Pinning Studies for Superconducting Magnets and Insights for SRF

Centre for Materials Physics

Fusion Energy Reference Lab

www.durham.ac.uk/cmp

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and Prof. Damian P. Hampshire

Durham University

Professor Damian Hampshire

- Undergraduate degree in Physics at New College, Oxford – Open Scholar
- PhD in Clarendon Lab. Oxford – Profs Harry Jones and Sir Prof. E W J Mitchell
- Post-Doc at Madison Wisconsin USA – Prof. Larbalestier
- Lecturer/Reader/Professor in the Physics Department at Durham University, UK.

  EPSRC Advanced Fellow for 5 years……

- Teaching: 250 students Maxwell's equations – Core Physics Course
- Research: 1 Research Fellow + 6 PhD students (J_c for ITER project)
- Published about > 120 papers.

Thanks to for inviting me to the workshop: David Longuevergne

Why we work on High Field Superconductors for Fusion in Durham

Be brave about Terminology !!

Durham is safe !

Cambridge is underwater

Oxford has beaches

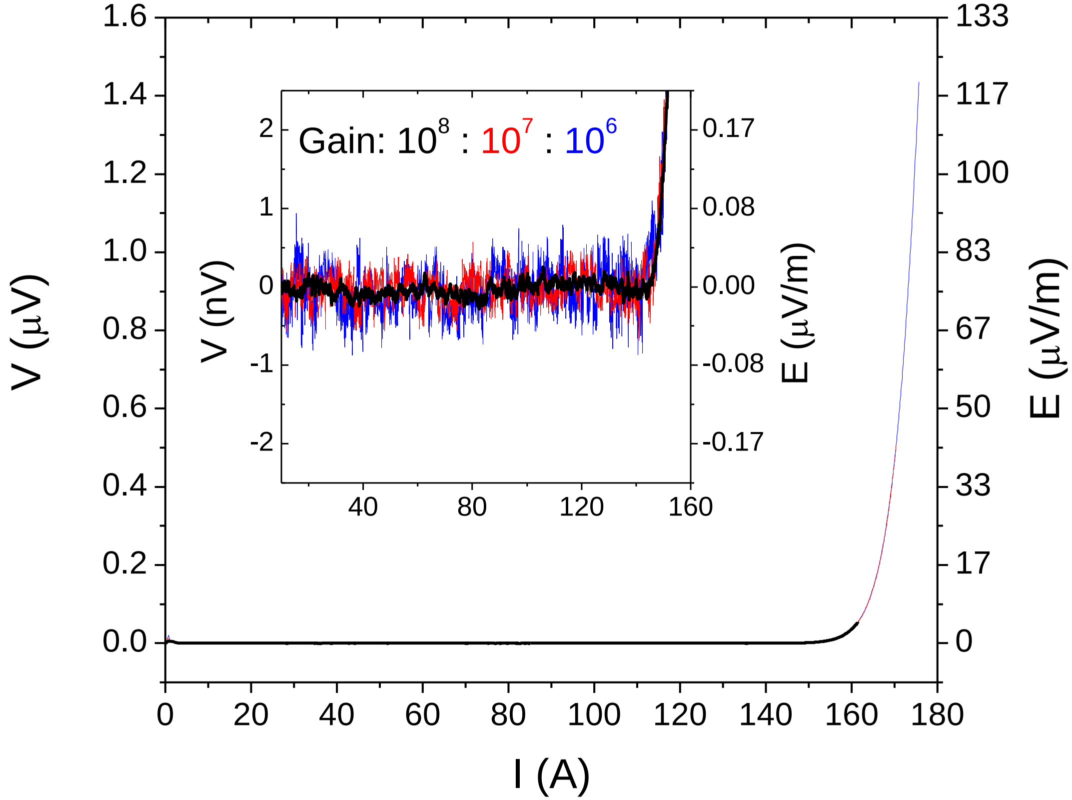
OUTLINE OF THE TALK

I. A short review of the different pinning mechanisms that operate in useful superconductors.

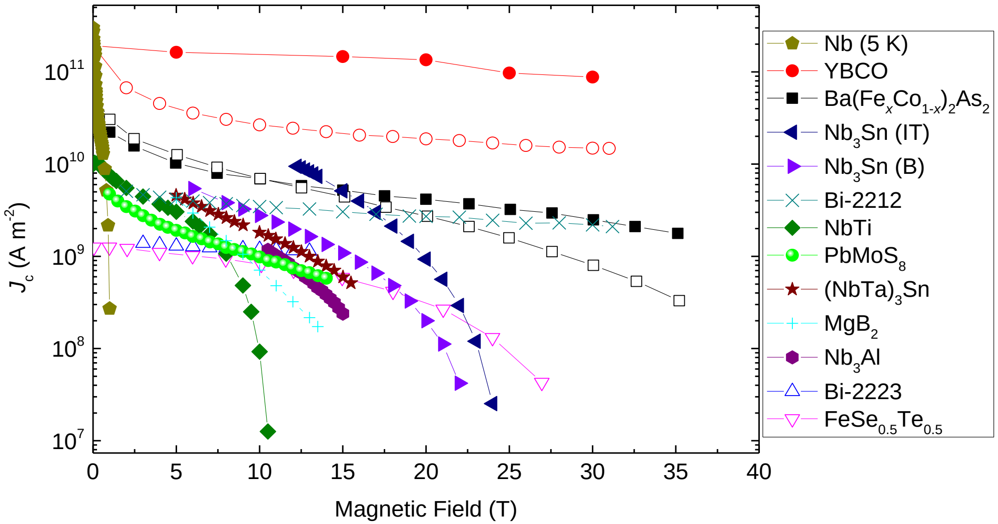
II. Visualisation of the different pinning processes that operate and discussion of the theoretical descriptions for such processes.

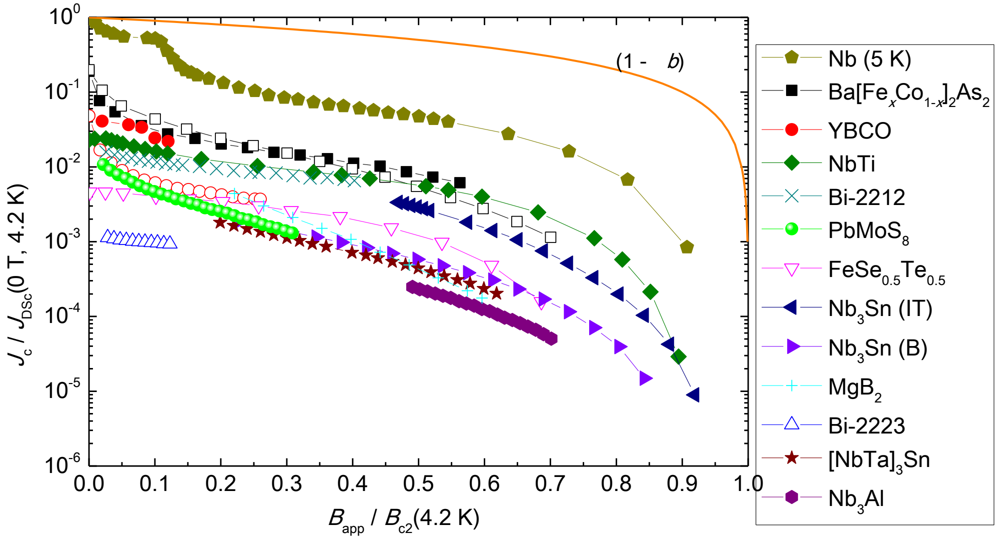
III. Identify the experimental measurements best suited for characterising **"pinning"**.

Critical Current Density Measurements



The Challenge – J_C and J_{DSc}

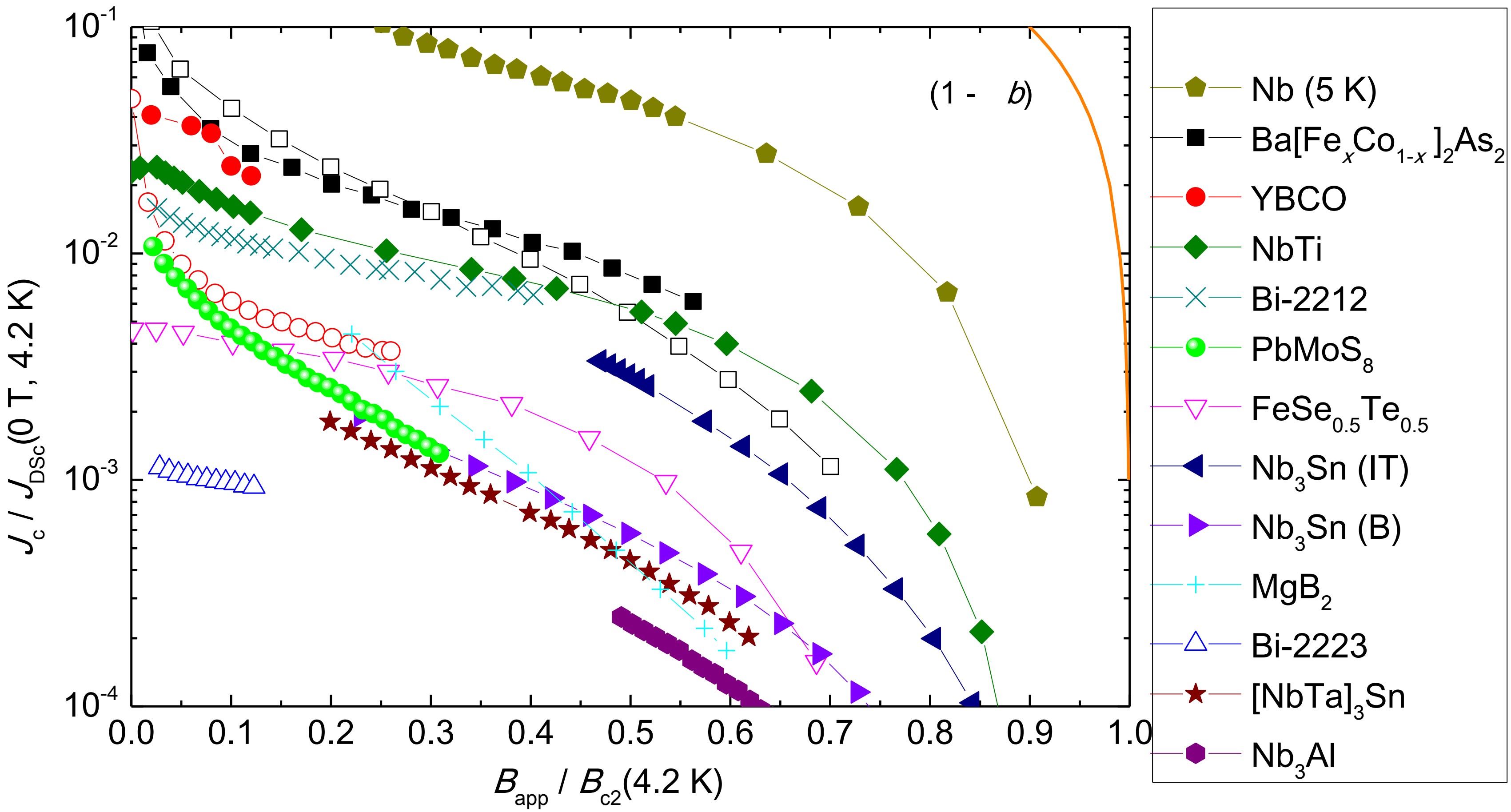




$$J_{\mathrm{DSc}}^{ab}(T) = \frac{\Phi_0}{3\sqrt{3}\pi\mu_0\lambda_{ab}^2(T)\xi_{ab}(T)}$$

Guanmei Wang, Mark J. Raine, and Damian P. Hampshire. How resistive must grain boundaries in polycrystalline superconductors be, to limit Jc? - SUST 20 104001 (2017) Open Access

The Challenge – J_C and J_{DSc}



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Flux pinning mechanisms in type II superconductors

By D. Dew-Hughes
Department of Physics, University of Lancaster, Lancaster, England

[Received 25 March 1974]

Type of interaction	Geometry of pin	L	x	Type of centre	ΔW	Pinning function, $F_p(h)$	Equation No.	Position of maximum
Magnetic	Volume	$\frac{S_v}{d}$	λ	Normal	$\frac{-\phi_0(H_{c2}-H)}{2{\cdot}32\kappa^2}$	$\frac{\mu_0 S_v H_{c2}{}^2 h^{1/2}(1-h)}{\kappa^3}$	8	$h=0{\cdot}33$
				$\Delta\kappa$	$\frac{-\phi_0(H_{c2}-2H)\Delta\kappa}{2{\cdot}32\kappa^3}$	$\frac{\mu_0 S_v H_{c2}{}^2 h^{1/2}(1-2h)\Delta\kappa}{\kappa^4}$	9	$h=0{\cdot}17, 1$
Core	Volume	$\frac{S_v}{d}$	d	Normal	$\frac{-\mu_0\phi_0(H_{c2}-H)^2}{4{\cdot}64\kappa^2 B}$	$\frac{\mu_0 S_v H_{c2}{}^2(1-h)^2}{5{\cdot}34\kappa^2}$	10	—
				$\Delta\kappa$	$\frac{-\phi_0(H_{c2}-H)\Delta\kappa}{2{\cdot}32\kappa^3}$	$\frac{\mu_0 S_v H_{c2}{}^2 h(1-h)\Delta\kappa}{2{\cdot}67\kappa^3}$	11	$h=0{\cdot}5$
	Surface	$\frac{S_v}{d}$	ξ	Normal	$\frac{-\pi\xi^2\mu_0(H_{c2}-H)^2}{4{\cdot}64\kappa^2}$	$\frac{\mu_0 S_v H_{c2}{}^2 h^{1/2}(1-h)^2}{4\kappa^2}$	12	$h=0{\cdot}2$
				$\Delta\kappa$	$\frac{-\pi\xi^2\mu_0 H(H_{c2}-H)\Delta\kappa}{2{\cdot}32\kappa^3}$	$\frac{\mu_0 S_v H_{c2}{}^2 h^{3/2}(1-h)\Delta\kappa}{2\kappa^3}$	13	$h=0{\cdot}6$
	Point	$\frac{BV_f}{\phi_0}$	$\frac{a}{2}$	Normal	$\frac{-\pi\xi^2\mu_0(H_{c2}-H)^2}{4{\cdot}64\kappa^2}$	$\frac{\mu_0 V_f H_{c2}{}^2 h(1-h)^2}{4{\cdot}64 a\kappa^2}$	14	$h=0{\cdot}33$
				$\Delta\kappa$	$\frac{-\pi\xi^2\mu_0 H(H_{c2}-H)\Delta\kappa}{2{\cdot}32\kappa^3}$	$\frac{\mu_0 V_f H_{c2}{}^2 h^2(1-h)\Delta\kappa}{2{\cdot}32 a\kappa^3}$	15	$h=0{\cdot}67$

D. Dew-Hughes

HTS materials are quasi single-crystalline and may have simple columnar pinning

D. Dew-Hughes, "Flux pinning mechanisms in type II superconductors," *Philosophical Magazine,* vol. 30, pp. 293-305, 1974.

