Flux Penetration in SRF Cavity quality Nb – especially at Grain Boundaries

Anatoly Polyanskii, Peter Lee, Alex Gurevich, Alex Squitieri, David Larbalestier
Applied Superconductivity Center at the University of Wisconsin-Madison

Pierre Bauer, Leo Bellantoni, Christian Boffo and Helen Edwards
Fermilab, Batavia, IL

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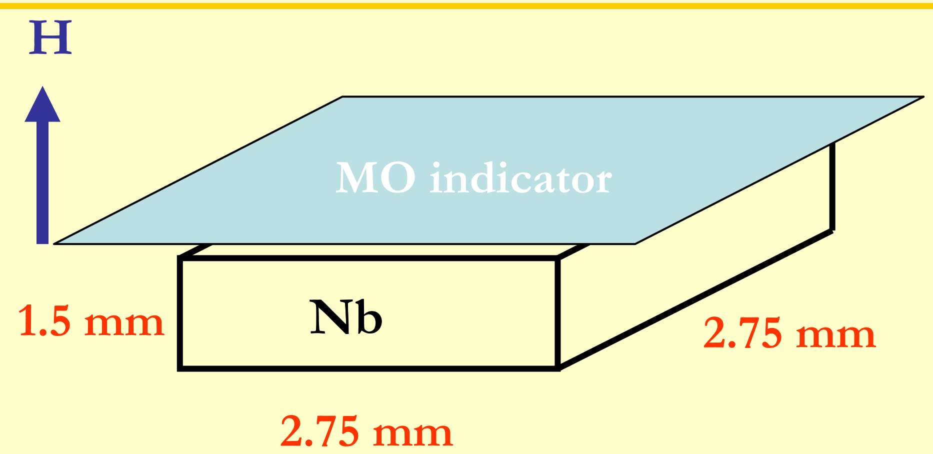
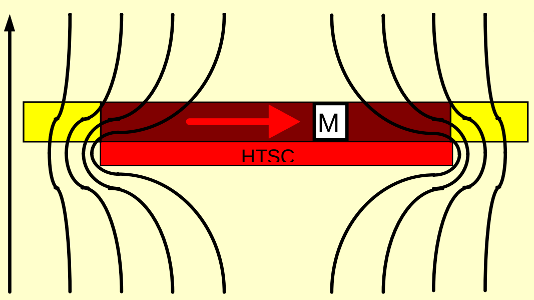
Motivation, methods and approach

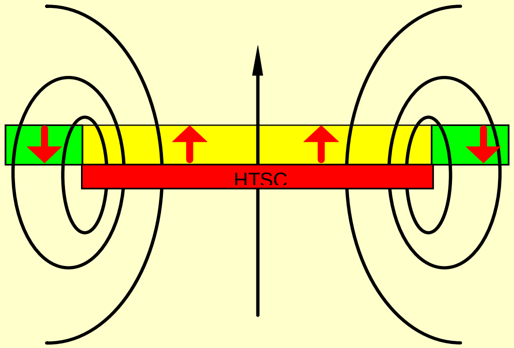
- In 2004 we found by magneto-optical (MO) imaging that some Nb grain boundaries (GBs) showed preferential flux penetration below that seen in the grains
  - Was this evidence for depressed superconductivity at some Nb GBs and if so what causes it?
  - Nb has a long coherence length (~40nm), as compared to all high field superconductors, yet is seemed to be showing some characteristics of a high-Tc superconductor with low carrier density and much shorter ξ (1-3nm)
- Plan: Observe the MO flux penetration, the magnetization and the surface topology of a through-process sample set made at Fermilab
  - In early 2005 ingot slices from the JLab single crystal cavities became available
    - we cut slices from large grain material so as to observe single GB properties in transport too
  - Model the RF performance of Nb (Alex Gurevich)

MO method



Working range is down to 6K and up to about 130 mT – to above H_{c2}





Zero field cooled (ZFC) to the superconducting state, then field applied.

Field cooled (FC) into the superconducting state, then field reduced to zero.

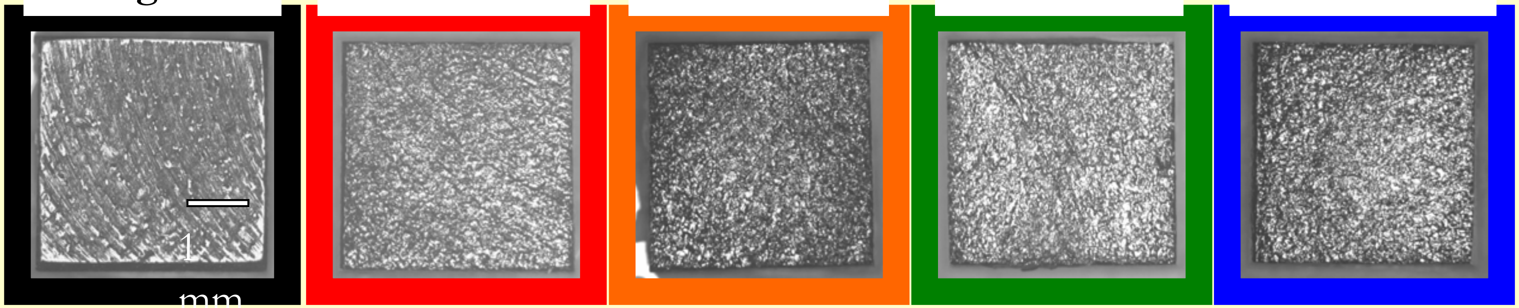
Experiment Sequence

- Regular fine grain Nb Cavity sheet
- Simulated welds in the same sheet
- Samples cut from large-grain JLab ingot

