About the Amplitude Dependence of the Surface Resistance of Niobium Coated Copper Cavities

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1 Introduction.

Now there are two ways to overcome a thermomagnetic break while creating superconducting cavities to provide accelerating fields $Ea > 5$ MV/m for colliders and linear accelerators. One of them is to create cavities from super pure Nb [1, 2, 3], the accelerating fields of more than 20 MV/m [3] have been obtained in the experimental samples but this way is very expensive. The other way is creating copper cavities with a sputtered thin film of Nb (NbCu cavities) [4, 5]. In the second case there is substantial decreasing of the Q-value cavity at $E_\alpha > 1 \div 2$ MV/m [5] using Nb films by a magnetron-sputtered method. It has been found that the characteristics of these films (except critical temperature of the superconducting transfer T_C) are substantially worse than the characteristics of bulk Nb [6] and Q decreasing is determined by the quality of these very films. Experimental and theoretical research to clarify the reasons of this phenomenon is energetically carried out as well as the search for the ways to overcome it.

This work is dedicated to the experimental background of the reasons of the Q-value drop of NbCu cavities with the magnetron-sputtered film, to theoretical background of the Q dropping law and the opportunities of electronbeam-plasma technology are discussed for sputtering Nb films to overcome this phenomenon.

2 Magnetic characteristics of magnetron - sputtered films.

For magnetron-sputtered Nb films, the experimental values of the second critical field $B_{C2} = (2,5 \div 3,5)\ T$ at $4,2\ K$ [6, 7, 8].

From our experiments at 4.2K on measuring the first critical field (B_{C1}) of Nb films sputtered at different operating regimes of the magnetron (U, I, P_{Ar}), it follows that $B_{c1} = (9 \div 12)\ mT$. These results are complementary with the well-known limit of the amplitude independence of the Q-value cavity of type Nb/Cu ($B_{c1} \cong 9\ mT$) [9]. Measurements of relative dropping of the specific resistance from the ambient temperature till the temperature of the super conducting transfer have given the results—$\rho_{n}/\rho_{300} = 0,4 \div 0,6$. Similar results were obtained in [10].

At these values(B_{c1} = 10mT,B_{c2} = 3T) from the formula of Abrikosov[11]

$$B_{c2} = B_{ct}\sqrt{2}\kappa, \tag{1}$$

$$B_{c1} = B_{ct}\frac{ln\,\kappa + 0,08}{\sqrt{2}\kappa}\ ^{1} \tag{2}$$

and the formula of Ginsburg and Landau [12]

$$\kappa = \pi\sqrt{2}\frac{B_{ct}\lambda^2}{\varphi_0}, \tag{3}$$

where φ_0 = 2, 07•10^{-15} ′? is a magnetic flow quant, $\kappa = \lambda/\xi$ — ratio of the field penetrating depth to the coherence length, B_{ct}—thermodynamic critical field, it follows that $\kappa \cong 22$, $B_{ct} \cong$ 100mT, $\lambda \cong 330$ nm and $\xi \cong 15nm$. It is clear that the characteristics of the magnetron-sputtered Nb films are substantially worse than the characteristics of the bulk Nb (B_{c10} = 198mT, B_{c20} = 300 mT, λ_0 = 39nm, (ξ_0 = 38nm, κ_0 = 1.04 at T = 0K (these data do not quite agree with (1) and (3)) and from our measurements $B_{c1} \cong 200$ mT at T = 1.8 K, $B_{c1} \cong 170$ mT at T = 4.2 K).
From (3) and (1) follows that ξ is completely determined by B_{c2}

$$\xi^2 = \frac{\varphi_0}{\pi B_{c2}}. \tag{4}$$

3 Conditions to hold vortices.

In the mixed state zone where in the cavity operating layer $H_e > H_{c1}$ the codition to overcome the pinning force F_p by the force of Lorentz F_l, i.e. when the vortices become free, taking into account (2) and (3) and the above characteristics of films Nb, it is possible to write [13] as

