IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019.
Invited presentation 1MOr1B-02 given at ASC 2018, October 28-November 02, 2018, Seattle, (USA).

APPLIED SUPERCONDUCTIVITY CONFERENCE
ASC SEATTLE 2018
WASHINGTON STATE CONVENTION CENTER
OCT 28—NOV 2

What the legacy of pinning Abrikosov vortices in LTS implies for…

Further exploration of ultimate limits of flux pinning in Nb_3Sn

Lance Cooley

Applied Superconductivity Center

National High Magnetic Field Laboratory & Florida State University

With many thanks to those identified on slides

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In honor of Alexi Abrikosov

- The Abrikosov Vortex, the Vortex Lattice
- A lasting legacy for applications of superconductors: flux pinning
  - Much of Applied Superconductivity is about pinning Abrikosov vortices to enable technologically important currents in superconducting wires
- My main messages today:
  - Nb_3Sn is the present workhorse of advanced LTS magnets, in particular magnets for fusion and particle accelerators
    - This ASC is a special one, because a ***new paradigm of flux pinning in Nb_3Sn*** will be described in the next oral session (1MOr2B) today!
  - Nb-Ti magnet conductors drove us to probe ultimate limits for Abrikosov vortices, flux lattices, and pinning forces
    - We sought to ***destroy*** vortices and ***deform*** lattices to the greatest degree possible!
  - Discussions relevant to vortices in superconducting electronics also played a role in LTS flux-pinning discussions

The mad Flux Pinners of the Applied Superconductivity Center

Abrikosov's vortex

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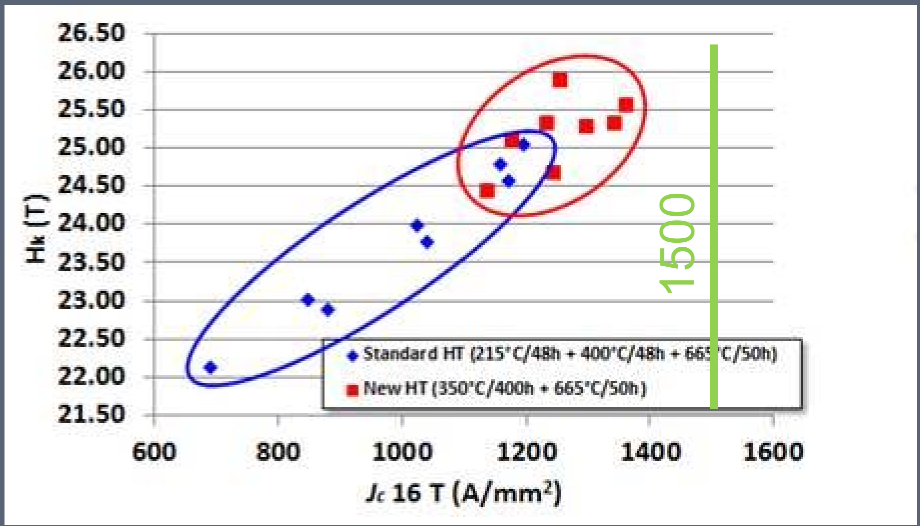
The challenge for future Nb_3Sn wires

- The present state of the art for high current Nb_3Sn
  - HL-LHC upgrade strand in production reaches about 400 A at 15 T, 4.2 K, or 1500 A/mm^2 (Nb_3Sn layer performance is about 5,000 A/mm^2)
  - Equivalent performance at 16 T is about 1050 A/mm^2
  - Alterations of the heat treatment, which maximize fine-grain area and minimized material lost to the Sn core, can reach about **1350** A/mm^2 at 16 T
- **Future: 1500 A/mm^2 at 16 T = 30% increase**
  - Bottura and Ballarino – target for CERN Future Circular Collider



To do:

1. **Raise H_K and B_{c2} further (see Tarantini talk, 1MOr2B-03)**
2. **Improve or add pinning (see exciting talks by Xu et al.1MOr2B-05 and Balachandran et al. 1MOr2B-06)**

Charlie Sanabria *et al* 2018 *Supercond. Sci. Technol.* **31** 064001

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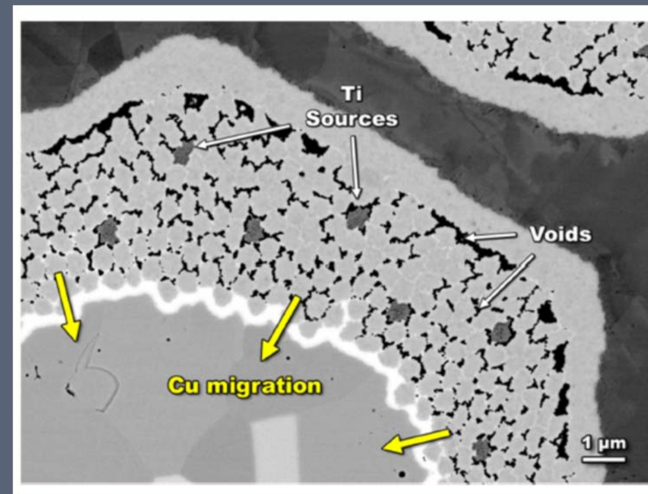
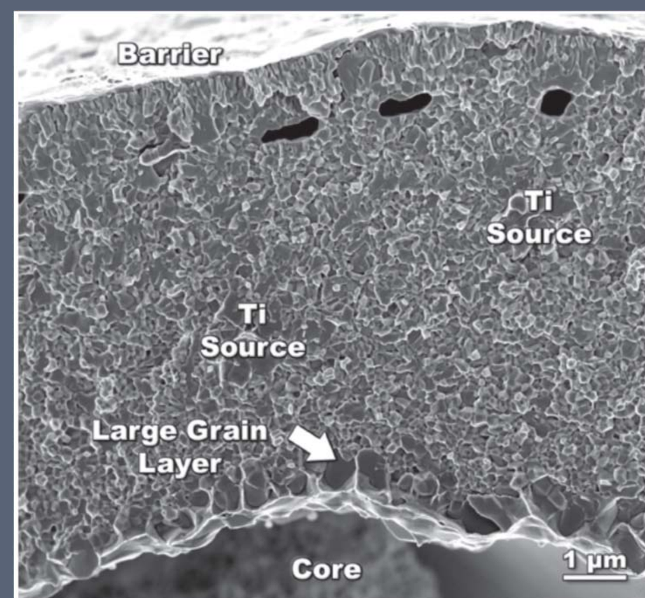
Can the present Nb_3Sn get to the target?

C. Sanabria (now LBNL) PhD thesis:
Charlie Sanabria *et al* 2018 *Supercond. Sci. Technol.* **31** 064001

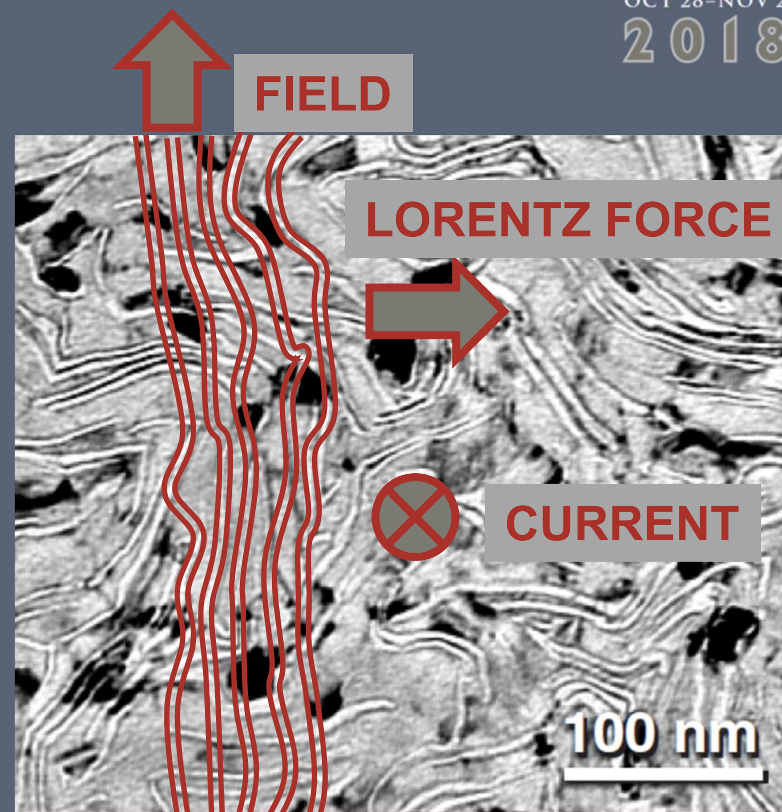
- A “Nausite” membrane forms, which assists in metering the flow of Sn toward the reacting Nb
  - see also Pong, Oberli, Bottura 2013 Supercond. Sci. Technol. 26 105002
- The membrane facilitates forming as much fine-grained Nb_3Sn as possible
- The membrane thickness must be minimized → lost Nb
- **Work is now underway to push this as far as possible, but how much farther can we go with the basic conductor package?**
- **What lessons from other efforts to seek ultimate pinning in LTS might be helpful?**