Ginzburg-Landau Theory

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

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

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

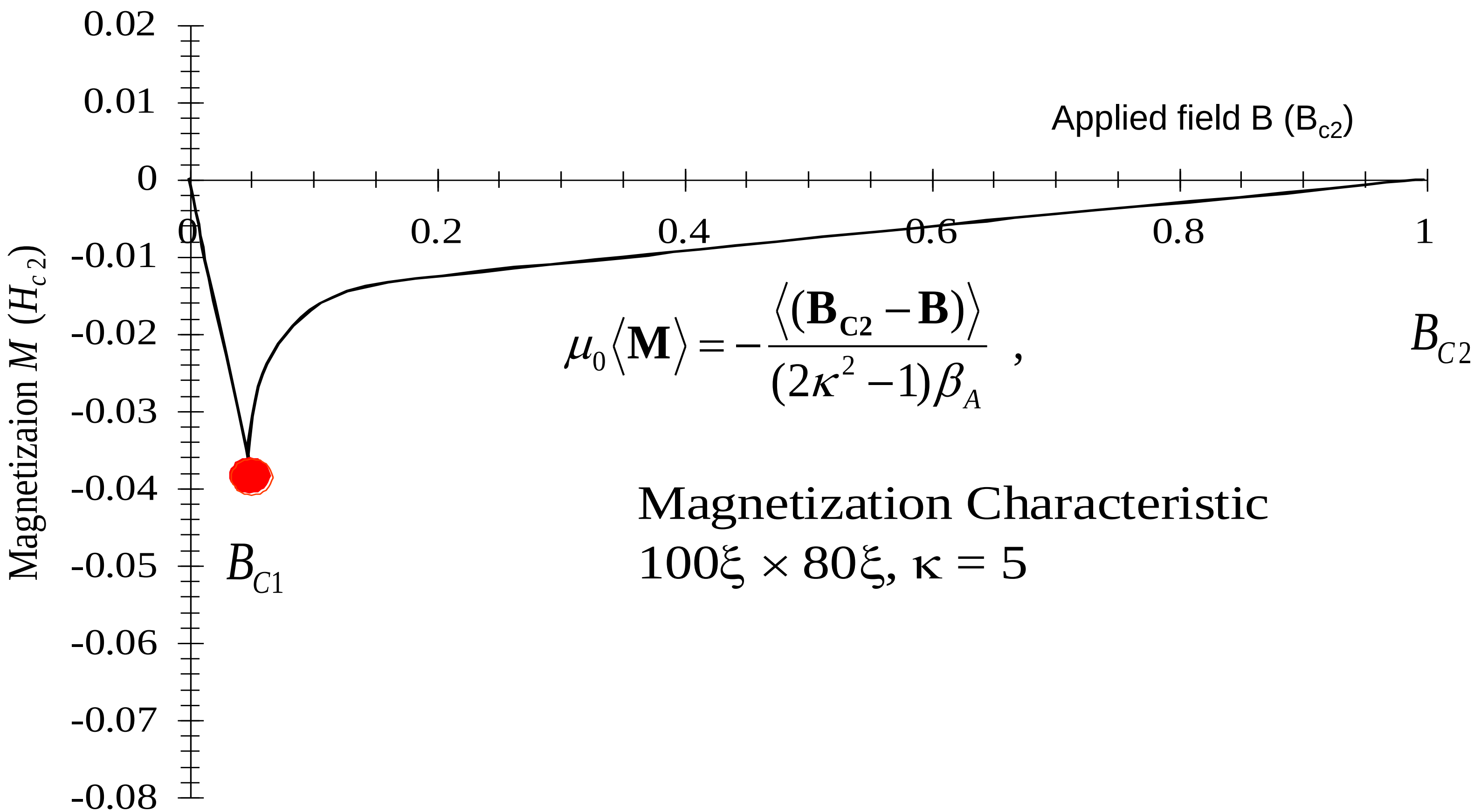
$$\frac{1}{\xi_0^2}\left(|\Delta|^2 - \left(1 - {T}/{T_c}\right)\right)\Delta + \left(\frac{\nabla}{i} - \frac{2e}{h}\mathbf{A}\right)^2\Delta + \frac{1}{D}\left(\frac{\partial}{\partial t} + i\,\frac{2e\varphi}{h}\right)\Delta = 0$$

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

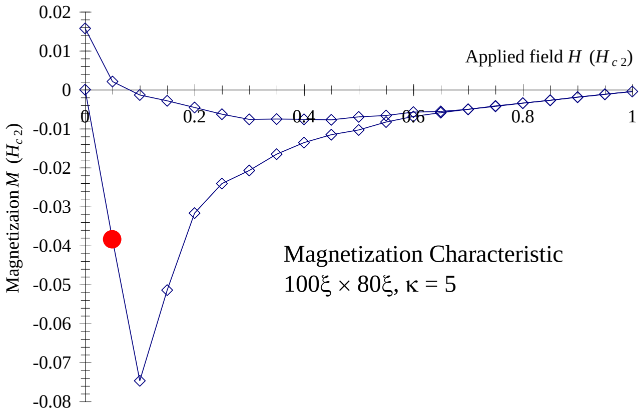
- *These equations were postulated by Schmid (1966), and then derived using microscopic theory in the gapless case by Gor'kov and Eliashberg (1968)*
- *Time dependant Ginzburg-Landau theory provides the framework for understanding flux pinning*

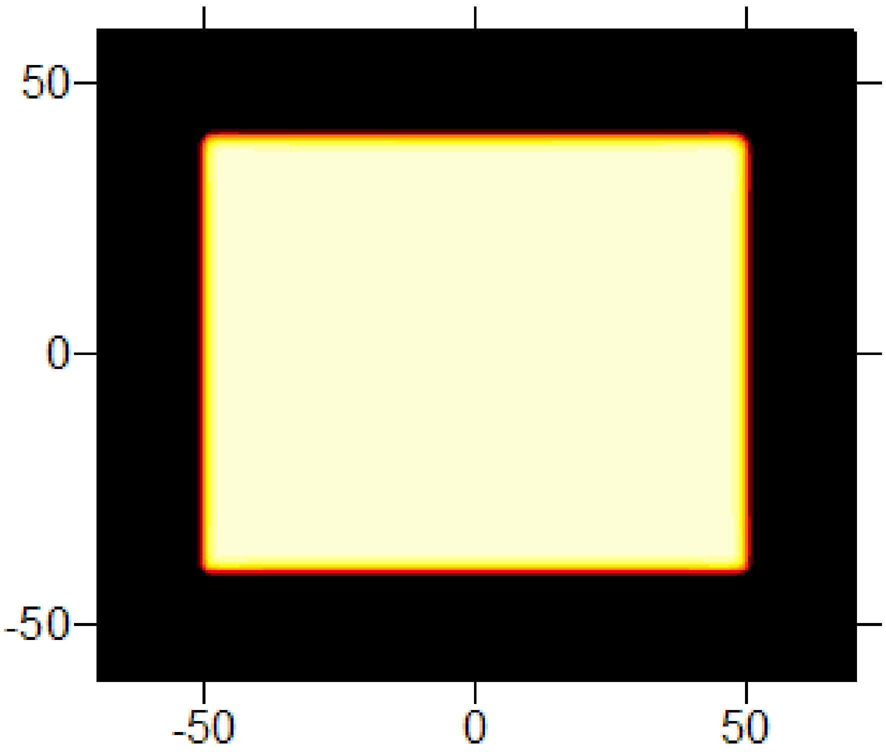
Reversible Magnetization Loop

- The reversible response of a superconductor



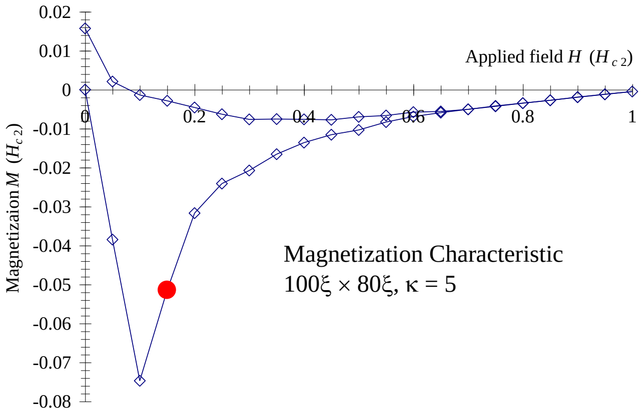
M vs. H for a Superconductor Coated With a Normal Metal, $\kappa = 5$

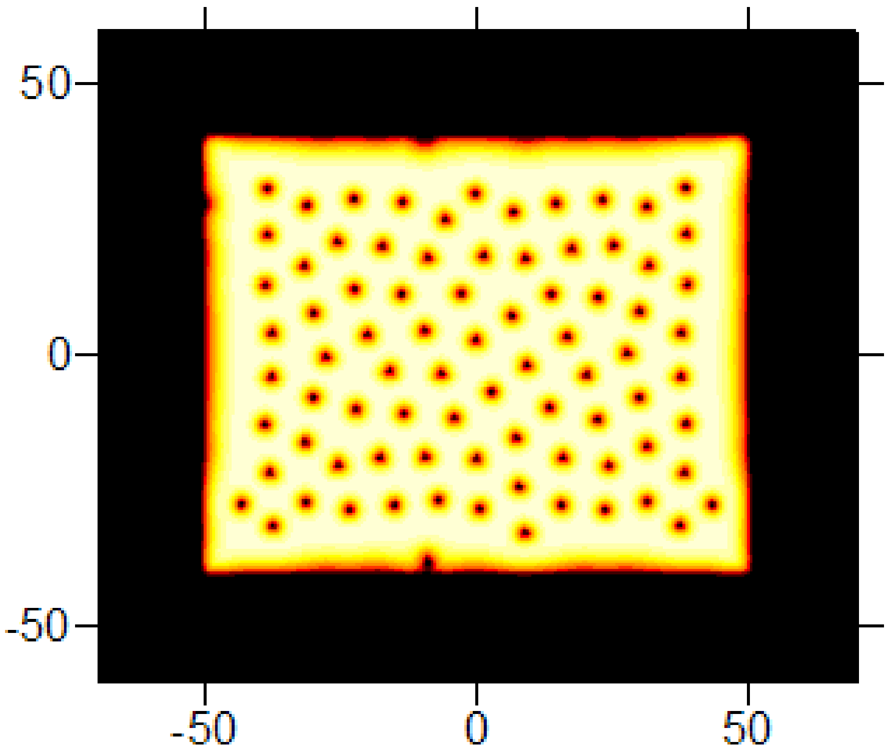




- $B = 0.05\ B_{c2}$
- The material is in the Meissner state

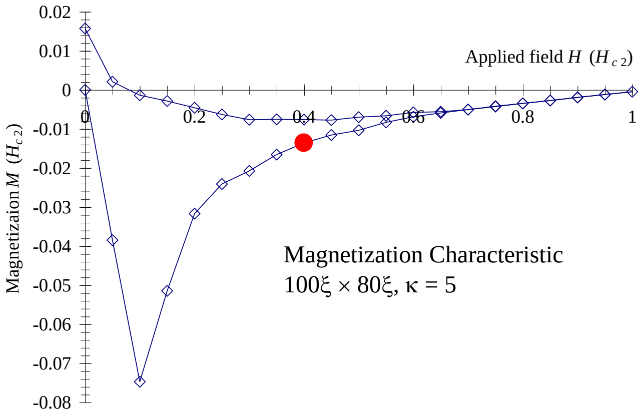
Magnetization Loop

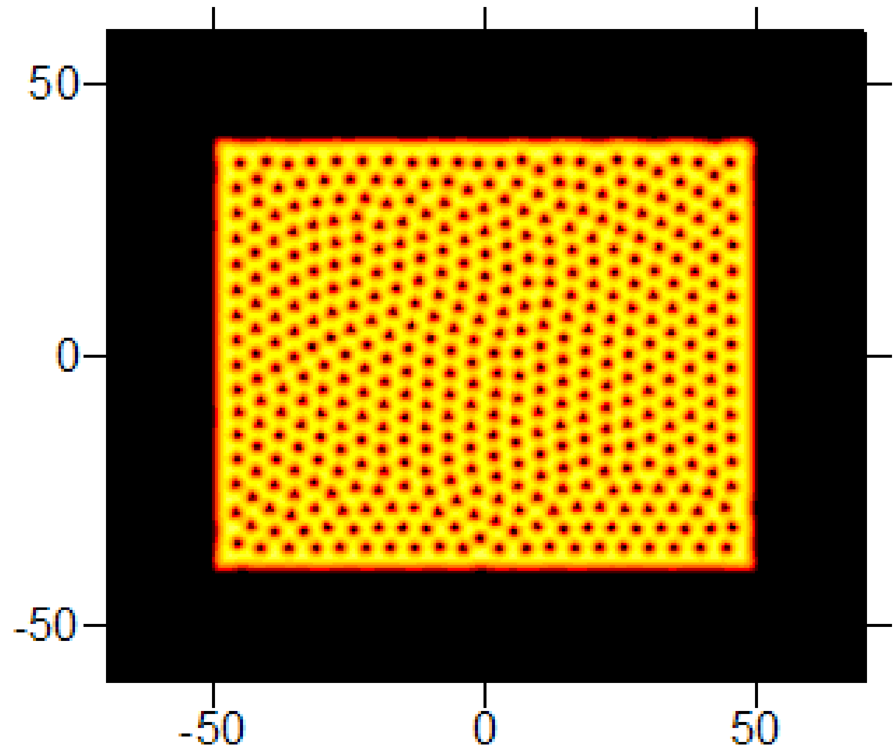




- $B = 0.15\ B_{c2}$
- The material is in the mixed state

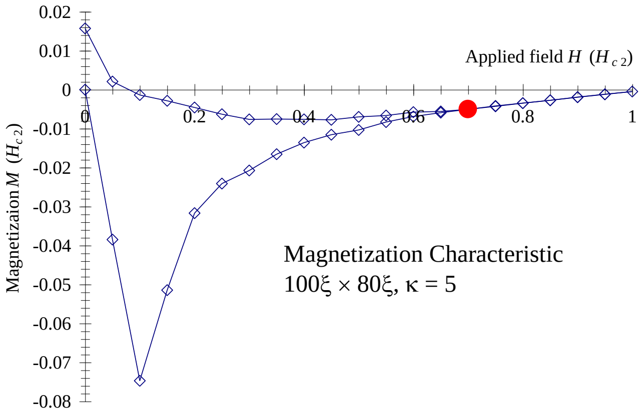
Magnetization Loop

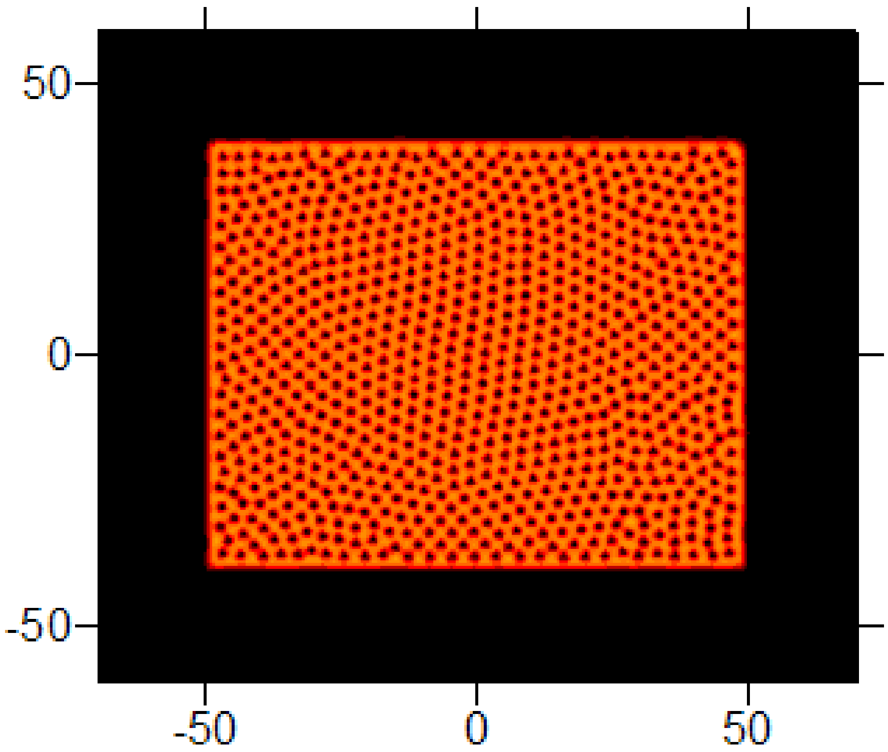




- B = 0.40 B_{c2}
- Note the nucleation of fluxons at the superconductor-normal boundary