$$\frac{F_p}{F_l} = P\frac{\pi}{2}\frac{H_{ct}B_{ct}\xi\lambda}{H_e\varphi_0 n_p} = \left[\frac{\kappa}{2(ln\,\kappa + 0,08)}\right]\frac{P}{n_p}\frac{H_{c1}}{H_e} \simeq 3,5\frac{P}{n_p}\frac{H_{c1}}{H_e} < 1, \tag{5}$$

where P =1 is a balancing parameter of the pinning force, n_p—quant number in the fluxoide held in the dislocation. It should be stressed that condition (5) in the cavities depends on the superconducting operating layer only through κ and P. The square bracket in (5) weakly depends on κ and decreases when the Nb film characteristics become better.

[1]This formula, as the author [11] noted, gives the lower value of B_{c1} but at large κ, a relative error is less than 0.2.

As soon as fluxoides in the cavity film have a view of toroides wih the nucleus radius $\xi \cong 15 nm$, then their holding on the borders of grains may be neglected (the middle size of the grains is the order of 60 *nm* [9] and, it follows that $P < 0.2$). So, fluxoide holding is possible only on the foreign inclusions (argon). If the mean distance between the argon atoms $l_{Ar} < \xi$ (relative quantity of argon in the film $n_{Ar} > 6 \cdot 10^{-6}$), they do not create extracted pinning channels. At $l_{Ar} \geq \xi$ P $\cong /\xi l_{Ar} \leq 1$ and, according to (5), the pinning force may be neglected.

Thus, it is possible to consider that in the cavities with the magnetron-sputtered film Nb in the mixed zone $H_e > H_{c1}$, the force of Lorentz is higher than the pinning force and there is a free motion of fluxoides as well as their production on the film surface and inside the mixed state zone.

4 On the time of fluxoide penetration.

At free fluxoides, when condition (5) is fulfilled at $n_p = 1$, their drift velocity v, according to [13], is written as follows:

$$v = \rho_n \frac{H_e}{\lambda} \frac{\pi \xi^2}{\varphi_0} \simeq 6 \cdot 10^2 \frac{B_e}{B_{c1}} m/s, \tag{6}$$

where $\rho_n \cong 8\ 10^{-8}$?*mm*—specific resistance in the normal state of magnetron-sputtered films. Correspondingly, the shift time of fluxoides by the diameter of its nucleus $\tau < 5\ 10^{-11}\ s$, and this is substantially shorter than the field RF periods of the cavities under discussion.

5 Explanation of non-quadratic losses.

At weak pinning, when condition (5) is fulfilled, and vortices can shift under the force of Lorentz, the specific resistance p_f, defined by this motion, is as follows:

$$\rho_f = \rho_n R(B_e), \quad R(B_e) = \frac{B_e - B_{c1}}{B_{c2} - B_{c1}} \theta(B_e - B_{c1}), \tag{7}$$

where p_n — specific resistance in the normal state, and θ —function of Heaviside. In cavity $B_e = B_a F(x) sin\ wt$, where $F(x)$ *is* a function characterizing the magnetic field distribution on depth x of the surface layer of the cavity (F(0) = 1). In the mixed state zone ($B_e > B_{cl}$), it is evident that $F(x) \neq exp(-x/\sim)$. At $B_a \leq B_{C2}$, when the fluxoide density is small, we suppose $F(x) = exp(-x/\lambda)$.

