PROGRESS IN THIN FILM TECHNIQUES

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Abstract:
Progress since the last Workshop is reported on superconducting accelerating RF cavities coated with thin films. The materials investigated are Nb, Nb_3Sn, NbN and NbTiN, the techniques applied are diffusion from the vapour phase (Nb_3Sn, NbN), the bronze process (Nb_3Sn), and sputter deposition on a copper substrate (Nb, NbTiN). Specially designed cavities for sample evaluation by RF methods have been developed (triaxial cavity). New experimental techniques to assess the RF amplitude dependence of the surface resistance are presented (with emphasis on niobium films sputter deposited on copper). Evidence is increasing that they are caused by magnetic flux penetration into the surface layer.

I. INTRODUCTION AND SCOPE

An ideal sc cavity has the following features:

- the sc layer has low RF losses independent of the RF field amplitude;
- the maximum accelerating gradient obtained is determined by the critical magnetic field of the sc layer;
- the cavity is operated preferentially at the boiling temperature of a cryogenic liquid under atmospheric pressure (for all practical applications liquid helium at about 4.2 K);
- unavoidable heat sources located on the sc layer do not give rise to a temperature increase or runaway ("quench"), i.e. the temperature should be low enough such that the cavity is operated in the regime of residual surface resistance;
- the supporting structure must guarantee mechanical stability and efficient removal of heat.

The preceding features could in principle be realized by a sc metal of large critical temperature T_c and large thermal conductivity. According to the BCS theory a large T_c also implies a large energy gap Δ and thermodynamic critical field B_c. The larger the energy gap, the smaller the density of normal conducting (nc) electrons for a given temperature. Or, equivalently, the same RF losses occur at higher temperature (say 4.2 K instead of 1.8 K) as compared to a sc metal with a smaller energy gap.

However, these two prerequisites are conflicting. A large T_c is common with a sc alloy, whereas a large thermal conductivity is obtained in a pure metal. Nevertheless, an approach towards this idealized sc cavity could be achieved by separating the sc layer from the substrate, as in thin films. The features of the sc layer could be optimized independently from those of the substrate.

Copper cavities with a sputter deposited niobium film inside (NbCu cavities) are well studied. Therefore I will concentrate on them as a typical realization of thin film cavities. Whenever necessary in order to present a well balanced status on the work done so far, I will refer to bulk niobium cavities and to work done prior to the recent two years (as in ref. [1]).

Two species of thin film technologies have been successfully applied to manufacture structures for existing accelerators: Pb films for heavy ion accelerator cavities [2] and Nb thin films for LEP2 cavities [3].

In the first part of the review I will concentrate on new techniques of thin film production (in particular Nb_3Sn, NbN and NbTiN), and RF assessment of thin films (TE_{011} cavity, triaxial cavity).

In the second part experimental techniques will be presented which may allow understanding the physics of the slope of $Q(E_a)$. They include measurements of the $Q(E_a)$ - curve and its dependence on the RF magnetic field, the trapped static magnetic field, the temperature, and the RF frequency. As important are tests on thin film samples cut off cavities. They allow the determination of the film thickness, Residual Resistivity Ratio RRR, T_c, B_{c2}, and surface analysis by Secondary Neutral Mass Spectroscopy SNMS, Scanning Electron Microscopy SEM, Transmission Electron Microscopy TEM, and Atomic Force Microscopy AFM, and others.

Finally, theoretical models that describe this slope will be confronted with the experimental data. Possible cures, although not yet confirmed, will be presented, too.

II. MATERIALS FOR RF APPLICATIONS AND TEST DEVICES

1. New materials

1.1 Nb_3Sn cavities

It is well known that Nb_3Sn layers can be obtained by diffusion of Sn vapour into the niobium sheet at an elevated temperature (about 1100 °C) [4]. Sometimes sc phases of Nb and Sn with poor RF performance have been observed near the surface. They have to be removed by chemical etching of the superficial layer ("oxipolishing"), in order to uncover the wanted phase of Nb_3Sn underneath. The (residual) Q-values were obtained already near 4.2 K and amounted up to 10^{11}. However, the thermal conductivity (or equivalently the RRR-value) of the niobium substrate was poor (RRR = 40 to 100), which had the consequence that the maximum accelerating gradients obtained were often limited by a thermal quench.