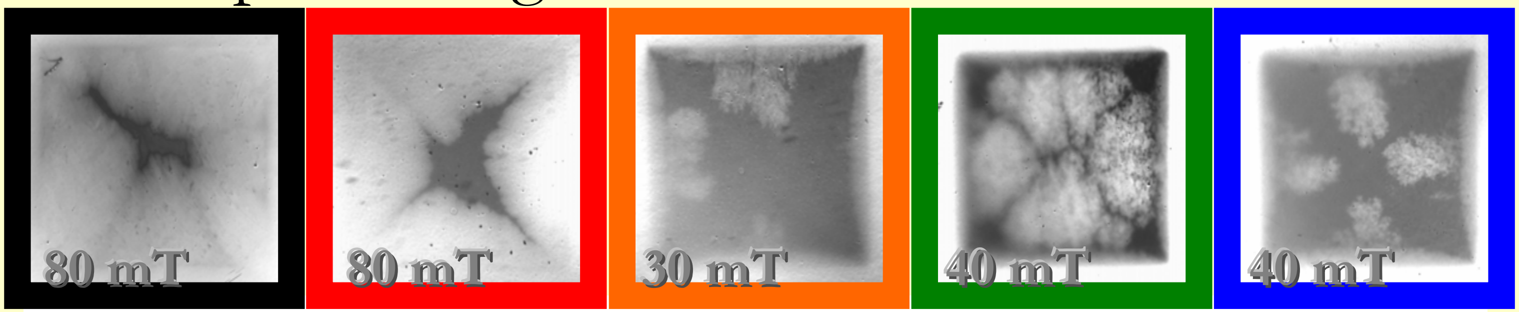
Regular samples

Process sequence

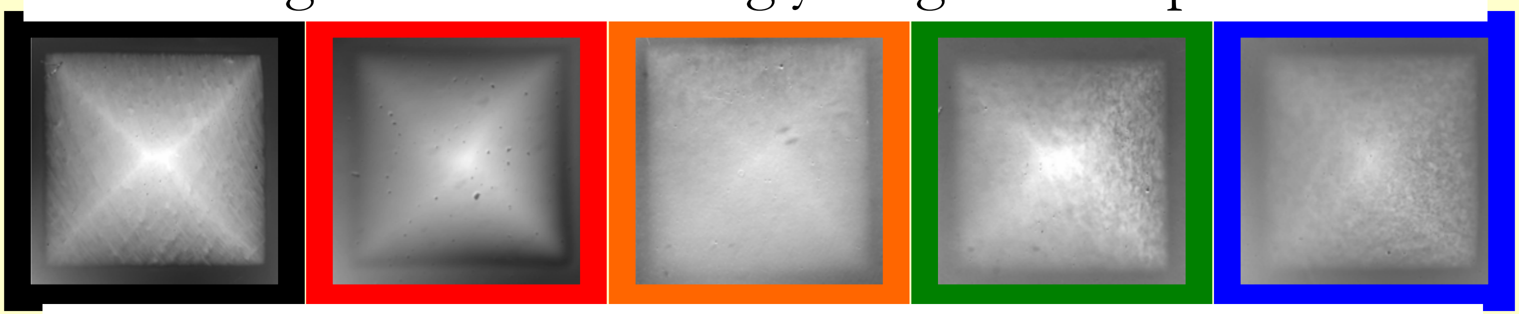
Cold work + degrease	… + 100 min etch	… + 750°C HT	… + 20 min etch	… + 120°C bake



Optical images of surface machine marks



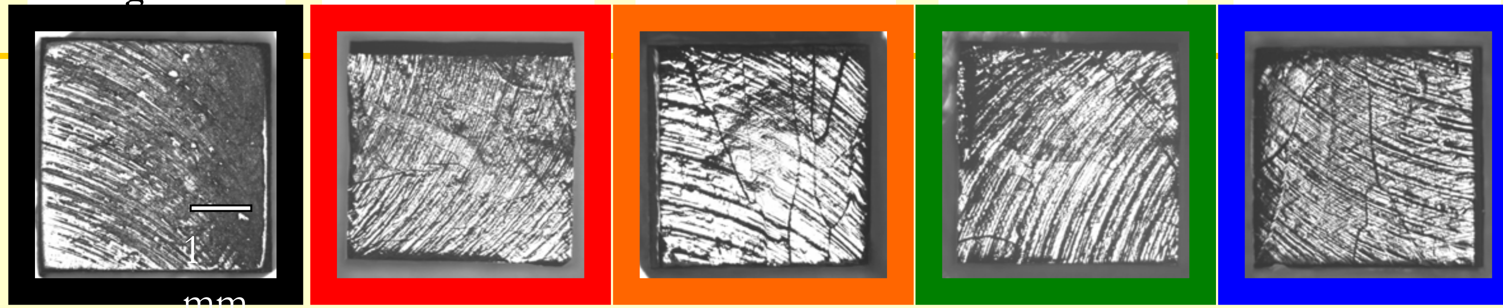
ZFC images show increasingly irregular flux penetration



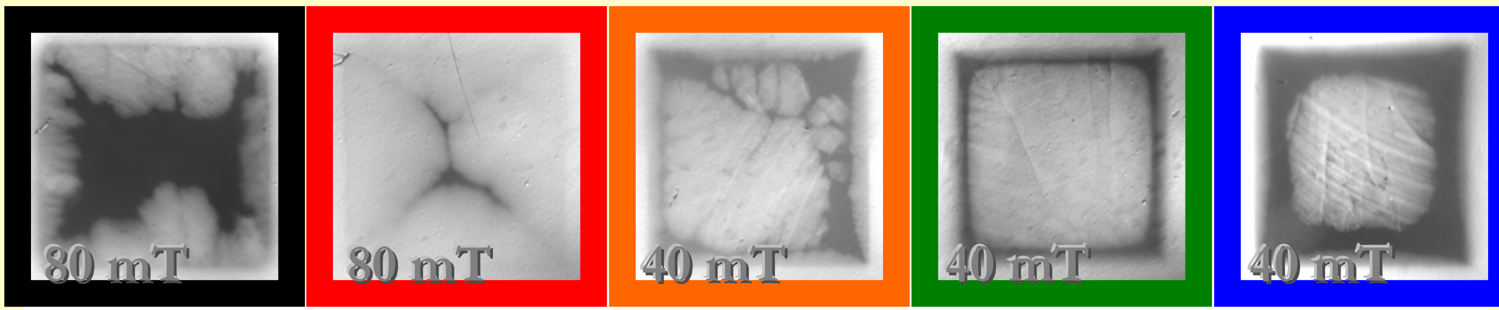
FC images after cooling to 7 K in $H \geq H_{c2} = 110$ mT show more uniform flux distribution

