Magnetic impurities in the surface oxide layer as the origin of residual surface resistance of SRF cavities

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Collaboration

- Thomas Proslier, Andreas Glatz, Mike Pellin - Argonne Laboratory
- John F. Zasadzinski - Illinois Institute of Technology
- P. Kneisel, Gianluigi Ciovati - Jefferson Laboratory
- MK - Rutgers University

Funding

ARRA-DOE, Office of Science, High Energy Physics

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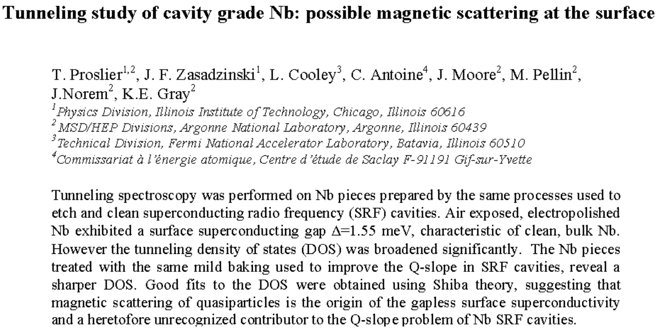
Objectives

- identify the dominant dissipation mechanism in SFR cavities
  Claim: magnetic impurities at the surface
- Advance/develop techniques to reduce losses:
  Atomic Layer Deposition ⇒ improved performance

Suppression of superconductivity at the surface of SRF cavity



Tunneling study of cavity grade Nb: possible magnetic scattering at the surface

T. Proslier[1,2], J. F. Zasadzinski[1], L. Cooley[3], C. Antoine[4], J. Moore[2], M. Pellin[2], J.Norem[2], K.E. Gray[2]

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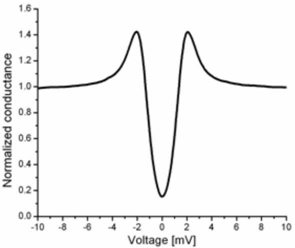
[3] *Technical Division, Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[4] *Commissariat à l'énergie atomique, Centre d'étude de Saclay F-91191 Gif-sur-Yvette*

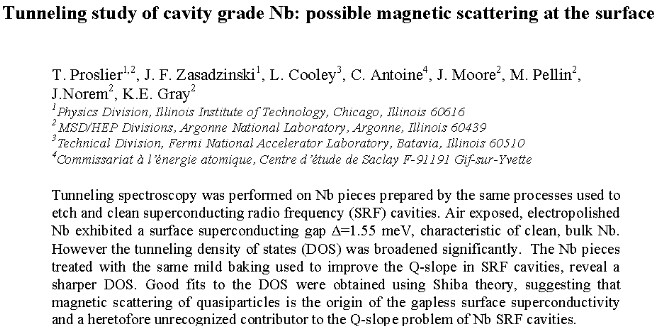
Tunneling spectroscopy was performed on Nb pieces prepared by the same processes used to etch and clean superconducting radio frequency (SRF) cavities. Air exposed, electropolished Nb exhibited a surface superconducting gap Δ=1.55 meV, characteristic of clean, bulk Nb. However the tunneling density of states (DOS) was broadened significantly. The Nb pieces treated with the same mild baking used to improve the Q-slope in SRF cavities, reveal a sharper DOS. Good fits to the DOS were obtained using Shiba theory, suggesting that magnetic scattering of quasiparticles is the origin of the gapless surface superconductivity and a heretofore unrecognized contributor to the Q-slope problem of Nb SRF cavities.



STM measurement of the DOS at the surface of SRF cavity:

- significant "subgap" contribution
- Conjecture: magnetic impurities

Suppression of superconductivity at the surface of SRF cavity



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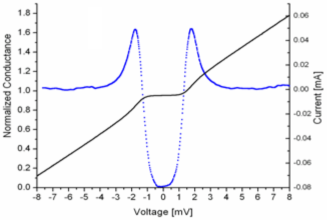
vs clean surface:



STM measurement of the DOS at the surface of SRF cavity:

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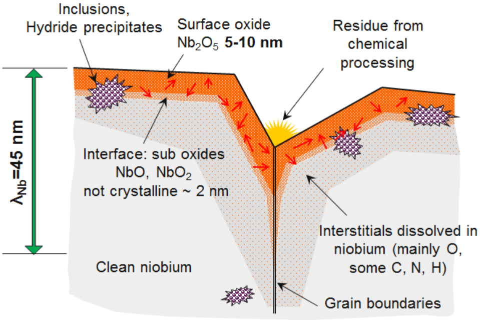
Oxide surface layer of Nb sample

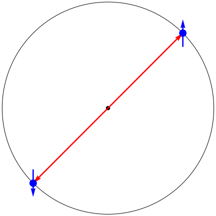
Nb materials for SFR cavities

- bulk – very clean
- but surface layer – oxidized, disordered



- Local magnetic moments can arise in Nb_2O_5, oxygen vacancies
- typical thickness $\sim 5 - 10$nm
- considerable fraction of the “operating” volume $\sim$ 45nm

Mechanisms of superconductivity suppression



- Nonmagnetic disorder (preserved time-reversal symmetry):
  SC insensitive in the leading order in $1/(\tau\epsilon_F)$ (Anderson theorem)
  $\Rightarrow$ Strong disorder $\tau\epsilon_F \sim 1$ required
- Magnetic impurities (broken time-reversal symmetry)
  at $T_{c0}\tau_s < \pi/(2e^C)$ - SC completely suppressed.
  $\Rightarrow$ much weaker (10^3 times) disorder is enough

Gapless superconductivity regime ($T_{c0}\tau_s > \pi/(2e^C)$)

- order parameter Δ is nonzero
- but – nonzero ‘subgap’ DOS $\nu(\epsilon)$ at $|\epsilon| < \Delta$.
- if nonzero $\nu(0) \Rightarrow$ gapless system $\Rightarrow$ finite dissipation at $T = 0$.

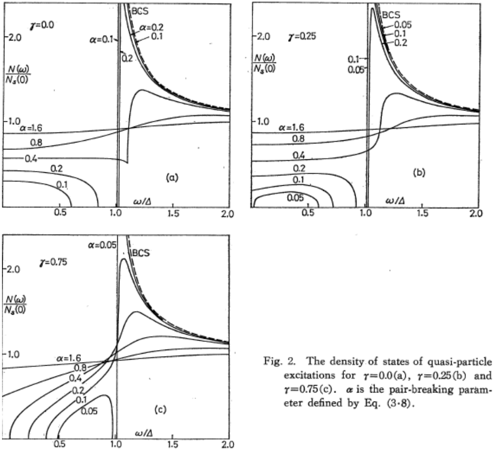
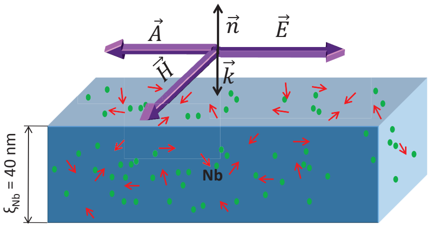


Fig. 2. The density of states of quasi-particle excitations for $\gamma=0.0$(a), $\gamma=0.25$(b) and $\gamma=0.75$(c). α is the pair-breaking parameter defined by Eq. (3·8).

Quite generic: stronger impurity potential; “Lifshitz tails” for weak scattering

Our work: microscopic theory of the surface impedance of s-wave superconductor with magnetic impurities (for now – spatially homogeneous distribution)



$$\zeta(\omega) = -\mathrm{i}\frac{\omega\,\delta(\omega)}{c}$$

$$\delta(\omega) = \frac{2}{\pi}\int_0^{+\infty}\frac{\mathrm{d}k}{k^2 + 4\pi Q(\omega,k)/c^2}$$

$$Q(\omega,k) = Q_1(k) - \mathrm{i}Q_2(\omega,k)$$

$$Q_1(k) = 2_s(ev_F)^2\nu_F\frac{\mathrm{i}}{2}\int \mathrm{d}\epsilon \tanh\frac{\epsilon}{2T}\left\{[f(\epsilon)]^2\langle n_\alpha^2 D_0^{RR}(\epsilon,0,\mathbf{nk})\rangle_{\mathbf{n}} - [f^*(\epsilon)]^2\langle n_\alpha^2 D_0^{AA}(\epsilon,0,\mathbf{nk})\rangle_{\mathbf{n}}\right\}$$

