Vortices and Flux Pinning Coated Conductors

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INVITED PRESENTATION

MURI-CC-03 Workshop
Madison, WI
June 11–13, 2003

prepared by
CONDENSED MATTER SCIENCES DIVISION
OAK RIDGE NATIONAL LABORATORY
Managed by
UT- BATTELLE, LLC
under
Contract No. DE-AC05-00OR22725
with the
U.S. DEPARTMENT OF ENERGY
Oak Ridge, Tennessee

July, 03

Vortices and Flux Pinning Coated Conductors

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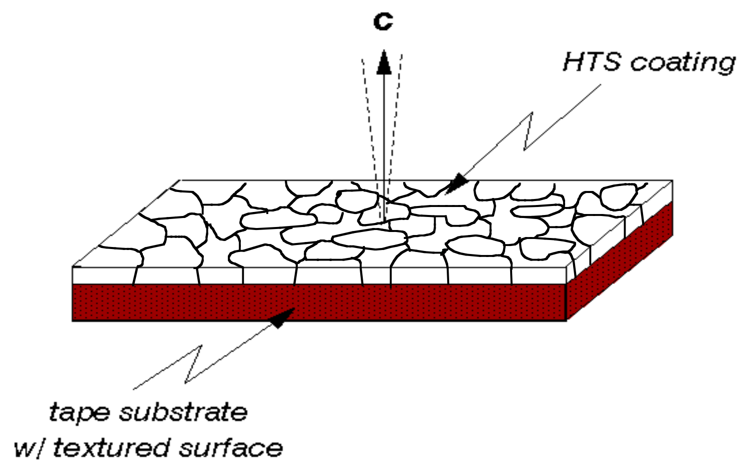
Coated Conductors as imperfect films

- ***epitaxial, c-axis growth from textured substrate surface***
- ***~planar grain boundaries through entire thickness***
- ***grain boundaries may limit critical currents***
- ***Must be thick (for large currents)***



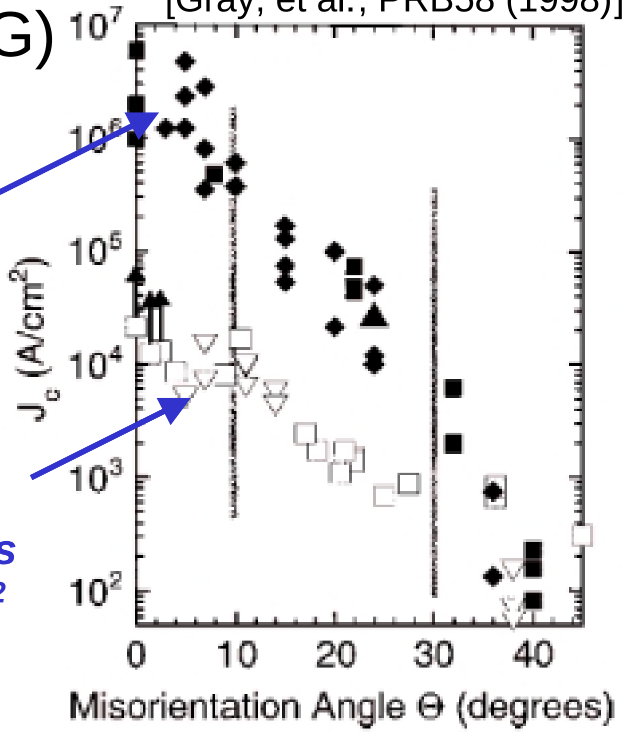
Why is it important to optimize flux pinning for intragrain J_c?

Why Flux Pinning in Coated Conductors?

For low-angle grain boundaries,

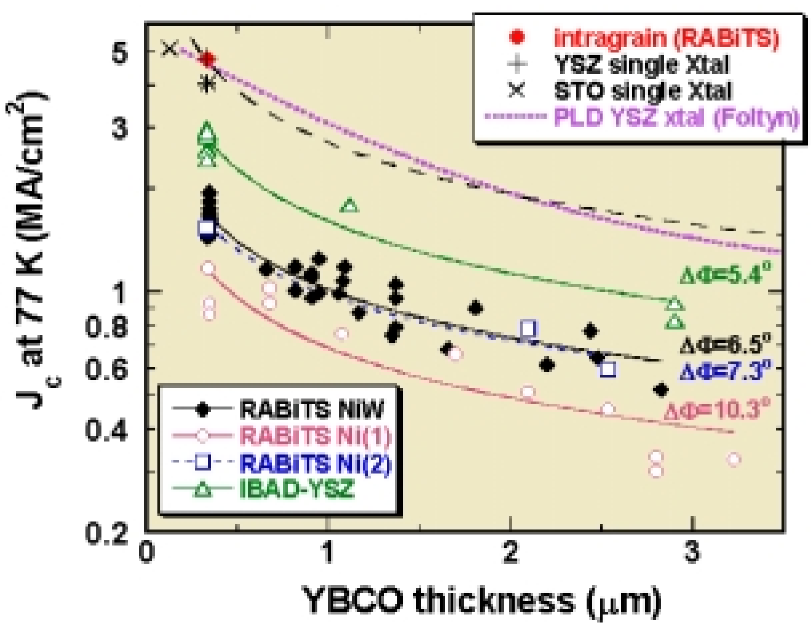
- Evidence suggests J_c(GB) scales with J_c(G)
  - melt-processed vs epitaxial films
  - irradiated film bicrystals
    7° GB dissipation decreases
    [Gurevich, et al. PRL **88** (2002)]
  - CC J_c(d) scales with texture

[Gray, et al., PRB58 (1998)]



Epitaxial film YBCO bicrystals $J_c(G)>10^6$ A/cm^2

Melt-processed YBCO bicrystals $J_c(G)<10^5$ A/cm^2



Need optimal intragrain flux pinning for highest J_c(GB)