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[1] C. Durand, W. Weingarten, P. Bosland, J. Mayer, Non quadratic RF losses in Niobium Sputter Coated Accelerating Structures, IEEE Trans. Appl. Supercond. 5 (1995) 1107.

[2] D. Storm, Review of low beta superconducting structures, Proc. 6th Workshop RF Supercond., 4 - 8 October 1993, CEBAF, Newport News, VA, USA, ed. R. Sundelin, p. 216.

[3] E. Chiaveri, Production by Industry of a large number of cavities, this Workshop.

[4] M. Peiniger, M. Hein, N. Klein, G. Müller, H. Piel and P. Thüns, Work on Nb_3Sn cavities at Wuppertal, Proc. 3rd Workshop RF Supercond. Argonne, Ill, USA, 14 - 18 September 1987, ANL-PHY-88-1, January 1988, ed. K. W. Shepard, p. 503.

New results in Nb_3Sn coatings have been presented by a collaboration between CEBAF and Wuppertal University [5]. Two 1500 MHz mono-cell cavities have been manufactured from high RRR Nb sheet (RRR = 1000). It has been demonstrated, that this RRR - value could be maintained during the diffusion process, such that the peak electric field in these cavities is not limited by thermal quench up till at least 20 and 27 MV/m. The treatment is based on the description given in ref. [4], being pushed further: the diffusion started from a cavity surface with the naturally grown oxide (no anodization). The creation of diffusion nuclei was favoured by adding Sn halogenides to the Sn metal. A thin titanium layer at the outer surface of the cavity prevented oxygen diffusion inside the bulk niobium [6].

1.2 NbTiN - samples in a TE_{011} cavity

At Saclay, samples of sputter coated NbTiN have been produced and characterized in a TE_{011} cavity at 4 GHz [7]. Prior to sputtering, these samples have been mechanically polished and ion etched. Interesting correlations have been found for the residual surface resistance R_S and the slope of the surface resistance $\Delta R_S / \Delta B$ with the RF magnetic field amplitude B at the sample (later called "non quadratic losses", cf. below). Both of them increase with the number of peaks detected on the surface. A peak is defined as a surface irregularity the height of which is more than twice the width of the base. This result corroborates a finding on early tests of 500 MHz Nb sputter coated copper cavities at CERN [8]. In addition, some of these samples showed a remarkably small slope $\Delta R_S/\Delta B \approx 2$ nΩ/mT.

2. New test devices

2.1 Material research with a TE_{011} cavity

At Genoa University, a 7.9 GHz TE_{011} cavity has been used for RF characterization of samples of NbN, Nb_3Sn, and NbTiN [9]. NbN was formed by diffusion of N_2 at a temperature of about 1100 °C. The base material of Nb_3Sn was bronze, which was sputter coated with Nb. Very much alike as in the manufacture of sc wires, above a temperature of 700 °C, the Sn starts diffusion into the Nb, thus forming Nb_3Sn. NbTiN was formed from a NbTi alloy used for sc cable manufacturing into which N_2 was injected by diffusion process similar to the first one. The surface impedance and other material parameters (the critical

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[5] Lab talk CEBAF and Wuppertal, this Workshop.

[6] R. Röth, private communication.

[7] S. B. Cantacuzène, Elaboration et caractérisation de couches minces de $(Nb_xTi_{1-x})N$ pour des applications en hyperfréquences, Thèse, Université de Paris Sud, Centre d'Orsay 1995.

[8] G. Arnolds-Mayer, C. Benvenuti, D. Bloess, G. Cavallari, E. Chiaveri, M. Hauer, N. Hilleret, M. Minestrini, V. Palmieri, L. Ponto, F. Scalambrin and W. Weingarten, On niobium coated copper cavities at 500 MHz, CERN Internal Report CERN/EF/RF 86-1 (4 March 1986).

[9] G. Gemme, P. Fabbricatore, R. Musenich, R. Parodi, M. Viviani, and B. Zhang, RF surface resistance measurements of binary and ternary niobium compounds, J. Appl. Phys. 77 (1995) 257.

temperature T_c, the energy, the coherence length and the electron mean free path) for these samples were obtained by a data reduction routine based on a code written by Halbritter [10].

