RF breakdown in multilayer coatings: a possibility to break the Nb monopoly

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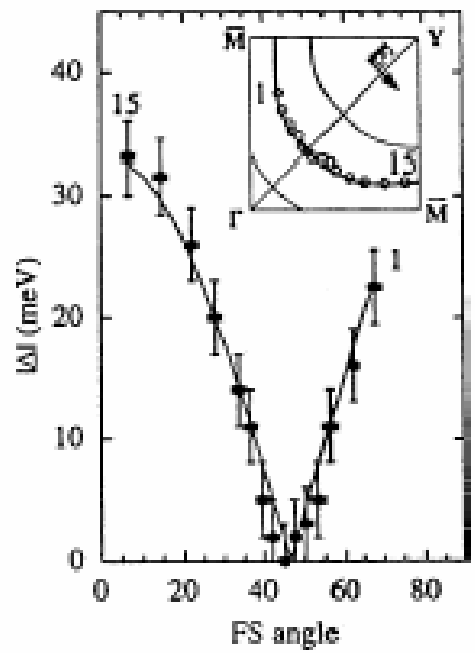
Motivation

- **Why Nb?**
  BCS surface resistance: $R_s \propto \lambda^4 \exp(-\Delta/k_B T)$
  Minimum R_s implies maximum Δ, that is, maximum $T_c \cong 1.87\Delta/k_B$ and minimum London penetration depth λ

Exceptions:

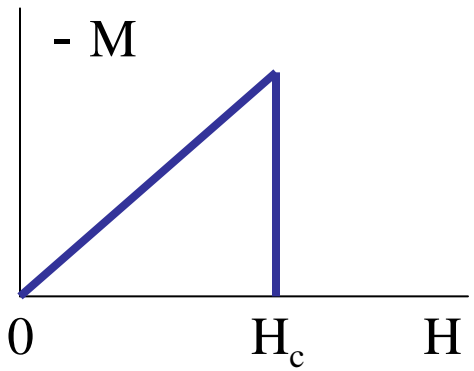
- **Does not work for the d-wave high-T_c superconductors for which $R_s \propto T^2$ due to nodal lines in $\Delta(k) = 0$.**
- **Two gap MgB_2 with $\Delta_\pi \cong 2.3$ meV $\Delta_\sigma \cong 7.2$ meV: T_c is proportional to Δ_σ, while $R_s \propto \exp(-\Delta_\pi/k_B T)$ is limited by Δ_π**



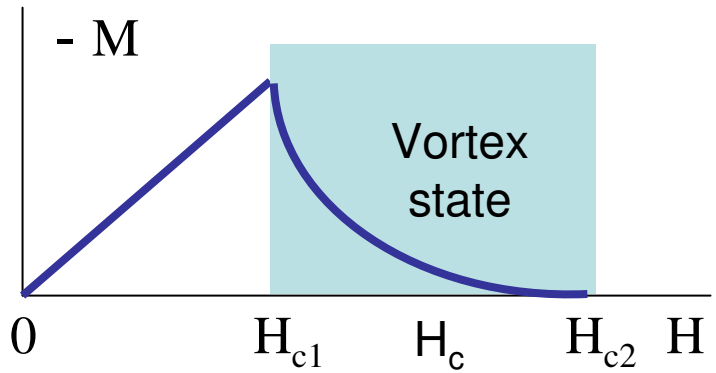
Vanishing $\Delta(k) = 0$ along [110] directions in HTS

Problem with vortices

- All superconductors with T_c > 9.2K are strong type – II SC with the lower critical field H_{c1} much smaller than H_c = 0.18T for Nb



