High-field current transport at 300K: can a compromise between vortex fluctuations, anisotropy, pinning, competing orders, and d-wave pairing be reached?

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Outline

- Suppose that a RTS with T_c = 350K has been discovered. What mechanisms/materials restrictions should be satisfied so that it could be used in power/magnet applications at 300K?

- Competing charge/spin/HTS orders + d-wave pairing + layered structure may be a deadly combination for RTS applications at 300K

Lessons learned after 20 years of HTS

1. higher T_c $\rightarrow$ shorter coherence length $\xi \sim \hbar v_F/2\pi k_B T_c$ $\rightarrow$ pairbreaking induced by benign (in LTS) atomic defects (vacancies, nonmagnetic impurities, dislocations, grain boundaries)

2. d-wave pairing $\rightarrow$ pairbreaking by nonmagnetic impurities and interfaces

3. competing orders $\rightarrow$ precipitation of intrinsic nonsuperconducting phases on grain boundaries $\rightarrow$ strong current blocking in polycrystals

4. crystalline anisotropy and low carrier density
   $\rightarrow$ weaker charge screening aggravates current-blocking effect of grain boundaries
   $\rightarrow$ enhancement of vortex fluctuations $\rightarrow$ strong decrease of the T-H space where pinning of vortices can provide supercurrents

Mean field parameters

Upper critical field:

$$H_{c2}(0) = \frac{\phi_0}{2\pi\xi^2} \propto \mu_B \frac{T_c^2}{E_F}$$

$H_{c2}(0)$ > 100 Tesla

GL depairing current density

$$J_d = \frac{c\phi_0}{12\sqrt{3}\pi^2\lambda^2\xi}\left(1 - \frac{T}{T_c}\right)^{3/2}$$

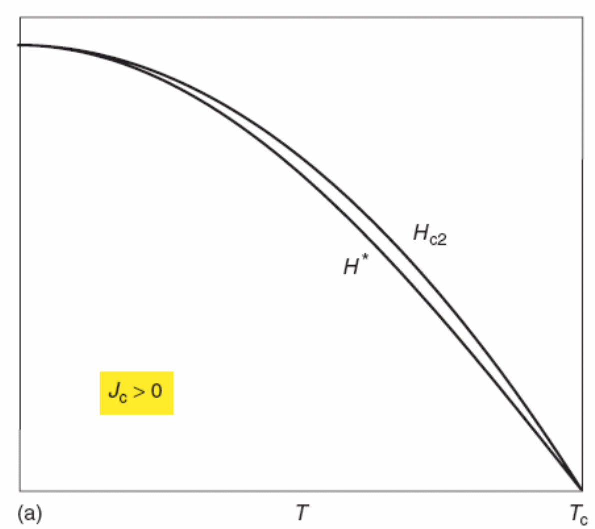
T = 300K, T_c = 350 K,

$J_d(300)$ = 40 MA/cm^2

for the parameters of YBCO

It is neither room T_c nor kTesla H_{c2}, but the higher irreversibility field H_{irr} (T), which can make RTS useful

H



LTS

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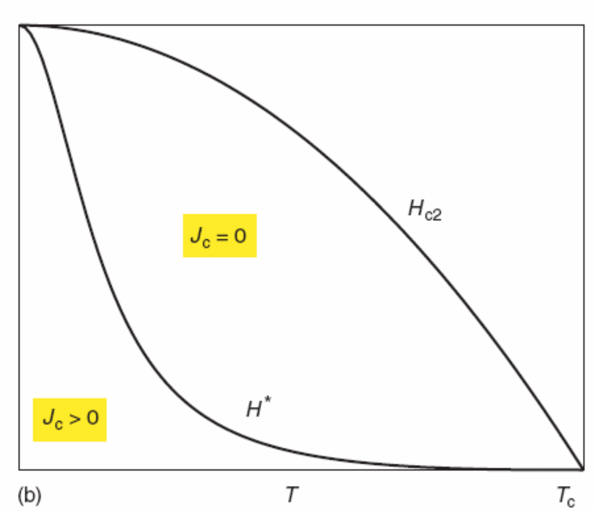
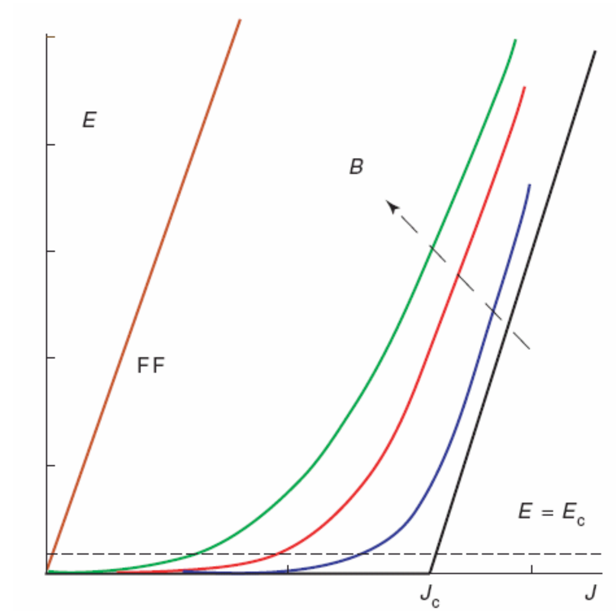


HTS



- **Thermally-activated vortex creep,** $E \sim J\rho_F \exp[-U(T,B,J)/T]$
- **Irrevesibility field B_{irr} above which E(J) becomes ohmic:** $J_c(T,B_{irr}) = 0, \quad U(T,B_{irr}) \approx T$

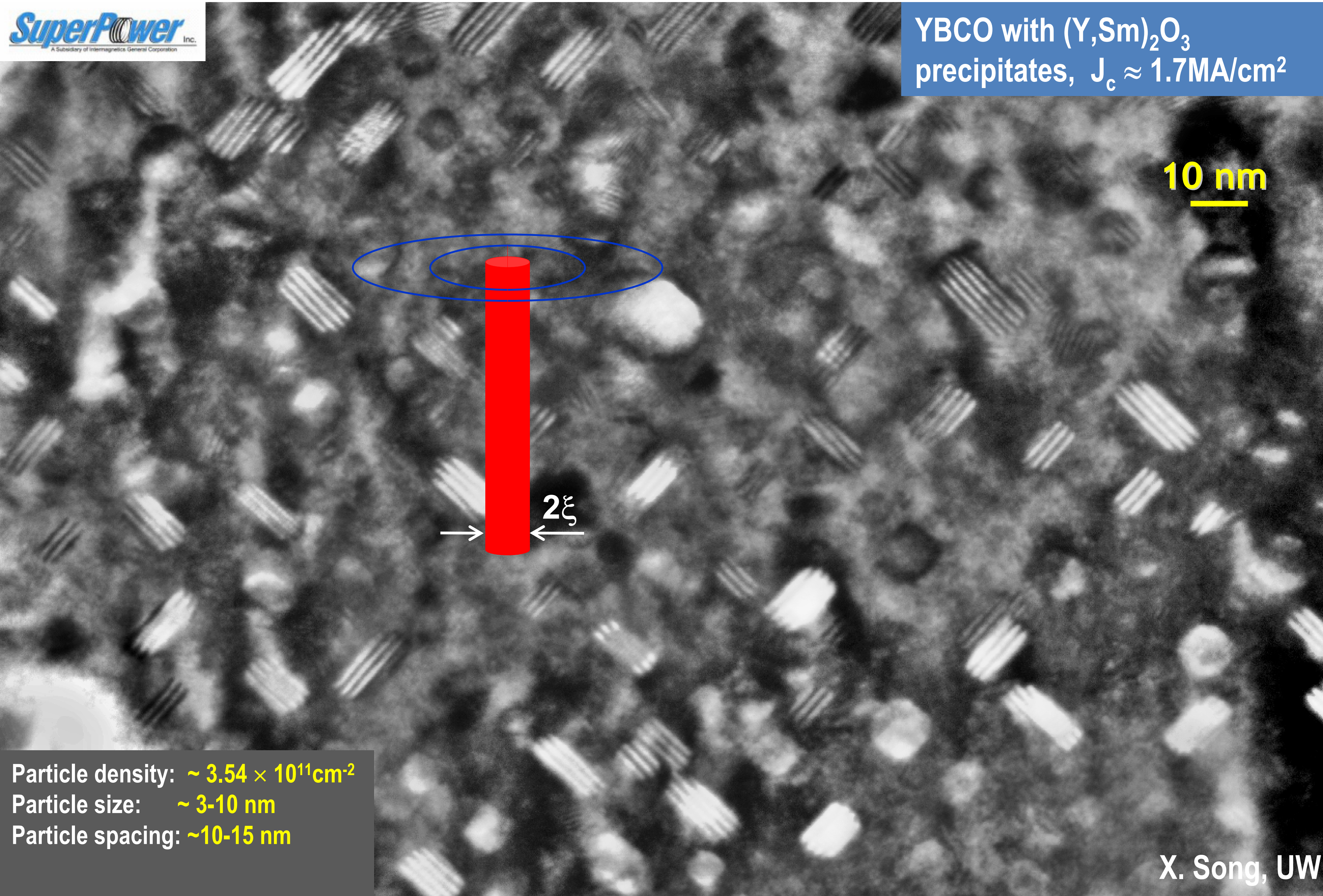
Brute force approach in LTS: the more pinning centers the better

