Using impurities to tune superheating and RF break-down fields

Fareh Pei-Jen Lin and Alex Gurevich

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Center of Accelerator Science
Physics Department, Old Dominion University

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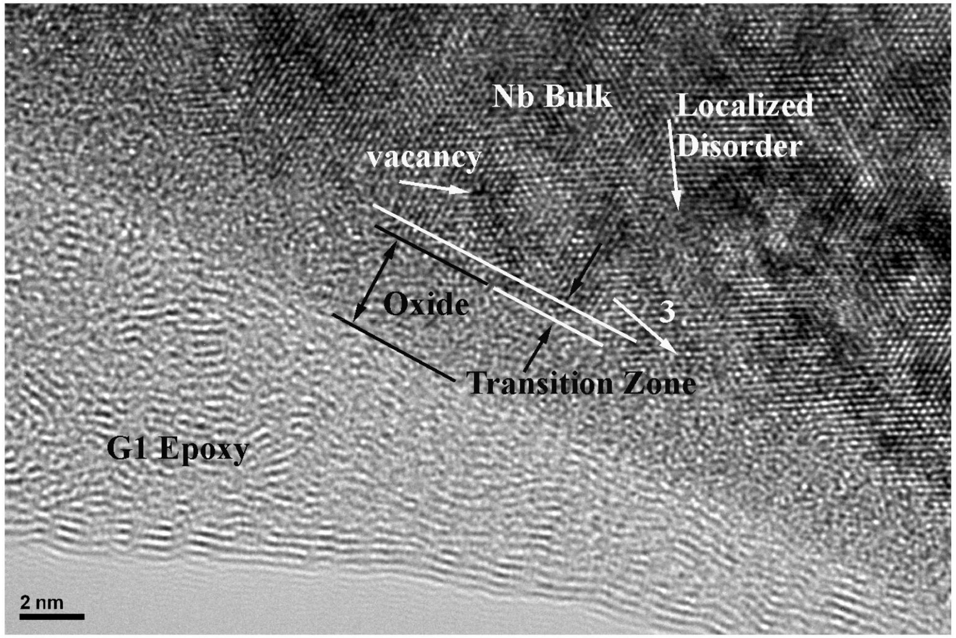
How to improve performance of an SRF cavity?

(Wu and Baumgart 09)



RF penetration depth ~ 45 nm
Clean Nb bulk: $\lambda \approx \xi \sim 40$ nm

- Does cleaner mean better? No.
  - dissipation, AC field, $H \sim H_{sh}$
- Is 'dirty' good? Yes.
  - H_{sh} : $\pm 4\%$
  - dissipation suppressed

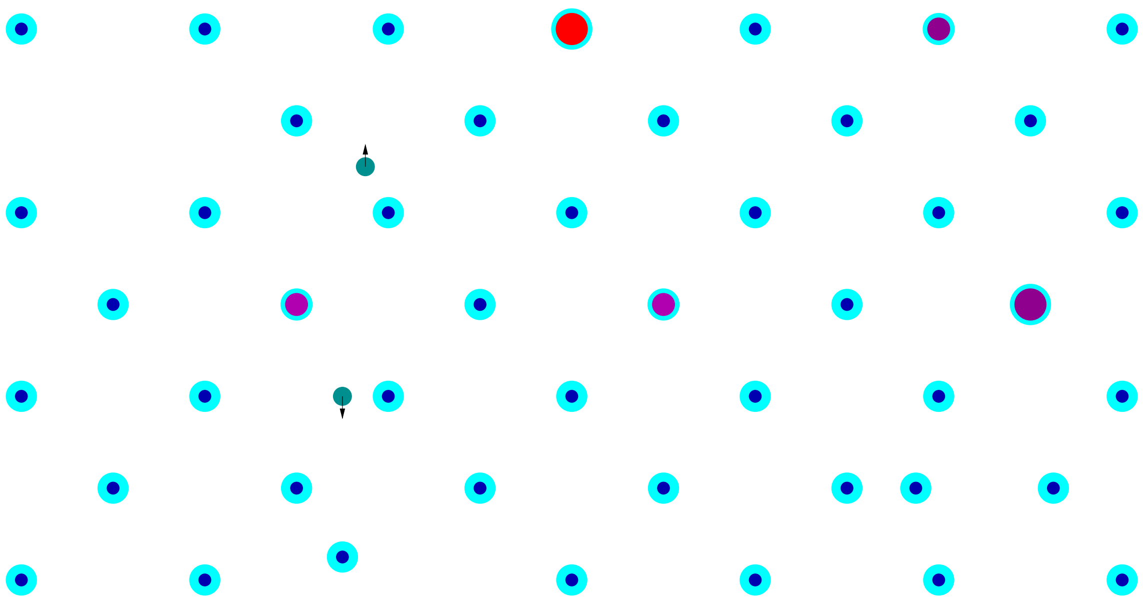
impurities reduce the high field surface resistance and decrease the high-field Q slope: a possible mechanism of the baking effect.