Strong pinning in Nb-Ti wires developed at about the same time as flux-pinning theories

- Campbell & Evetts, 1972: Pb-Bi alloys, ΔH_c and $\Delta\kappa$ as mechanisms
  - Recently discussed as ΔT_c and $\Delta\ell$
- Core pinning theories 1980s: Kramer-Freyhardt; Matsushita, Thuneberg… α-Ti precipitates are very strong pinners
- E.H. Brandt, others 1980s: vortices are flexible enough to follow subtle contours of the nanostructure
  - **This beautiful microscopy, and that in other slides, is the masterwork of Peter Lee** 3PL1A



Concepts of pinned vortices superimposed on Peter Lee's TEM image of an optimized Nb-Ti nanostructure (Meingast, Lee, Larbalestier, J. Appl. Phys. 66, 5962, 1989 and later work)

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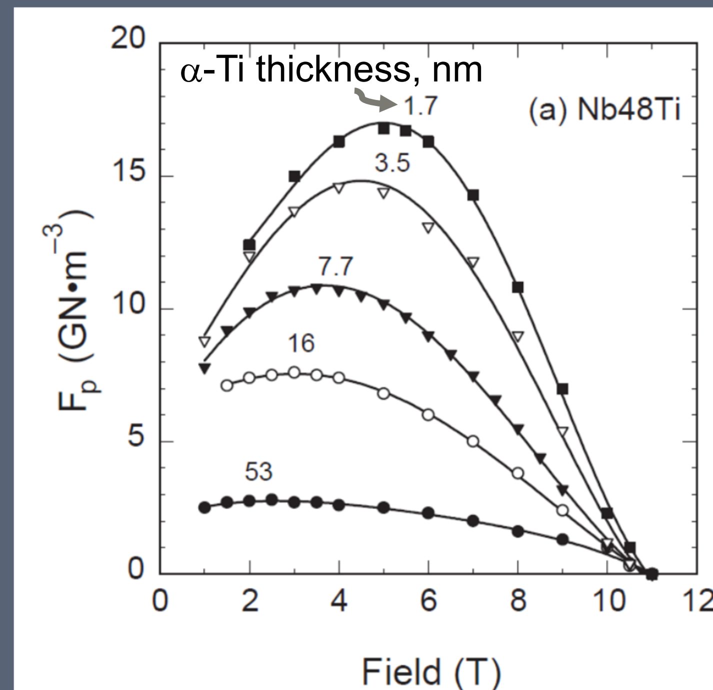
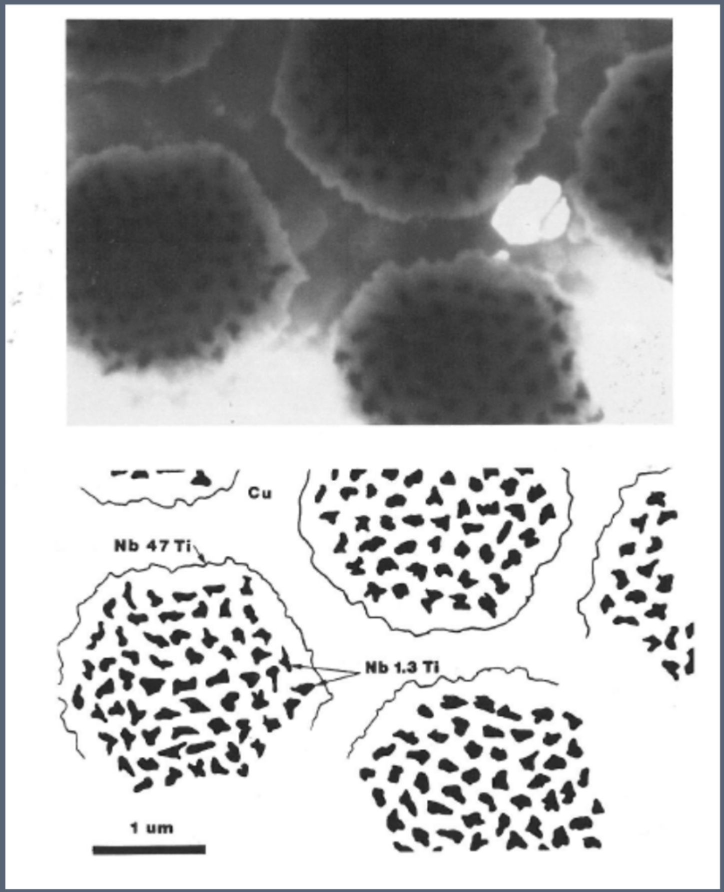
- E.H. Brandt, others 1980s: vortices are flexible enough to follow subtle contours of the nanostructure
  - **This beautiful microscopy, and that in other slides, is the masterwork of Peter Lee** 3PL1A
- Every vortex has a pin → Direct summation: $F_p = n_p f_p$
  - Bulk pinning force F_p = bulk Lorentz force $J_c B$
  - Elementary pinning force $f_p \propto (\varepsilon_0 / \xi) \bullet (1-b)$
    - ε_0 is vortex line tension, ξ is coherence length, $b = B / B_{c2}$
  - Number of pins n_p ~ number of vortices ~ b
  - So, $F_p(b) \propto b\,(1-b)$



The very advantageous pinning force behavior that develops as the nanostructure of Nb-Ti wire is refined to the ~10 nm scale of vortices (IOP Handbook on Superconductivity, Chapter B3.3.1)

Ultimate pinning in Nb-Ti by selecting and hand-assembling the eventual characteristics of the nanostructure

- Dorofeev *et al.*, 1986: Artificial Pinning Center (APC) Nb-Ti composites
- Several ASC PhDs: Cooley, Jablonski, Heussner
- Excellent collaboration and competition in the community: Motowidlo, Zeitlin, Matsumoto, Prober group, …



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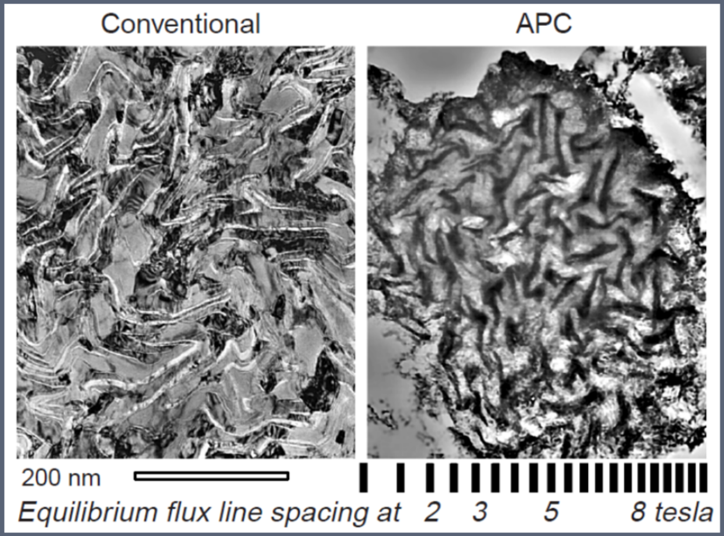

Excellent arrays at 100 nm scale, but realities of material hardening set in below this scale (Images: Peter Lee)

Ultimate pinning in Nb-Ti by selecting and hand-assembling the eventual characteristics of the nanostructure

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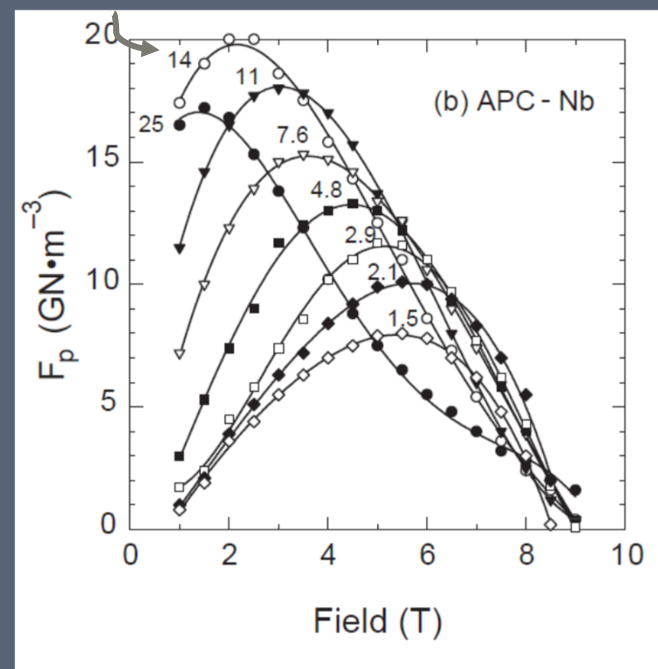
- Several ASC PhDs: Cooley, Jablonski, Heussner
- Excellent collaboration and competition in the community: Motowidlo, Zeitlin, Matsumoto, Prober group, …
- The quest for the ultimate pinning force explored Nb, Nb1Ti, Fe, Ni, Cu, Cu-Ni, Ti, Nb-Ta, Nb-W, … and even salt!
- Some unusual things happened along the way:
  1. The pinning force grew at low field, but not at high field, despite the expectation that core pinning was active!
  2. Vortex-pin matching effects appeared, in the form of periodic peaks on $F_p(B)$