α-Ti ribbons in a Nb-Ti alloy **(P. Lee, University of Wisconsin)**

- **Defects chop vortices into short strongly pinned segments**
- **Normal vortex cores are strongly deformed**

Can nanoprecipitates in HTS be as effective ?

YBCO with $(Y,Sm)_2O_3$ precipitates, $J_c \approx 1.7 MA/cm^2$



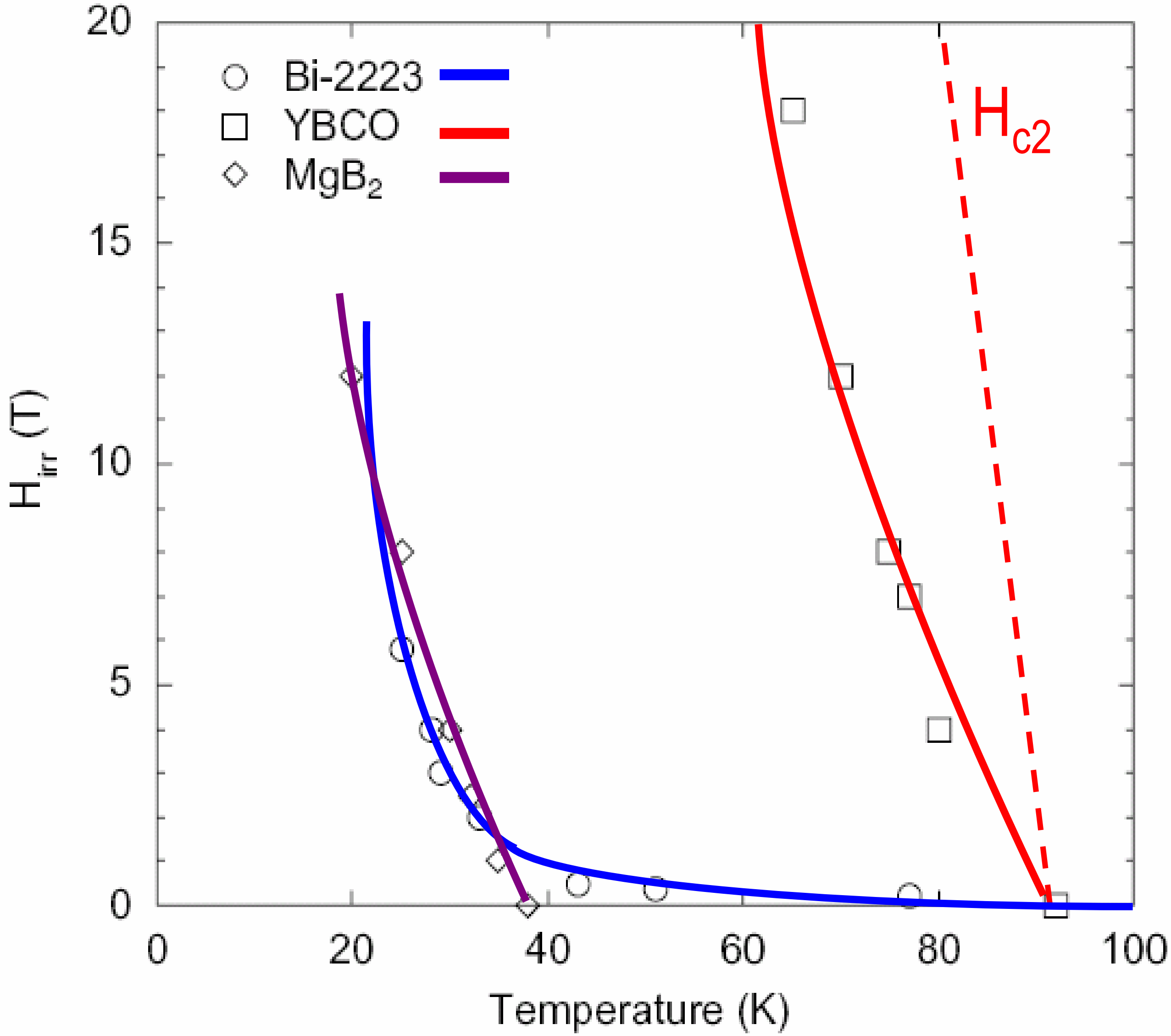
Particle density: ~ $3.54 \times 10^{11} cm^{-2}$
Particle size: ~ 3-10 nm
Particle spacing: ~10-15 nm

Comparison of LTS and HTS

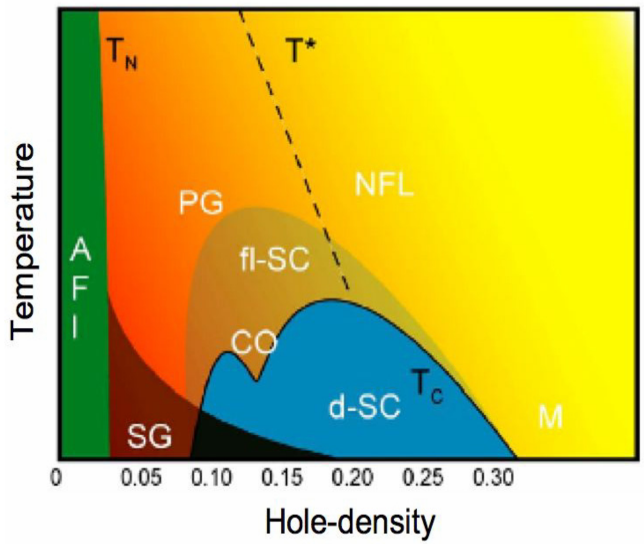
- **Strong anisotropy can eliminate all benefits of higher T_c and H_{c2}**

