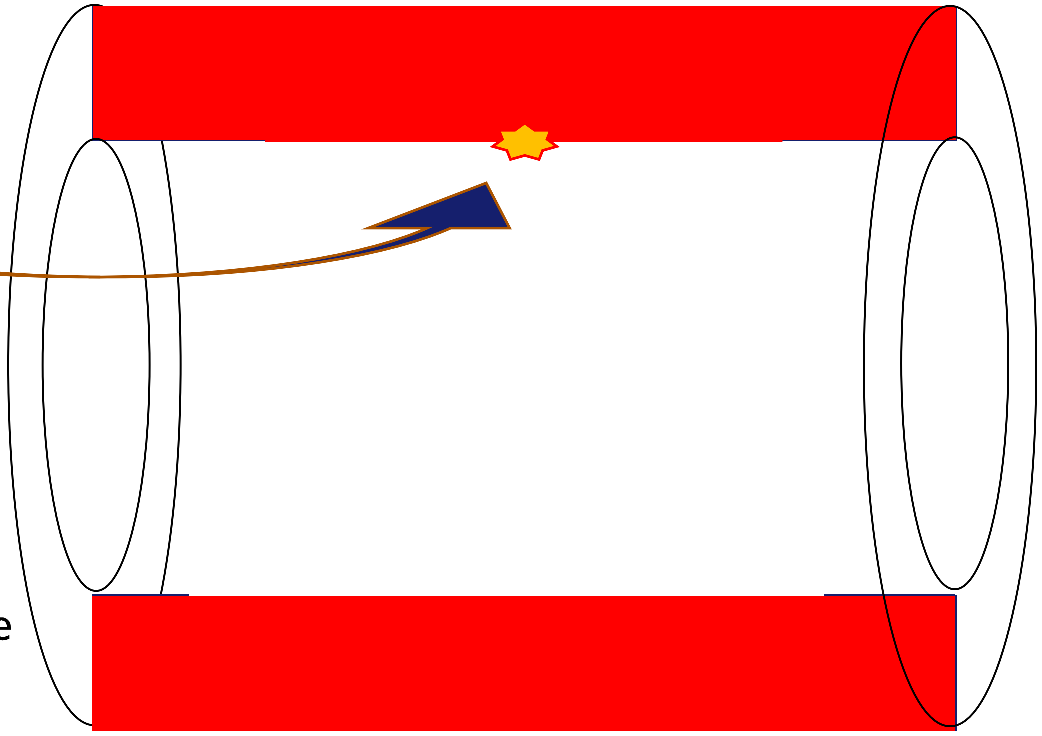
Resistive matrix around the filament

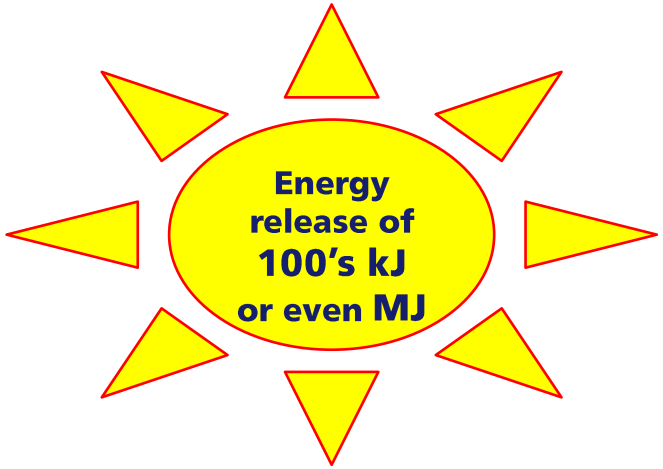
Ohmic heating

A release of µJ of energy



Low specific heat + local disturbance raises temperature beyond θ_c





Energy release of 100's kJ or even MJ

With potential problems

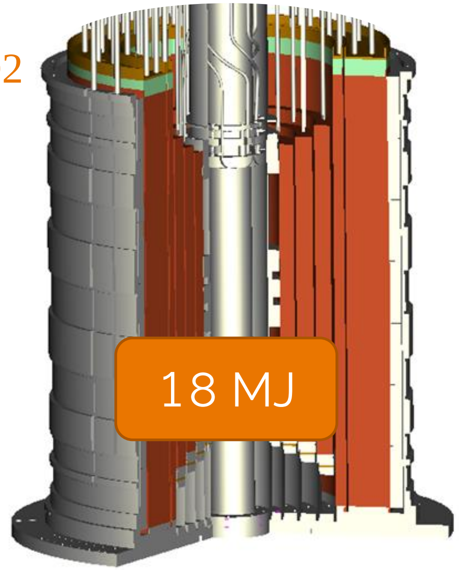
- Localised heating
- High voltages
- Mechanical stresses

