MATERIAL SCIENCE OF Nb RF ACCELERATOR CAVITIES: WHERE DO WE STAND 2001?

J. Halbritter
Forschungszentrum Karlsruhe, Institut für Materialforschung I
Postfach 3640, 76021 Karlsruhe, Germany

Abstract
The rf losses, especially actual level and increase with rf fields, limit most stringently the application of superconducting rf cavities. This is due to the needed cooling power to be supplied locally to the high field region causing rf breakdown. The rf losses are due to two sources based on different physics: dielectric rf losses proportional to $R^E E^2$ and shielding current losses proportional to $R^H H^2$. Material science wise intrinsic losses $R_{\text{BCS}}$ are separate from extrinsic, rf residual losses $R_{\text{res}}$. The separation of $R_{\text{res}}(T,f,H)$ from the BCS losses $R_{\text{BCS}}(T,f,H)$ yields the quasi-exponential increases of the electric surface resistance with the electric field $E$ perpendicular to the surface $\delta R^E(E\perp) \propto \exp(-c/E\perp)$ and the power law increases of the magnetic surface impedances with the magnetic field $H$ parallel to the surface $\delta R^H(H\parallel) \propto (H\parallel)^n (n = 1, 2, \ldots)$. By Nb/Nb$_2$O$_3$ interfaces of external and internal surfaces $R^E_{\text{res}}(T,f)$ and $R^E_{\text{res}}(f,E\perp)$ can be explained quantitatively by localized states $n_L$ of Nb$_2$O$_5$-$y$ in close exchange with extended states $n_m$ of Nb. Especially, the Q-drop $\propto 1/R^E(E\perp)$ and its reduction by EP- and BCP-smoothening and by UHV anneal at $T = 100\,^\circ\text{C}$ are well accounted for by interface tunnel exchange. The UHV anneal not only reduces surface scattering and $R^E$ but also enforces the $R_{\text{BCS}}(1.3\,\text{GHz}, H < 10\,\text{mT})$-drop and reduces $R_{\text{BCS}}(T = \text{GHz}, = 10\,\text{mT})$ by more than a factor 2. The interrelations $R_{\text{BCS}}$-$drop$, $R^E$ and $R_{\text{BCS}}$ with the material science of Nb$_2$O$_3$-$y$/Nb interfaces, e.g., by EP or UHV anneal, will be elucidated.

1 INTRODUCTION
The technology to produce Nb rf accelerator cavities with gradients above $E_{\text{acc}} = 10\,\text{MeV/m}$ and $Q_0$ (2K; 1 GHz) $= 10^{10}$ is now in hand and delivered by industry, as the result of more than 30 years intensive research and developments started first at Stanford [1] and Karlsruhe [2]. But still progress is needed to fulfill the ever growing desire of, e.g., the high energy physics community [3]. Highlights in the recent progress are discussed below. Progress usually starts with a name, like Q-decrease or Q-drop, followed by quantification and then the decay can be overcome. The progress to be reported in Nb cavity performance is based on basic research carried through by groups at CEBAF, DESY, INFM, KEK and SLAC, discussed in Sects. 4 and 5.

Where stands the materials science of superconducting Nb rf cavities and surfaces at the moment? Firstly, Nb free of inclusions, like big Ta- or NbO$_x$-lumps, with a dc resistance ratio $\text{RRR} > 200$ is now available [3]. Secondly, high pressure (80 bar) water rinsing (HPR) [4] is able to reduce the dust on Nb surfaces sufficiently. Thirdly, we are left with intrinsic Nb corrosion yielding after electropolishing (EP) or buffered chemical polishing (BCP), followed in both cases by HPR, some inhomogeneities, as sketched in Fig. 1.

Crucial are the scales: Nb is coated by less than 0.5 nm NbO$_x$($x \leq 1$) and by 1 - 3 nm Nb$_2$O$_3$-$y$ covered with hydrogen bonded H$_2$O/C$_x$H$_y$ (OH)$_z$ of similar thickness. Optimal superconducting Nb properties have to hold, at least, in a penetration depth $\lambda_{\parallel}(T\leq T/2) = 40\,\text{nm}$. Another scale is the dimension of Cooper pairs $\xi_{\parallel} = 60\,\text{nm}$, where metallic defects in Nb have to be much smaller in size to sustain overall good Nb properties. Similarly on Nb$_2$O$_3$, dust and protrusions have to be reduced in amount and size to get good electric field properties. This needed homogeneity in and on Nb is achieved now yielding $E_{\text{acc}} \geq 30\,\text{MeV/m}$ The scales of 1 - 10 nm for Nb cleanliness and homogeneity have to be compared to accelerator lengths of 0.1 - 1 km, showing a reproducibility over 10 order in magnitude being now achieved. This, by itself, is a big achievement. But as we see from semiconductor industry, there is still more to come. As material scientist, I will not dwell on this but I want to outline old and new Nb results and understandings, where, in my view, progress, has been made in the last years and will be made in the next years.

![Fig. 1: Nb surface with crack corrosion by oxidation by Nb$_2$O$_3$ volume expansion (factor 3), Nb$_6$O$_{14}$-$y$-$y$ weak links/segregates ($y$, $x < 1$) extend up to depths between 0.01 - 1/1 - 10 $\mu$m for good - bad Nb quality and weak - strong oxidation [8]. Embedded in the adsorbate layer of H$_2$O/C$_x$H$_y$ (OH)$_z$ being chemisorbed by hydrogen bonds to NbO$_x$($OH$)$_z$, adsorbate covered dust is found. This dust yields enhanced field emission (EFE [7]) summarized in Sect. 3.1.](image-url)
shear planes shown in Fig. 2 to achieve the proper valence 5 [8]. At shear planes oxygen vacancies occur easily yielding for 300 K surface oxides nL ≤ 10¹⁰/cm² localized states at EF, which tunnel along those shear planes with φ = 0.1 eV as barrier height [8]. The states nL(z < 2 nm) are in fast (< 10⁻¹⁰sec) interface tunnel exchange (ITE) with Nb conduction electrons of density nm as sketched in Fig. 3 and summarized in Sect. 3.2.

![Fig. 2: Nb₂O₅₋ₓ drawn as idealized octahedra, where the black circles are Nb atoms in tetragonal positions and outline the unit cell in projection, with octahedra sharing corners (Type 1 O) and sides (Type 2 O) yielding crystallographic shear planes where O-vacancies occur most easily, as insert Top: Nb₂O₅. The lighter form the 2 – 5 blocks at one level, the heavier forms are the 3 x 4 blocks at the second level. The levels are connected via corner sharing octahedra and via side sharing octahedra. Adjacent to the planes of side sharing octahedra are the crystallographic shear planes. Bottom: Nb₂O₄₋₅. The octahedra form 3 x 3 and 3 x 4 blocks at the second level with one O-vacancy at a shear plane.

