Superconductors for fusion magnets

Centre for Materials Physics

Superconductivity Group

www.durham.ac.uk/cmp

Durham University

Presentation by

Prof. Damian Hampshire and Dr. Mark Raine

Structure of the talk

1. Applications that use superconducting materials.
2. The Icy Durham Practical Course.
3. Soldering the high temperature superconductor (HTS) $GdBa_2Cu_3O_7$ for critical current (Ic) measurements.

4. The critical current (Ic) of superconducting materials.
5. Basic superconductivity.
6. The flux-line lattice, fluxons and supercurrents.
7. Reference Laboratory measurements.

8. The 3 Industrial Superconducting Materials.
9. Advanced measurements on superconductors.
10. The Icy Durham practical course lectures.

11. Post lecture discussion

Applications that use superconducting materials

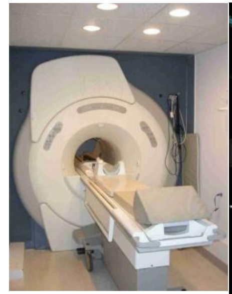
Current LTS applications:

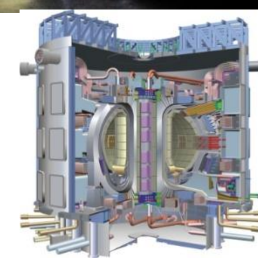
i) MRI Body scanners

ii) Transport (Maglev)

iii) High Energy Physics (CERN)

iv) Fusion (ITER)



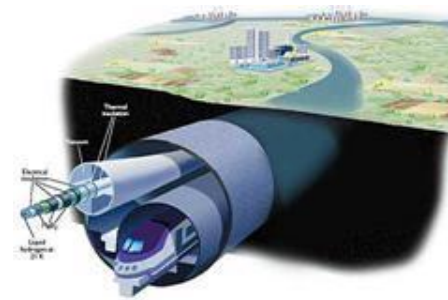


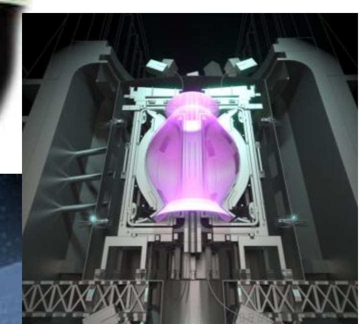
Future HTS applications:

i) Power transmission

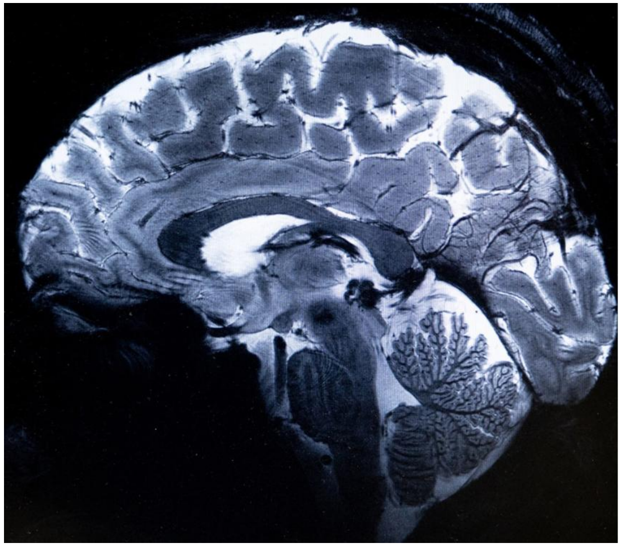
ii) Fusion (STEP, ITER, SPARC/ARC)

iii) Rotating machinery





Functional magnetic resonance imaging (*f*MRI).



- Saclay, France: 11.7 Tesla, 132 tonnes, 1500 Amps.
- Faces and words activate distinct parts of the brain
    - Alzheimer's disease – how do cells work in the cerebral cortex.
    - Bipolar disorder – how does lithium distribute through the brain… and how effective is it for different patients.
    - …….
- The UK fabricates more than one half of all the MRI magnets in the world.

The Tokyo-Nagoya Maglev

- The Chuo Shinkansen - will connect Tokyo and Nagoya: ~500 km/h, ~250 km of tunnels, £50B, 2035.

The CERN particle accelerator

CERN experienced a quench
on September 19, 2008

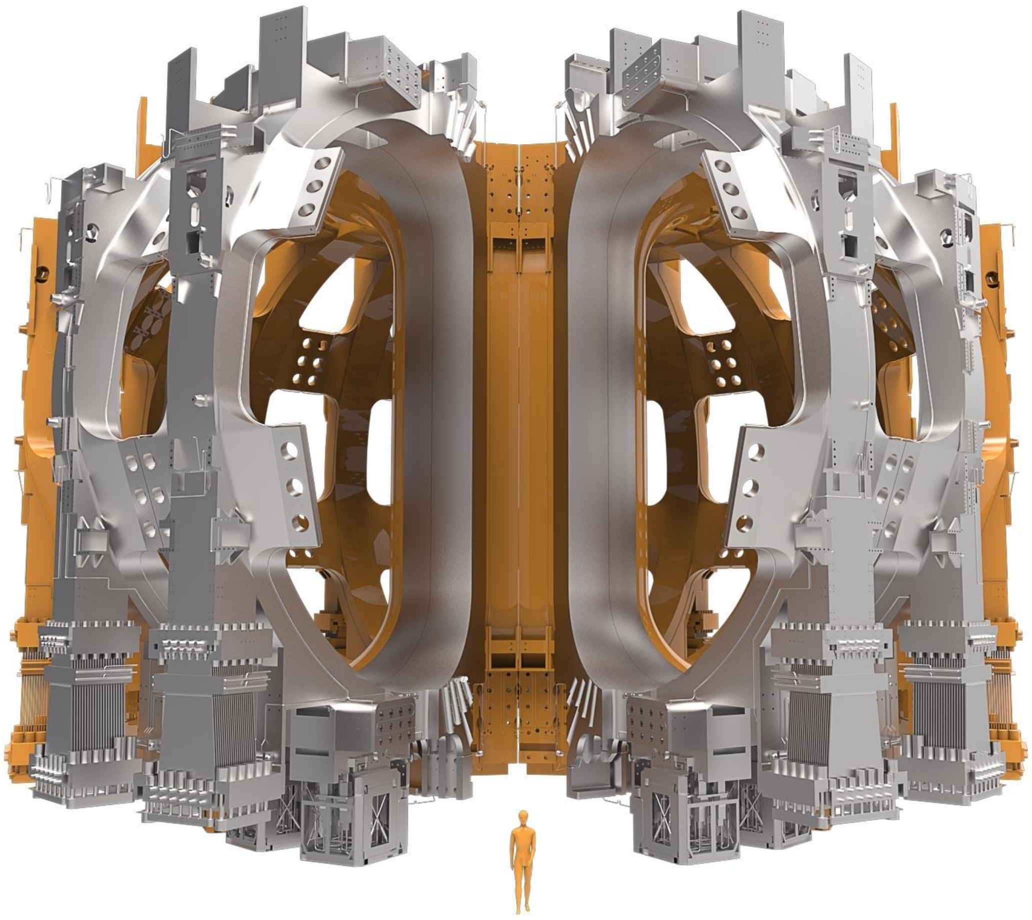
- Research at the forefront of human knowledge.
- Unite people from all over the world.
- Train new generations of physicists, engineers and technicians.
- Discover what the universe is made of.

The ITER Magnets

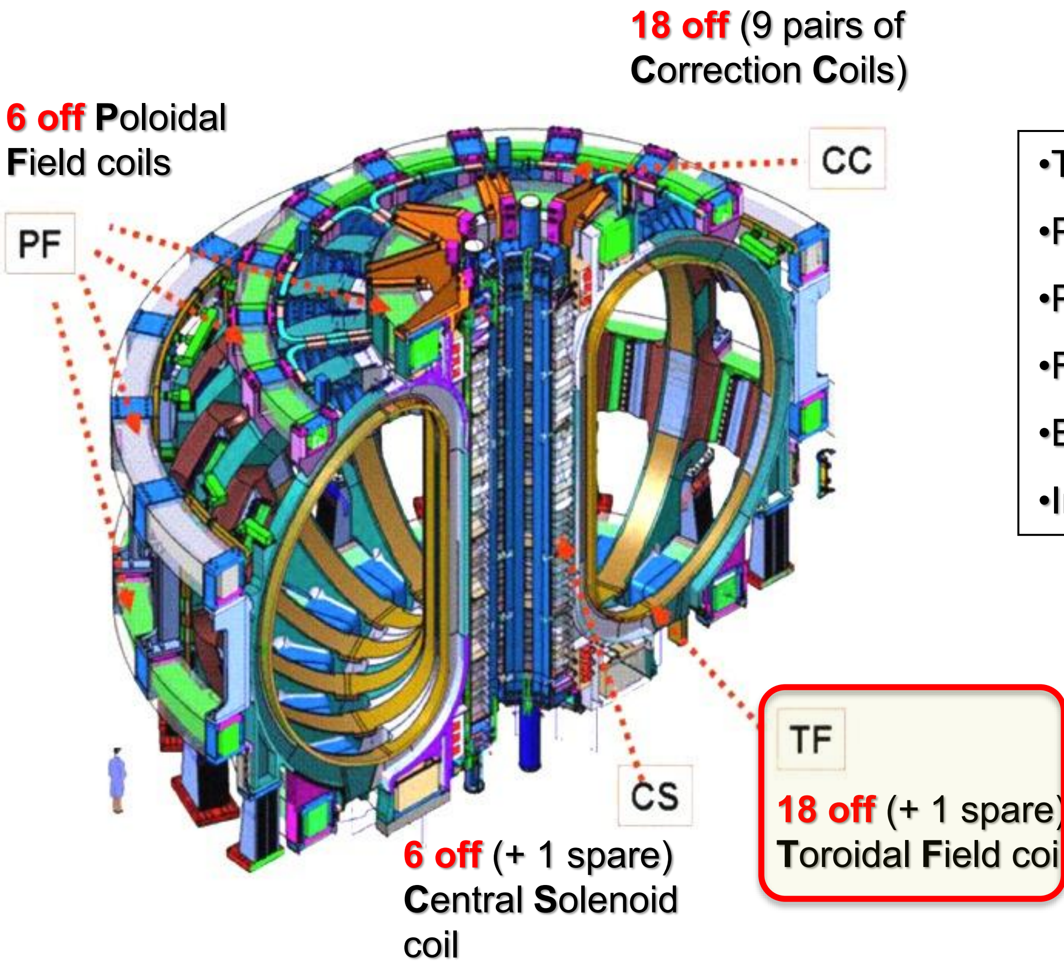
ITER Magnets:
- 18 + 1 spare
- Magnetic field = ~14T
- Operating current = 68 kA
- Dimensions ~ 9 x 17 m
- Weight (each) = 310 tonnes

Supercritical LHe (forced flow): is used to cool the magnets

ITER: 14T
STEP: 17 T
SPARC: 20 T
ARC: 23 T



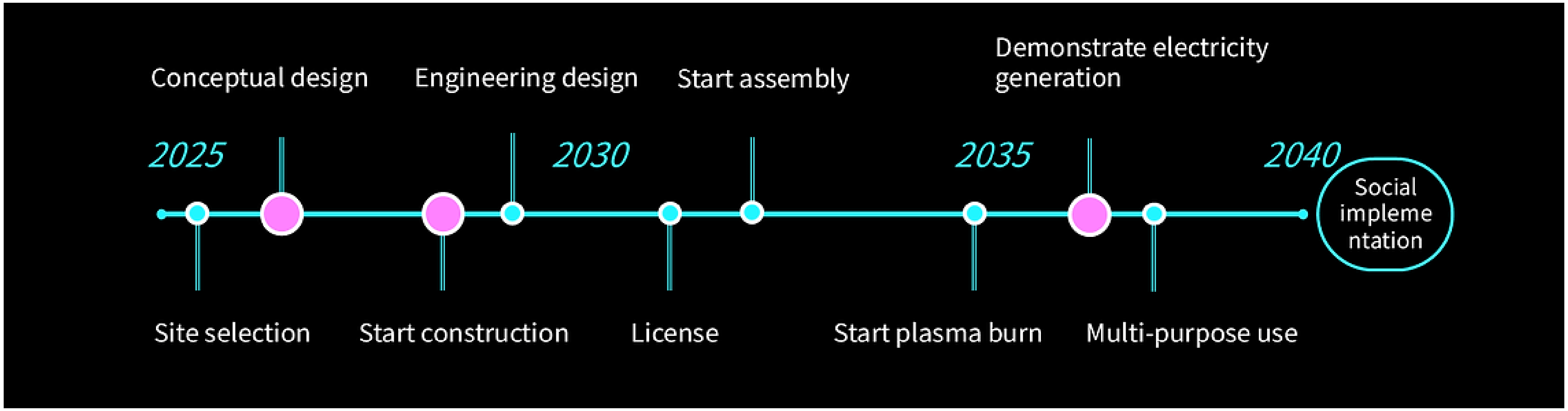
The Icy Durham practical course lectures



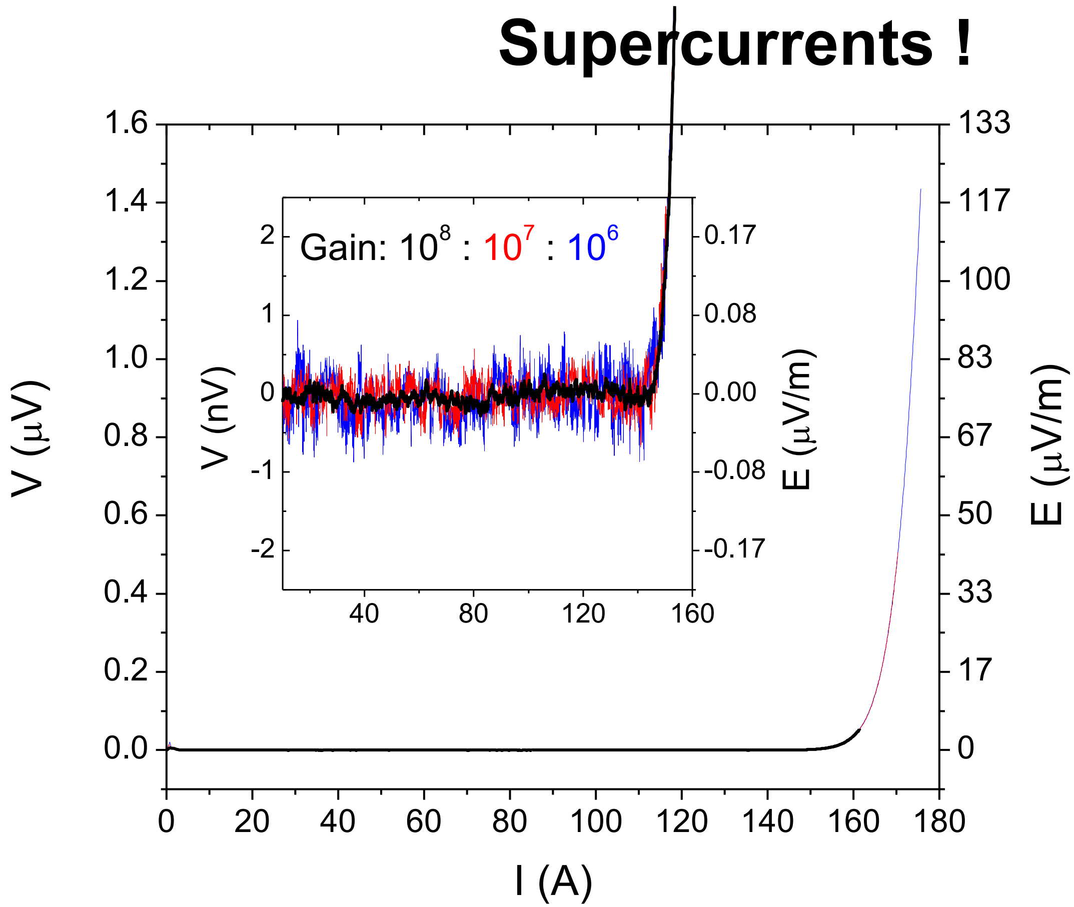
- •TF @ 6.2 m = 5.3 T (½ to ⅓ of peak field).
- •Plasma Current = 15 MA
- •Plasma volume = 837 m^3
- •Fusion power = 500 MW
- •Electricity input 20 MW!
- •Inductive burn time ~ 500 s

[1] C. Sborchia, *et. al*., "Overview of ITER Magnet System and European Contribution," presented at the 2011 IEEE 24th Symposium on Fusion Engineering (SOFE), 2011, pp. 1–8.

Japan launches Fusion by Advanced Superconducting Tokamak (FAST) HTS tokamak



The critical current (Ic) in superconducting materials



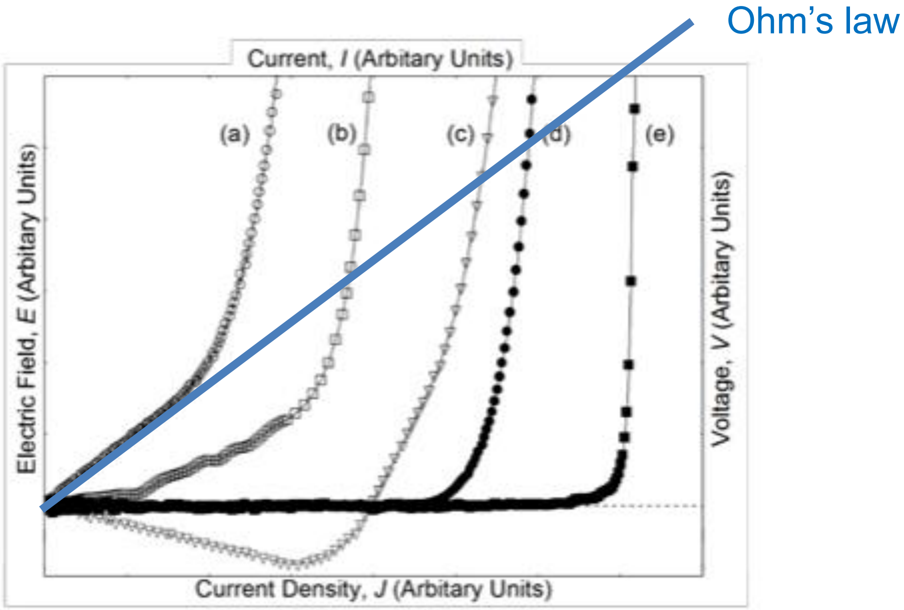
T= 4.2 K, B = 7T

V_{theory} ~ 54 pV

Measurements are about a factor of 3 above the theoretical Johnson noise limit

Prapaiwan (Bew). Sunwong, J. S. Higgins, and D. P. Hampshire – **Probes for investigating the effect of magnetic field, field orientation, temperature and strain on the critical current density of anisotropic high-temperature superconducting tapes in a split-pair 15 T horizontal magnet – Review of Scientific Instruments 85 065111 (2014)**

Critical current measurements on short samples in high magnetic fields



Five *E-I* traces found when measuring different superconductors

M J Raine, S A Keys and D. P. Hampshire **Characterisation of the Transport Critical Current Density for Conductor Applications** Handbook of Superconductivity. Publisher: Taylor and Francis (2021)

Icy Durham Practical Course

Wed 7th Jan – Fri 9th Jan 2026
(Registration: 09.00 Wed 7th Jan 2026 - Sir James Knott Library, Rm.132, Phys. Dept. Durham U.).

https://superconductivitydurham.webspace.durham.ac.uk/cdt-workshop-critical-current-measurements-on-hight-temperature-superconducting-tapes/

Wednesday 7th January - Day 1: Core HTS skills and knowledge			
8.45	9.10	Registration. Welcome/On-line lecture consent.	Registration + Coffee: SJK Library in Physics Dept.
9.10	9.45	Lecture: Safety talk (M. Raine)	SJK Library
9.45	11.15	Lecture: Superconductivity for Fusion (D. Hampshire: 55 min Lect. + 25 mins conv.)	SJK Library
11.15	11.45	RISK Consent + Menu Choices + Coffee	
11.45	13.00	Lab: Solder up HTS samples	Labs 42(ED1), 44(ED2), 72 (ED3) + 48(CD1) + MJR
13.00	14.00	Lunch (Palatine Centre)	
2.00	3.30	Lecture: Cryogenics (C. Monroe: 55 min Lect.+ 25 min conv.)	SJK Library
3.30	3.45	Coffee	
3.30	5.00	Labs: Soldering HTS + I_c (critical current) measurements (1).	Labs 42(ED1), 44(ED2), and 72 (ED3)

Thursday 8th January - Day 2: I_C measurements and magnets			
9.00	10.30	Lecture: Computational magnet design (A. Blair: 55 min Lect. + 25 min conv.)	SJK Library/Coffee
10.30	11.00	Coffee break	
11.00	13.30	I_C measurements (Surnames A-K) or Computational workshop (L-Z) - (A.Blair)	Labs 42(ED1), 44(ED2), and 72 (ED3) + SJK Library(CD1 + CD2)/Coffee
13.30	14.30	Lunch (Palatine Centre)	
14.30	17.00	I_C measurements (Surnames L-Z) or Computational workshop (A-K) - (A.Blair)	Labs 42(ED1), 44(ED2), and 72 (ED3) + SJK Library(CD1 + CD2)/Coffee
18.30 – 19.30: Durham Cathedral tour. 20.00: Bistro Italiano, 70 Claypath DH11QT. > 21.30:Ill-defined thereafter…			
Friday 9th January - Day 3: Fusion cables and magnet engineering			
09.00	09.10	Choices	SJK LIbrary/Coffee
9.10	10.50	I_C lab surgery or Poster/analysis activity support.	Labs 42(ED1), 44(ED2), and 72 (ED3)+ SJK Library(CD1 + CD2)/Coffee
10.50	11.00	Informal data review (2 Students + Exp. Demonstrators)	SJK Library
11.00	11.30	Coffee break	
11.30	13.00	Lecture: Cables and fusion magnets (S. Wimbush: 55 min Lect. + 25 min conv.)	SJK Library
13.00	14.00	Lunch (Palatine Centre) + Journey home	

Lecture 1 : We need ~~world-class~~ high-field superconductivity
Lecture 2 : We need cryogenics.
Lecture 3: We need magnet design and quench control.
Lecture 4 : We need HTS cables and magnets.

We need fusioneers!