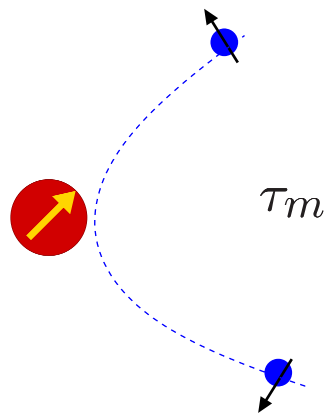
Impurities at atomic scale

+ regular: C, O, H, etc. (non-magnetic)

$$\sigma = ne^2\tau/m \qquad (1)$$

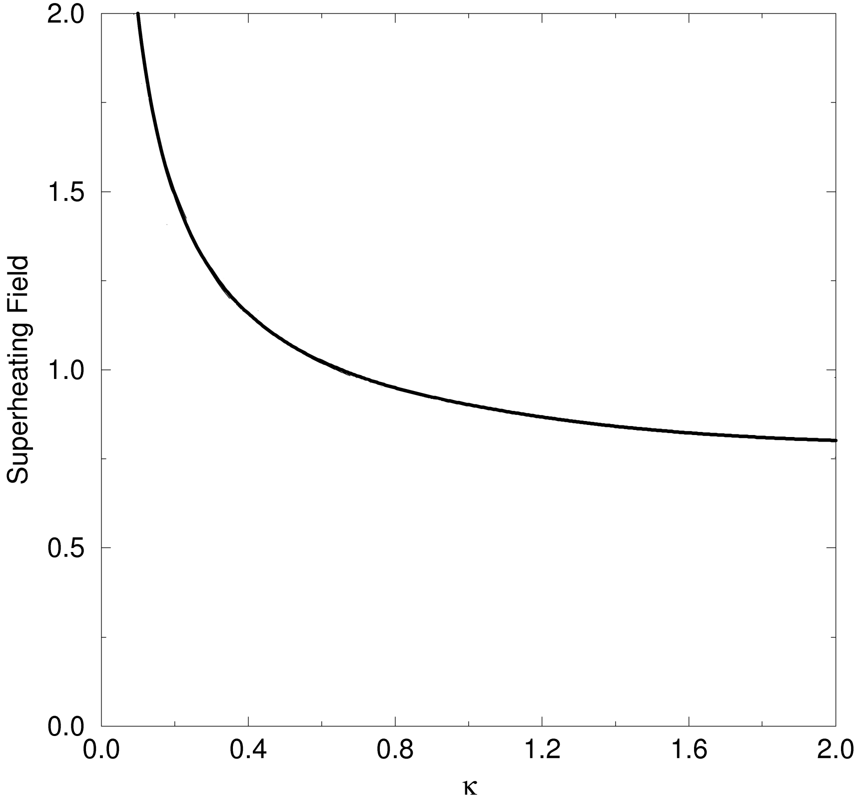
– magnetic: Fe, etc.





Previous results

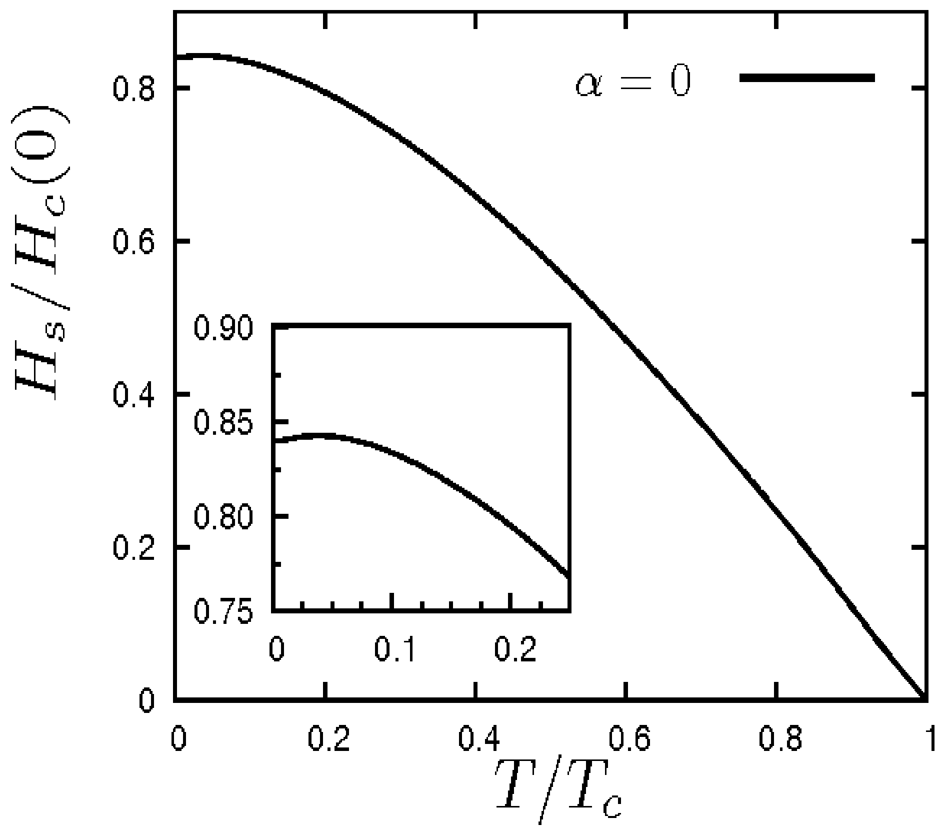
•Ginzburg-Landau, H_{sh} vs κ, $T \approx T_c$



