What to look for in new superconductors if we want to make them useful?

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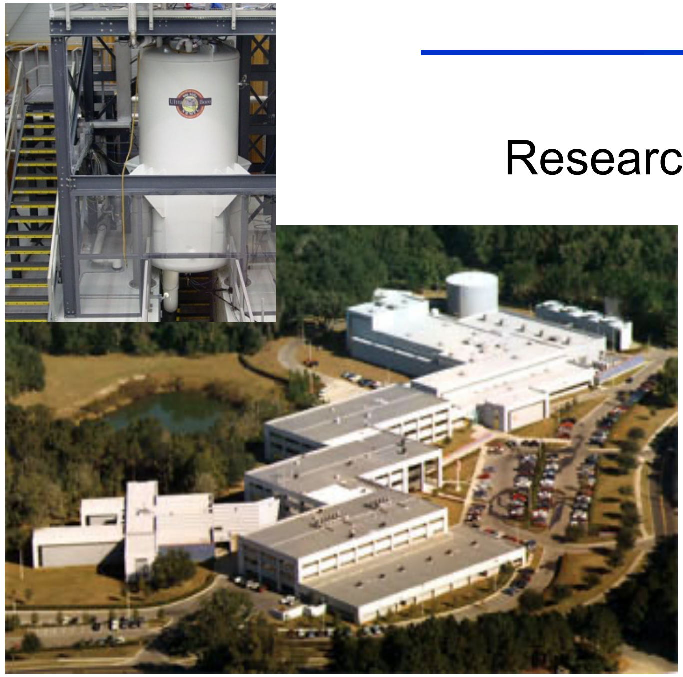
Useful for: power/magnet applications?

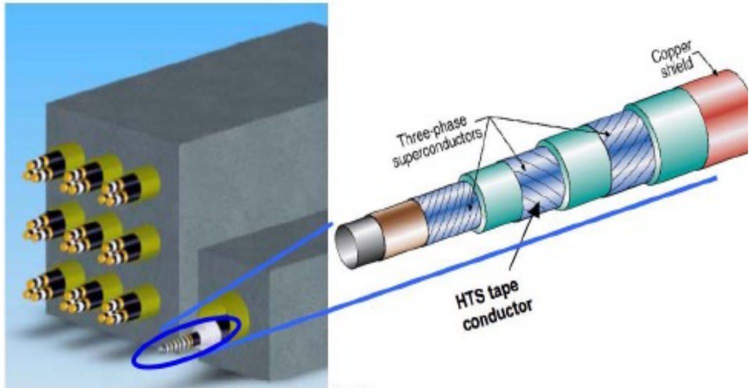
Research magnets



Medical MRI

HTS motors & generators

Power transmission lines



Ultera/Southwire

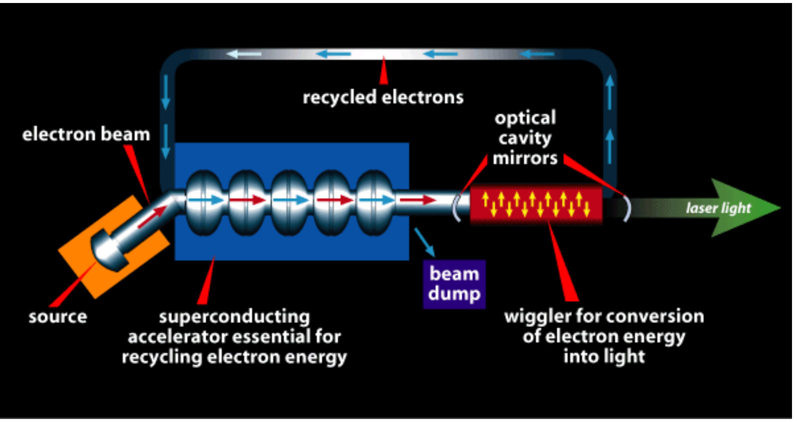
Figure 1 Schematic comparison of the 3×3 duct bank of an underground copper distribution system vs. a single triaxial HTS cable operating at 13 kV and transferring 69 MVA of power.

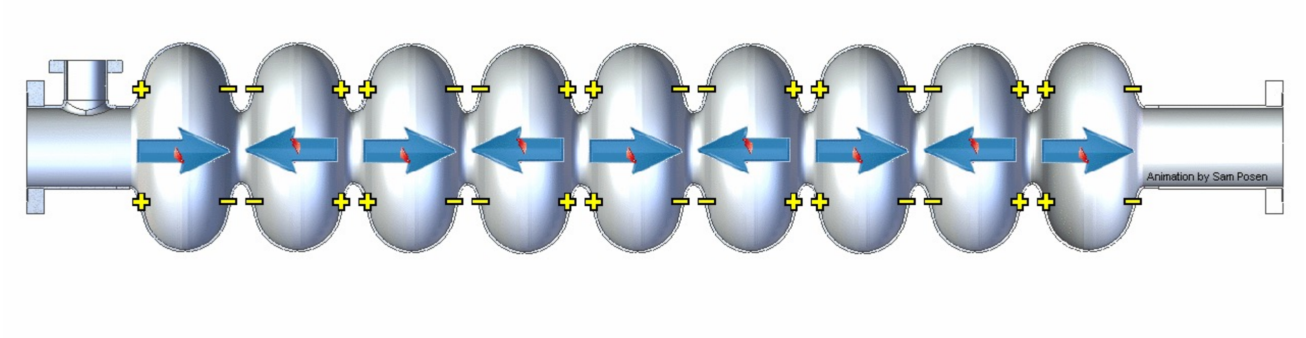
MagLev

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Useful for: high-Q SRF resonators?

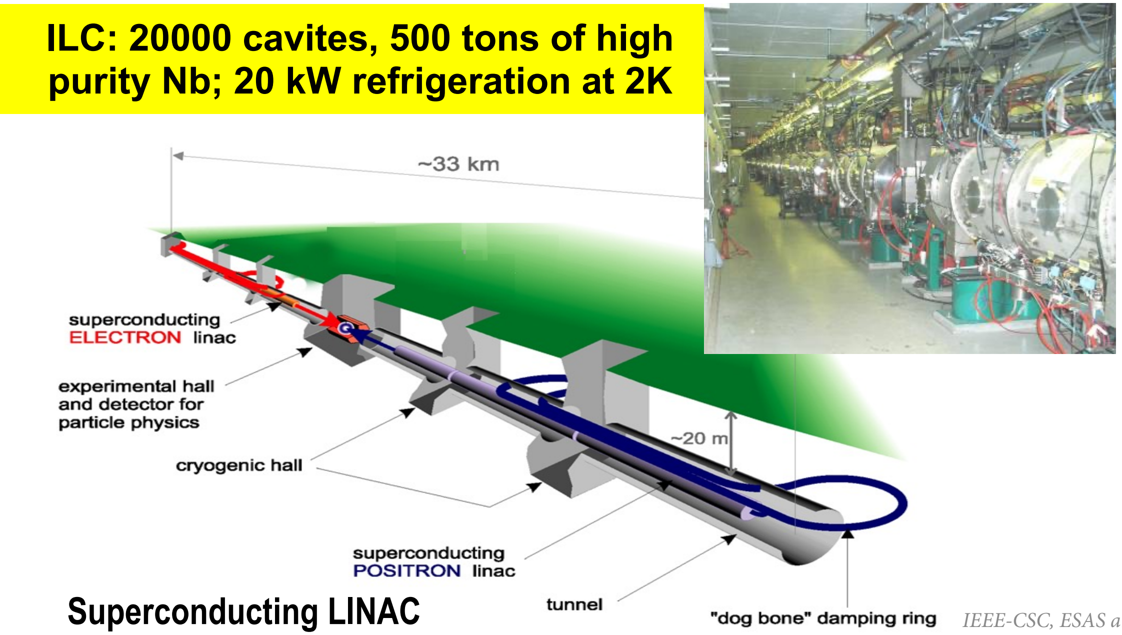
X-ray free electron laser





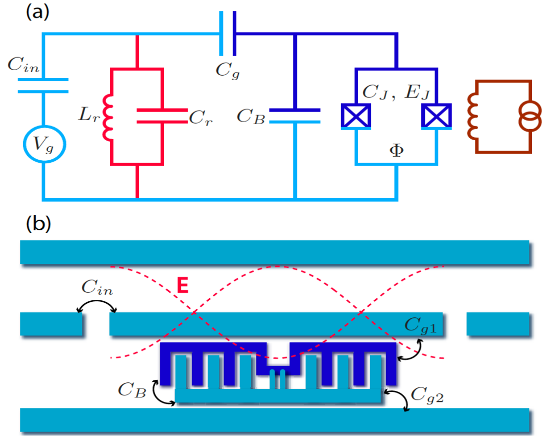
- Football-size Nb or Cu cavities 2-3 mm thick
- TM_{010} resonance mode with f = 1-2 GHz
- Cooled by superfluid He at 2 K

ILC: 20000 cavites, 500 tons of high purity Nb; 20 kW refrigeration at 2K

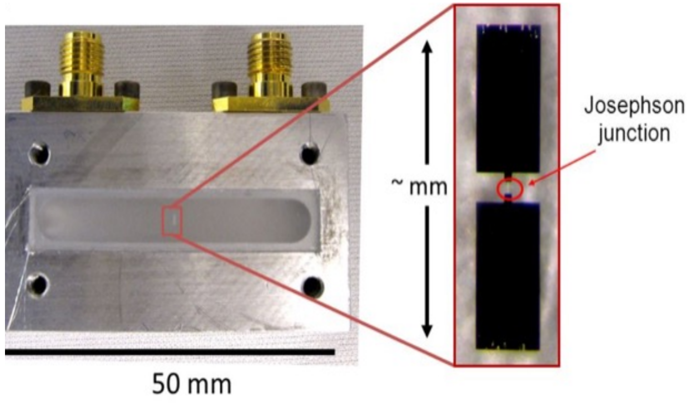


Superconducting LINAC

Transmon in a coplanar waveguide



Transmon in a 3D superconducting cavity



Define useful superconductors

What application?

- Materials parameters of merit depend on operating temperature, magnetic field and frequency
  - high field dc magnets, SMES: high J_c and irreversibility field
  - motors and generators: high J_c, low ac losses, twisted multifilamentary wires
  - transmission lines, FCL: high J_c at low fields

- Requirements for electronic, QIT and high-Q resonators are best satisfied by conventional superconductors
  - High Q resonators: no vortices, s-pairing, large SC gap, lowest density of subgap states
  - Engineering of optimum density of states to minimize very weak RF dissipation in the vortex-free state

  As a review, see Gurevich, SUST, 36, 063002 (2023)

- Lots of SC materials (conventional, cuprates, pnictides) are available for applications at 4.2K
- Very few SC can perform at 77 K, and T_c is not the only reason

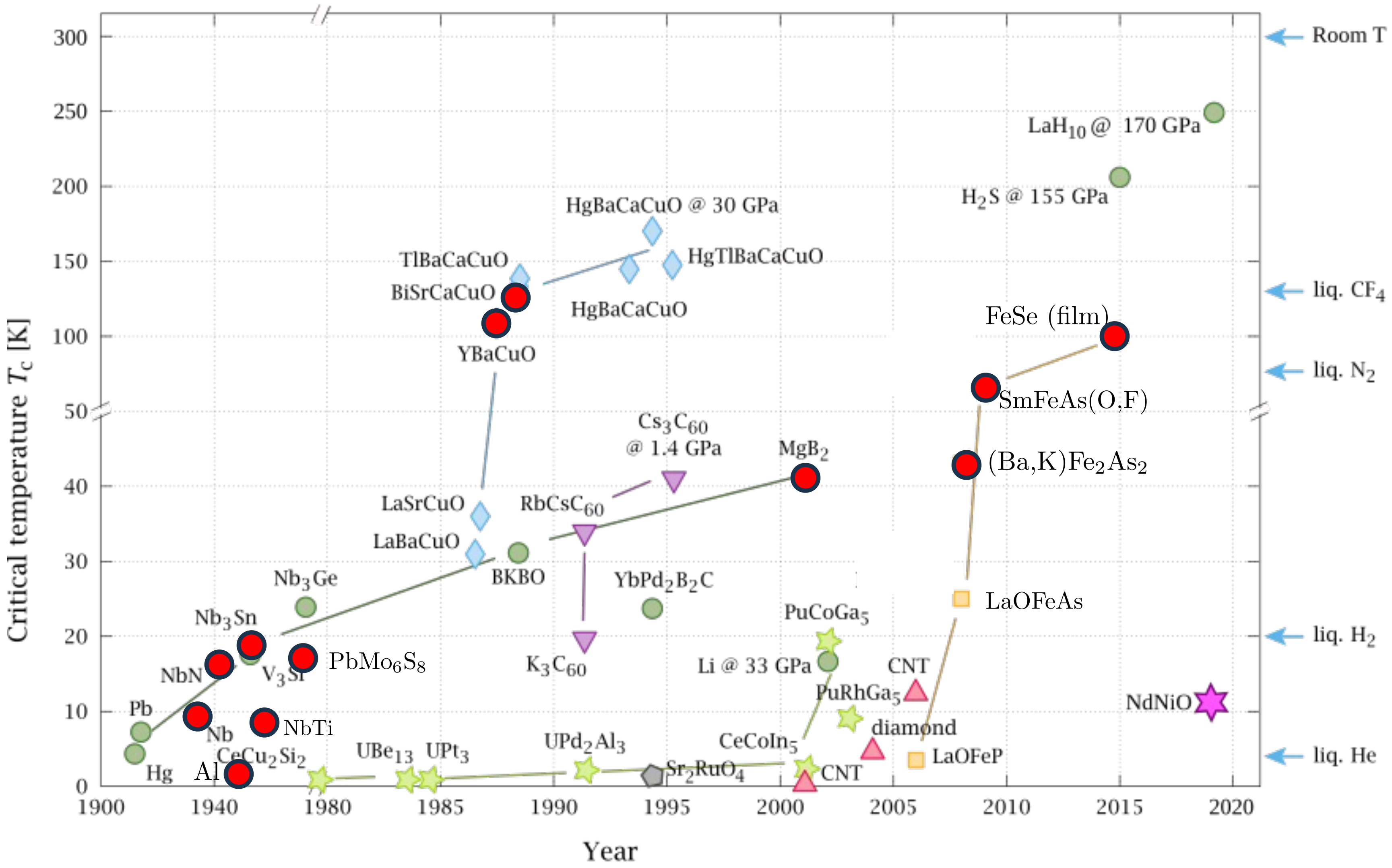
- The best performance does not always require the highest T_c and H_{c2}
- To operate at T>77K, tough materials requirements are to be satisfied
- Can they help in searching for new superconductors?

Superconducting materials

Is T_c the most important parameter of merits for applications?

Should the search for new superconductors be primarily focused on T_c?

Does high T_c ensure applications at high temperatures and fields?



Search for new superconductors

Matthias rules of maximizing T_c: BCS physics + materials experience + legendary insights:

1. High symmetry is good; cubic symmetry is the best
2. High density of electronic states is good
3. Stay away from oxygen
4. Stay away from magnetism
5. Stay away from insulators

Works for LTS but fails for unconventional SC (HTS cuprates and FBS)

- The higher the operating temperature, the less relevant T_c and H_{c2} become.
- Performance at high fields and temperature is mostly limited by thermal fluctuations of vortices and current-blocking grain boundaries
- The higher the electron density and more isotropic the better (1,2)
- Avoid competing orders: superconductivity with antiferromagnetic or structural transitions (4,5)

Dream and challenges of RTS: If a superconductor with T_c > 300K and B_{c2}=1000 T has been discovered, can it be used at 300K? What would be the materials requirements to enable RT magnet applications?

M.R. Beasley, MRS Bull, 36, 597 (2011); Gurevich, Nature Mater. 10, 255 (2011); Annu. Rev. Cond. Mat. Phys. 5, 35 (2014); A.P. Malozemoff, MRS Bull. 36, 601 (2011), Physica C (2013)

Is there a T_c limit for conventional superconductors?

