Multilayer coating of superconducting cavities: challenges and opportunities

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TSRF opportunities

- **Best Nb cavities have already reached the breakdown fields H_p close to $H_c \approx 200$ mT of Nb (Jlab, Cornell, KEK).**

- **TFML coating offers a possibility to break the Nb monopoly, increasing H_p beyond 200 mT up to $H_c = 0.5 - 1$T of the coating material**

- **Higher T_c thin film coating may result in a great reduction of the BCS surface resistance,**

$$R_s = \frac{A\omega^2}{T} exp\left[-\frac{1.8T_c}{T}\right] + R_i$$

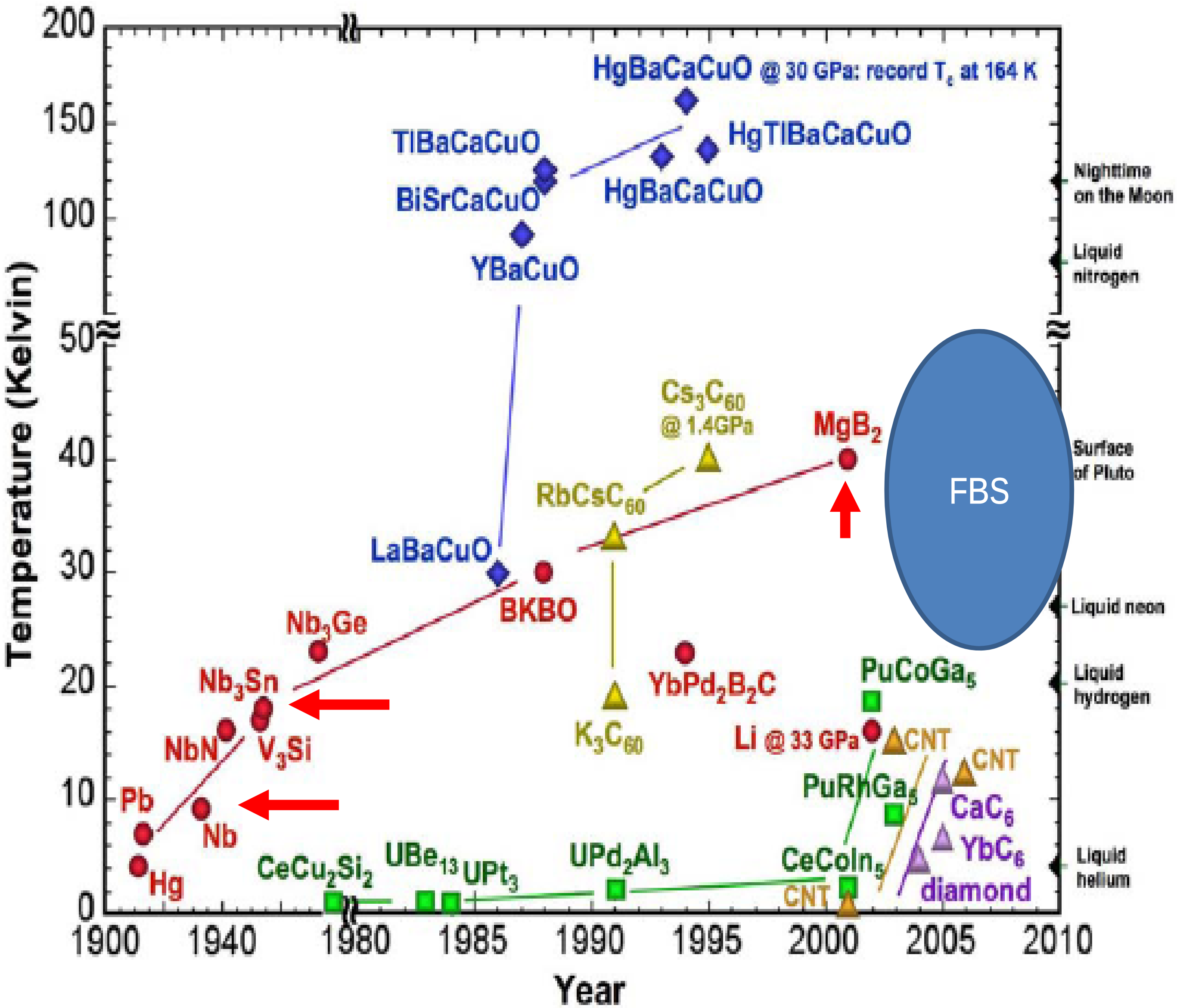
- **TFML with T_c > 18K may offer a possibility to work at 4.2K at the same level of the surface resistance and Q(H) curve.**

- **Reducing size, cost and power consumption of LINACs**

Challenges

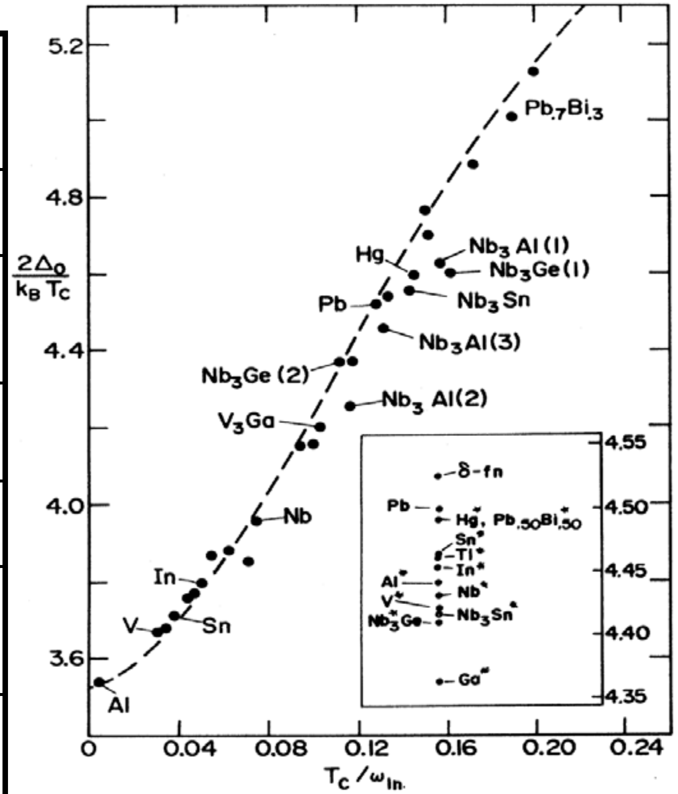
- **Tricky choice of the optimum TFML materials among lots of good-looking candidates**
- **Dealing with chemically more complex materials with coexistence of superconductivity with competing states (close to AF or structural phase transitions) and unconventional pairing symmetries.**
- **Impurities can be more damaging than they are in Nb. Understanding the pairbreaking mechanisms by impurities in strong RF fields.**
- **Higher T_c superconductors have shorter coherence length – stronger current-limiting effect of grain boundaries than in Nb.**
- **Overheating in S-I-S-I multilayers?**
- **RF band decoupling in multiband superconductors (MgB_2)**

Lots of materials to play with



Possible TFML materials

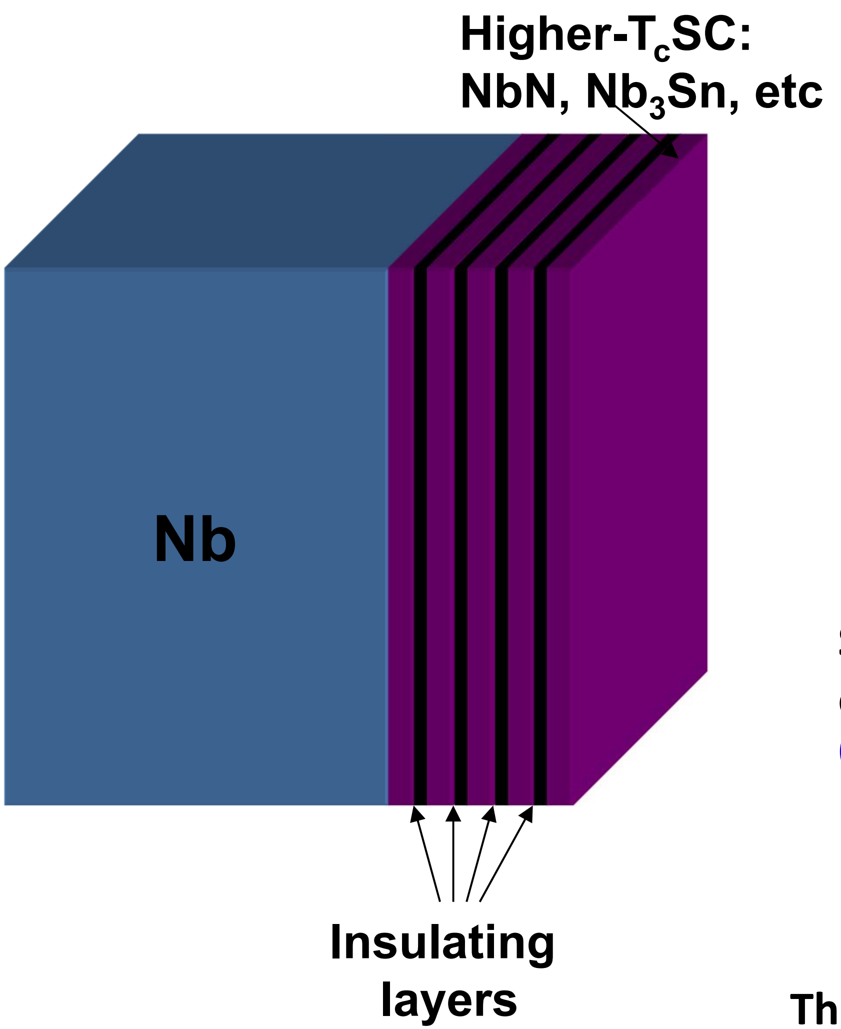
Material	T_c (K)	H_c [T]	H_{c1} [mT]	H_{c2} [T]	$\lambda(0)$ [nm]	Δ [meV]
Nb	9.2	0.2	170	0.4	40	1.5
$B_{0.6}K_{0.4}BiO_3$	31	~0.44	30	30	160	4.4
Nb_3Sn	18	~0.5	40	30	85	3.1
NbN	16.2	~0.23	20	15	200	2.6
MgB_2	40	~0.32	20-60	3.5-60	140	2.3; 7.1
$Ba_{0.6}K_{0.4}Fe_2As_2$	38	~0.5	20	>100	200	>5.2