Weld samples

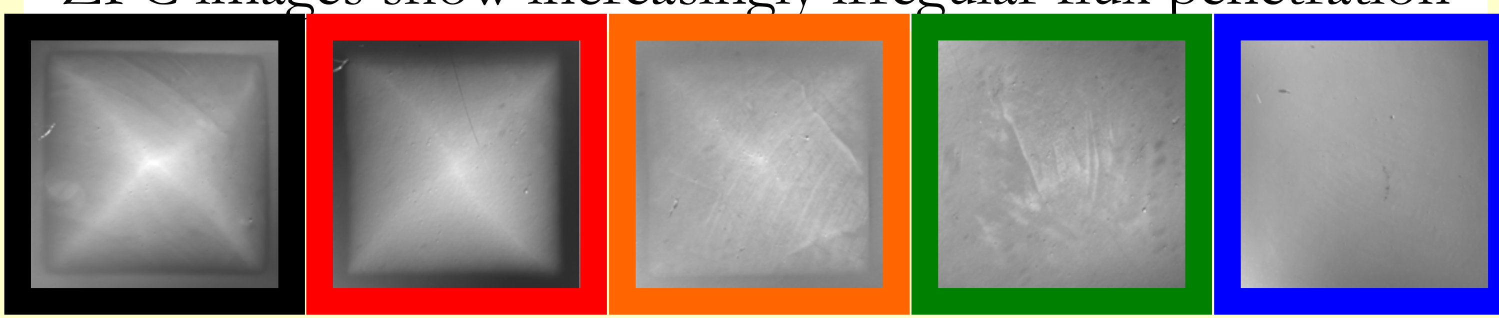
Cold work + degrease	… + 100 min etch	… + 750°C HT	… + 20 min etch	… + 120°C bake



GBs are visible through the surface machining marks

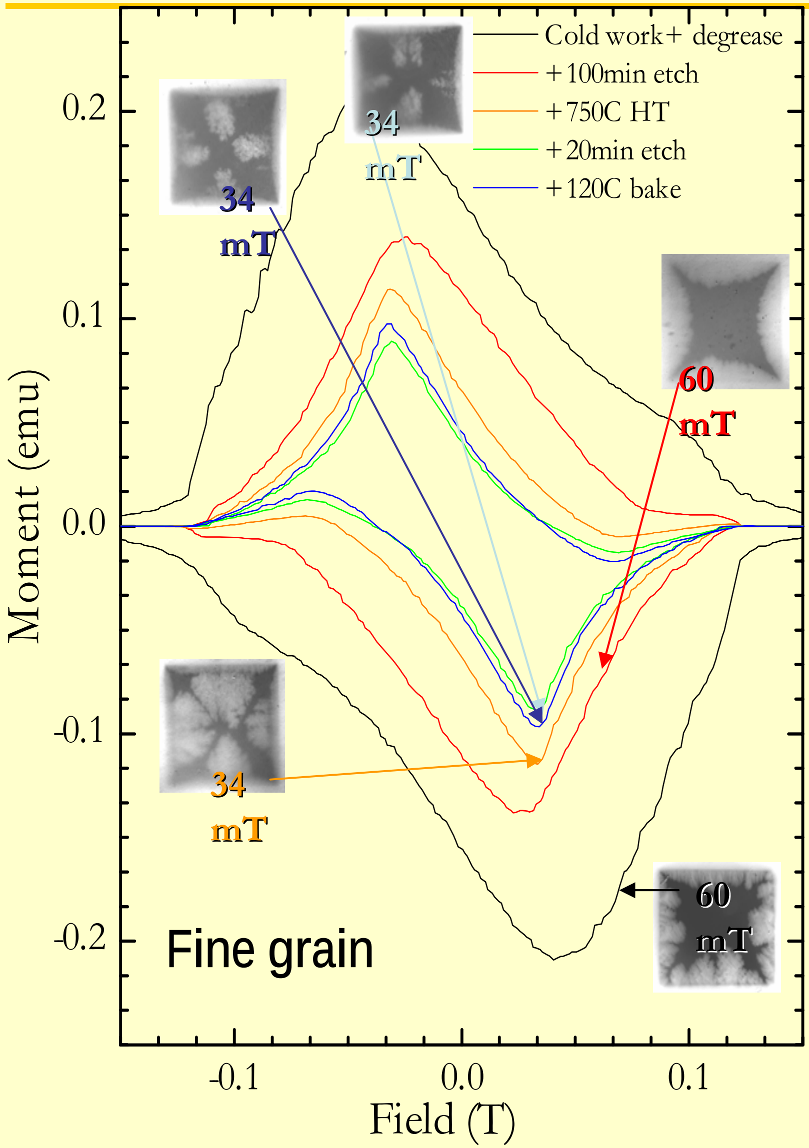


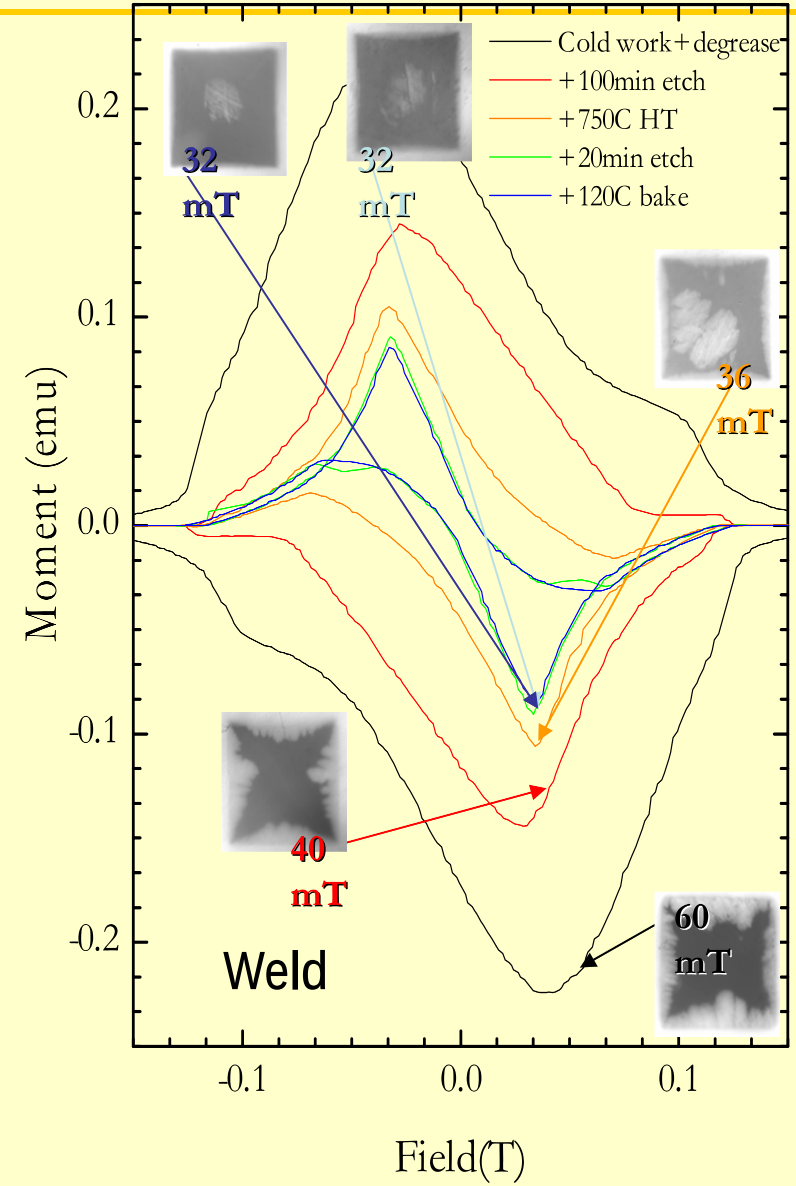
ZFC images show increasingly irregular flux penetration