Course Team Members/Demonstrators

Course Leaders

Prof. Damian Hampshire

Dr. Mark J. Raine

Course Demonstrators

Computational

Prof. Rifa El-Khozondar

Yahya Nasir

Experimental

Rollo Hudson

Daniel Scobbie

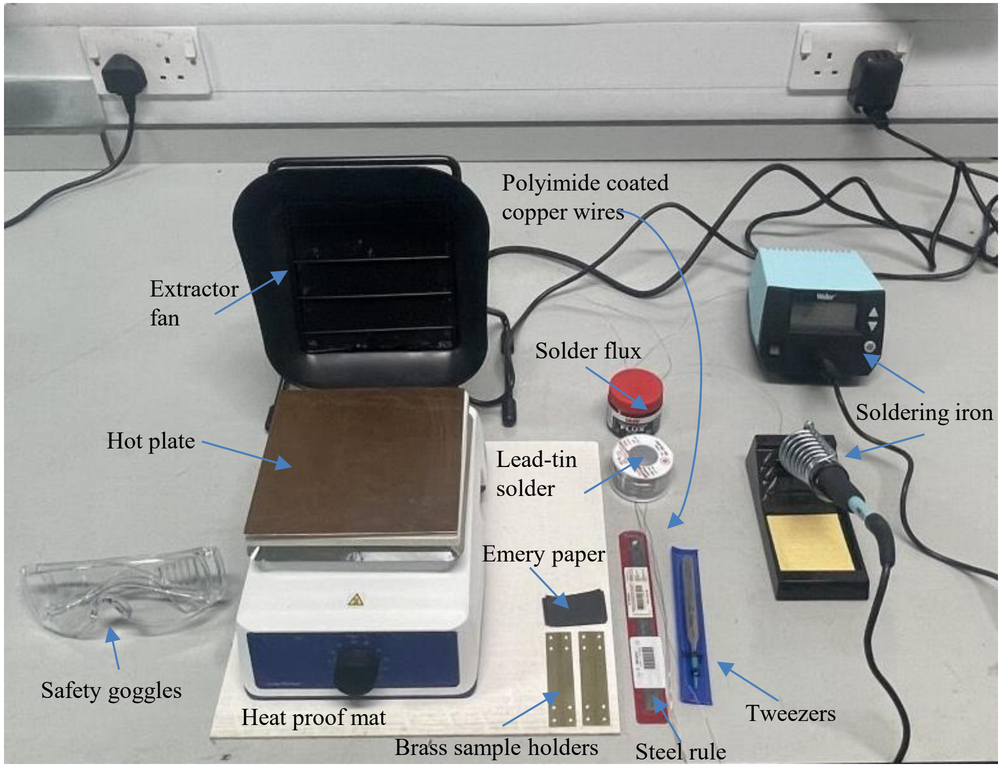
Freddie Daniels

STEP-BY-STEP: CRITICAL CURRENT MEASUREMENTS ON HIGH TEMPERATURE SUPERCONDUCTING TAPE

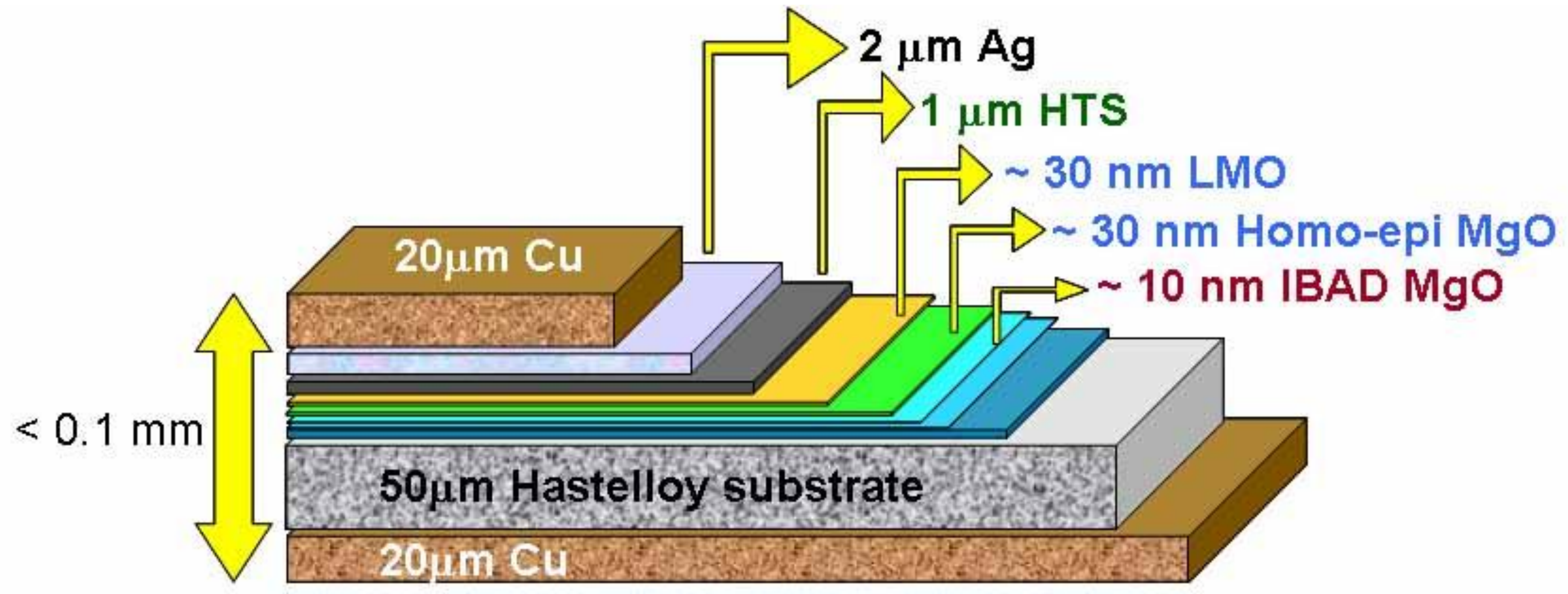
Dr. Mark J. Raine, Daniel Scobbie, Rollo Hutson, Emma Gillard and Prof. Damian P. Hampshire.
Superconductivity Group, Centre for Materials Physics, Physics Department, Durham University,
Durham DH1 3LE, UK.

1. Document Reference	Step-by-step for I_c	Version:	3
2. Order Title	STEP-BY-STEP: CRITICAL CURRENT MEASUREMENTS ON HIGH TEMPERATURE SUPERCONDUCTING TAPE		
3 Contact details	Dr. Mark Raine		
4. Date	24th December 2024		

The equipment that makes up the soldering station.



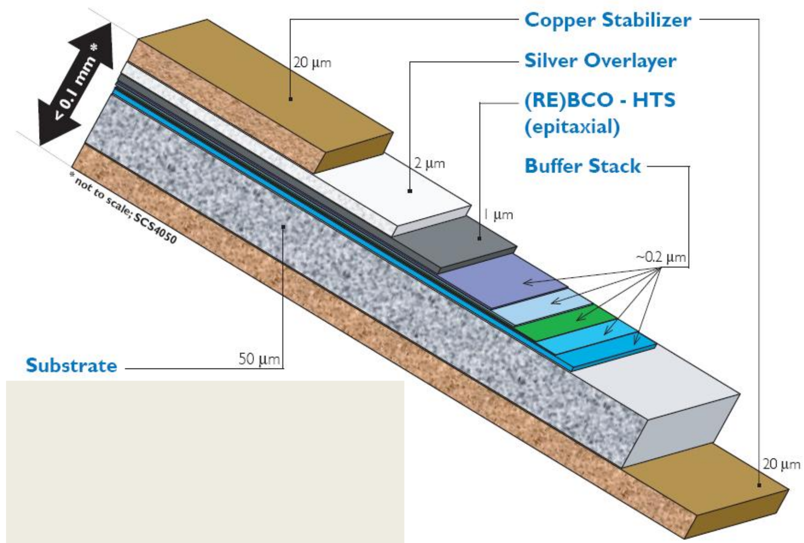
High temperature superconductor (HTS) $GdBa_2Cu_3O_7$- Kilometre long single crystals, REBCO (RE: Rare-Earth)



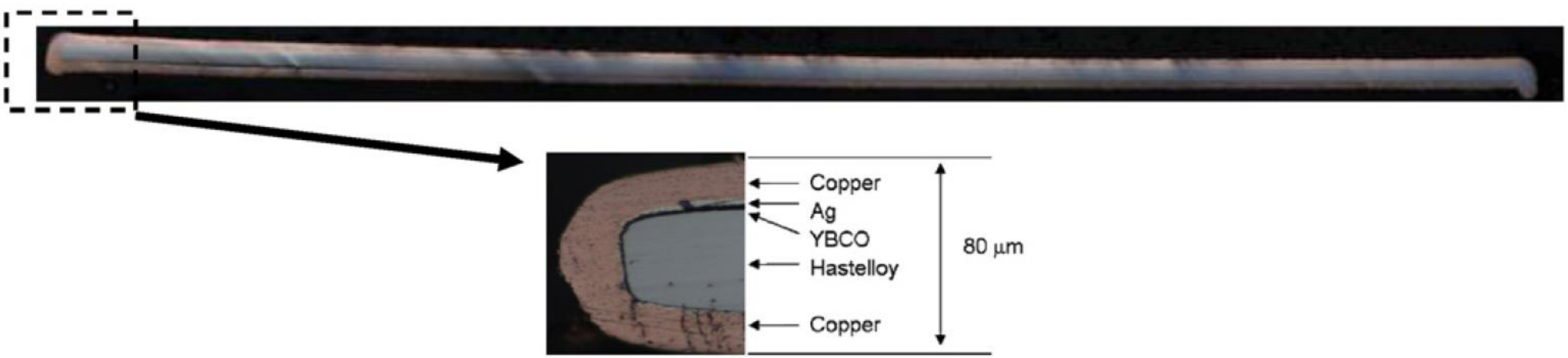
Configuration of SuperPower 2G HTS Wire™

REBCO Conductors

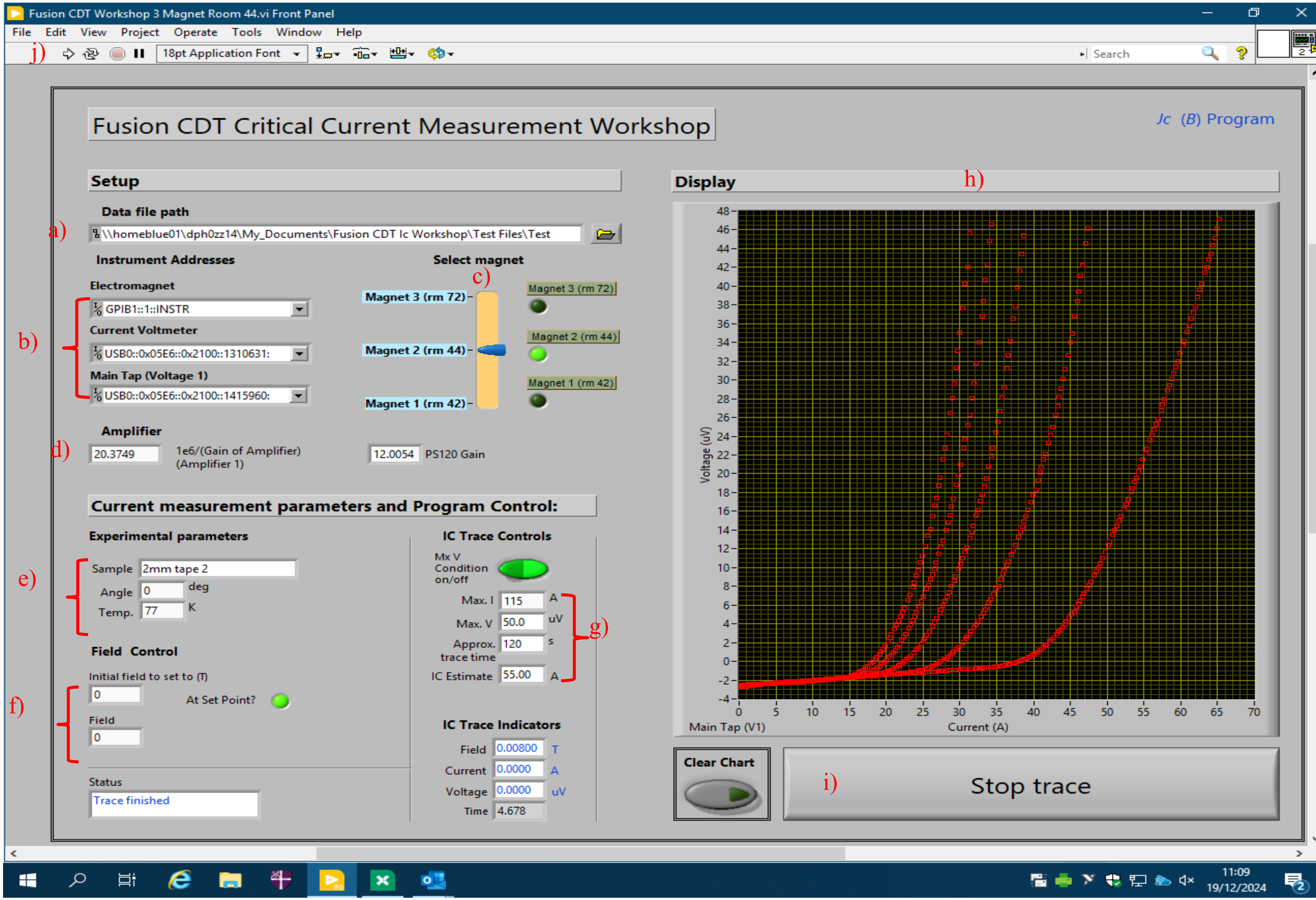
COST !



- Substrates: Ni, Ni-W, Hastelloy (Trade name for a superalloy consisting of Ni, Cr, Co, Mo, W, Fe)
- Stabilizers: stainless steel, brass, copper
- Buffer layers: chosen to promote high alignment of the YBCO grains



I_C (critical current) measurements



Icy Durham Practical Course

---- README

---- THINGS TO BE AWARE OF/DO BEFORE YOU ARRIVE ----

---- THINGS TO DO BEFORE YOU ARRIVE ----

---- THREE DOCUMENTS TO SIGN AT REGISTRATION ----

---- OUTCOMES TO ACHIEVE ----

Have fun, meet some new scientists and do some in-field Ic (critical current) measurements.

January 2026. Dr. Mark Raine: m.j.raine@durham.ac.uk Prof. Damian Hampshire: d.p.hampshire@durham.ac.uk

ANY QUESTIONS?

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Questions to discuss after the end of the 'Superconductors for Fusion Magnets' Lecture

i) What are the materials components of HTS ReBCO tapes and Nb_3Sn superconducting wires?

ii) What is the highest magnetic field inside the ITER, STEP, SPARC and ARC tokamaks?

iii) What is the approximate energy stored in the magnets in the ITER fusion tokamak ?

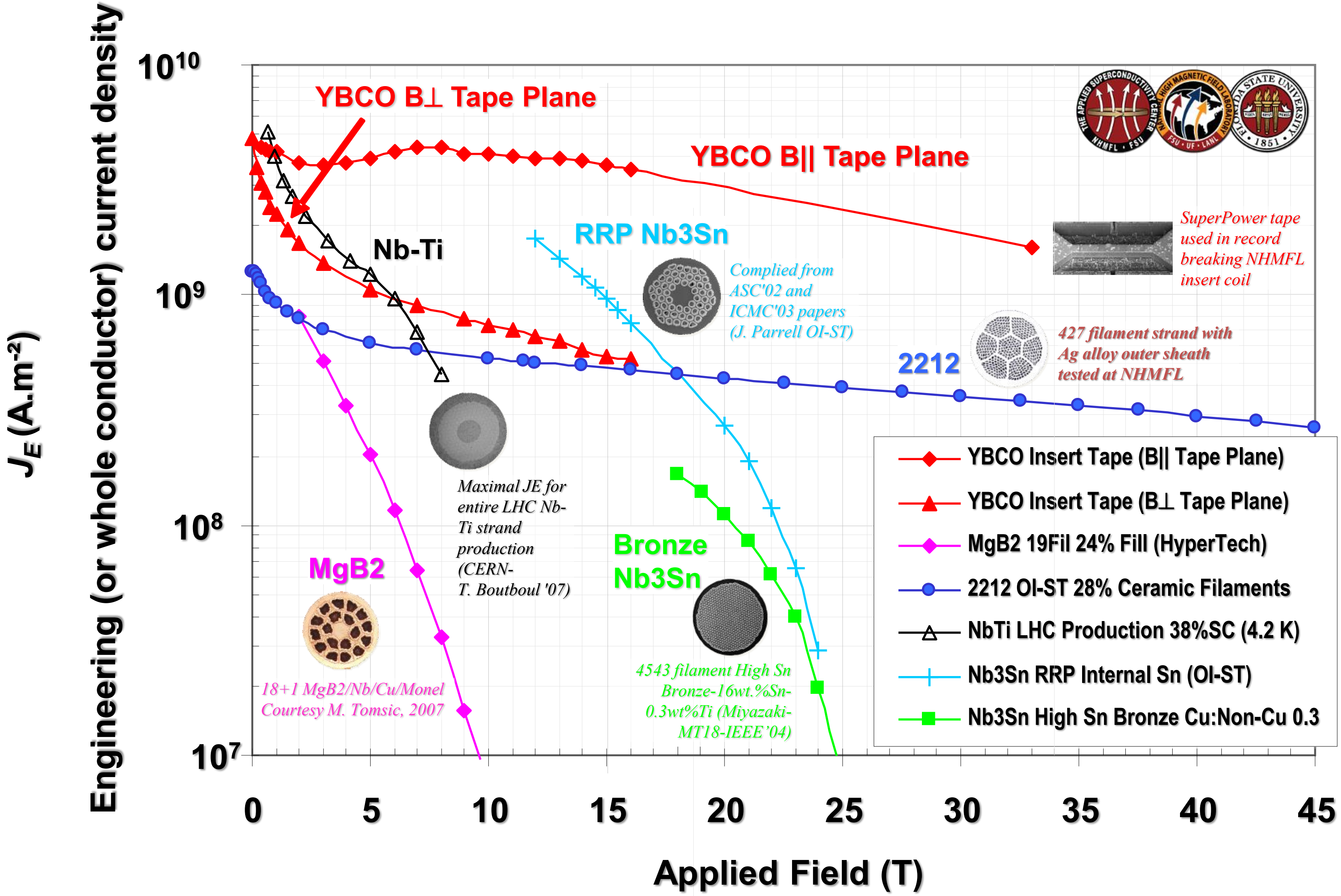
iv) Name the superconductors that are used to build (any) commercial magnets – state their critical temperature and upper critical field (at zero temperature).

v) Name the superconductors (to be) used in ITER, STEP, SPARC and ARC.

vi) What is the typical current density in a magnet? How can we make it larger? What impact would it have if we increased current density in superconductors by a factor 5.

vii) Either : If a room temperature superconductor was discovered would it affect your thesis research/ the magnetic confinement system for STEP and SPARC/ARC ?
or: List the important properties of the current superconductors used to build fusion magnets.
Rank a five-fold improvement in the important state-of-the-art properties of a superconductor for fusion applications.

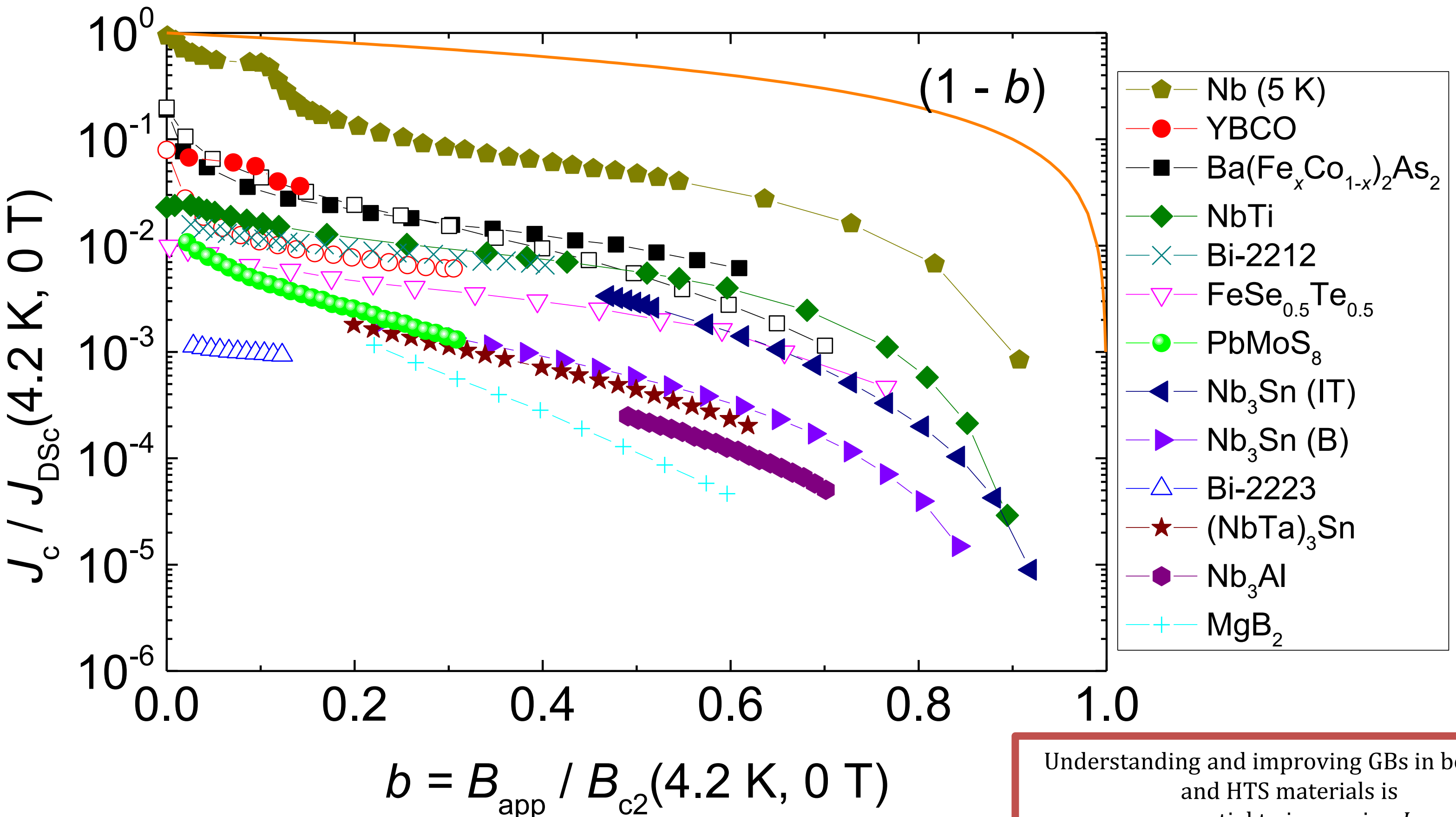
Industrial Superconducting Materials



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

The theoretical limit to J_C in high-field superconductors

Theoretical maximum depairing current density of a superconductor: $J_{\mathrm{DSc}}(T) = \frac{\Phi_0}{3\sqrt{3}\pi\mu_0\lambda^2(T)\xi(T)}$



Understanding and improving GBs in both LTS and HTS materials is essential to improving J_c

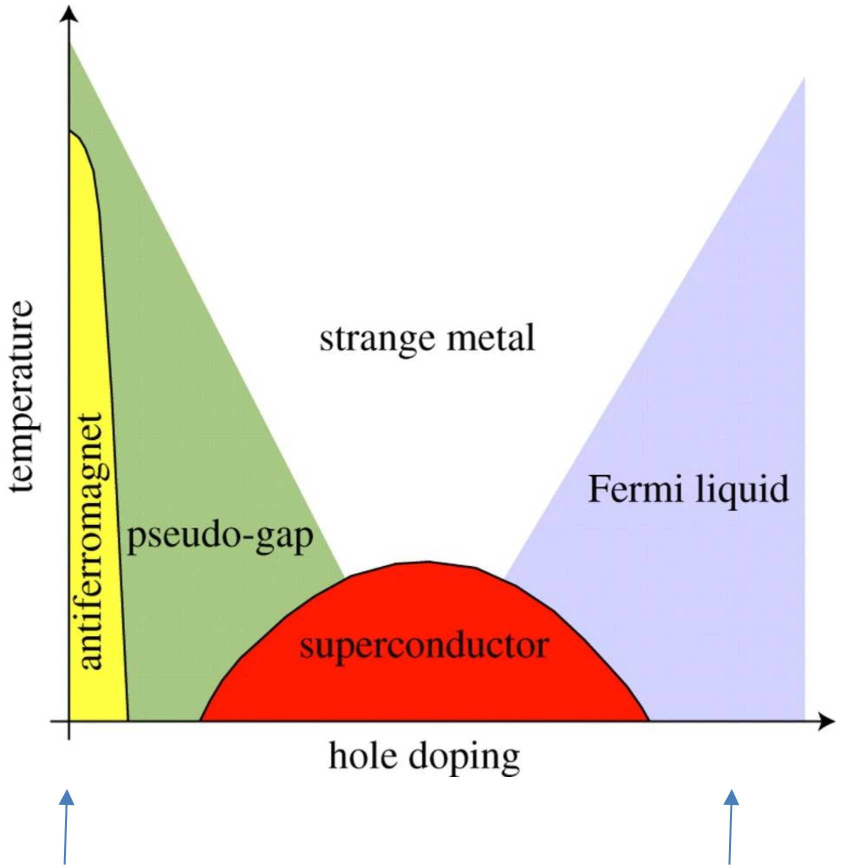
Basic Superconductivity

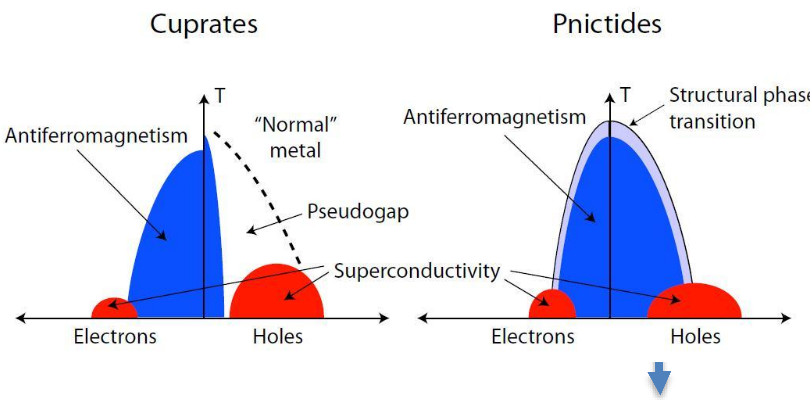
The two fundamental properties of a superconductor: Zero resistance and the Meissner state

i) Basic properties through phase diagrams

The phase diagram of High Temperature Superconductors

- Why are some materials superconducting and others not?