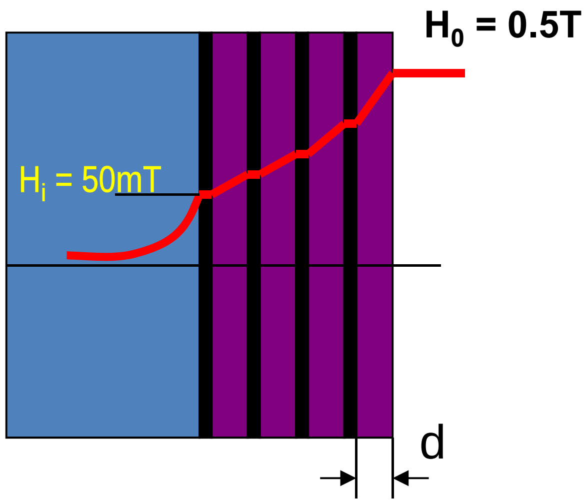


High-T_c d-wave cuprates are SRF unsuitable ($R_s \propto T^2$ instead of $R_s \propto \exp(-\Delta/T)$

Large s-wave gap (good for SRF) is usually accompanied by low H_{c1} (bad for SRF)

Boost of H_{c1} by multilayer coating





Multilayer coating: high-T_c SC layers with $d < \lambda$ which screen the Nb cavity

Suppression of vortex penetration due to the enhancement of H_{c1} in a thin film with $d < \lambda$
(Abrikosov, 1964)

$$H_{c1} = \frac{2\phi_0}{\pi d^2}\left(\ln\frac{d}{\xi} - 0.07\right)$$

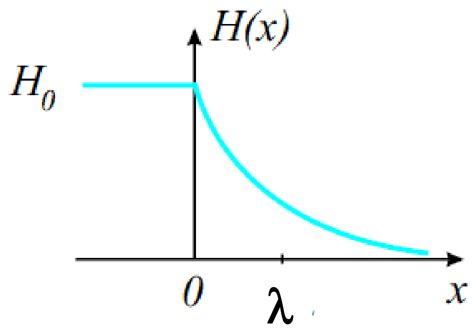
The breakdown field could be increased up to superheating field of the coating material: ~ 500 mT for Nb_3Sn

Gurevich, APL 88, 012511 (2006)

Superheating field

- **Meissner state can only exist below the superheating field H < H_s**

- **Periodic vortex instability of the Meissner state as the current density $J_s = H_s/\lambda$ at the surface reaches the depairing limit**



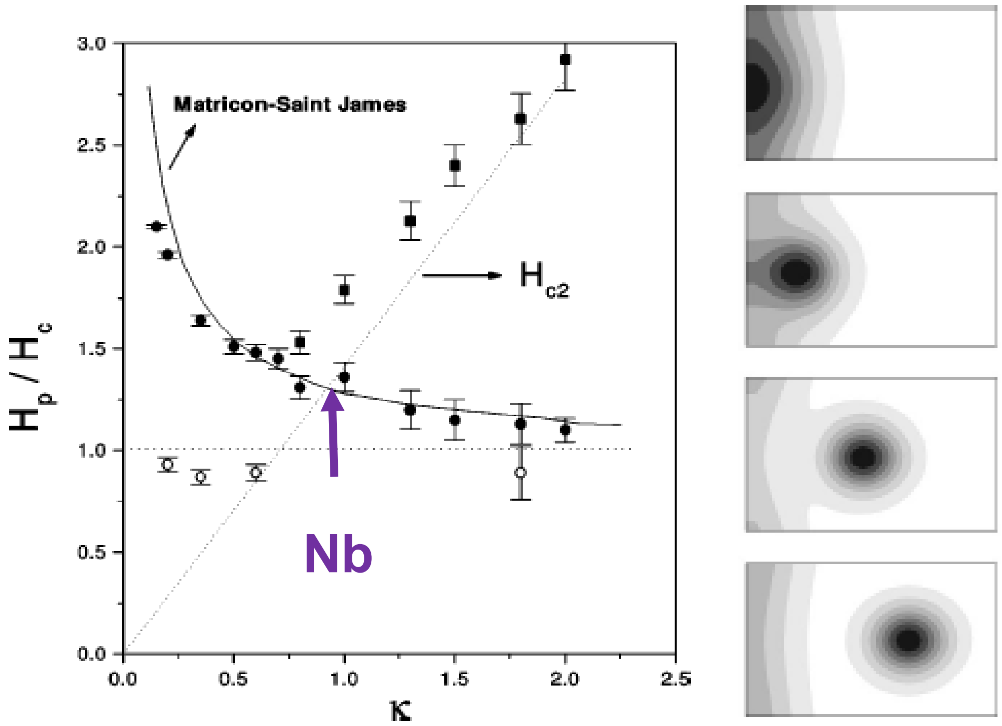
- **GL calculations of the superheating field H_s at T ≈ T_c** (Matricon and Saint-James, 1967)

$$B_s \approx 1.2 B_c, \qquad \kappa \cong 1,$$
$$B_s \approx 0.745 B_c, \qquad \kappa >> 1$$

- **T << T_c clean limit at κ >> 1:** (Galaiko, 1966; Catelani and Sethna, 2009)

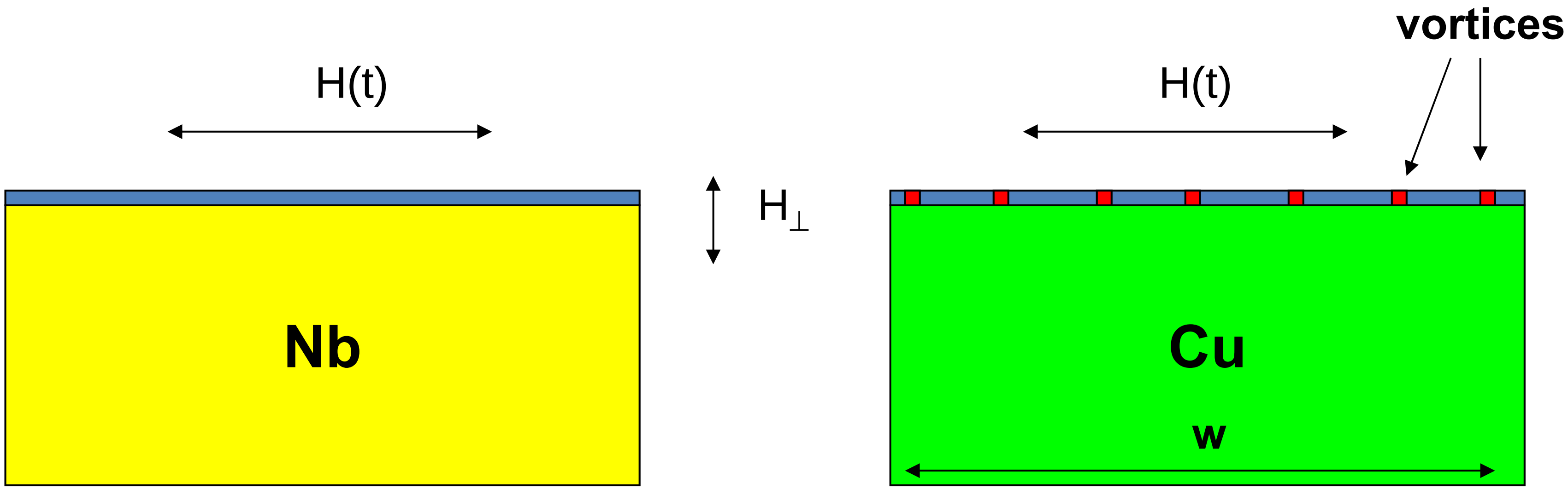
$$B_s \approx 0.84 B_c$$

but this corresponds to a gapless state



Hernandez and Dominguez, PRB 65, 144529 (2002)

Why is Nb_3Sn on Nb much better than Nb_3Sn on Cu?