(Ginzburg 58, Maricon and Staint-James 67, kramer 68, Chapman 95,Golgert 95,Transtrum 11 $\cdots$ etc)

•Eilenberger/Gorkov, H_{sh} vs T, $\kappa \gg 1$, clean

(Galaiko 66, Catelani and Sethna 08)



Quasiparticles

QP Density of states at $J \neq 0$

(Maki 63, Fulde 65)

- DC field:
  - + Cooper pairs move
- AC field:
  - + Cooper pairs move
  - − QPs move ⇒ dissipation

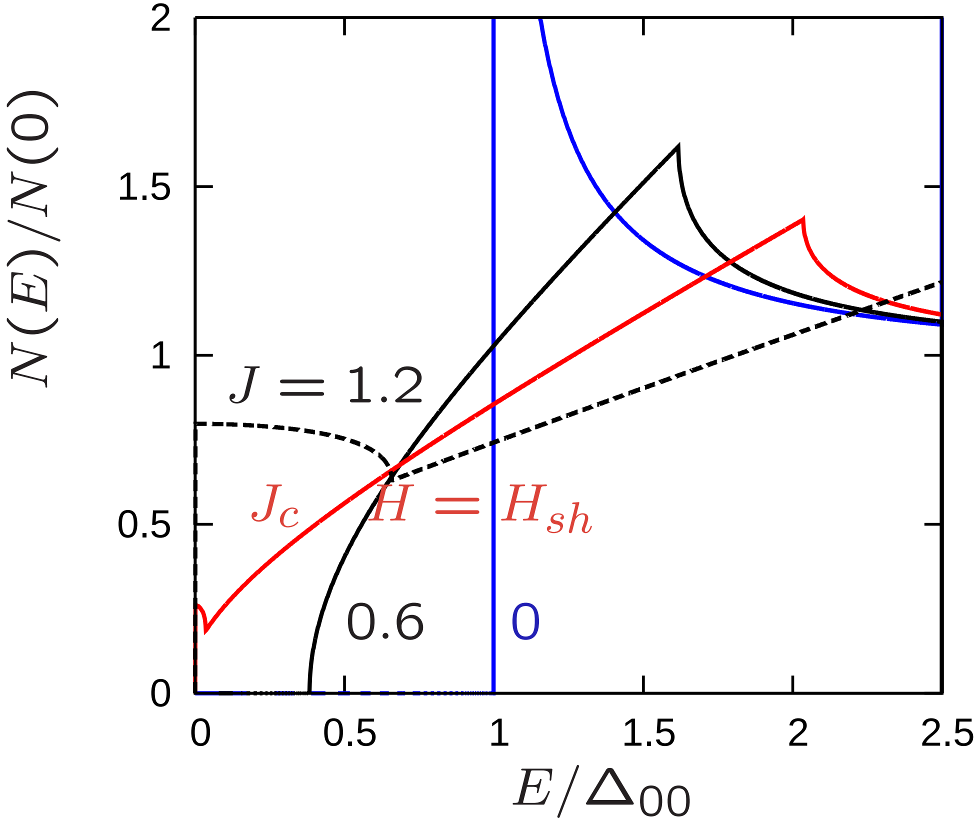
    numbers of QPs

- ∘ Weak field:

$$\log R_s \propto \Delta/T \qquad (2)$$

- ∘ Stong field:

$$\log R_s \propto \epsilon_g/T \qquad (3)$$



Eilenberger Theory of SC with impurities

•two Green functions: $f_\omega(\mathbf{r})$,$g_\omega(\mathbf{r})$

$$(2\omega + i\mathbf{v}_F \cdot (\nabla + i\mathbf{A}))f = 2\Psi g + \left(\frac{1}{\tau} - \frac{1}{\tau_m}\right)\langle f\rangle g - \left(\frac{1}{\tau} + \frac{1}{\tau_m}\right)\langle g\rangle f \quad (4)$$

•Gap equation

$$\Psi \log\frac{T}{T_c} + T\sum_{\omega=0}^{\infty}\left(\frac{\Psi}{\omega} - \langle f\rangle\right) = 0 \quad (5)$$

•Current density

$$\mathbf{J} = eT\mathrm{Im}\sum_{\omega=0}^{\infty}\langle g\mathbf{v}_F\rangle \quad (6)$$

•Free energy

Calculating the superheating field

- H_{sh}: Threshold H of the Meissner state
  $\xi \ll \lambda$, J homogeneous, $H = H_{sh}$, $J = J_c$ at $x = 0$.
  J_c:depairting current density

$$H_{sh}^2(T) = H_c^2(T) + T\sum_{\omega} \omega(2 - \langle g_c \rangle - 1/\langle g_c \rangle) \tag{7}$$

