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Non Quadratic RF Loss in Superconducting Niobium Sputter Coated Copper Cavities for the e+e- Collider LEP

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ABSTRACT

A model to explain non quadratic RF losses in niobium sputter coated copper cavities will be proposed and confronted to experimental data.

1. INTRODUCTION

The LEP collider at CERN is being upgraded to a centre of mass energy of 90 GeV by means of superconducting (SC) cavities, the major part being of the niobium sputter coated copper (NbCu) cavity type. These cavities - though superior to conventional niobium sheet metal cavities - may show a steeper decrease of the Q-value with the accelerating gradient. This indicates dissipation that follows the RF magnetic surface field amplitude H more than quadratically. Hence we call it non quadratic loss (NQL). For accelerating gradients envisaged for LEP (5 to 6 MV/m), NQL contributes to about half of the total loss, which still may be tolerated. In view of an improvement of performance of LEP, and for future SC linear colliders, at higher gradients, they will make up the dominant part, if not understood in more detail and eventually be reduced.

NQL is observed in granular and in high T_c superconductors. A couple of models have been proposed [1, 2, 3]. In order to understand the underlying mechanism, it is mandatory to confront them with the experimental results as thoroughly as possible.

We will present in this paper a model to explain NQL and some more experimental checks. We will propose some other checks to be done in the conclusion. It is in this sense that we will give a status report on the subject.

The most easily accessible quantity by experiment is the Q-value. Under certain tacit assumptions (RF loss is quadratic with H) one extracts the average surface resistance R_s from

$$R_s = G / Q, \tag{1}$$

G being the geometry factor (~280 Ω). Then the RF loss per unit area is

$$P = \frac{1}{2} R_s H^2. \tag{2}$$

If R_s is independent of H, the RF loss follows H quadratically and the Q value is constant with H. In a number of cases, however, R_s depends on H, and we can write R_s as a sum of two terms, the first of which (R_{s0}) is independent of H and the second (R_{snq}) depends on H:

$$R_s(H) = R_{s0} + R_{snq}(H). \tag{3}$$

The first term takes into account the residual surface resistance R_{res} and the BCS surface resistance R_{BCS}. The second term represents the NQL.

One word of caution might be in order. A Q-value depending on the RF amplitude does not necessarily mean that NQL be present. For example, if a cavity is suffering from strong electron dark current activity (electron loading), the Q-value is not constant with RF field amplitude. Nevertheless, in this case it would be incorrect to describe the corresponding loss by a term R_{snq}, because it does not depend on H.

2. KNOWN EXPERIMENTAL RESULTS

The experimental findings for NbCu cavities, known so far, are quoted here [4-8].

- NQL is generated by the RF magnetic surface field amplitude H.
- R_{snq} depends linearly on H,

$$R_{snq}(H) = R'_s \cdot H. \tag{4}$$

- R_{snq} decreases with increasing RRR (residual resistivity ratio).
- R_{snq} shows no (or a very small) frequency dependence.
- R_{snq} increases with temperature according to an empirical law

$$R_{snq} = R'_s \cdot H = \frac{\beta}{1 - \frac{T}{T^*}} \cdot H, \tag{5}$$

with $T < T^*$, T^* between 4 and 7 K, and β between .5 nΩ/mT at best and more than one order of magnitude larger at worst.

- NbCu cavities exhibit a low sensitivity to trapped magnetic flux from a static external magnetic field up to about .1 mT.
- The residual surface resistance of NbCu cavities grows quadratically with the RF frequency (between 1.5 and 3 GHz).
- Sputter deposited niobium contains a relatively large amount of foreign elements (O, C, Cu).
- Sputter deposited niobium has a larger transition width than sheet metal Nb at the critical temperature.
- Sputter deposited niobium has a relatively large critical field H_{c2} at 4.2 K (1.5 T) with a large transition width of 1 T (recently we measured 2.5 to 3.5 T).

In a first paper [4], the hypothesis was proposed, that vortices generated by the RF field are the origin of the NQL. In a second paper [7], the residual surface resistance was explained by resistive loss in a superconductor (thin normalconducting surface layer or grain boundaries). In a third paper [8], spots of dirty niobium, embedded in clean niobium, and with a larger Ginzburg-Landau parameter κ (about 20), were postulated to explain the low sensitivity to a small static magnetic field.