2.2 Triaxial cavity

At CEBAF, a 1500 MHz "triaxial cavity" has been developed in order to measure the surface resistance of samples [11]. It has a compact shape (compared to a TE_{011} cavity), and the field distribution is similar to a re-entrant cavity, which is operated in a higher order mode. It has a non zero magnetic field on the top cover with a zero crossing at about 40 % of the distance between the central axis and the outer diameter and a negligible magnetic field further outside. The sample may be placed in the central part, the border of which coincides with the zero crossing (to minimize RF border losses). The surface resistance is measured calorimetrically by thermometers located outside the cover plate in an evacuated can. The heat produced on the sample is flowing radially. In principle, by an appropriate choice of the thermal impedance represented by the cover, the sensitivity of the device can be properly adjusted without overheating the sample. The thermometers have to be calibrated prior to use. The authors claim the device's sensitivity can be as large as 0.02 nΩ with 25 mT RF field on the sample.

III. NEW EXPERIMENTAL TECHNIQUES TO ASSESS NON QUADRATIC RF LOSSES

1. Nomenclature and parametrization of RF losses

RF cavities with thin sc films generally show a stronger dependence of the Q-value on the RF field amplitude (slope in $Q(E_a)$) than bulk cavities. The relation of current and voltage is non-linear, or the RF losses increase with the RF field amplitude more than quadratically. It is uniformly distributed and caused by the RF magnetic field amplitude (cf. below). It has to be well distinguished from other loss mechanism which give rise to a slope in the $Q(E_a)$ curve (for example field emitted electrons). It is not only restricted to thin film cavities, but has also been observed in bulk Nb cavities after electropolishing (Fig. 1, lowest curve). For these reasons, a specific name is justified, and I call it non quadratic RF losses (NQL).

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[10] J. Halbritter, Comparison between measured and calculated RF losses in the superconducting state, Zeitschr. für Physik C 238 (1970) 466.

[11] Changnian Liang, Larry Phillips, and Ronald Sundelin, A new method of surface resistance measurement with a niobium triaxial cavity working at 2 K, Rev. Sci. Instrum. 64 (1993) 1937.

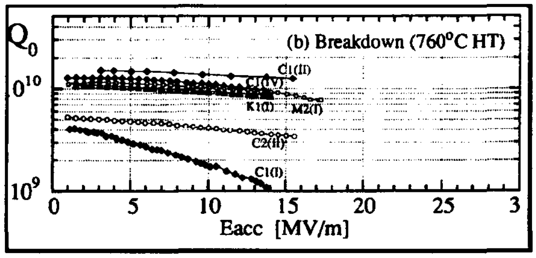

Fig. 1: NQL in niobium sheet cavity: the lowest curve was obtained after electropolishing and chemical polishing without heat treatment at 760 °C.[12].

As is the case with the other magnetically induced RF losses (BCS losses or specific residual losses from nc defects), it can be described by a surface resistance R_S = G/Q (geometry factor G) which depends on the frequency ω, the static magnetic field amplitude B_{ext}, the peak RF magnetic field amplitude in the cavity B_p [13] and the temperature T. To first order in B_p, a suitable parametrization for the total surface resistance R_S is the following:

$$R_s\left(B_p,\omega,T,B_{ext}\right)=$$

$$\frac{R_0(\omega)}{T}\exp\left(-\frac{\Delta}{kT_c}\right)+R_{res}(\omega,B_{ext})+R_s'(\omega,T,B_{ext})\cdot B_p+\ldots \qquad (1)$$

The first terms describes the BCS losses, the second one the residual losses and the third one the NQL (described by the parameter R_S', measured in nΩ/mT).

2. Experimental results

Among the three contributions to the RF losses (eq. 1), the BCS losses are fixed after the material and the operating temperature have been chosen. On the contrary, the residual losses and the NQL depend much on the parameters during cavity manufacture. Therefore they were studied in more detail.

In the past, for large sc RF systems, niobium sheet cavities have been successfully built and operated. The physics of the sc metal was of minor importance. What really mattered was the surface, which had to be free from defects, residuals and dust. On the contrary, today's niobium film cavities deserve a careful investigation of the parameters of the superconductor. Therefore, in what follows, the dependence of the residual surface resistance and of the NQL on different parameters, as for example ω, B_p, B_{ext}, T, etc., will be summarized.