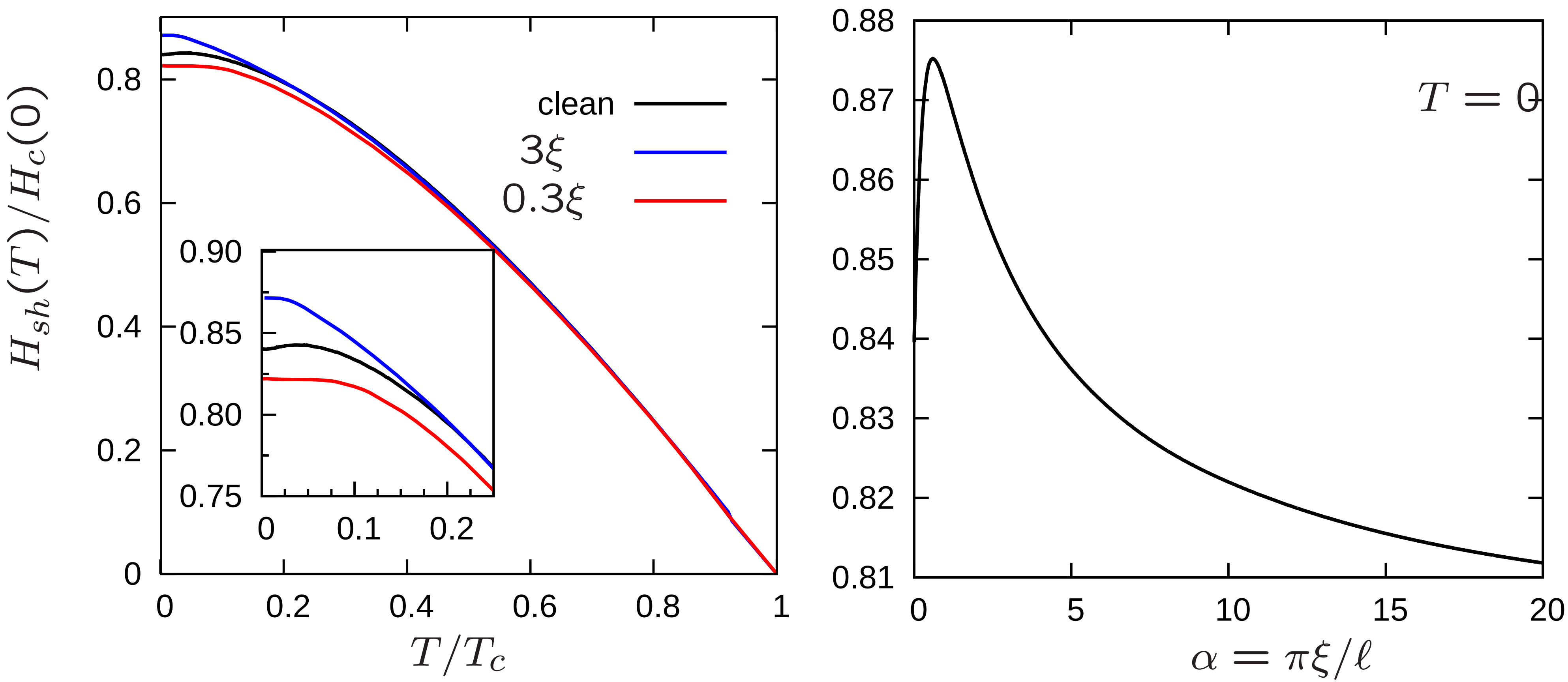
◦ $H_{sh} > H > H_{c1}$: metastable Meissner state

◦ surface effect, $H_{sh} > H_{c1}$

- effect of impurities plus current? DoS?