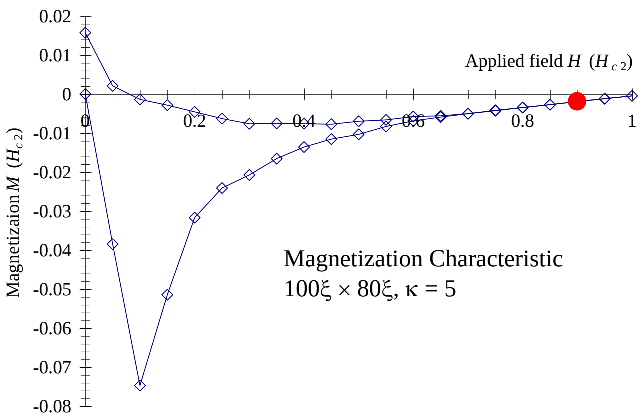
Magnetization Loop

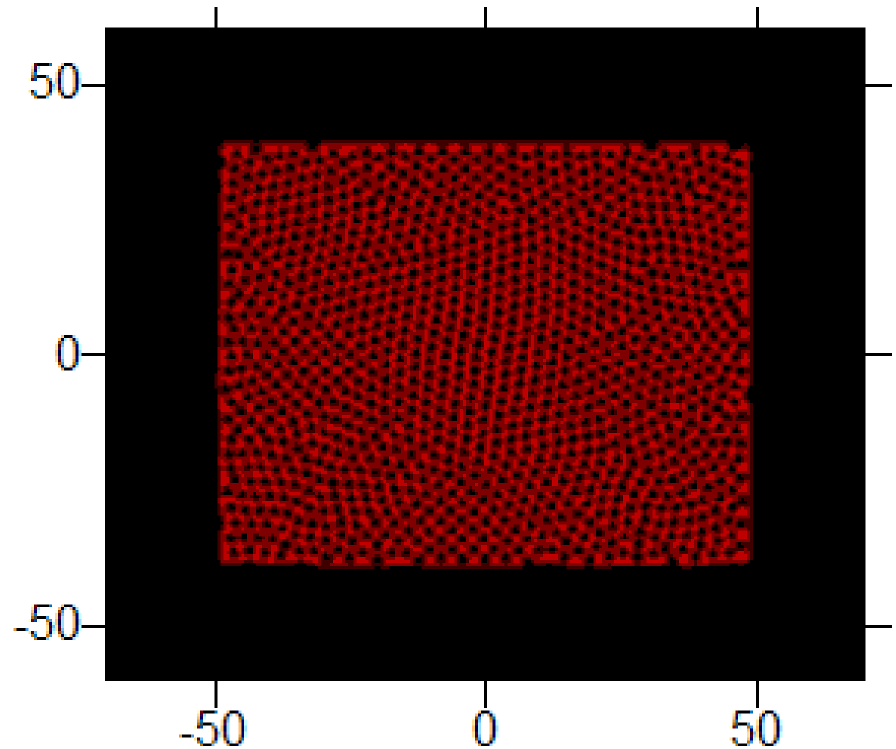




- $B = 0.70\ B_{c2}$
- In the reversible region, one can determine κ

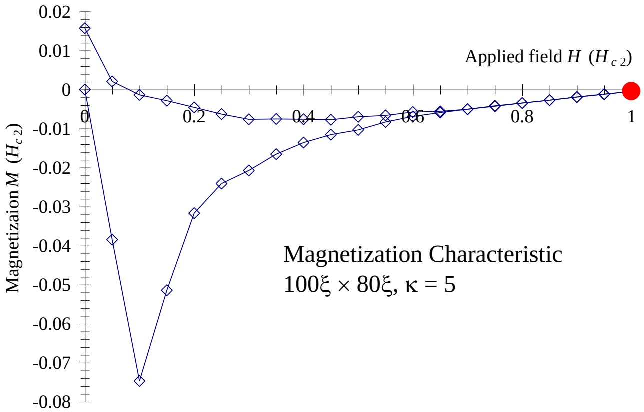
Magnetization Loop

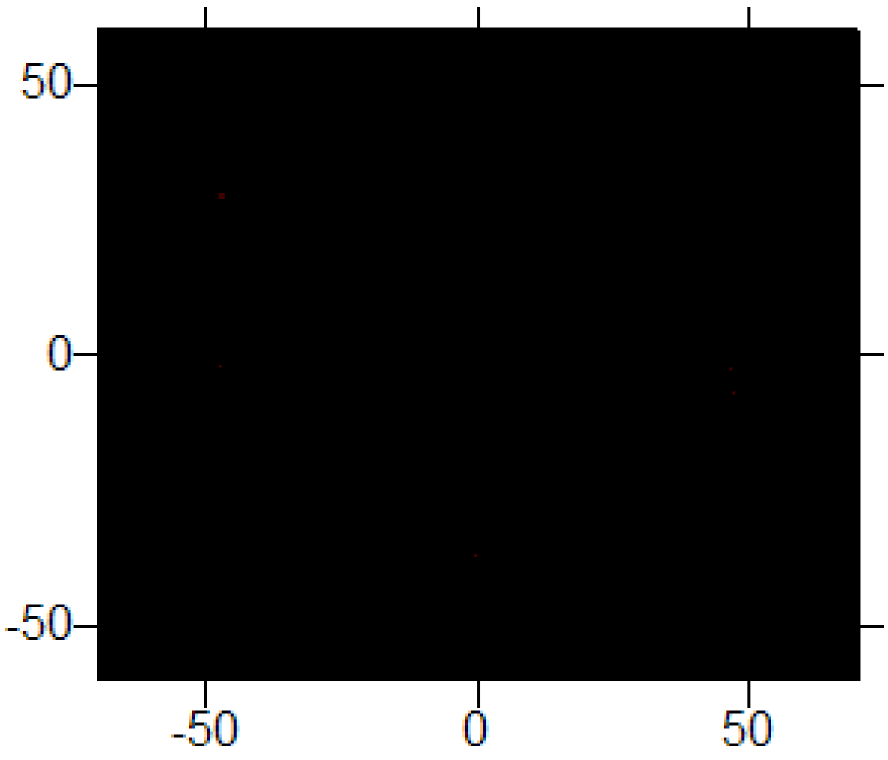




- $B = 0.90\ B_{c2}$
- The core of the fluxons overlap and the average value of the order parameter drops

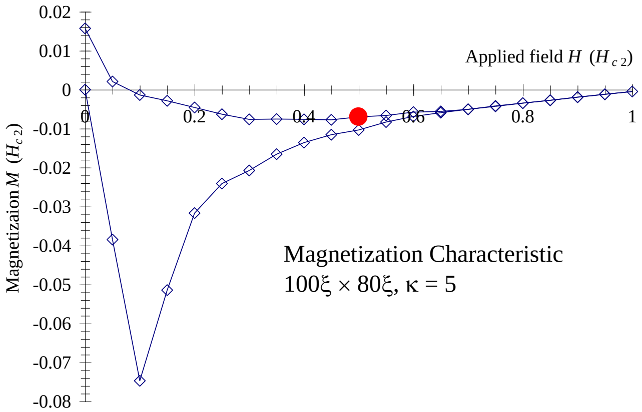
Magnetization Loop

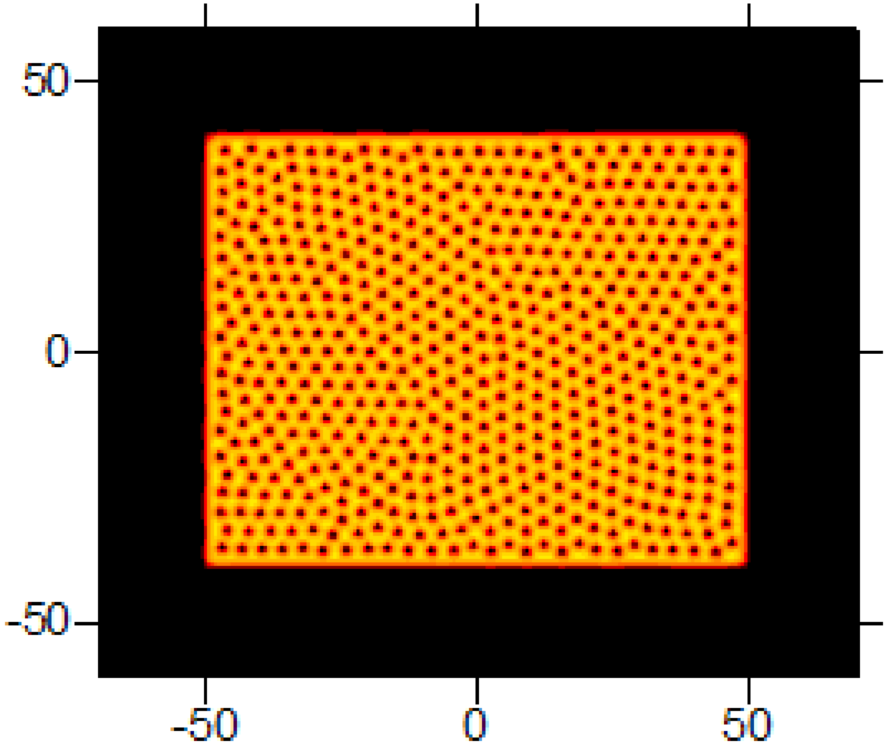




- $B = 1.00\ B_{c2}$
- Eventually the superconductivity is destroyed

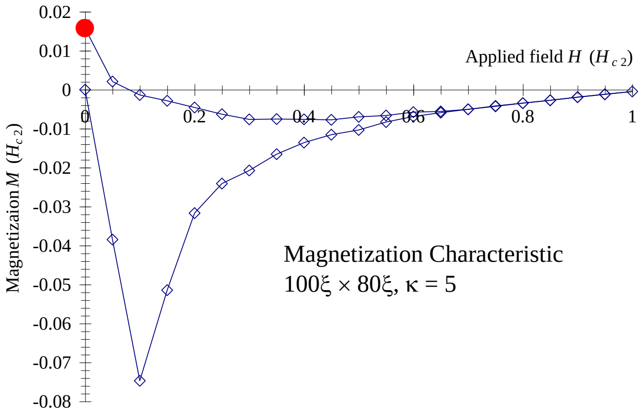
Magnetization Loop

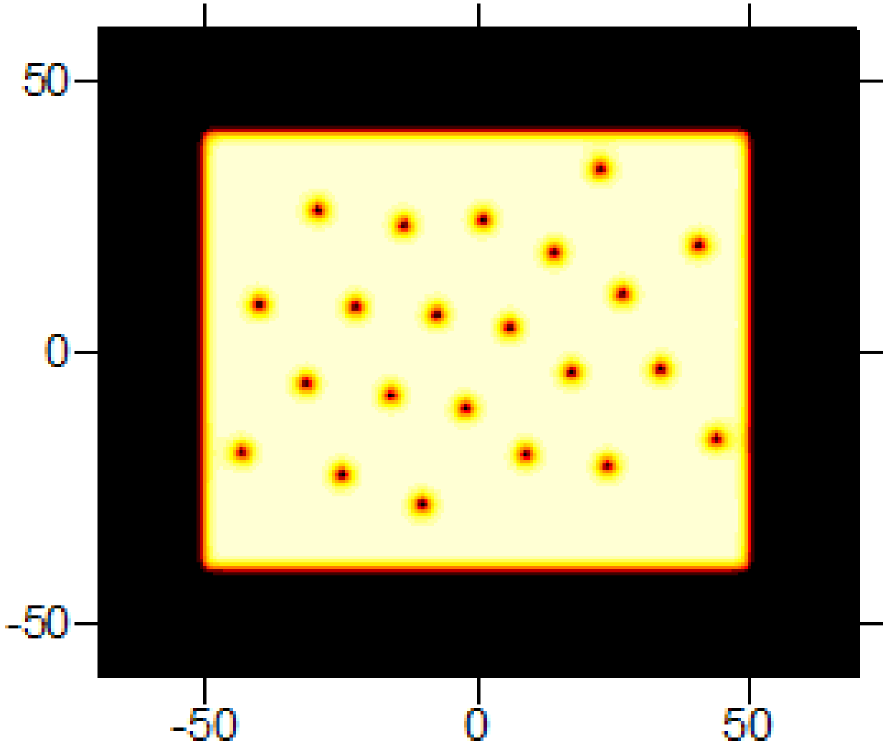




- $B = 0.50\ B_{c2}$
- Note the Abrikosov flux-line-lattice with hexagonal symmetry