APC thickness, nm



The advantages of conventional Nb-Ti were not greatly improved at high fields (IOP Handbook on Superconductivity, Chapter B3.3.1)

Destruction of the Abrikosov vortex → AJ vortices

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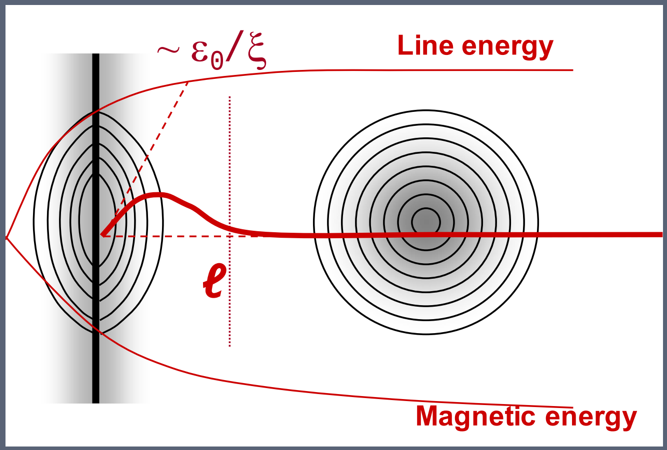
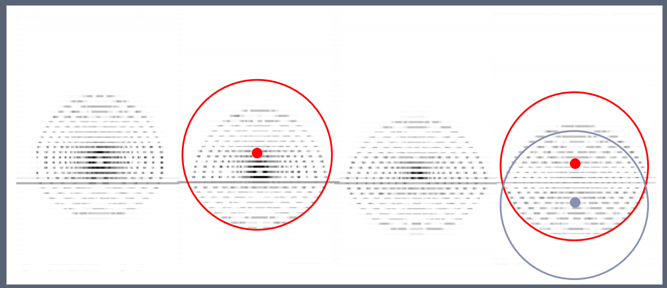
- Alex Gurevich contemplated a different structure of a vortex at a grain boundary → Abrikosov-Josephson (AJ) vortices
- In technological superconductors:
  - J_c is few% of the depairing current density J_d
  - Boundaries have high transmission current density $J_B > J_c$
- Boundaries can still obstruct the vortex core, $J_B < J_d$ → pinning
  - The boundary looks like a free surface when the vortex is near → image vortex
  - Non-local sine-Gordon equations apply → a new length ("**Gurevich length**") ℓ sets the scale of interactions

$$\xi < \ell < \lambda \qquad \ell \sim J_d\, \xi / J_B$$

$$f_p \sim \varepsilon_0 / \xi$$





Gurevich PRB **46**:3187 (1992) ; **48**:12857 (1993)
Gurevich Cooley PRB **50**:13563 (1994)

Important implication: grain boundaries can pin as strongly as core pinning centers

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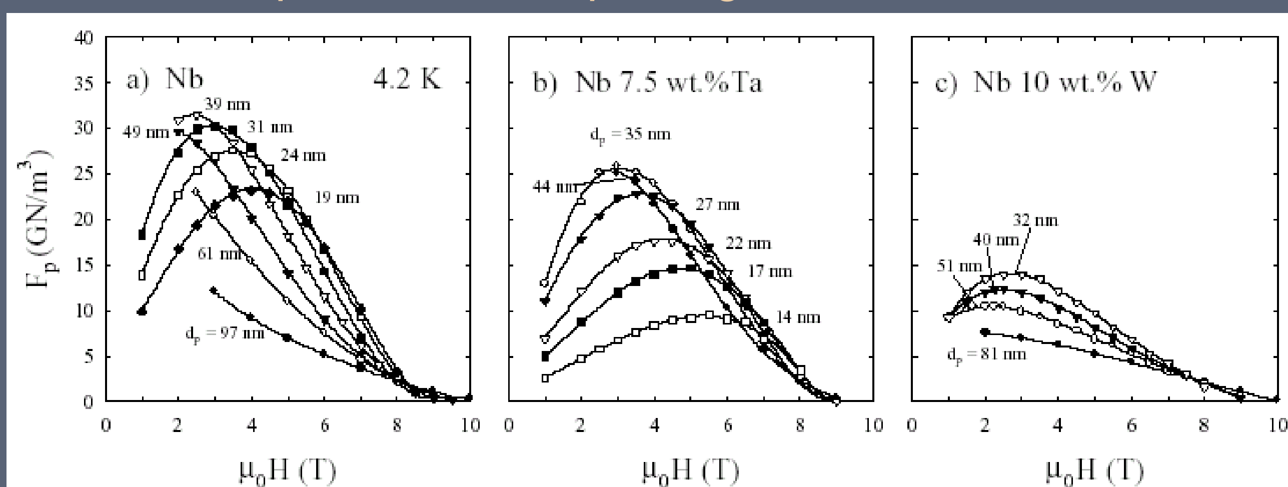
Pinning behavior changes with composition of pin

- Thin, ribbon like pins (e.g. APC) act like boundaries when coupled by the proximity effect → Modify the Gurevich pinning model
  - $J_B \sim J_0 \exp[-t / \xi_N(T)]$ where t is the thickness of the pin and ξ_N is the proximity length

    → *Thick clean and thin dirty pins affect Abrikosov in the same way*
  - Pin number density is higher for dirty pins → alloys have small ξ_N and therefore favor direct summation (but they work harden quickly and are difficult to make into wires)
  - This was our best explanation why the APC pinning response depended on the composition of the pinning-center material.

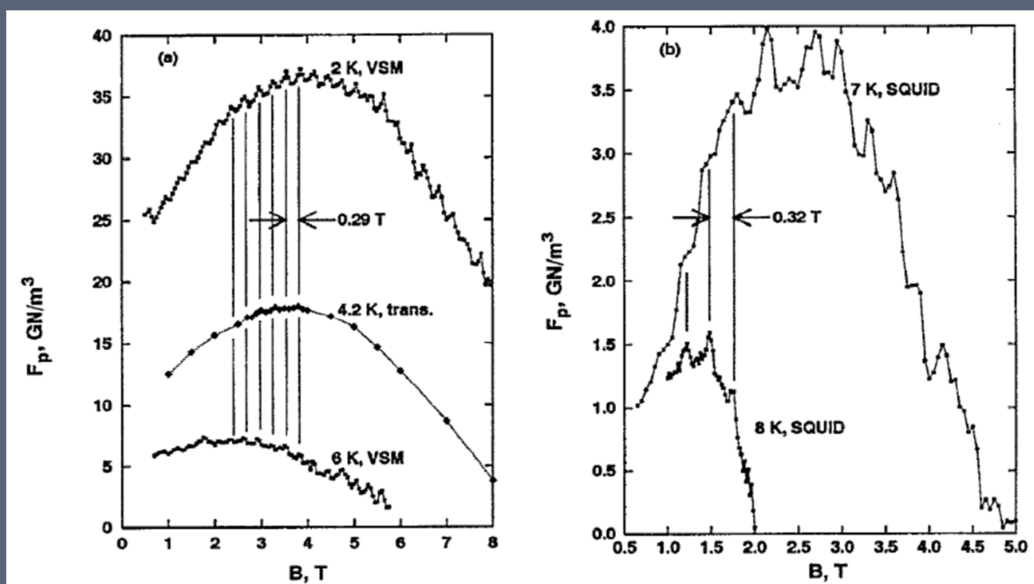
Cooley, Lee, and Larbalestier PRB **53**:6638 (1996)



R. Heussner et al., IEEE Trans. ASC 7:1142 (1997)

APC Nb-Ti forced us to look into periodic pin arrangements

- Periodic features appeared on pinning-force curves, which could not be explained by the existing (and, at the time, still growing) literature for matching to periodic arrangements of holes
  - This was c. 1992, prior to the huge contributions by Schuller, Baert, Moschalkov, Metlushko, Reichart & Olson, the Vortex collaboration, and many others…



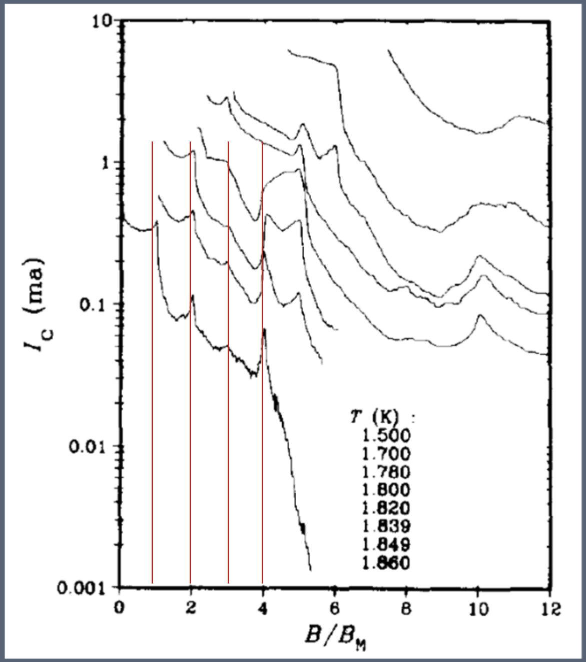
APC wire with pin spacing a_p = 29 nm

Periodicity = 0.3 T = $\phi_0 / \lambda\, a_p$

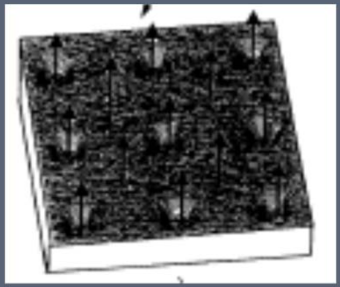
Cooley, Lee, Larbalestier, O'Larey. APL 64 (1994) 1298-1300.

