Basic principles of RF Superconductivity 2/2

Tobias Junginger

In this lecture we will address these questions:

- **Superconductivity means no resistance. Why can’t we reduce the losses zero?**
- Why is niobium the material choice which requires costly helium cooling?
- What are the fundamental and technical limitations of niobium SRF cavities?
  - Highest Energy Gain → Maximum Accelerating Gradient?
  - Lowest cryogenic losses → Maximum Quality Factor?
- What are possible future materials and what are the challenges?

Recap - The RF surface resistance

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_1 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

This equation implies R_s:

- Has a minimum for medium purity
- Is proportional to ω^2
- Decreases exponentially with temperature
- Vanishes as $T \rightarrow 0$ K
- Is independent of RF field strength

In the following we will compare these assumptions to experimental data and modify the formula if necessary

Recap -Material purity dependence of R_s

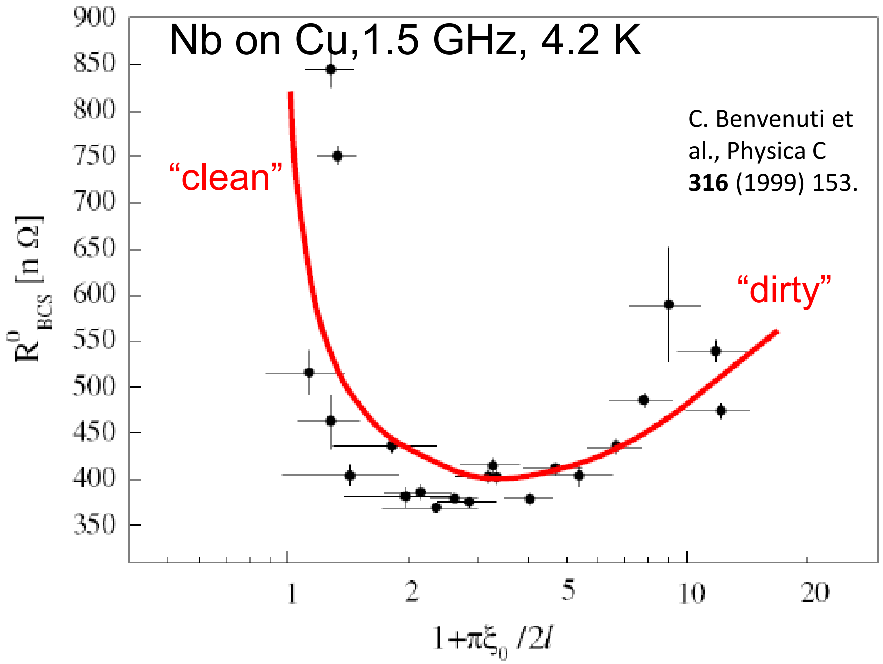
$$R_{BCS} = \omega^2 \lambda^3 \sigma_1 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

- The dependence of the penetration depth on l is approximated as $\lambda(l) \approx \lambda_L \sqrt{1 + \frac{\pi \xi_0}{2l}}$
- $\sigma_1 \propto l$

$$\Rightarrow R_S \propto \left(1 + \frac{\pi \xi_0}{l}\right)^{3/2} l \quad \Rightarrow$$

$R_s \propto l$ if $l \gg \xi_0$ ("clean" limit)

$R_s \propto l^{-1/2}$ if $l \ll \xi_0$ ("dirty" limit)

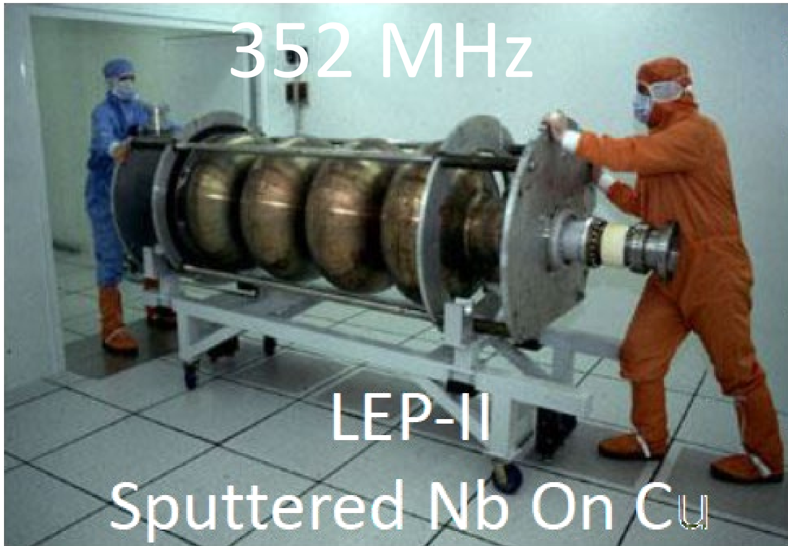


$\boxed{R_s \text{ has a minimum for } l = \pi\xi_0/4}$

Example: Nb films sputtered on Cu substrate

- By changing the sputtering species, the mean free path was varied
- RRR of niobium on copper cavities can be tuned for lowest R_S.

Recap - CERN – Nb on Cu cavities



CERN first started to use Nb on Cu technology for LEP-II cavities.
Du to the low frequency and optimal mean free path economical operation at 4.5K was possible

The technology was then adopted for the 400 MHz LHC cavities

Hie-Isolde Quarter Wave Resonator commissioned in 2015

The RF surface resistance

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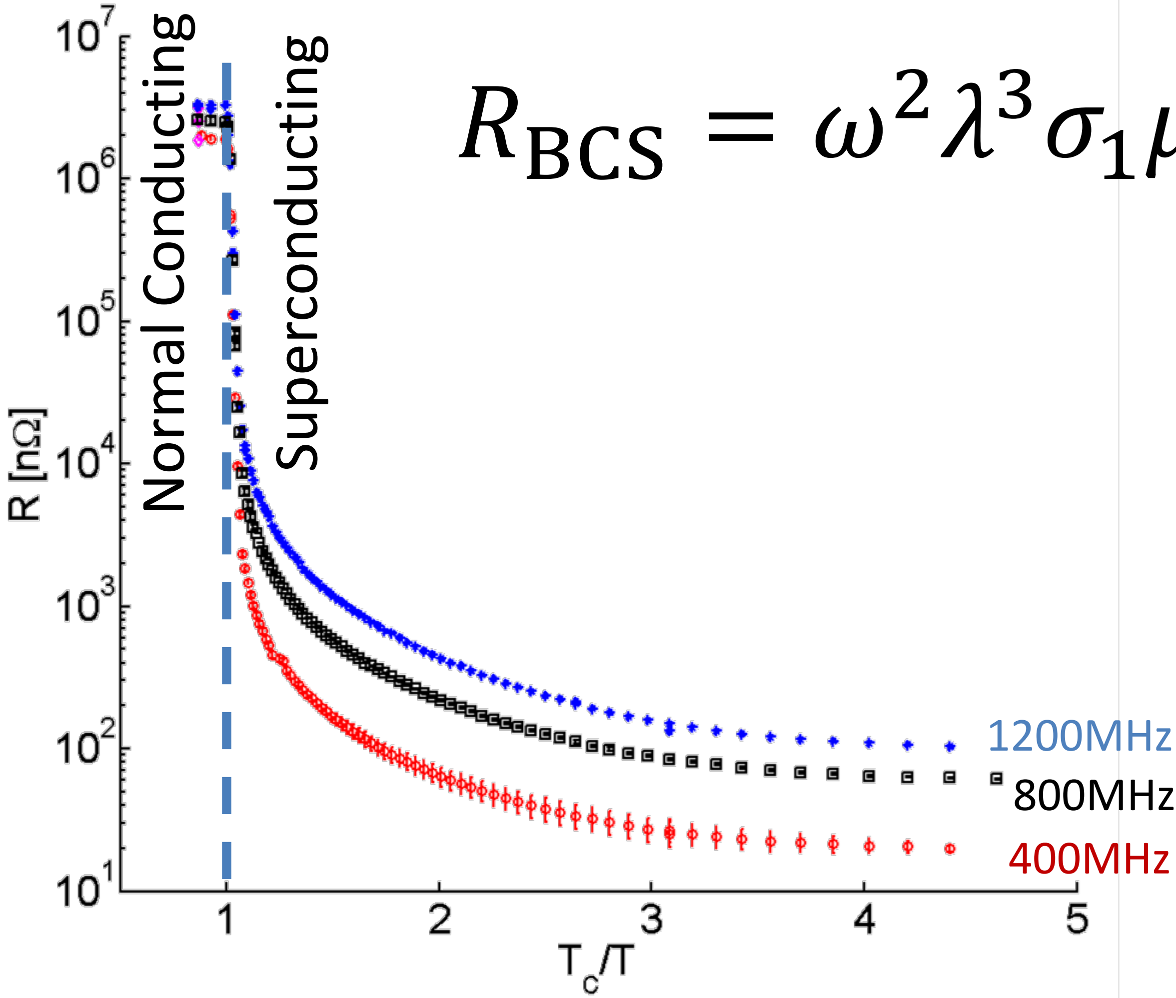
The RF surface resistance