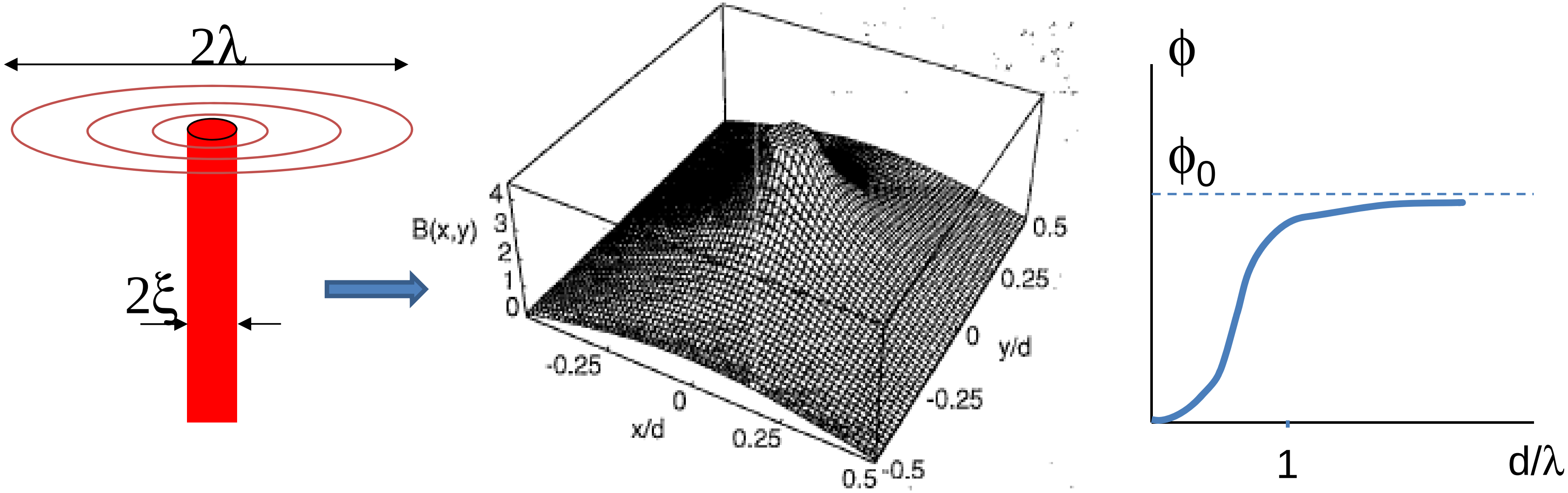


Nb_3Sn/Nb cavity is much better protected against perpendicular vortices produced by weak transverse stray fields $H_\perp$ than Nb_3Sn/Cu cavity

Meissner state persists up to $H_\perp < H_{c1}^{(Nb)}$. Perpendicular vortices in the film have very large energy ~ $\ln(w/\xi)$

Meissner state is destroyed for small $H_\perp < (d/w)H_{c1}^{(Nb_3Sn)} \ll H_{c1}^{(Nb_3Sn)}$ due to large demagnetization factor $w/d \sim 10^3$-10^5

Enhanced parallel H_{c1} in a film



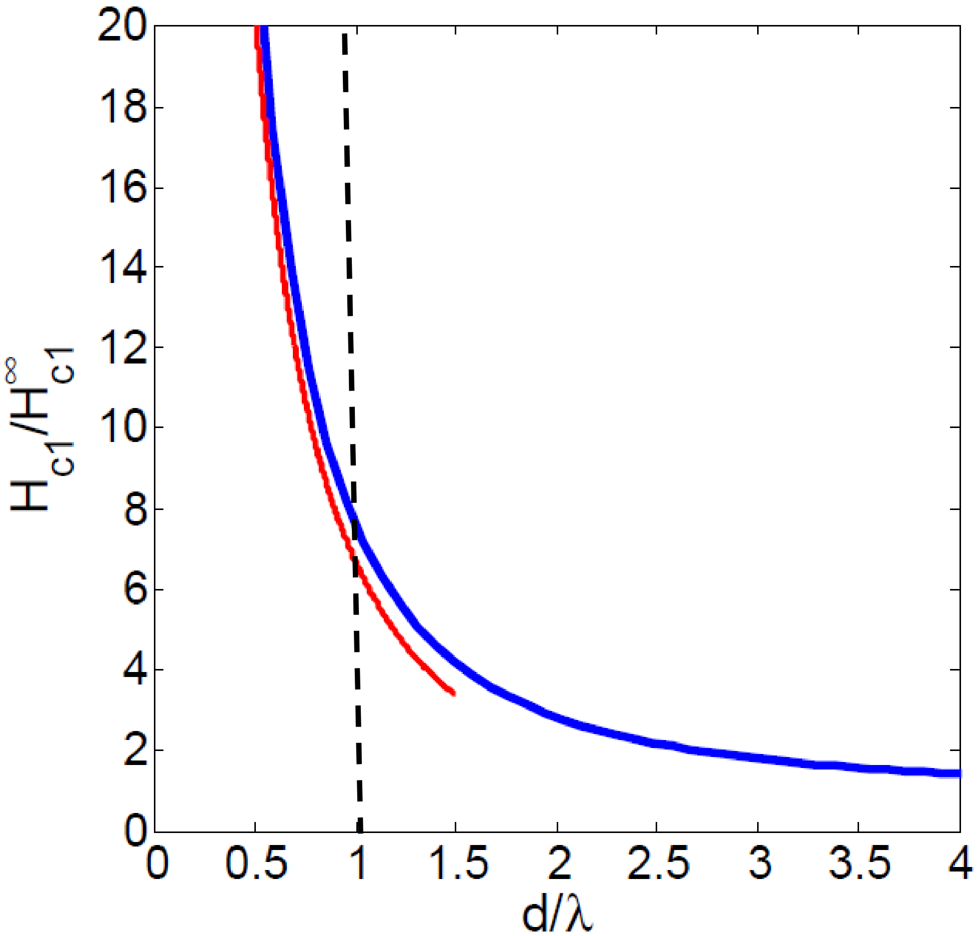
Squeezed vortex in a thin film has the reduced magnetic flux: $\phi(d) = \phi_0[1 - \mathrm{sech}(d/2\lambda)]$

Vortex is thermodynamically stable if : $\delta\Omega = \varepsilon_0 - \phi(d)H/4\pi < 0.$

Since $\phi(d) \approx \phi_0\,(d/\lambda)^2/8$ for $d < \lambda$ is reduced, $H_{c1}(d) = 4\pi/\varepsilon_0\,\phi(d)$ is enhanced

Can we get away with TFL thicker than λ?

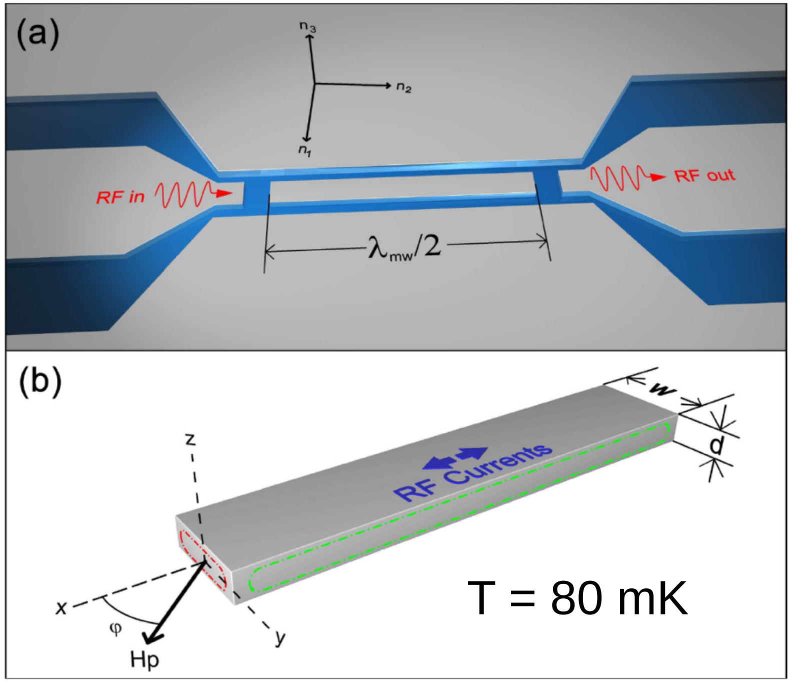
$$H_{c1} = H_{c1}^{\infty}\left[1 + \int_0^{\infty} \frac{\left(\tanh d\sqrt{k^2+\lambda^{-2}} - 1\right)dk}{(ln\kappa + 0.5)\sqrt{k^2+\lambda^{-2}}}\right] \Bigg/ \left[1 - \mathrm{sech}\,\frac{d}{2\lambda}\right]$$



- **To be better than Nb, the TF coating must have $H_{c1}(d) > 200$ mT**
- **Most high-H_c superconductors have H_{c1} = 20-60 mT**
- **For Nb_3Sn with H_{c1} = 40 mT, the TF layer should provide $H_{c1}(d)/H_{c1} > 5$, giving $d < 1.2\lambda$**
- **However, to reach $H_b \approx H_s^{TF}$, the TF thickness should be $d < \lambda$**