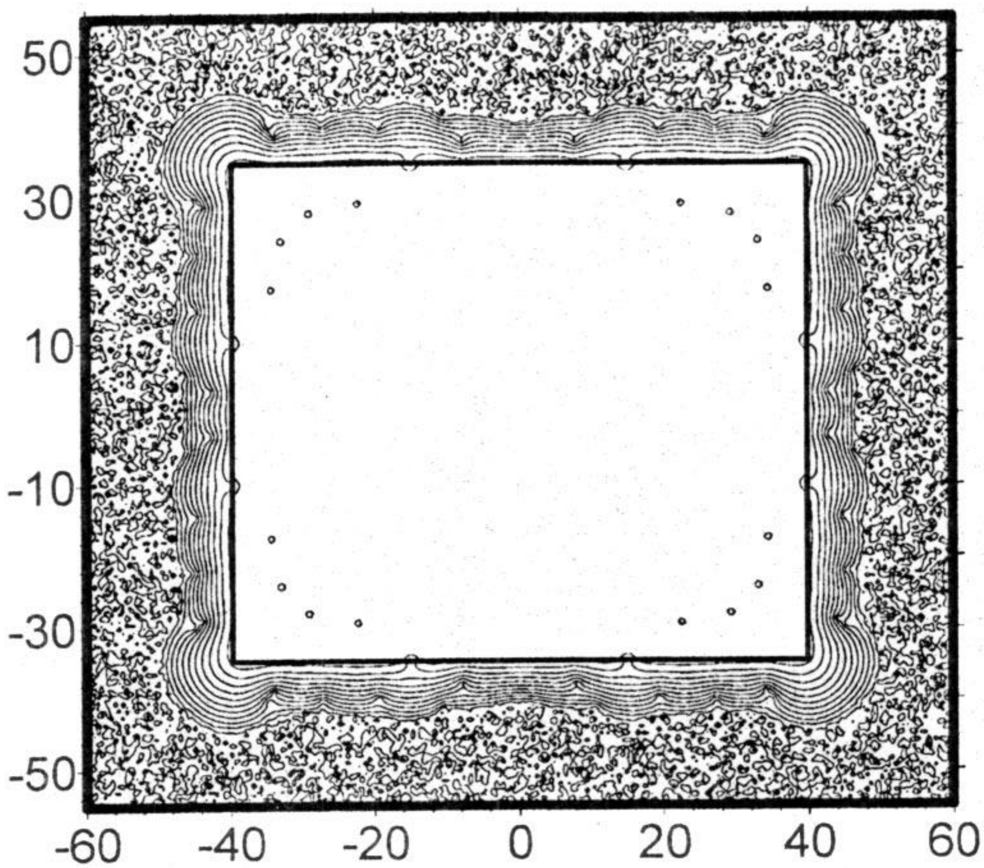
Magnetization Loop



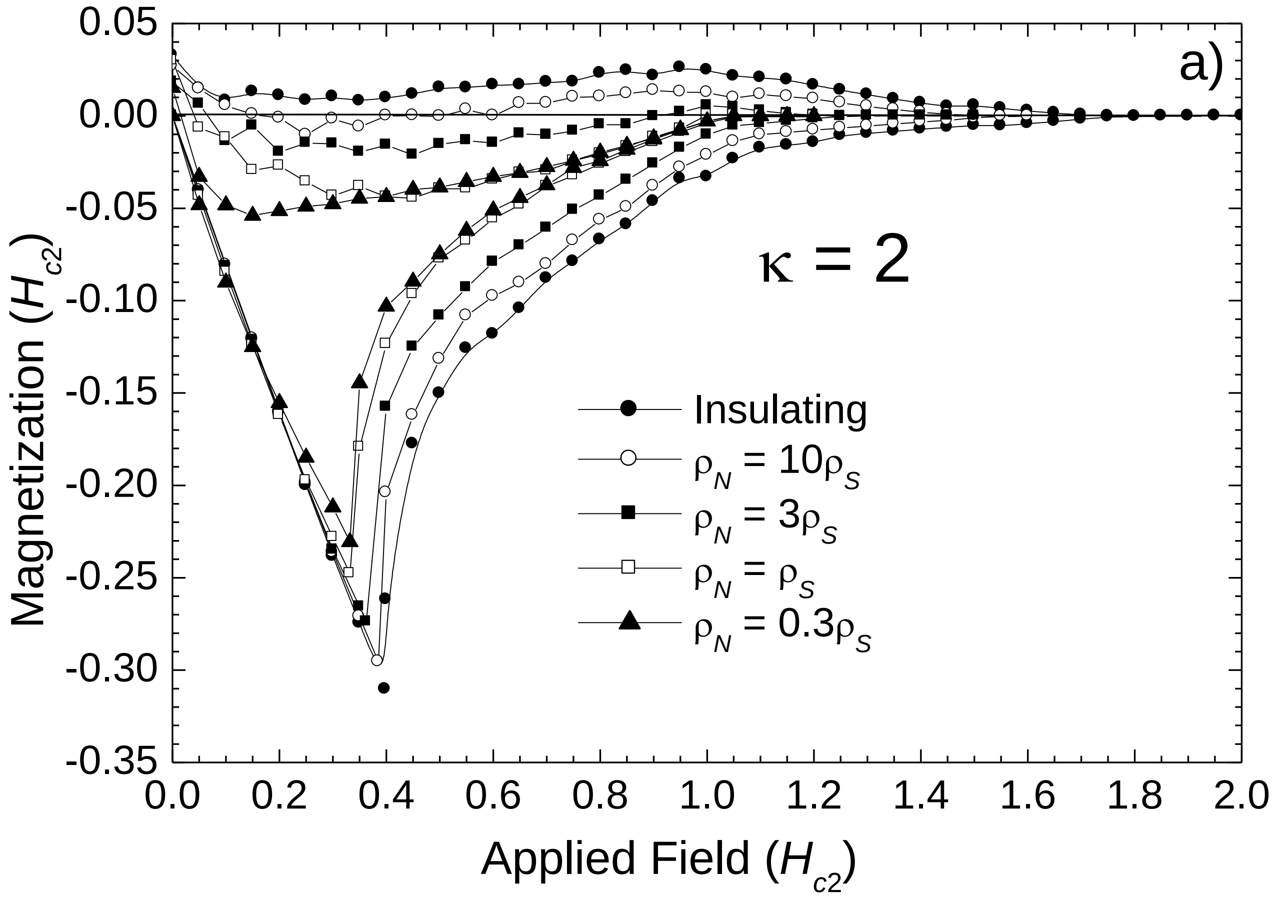


- $B = 0.00\ B_{c2}$
- A few fluxons remain as the inter-fluxon repulsion is lower than the surface pinning

Fluxon nucleation
– laminar and turbulent flow

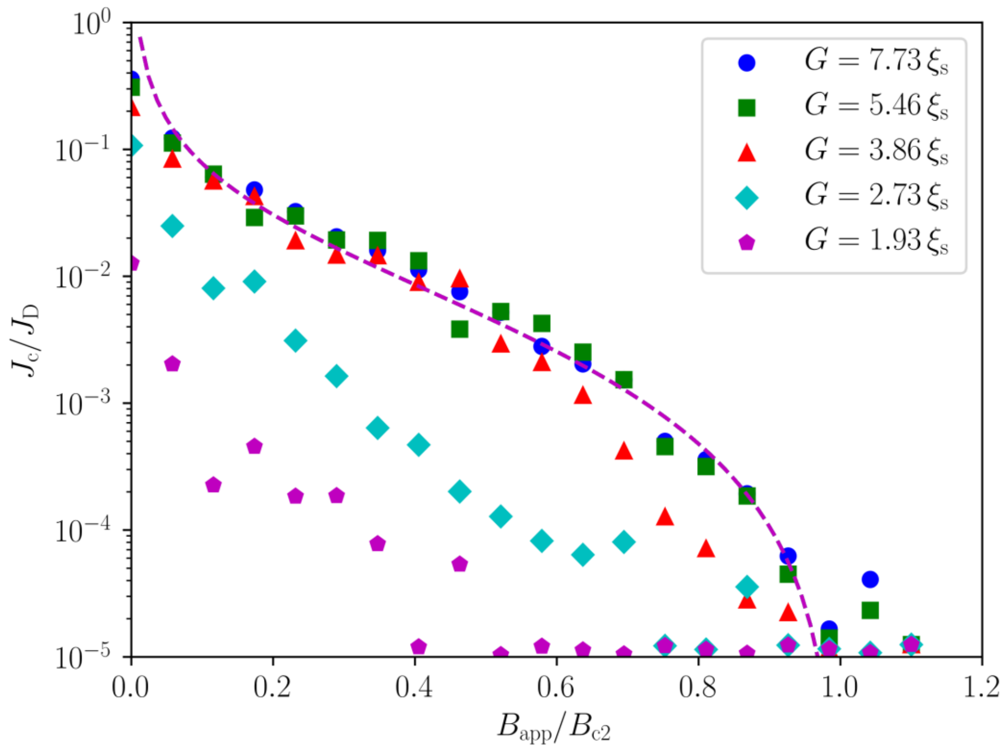


Surface pinning simulation



G. J. Carty, M. Machida, and D. P. Hampshire, "Numerical studies on the effect of normal metal coatings on the magnetisation characteristics of type-II superconductors," *Physical Review B,* vol. 71, p. 144507, 2005.

Surface pinning



$$J_c = \frac{J_D \xi_s}{\sqrt{2}\, 2w_s}\, b^{-1}(1-b)^2$$

J_D is the depairing current, G is the grain size and w_s is the width of the superconductor.

Modelling the Critical Current of Polycrystalline Superconducting Films in High Magnetic Fields . A. I. Blair and D P. Hampshire Submitted to IEEE Trans Super ASC2018.

Theory of RF superconductivity for resonant cavities

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Received 30 June 2016, revised 20 September 2016

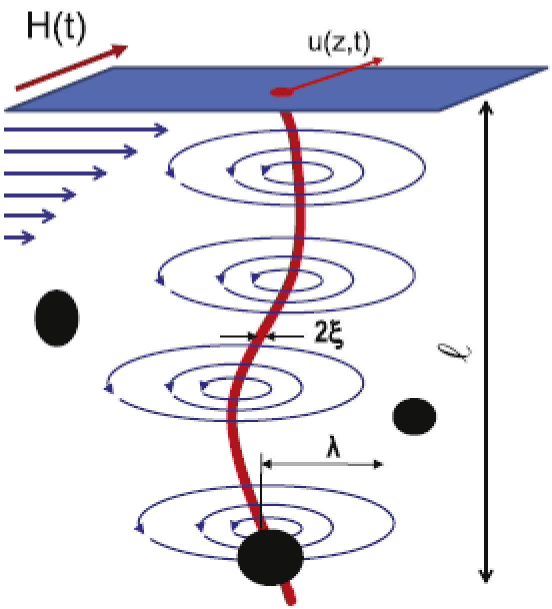


Figure 5. Pinned vortex segment oscillating under the RF Meissner current at the surface. Circular streamlines show vortex currents around the normal core (red) and black dots depict pinning centers. Reprinted figure with permission from [70], Copyright (2013) by the American Physical Society.

Point and surface pinning

$$F_{\mathrm{p}} = J_{\mathrm{c}} B = A \frac{B_{\mathrm{c2}}^{n}}{(2\pi\phi_0)^{1/2}\mu_0\kappa_1^{m}} b^{p}(1-b)^{q},$$

where B_{c2} is the upper critical field, κ_1 is the Ginzburg–Landau parameter, T_{c} is the critical temperature, $b = B/B_{\mathrm{c2}}$ is the reduced field, μ_0 is the vacuum permeability, ϕ_0 is the magnetic flux quantum, A is a material dependent constant, and n, m, p and q are constants.

Scaling laws for flux pinning in hard superconductors

Edward J. Kramer

Department of Materials Science and Engineering, Cornell University, Ithaca, New York 14850
(Received 17 October 1972)

τ_{max} is exceeded. Following Frenkel[26] we can estimate the maximum shear stress, τ_{max}[27] to be

$$\tau_{max} = C_{66}/2\pi, \tag{18}$$

and the elastic energy stored per unit volume as

$$E_s = (C_{66}/24\pi^2)[1/(1 - a_0\sqrt{\rho})]^2. \tag{19}$$

In deriving Eq. (19) (Appendix II) a model of unbreakable pins lying in planes, separated by a distance $1/\sqrt{\rho}$ and parallel to the Lorentz force, has been assumed. The pinning force per unit volume, from Eqs. (4) and (19), is then

$$\mathscr{F}_s(h) = K_s h^{1/2}(1-h)^2. \tag{20}$$

As demonstrated in Appendix II, the parameter K_s is given by

$$K_s = C_s(H_{c2})^{5/2}/\kappa_1^2 \text{ dyn/cm}^3 \tag{21a}$$

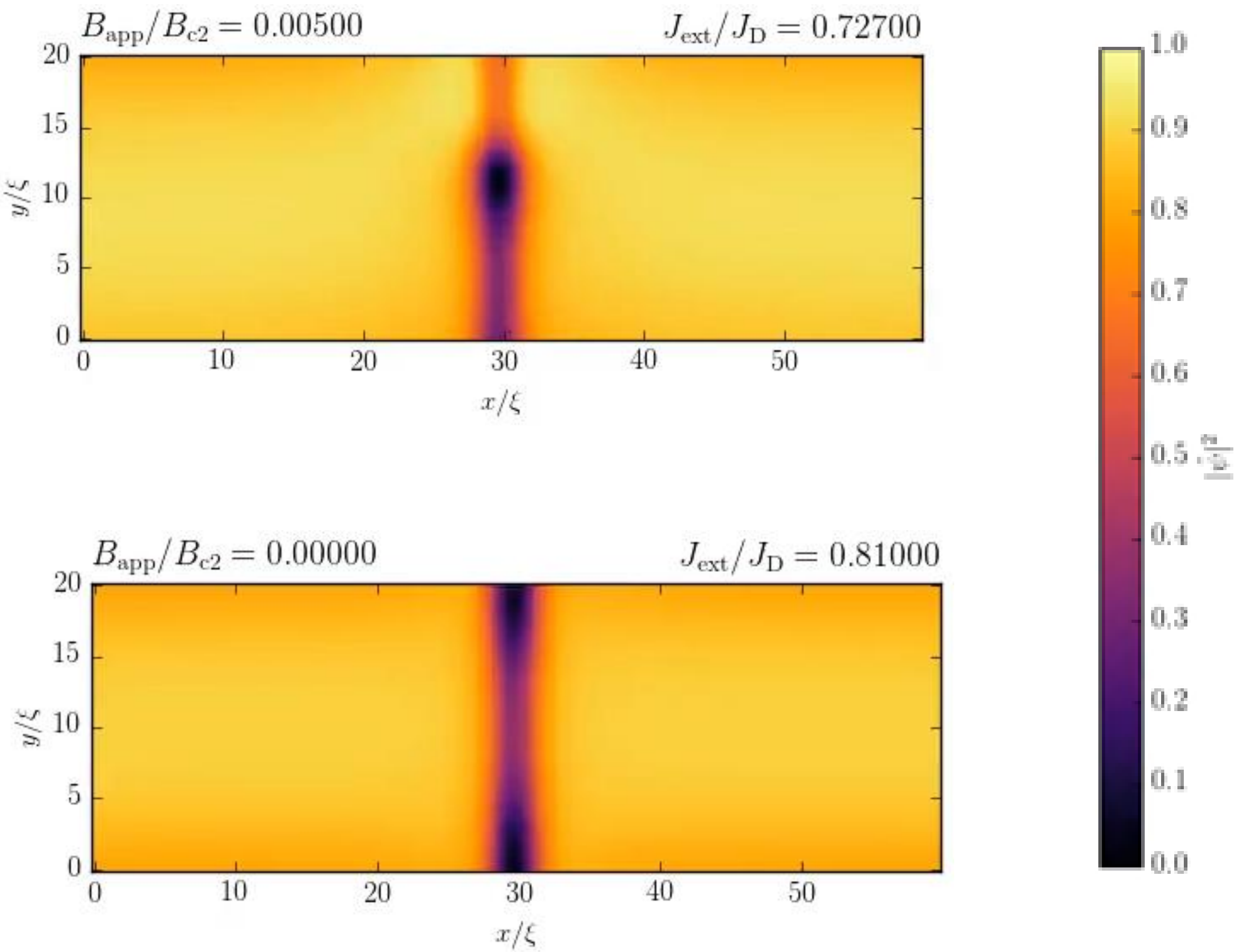
or

E. J. Kramer, "Scaling Laws for Flux Pinning in Hard Superconductors," *Journal of Applied Physics,* vol. 44, pp. 1360-1370, 1973.