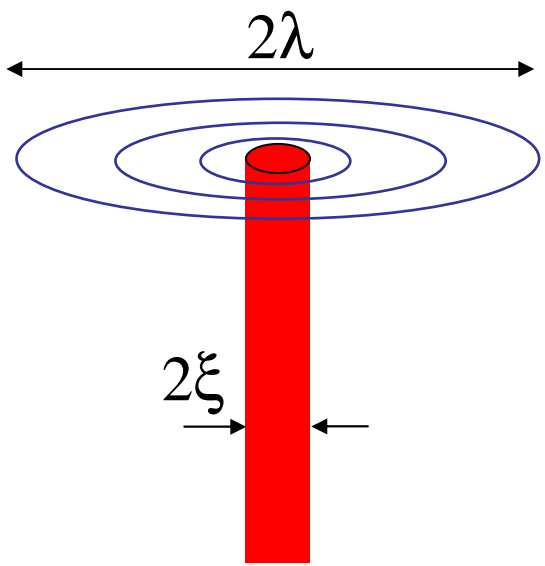
Complete Meissner effect in type-I superconductors

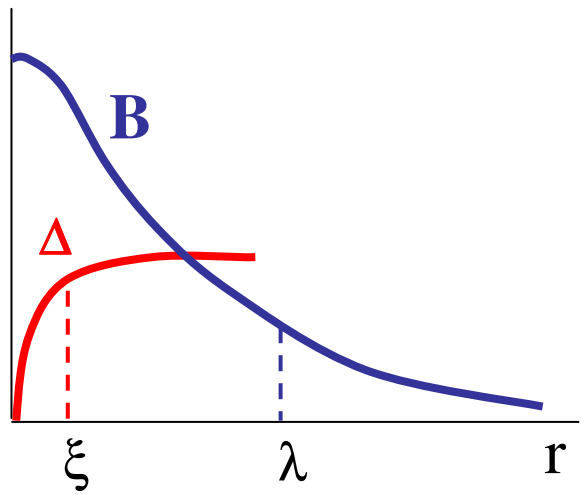


High-field partial Meissner effect in type-II superconductors

- Vortices penetrating at H > H_{c1} cause rf dissipation much stronger (due to normal cores) than what results from the BCS surface resistance in the Meissner state

Single vortex line





- Core region $r < \xi$ where $\Delta(r)$ is suppressed
- Region of circulating supercurrents, $r < \lambda$.
- Each vortex carries the flux quantum ϕ_0

Important lengths and fields

- Coherence length ξ and magnetic (London) penetration depth λ

$$B_{c1} = \frac{\phi_0}{2\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right), \qquad B_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}, \qquad B_{c2} = \frac{\phi_0}{2\pi\xi^2}$$

For clean Nb, $H_{c1} \approx 170$ mT, $H_c \approx 180$ mT

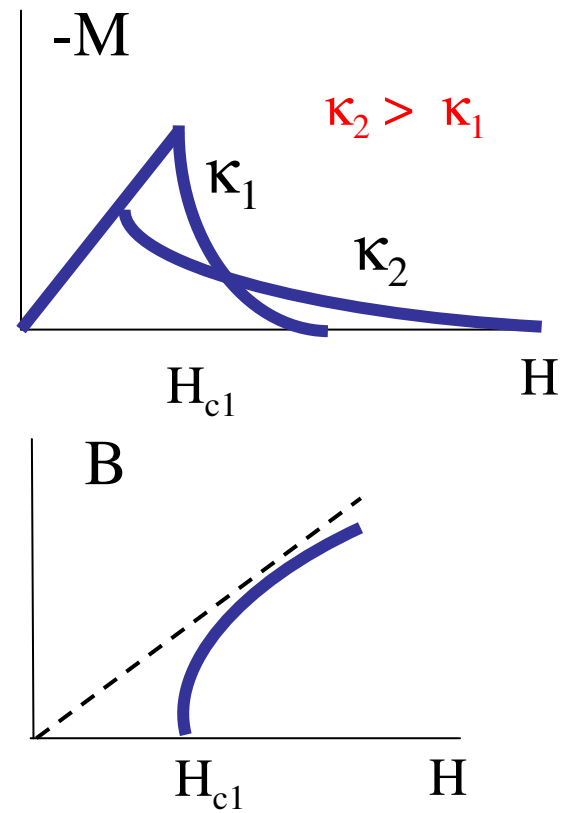
Intermediate fields, $H_{c1} << H << H_{c2}$