![Fig. 3: Band structure at Nb-NbOₓ-Nb₂O₅₋ₓ interfaces with E_C - E_F = φ ≈ 0.1 – 1 eV as barrier heights for tunneling along crystallographic shear planes (~0.1 eV) or of Nb₂O₅₋ₓ crystallites (~1 eV). Added is the superconducting energy gap Δ*(z) < Δ₀, being reduced in NbOₓ clusters or interfaces and being normal conducting Δ*(z) ≥ 0.5 nm) in localized states of NbOₓ₋₅₋ₓ. By their volume expansion those clusters locally enhance T* and Δ* > Δ₀ in adjacent Nb by the uniaxial strain yielding a smeared BCS DOS.

For the conduction electrons ITE yields inelastic surface scattering described by a surface mean free path l, whereas the actual exchange with NbOₓ₋₅₋ₓ states under influence of an rf electric field Eᵣ(t) correspond to dielectric interface losses Rₑ. According to [5,6] two major types of NbOₓ₋₅₋ₓ coatings exists:

- fast, electrochemically grown wet oxide, e.g., by EP, of above 2 nm thick NbOₓ₋₅₋ₓ coated by 5 – 10 ML water and hydrocarbons, with a high density of nL and with a cracked Nb surface [8]. The crack density and the size of NbOₓ(x < 0.2)-precipitates and the amount and lengths of Nb₂O₅₋ₓ filled weak links are enforced by strain and defects inside the Nb.
- dry oxidation yields thinner (< 2 nm), more uniform NbOₓ₋₅₋ₓ coatings with only 2 – 3 ML water and hydrocarbons on top, with reduced charging, reduced ITE, reduced secondary emission [7] and reduced cracking [5,6,8].

The unperturbed bulk Nb has a T_c = 9.25 K and an average energy gap Δ₀(0) = 1.56 meV, where 2 % O degrades T_c down to 7 K and Δ₀ down by 20 to 30 %. The 2 – 3 ML thick metallic NbOₓ(x = 1) - layer between NbOₓ₋₅₋ₓ and Nb has a reduced energy gap Δ* < Δ₀. Inside the Nb below 600 K NbOₓ₋₅₋ₓ-weak links or NbOₓ(0.2 ≥ x ≥ 0.02) precipitate (Fig. 1) out of the Nb-O lattice gas [8]. By the enhanced volume of NbOₓ₋₅₋ₓ-precipitates and of Nb₂O₅₋ₓ-interfaces the surrounding Nb lattice is compressed enhancing Δ* > Δ₀ by up to 10 %, whereas at NbOₓ Δ* < Δ₀ is depressed by 10 to 20 % [8].
intermingled enhanced and depressed Δ* regions of sizes below about 5 nm < ξF smear the BCS density of states and depress the average energy gap Δ < Δo.

Like the Nb-O system below 600 K, picked up hydrogen precipitates to Nb-H below about 130 K preferably to NbN precipitates are removed to larger depth by lattice compression by NbOx-precipitates in the surface layer. Better is UHV anneal above 800°C, where H2 is evaporated, and then sealing the surface by Nb2O5-y to prevent H-pick-up.

3 INTERACTION OF RF-FIELDS WITH Nb CAVITY SURFACES

The rf fields at metallic surfaces can be separated in a rotational free component rot E = 0, namely E⊥ giving rise to an electric field surface impedance ZE = R ⊥ + iωμoε⊥ and in a divergence free component div E = 0, namely H∥ giving rise to rf shielding currents and magnetic surface impedance ZH = R∥ + iωμoε∥. Whereas the dielectric surface impedance ZE of clean metals is negligible because of λ⊥ ≤ 0.1 nm [10], Nb-Nb2O5-y by ITE cause a measurable ZE being discussed in Sect. 3.2. By a penetration depth λ(T < Tc/2, f < 100 GHz) ≥ 40 nm and λ∥(T > Tc) > μm/√f/GHz the shielding currents cause the dominant impedance ZH in superconducting and normal conducting rf cavities, the first being summarized below.

3.1 Electron loading

The E⊥-component causes electron emission where the gained energy of e- in the electric field then impinging on dielectric interfaces can cause enhanced electron emission, e.g. via secondary emission, via plasma generation [7] or via solid state double layers [11] enhancing the field emission directly or indirectly, described by the field enhancement factor β. HPR [3,4] has proven to be the adequate method to reduce dust and, hence, to reduce β to values 100 yielding now Eacc > 10 MeV/m regularly.

3.2 Electric surface impedance ZE by ITE

Whereas the intrinsic ZE of metals is negligible small [10,12b], the localized states nL of Nb2O5-y, at the Fermi energy EF (Fig. 3) by interface tunnel exchange (ITE) with the high DOS of Nb nF(EF) enhances ZE by several orders of magnitude. Quantitatively, the exchange is governed by a tunnel rate (Fig. 3)

\[ \lambda^E_n = - z^*(ω)^2 / 2y_n^2 \]

\[ R^E_n = \frac{\omega_0^2}{4K^2} \left( 1 - e^{-2\kappa^*(ω)} \right) \]  (1.2)

According to Eqs. (1), ZE is proportional to z*nL(z*), i.e. linearly increasing with nL and exponentially with lowered barrier height φ. The latter is quite small in Nb2O5-y for crystallographic shear planes with φ = 0.1 eV which house also the localized states nL = 10⁹/cm³ [8,10b]. For normal conducting Nb estimates gave with ε = εF and εF(Nb2O5-y) = 10 – 15 at the interface [10, 12b] z* = 1 nm and

\[ \phi^{E}_S(Nb-Nb_2O_{5-y}) \approx 10^{-3} \Omega / \varepsilon^2_\perp \approx 10^{-6} - 10^{-7} \Omega \]  (2.1)

at about 1 GHz. In the superconducting state an energy gap |e| < Δ opens in nF(ε) blocking ITE. But for fields higher than εzEy*.Eg/εF = Δ ITE sets in where with the static, geometric field enhancement factor β* < 10 the dielectric shielding E*ε = β*Eg overcomes the energy gap Δ, β* is smaller than β = 10² - 10³ being the dynamic field enhancement factor [7]. With Eq. (1.2) the high field ZE writes:

\[ R^{E}_{res} = \frac{\omega_0^2}{\varepsilon^2_\perp} \frac{1}{2y_n} (e^{-2\varepsilon^*_\perp} - e^{-2\varepsilon^*}) \]  (2.2)

i.e. only states between zEy and z* (ω) cause ITE rf losses. Hence Rres shows an onset at E*rf increasing exponentially like exp(-2εΔε/εβ*Eg) with E* conforming to E*res(Eg) saturates when all states nL between {0, min[z*, d oxide]} participate in ITE, i.e. Rres decreases with oxide thickness d oxide < z*. The small exponent Δ/β* in Eq. (2.2) is fitted by a power series Eln starting with 4 < n < 16 with n increasing by surface smoothness and reduced nF [10]. ITE in Eq. (2.2) develops out of standard field emission [7] by substituting φ = E – Eγ = eV and β ≥ 10² by Δ = meV and β* < β yielding as ratio between FE- and ITE-exponents Φ/Δ = 10³ due to resonant tunneling via intermediate states.

3.3 Intrinsic magnetic surface impedance ZH

The BCS-theory [12] is an excellent tool to obtain Nb material parameters as shown in [8] or Fig. 4 with agreement experiment / theory above 6 orders in magnitude in R(T). The parameters describing ZH of Nb are: the London penetration depth λL(T=0) = 32 nm, the dimension of Cooperpairs ξF = 60 nm and a mean free path l, the latter with its upper limit l ~ λd/sin 30° = 3 λd by inelastic surface scattering via ITE by Nb2O5-y [10] by trajectories with θ ≈ 30° relative to the surface enhancing with 1/l = 1l/λo + 1l/λl

\[ \lambda^H(T, l) \approx \lambda^L(T) f(γ) \sqrt{1 + ξF / l} \]  with γ = ξF / ξF  (3)

with f(γ) ~ 1/γ³ for γ < 0.1 by non-local effects [12a]. λH(T) > λd(T) is only weakly depending on temperature below Tc/2, whereas above Tc/2 strong and preparation dependent λH(T) increases have been reported [8].
Fig. 4: Surface resistance as a function of temperature T at 12.6 GHz of RRR = 30 Nb.

Especially the $\lambda^H(T^*)$ jump being related to stretches of NbO$_{0.02}$-clusters with $T^* = 6$-7 K are worth mentioning [8] being indicated in Fig. 1.

In contrast to $\lambda^H(T < T_c/2, \Delta/10) \approx \text{const.}$, the surface resistance $R^H(T,f,H)$ has been studied intensively in the last years because of its direct relevance to superconducting rf accelerator performance [3]. The surface resistance in the BCS theory needs a complex computer code, hence in the following the relevant dependencies for Nb-material science are made obvious only:

$$R^\text{BCS}(T,f) = c(h\omega) \int \frac{d^3k}{\Delta} \frac{2}{\gamma^2q^2 + 1} \frac{f(\epsilon) - f(\epsilon + h\omega)}{N(\epsilon)} N(\epsilon + h\omega) \cdot$$

with $f(\epsilon) = 1/(\exp(\epsilon/kT) + 1)$ the Fermi function, with the density of states $N(\epsilon) = (|k|^2/\gamma^2 - \Delta^2)^2$ with the BCS gap of 2$\Delta$, with A($k$) the photon momenta $k = k^\perp$ available for absorption with rot $A = H$ and $p_i$ (initial) and $p_f$ (final) momenta of the quasiparticles absorbing the photons ($\hbar k$, $\hbar \omega$) in dipole approximation. In Fig. 5 the normalized absorption rate of photons is plotted versus $\hbar \omega/2\Delta$ with $\gamma$ as parameter. Obvious is the strong dependence of the photon absorption rate $r = R/\lambda^H\omega$ on $\gamma$ in clear contradiction to any two fluid model. Also the frequency dependence deviates from $R \propto \omega^2$, i.e. $r \propto \omega$, in the direction of $R \propto \omega^{3/2}$ which is due to the BCS singularities in $\int f(\epsilon)N(\epsilon + h\omega)$ in Eq. (4.1) [12] yielding:

$$R^\text{BCS}(T,\omega) = c_{BCS}^\omega N(\Delta + h\omega) \left[ f(\Delta) - f(\Delta + h\omega) \right] M^2$$

$$= e^2 \omega^2 \Delta/\sqrt{2\hbar\omega \Delta} \exp(-\Delta/kT)$$

for $T < T_c/2, \Delta \ll \hbar \omega < 2\Delta$.

Under the dominance of BCS-singularly the matrix element $M^2(\xi,\lambda L,\hbar \omega)$ containing momenta $p_i - p_f = k$ and energy conservation $p_i^2 - p_f^2 = (\epsilon + \hbar \omega) - \Delta^2 - \sqrt{\epsilon - \Delta^2}$, Eq. (4.2) can be approximated by [12]

$$R^\text{BCS}(T,\omega,\lambda L) \approx \frac{\hbar \omega \exp(-\Delta/kT)}{\sqrt{2\hbar \omega \Delta}}$$

yielding for $\gamma \geq 1$ $R/\omega \lambda^L \approx \gamma$. The mean free path dependence for Nb is shown in Fig. 6, and like Fig. 5, with changes in clear contradistinction to two fluid models, i.e. $R^\text{BCS}(T)$ decreases ($l > \xi$) with enhanced scattering whereas $\lambda(T)$ increases according to Eq. (3).
3.4 Nonlinearities of homogeneous Nb

Intrinsic nonlinearities, like R-increases due to heating, can be cast in a power series [10a, 13]

\[ R(T, f, H) = R(T, f, 0^{+}) + \gamma_{T}^{*} H + \gamma_{T}^{*} \frac{H^{2}}{2} + \ldots \] \hspace{1cm} (5.1)

where for Nb as scaling field \( H_{c}(0) = 0.2 \) T is used substituting \( H_{c}(T) \). For intrinsic nonlinearities \( \gamma_{T}^{*} < 0.2 \) is estimated as upper limit [13], whereas heating yields larger \( \gamma_{T}^{*} \) values.

\[ \gamma_{T}^{*} = \frac{\partial R}{\partial T} \bigg|_{T = 0} \] \hspace{1cm} (5.2)

Here \( d_{1} \) and \( \kappa \) are thickness and thermal resistance of Nb, then for sputtered Nb/Cu the interface resistance has to be added and, at least, the Kapitza resistance \( R_{K} \) toward the He-bath has to be overcome. The heat transfer by phonons is given by their scattering at quasiparticles and the in quasi-amorphous Nb-Cu sputter transition layers \( l_{sp} = \mu m \) and \( \kappa < 0.1 \) W/cm K holds [14], yielding \( \gamma_{T}^{*} \geq 20 \) [10a]. But always the Kapitza resistance has to be overcome, with \( \gamma_{T}^{*}(T) \geq 0.3 \) increasing below 2 K < \( T_{k} = 2.17 \) K [15].

