Critical current density in HTS for fusion: TDGL, Experiments, and Irradiation.

Centre for Materials Physics

Durham University

www.durham.ac.uk/cmp

Prof. Damian P. Hampshire, P. Branch, B. Din, J. Greenwood, C. Haddon, and M. J. Raine.

Talk Outline

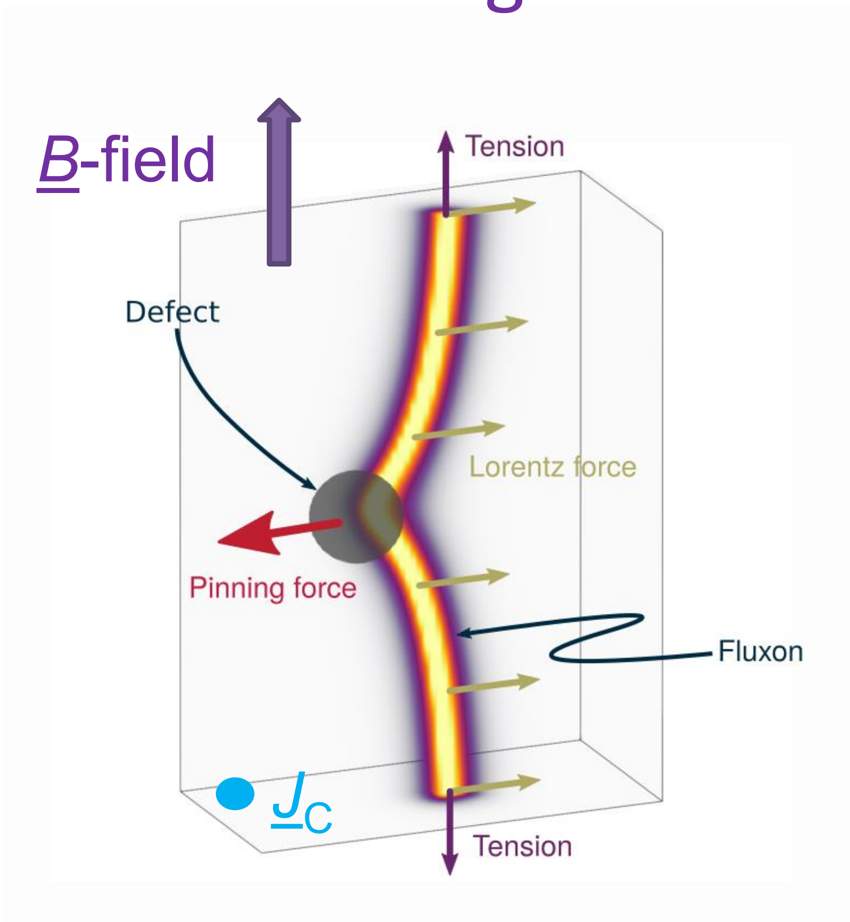
1. Time-dependent Ginzburg-Landau Theory - Flux pinning visualisation.

2. Critical current experiments on HTS

3. Irradiation

4. Concluding comments.

Flux Pinning (Parametrisation)
- Magnitude of the order parameter



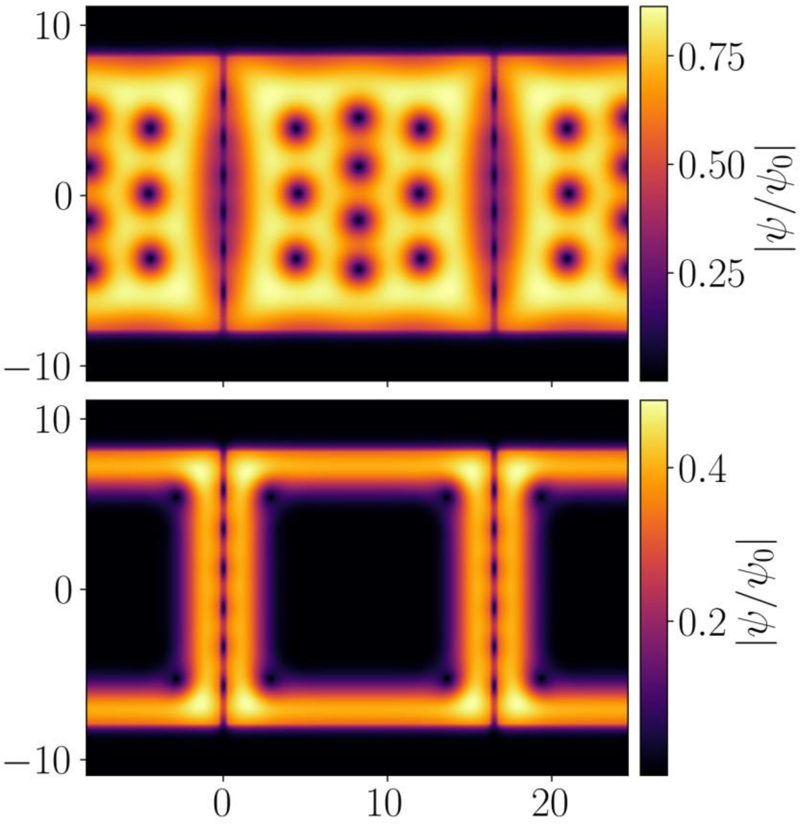
$\underline{F}_V = - \underline{J}_C \times \underline{B}$

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

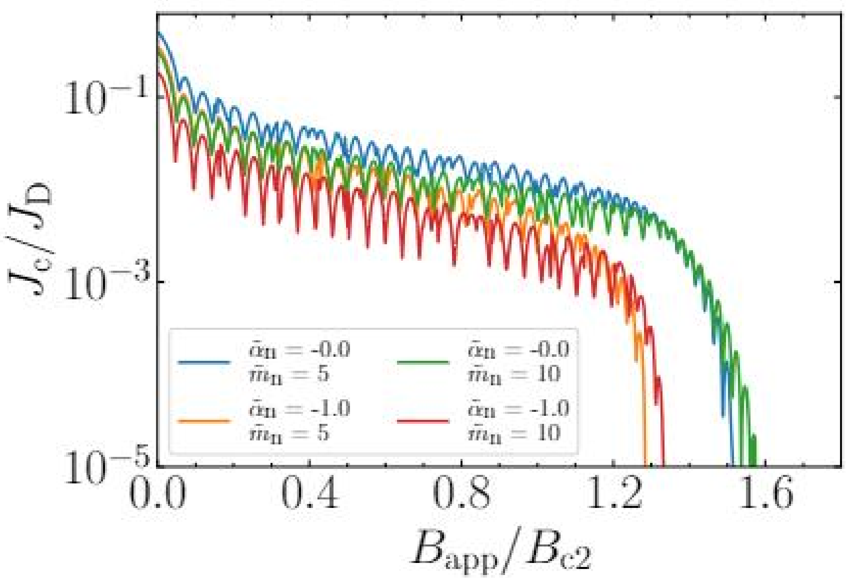
Flux pinning curve scales well with field, temperature and strain

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

Josephson junctions
- Phase of the order parameter.



The normalized order parameter magnitude at B = 0.5 Bc2 (top) and B = 1.1 Bc2 (bottom) for two SNS junctions.



Critical current density as a function of applied magnetic field for an SNS junction with a range of different junction properties.

Ginzburg-Landau theory

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

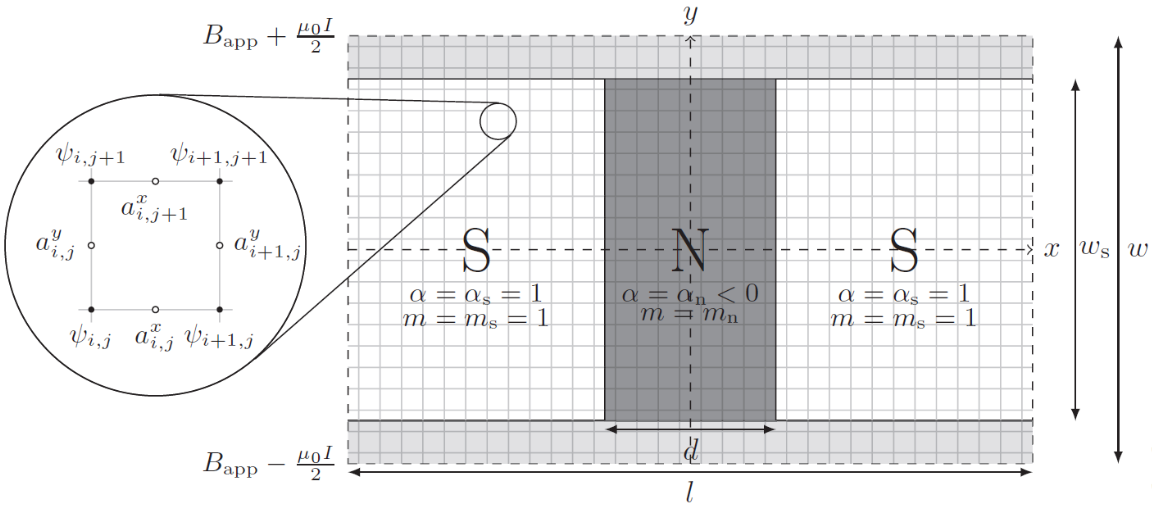
$$f = \alpha|\psi|^2 + \frac{1}{2}\beta|\psi|^4 + \frac{1}{2m}|(-i\hbar\nabla - 2e\boldsymbol{A})\psi|^2 + \int \boldsymbol{H}\,\mathrm{d}\boldsymbol{B}$$