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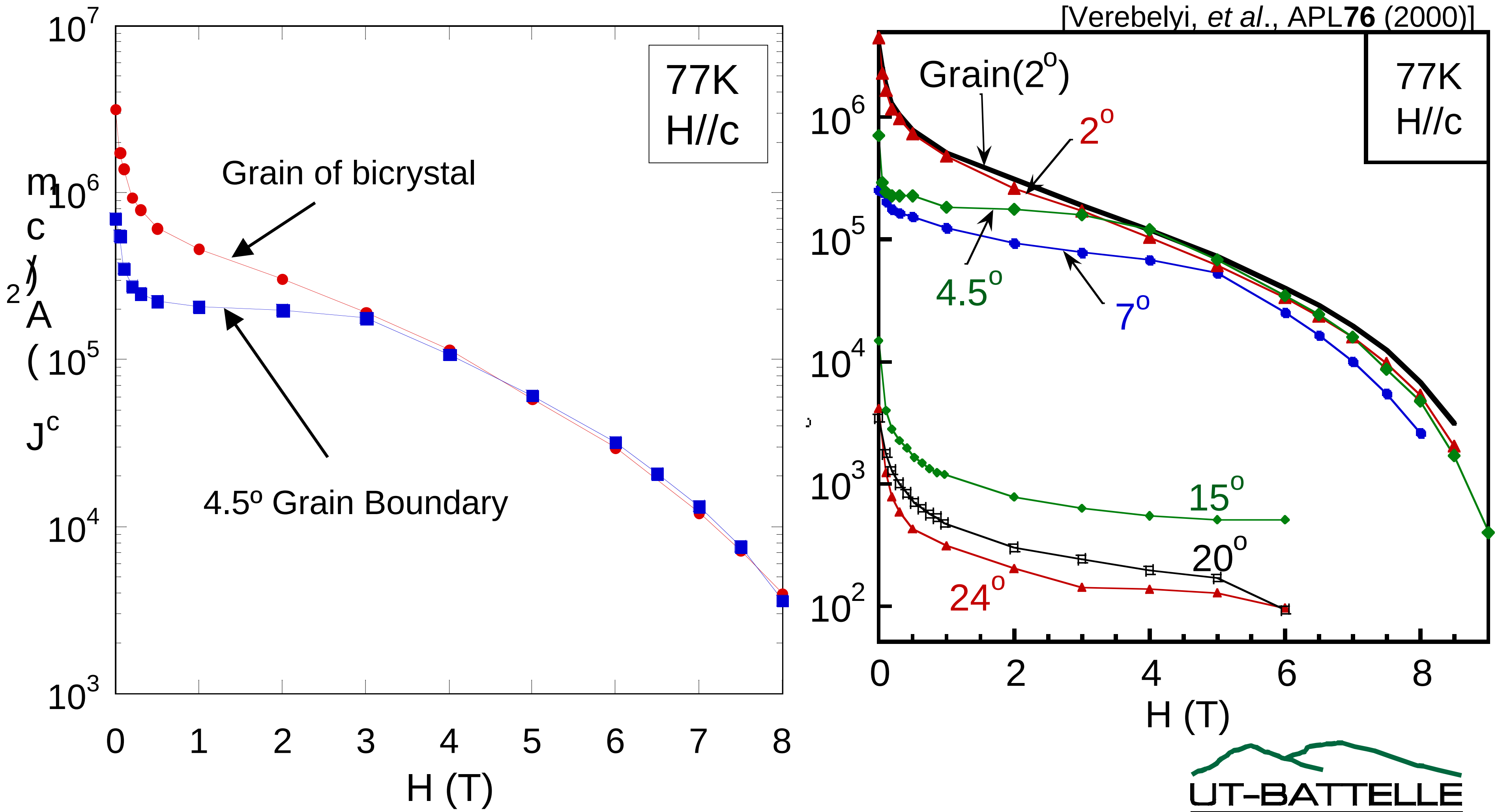
Field Dependence of J_c(GB) and J_c(G)

For low-angle GB's:

- J_c limited by GB at low fields, but
- Grain dissipation dominates at high-field



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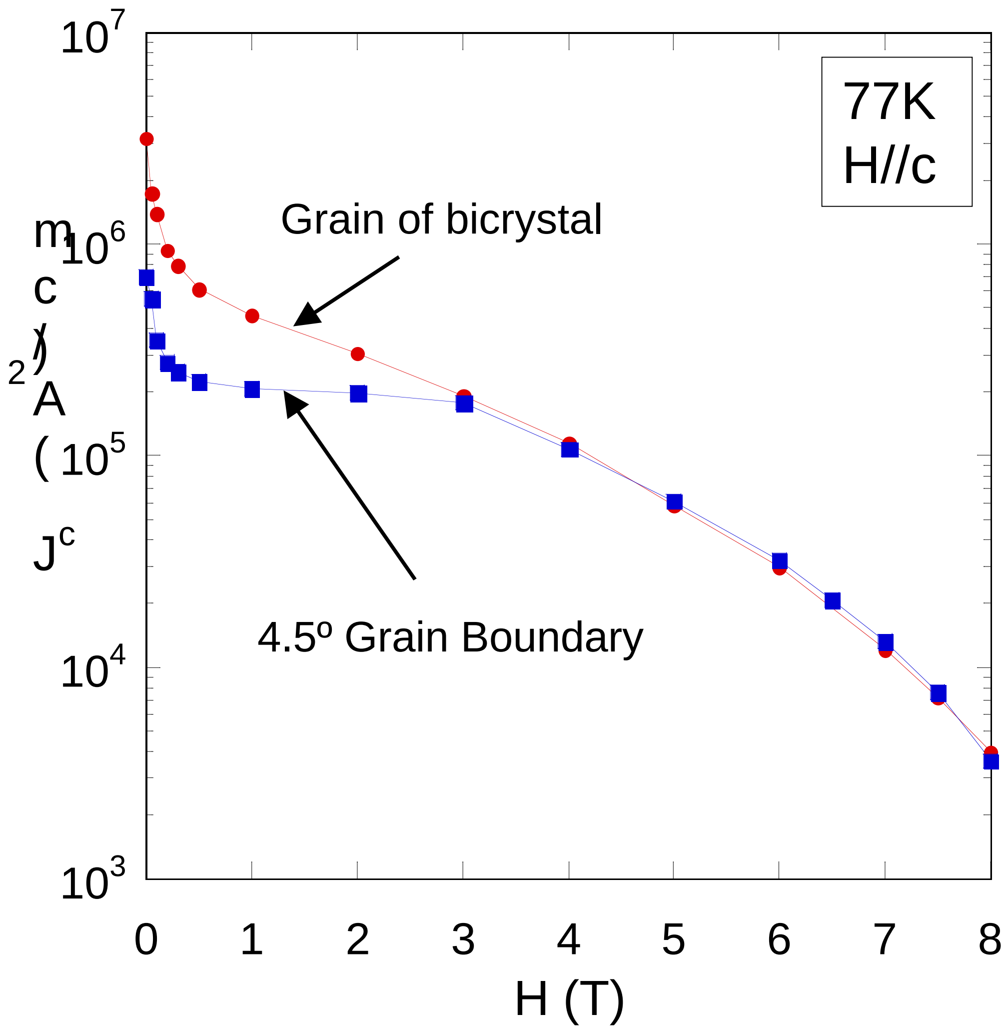
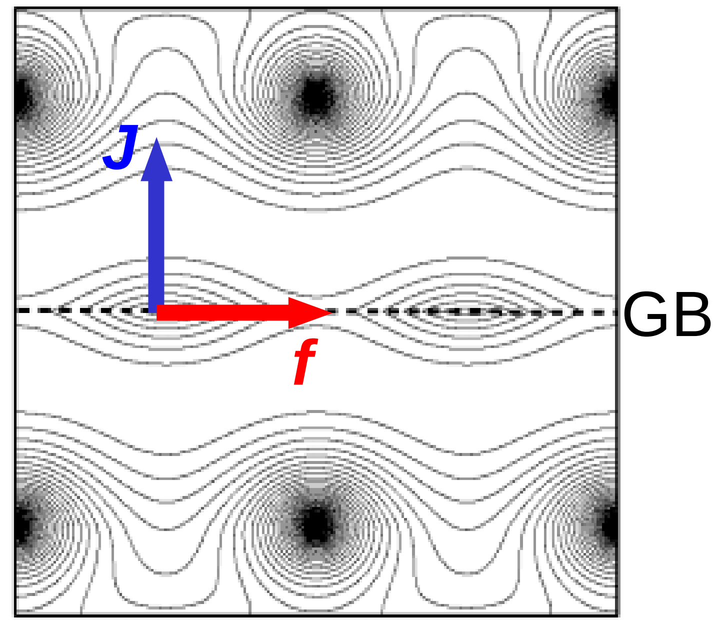