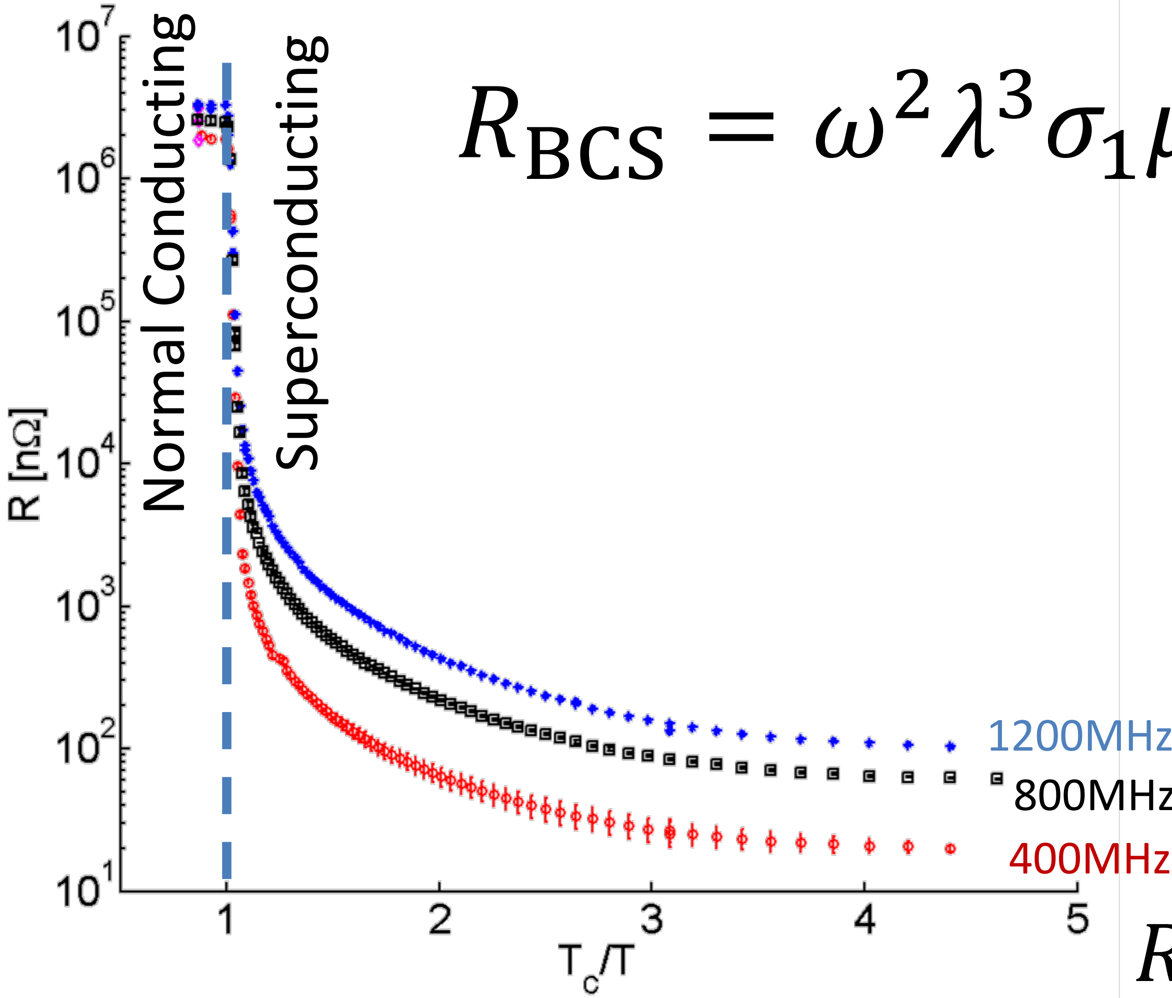


$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_1 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

$R_S(0\mathrm{K}) \neq 0$

Measurement of the surface resistance at low field of niobium at three frequencies with the Quadrupole Resonator

The RF surface resistance



$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_1 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

$$R_S(0\mathrm{K}) \neq 0$$

$$R_S = R_{\mathrm{BCS}}(T) + \mathrm{R}_{\mathrm{res}}$$

Measurement of the surface resistance at low field of niobium at three frequencies with the Quadrupole Resonator

The RF surface resistance

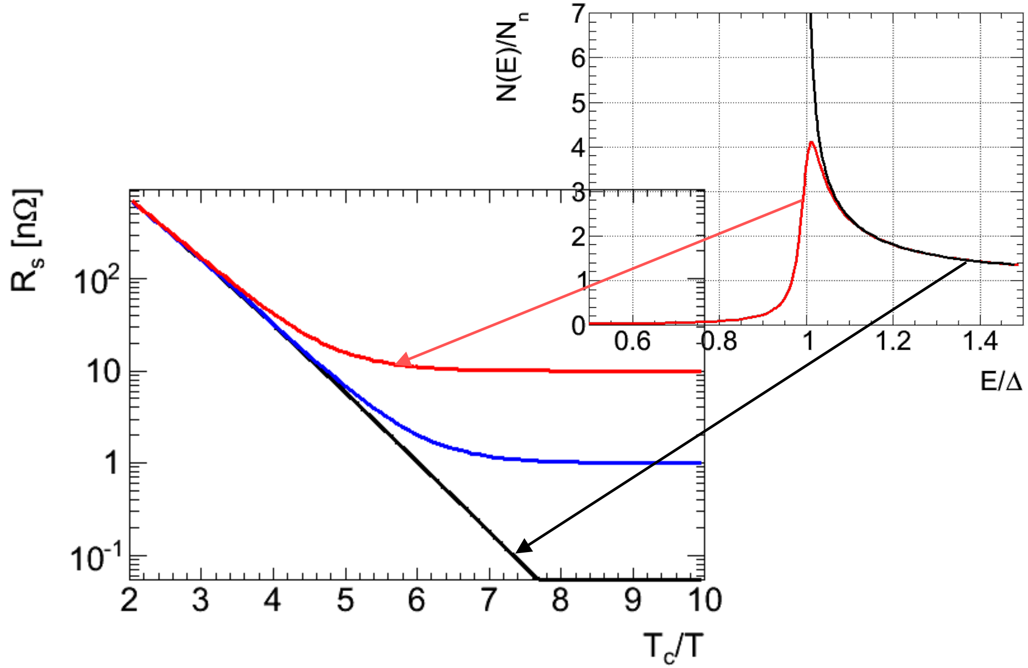
$$R_S = \omega^2 \lambda^3 \sigma_1 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right) + R_{\mathrm{res}}$$

This equation implies R_S:

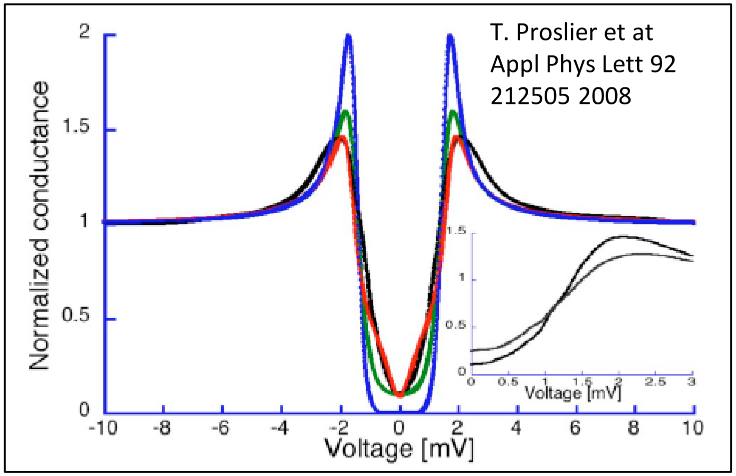
- Has a minimum for medium purity ✓
- Is proportional to ω^2 (✓)
- Decreases exponentially with temperature ✓
- Vanishes as T→0 K ✗
- Is independent of RF field strength

The residual resistance

- According to the BCS theory there are no quasiparticle states within the energy gap Δ
- Smearing of Density of States leads to a residual resistance



Subgap states will yield a finite R_S(0K) irrespective of physical mechanism



Point contact tunneling experiments on Nb and Nb_3Sn have found finite density of states (DOS) inside the energy gap

The residual resistance

DoS smearing is not the only cause of residual resistance

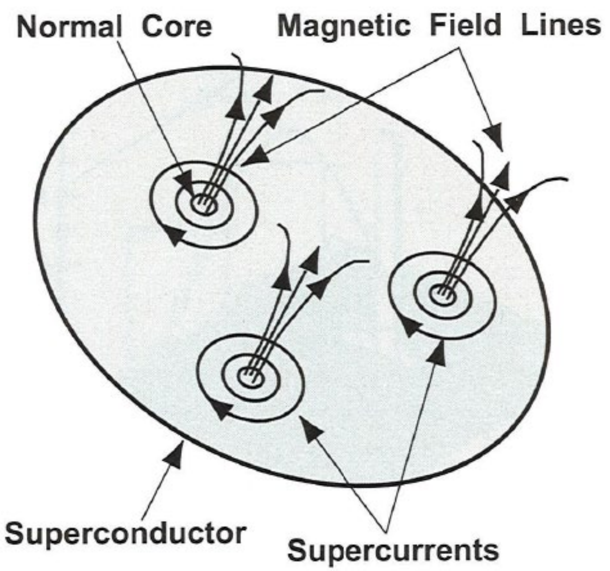
Other contributions to R_{res}:

- Trapped magnetic flux and thermal currents
- Lossy oxides, metallic hydrides
- Normal conducting precipitates
- Grain Boundaries
- Interface Losses
- Magnetic Impurities

Trapped Magnetic Flux

- Well understood contribution to R_{res}
- When a cavity is cooled down in an ambient DC magnetic field not all flux is expelled – Incomplete Meissner effect
- In fact fields of a few μT (order earth magnetic field) can be completely trapped
- In cryomodules thermal currents can cause additional magnetic fields which can be trapped

