Effect of materials defects on the physics of SRF

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What defects may be important

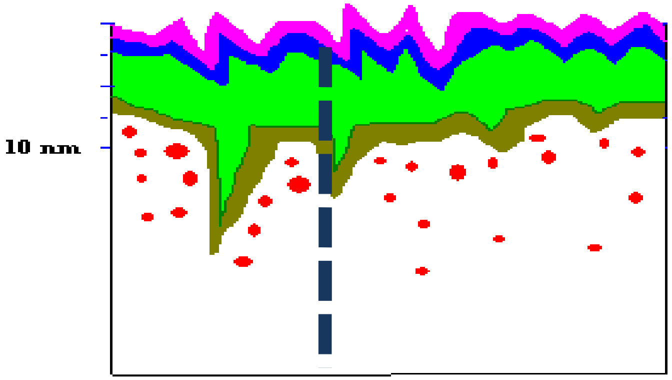
- Only defects in the <u>100-400</u> nm surface layer are relevant for SRF

- Nanoscale oxide layers
  - Normal surface layers: suppression of superconductivity by proximity effect
  - Supply of impurities which suppress superconductivity at the surface

- Impurities
  - nonmagnetic
  - magnetic

- Grain boundaries
  - current blocking effects
  - impurity segregation

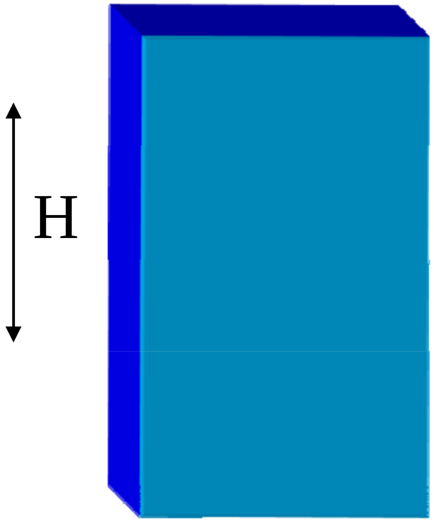
- Is pinning of vortices important for SRF?
  - penetration of vortices
  - trapped vortices
  - vortex hotspots



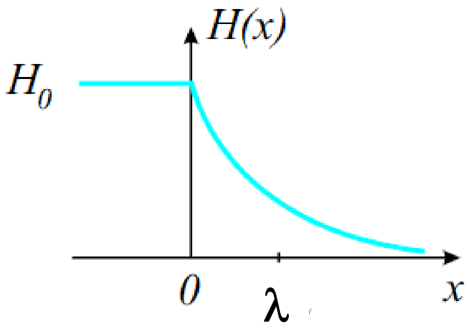
Hydrocarbons & impurities
Nb hydroxides
Nb_2O_5, dielectric
NbO_x $(0.2 < x < 2)$, metallic
NbO_x precipitates
$(0.02 < x < 0.2)$

It is always “yes/no, but…”

RF field and current density scales



- **Meissner current density $J_s(y)$:**



$$H(y) = H_0 e^{-y/\lambda}, \qquad J_s(y) = \frac{H_0}{\lambda} e^{-y/\lambda}$$

- **For H = 100 mT the Meissner current density in Nb:**

$J_s(0) \approx 2$⑨$10^8$ A/cm^2

- **Maximum (pairbreaking) current density:**

$$J_d \cong \frac{H_c(T)}{\lambda(T)}$$

$J_d(0) \approx 4$ MA/mm^2
for pure Nb

Can pinning of vortices be important in SRF?

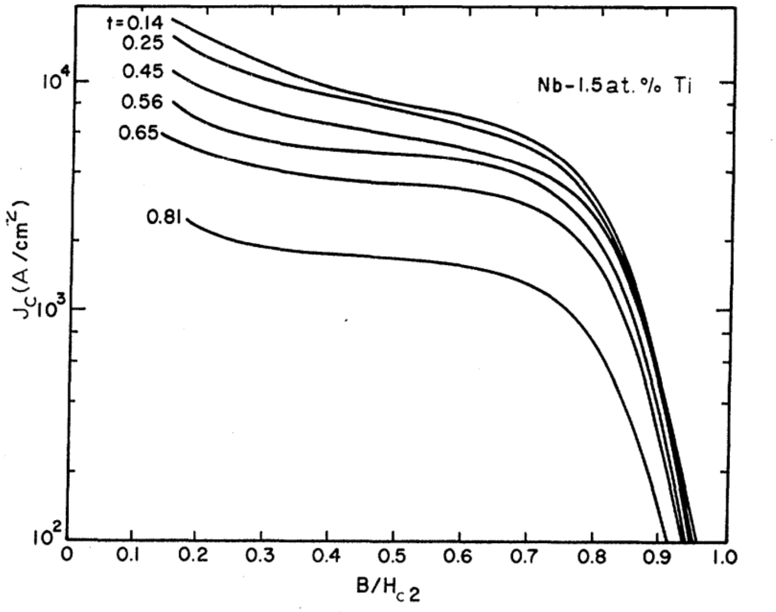
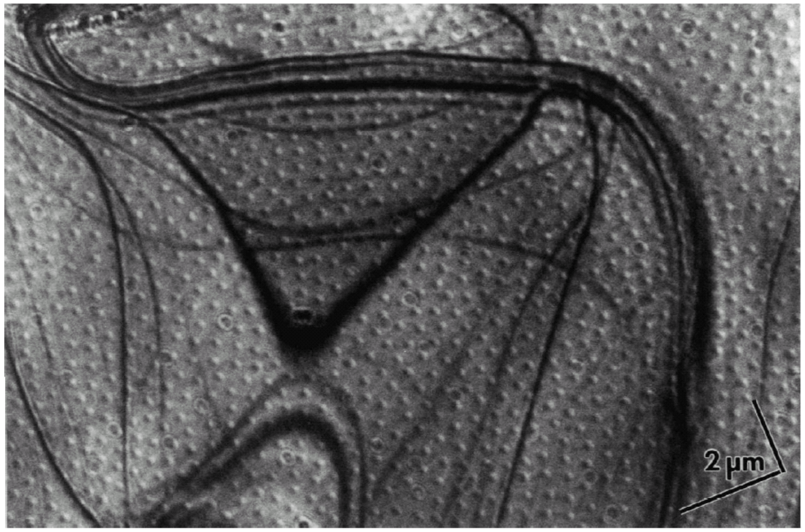


FIG. 4. Logarithmic plot of the critical current density versus reduced field for Nb-1.5 at.% Ti.

