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Non Quadratic RF Losses in Niobium Sputter Coated Accelerating Structures

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Abstract

Low field Q-values of more than 10^{10} and maximum accelerating gradients E_a between 10 and 15 MV/m have been obtained in superconducting mono-cell and multi-cell accelerating cavities between 350 and 1500 MHz. The superconductor is niobium, which is magnetron-sputtered as a thin film ($\sim 1 - 2 \mu\text{m}$) on a cavity made from copper sheet. The dependence of the slope of Q vs. E_a on temperature and frequency can be explained by RF magnetic flux trapped within intrinsic defects.

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I. INTRODUCTION

The RF system for the circular e^+e^- collider LEP is going to be upgraded by the addition of superconducting (sc) RF cavities. The major part consists of copper cavities coated by magnetron sputtering with a thin layer of niobium (NbCu cavities). They are designed for 352 MHz, an accelerating gradient $E_a = 6$ MV/m and a Q-value of $4 \cdot 10^9$ at 4.2 K. Maximum gradients as large as 10 MV/m at Q-values of $4 \cdot 10^9$ have been obtained [1]. However, the Q-value decreases by more than a factor two between low gradient and the operating gradient. If any further energy upgrade for LEP were envisaged, operation between 6 and 10 MV/m could be possible in principle at the expense of more cryogenic power. If the Q-value at these gradients could be increased, operation would be even possible near the economic optimum [2]. For linear collider applications such as TESLA [3] yet larger gradients (25 MV/m) and Q-values ($5 \cdot 10^9$) have to be reliably mastered in multi-cell cavities at an operating frequency around 1.3 GHz. Sputter technology [4], [5] opens up an avenue towards this goal, because it has as principal advantage the absence of thermal quenching from normal conducting (nc) defects. Low field Q-values of more than 10^{10} and maximum gradients between 10 and 15 MV/m have been obtained in single cell and five-cell cavities at 1.5 GHz [6], [7]. The Q-value also decreases by about one order of magnitude up to the maximum gradient obtained (Fig. 1). This observation needs to be analysed, with the aim to maintain the large Q values up to the maximum gradient, before an application of NbCu cavities for linear colliders can be envisaged.

If the Q-value did not change with the accelerating gradient, the RF losses would be quadratic with the RF field amplitude. All mechanisms, which make the Q-value decrease with the RF field give rise to what we call non quadratic RF losses (NQL).

Vortex creation by an RF magnetic field was hypothesized as one possible explanation [7], [8]. A number of attempts have been made to model the NQL in low and high T_c superconductors [9] - [26].

In this note we will summarize the experimental results on NQL that we have obtained so far [6] - [8], [27], [28]. We will then explain these losses by magnetic flux trapped within intrinsic defects [15] - [18]. The underlying idea of this note is to use as few and as basic terms as possible. All numerical calculations are understood as estimations. They are done for 4.2 K and 1.5 GHz, unless indicated differently.

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Fig. 1: Q-value vs. accelerating gradient E_a for a mono-cell NbCu cavity at 1500 MHz and 1.8 K. For $E_a \leq 2.0$ MV/m, the Q-value is independent of E_a . The corresponding surface peak magnetic field is $B = 9$ mT (arrow).

II. EXPERIMENTAL RESULTS

A. Definition of non quadratic RF losses

The losses P generated per m^2 by the RF magnetic field of amplitude B can be split into magnetic and non-magnetic losses:

$$P = R_s (B/\mu_0)^2 / 2 + \text{others} \quad , \quad (1)$$

where R_s is the surface resistance and "others" comprise dielectric losses, electron impact, nc spots, etc.. R_s can be separated into the BCS, the residual terms and R_s' , which takes into account NQL:

$$R_s = R_{BCS} + R_{res} + R_s' \cdot B + \dots \quad (2)$$

B. Summary of experimental results

1) DC magnetic field:

- Sputter deposited niobium cavities are, compared to bulk ones, relatively insensitive to a small static external magnetic field, to which the cavity is exposed during cool down. For a local magnetic flux B_{ext} the local residual surface resistance increases linearly as

$$R_{res}(B_{ext}) = \alpha \cdot B_{ext} \quad (3)$$

with α around 400 nΩ/mT at 1.8 K [27].

2) RF magnetic field:

- NQL are generated by the RF surface magnetic field amplitude B . They cannot be explained by an increase of the BCS losses due to a uniform temperature increase of the Nb surface [8].

- R_S' depends linearly on B (for $B \ll B_c$) [8],

$$R_S(H) = R_S' \cdot B. \quad (4)$$

- R_S' increases with temperature according to the empirical relations [7], [8], [27]

$$R_S'(T) = \frac{\beta}{1-T/T^*} \text{ or } \frac{\beta}{(1-T/T^*)^2} \text{ or } \frac{\beta}{1-(T/T^*)^2}, \quad (5)$$

for $T < T^*$, T^* between 4 and 7 K, and β around 1 n Ω /mT.

- R_S' is sensitive to surface condition, as it may change after rinsing with high pressure water [6].