- **YBCO (T_c = 92K) is much better than Bi-2223 (T_c = 110K)**

- **MgB_2 (T_c = 40K) can ba as good as Bi-2223 for 20K < T < 35K, and B < 15T**

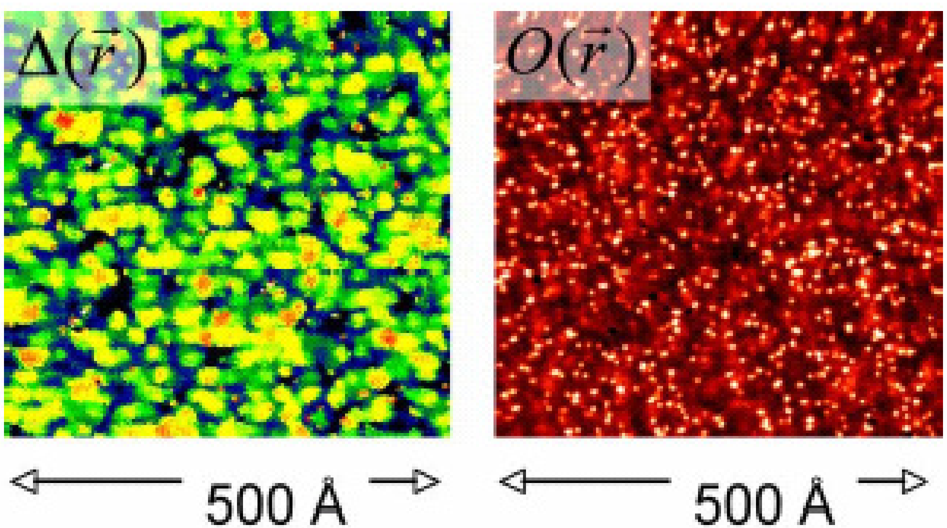


Competing orders/d-wave



- Coulomb/magnon/exciton mechanisms: d-wave pairing: strong suppression by impurities

- Competing orders: emerging HTS at the expense of charge/spin phase separation



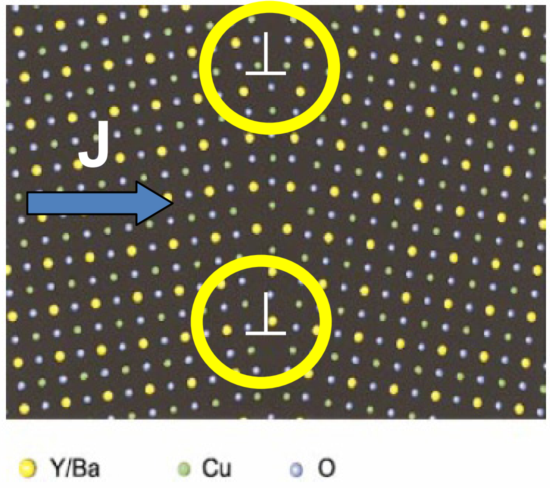
Left: The nanoscale superconducting energy gap disorder in $Bi_2Sr_2CaCu_2O_x$. Right: A simultaneous image of the dopant atom locations from SI-STM. Seamus Davis et al

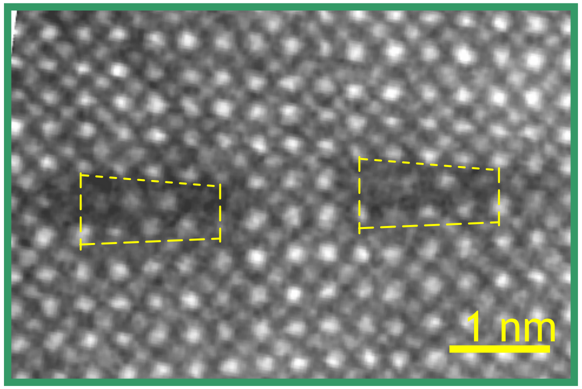
Intrinsic phase separation

As the size of the Cooper pair $\xi \sim \hbar v_F/2\pi k_B T_c$ drops below 2-3 nm, any "typical" lattice defects locally suppress Δ(r)

The grain boundary problem

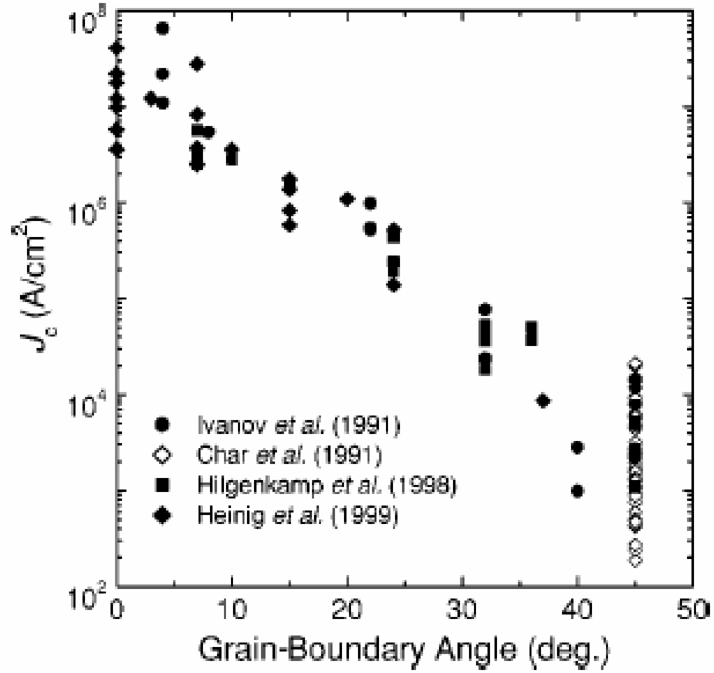
16^{O} [001] tilt grain boundary in YBCO





X. Song et al. Nature Mat. 4, 470 (2005)

$J_c(\theta) = J_0\cos^2 2\theta$ **- too weak to explain the observed exponential decrease of $J_c(\theta)$**

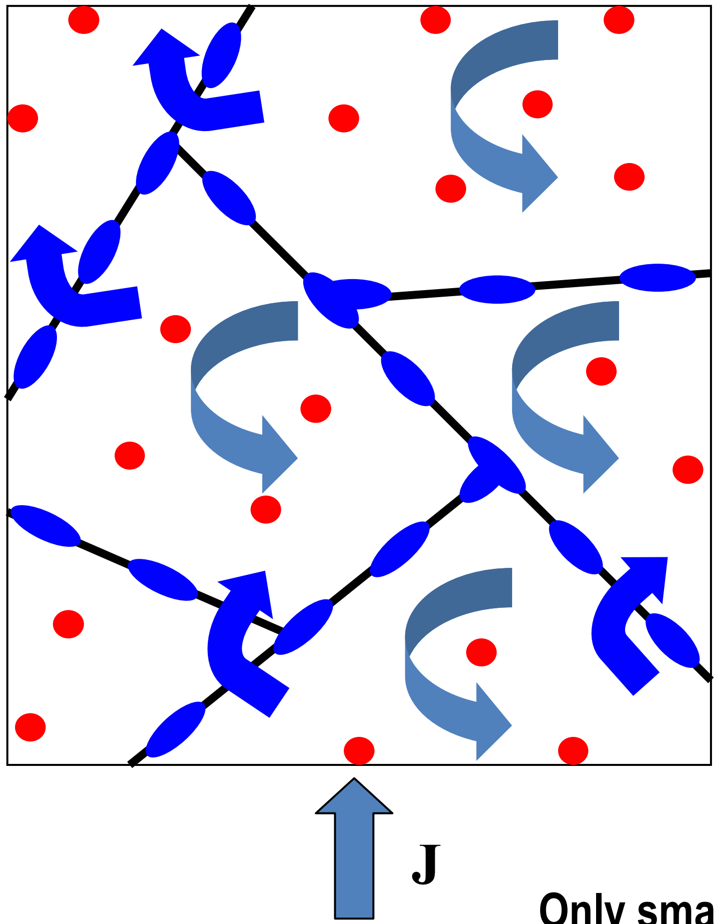


- **Precipitation of AF phase at grain boundaries**
- **Charge and strain coupling of dislocation cores due to short ξ and long TF screening length**