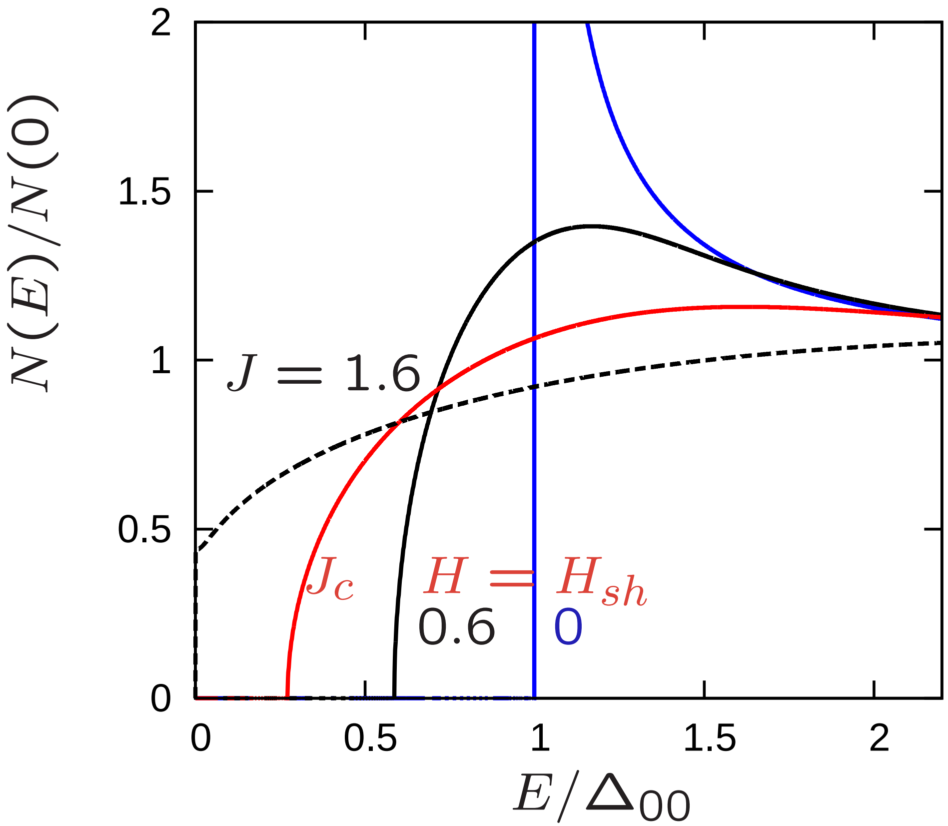
H_{sh}, non-magnetic impurities

- $H_{sh}(T)$ is similar to clean SC
- $H_{sh}^{\text{nonmag}} - H_{sh}^{\text{Clean}} \approx \pm 4\% H_{sh}^{\text{Clean}}$



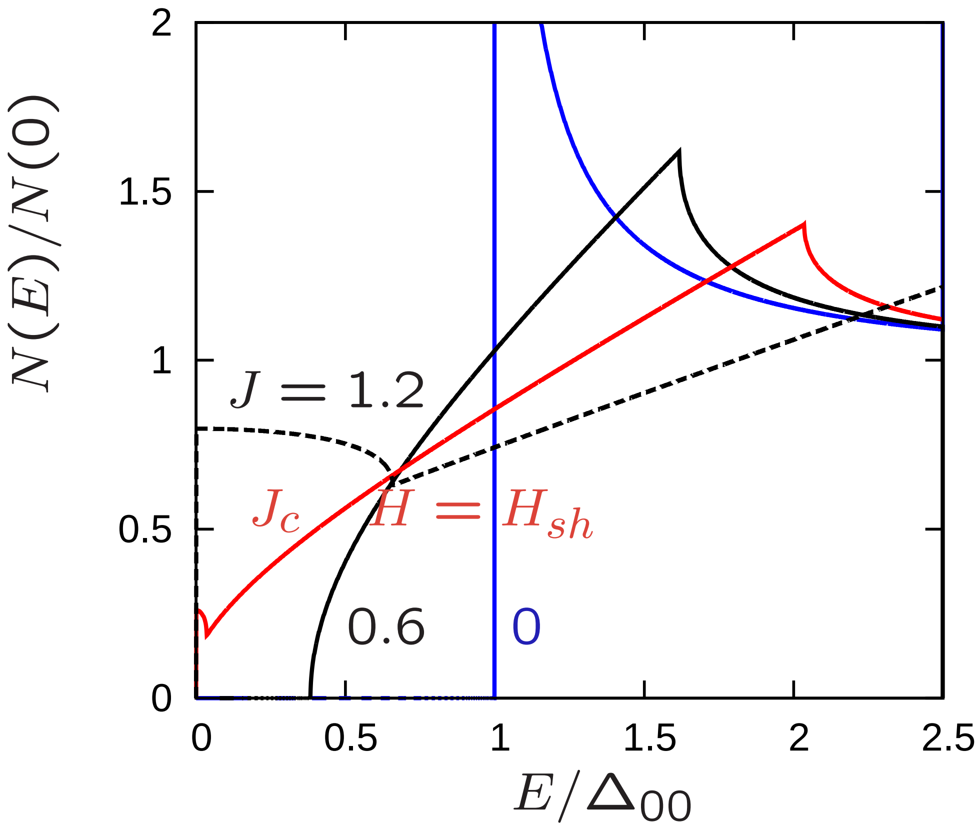
QP DoS at $H = H_{sh}$, non-magnetic impurities