Trapped Magnetic Flux



H. Padamsee et al. RF Superconductivity for Accelerators

Simple model with these assumptions:
- Fluxoids are perpendicular to the cavity surface
- Fluxoids are static, no displacement due to RF fields
- RF currents flow around them
- Flux completely trapped
- Losses are independent on RF field

$$R_{mag} = \frac{B_{ext}}{2B_{c2}} R_n$$

Additional residual resistance=Ratio nc/sc area×Normal conducting surface resistance

$$R_{mag}[\mathrm{n\Omega}] = 3B_{ext}[\mathrm{\mu T}]\sqrt{f[GHz]}$$ for RRR=300

The RF surface resistance

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- Has a minimum for medium purity ✓
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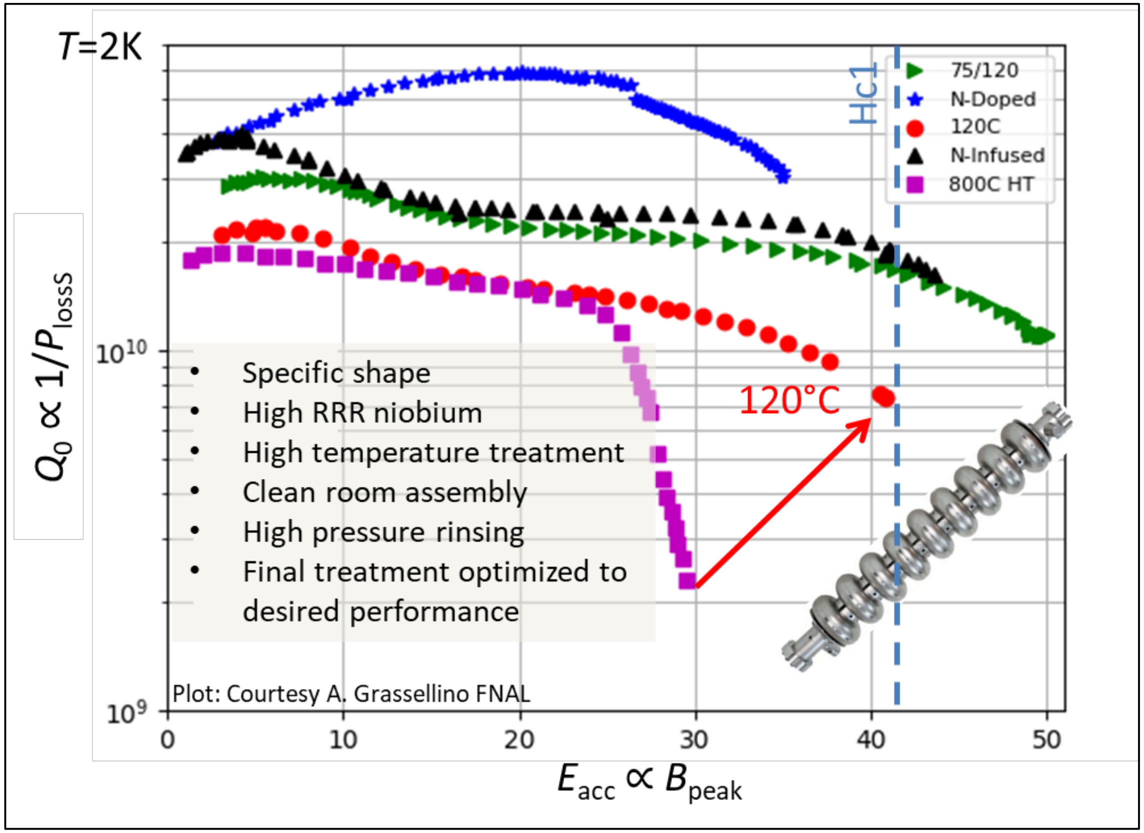
- Vanishes as $T \rightarrow 0$ K ✗
- Is independent of RF field strength

Surface treatments for State of the art SRF cavities



Maximum quality factor and accelerating gradient depend on surface treatment but also on RF frequency, cavity shape (surface field configuration), ambient magnetic flux in a correlated and not fully understood way

The RF surface resistance

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This equation implies R_S:

- Has a minimum for medium purity ✓
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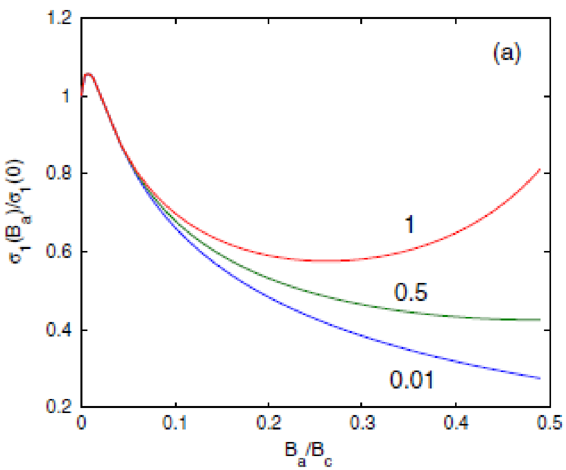
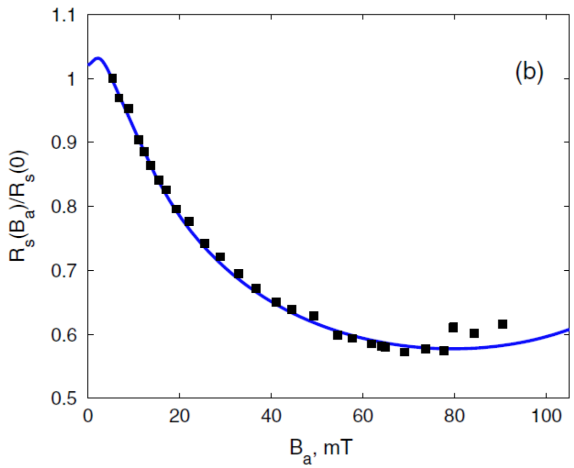
- Decreases exponentially with temperature ✓
- Vanishes as T→0 K ✗
- Is independent of RF field strength ✗

Not only do R_{BCS} and R_{res} depend on the RF field strength there can also be additional extrinsic losses limiting the cavity performance

Field dependence of Rs

- Strong RF currents affect superconducting properties, in particular the DOS
- Observed normal $\Delta R_S/\Delta B>0$ mainly due to external sources and dependent on material preparation
- Inversed $\Delta R_S/\Delta B <0$ is thought to be intrinsic
- A theory of non-linear R_s at high field [A. Gurevich, *Phys. Rev. Lett*. **113**, 087001 (2014)]
- $R_s(H)$ was re-derived from first principles (BCS) taking into account oscillations of $N(\varepsilon, t)$ due to RF current pairbreaking and non-equilibrium distribution function of quasiparticles in the dirty limit

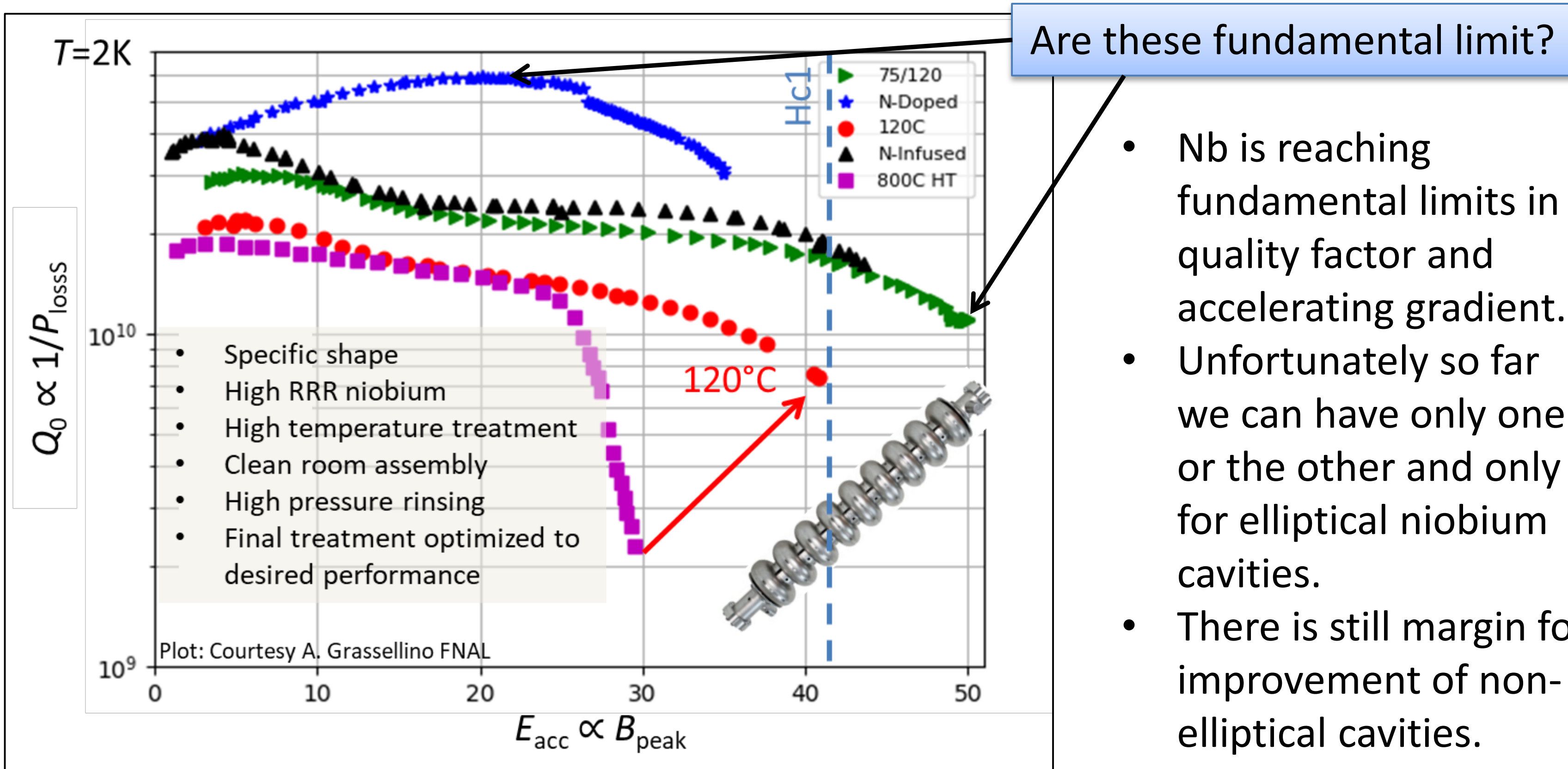




$$R_{\mathrm{BCS}} = \omega^2\lambda^3\sigma_1\mu_0^2\exp\left(-\frac{\Delta}{k_bT}\right)$$