We summarise that the sputter deposited Nb is a mixture of relatively clean Nb metal with minute impurities of weak SC and normalconducting metal.

3. VORTEX MOTION DISSIPATION IN THE FLUX FLOW REGIME

R. Marcon et collaborators have analysed the vortex motion dissipation in a static magnetic field H_{ext} of high-T_c superconductors at microwave frequencies [9]. A similar approach was pursued by A. M. Portis and collaborators [10]. If H_{ext} is larger than the lower critical field H_{c1} of the metal, vortices are created (mixed state). For $H_{ext}/H_{c2} < 5$ %, the corresponding surface resistance R_f (the subscript f means flux flow regime) is linear in H_{ext}:

$$R_f(t,H_{ext}) = \frac{\rho_n f(t)}{2\gamma(t,H_{ext})\,\lambda_L(t)H_{c2}(t)} H_{ext}, \quad (6)$$

where ρ_n is the normal state resistivity, f is the fraction of weakly pinned vortices, γ is a coefficient near 1, λ_L is the London penetration depth, H_{c2} is the upper critical field, and $t = T/T_c^*$ is the reduced temperature, T_c^* being the critical temperature of the material with flux flow dissipation.

In our case, we will now refine our old hypothesis [4]. We will analyse the data by an approach similar to the one of ref. 9. Meanwhile, independently, Rezende and Aguiar have proposed a similar hypothesis to explain what they call "nonlinear response" in high T_c superconductors [11].

The model to explain NQL is the following:

In the niobium layer there are spots of dirty niobium. They have a very small lower critical field H_{c1}, such that vortices will be created there by a small RF magnetic field amplitude H and pushed in and out by the RF magnetic field. The way how these vortices are generated is the only difference compared to the model of ref. 9. Otherwise we apply the same idea, which means, these vortices are driven by a Lorentz force from the RF surface currents to a viscous movement all through the dirty niobium, perpendicular to the surface. By induction, an electric field is produced, collinear with the surface current. This will lead to dissipation, what we call NQL.

Hence we will replace H_{ext} in eq. 6 by the RF magnetic field amplitude H. The justification will be given in the appendix, where we derive the formula for RF in close connection to ref. 9. We set $\gamma = 1$ and neglect any temperature dependence of γ, f and λ_L (we know that below 4.5 K the dependence of λ_L on T is weak anyhow). For the temperature dependence of H_{c2} we use an empirical law (other authors [12] have found a linear H_{c2} vs. T curve for Nb films, too)

$$H_{c2}(T) = H_{c20} \cdot (1 - \frac{T}{T_c^*}). \quad (7)$$

We end up with

$$R_{snq}(T,H) = \frac{\rho_n f}{2\,\lambda_L H_{c20}(1 - \frac{T}{T_c^*})} H. \quad (8)$$

By comparing eq. 8 and eq. 5 we get

$$\beta = \frac{\rho_n f}{2\,\lambda_L H_{c20}}. \quad (9)$$

4. EXPERIMENTAL

For sake of clarity we will not reproduce the experimental results which led to the conclusions mentioned in chapter 2. We will only add two recent results, which confirms the preceding ones. In fig. 1 the Q-value vs. accelerating gradient at three different temperatures for a LEP type NbCu cavity produced by industry is plotted. The data can be reproduced by the relation given at the bottom, where we have replaced the accelerating gradient E_a by the maximum RF magnetic surface field amplitude H (1 MV/m is 4 mT). The first term describes the residual surface resistance, the second one the BCS surface resistance and the third one NQL.

We read $\beta = R_{snq}/H\,|_{T=0\,K} = .85$ nΩ/mT.

In Fig. 2 we have plotted the residual surface resistance R_{res} vs. R_s' (cf. eq. 4) at 4.5 K for LEP type NbCu cavities from industry tested so far [13]. R_s' varies in a

range from about .01 nΩ/mT to about 3 nΩ/mT, a similar (though somewhat lower) interval as quoted before.

5. DISCUSSION

We know, that about 10^{-5} to 10^{-4} of the niobium matrix is composed of a lattice of dirty SC niobium with $\kappa \approx 20$ and $H_{c2} \approx 2.5$ T at 4.2 K [8] (hence H_{c20} is about 7 T by eq. 7).