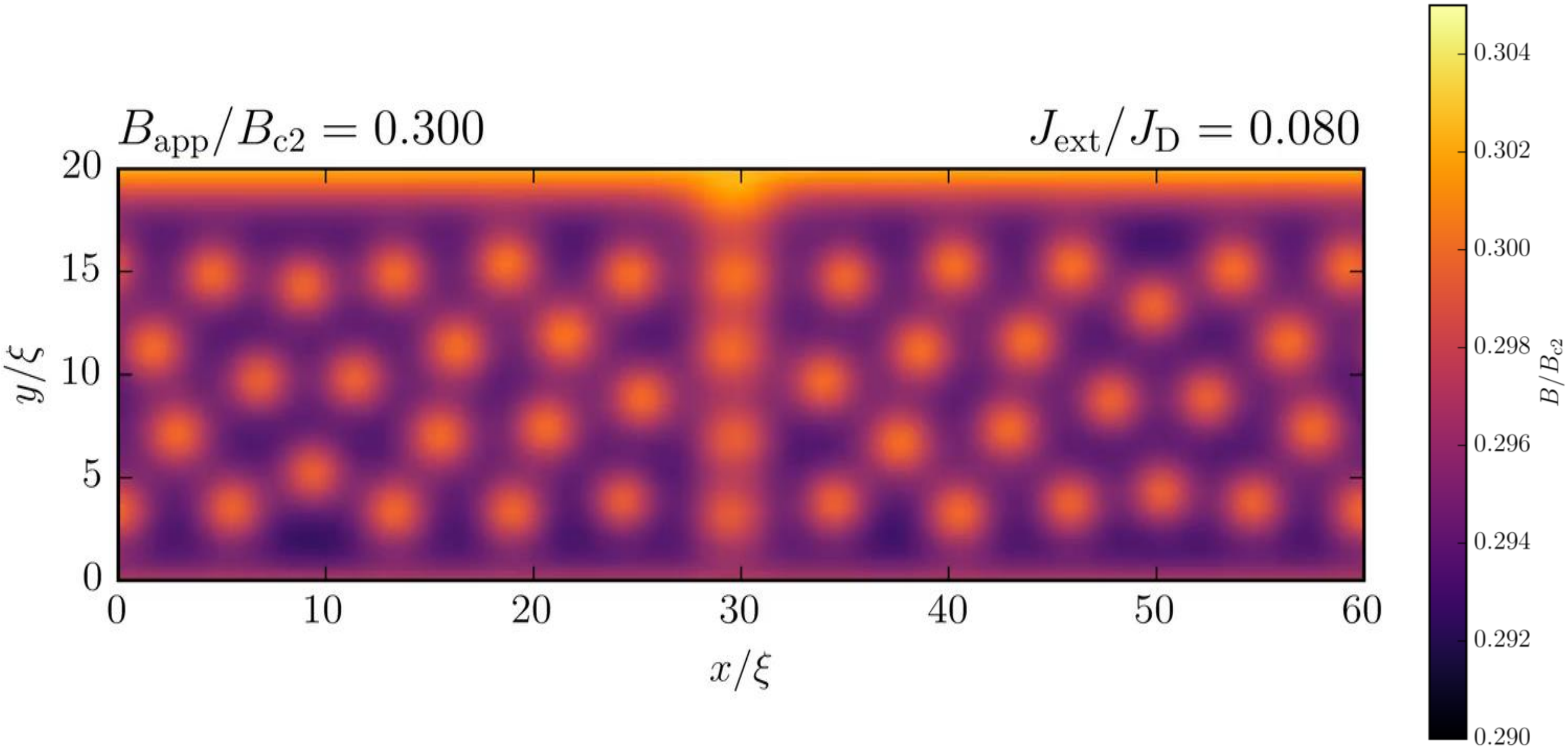
Point and surface pinning and also Flux shear mechanism – Kramer dependence

$$F_{\mathrm{p}} = J_{\mathrm{c}}B = A\frac{B_{\mathrm{c2}}^{n}}{(2\pi\phi_0)^{1/2}\mu_0\kappa_1^{m}}b^{p}(1-b)^{q},$$

where B_{c2} is the upper critical field, κ_1 is the Ginzburg–Landau parameter, T_{c} is the critical temperature, $b = B/B_{\mathrm{c2}}$ is the reduced field, μ_0 is the vacuum permeability, ϕ_0 is the magnetic flux quantum, A is a material dependent constant, and n and m are constants, and for flux shear $p = 1/2$ and $q = 2$.



Modelling the Critical Current of Polycrystalline Superconducting Films in High Magnetic Fields . A. I. Blair and D P. Hampshire Submitted to IEEE Trans Super ASC2018.



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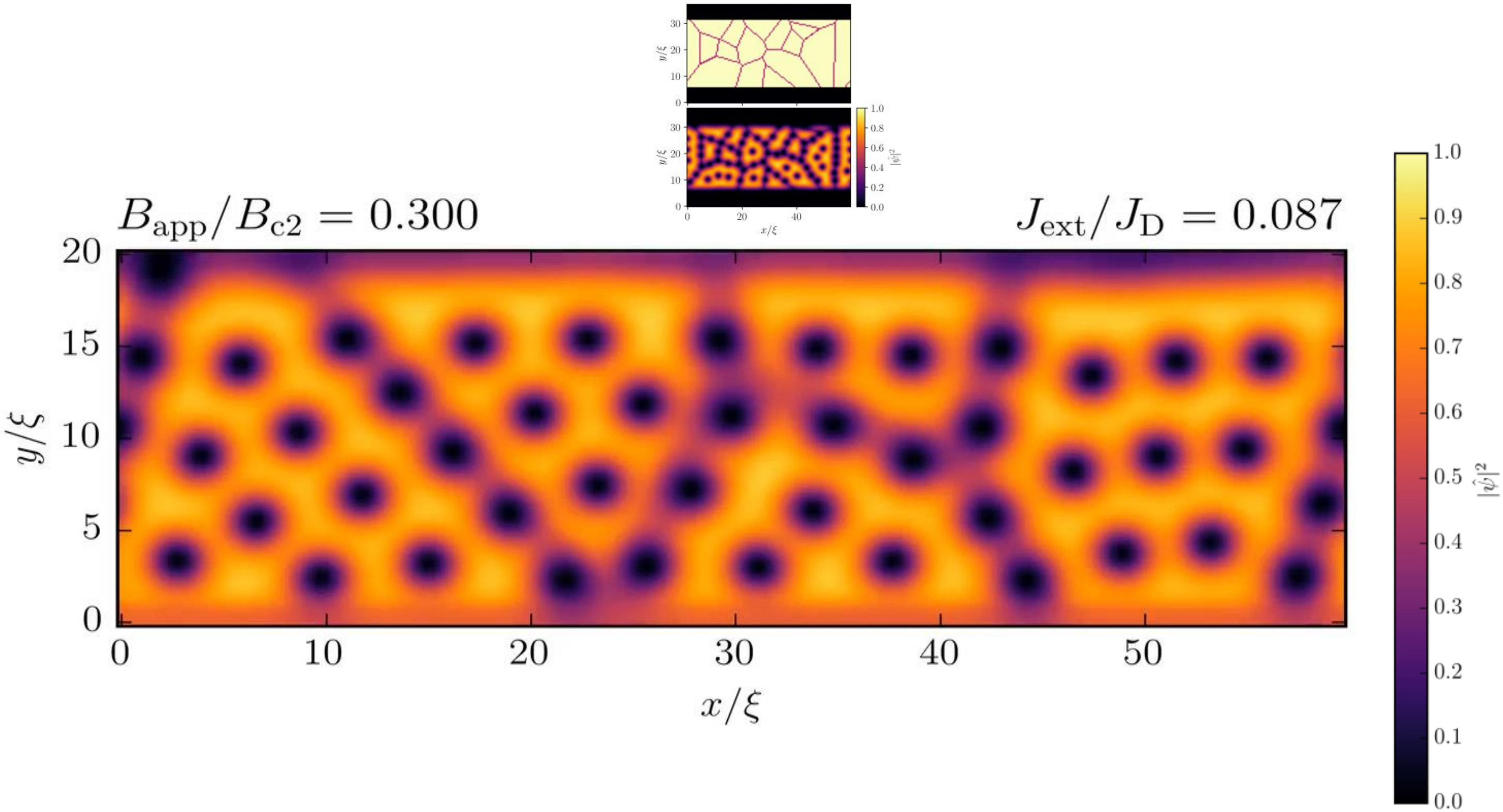

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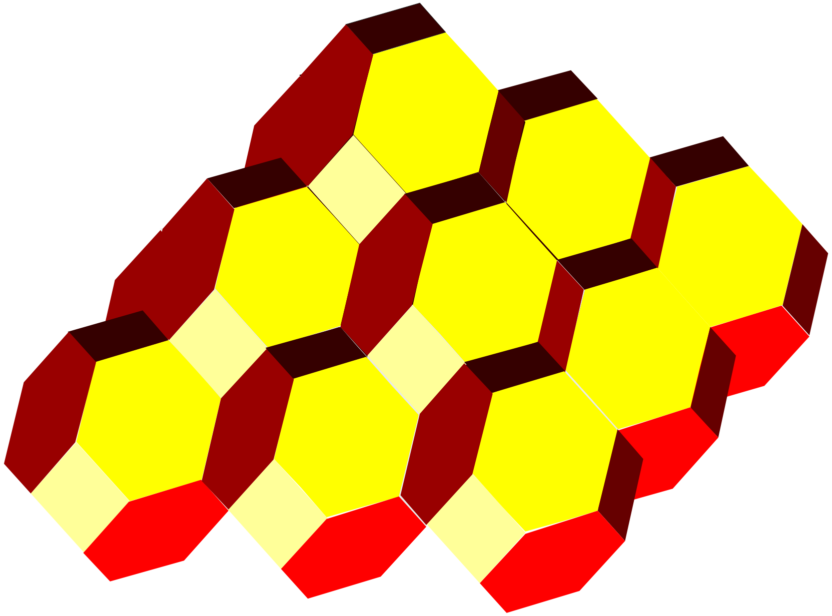
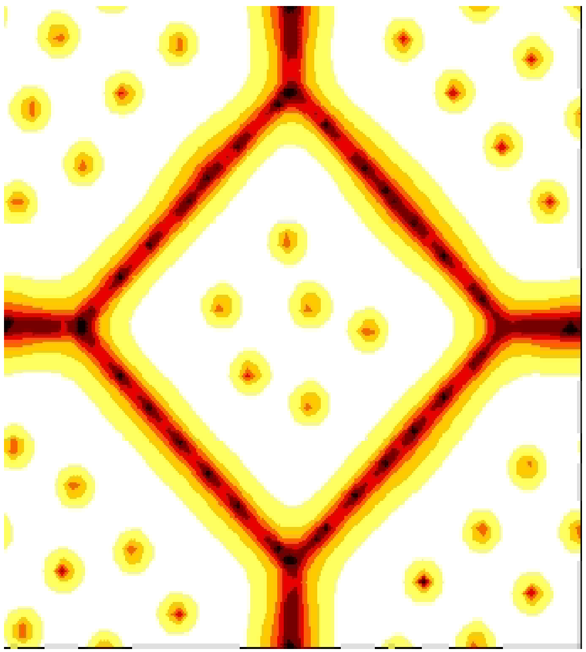
Model for a polycrystalline superconductor

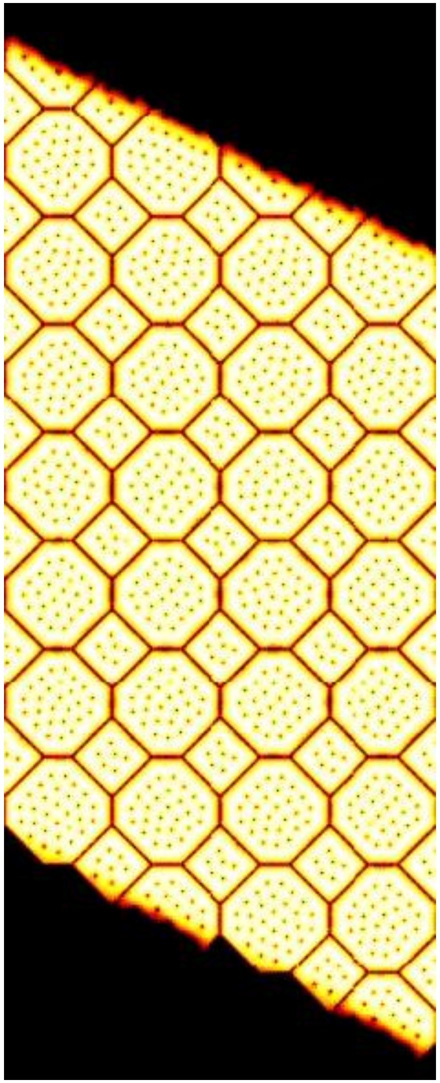
- A collection of truncated octahedra



Order Parameter at 0.43 B_{c2}

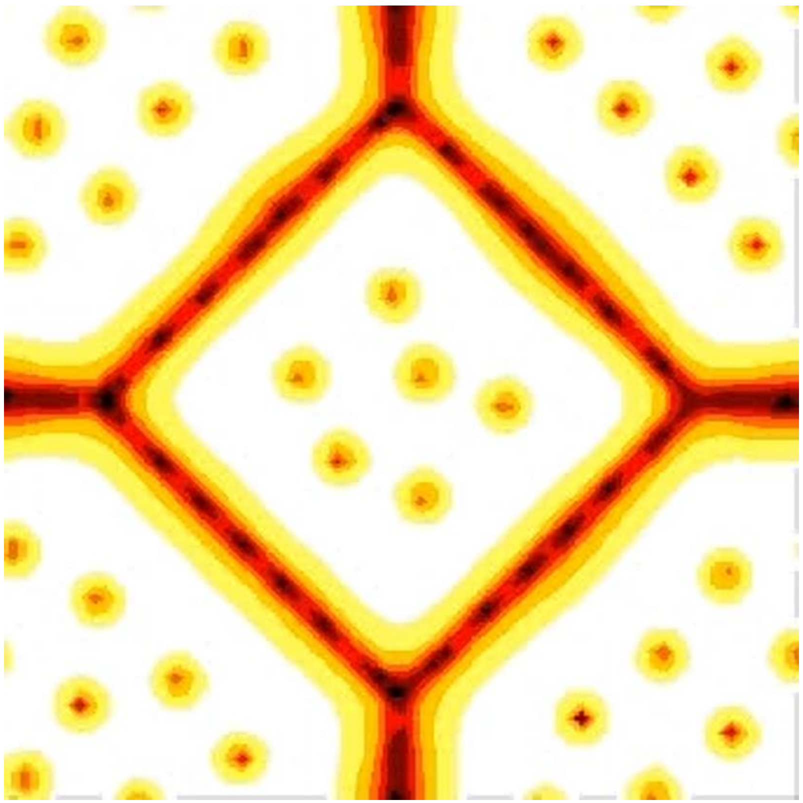
- The motion of flux through the system takes place predominantly along the grain boundaries.