•DoS at various J, $\ell \sim \xi$



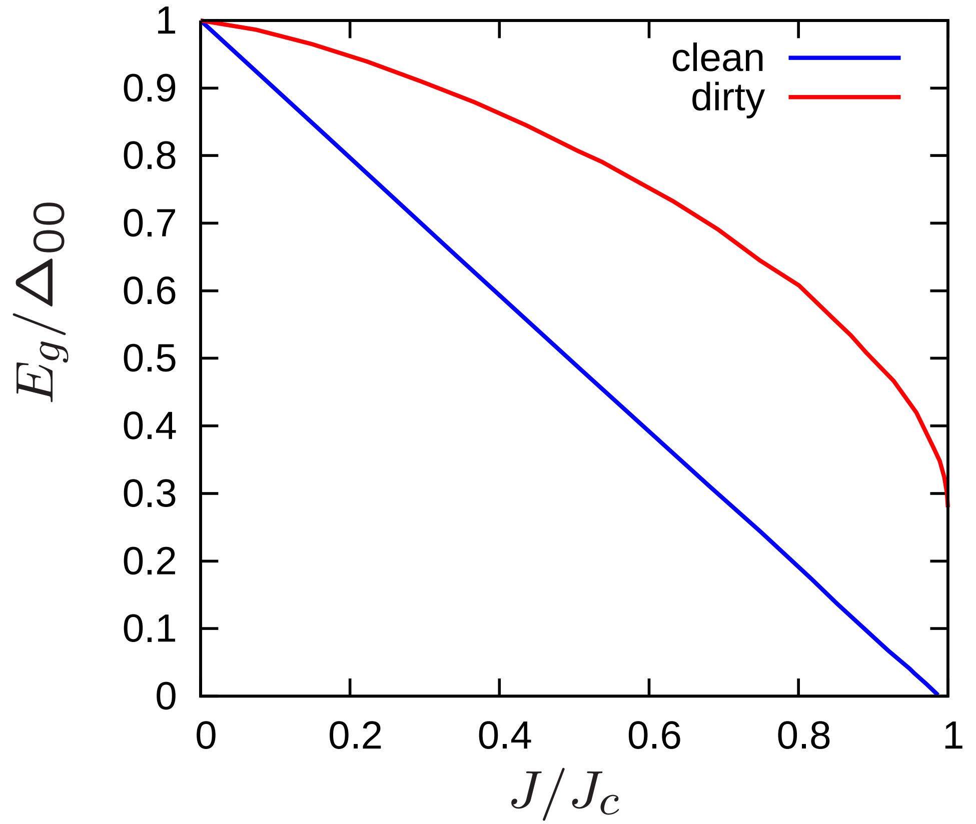
•DoS at various J, clean

(Maki 63, Fulde 65)