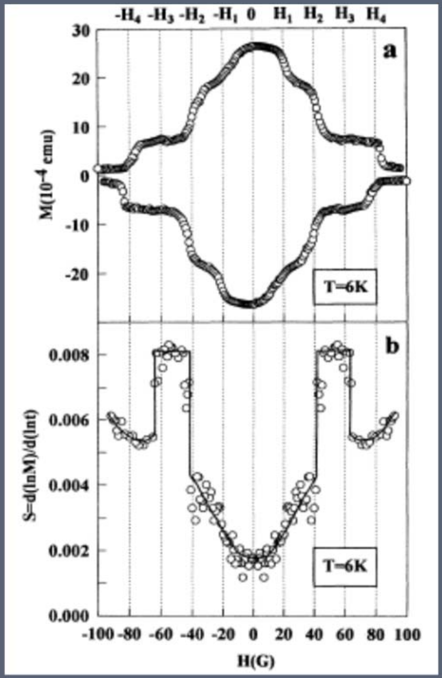
What is the best way to pin the flux lattice?

- School 1: The periodic flux lattice needs periodic arrangements of pins for maximum efficiency
  - Periodic peaks
  - B_m denotes the matching field ϕ_0 / a_p^2



Fiory, Hebard, Somekh – APL 1978 – Al film with triangular lattice of holes





Baert, Metlushko, Jonckheere, Moshchalkov, Bruynseraede PRL 1995 – Nb film with square array of holes

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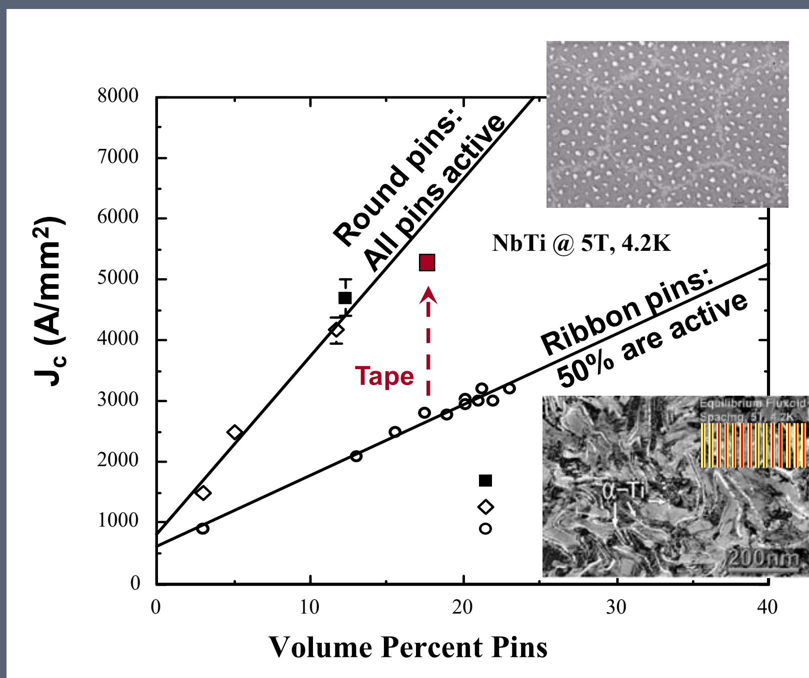
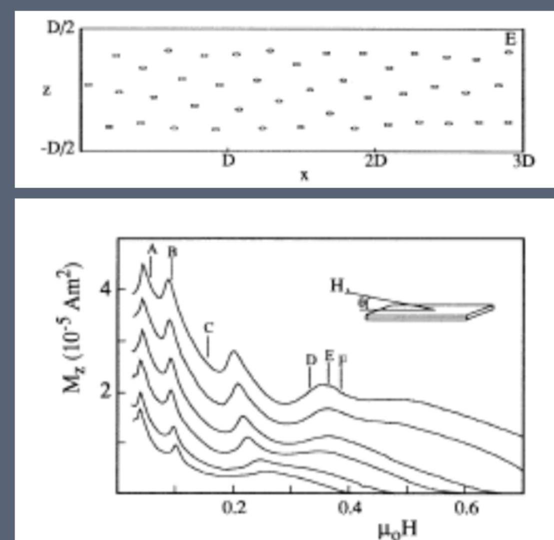
What is the best way to pin the flux lattice?

- School 2: Wires should be more like multilayers, and the pins can be continuous along the dimension parallel to current
  - Vortex chains form along the pins
  - Non-periodic peaks



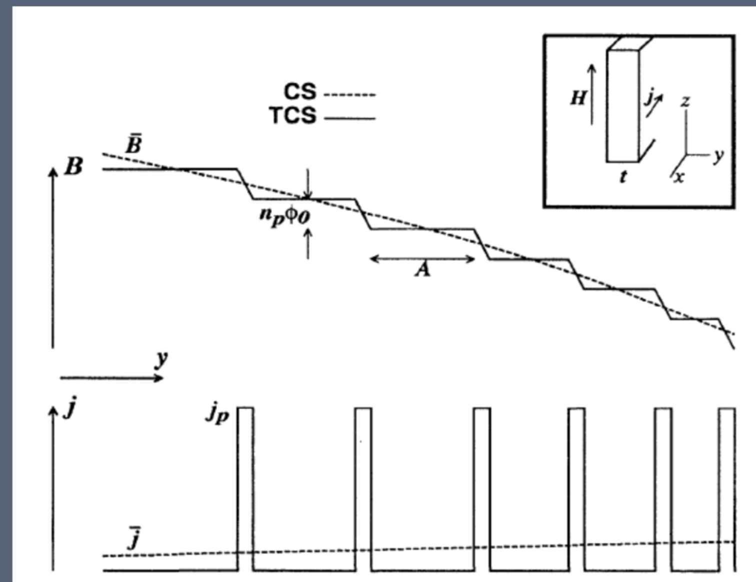
Motowidlo et al. 2003 IEEE Trans. ASC



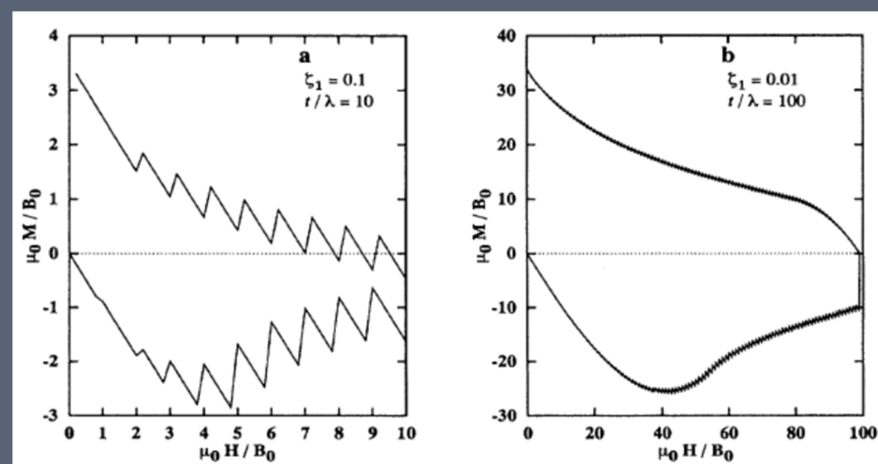
SH Brongersma et al. 1993 PRL 71, 2319

Terraced critical state

- High current creates a flux gradient → incompatible with periodic pin arrangements
  - A 1 mm diameter wire can carry 1 kA, which makes self field approaching 1 T across the wire, or ~0.1 T across filaments.
  - A flux lattice at 5 T field experiences a strain $\Delta a_0 / a_0$ of 1% (very large)
- The critical state responds by decomposing into terraces
  - Flux lattice minimizes expansion or compression by matching to pins within terrace
  - Large flux gradients, and therefore high currents, form at terrace edges