Left: σ_1 calculated for different levels of quasiparticle overheating parametrized by α. Right: Nb cavity at 1.75 GHz fitted with α=0.91

Surface treatments for State of the art SRF cavities



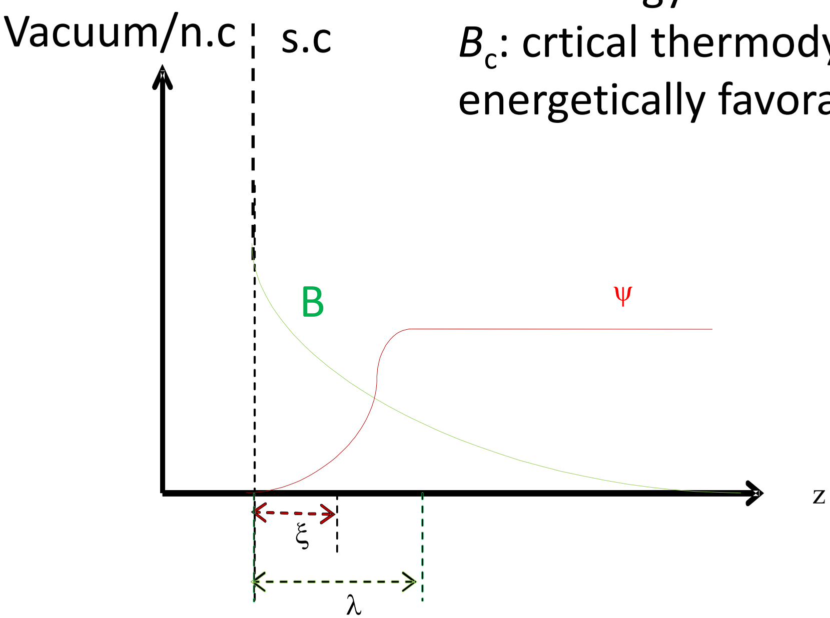
Maximum quality factor and accelerating gradient depend on surface treatment but also on RF frequency, cavity shape (surface field configuration), ambient magnetic flux in a correlated and not fully understood way

- Nb is reaching fundamental limits in quality factor and accelerating gradient.
- Unfortunately so far we can have only one or the other and only for elliptical niobium cavities.
- There is still margin for improvement of non-elliptical cavities.
- For performance far beyond the state of the art of elliptical cavities materials other than Nb need to considered

Outline

- Quick recap of London theory and demonstration of the Meissner effect
- Surface Resistance
  - Electrodynamics of normal conductors
    - Normal and anomalous skin effect
  - Electrodynamics of superconductors
    - Surface impedance of superconductors in the two fluid model and the BCS theory
    - Residual resistance
    - Field dependence of surface resistance
- **Maximum RF field**
  - **DC critical fields, Hc, Hc1, Hc2, Hsh**
  - **Critical field under RF**
- Materials for SRF
  - Why niobium
  - Materials beyond niobium
  - Multilayers

Energy balance at a SC-NC interface



ΔE : Energy difference at a NC-SC boundary compared to the SC state
B_c: crtical thermodynamic field, above B_c the normal conducting state is energetically favorable

$$\Delta E = \Delta E_c - \Delta E_B =$$

$$= \underbrace{\frac{1}{2\mu_0} B_c^2 A \xi}_{\text{Energy loss}} - \underbrace{\frac{1}{2\mu_0} B^2 A \lambda}_{\text{Energy gain}}$$

<u>Energy loss:</u>
The density of cooper pairs is suppressed over the distance ξ

<u>Energy gain:</u>
Field does not need to be expelled over the distance λ

ΔE=0 and resolve wrt ***B***

$$B_{c1} = \sqrt{\xi/_\lambda}\, B_c$$

- If $\xi < \lambda$, it is energetically favourable to create normal-superconducting boundaries above the lower critical field B_{c1}
- These superconductors are referred to as type-II

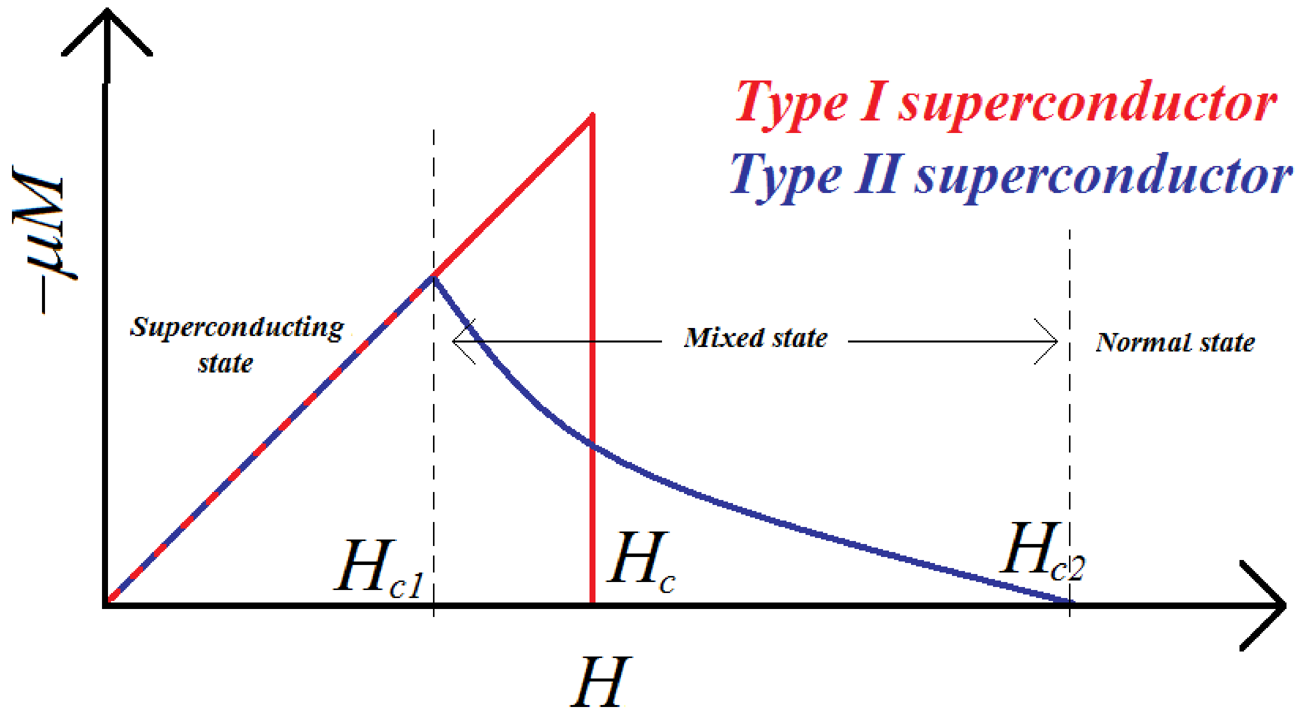
Exact result from GL theory

$$\kappa_{GL} = \frac{\lambda_L}{\xi_{GL}} > \frac{1}{\sqrt{2}}$$

Two types of superconductors

- Type II Superconductors
  - $\kappa > 1/\sqrt{2}$
  - Impure metals including high RRR niobium as used for SRF cavities
  - All alloys
  - For κ>>1 local electrodynamics (London theory) applicable
- Type I Superconductors
  - $\kappa < 1/\sqrt{2}$
  - All elements including very pure niobium **Phys. Rev. B 106, L180505 (2022)**
  - Non-local electrodynamics needs to be considered

The Magnetization Curve



- Under DC fields flux tubes can be pinned – no dissipation
  - SC magnets are operated between H_{c1} and H_{c2}
- Under RF fields flux tubes oscillate – dissipation
  - RF cavities are operated in the Meissner state