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[12] E. Kako, S. Noguchi, M. Ono, K. Saito, T. Shishido, T. Tajima, P. Kneisel, M. Matsuoka, H. Miwa, T. Suzuki and H. Umezawa, Test results on high gradient L-band superconducting cavities, ibid. ref. 2, 918.

[13] I distinguish between Bp, the amplitude of the peak magnetic surface field in a cavity, and B, the amplitude of the local magnetic surface field, which is supposed to be uniform in the region of interest.

2.1 Residual surface resistance

(i) Dependence on frequency

The frequency dependence of the residual surface resistance has been studied in a NbCu cavity by exciting the fundamental mode at 1500 GHz and higher order (quadrupole) modes at 2450 and 2750 MHz [14]. They were chosen because they are strongly damped in the cut-off tubes and have therefore low losses in the end flanges. R_{res} depends quadratically on the frequency, a fact which is corroborated by the data shown in Fig. 2.

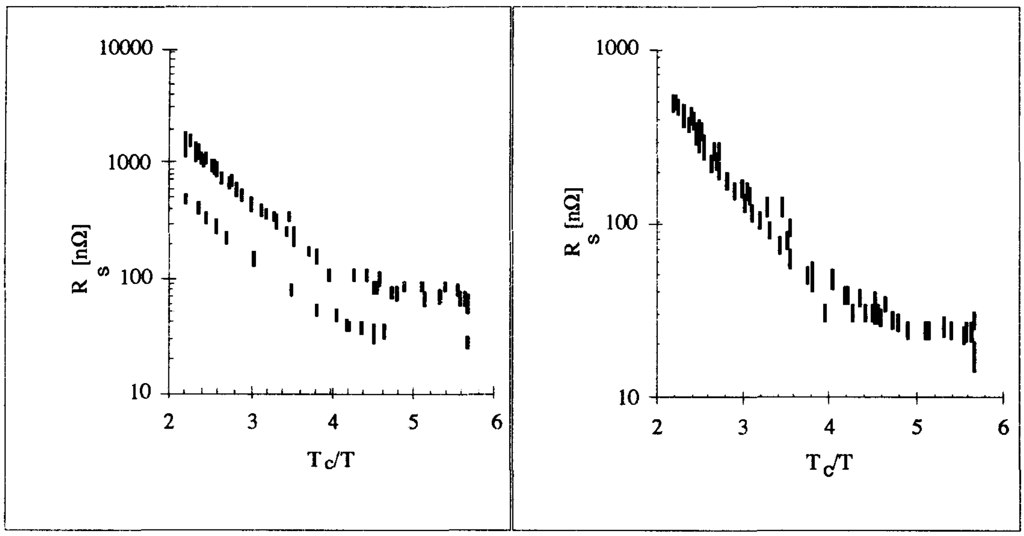

Fig. 2: Surface resistance at low RF field vs. inverse temperature for a NbCu cavity measured in three different modes (1.50, 2.45, 2.79 MHz, left). After scaling the data of the two upper modes with the frequency ratio squared they coincide with those of the fundamental mode (right).

(ii) Dependence on a static magnetic field

It is well known that the RF losses in sheet niobium cavities depend on the static magnetic field to which the cavity is exposed during cool down at the moment of the transition from the nc to the sc state. The magnetic field is entirely trapped [15]. Therefore, ambient fields of the order of the earth's magnetic field have to be shielded off cavities made of sheet metal. However, it came as a surprise that the sensitivity of 500 MHz NbCu cavities to ambient fields is much lower, although the magnetic field was trapped as well [16]. Later measurements

[14] Ph. Bernard, D. Bloess, W. Hartung, C. Hauviller and W. Weingarten, P. Bosland and J. Martignac, Superconducting niobium sputter-coated copper cavities at 1500 MHz, Proc. 5th Workshop RF Supercond. 19 - 23 Aug. 1991, DESY, Hamburg (Germany), ed. D. Proch; CERN/AT-RF 91-26.

[15] C. Vallet, M. Bolore, B. Bonin, J. P. Charrier, B. Daillant, J. Gratadour, F. Koechlin, H. Safa, Flux trapping in superconducting cavities, Proc. 3rd EPAC, Berlin, March 24 - 28, 1992, ed. H. Henke, H. Homeyer and Ch. Petit-Jean-Genaz, Gif-sur-Yvette, 1992, p. 1295.