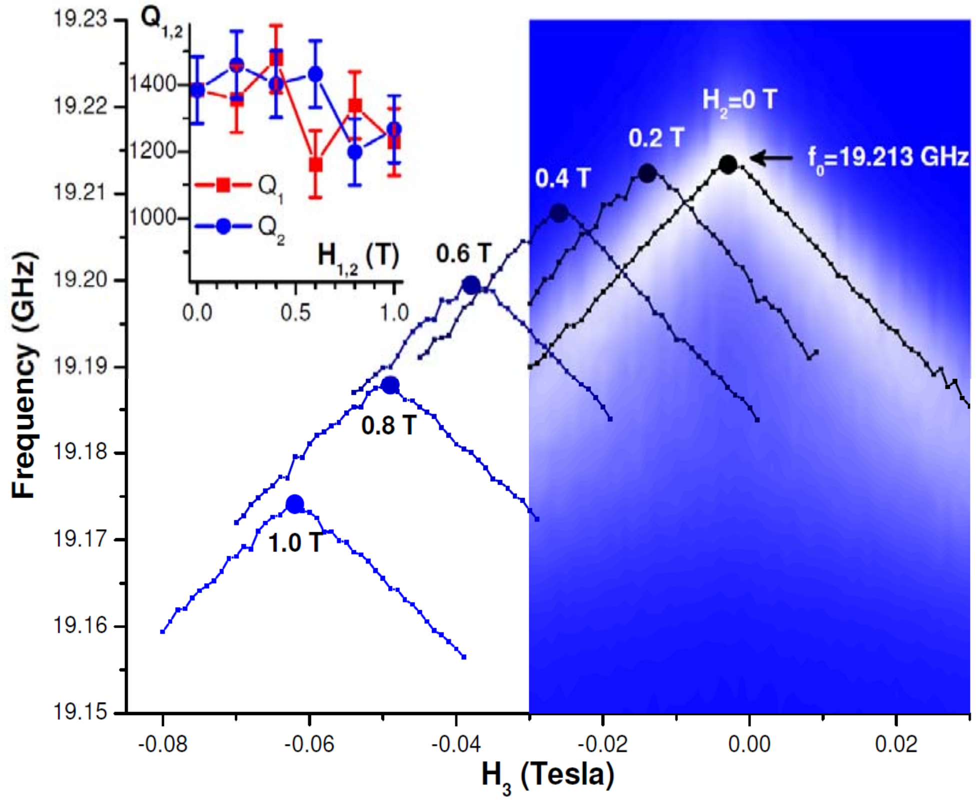
o Gurevich, APL 88, 012511 (2006)

Six-fold increase of H_{c1} in a dirty Nb film



Groll, Gurevich, and Chiorescu, Phys. Rev. B81, 020504(R) (2010)

65 nm Nb thin film strip line w = 100 μm, s = 3mm
Nonlinear Meissner effect



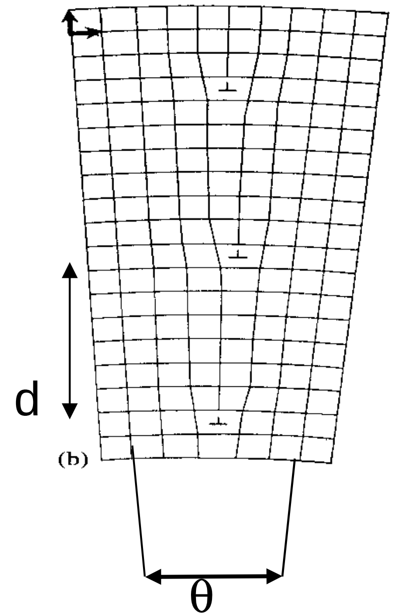
Measure the change of the resonance frequency $f = 1/2\pi(CL)^{1/2}$ **as a function of the parallel dc magnetic field:**

$$\frac{\delta f}{f} = \frac{L_k(0) - L_k(H)}{2L_0}$$

Q(B) does not change much up to B = 1T and drops for B > 1T. Consistent with H_{c1}^{theor}**(65nm) = 0.93T**

Types of grain boundaries

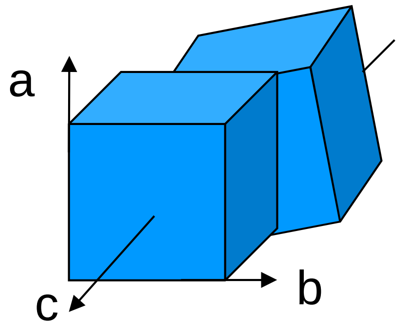
[001] tilt GB (parallel c-axis)

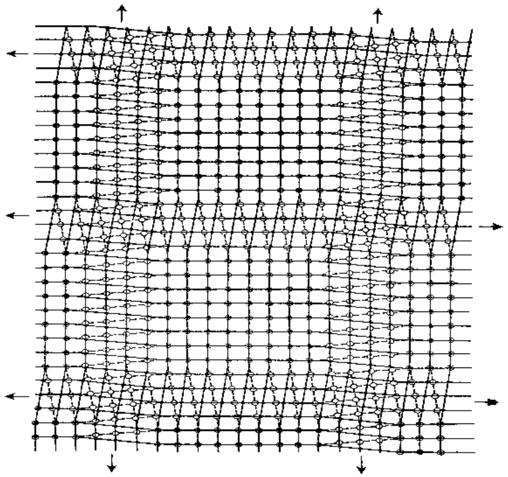


Chain of edge dislocations spaced by

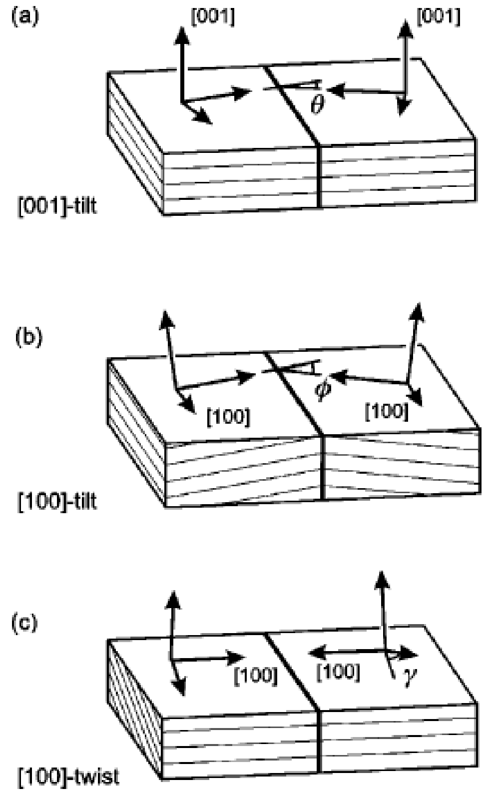
d = b/2sin(θ/2)

Twist GB



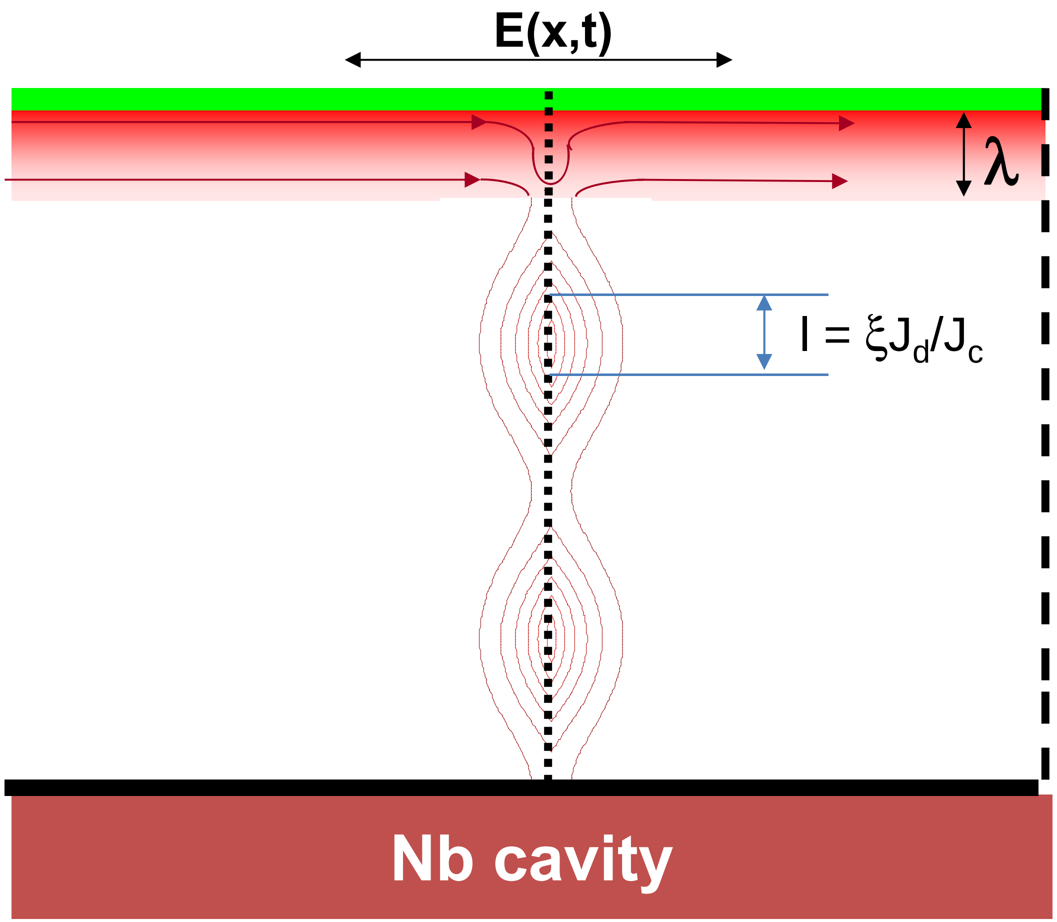


Cellular structure of twist dislocations in the ab plane



Grain boundaries in TF coatings

- High-H_c superconductors have shorter coherence length, so they may be more prone to weak link grain boundaries than Nb
- GB becomes weak link if its critical current density J_c is much smaller than the depairing current density $J_d = H_c/\lambda$



$$H > H_J \cong H_c \frac{J_c}{J_d}$$

For $J_c < 0.1J_d$, the field onset of vortex penetration along GBs in Nb_3Sn TFL drops below 50 mT

Breakdown fields of 160-200 mT of the best polycrystalline Nb cavities seem to rule out the weak link behavior of GBs

Dissipation in “strong GB”

- **High-J_c GB: overdamped Josephson junction with high J_c and low GB sheet resistance R_b**