3.5 Inhomogeneous Nb

Whereas microscopic cluster of, e.g., Ta of 10 \( \mu m \) size, act by their own, weak superconducting properties, small NbO\(_{x}\)(x < 0.1) cluster of sizes below 5 nm < \( \xi_{c} \) show only a slightly depressed order parameter \( \Delta^{*} < \Delta \), by depressed superconductivity compensated in part by proximity to bulk Nb, whereas their strain onto the surrounding enhances \( \Delta^{*} > \Delta \). Those NbO\(_{x}\)-cluster broaden the BCS square root singularity to \( \Delta^{*} \) yielding a reduction of \( R_{BCS} \) in Eqs. (4.2 and 4.3) and Fig. 8 to

\[ R_{BCS}(T, f) \propto (\hbar \omega)^{2} \exp(-\Delta^{*}/kT)^{1/2} \] \hspace{1cm} (4.4)

Clearly, those cluster reduce also the mean free path \( l_{m} \), which by inelastic surface scattering at \( n_{l} \)-sites of Nb\(_{2}\)O\(_{3}\) is already reduced to \( l_{m} = 3\Delta_{l} \). At NbO\(_{x}\)/Nb\(_{2}\)O\(_{3}\) interface layer the energy transferred to quasiparticles is effectively transferred to phonons via localized states \( n_{l} \). This is different to NbO\(_{x}\)-cluster depicted in Fig. 1, where quasiparticles are weakly localized by \( \Delta^{*} > \Delta \) with an electron-phonon coupling like in bulk Nb at this temperature. This electron phonon coupling is weak as shown by the inelastic scattering time for \( \hbar \omega = \Delta \) excitations

\[ \tau_{in} = 1.15 \times 10^{-10} \left( \frac{T}{4.2} \right)^{3} \text{sec} \] \hspace{1cm} (6.1)

where for \( T < 4.2 \) K the recombination time of two quasi particles is negligible. This has to be compared to the quasi particle absorption rate \( \tau_{qp} \) [14]

\[ \frac{1}{\tau_{qp}} = \frac{B_{2}^{rf}}{h^{2} \mu_{b}} \frac{1}{n_{l} \hbar \omega} \frac{R}{X} \] \hspace{1cm} (6.2)

where for Nb with \( n_{m} = 3.6 \times 10^{22}/\text{eVcm}^{3} \) as density of states, \( \hbar \omega = 10^{5} \) eV, \( B_{2}^{rf} = 1 \) mT and \( X/R = 200 \) \( \tau_{qp} = 10^{8} \) sec is obtained comparable to \( \tau_{in} \). For \( B_{2}^{rf} > 1 \) mT this bottleneck enhances the local temperature \( T^{*} > T \) at NbO\(_{x}\)-clusters and, thus, according to Eq. (4.2) by \( [\hbar \varepsilon - f(\epsilon - \hbar \omega_{0})] \propto \exp(-\Delta^{*}/kT^{*}) \), the absorption is reduced. In contrast, adjacent Nb with the mean energy gap \( \Delta \), with the absorption given by \( \exp(-\Delta/kT) \), easily dissipate the absorbed quanta somewhere in the Nb-wall because of \( \tau_{in} \approx 2 \) mm, in \( \Delta^{*} > \Delta \)-regions confined states overheat by 1/\( \tau_{qp} \) > 1/\( \tau_{in} \) holding locally. This overheating of regions with enhanced rf losses proportional to \( \exp(-\Delta^{*}/kT^{*}) \) decreases toward \( \exp(-\Delta^{*}/kT^{*}) \) by overheating, where according to Fig. 9 and [16]

\[ R_{*}^{H_{rf}} = \text{const.} \frac{H}{H_{max}} = \hbar \omega \varepsilon_{F} / 3 \lambda_{H}^{3} \] \hspace{1cm} (6.3)

for \( \epsilon \) energy independent \( \tau_{in} \), \( R_{BCS} \) is reached above about 10 mT where thermal equilibrium is guarantied because of \( \varepsilon_{F} \tau_{in} > \lambda \) for quasiparticles with energies \( \epsilon \geq \Delta \). In line with \( \Delta^{*} = \Delta/2 \) for \( H \leq H_{max} \) in Fig. 9, the BCS-like absorption (Eqs. 4) adds to the \( \Delta^{*} \)-region rf losses. Aside of those processes where momentum \( p_{\|} = p_{\perp} = k \) is transferred to the photon field, the momentum of extended states \( [\Delta p] = e\hbar \max / V_{F} \lambda_{H}^{3} \) can be transferred to the \( \Delta^{*} < \Delta \) localized states, yielding the resonance obvious in Fig. 9 quantified in Eq. (6.3).

3.6 Residual rf magnetic losses \( R_{res}^{H} \)

As discussed in [10a] the NbO\(_{2}\)-interface with normal conducting states \( n_{l}(z \geq 0.3 \) nm) yields inelastic surface scattering and coherent momentum transfer to the lattice staying finite for \( T \to 0 \) with the ITE \( \tau(\epsilon^{*}) \) of Eq. (1b)

\[ R_{*}^{H_{rf}} = \text{const.} \frac{H}{H_{max}} = \hbar \omega \varepsilon_{F} / 3 \lambda_{H}^{3} \] \hspace{1cm} (6.3)

Fig. 7: (T, H)-dependencies of a spun cavity after 150\( \mu m \) chemical polish (BCP) [10]. Obvious is a \( \delta H / Q(H) \approx \gamma_{e}^{*} (H/0.2) T^{2} \) loss increase above 10 mT turning at \( E_{crit}^{\bullet} \) to a quasi exponential \( \delta H / Q(E) \approx E^{\gamma_{e}}(n = 8) \) increase ending in the breakdown at \( R(T, H) H_{2}^{\text{crit}} = \text{const.} \) with a jump at \( T_{cr} = 2.17 \) K. The \( \tau^{\gamma}(T) \) values show a corresponding jump at \( T_{s} \) from \( \tau^{\gamma}(T < 2 K) = 2 \) to \( \tau^{\gamma}(T > T_{s}) > 10 \), whereas the \( E^{\gamma_{e}} \)-increase is temperature independent – see Sect. 4 and [10a].
At weak links filled with Nb$_2$O$_{5-y}$ one has not only reflection but also a normal current in parallel to the Josephson critical current $j_{cJ}$ across the junction (Fig. 1), which yields the Josephson penetration depth $\lambda_j(T,H) = \sqrt{\hbar / 2e\mu_o \lambda_\mu(T)} j_{cJ}(T)$. For weak links in a mean distance $a_j$ with $R_{id} \propto 1/m_d(\geq 0.3 \text{ nm})$ as leakage current resistance rf residual losses are obtained.