In order to get an idea, to which extent impurities may change the parameters of niobium, we quote experimental results by DeSorbo [14] and Koch and collaborators [15].

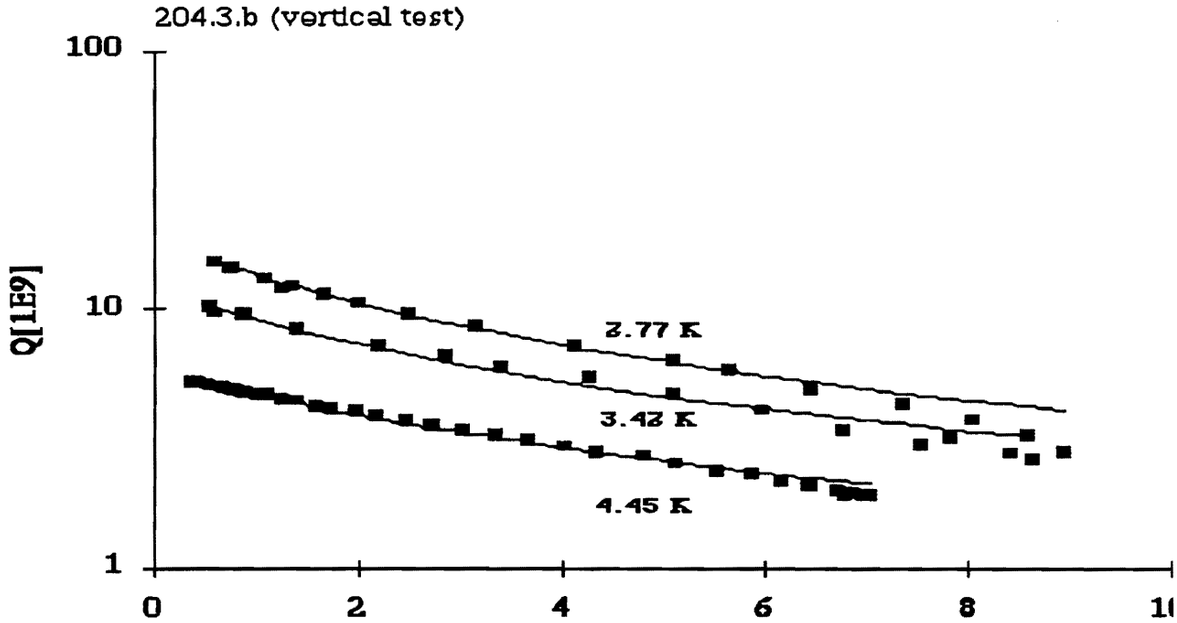

Fig. 1: Q-value vs. accelerating gradient for a LEP type cavity produced from industry, showing non quadratic RF loss. The data can be represented (up till 6 MV/m) by the formula at the bottom (4 mT surface magnetic field is 1 MV/m accelerating gradient). Above 6 MV/m, electron loading is observed.