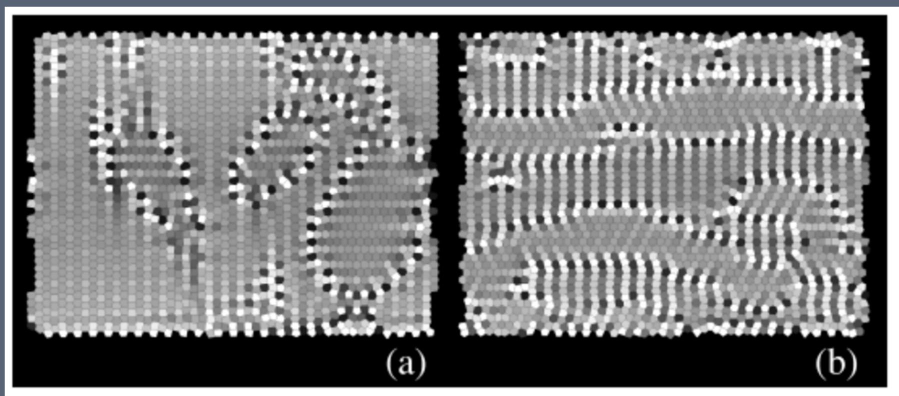
Cooley and Grishin 1995 PRL 74 2788



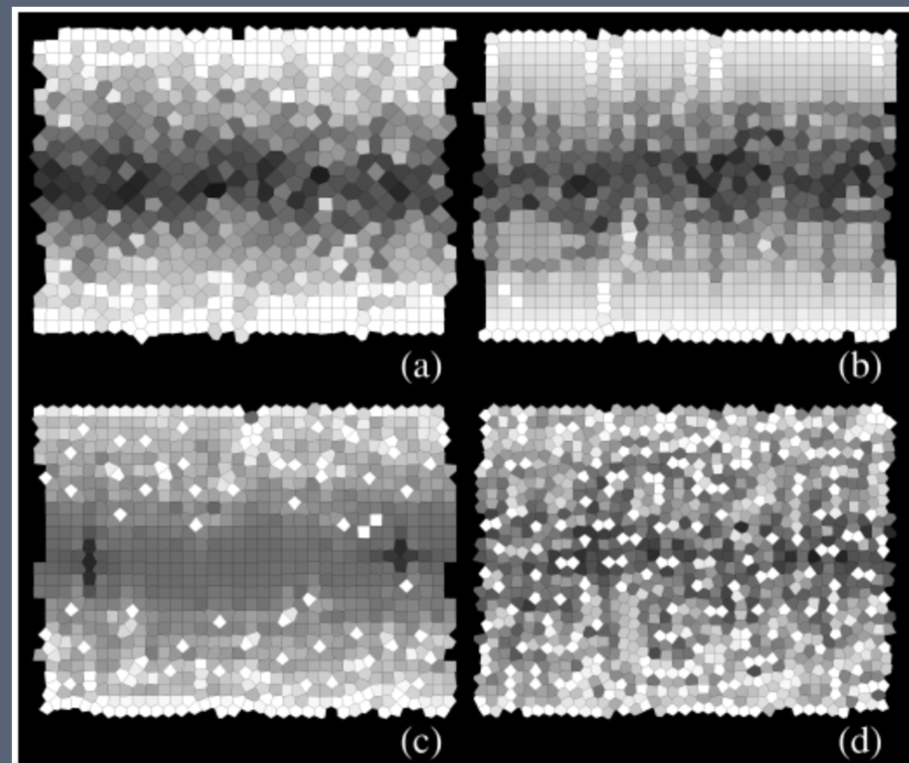
Periodic peaks for magnetization with periodicity given by $\Delta B \approx \phi_0 / a_p \lambda$

Terraced critical state

- Terraced critical state in simulations

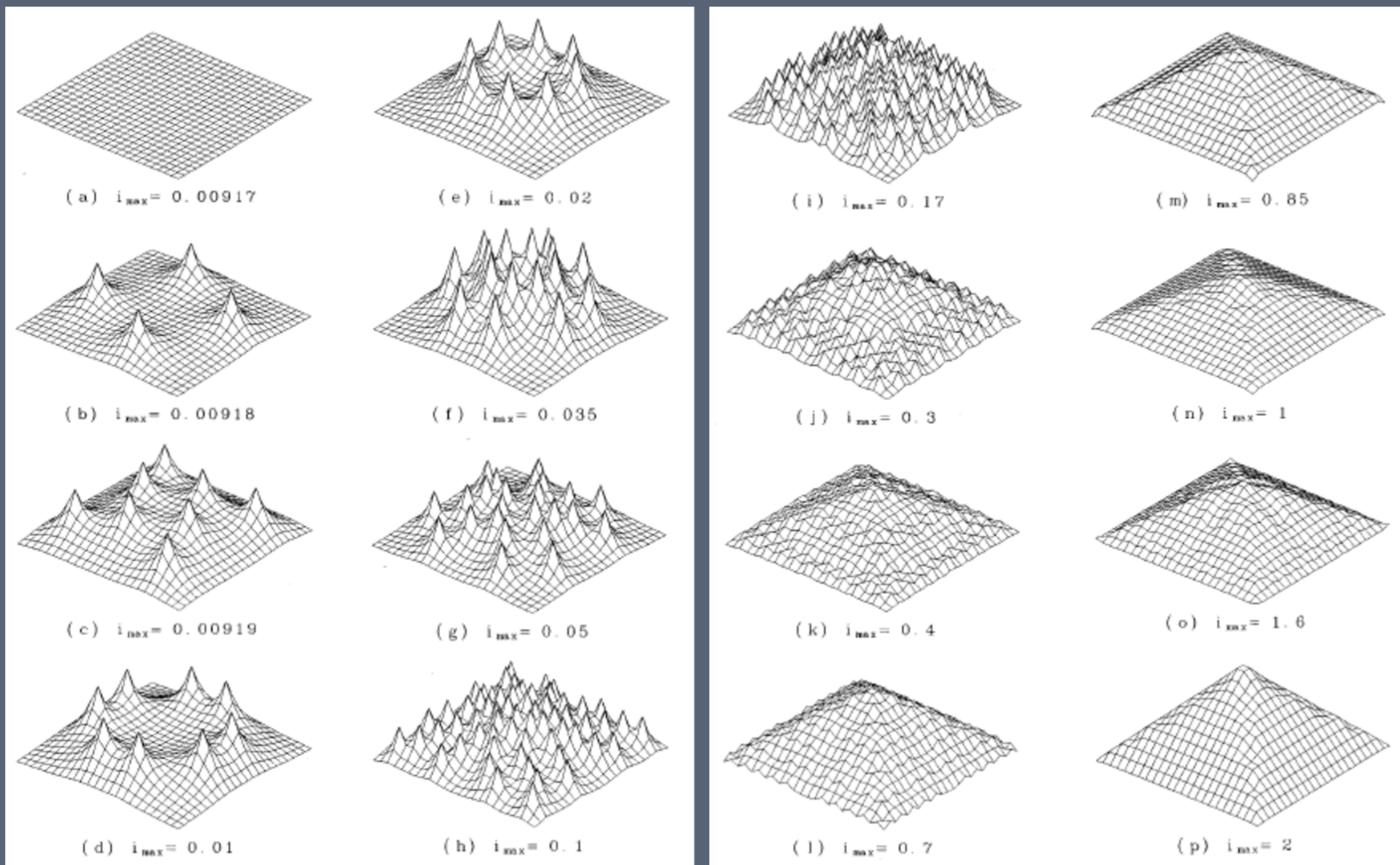


Reichhardt *et al.*, *op. cit.*, here showing domains with boundaries for simulated field of 2.1 and 2.2 B_m



Vortices simulated by molecular dynamic simulations with square and triangular pin arrays Reichhardt, Groth, Olson, Field, and Nori 1997 PRB 54 16108

Terraces in Josephson junction arrays



Evolution of a 25 x 25 Josephson-junction array with field
D-X Chen, JJ Moreno, A Hernando 1996 PRB 53 6579

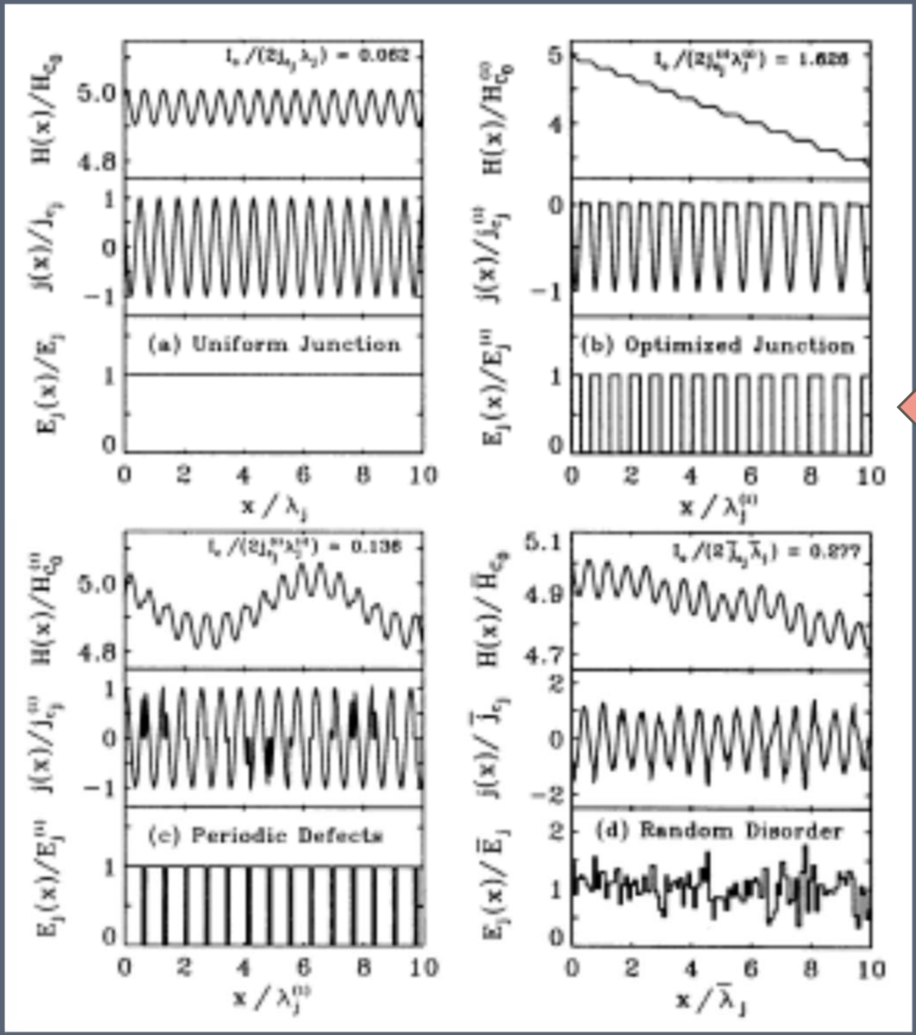
Vortex grains?