Consistent with model:

Pinning of GB vortices by pinned G vortices

[Gurevich, *et al*., PRL **88** (2002)]



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Issues Affecting Intragrain Flux Pinning in Imperfect Films (Coated Conductors)

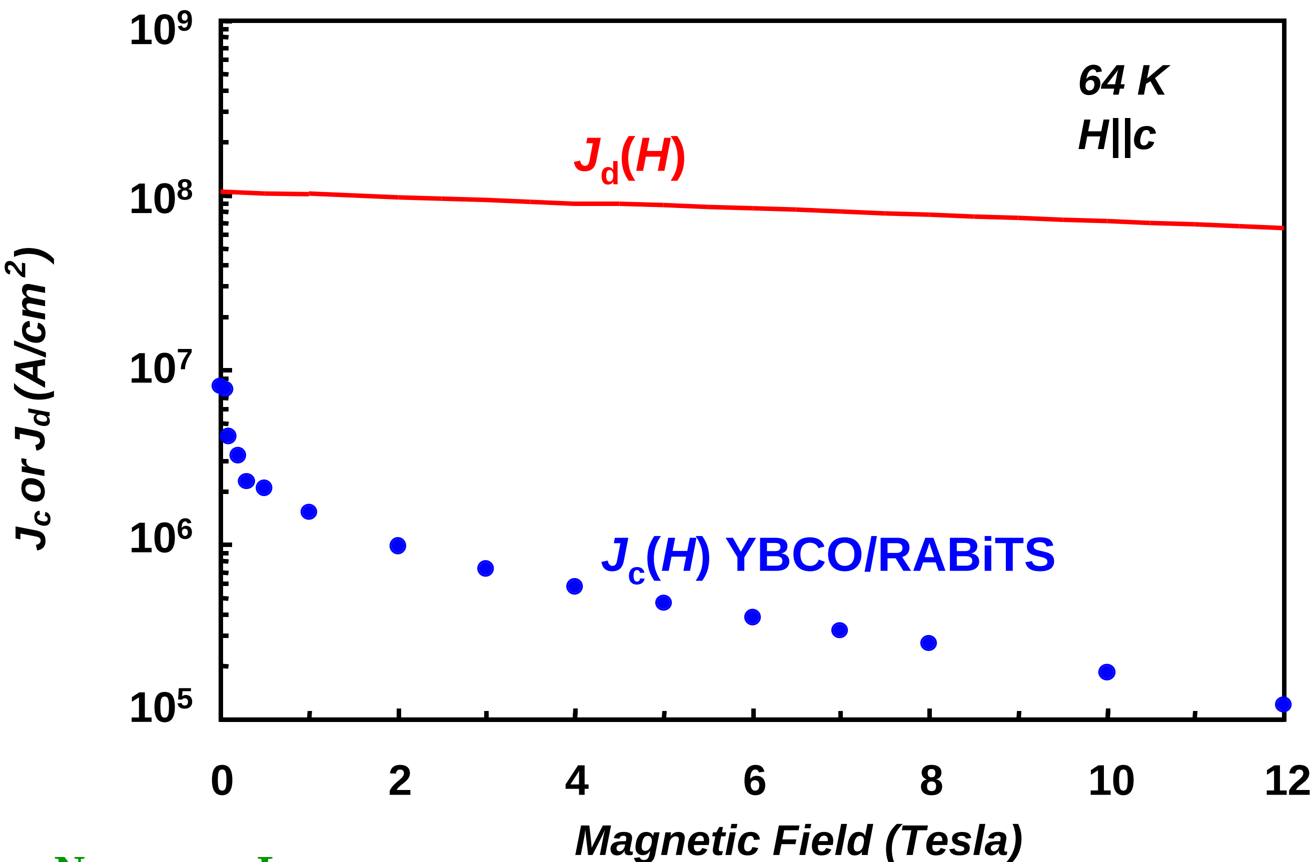
- ***Intrinsic HTS material properties***
  - ➢ T_c
  - ➢ *Anisotropy*
  - ➢ *Charge doping levels*

- ***Microstructure/ Defects***
  - ➢ *Compositional/Growth Effects*
    - – *growth on vicinal or rough substrate surfaces (dislocations, anti-phase boundaries)*
    - – *twin boundaries, screw and edge dislocations and loops, phase segregation*
  - ➢ *c-axis tilt grain boundaries*
    - – *Dislocation core pinning in low-angle limit*
    - – *oxygen vacancies; cation disorder; isolated a⊥; …*

Flux-pinning in as-grown YBCO films is strong

- ***J_c ~ 1/10 J_d in self-field, but***
- ***far from optimal in field***

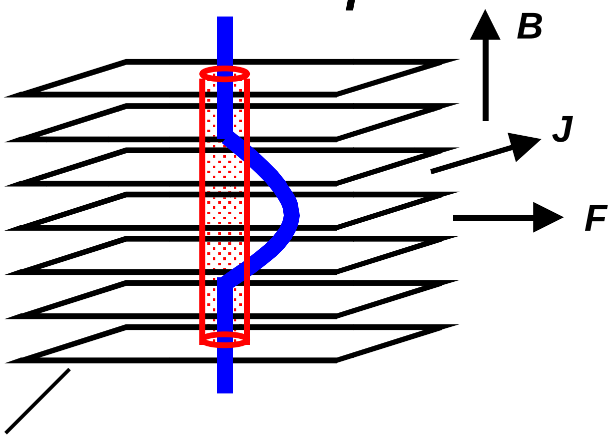
In principle, $J_c \rightarrow J_d$ for pinning by matched columnar holes of radius ~$\sqrt{2}\ \xi$