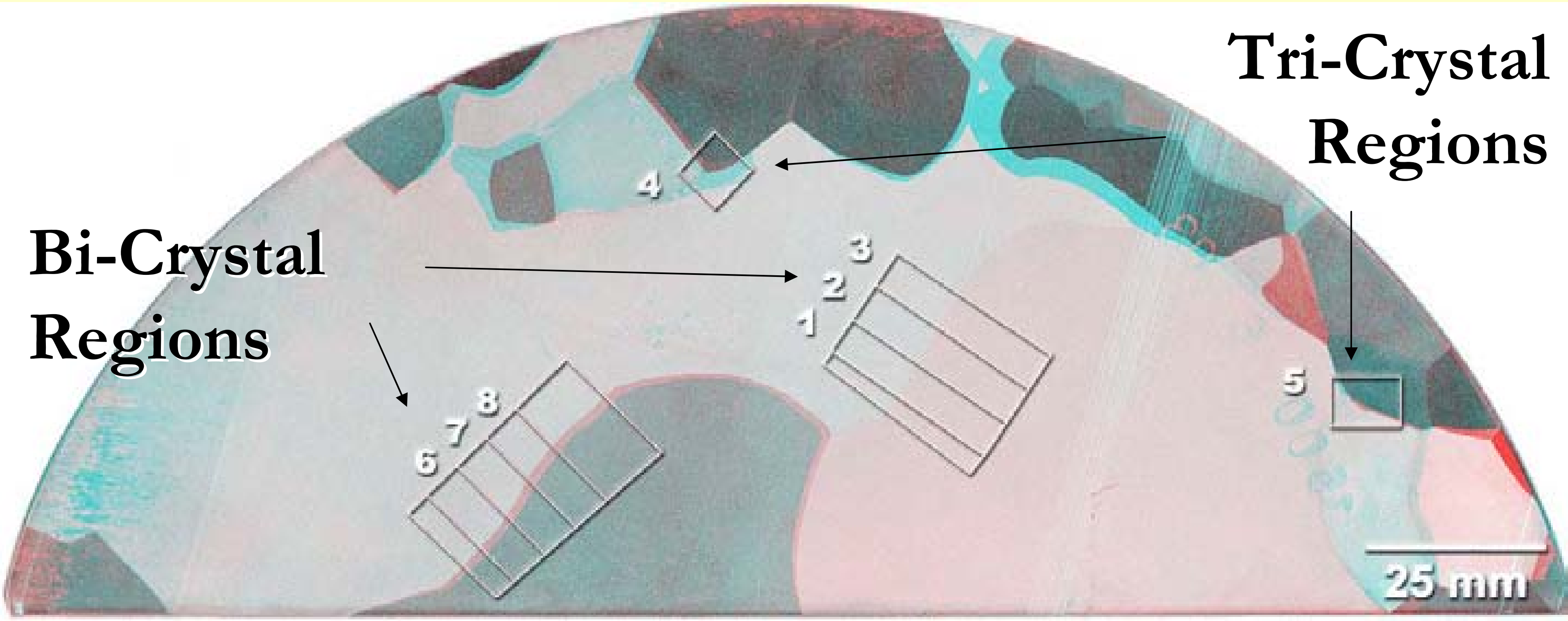
H=0 FC images after cooling to 7 K in $H \geq H_{c2} = 110$ mT show initially uniform flux distribution, which is progressively more perturbed in later process steps

MO images and magnetization on same samples





Large Grain Ingot Slice Experiments

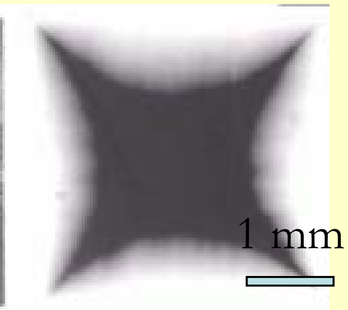


Ingot slice courtesy of Peter Kneisel
(Reference Metals Nb)