Lorentz microscopy of vortex interaction with dislocations. A. Tonomura et al, 2002



Pinning by single dislocations in clean Nb is very weak

Pinning by dislocations in Nb:

W.A. Fietz and W.W. Webb, Phys. Rev. 178, 657 (1967)
A.M. Campbell and J.E. Evetts, Adv. Phys. 20, 199 (1972)

Dislocation networks caused by strong plastic deformation can produce

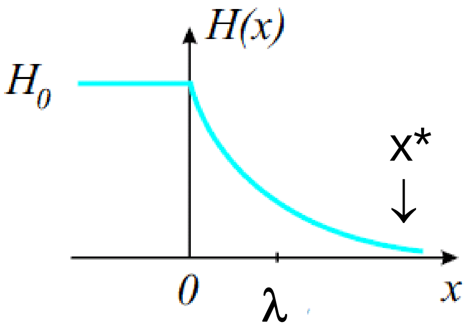
$J_c \sim 10^4 - 10^5$ A/cm^2

Depinning J_c is 3-4 orders of magnitude smaller than the Meissner RF currents at 100mT

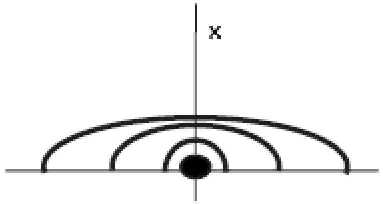
Trapped vortices

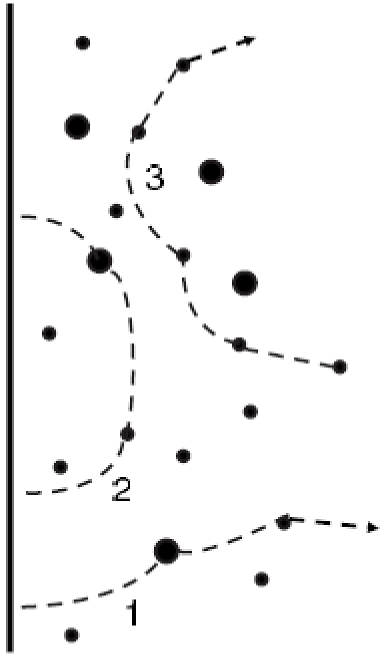
Vortex can be trapped by pinning at the distances above x* from the surface where $J_s(x^*) \sim J_c$

$$x^* \approx \lambda \ln \frac{J_d}{J_c} \cong (8-10)\lambda = 300-400nm$$

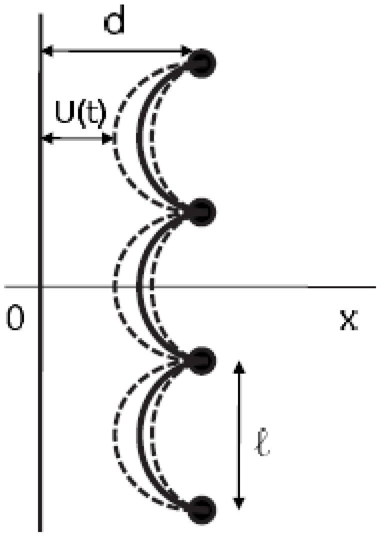


Penetration of single vortices through reduced surface barrier





Oscillating trapped vortices produce hotspots and Q slope

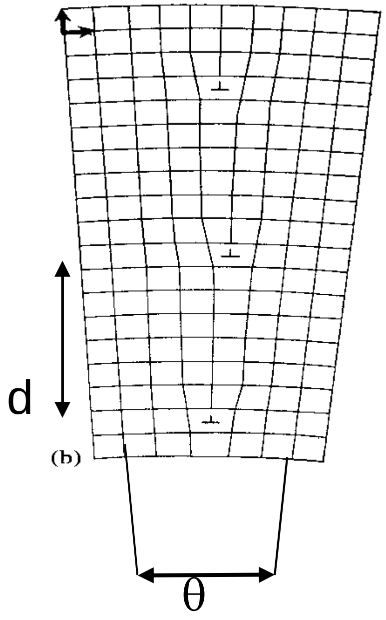


Vortex hotspots can be swiped away by thermal gradients (Ciovati, 2008)

Gurevich and Ciovati, Phys. Rev. B 77, 104501 (2008)
Ciovati and Gurevich Phys. Rev. STAB 11, 122001 (2008)

Types of grain boundaries

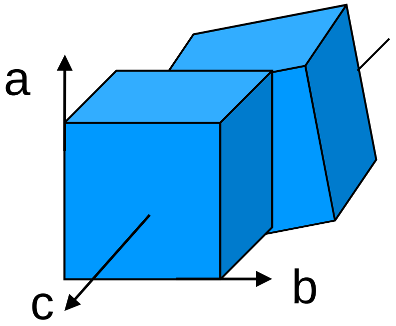
[001] tilt GB

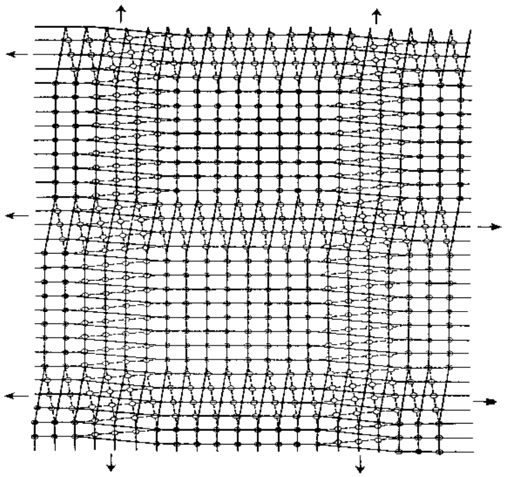


Chain of edge dislocations spaced by

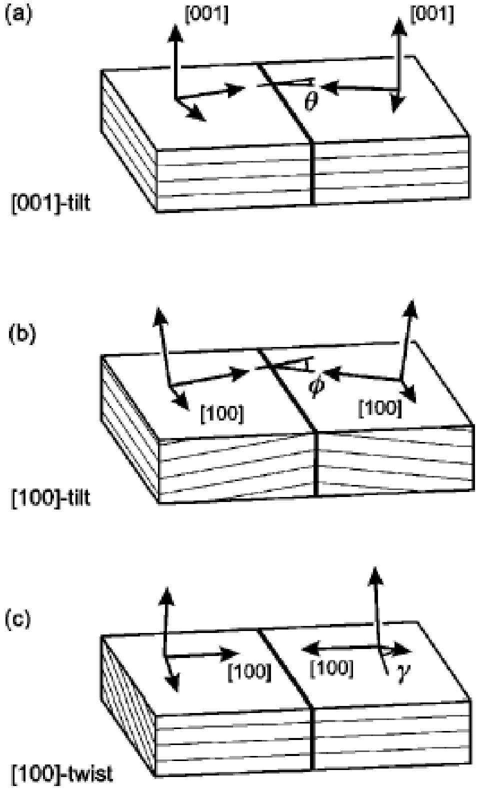
d = b/2sin(θ/2)