$$Q_2(\omega,k) = 2_s(ev_F)^2\nu_F\omega\int_{-\infty}^{+\infty}\mathrm{d}\epsilon\left(-\frac{\mathrm{d}n_0(\varepsilon)}{\mathrm{d}\epsilon}\right)\bar{Q}_2(\epsilon,k),$$

$$\bar{Q}_2(\epsilon,k) = \frac{1}{2}\left\{[f(\epsilon)]^2\langle n_\alpha^2 D_0^{RR}(\epsilon,0,\mathbf{nk})\rangle_{\mathbf{n}} + [f^*(\epsilon)]^2\langle n_\alpha^2 D_0^{AA}(\epsilon,0,\mathbf{nk})\rangle_{\mathbf{n}}\right.$$
$$\left. + \langle n_\alpha^2 D_0^{RA}(\epsilon,0,\mathbf{nk})\rangle_{\mathbf{n}}[1 + |g(\epsilon)|^2 + |f(\epsilon)|^2]\right\}$$

$g(\epsilon) = \frac{v}{\sqrt{v^2-1}}$, $f(\epsilon) = \frac{1}{\sqrt{v^2-1}}$, $v\Delta = \epsilon + \frac{1}{\tau_s}\frac{\sqrt{1-v^2}}{\gamma^2-v^2}v$. – from Shiba theory

Theory of the surface impedance of superconductor with magnetic impurities

3 micro parameters

- nonmagnetic scattering time τ
- magnetic scattering time τ_s; exchange coupling strength (Shiba's γ)

Valid at arbitrary

- frequency ω
- temperature T
- nonmagnetic $(1/\tau)$
- and magnetic $(1/\tau_s)$ scattering rates

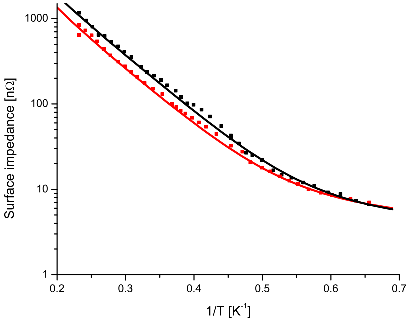
compared to T_c.

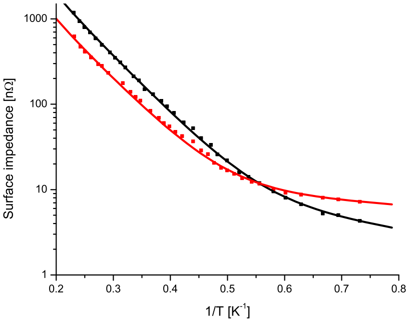
Theory of the surface impedance of superconductor with magnetic impurities

Key result

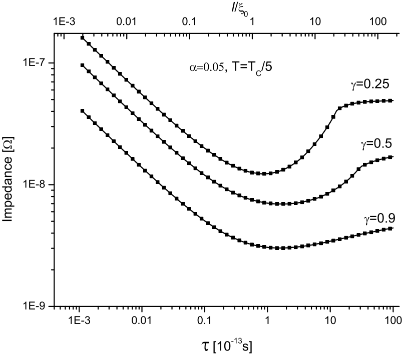
In the gapless SC regime – saturation of the surface resistance at $T = 0$

Fits for the temperature dependence of the surface resistance

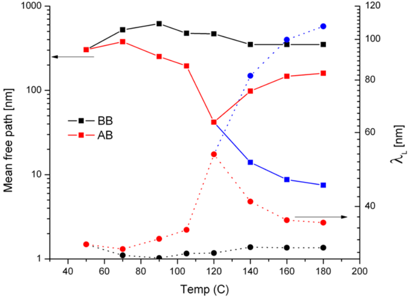




Nonmonotonic dependence on nonmagnetic disorder and baking effect



Baking effect: increases disorder



Conclusion

Theory

- First(?) microscopic theory of the residual resistance
- Case for magnetic impurities further substantiated
- Future development: model of the disordered surface layer (numerically)

Experiment (current and future)

develop technique to protect from/get rid of the surface oxides: atomic layer deposition (coating with insulating layers)