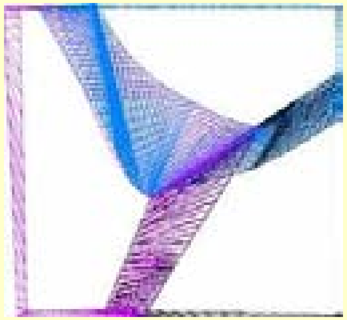
Some GBs admit flux, others do not…………

Uniform roof top pattern for sample #4 with inclined GB

Top Surface Light Image

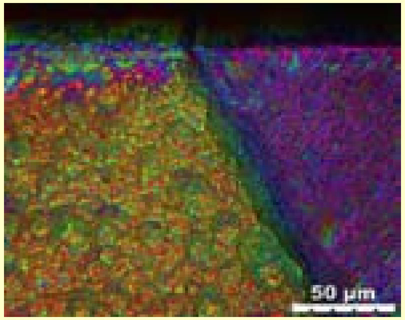


T=5.5 K, H=120 mT



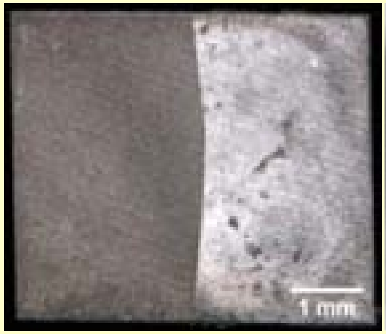
3D Model

ZFC T=5.7 K H=60 mT

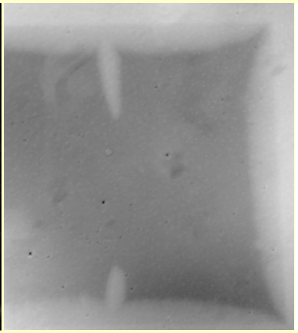


Depth Map, 15 µm Range

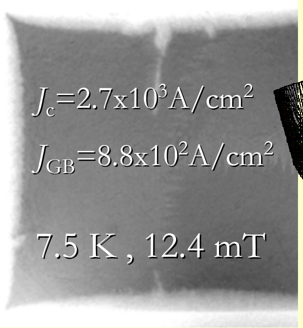
Non-uniform roof top pattern for sample #5 with almost straight GB

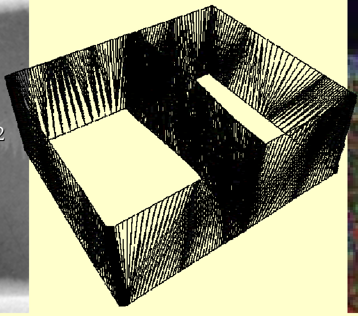


Top Surface Light Image

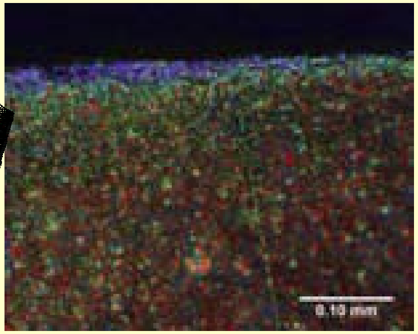


ZFC T=5.6 K H=8.4 mT





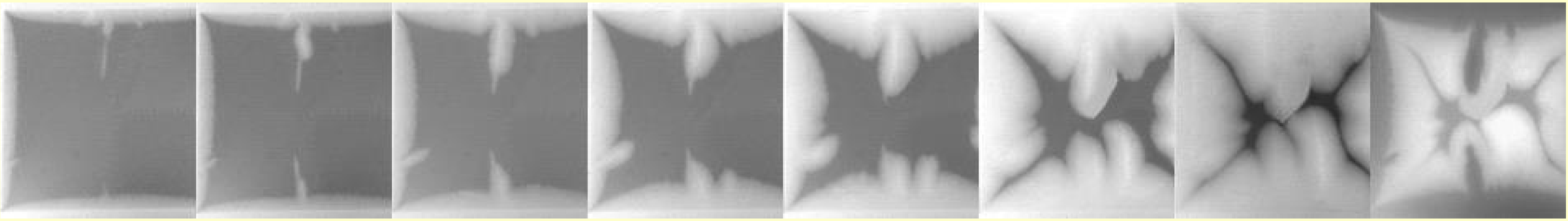
3D Model



Depth Map, 5 µm Range

Field dependence of flux penetration

Sample #5 ZFC T=7.5K



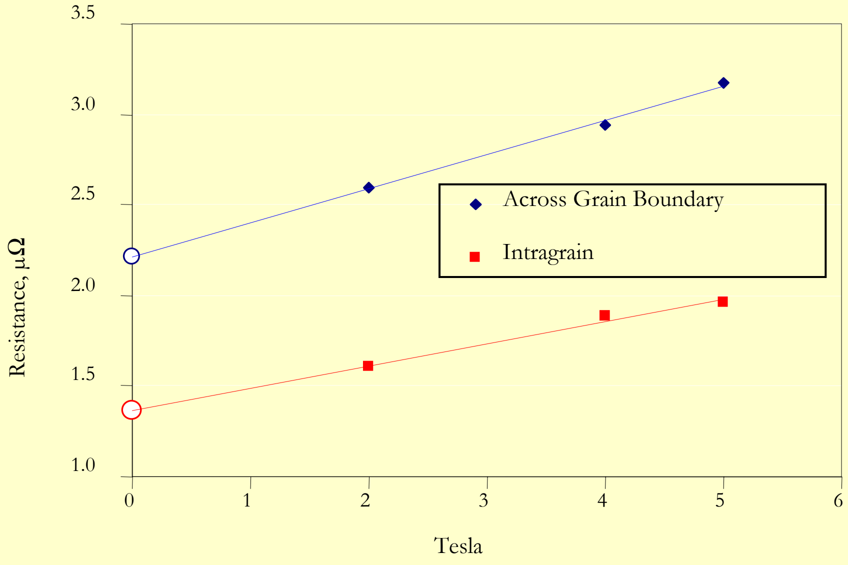
12 mT	12.4 mT	14.8 mT	16.8 mT	18.8 mT	20 mT	22.8 mT	-12.0 mT

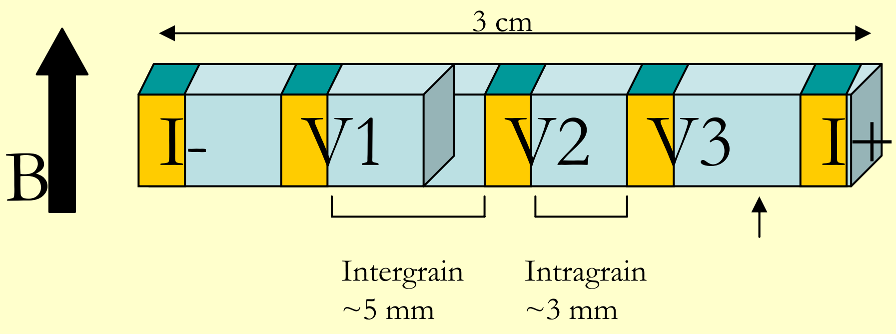
Grain boundary clearly distorts the field penetration

RRR across GB vs. the grain

Measured at Room (291K) Temp and 4.19K using the zero field resistance back extrapolated from in-field measurements between 2-5T