[16] G. Arnolds - Mayer and W. Weingarten, Comparative measurements on niobium sheet and sputter coated cavities, IEEE Trans. Magn. MAG - 23 (1987) 1620.

on 1500 MHz confirmed this [17] and proved that the magnetic field was entirely trapped[18], too. This finding was one of the first marked differences between niobium sheet and film cavities. It allows insight into the metallurgical differences and is therefore worth being looked at more closely.

Data are available from RF tests of cavities placed inside the magnetic field of a solenoidal coil. From the Q-value measured the dependence of the local surface resistance on the ambient magnetic field can be determined [19].

The (magnetically induced) local residual surface resistance R_s^m is proportional to the ambient field's component normal to the surface B_{ext}:

$$R_s^m = \frac{B_{ext}}{B_{c2}} \cdot R_n \ . \qquad (2)$$

B_{c2} being the upper critical field and R_n the surface resistance at low temperature in the nc state,

$$R_n = 25 \cdot \sqrt{f[GHz] / RRR} \qquad (3)$$

with RRR the residual resistivity ratio.

For a 500 MHz Nb sheet metal cavity (ambient field perpendicular to the cavity axis, RRR = 100) the increase of the local surface resistance per mT ambient field is 5000 nΩ [16]. By inserting this number into eq. 2, using eq. 3, we obtain B_{c2} = 0.36 T, which is close to the measured value (0.35 - 0.4 mT [20 21]). This confirms the validity of eq. 2.

A direct comparison of the sensitivity of the surface resistance to the ambient field between film and sheet niobium cavities at 500 MHz under otherwise identical conditions has been done. The sensitivity of sheet metal is by at least a factor of 10 larger [8, 18]. Taking into account the different RRR values of the niobium sheet (~ 100) and the film (~ 10) and using eq. 2, the upper critical field B_{c2} for the film is by a factor of 30 larger than for the sheet (10 T) [22]. Measurements of B_{c2} range from 1.5 T with a transition width of 1 T to above 3.5 T [20 21 23] (which is the maximum field obtained in the sc coil).

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[17] Ph. Bernard, D. Bloess, T. Flynn, C. Hauviller and W. Weingarten, P. Bosland and J. Martignac, Superconducting niobium sputter-coated copper cavities at 1500 MHz, ibid. ref. 15, p. 1269.

[18] P. Darriulat, C. Durand, P. Janot, N. Rensing, and W. Weingarten, P. Bosland, J. Gobin, and J. Martignac, Dependence of the surface resistance of niobium coated cavities on the coating temperature, this Workshop.

[19] The difference between the average surface resistance R_s = G/Q (G is the usual geometry factor) and the local magnetically induced surface resistance R_s^m has to be taken into account by a geometry dependent parameter α: $R_s^m = \alpha\, R_s$. For a magnetic field perpendicular (parallel) to the cavity axis and the cavity being excited in the fundamental accelerating mode, α = 3.0 (1.6).

[20] D. Reinhard, Upper critical field (H_{c2}) measurements in superconductive samples for LEP cavities - Report on a summer student's work, CERN/EF/RF/ 86-4, 23 December 1986.

[21] W. Weingarten, G. Müller and A. Welti, Measurements of the upper critical field H_{c2} of Nb sheet material from various suppliers, CERN/EF/RF-87-2, 28 April 1987.

[22] This is only true if there are no pinholes in the coating (filled with insulating or nc material or empty) into which the magnetic flux might get trapped. The upper critical field of 10 T is therefore an upper limit. In fact D. Bloess investigated samples cut off cavities by AFM which showed pinholes.

[23] D. Bloess, E. Chiaveri, C. Durand, C. Hauviller and W. Weingarten, P. Bosland, S. Cantacuzène, Superconducting, hydroformed, niobium sputter coated cavities at 1.5 GHz, Proc. EPAC London 27 June - 1 July 1995, eds. V. Suller, Ch. Petit-Jean-Genaz, Singapore 1994, p. 2057.

2.2 Non quadratic losses

In the LEP2 cavities, made from Nb sputter coated on copper, the decrease of the Q-value is about a factor two between low field and the specified accelerating gradient of 6 MV/m. At larger gradients, of interest for future linear colliders, the effect is even more pronounced. If the non-quadratic RF losses could be substantially reduced, thin film cavities would be an ideal solution for future applications.