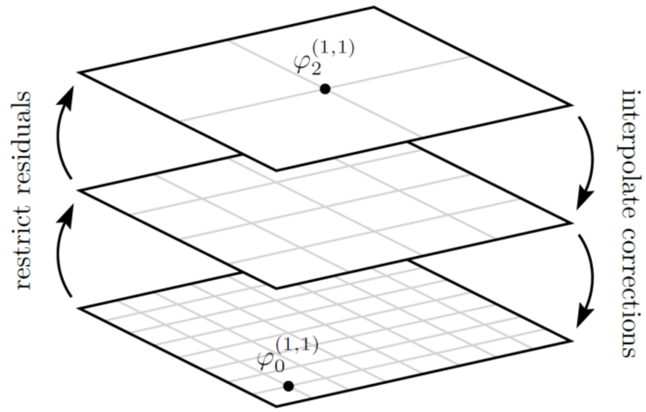
Condensation energy

Kinetic energy

Magnetic field energy

Multigrid speed-up for computational TDGL

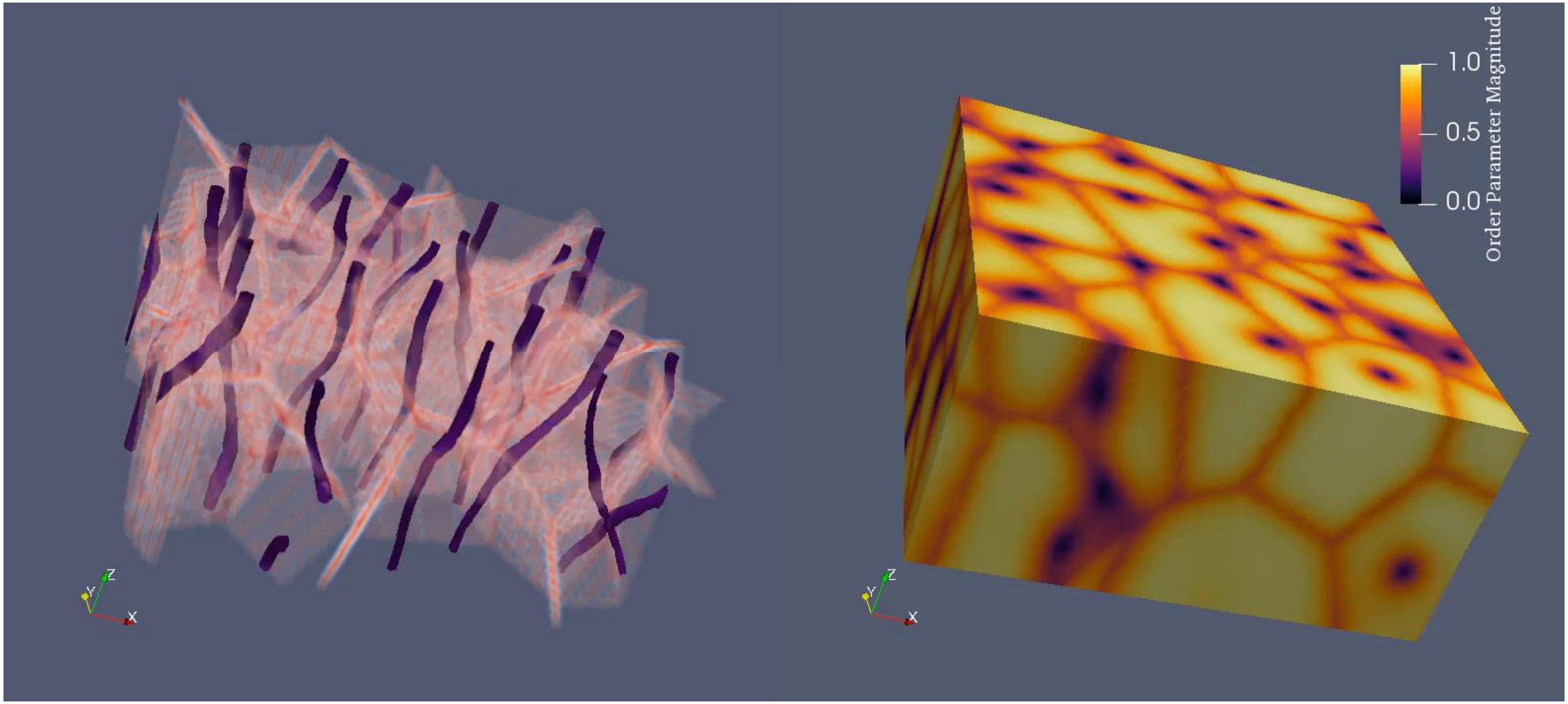




Schematic of the 2D computational domain of width *w* and periodic length *l* used to model the junction system.

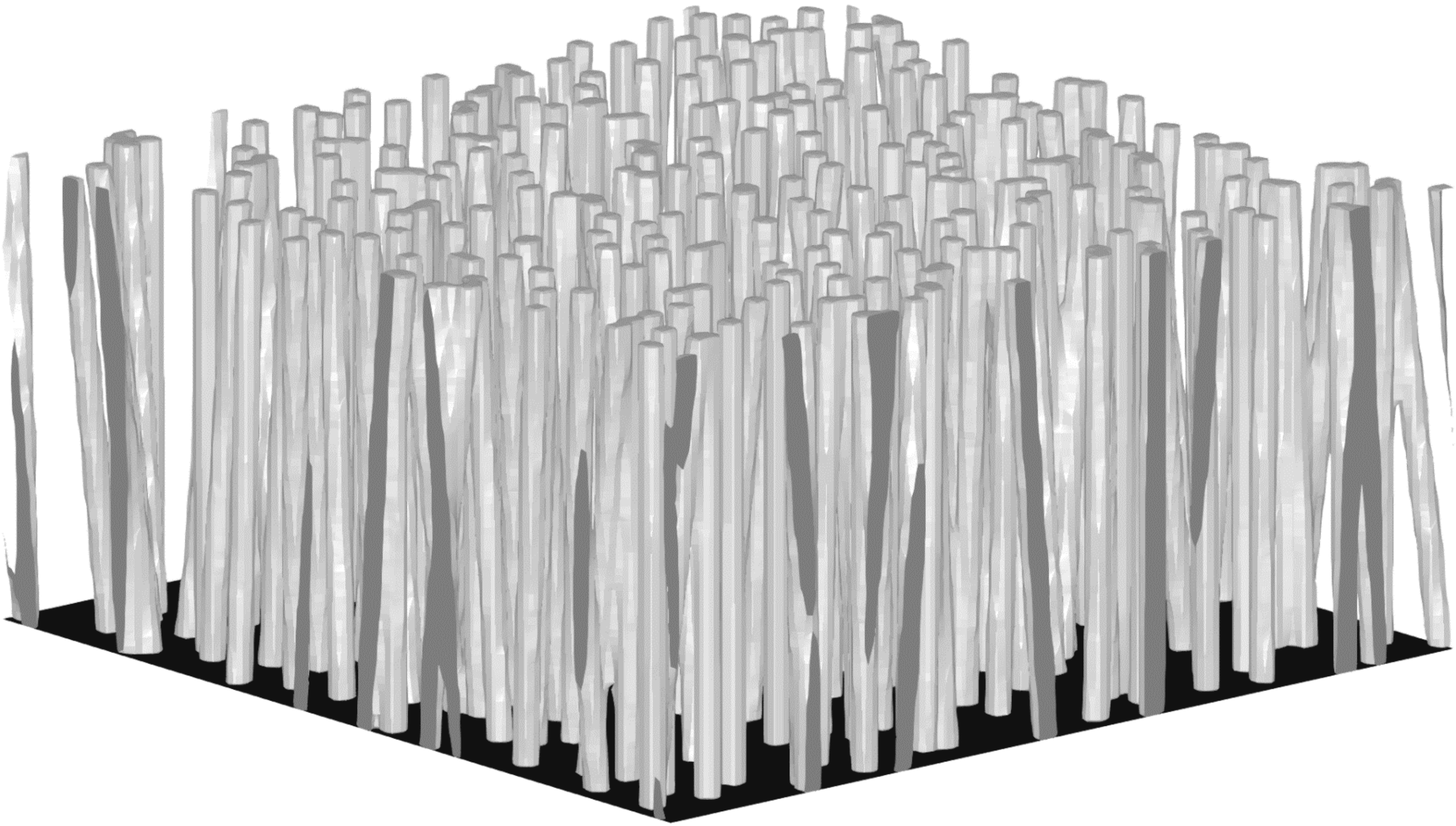
A. I. Blair and D. P. Hampshire **Critical current density of superconducting-normal-superconducting Josephson junctions and polycrystalline superconductors in high magnetic fields**, Phys. Rev. Research **4**, 023123, 16 May 2022

Flux motion in polycrystalline superconductors – Nb_3Sn



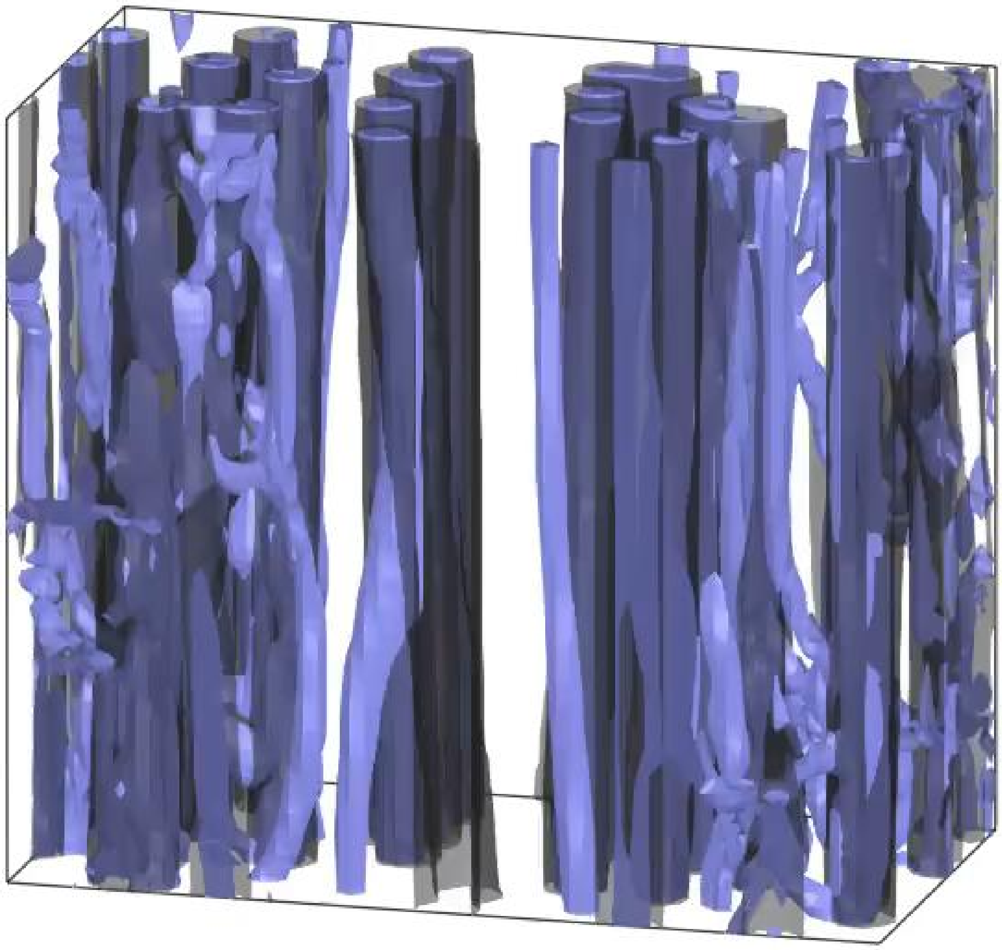
The Critical Current Density of SNS Josephson Junctions and Polycrystalline Superconductors in High Magnetic Fields. Alex I. Blair, D. P. Hampshire October 2021. arXiv:2110.02053 [pdf]

HTS materials with insulating pins

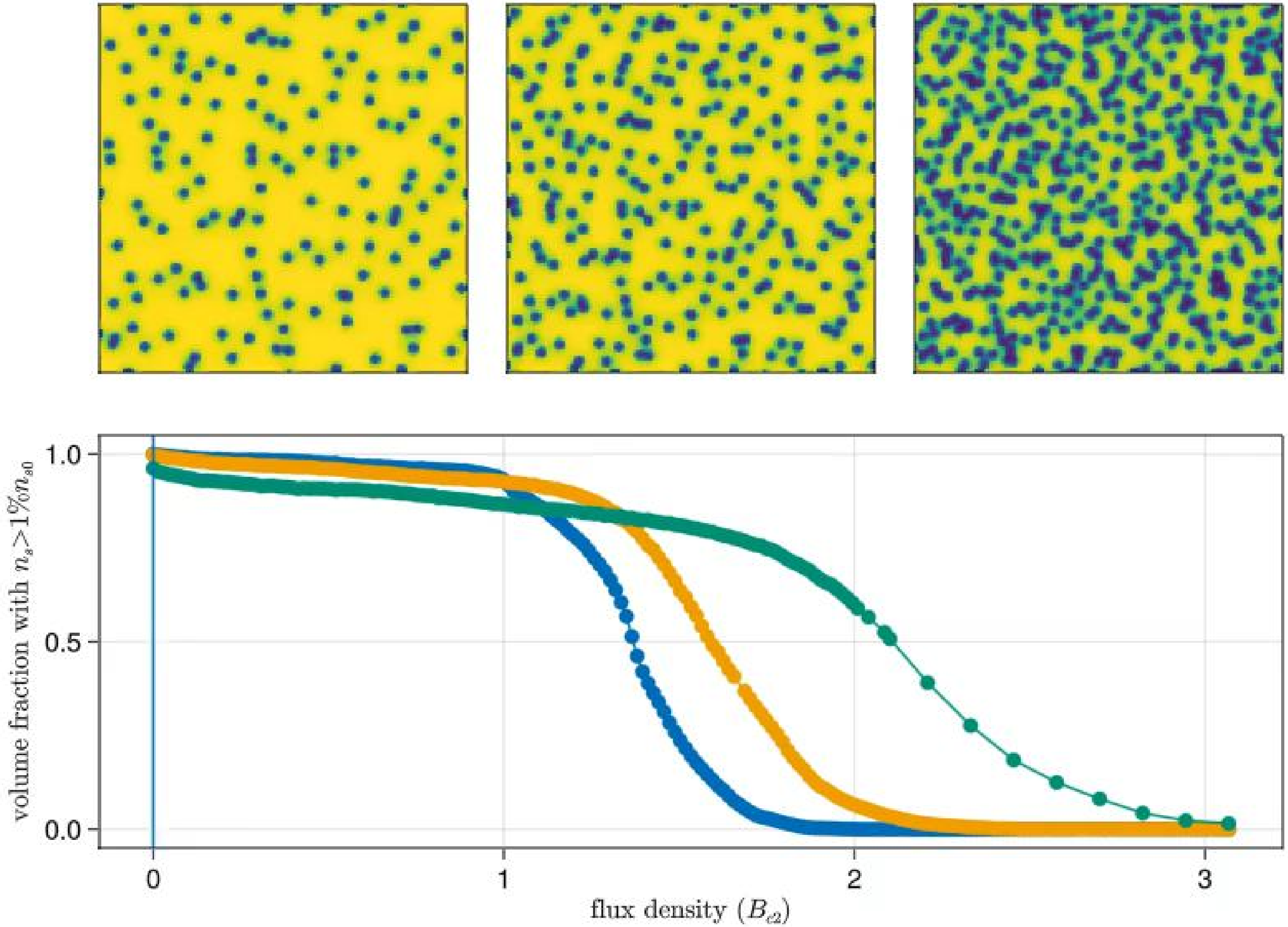


C.W.W. Haddon, A.I. Blair, F. Schoofs, and D.P. Hampshire **Computational Simulations using Time-Dependent Ginzburg–Landau Theory for Nb–Ti-like Microstructures** IEEE Transactions on Applied Superconductivity, Article vol. 32, no. 4, p. 5, Jun 2022