G. J. Carty and D. P. Hampshire, "Visualising the mechanism that determines the critical current density in polycrystalline superconductors using time-dependent Ginzburg-Landau theory," *Physical Review B,* vol. 77, p. 172501, 2008.

Order Parameter at 0.43 B_{c2}



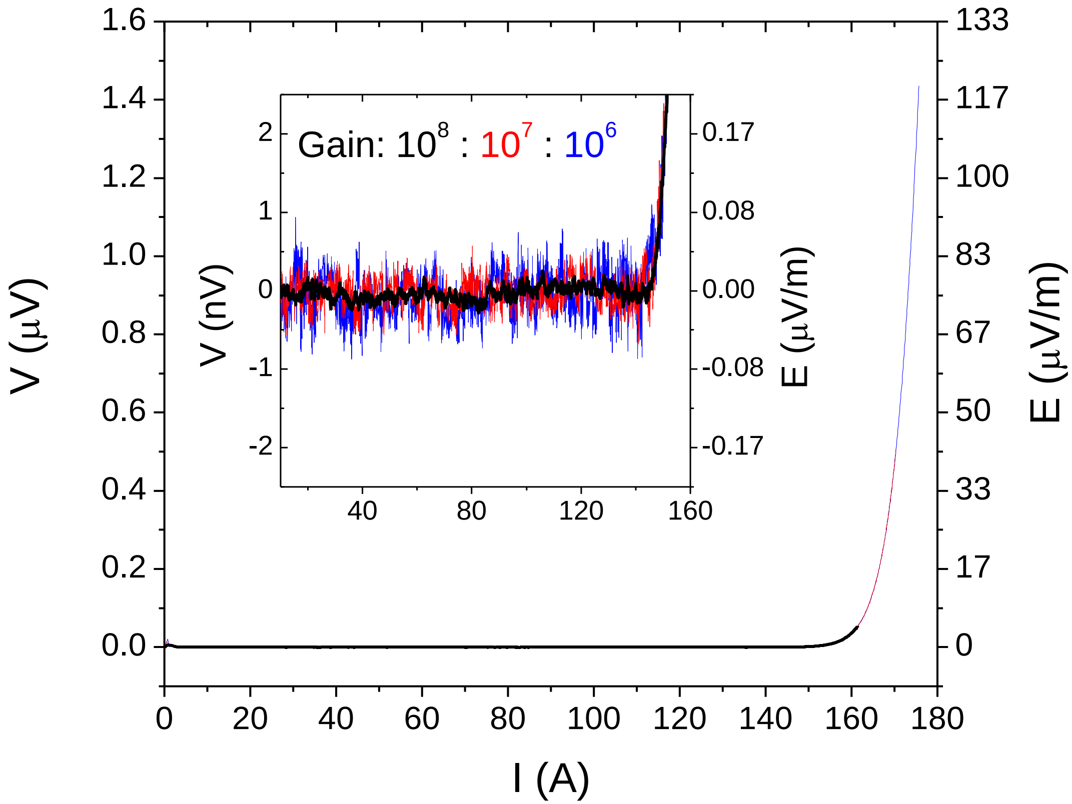
- Flux flows predominantly along the grain boundaries.
- There are macroscopic current loops and microscopic current loops

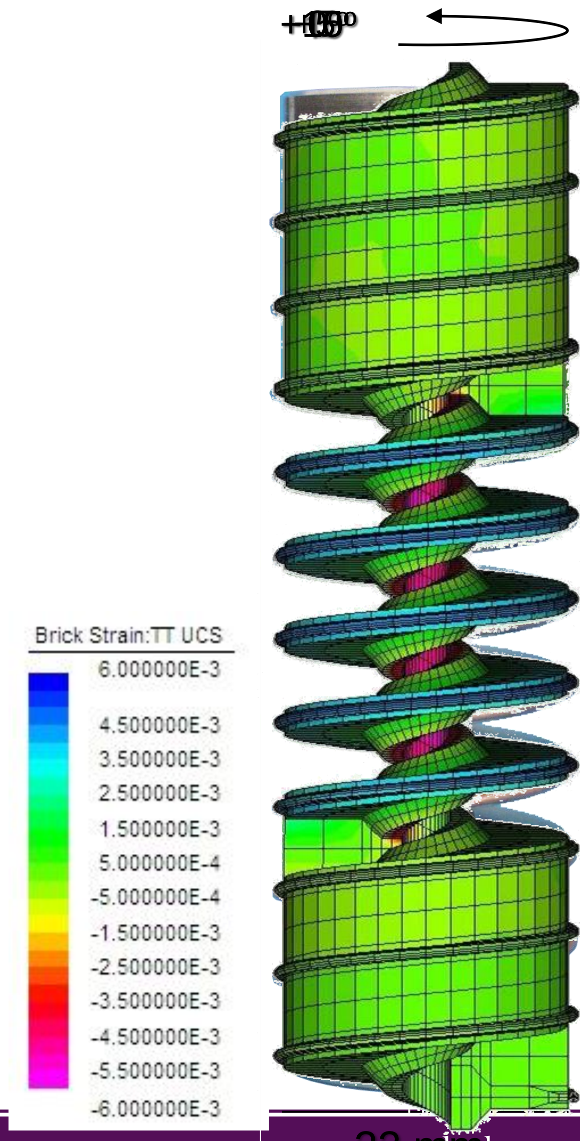
Pinning

$$F_{\mathrm{p}} = J_{\mathrm{c}}B = A\frac{B_{\mathrm{c2}}^{n}}{(2\pi\phi_0)^{1/2}\mu_0\kappa_1^{m}}b^{p}(1-b)^{q},$$

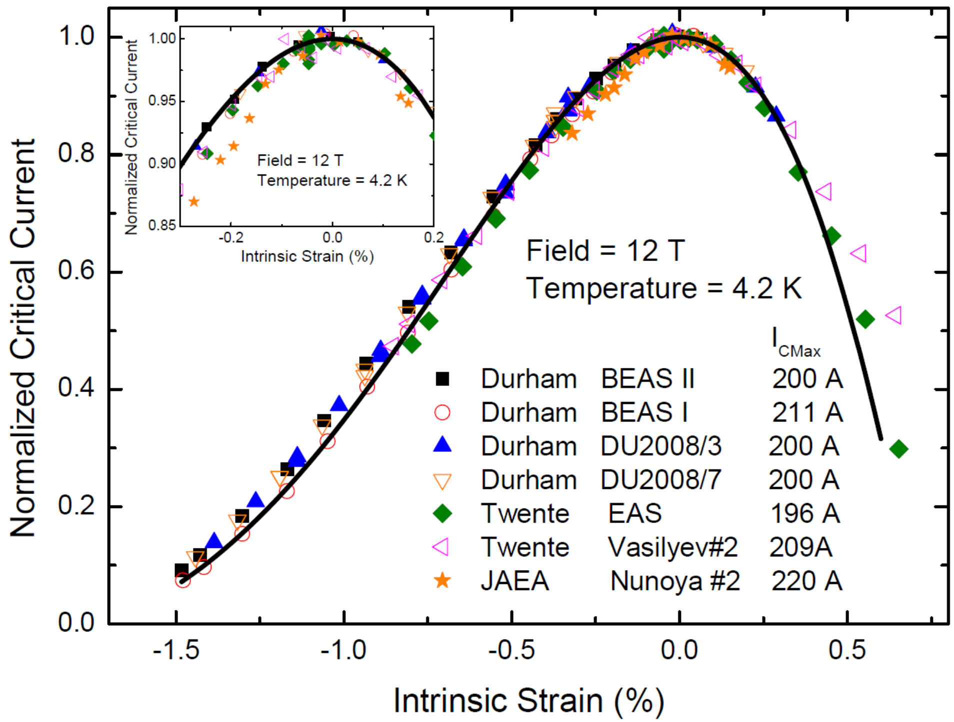
- Universal scaling law

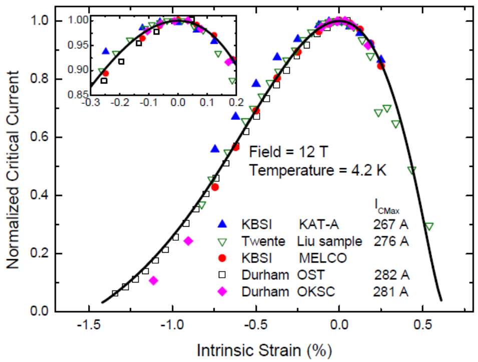
Measurements on LTS Materials using Springs



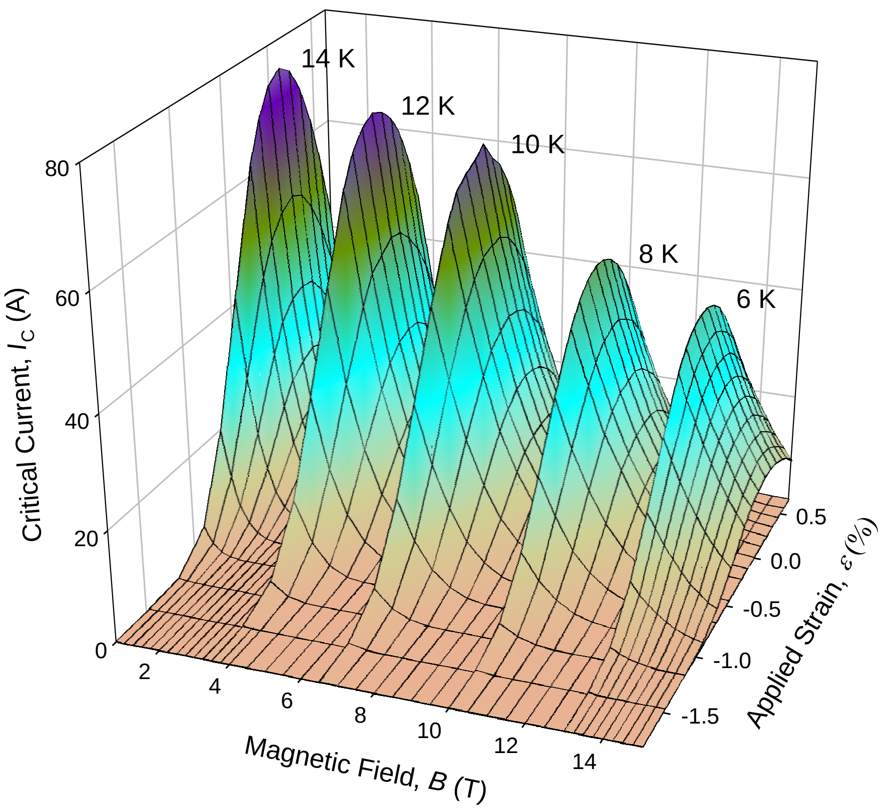


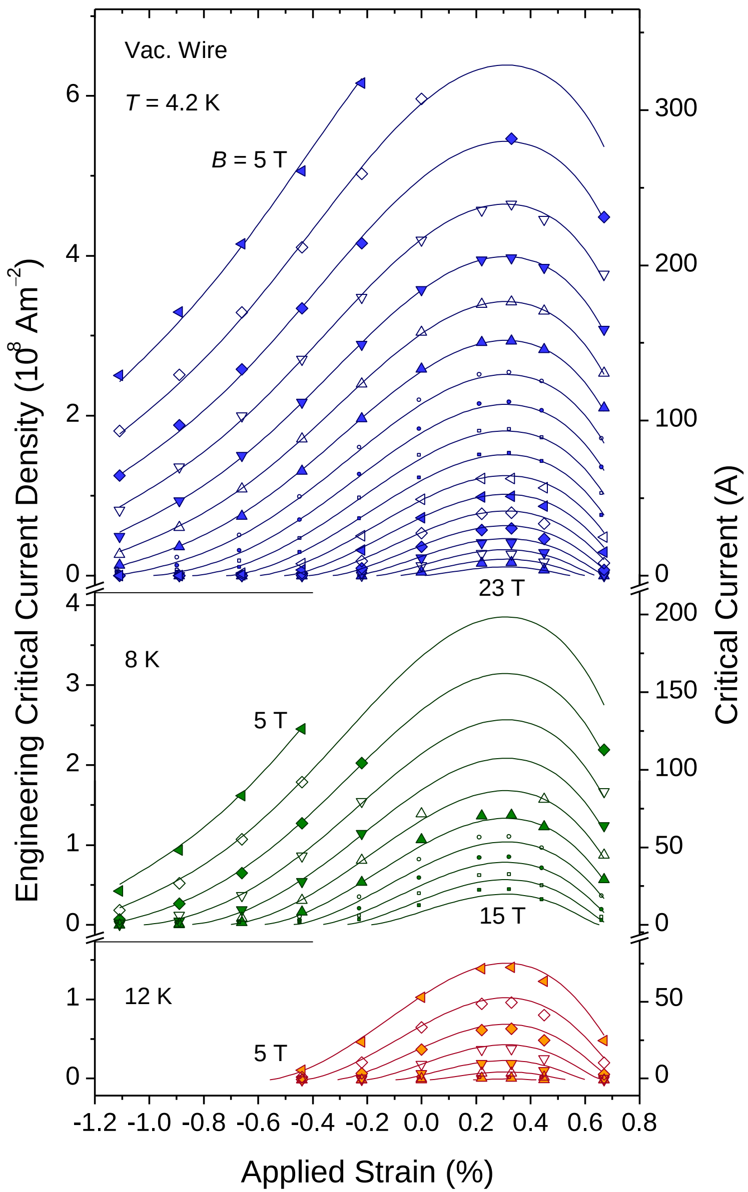
Variable Strain measurements





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





HTS Tape

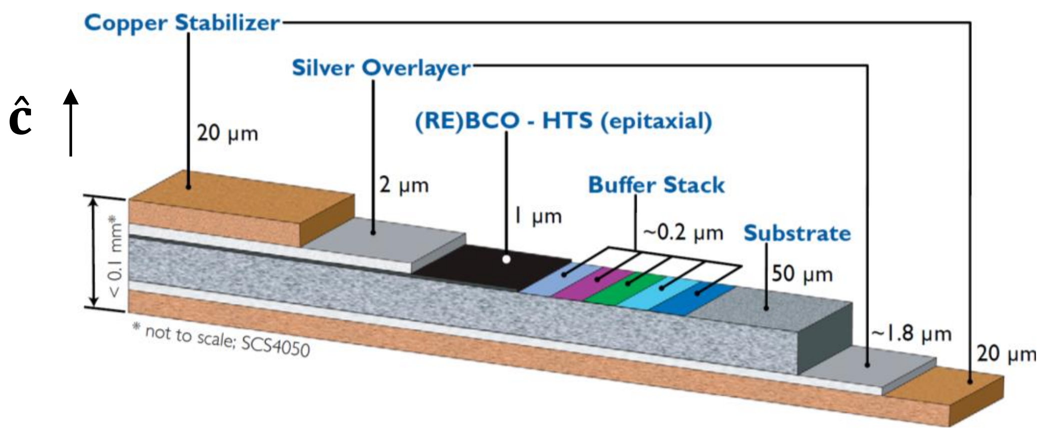
4 mm wide SuperPower Tape (non-AP)