- **If the TFL thickness is smaller than the Josephson core size $l = J_d\xi/J_c$, the grain boundary behaves like a RSJ small Josephson junction.**

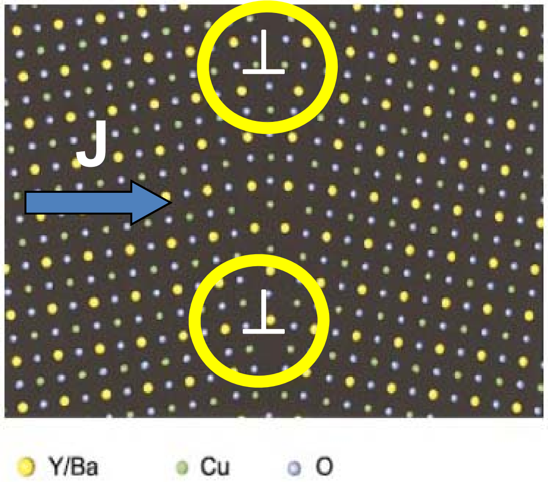
- **Quasi-static rf field if $J_cR_b >> \omega\phi_0 \sim 1\ \mu V$**
- **Averaged RF dissipated power $q = R_b \frac{\omega d}{2\pi L}\oint J(t)\left[J^2(t) - J_c^2\right]^{1/2} dt$:**

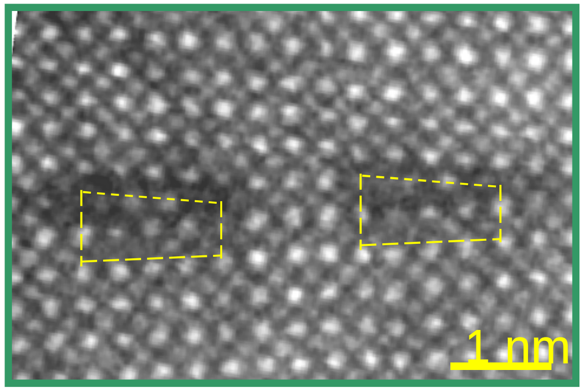
$$q = \frac{R_b d}{2L\lambda^2}\left(H^2 - H_v^2\right), \qquad H_v = \lambda J_c$$

- **GB contribution to the surface resistance:**
- **Is frequency independent**
- **Has a field threshold H_v**
- **Increases as the grain size L decreases**
- **May be reduced for cleaner GBs with smaller R_b**

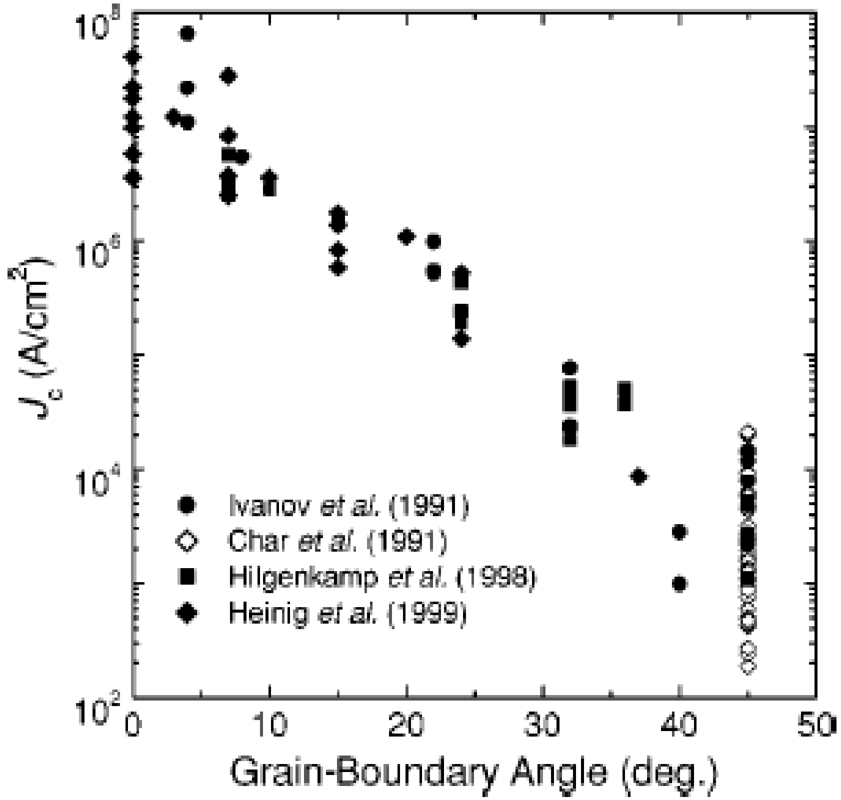
How bad can grain boundaries be?

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





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



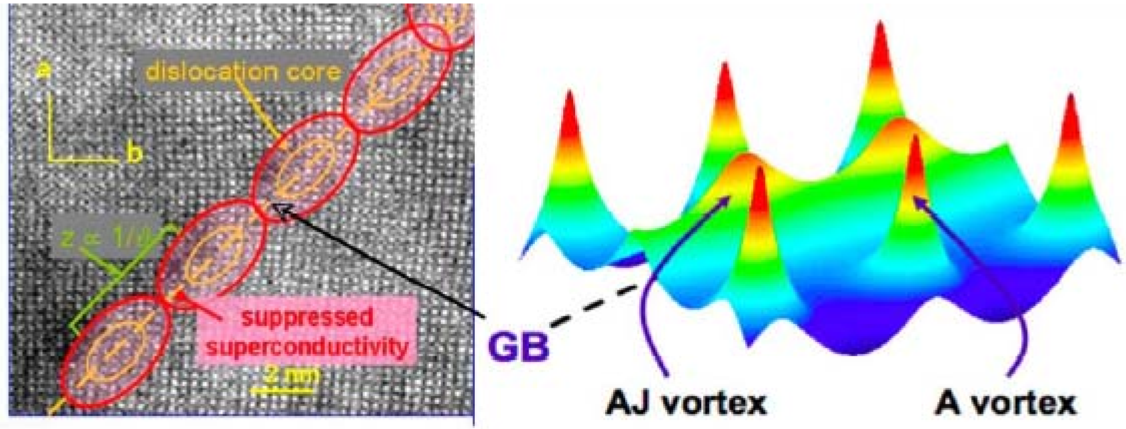
Strong suppression of superconductivity at GBs

Exponental drop of J_c with the misorientation angle

Current blockage by weak link GBs in polyscrystals

Very serious problems for applications

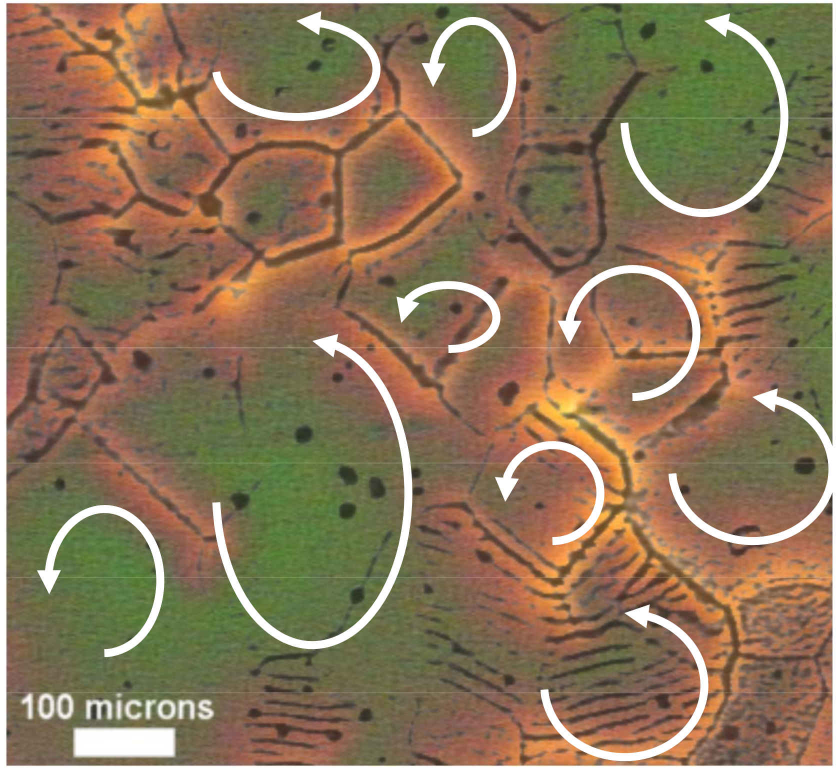
Electromagnetic granularity



Magnetic granularity caused by grain boundaries

PRB, 46, R3187 (1992); PRB 48, 12857 (1993);
PRB 50, 13563 (1994); PRB 65, 214531 (2002).
PRL 88, 097001 (2002).