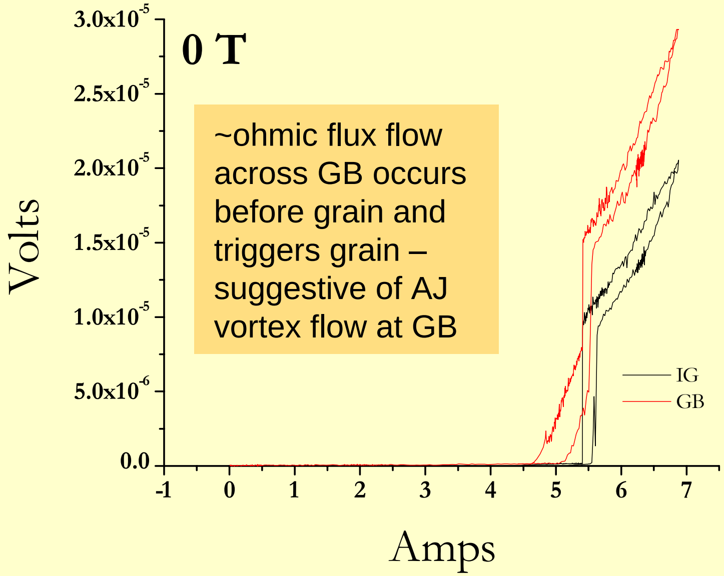
Normal State Resistance vs Field 4.19 K

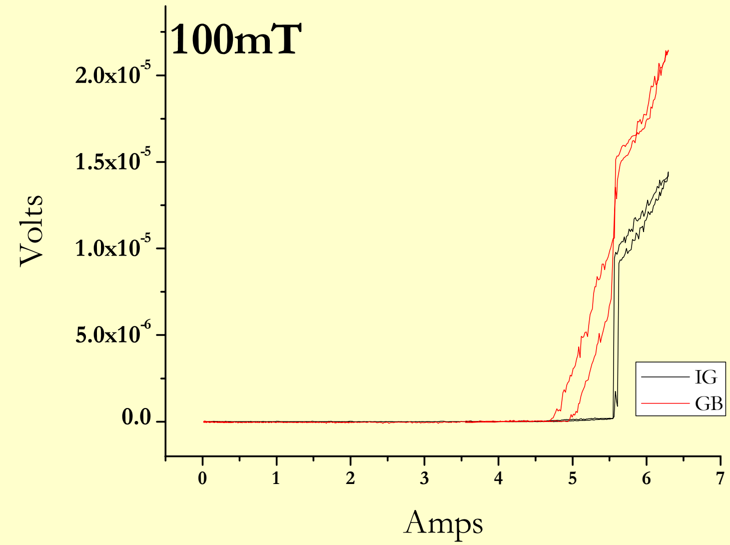


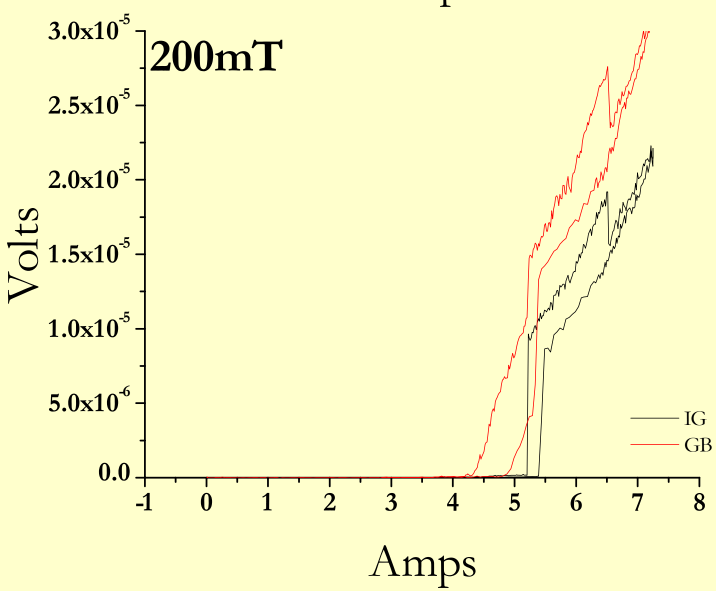


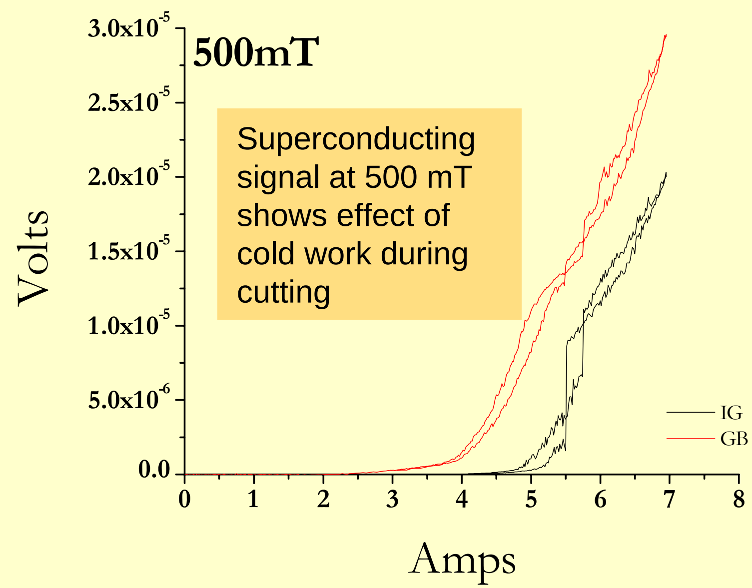
- **RRR across grain boundary – 187**
- **Within grain - 211**