HTS materials with insulating pins

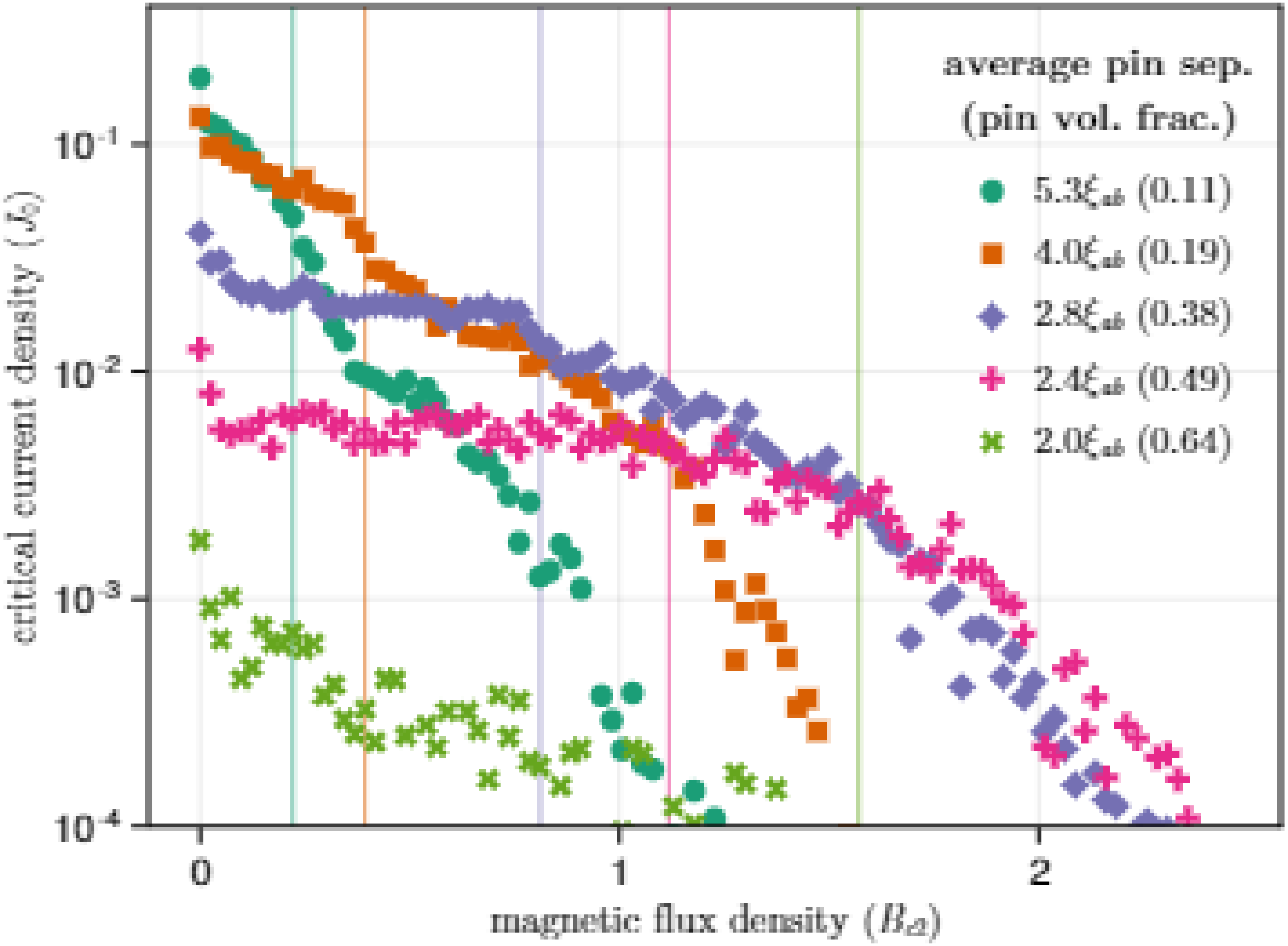


HTS materials – percolation



C. W. W. Haddon and Damian P. Hampshire "**Fast Multigrid Simulations of Pinning in REBCO with Highly Resistive Nanorods**" IEEE Transactions on Applied Superconductivity, IEEE Xplore, doi: 10.1109/TASC.2023.3253065.

HTS materials with insulating pins



Increasing pin density

Talk Outline

1. Time-dependent Ginzburg-Landau Theory - Flux pinning visualisation.
   – Irradiation affects Jc (pinning) and Bc2

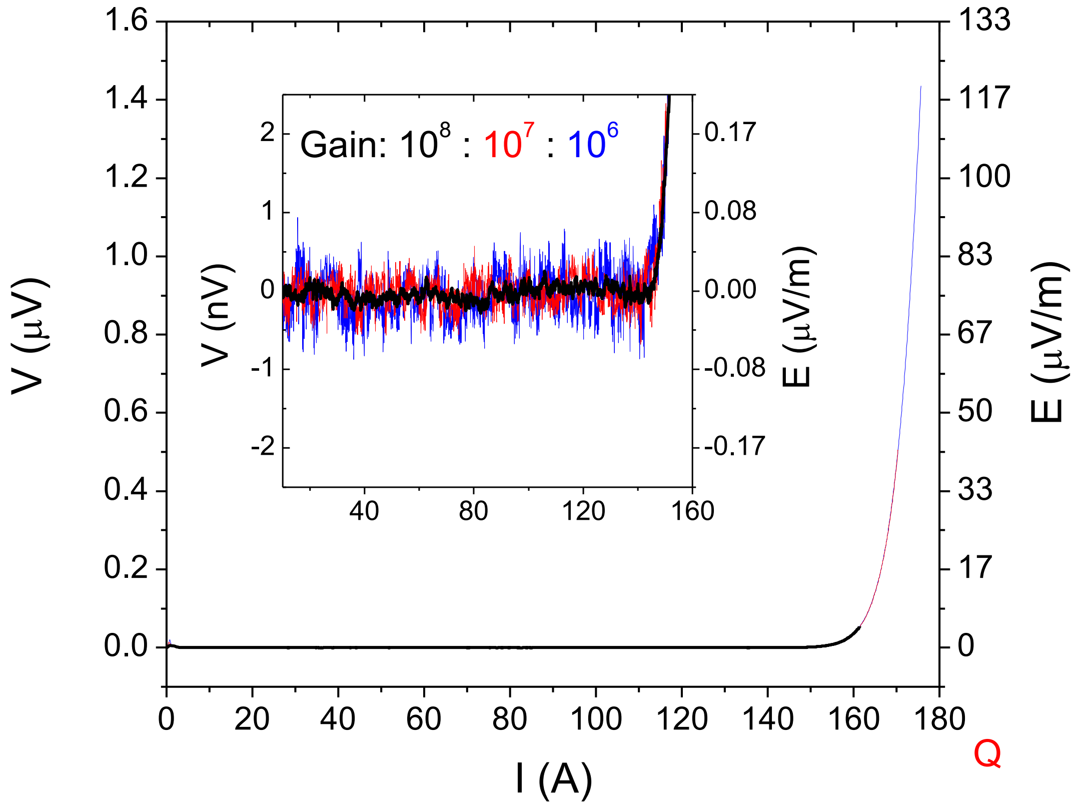
2. Critical current experiments on HTS

3. Avoiding hell in a handcart.

4. Concluding comments.

Critical current density in high magnetic fields

Supercurrents !



T= 4.2 K, B = 7T

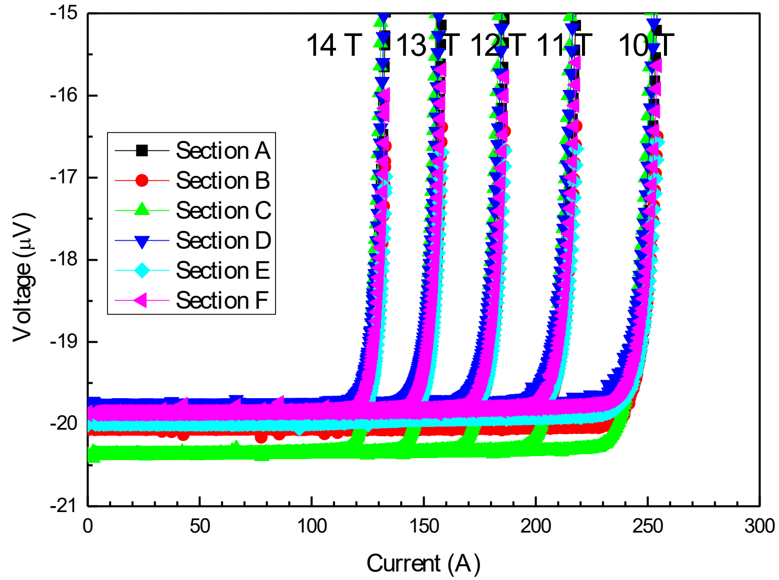
V_{theory} ~ 54 pV

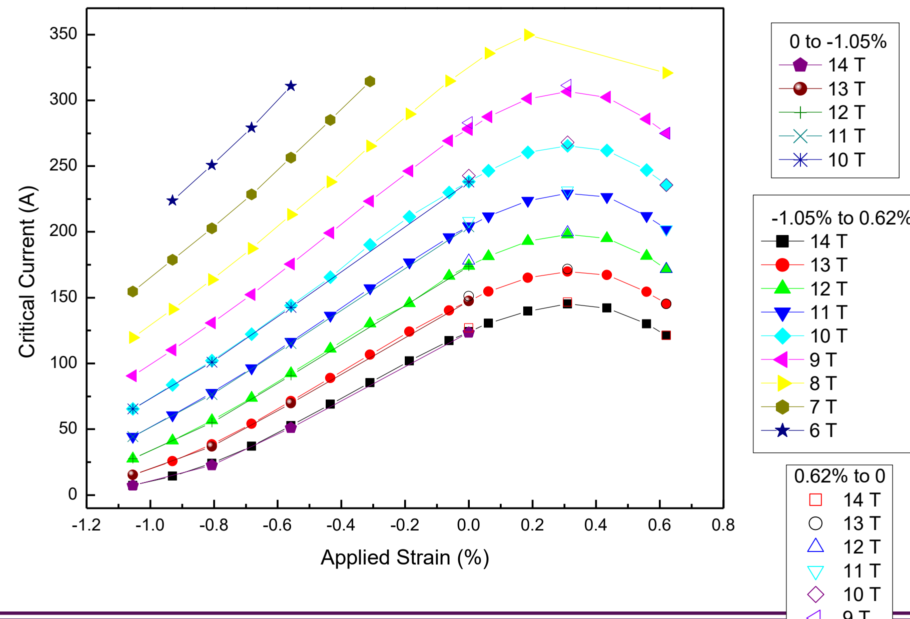
Measurements are about a factor of 3 above the theoretical Johnson noise limit