MO imaging of YBCO

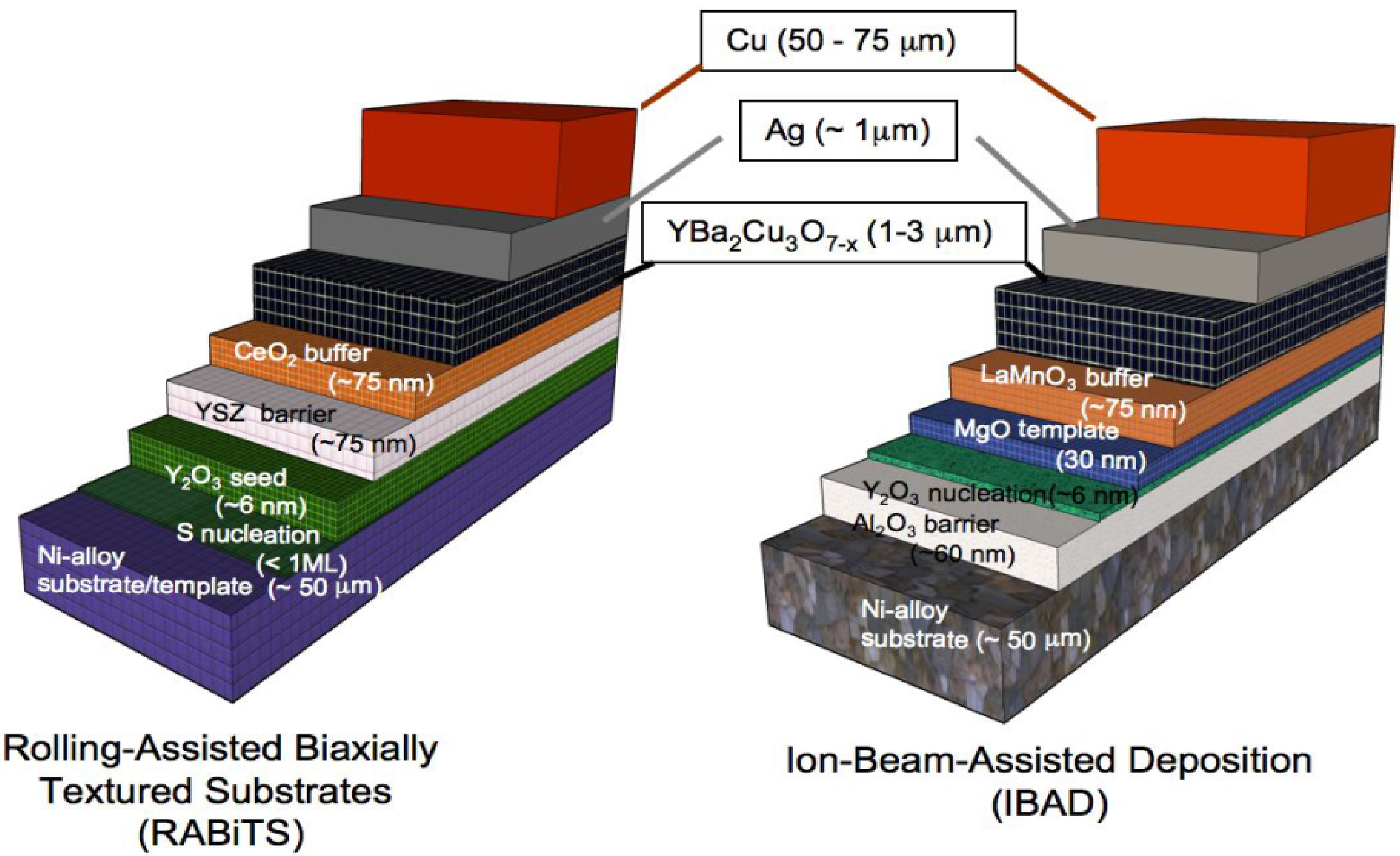


Polyanskii, 2001

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

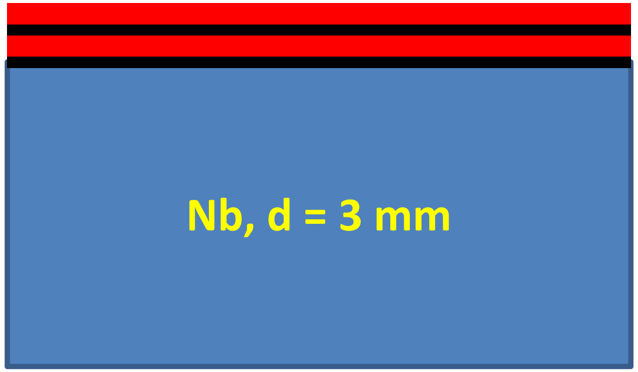
- Fragmentation of uniform current flow into decoupled current loops in the grains

Coated conductor technology to ameliorate current blocking by grain boundaries in HTS



Single crystal by the mile

Weak overheating in multilayers



Total thermal impedance:

$$\alpha = \frac{\alpha_K}{1 + \alpha_K \left[\frac{d}{\kappa} + N \left(\frac{d_i}{\kappa_i} + \frac{d_s}{\kappa_s} \right) \right]}$$

Nb contribution

ML contribution

Nb cavity with d = 3mm, κ = 10 W/mK
Nb_3Sn coating with Nd_s = 100 nm, $\kappa = 10^{-2}$ W/mK
Insulating Al_2O_3 layers, Nd_i = 10 nm, κ = 0.3 W/mK (Nemoto et al, Cryogenics, 25, 531 (1985))

$d_i/\kappa_I = d_s/300\kappa_s$ - I layers are negligible
$d/\kappa = 3Nd_s/\kappa_s$ - TFML adds only 30% to the thermal resistance of the Nb shell

- **Thickness of I layers d = 1-2 nm is smaller than the wavelength ~ 100 nm of thermal phonons at 2K so I layers weakly impede phonons generated by warm quasiparticles**

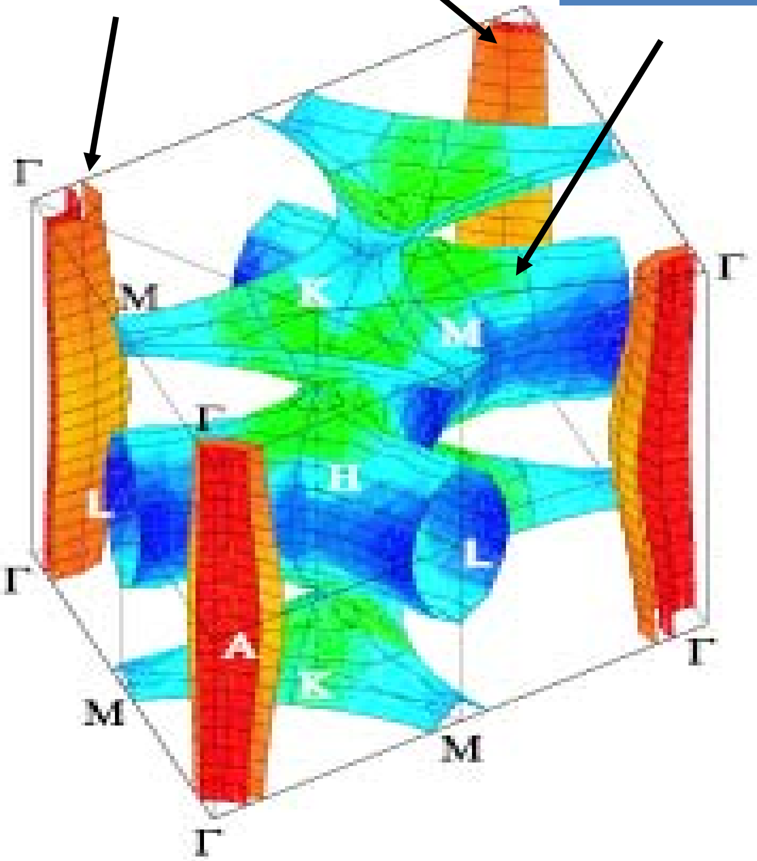
- **More effective ballistic heat transfer from TFML structure for $d < l_{Ph}$**

Two-gap superconductivity in MgB_2

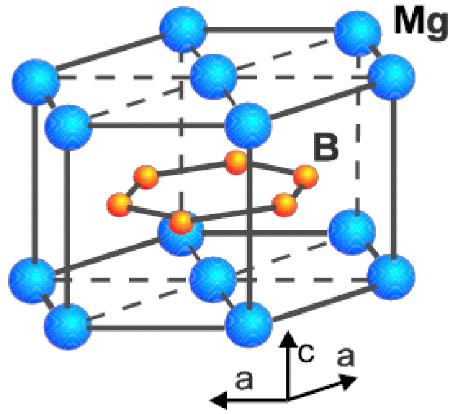
J. Akimitsu et al, Nature 410, 63 (2001)

Big gap, $\Delta_\sigma \approx 7.2$ meV

Small gap, $\Delta_\pi \approx 2.1$meV



Liu, Mazin and Kortus (2002);
Choi et al, (2002)



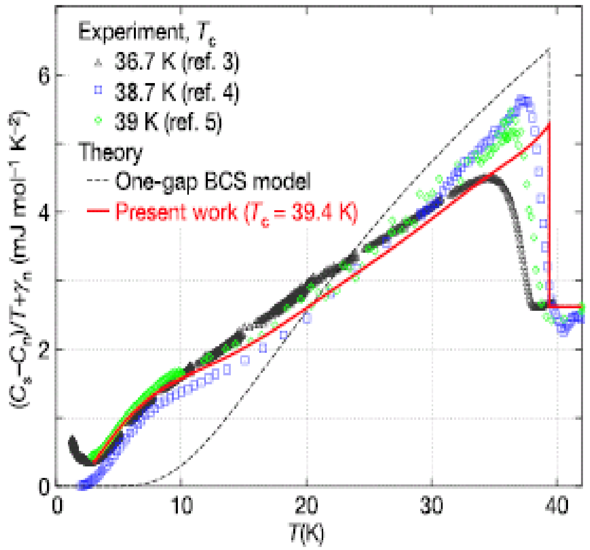
- 2D big gap for in-plane σ-orbitals s and 3D small gap for out-of-plane π-orbitals

- Weak interband coupling due to orthogonal p_z and p_{xy} orbitals of B

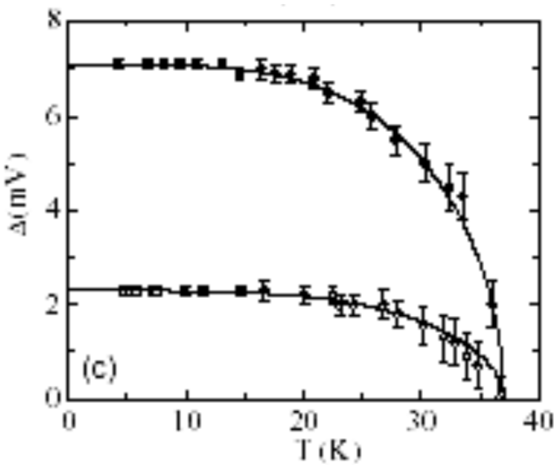
High T_c = 40K

Is two-gap superconductivity in MgB_2 good for TSRF?