McMillan formula for intermediate coupling

$$T_c = \frac{T_D}{1.45} \exp\left[-\frac{1.04(1+\lambda_p)}{\lambda_p - (1+0.62\lambda_p)\mu^*}\right] \lesssim 0.2T_D \qquad \lambda_p \lesssim 1.5$$

$$T_c \simeq 0.2T_D\sqrt{\lambda_p}, \qquad \lambda_p \gtrsim 2$$

Allen and Dynes, Phys. Rev. B 12, 905 (1975)

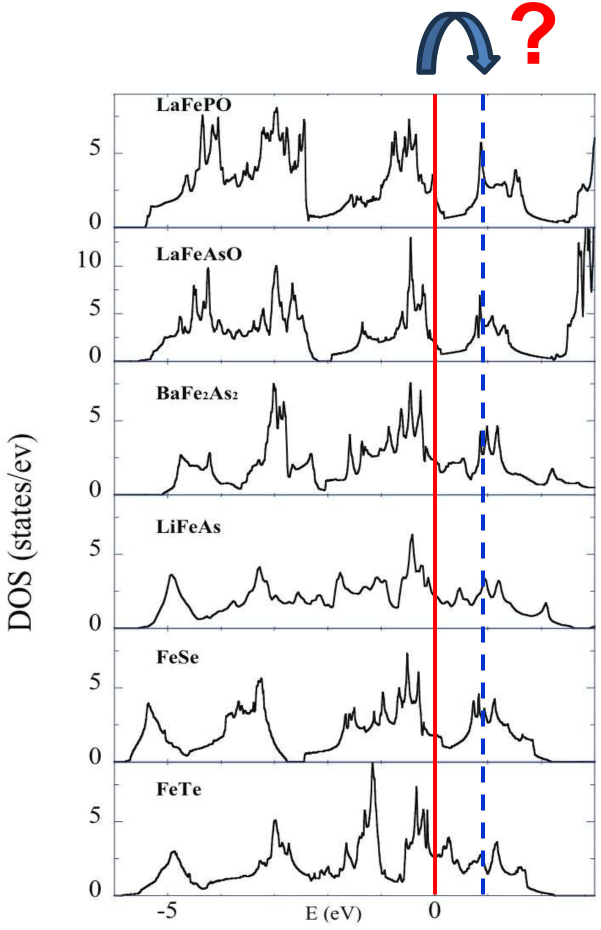
High Debye temperature $T_D \propto M^{-1/2}$ for light atoms line H, strong electron-phonon coupling $\lambda_p = \langle VN(E_F)\rangle$ and peaks in DOS at the Fermi surface

T_c enhancement by pressure:

Ti: T_c from 0.5 K to 25 K at 248 GPa (2.5M atm)
Zhang et al, Nature Commun. 13, 5411 (2022)

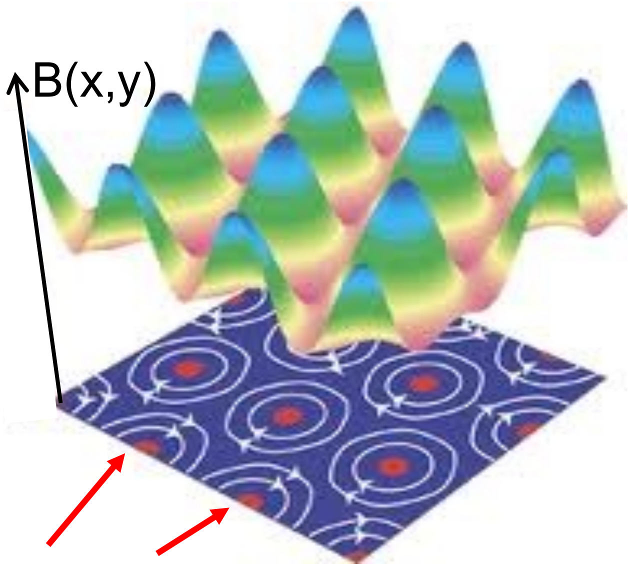
NbTi: T_c from 9.6 K to 19.1 K, B_{c2} from 15.4T to 19.1T
at 262 GPa , **Guo et al, Adv. Mater, 1807240 (2019)**

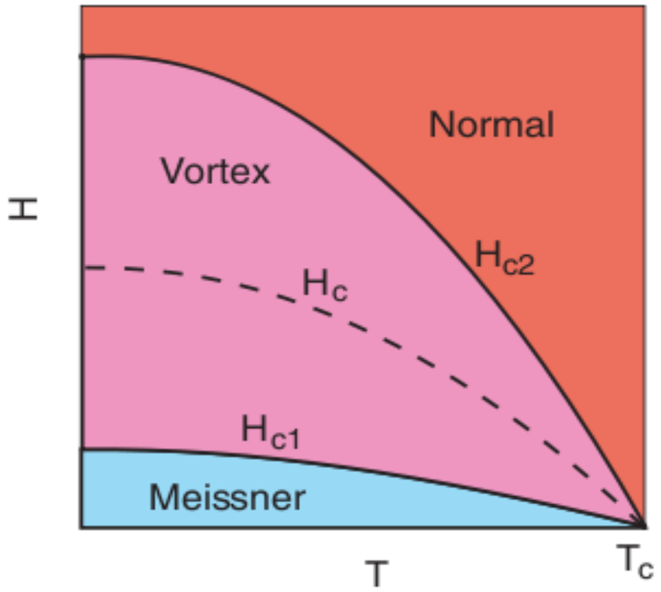
Superhydrides: LaH_{10} T_c = 250 K (-23C) @ 170 GPa (1.7M atm)
Drozdov et al Nature 569, 528 (2019)



Tune the Fermi energy to match the DOS peaks by chemical or applied pressure

In-field performance is controlled by vortices





High-field superconductors:

- HTS cuprates, $B_{c2}(0) > 100\text{-}200$ T
- FBS. $B_{c2}(0) > 50\text{-}100$ T
- $PbMo_6S_8$, $B_{c2}(0) = 50$ T

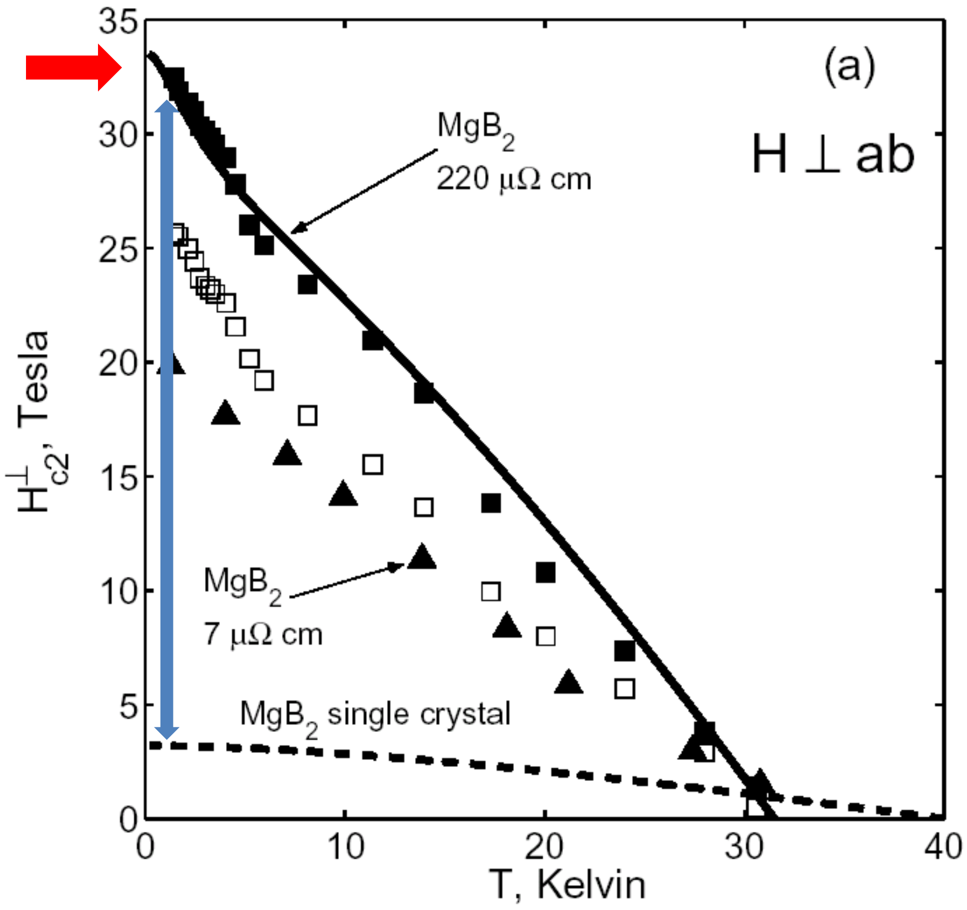
Seeber, Phys. Plasmas. 30, 120604 (2023)

- Quantized vortices in which supercurrents circulate over $\lambda = 40\text{-}400$ nm around normal cores of radius $\xi = 2\text{-}40$ nm.
- Short coherence length $\xi \sim \hbar v_F/2\pi k_B T_c = 2\text{-}4$ nm yields high B_{c2}, which can be further increased by alloying with nonmagnetic impurities

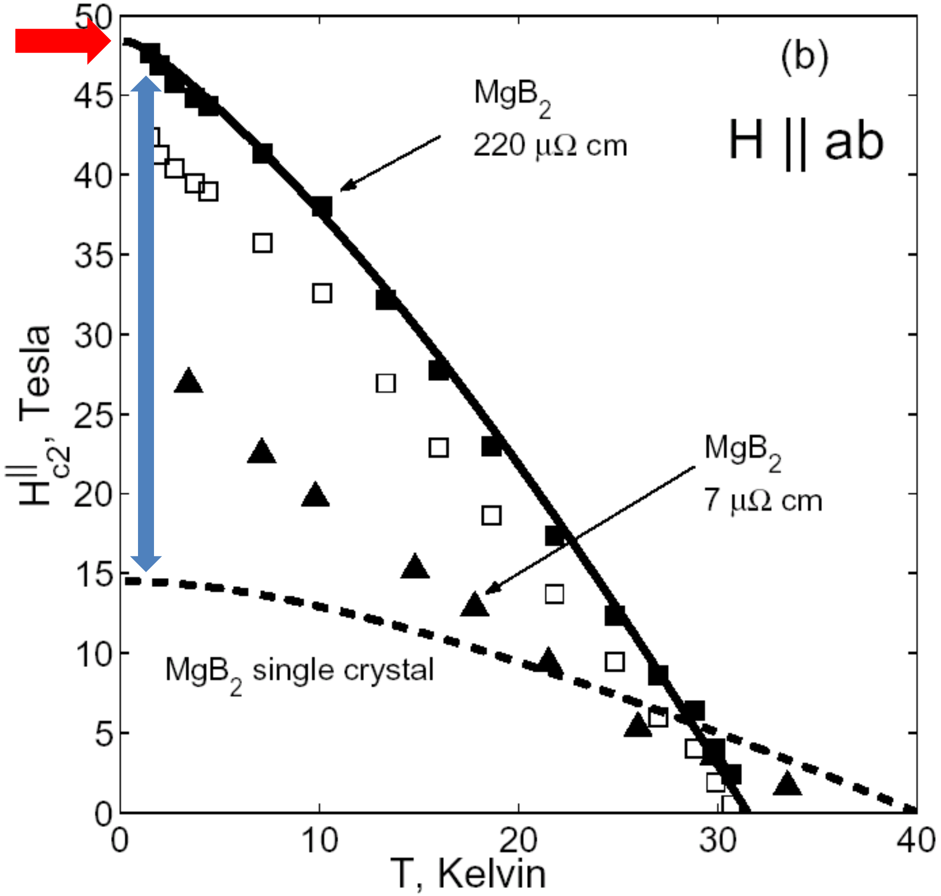
clean limit: $B_{c2} = \phi_0/2\pi\xi^2 \propto mT_c^2/E_F$ dirty limit: $B_{c2} = \phi_0/2\pi\xi l \propto T_c\rho_n$

- Higher T_c does result in high $B_{c2} = 20\text{-}100$ T to be used in superconducting magnets

Ten-fold increase of B_{c2} by materials disorder in MgB_2



From 3 to10 - fold increase of B_{c2} as compared to MgB_2 single crystals.



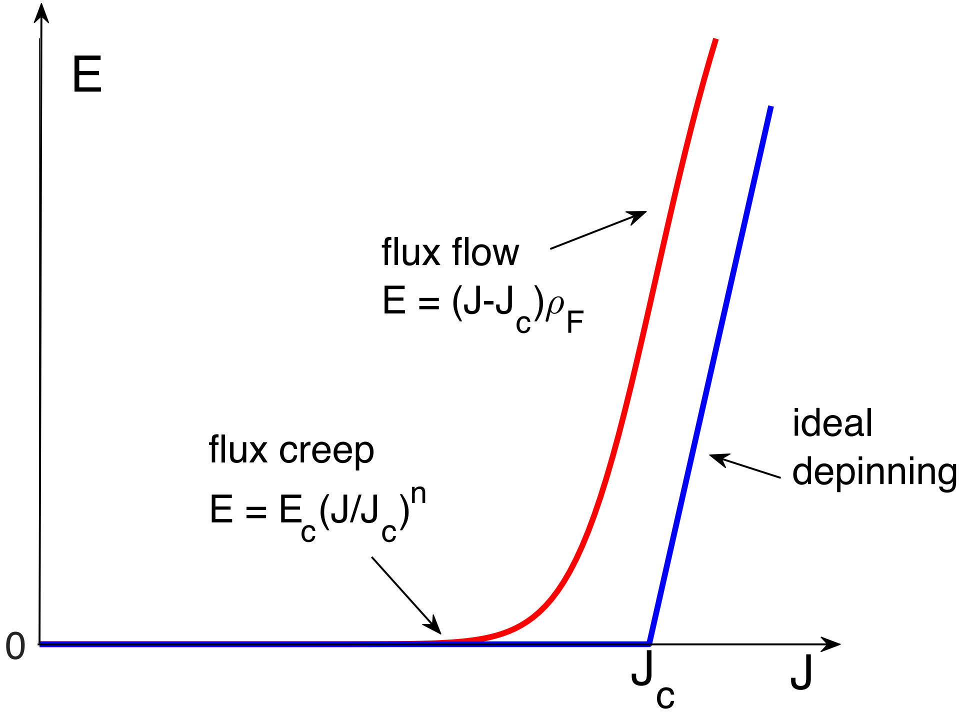
Anomalous increase of B_{c2} by two-band SC. Selective tuning of impurity scattering in π and σ bands in MgB_2

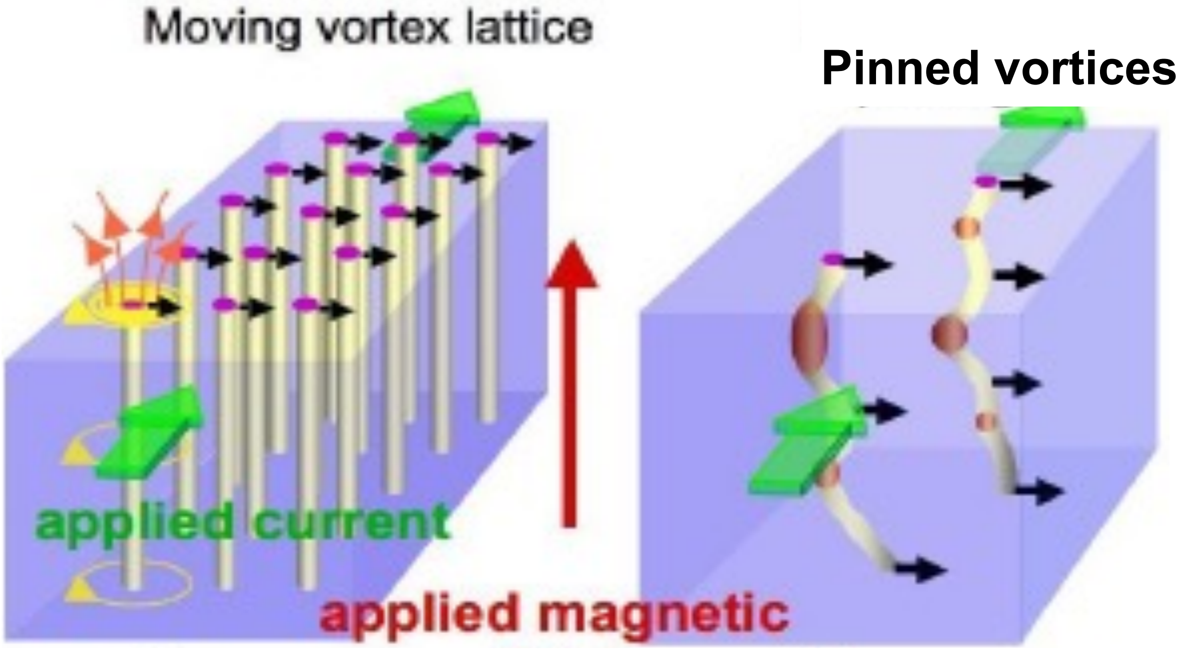
Gurevich et al., SUST, 17, 278 (2004)
Braccini et al, PRB 71, 012504 (2005)

Gurevich, PRB 67, 184515 (2003)

Critical current density $J_c(B)$ – one of main parameter for applications

Type –II superconductors can carry nondissipative currents if vortices are pinned by materials defects





field

J_c ~ 0.1-1 MA/cm^2 and n=10-100
@ 0-10T are needed

Thermally-activated flux creep

Moving vortices driven
by the Lorentz force: $f_L = [\check{z} \times J]\phi_0$

Vortices immobilized
by materials defects.
Depinning condition:

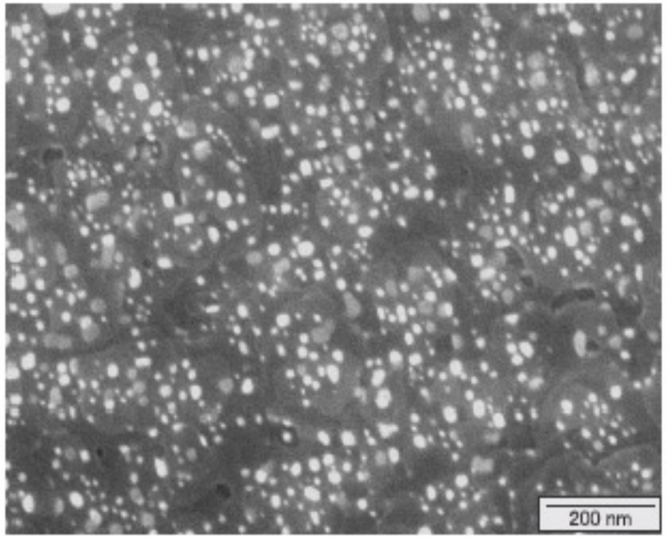
$$BJ_c = F_p(T,B)$$

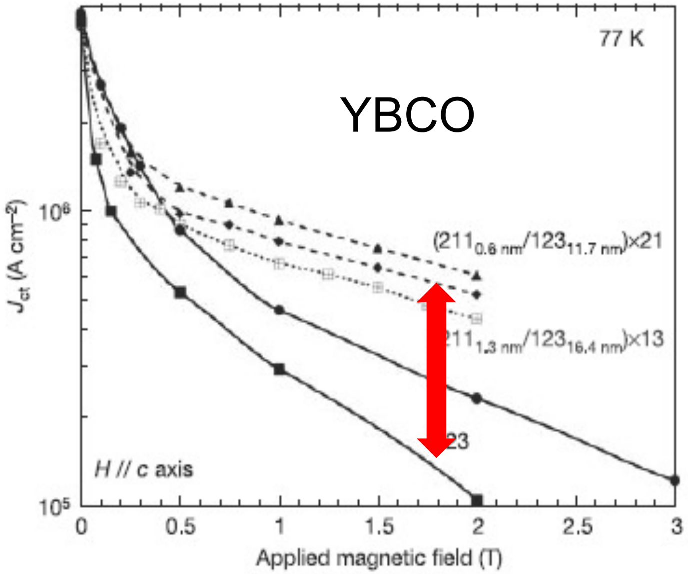
High-J_c at low T: the more pinning centers the better

α-Ti ribbons in a Nb-Ti alloy **(Larbalestier & Lee)**

Can produce self-field J_c up to 10-30% of the depairing current density:

$$J_d \approx \frac{H_c}{\lambda} \approx \frac{\phi_0}{3\sqrt{3}\pi\mu_0\lambda^2\xi}$$





- Vortices are chopped into short, strongly pinned segments
- From weakly pinned vortex spaghetti to strongly pinned vortex pasta.
- Can produce very high $J_c \sim (0.1\text{-}0.3) J_d$.