It is expected that in the mixed state zone defined by the condition

$$B_a exp(-x/\lambda) sin\, \omega t > B_{c1}, \tag{8}$$

the fluxoide density is quasistationary, i.e. in every moment it corresponds to the equal weight, and proportional to $R(Bc)\ (7)^2$, and beyond this region the fluxoides are absent. This supposition is valid at the condition when the times of relaxation τ_r, i.e., production and disappearance of fluxoides, are small in comparison with reconstruction times τ_r and their density. The reconstruction time can be determined through the number of fluxoides which appear in the area of radius λ on the border of the operating layer during a quarter of the RF period. Then this criterion is written as

$$\tau_r < \tau_p = \frac{1}{4\nu\kappa^2}\frac{B_{c2} - B_{c1}}{B_a - B_{c1}}, \tag{9}$$

where ν — frequency of RF. At B_a = 0,1T and ν = 0, 35GHz—$\tau_r < 5\ 10^{-11}$ 5 that agrees with (6).

In this model the additional power of losses per the unit of cylindrical surface *Pn* which picks out into mixed state zone (8) can be shown as

$$P_n = P_j + P_\nu + P_q\ ^3. \tag{10}$$

P_j is defined by the fluxoide drift (6) and does not depend on frequency. P_ν is determined by the dissipation of the reconstruction of the fluxoide density, i.e. thermodynamic state, quadratically depends on frequency as well as absorption of the second sound in super fluid helium [15]. P_j and P_ν are proportional to $R(B_e)$ (7) and presented by the integral on the region (8). P_q *is* determined by the fluxoide flow through the surface of the operating layer [4] which involves the warmth dissiping in this layer per the unit of their length $\Delta Q = \pi\xi^2 B_{ct} H_{ct}/2$ and is presented by the integral on the near surface part of the mixed state zone (8) from which the Huxoides are carried to the depth of the mixed state zone layer by the force of Lorentz. Taking into account (1-3)

$$P_j + P_\nu = \rho_n \left[1 + \frac{\nu^2}{\nu_g^2}\right] \frac{H_a^2}{\lambda} \frac{B_{c1}}{B_{c2} - B_{c1}} F(B_{c1}/B_a), \tag{11}$$

$$P_q = \rho_n \frac{H_a^2}{\lambda} \frac{1}{2(ln\,\kappa + 0.08)} \frac{B_{c1}}{B_{c2} - B_{c1}} F_q(B_{c1}/B_a), \tag{12}$$

$$F(B_{c1}/B_a) = \frac{1}{18\pi}\left[\frac{cos\,\phi_1}{sin\,\phi_1}(3 + 5cos^2\phi_1) - 3(\frac{\pi}{2} - \phi_1)(1 + 2cos^2\phi_1\right] \theta(B_a - B_{c1}),$$

$$F_q(B_{c1}/B_a) = \frac{2}{\pi}\left[(\frac{\pi}{2} - \phi_1) - sin\,\phi_1\ cos\,\phi_1\right] \theta(B_a - B_{c1}),$$

$$sin\,\phi_1 = (B_{c1}/B_a)\theta(B_a - B_{c1})\theta(B_a - B_{c1}),$$

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[2] This dependence approximates the formula of Abrikosov [11] in a rather good way and it agrees with the experiment.

[3] Here at $B_a \le B_c1$ the proportional $(B_a — B_c1)/(B_{c2}—B_{C1}.)$ decrease of the usual losses is neglected in the mixed state zone.

[4] Irreversible process at condition (5) is illustrated experimentally in [14].

where ν_g — frequency determined from the experiment, at which $P_j = P_\nu F(Bc_1/B_a) \cong 0.25 (B_a B_{c1}—l) \tanh(B_a/B_{cl}—l) \theta(B_a—B_{c1})$, and $0 < F(_{Bcl/Ba}) < 1$. The corresponding mean specific resistances ρ_j, ρ_ν, ρ_q are defined by the following expressions

$$\rho_j+\rho_\nu = \rho_n \left[1+\frac{\nu^2}{\nu_g^2}\right] \frac{4B_{c1}}{B_{c2}-B_{c1}} F(B_{c1}/B_a),\ \rho_q = \rho_j \left[\frac{1}{2(ln\,\kappa+0,08)}\right] \frac{F_q(B_{c1}/B_a)}{F(B_{c1}/B_a)}. \quad (13)$$