Twist GB

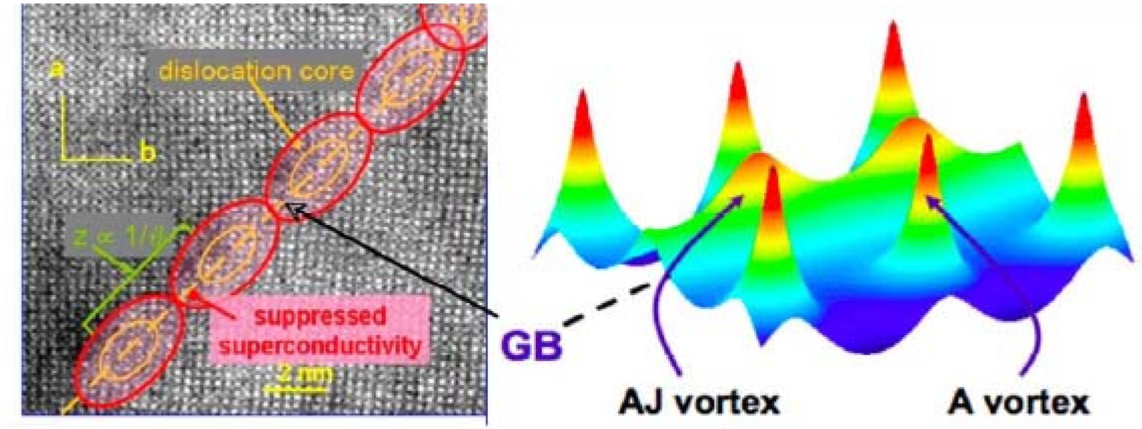




Cellular structure of twist dislocations in the ab plane



Magnetic granularity in polycrystals

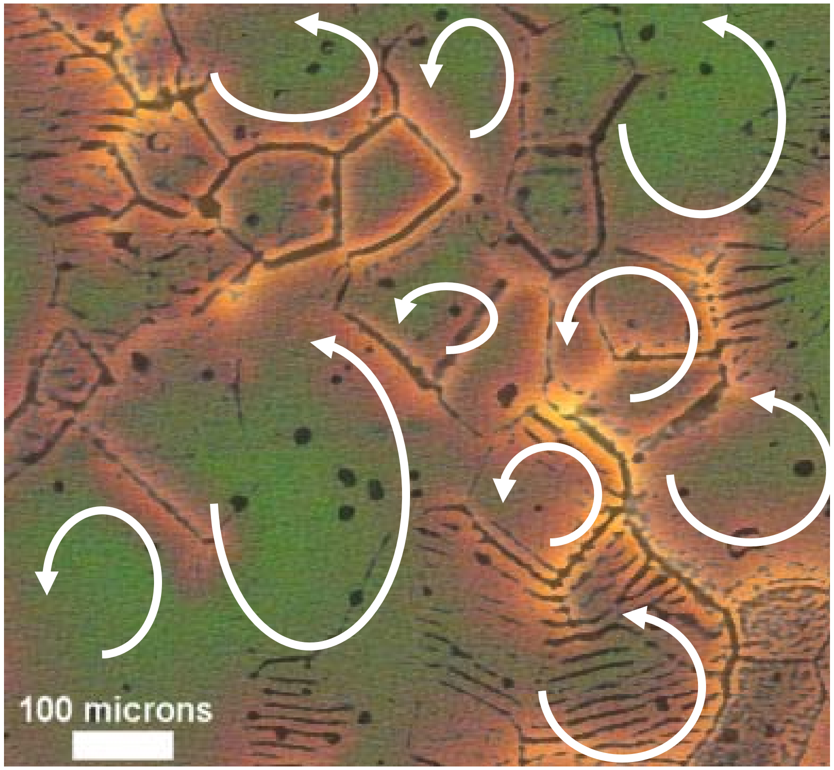


Phys. Rev B, 46, R3187 (1992); Phys. Rev. B 48, 12857 (1993);
Phys. Rev. B 50, 13563 (1994); Phys Rev B 65, 214531 (2002).
Phys Rev Lett 88, 097001 (2002).

- Only small currents can pass through GBs
- Current blocking by GBs is weak if:

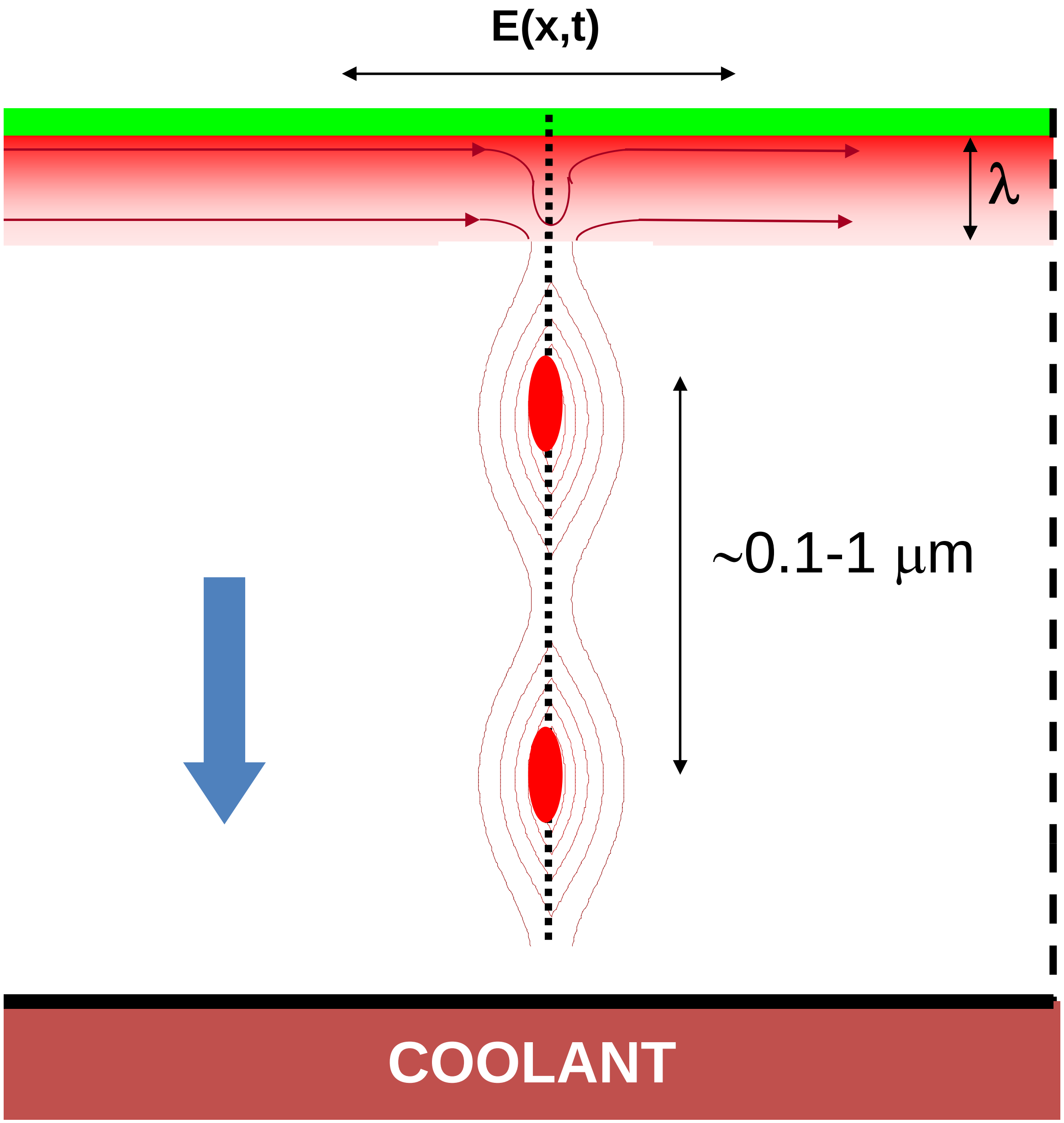
- ξ = 40nm >> lattice spacing √
- screening length << ξ √

Magneto-optical imaging



Polyanskii, Feldmann, 2001

Penetration of vortices along grain boundaries



Are grain boundaries always weak links?

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

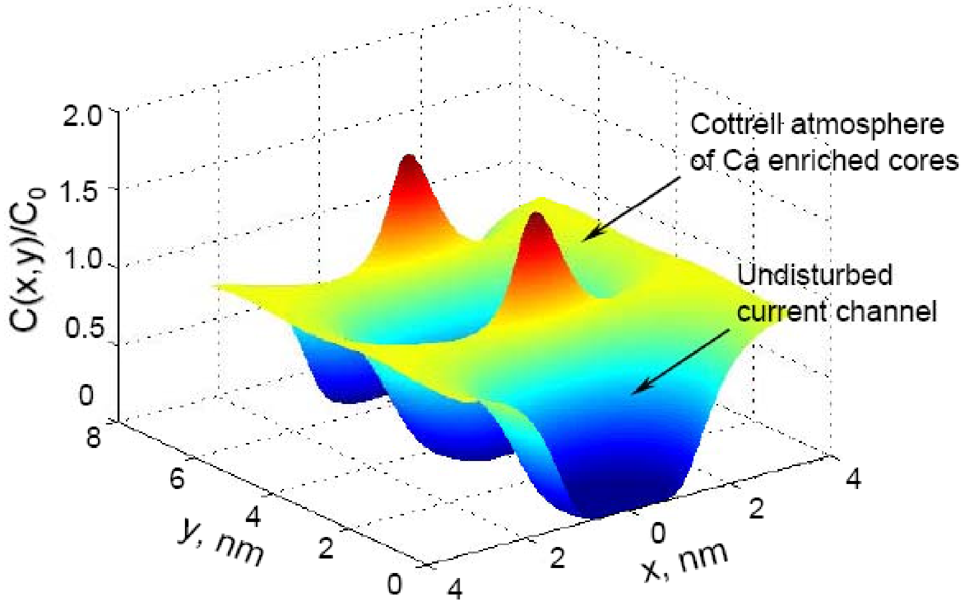
For $J_c < 0.1J_d \sim 10$ MA/cm^2, the onset of vortex penetration along GBs drops below 60 mT

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

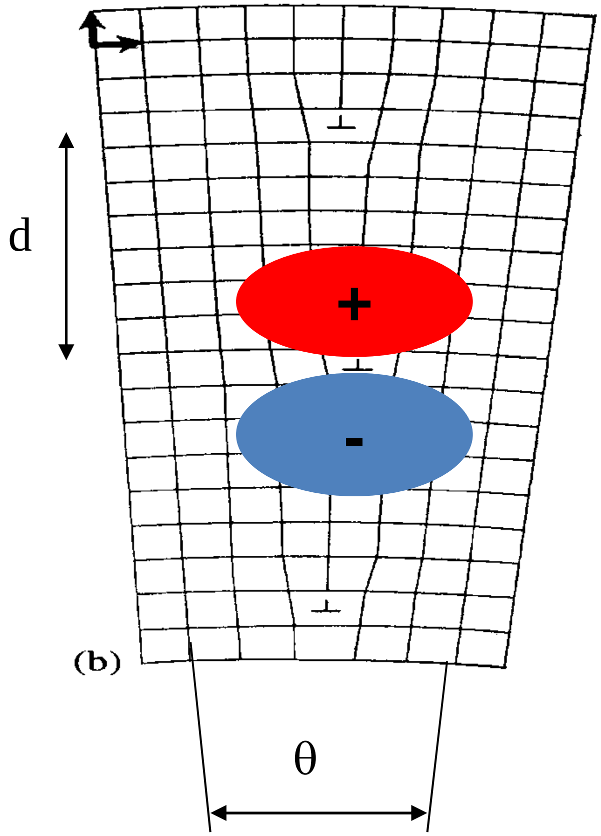
Are grain boundaries in Nb always benign ?