$$R_{res}(T,f) \approx (\lambda_j(T) 2\omega(z^*)) < 5 \cdot 10^{-9} \Omega(f/\text{GHz})^2$$

(7.1)

$$R_{res}(T,f) \approx (\lambda_j(T))^3 \frac{a_j R_{id}}{1+(\omega \tau_f)^2}$$

(7.2)

with $1/\tau_f = \frac{2e}{\hbar a_j(T) R_{id}}$

as Josephson frequency. For Nb $\lambda_j(T \leq T_c/2) = \lambda (0)$ holds and, hence, below $T_c/2$ the rf residual losses are constant. $= R_{res}(T)$.

**4 EXPERIMENTAL RESULTS**

Experimentally, eigenfrequency changes $\Delta f/f_0$ and $\gamma^*$-losses, e.g. a decay time, $\tau = Q/\omega_0$ are the observables in rf measurements, being related to the surface impedances by [10,13]:

$$\Delta \omega = \frac{1}{\omega_0} \int dz Z(E) \Delta z = \frac{e}{2 \omega_0 \mu_o} \int [d\omega / \omega^2]$$

$$= \frac{Z(E)}{2 G} \Delta z$$

For TEM modes $G^H = G^E$ holds, being weakened in TM-modes to $G^H \leq G^E$ approaching $G^E \to \infty$ for TE-modes. In our analysis of the TM$_{010}$-mode we assume $G^H = G^E$ with $G^H = 290 \Omega$ and peak field ratios $H_p/E_p = 2.5 \text{ mT/mV/m,}$ and $E_p/E_{acc} \equiv 1.8$.

In Figs. 4, 7, 8 and 12 the surface resistances $R(T_c = 10 \text{ mT}) = R_{BCS}(T) + R_{res}$ have been quantified by the BCS theory, resulting in material parameters of Nb in a 40 nm Nb-$\text{Nb}_2O_5$-Y interfaces, especially weak links. As obvious in Fig. 8 the BCS-theory shows a slower decrease $R(f < 10 \text{ GHz}) = f^{1.6}$ than experimental results with oxidized RRR = 30 Nb $R_{res}(f) = f^2$. At 1.5 GHz differences are found between “clean Nb” and UHV-annealed Nb [10], where $R_{BCS}$ decrease by a factor 2 for RRR > 100 Nb and 1.5 for RRR = 30 Nb to the identical lower level. Corresponding to this $R_{BCS}(10 \text{ mT})$-decrease seems the $R(H<10 \text{ mT})$-drop shown in Fig. 9 with an effective gap $\Delta^*/kT = \Delta^*/kT^*$ increasing in this direction. For enforced oxidation this drop strengthen (Fig. 10), especially for coldworked Nb. For the same corrosion processes $R_{res}$ is largest for coldworked Nb, see Fig. 8 and 10.

In Figs. 7 and 10 above $E_p = 10 \text{ MV/m}$ electric peak field the dependencies are fitted by $\gamma^*(H/H_c)^2$ which depends on $T$ only and not on surface treatment [17-22]. In the Nb cavity with the highest $H_p$ obtained to date, $\gamma^* = 0.25$, $R_{res} = 2 \cdot 10^{-9} \Omega$ and $H_p = 185 \text{ mT} > H_c(1.6 \text{ K}) = 168 \text{ mT}$ has been achieved [17]. Hence, $\gamma^*(T < T_c) = 3$ with $H_p = 100 \text{ mT}$ and $\gamma^*$ jumping to 12 above $T_c = 2.17 \text{ K}$ in Fig. 7 are clearly extrinsic in nature.

Whereas $R_{BCS}$ in Eqs. (5.1) are a standard Taylor series, $Z^E$ depends exponentially on $E^2$ by tunnel effect for FE and ITE, with a clear onset at $E^*_{rf}$ by $z_E = \text{min}(z^*(0), d_{oxide})$ according to Eqs. (1.2) and (2.2). At this onset an exponential increase sets in which, for experimental analysis, is cast in $E^2 \gamma^* \propto E^L$.
\[
\frac{E_{\text{rf}}}{R_{\text{E}}} \cdot \frac{dR_{\text{E}}}{E_{\text{rf}}} = \frac{E_{\text{rf}}}{R_{\text{E}}} \cdot \frac{2k\Delta}{\beta \tau} c_{\text{E}} \left( 1 \cdot \frac{E_{\text{rf}}}{E} \right)^2 \cdot R_{\text{E}}
\]

For the identification of this \( R_{\text{E}} \) component
\[
R(T,f,H) = (R_{\text{E}}^{R_{\text{res}}} + R_{\text{E}}^{H_{\text{BCS}}}(T,f) + R_{\text{E}}^{E_{\text{crit}}}))
\]

\[
(1+\gamma^* (H/0.2T)^2 +)
\]