Propagation of resistance through the superconducting coil

Quench energies

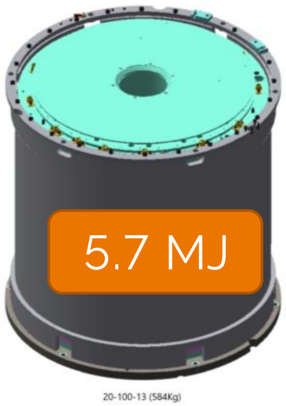
1 MJ = 0.27 kWh…
Quench time is approx. 1 s so
power = **1 MW**

A more compact product range was developed…

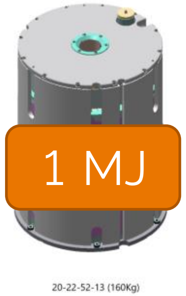


22 T, T=2.2K, 87mm

15 T, 250mm

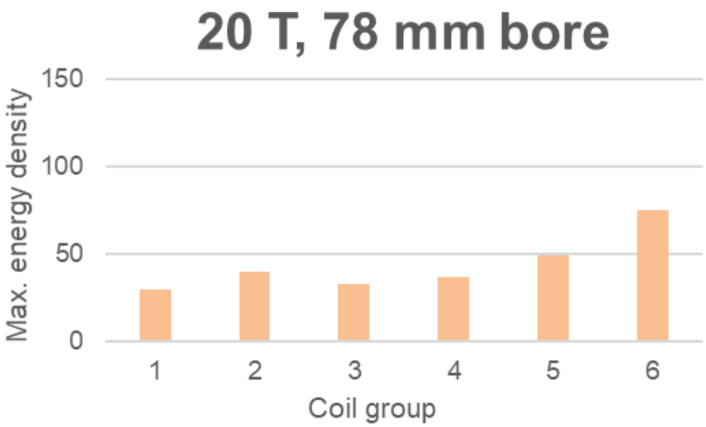


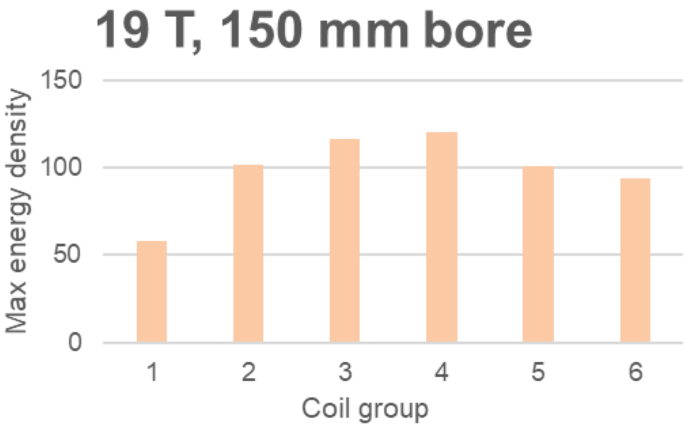
20 T, 100mm



20 T, 52mm

Decreasing quench energy by increasing energy density





20 tesla @ T=4.2 K	19 tesla @ T=4.2 K
Stored Energy 16 MJ	Stored Energy 5.7 MJ
Magnet volume 320 litre	Magnet volume 130 litre

Utilising
Higher J_c &
Bronze route
Nb_3Sn.

Reliable and repeatable magnets at these higher energy densities require advanced engineering, especially in terms of high field quench.

Utilising
Higher J_c
Nb_3Sn
today.

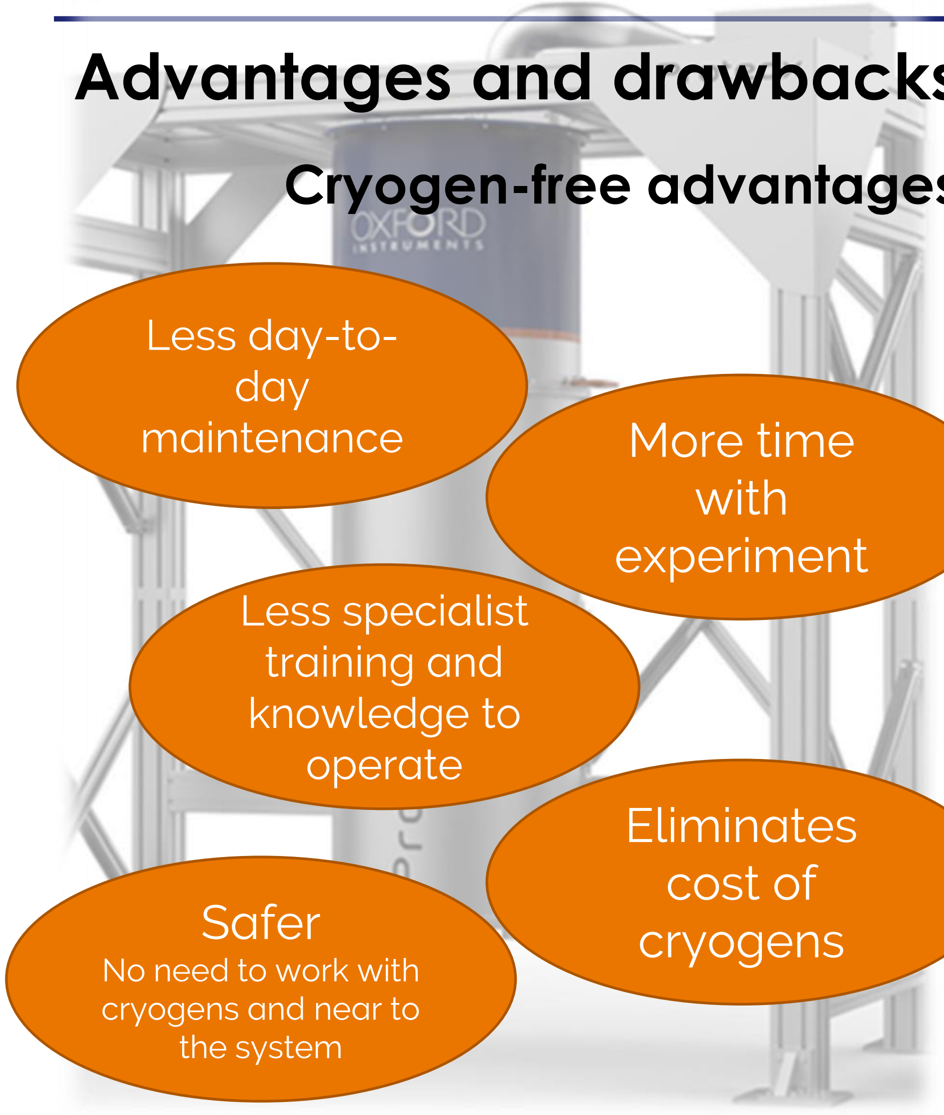
Wet or Dry - how will you be cooling your magnet?