- Impurity poisoning due to segregation and diffusion along GBs

- Cottrell atmospheres of impurities in strain and electric fields of dislocation cores



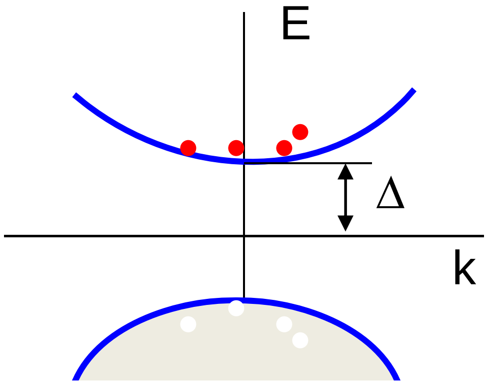
Song, Daniels, Feldmann, Gurevich, Larbalestier, Nature Materials, 4, 470 (2005)



Segregation of big impurities in tensile (-) regions

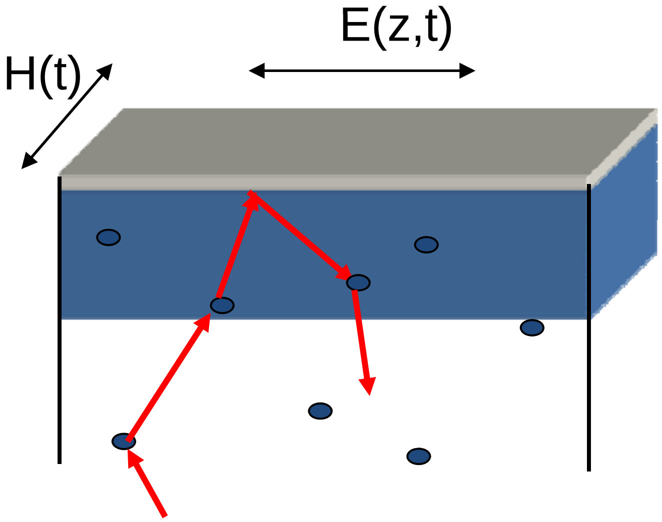
depletion in compressed (+) regions

RF dissipation



- Thermal activation of normal electrons

- **Scattering mechanisms and normal state conductivity**: $\sigma_n = e^2 n_0 \ell / p_F$, $p_F = \hbar (3\pi^2 n_0)^{1/3}$



- **Normal skin effect** ($\ell \ll \lambda$): multiple impurity scattering in the λ - belt:

$$R_s \sim (\mu_0^2 \omega^2 \lambda^3 \sigma_n \Delta / T) \exp(-\Delta/T)$$

- **Anomalous skin effect in the clean limit** ($\ell \gg \lambda$): scattering by the gradient of the rf field:

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

Nonmagnetic impurities

- **Effect on the linear surface resistance**

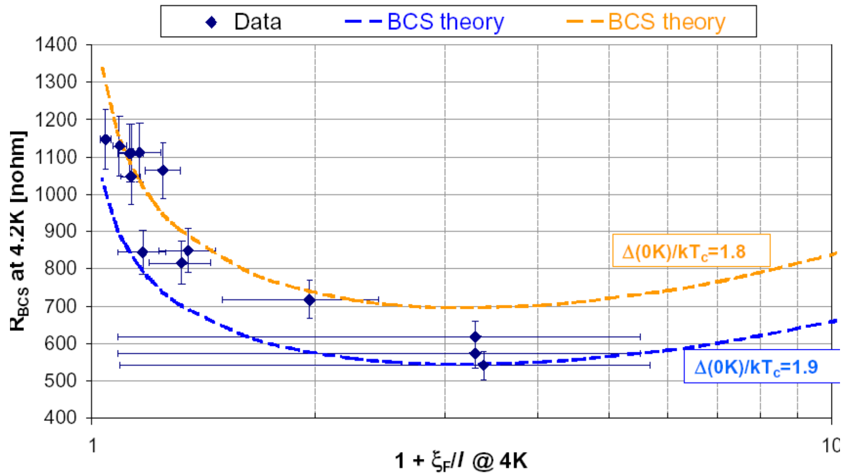
- No suppression of the superconducting gap (Anderson theorem)

- Increase of the London penetration depth

- Increase of the BCS surface resistance

- Decrease the lower critical field (the onset of vortex penetration)

BCS surface resistance vs. mean free path



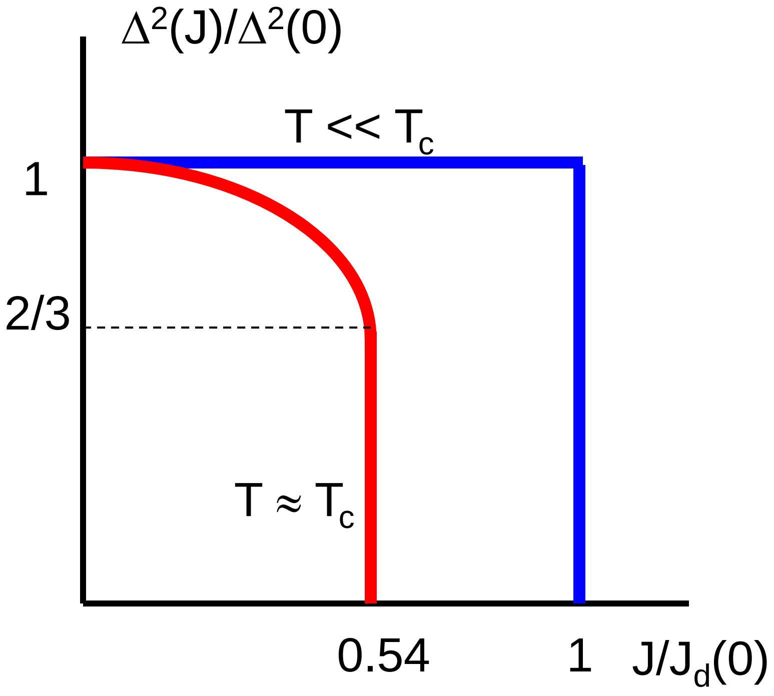
11th SRF Workshop, Travemünde, September 8th – 12th 2003