has to be used, where the geometry factors \( G \) weighing in Eq. (8) \( Z \) are not correct for non-linear interaction mechanisms, hence local measurements are more appropriate. Those are depicted as temperature maps in Fig. 11, showing no pronounced bad spot but critical \( R_{\text{E}} \) via \( \Delta T \) yields breakdown on a ring with \( E = E_{\text{crit}} \) in this TM\(_{010}\)-mode, which change by surface smoothing to higher \( E_{\text{crit}} \) moving closer to the equator where \( R_{\text{E}}^{H_{\text{BCS}}}(T) \) enhanced by \( R_{\text{E}}^{E_{\text{crit}}} \) reaches \( Ecrit \approx 0.8 \) decreasing to \( 0.55 \) by UHV anneal, whereas \( R_{\text{E}} \geq 200 \) Nb with \( R_{\text{BCS}} \) \( 4.2 \) K/\( \mu \Omega \) decreases to \( 0.55 \) also. Correspondingly, \( \Delta kT_c \) decreased for \( RRR = 30 \) Nb by \( 3 \% \) and for \( RRR = 200 \) up to \( 1 \% \) only. The \( R_{\text{BCS}} \) decrease down to \( 0.55 \) \( \mu \Omega \) for UHV annealed or oxidized Nb cannot be explained by a mean free path reduction of homogeneous Nb, which allows at \( 1.5 \) GHz for ideally clean Nb a factor \( 1.6 \) or for \( l_0 \approx 10^{-7} \) nm by ITE a factor 1.2 only as shown in Fig. 6. But smearing the BCS DOS by additional NbO\(_x\)-precipitates caused by O-in-diffusion and O-precipitation, extending up to \( 100 - 200 \) nm deep into the Nb [24] in accordance with O-diffusion into Nb, explains the \( R_{\text{BCS}} \)-reduction up to a factor around \( 2 \) at \( 1.5 \) GHz with the changed frequency dependence obvious in Fig. 8 and Eq. (4.2). Also the \( \Delta kT_c \)-reductions, summarized above, growing with already present defect density down to \( \Delta kT_c \approx 1 \) are in line with NbO\(_x\)-precipitates, as has been quantified for \( RRR = 30 \) Nb in [8], where the \( \Delta kT_c \)-reduction are proportional the BCS DOS smear by the changed frequency dependence of \( R_{\text{BCS}}(T,f) \).

5.1 BCS-Theory and \( R_{\text{BCS}}(T) \)-fits for \( H_{\text{rf}} = 10mT \)

Because of \( R_{\text{res}}(T \leq T_c/2) = R_{\text{res}} \), \( R_{\text{BCS}}(T \leq T_c/2) \) yields with great accuracy \( \Delta kT_c \) and \( R_{\text{BCS}}(4.2 \) K,\( f) \) as presented in Sect. 3.3 and shown in Fig. 4. In rf cavities for shortest oxidation best \( \Delta kT_c \) values of 1.92 are obtained being still \( 5 \% \) below clean Nb. This \( 5 \% \) hints to the standard 3 ML NbO\(_x\)(\( x = 1 \)) at the surface and NbO\(_x\)-cluster depleting locally the gap parameter by more then \( 30 \% \).

Additional 20 min oxidation yields [8] \( \Delta kT_c = 1.84 - 1.86 \) by additional O injection and NbO\(_x\)-precipitation which is enforced by oxidation or 'UHV anneal' at \( 400 \) K in excess of \( 10 \) h reducing \( R_{\text{BCS}} \) as found in air anneal already 20 years ago [8] and repeated by Saclay [18]. The reduction starts from \( R_{\text{BCS}} \)-values depending on the initial purity of the Nb after BCP. \( RRR = 30 \) Nb has a bulk \( I_0 = 10^5 \) nm, with \( l_0 = l_0/2 \) at the surface and \( R_{\text{BCS}}(4.2 \) K)/\( \mu \Omega \) = \( 0.8 \) decreasing to \( 0.55 \) by UHV anneal, whereas \( RRR \geq 200 \) Nb with \( R_{\text{BCS}} \) \( (4.2 \) K)/\( \mu \Omega = 1 \) decreases to \( 0.55 \) also. Correspondingly, \( \Delta kT_c \) decreased for \( RRR = 30 \) Nb by \( 3 \% \) and for \( RRR = 200 \) up to \( 1 \% \) only. The \( R_{\text{BCS}} \) decrease down to \( 0.55 \) \( \mu \Omega \) for UHV annealed or oxidized Nb cannot be explained by a mean free path reduction of homogeneous Nb, which allows at \( 1.5 \) GHz for ideally clean Nb a factor \( 1.6 \) or for \( l_0 \ll 10^{-7} \) nm by ITE a factor 1.2 only as shown in Fig. 6. But smearing the BCS DOS by additional NbO\(_x\)-precipitates caused by O-in-diffusion and O-precipitation, extending up to \( 100 - 200 \) nm deep into the Nb [24] in accordance with O-diffusion into Nb, explains the \( R_{\text{BCS}} \)-reduction up to a factor around \( 2 \) at \( 1.5 \) GHz with the changed frequency dependence obvious in Fig. 8 and Eq. (4.2). Also the \( \Delta kT_c \)-reductions, summarized above, growing with already present defect density down to \( \Delta kT_c = 1 \) are in line with NbO\(_x\)-precipitates, as has been quantified for \( RRR = 30 \) Nb in [8], where the \( \Delta kT_c \)-reduction are proportional the BCS DOS smear by the changed frequency dependence of \( R_{\text{BCS}}(T,f) \).

5.2 UHV-anneal, NbO\(_x\)-cluster and deviations from thermal equilibrium

In \( 100^\circ \) C UHV anneal Nb\(_2\)O\(_{3.5}\) becomes thinner on account of O diffusion and NbO\(_x\)(\( x \ll 1 \)) precipitation into Nb. The Nb\(_2\)O\(_{3.5}\)-thinning has been measured by ARXPS [6] and by ITE (Fig. 12 and Sect. 5.5), the NbO\(_x\) diffusion depth has been measured by stripping [24] and the NbO\(_x\)-precipitates by \( \Delta kT_c \)-reductions, by \( R_{\text{BCS}} \)-reductions analyzed above and by \( R_{\text{res}} \) increases discussed in Sect. 5.3. All those degradations are observed also for standard oxidation already - see Sect. 5.1. The finite size of NbO\(_x\)-cluster localize quasi particles in the \( \Delta^* < \Delta \) potential, which are easily driven out of thermal equilibrium. This has been worked out in Sect. 3.5 yielding \( R_{\text{res}}(H < 10 \) mT) \( \propto 1/H^2 \) as decrease. As shown in Figs. 9, 10 and 12 this effect is the more pronounced the more NbO\(_x\)-cluster are present, as, e.g., for cold worked Nb in Fig. 10 or \( RRR = 30 \) Nb in Fig. 9. There, reduced gap values for \( H < H_{\text{max}} \).
are obvious also. The peak shown in Figs. 7, 9, 10, 12 and 13 is due to the energy gain transferred to those cluster explained in Eq. (6.3).