The traditional way – liquid helium

Cryofree™ / ‘Dry’ magnets

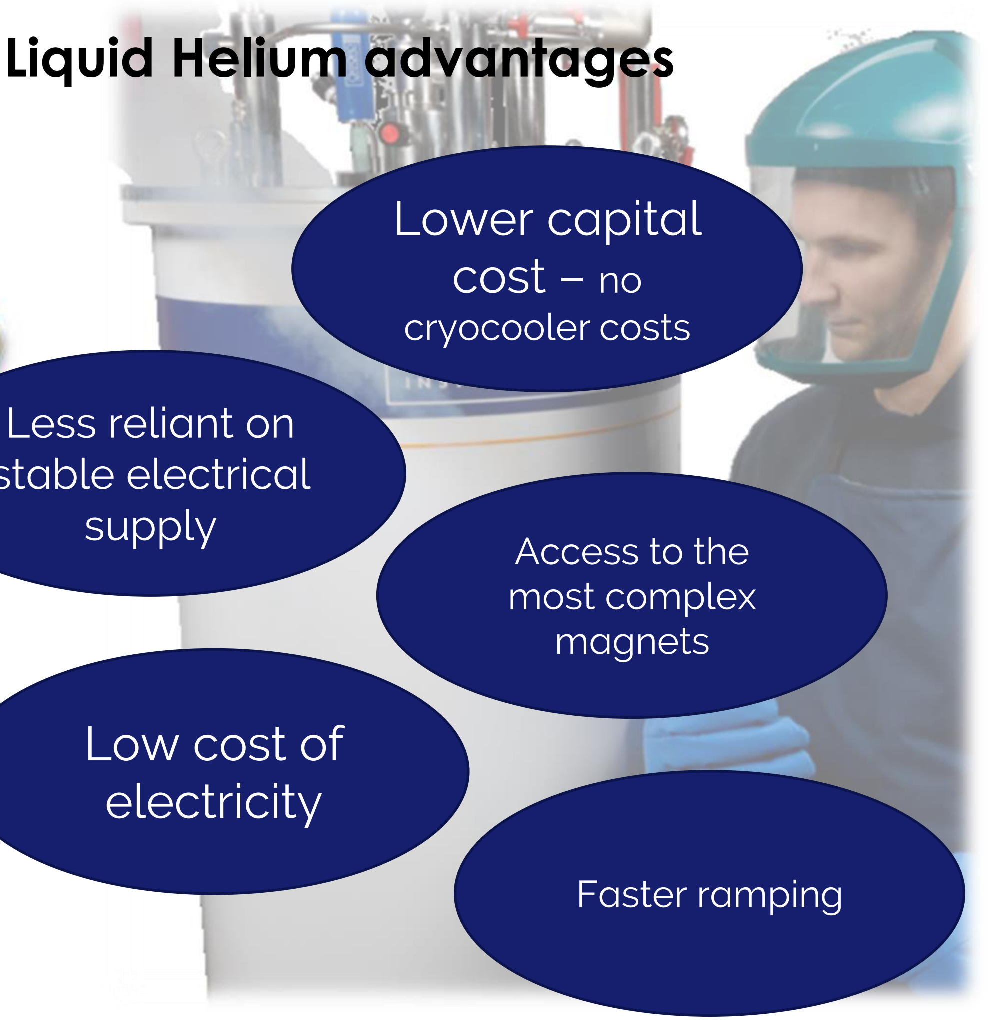
Wet or Dry? Cryofree™ magnets

Advantages and drawbacks – compared with liquid Helium bath magnets



Cryogen-free advantages

- Less day-to-day maintenance
- More time with experiment
- Less specialist training and knowledge to operate
- Eliminates cost of cryogens
- Safer
  No need to work with cryogens and near to the system