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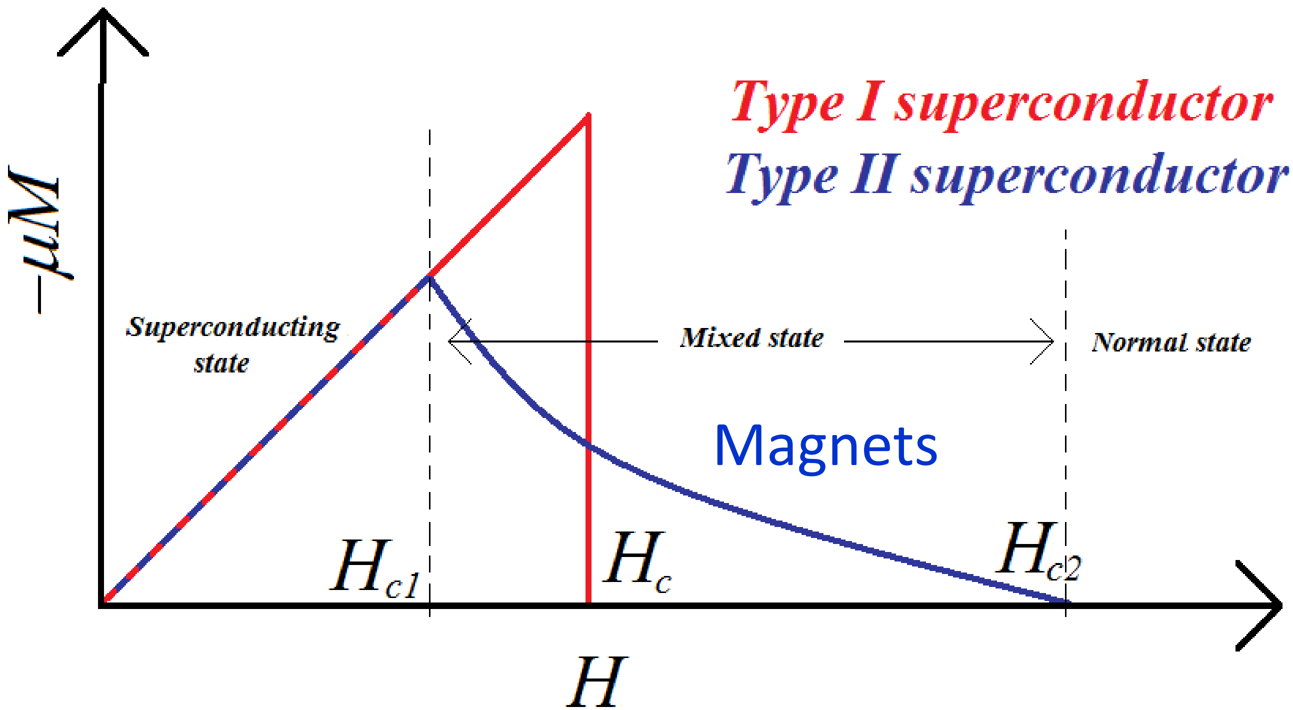

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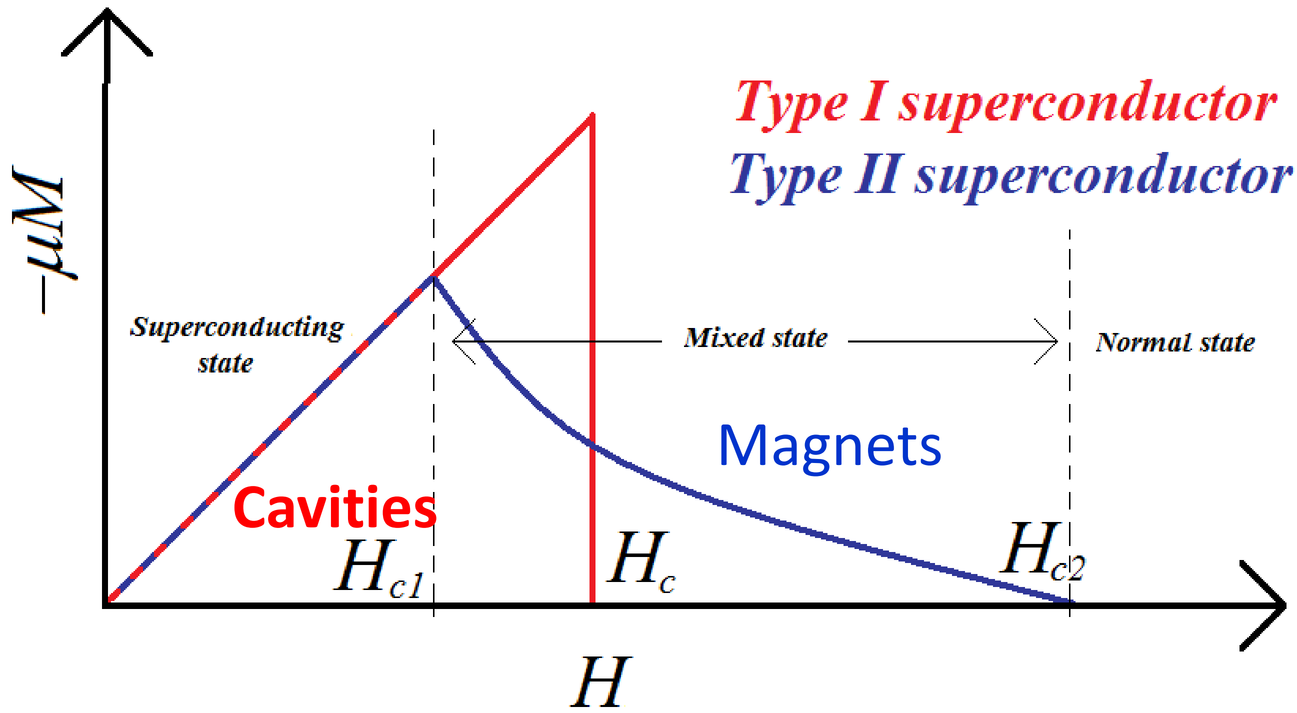

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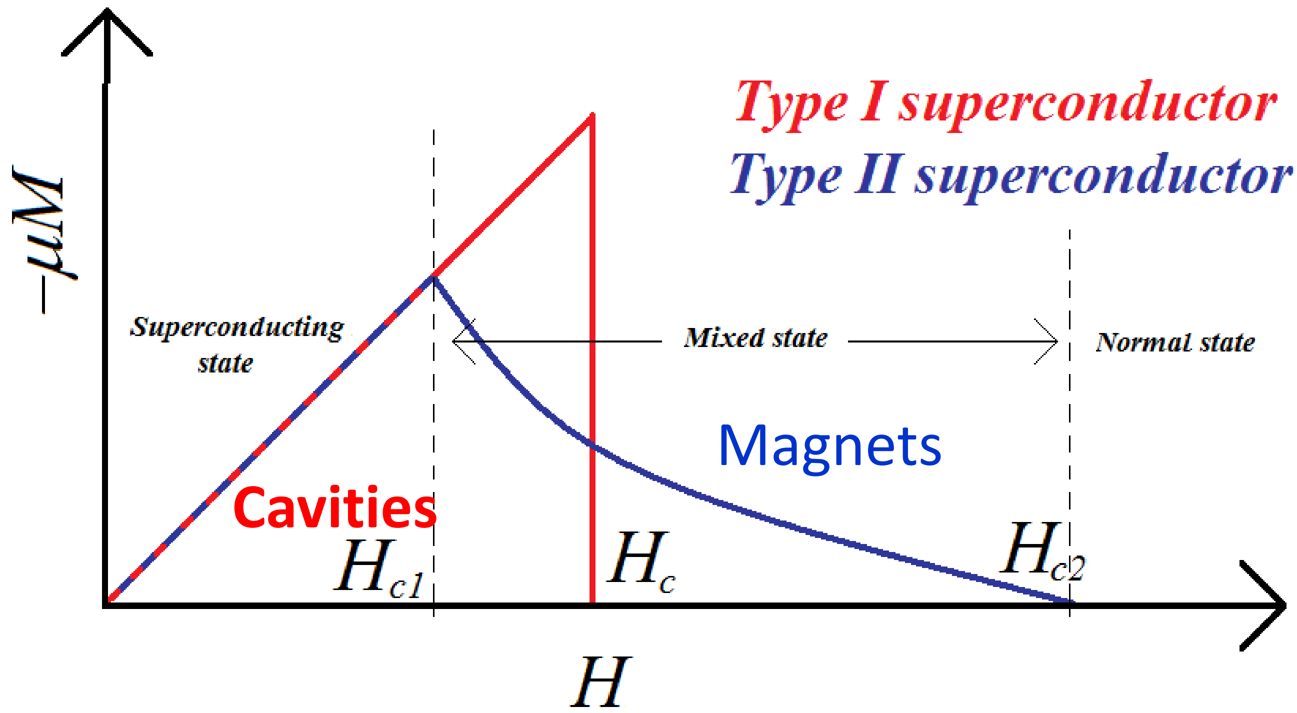