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

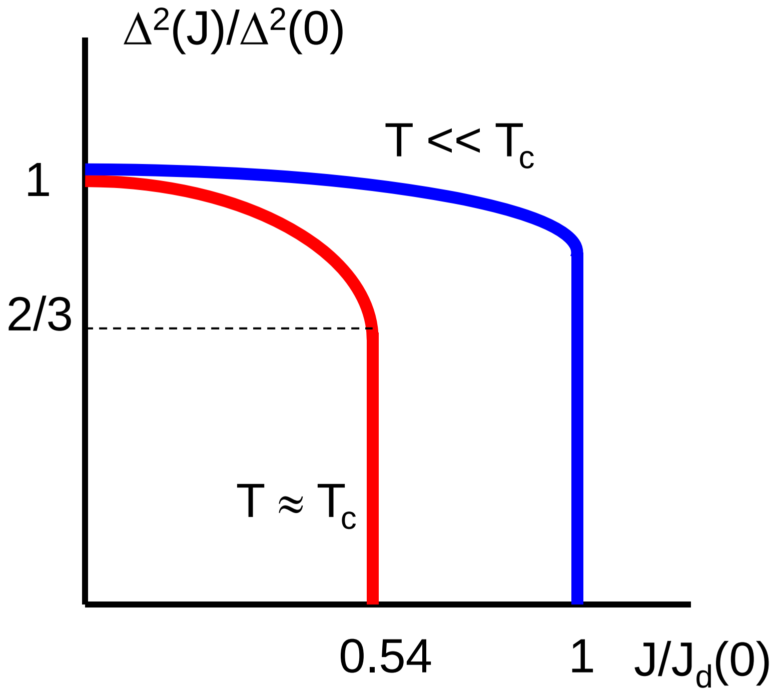
E. Palmieri

Current dependence of the SC gap

- **Clean limit ($\ell >> \xi_0$)**



- **Dirty limit ($\ell << \xi_0$)**



In the clean limit the gap $\Delta(J)$ is independent of RF field at low T

J. Bardeen, Rev. Mod. Phys. 34, 667 (1962).

Nonlinear Meissner effect

- Linear Meissner effect in the clean limit up to $H = H_c$

- Nonlinear Meissner effect in the dirty limit: Field-dependent penetration depth calculated from the Usadel equations:

$$\lambda^2(H) \cong \lambda^2\left[1 + a\left(\frac{H}{H_c}\right)^2\right], \qquad a = \frac{3\pi}{64} + \frac{1}{4\pi} \approx 0.23$$

- Increase R_s ✪ $\lambda^3(H)$ and the kinetic inductance L_K of the Cooper pairs in a film of length ℓ , width w and thickness $d < \lambda$:

$$L_k = \mu_0 \lambda^2(H)\ell / wd$$

- Shift of the resonance frequency $f = (C/L)^{1/2}$ of a thin film resonator

$$\delta f / f = -\mu_0 \ell[\lambda^2(H) - \lambda^2]/2Ldw$$

enabled us to measure the nonlinear Meissner effect in a dirty 65 nm Nb film

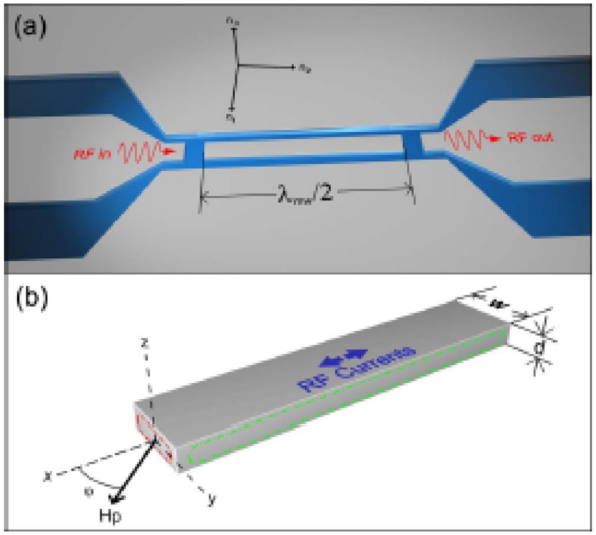
Groll, Gurevich and Chiorescu, Phys. Rev. B81, 020504(R) (2010).

Nonlinear Meissner effect in a thin Nb film

f ≈ 20 GHz, T = 80 mK

GROLL, GUREVICH, AND CHIORESCU

PHYSICAL REVIEW B **81**, 020504(R) (2010)



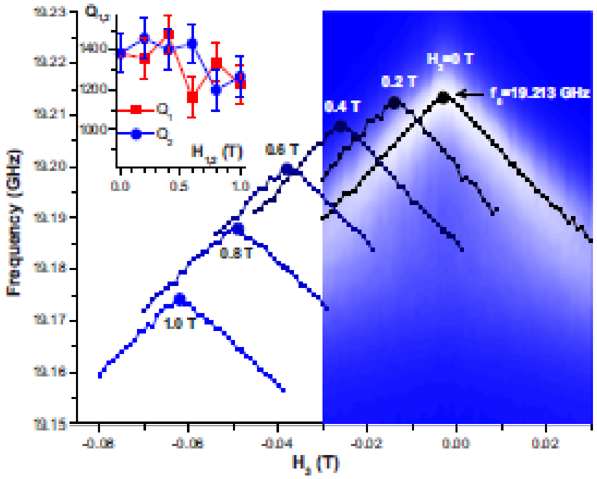
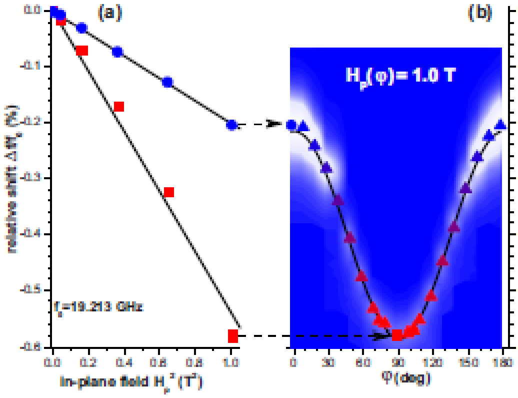


FIG. 2. (Color online) Contour plot of amplified cavity trans-mission for variable H field while H=0 T (blue/gray; 0 μW

MEASUREMENT OF THE NONLINEAR MEISSNER EFFECT…



Dependence of δf on the orientation of the in-plane dc magnetic field:

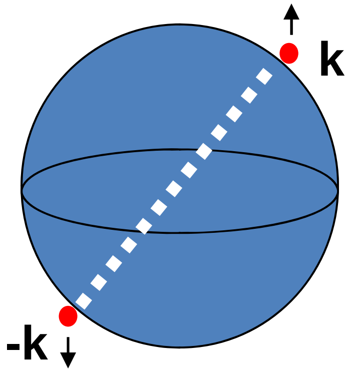
δf ✪ $2 - \cos 2\varphi$

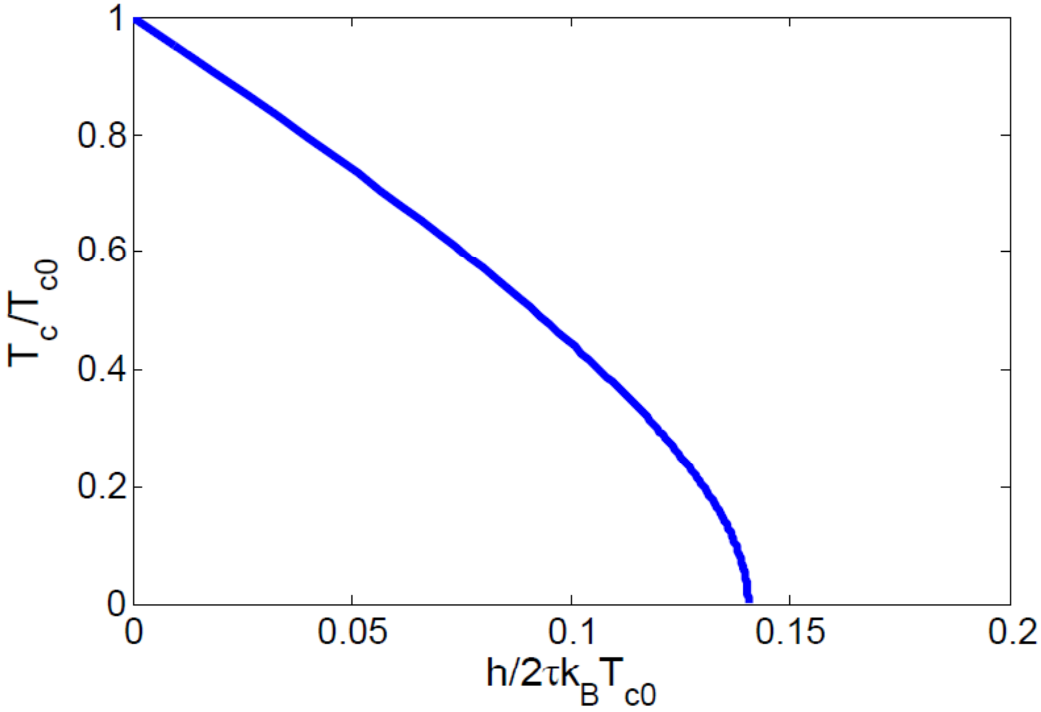
- **Excellent agreement between theory and experiment**
- **Seven-fold increase of the onset of the vortex field penetration in a dirty Nb thin film with $d < \lambda$ up to 1T: $H < H_{c1} = (2\phi_0/\pi d^2)\ln(d/\xi)$**
- **Proof of principle of the multilayer coating idea**

Magnetic impurities

- **Suppression of T_c and superconducting gap by spin-flip scattering by magnetic impurities**

- **Gapless superconductivity**





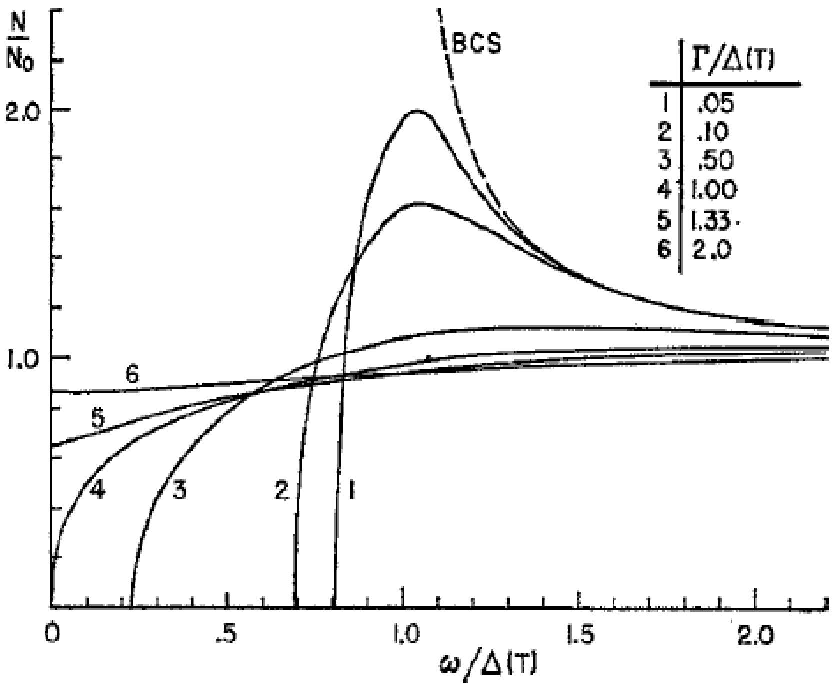
Spin flip scattering time:

$$\frac{1}{\tau_s} = n_s N_F S(S+1) \int |J(k)|^2 \, d\Omega$$

Magnetic impurities in the 100 nm surface layer strongly increase R_s

Abrikosov and Gorkov, 1960

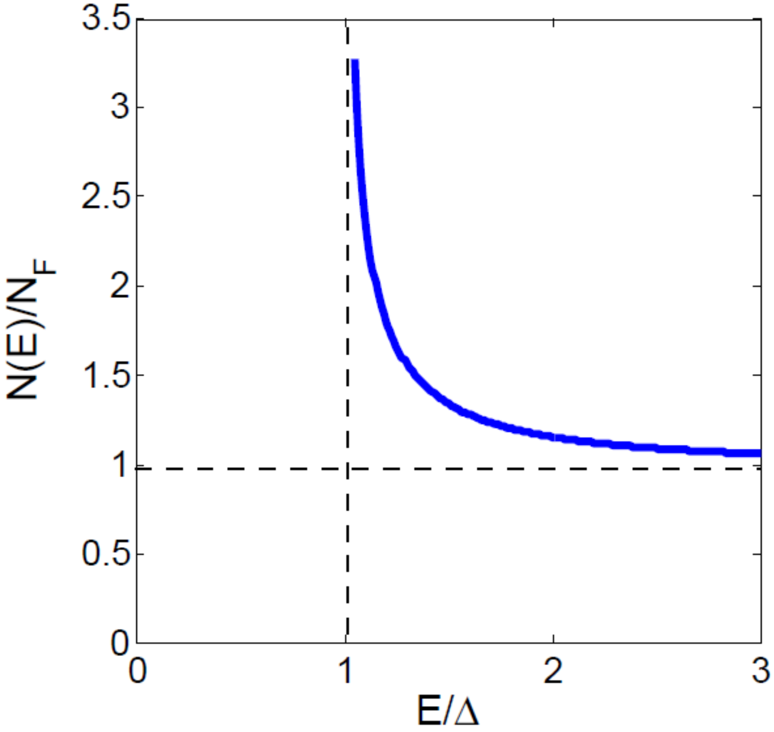
Filling up the superconducting gap



Skalski et al (1964); Ambegaokar and Griffin (1965)