(i) Correlation of residual losses and NQL

A correlation has been found between the NQL (R_s') and the residual surface [18]. For the industrial cavities [3] it is shown in Fig. 3.

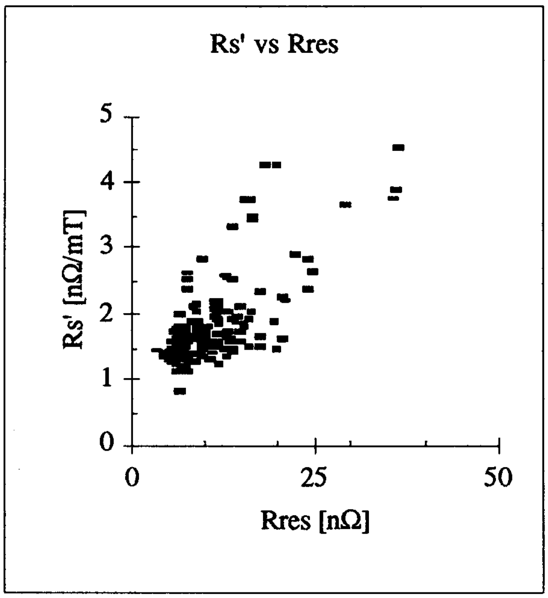

Fig. 3: Correlation between NQL and residual losses measured for the cavities for LEP2 from industry.

(ii) Origin of NQL

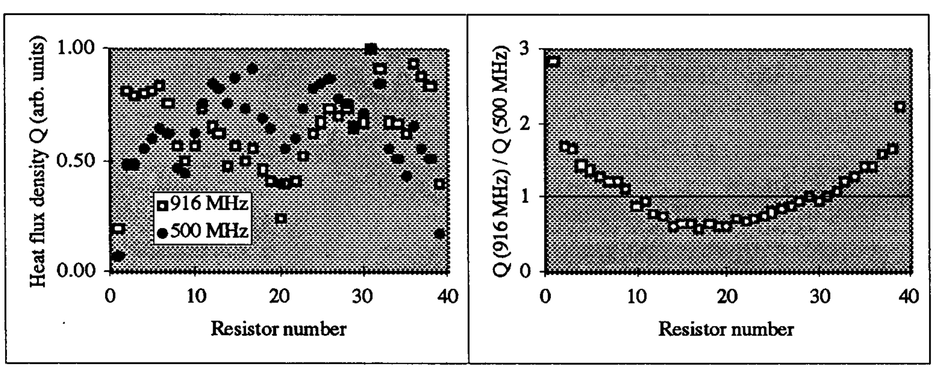

Fig. 4: Heat flux density Q per latitude for accelerating mode (TM010) at 500 MHz and higher mode (TM011) at 916 MHz. The resistor 20 is located on the equator, resistors 1 and 39 are located near the beam tube (left). The different sensitivities of the resistors are eliminated by taking the ratio of Q in the two modes. The losses in the TM010 (TM011) mode are concentrated near the equator (beam tube, right).

In Fig. 4 results from "temperature maps" obtained in the accelerating mode and in the TM_{011} - like mode are compared for a diode sputter-coated mono-cell NbCu cavity, which had large NQL. The magnetic field has a maximum near the equator for the fundamental mode and a maximum closer to the irises for the higher order mode. One can see that the losses follow the magnetic field amplitude. Hence NQL are linked to the RF magnetic field [16].

(iii) Static magnetic field dependence

The dependence of R_s' on the static magnetic field B_{ext} has been studied in a 500 MHz cavity [16]. R_S' increases with B_{ext}. These results have been complemented by new data obtained on 1500 MHz cavities 18.

(iv) RF magnetic field dependence

The dependence of the surface resistance R_S on the peak RF magnetic field B_p inside the cavity is shown in Fig. 5. That R_S depends on B_p is as such not new. In ref. [24] it was argued, that the sc energy gap should decrease with B_p^2. What is new, is the importance of this effect and the presence of a linear term in B_p [16].