Δ_π~2 .3 meV and Δ_σ~7.1 meV

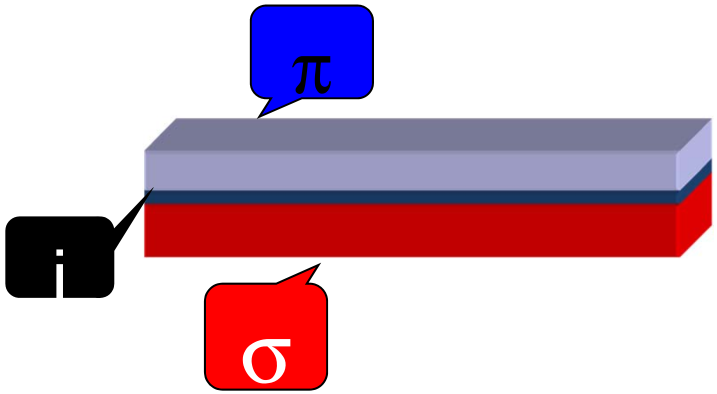


F. Bouquet *et al.*, PRL 87 (2001) 047001



M. Iavarone *et al.*, PRL 89, 187004 (2002)

$$R_s = \frac{A_\sigma \omega^2}{T}\exp\left(-\frac{\Delta_\sigma}{T}\right) + \frac{A_\pi \omega^2}{T}\exp\left(-\frac{\Delta_\pi}{T}\right)$$

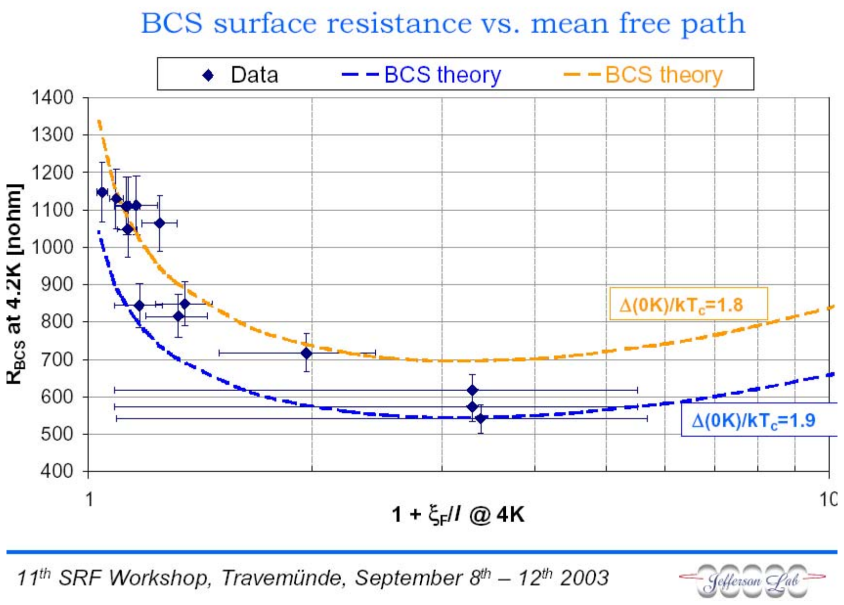


R_s is dominated by the smaller gap, so the BCS resistance of MgB_2 may not be better than R_s for Nb_3Sn because Δ_π^{MgB2} = 2.3 meV < Δ^{Nb3Sn} = 3.1 meV.

Effect of nonmagnetic impurities on low field R_{BCS}

- **Effect of intraband scattering on the linear surface resistance of MgB_2 is similar to single-band superconductors:**

- **No suppression of the superconducting gap (Anderson theorem)**
- **Increase of the London penetration depth**
- **Increase of the BCS surface resistance**
- **Decrease the lower critical field (the onset of vortex penetration)**

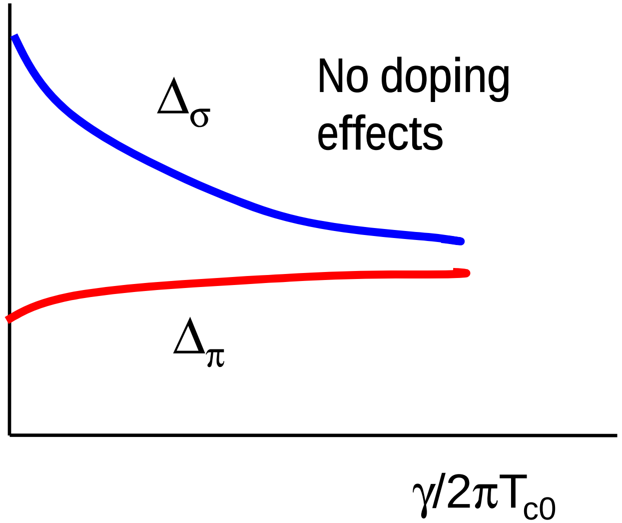


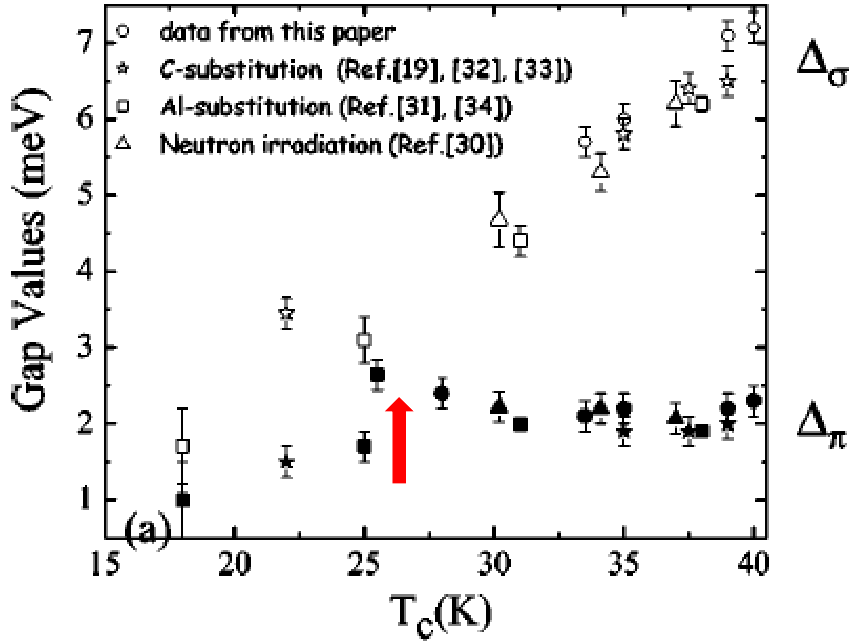
Nonmagnetic impurities appear to be not too bad for R_{BCS}, but are they benign at high rf fields?

E. Palmieri

Effect of interband impurity scattering on R_s

- Interband scattering increases Δ_π and decreases Δ_σ





M. Iavarone et al, Phys. Rev B 71, 214502 (2005)

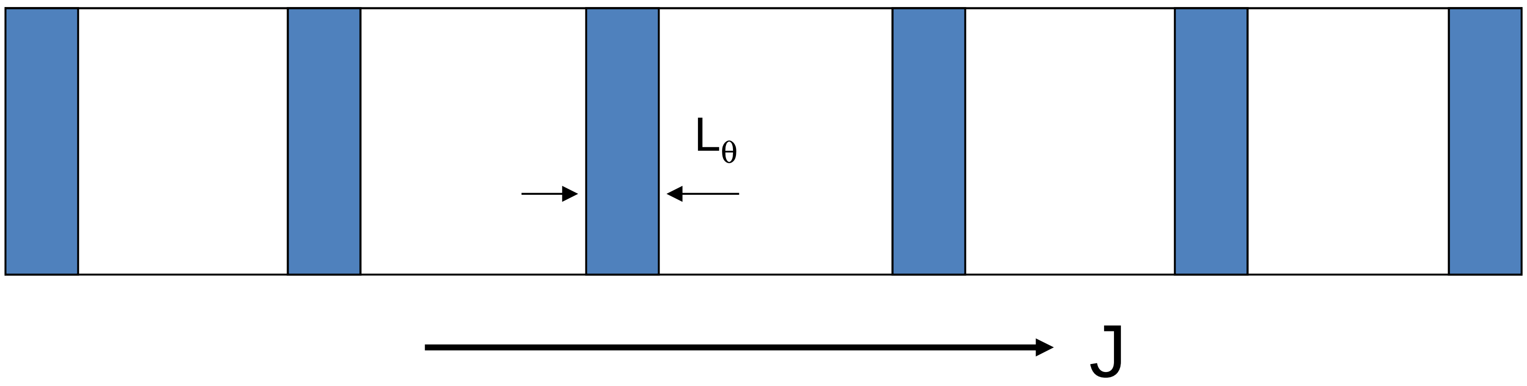
- The observed increase of Δ_π from 2.1 meV to 2.8 meV by impurities may decrease R_s at low T despite suppression of T_c by doping and interband scattering