Experimental Results for Nb_3Sn and $RE_1Ba_2Cu_3O_7$

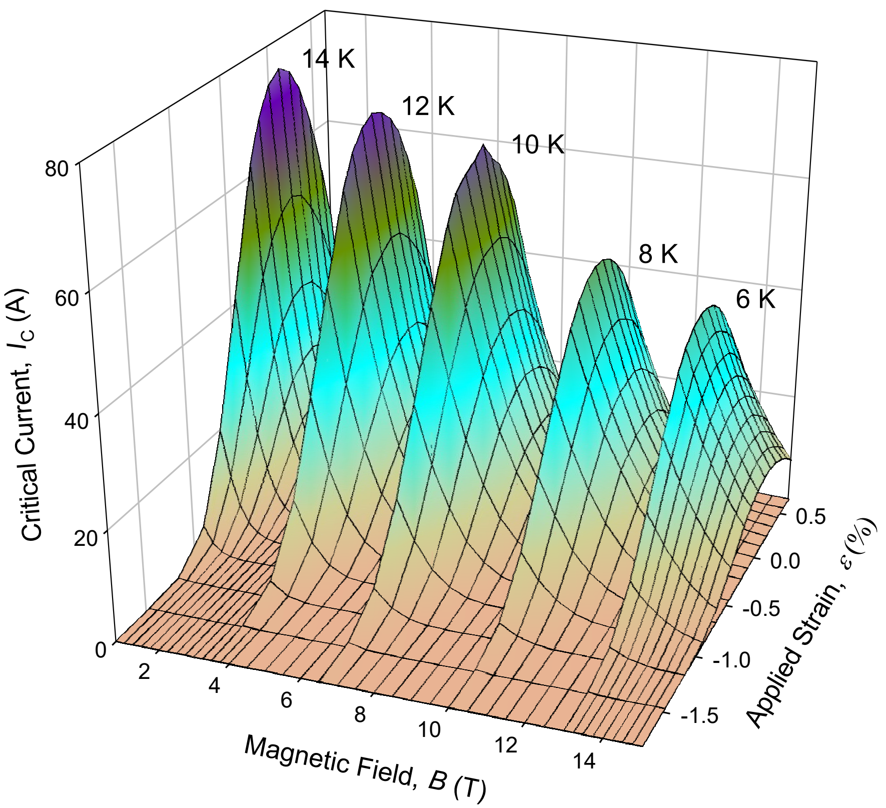
① Springboard used to apply compressive and tensile strain on tapes

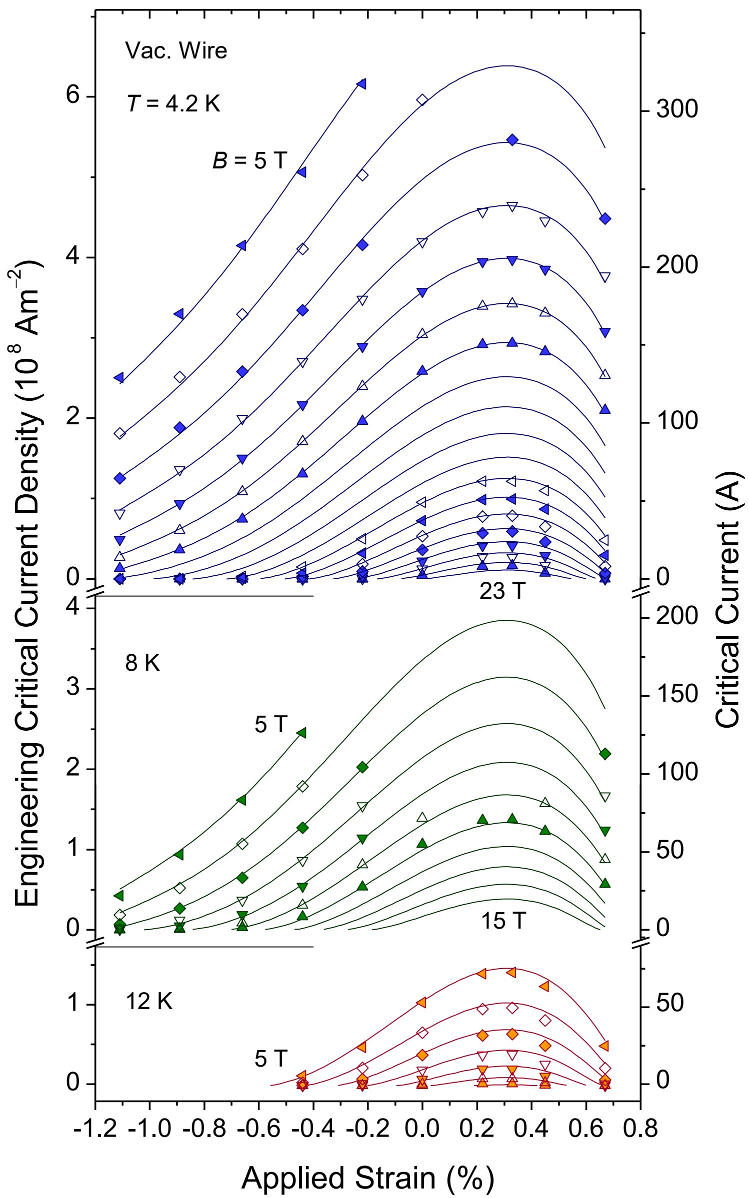
② Tee-shaped spring for applying compressive and tensile strain to wires





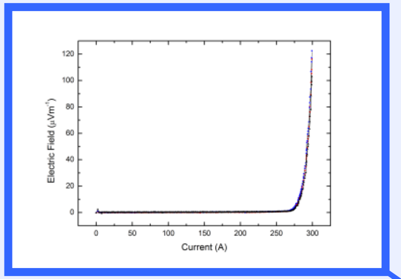
J_C(Magnetic field *B*, Temperature *T*, Strain ε) - Nb_3Sn



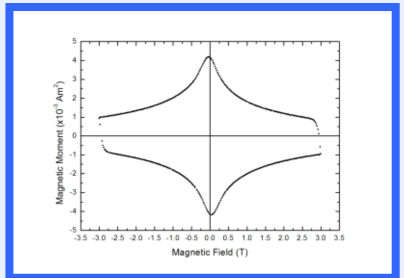


Durham's Role in the ITER project – Engineering approach

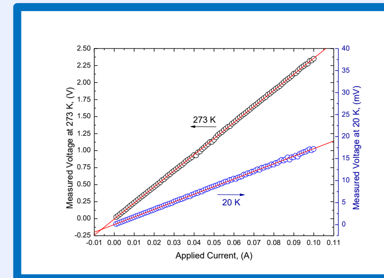
Critical Current, I_c > 190 A



Hysteresis < 500 mJ/cm^3



Residual Resistivity Ratio > 100



1000

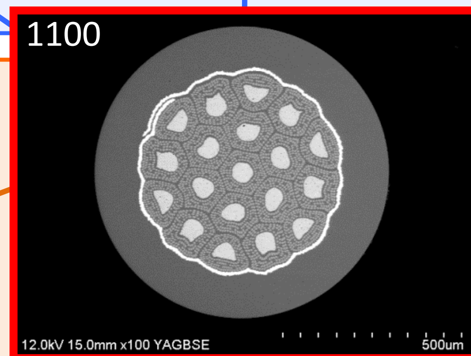
500

1000

Cryogenic measurements (down to -269 °C)

Cryogenic measurements (down to -269 °C)