5.3 Magnetic rf residual losses $R^H_{res}$

As obvious by Fig. 7, coldworking and enforced oxidation enhances $R_{res}$ via $\omega^\beta$ [25] by enforced weak link growth, discussed in Section 3.5 and [8]. By enforced UHV anneal, e.g., above 150°C or heating Nb in air above about 90°C. $R_{res}$ is systematically growing [8,20-25] in line with Sect. 3.5. $R_{res}(1.5 \, \text{GHz}) \leq 10^8 \Omega$ is dominated by short junctions $t < 20$ nm and inelastic surface scattering [25c,d] discussed in Sect. 3.5. The short junction depicted in Fig. 1 penetrate into Nb by crack corrosion [5,8] yielding $R_{res}(T < T_c/2, H_p < 1 \, \text{T}) = R_{res}$ [12a,25b].

5.4 Dielectric surface resistance $R^E(T,E)$

Dielectric losses in the insulator coating are an old proposal for rf residual losses quantified by [25a]

$$R^E \approx \frac{\varepsilon_\infty}{\kappa} \frac{\Delta \varepsilon_{dep}}{\epsilon_r} \cdot 10^{-5} \cdot 4 \cdot 10^{-11} \Omega,$$

(2.3)

being much smaller than the observed ones – see Fig. 8. For anodized Nb $R^\varepsilon_{die}$ becomes measurable in TM-modes above $10^4$ nm $\text{Nb}_2\text{O}_5$ only, despite all those defects existing in wet or galvanic $\text{Nb}_2\text{O}_5\text{y}$. The dielectric loss mechanism introduced in Sect. 3.2 is a specific interface mechanism making use of the high density of states in metals $n_L$ adjacent to an oxide layer containing localized states $n_B$. Systematic studies on $R^E(T,E)$ are rare because of its smallness, but ITE grows linearly with $n_1(e)$ and, hence, $\text{Nb}/\text{Nb}_2\text{O}_5, \text{Ta}/\text{Ta}_2\text{O}_5$ and high Tc superconductors (HTS) show the largest effective ITE’s [10,12b]. Because $R^E$ and $R^H$ are intermingled - see Sect. 3 - a clear separation of both rf residual losses is not possible. But at high fields $R^E(H)$ follows a Taylor expansion (Eq. (5.1)) being distinctively different from the exponential, tunnel current like increase of $R^H(E^\bot)$ allowing to separate both effects.

In TM$_{00p}$ mode Nb cavities at fields $E^\bot > 10$ MV/m the Q-drop or ‘European decease’ [17-24] is encountered. That is, an electron loading free, field emission like increase occurs at equatorial rings which shifts to smaller $E_p/E_{max}$ values with BCP-smoothing where, in addition, Eq. (7.3) yields $\Delta T \approx E_{max}^{n+2}$ a multiplication by an $R^H_{res}^{n+2}$ increase obvious in Fig. 11b. Further smoothing of the BCP surfaces by EP reduces $R^E(T)$ with increased $E^\bot_{res}$ and $n$ values, as obvious in Fig. 13 allowing to reach $E_{acc} > 30$ MeV regularly [22]. Those values are obtained by UHV anneal after BCP shown in Fig. 12, where $R^E(E) = A E^\delta$ decreased in A by a factor 10.

As proven above, ITE gives a quantitative description of the Q-drop with accepted interface parameters. $R^E$ decreases with smoothening of surfaces by BCP followed by EP [22], in line with the $\beta^* E_p$-dependence in Eqs. (2). The temperature dependencies presented in [10] confirm, that $R^E_{res}$ is temperature independent below 3 K, which is in line with Sect. 3.2 and $\Delta^\beta E_p = \Delta^\beta(0)$ below $T_c/2$. The result of Fig. 12 of $R^E$-reduction by UHV anneal thinning the dielectric Nb$_2$O$_5$ layer to thicknesses below 1 nm $< z_{nd}(35 \, \text{MeV/m})$ for most of the surface confirm Sect. 3.2 also.

5.5 Magnetic field dependencies $R^H(T,f,H^\bot)$

If hydrogen is removed properly from the surface layer either by UHV 800°C anneal or by NbO$_x$-precipitates at the Nb surface, the linear $R^H(F,f,H^\bot)$ increase by flux
penetration \[9,25d\] is absent. Then \(R_H \approx \text{const.}\) above \(H_{rf} > 10-20\, \text{mT}\) holds as overall and consistent description of \(R_B(T,H)\) of Nb cavities fabricated from Nb sheeth. As uppermost limit for intrinsic BCS nonlinearities \(\gamma^\alpha < 0.2\) is estimated. Clearly, Figs. 7 and 10 with \(\gamma^\alpha(T) \geq 1\) are extrinsic and due to heating as the temperature dependence of \(\gamma^\alpha(T)\), especially the jump at \(\lambda = 2.17\, \text{K}\), proves. This and the ballistic phonon heat transfer through 0.3 cm Nb due to a phonon mean free path \(l_p = 2\, \text{cm}\) for \(T < T_c/4\) hints to the phonon escape via the Nb/NbO\(_x\) interface (Fig. 1) into the He as bottle neck, i.e. to an enlarged Kapitza resistance \(R_K = 1\, \text{cm}^2\) \(W/(T/K)^4\) \[15\]. As given by Eq. (5.2) \(\gamma^\alpha(T_o) \propto R_{BCS}(T_o)/T_o\) increases for \(T > T_\lambda\), whereas below \(T_\lambda\) the Kapitza resistance \(R_K \propto 1/T^2\) overcompenses the \(R_{BCS}(T)/T^2\) dependence in Eq. (5.2) yielding the observed \(\gamma^\alpha(T)\) increase below \(2\, \text{K}\) in Fig. 7. At \(E^\alpha\) fields where \(R^\alpha\) becomes comparable to \(R_{BCS}(T)\) locally the \(R^\alpha\) induced heating \(\Delta T\) gets multiplied exponentially by \(R_{BCS}(T + \Delta T)\) yielding the heat map and breakdown at rings in small distance to the equator in Fig. 11b, which in their grainy structure reflect ITE governed by the local field enhancement factors \(\beta^\alpha\).

The exchange rate \(1/\tau(z)\) of Eq. (1.1) has to be faster than \(1/2\tau\) to yield ITE as one-hop up to distances of 1.5 nm along the shear planes in Fig. 2. Consequently ITE is more pronounced at 0.1 GHz than at 1.5 GHz. Shear planes ending at NbO\(_x\) \((x \leq 1)\) seem to be less frequent in the smoother, dry oxides yielding a smaller \(\xi^\alpha\) term than in wet oxides. Because ITE is confined to a interface layer at forthcoming changes of the outer surface (Fig. 1) by oxide growth or water and hydrocarbo chemisorption will change ITE negligibly only. This is in contrast to electron loading depending on those outer layers, as discussed in \[7,26\].