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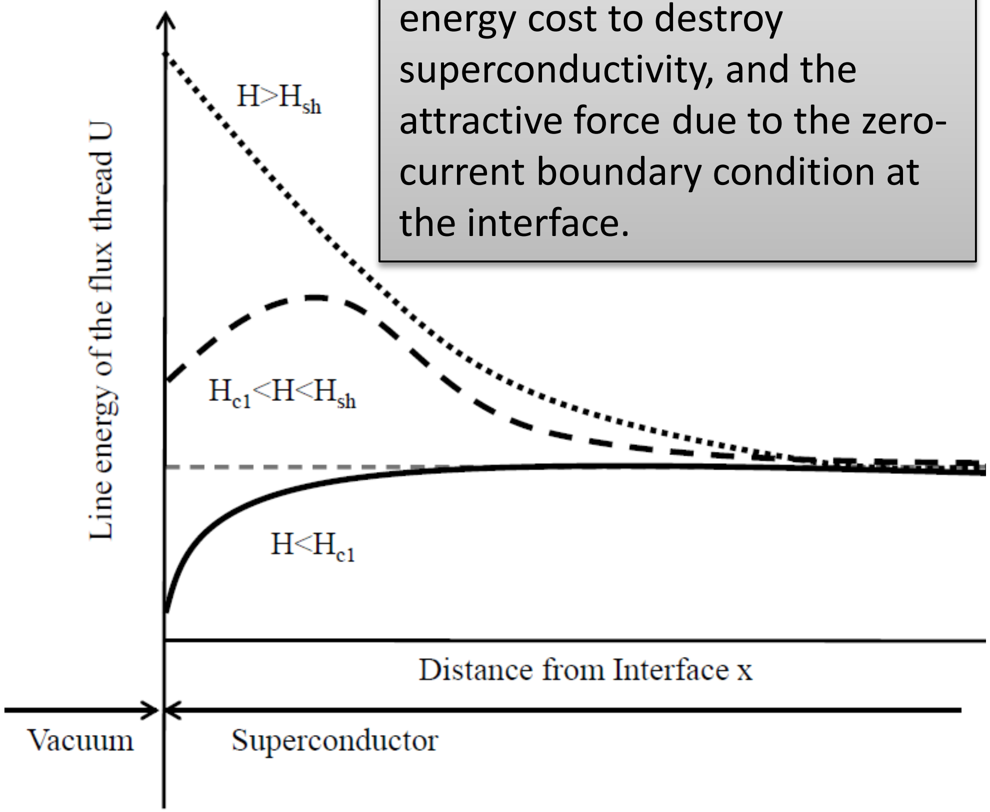
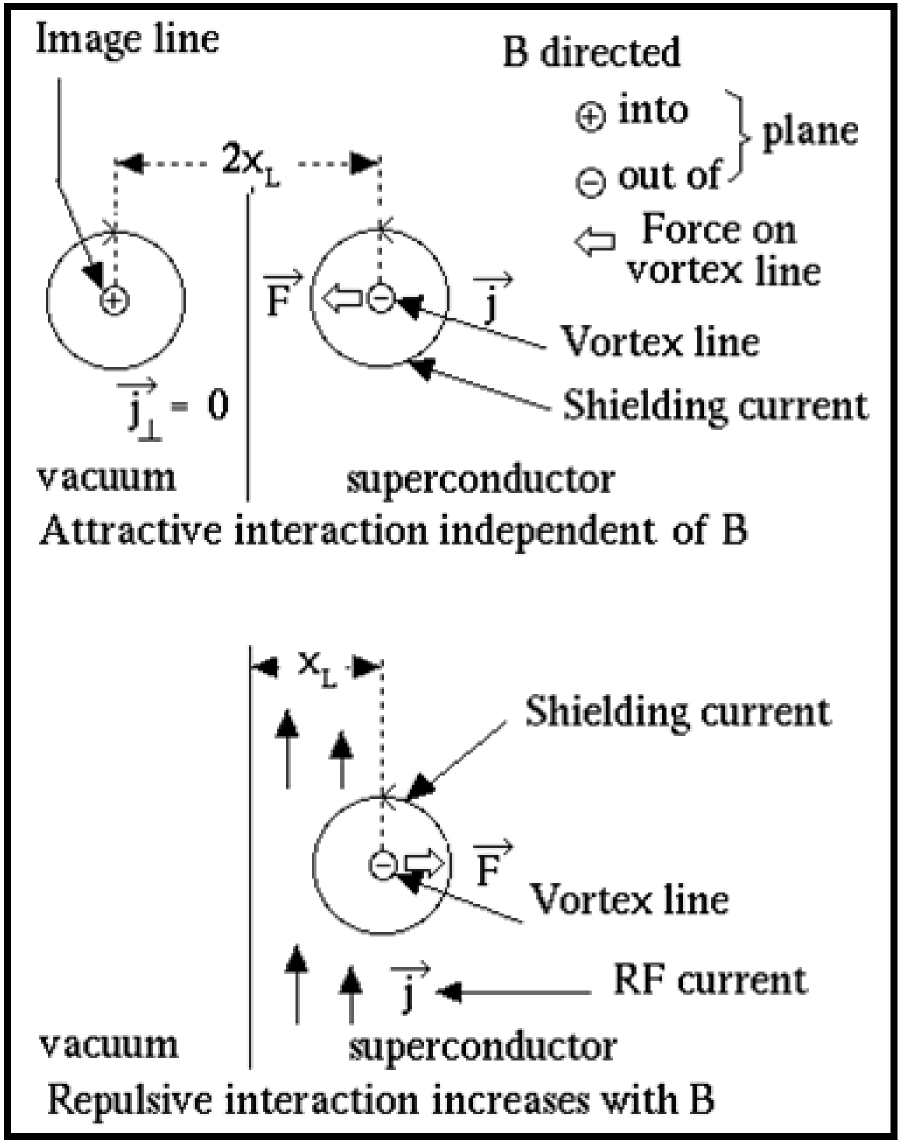
Can the Meissner state persist metastable beyond H_{c1}?

The superheating field

The superheating field H_{sh} is set by the competition between magnetic pressure (imposed by the external magnetic field), the energy cost to destroy superconductivity, and the attractive force due to the zero-current boundary condition at the interface.





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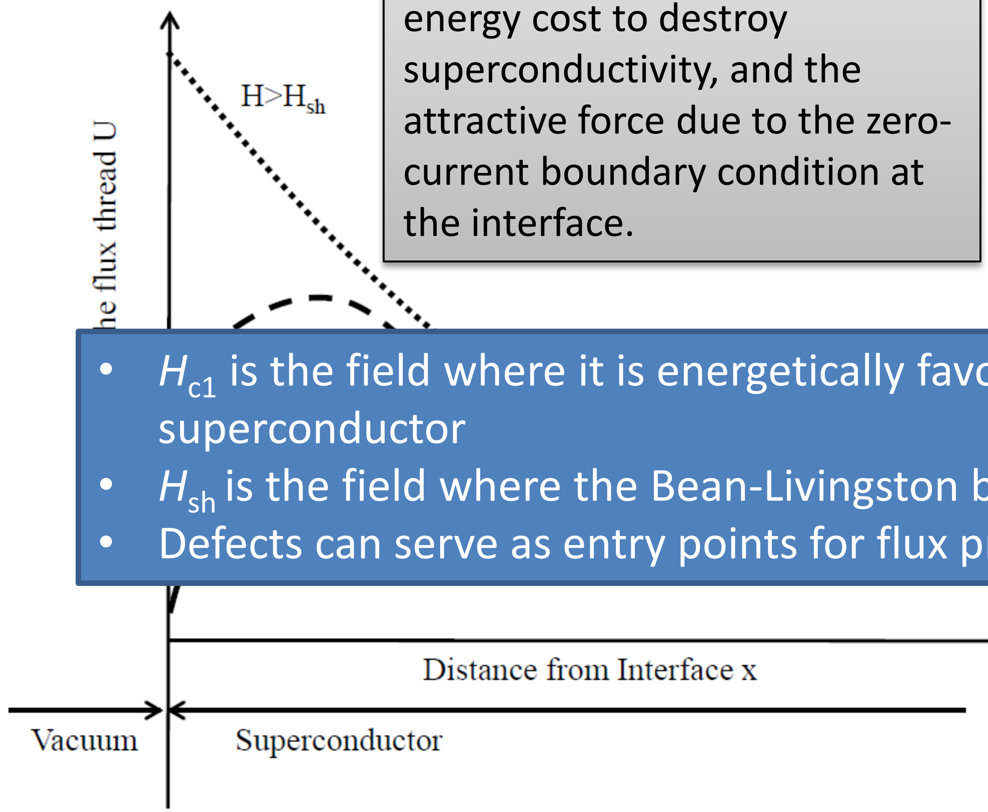

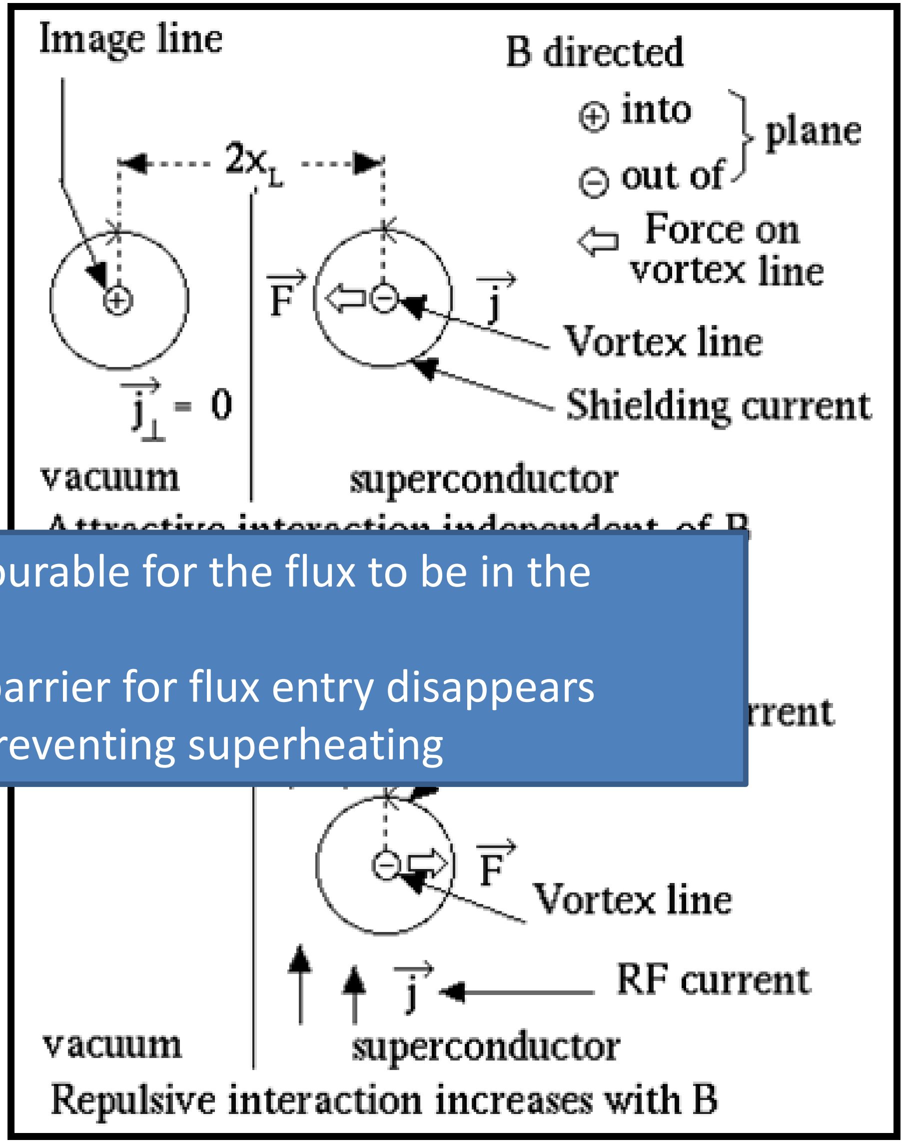

- H_{c1} is the field where it is energetically favourable for the flux to be in the superconductor
- H_{sh} is the field where the Bean-Livingston barrier for flux entry disappears
- Defects can serve as entry points for flux preventing superheating