1100

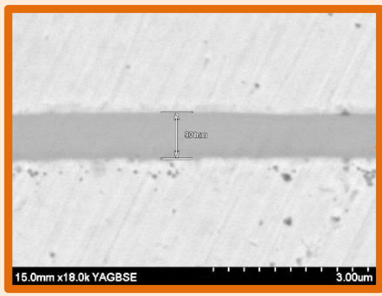


Room temperature measurements

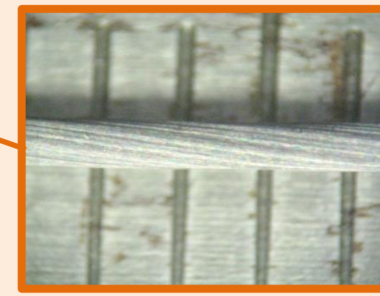
Room temperature measurements

1000

1000



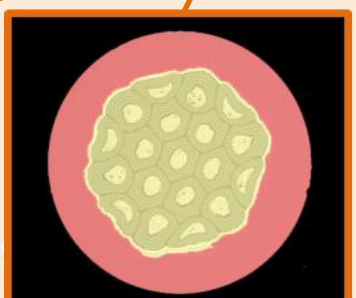
Chromium Plating Thickness, 1 to 2 μm



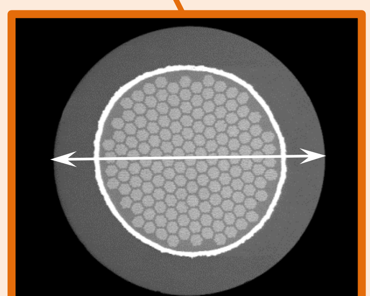
Twist Pitch 15 ± 2 mm

1000

1000



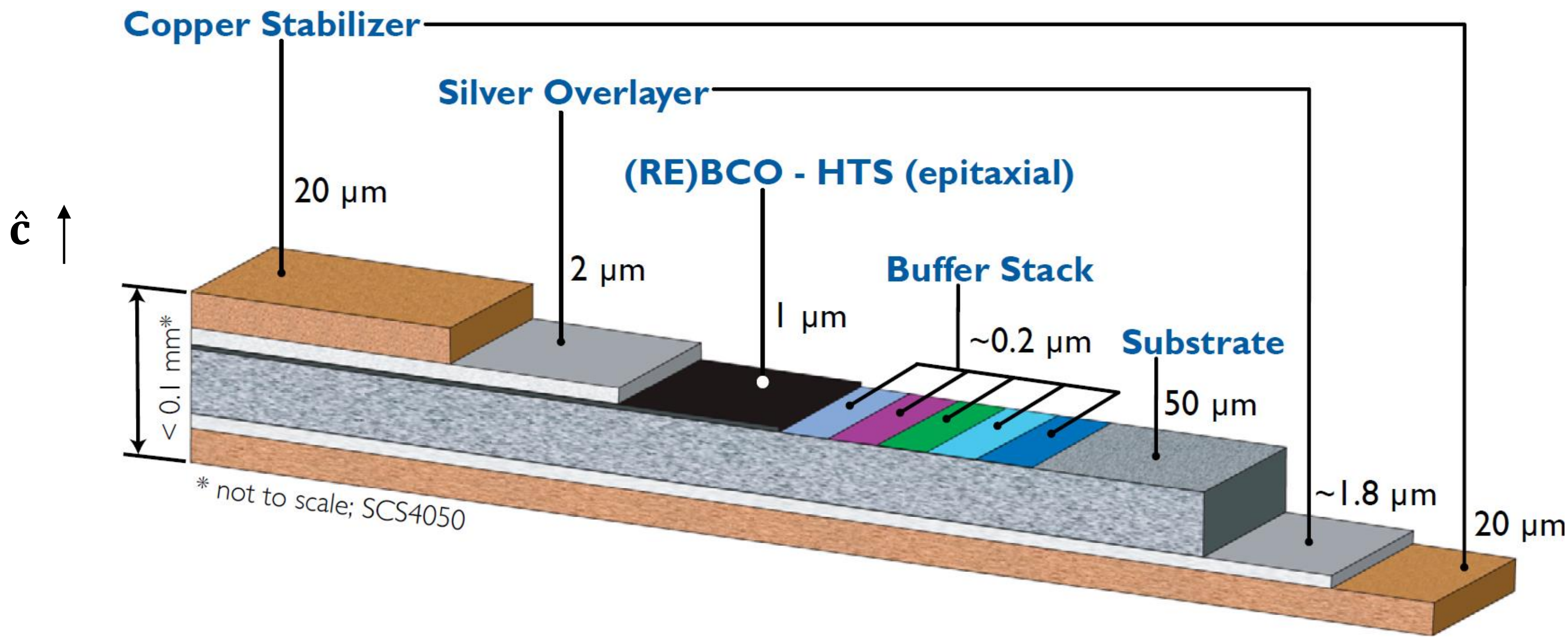
Cu-non-Cu Ratio, 1.0 ±0.1



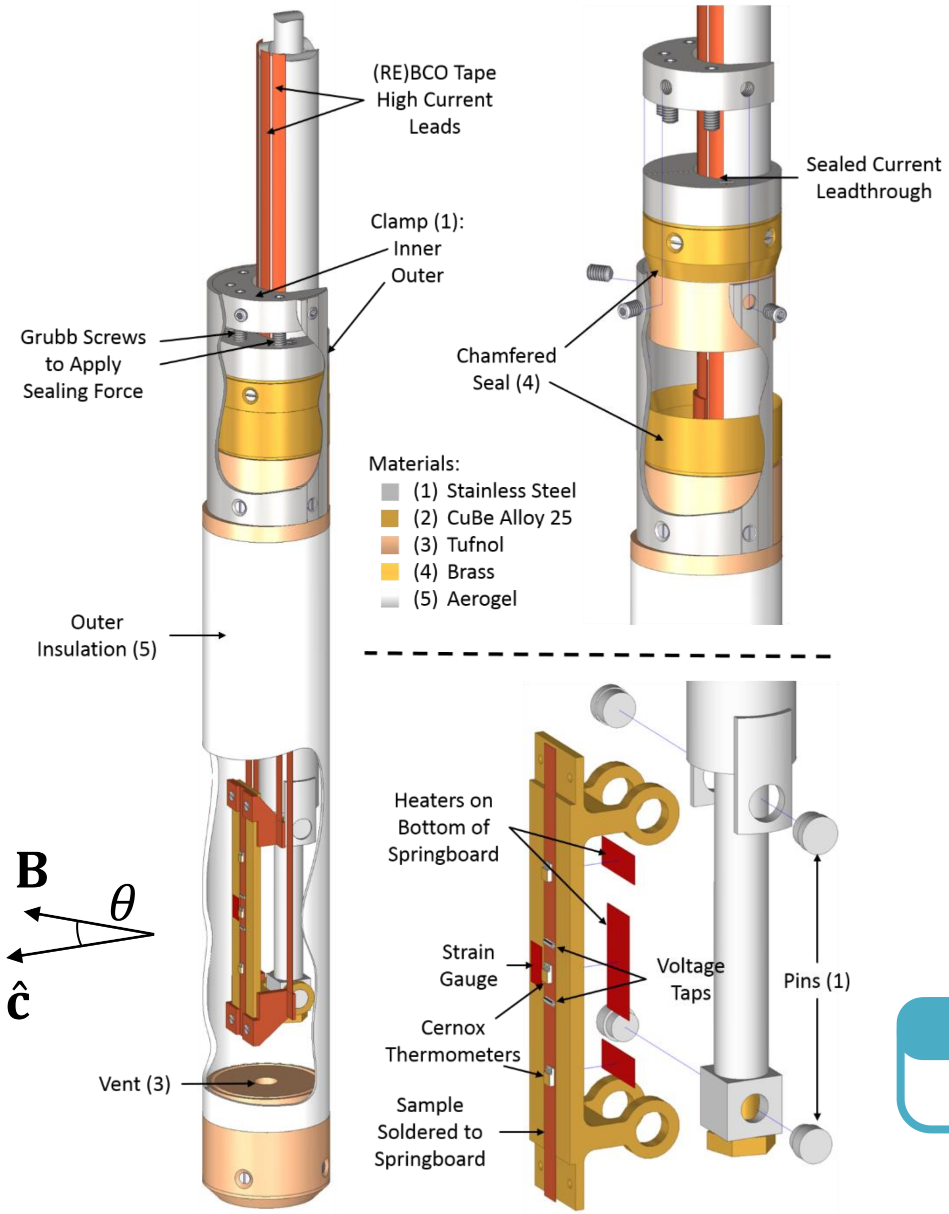
Diameter, 0.820 ± 0.005 mm

The HTS Samples

4 mm wide SuperPower Tape (AP and non-AP): $(RE)Ba_2C_3O_{7-\delta}$ (RE = Rare Earth), $T_c \approx 90$ K



Variable strain experimental Setup



Applied Strain

$-1.0\ \% \lesssim \varepsilon \lesssim +0.5\ \%$

Temperature

$4.2\ \text{K} \leq T \lesssim 150\ \text{K}$

Current

$I \leq 250\ \text{A}$

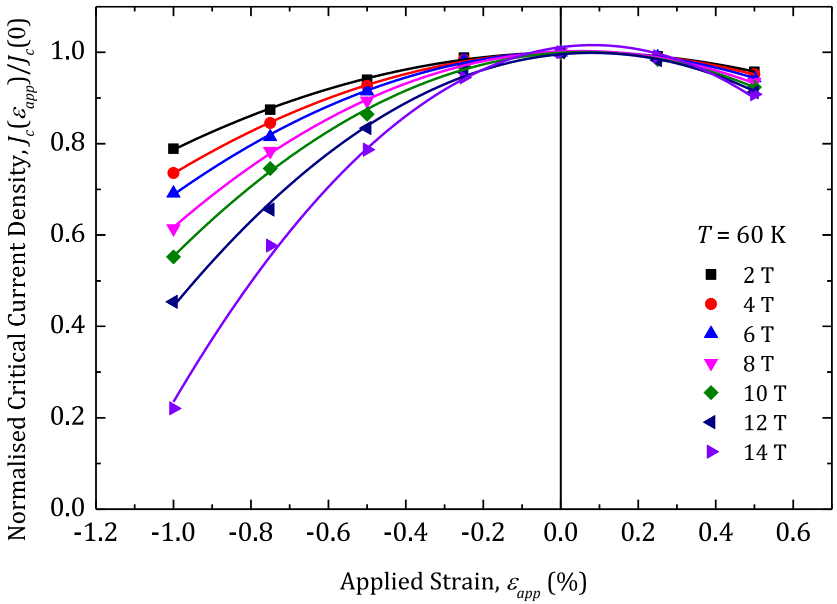
Angle

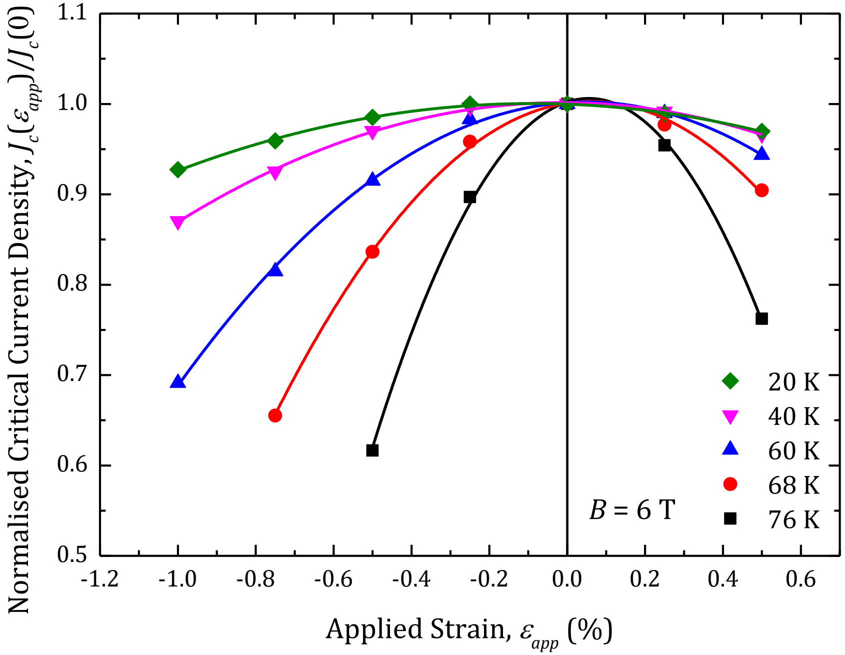
$0^\circ \leq \theta \leq 360^\circ$

Magnetic Field

$B \leq 15$ T – 40 mm Split – pair magnet

Parabolic Behaviour of $J_c(\varepsilon_{app})$

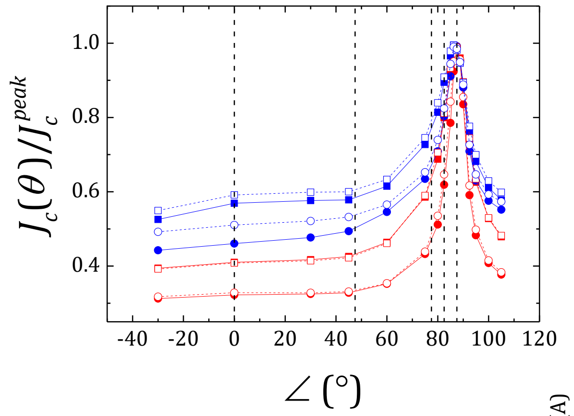


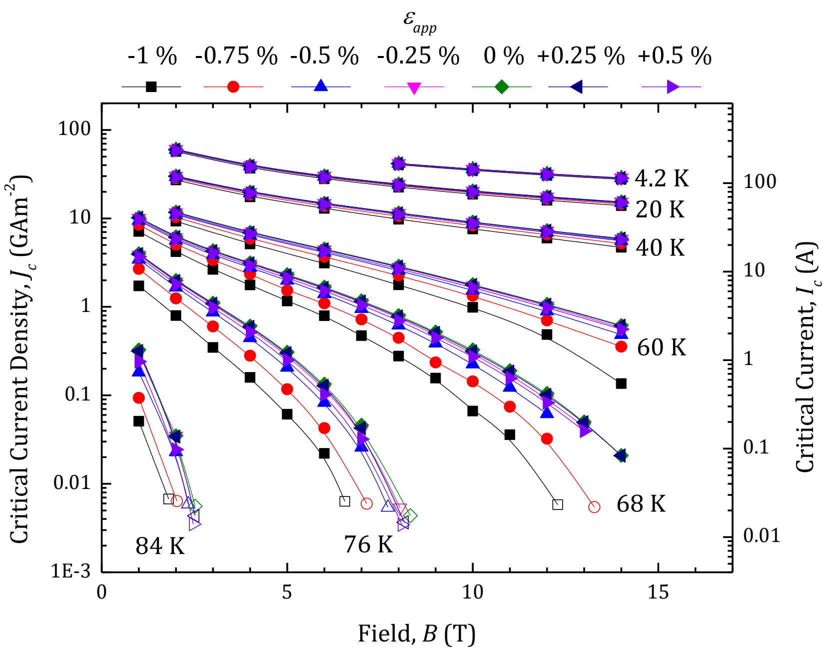


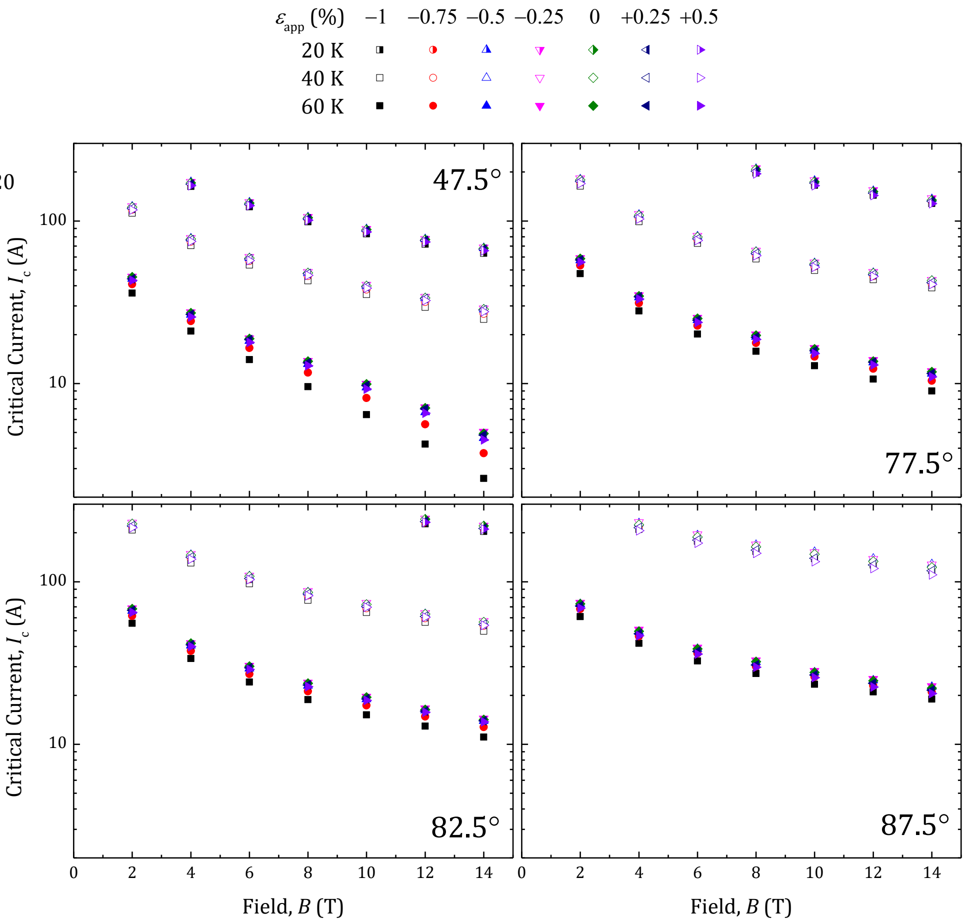
Parabolic fits to variable strain data

$$\frac{J_{\mathrm{c}}(\varepsilon_{\mathrm{app}})}{J_{\mathrm{c}}(0)} = 1 - \beta\left(\varepsilon_{\mathrm{app}} - \varepsilon_{\mathrm{peak}}\right)^2 + \beta\varepsilon_{\mathrm{peak}}^2$$