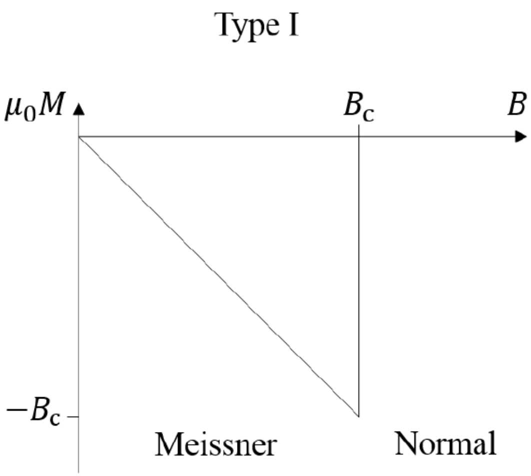


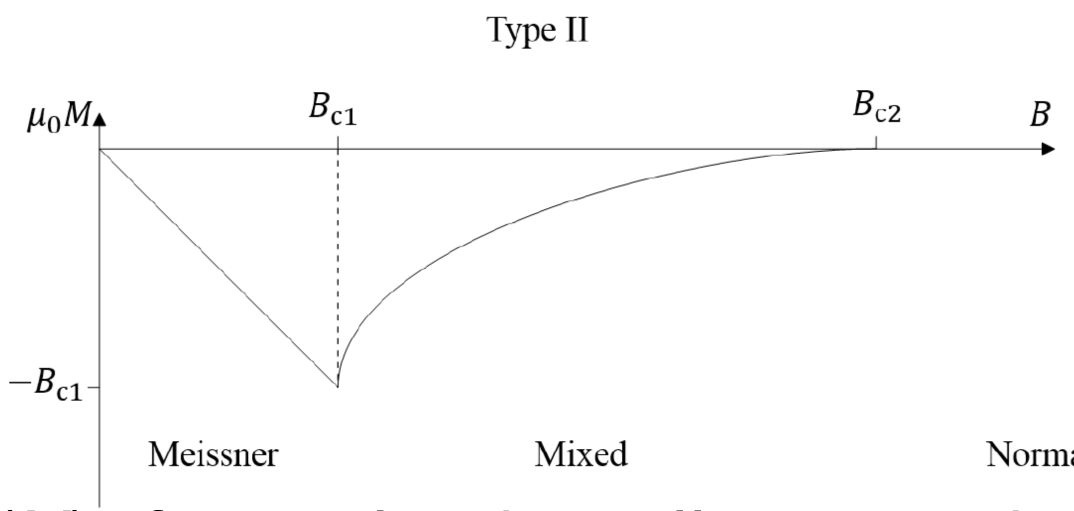


Insulating

Metallic

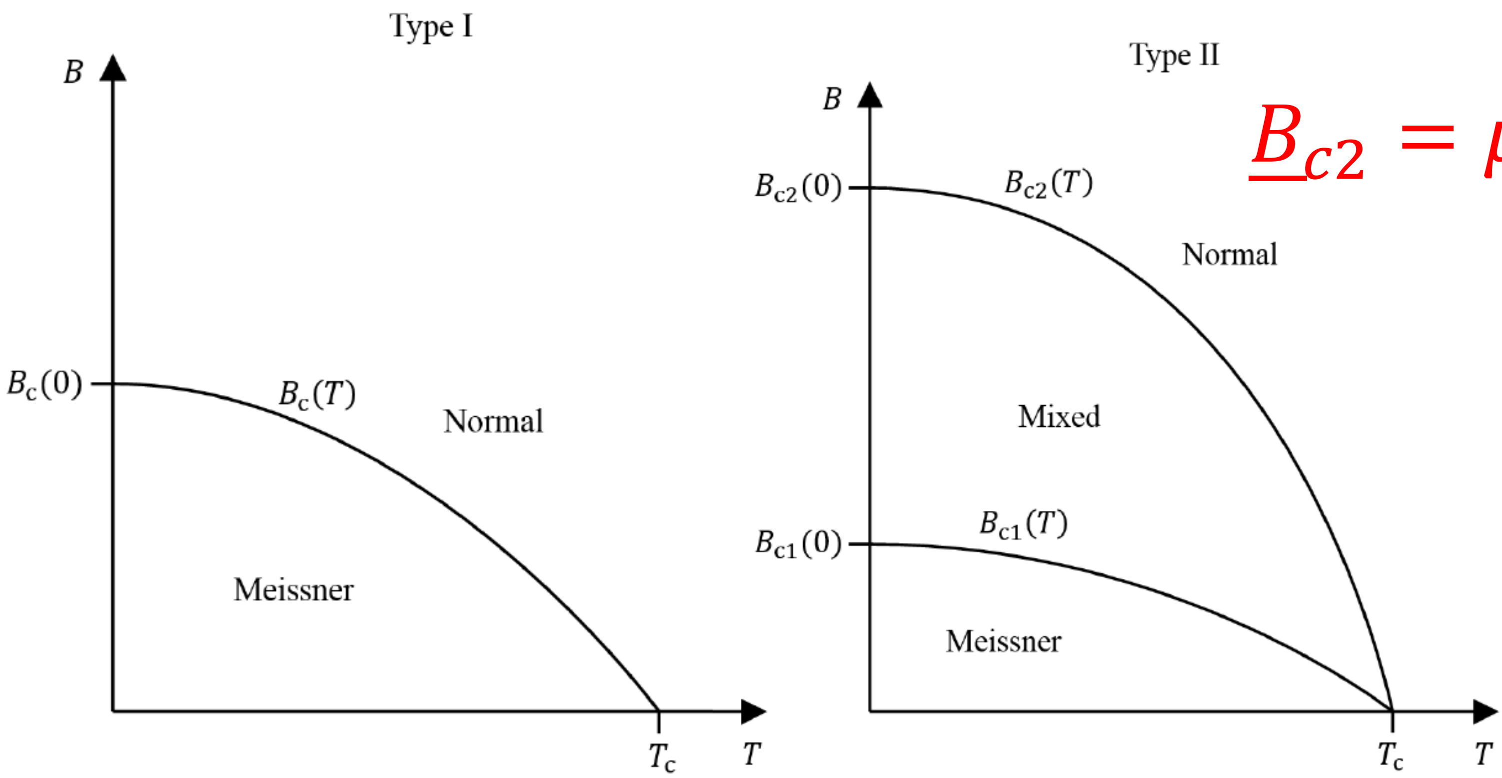
Magnetisation of superconductors





The magnetisation (*M*) of a type I and type II superconductor, with the same B_c as a function of applied magnetic field (*B*). **Inset:** The phase diagrams of type I and type II superconductors.

The Phase diagram of Type I and Type II Superconductors – for Physicists



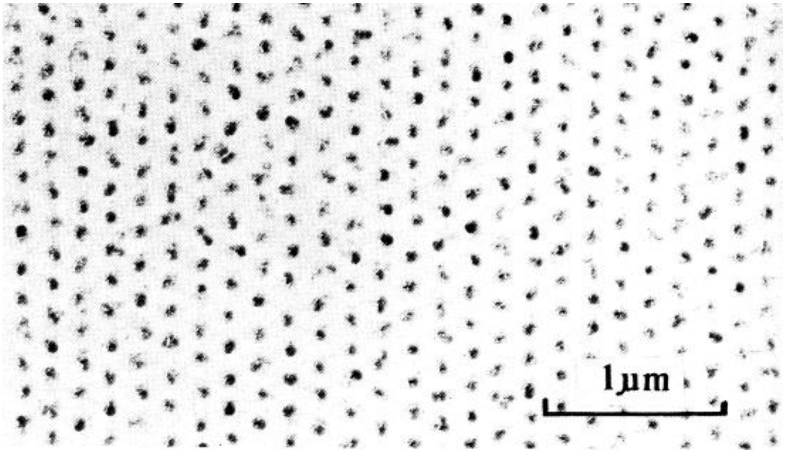
$$\underline{B}_{c2} = \mu_0 \underline{H}_{c2}$$

IN HIGH FIELD SUPERCONDUCTORS:

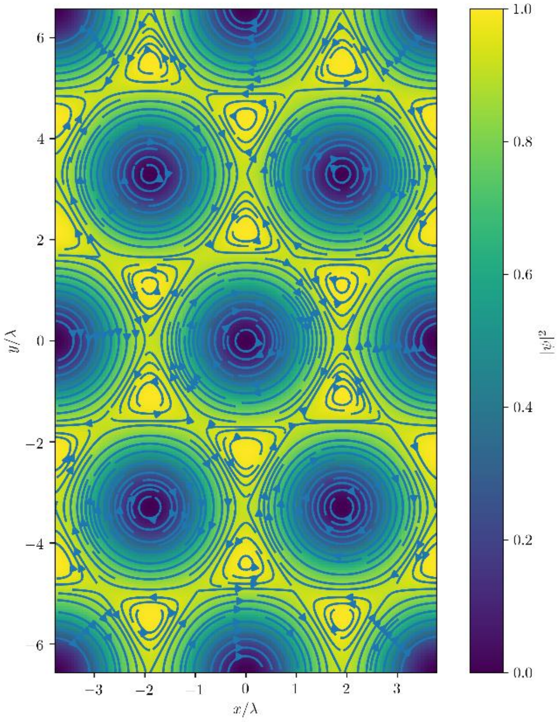
$\underline{B}_{c2}$ *is tens of Tesla,* $\underline{B}_{c1}$ *is tens of mT*

The Mixed State in Nb

Experiment on Nb

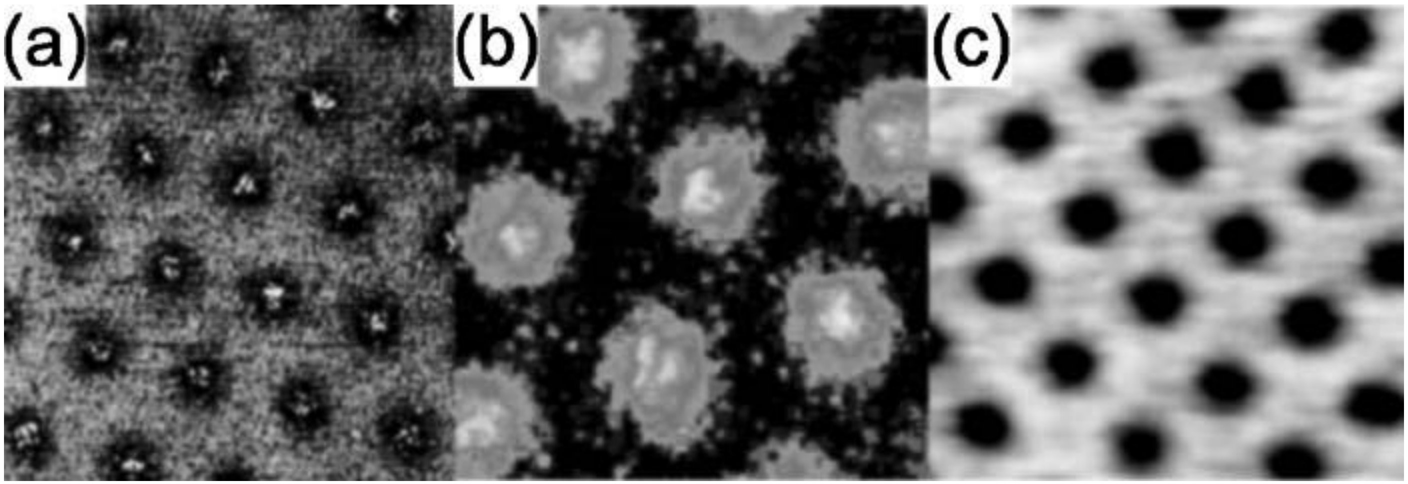


Calculation using G-L theory



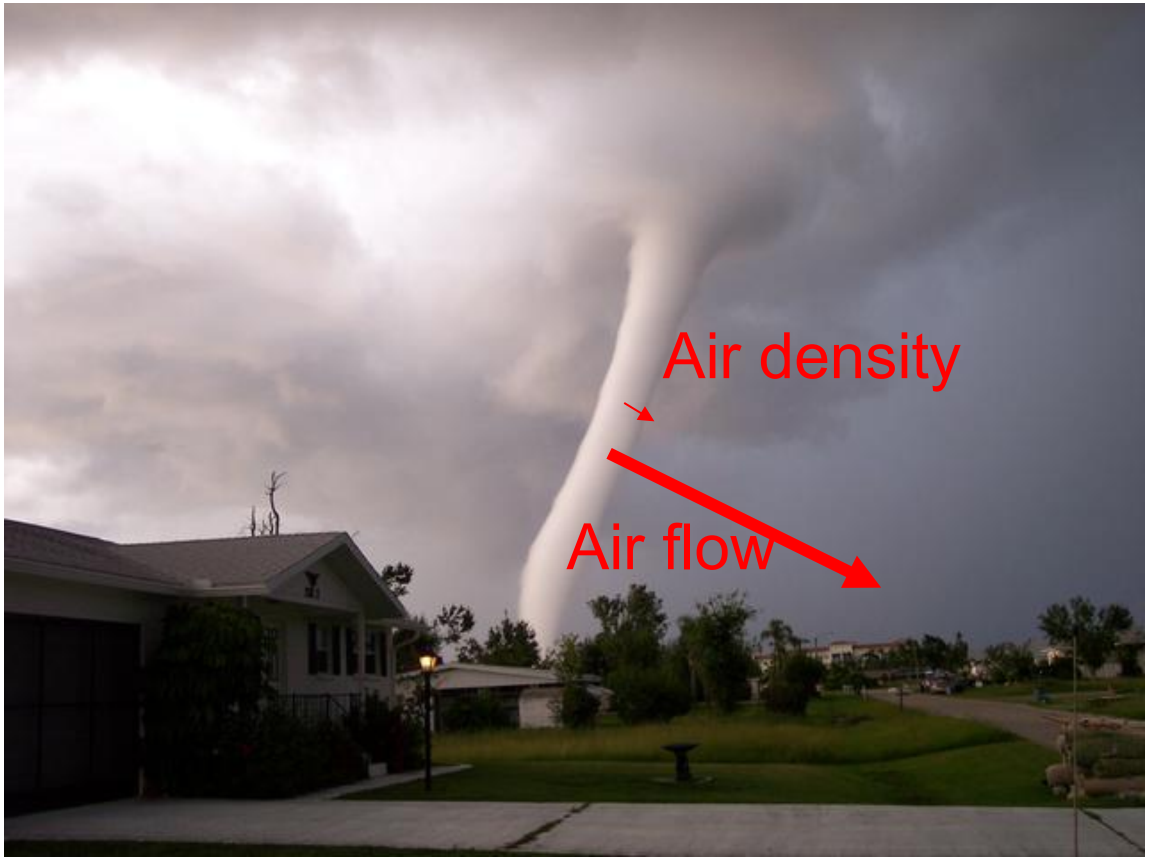
Vortex lattice in niobium – the triangular layout of the flux-line-lattice can clearly be seen. (The normal regions are preferentially dark because of the ferromagnetic powder).

The Flux-Line-Lattice, Fluxons and Supercurrents

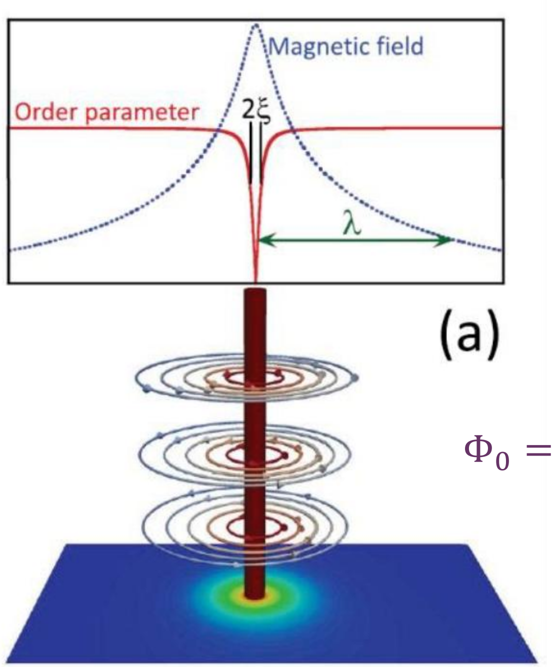


- STS images of ordered vortex lattices in superconductors. (a) $NbSe_2$ *(b)* MgB_2 *(c)* $LuNi_2B_2C$

A fluxon
- its structure has similarities with a tornado
- there are two length scales: density and flow

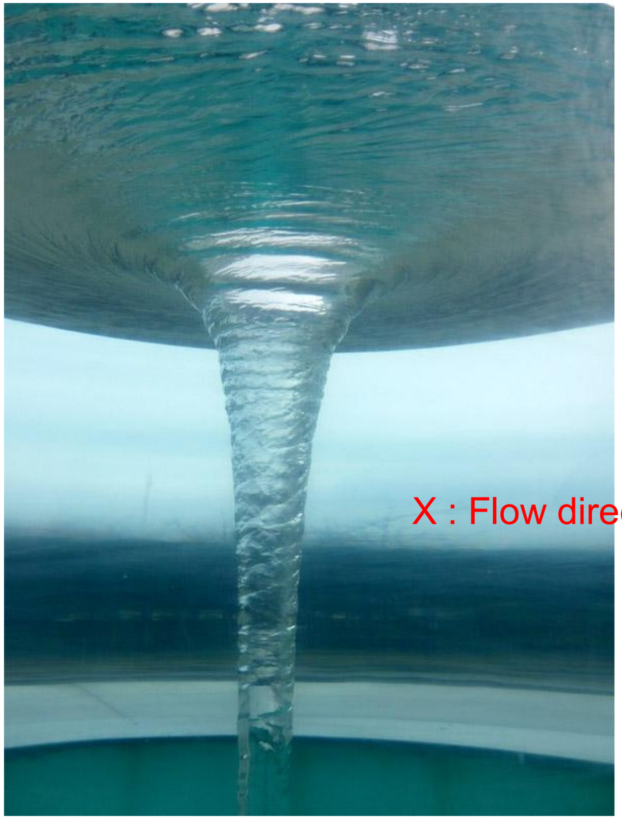


A fluxon and a vortex



$$\Phi_0 = \frac{h}{2e}$$

Wai-Kwong Kwok *et al* 2016 *Rep. Prog. Phys.* **79** 116501



X : Flow direction

Ginzburg-Landau Theory (Magnetisation in magnetic fields)

Ginzburg and Landau (G-L) postulated a Helmholtz energy density for superconductors of the form:

$$f = \alpha|\psi|^2 + \frac{1}{2}\beta|\psi|^4 + \frac{1}{2m}|(-i\hbar\nabla - 2e\boldsymbol{A})\psi|^2 + \int \boldsymbol{H}\mathrm{d}\boldsymbol{B}$$

where α and β are constants and ψ is the wavefunction. α is of the form $\alpha'(T-T_C)$ which changes sign at T_C

Time-dependent Ginzburg-Landau equations

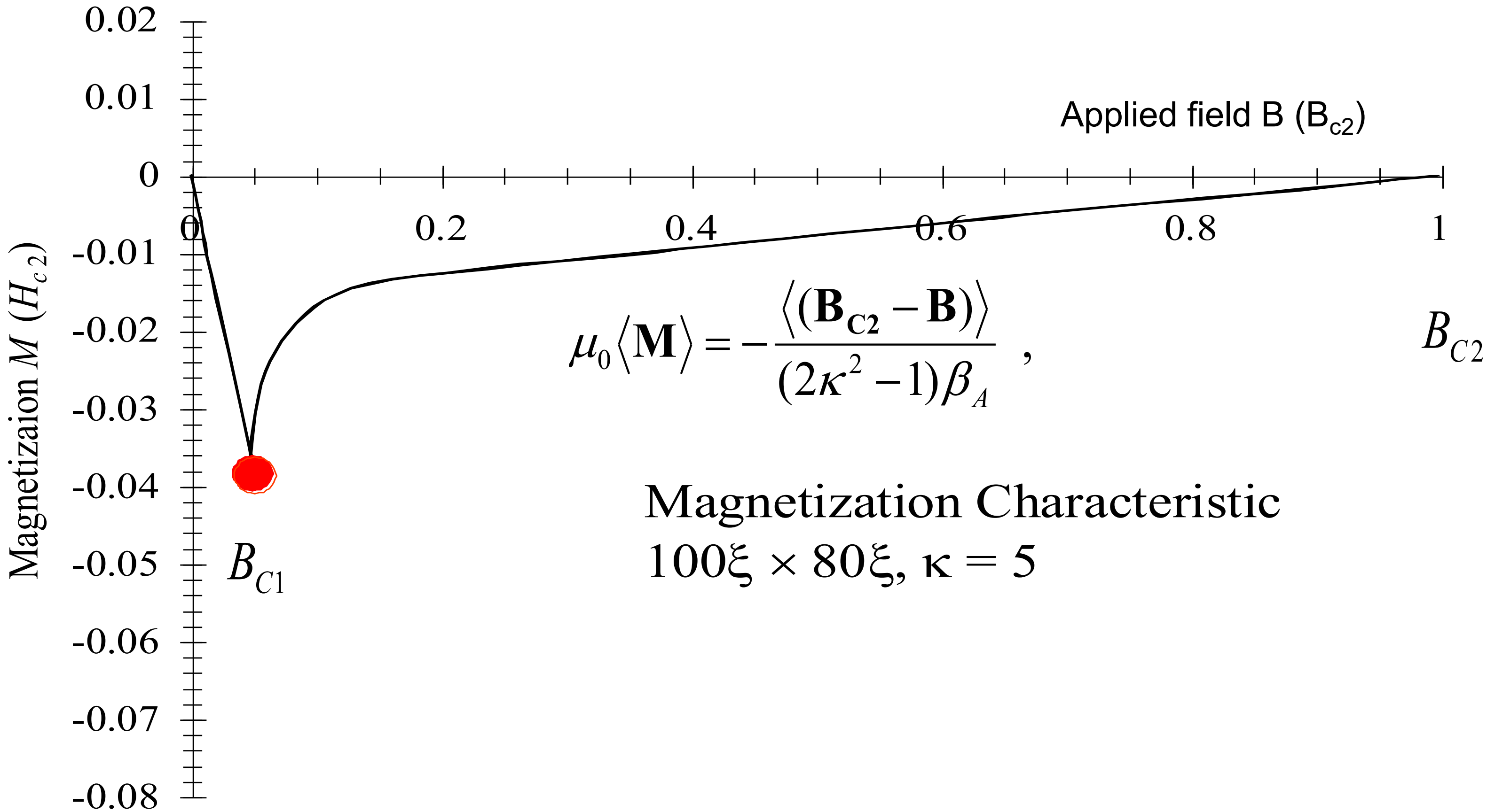
$$\frac{1}{\xi_0^2}\left(|\Delta|^2-\left(1-{T}/{T_c}\right)\right)\Delta+\left(\frac{\nabla}{i}-\frac{2e}{\hbar}\mathbf{A}\right)^2\Delta+\frac{1}{D}\left(\frac{\partial}{\partial t}+i\frac{2e\varphi}{\hbar}\right)\Delta=0$$

$$\mathbf{J}_e=\frac{1}{2e\mu_0\lambda_0^2}\mathrm{Re}\left(\Delta^*\left(\frac{\hbar}{i}\nabla-2e\mathbf{A}\right)\Delta\right)-\sigma\left(\nabla\varphi+\frac{\partial\mathbf{A}}{\partial t}\right)$$