For the Nb films with the above characteristics, at $B_a>B_{cl}$, the quantity dependence of the specific resistance $\rho_c = \rho_j + \rho_\nu$, on B_a is determined by the expression (the estimation has shown that in this case ρ_q may be neglected)

$$\rho_c(B_a/B_{c1},\nu) \simeq 1\cdot 10^{-9} F(B_{c1}/B_a) \left[1+\frac{\nu^2}{\nu_g^2}\right] \ \Omega\cdot m. \quad (14)$$

This relation explains the observable frequency dependence of the cavity resistance [9]. A good agreement with experimental data [9, Fig. 2] takes place at $\nu_g = 0.6$ *GHz* (Fig. 1).

The dependence of the cavity Q-value on B_a is determined by the expression:

$$Q = Q_0 \frac{\rho_0}{\rho_0+\rho G} \theta(B_a - B_{c1}), \quad (15)$$

where Q_0 and ρ_0—the Q-value and specific resistance at $B_a<B_{cl}$,correspondingly, and $G(Ba) < 1$—ratio formfactors of the mixed state zone and the cavity. Apparently $G(B_a) < 1$ monotonously increases with B_a and approach to 1. Fig. 2 shows the comparison (15) at $G = 1$ with the approximation of the experimental data [9, Fig. 1]. The difference of the results in fig. 2 can be explained by the indicated dependence $G(B_a)$.

6 H_{c1} of the films obtained by the electronbeam-plasma technology.

The technology of vacuum sputtering the Nb film with thickness of $d = 1\ \mu m$ over the copper cavity surface has been recognized the most promising now. This very method has been offered at JINR at the end of 60ties [4] to create superconducting RF cavities, and since 80ties it has been successfully studied at CERN [5]. At JINR there is an experience of creating and research of experimental superconducting RF cavities with the working layer as supercon ductor film obtained by the electronbeam-plasma method as well as with the working layer from Nb [16] and NbTi [4]. The film characteristics were comparable with the properties of bulk materials. In particular, the characteristics of the Nb films have been obtained: $T_c = 9,25 \pm O,5\ K$, $\Delta T_c \leq 0,01\ K \Delta T_c\ (f = 2,9\ \text{GHz}) = 0,2\ K$, $B_{cl} = 0.14\ T \Rightarrow 4,2\ K$, $B_{cl} = 0.165\ T \Rightarrow 1,8$

K [16]. It should be stressed that in some cases the Nb film was sputtered onto the sapphire cavity cycling continuonsly with the type of the wave E_{010}.

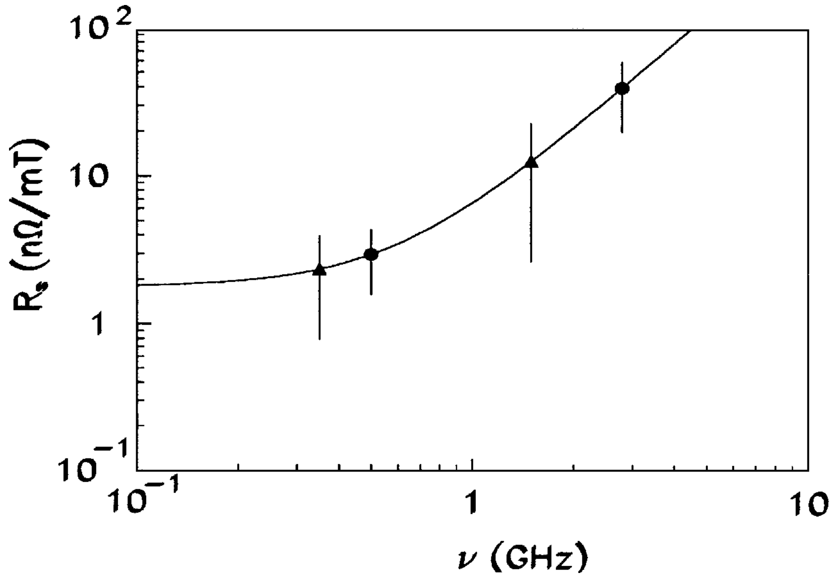

Figure 1: Dependence of the NbCu cavities resistance (14) normalized on the field amplitude B_a on frequency ν. The dependence is normalized on the data at ν = 0.5 *GHz* and ν = 2.79 - *GHz*—•.