Liquid Helium advantages

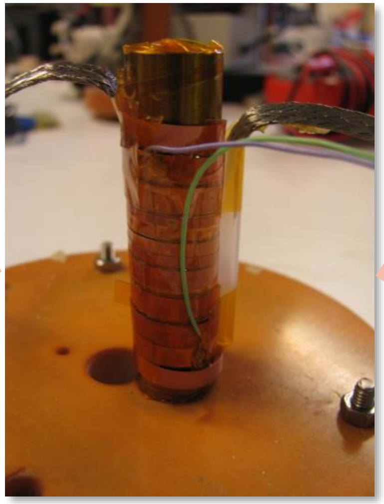
- Lower capital cost – no cryocooler costs
- Less reliant on stable electrical supply
- Access to the most complex magnets
- Low cost of electricity
- Faster ramping

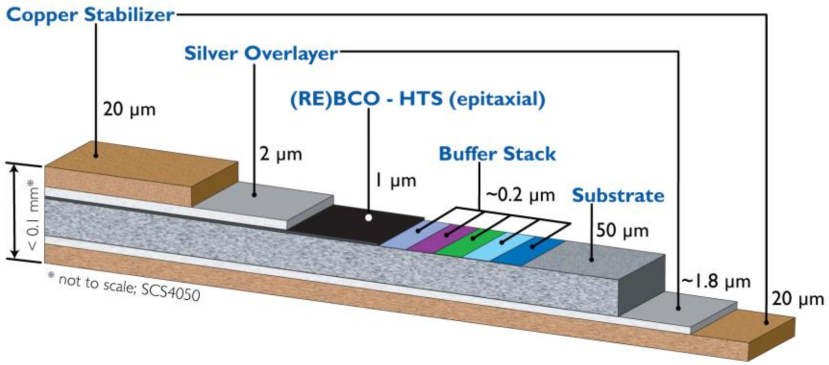
A brief career history at Oxford Instruments

Oxford University Physics Masters project

“Measurement and modelling of small high-temperature superconductor coils”