- For a << λ, and κ >> 1, the magnetization M(H) is:

$$M \cong -H_{c1}\frac{\ln(H_{c2}/H)}{2\ln\kappa}$$

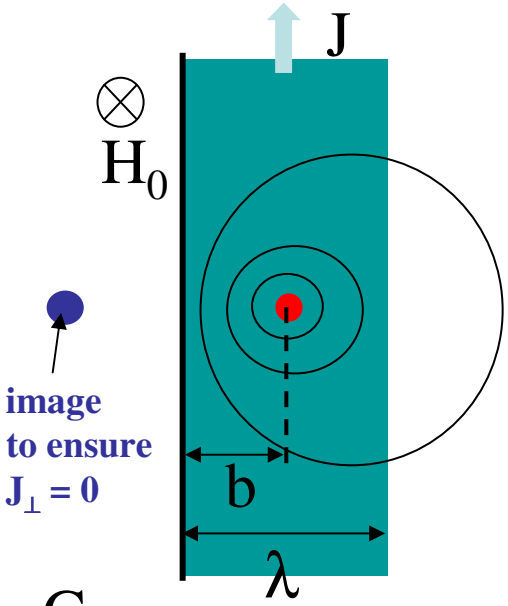
Superconductivity disappears at $B_{c2} = \phi_0/2\pi\xi^2$ as nonsuperconducting vortex cores overlap

Material	T_c (K)	λ(0), nm	ξ(0), nm	H_{c2} (T)
Nb-Ti	9.5	240	4	13
Nb-N	16	200	5	15
Nb_3Sn	18	65	3	30
MgB_2 (dirty)	32-39	140	6	35
$YBa_2Cu_3O_7$	92	150	1.5	>100
Bi-2223	108	200	1.5	>100



Nb_3Sn has maximum T_c and minimum λ to provide the optimum R_s

Surface barrier: How do vortices get in a superconductor at $H > H_{c1}$?



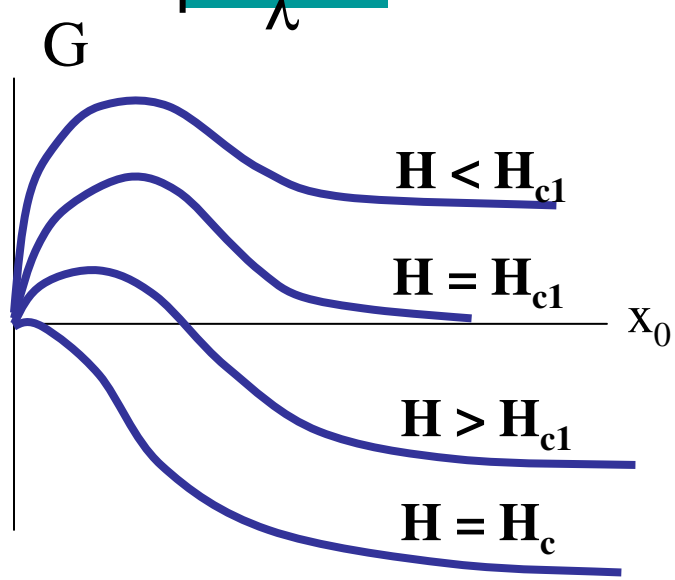
Two forces acting on the vortex at the surface:

- Meissner currents push the vortex in the bulk
- Attraction of the vortex to its antivortex image pushes the vortex outside