Thermally Activated Depinning from Columnar Defects

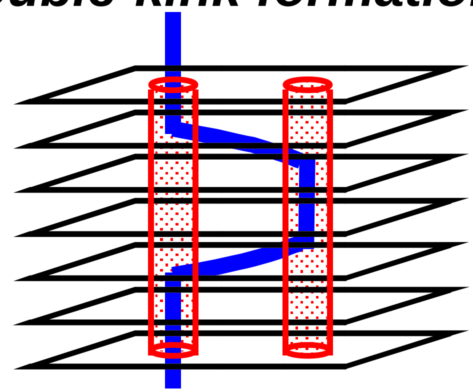
Vortex density less than columnar defect density, depinning can occur by:

Vortex half-loop formation



CuO_2 plane group

double-kink formation



ENERGY CONSIDERATIONS

Pinning line energy : u_p

Vortex line tension: $\tilde{\varepsilon} = \varepsilon / \gamma^2$

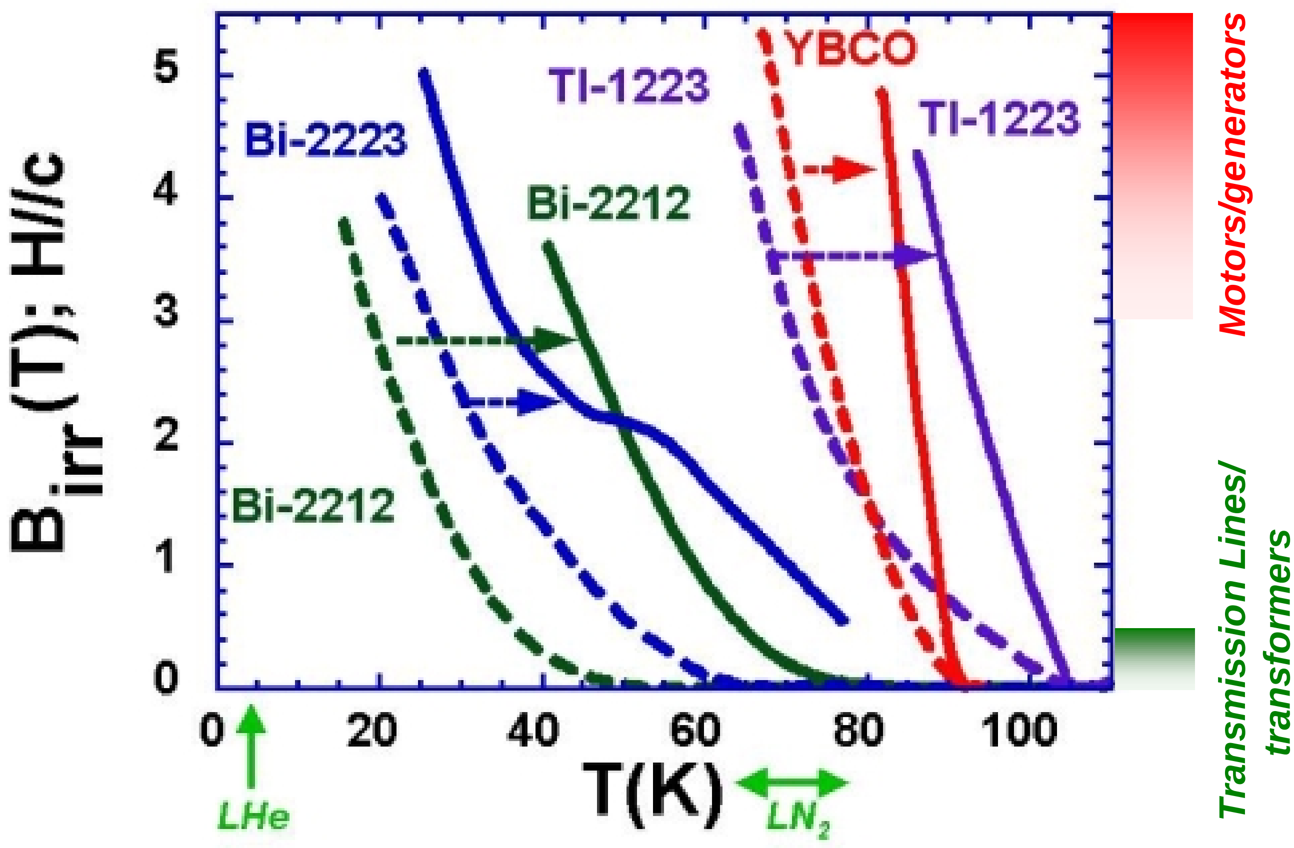
Anisotropy $\gamma^2 = m_c/m_{ab}$ limits the depinning energy scale $U_{eff} \propto (u_p \tilde{\varepsilon})^{1/2}$