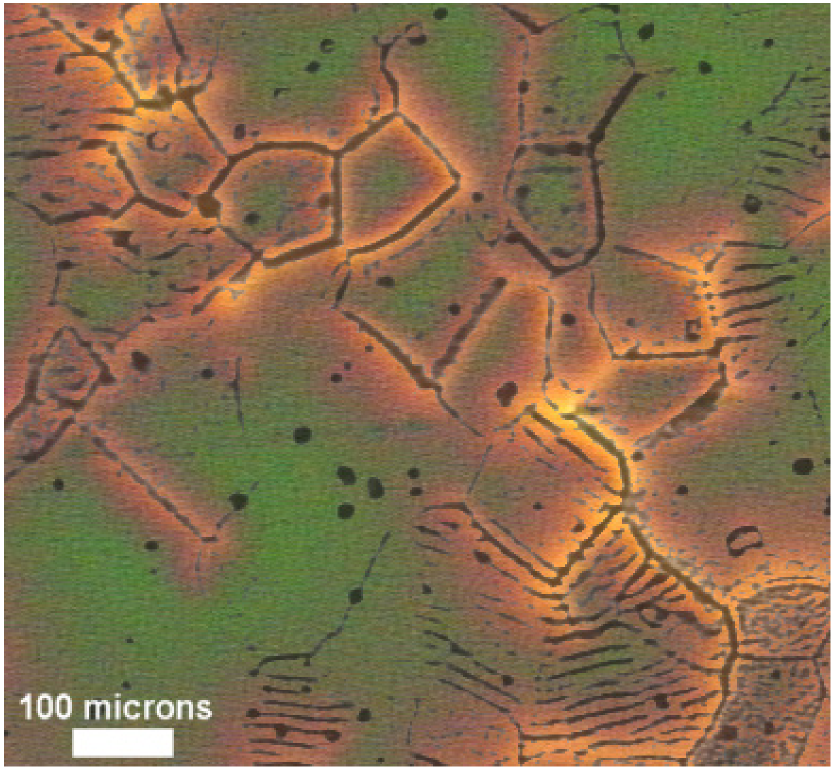
Gurevich and Pashitskii, PRB 57, 13875 (1998);
Hilgenkamp and Mannhart, APL 73, 265 (1998); RMP 74, 485 (2002)

Magnetic granularity in polycrystals

Magnetic granularity caused
by grain boundaries



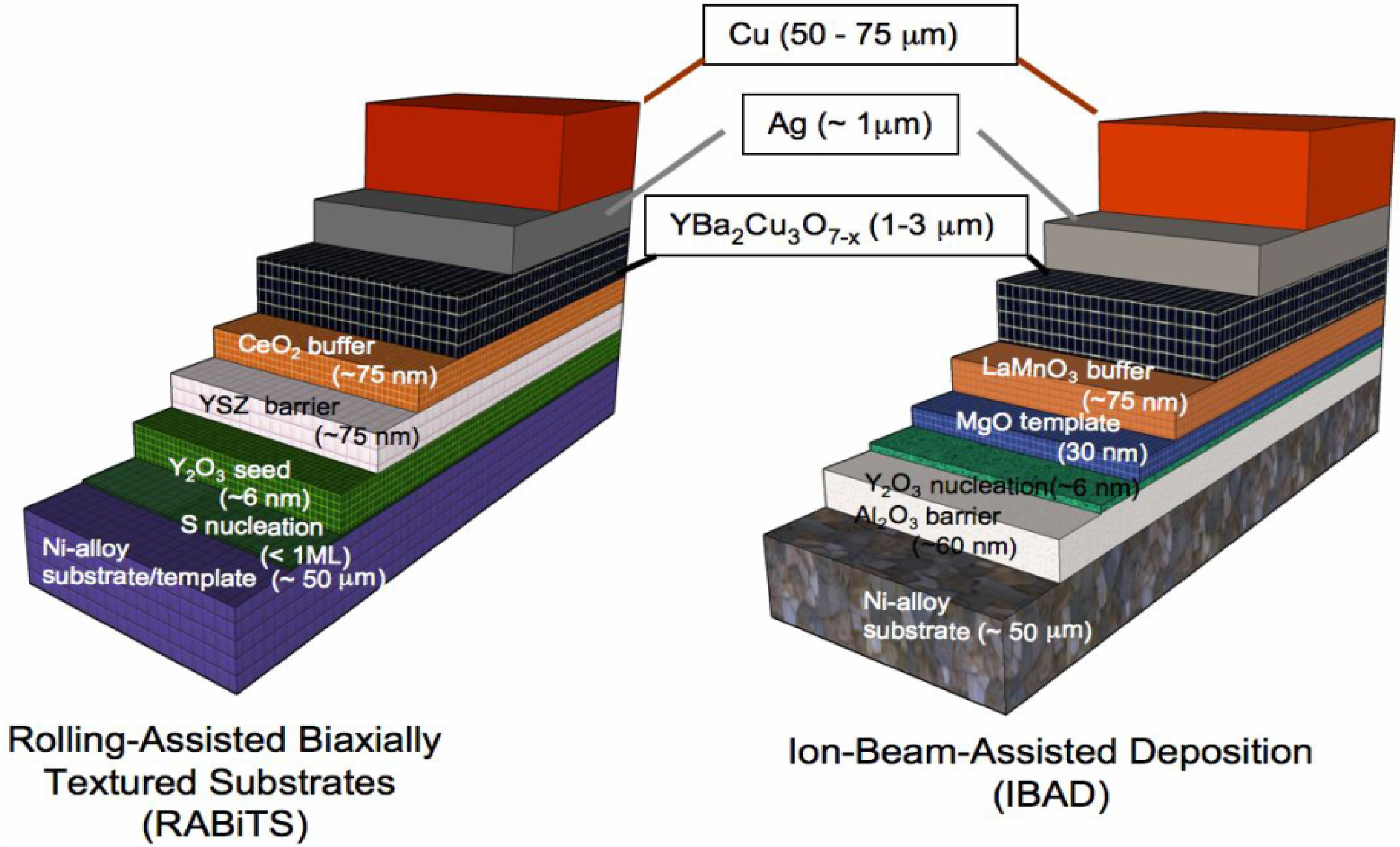
Magneto-optical imaging of current
Blocking by grain boundaries in YBCO



Polyanskii, Feldmann, 2001

Only small currents can pass through GBs despite
strong pinning of vortices caged in the grains

What has been done to ameliorate current blocking by grain boundaries in HTS



State of the art: complex, expensive, only a small fraction carries current, high ac losses

Thermal fluctuations in RTS

- **Critical fluctuation region:** $\Delta T = T_c - T < T_c Gi$

- **Ginzburg parameter:**

$$Gi = \frac{\Gamma^2}{2}\left(\frac{k_B T_c}{H_c^2 \xi^3}\right)^2 \propto \left(\frac{T_c^2 m \Gamma}{v_F n^2}\right)^2$$

- **Anisotropy parameter and the London penetration depth in a uniaxial superconductor:**

$$\Gamma = \left(\frac{m_c}{m_{ab}}\right)^{1/2} = \frac{\lambda_c}{\lambda} = \frac{\xi}{\xi_c}$$

$$\lambda = \left(\frac{mc^2}{4\pi e^2 n_s}\right)^{1/2}$$

- **LTS: Gi $\sim 10^{-8}$, $\Delta T \sim 10^{-7}$ K**
- **YBCO: $\Gamma = 5$, Gi $\sim 10^{-2}$, $\Delta T \sim 1$K**
- **BSCCO: $\Gamma \sim 50$-100, Gi ~ 0.1, $\Delta T \sim 10$K**
- **T_c reduction by phase fluctuations (Emery & Kivelson, 1995; Sudbo et al, Tesanovic et al)**
- **In RTS fluctuations may be stronger unless a less anisotropic RTS with a higher superfluid density is discovered**