- *These equations were postulated by Schmid (1966), and then derived using microscopic theory in the gapless case by Gor'kov and Eliashberg (1968)*

Reversible Magnetization Loop

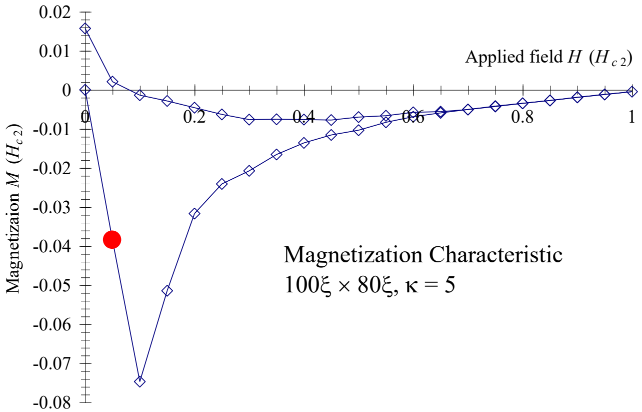
- The reversible response of a superconductor

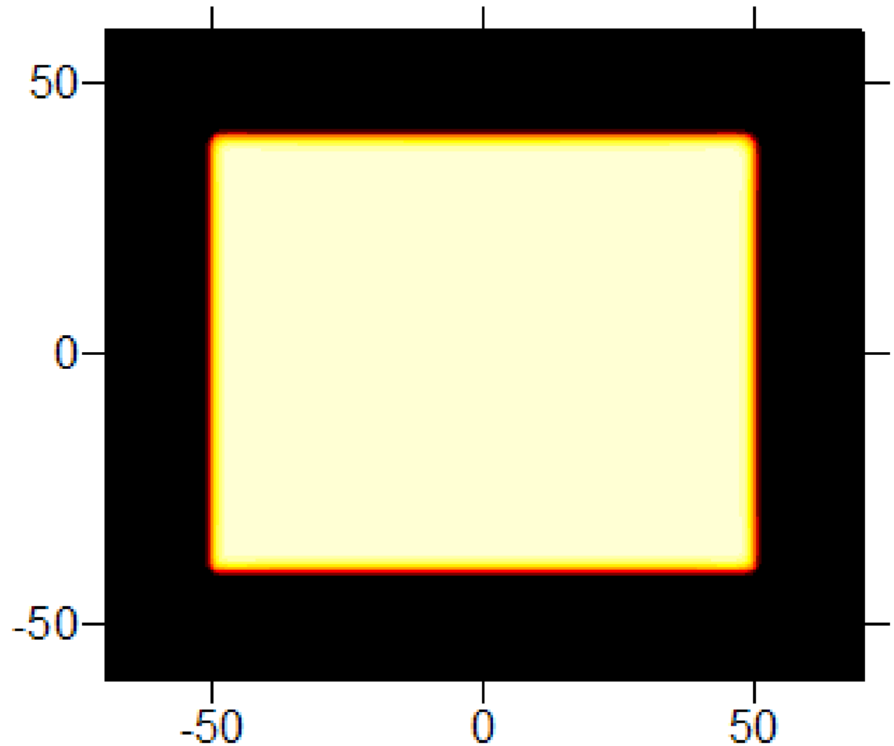


$$\mu_0 \langle \mathbf{M} \rangle = -\frac{\langle (\mathbf{B_{C2}} - \mathbf{B}) \rangle}{(2\kappa^2 - 1)\beta_A} \quad ,$$

Magnetization Characteristic
$100\xi \times 80\xi$, $\kappa = 5$

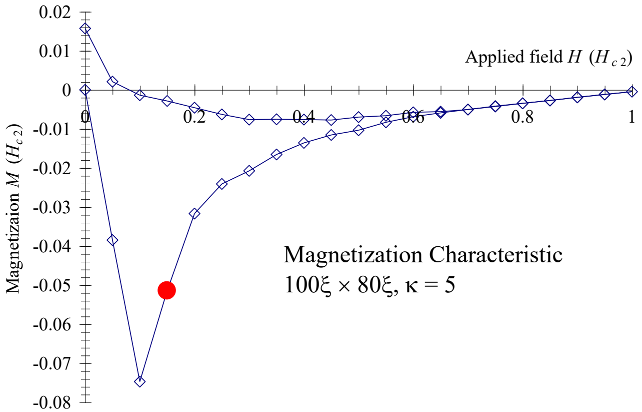
M vs. H for a Superconductor Coated With a Normal Metal, κ = 5

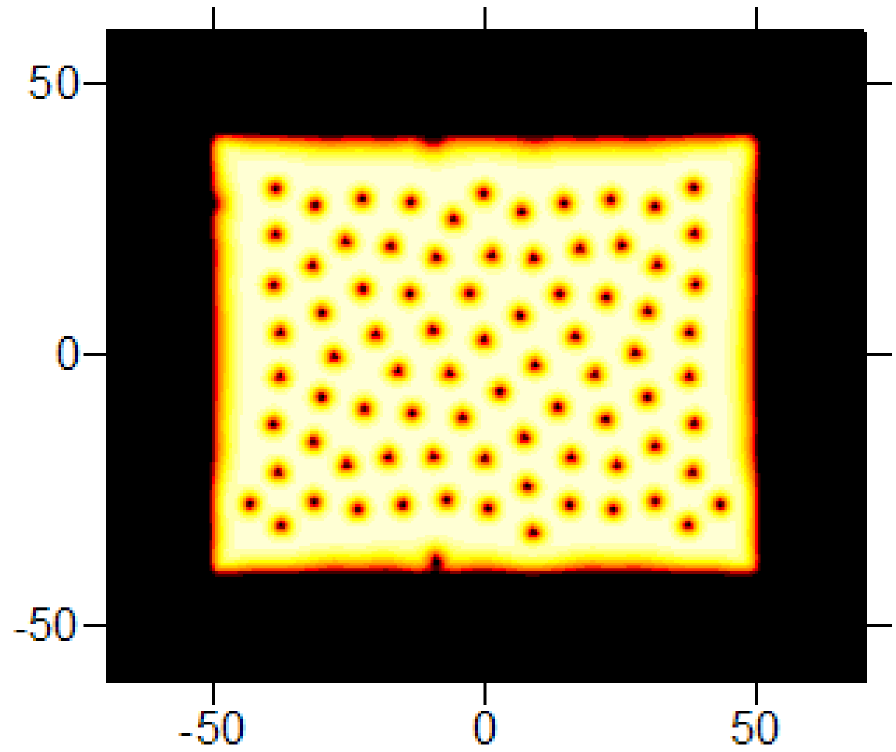




- B = 0.05 B_{c2}
- The material is in the Meissner state

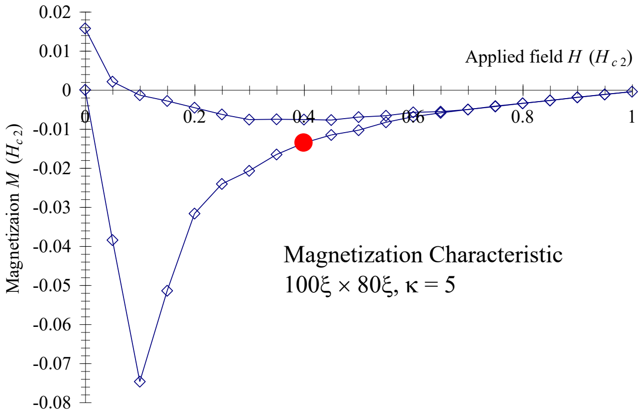
Magnetization Loop

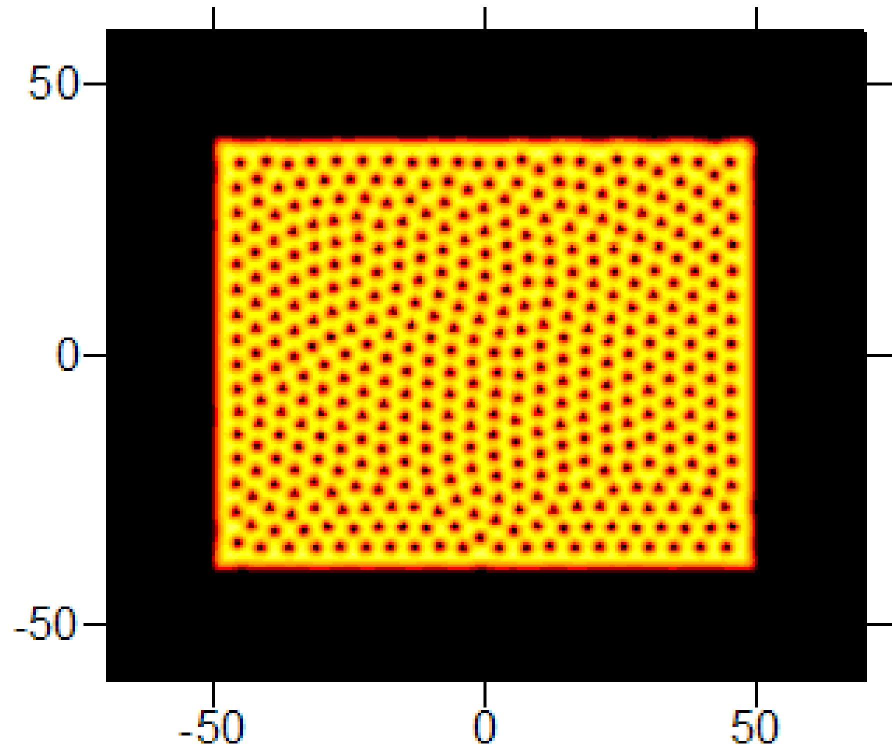




- $B = 0.15\ B_{c2}$
- The material is in the mixed state

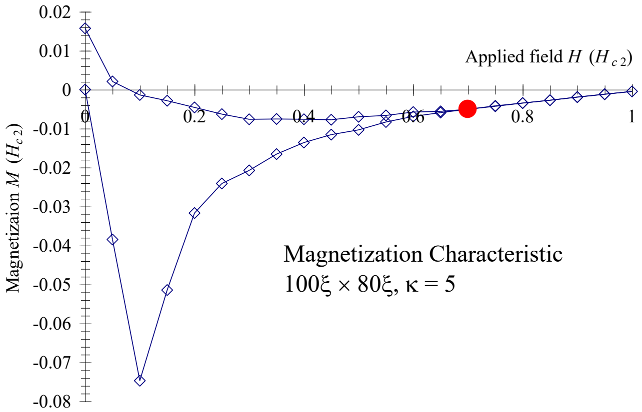
Magnetization Loop

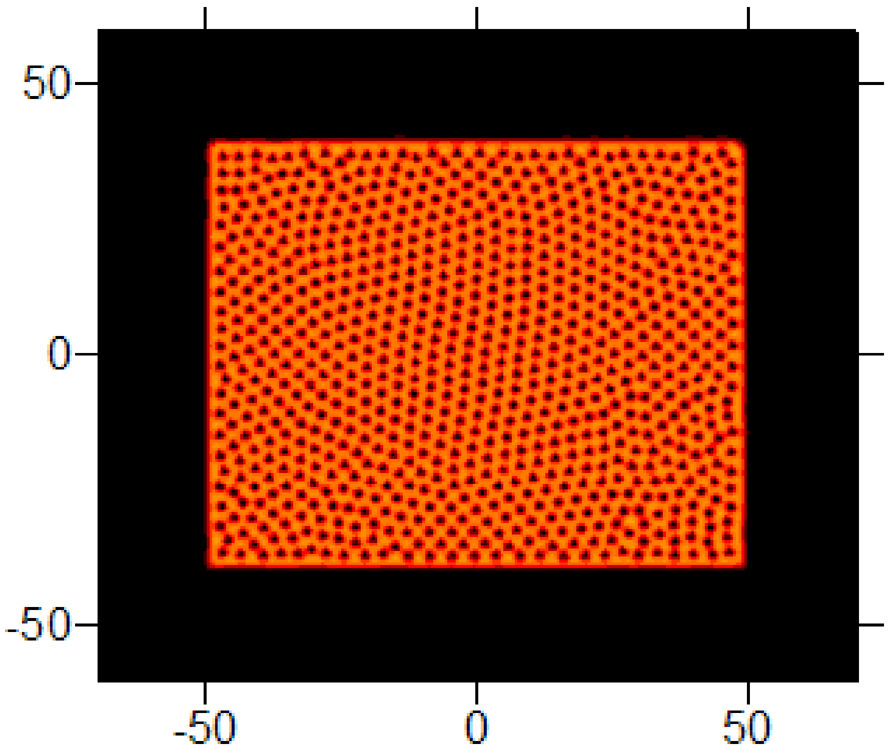




- B = 0.40 B_{c2}
- Note the nucleation of fluxons at the superconductor-normal boundary

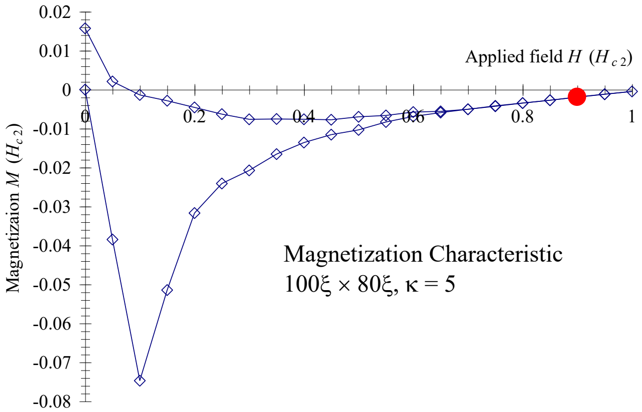
Magnetization Loop

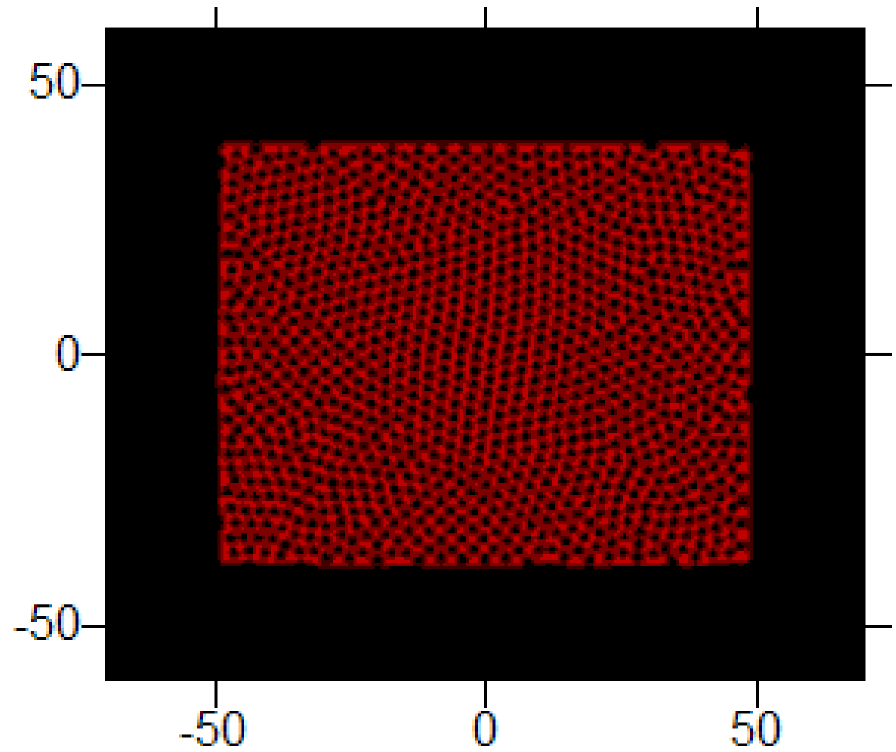




- $B = 0.70\ B_{c2}$
- In the reversible region, one can determine κ

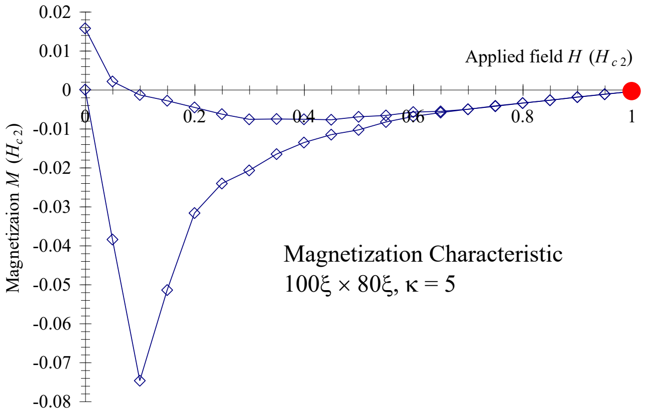
Magnetization Loop

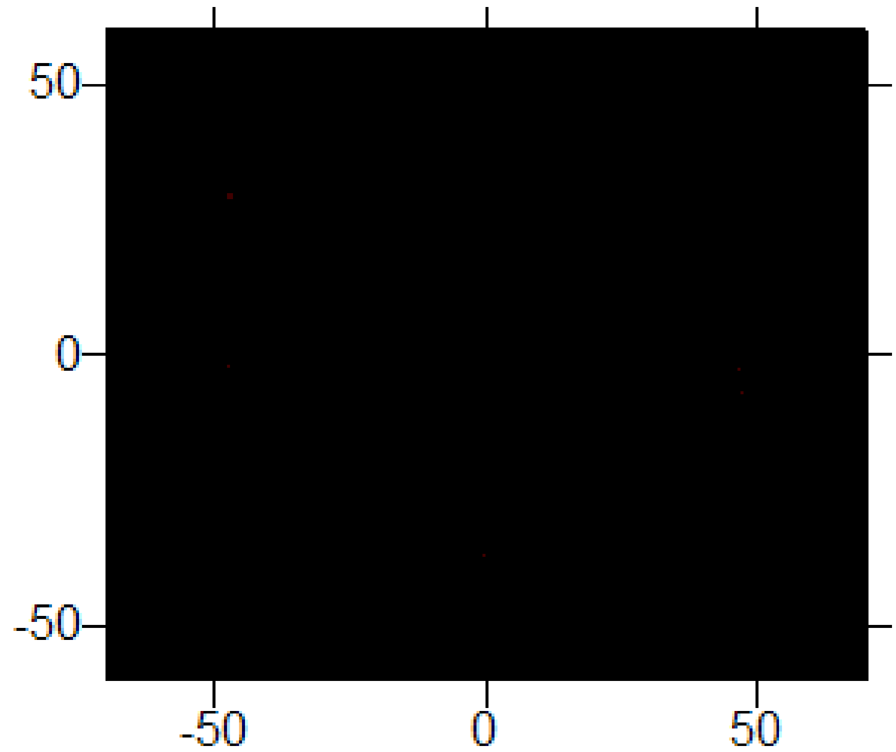




- $B = 0.90\ B_{c2}$
- The core of the fluxons overlap and the average value of the order parameter drops