Depinning Probability

$\exp[-U_{eff}/k_B T]$

Intrinsic Properties Define Limits of HTS Material Classes

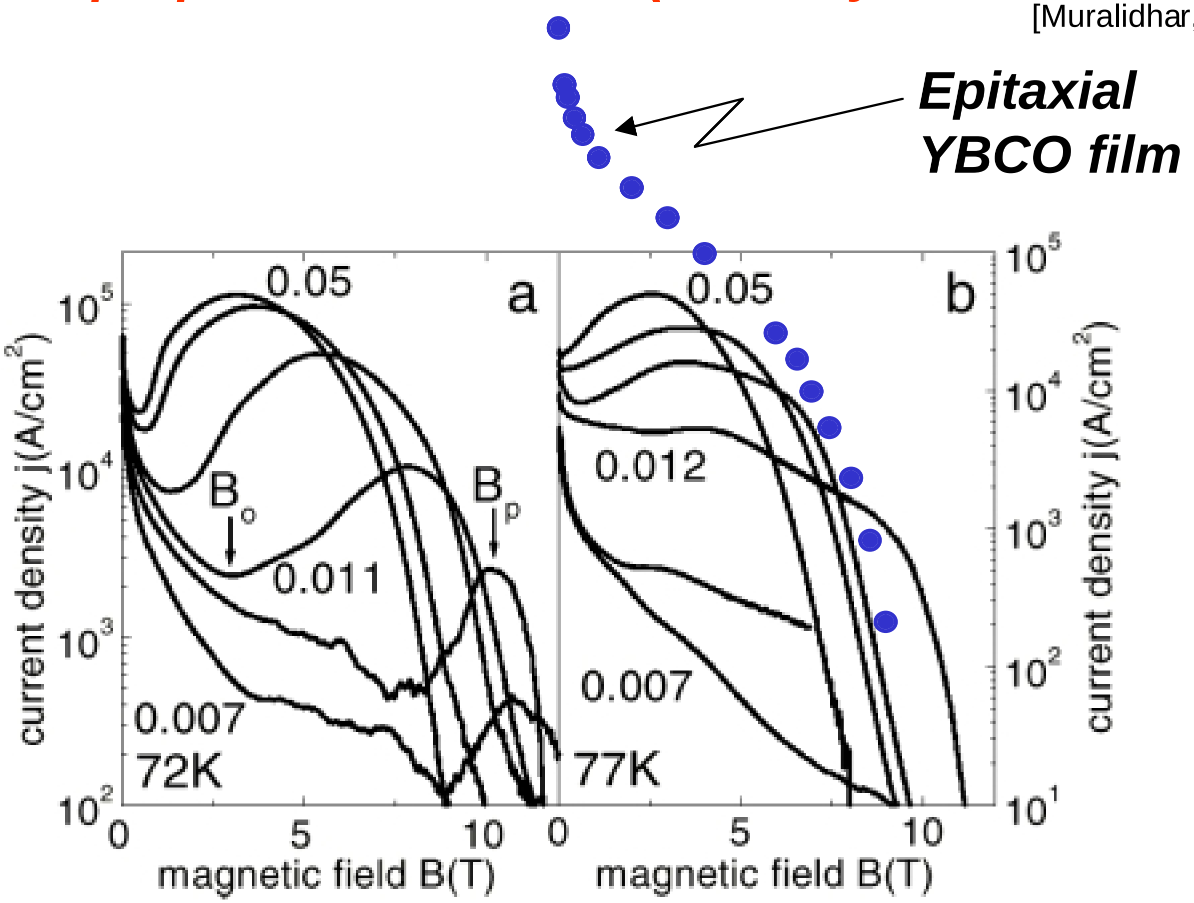
- *For optimized flux pinning, the energy scale* $U_{eff} \propto (u_p\ \varepsilon)^{1/2}/\gamma$
  e.g., $\gamma \approx 5$ *for YBCO,* $\gamma \approx 100$ *for BSCCO*
- *Optimized pinning extends the operating range to higher H, T*



Flux pinning in as-grown YBCO films is strong

- *Bulk, melt-processed crystals show “fishtail” J_c peak*
- *Epitaxial films show much stronger low-field J_c*
- *High-field properties are similar (MPG crystals better?!)*

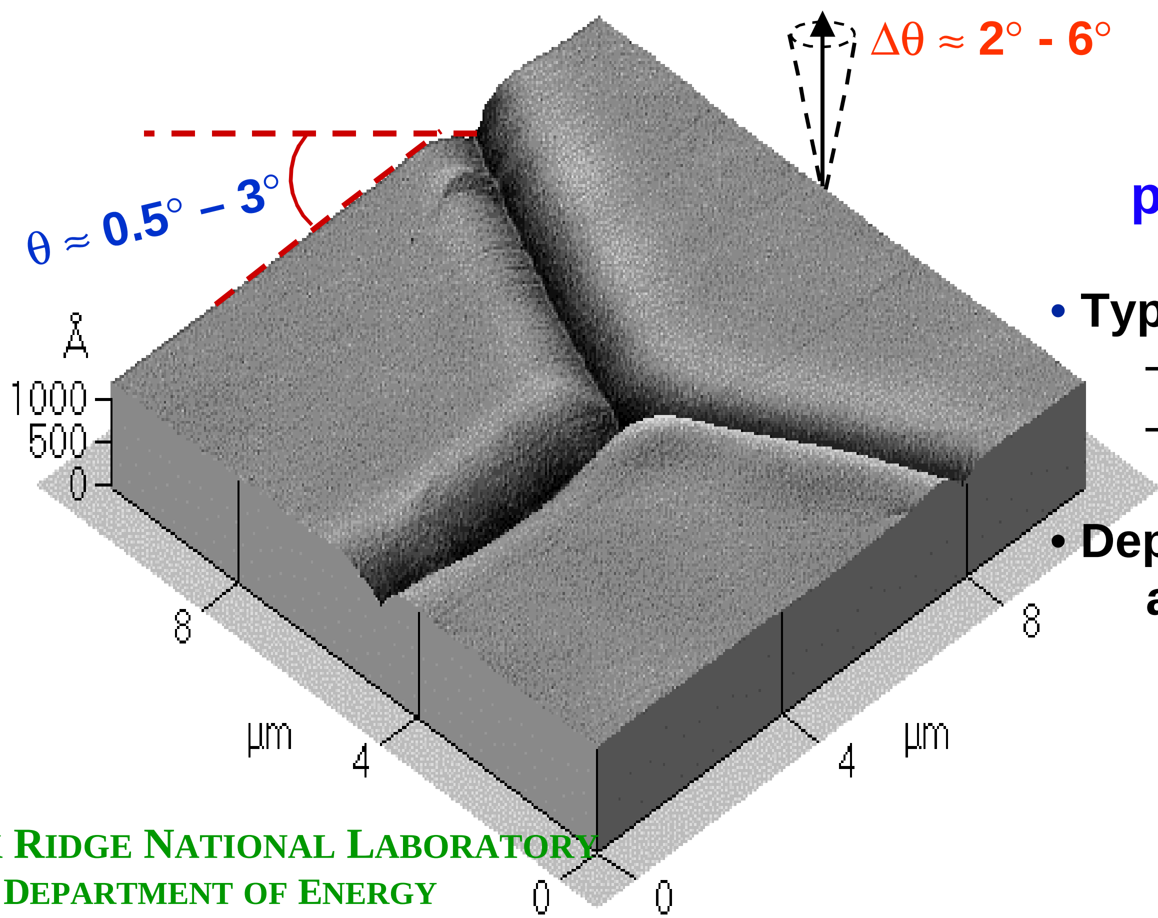
[Muralidhar, *et al.*, APL **82** (2003)



Kupfer, etal. IWCC (1999)