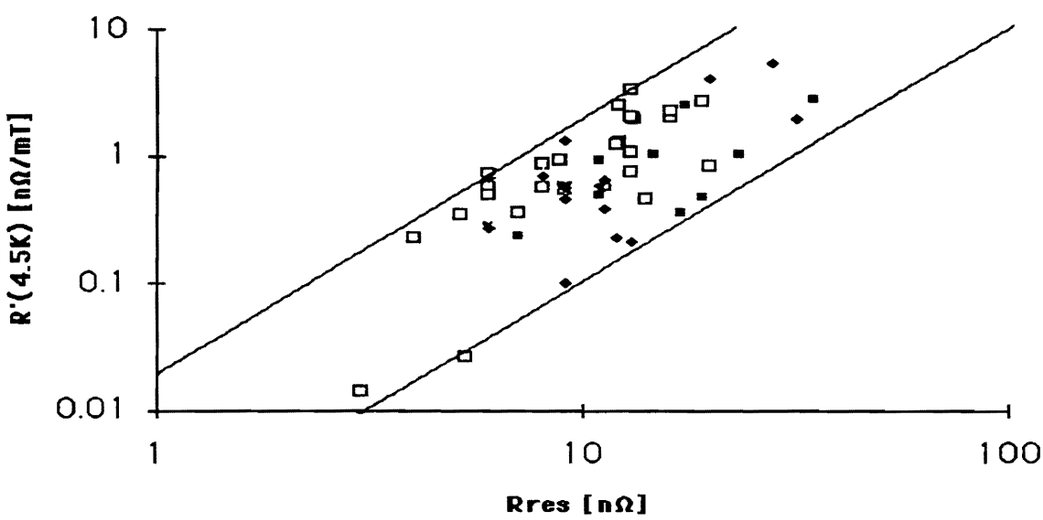

Fig. 2: Correlation of R_s' (describing NQL) vs. residual surface resistance R_{res} of LEP type NbCu cavities produced so far in industry. The lines indicate $R_s' \sim R_{res}^2$.

For 3.5 atomic percentage oxygen as contamination (oxygen is the most prominent contamination [4, 5]), we get $T_c^* = 6.1$ K, RRR = 1.86, $\rho_n = 17.5$ μΩcm at 4.2 K, H_{c2}=.85 T, $\kappa = 10$ at 4.2 K (H_{c1} was not quoted).
Now we will put the following numbers into eq. 9: λ_L = 32 nm [16], f =10^{-5}, H_{c20} = 7 T, ρ_n = 17.5 μΩcm. We obtain β = 4 nΩ/mT. This result is in the range of values obtained experimentally.
Fig. 2 indicates a correlation of NQL and residual loss ($R_s' \sim R_{res}^2$).
It seems plausible to us, that the larger is the number N of impurities, the larger is both the volume V of the normalconducting material and the number N_{sc} of dirty SC spots. It seems also plausible to us, that the larger N the larger is also the resistivity ρ_n of the dirty SC spots.
Let us assume that the (most prominent contribution to the) residual loss is proportional to the normalconducting volume V. In other words the normalconductor is fully penetrated by the RF wave. This assumption would also naturally explain the dependence of the residual loss on the square of the frequency (cf. chapter 2), as was pointed out by J. Carini et al. [17].
According to eq. 8 the NQL is proportional to the product of f (which is essentially the number N_{sc} of dirty SC spots) and their resistivity ρ_n. Hence we would expect a correlation as $R_s' \sim f\,\rho_n \sim N_{sc}\,\rho_n \sim N^2 \sim V^2 \sim R_{res}^2$, as indicated in Fig. 2.
All the observations quoted confirm our model: the residual loss being due to normalconducting material, and the NQL being due to flux flow dissipation in dirty superconducting spots.

6. CONCLUSION

We propose a mechanism to explain NQL in SC NbCu cavities: vortex motion dissipation. A quantitative analysis gives the correct order of magnitude of observed NQL, and explains in particular that NQL is frequency independent, and increases with temperature and RRR in a way which is predicted by the model (eq. 8). Until now we did not find any experimental result that contradicts this model. But we believe that more experiments will have to be performed, in particular to visualise the dirty SC spots and to look for a transition near T_c^*.

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APPENDIX

Eq. 8 is derived within the two fluid model of a superconductor. The London electrodynamics is summarised in Table 1. The first London equation 1-1 is modified to

$$\boldsymbol{j} = -\frac{1}{i\omega\,\mu_0\,\lambda_L^2}(\boldsymbol{E} - \boldsymbol{v} \times f\mu_0\boldsymbol{H}). \qquad (10)$$

v is the velocity vector of the vortex, the other symbols are explained in the text. For v = 0 eq. 10 reduces to the usual London equation if no normalconducting electrons are present. For v ≠ 0 there is an additional electric field from a Lorentz force due to flux flow motion which acts

on the SC electrons [18]. The displacement **X** of a single vortex line is described by the equation of harmonic motion (m_v its mass per unit length, η its viscosity, p the restoring force per unit length, $j\times\Phi_0$ the driving force per unit length, Φ_0 is the flux quantum):

$$m_v \ddot{X} + \eta \dot{X} + pX = j \times \Phi_0. \qquad (11)$$

It turns out that p and m_v are negligibly small, which leads to ($v = dX/dt$)

$$\eta v = j \times \Phi_0. \qquad (12)$$

Eliminating v from eq. 10 and eq. 12, we get the resistivity ρ_f due to flux flow motion,

$$\rho_f = \frac{E}{j} = \frac{\Phi_0 f \mu_0 H}{\eta} - i\omega \mu_0 \lambda_L^2. \qquad (13)$$