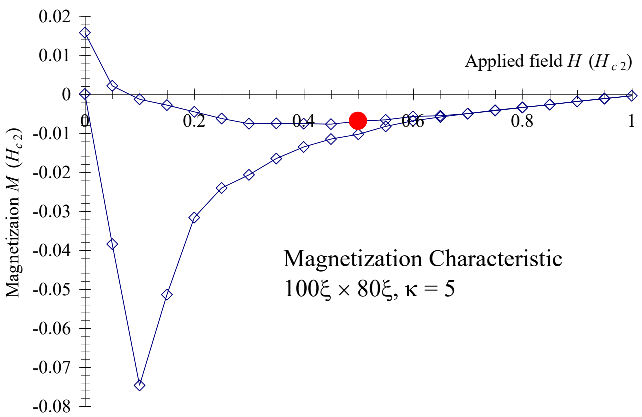
Magnetization Loop

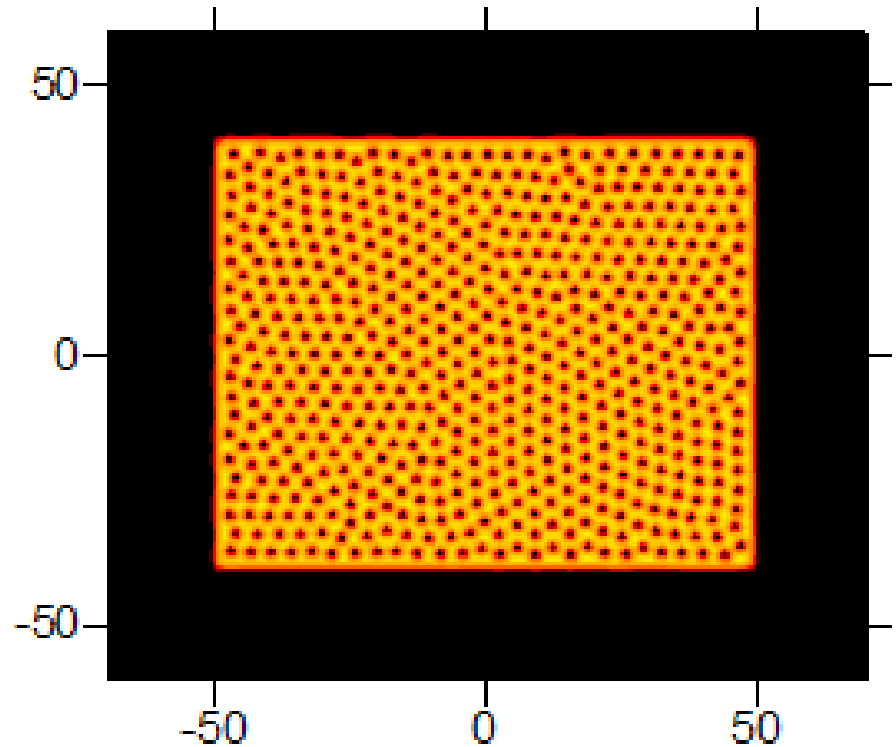




- B = 1.00 B_{c2}
- Eventually the superconductivity is destroyed

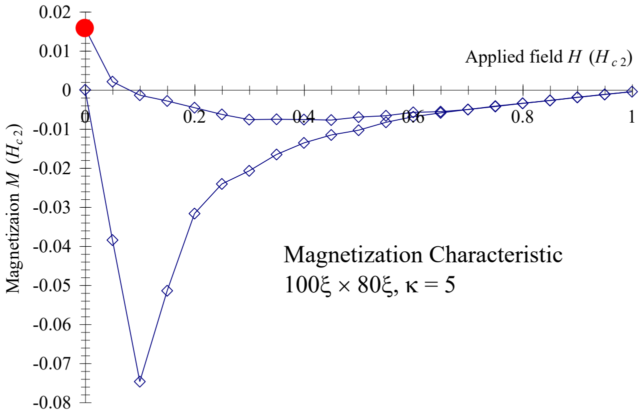
Magnetization Loop

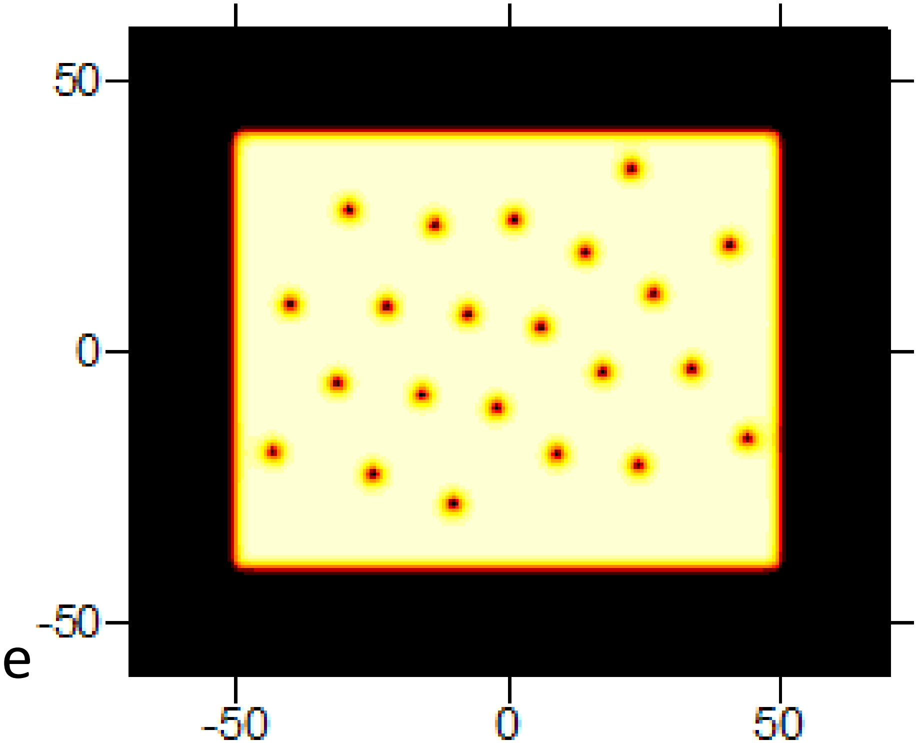




- B = 0.50 B_{c2}
- Note the Abrikosov flux-line-lattice with hexagonal symmetry

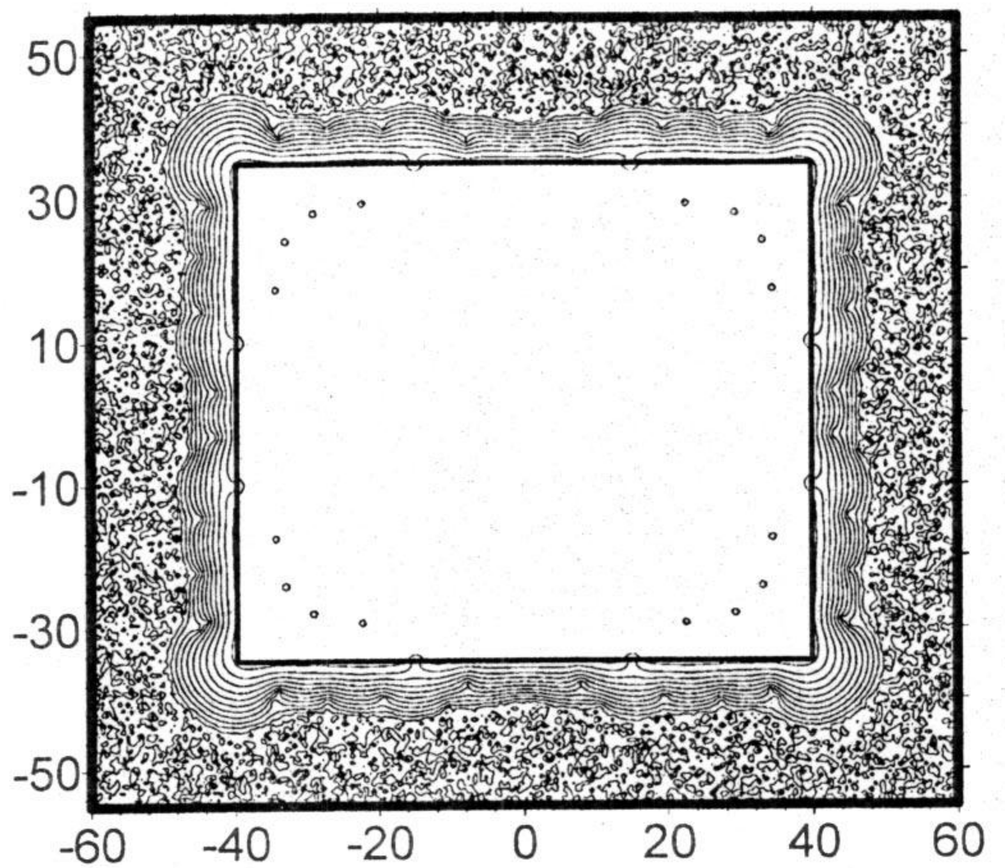
Magnetization Loop



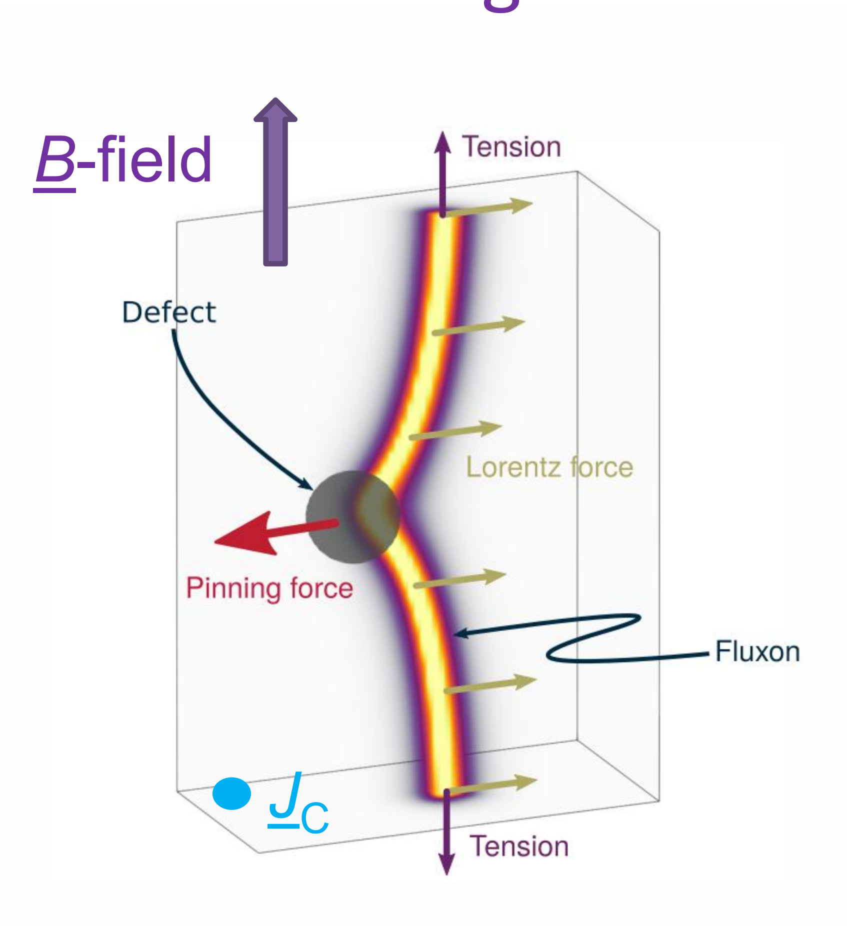


- $B = 0.00\ B_{c2}$
- A few fluxons remain as the inter-fluxon repulsion is lower than the surface pinning

Fluxon nucleation
– laminar and turbulent flow



Fux Pinning (C20th) - Magnitude of the order parameter



Flux pinning curve scales well with field, temperature and strain

$$F_p = J_c B = C\left(\frac{B}{B_{c2}}\right)^p \left(1 - \frac{B}{B_{c2}}\right)^q$$

NbTi : p = 1, q = 1

Nb_3Sn : (Kramer) p = 0.5, q = 2

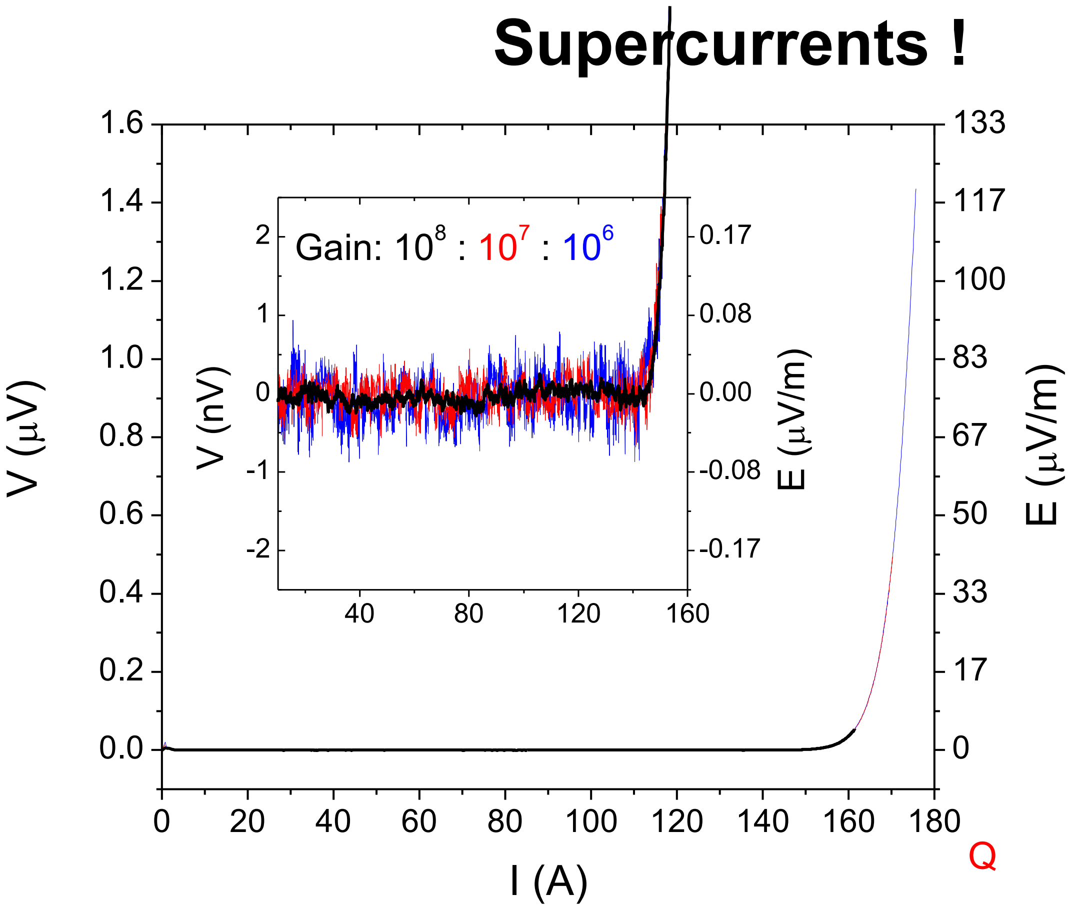
Dew-Hughes : variable p and q.

REBCO : p = 0.45 – 0.6 in intermediate fields

$$\underline{F}_V = -\underline{J}_C \times \underline{B}$$

$\underline{F}_V$: Lorentz Force on fluxon

Critical current density in high magnetic fields



T= 4.2 K, B = 7T

V_{theory} ~ 54 pV

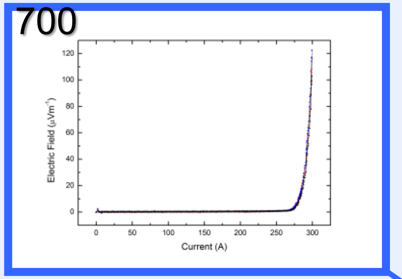
Measurements are about a factor of 3 above the theoretical Johnson noise limit

Prapaiwan (Bew). Sunwong, J. S. Higgins, and D. P. Hampshire – **Probes for investigating the effect of magnetic field, field orientation, temperature and strain on the critical current density of anisotropic high-temperature superconducting tapes in a split-pair 15 T horizontal magnet – Review of Scientific Instruments 85 065111 (2014)**

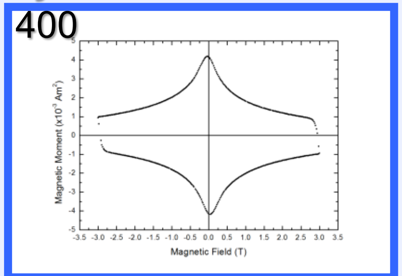
European Reference Laboratory measurements

Cryogenic measurements (down to -269 °C)

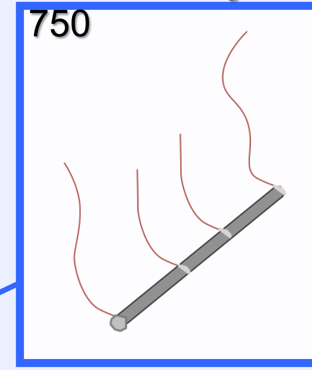
Critical Current, I_c > 190 A

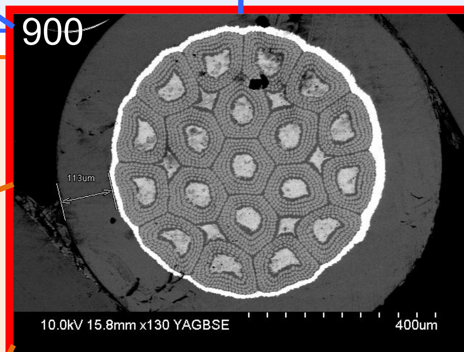


Hysteresis < 500 mJ/cm³

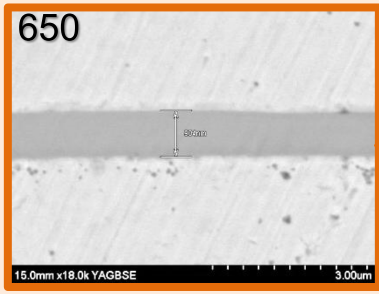


Residual Resistivity Ratio > 100

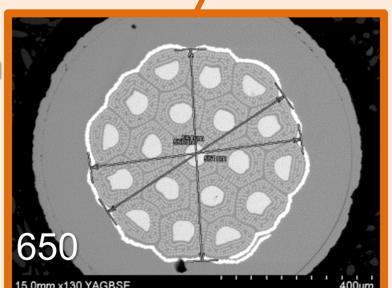




Room temperature measurements

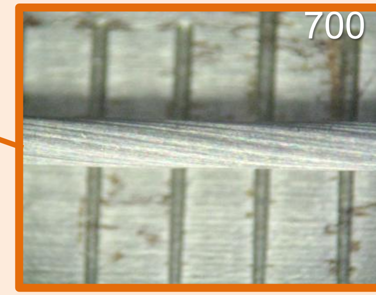


Chromium Plating Thickness, 1 to 2 µm



Cu-non-Cu Ratio, 1.0 ±0.1

Diameter, 0.820 ± 0.005 mm



Twist Pitch 15 ± 2 mm

European Reference Laboratory for Fusion Energy

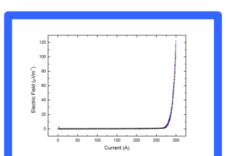
Cryogenic measurements:

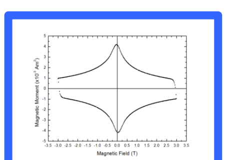
- Excellent agreement between different labs.
- *Observations*:
  1. Heat-treatment (temperature accuracy, purity and reproducibility) is a dominant source of variability in samples
  2. High RRR requires high gas purity

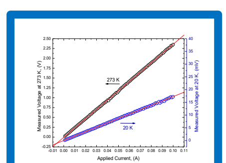
Summary of Data				
Measurement	**Diff. in mean between Durham and Manufacturer**		**Spread of data (σ %)**	
Strand type	**BR**	**IT**	**BR**	**IT**
Critical current	**1 %**	**2 %**	**1 %**	**4 %**
n-value	**2 %**	**7 %**	**4 %**	**14 %**
Hysteresis losses	**11 %**	**12 %**	**7 %**	**23 %**
RRR	**8 %**	**8 %**	**6 %**	**22 %**
Diameter	**0.1 %**	**0.1 %**	**0.1 %**	**0.1 %**
Cu to non-Cu ratio	**0.5 %**	**2 %**	**2 %**	**6 %**
Twist pitch		**9 %**		**7 %**
Ch. Plating		**6 %**		**9 %**

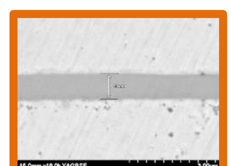
Room temperature measurements:

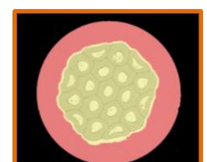
- Good agreement between different laboratories.

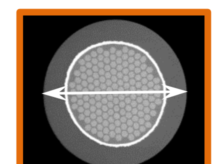












Structure of the talk

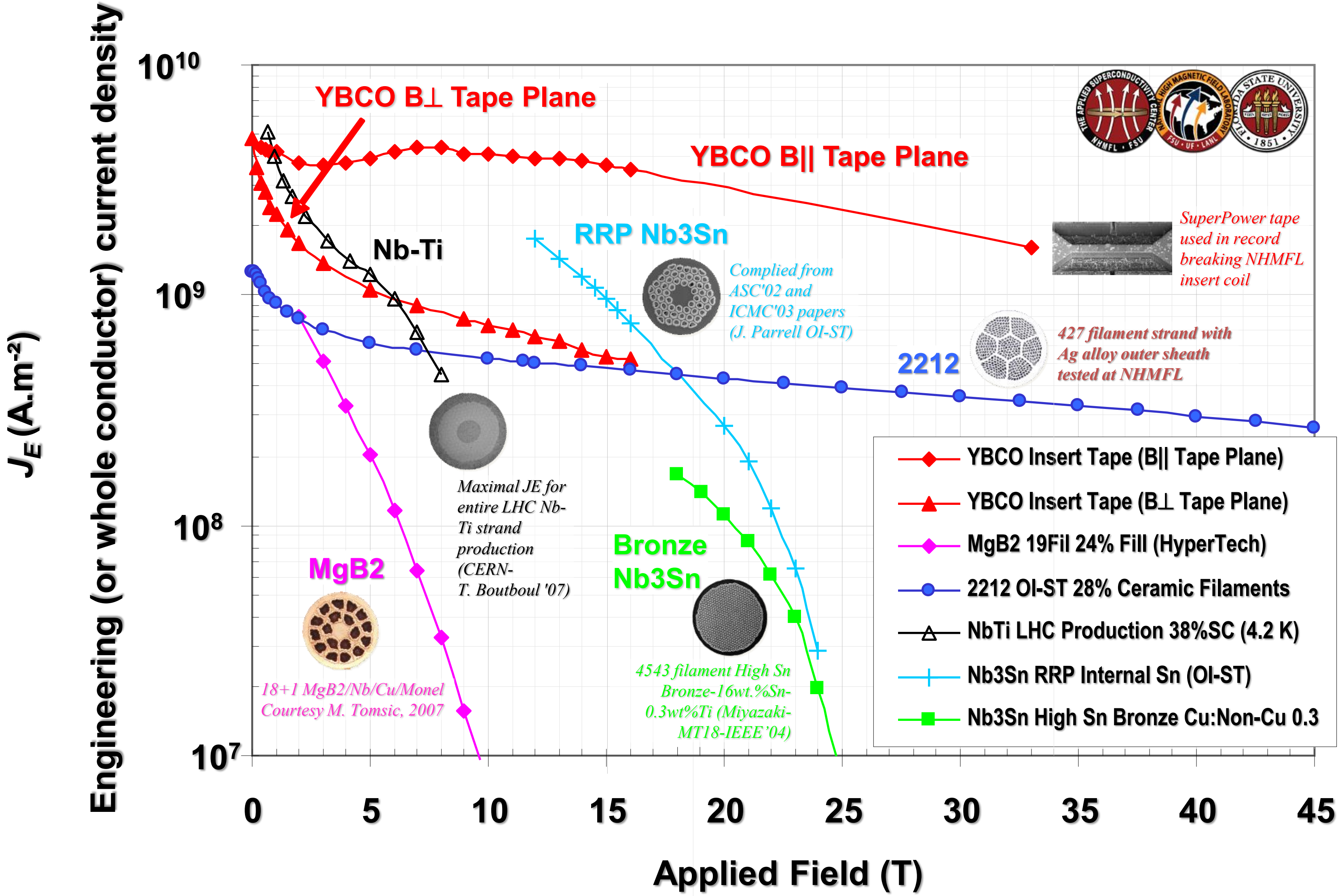
1. Applications that use superconducting materials.
2. The Icy Durham Practical Course.
3. Soldering the high temperature superconductor (HTS) $GdBa_2Cu_3O_7$ for critical current (Ic) measurements.

4. The critical current (Ic) of superconducting materials.
5. Basic superconductivity.
6. The flux-line lattice, fluxons and supercurrents.
7. Reference Laboratory measurements.

8. The 3 Industrial Superconducting Materials.
9. Advanced measurements on superconductors.
10. The Icy Durham practical course lectures.

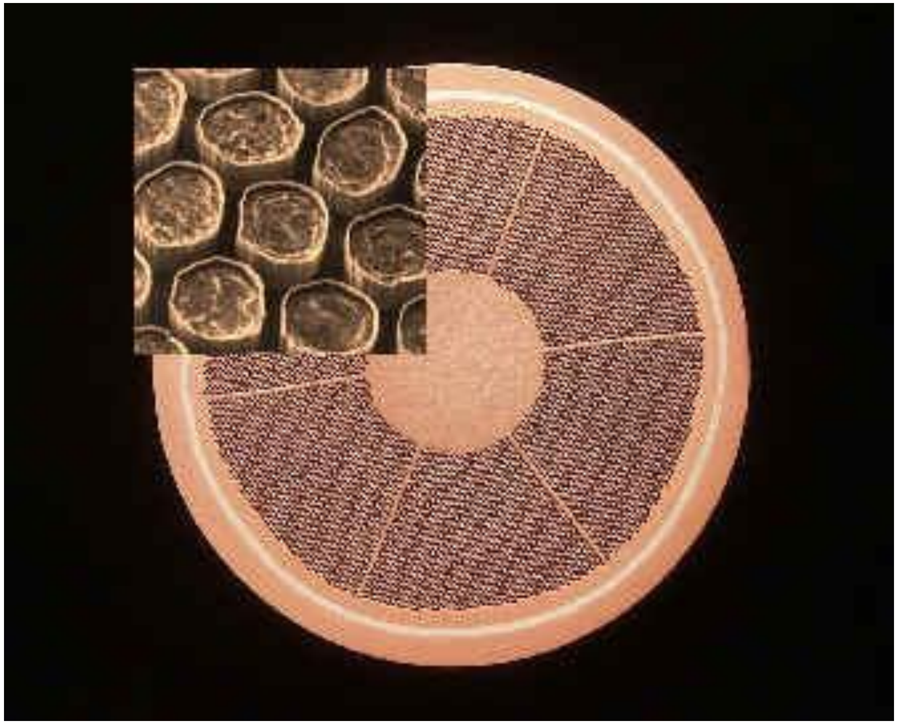
11. Post lecture discussion

Industrial Superconducting Materials



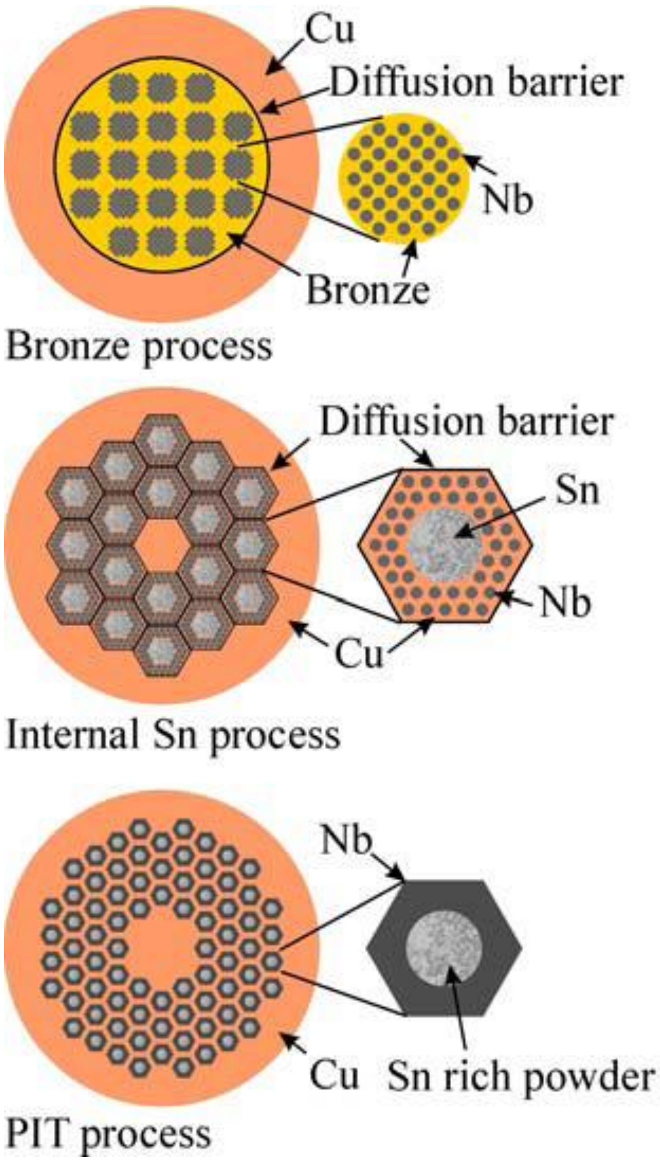
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

NbTi multifilamentary wire
– the workhorse for magnetic fields B < 12 T.