Critical current in grain and across GB





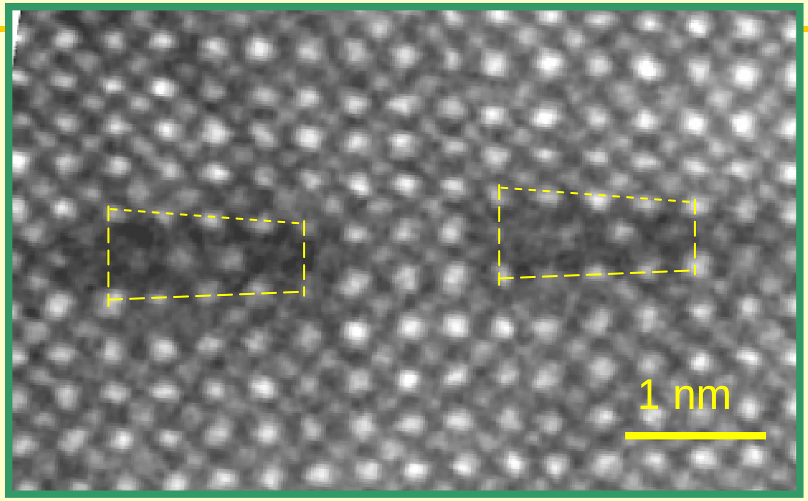


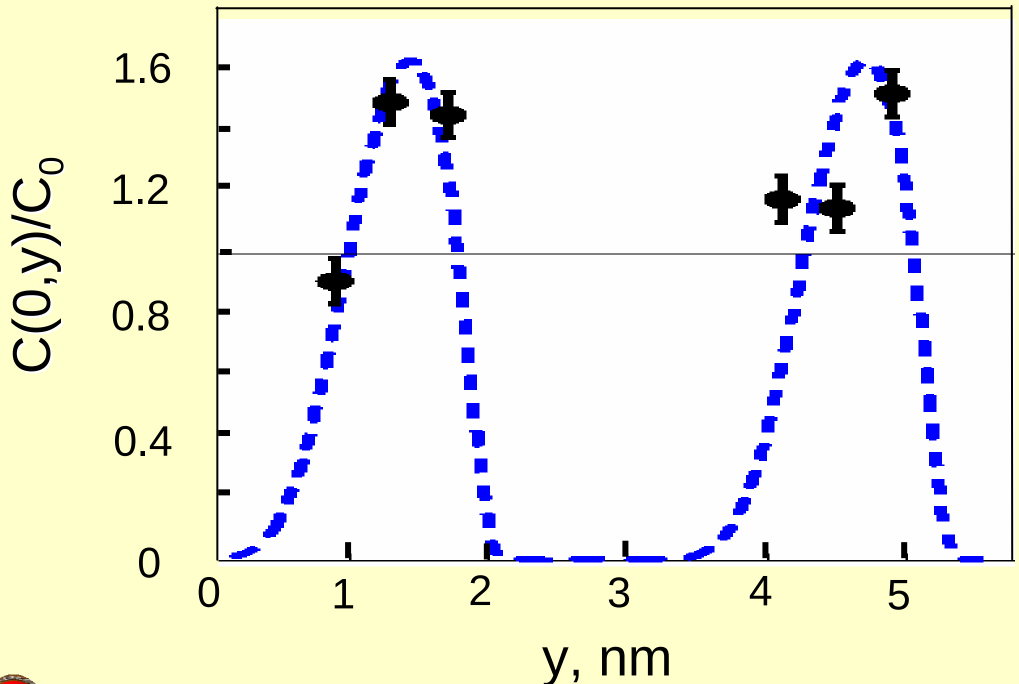


Summary

- There is abundant evidence that *some* Nb grain boundaries show early flux penetration
  - Sensitivity is greatest close to Hc1
- Penetration has some dependence on the applied treatment
  - Optimization treatments seem to be enhancing the variability of properties
  - Crystallography of the GB may be important
  - Topology on the micron scale does not seem to be driving the penetration
- It is very striking that we can reproduce some aspects of High-Tc performance in Nb!
  - A near-term goal is to apply our well developed understanding of HTS GBs to Nb
    - AJ vortices, atomic scale segregation (Song et al. Nature Materials 4, 470-475 2005)
- Plans - MO to sort good and bad GBs, topography using SEM or confocal, crystallography by EBSD, transport across single GBs, TEM of the good and bad GBs

The HTS analog - Ca segregation at a YBCO GB

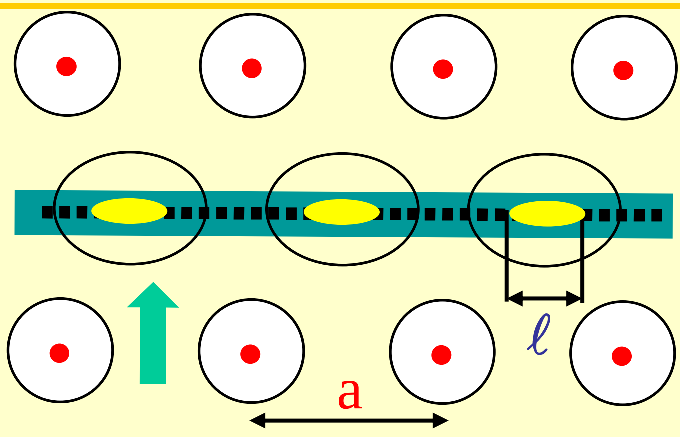




Large peaks Ca segregation in tensile regions, troughs in compressive regions

X. Song, G. Daniels, D. M. Feldmann, A. Gurevich, and D. C. Larbalestier, "Electromagnetic, Atomic-Structure and Chemistry Changes Induced by Ca-doping of Low Angle YBCO Grain Boundaries," Nature Materials, 4, 470-475, 2005.

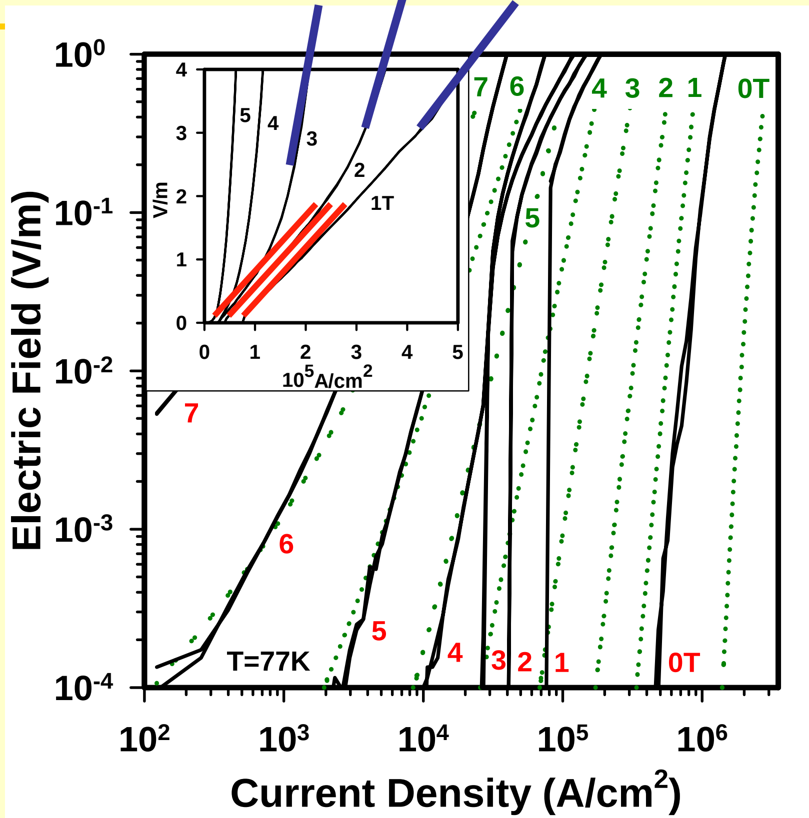
Single vortex-chain motion along pure YBCO GB