Vortex elasticity and thermal fluctuations

- **Elastic deformation energy of the FLL and thermal vortex displacements:** (Brandt; Blatter et al)

$$F=\frac{1}{2}\sum_k[c_{66}(u_xk_y-u_yk_x)^2+c_{44}(k)u^2k_z^2],\qquad \langle u^2\rangle\approx\int\frac{d^3k}{(2\pi)^3}\frac{T}{c_{66}k_\perp^2+c_{44}(k)k_z^2}$$

- **Dispersive line tension of a single vortex**

$$\varepsilon_l(k)=\frac{\varepsilon_0}{2\Gamma^2}\ln\frac{\lambda_c^2}{\xi^2(1+\lambda^2k_z^2)}+\frac{\varepsilon_0}{2\lambda^2k_z^2}\ln(1+\lambda^2k_z^2),$$

$$\boxed{\varepsilon_0=\left(\frac{\phi_0}{4\pi\lambda}\right)^2=\frac{\pi\hbar^2n_s}{4m}}$$

- **Anisotropy strongly reduces vortex rigidity for short-wave length bending modes:**

$$\varepsilon_l\approx\frac{\varepsilon_0}{\Gamma^2}\ln\frac{1}{\xi_ck_z},\qquad \lambda k_z\gg 1$$

$\varepsilon_0\approx 10^2$ K/Å for HTS

Melting of vortex lattice

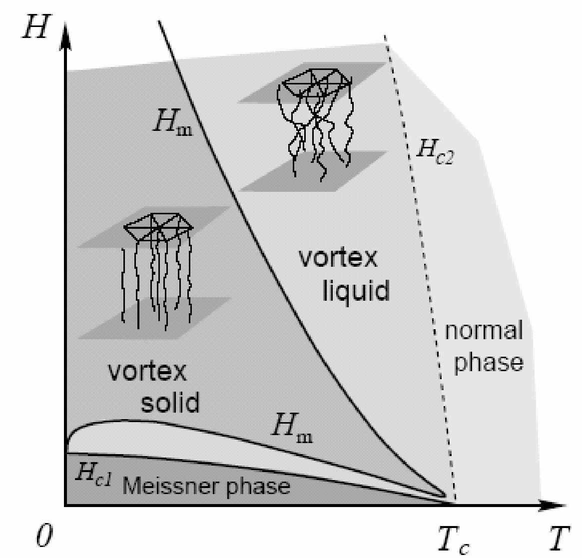
- Weak pinning: $J_c = 0$ in the vortex liquid phase $B > B_m$
- Lindemann criterion: $\langle u^2(T,B_m)\rangle = c_L^2\phi_0/B_m$, $c_L \approx 0{,}1\text{-}0.3$ (Nelson et al; Hougtion, Pelcovits, Sudbo; Blatter et al, Brandt et al; Tesanovic et al; …)
- Upper branch of the melting field $B_{c1} \ll B_m \ll B_{c2}$:

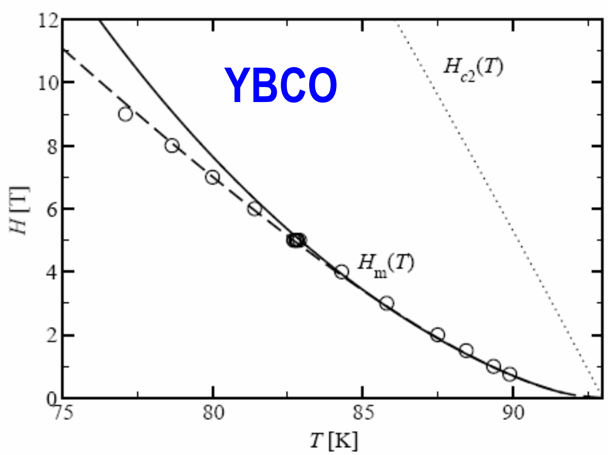
$$B_m[Tesla] \approx \frac{8\times 10^{18}}{\Gamma^2}\left[\frac{c_L^2(T_c/T-1)}{\lambda_0^2[nm]T_c[K]}\right]^2$$

For YBCO, $B_m(77K) \approx 9T$, $B_{c2}(77K) \approx 20T$

For an RTS analog of YBCO with $T_c = 350K$:

B_m (300K) ~ 0.45 T for $\Gamma = 5$
B_m (300K) ~ 11 T for $\Gamma = 1$

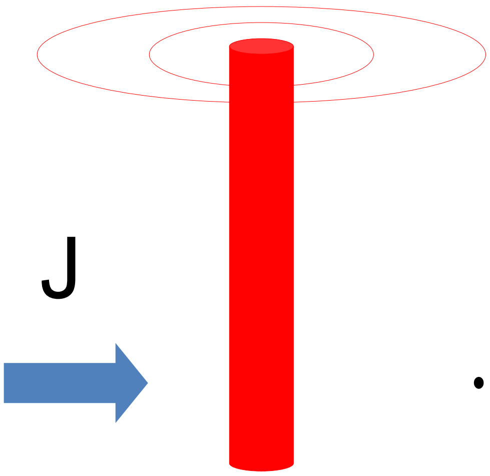




Calorimetric measurements by A. Schilling et al PRL, 78, 4833 (1997); Nature, 382, 791 (1996)

Strong pinning

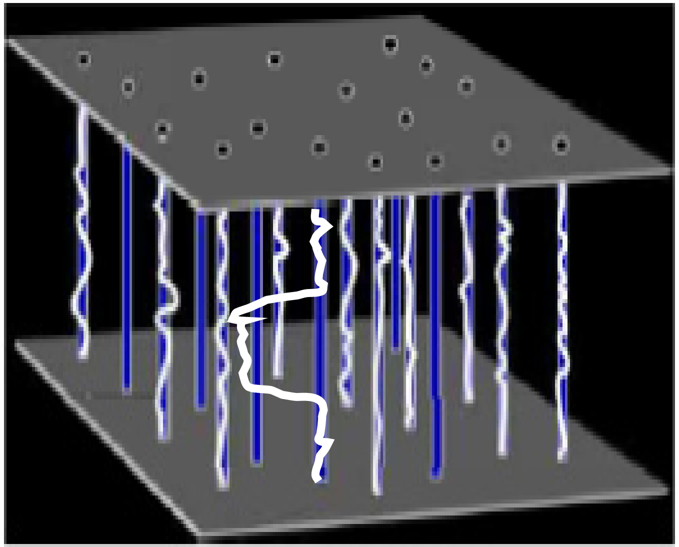
- Melting of the vortex lattice is only relevant for weak pinning
- Pinning destroys long range order in the FLL; amorphous vortex lattice (Larkin, 1970)
- Very strong single-vortex pinning limit: each vortex is pinned by either columnar pins or nanoprecipitates which chop vortex lines into short weakly coupled segments
- Produces low-field J_c comparable (20-30%) to the depairing current density circulating near the vortex core (J_c ~ 10 MA/cm^2 and J_d ~ 40 MA/cm^2 YBCO at 77K)



$$J_d = \frac{c\phi_0}{12\sqrt{3}\pi^2\lambda_a^2\xi_a}$$

- maximum J_c for a vortex pinned by a columnar radiation defect of radius r_0

Thermal depinning of vortices from columnar pins



J_c renormalized by thermal fluctuations of vortex half-loops
Nelson and Vinokur, PRB 48, 13060 (1993)

$$J_c \cong J_d\left(\frac{r_0}{\ell}\right)^3\left(\frac{T^*}{T}\right)^4, \qquad T > T^* \cong \frac{r_0\varepsilon(T^*)}{\Gamma}\ln^{1/2}\left(\frac{r_0}{\xi}\right)$$