Haugan, et al. Nature 430, 867 (2004)

8 nm YBa_2CuO_5 nanoparticles

Conventional materials optimization for low-T applications

- Materials with higher T_c tend to have higher B_{c2} and J_c and generate stronger magnetic fields
- B_{c2} can be further increased by alloying with nonmagnetic impurities
- Incorporate defect structures or APC to pin vortices. The more pinning defects the better
- Produce twisted multifilamentary round wires to suppress thermo-magnetic instabilities and reduce ac losses

Bi-2212 round wire

Larbalestier et al, Nature Mater

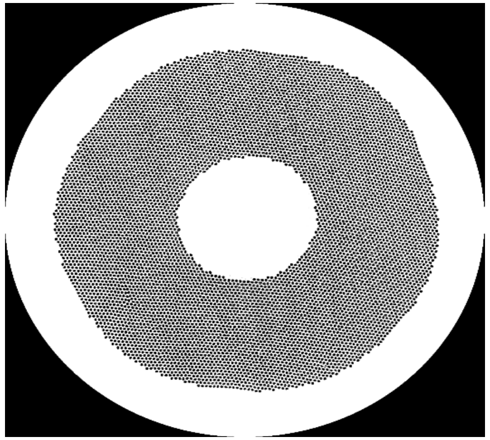
Jiang et al IEEE TAS 29, 6400405 (2019)

$Sr_{06}K_{04}Fe_2As_2$

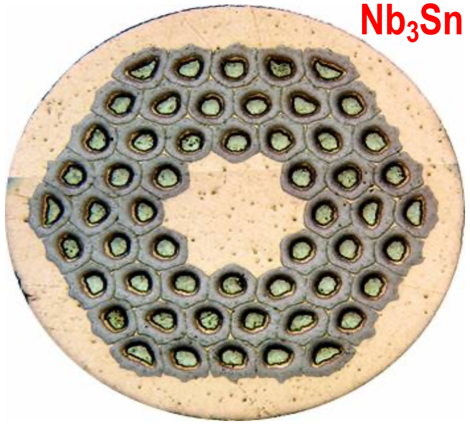
Yao et al,

APL 102, 082602 (2013)

All work fine at 4.2 K

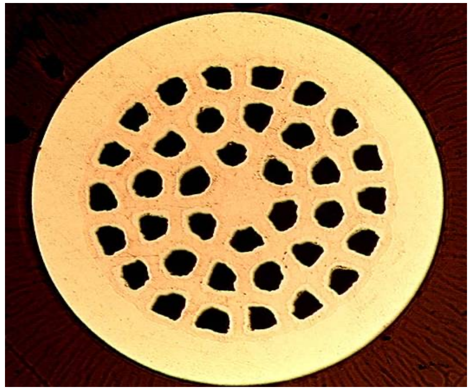


NbTi



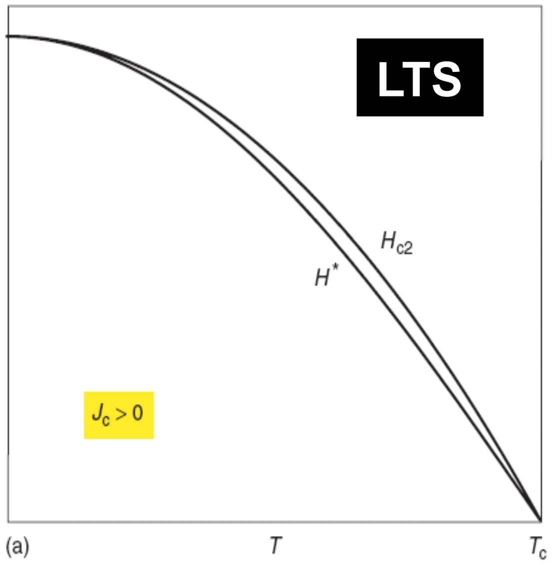
Nb_3Sn

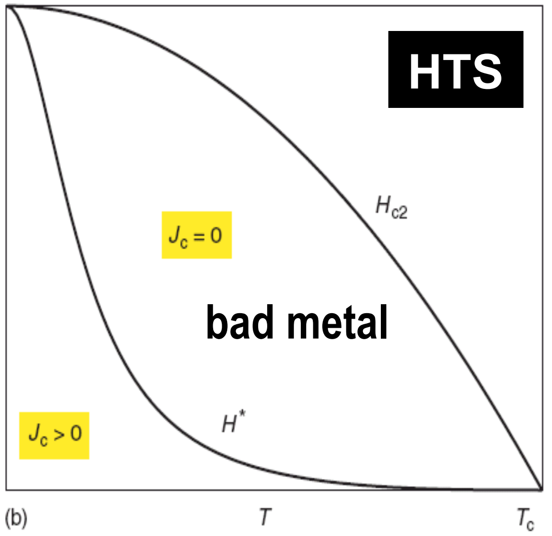
MgB_2 in Cu



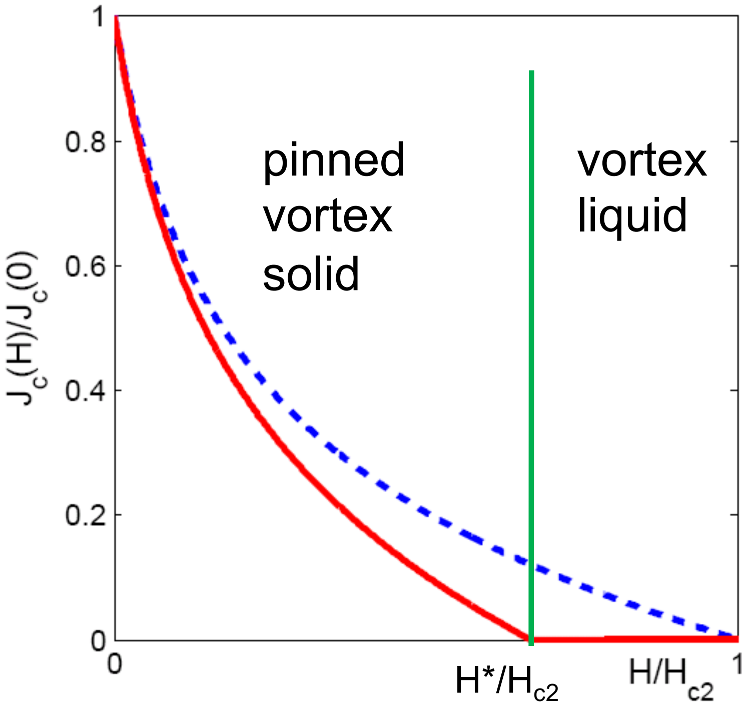
Applied Superconductivity Conference, Salt Lake City, Sept. 6, 2024

Why cannot it work at 77 K?





- Irreversibility field $H^*(T)$ above which $J_c(T,H) = 0$
- H^* is limited by thermal fluctuations of vortices and strong magnetic flux creep



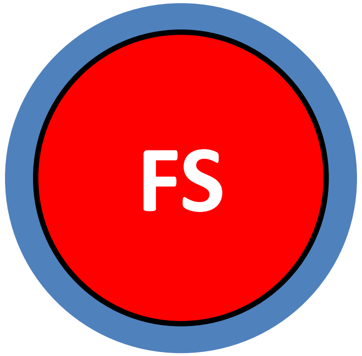
- **It is neither T_c nor H_{c2}, but high J_c and $H^*(T)$, which make superconductors useful**
- **Above 77 K, very high H_{c2} of cuprates becomes irrelevant and $H^* << H_{c2}$**
- **Mechanisms responsible for high T_c can cause problems with magnet applications at 77K**

Conventional vs unconventional pairing

Conventional: the wave function of the Cooper pair Ψ has the same symmetry as the Fermi surface: s-wave BCS superconductivity mediated by phonons. Weak sensitivity to nonmagnetic impurities. Majority of high-field LTS

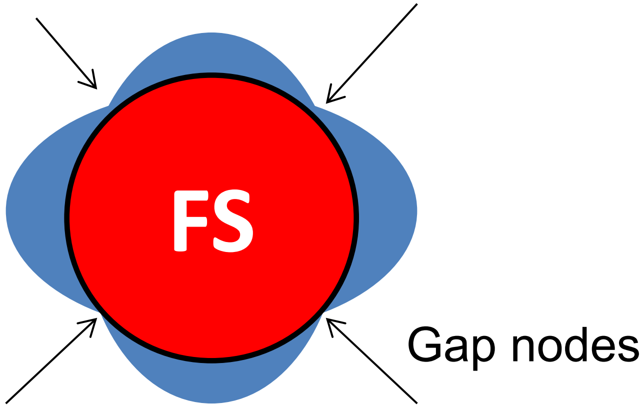
Unconventional: d-wave or multiband superconductivity mediated by magnetic excitations. Stronger sensitivity of T_c to impurities, the grain boundary problem. HTS cuprates, heavy fermions, iron pnictides.

s-wave



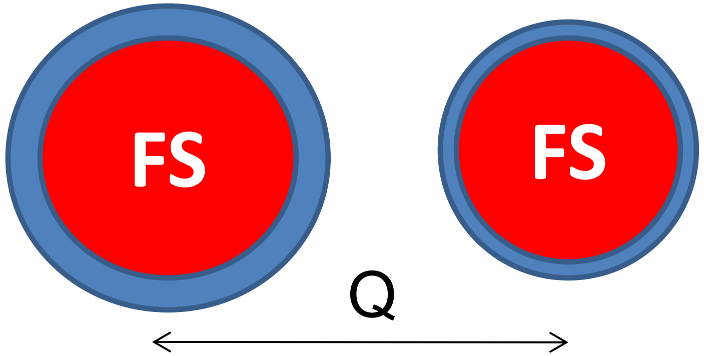
Most traditional LTS:
Nb, Pb, NbTi, Nb_3Sn

d-wave



High-T_c cuprates, heavy fermions, some of FBS

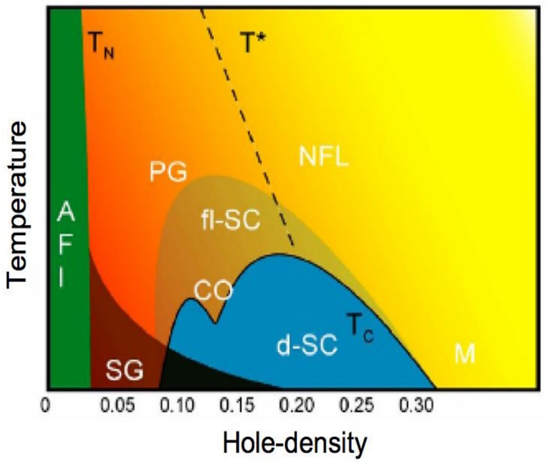
Multi-gap:

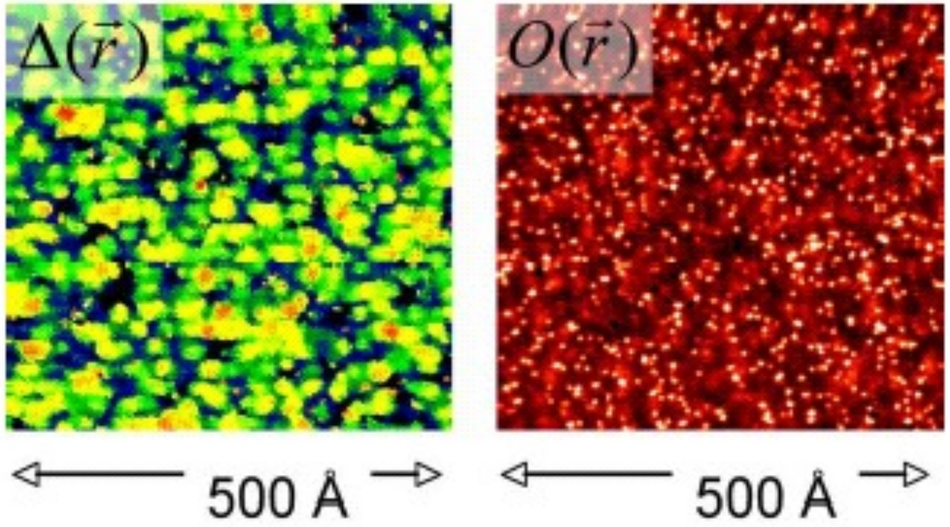


- **MgB_2, FBS**
- **Different superconducting gaps on disconnected pieces of FS**

Competing orders. What helps T_c can harm J_c

cuprates

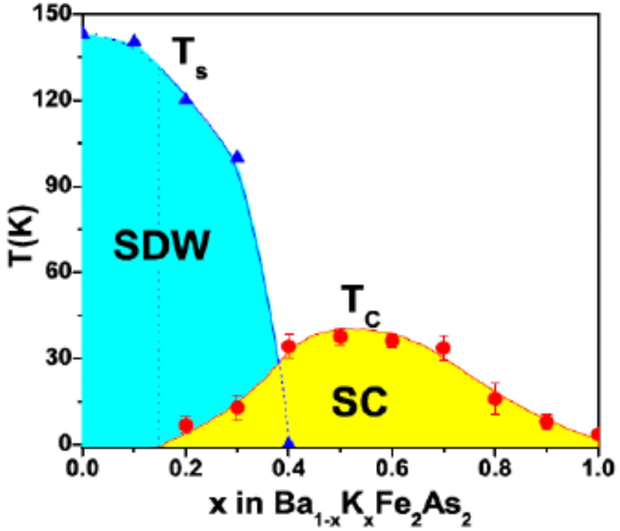




Left: The nanoscale superconducting energy gap disorder in $Bi_2Sr_2CaCu_2O_x$. Right: A simultaneous image of the dopant atom locations from SI-STM.

S. Davis et al

pnictides

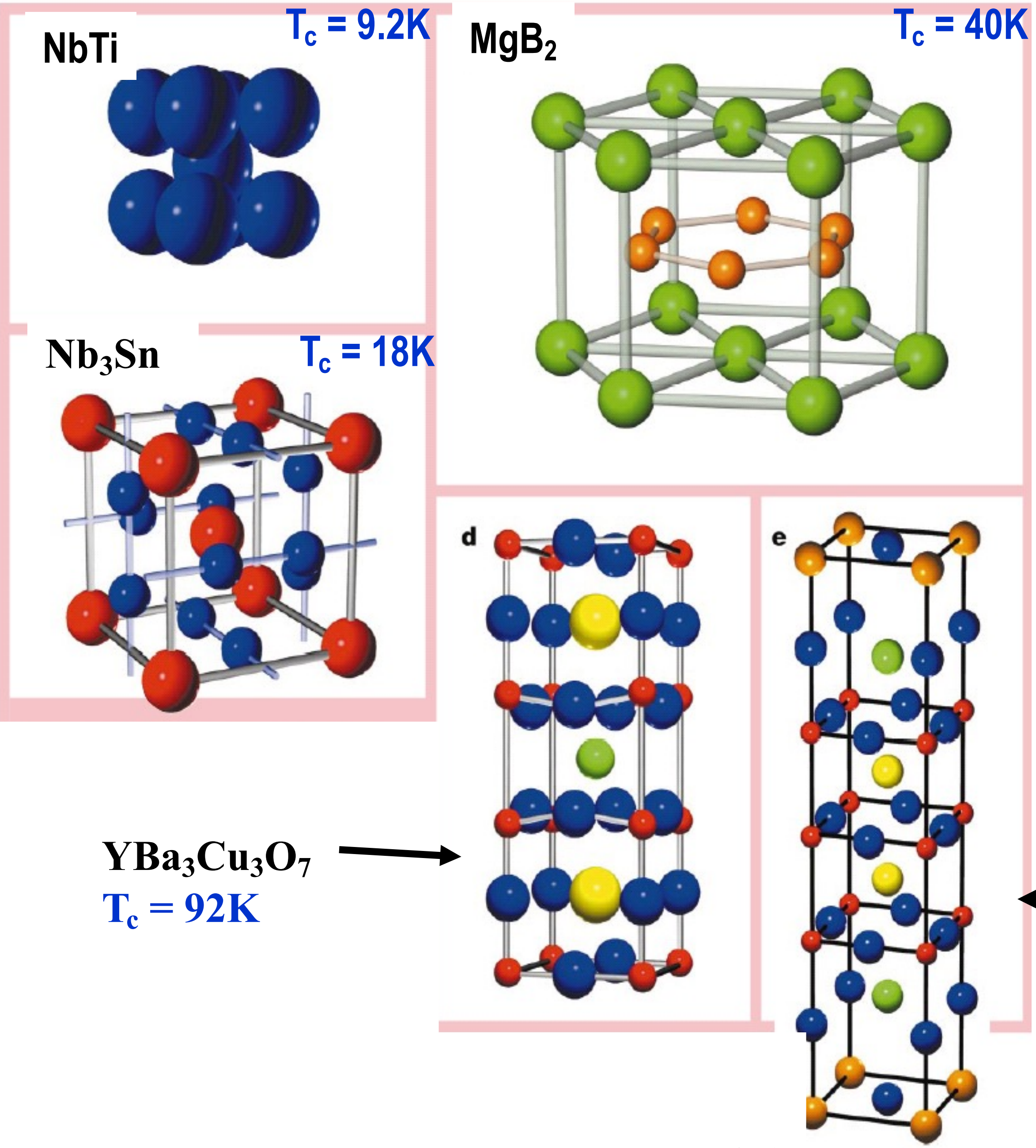


- Enhancement of SC by proximity to an AF phase

BUT

- As $\xi \sim \hbar v_F/2\pi k_B T_c$ drops below 1-2 nm, so any generic lattice defects can locally suppress $\Delta(r)$
- Precipitation of nonsuperconducting phase on grain boundaries and other materials defects