Thermodynamic potential $G(x_0)$ as a function of the position x_0:

$$G(b) = \phi_0[H_0 e^{-x_0/\lambda} - H_v(2x_0) + H_{c1} - H_0]$$

Meissner Image



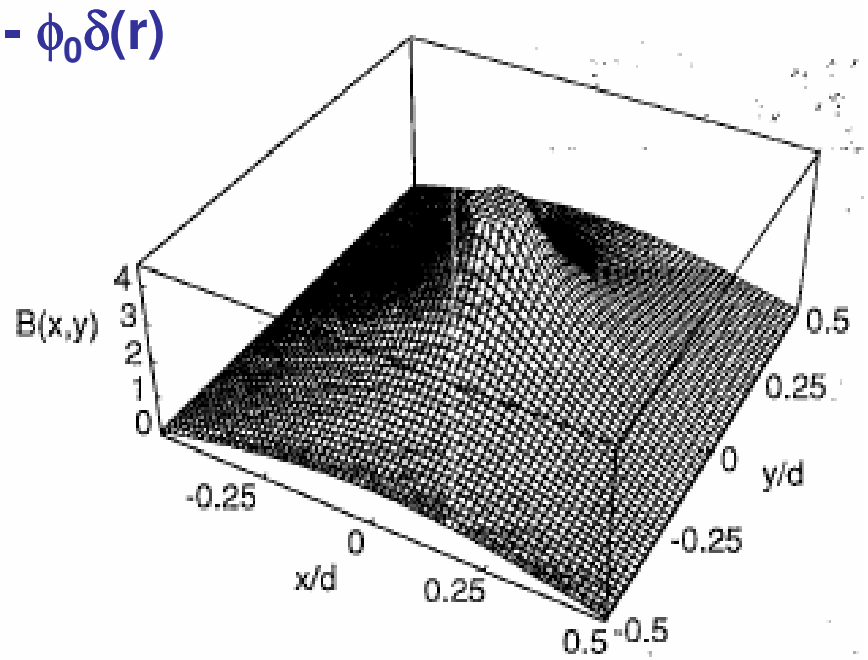
Vortices have to overcome the surface barrier even at $H > H_{c1}$ (Bean & Livingston, 1964)

Surface barrier disappears only at the overheating field $H = H_c > H_{c1}$ at which the surface J becomes of the order of the depairing current density

Vortex in a thin film with d < λ

London screening is weak so $\lambda^2\nabla^2 B = -\phi_0\delta(r)$

$$B(x,y)=\left(\frac{\phi_0}{4\pi\lambda}\right)^2 \ln\frac{\cosh\frac{\pi}{d}(y-y_0)+\cos\frac{\pi}{d}(x+x_0)}{\cosh\frac{\pi}{d}(y-y_0)-\cos\frac{\pi}{d}(x-x_0)}$$



Vortex field in a film decays over the length d/π instead of λ (interaction with many images)

Vortex free energy as a function of the position x_0

$$G(x_0)=\left(\frac{\phi_0}{4\pi\lambda}\right)^2\left[\ln\left(\frac{2d}{\pi\xi}\cos\frac{\pi x_0}{d}\right)+0.38\right]-\frac{H\phi_0 d^2}{32\pi\lambda^2}\left(1-\frac{4x_0^2}{d^2}\right)-\frac{J\phi_0 x_0}{c}$$