Fig. 2: Non quadratic RF losses (R_S') averaged over all RF tests done at CERN in the last three years [29] (criterion $B < 20$ mT). The total number of tests is 283, 11, 11 and 3 at four different frequencies, 352, 500, 1500 and 2790 MHz. The coating corresponding to the two data points at 350 and 500 MHz has been done at CERN [30], [31], the one corresponding to 1500 and 2790 MHz has been done at Saclay [6].

- R_S' has been found to increase linearly with the RF frequency [7]. However, the data available do not allow to exclude a quadratic rise (Fig. 2).
- There are indications that the Q-value remains constant with the RF field up to a threshold field of about $E_a = 0.5$ to 2 MV/m (equivalent to 2 to 8 mT), above which the Q-value decreases (Fig. 1).

3) Sample tests:

- Sputter deposited niobium has a critical temperature $T_c = 9.2$ K like bulk niobium and a large transition width compared to bulk niobium with superconductivity completely established only below 5 - 7 K [7], [8].
- Sputter deposited niobium has a relatively large upper critical field B_{c2} (2.5 to 3.5 T at 4.2 K) compared to bulk niobium and large transition width with a first sign of normal conductivity above 300 mT [7], [27], [32]. In the experimental set-up used B_{c2} is defined as in percolation models as the magnetic field, above which there exists no macroscopic sc path within the sample. Minute sc spots may still survive above B_{c2} (cf. III.B.) and will remain undetected.

4) Microstructural characterisation:

In the process of chemical removal of the Nb layer or after high pressure water rinsing, the Nb may come off in leaves. These were taken as samples. Other ones were produced by mechanical cutting of the cavity. The samples have been analyzed by conventional and analytical transmission electron microscopy (TEM) by means of a Zeiss EM 912 OMEGA instrument. The TEM samples were cut perpendicular (cross-section) and parallel (plan-view) to the niobium film plane. Standard preparation techniques involving mechanical polishing and ion beam thinning were used. A typical cross section through the niobium film is shown in Fig. 3 (a). The Nb film is formed via columnar grain growth perpendicular to the interface. The rod like Nb grains reach dimensions of up to 1 μm along their long axis and between 10 and 150 nm in diameter. The Nb-Cu interface is planar and no indication for impurity segregation has been found (detection limit about one monolayer). In plan-view (Fig. 3 (b)), the microstructure is given by a section through the columnar arrangement of grains. Similar results have been found elsewhere [33].

The grain-size distribution is revealed by the histogram in Fig. 4. The individual grains show a high density of defects. The defects consist of dislocations and point defect agglomerates. The distances between two defects vary between 2 and 20 nm.

Fig. 3: (a) Cross section through the niobium film of a 352 MHz cavity [1]. The lateral scale is indicated by the arrows at the bottom right (b) Plan-view of niobium film of a 1500 MHz cavity. The width of the photo amounts to 470 nm.

Chemical analysis by electron energy-loss spectroscopy (EELS) and energy dispersive X-ray analysis (EDX) revealed the presence of 5-10% of oxygen in the thin part of the TEM samples. This can, however, be attributed to surface oxidation of the TEM sections and no indication for segregation of oxygen to the grain boundaries or the Nb-Cu interface could be found. No other impurities elements could be detected within the film (detection limit about one atom percent for a diameter of the electron beam between 10 and 100 nm).

Fig. 4: Histogram of grain size (plan-view, same sample as in Fig. 3 (b)).

III. DISCUSSION

A. Localized heating

The assumption suggests itself that local heating in the vicinity of nc defects explains NQL. The RF magnetic field may heat up a nc defect in such a way that the temperature around that defect will increase. The BCS term of the surface resistance increases exponentially with the temperature, which will lower the Q-value with the RF field amplitude. However, within a range of about a factor 10 around reasonable values for the thermal conductivity (2.5 W/(mK)), the RF magnetic field (20 mT), the defect size ($0.1 \mu\text{m}$) and for a BCS surface resistance of $\sim 30 \text{ n}\Omega$, the increase of the temperature is insignificant. Hence we rule out this effect as a sensible explanation. Similar results have been found elsewhere [34].

B. TEM of samples

The superconducting properties of the Nb films are dominated by the microstructure in planes parallel to the film plane, which is revealed by the plan-view TEM investigations. The results indicate that the high density of grain boundaries and "intrinsic defects" (located inside grains without enrichment by foreign atoms) is responsible for the degradation of the superconducting properties. The hypothesis that these defects are rich in oxygen [8], [10], [35] is less probable. The electron mean free path l and the Ginzburg-Landau coherence length ξ are reduced, and the effective penetration depth λ_{eff} and the Ginzburg-Landau parameter κ are increased. The intrinsic defects may be identical with "intragranular weak links" [10] - [12], [17], [18] in the following sense. They are conducting junctions of less than nanometer size located inside larger grains and have a reduced critical magnetic field compared to the bulk.