Main players



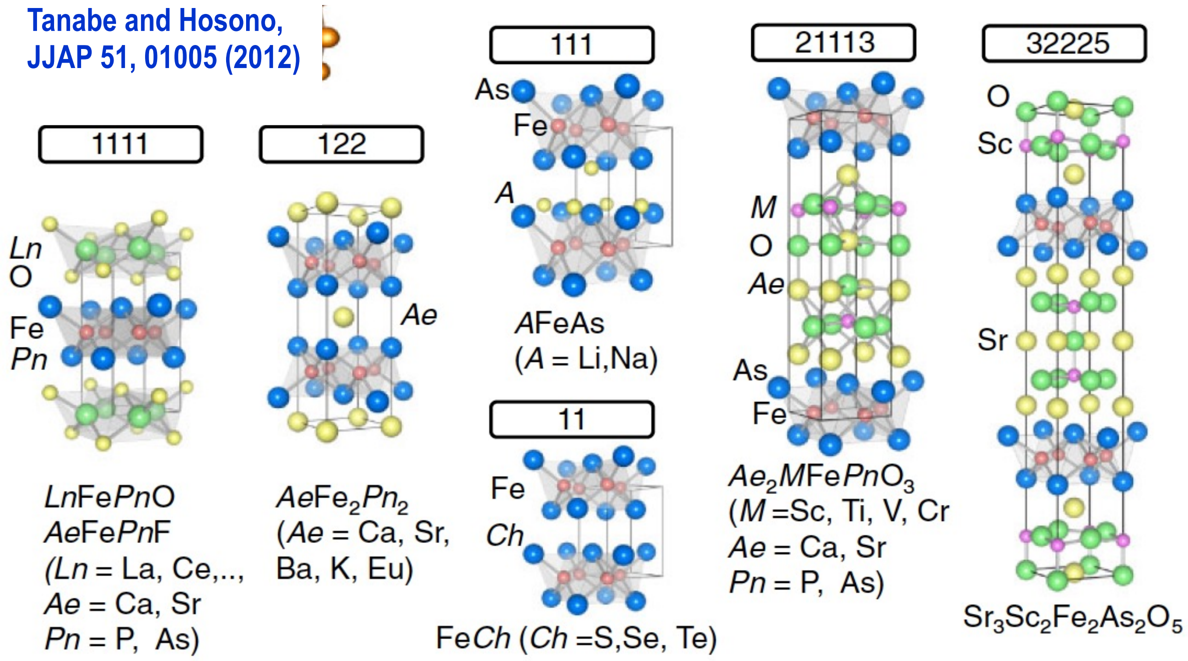
- Cubic, or hexagonal low-T_c superconductors
- Highly anisotropic layered high-T_c superconductors
- T_c seems to scale with chemical complexity
- Layered cuprates with large electron effective mass anisotropy ratio along the c axis and the CuO ab plane:

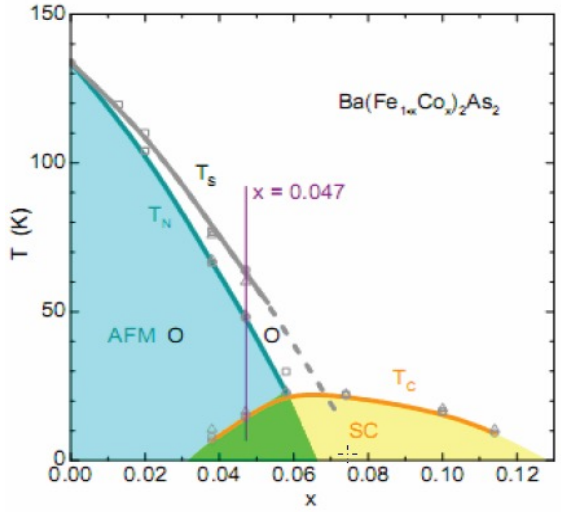
$$\Gamma = (m_c/m_{ab})^{1/2}$$

$YBa_3Cu_3O_7$
T_c = 92K

$Bi_2Sr_2Ca_2Cu_3O_x$
T_c = 108K

New Iron age: Fe-based superconductors

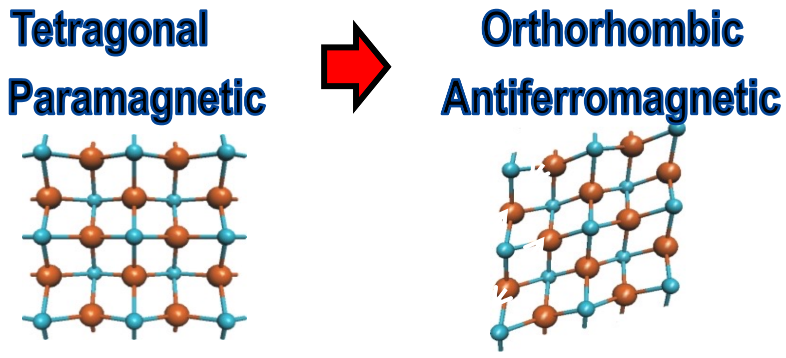

Tanabe and Hosono, JJAP 51, 01005 (2012)



Superconductivity from magnetic Fe^{2+} ions

ReOFeAs based (1111) (T_c = 55K) (Re = Sm, Nd)
$Ba_{1-x}K_xFe_2As_2$ based (122) (T_c = 38 K)
$FeSe_xTe_{1-x}$ based (11) (T_c = 18 K)

Poor metals, low E_F = 3-100 meV, short ξ=1-2 nm, huge B_{c2} > 100 T
Less anisotropic than cuprates

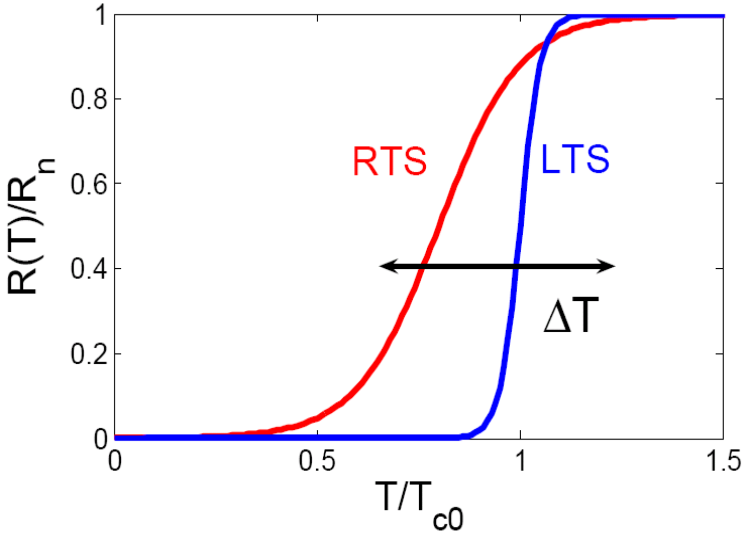

Tetragonal Paramagnetic → **Orthorhombic Antiferromagnetic**

Why does performance of LTS scale with T_c?

1. Large coherence length $\xi > 3$ nm, large Fermi energy and s-wave pairing result in weak suppression of T_c by impurities and extended defects.

2. No magnetic states competing with superconductivity (structural transition in A15 may enhance T_c)

3. Thermal fluctuations of vortices are weak. The Ginzburg number (squared ratio of thermal energy and condensation energy per Cooper pair) is very small:



Fluctuation region: $\Delta T = T_c - T < T_c Gi$

Ginzburg parameter:

$$Gi = \frac{1}{2}\left(\frac{k_B T_c}{H_c^2 \xi^2 \xi_c}\right)^2 = 2\left(\frac{m\Gamma k_B T_c}{\pi\hbar^2 n_s \xi_0}\right)^2$$

In LTS $Gi \approx 10^{-10}$ -10^{-5} but Gi is strongly increased by the large anisotropy parameter $\Gamma = \xi/\xi_c$ and low carrier density

Hard lessons of 30 years of R&D of cuprates and iron pnictides

- Competing charge/spin/… orders + unconventional pairing + layered structure + low carrier density may provide higher T_c but is a bad combination for applications

- **Higher T_c and non s-wave pairing** → small Cooper pairs $\xi \sim \hbar v_F/2\pi k_B T_c$ → sensitivity to benign (in LTS) materials defects

- **Competing orders** → precipitation of competing AF phase on grain boundaries → current blocking in polycrystals

- **Crystalline anisotropy and low carrier density**

→ Strong enhancement of superconducting and vortex fluctuations → significant decrease of the T-H space where pinning of vortices can provide supercurrents

→ Low irreversibility field H^* and strong thermally-activated flux creep

→ Weaker charge screening aggravates current-blocking grain boundaries

Applications at 77K and higher T require addressing many conflicting physics and materials science problems which can be formulated even if we do not know microscopic mechanisms of T_c

Thermal fluctuations of vortices

- Dispersive line tension of a vortex

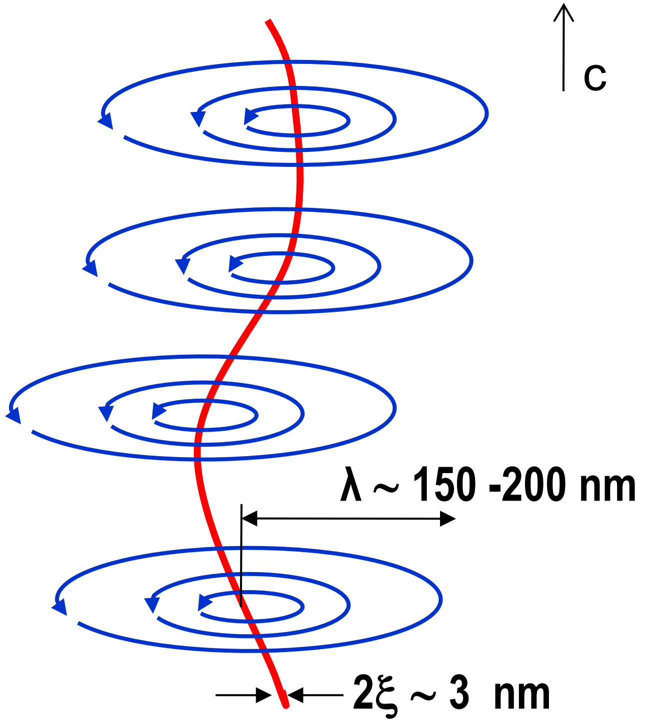
$$\varepsilon_l = \frac{\varepsilon_0}{\Gamma^2}\ln\frac{1}{k\xi_c}, \qquad \varepsilon_0 = \left(\frac{\phi_0}{4\pi\lambda}\right)^2 = \frac{\pi\hbar^2 n_s}{4m}$$

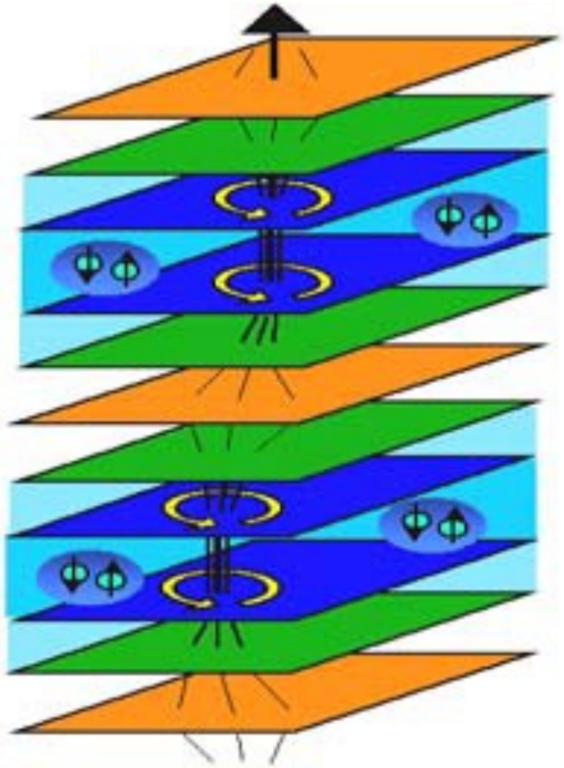
Brandt, Rep. Prog. Phys. 58, 1465 (1995); Blatter et al, RMP 66, 1125 (1994)

- Electron mass anisotropy, **$\Gamma^2 = m_c/m_{ab}$** >> 1 strongly reduces bending rigidity of the vortex:

$\varepsilon_\ell \sim 10^4$ K/nm for LTS → **rigid rods**

$\varepsilon_\ell \sim 30$ K/nm (YBCO @ 0K)
$\varepsilon_\ell \sim 5$ K/nm (YBCO @ 77K) → **soft filaments**





Mostly limited by the superfluid density $n_s(T) = (1 - T^2/T_c^2)n$, low carrier density n and large mass anisotropy Γ^2 = 30-50 in YBCO and $\Gamma^2 = 10^3$ -10^5 in BSCCO.

Melting and thermal depinning of solid vortex structure

- $J_c = 0$ in the vortex liquid phase $B > B_m$ where $B_m \approx$ the irreversibility field $B^*(T)$

- 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; Blatter et al, Brandt et al; …)**

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

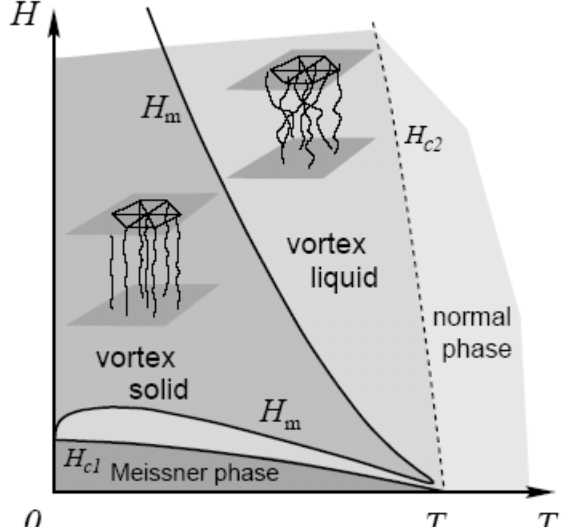
$$H_m(T) = \frac{\pi^3\phi_0 c_L^2}{4k_B^2}\left(\frac{\hbar^2 n_s}{m\Gamma}\right)^2\left[\frac{1}{T}-\frac{1}{T_c}\right]^2$$

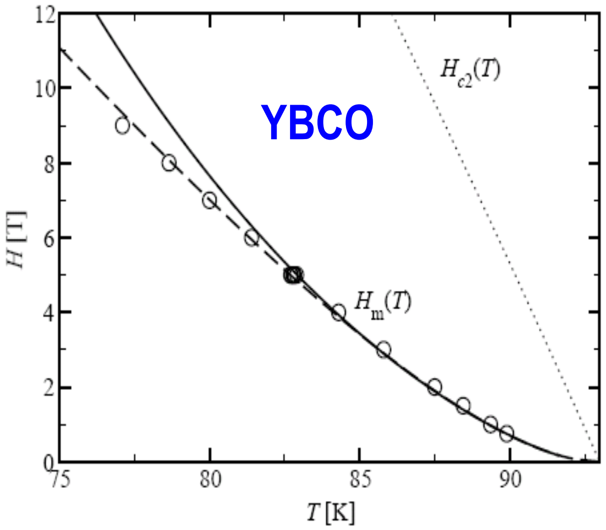
Independent of H_{c2}

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

The melting field $H_m(T)$ is determined by the ratio **$g = (n_s/m\Gamma)^2$** insensitive to pairing mechanisms

Blatter et al, RMP 66, 1125 (1994)

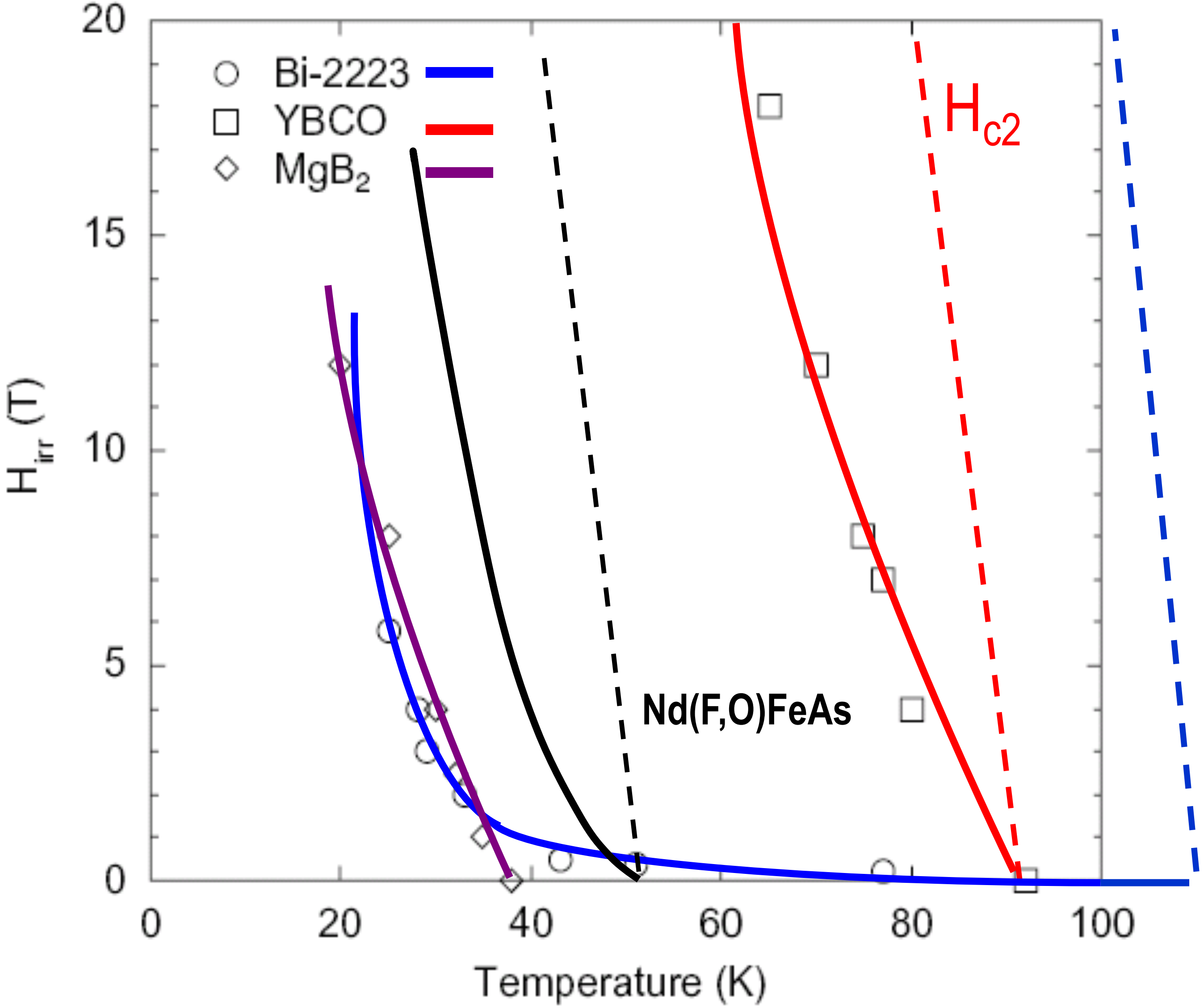




Calorimetric measurements of $H_m(T)$, Schilling et al PRL, 78, 4833 (1997); Nature, 382, 791 (1996)