Self-energy | **Magnetic energy** | **Lorentz force × x_0**

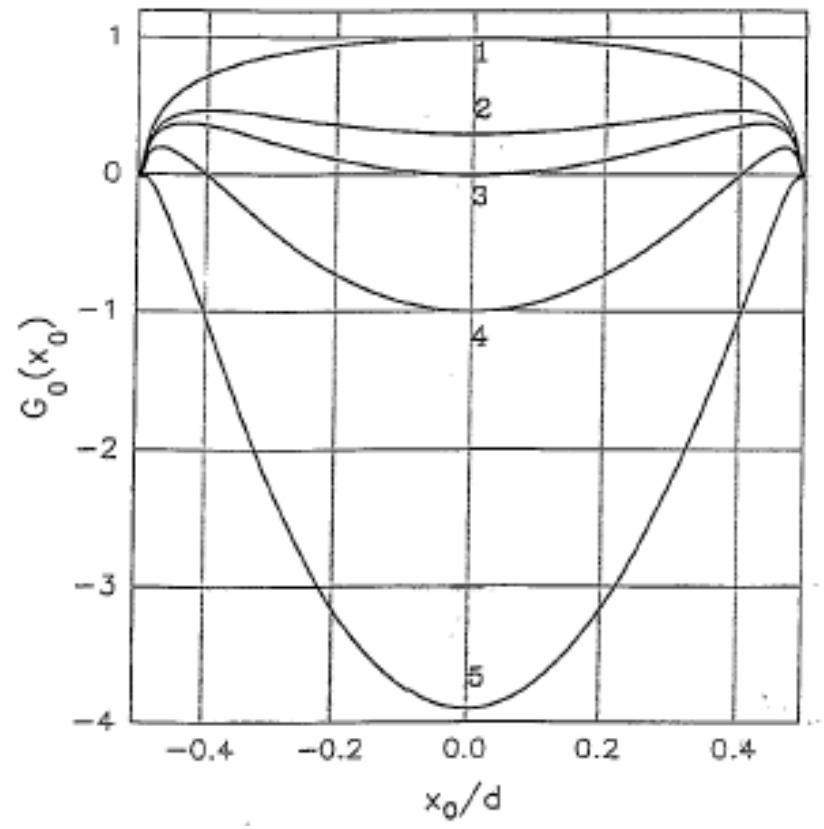
Enhanced lower critical field and surface barrier in films

Use thin films with d < λ to enhance the lower critical field

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

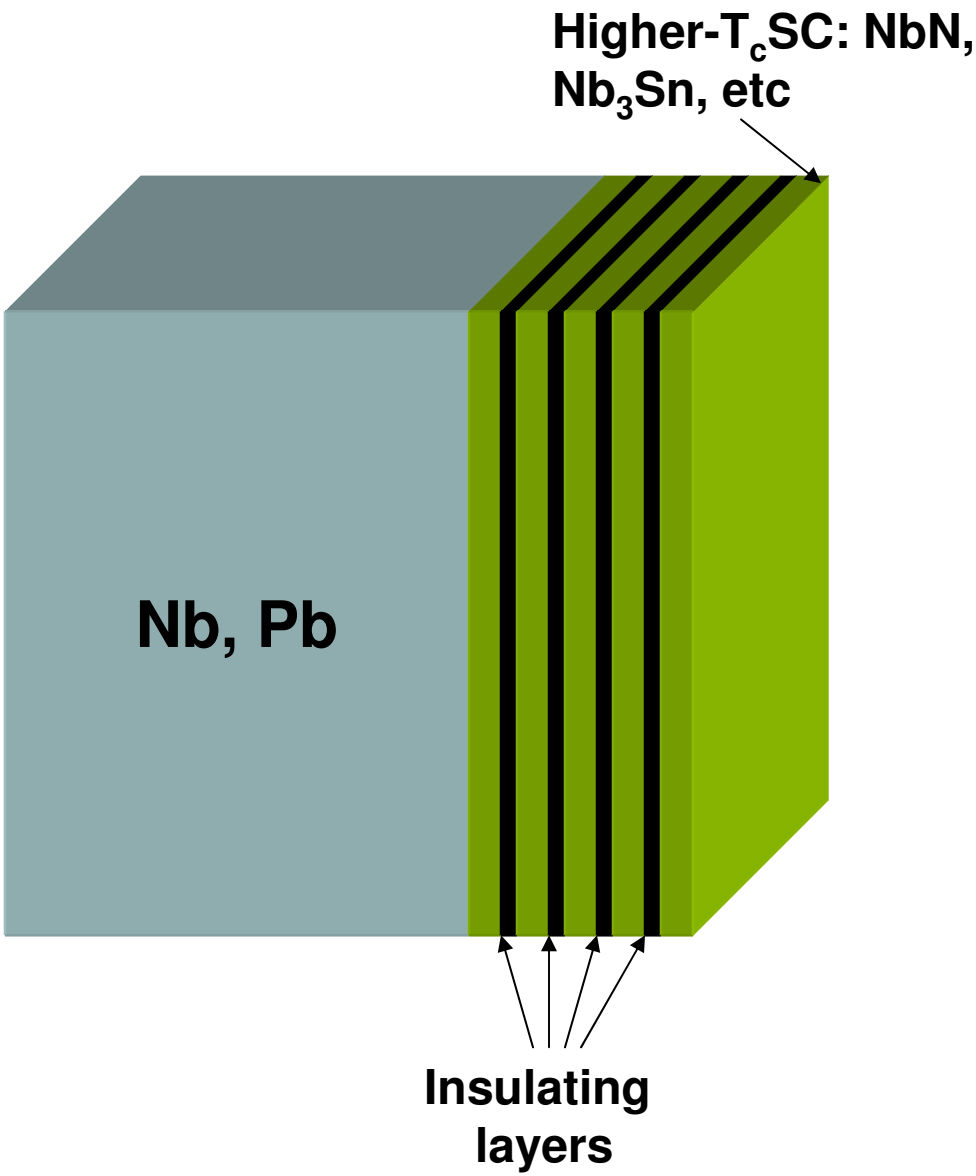
Field at which the surface barrier disappears