- Josephson core size: $\ell = \lambda_J^2/\lambda = \xi J_d/J_b$
- The Josephson cores overlap if $\ell > a$
  (Gurevich, PRB48, 12857 (1993); PRB46, R3187 (1992)):

$$H > (J_b/J_d)^2 H_{c2}$$

- Viscous flux motion $V = (I - I_b)R$
- R(B) is independent of B, if a single vortex chain moves along GB, while $\ell > a$



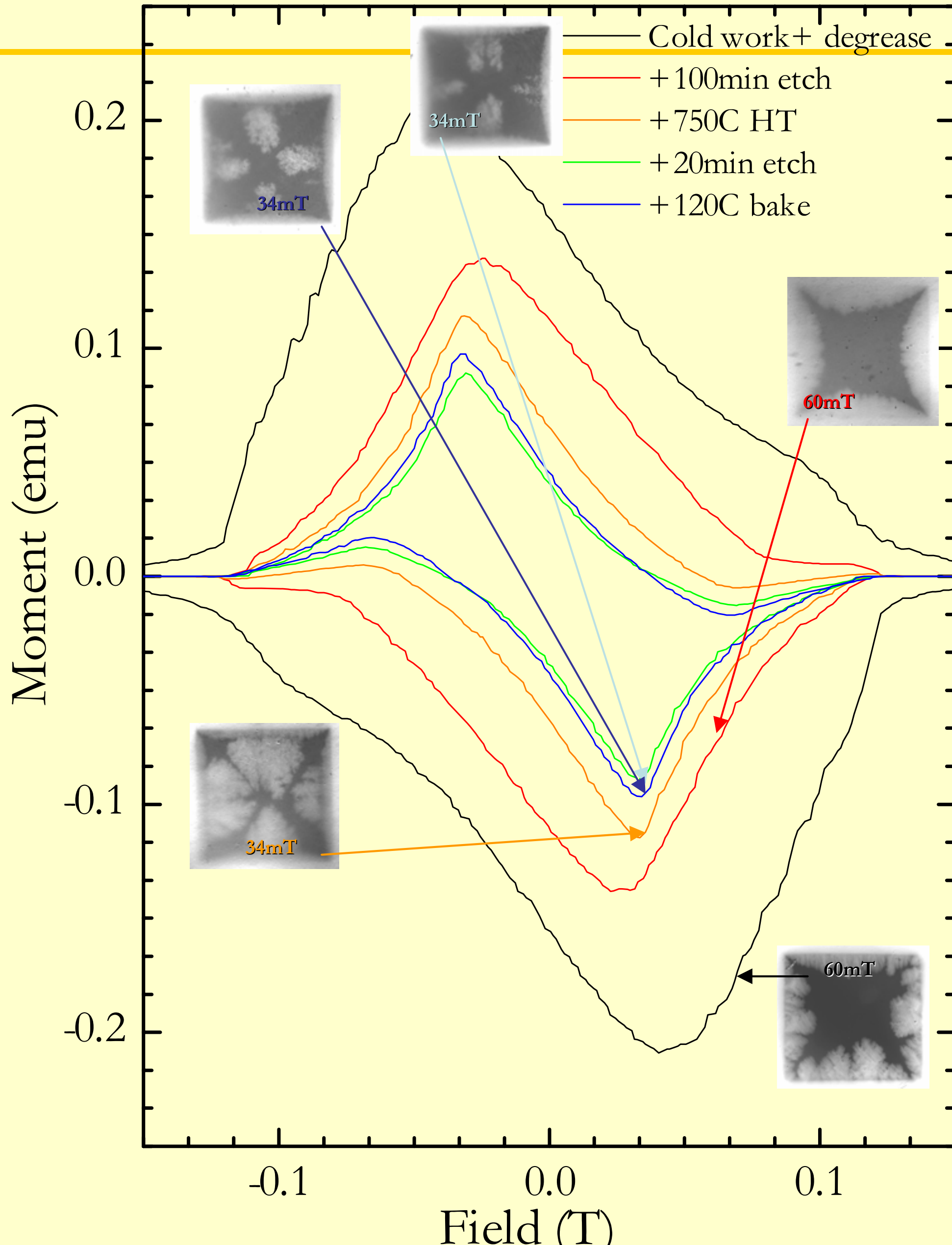
Collective depinning of multiple vortex rows along GB:

$$R(B) = w(B)\rho_n B/B_{c2}$$

Gurevich et al. PRL 88, 097001 (2002)

Regular sheet –

Magnetization and MO images on the same sample



Flux enters irregularly near Hc1 and becomes more regular at higher fields

Suggests that the surface barrier is locally determined

Magnetic Flux Penetration - UW

- Vortices (whatever type) have to overcome the surface barrier; for Abrikosov vortices the surface barrier disappears only at $H = H_c$ (~180 mT @ 2 K)! For "mixed" vortices the penetration field is much lower (~ 0.1 H_c) What type of vortices?

- Surface barrier is reduced by defects (which – topology, weakened superconductivity?) How can we disentangle topology and suppressed superconductivity effects?

- Which roughness scale drives the topological contribution ? Is that the reason for difference between baking effect in EP and BCP? (e.g. baking cures the chemical issue but topology is still there)

- What does the superior performance of single crystal cavities tell us? No grain boundaries, very low roughness – but still Q-drop (albeit onset at higher field)!

“Weld” sheet

– Magnetization and MO images on the same sample

Flux enters irregularily near Hc1 and becomes more regular at higher fields

Suggests that the surface barrier is locally determined

Q Slope Explanations

- Weak surface superconductivity
  - But is this general or at GBs too and what is the balance between them?
- Grain-edge enhancement
- Fluxon penetration
- Wet-dry oside formation and localized states at the GB or surface
- Thermal feedback