- Competition between interband and intraband impurity scattering: optimum R_s at intermediate impurity concentrations different from that of single-band SC

Decoupling of phase-locked bands by rf current

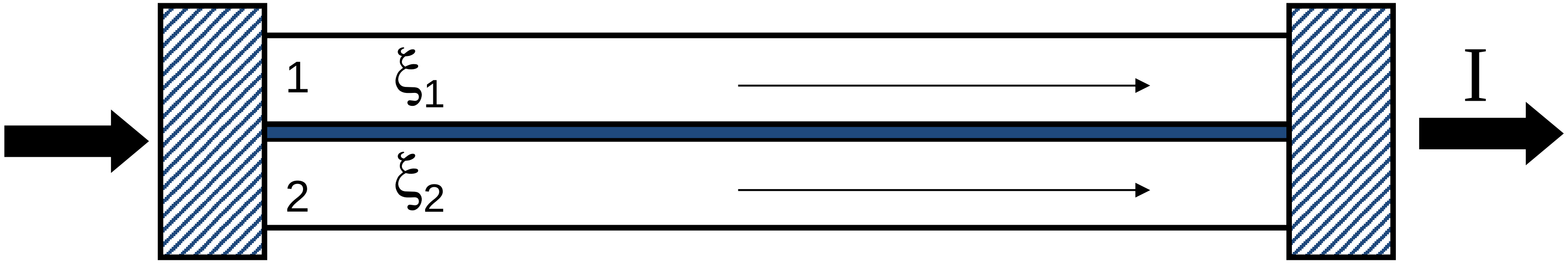
- **Band decoupling by electric fields and currents well below the depairing limit**
- **Formation of interband phase textures: periodic structure of interband phase slips along the direction of current**

Gurevich and Vinokur, PRL 90, 047004 (2003); PRL 97, 137003 (2006)



Domain walls of width $L_\theta >> \xi$. Period depends on current.

Phase locked current state



Same phases $\chi_1 = \chi_2$ to minimize the Josephson energy,

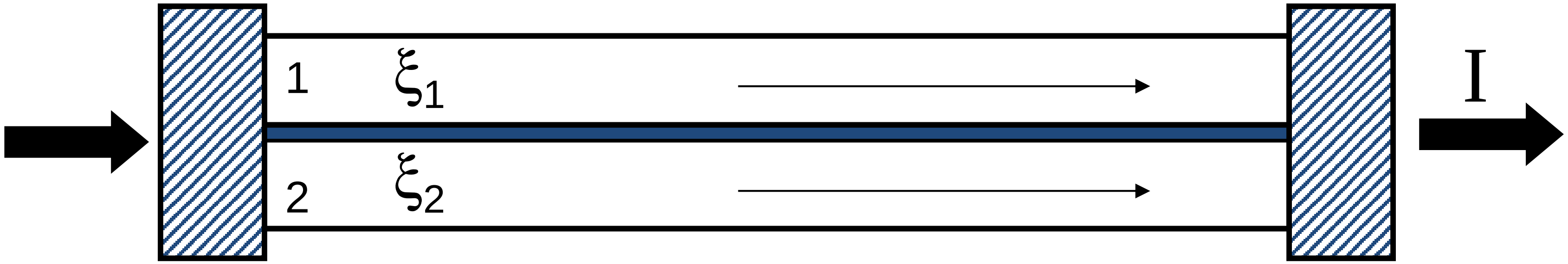
$$W_J = (\hbar J_c/2e)[1 - \cos(\chi_1 - \chi_2)]$$

Current-carrying state: $\Psi_1 = \Delta_1 \exp(i\chi_1)$, $\Psi_2 = \Delta_2 \exp(i\chi_2)$,

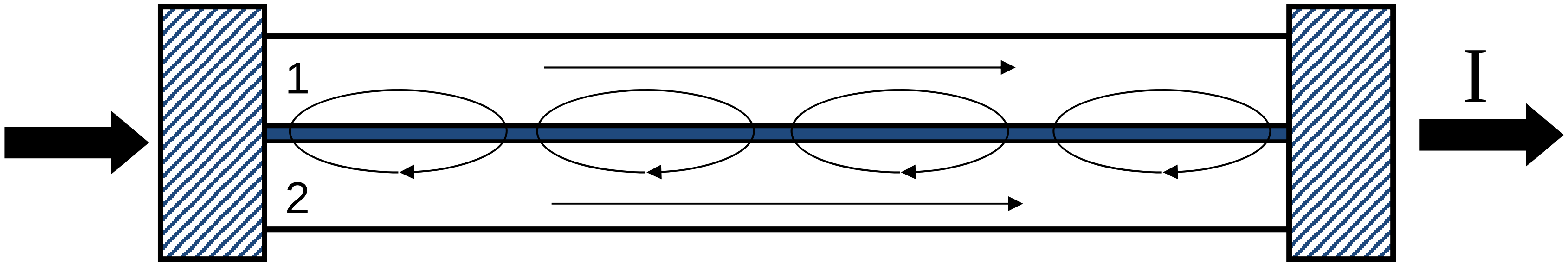
$$\nabla\chi_1 = \nabla\chi_2 = Q$$

What happens at higher currents?

Transition to a phase slip state



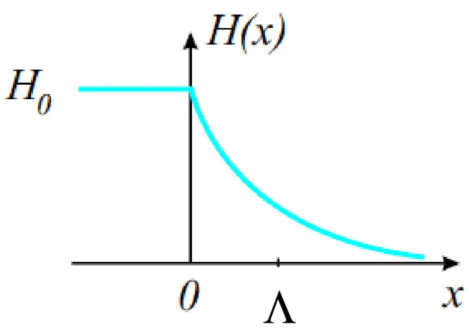
- What happens if the depairing limit $Q\xi_2 \sim 1$ is reached in film 2, but $Q\xi_1 << 1$ in film 1?
- Current redistribution enforces different $Q_1 \neq Q_2$ competing with the Josephson energy



- Current-induced interlayer phase slip texture provides current sharing between films (bands) 1 and 2
- For weak Josephson coupling, the lock-in transition occurs at $I << I_d$

Interband phase textures in MgB_2

- For the parameters of MgB_2, J_{c1} is not much smaller than J_{c2}.
- Static interband phase textures $\theta(x)$ along the current direction at $Q \approx 1/\xi_\pi$



Screening current: $cH/4\pi\lambda_L \approx c\phi_0/16\pi^2\lambda_L^2\xi_\pi$

Band decoupling by magnetic field

$$H_\theta = \frac{\phi_0}{4\pi\lambda_L\xi_\pi} \cong 30mT \cong H_{c1}$$

for λ_L = 105 nm (Zehetmayer et al, Phys. Rev. B 56, 052505 (2002))
and ξ_π = 50 nm (STM by Eskildsen et al, PRL 89, 187003 (2002))

- Textures facilitate vortex penetration over the surface barrier
- Breakdown of the linear London electrodynamics, increase of R_s
- Nonlinearity of the rf surface impedance at $H \approx H_\theta$ (not good for TSRF)

Increase of H_θ by nonmagnetic impurities

- **Increase of interband Josephson coupling by interband impurity scattering**

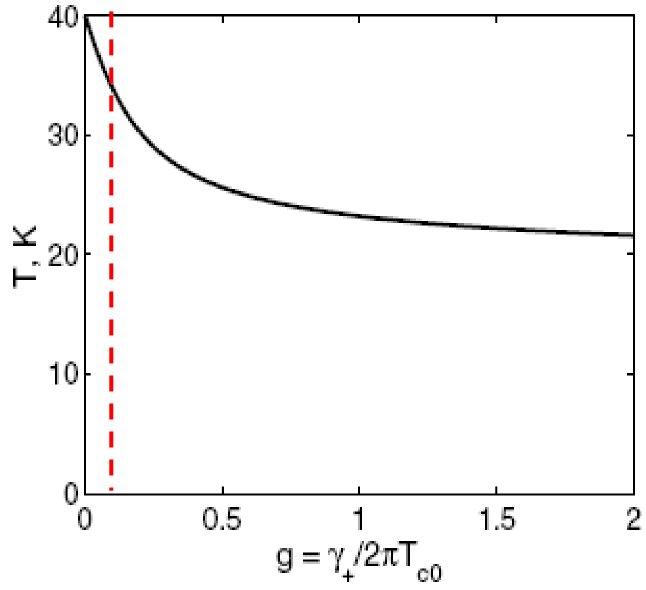
(Gurevich, Physica C456, 160 (2007))

$$\varepsilon_J = N_1 \Delta_1 \Delta_2 \left(\frac{\lambda_{12}}{w} + \frac{\pi \gamma_{12}}{4T_c} \right)$$

with $w = \lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}$. For MgB_2, $\lambda_{12}/w \sim 0.3$, so interband coupling and H_θ is significantly enhanced by impurities if

$$\gamma_{12} \geq 0.4 T_c$$

Interband mixing due to impurity scattering may increase H_θ up to H_c without significant suppression of T_c



CONCLUSIONS

- **TFML coating can break the Nb cavity monopoly if the physics of unconventional superconductors in strong rf fields is understood.**

- **The TFML technology requires the ALD (or other magic techniques) + the right choice of the TFML grail material + proper impurity management , so …**

You must choose, but choose wisely…