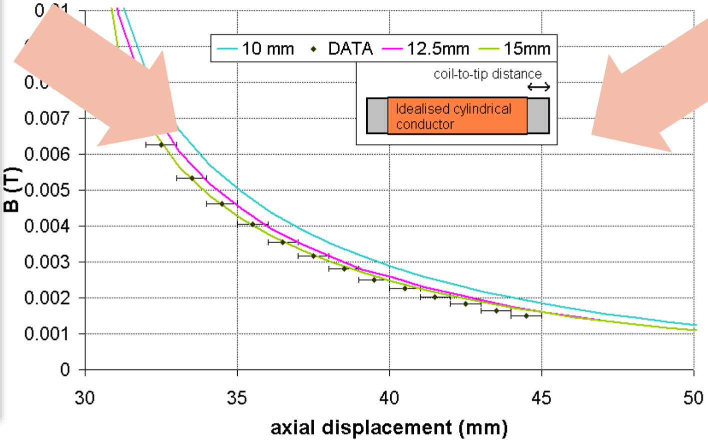
Hall probe measurements





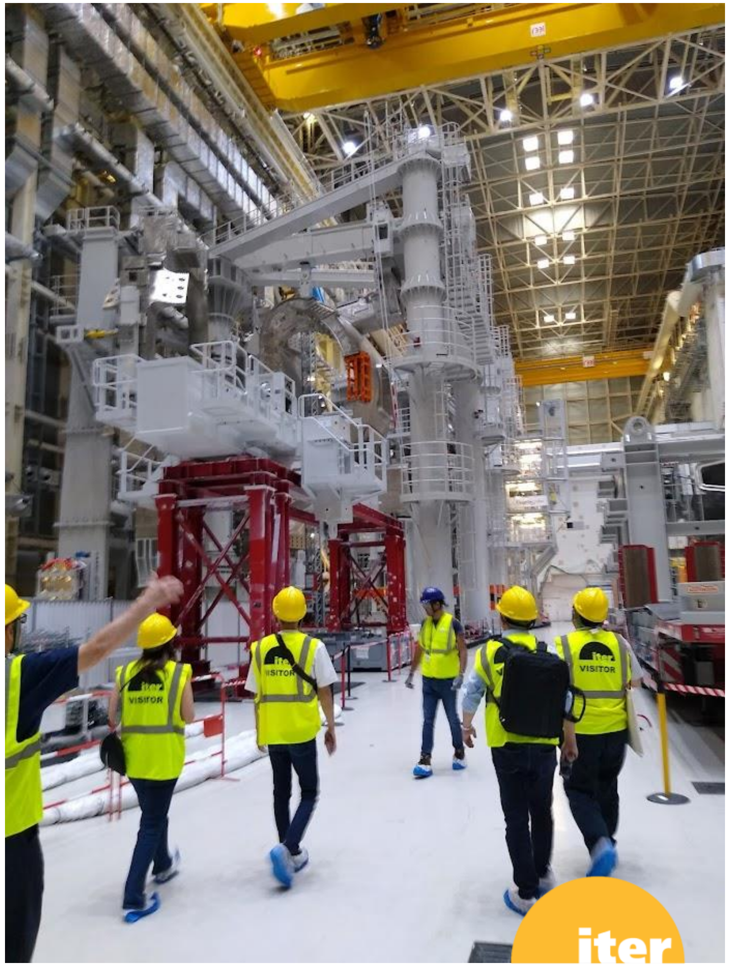
FEM Modelling

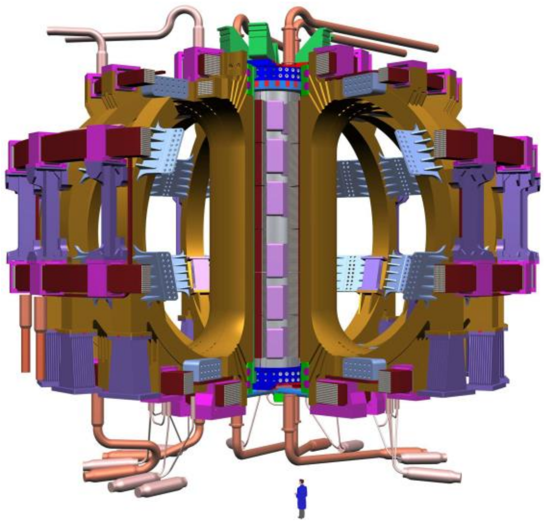
No Swan So Fine CC BY-SA 4.0



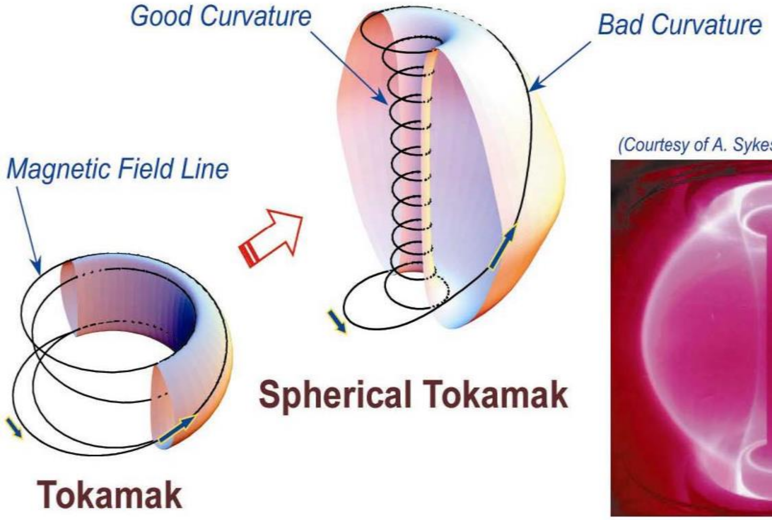
ST25 Tokamak Project

ITER project

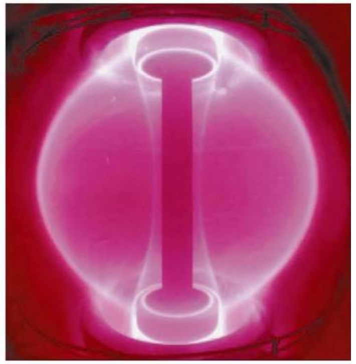




"Can a smaller, high current-density, spherical tokamak, utilizing HTS materials lead to more rapid development of technology for fusion energy?"



(Courtesy of A. Sykes & START Team, U.K.)