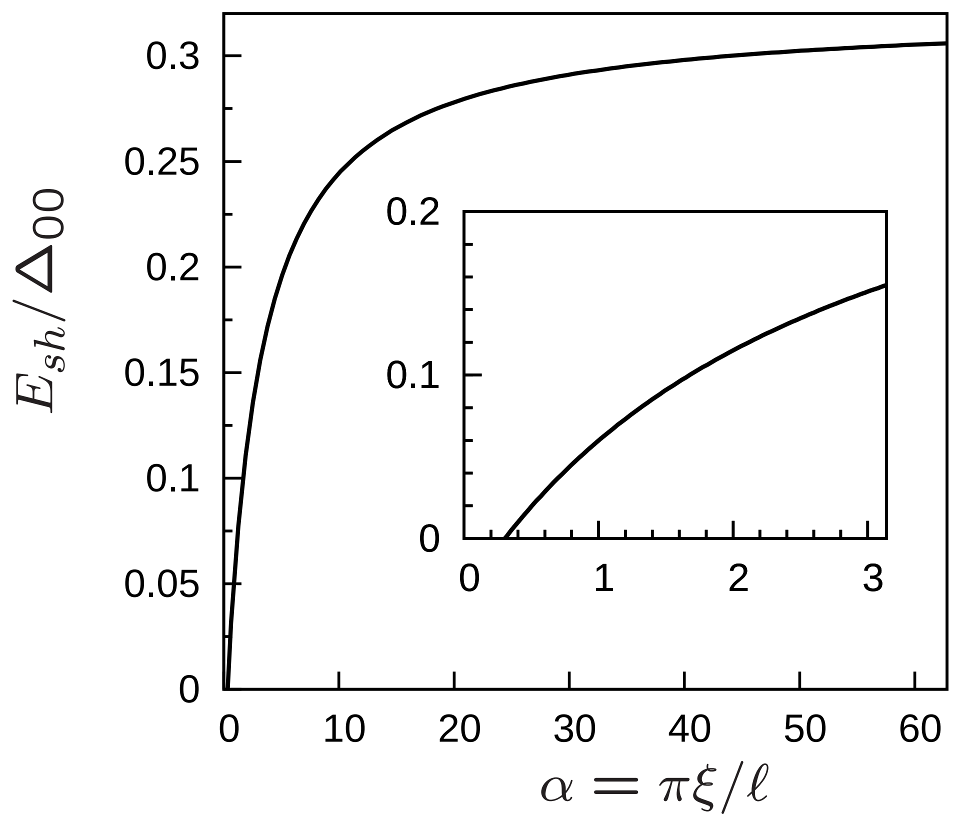


Gap in the spectrum

•E_g vs H

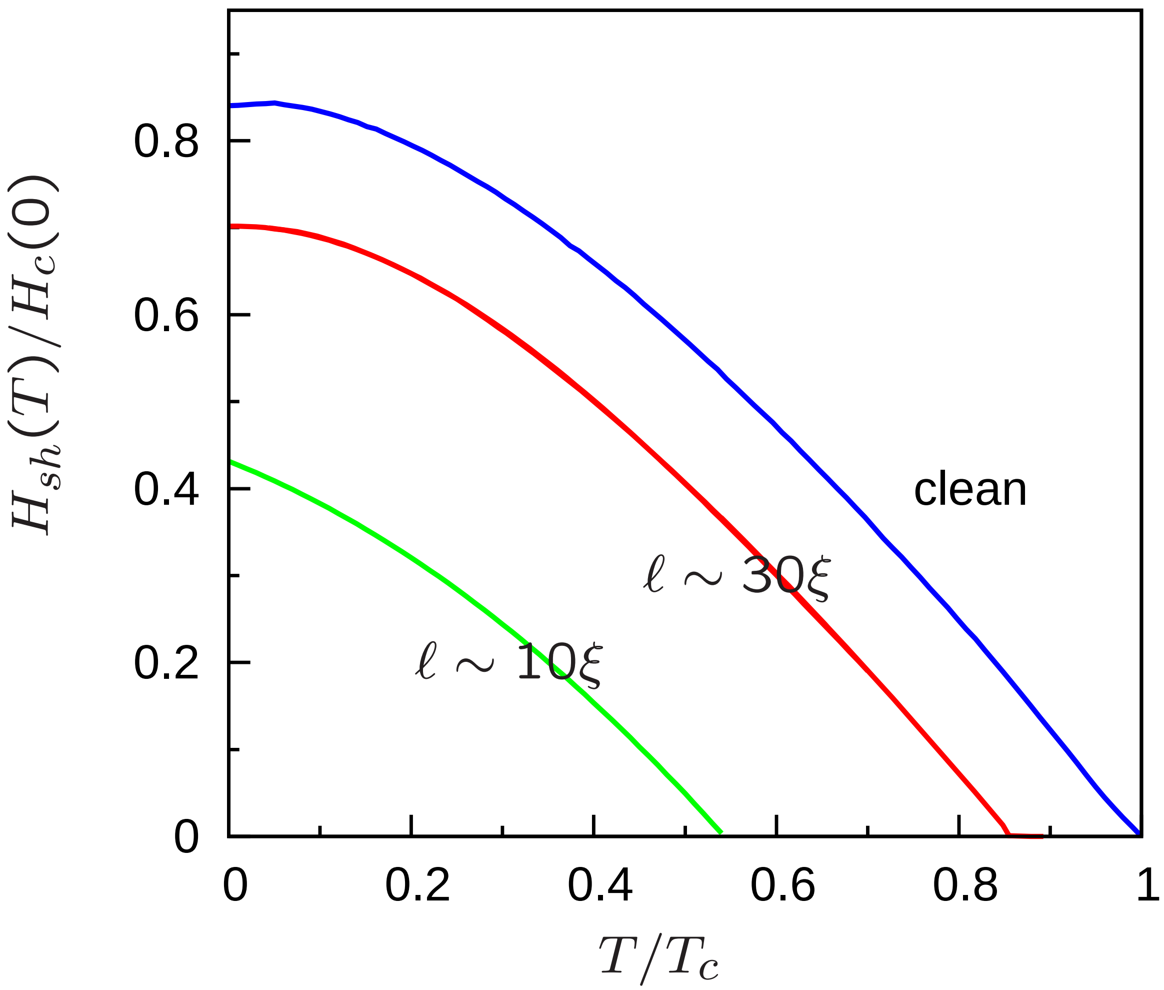


•Gap at $H = H_s$ vs α



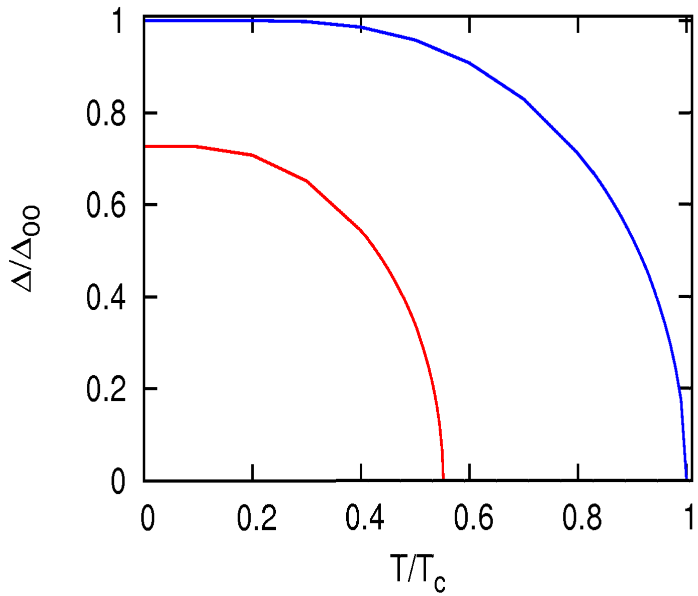
Detrimental effect from magnetic impurities