Ductile alloy - NbTi
T_C ~ 9 K
$B_{C2}(0)$ ~ 14 T
Multifilamentary

Fabrication of Nb_3Sn



Brittle Intermetallic – Nb_3Sn

T_C ~ 18.6 K

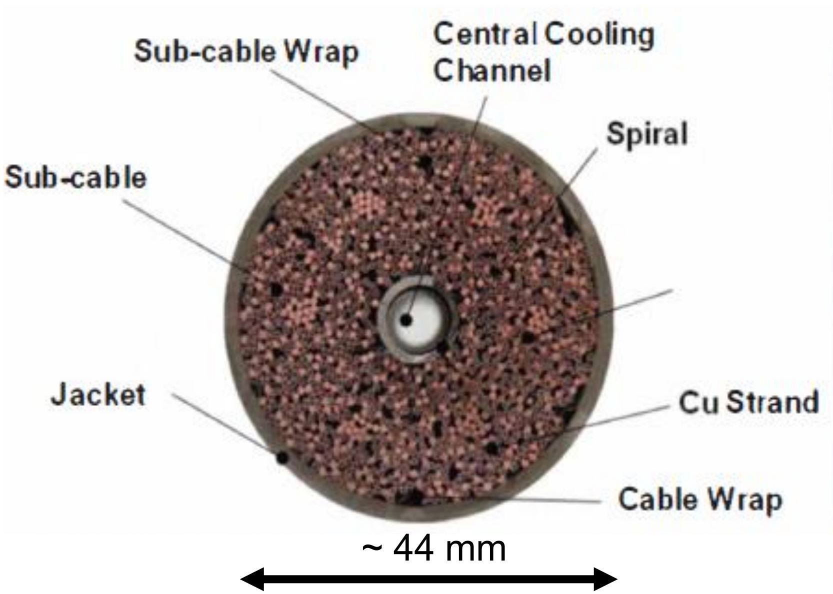
$B_{C2}(0)$ ~ 30 T

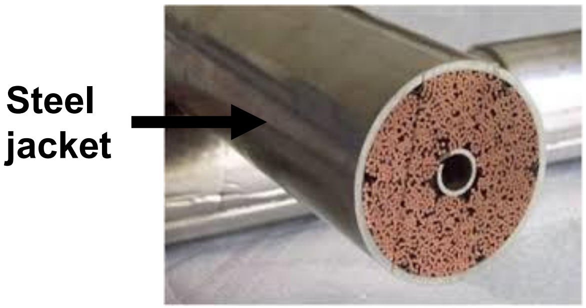
Multifilamentary

Brittle Nb_3Sn Cables for ITER B > 10 T
- See display in corridor outside laboratories

- Operation:
  - High currents (67 kA)
  - High fields (13 T)
  - Forced flow supercritical helium

- Cable-in-conduit construction:
  - Strand: diameter ~ 0.82 mm; 10μm filaments
  - Cable: diameter ~ 44 mm; 900 Cr-plated Nb_3Sn strands; 552 Cr-plated Cu strands.



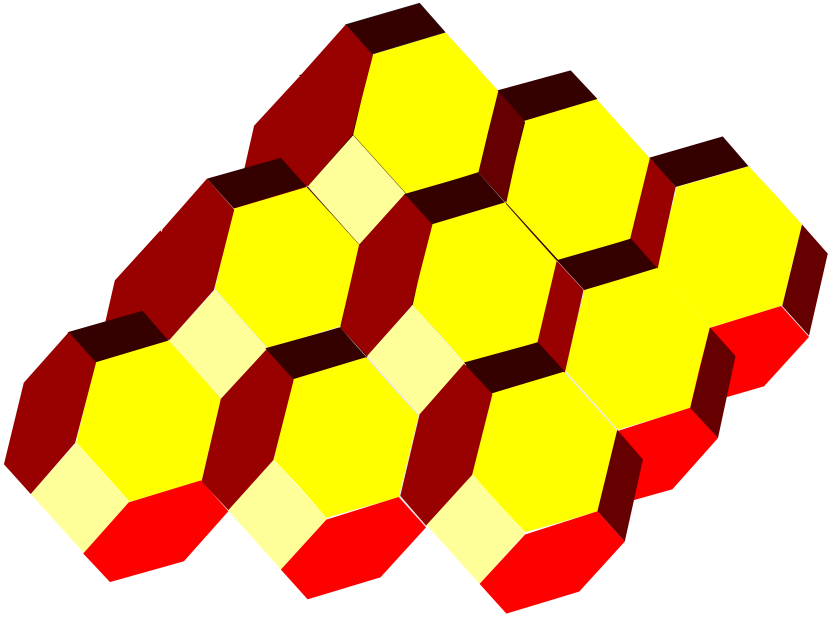


Brittle Nb_3Sn Cables for ITER B > 10 T
- See display in corridor outside laboratories

- C
- C

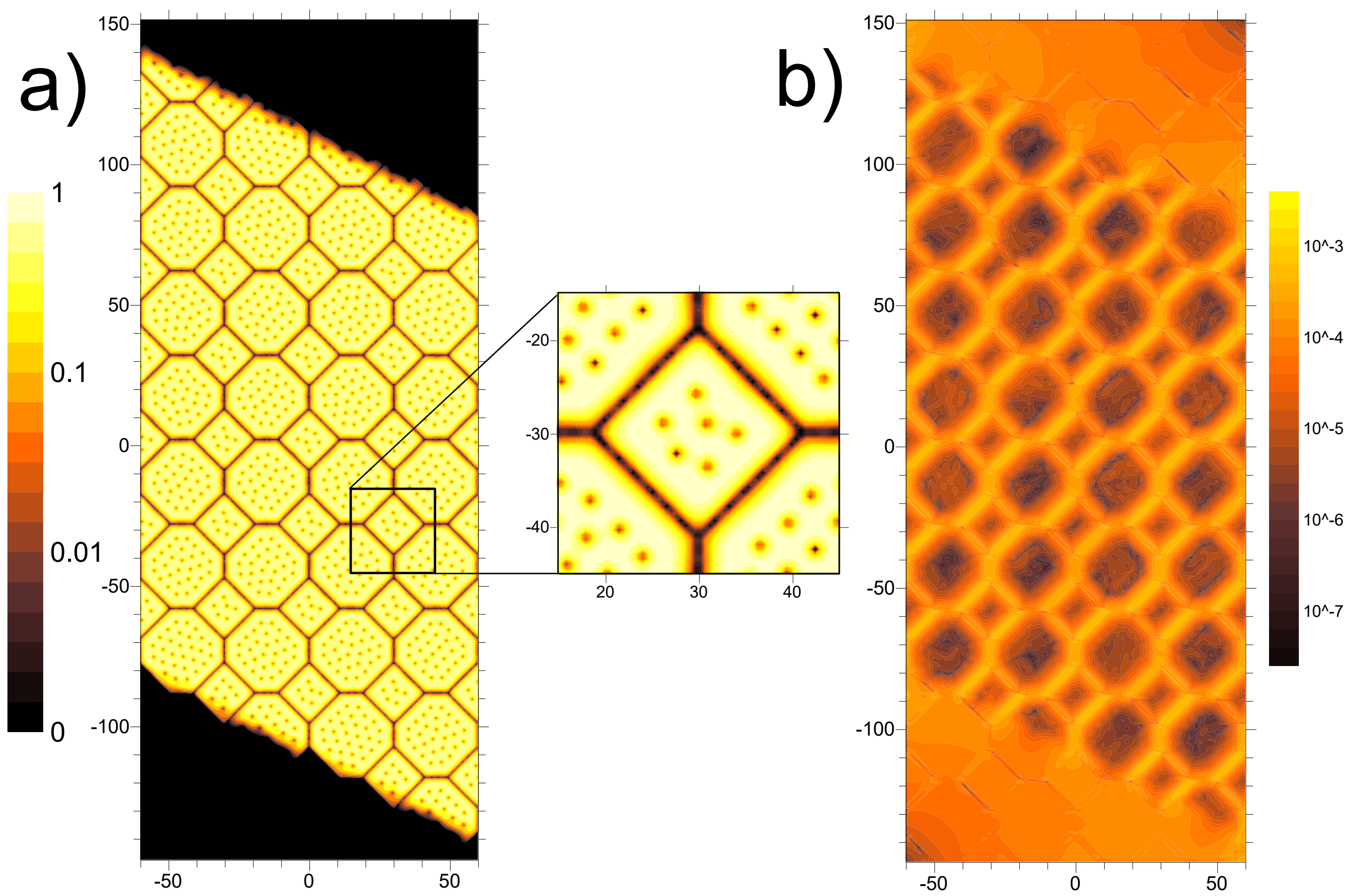
Model for a polycrystalline superconductor

- A collection of truncated octahedra



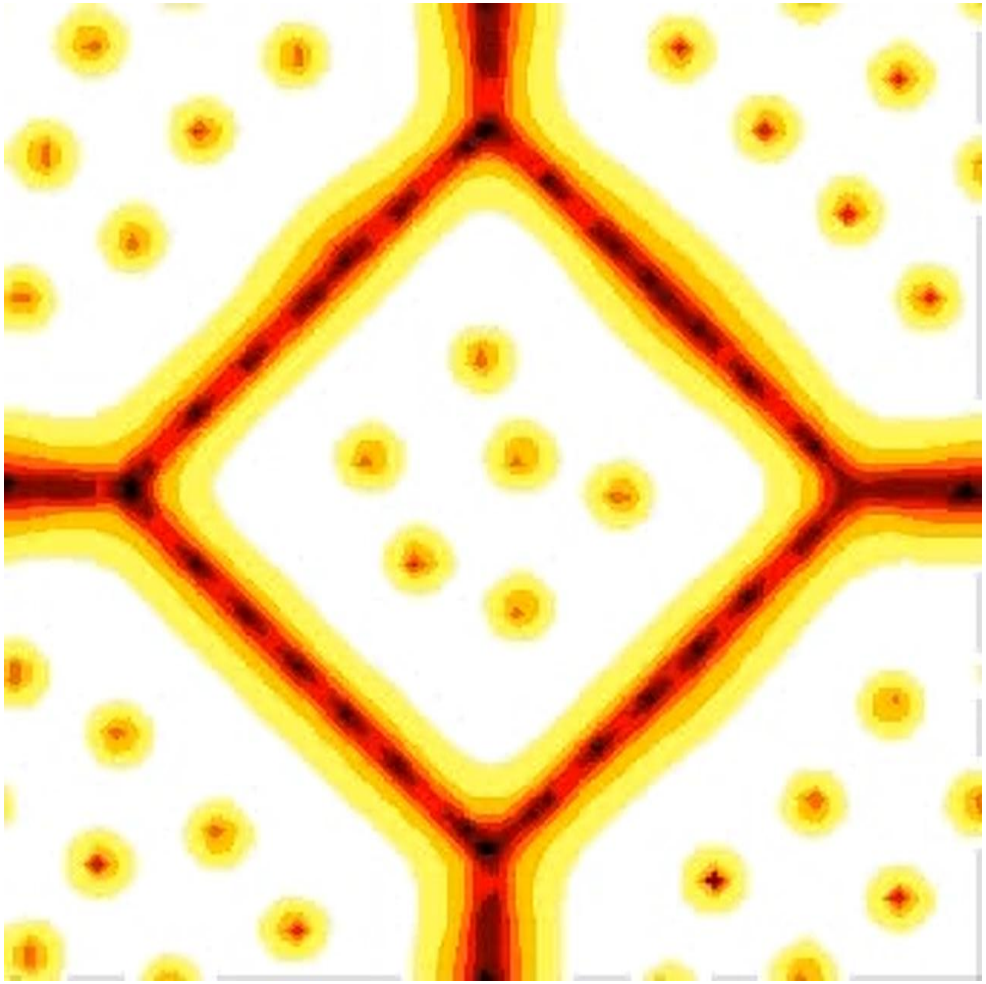
George. J. Carty and D. P. Hampshire – **Visualising the mechanism that determines the critical current density in polycrystalline superconductors using time-dependent Ginzburg-Landau theory – *Phys. Rev. B.* 77 (2008) 172501 also published in Virtual journal of applications of Superconductivity 15th May 2008**

Flux motion in low fields (0.43 H_{C2}) along grain boundaries



(a) Order parameter (b) Normal current

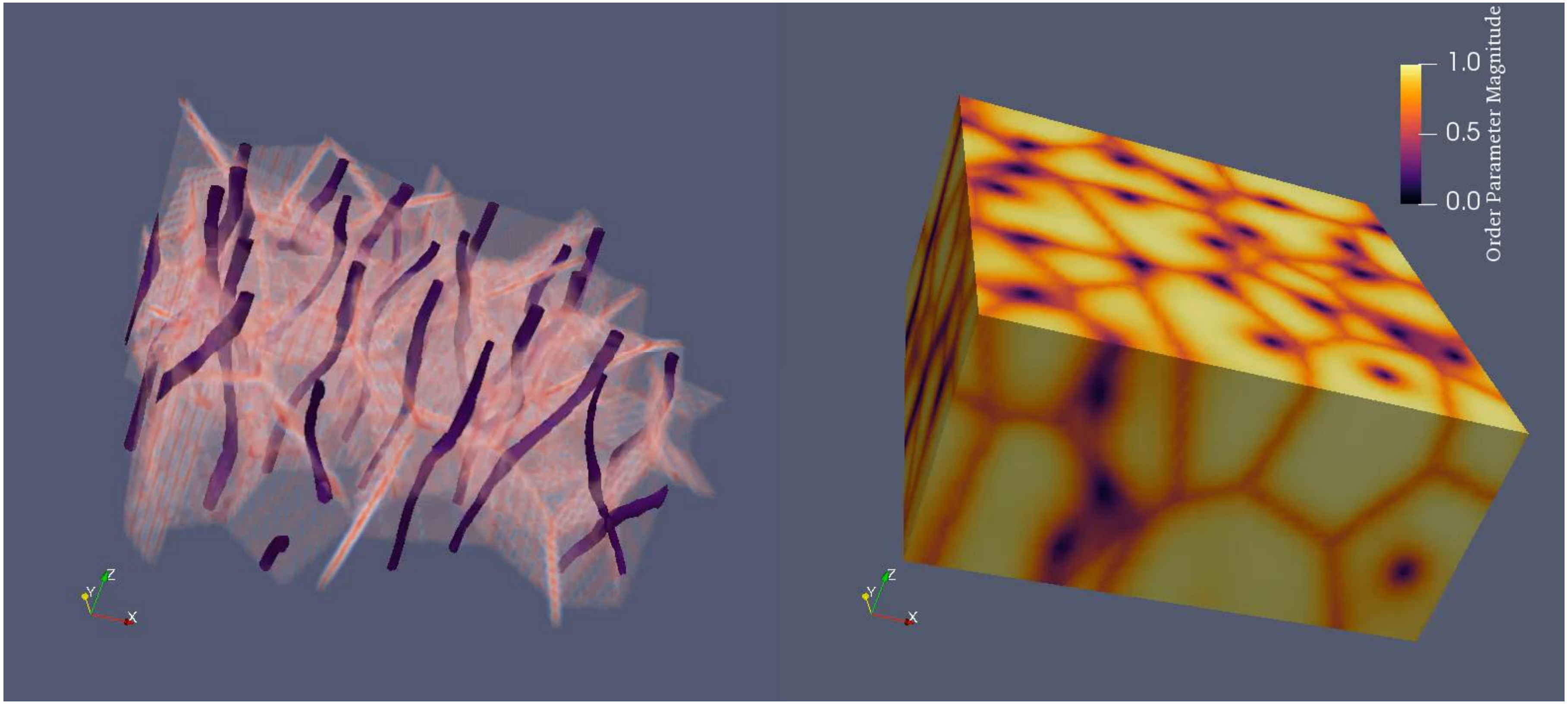
Order Parameter at 0.43 B_{c2}



Q

- Flux flows predominantly along the grain boundaries.
- There are macroscopic current loops and microscopic current loops

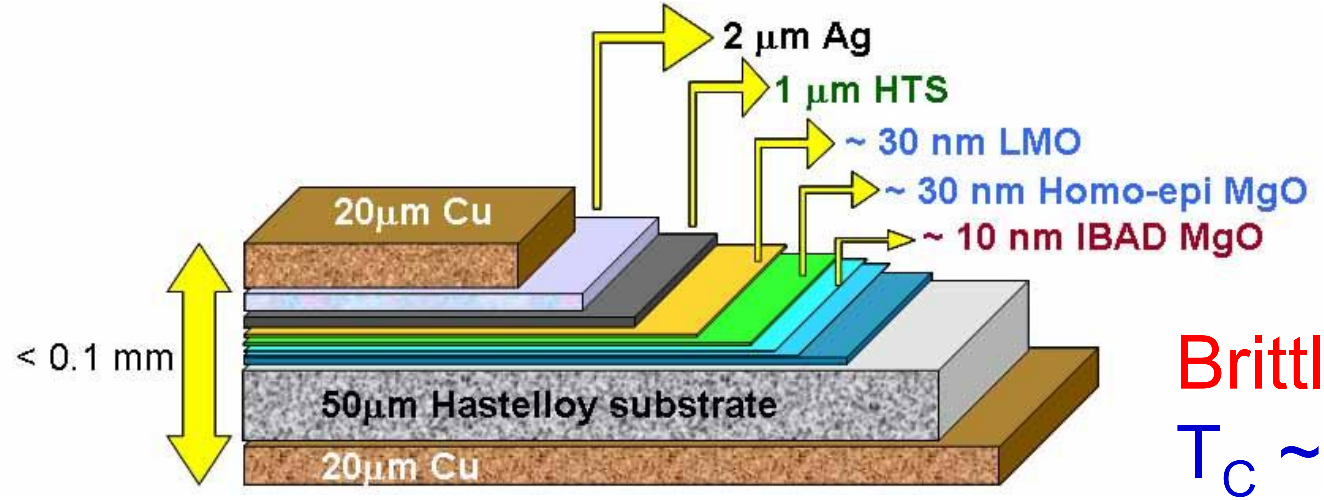
Flux motion in polycrystalline superconductors



The Critical Current Density of SNS Josephson Junctions and Polycrystalline Superconductors in High Magnetic Fields. Alex I. Blair, D. P. Hampshire October 2021. arXiv:2110.02053 [pdf]

HTS (REBCO) coated conductors
- Kilometre long single crystals

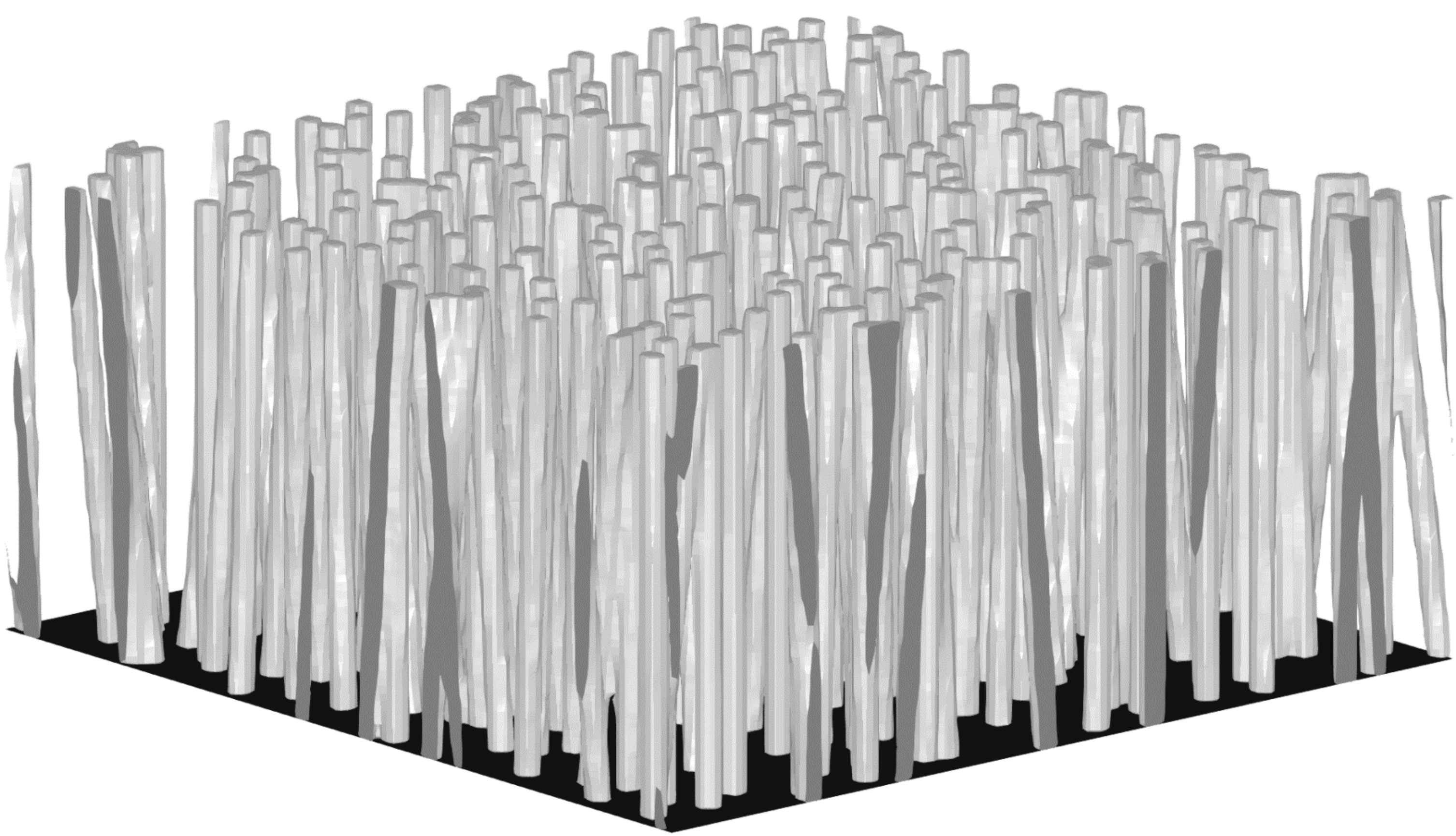
REBCO (RE:Rare-Earth) – eg $GdBa_2Cu_3O_7$