5.6 RF-breakdown

The above analysis of Nb cavities of superior quality, i.e. no local degradations of superconductivity, e.g. by Ta- or Fe-cluster, enhancing \(R^\alpha\) or no dust or no electron loading enhancing \(R^\delta\), show that for bulk Nb the heat transfer at the Nb-NbO\(_x\)-He interface and \(R_D(E^\delta) \propto \exp(-c/E^\delta)\) defines the nonlinearities and the rf breakdown roughly with \(H^2_{crit}\) \(R(E_{crit}) \approx \text{const.}\) for \(T < T_\lambda\). For the best cavity with \(E_{crit} = 44\, \text{MeV/m}\) and \(H_p = 0.19\, T > H_{c1}(1.6K) = 0.168T\) \[17\]. In this cavity, the critical heat load \([R^\delta(E_{crit})+R^\alpha(H_{crit})]\) \(H_{crit}/2\) is a factor of about 2.5 larger after 2 years, where \(E_{crit} = 27\, \text{MeV/m}\) have been reached only, with an indication of \(R^\alpha\). In the spun cavities the critical heat load below \(T_\lambda\) is more than a factor 5 higher then for the \(44\, \text{MeV/m}\) BCP cavity and in those cases the \(R^\delta\)-term yields a grainy heating on rings close to the equator – see Fig. 11 – for \(E_{sec} > 20\, \text{MeV/m}\) becoming more grainy for \(E_{crit} < 15\, \text{MeV/m}\) on rings close to the iris. Those very grainy appearances below \(E_{crit} < 15\, \text{MeV/m}\) become unstable at critical heat flows being a factor 25 higher than for \(E_{crit} = 44\, \text{MeV/m}\), hinting to the fact, that ITE by local field enhancements causes high losses locally, stabilized by the surrounding, especially by the lateral heat flow caused by \(R_K\). This stabilization grows for \(T > T_\lambda\) by the higher boundary resistance \[15\] even more, as shown by critical heat flows jumping at \(T > T_\lambda\) by factors larger than 2. This will not happen for \(H_p\) approaching \(H_{ab}\) where the surface properties and heating are more uniform and, hence, the critical heat flux lower.

What is the reason for the rf breakdown? Not talking about extrinsic but intrinsic causes only, line nucleation yield in \[27a\] for clean Nb the critical superheating field \(H_{ab} = 0.2\, T\). Close to \(H_{ab}\) also the penetration depth \(\lambda\) increases with \(H\) \[27b\] yielding in \(R_{BCS}(H)\) higher powers in \(H^\alpha\), intrinsically not to be discussed here. Because near the surface local defects (NbO\(_x\), . . . – see above) causes a mean gap reduction of 10 % or more, line nucleation may be eased averaging over \(2\xi^\alpha > 100\, \text{nm}\) Nb, which may correspond to the observed 5 % \(H_{ab}\) reduction \[17a\]. The above mentioned small \((\xi^\alpha)\) defects by themselves will not cause breakdown because their deteriorated \(\Delta^\alpha\) values by up to 30 – 50 % are stabilized by proximity and deviation from thermal equilibrium discussed above.

6 SUMMARY AND CONCLUSION

As shown in the above analysis the present state of Nb surface preparation yields dielectric Nb\(_2\)O\(_x\)-\(y\) layers of thicknesses above 2.5 (wet) or 1.5 nm (dry) containing more (wet) or less (dry) shear planes per surface area with localized states \(n_{11} \leq 10^{19}/\text{cm}^3\). The enhanced Nb\(_2\)O\(_x\)-\(y\) or NbO\(_x\) \((x \leq 1)\)-volume compared to Nb creates Nb\(_2\)O\(_x\)-\(y\) weak links and NbO\(_x\) cluster, depending on Nb quality or oxidation process. Those surface deteriorations act on high \(Q_o\) Nb cavities at high fields (\(>10\, \text{MeV/m}\)) mainly by ITE between the \(n_L(z \leq 1.5\, \text{nm})\) states and the conduction electrons of the metallic NbO\(_x\) surface causing \(R^\delta \propto \exp(-c/E^\delta)\) and inelastic surface scattering. The local electric field \(E^\delta\) is reduced by surface smoothing by BCP, being enforced by EP, where the \(n_L\)-density is reduced by

---

**Fig. 12:** UHV anneal for 40 h at 145°C of the spun Nb (P5; RRR \(\approx 250\)) cavity after 100 \(\mu\)m BCP reducing the \(E^\alpha\)-term. Worth mentioning is the deepened \(R(H)\)-minimum below 5 MeV/m by baking and the reduced \(E^\alpha\)-term by a factor 10.
UHV anneal, in addition.

The $\Delta/kT_c$ reduction compared to bulk Nb in the standard, oxidized Nb surface layer ($\approx 40$ nm) by 10% to about 1.84 by NbO$_x$-layers and –cluster enhances $R_{BCS}(T)$ which is reduced by BCS-density of states smearing, being enhanced by mild (< 150°C) UHV anneal. The 10% gap reduction may yield some Hsh-reduction but because of the $\xi_F \approx 60$ nm stabilization this reduction is smaller than 10%. The reduction may be avoided by an NbN-surface layer with $T_c \approx 15$ K being more corrosion resistant avoiding NbO$_x$-cluster in Nb and wet-oxides on Nb$_2$O$_5$-[8]. The Kapitza resistance $R_k \propto T^{-4}$ for present day RRR > 100 Nb dominates the heating enhancing rf losses causing finally rf breakdown, favoring working temperatures around 2 K.

ACKNOWLEDGMENT

Many thanks are due to A. Dacca, P. Kneisel, L. Lilje, K. Saito and B. Visentin for their interesting and intense discussions. The author thanks KEK, especially S. Noguchi and K. Saito, for the support making the presentation and this paper possible.

REFERENCES

b) J. Halbritter, IEEE Trans Appl. Superconductivity 11, 1864 (2001) and references therein
[14] J. Halbritter, Primärbereitung 08.02.02 PO6B (IKP, FZK, 1979) and to be published
[18] M. Pekeler, ibid, p. 820
[19] K. Saito et al., ibid p. 795
b) P. Kneisel, Proc. 9 workshop on Rf superconductivity, Los Alamos, Oct. 99, p. 446
[22] K. Saito et al., ibid, p. 179 and 288
[23] C. Antoine et al., ibid p. 295
b) M. Regier et al., IEEE Trans Appl. Superconductivity 9, 2375 (1999)
a) T. Yogi, PhD thesis (CalTech, 1976)