Effect of weak magnetic impurities:

- **smearing up N(E) and reduction of the gap**
- **gapless superconductivity at large $\Gamma=1/\tau_s$**
- **giant increase of R_s**



Ideal BCS density of states which provides the BCS surface resistance

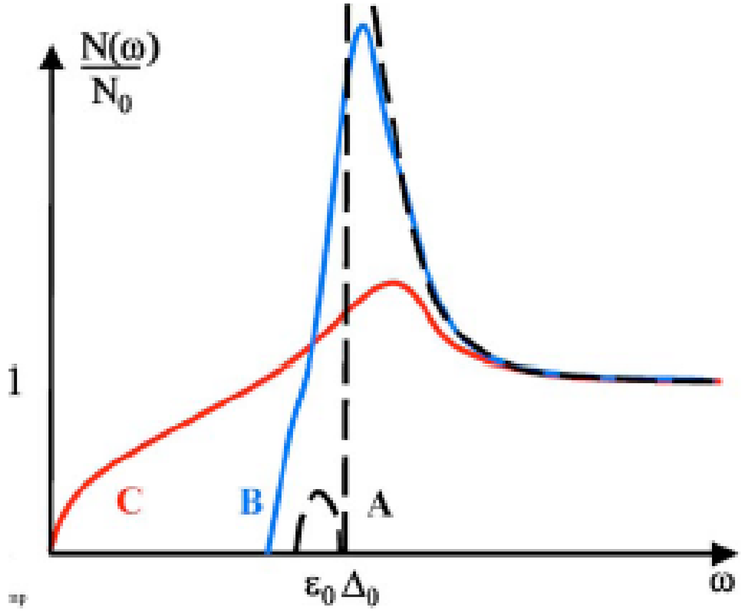
Small concentration of magnetic impurities

Localizes states on magnetic impurities at energies below the SC gap

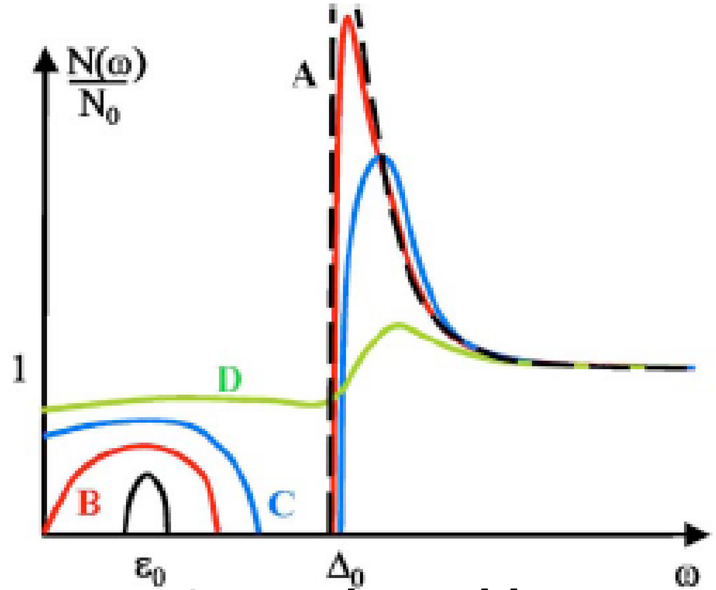
(Shiba (1968); Rusinov (1968))

Can be revealed by point contact tunneling spectroscopy

(Prosslier, Zasadzinskii, Cooley, Pellin et al, Appl. Phys. Lett. 92, 212505 (2008),



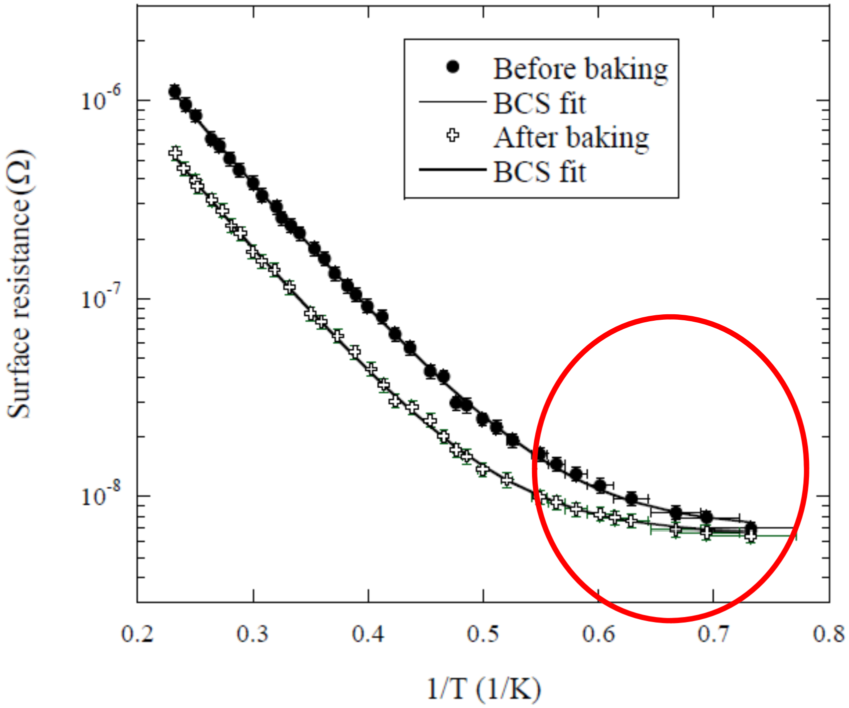
Weak impurities



Strong impurities

- Shiba magnetic impurity band reduces the activation energy of $R_s(T)$
- Finite density of states at E=0 causes non-exponential $R_s(T)$
- A mechanism of residual resistance

Defects and residual resistance



Ciovati, 2005

Requires a finite density of states at the Fermi surface

Can result from hotspots caused by:

- Trapped vortices
- Thin normal islands of sub-oxides
- Magnetic impurities at the surface

Neither of these factors can be definitive, to be compatible with $Q = 10^{10}$

Conclusions

- **Point and extended defects can seriously limit the SRF performance but universal answers good for all circumstances can be obtained**
- **Some defects (i.e. impurities or GBs) can be both bad and benign depending on the rf field and temperature**
- **Magnetic impurities and vortices are always bad for SRF**
- **New SRF physics produced by defects (nonlinear Meissner effect, vortex hotspots, residual resistance, etc.)**
- **Measurements of the nonlinear Meissner effect revealed the 5-fold increase of the vortex penetration field in a thin Nb film**