Significance of Vicinal Substrate Surfaces in Coated Conductors

- ***Coated conductor substrates have vicinal surfaces from:***
  - ***Out-of-plane texture, typically 2 - 6°, of textured metal (RABiTS) or buffer layer (IBAD or ISD)***
  - ***Thermal grain-boundary grooving of textured metal tape (RABiTS)***



RABiTS Nickel processed at 800°C

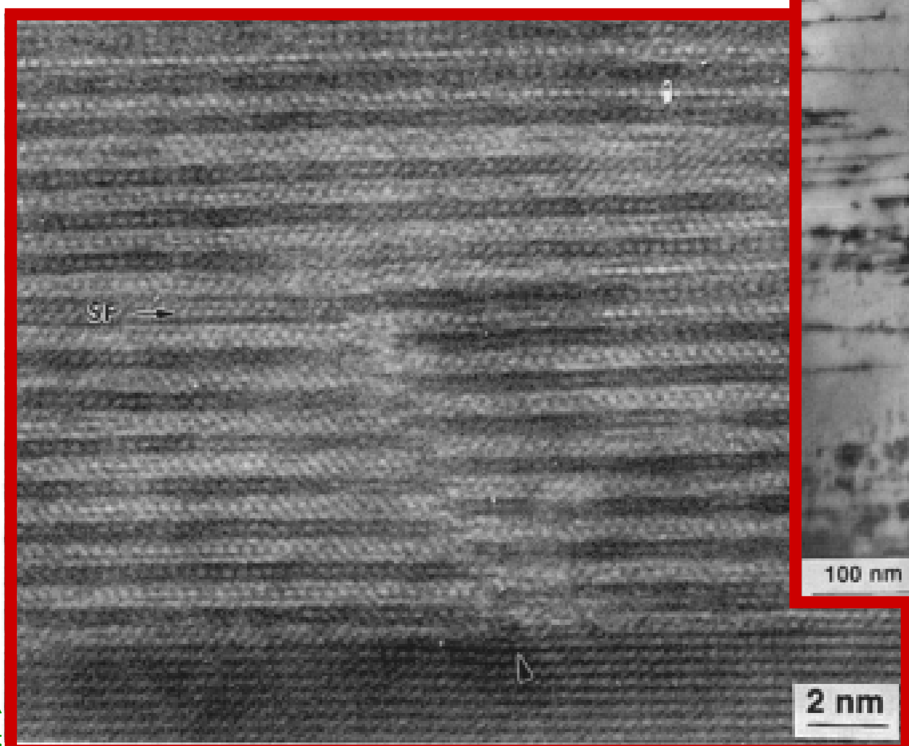
- **Typical groove dimensions:**
  - **Width = 1.3-1.8 μm**
  - **Depth = 15 - 20 nm**
- **Depth depends on g.b. angle and crystal plane**

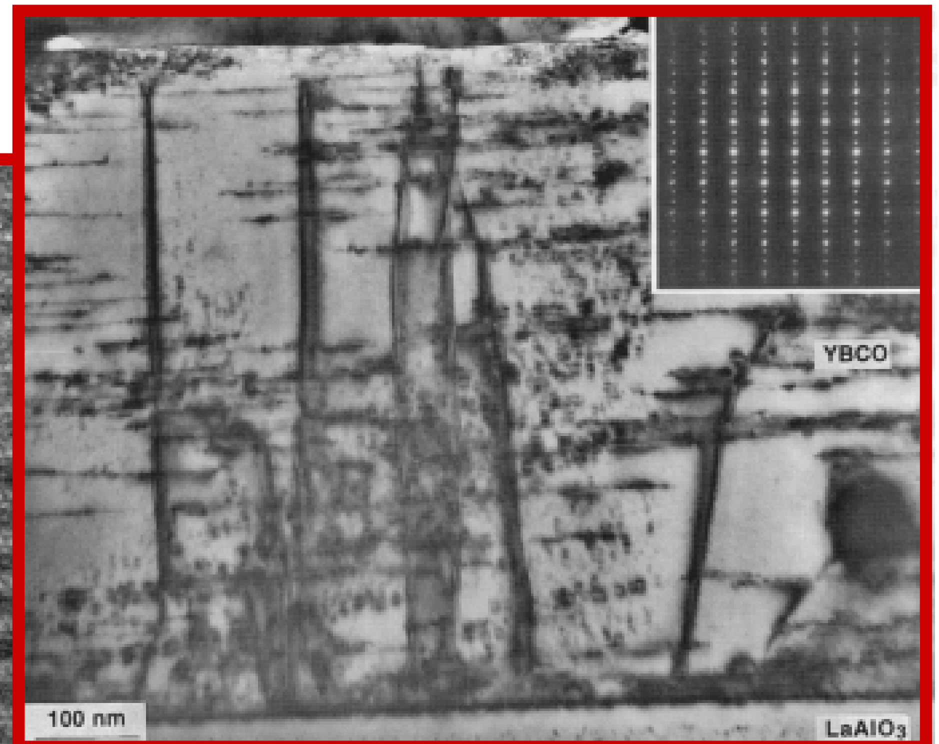
Origin of Pinning in Coated Conductors?

Extended Defects from YBCO Growth on Vicinal Surfaces

c/3, anti-phase boundaries arise from YBCO growth on either side of substrate-surface step