Two implications of the terraced critical state

1. When stressed by high transport current or magnetization, will the Abrikosov vortex lattice decompose into **"domains" or "grains" of ordered vortices** surrounded by **"domain walls" or "grain boundaries" with disordered vortices**?
   - NOT collective pinning; implies plastic deformation at boundaries
   - What are the implications of a granular vortex solid?
   - Especially, what are the implications for Nb_3Sn?
2. The maximum current-carrying state should be the state that **eliminates all ordered domains**
   - How is this accomplished? Artificial pinning-center ***gradients*** ?
   - What is the ground state of a pinning-center gradient? Does it have non-zero current?
     - Will cooling a pin-gradient superconductor in a constant field result in a non-zero bulk current?
     - Will rectification of current occur, i.e. with and against the gradient?
     - What other novel physics will result?

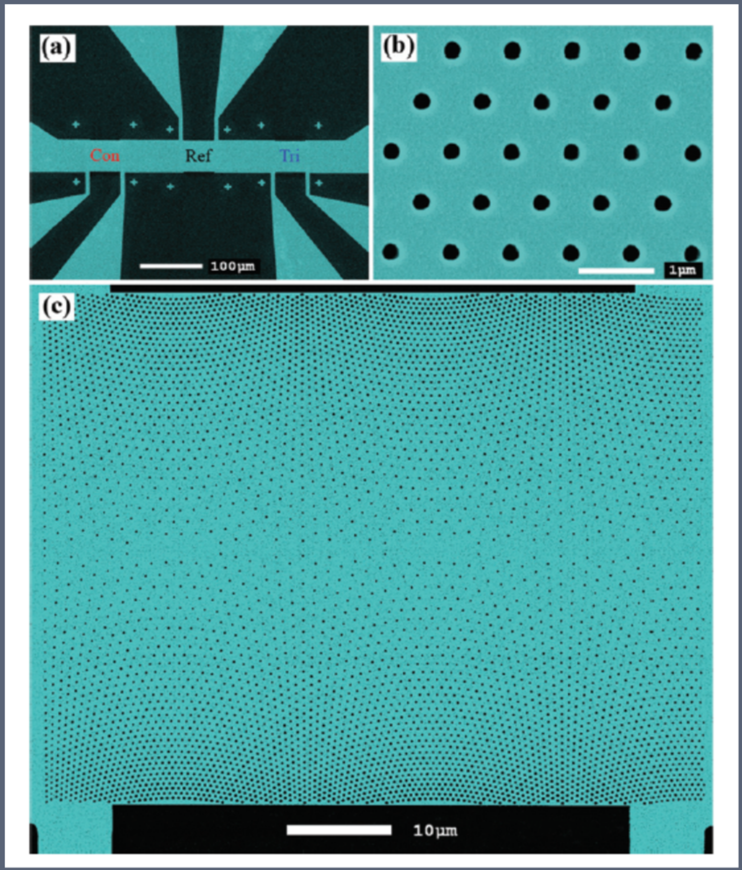
Model systems of vortices vs. pin gradients

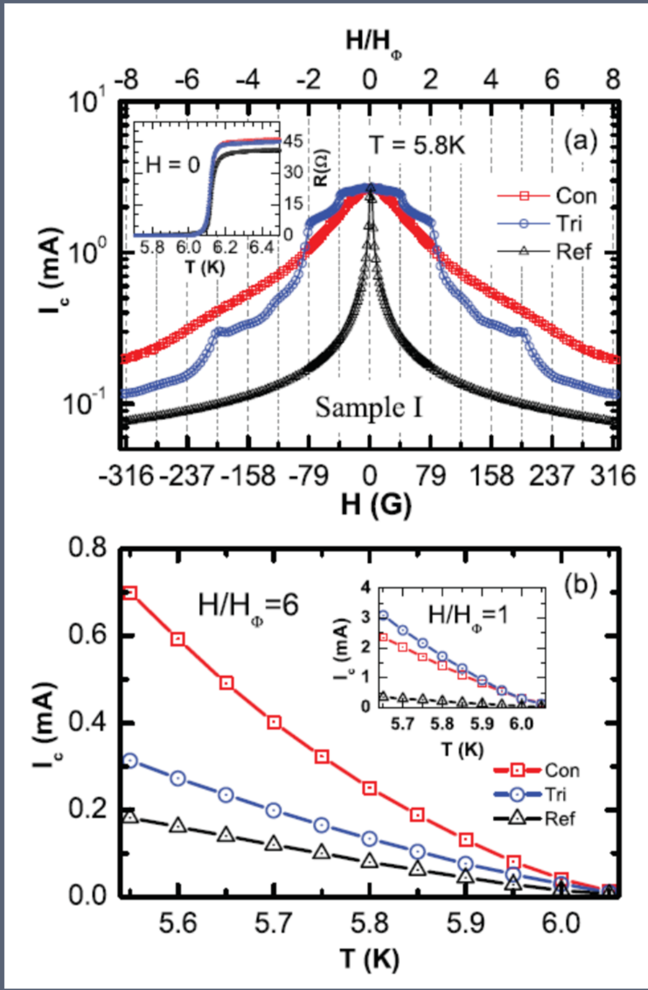
Simulation of a long junction with defects that pin Josephson vortices by Fehrenbacher, Geshkenbein, and Blatter 1992 PRB 45, 5450



Gradient

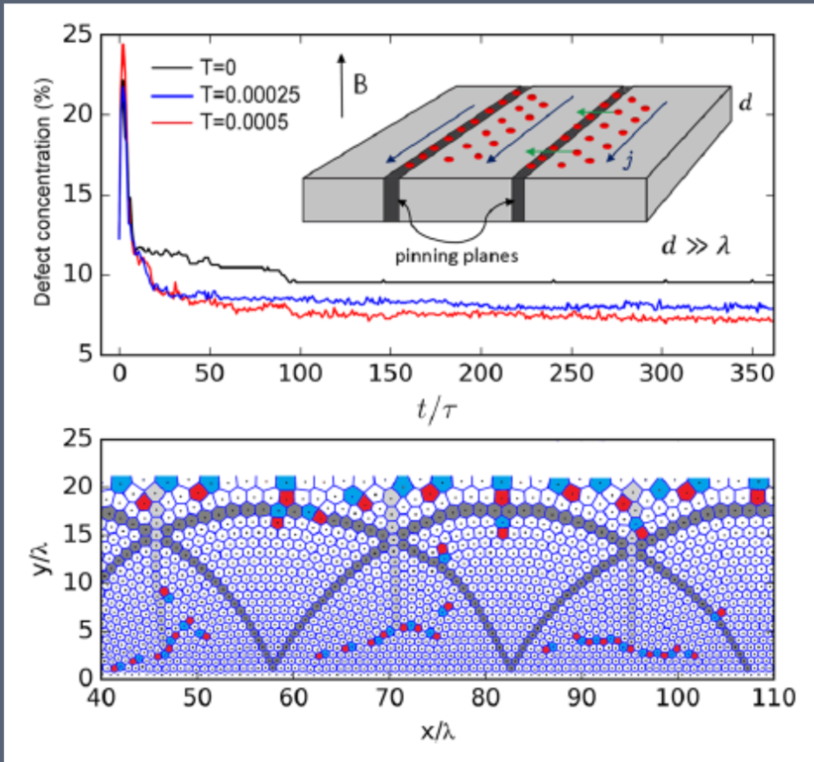
Model systems of vortices vs. pin gradients





Conformal array of pins in MoGe films showing advantages of the gradient, from Wang, Latimer, Xiao, Divan, Ocola, Crabtree, and Kwok 2013 PRB 87 220501 (R)

Model systems of vortices vs. pin gradients



The *inverse* effect: Vortex simulations result in the formation of a conformal array of *vortices* when constrained by pinning center walls and acted upon by a current density. Menezes, Raí M., and Clécio C. de Souza Silva. "Conformal Vortex Crystals." *Scientific reports* 7, no. 1 (2017): 12766.