We will look for the leading terms in eq. 1-2. With the conductivity $\sigma_f = 1/\rho_f$ and $f = 10^{-5}$ we have

$$\sigma_f \mu_0 \omega \lambda_L^2 \gg 1 \gg \varepsilon_0 \mu_0 \omega^2 \lambda_L^2,$$
$$K^2 = i\sigma_f \mu_0 \omega$$

Then, according to eq. 1-3, the surface impedance Z is

$$Z = \sqrt{-i\omega \mu_0 \rho_f} = \omega \mu_0 \lambda_L \sqrt{-\frac{i\Phi_0 f H}{\eta \omega \lambda_L^2} - 1}. \qquad (14)$$

We obtain the surface resistance (real part of Z),

$$R_s = \mathrm{Re}\,(Z)$$
$$= \frac{\omega \mu_0 \lambda_L}{\sqrt{2}} \left\{ -1 + [1 + (\frac{\Phi_0 f H}{\eta \omega \lambda_L^2})^2]^{1/2} \right\}^{1/2}. \qquad (15)$$

Because of

$$\frac{\Phi_0 f H}{\eta \omega \lambda_L^2} \ll 1,$$

and with the result of Bardeen and Stephen [18],

$$\eta = \frac{\Phi_0 \mu_0 H_{c2}}{\rho_n}, \qquad (16)$$

we finally get eq. 8:

$$R_s = \frac{\rho_n f}{2\,\lambda_L H_{c2}} H. \qquad (17)$$

Table 1: Comparison of superconductor (London two fluid model) with normal conductor

s.c.	n.c.
curl $\boldsymbol{H} = \boldsymbol{j} + \varepsilon_0 (d/dt)\boldsymbol{E}$ curl $\boldsymbol{E} = -\mu_0 (d/dt)\boldsymbol{H}$ div $\boldsymbol{H} = 0$ div $\boldsymbol{E} = 0$	
$(d/dt)\boldsymbol{j} = \boldsymbol{E} / (\mu_0 \lambda_L^2) + \sigma_n (d/dt)\boldsymbol{E}$ (1-1) curl$\boldsymbol{j} = -\boldsymbol{H} / \lambda_L^2 - \sigma_n \mu_0 (d/dt)\boldsymbol{H}$	$\boldsymbol{j} = \sigma_n \boldsymbol{E}$
$\Delta \boldsymbol{E} = -K^2 \boldsymbol{E}$ $\Delta \boldsymbol{H} = -K^2 \boldsymbol{H}$	
$K^2 = -\lambda_L^{-2} (1 - i\sigma_n \mu_0 \omega \lambda_L^2 - \varepsilon_0 \mu_0 \omega^2 \lambda_L^2)$ (1-2)	$K^2 = \varepsilon_0 \mu_0 \omega^2 (1 + i\sigma_n) / (\omega \varepsilon_0)$
$Z_{s.c.} = (1/2)\omega^2 \mu_0^2 \lambda_L^3 \sigma_n + i\omega \mu_0 \lambda_L$, if $\varepsilon_0 \mu_0 \omega^2 \lambda_L^2 \ll \sigma_n \mu_0 \omega \lambda_L^2 \ll 1$.	$Z_{sn,c.} = (\omega \mu_0 \delta / 2)(1+i) =$ $= \sqrt{[\omega \mu_0 / (2\sigma_n)]}\,(1+i)$, if $\omega \varepsilon_0 / \sigma_n \ll 1$
Legend: Effective electron mass m Electron mean free path l Conductivity of the n.c. electrons $\sigma_n = l n_n e^2 / (m v_F)$ London penetration depth $\lambda_L = \sqrt{[m/(n_s e^2 \mu_0)]}$	Surface impedance $Z_s = (E_z/H_y)\|_{x=0} = \mu_0 \omega / K$ (1-3) Skin depth $\delta = \sqrt{[2/(\mu_0 \sigma_n \omega)]}$ Fermi velocity v_F Density of n.c. electrons n_n Density of n.c. electrons n_s