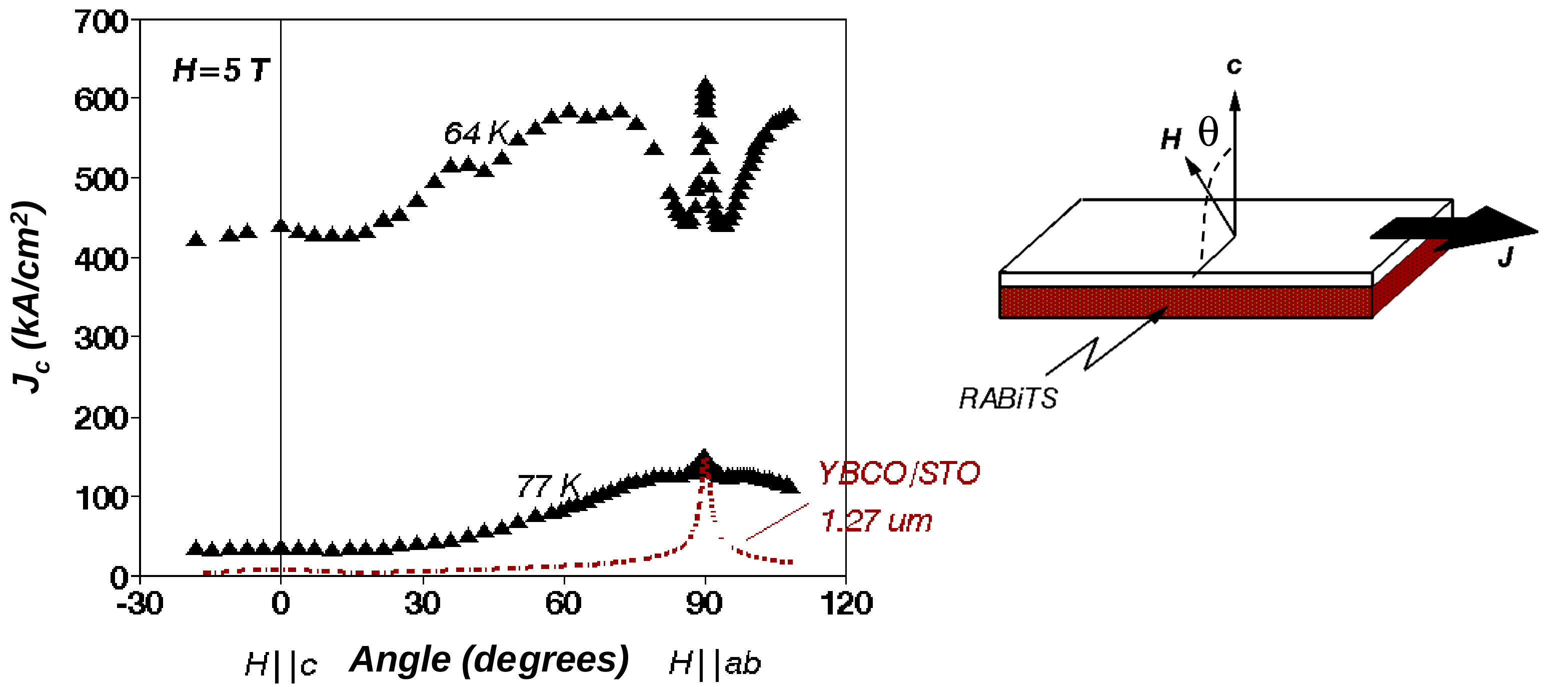
- *Localized strain, but defects can extend throughout film thickness*





Anomalous Angular Dependence of J_c

YBCO/RABiTS, 0.6 μm thick with J_c = 1.4 MA/cm^2



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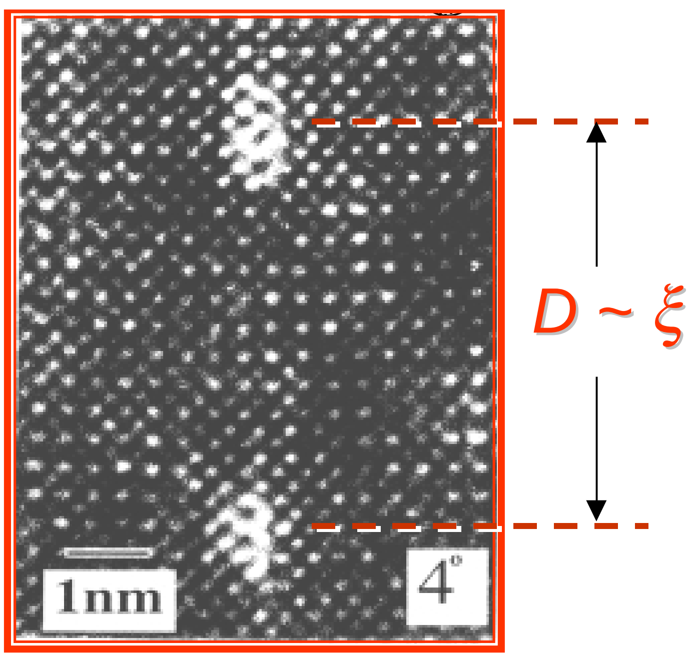
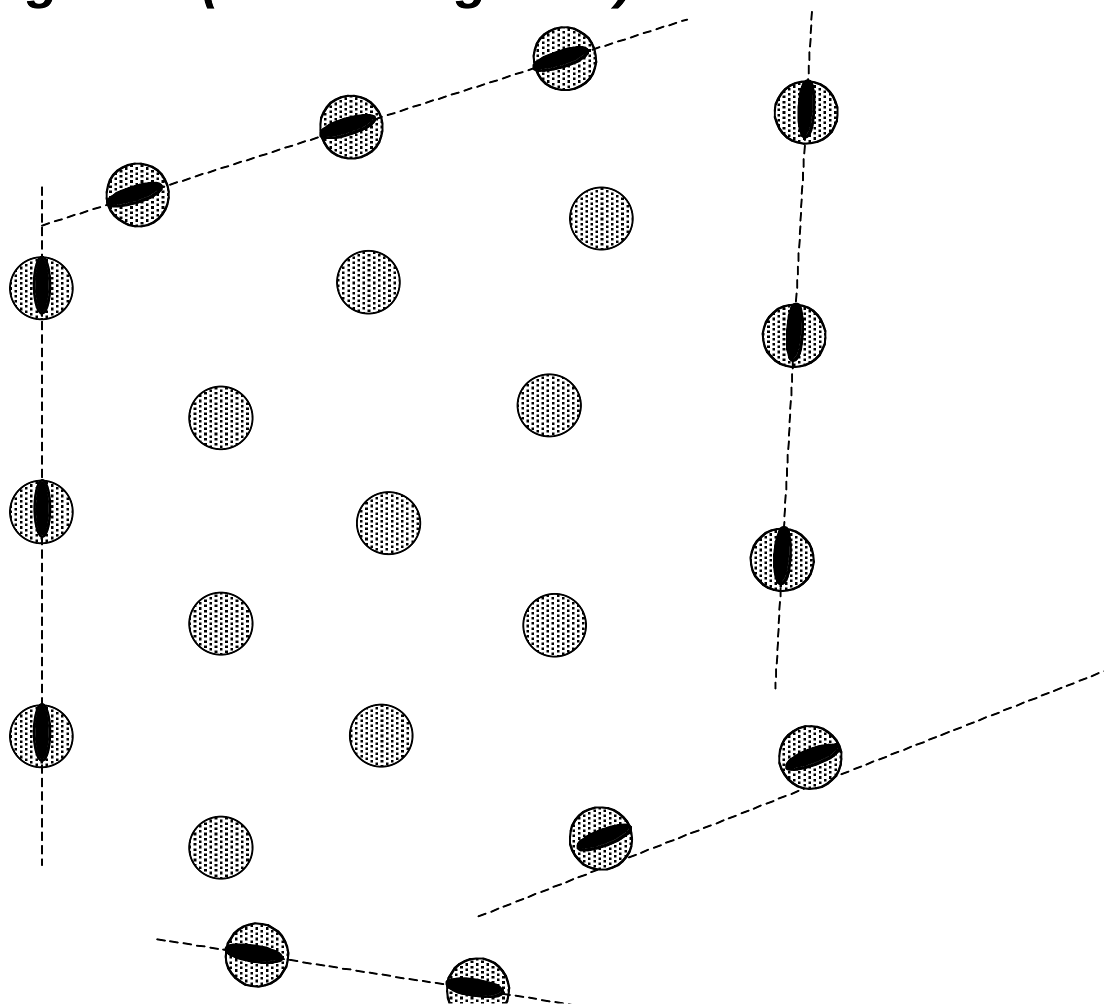
Possible Effects of Dislocation Cores in Low-Angle Boundaries