$(RE)Ba_2C_3O_{7-\delta}$ (RE = Rare Earth), $T_c \approx 90$ K

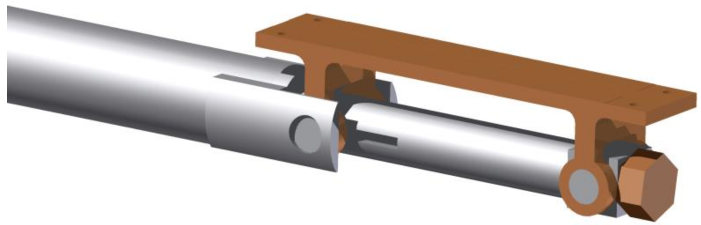
Quasi single crystal, kilometres in length

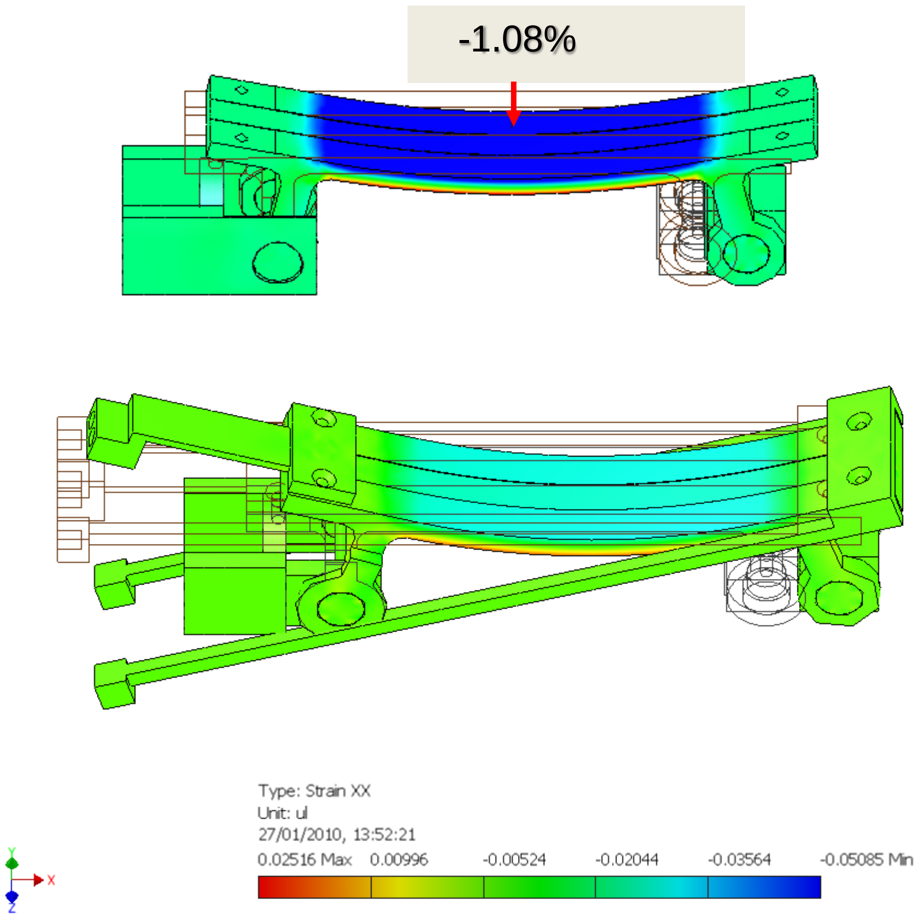
The resultant conductor:

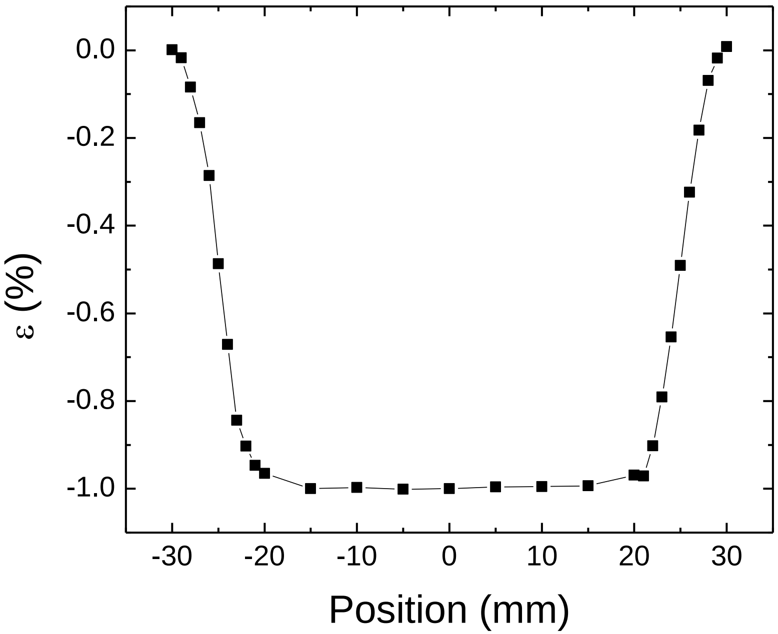
- A tape
- Crystal c-axis is aligned normal to the tape surface
- Highly anisotropic



Variable strain measurements on HTS superconductors

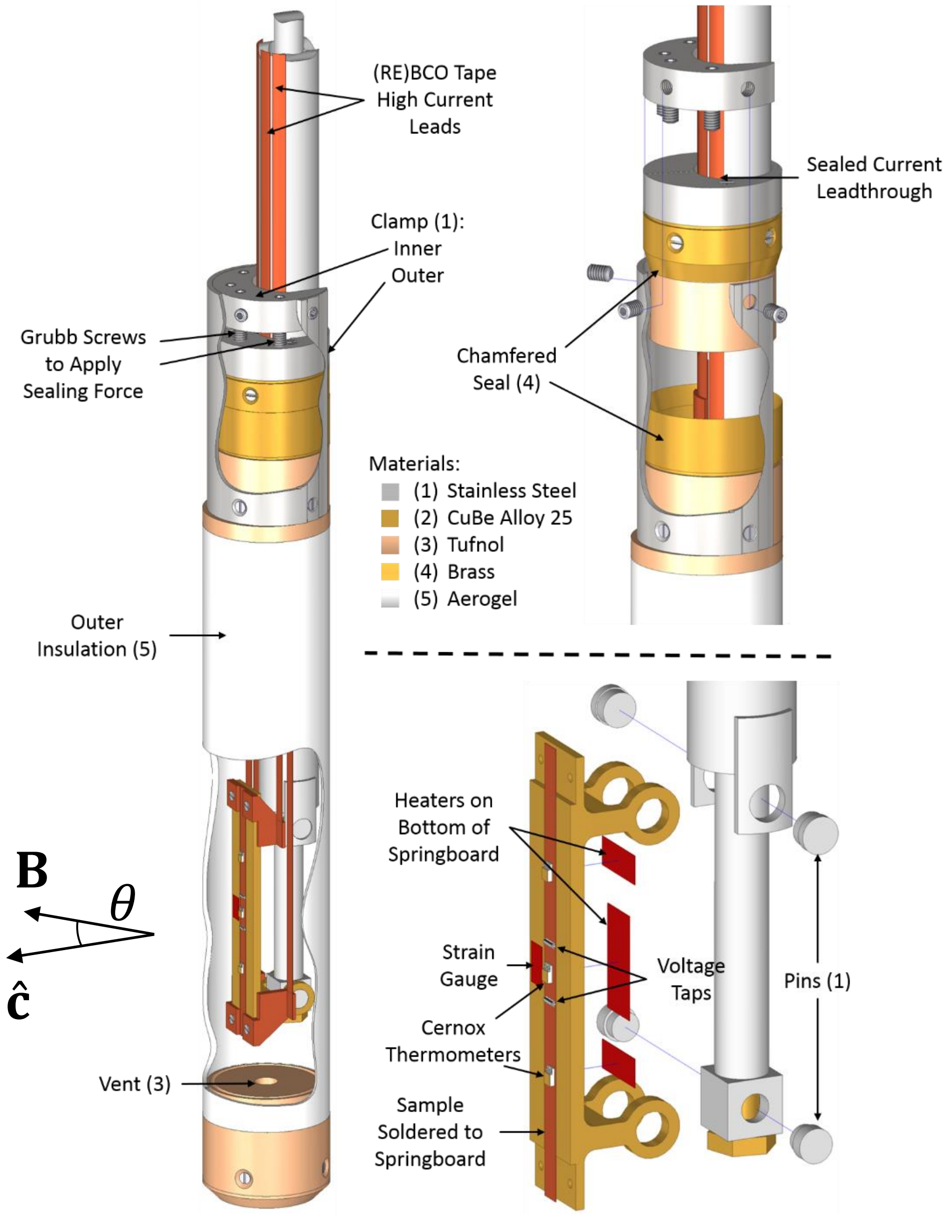






homogeneous strain along length to 7 parts in 1000

Bending apparatus tested from - 1.4% to +0.5%



Applied Strain

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

Temperature

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

Current

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

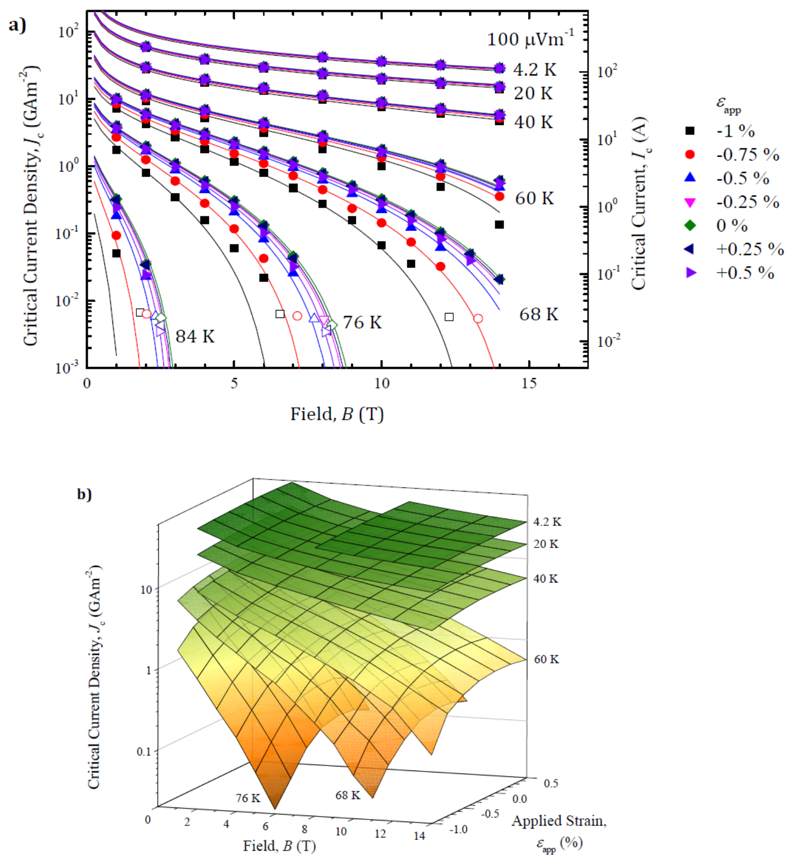
Angle

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

Magnetic Field

$B \leq 15\ \mathrm{T}$

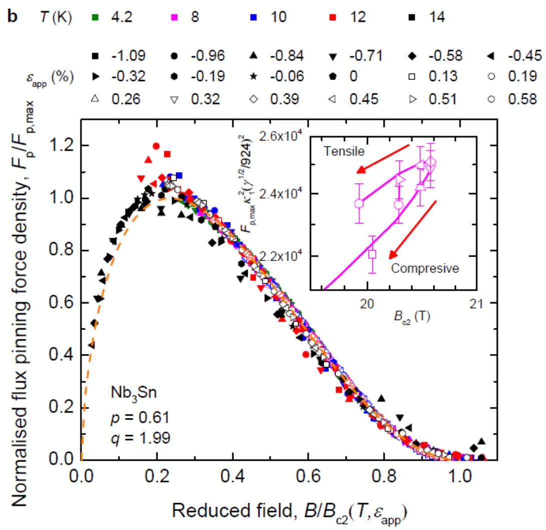
Strain Behaviour of J_c in $Y_1Ba_2Cu_3O_7$



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

Multimodal strain dependence of the critical parameters in high field technological superconductors. P Branch, Y Tsui, K Osamura, D Hampshire submitted to Super. Sci and Technol. November 2017.

- Universal scaling laws for Nb_3Sn and REBCO



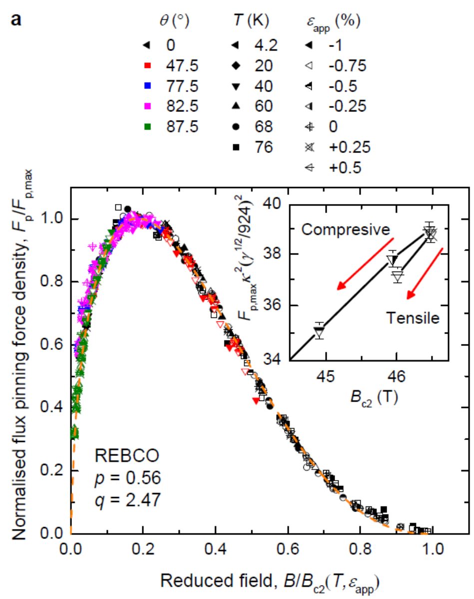
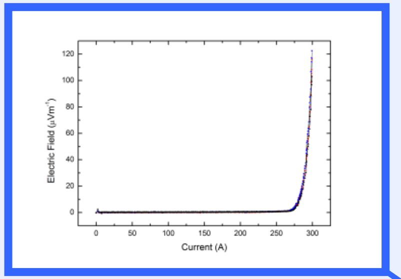


Figure 4: Universal temperature and strain independent flux pinning scaling curves for a) REBCO coated c

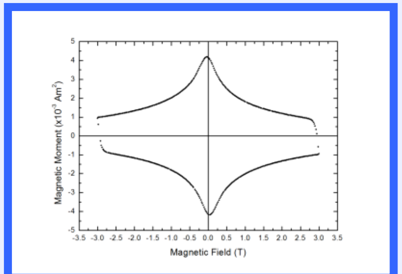
Durham's Role in the ITER project

Critical Current, I_c > 190 A



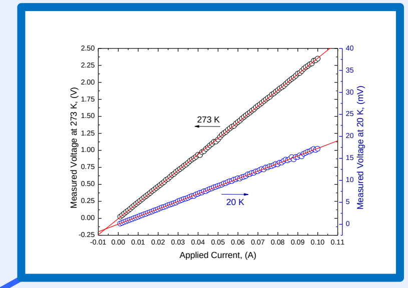
1000

Hysteresis < 500 mJ/cm³



500

Residual Resistivity Ratio > 100

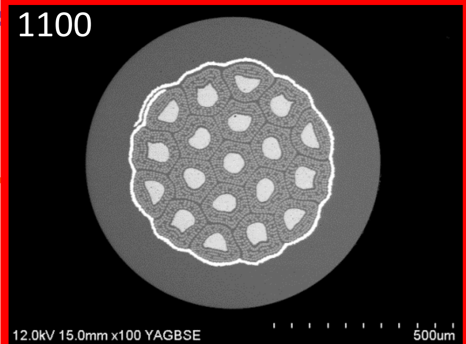


1000

Cryogenic measurements (down to -269 °C)