First takeaway for Nb_3Sn – gradients by irradiation?

- Can we engineer pinning-center gradients on the nanoscale, i.e. at the same length scales as for artificial pins in Nb-Ti wires?
- Can this be done for Nb_3Sn?
  - Interesting results from irradiation with neutrons (Baumgartner et al. 2014 Supercond. Sci. Technol. 27 015005) and protons (T Spina et al 2014 J. Phys.: Conf. Ser. 507 022035), although difficult to envision treatment of wires.
  - The divergence should be about 10% across the sample, e.g. for a self field of 1 T in a 10 T background (as just calculated for a 1 mm strand carrying 1 kA).
- **Experiment example: Irradiate Nb_3Sn with a proton beam having diverging flux** (such as for the beam at FSU Fox Accelerator Lab)

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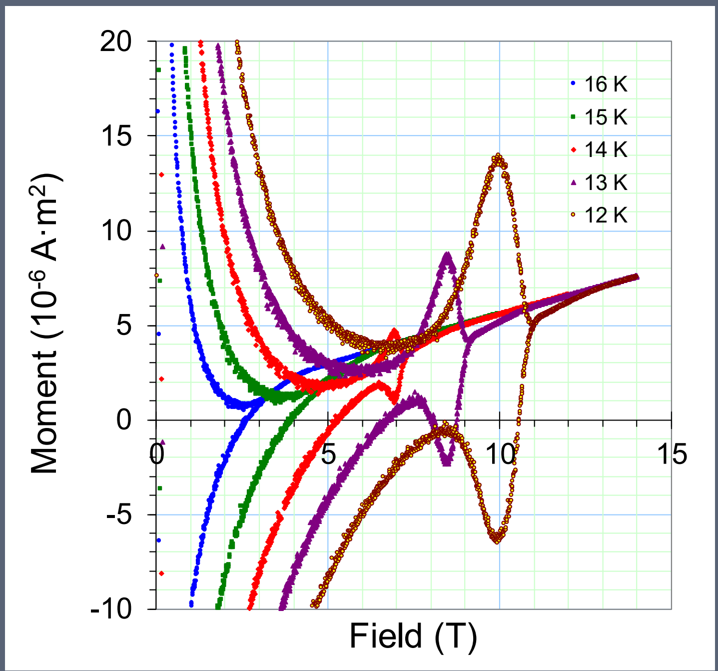
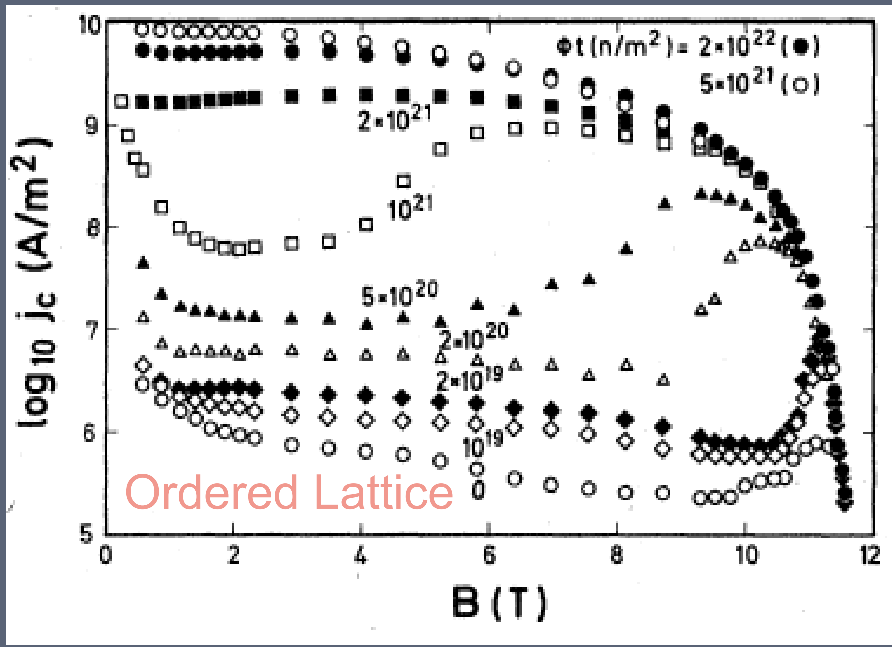
We should expect Abrikosov's lattice to be deformed in technological Nb_3Sn wires



Magnetization of Nb_3Sn with grain size ~1 mm made by hot pressing (R Lund, M Jewell, U. Wisconsin)

Disordered



V_3Si crystal magnetization measured as a function of irradiation dose.
Maier-Hirmer, Kupfer, and Scheurer 1985
PRB v31 p183

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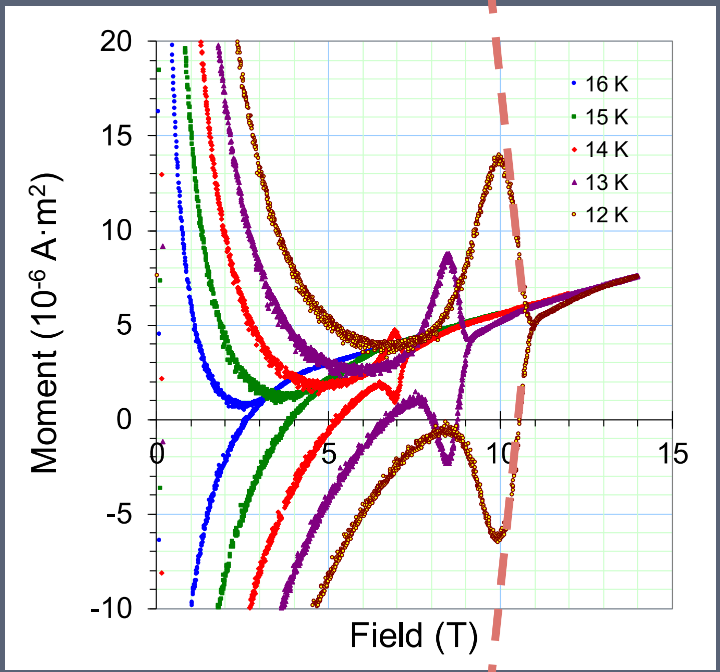

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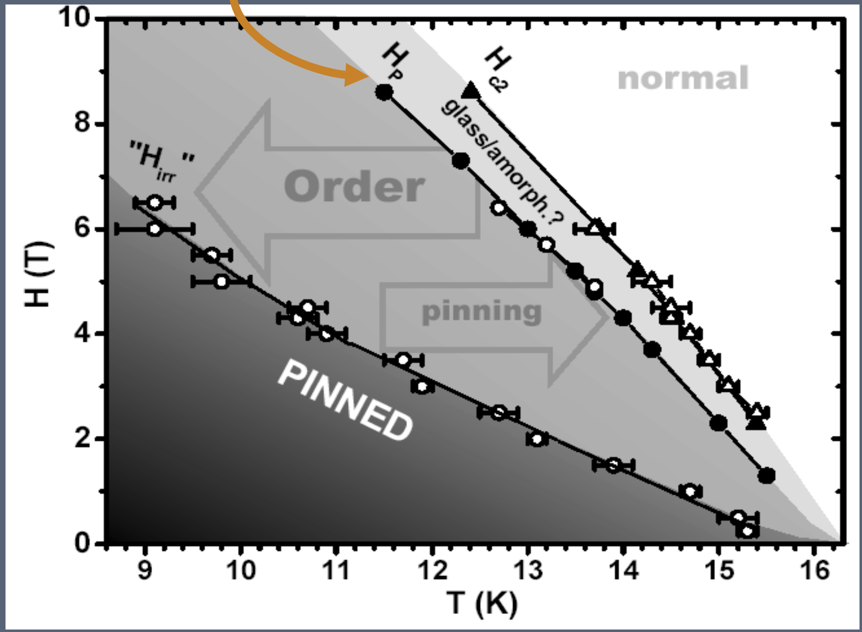
Fine-grain Nb_3Sn

M(H) peak



Correlation of structural order by small angle neutron scattering with the position of the magnetization peak in single crystal V_3Si
Gapud, Christen, Thompson, Yethiraj 2003 PRB 67 104516

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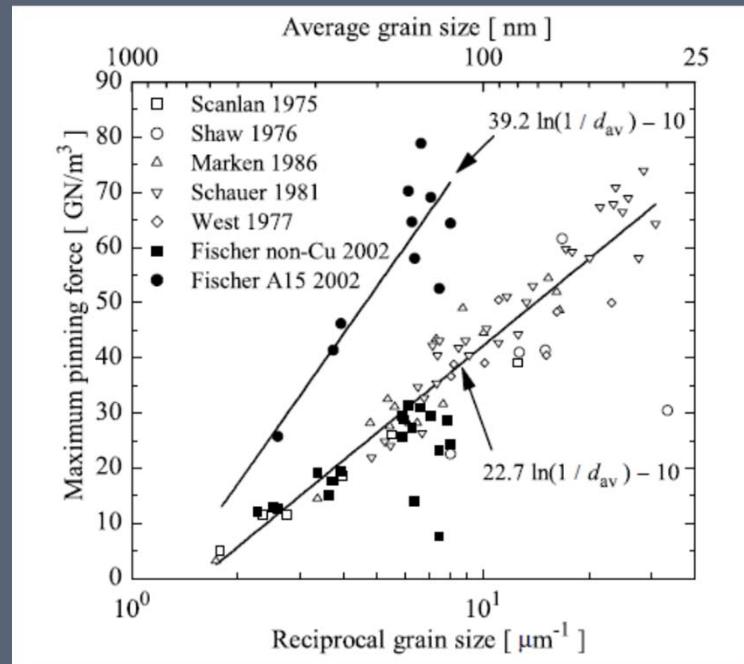
Further development of the Nb_3Sn pinning mechanism