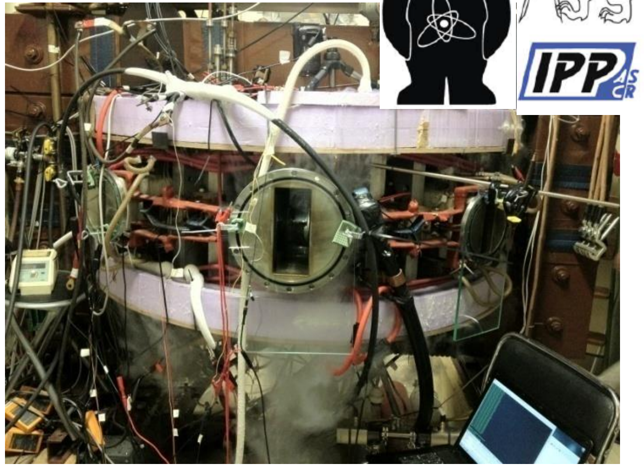


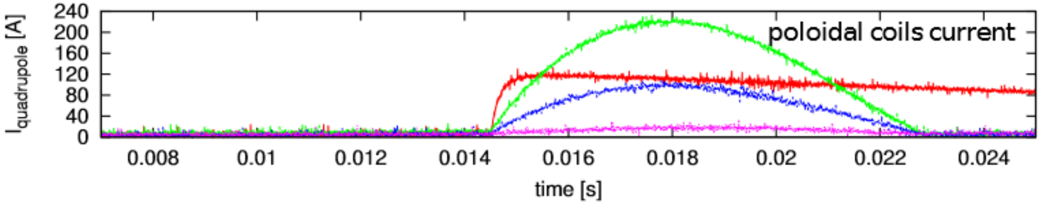
ST25	
R/a	25/12.5 cm
B_t	0.1 T
I_{pl}	5 kA
Pulse	1-5s Cu / ss HTS

ST25
tabletop tokamak

ST25 Tokamak Project

My first installation as magnet Engineer
GOLEM project
First test of HTS coils on a tokamak

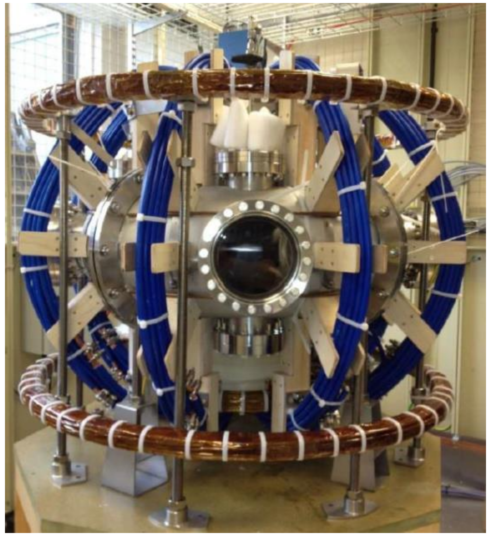




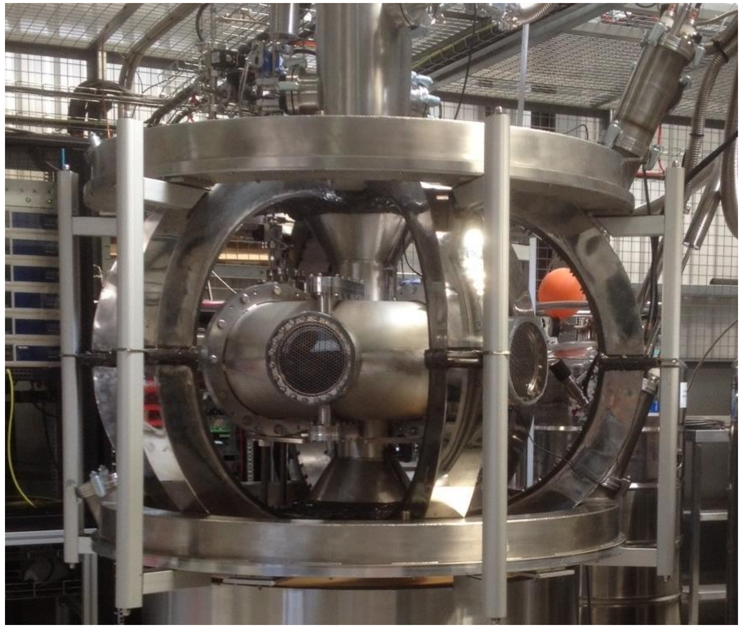
SOFT 2014 – San Sebastian

First Application of High Temperature Superconducting (HTS) TF Coils on a Tokamak

Steven Ball[1], Alan Sykes[2], Antti Jokinen[1], Robin Brzakalik[1], Steve Chappell[1], Ziad Melhem[1], Mikhail Gryaznevich[2], David Kingham[2], David Hawksworth[1], Andy Twin[1], Gideon Hammond[2], Steve Daughtry[2], Paul Apte[3], Billy Huang[2]