- ***The grain boundary becomes "invisible" for $B>B_{core}$***

  e.g. for $\theta < 2^{\circ}$, GB $B_{core} \lesssim 9$ Tesla
- ***The cores can act as additional, strong pinning defects "caging" of vortices within grains (for small grains)***

Dislocations cores, ~5nm apart, according to *$2D\sin(\theta/2)=b$*





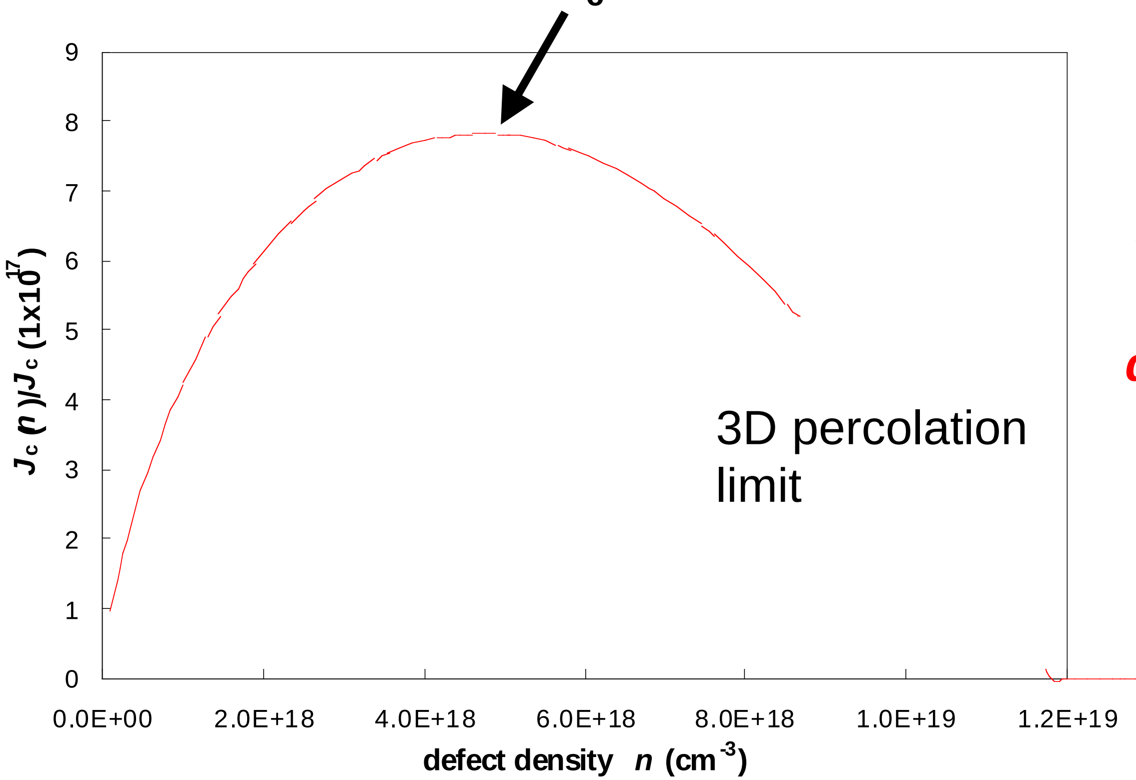
Flux pinning by random, weak point-defects

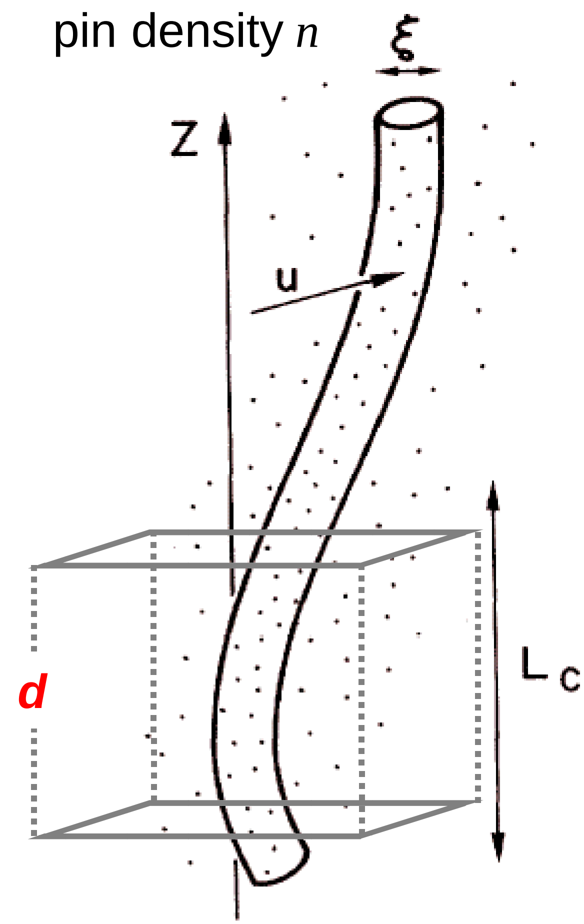
Maximum J_c: collective pinning of single vortex

$d^{1/2}$

But, calculated L_c~10 nm << CC thickness *d*

And, calculated max. J_c~1-3 MA/cm^2





[Blatter, *et al.*, Rev. Mod. Phys **66** (1994)

Summary and Discussion Points

- ***GB's limit J_c at low fields, but benefit from intragrain flux pinning***
  - *Why are high-field properties limited by flux pinning?*
  - *Do the dislocation cores pin at high fields?*

- ***Extended or correlated defects should be important for intragrain flux pinning***
  - *Are they present in sufficient density?*
  - *What is their origin?*
  - *Can random point pins account for observed J_c's?*
  - *…*