- H_{sh} vs T with magnetic impurities



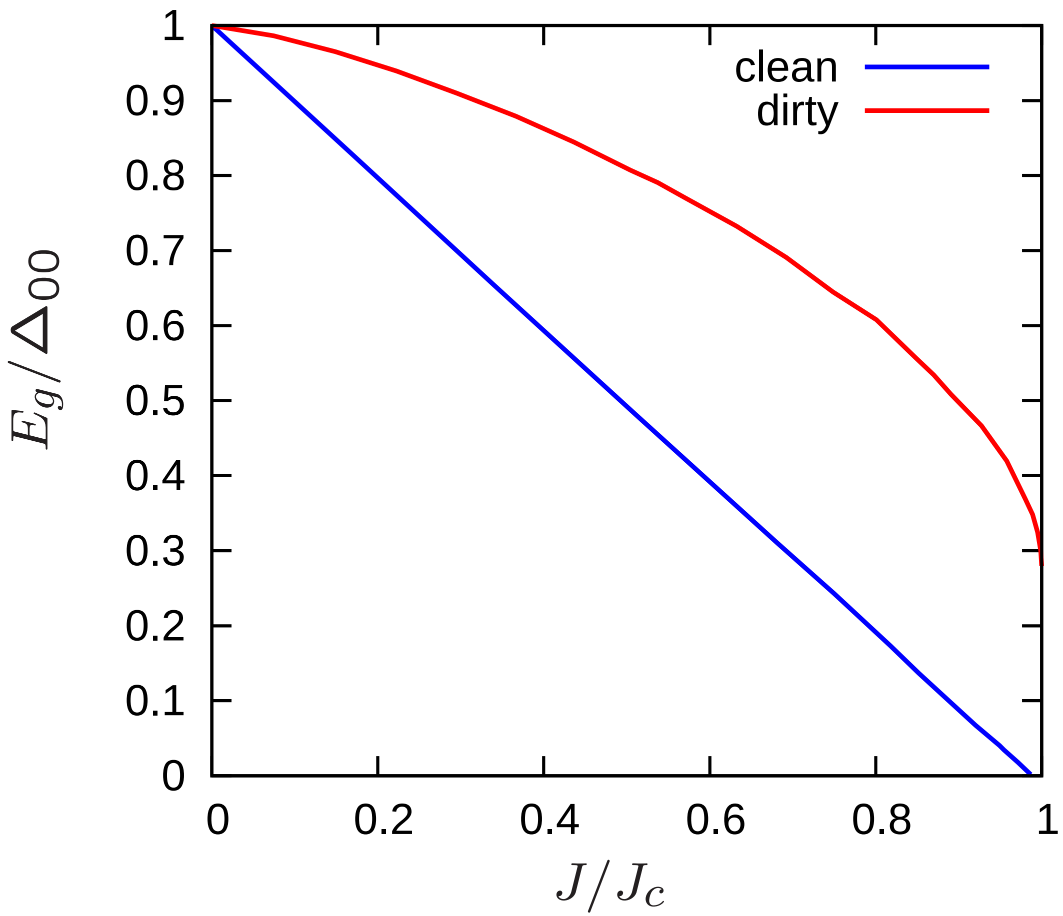
- Δ vs T

(Abrikosov and Gorkov 61)



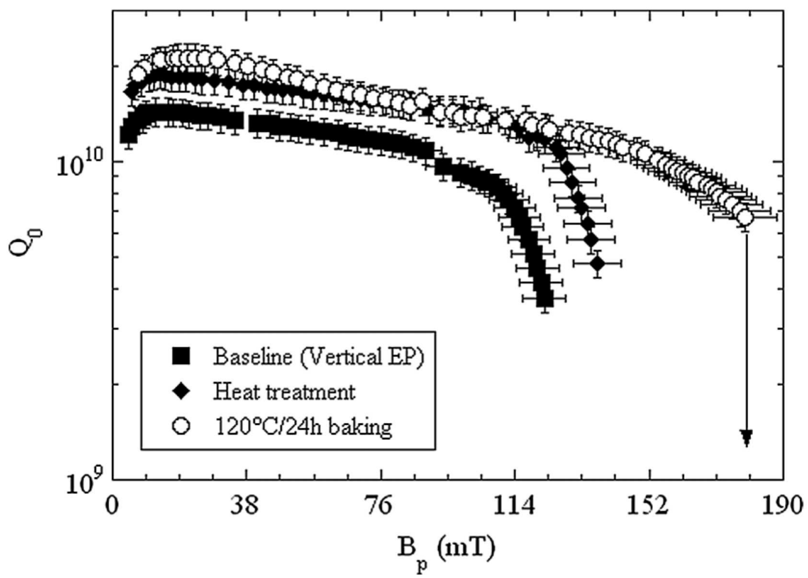
Q slope and impurity level:Possible mechanism of the baking effect

•E_g vs H



•Q vs H, various treatments

(Giovati 10)



Conclusion: When is H_{sh} relevant for SRF cavity application?

- Absence of quasiparticles

- Non-magnetic impurities can improve SRF performance
  - H_{sh} $\pm 4\%$.
  - Gapped state, $H = H_{sh}$.
  - No state for QPs; $E < \epsilon_g$.
  - Dissipation suppressed.

  Impurities reduce the field dependence of R_s and reduce the high-field Q slope. Possible mechanism of the baking effect.

- Cleaner is not better
  - Gapless state; $H \sim H_{sh}$.
  - AC field; QPs dissipate energy.