Extensive critical current data taken at selected angles

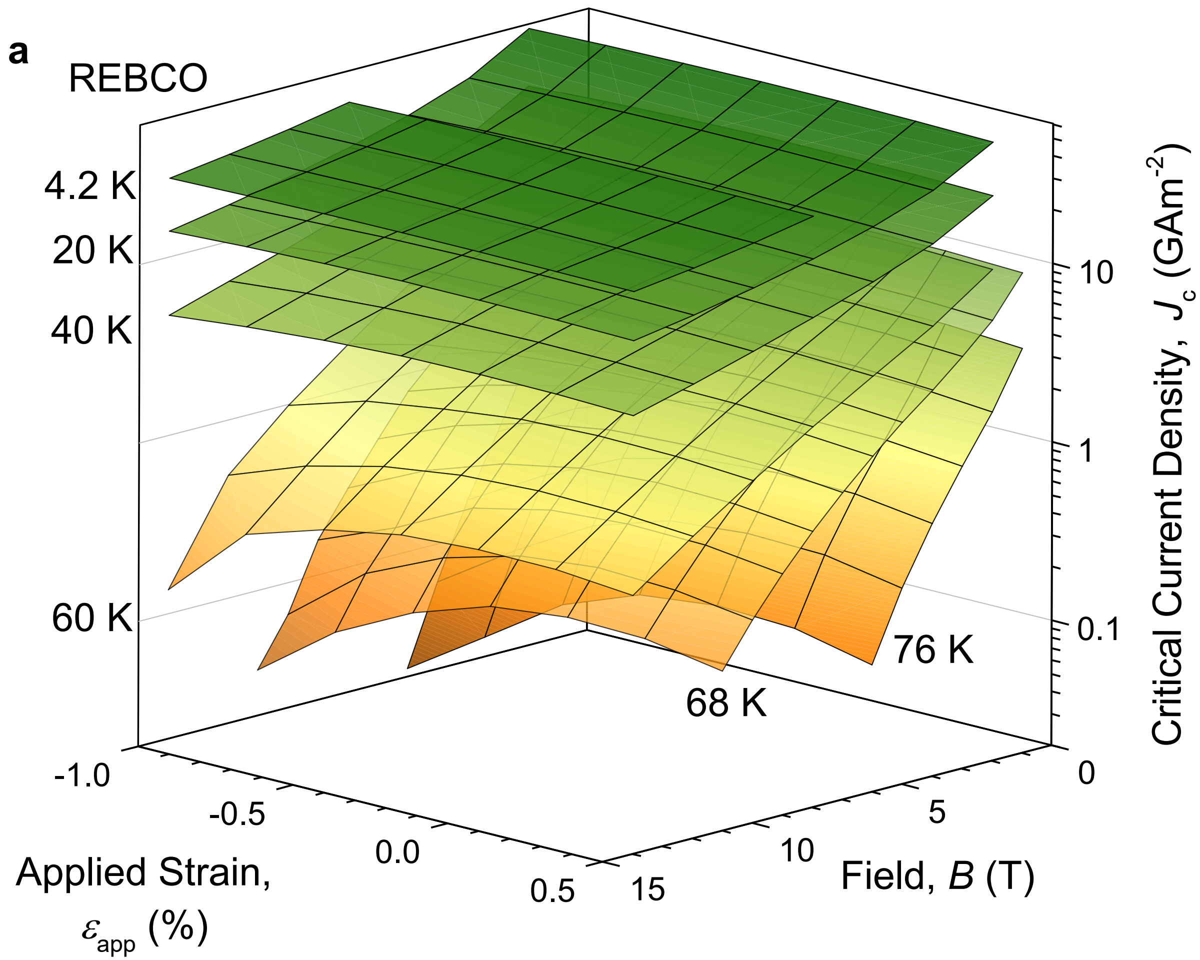




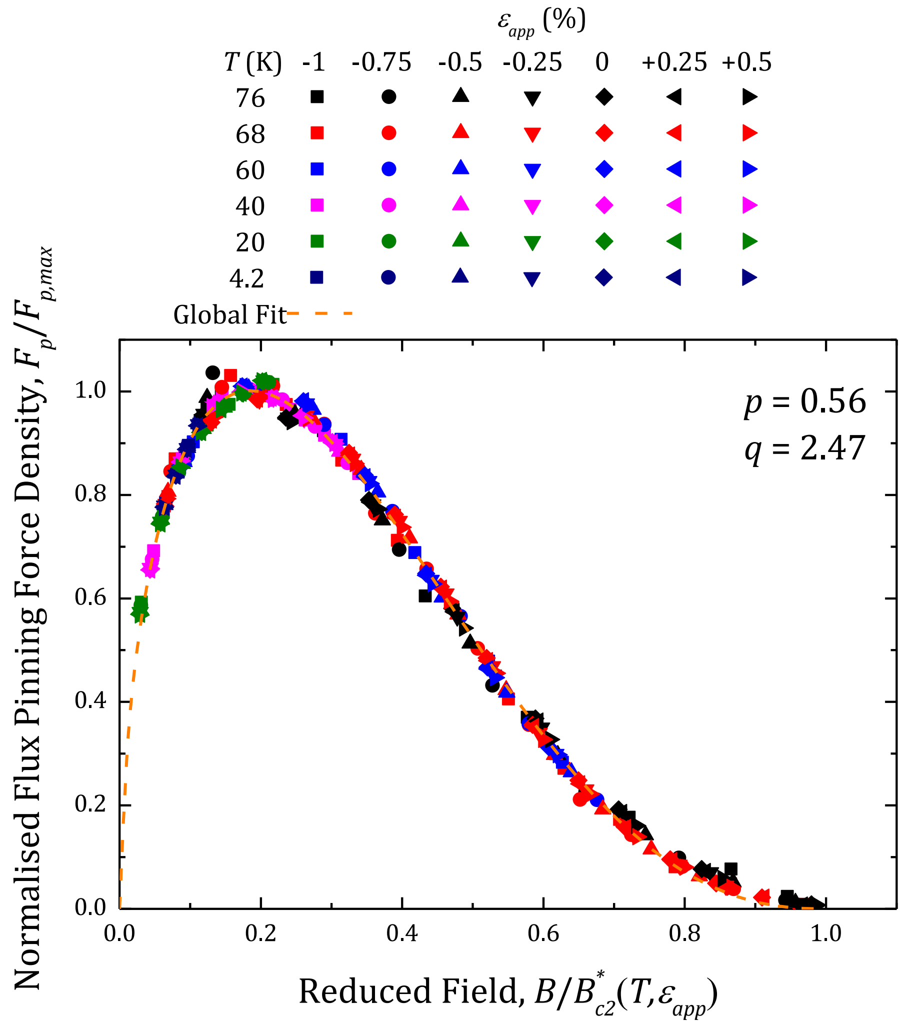


High quality critical current data over a large region of parameter space

Experimental Jc data for REBCO

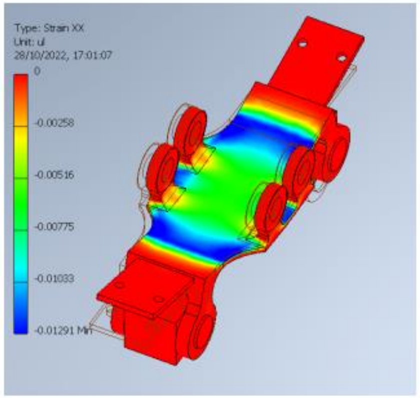


$F_p\left(T, B(\theta = 0°), \varepsilon_{app}\right)$



Flux pinning curve scales well with temperature and strain

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



2D measurements

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3. Irradiation.

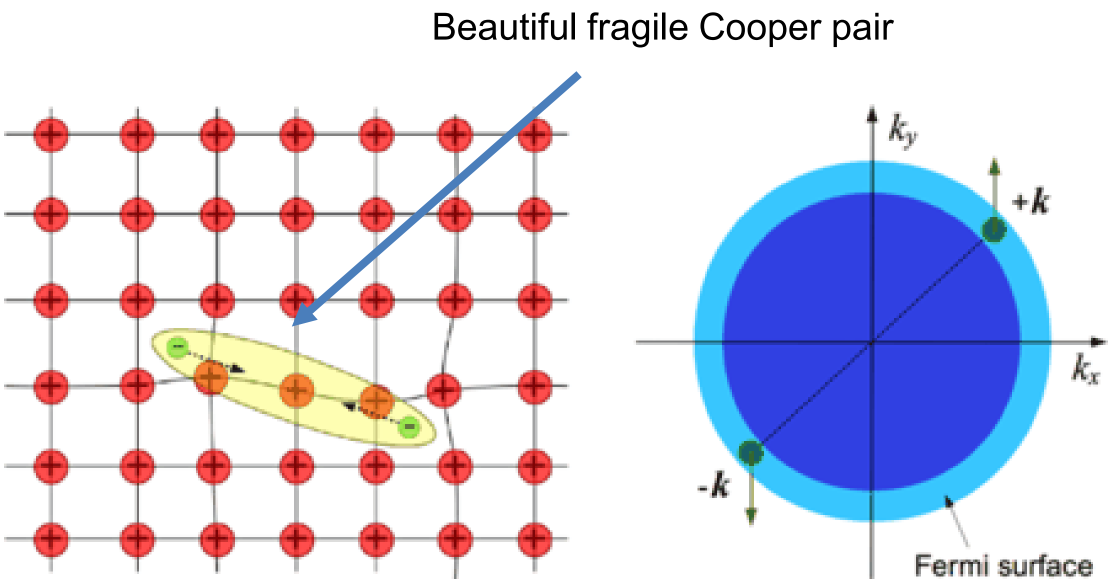
4. Concluding comments.

Avoiding hell in a hand-cart

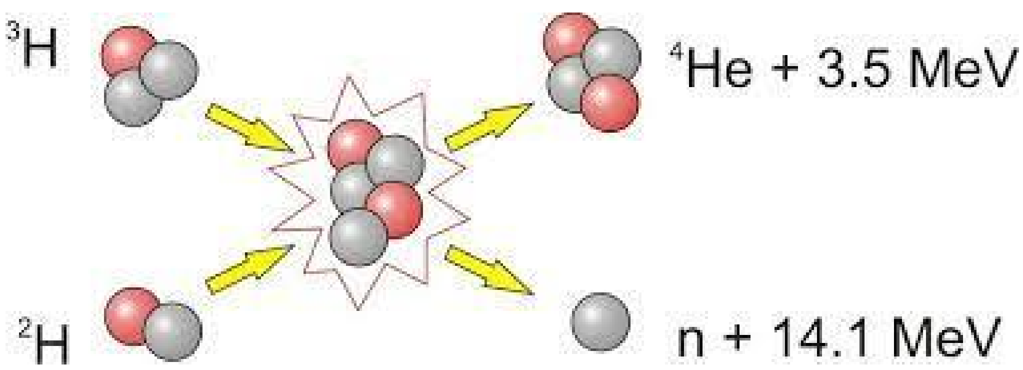
To hell

**Turn the D-T plasma on
and simultaneously turn the
superconducting magnets off**

Nine orders of magnitude energy range.