C. DC magnetic field

The external static magnetic field dependence of the surface resistance can be used to probe these defects, because the magnetic flux will be preferentially trapped there (which minimizes the free energy). According to (3), the residual surface resistance depends on a static external magnetic field as [36], [37]

$$\alpha = R_{sn} / B_{c2}, \quad (6)$$

with R_{sn} the nc surface resistance. Hence, for $\alpha = 400 \text{ n}\Omega/\text{mT}$ and $R_{sn} = 7 \text{ m}\Omega$ at 1500 MHz [27], one obtains the upper critical field $B_{c2} = 18 \text{ T}$ at 1.8 K (12 T at 4.2 K).

From the relation

$$B_{c2} = \sqrt{2} \kappa B_c, \quad (7)$$

with B_c the thermodynamic critical field of niobium ($B_c \approx 0.2 \text{ T}$), it follows $\kappa = 42$. The lower critical magnetic field B_{c1} is

$$B_{c1} = B_c \ln \kappa / (\sqrt{2} \kappa) = 12 \text{ mT}. \quad (8)$$

Hence we conclude that for an RF field amplitude of 12 mT (or somewhat lower due to demagnetization effects) these intrinsic defects will enter into the mixed state. The corresponding threshold accelerating field is $E_a \approx 3 \text{ MV/m}$, close to the observed one (Fig. 1). From $\kappa = 0.715 \cdot \lambda_L / l$ (dirty limit) and $\lambda_L = 40 \text{ nm}$, one obtains the electron mean free path $l = 0.7 \text{ nm}$.

D. RF magnetic field

1) *The critical temperature of the intrinsic defects:* The intrinsic defects will react sensitively to energy fluctuations and become nc if the thermal energy of the lattice $E_{th} = kT$ is sufficiently large to compensate their coupling energy $E_J \sim (T_c - T)$. This will happen at a temperature T^* [16], [38] - [40], which is for weak coupling significantly lower than T_c of the bulk.

2) *RF amplitude and temperature dependence:* We define n as that fraction of the surface which the RF magnetic field B has driven nc. By increasing B by a differential amount dB , n will increase by a differential amount dn , which is

$$dn = p(B) \cdot dB. \quad (9)$$

p is the surface fraction which is driven nc between B and $B+dB$. Taking p as constant, one obtains ($B_{c1} \ll B_{c2}$)

$$p \int_{B_{c1}}^{B_{c2}} dB = 1 \Rightarrow p = (B_{c2} - B_{c1})^{-1} \approx B_{c2}^{-1}. \quad (10)$$

The surface resistance being proportional to the nc fraction n , such that one obtains:

$$dR_s = R_s(B) \cdot dn = R_s(B) \cdot dB / B_{c2}(T), \quad (11)$$

or

$$dR_s/dB = R_s(B)/B_{c2}(T). \quad (12)$$

3) *Frequency dependence*: Magnetic flux threading the intrinsic defects may become hysteretically trapped [10] - [12], [15] - [25] due to pinning. The vortices feel an outward directed Lorentz force which is independent of the polarity of the RF current (RF field). When the field reverses, the remanent flux will be cancelled by flux of opposite polarity. Hence we adopt a B(H) relation as shown in Fig. 5.

Fig. 5: RF cycle with hysteresis of trapped magnetic flux.

A magnetic RF field of constant amplitude H_0 does the work (per volume) and per RF cycle of $\mu_0 H_0^2$ ($\mu_0 H_0 \gg B_{c1}$), corresponding to the work per m^2 , $W = \mu_0 H_0^2 \lambda$ (λ is the penetration depth); hence the dissipated power per m^2 is $P_C = \omega/(2\pi)W$. From the definition of the surface resistance R_s , $P_C = R_s H_0^2/2$, we obtain $R_s = 2\mu_0 \lambda \omega/(2\pi)$.

Combining this result with (12), we end up with

$$\frac{dR_s}{dB} = \frac{\omega}{2\pi} \frac{2\mu_0 \lambda}{B_{c2}}. \quad (13)$$

For $\lambda = 40$ nm, $\omega/(2\pi) = 350$ MHz, $B_{c2} = 12$ T, we obtain $R_s' = 3$ nΩ/mT, close to the observed value (1 to 3 nΩ/mT, cf. Figs. 2 and 6). A typical fit according to (13) is shown in Fig. 6.

Fig. 6: Q-value vs. accelerating gradient E_a for a 352 MHz NbCu cavity measured at different helium bath temperatures. The data can be fitted (line) as shown in the inset: the three terms are the residual surface resistance $R_{res} = 10 \text{ n}\Omega$, the BCS surface resistance and the term corresponding to the NQL according to (13) ($R'_s(4.2\text{K}) = 3\text{n}\Omega/\text{mT}$, $T^* = 6.25 \text{ K}$).

IV. CONCLUSION

In this status report we have proposed a model and compared it with experimental data to explain non quadratic RF losses in superconducting niobium sputter coated copper cavities. This model explains the data by remanent RF magnetic flux trapped within intrinsic defects.

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