$$H_s = \frac{\phi_0}{2\pi d\,\xi}$$



Example: NbN (ξ = 5nm) film with d = 20 nm has H_{c1} = 4.2T, and H_s = 6.37T, Much better than H_c = 0.18T for Nb

How one can get around small H_{c1} in SC cavities with T_c > 9.2K?



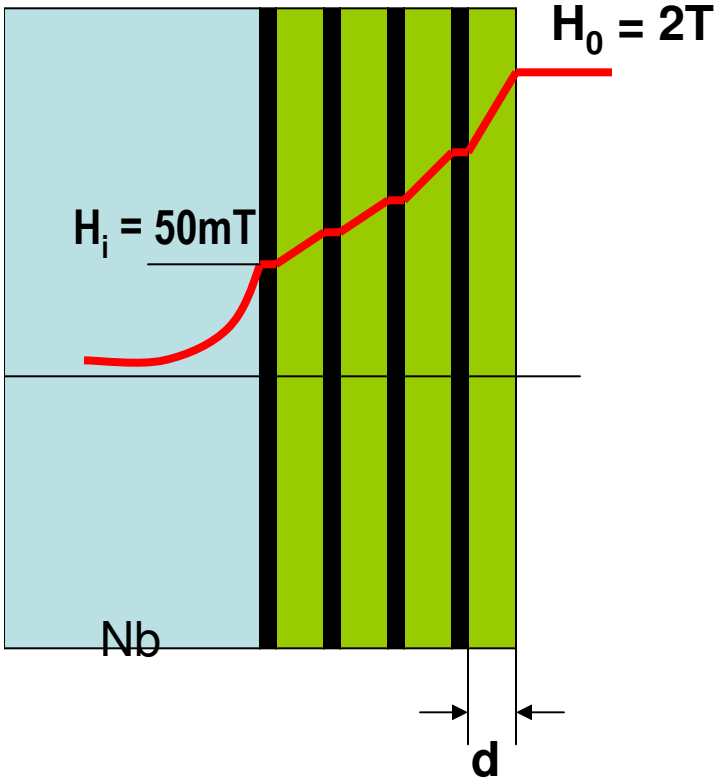
Multilayer coating of SC cavities: alternating SC and insulating layers with $d < \lambda$

Higher T_c thin layers provide magnetic screening of the bulk SC cavity (Nb, Pb) without vortex penetration

For NbN films with d = 20 nm, the rf field can be as high as 4.2 T !

