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

Alex Gurevich

National High Magnetic Field Laboratory, Florida State University
Tallahassee FL, USA
• Suppose that a RTS with $T_c = 350$K 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:

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

\[ H_{c2}(0) > 100 \text{ Tesla} \]

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,

\[ J_d(300) = 40 \text{ MA/cm}^2 \]

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.

- Thermally-activated vortex creep, $E \sim J_\rho F \exp[-U(T,B,J)/T]$

- Irreversibility 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

• Defects chop vortices into short strongly pinned segments

• Normal vortex cores are strongly deformed

α-Ti ribbons in a Nb-Ti alloy (P. Lee, University of Wisconsin)
Can nanoprecipitates in HTS be as effective?

YBCO with (Y, Sm)$_2$O$_3$ precipitates, $J_c \approx 1.7\text{MA/cm}^2$

Particle density: $\sim 3.54 \times 10^{11}\text{cm}^{-2}$
Particle size: $\sim 3-10\text{ nm}$
Particle spacing: $\sim 10-15\text{ nm}$
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 be as good as Bi-2223 for $20K < T < 35K$, and $B < 15T$. 

![Graph showing comparison of LTS and HTS materials]
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

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 $\Delta(r)$

Seamus Davis et al
The grain boundary problem

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

16° [001] tilt grain boundary in YBCO

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

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

X. Song et al. Nature Mat. 4, 470 (2005)
Magnetic granularity in polycrystals

Magnetic granularity caused by grain boundaries

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

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: \( \Delta T = T_c - T < T_c G_i \)

- Ginzburg parameter:

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

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

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

\[
\lambda = \left( \frac{m c^2}{4 \pi e^2 n_s} \right)^{1/2}
\]

- LTS: \( G_i \sim 10^{-8}, \Delta T \sim 10^{-7} \text{ K} \)
- YBCO: \( \Gamma = 5, G_i \sim 10^{-2}, \Delta T \sim 1 \text{ K} \)
- BSCCO: \( \Gamma \sim 50-100, G_i \sim 0.1, \Delta T \sim 10 \text{ K} \)
- \( T_c \) 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)*

\[
F = \frac{1}{2} \sum_{k} [c_{66}(u_{x}k_{y} - u_{y}k_{x})^2 + c_{44}(k)u_{z}^2k_{z}^2],
\]

\[
< u^2 > \approx \int \frac{d^3k}{(2\pi)^3} \frac{T}{c_{66}k_{z}^2 + c_{44}(k)k_{z}^2}
\]

- Dispersive line tension of a single vortex

\[
\epsilon_l(k) = \frac{\epsilon_0}{2\Gamma^2} \ln \frac{\lambda^2}{\xi^2 (1 + \lambda^2 k_z^2)} + \frac{\epsilon_0}{2\lambda^2 k_z^2} \ln (1 + \lambda^2 k_z^2),
\]

\[
\epsilon_0 = \left( \frac{\phi_0}{4\pi\lambda} \right)^2 = \frac{\pi\hbar n_s}{4m}
\]

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

\[
\epsilon_l \approx \frac{\epsilon_0}{\Gamma^2} \ln \frac{1}{\xi c k_z}, \quad \lambda k_z \gg 1
\]

\[
\epsilon_0 \approx 10^2 \text{ K/Å for HTS}
\]
Melting of vortex lattice

- Weak pinning: $J_c = 0$ in the vortex liquid phase $B > B_m$

- Lindemmann criterion: $<u^2(T,B_m)> = c_L^2 \phi_0 / B_m$, $c_L \approx 0.1 - 0.3$ (Nelson et al; Hougton, Pelcovits, Sudbo; Blatter et al, Brandt et al; Tesanovic et al; …)

- Upper branch of the melting field $B_{c1} << B_m << B_{c2}$:

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

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

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

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

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 (\( J_c \sim 10 \text{ MA/cm}^2 \) and \( J_d \sim 40 \text{ MA/cm}^2 \) 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

\[ J_c \text{ renormalized by thermal fluctuations of vortex half-loops} \]

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

\[ J_c(T) \text{ rapidly drops above the depinning temperature} \]

\[ T^* \cong \frac{T_c}{1 + \gamma}, \quad \gamma \cong \frac{\Gamma T_c}{r_0 \varepsilon_0} \]

- **YBCO:** \( \varepsilon_0 \approx 80 \text{ K/Å}, \Gamma \sim 5, T_c = 92\text{K}, r_0 \approx 20-50 \text{ Å} \) (heavy ion radiation treks, Civale, SUST, 10, A11 (1997))
  \( \rightarrow \gamma \approx 0.2, T^* \approx 77\text{K} \)