$J_c(T)$ rapidly drops above the depinning temperature

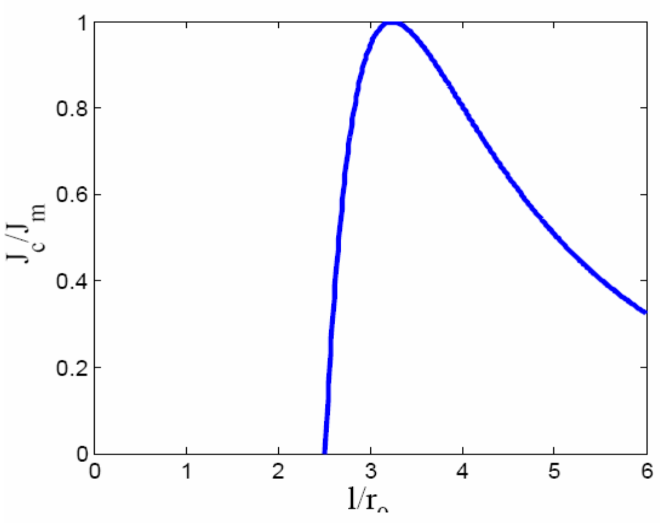
$$T^* \cong \frac{T_c}{1+\gamma}, \qquad \gamma \cong \frac{\Gamma T_c}{r_0\varepsilon_0}$$

- **YBCO:** $\varepsilon_0 \approx 80$ K/Å, $\Gamma \sim 5$, $T_c = 92$K, $r_0 \approx 20$-50 Å (heavy ion radiation treks, Civale, SUST, 10, A11 (1997)) $\rightarrow \gamma \approx 0.2$, $T^* \approx 77$K
- **BSCCO:** $\varepsilon_0 \approx 50$ K/Å, $\Gamma \sim 50$, $T_c = 110$K, $r_0 \approx 30$ Å $\rightarrow \gamma \approx 3.7$, $T^* \approx 23$ K
- **RTS:** $\varepsilon_0 \approx 50$ K/Å, $T_c = 350$K, $r_0 \approx 30$ Å $\rightarrow \gamma \approx 0.23\Gamma$, $T^* \approx 285$ K for $\Gamma = 1$, and $T^* \approx 106$ K for $\Gamma = 10$. The anisotropy kills $J_c \propto 1/\Gamma^4$ at 300K

Maximum J_c due to columnar defects

Competition between pinning and the reduction of current-carrying cross-section (x_c = 0.5)

$$J_c \cong J_d \left(\frac{r_0}{\ell}\right)^3 \left(\frac{T^*}{T}\right)^4 \left[1 - \frac{\pi r_0^2}{x_c \ell^2}\right]$$



Optimum $J_m \approx 0.012 J_d (T^*/T)^4$ occurs at $l_m = (10\pi/3)^{1/2} r_0$ or the matching field $H_\varphi = \phi_0 / l_m^2$:

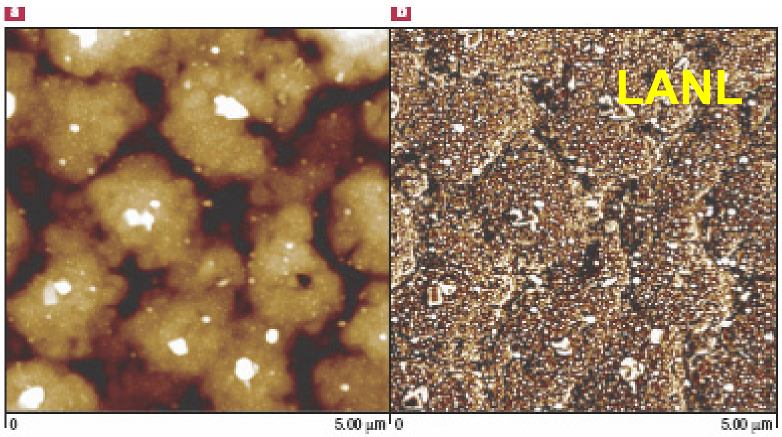
$$H_\varphi = \frac{3\phi_0}{10\pi r_0^2}$$

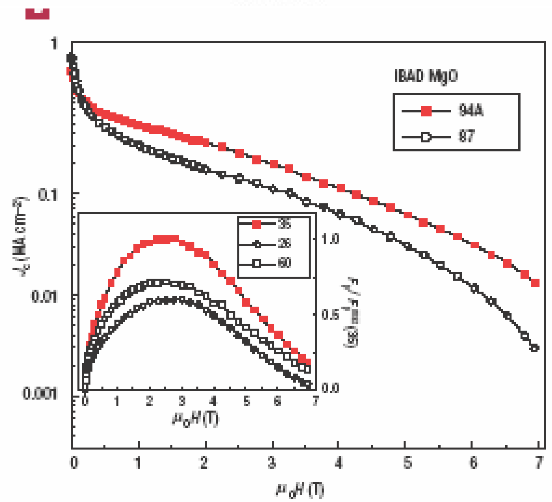
which gives H_φ = 7.6T for r_0 = 5nm

- J_m is not extremely high even for the optimum columnar defect spacing.
- J_m is strongly suppressed by anisotropy for $T > T^* \sim \varepsilon_0 r_0 / \Gamma$

Enhancement of J_c by nanoparticles at high fields

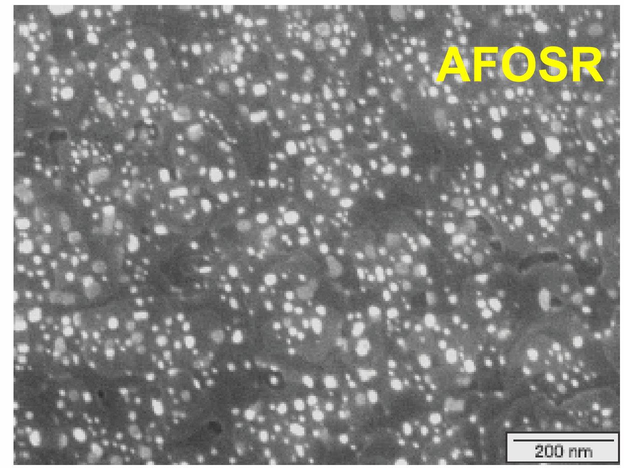
YBCO+$BaZrO_3$ films: dislocation pinning

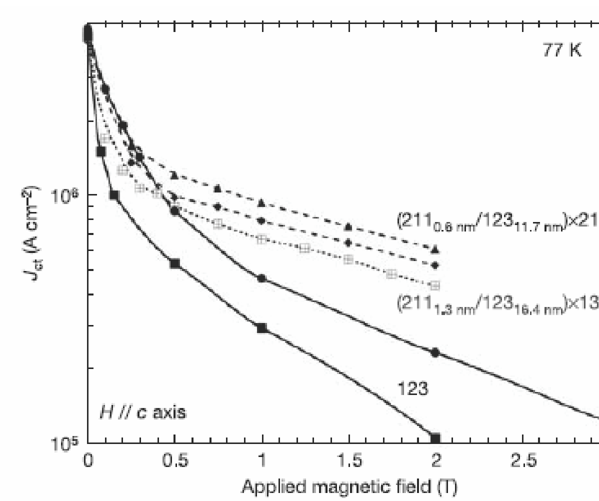




J.L. MacManus-Driscoll, S.R. Foltyn, Q.X. Jia, H. Wang, A.Serquis, L. Civale, B. Maiorov, M.E. Hawley, M.P. Maley, D.E. Peterson, Nature Mat. 3, 239 (2004)