No open ends for the cavity geometry to prevent flux leaks in the insulating layers

How many layers are needed for a complete screening?



Example: Nb_3Sn layers with d = 30nm
λ_0 = 65 nm and H_{c1} = 2.4T

Peak rf field H_0 = 2T < H_{c1}

Internal rf field H_i = 50 mT (high-Q regime)

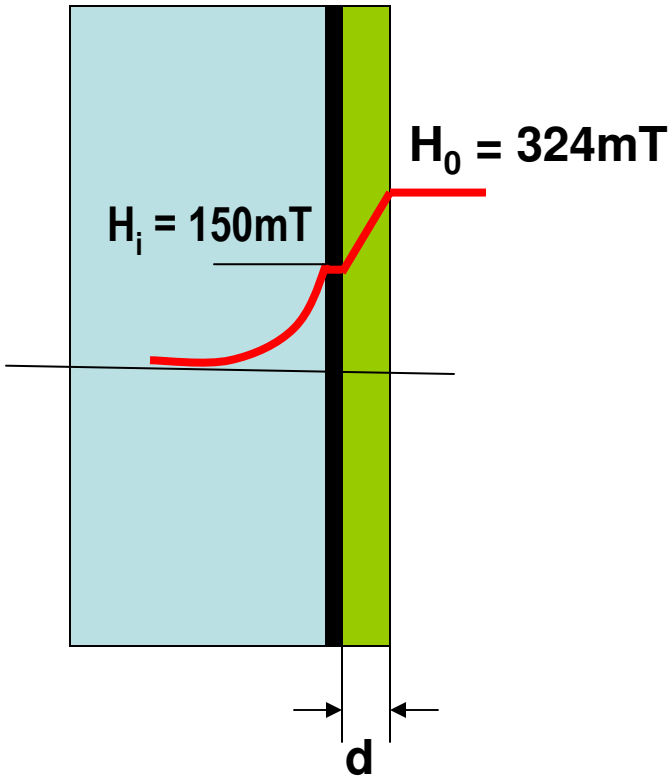
$$H_0 \exp(-\frac{dN}{\lambda_0}) = H_i \qquad \Rightarrow \qquad N = \frac{\lambda_0}{d} \ln \frac{H_0}{H_i}$$

N = (65/30)ln(40) = 8

Strong reduction of the BCS resistance by Nb_3Sn layers due to larger Δ and shorter λ:

$$R_s \propto \frac{\mu_0^2 \omega^2 \lambda^4 \Delta n_0}{k_B T p_F} \left[\ln\left(\frac{\Delta}{\hbar\omega}\right) + C_0 \right] \exp\left(-\frac{\Delta}{k_B T}\right)$$

A minimalistic solution



A Nb cavity coated by a single Nb_3Sn layer of thickness d = 50nm and an insulator layer in between

If the Nb cavity can withstand H_i = 150mT, then the external field can be as high as

$$H_0 = H_i \exp(d/\lambda_0) =$$
$$150 \exp(50/65) = 323.7 mT$$

Lower critical field for the Nb_3Sn layer with d = 50 nm and ξ = 3nm:
H_{c1} = 1.4T is much higher than H_0

A single layer coating more than doubles the breakdown field with no vortex penetration, enabling E_{acc}~ 100 MV/m

Conclusions:

- Multilayer S-I-S-I-S coating could make it possible to take advantage of superconductors with much higher H_c, than those for Nb without the penalty of lower H_{c1}

- Strong increase of H_{c1} in films allows using rf fields >> H_c of Nb, but lower than those at which flux penetration in grain boundaries may become a problem

- Strong reduction of BCS resistance because of using SC layers with higher Δ (Nb_3Sn, NbN, etc)

- The significant performance gain may justify the extra cost.