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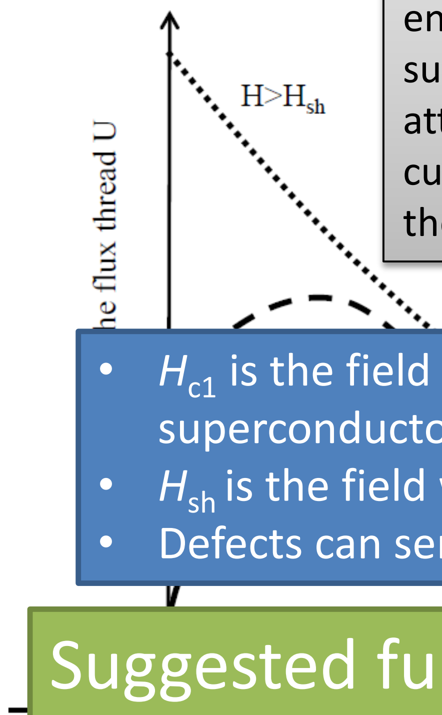

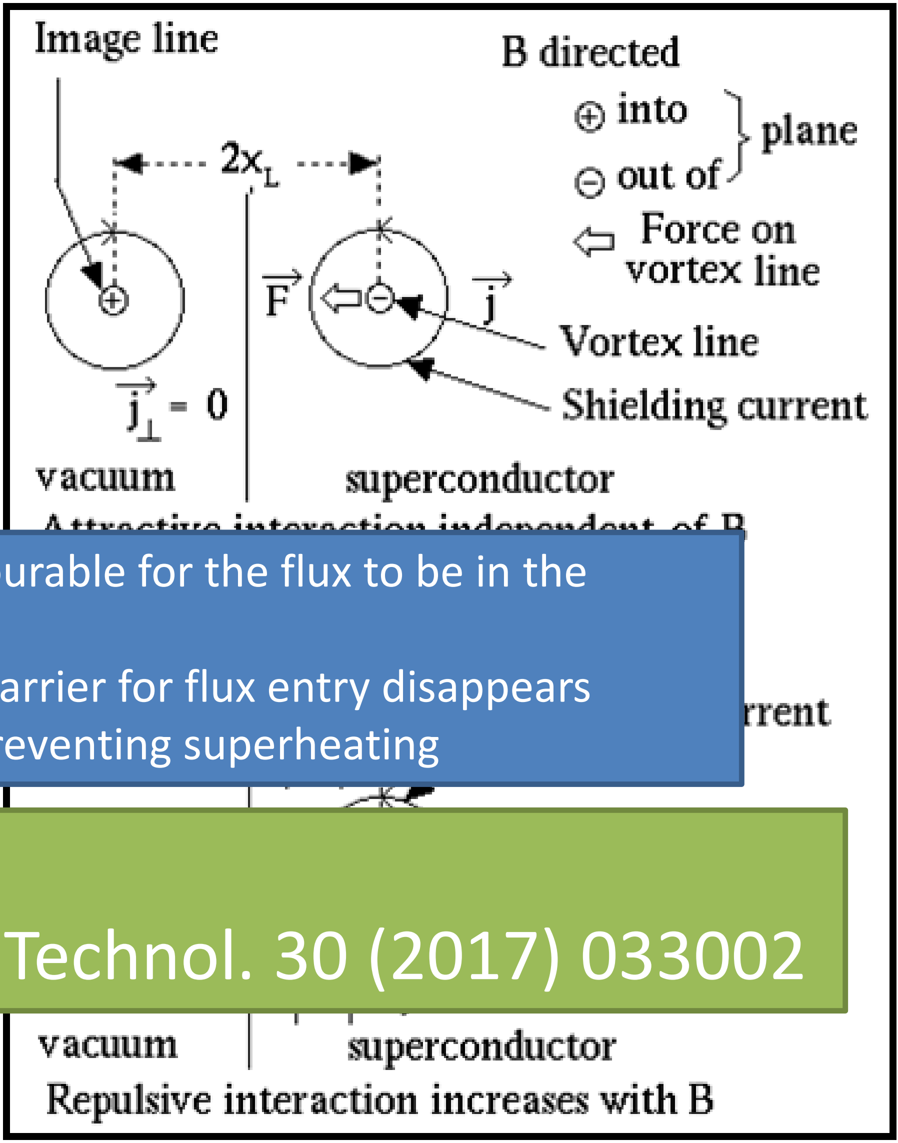

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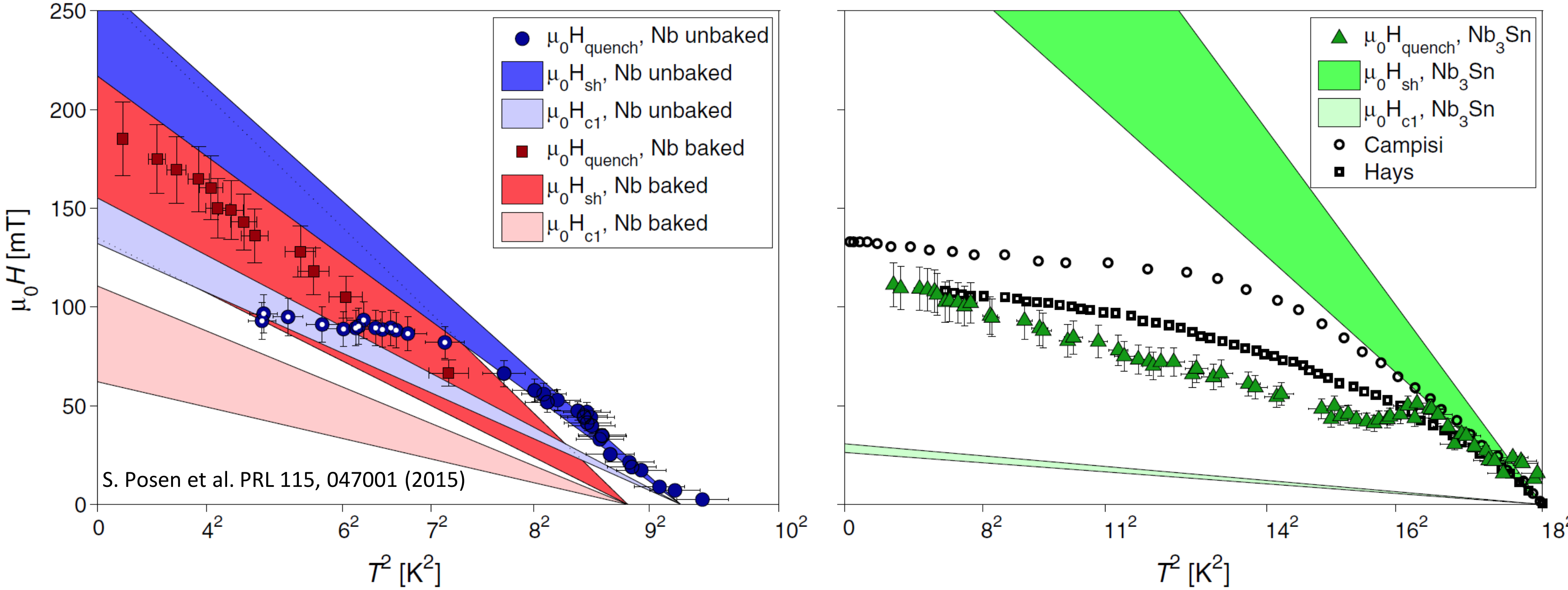
Suggested further reading:
B. Liarte et al. - Supercond. Sci. Technol. 30 (2017) 033002

The superheating field



<u>Niobium:</u>

- Close to T_c H_{entry}=H_{sh}
- T<<T_c usually H_{entry}<H_{sh}

<u>Nb_3Sn:</u>

- Close to T_c H_{entry}=H_{sh}
- T<<T_c H_{entry}<<H_{sh}

- RF heating proportional to H^2. Close to T_c less power is dissipated. Flux entry less likely.
- Coherence length of Nb_3Sn smaller than Nb. Flux entry at defects more likely.
- **The good news is H_{c1} is not a general limitation!**

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  - **Why niobium**
  - **Materials beyond niobium**
  - **Multilayers**