ST25-HTS complete system

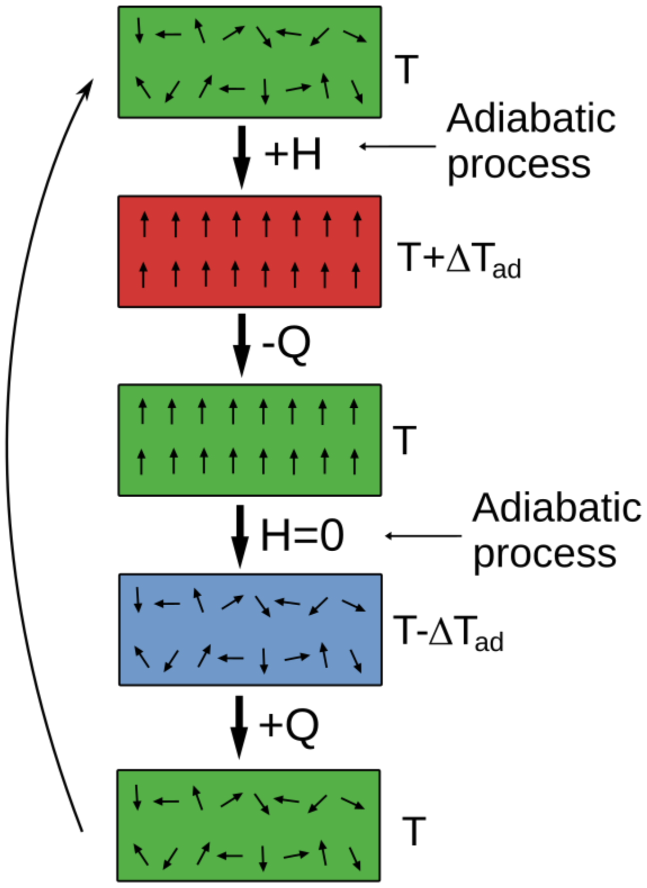


0.1 Tesla Central field on plasma

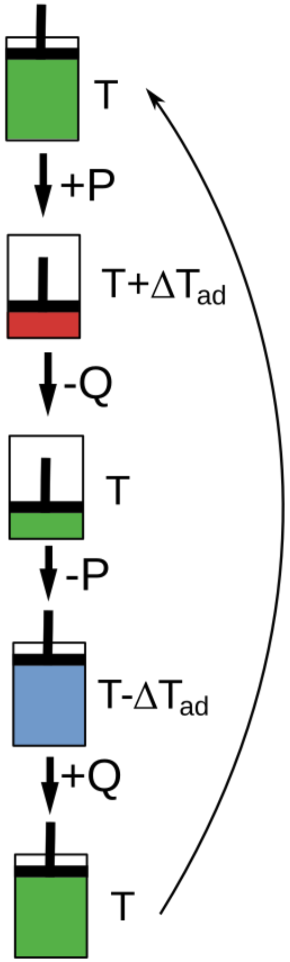
Magnetic refrigeration

Adiabatic nuclear demagnetisation cooling, or ‘demag’ in OI magnet speak

…is a heat cycle…



Magnetic refrigeration



Vapor cycle refrigeration

Rafa3lindo - CC BY-SA 4.0

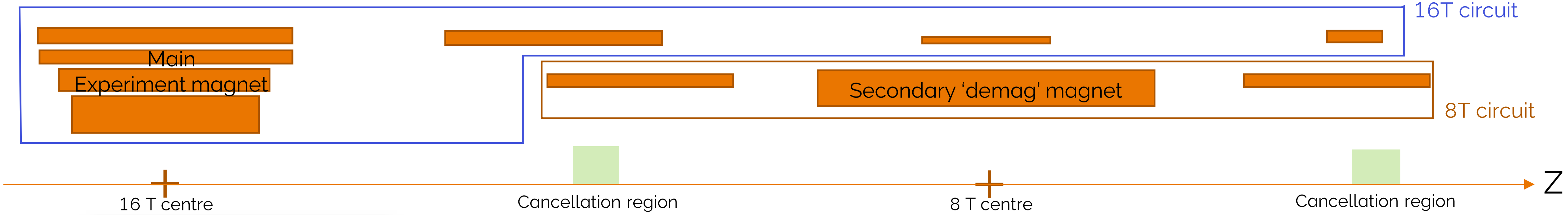
…analogous to …

Vapor cycle refrigeration

Multi-magnet system for nuclear demag cooling

I was System Engineer for this highly customised magnet – several firsts for OI magnets

Complete system, successfully installed in 2021 in customer lab



16T circuit

Main Experiment magnet

Secondary 'demag' magnet

8T circuit

16 T centre

Cancellation region

8 T centre

Cancellation region

Z

Central flux density - Main magnet	**16 T**
- Secondary magnet	**8 T**
Magnet central bore diameter	**80 mm**
Stored Energy	0.85 MJ (main magnet)
Inductance	**77 H** (main magnet)
Operating current	150 A (main magnet)
Homogeneity (over 10mm DSV)	1000 ppm
Cooling type	Cryogen free
Cooling source	2x 1.5 W GM cold heads

Features:

Room temperature bore for customer nuclear demagnetisation insert

Cancellation coils

Highest stored energy of Cryofree™ magnet

Total magnet structure length > 1.5 m

PhD - Heat transfer modelling for quench

My part-time PhD (Maths) with Brunel University (EPSRC/OI funding) started in 2022

HTS quench modelling with Fourier series to allow parallelisation of solution.