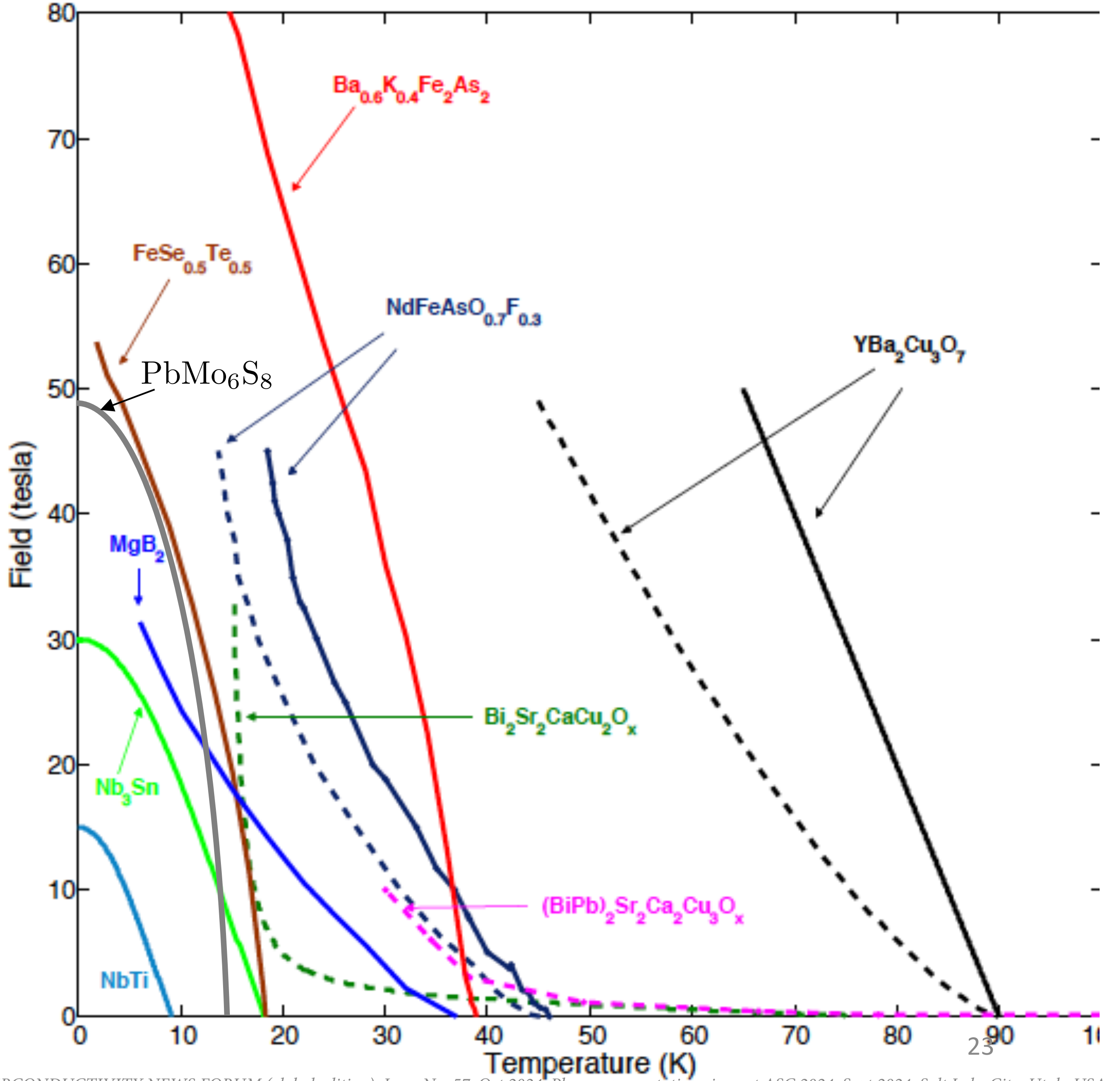
Strong suppression of H* by crystal anisotropy

- Vortex fluctuations amplified by anisotropy cancel the benefits of higher T_c and H_{c2} ин Bi-2223
- At 77 K YBCO (T_c = 92K) is much better than Bi-2223 (T_c = 108K)
- MgB_2 (T_c = 40K) or FBS (T_c < 55K) can be as good as Bi-2223 at 20K < T < 35K, and B < 15T



H-T diagrams of high-field superconductors

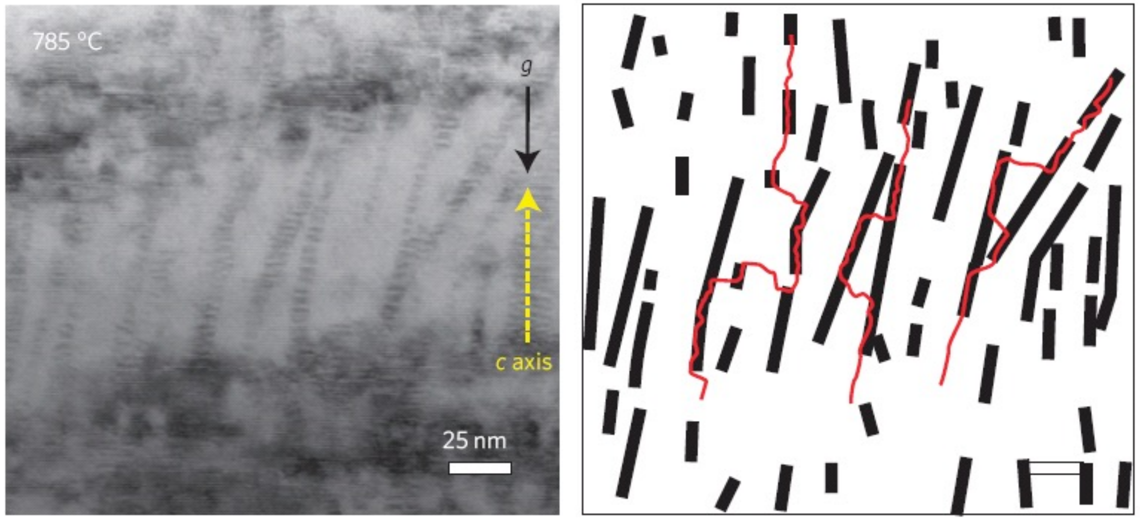
- Only YBCO can be used in magnets at 77 K
- Many choices at 4.2K: $MgB_{2,}$ $PbMo_6S_8$ and $FeSe_{05}Te_{05}$, Bi-2212 can outperform Nb_3Sn
- At 20-35 K, $Ba_{06}K_{04}Fe_2As_2$ has the second highest H_{c2} and H^* after YBCO
- For FBS, the difference between $H_{c2}(T)$ and $H^*(T)$ is not as big as for cuprates
- Low $H^*(T)$ above 77K can be mitigated by lower anisotropy or higher carrier density. Example: Pb doped Bi-2223.

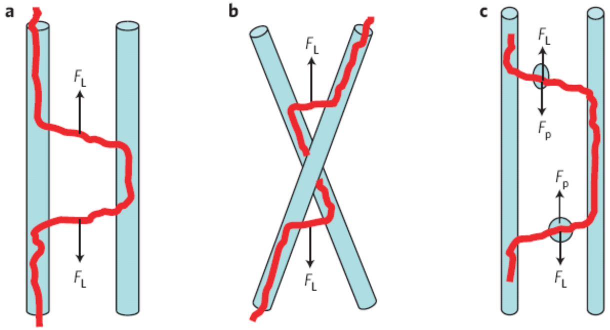


Can J_c and H* be improved if we pin every 5-10 nm of the vortex line?

McManus-Driscoll, Nature Materials 3, 439 (2004) (BZO); Harrington et al, SUST 22, 022001 (2009); Haugan et at, Nature 430, 867 (2004) Yamada et al, APL 87, 132502 (2005); Matsumoto et al, JJAP, 44, L246 (2005).; Gutierrez et al, Nature Materials, 6 367 (2007); Obradors et al, SUST 19, S1 (2006); Solovyev et al, SUST, 20, L20 (2007). Rupich et al, MRS Bull., 29, 572 (2004) Obradors and Puig, SUST 22, 044003 (2014)

Combination of nanoparticles and columnar pins

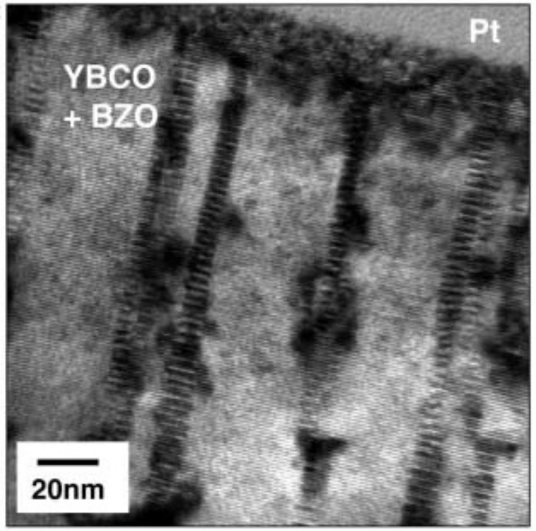




Maiorov et al,
Nature Materials 8, 398 (2009)

Self assembled BZO nanoparticles

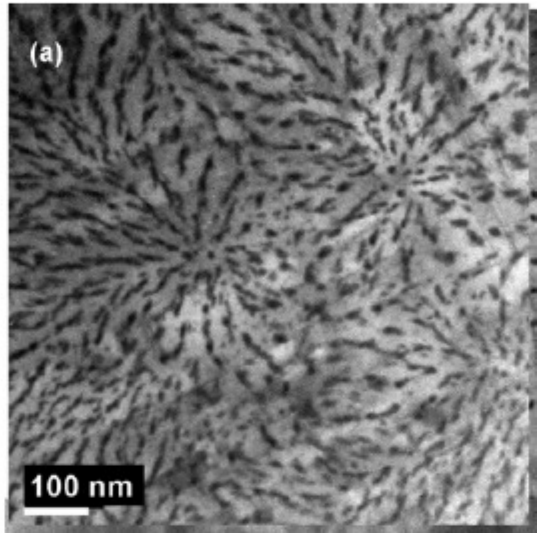
Kang et al, Science 311, 19111 (2006)

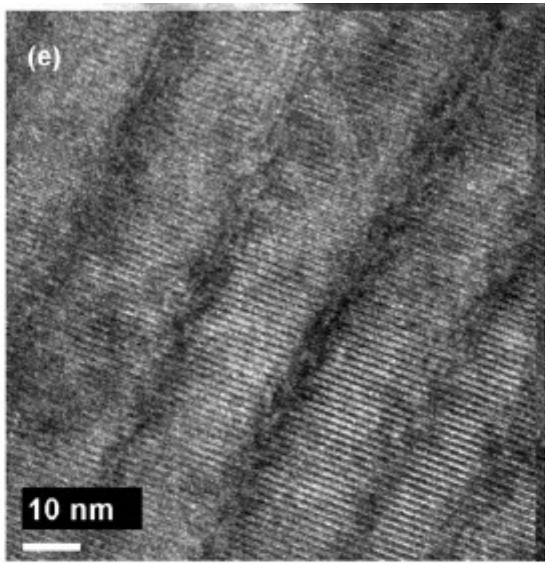


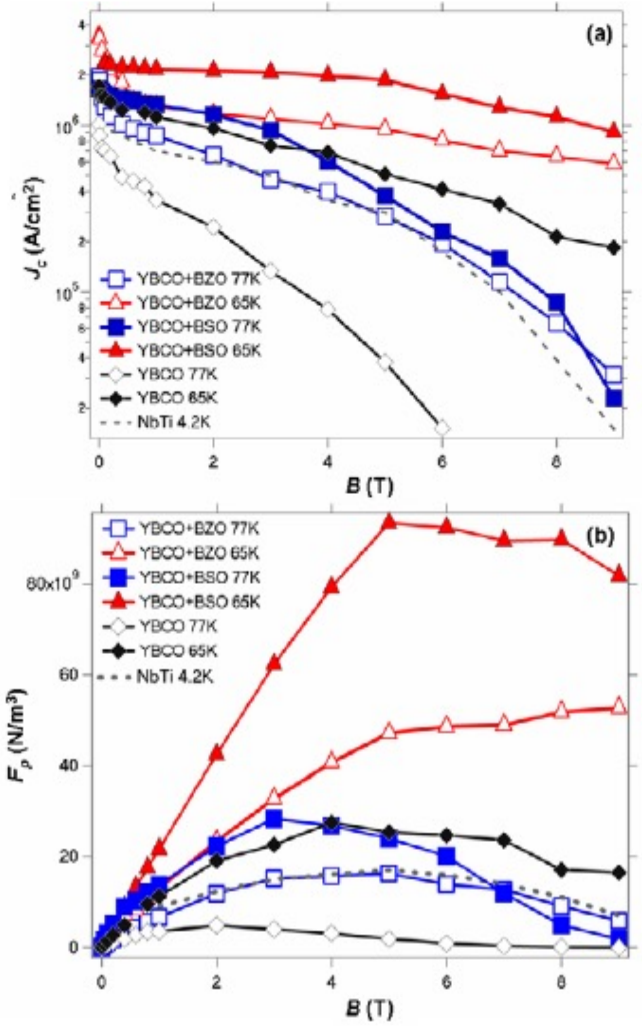
- Splayed columnar defects reduce flux creep at high fields
- Weaker field dependence (reduced α in $J_c \propto H^{-\alpha}$)

"Designer" APC nanoparticle structures to increase J_c

Self-assembled chains of BZO nanoparticles

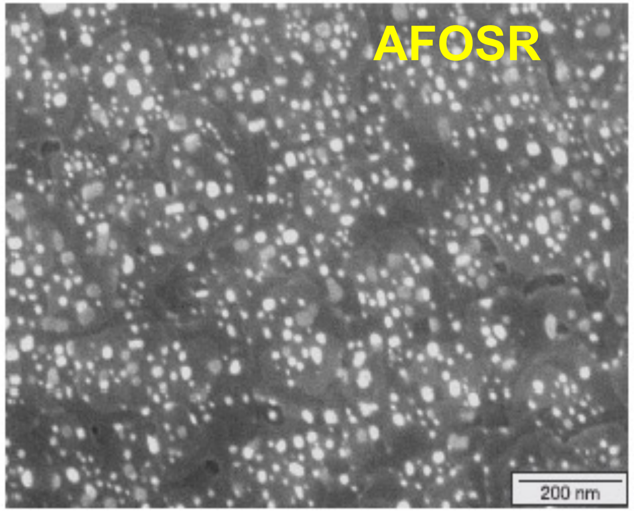


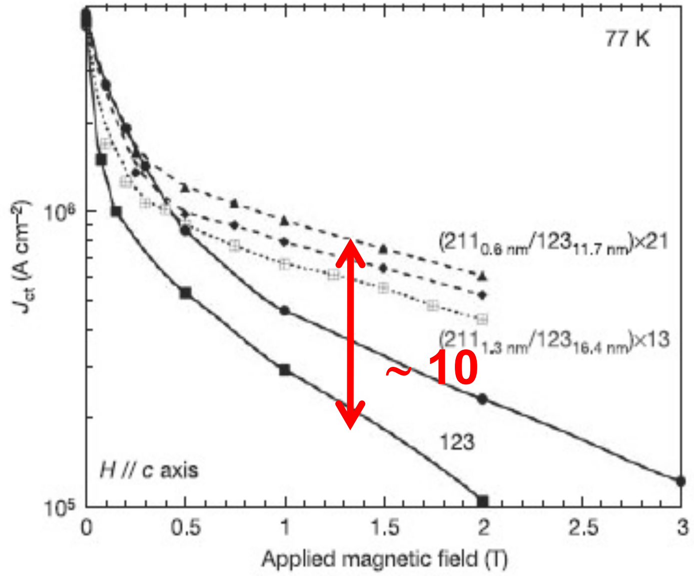




Mele, et al SUST 21, 032002 (2008)