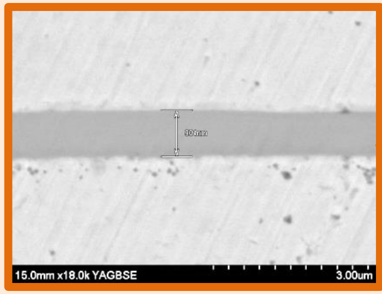
Cryogenic measurements (down to -269 °C)

1100



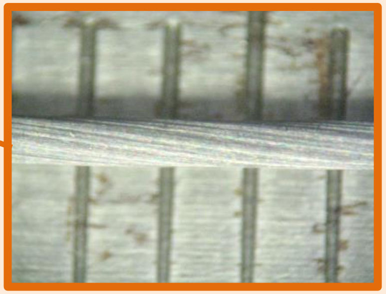
Room temperature measurements

Room temperature measurements



1000

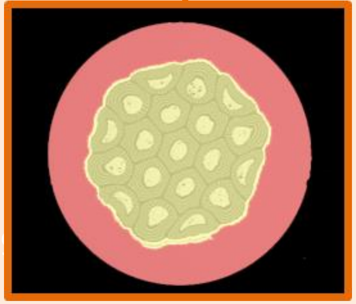
Chromium Plating Thickness, 1 to 2 µm



1000

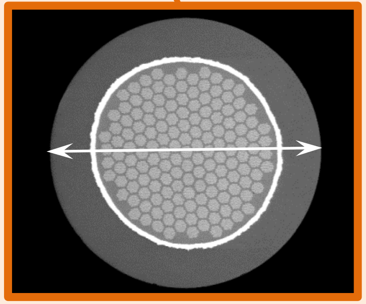
Twist Pitch 15 ± 2 mm

1000



Cu-non-Cu Ratio, 1.0 ±0.1

1000

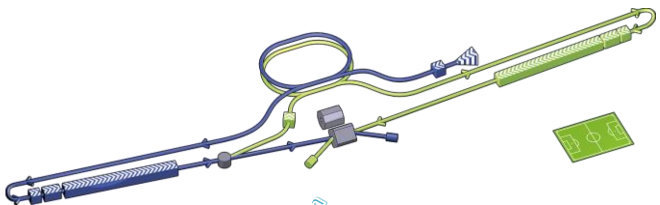


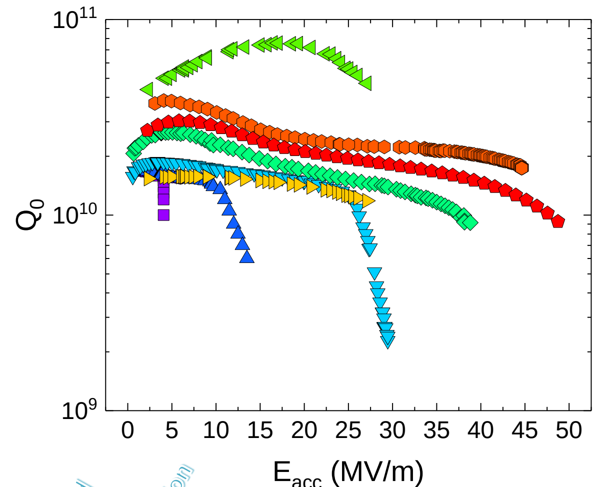
Diameter, 0.820 ± 0.005 mm

Manager:
Dr Mark Raine

ASC2018 Talk

Thanks to Alexander Romanenko | ASC'2018 - Seattle





3 – 4 MV/m Multipacting

5 MV/m Thermal Breakdown

10 – 15 MV/m Field Emission

20 - 25 MV/m Q-SLOPE

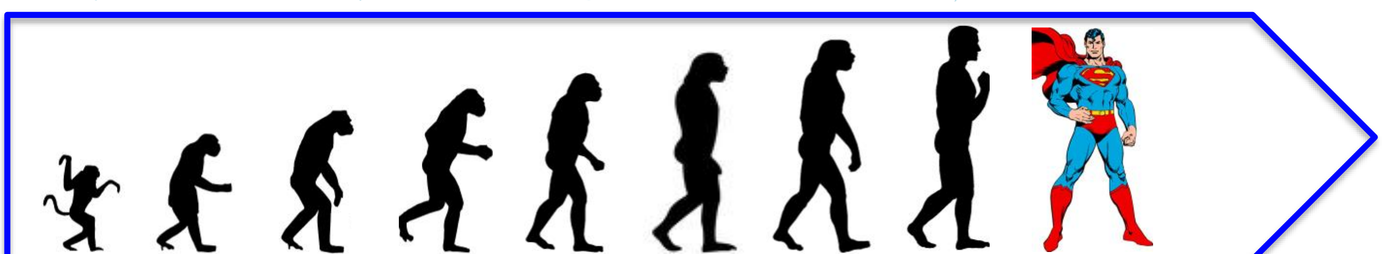
35 – 40 MV/m

Q > 5e10 At medium field

Flux dissipation Flux expulsion

Q > 2e10 At high field

49 MV/m !!!

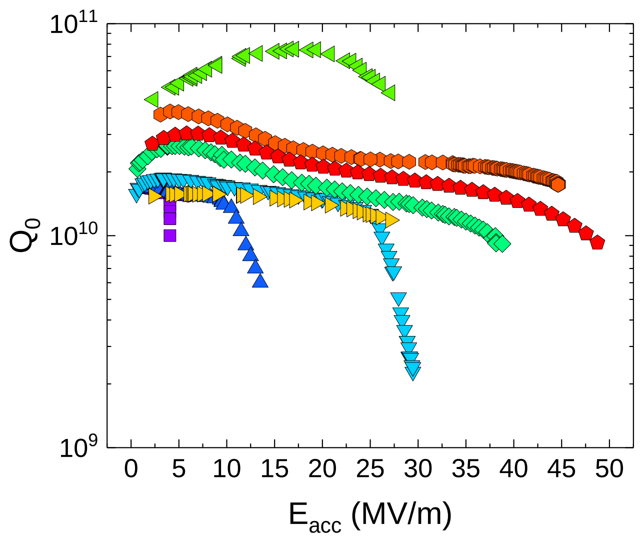


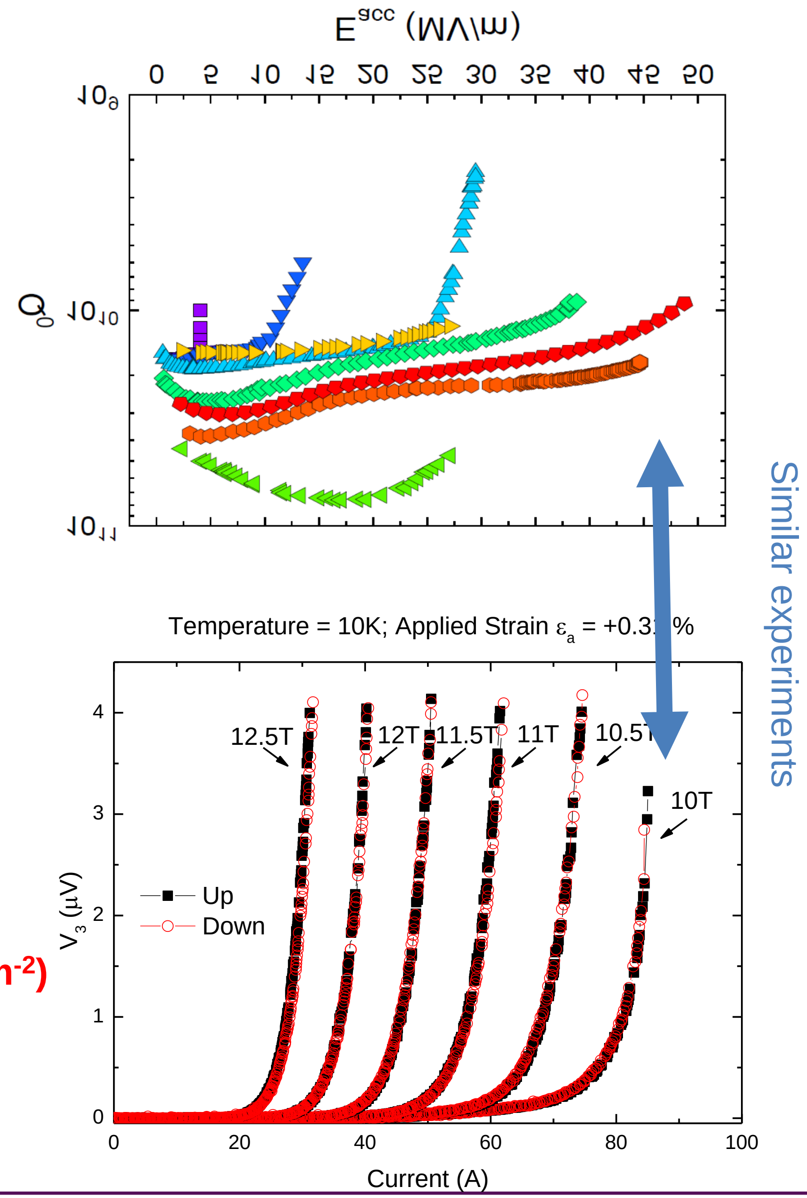
FEYNMAN claims there are 7 equations that describe all of classical Physics

Maxwell's 4 equations
Newton's law of motion
Newton's law of Gravity
Force on a moving charge in a magnetic and electric field

… and after we have quantised flux, SRF and high fields communities are doing "classical experiments".

Pinning measurements and Q measurements are similar





SRF measurements : Q (10^{10}) versus E (50 MV.m^{-1})

(1 Ghz, Surface pinning, self-field)

are just

Jc measurements : E (100 μV.m^{-1}) versus J (10^{10} A.m^{-2})

(Dc., bulk pinning, high magnetic fields.

Experiments

Typical pinning information:

i) Tc (x)
ii) Jc (x)
iii) J_D (x)
iv) Bc2 (x)
v) ρ (x)
vi) Surface quality
vii) Microstructure
viii) Composition

Small sample (”Coupon” ASC2018) measurements – optimisation of cavity properties

Bespoke slabs and cylindrical samples and samples extracted from the cavities – change the size to measure local properties – mm sized samples and FIB samples.

Susceptibility and magnetisation measurements (B,T):
i) Tc , (ii) Jc , (iv) Bc2
Heat capacity measurements (B,T);
(iii) J_D (depairing current density via density of superelectrons)
Transport measurements (T)
v) ρ (x)
Microscopy
vi) Surface quality vii) microstructure viii) composition

Concerns: are extracted samples representative of the cavity?
Advantages: relatively cheap samples

Cavity measurements

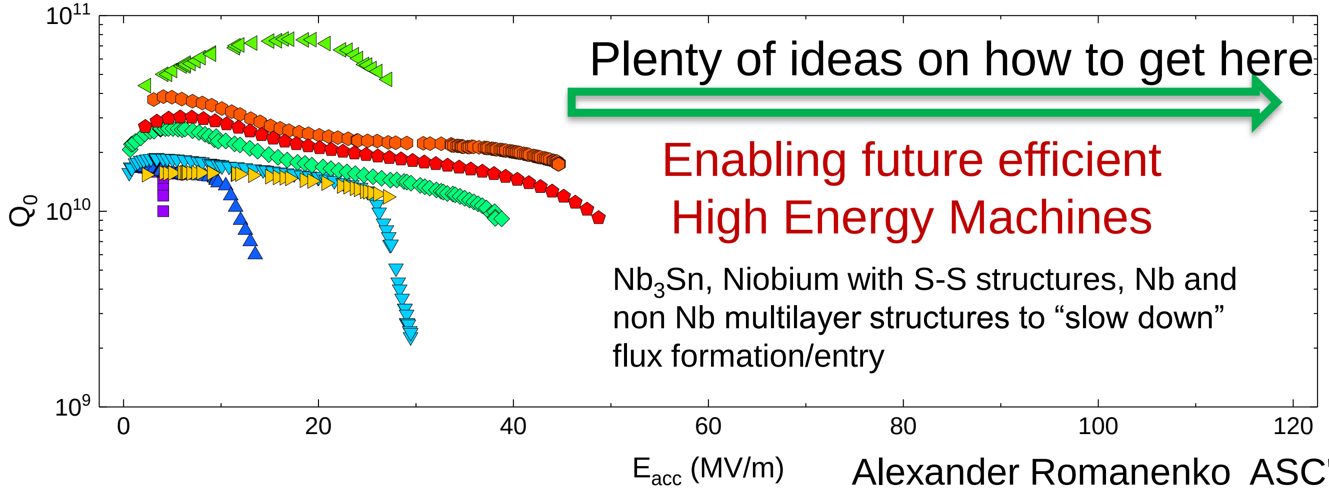
Q versus E (B,T, range of frequencies in the cavity)
i) Tc , (ii) Jc , (iii) Bc2 iv) ρ (x) for T>Tcvi

Microscopy
vi) Surface quality vii) microstructure viii) composition

Can you wire-up the cavity to identify where the local dissipation occurs above Jc (reduction in Q) ?

Concerns: cost and expertise
Advantages: correct sample

Future SRF cavities



Alexander Romanenko ASC'2018 - Seattle

Observations/suggestions (collaborate/read literature from flux pinning community):

Nitrogen increases RRR in Cu. Scratches change magnetic properties of crystals – short coherence length materials (Nb_3Sn) will need smooth surfaces. Hard superconductors (High Jc + cold worked) and soft superconductors (Low Jc).

Nb shielding ?electroplated with copper?. Produce a separate Nb shielding sheet with a gradient in the thickness to drive the trapped flux out (+ temperature gradient if necessary). Does inevitable variation in sheet thickness explain the different expulsion behaviour currently observed for different cool-down procedure ? *Separate* the material that meets cavity requirements (stiff material – no deformation/detuning) from the material meeting shielding requirements (soft material).

Nb-N-Nb multilayers (Gurevitch) that *eliminate* flux entry into Nb: N is a high electrical resistivity, high thermal conductivity material . The thickness of the Nb layers probably should be about ½ penetration depth. The choice of the normal layer is complicated by fabrication constraints, materials properties including thermal properties of thin films. ?High purity titanium or Ti-alloy?

Operational consideration for Nb and for multilayers: Increase E to be as high as possible and measure Q on decreasing E-field

Concluding Comments

Outline of flux pinning

Flux pinning is fun - everyone has a view . I have suggested some ideas.

Systems cost ? How close to theoretical limits are state-of-the-art cavities?