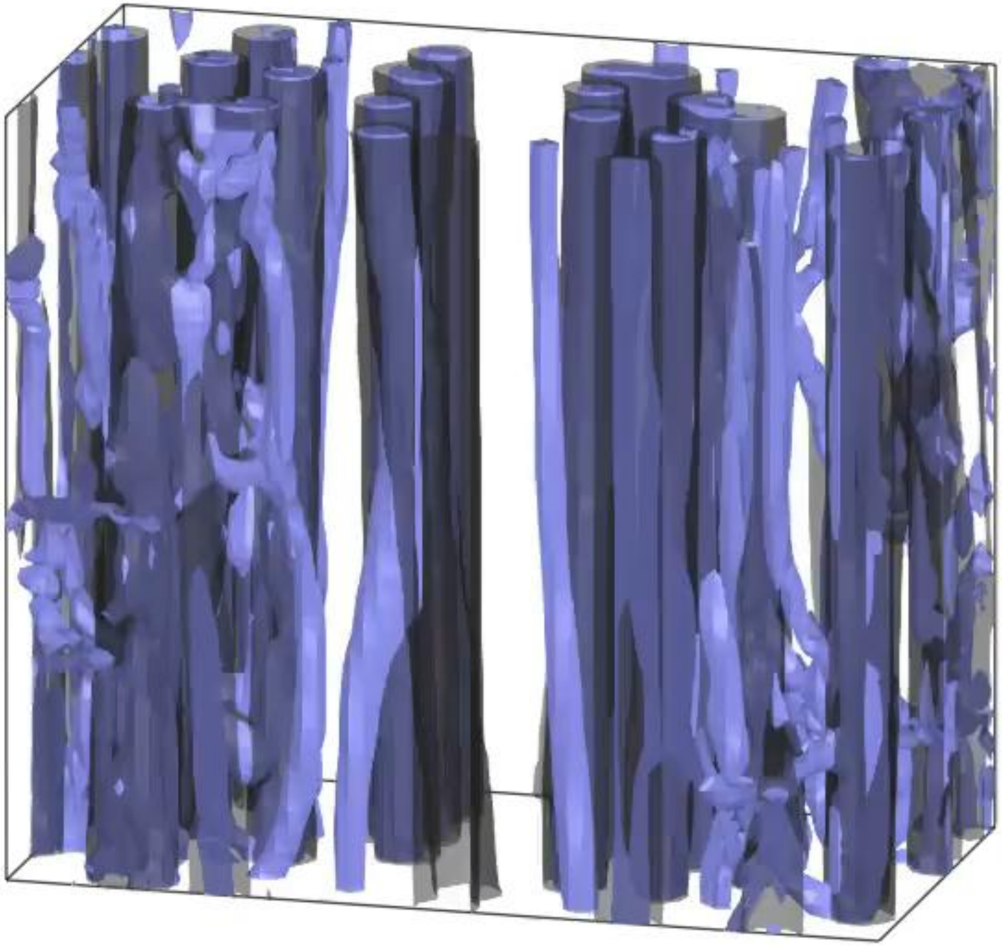
Configuration of SuperPower 2G HTS Wire™

Brittle oxide - NbTi
T_C ~ 90 K
$B_{C2}(0)$ ~ 50 T
Tape

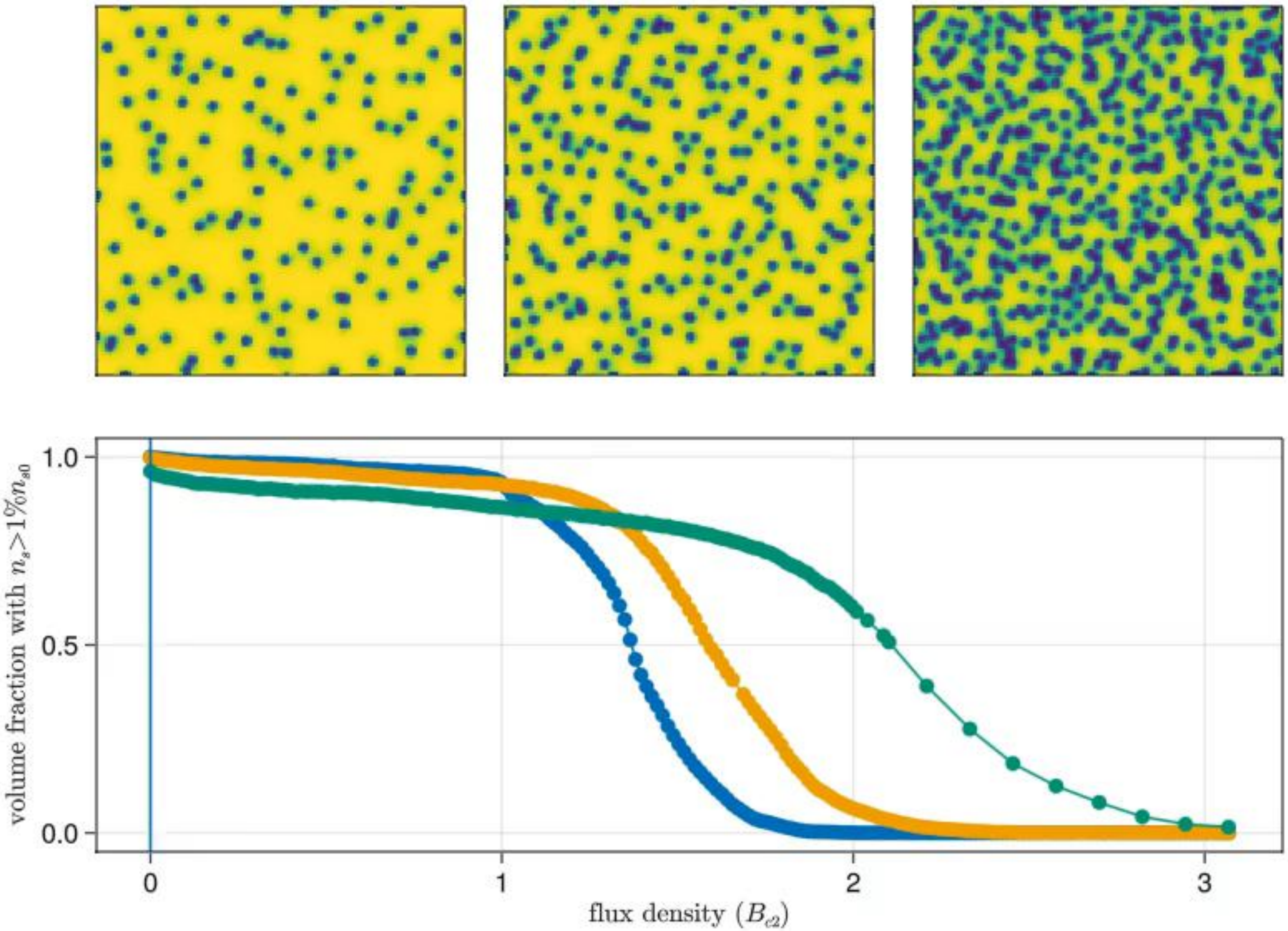
HTS (YBCO) with insulating pins



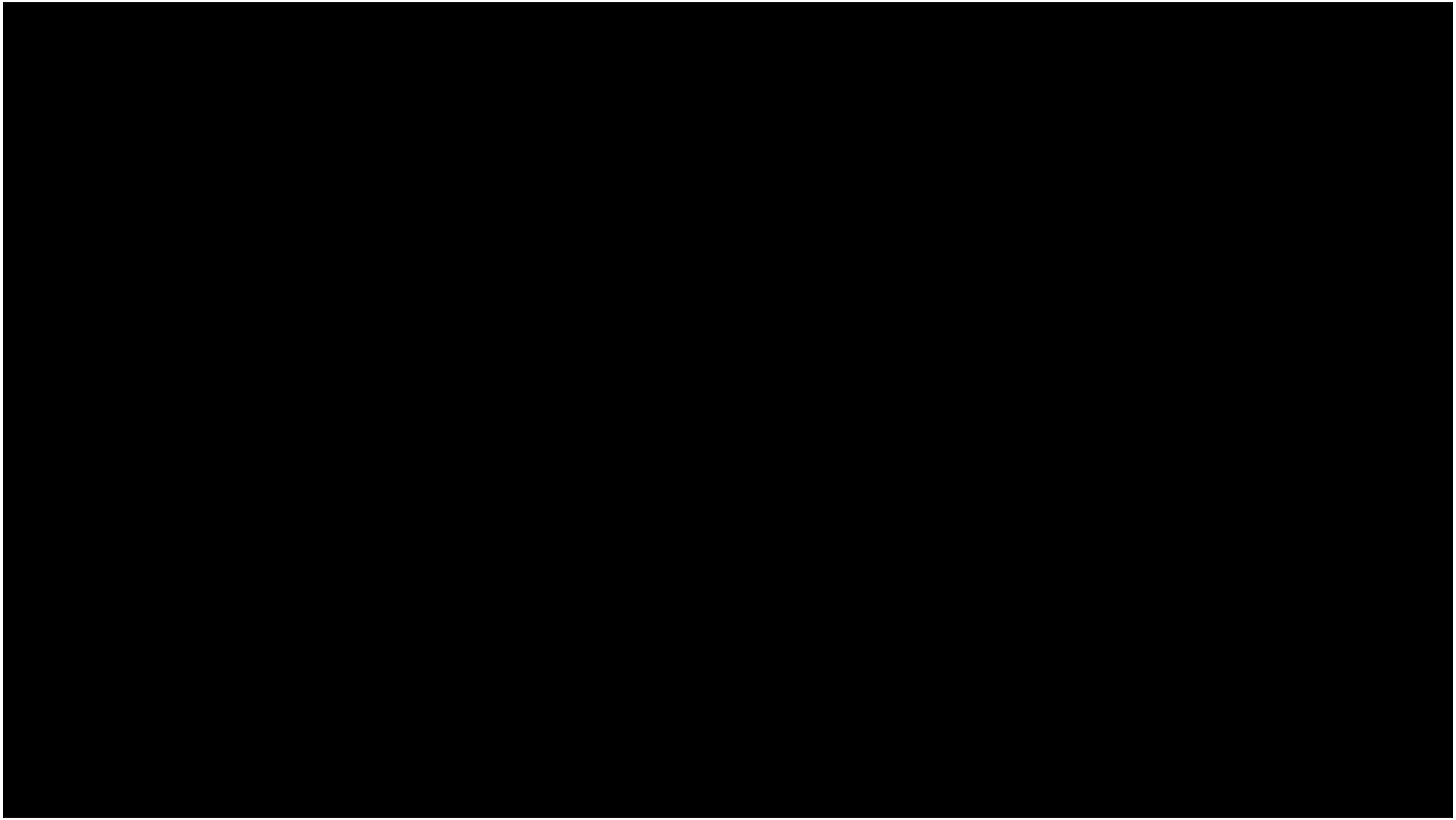
HTS materials with insulating pins



HTS materials – percolation



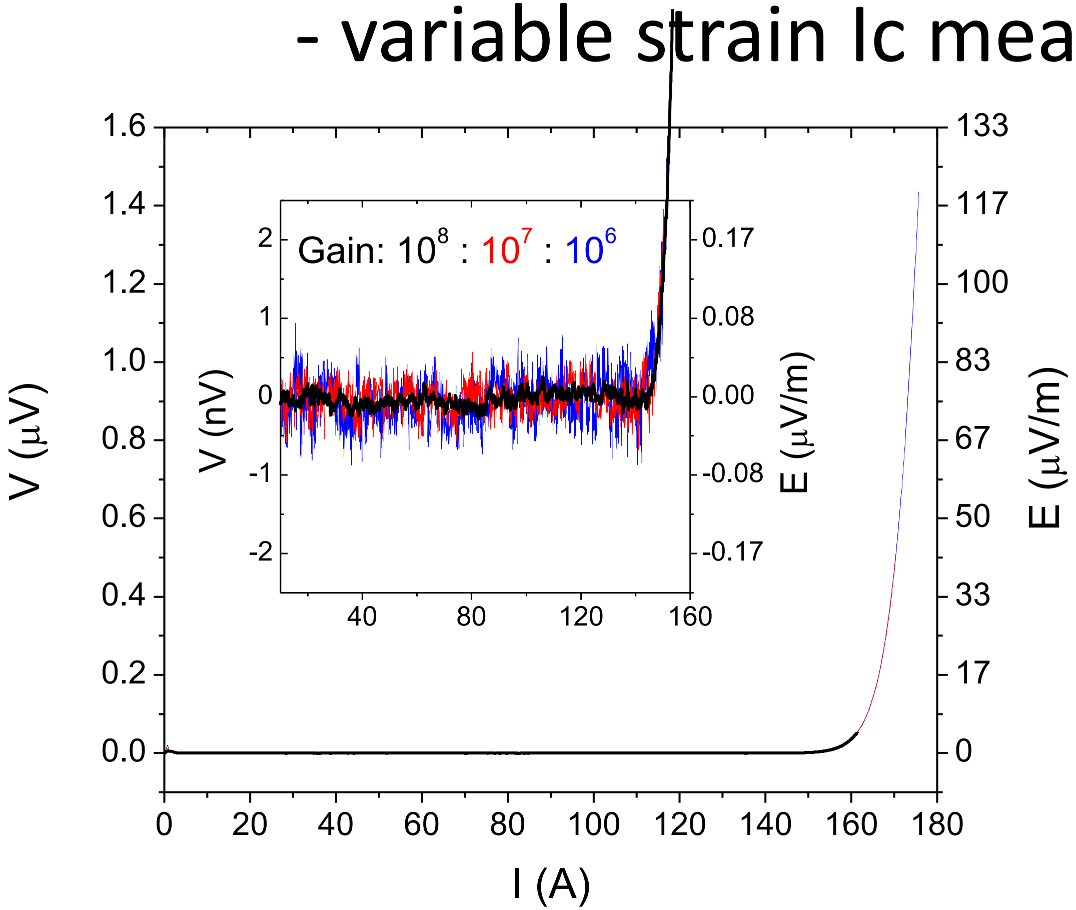
Flux pinning by point pins produced by radiation

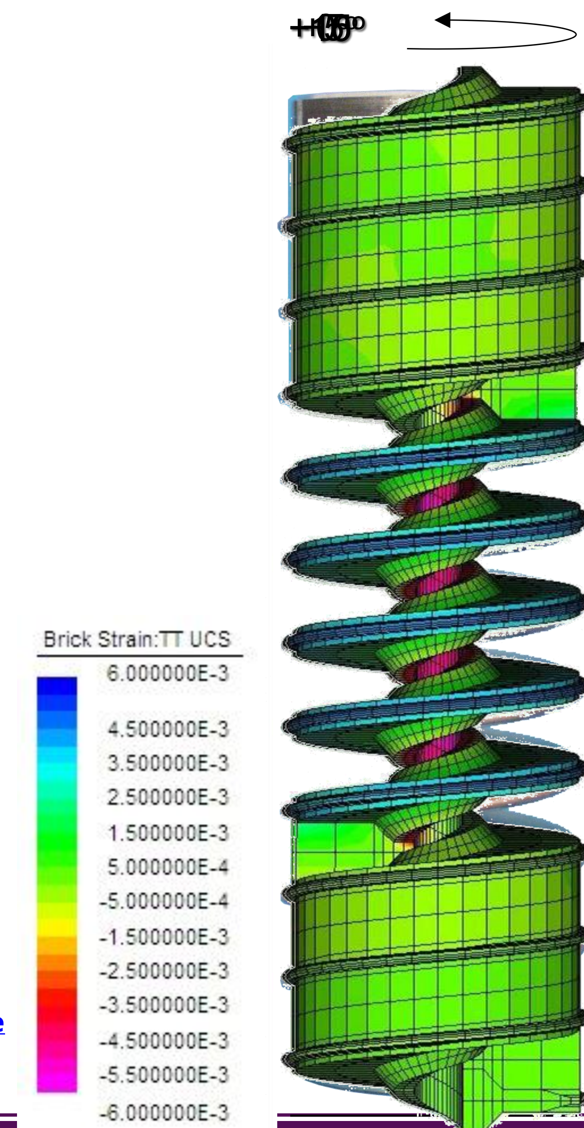


"Strong pinning regimes by spherical inclusions in anisotropic type-II superconductors" by R. Willa, A. E. Koshelev, I. A. Sadovskyy, and A. Glatz, Supercond. Sci. Technol. 31, 014001 (2018)

Advanced measurements on superconductors

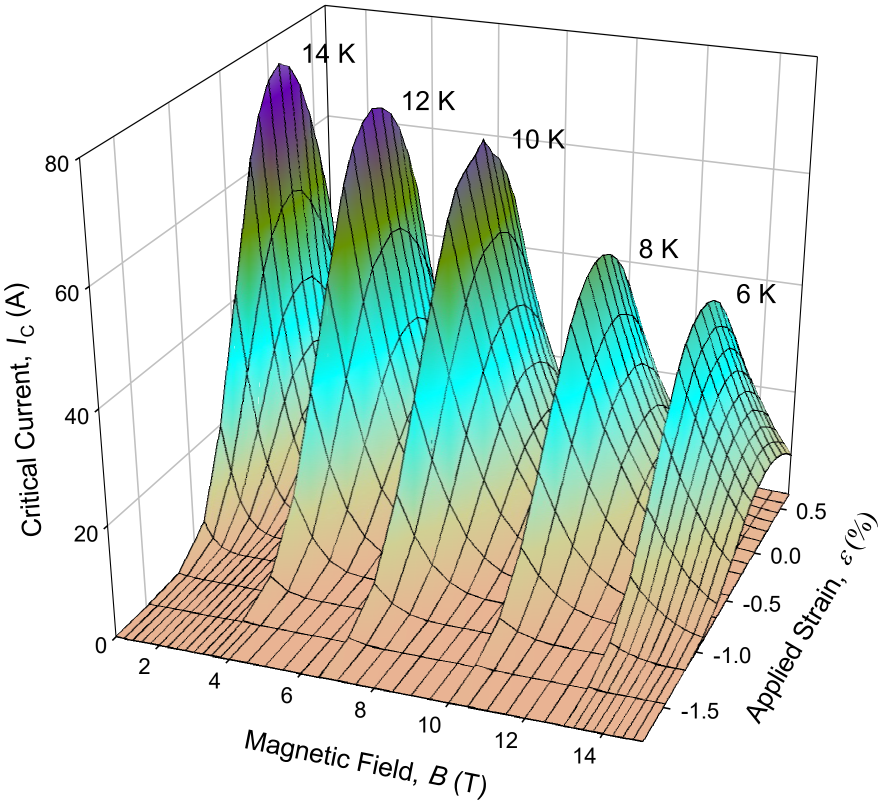
- variable strain Ic measurements

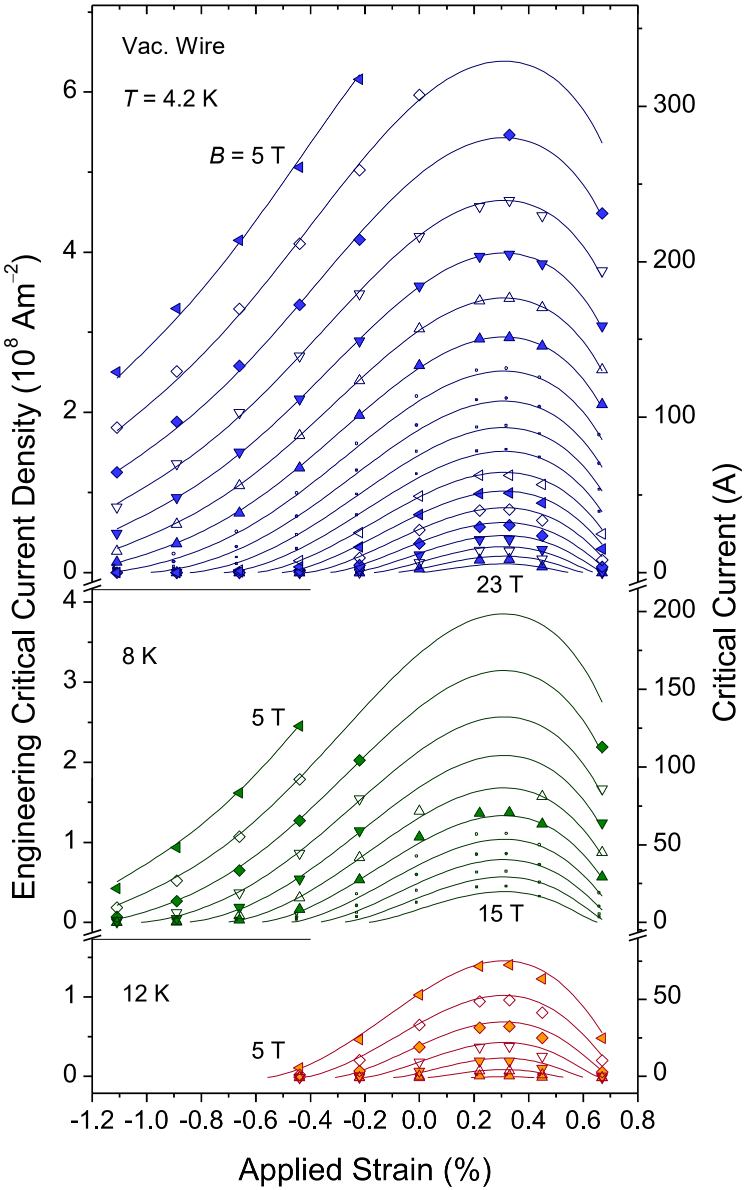




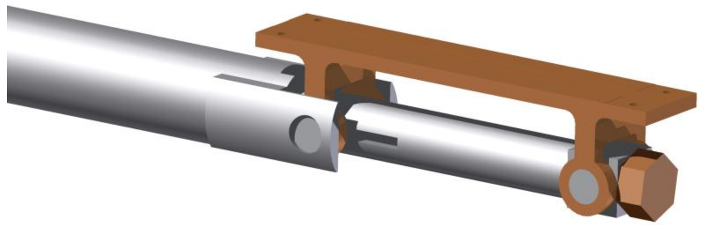
David M. J. Taylor and D. P. Hampshire – **Properties of helical springs used to measure the axial strain dependence of the critical current density in superconducting wires – *Supercond. Sci. Tech.* 18 (2005) 356-368**