8 nm YBa_2CuO_5 nanoparticles



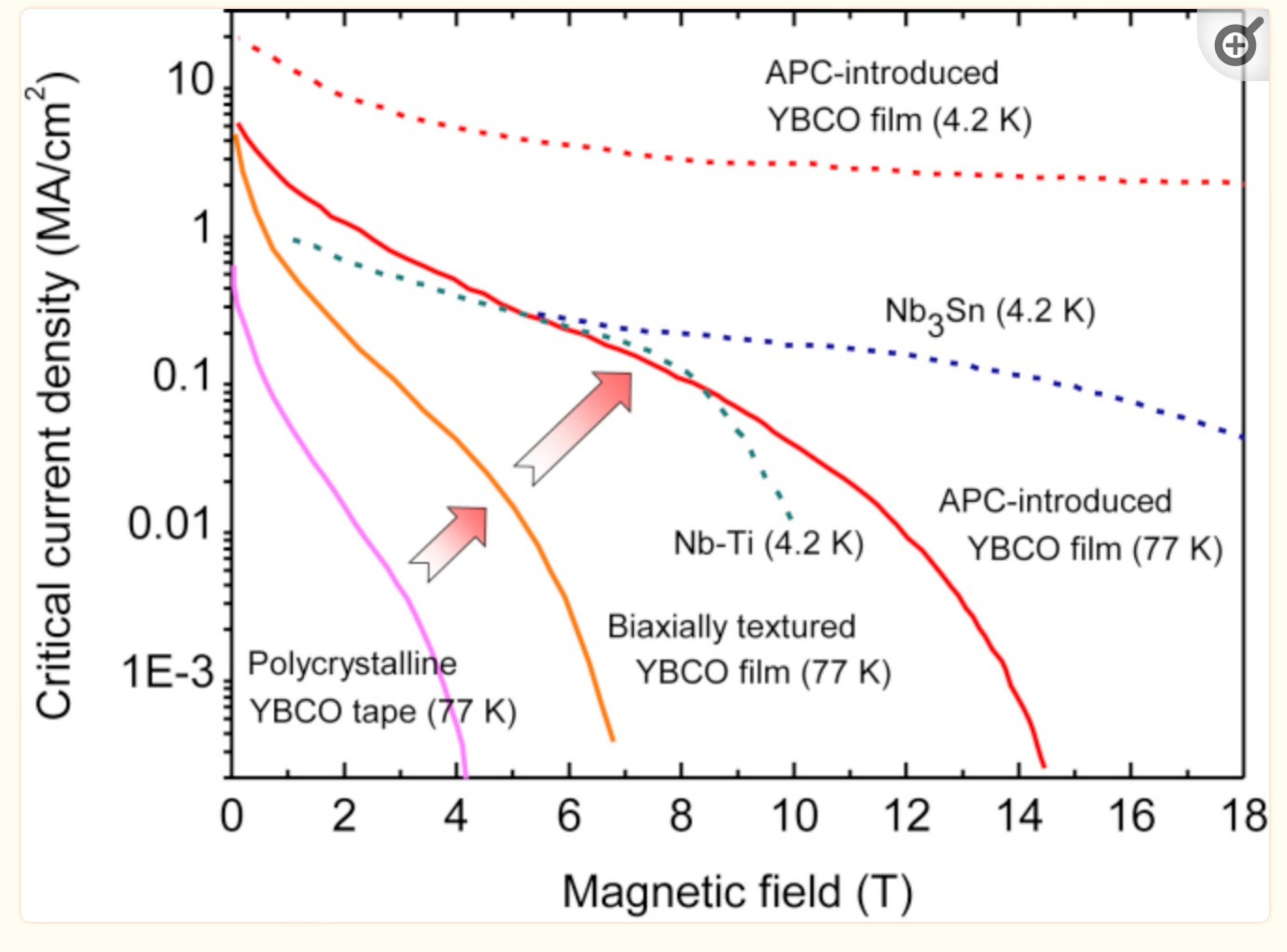


Haugan, et al. Nature 430, 867 (2004)

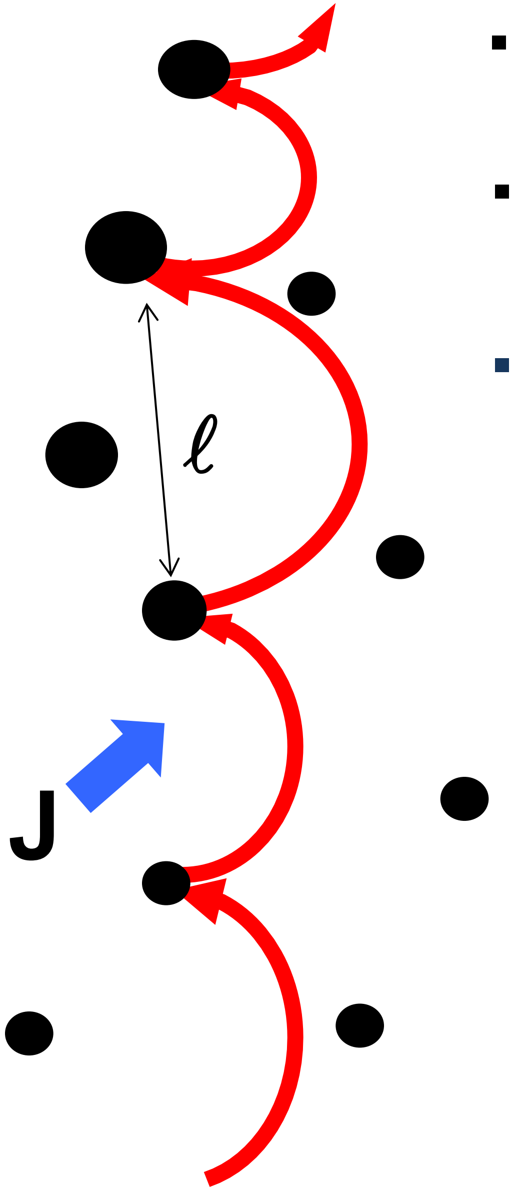
Improvement of Jc at high fields by designer pinning in YBCO

- J_c(77K,B) is increased by several orders of magnitude at 5<B<14 T
- Irreversibility field at 77 K only doubles, from 7 to 14.5 T
- Why does Nb_3Sn at 4.2K outperform YBCO at 77 K and B > 8T, although they have the same B_{c2} and pinning in Nb_3Sn seems weaker than in YBCO?
- Why cannot pinning push B*(77K) all the way to B_{c2}(77K) = 30 T?

Obradors and Puig, SUST 22, 044003 (2014)



Pinning limit by dielectric 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 $L_{\perp} \sim \ell\Gamma^{-1/2}$, $\varepsilon/R = \varphi_0 J/c$

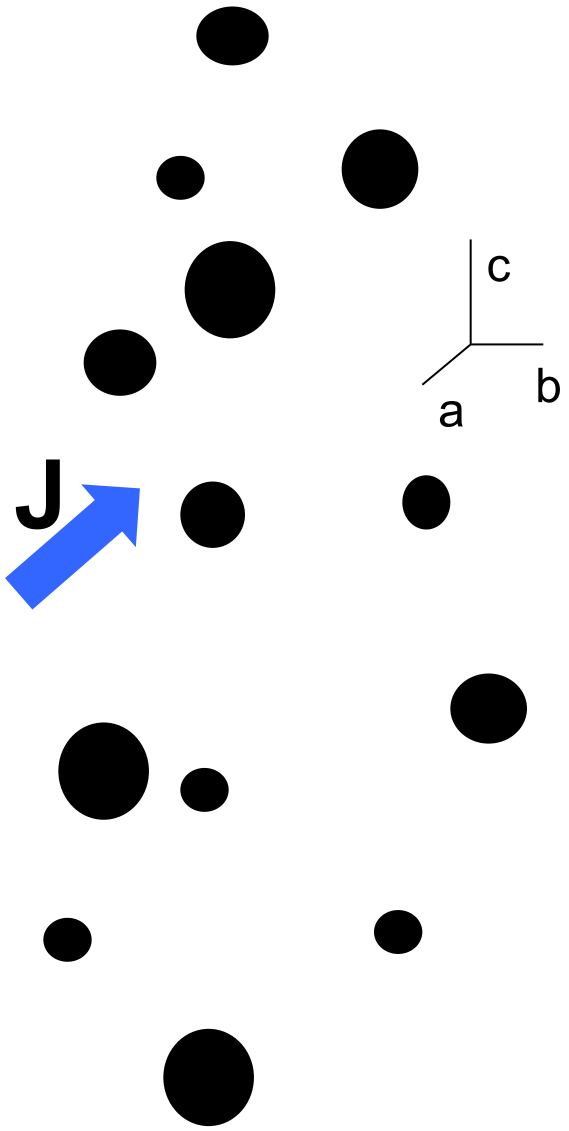
- Depinning due to reconnection of parallel vortex segments: the smaller the pin spacing the higher J_c:

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

- J_c(77K) ~ 9 MA/cm^2 in YBCO is obtained at average pin spacing $\ell \sim 30$ nm

- Too many pins cause T_c suppression and current blocking

Reduction of current-carrying cross section by pins



- 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 current-carrying cross section $A_{eff}(x)$ vanishes at the percolation threshold x_c
- **$x_c = 0.5$ in 2D**
- **$x_c \approx 2/3$ in isotropic 3D**

Optimum pin density: pinning vs current blocking

- J_c due to random insulating precipitates of radius r_0

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

Pinning

Cross-section

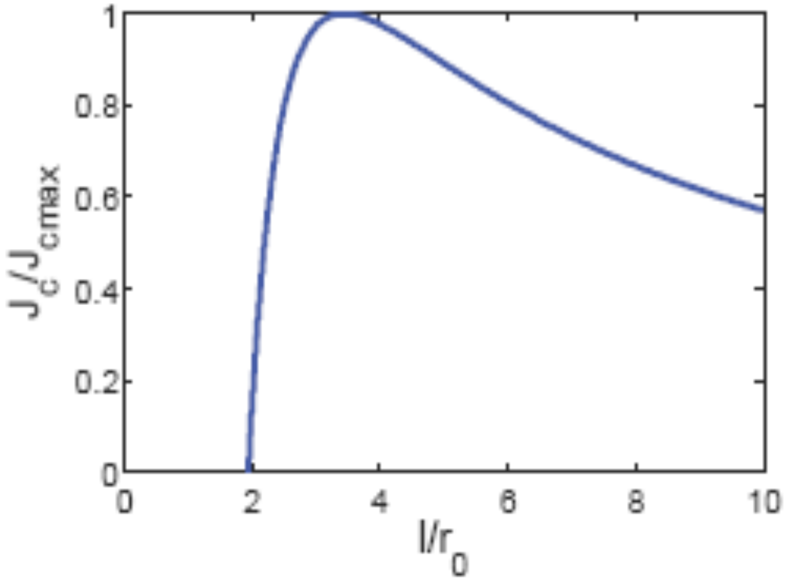
- Optimum pin spacing and volume fraction:

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

- Optimum critical current density:

$$\frac{J_{max}}{J_d} \approx \frac{2\xi_a}{l_m\sqrt{\Gamma}} \ln\frac{l_m}{\xi_c}$$

Gurevich, SUST 20, S128 (2007); Annu. Rev. Cond. Mat. Phys. 5, 35 (2014)
Kwok, et al. Prog. Phys. 79, 116501 (2016).

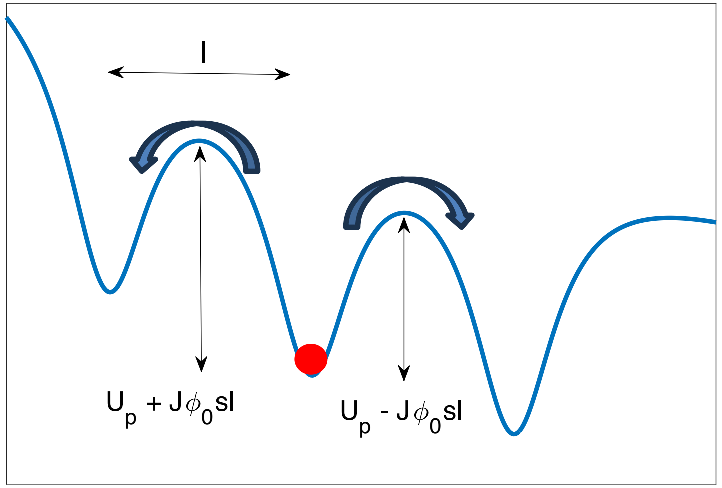


For $\Gamma = 7$ in YBCO, $J_{cmax} \approx 0.5J_d$ for $r_0 = \xi$, and

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

Upper limit for small pins, no fluctuations and no T_c suppression by pins.

Why cannot pinning increase B* to B_{c2} in cuprates?

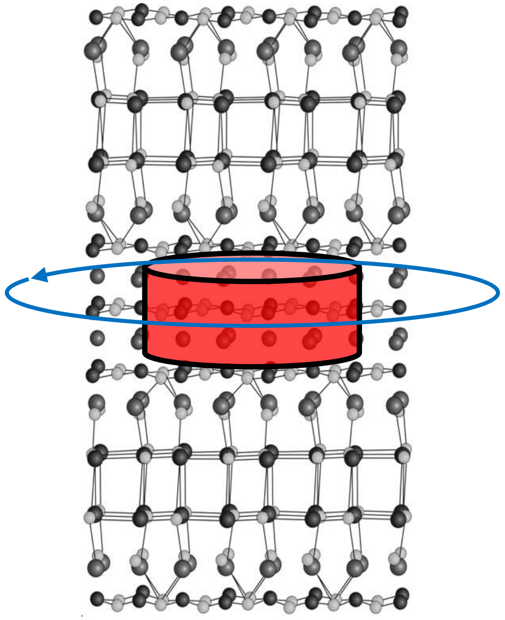


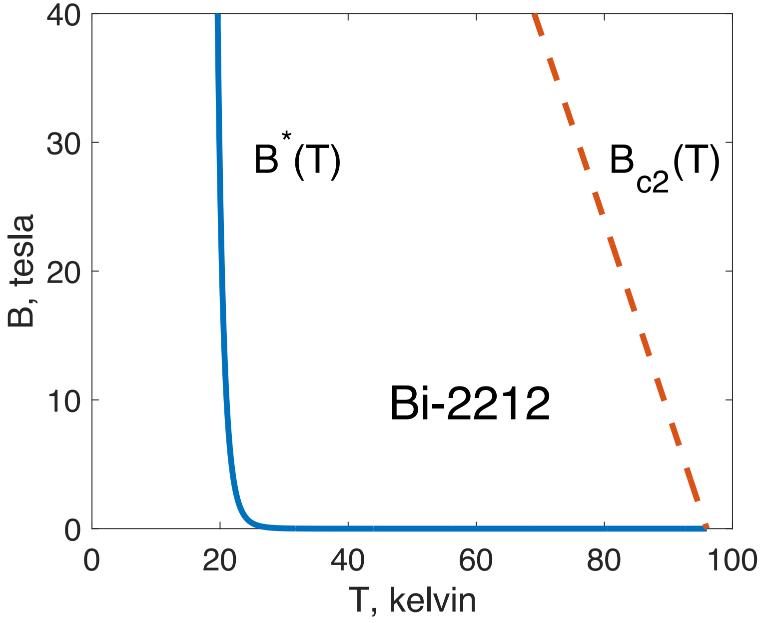
Shorter soft vortex segments hop easier between pins. increasing pin density can accelerate flux creep

In BSCCO the maximum pinning energy of a short (s =1.5 nm) pancake vortex, $U_0 = \phi_0^2 s/8\pi\mu_0\lambda_0^2 \simeq 350\,K$. E-J characteristic caused by uncorrelated hopping of vortex pancakes at B<< B_{c2}:

$$E = J_1\rho_n \frac{B}{B_{c2}} \sinh(\frac{J}{J_1})e^{-U(T)/k_BT}$$

where $J_1 = k_BT/\phi_0 s\ell$. Irreversibility field at which E(J) turns ohmic at $E_c = 10^{-6}$ V/cm. Case study: Bi-2212 at l = 30 nm.





In YBCO $\varepsilon_l \approx 5$ K/nm @ 77K, thermal depinning occurs at $T > T^* \sim \epsilon_l \ell/k_B \sim 100\,K$ at $\ell \approx 20$ nm.
ε_l (77) ≈ 5 K/nm seems sufficient for magnet applications at 77K

Thermodynamic enhancement of in field $J_c(B)$ and B*

To find dopants which can increase the carrier density and reduce electronic anisotropy (increase coupling of ab planes) without suppressing Tc too much

Bi-Pb-substitution in Bi-2212 and 2223

Reduces anisotropy of B_{c2} and increases B* at high T but not enough to enable magnet applications at 77K

$(Cu,C)Ba_2Ca_3Cu_4O_{11+x}$, T_c= 116 K, B*(77)= 12-14 T

Zhang et al, Sci. Adv. 4, 0192 (2018).

Y → RE (Ho, Sm, Nd, Eu, Co, Tb, Ce, Pr, La, Dy…) atomic substitutions in YBCO

Improves high-field $J_c(B)$ and increases B*(77K) up to 12-13 T, **Jha and Matsumoto, Front. Phys. 7, 82 (2019)**

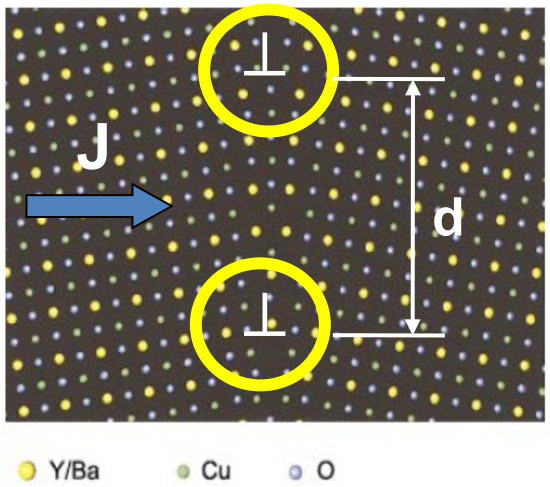
Nanoprecipitates or reduced anisotropy?