- **BSCCO:** \( \varepsilon_0 \approx 50 \text{ K/Å}, \Gamma \sim 50, T_c = 110\text{K}, r_0 \approx 30 \text{ Å} \) \( \rightarrow \gamma \approx 3.7, T^* \approx 23 \text{K} \)

- **RTS:** \( \varepsilon_0 \approx 50 \text{ K/Å}, T_c = 350\text{K}, r_0 \approx 30 \text{ Å} \) \( \rightarrow \gamma \approx 0.23\Gamma, T^* \approx 285 \text{K} \) for \( \Gamma = 1 \), and \( T^* \approx 106 \text{K} \) 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 ($x_c = 0.5$)

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

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 $H_\phi = \phi_0/l_m^2$:

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

which gives $H_\phi = 7.6T$ 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

8 nm YBa$_2$CuO$_5$ nanoparticles


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:

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

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

- Too many pins result in $T_c$ suppression and current blocking
The effective current-carrying cross section $A_{\text{eff}}(x)$ vanishes at the percolation threshold $x_c$. 

$$ \rho = \rho_0 \frac{A}{A_{\text{eff}}}, \quad A_{\text{eff}} = \left(1 - \frac{x}{x_c}\right)A $$
Optimum pin density: pinning vs current blocking

$J_c$ due to random insulating precipitates of radius $r_0$ spaced by $\ell$

\[
J_c(l) \approx J_0 \frac{\xi}{\ell} \ln \frac{\ell}{\xi_c} \left(1 - \frac{4\pi r_0^3}{3\xi^3}\right)
\]

Optimum pin spacing and volume fraction:

\[
\ell_m \approx 3 - 4r_0, \quad x_m = \frac{4\pi r_0^3}{3\ell_m^3} \approx 8 - 12\%
\]

Optimum critical current density:

\[
\frac{J_{c,\text{max}}}{J_d} \approx \frac{9\sqrt{3}\xi}{8\Gamma^{1/2}} \ln \frac{\ell_m}{\xi_c}
\]

For $\Gamma = 7$, $J_{c,\text{max}} \approx 0.5J_d$ for $r_0 = \xi$, and $J_{c,\text{max}} \approx 0.25J_d$ 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
  \[ U_0 \approx \frac{\varepsilon_0}{2\Gamma^2} \int_0^{L_\perp} \left( \frac{\partial u}{\partial z} \right)^2 dz = \frac{8\varepsilon_0 \ell}{3\sqrt{\Gamma}} \]

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

- Vortex thermal wandering reduces \( J_c \)

\[ J_c = J_{c0} \left( 1 - \frac{T}{U_0} \ln \frac{E_0}{E_c} \right), \quad E_0 \approx \rho_F J_{c0} \]

- \( E_c \) 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

\[ J_c(l) \approx J_0 \frac{\xi}{\ell} \ln \frac{\ell}{\xi_c} \left(1 - \frac{\ell}{\ell}\right), \]

\[ \ell_T(t) = \frac{\ell_0 t}{1 - t^2}, \quad \ell_0 = \frac{3T_c \sqrt{\Gamma}}{8\epsilon_0} \ln \left(\frac{E_0}{E_c}\right) \]

For YBCO, we have \( \epsilon_0 \approx 10^3 \) K/nm,
\( \Gamma = 5, T_c = 90K, \rho_F \sim 100 \ \mu\Omega \text{cm}, \)
\( J_{co} = 5\text{MA/cm}^2, \) and \( n = 30. \)

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

Optimum at \( \ell_m \sim 4\ell_T. \)
Critical current in field

$L_{||} = a = (\phi_0/H)^{1/2}$

- Parabolic critical semi-loop:

\[ u(z) = \frac{J_0 \phi_0}{8c\varepsilon_0} \left( l^2 - 4z^2 \right), \quad u(0) \approx a \]

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

- Competition of pinning and current blocking:

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

- Optimum volume fraction of pinning centers, $x_m = 2x_c/5 \approx 20\%$
Effect of thermal fluctuations in field

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

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

- Critical current density:
  \[ J_c \approx \frac{8c\varepsilon_0}{\Gamma^2 l^2 \sqrt{\phi_0 H}} \left( 1 - \frac{4\pi r_0^3}{3x_c l^3} \right) \left( 1 - \frac{H}{H^*} \right), \quad H^* \approx \frac{16c\phi_0\varepsilon_0 ln(l/\xi_c)}{3\Gamma^2 \ln(E_0/E_c)} \left( 1 - \frac{T}{T_c} \right) \]

- 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 ($\Gamma < 10$) may be very useful for high field applications at 77K

• Nearly isotropic FRTS (freezing room temperature superconductors) $150 < T_c < 300K$ or cubic 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