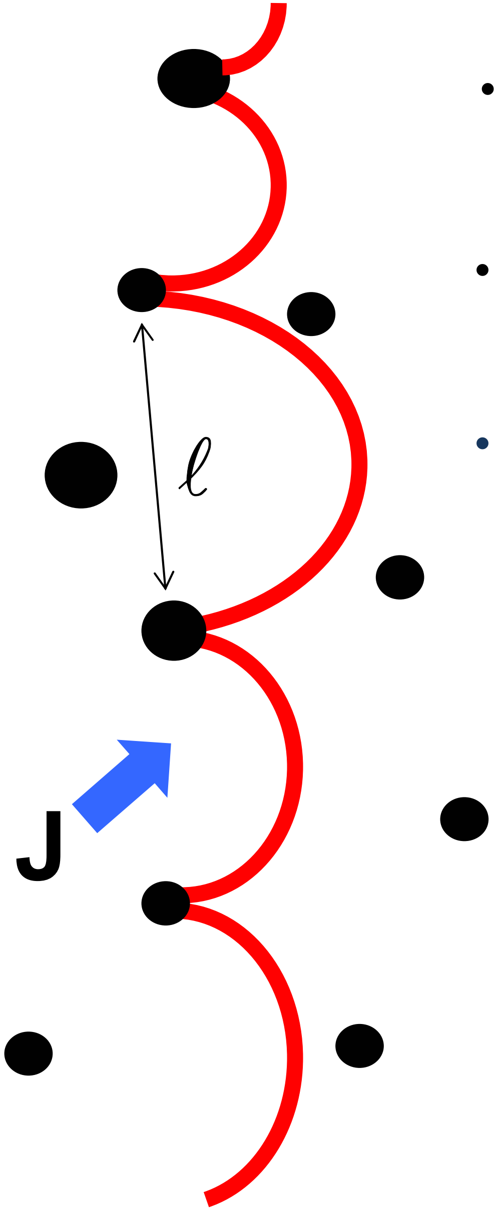
8 nm YBa_2CuO_5 nanoparticles





T. Haugan, P.N. Barnes, R. Wheeler, F. Meisenkothen & M. Sumption, Nature 430, 867 (2004)

Strong 3D pinning limit by nanoprecipitates/pores



- Elliptic critical vortex loops: $L_{||}L_{\perp} = \ell^2$, $L_{||} = \Gamma L_{\perp}$

- Analog of the Frank-Reed dislocation source with the effective loop width $L_{\perp} \sim \ell\Gamma^{-1/2}$, $\varepsilon/R = \phi_0 J/c$

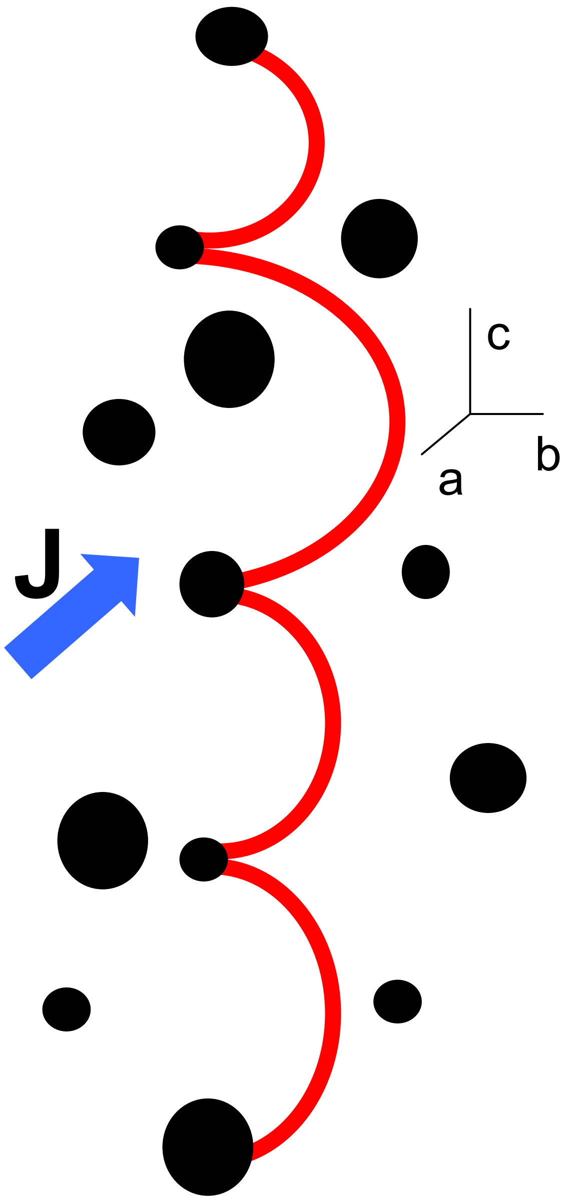
- Depinning due to reconnection of parallel vortex segments:

$$J_c \cong \frac{c\phi_0}{8\pi^2\lambda^2\Gamma^{1/2}\ell}\ln\frac{\ell}{\xi_c}$$

- To get J_c(77K) ~ 9 MA/cm^2 in YBCO, an average pin spacing should be ℓ ~ 30 nm

- Too many pins result in T_c suppression and current blocking

Current-carrying cross section



Effective medium theory for an anisotropic matrix with dielectric precipitates of volume fraction x

$$\rho = \rho_0 \frac{A}{A_{eff}}, \qquad A_{eff} = \left(1 - \frac{x}{x_c}\right) A$$

The effective current-carrying cross section $A_{eff}(x)$ vanishes at the percolation threshold x_c

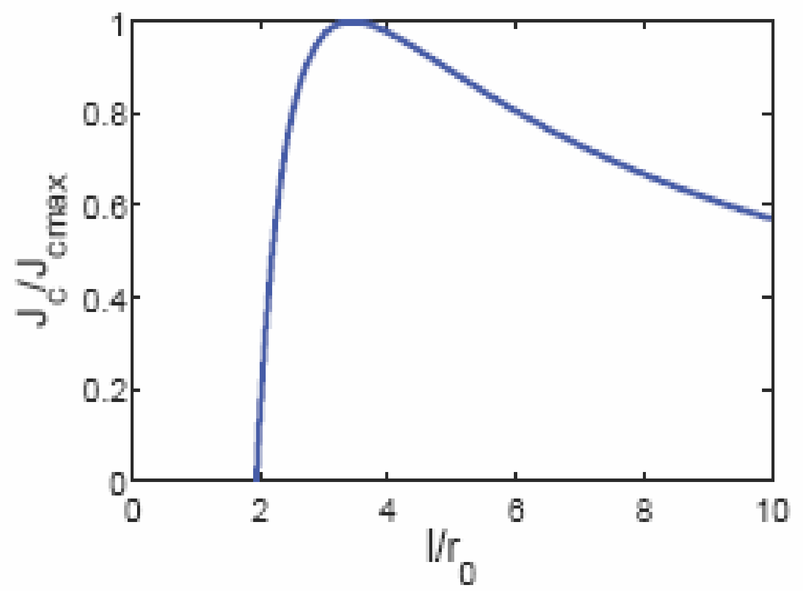
Optimum pin density: pinning vs current blocking

J_c due to random insulating precipitates of radius r_0 spaced by ℓ

$$J_c(l) \cong J_0 \frac{\xi}{\ell} \ln \frac{\ell}{\xi_c} \left(1 - \frac{4\pi r_0^3}{3x_c\ell^3}\right)$$

Pinning

Cross-section



Optimum pin spacing and volume fraction:

$$\ell_m \approx 3 - 4r_0, \qquad x_m = \frac{4\pi r_0^3}{3\ell_m^3} \approx 8 - 12\%$$

Optimum critical current density:

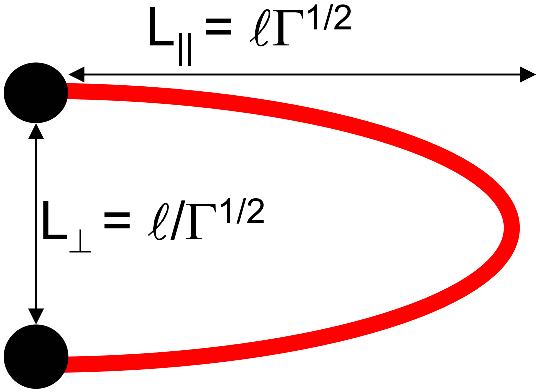
$$\frac{J_{c\max}}{J_d} \approx \frac{9\sqrt{3}\xi_a}{8\Gamma^{1/2}\ell_m} \ln \frac{\ell_m}{\xi_c}$$

For $\Gamma = 7$, $J_{cmax} \approx 0.5J_d$ for $r_0 = \xi$, and

$J_{cmax} \approx 0.25J_d$ for $r_0 = 3\xi$

Upper limit for small pins, no fluctuations and no proximity effect T_c suppression

Effect of thermal fluctuations for H=0



- **Activation energy for the optimum vortex loop**

$$U_0 \cong \frac{\varepsilon_0}{2\Gamma^2}\int_0^{L_\perp}\left(\frac{\partial u}{\partial z}\right)^2 dz = \frac{8\varepsilon_0\ell}{3\sqrt{\Gamma}}$$

- **Thermally-activated vortex drift: $E \propto \exp[-(U_0/T)(1 - J/J_{c0})]$**

- **Vortex thermal wandering reduces J_c**

$$J_c = J_{c0}\left(1 - \frac{T}{U_0}\ln\frac{E_0}{E_c}\right), \qquad E_0 \cong \rho_F J_{c0}$$

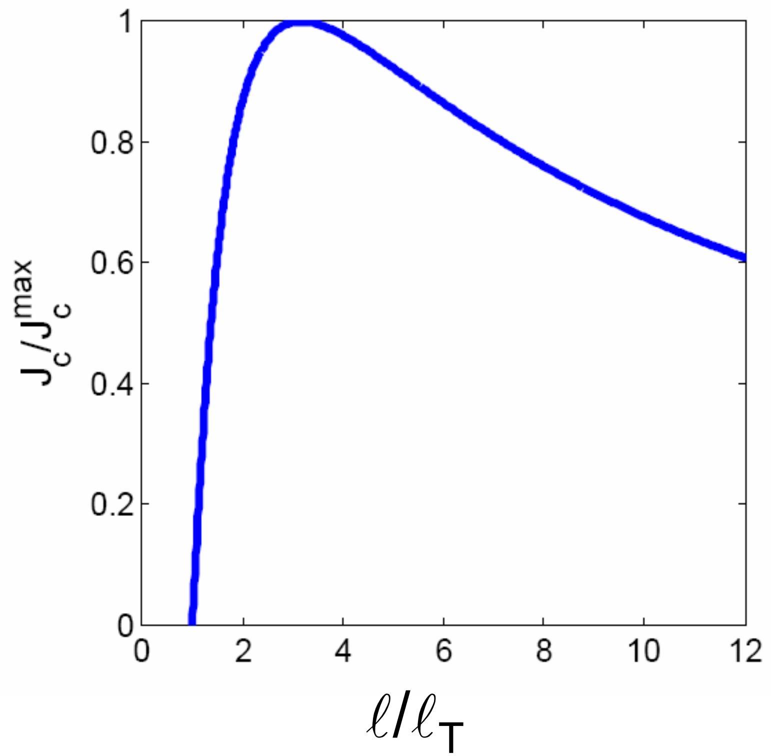
- **E_c is the electric field criterion for J_c**

- **Competition between pinning and thermal fluctuations causes maximum in J_c as a function of pin spacing**

Optimum pin spacing depends on temperature

$$J_c(l) \cong J_0 \frac{\xi}{\ell} \ln \frac{\ell}{\xi_c}\left(1 - \frac{\ell_T}{\ell}\right),$$

$$\ell_T(t) = \frac{\ell_0 t}{1-t^2}, \qquad \ell_0 = \frac{3T_c\sqrt{\Gamma}}{8\varepsilon_0}\ln\left(\frac{E_0}{E_c}\right)$$

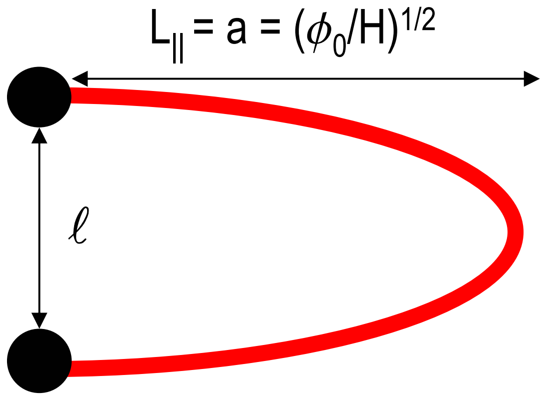


For YBCO, we have $\varepsilon_0 \cong 10^3$ K/nm,
Γ= 5, T_c = 90K, $\rho_F \sim 100\ \mu\Omega$cm,
J_{co} = 5MA/cm^2, and n = 30.

Optimum at $\ell_m \sim 4\ell_T$,

Optimum J_c at $\ell_{mt} \sim 16$ nm at 77K

Critical current in field



- **Parabolic critical semi-loop:**

$$u(z) = \frac{J\Gamma^2\phi_0}{8c\varepsilon_0}\left(l^2 - 4z^2\right), \qquad u(0) \cong a$$

- **Low-field critical current density**
- **Strong effect of anisotropy**

$$J_c \cong \frac{8c\varepsilon_0 \ln(l/\xi_c)}{\Gamma^2 l^2 \sqrt{\phi_0 H}}$$

- **Competition of pinning and current blocking:**

$$J_c \cong \frac{8c\varepsilon_0}{\Gamma^2 l^2 \sqrt{\phi_0 H}}\left(1 - \frac{4\pi r_0^3}{3x_c l^3}\right)$$

- **Optimum volume fraction of pinning centers, $x_m = 2x_c/5 \approx 20\%$**

Effect of thermal fluctuations in field

- **Activation barrier**

$$U = \int \left(\frac{\varepsilon_0}{2\Gamma^2} \left(\frac{\partial u}{\partial z} \right)^2 - \frac{J\phi_0 u}{c} \right) dz,$$

$$U = U_0 \left(1 - \frac{J}{J_c} \right), \qquad U_0 = \frac{16 c \phi_0 \varepsilon_0}{3 l \Gamma^2 H} \ln \frac{l}{\xi_c}$$

- **Critical current density:**

$$J_c \cong \frac{8 c \varepsilon_0}{\Gamma^2 l^2 \sqrt{\phi_0 H}} \left(1 - \frac{4\pi r_0^3}{3 x_c l^3} \right) \left(1 - \frac{H}{H^*} \right), \qquad H^* \cong \frac{16 c \phi_0 \varepsilon_0 \ln(l/\xi_c)}{3 l \Gamma^2 \ln(E_0/E_c)} \left(\frac{1}{T} - \frac{T}{T_c^2} \right)$$

- **The irreversibility field is strongly suppressed by anisotropy**

Conclusions

- RTS with T_c = 350K can only be useful at 300K if they are:
  - nearly isotropic
  - exhibit neither intrinsic phase separation nor precipitation on grain boundaries
  - have a higher superfluid density than HTS

- Moderately anisotropic RTS (Γ < 10) may be very useful for high field applications at 77K

- Nearly isotropic FRTS (freezing room temperature superconductors) 150 < T_c < 300K or qubic superconductors with T_c = 90-150K can be revolutionary for power/magnet applications at 77K

- The success of the 40K s-wave MgB_2 should inspire further extensive search of other moderately anisotropic “intermediate/high T_c“ superconductors