$SmFeAsO_{1-x}H_x$, T_c = 45 K
H substitution + proton irradiation
Miura et al, Nature Mater. (2024)

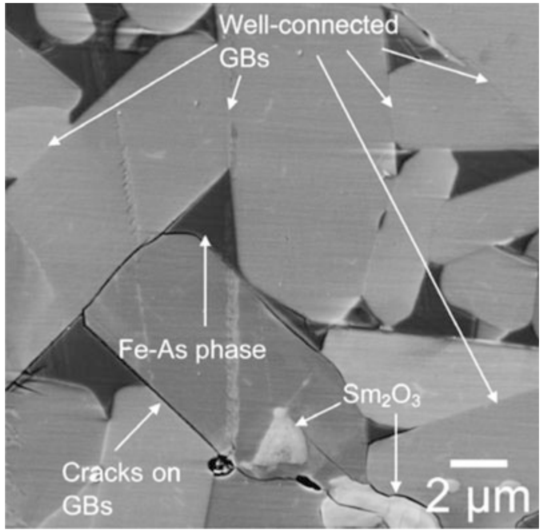
- Quadruples the depairing current density $J_d \rightarrow$ 415 MA/cm^2 and J_c(4.2K, 0T) → 140 MA/cm^2
- Quadruples the carrier density and reduces λ down to 120 nm
- Decreases the anisotropy to $\Gamma \approx 4$
- Vortex line tension $\epsilon_l(0) \simeq 80$ K/nm, better than YBCO

The grain boundary problem

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



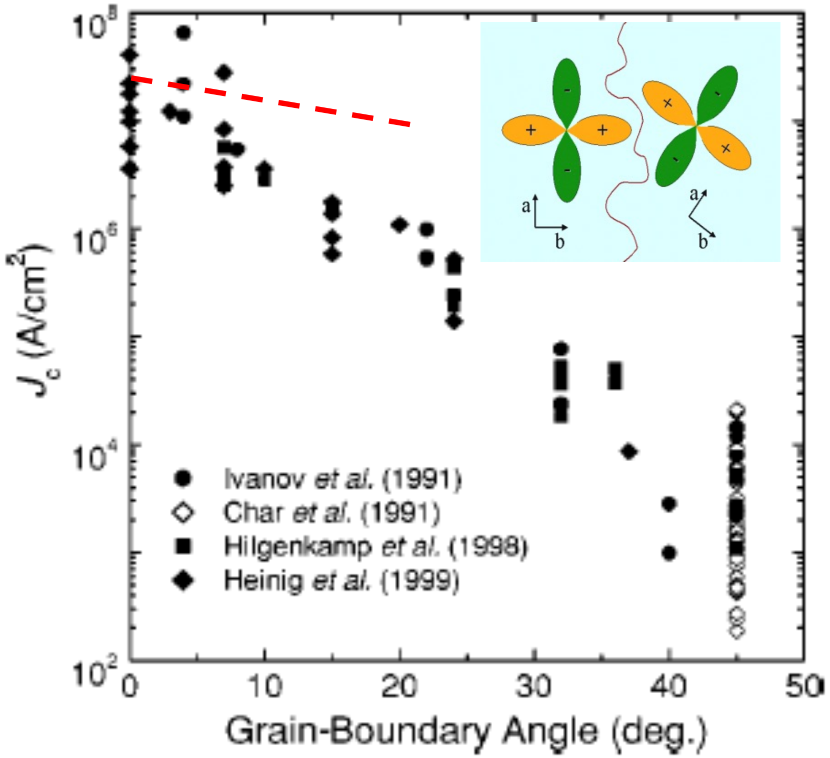
$$d = b/2\sin(\theta/2)$$



Partial grain connectivity
In Sm-1111

Kametani et al, SUST 21, 015010 (2009)

Dimos, Chaudhari and Mannhart, PRB 41, 4038 (1990)
Hilgenkamp and Mannhart, APL 73, 265 (1998); RMP 74, 485 (2002)



2 orders of magnitude drop in Jc with the misorientation angle

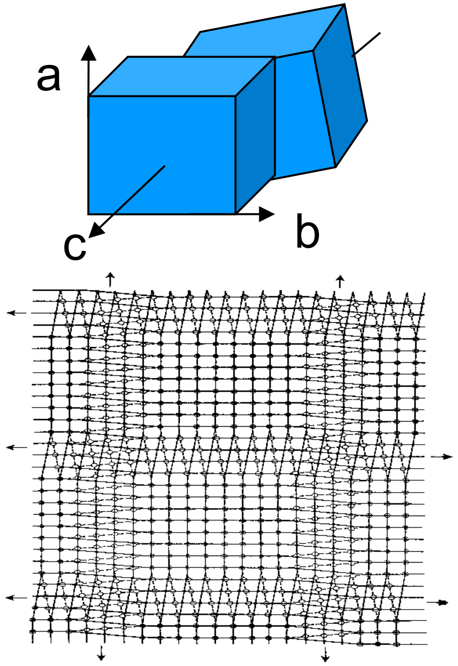
Similar in FBS

- Precipitation of AF phase at grain boundaries
- Charge and strain coupling of dislocation cores
- d-wave pairing symmetry

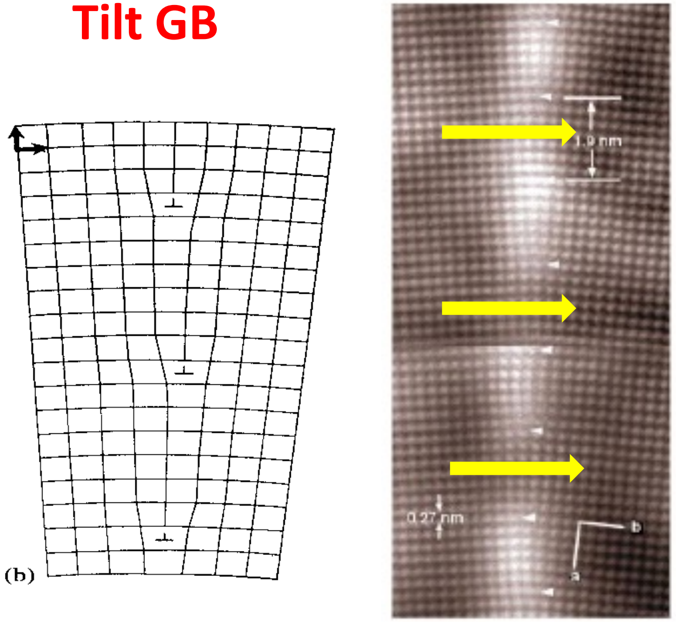
Gurevich and Pashitskii, PRB 57, 13875 (1998); Grazer et al, Nat. Phys. 6, 609 (2010)

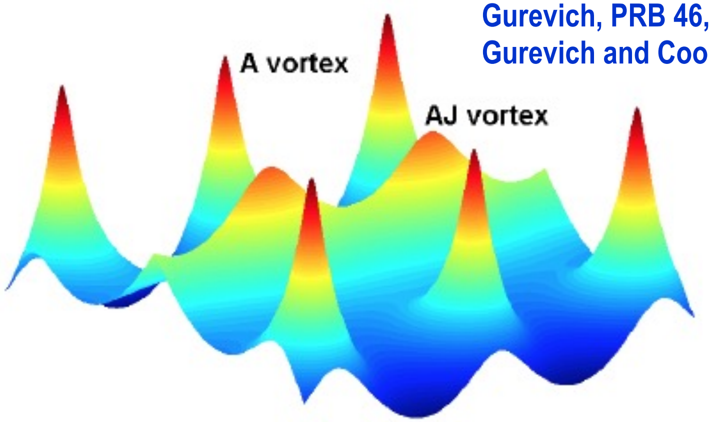
Magnetic granularity in HTS polycrystals

Twist GB



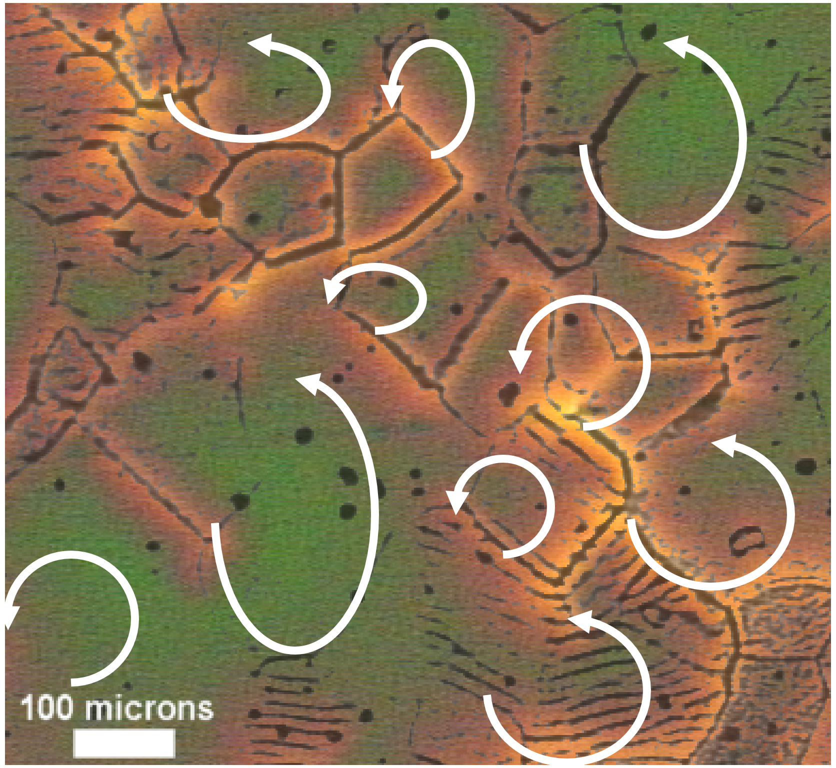
Tilt GB





Gurevich, PRB 46, R3187 (1992),
Gurevich and Cooley, PRB 50, 13563 (1994)

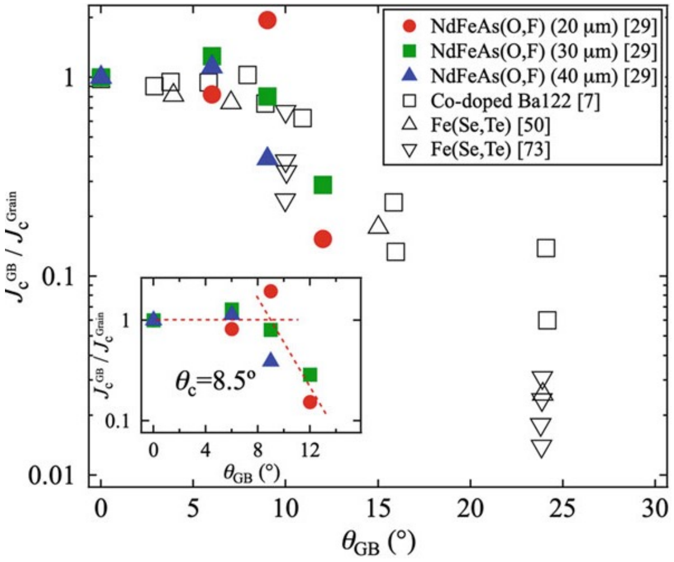
MO of YBCO by Polyanskii and Feldman



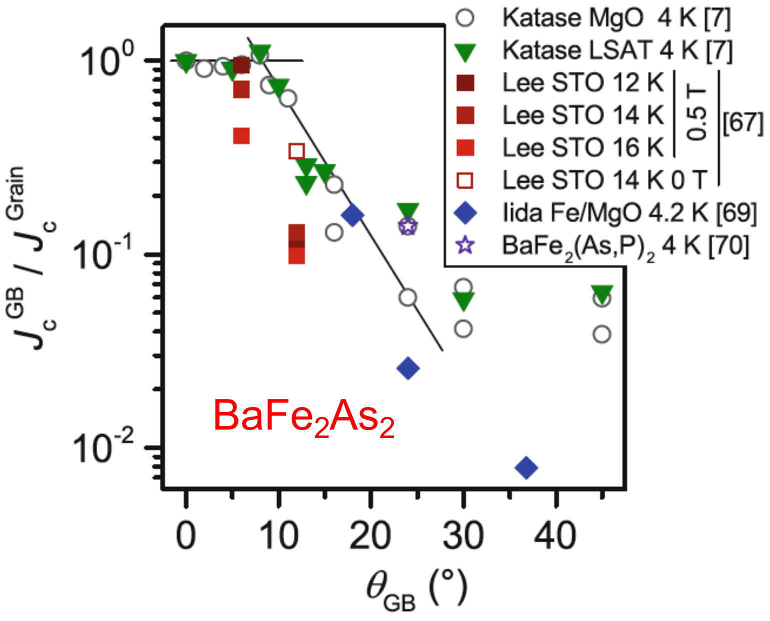
- Only small currents can pass through GBs despite strong pinning of vortices caged in the grains
- Fragmentation of current flow into decoupled current loops in the grains, low transport critical current

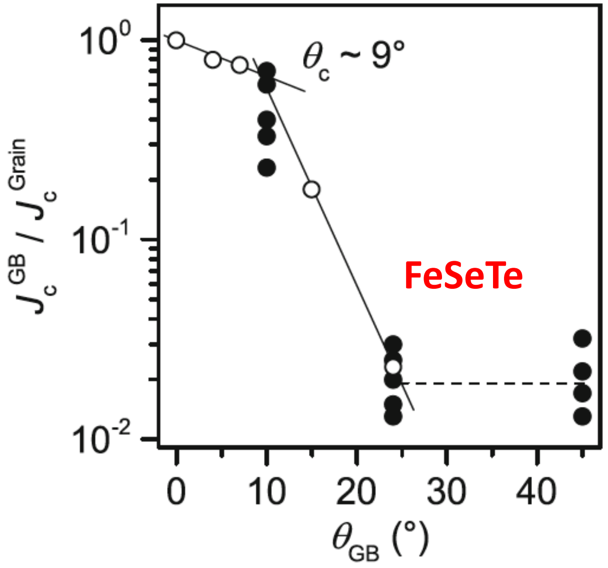
GB weak links in FBS

- Degradation of J_{gb} (θ) with the misorientation by 1-2 orders of magnitude
- larger critical angle in FBS might result from weaker pinning in the grains than in YBCO
- GBs in K-doped 122 polycrystals appear better connected than others FBS



Iida, Hanisch and Yamamoto, SUST, 33, 043001 (2020)





Why are GBs weak links in cuprates and FBS so alike?

- Cannot be the pairing symmetry (d-wave in cuprates and multiband s-wave in FBS)
- Pairing mechanisms are different
- Phase diagram with competing AF states are similar
- Both are poor metals

Si et al APL 106, 32602 (2015);
Sarnelli et al. APL 104, 162601 (2014)

Why are GBs weak links in cupates and pnictides?

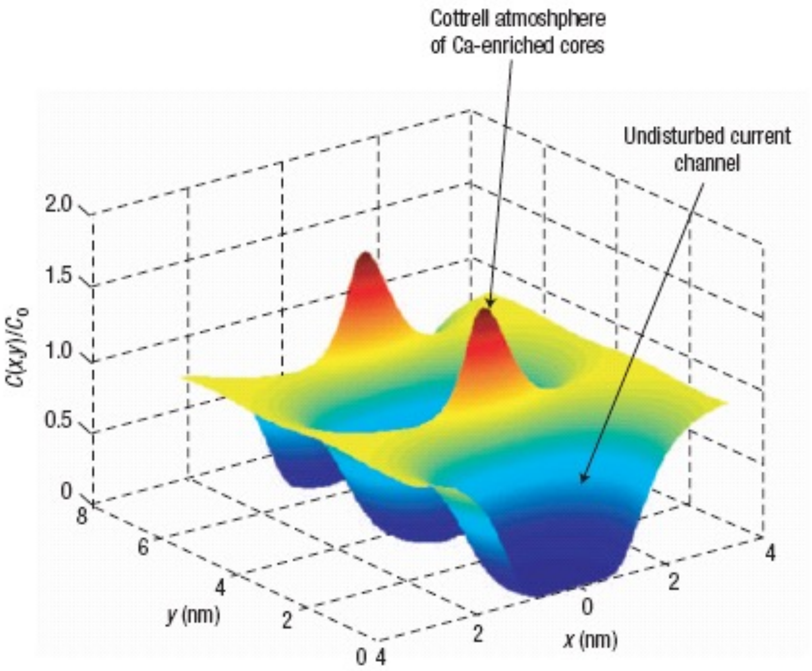
- Competing AF states, sensitivity of T_c to small shifts of chemical potential due to local non-stoichiometry, strains or GB charges

- Small E_F = 300-500 meV in cuprates and E_F = 10-200 meV in FBS.
  If E_F = 30 meV = 330K electron gas becomes classical at room temperatures.

- Poor screening, large TF screening length, $l_{TF} \approx \xi \approx$ 1-2 nm.
  GB charges revealed by electron holography Schofield, et al. PRL 92, 195502 (2004).

Suppression of SC gap on GB (Gurevich and Pashitskii, PRB Durrell et al, Rep. Prog. Phys. 74, 12451 (2011)

$$\frac{\Delta_0}{\Delta} = \frac{1}{\sqrt{1+\Gamma^2}+\Gamma}, \qquad \Gamma = \frac{2^{3/2}\pi q e l_{TF}^2}{sb\xi_0 T_c\sqrt{\tau}}\left[\frac{\partial T_c}{\partial \mu}\right]\sin\frac{\theta}{2}$$



Clouds of impurities in strain and electric fields around GB

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

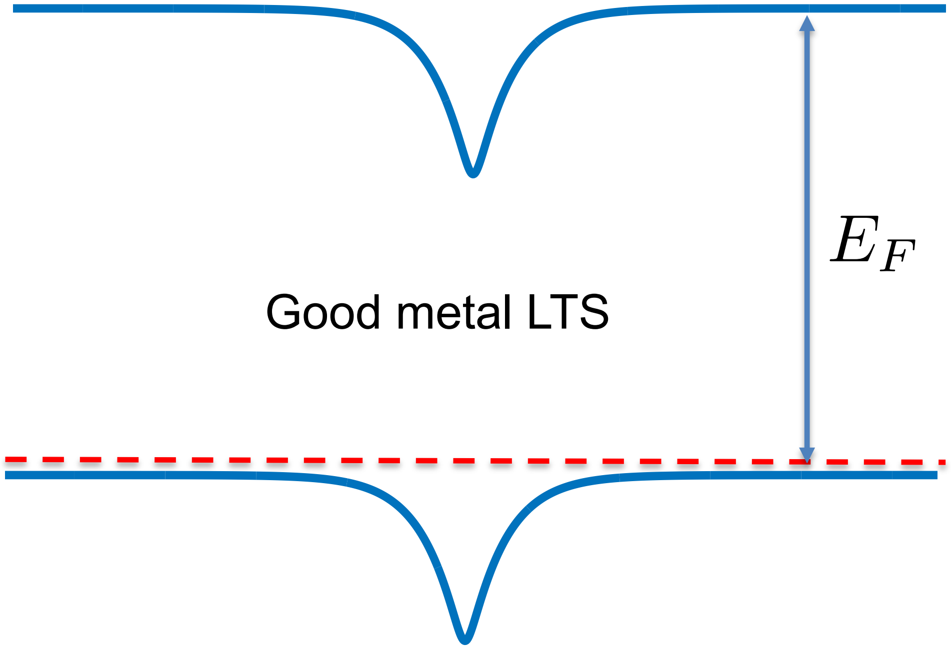
$l_{TF} \approx \xi_0 \approx$ 1-2 nm, and $dT_c/d\mu \approx$ 0.4-0.8 K/meV result in $\Gamma > 1$ at $\theta > 10^o$ and 77K ($\tau = 1 - T/T_c$)

Dislocation charge q = e (per ab plane) shifts μ by ≈ 250 meV. Strong band bending effects.