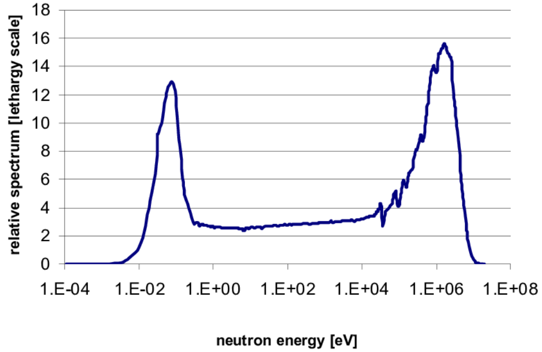


Cooper pair
E ~ 20 meV
d_0 ~ 2 nm
T ~ 10 ns



Neutron energy
~ 14 MeV

Electromagnetic Spectrum



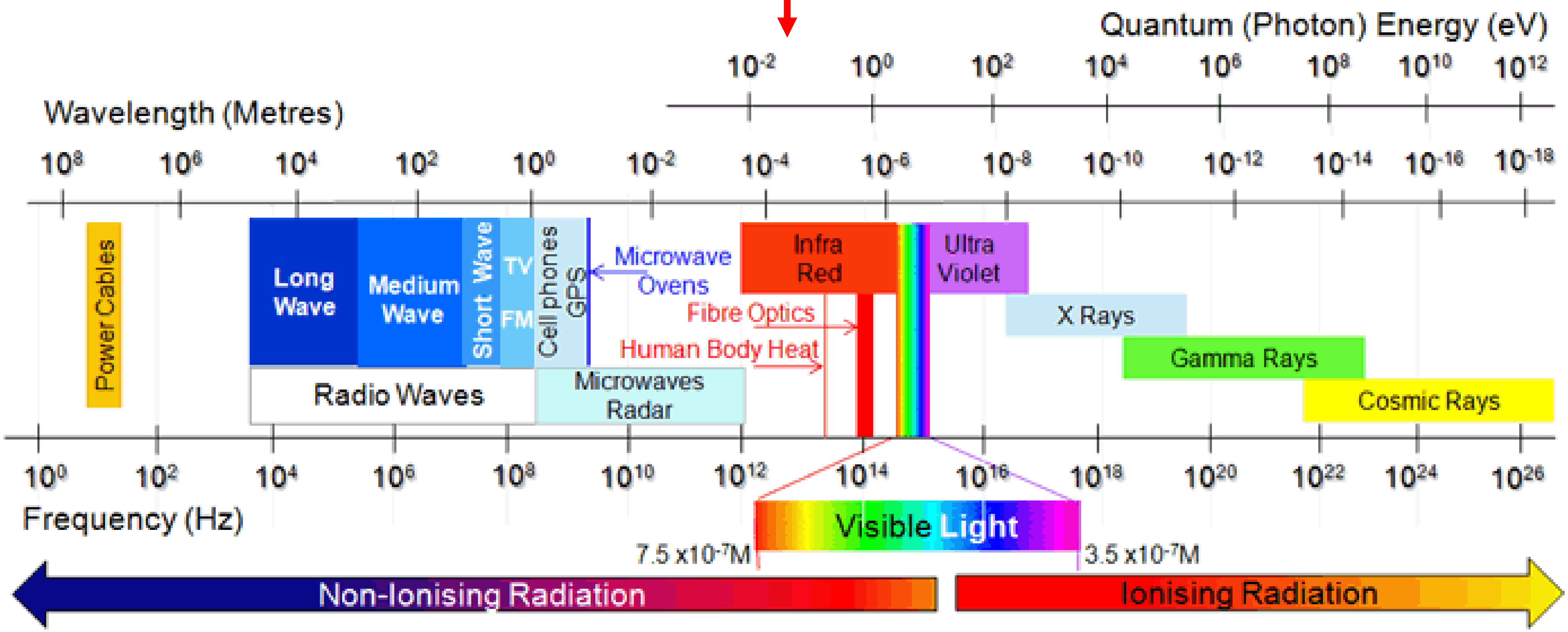
Triga III spectrum

9 Orders of Magnitude !!

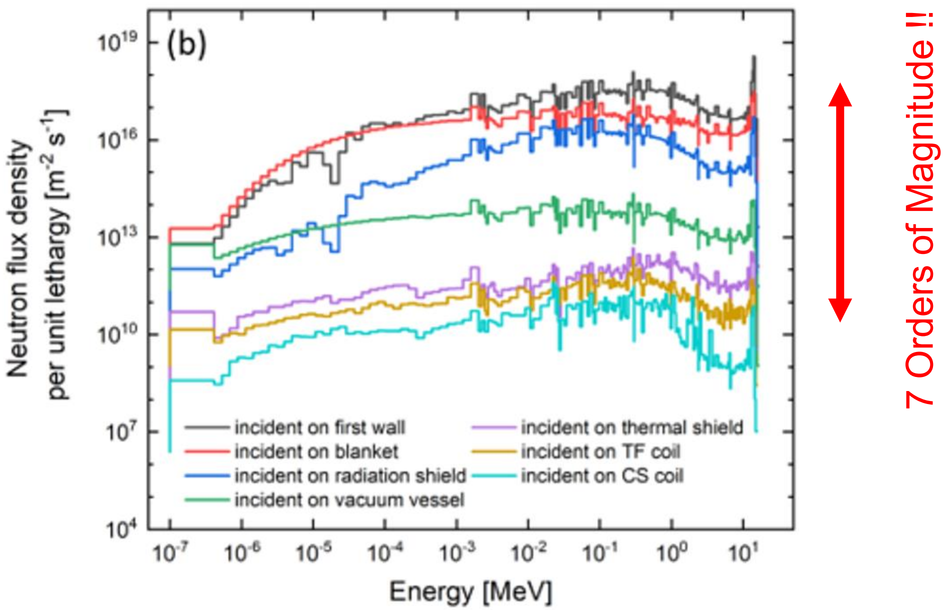
Fusion D-T energy ~ 14 MeV

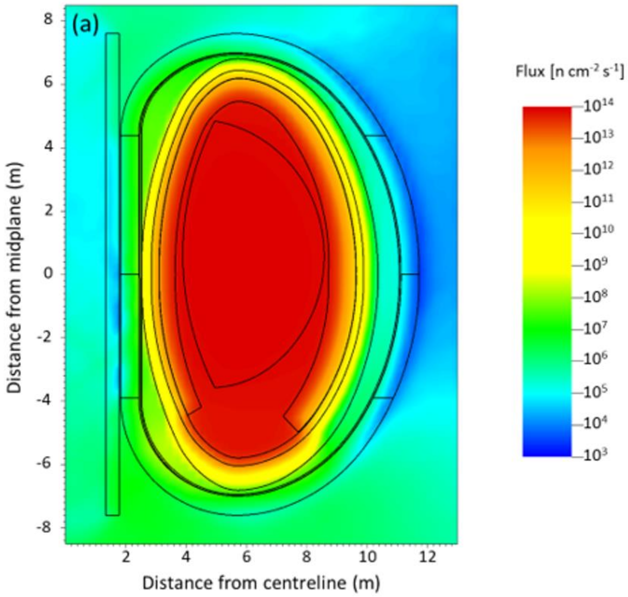
Cooper pair energy ~ 20 meV

Skin depth ~ ½ micron !



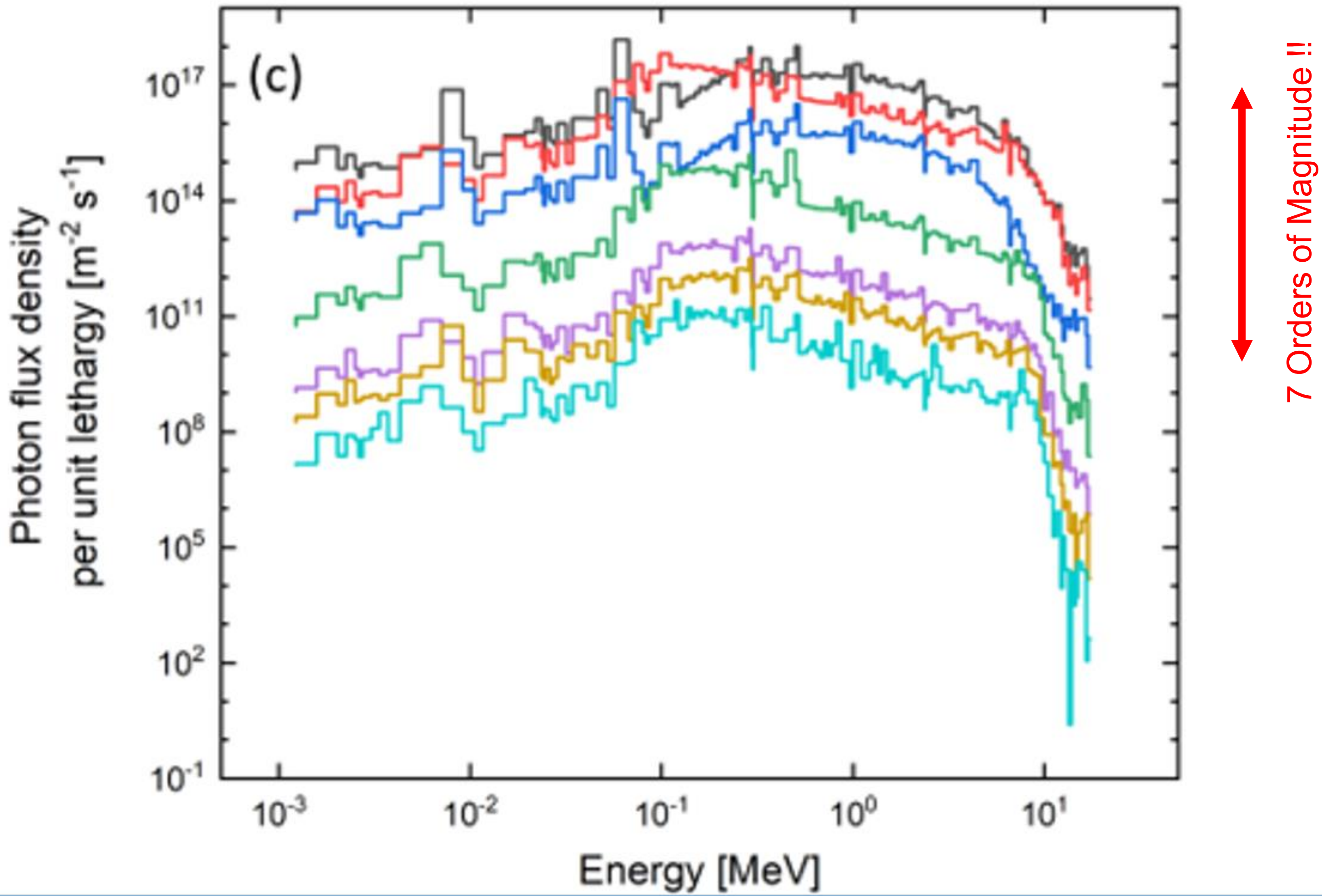
Neutron flux in a tokamak





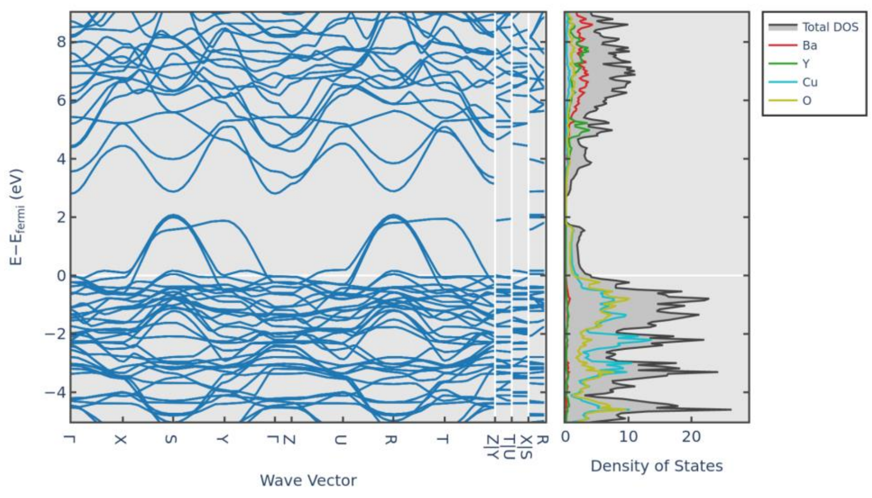
Chislett-McDonald S, Hampshire D P, et al. Training and Upgrading Tokamak Power Plants with Remountable Superconducting Magnets. Los Alamos archive: https://arxiv.org/abs/2205.04441v1 (2022)