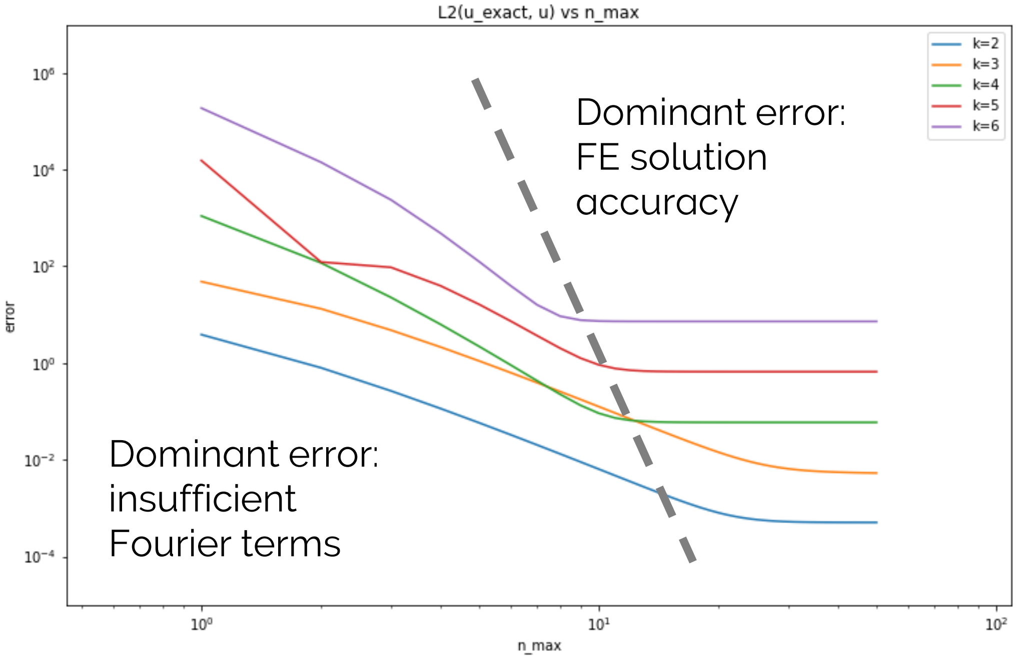
$$-\nabla^2 u(x,y) = f(x,y)$$

$$f(x,y) = \sum_{n=-\infty}^{\infty} f_n(y) e^{inx} \qquad u(x,y) = \sum_{n=-\infty}^{\infty} u_n(y) e^{inx}$$

$$-\sum_{n=-\infty}^{\infty} \frac{\partial^2 u_n}{\partial y^2} e^{inx} + \sum_{n=-\infty}^{\infty} n^2 u_n e^{inx} = \sum_{n=-\infty}^{\infty} f_n e^{inx}$$

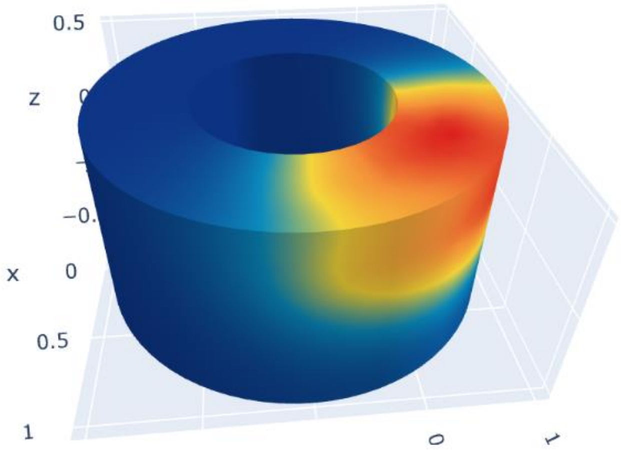
$$-\frac{\partial^2 u_n}{\partial y^2} + n^2 u_n = f_n$$

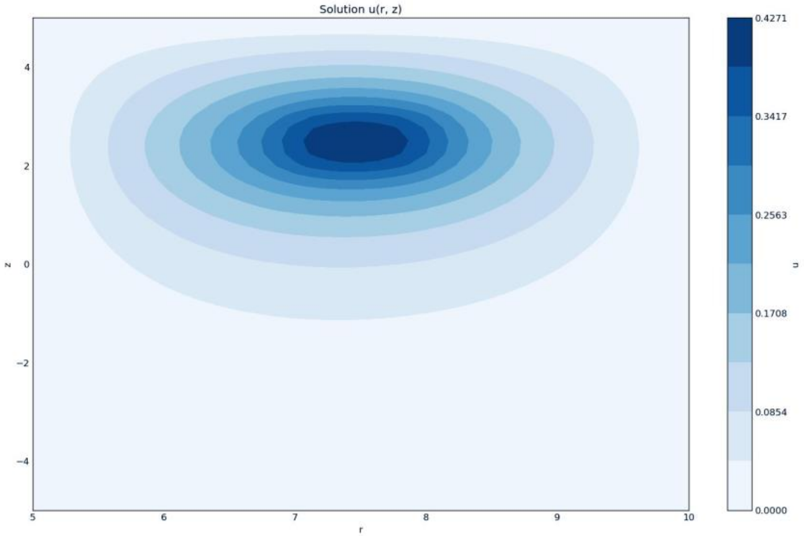
$$f_n = \frac{1}{2\pi} \int_0^{2\pi} f(x,y) e^{-inx} dx$$



Dominant error: FE solution accuracy

Dominant error: insufficient Fourier terms





Thank You!

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