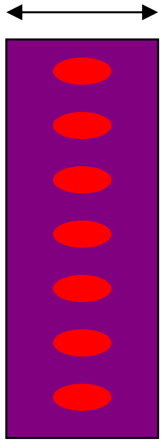
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

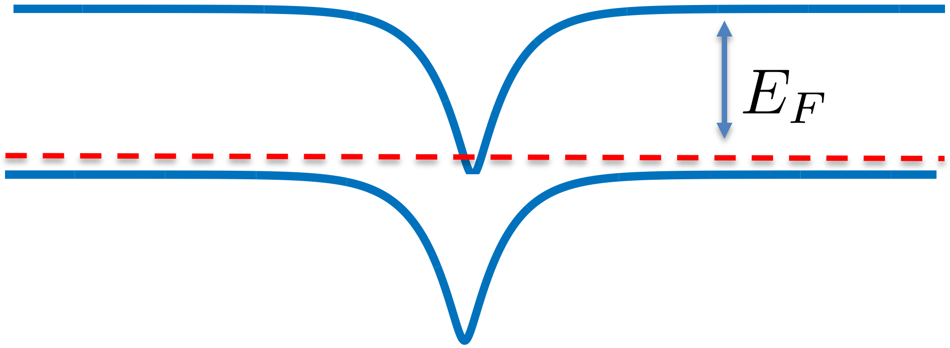
Low carrier density in cuprates and pnictides aggravates current-blockage by grain boundaries

Constant electrochemical potential in equilibrium: $\mu_e = E_F[n(x)] + e\varphi(x) = const.$



Good metal LTS





Band bending in poor metal HTS

Large E_F = 3-10 eV in good metals (Al, Nb, …)
Shift of potential by 0.5-1 eV on GB weakly affects SC

Small E_F in cuprates and FBS:
E_F = 300-500 meV in cuprates
E_F = 4-200 meV in FBS, especially FeSe

Shift by 100-500 mEV on GB can suppress SC, making GBs weak links

Improving grain boundaries

- Add more holes to GBs by local overdoping
- Reduce local strains at GBs
- Doping and stress can reduce T_c and B^*

YBCO

Ca overdoping: improves J_{gb} but reduces T_c and B^*.
Up to 8-fold increase of J_{gb} at 4K, 0T for a 24° tilt GB.
Replace 30% of Y^{3+} by Ca^{2+}

Schmehl et al., Europhys. Lett. 77, 110 (1999);
Hammerl et al., Nature 407, 162 (2000)

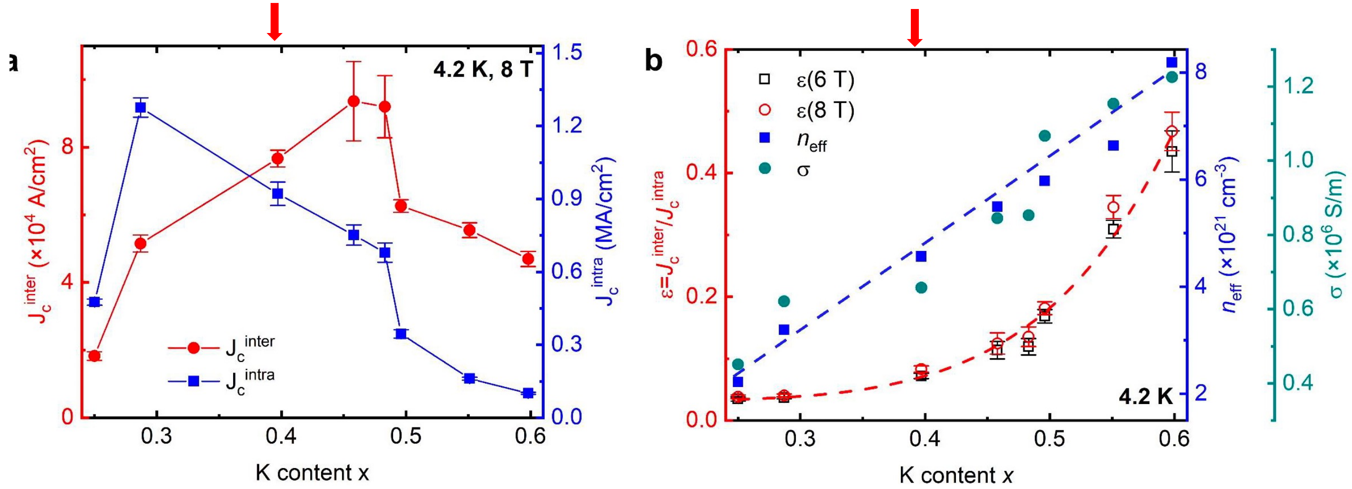
30-40% increase of J_{gb} for a 5° GB at 44K at 0-3 T
Daniels, Gurevich, Larbalestier, APL 77, 3251 (2000)

10% Nd^{3*} substitution for Y^{3+}
Strain management, critical angle increases to 6°, no T_c degradation, modest increase of J_c of a 9° GB
Kim and Larbalestier, SUST 34, 025008 (2021)

$Ba_{1-x}K_xFe_2As_2$ tapes

Improve intergrain connectivity by K overdoping at the expense of reduced T_c, (max T_c at x=0.497)

Cheng et al, Materials Today Phys. 28, 100848 (2022)



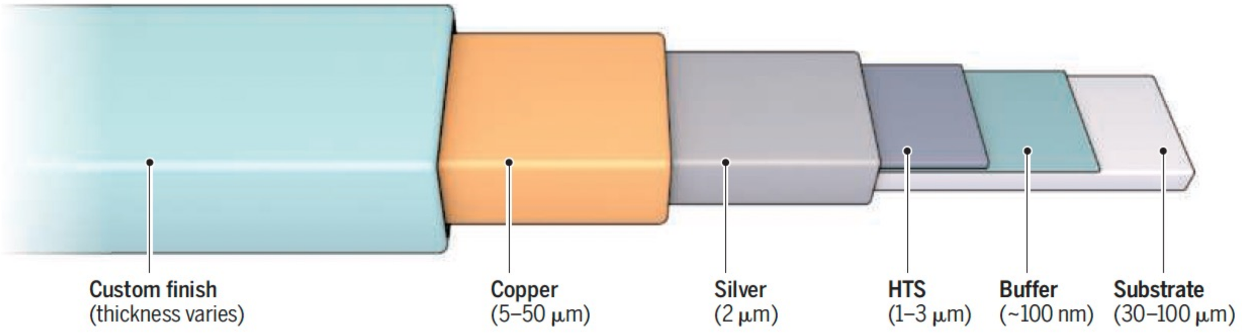
Conductor tape technology

On recent progress, see
Obradors et al., SUST 37, 053001 (2024)

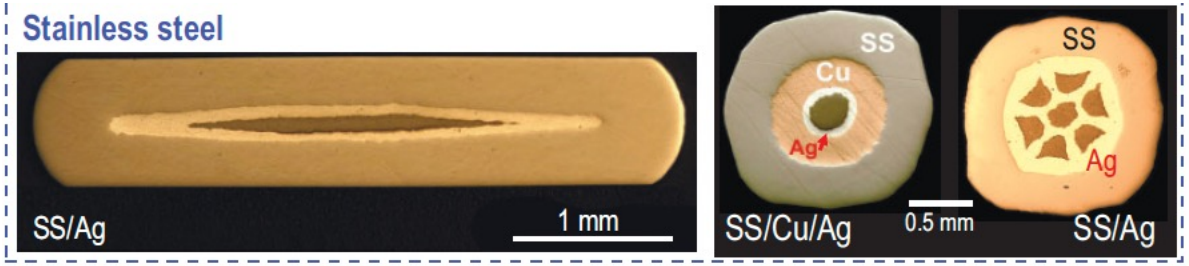
On progress in FBS films, see **Iida et al, SUST 36, 063001 (2023)**

BaK122 tapes and wires

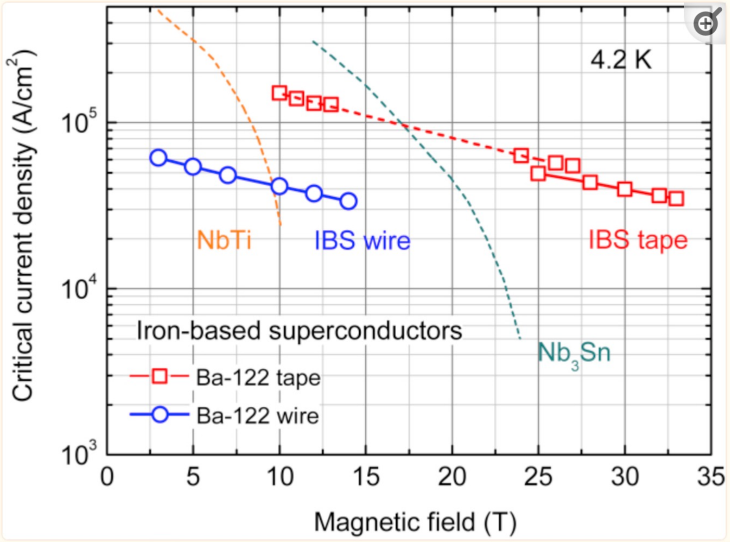
YBCO coated conductor



Molodyk and Larbalestier, Science, 380, 1220 (2023)



Dong, Hu and Ma, Nat. Sci. Rev. 11, 122 (2024)



- Grow YBCO on biaxially-textured substrates to eliminate high-angle GBs
- High price of the weak-linked grain boundaries
- Complex, expensive, only a tiny fraction carries current, high ac losses
- J_c of YBCO layer must be pushed to its limit
- Industry produces km long second generation YBCO coated conductors

Making old/new superconductors useful

For applications at T = 4.2 K, the conventional materials optimization works for all SCs: NbTi, A15, $PbMo_6S_8$, MgB_2, YBCO, Bi-2212, Bi-2223, …

- High T_c produce high H_{c2} which can be further increased by impurities. Large field space $0 < B < B^* \approx B_{c2} \lesssim 200\,T$
- Designer APC nanostructures to produce high critical current densities
- Ameliorate current-blocking GBs (Nb_3Sn, $PbMo_6S_8$, FBS, cuprates)

Intermediate temperatures 5 < T < 60 K

For not very anisotropic SCs with Tc < 55 K, (MgB_2, FBS,…) B^* is not much lower B_{c2}, and the conventional optimization still works if the GB problem is addressed.

Materials wish list for applications at T = 77K and higher: only YBCO for now.

In searching for new SCs with Tc > 90 K pay attentions to:

1. Carrier density: the higher the better
2. Electronic anisotropy: the smaller the better (less anisotropic than YBCO)
3. Thomas Fermi screening length: the smaller the better

- The higher the operation temperature, the less parameter space gets available to satisfy the constrains on carrier density and anisotropy
- The higher the operation temperature, the less relevant T_c and H_{c2} become, moderate increase of B^* by pinning
- Non-s-wave pairing and competing magnetic order complicate applications

Superconductivity limited by thermal fluctuations

Ginzburg number:

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

- LTS: Gi ~ 10^{-8},
- cuprates: Gi ~ 0.1-10^{-2},
- 122 pnictides and MgB_2: Gi ~ 10^{-4} -10^{-3}
- 1111 pnictides: Gi ~ 10^{-2}
- T_c reduction by fluctuations goes up rapidly with T_c and is increased by anisotropy and low carrier density

$$\Delta T \sim -T_c Gi^{1/2} \propto T_c^3 m^* \Gamma n_s^{-4/3}$$

Low vortex line tension: ε_l = 1-10 K/nm ➔ small energy barriers for vortex hopping between pins $U = l\varepsilon_0/\Gamma \cong 100$ K of soft vortex segments $l \cong$ 10-100 nm ➔ reduction of H^*, no matter how strong pinning is

$$B_m(T) = \frac{\pi^3 \phi_0 c_L^2}{4k_B}\left(\frac{\hbar^2 n}{m^*\Gamma}\right)^2\left(\frac{1}{T}-\frac{1}{T_c}\right)^2$$

$$\epsilon_l \simeq \frac{\pi\hbar^2 n}{4m\Gamma^2}\left(1-\frac{T}{T_c}\right)$$

Independent of T_c at low T

For a putative RTS with T_c = 400 K and B_{c2} = 1000 T and carrier density and anisotropy of YBCO, the irreversibility field may not exceed 15 T at 77K

Applications at 300 K and high fields would require a nearly isotropic RTS with T_c > 350 K and carrier density of LTS

If a RTS with T_c = 400K and B_{c2} = 1000T has been discovered, can its full potential be realized at 300K?

- Tough materials requirements to enable room temperature superconducting magnets even for isotropic RTS.

- Much easier to satisfy these requirements at 77K

- Cheap and environmentally safe liquid nitrogen cooling enables cryostability and ac loss management of composite conductors

- An isotropic superconductor with T_c = 240 K and LTS carrier density can be revolutionary for applications at 77K

- Chasing genuine RTS may not necessarily result in a magnet technology which can be used even at 77K

- Magnetic pressure In a magnet $p = B^2/2\mu_0$: 1T produces 4 atm, 10 T = 400 Atm, 100 T = 40,000 atm. Mass of mechanical support M = CB^2 , big problems with mechanical stability

Challenges and opportunities

Challenges of improving the existing HTS:

1. Reduce strong thermal fluctuations of vortices
2. Increase the irreversibility field
3. Reduce pairbreaking by grain boundaries
4. Multiparameter materials optimization and design optimum pinning nanostructures are required

Quest for new materials

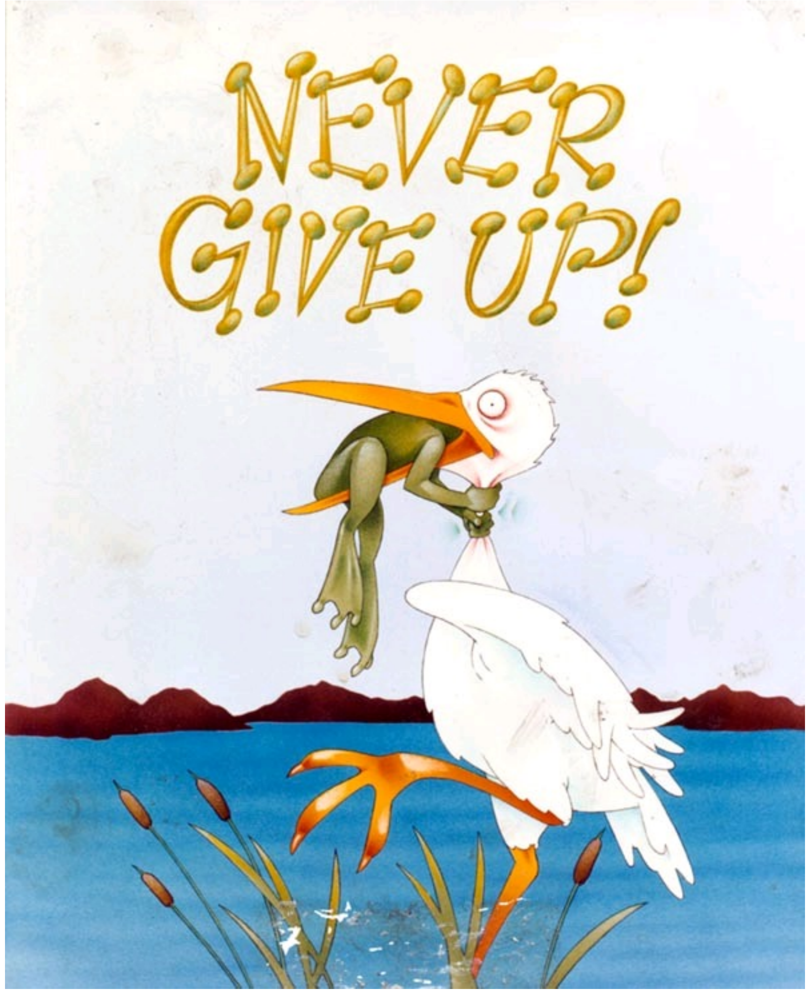
- RTS with T_c = 350K could be useful at 300K if they are:
  - nearly isotropic
  - exhibit no segregation of competing phases on grain boundaries
  - have a higher superfluid density, that is, $\lambda \leq 100$ nm like in Nb_3Sn or MgB_2
  - preferably non-d-wave

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

- Nearly isotropic HTS $150 < T_c < 300$K or cubic superconductors with T_c = 90-150K could revolutionize power/magnet applications at 77K

- The success of MgB_2 and weakly anisotropic pnictides should inspire search for moderately anisotropic "intermediate/high T_c" superconductors

History is full of grim predictions on superconductivity: no high-field, no high-T_c, no applications, no RTS, no …



The pessimist sees difficulty in every opportunity. The optimist sees the opportunity in every difficulty.

Winston Churchill

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