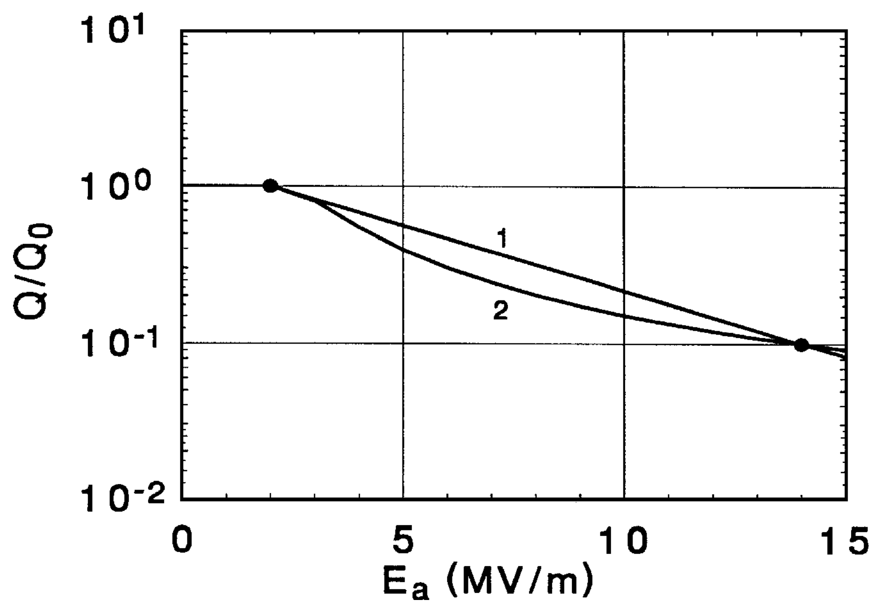

Figure 2: Dependence of the normalized Q-value Q/Q_0 on the field amplitude E_a, in the field of non-quadratic losses. The dependence approximate to the experimental data is marked 1. The calculated dependence (15) is normalized on the experimental data • and marked 2.

If there is a corresponding construction upgrading, the usage of these electronbeam-plasma evaporators would provide to produce the superconducting RF cavities with the required characteristics.

7 Discussion.

In [9] to explain the observable non-quadratic RF losses in the cavities, a model was offered on the remagnetization of fluxoides held on the dislocations. This model contradicts to (5) and thermodynamic theory of superconductivity in the mixed stare zone [11], which are in a good agreement with many experiments. The proposed model of free fluxoides thermodynamically quasibalanced in the mixed state zone is more adequate to modern ideas on superconductors of the second type and is in a rather good agreement with the experimental data.

Taking into account the experimental data on copper cavities with the Nb working layer, obtained by the magnetron-sputtered method and according to the main characteristics of the film samples produced on this very technology, it is possible to conclude that it is not available to create the cavities where at $E_a > 1 \div 2$ MV/*m* the non-quadratic losses would be absent at this level of magnetron technology obtained by the present moment. To reduce significantly the tempo of these losses seems to be not possible either.

The progress in using this method can be reached under the condition of obtaining the films with the essentially greater first critical field at the working temperature.

8 Conclusion.

The only way to exclude non-quadratic losses in NbCu cavities up to $E_a \cong 30$ MV/m is to transfer to the technology of covering the Nb working layer with the characteristics analogous to the bulk Nb. At present this is the electronbeam-plasma technology . But this technology requires further improvement to adapt to the modern construction of the cavities.

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