Nb_3Sn

Nb3Sn can have the same Rs at 4.2K as Nb 2K as $\Delta \propto T_c$

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

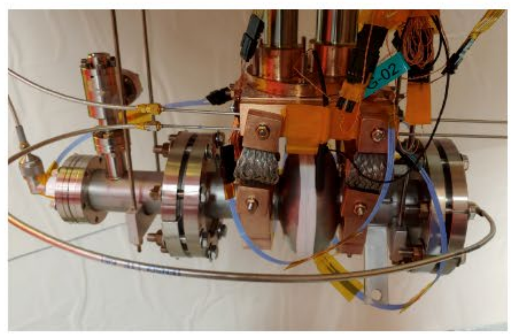
Cryocooler-Based Cooling

- Different labs seem to think that it is time for this technology: Fermilab, Cornell, and Jefferson Lab all have successfully operated Nb_3Sn cavities conduction cooled by cryocoolers

Fermilab

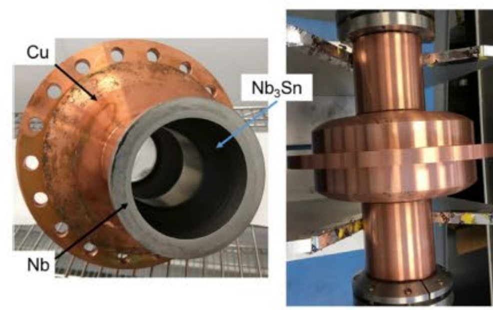
R.C. Dhuley et al, *Supercond. Sci. Technol.* 33 06LT01 (2020)

Cornell University



N. Stilin et al, arXiv:2002.11755v1 (2020)

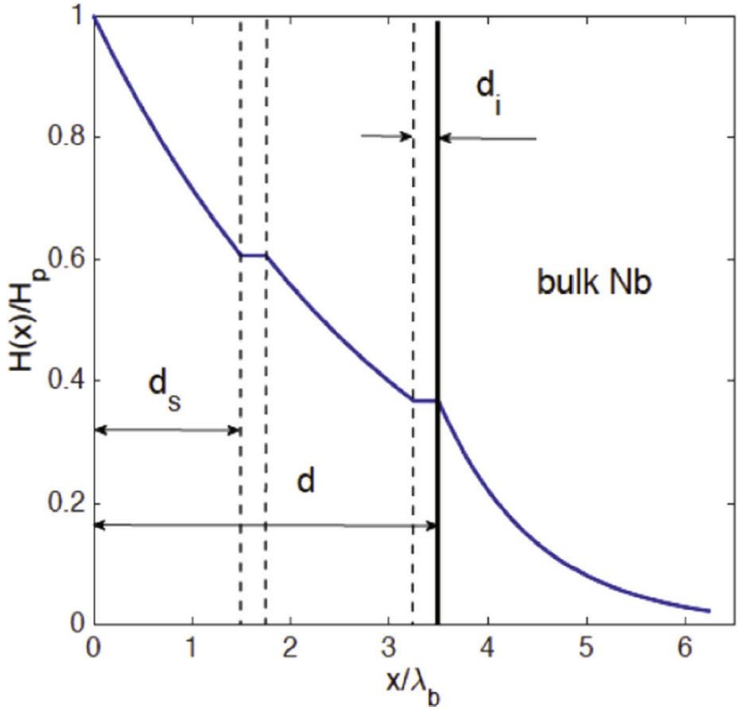
Jefferson Lab



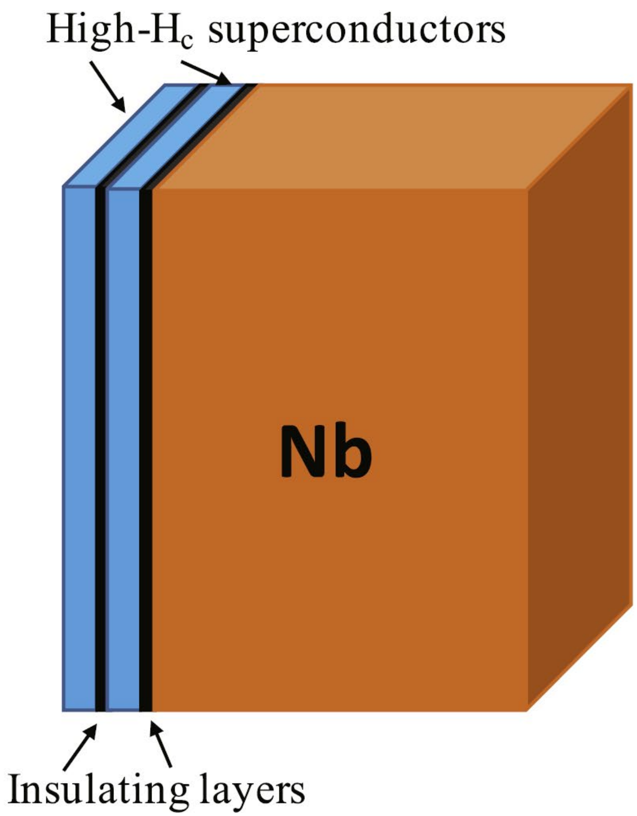
G. Ciovati et al, *Supercond. Sci. Technol.* 33 07LT01 (2020)

Fermilab

Multilayer



A. Gurevich - Supercond. Sci. Technol. 30 (2017) 034004

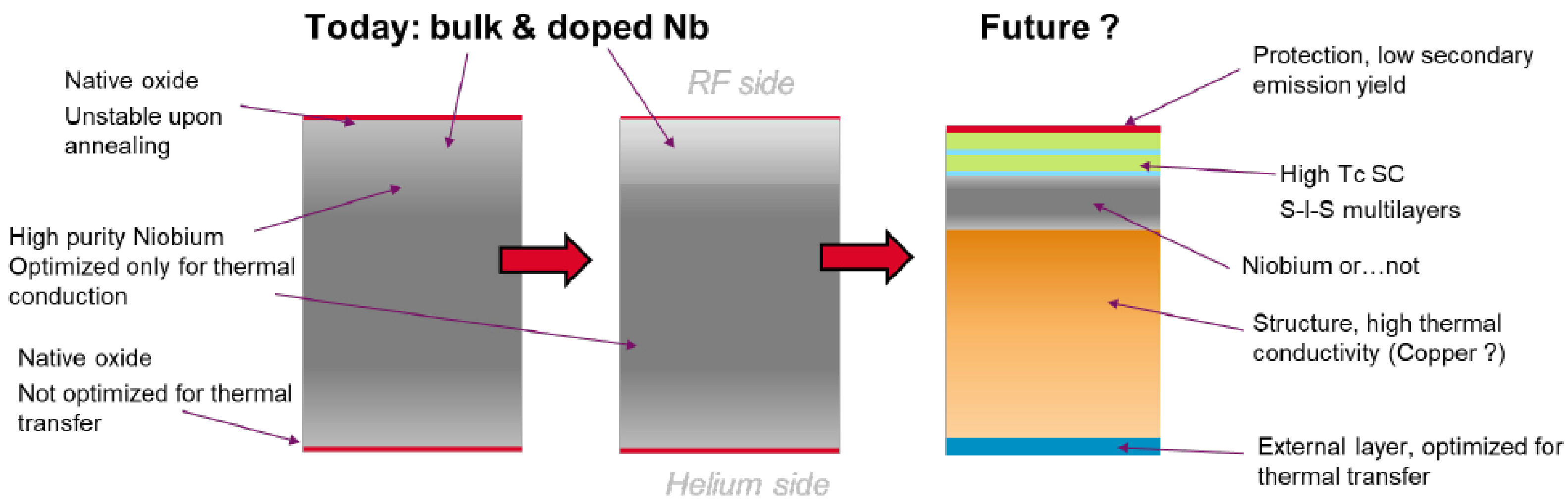


- To address the low-B_{c1} problem of high-B_c materials, it was proposed to coat the Nb cavities with multilayers of thin superconductors (S) separated by dielectric (I) layers
- For d_S<λ no thermodynamically stable parallel vortices in decoupled S layers

SRF Material of the future

IDEAL SRF MATERIAL: TAILORED FOR APPLICATIONS

High RRR not required for superconductivity but for thermal stabilization in case of defects

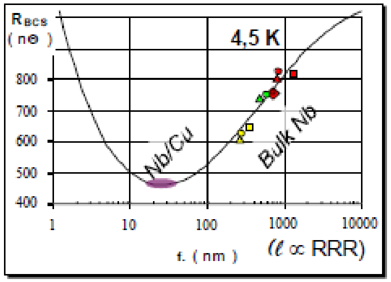


"RF" layer optimized for superconductivity:

Low surface resistance (medium m.f.p.)

and/or *High H_P (high H_{C1} or high H_{SH})

**Depends on the application*



Recommanded Literature

General solid state physics

- S.H Simon The Oxford Solid State BasicsGeneral, OUP Oxford, 2013

General Superconductivity

- W. Buckel and R. Kleiner, « Superconductivity: Fundamentals and applications», Wiley-VCH 2004
- V. V. Schmidt « The physics of superconductors », Springer 1997
- M. Tinkham, « Introduction to superconductivity », McGraw-Hill 1996
- Online lectures from Cambridge University: http://www.msm.cam.ac.uk/ascg/lectures/fundamentals/isotope.php

RF Superconductivity

- R. Padamsee, J. Knobloch and T. Hays – « RF Superconductivity for Accelerators », Wiley-VCH, 2008
- J. P. Turneaure, J. Halbritter, and H. A. Schwettman. « The surface impedance of superconductors and normal conductors: The Mattis-Bardeen theory. » Journal of Superconductivity 4.5 (1991): 341-355.
- A. Gurevich « Theory of RF superconductivity for resonant cavities. » Superconductor Science and Technology, 30(3), 034004 (2017).
- A. Gurevich «Tuning microwave losses in superconducting resonators. »
- Supercond. Sci. Technol. 36 063002 (2023)
- SRF23 Tutorial A. Miyazaki