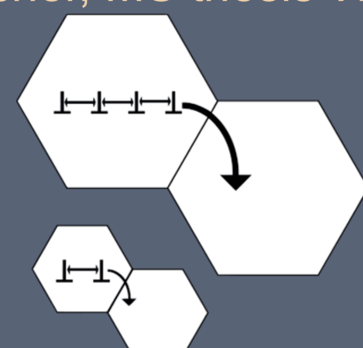
- The previous slides suggest that there could be plastic deformation of the Abrikosov vortex lattice in Nb_3Sn
- If so, does a work hardening mechanism apply?
  - Dislocations in vortex domains would encounter the strain fields of AJ vortex segments at boundaries
  - Yield stress

$$\sigma_y = Gb\sqrt{\rho_\perp} = C_{66}a_0\left({}^{1}\!/_{D}\right)$$

  - C_{66} is the shear modulus
  - a_0 is the flux-lattice constant and Burgers vector
  - D is the Nb_3Sn grain diameter
- If so, then pins added within grains would be additive to the strengthening effect of boundaries / domain walls in the vortex solid



C. Fischer, MS thesis Wisconsin



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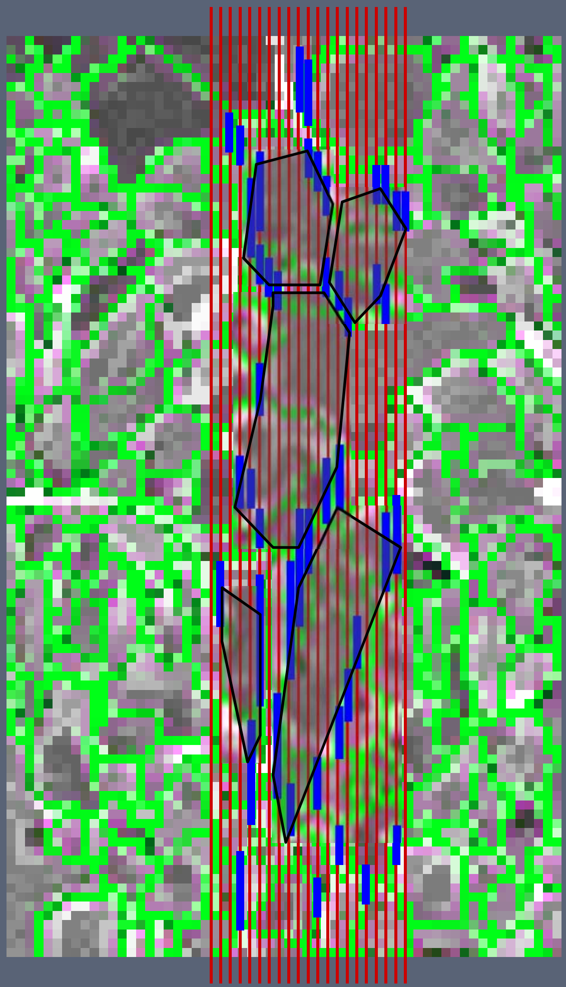

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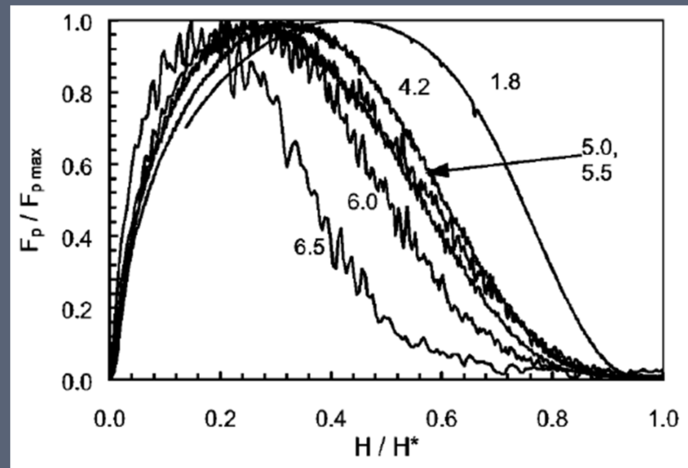
Second challenge – Ultimate pinning in granular LTS

Nb_3Sn is the workhorse magnet conductor

- Talks later today describe ***significant gains in Nb_3Sn flux pinning*** by combining point-like pinning centers with grain-boundary pinning
  - X. Xu et al 1MOr2B-05
  - S Balachandran et al. 1MOr2B-06
- Can "flux shear" be replaced by "core pinning"?
  - "Flux shear" → $F_p(B)$ peaks at 0.2 B_{irr}
  - "Core pinning" → $F_p(B)$ peaks at 0.5 B_{irr}



MgCNi$_3$ – a granular material with intragranular Ni$_3$C precipitates -- Cooley, L. D., X. Song, J. Jiang, D. C. Larbalestier, T. He, K. A. Regan, and R. J. Cava. Physical Review B 65, no. 21 (2002): 214518.

To further extend the limit in Nb_3Sn: make thin films with very small (<50 nm) grains, followed by irradiation

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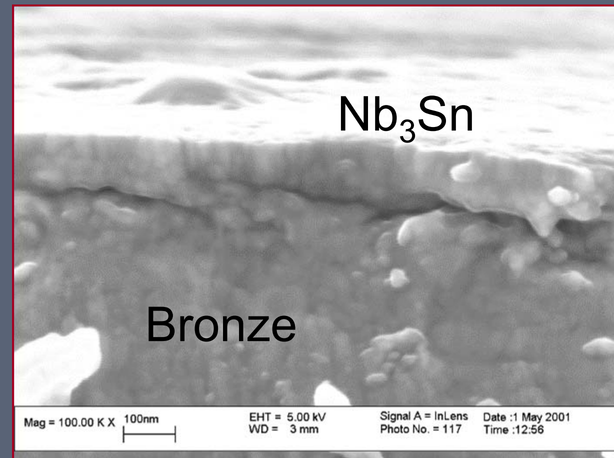
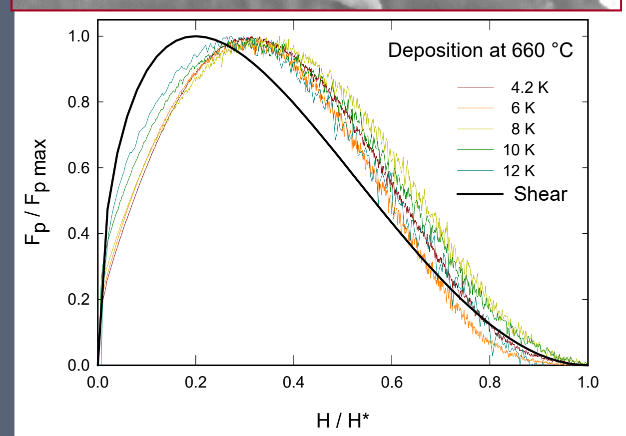
Second challenge – Ultimate pinning in granular LTS

Nb_3Sn is the workhorse magnet conductor

- Talks later today describe ***significant gains in Nb_3Sn flux pinning*** by combining point-like pinning centers with grain-boundary pinning
  - X. Xu et al 1MOr2B-05
  - S Balachandran et al. 1MOr2B-06
- Can "flux shear" be replaced by "core pinning"?
  - "Flux shear" → $F_p(B)$ peaks at 0.2 B_{irr}
  - "Core pinning" → $F_p(B)$ peaks at 0.5 B_{irr}

To further extend the limit in Nb_3Sn: make thin films with very small (<50 nm) grains, followed by irradiation





L D Cooley and P J Lee – *IEEE Trans ASC* **11,** 3820 (2001)

Conclusion – Abrikosov's legacy for LTS

- Pinning vortices enables all superconducting magnets, everywhere
- High current density only came about after key challenges were overcome to first understand and then optimize the nanostructures that powerfully interact with the nano-scale structure of the vortex
  - Seeing nanostructures
  - Engineering nanostructures
  - Understanding the nano-scale physics and modeling interactions
- Along the way, other inspiring opportunities emerged
  - The Abrikosov-Josephson vortex at boundaries and thin precipitates
  - Matching effects, the terraced critical state
  - Vortex-pin matched systems, ratchets, flux-flow devices
  - Conformal mapping
  - Vortex grains / domains
- And new challenges continue to present themselves
  - The next generation of added-pinning-center Nb_3Sn
  - New ideas about gradients