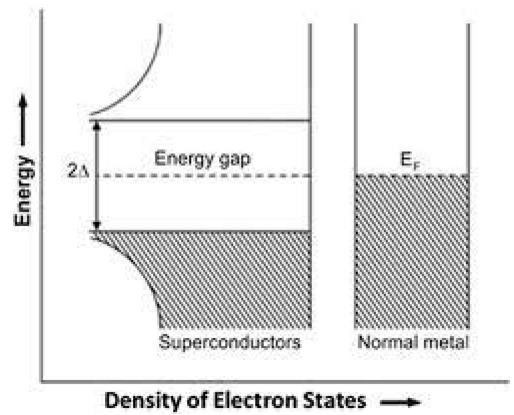
Photon flux in a tokamak



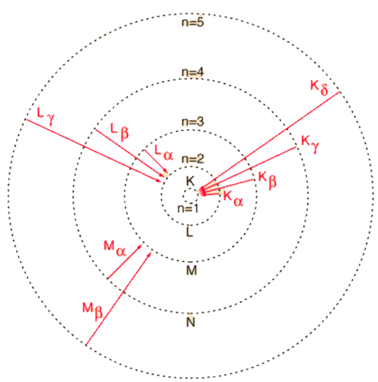
Charateristic energies in materials

Conduction electrons ~ eV



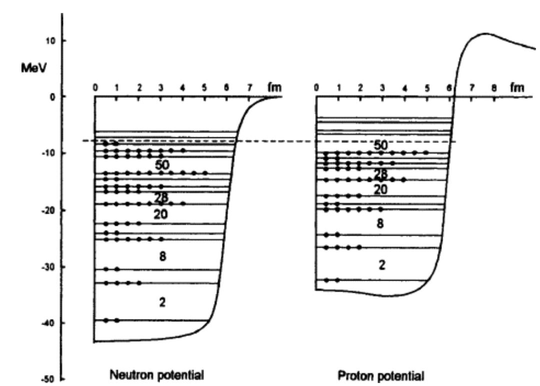


Fragile Cooper pair ~ 20 meV

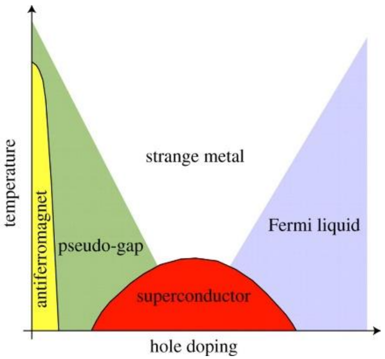


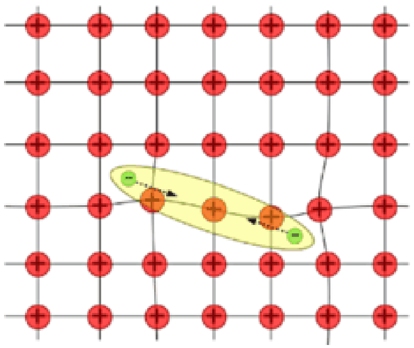
Core electrons
~ keV

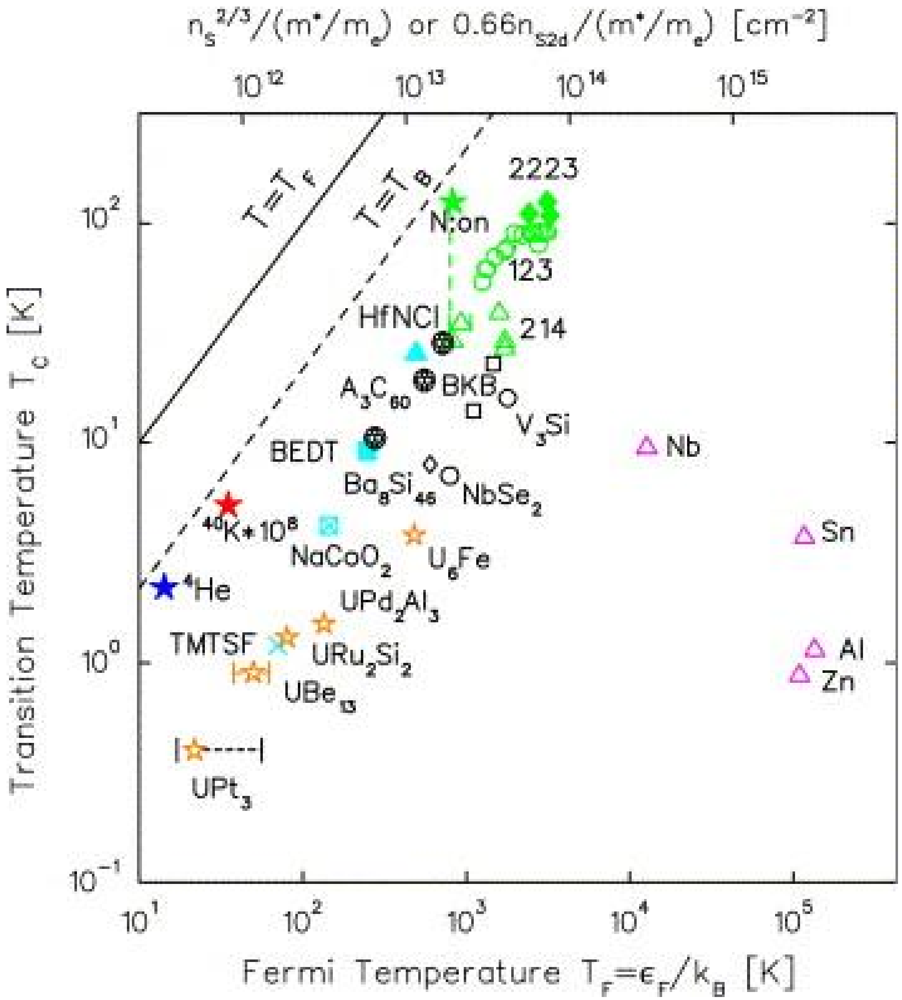
Nuclear structure ~ MeV



Unconventional Superconductivity ??
- The microscopic mechanism







Phonons
Spin waves
Antiferromagnetic magnons
Bose-Einstein condensate
……..

Low carrier density
Reduced dimensionality
d-wave
Metal-Insulator transition
…….

Dynamic equilibrium under a plasma flux

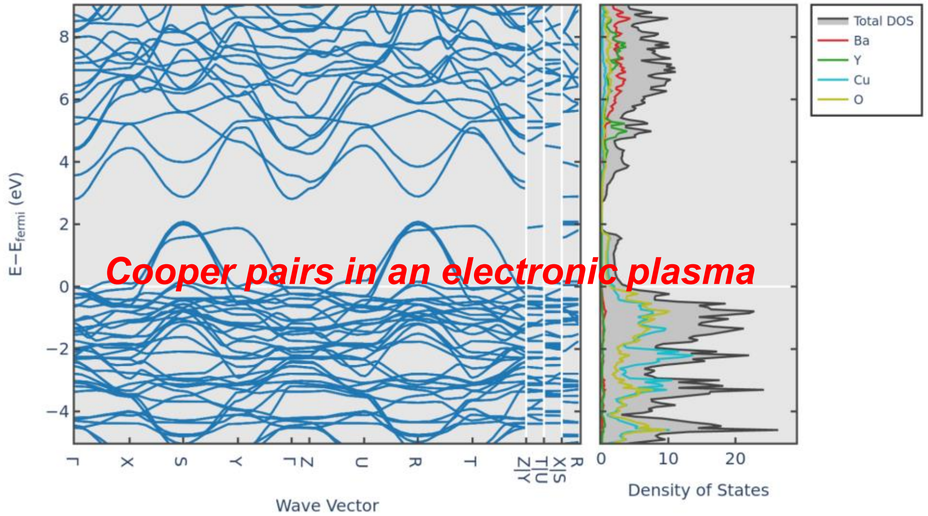
Whistling past in (real) space

Neutrons and photons with energies from MeV to meV.

Cascades of ions and defects.

Cascades of electrons.

- In dynamic equilibrium on time-scales from ns to years.



The k-space or E-space environment.

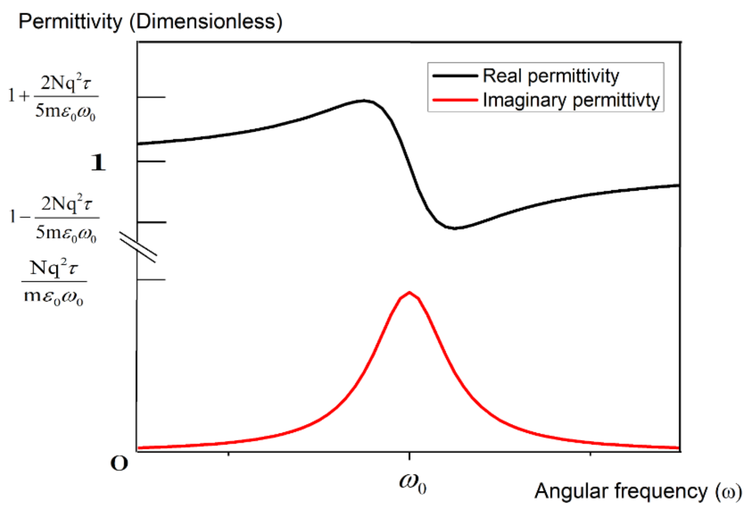
Cascades of electrons falling through energy levels from free electrons, through conduction electron levels to the core electron levels.

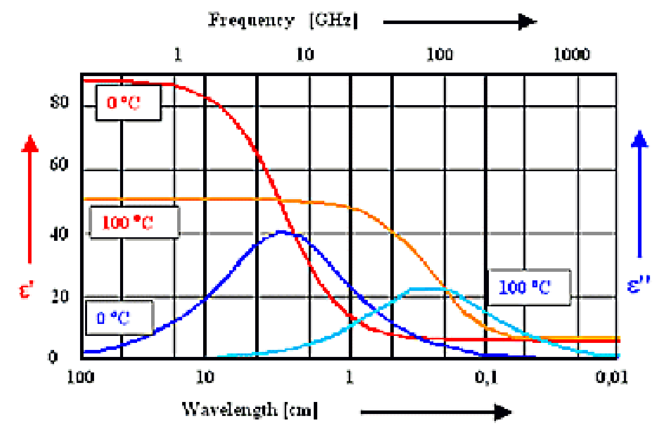
Disturbed phonon and magnons structures.

- All changing on time-scales upwards from ns.

Simple Harmonic Oscillator

"There are only two problems in physics: the simple harmonic oscillator problem and turning every other problem into the simple harmonic oscillator problem"





The Permittivity of a dielectric as a function of angular frequency

Computation:
Lattice: Calculations + measurements + oxygen annealing.
Electronic structure: DFT including correlations.

"Challenges: 'Time-scale of nanoseconds, lattice chaos and electronic plasma"

Superconducting-electronic-plasma ~10 ms (or ~ 10 s) experiment

Neutron source
(+ gamma source) → "Proxy" Shielding → Neutron cascades: meV, eV, keV and MeV
Photon cascades: meV, eV, keV and MeV
Electron and ion cascades….
→ Superconducting electrons in an electronic plasma

Two rules for experiment for the electronic plasma:

- The flux of neutrons and photons must be within a factor of 10 of that in the tokamak across the entire energy range from meV to MeV (Ic measurements are ~ 1% accurate).
- The irradiated superconductor must be irradiated and measured at cryogenic temperatures, under high field (and angle) at strain ***under operational conditions***.

For experimentalists:

- Following some beautiful data at IREF23, let's (avoid contradictory Jc data under irradiation) try to get the thermometer as close as possible/in good thermal contact with the sample.

Financial risk + reputational risk! Cost of EDF's new UK nuclear project rises to $40 billion:
https://www.reuters.com/business/energy/cost-edfs-new-uk-nuclear-project-soars-40-bln-2023-02-20/

Concluding Comments

TDGL shows Jc and Bc2 changes with irradiation

$J_C(B,T, \theta, \varepsilon)$ for HTS is broadly understood
- there is still headroom for improvement in magnitude.

Measurements of J_C are demanding and time consuming.

We need Jc measurements under ***<u>operational conditions</u>*** *including photon/neutron flux* with energies over 9 orders of magnitude.