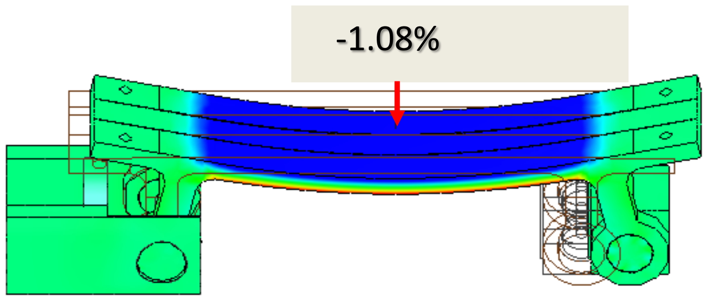
$J_C(B,T,\varepsilon)$ - Nb_3Sn

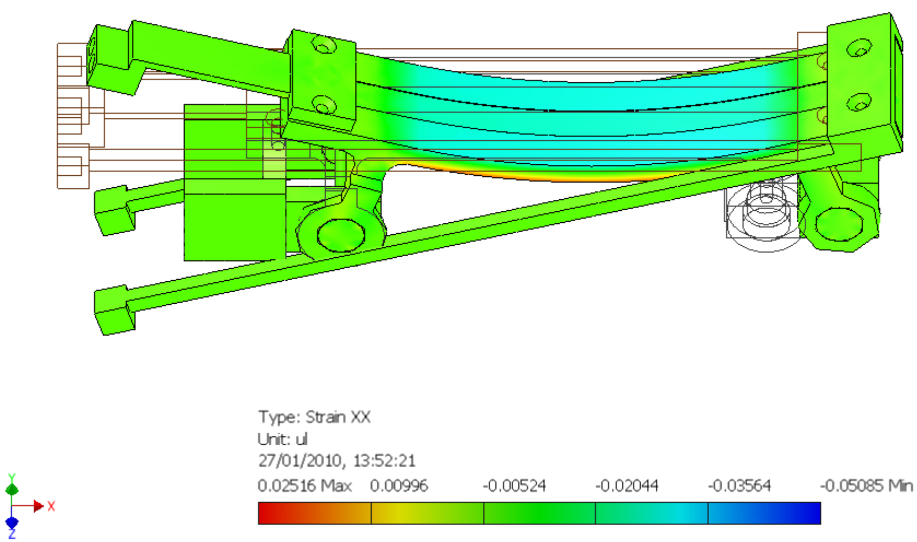


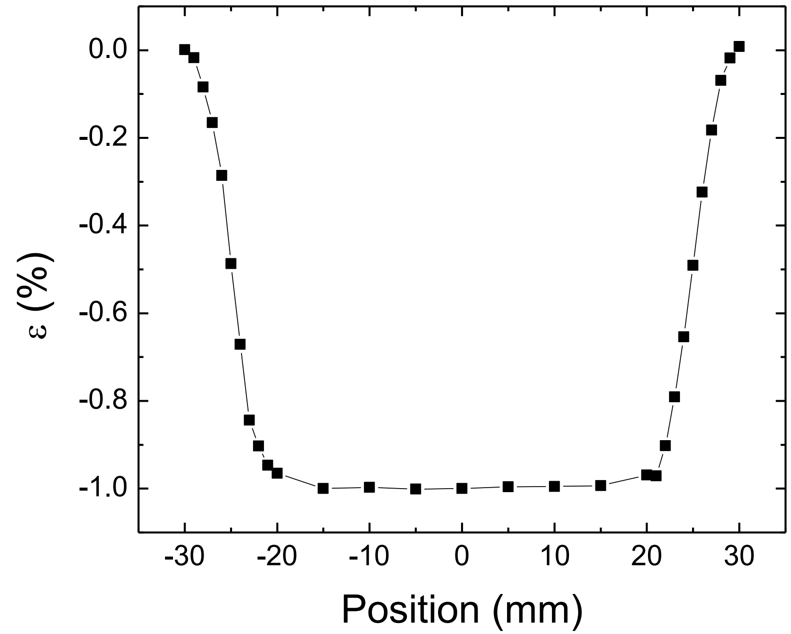


Variable strain measurements in HTS superconductors





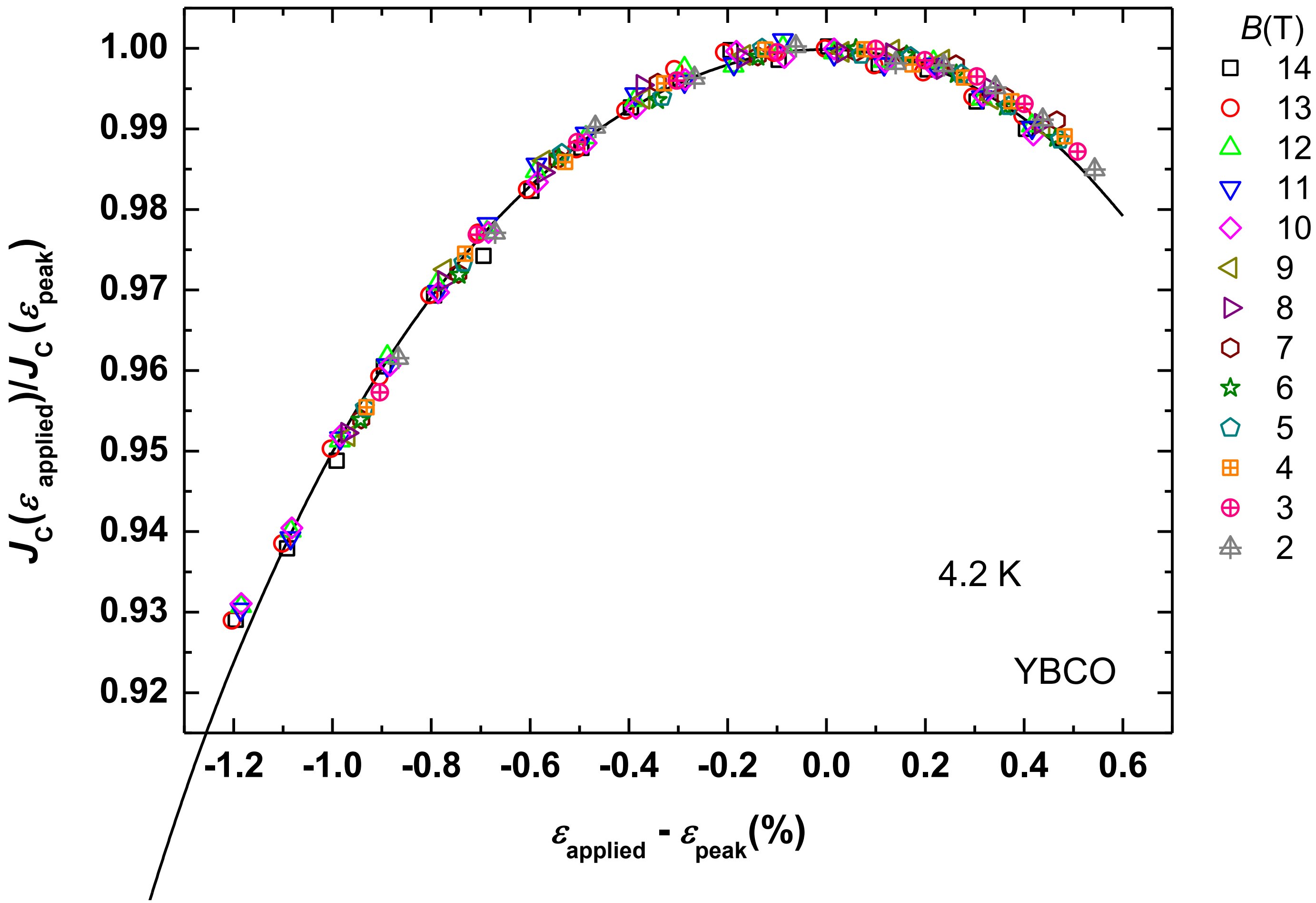




homogeneous strain along length
to 7 parts in 1000

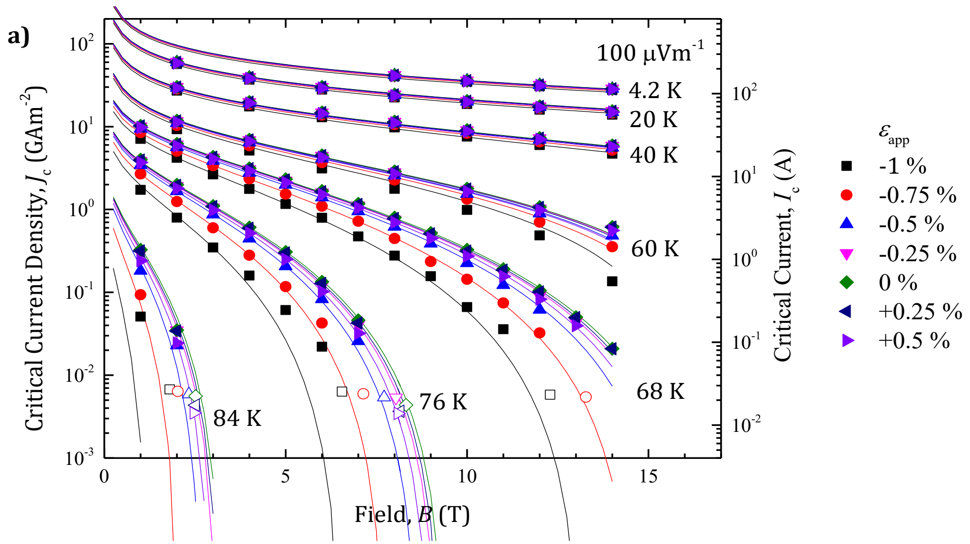
Bending apparatus tested from -1.4% to +0.5%

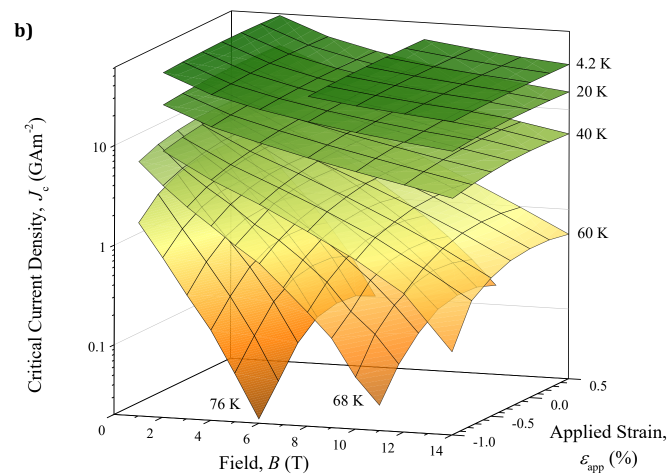
Strain Behaviour of J_c in $Y_1Ba_2Cu_3O_7$ at 4.2 K



Prapaiwan (Bew) Sunwong *et al* 2013 *Supercond. Sci. Technol.* **26** 095006

Strain Behaviour of J_c in $Y_1Ba_2Cu_3O_7$

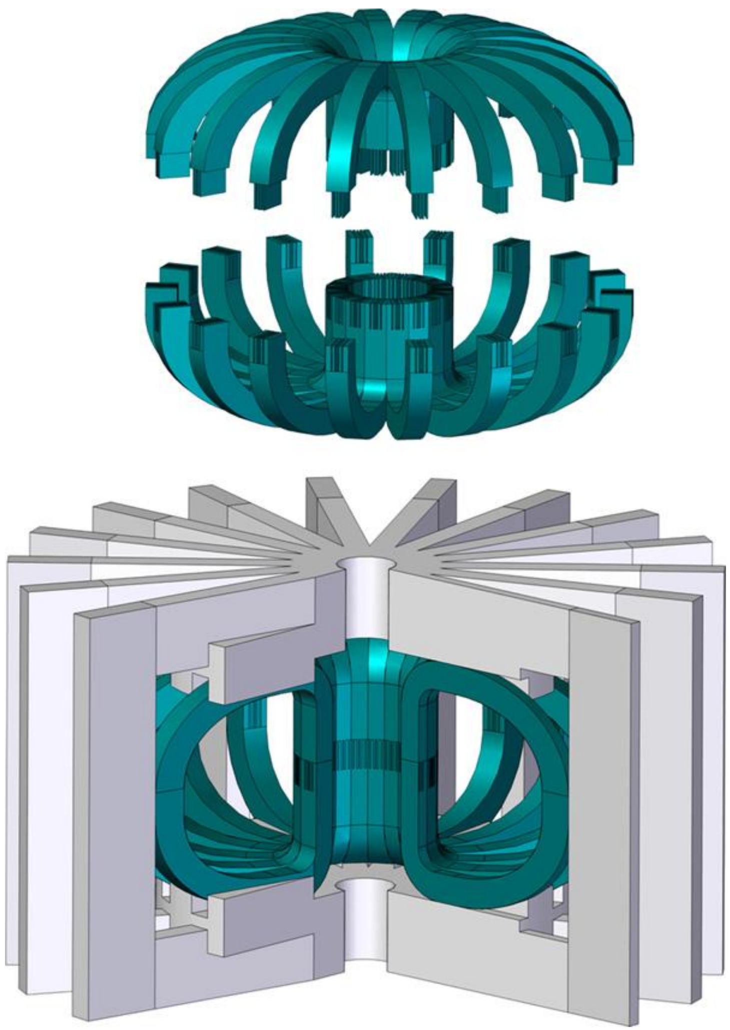


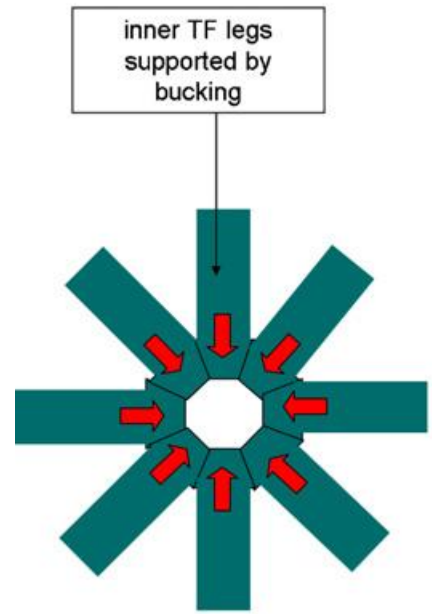


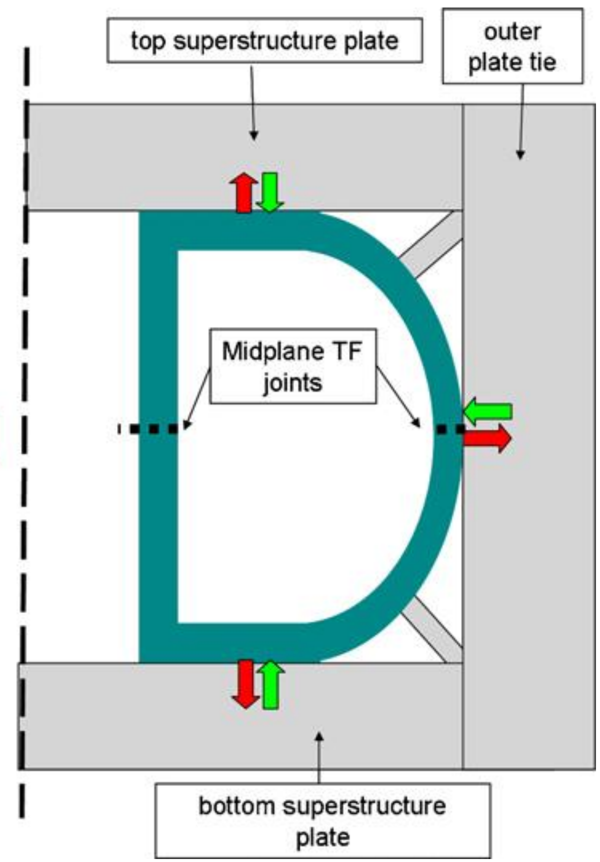
$Jc(B,T,\varepsilon_{app})$ for REBCO tape at the 100 μVm-1 E-field criterion

P.O. Branch, Y. Tsui, K. Osamura and D. P. Hampshire. **Weakly-Emergent Strain-Dependent Properties of High Field Superconductors. Nature Scientific Reports 9:13998 (2019).**

Joints in Superconductors





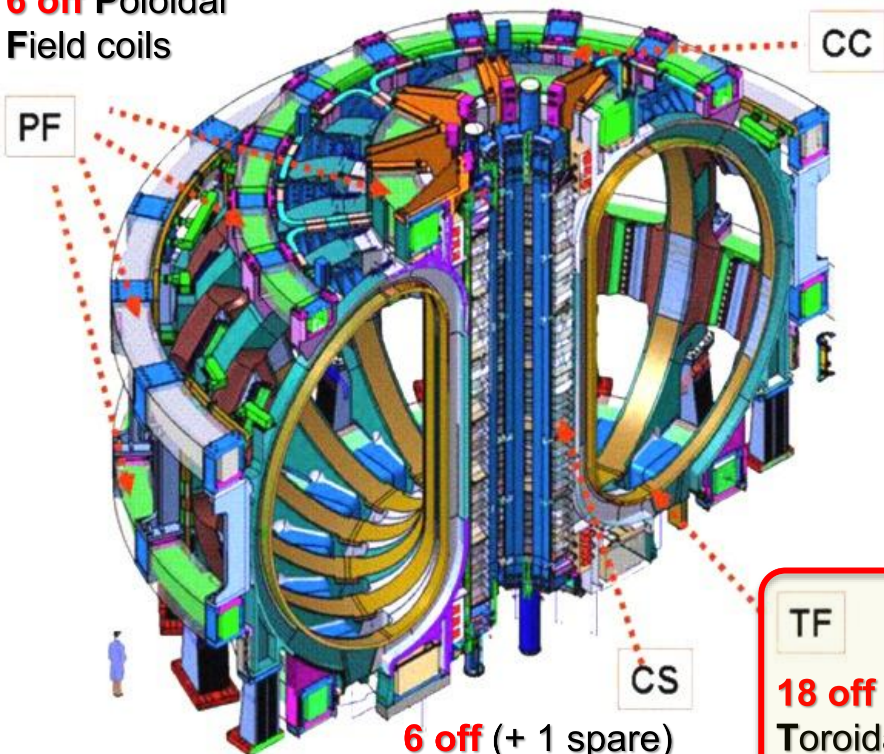


Z.S. Hartwig *et al.*, 2012 (Plasma Science and Fusion Centre, MIT).

The Icy Durham practical course lectures

18 off (9 pairs of **C**orrection **C**oils)

6 off Poloidal **F**ield coils



6 off (+ 1 spare) **C**entral **S**olenoid coil

18 off (+ 1 spare) **T**oroidal **F**ield coi

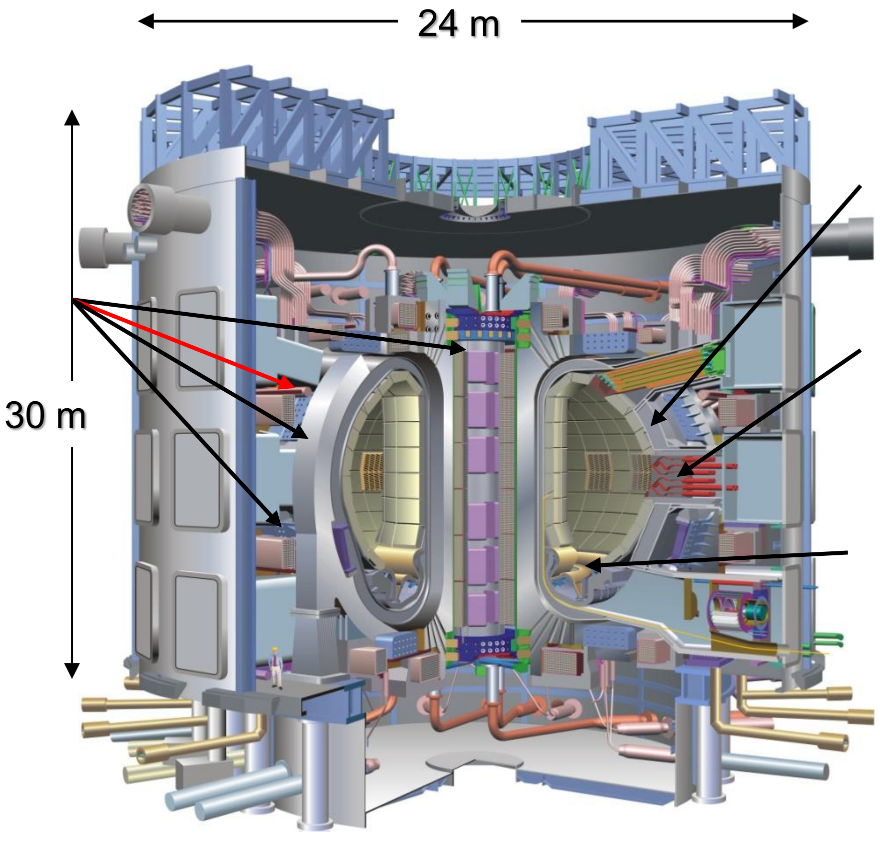
Nb_3Sn : T_c= 18 K, $B_{c2}(0)$ = 30 T :
18 toroidal field Nb_3Sn coils - 1100 wires, ~ 0.81 mm diameter, 820 m long in a 44mm tube (290 tonnes each). The central solenoid (840 tonnes).

Nb-Ti : T_c= 9 K, $B_{c2}(0)$ = 14 T :
Nb-Ti: 6 poloidal field coils.
The Nb-Ti correction coils.

- TF @ 6.2 m = 5.3 T
- Plasma Current = 15 MA
- Plasma volume = 837 m^3
- Fusion power = 500 MW
- Electricity input 20 MW!
- Inductive burn time ~ 500 s

[1] C. Sborchia, *et. al.*, "Overview of ITER Magnet System and European Contribution," presented at the 2011 IEEE 24th Symposium on Fusion Engineering (SOFE), 2011, pp. 1–8.

The Icy Durham practical course lectures



The ITER tokamak.

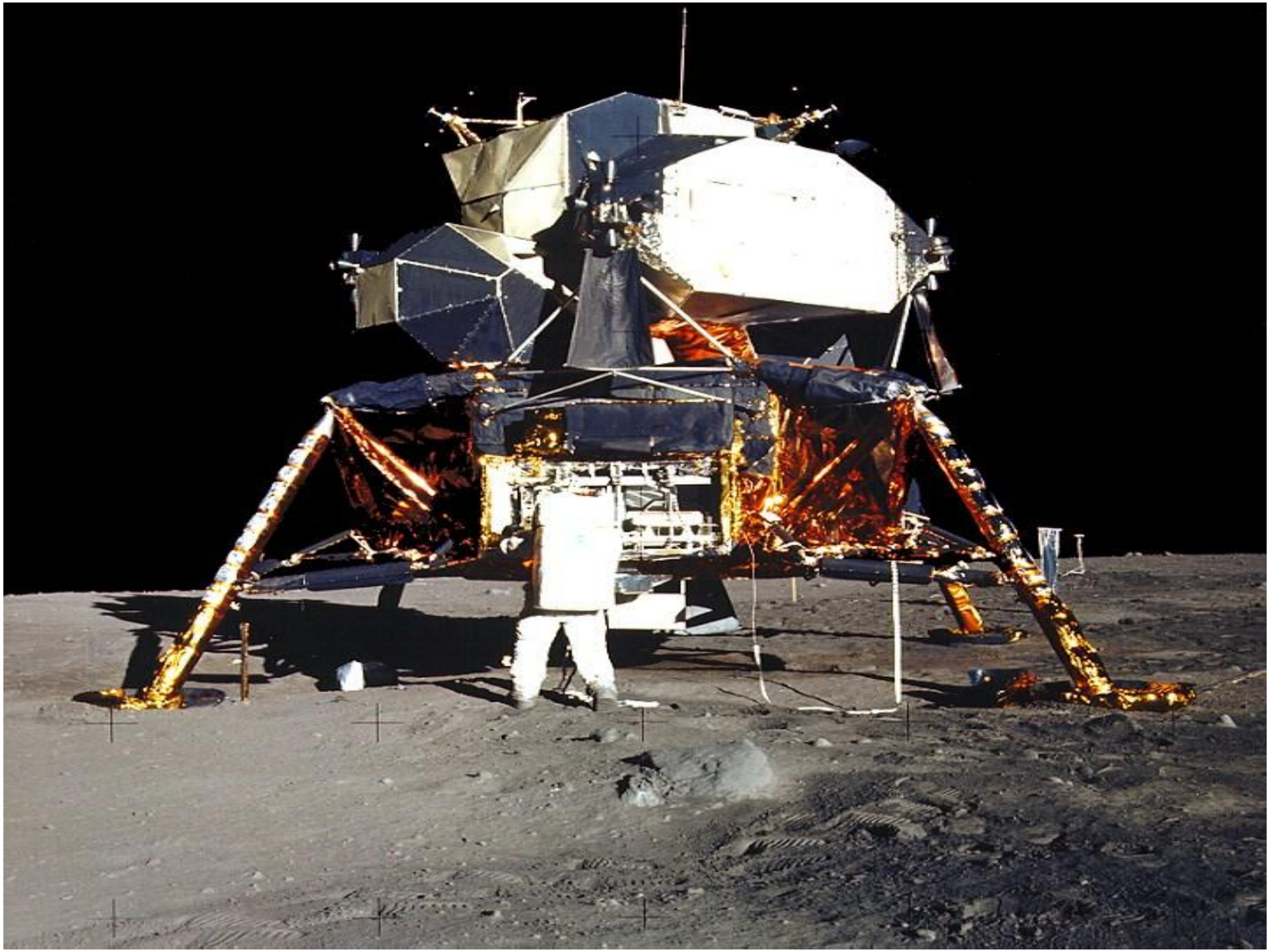
~~**Lecture 1: Superconductors for fusion magnets.**~~

Lecture 2: Cryogenics

Lecture 3 : Computational magnet design and quench control.

Lecture 4 : Cables and fusion magnets.

[1] C. Sborchia, *et. al.*, "Overview of ITER Magnet System and European Contribution," presented at the 2011 IEEE 24th Symposium on Fusion Engineering (SOFE), 2011, pp. 1–8.



Questions to discuss after the end of the 'Superconductors for Fusion Magnets' Lecture

i) What are the materials components of HTS ReBCO tapes and Nb_3Sn superconducting wires?

ii) What is the highest magnetic field inside the ITER, STEP, SPARC and ARC tokamaks?

iii) What is the approximate energy stored in the magnets in the ITER fusion tokamak ?

iv) Name the superconductors that are used to build (any) commercial magnets – state their critical temperature and upper critical field (at zero temperature).

v) Name the superconductors (to be) used in ITER, STEP, SPARC and ARC.

vi) What is the typical current density in a magnet? How can we make it larger? What impact would it have if we increased current density in superconductors by a factor 5.

vii) Either : If a room temperature superconductor was discovered would it affect your thesis research/ the magnetic confinement system for STEP and SPARC/ARC ?
or: List the important properties of the current superconductors used to build fusion magnets.
Rank a five-fold improvement in the important state-of-the-art properties of a superconductor for fusion applications.

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