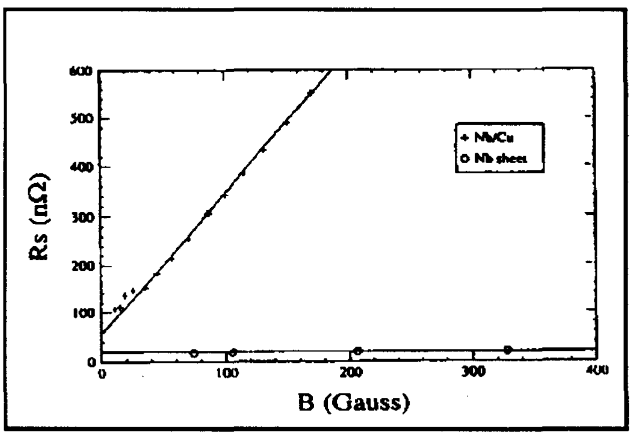

Fig. 5: The surface resistance R_s vs. the peak magnetic field amplitude B for 1500 MHz niobium film (upper) and sheet cavity [25]: R_s increases linear with B.

(v) Thermal impedance of the NbCu interface

Another issue to be addressed was the interface niobium - copper. If there is a mismatch, the niobium surface temperature under RF could be substantially larger than the bath temperature. The BCS term of the surface resistance would then lower the Q-value with increasing RF power.

[24] H. A. Schwettman, J. P. Turneaure, W. M. Fairbank, T. I. Smith, M. S. McAshan, P. B. Wilson, and E. E. Chambers, Low temperature aspects of a cryogenic accelerator, IEEE Trans. Nucl. Sci, June 1967, p. 336.

[25] B. Bonin and H. Safa, Power dissipation at high fields in granular RF superconductivity, J. Supercond. Sci. technol. 4 (1991) 257.

This hypothesis could be excluded [16]. The effect which was made use of was the dependence of the number of absorbed He atoms at the cavity surface on the bath temperature (with the pumping valves closed), which was - with no RF - identical to the bath temperature. The upper limit of change of the surface temperature observed under RF was by far too small to explain the corresponding decrease of Q-value.

(vi) Bath temperature dependence

Variation of the bath temperature T_B allowed further insight into the physical nature of NQL (Fig. 6). In the early NbCu cavities (coated with a diode bias system, RRR [26] $\approx$ 14 [27]), one obtained

$$R_s' \propto \frac{1}{1 - T/T^*}, \qquad (4)$$

with $T^* \approx 7.3 \pm 0.3$ K [17]. In 1500 MHz NbCu cavities manufactured in a magnetron system (RRR $\approx$ 17 - 27 [28]),

$$R_s' \propto \frac{1}{\left(1 - T/T^*\right)^2}, \qquad (5)$$

with $T^* \approx 6.8 \pm 0.3$ K [23]. Hence the NQL disappear above a temperature T^* which is significantly lower than the critical temperature T_c. A possible explanation will be given in chapter IV.

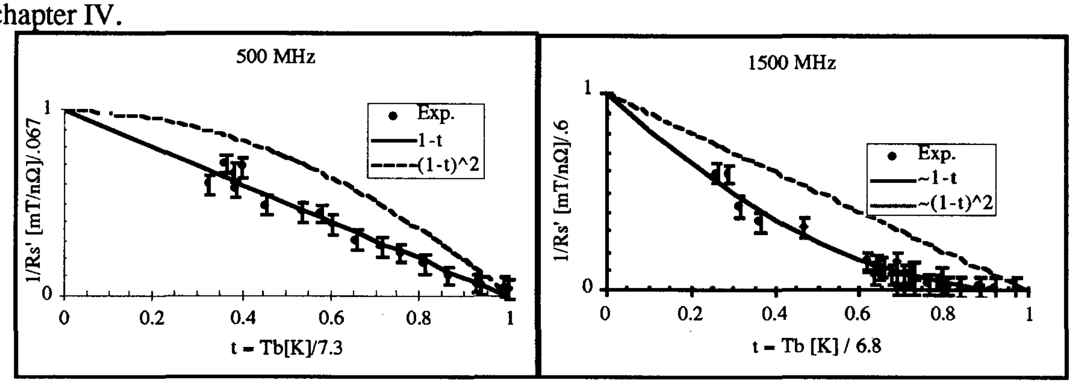

Fig. 6: $1/R_s'$, representing NQL, vs. bath temperature T_B for 500 MHz diode sputter coated cavity (left) and magnetron sputter coated cavity (right).

(vii) Frequency dependence

The frequency dependence of NQL is a sensitive parameter to check physical models. It is difficult to evaluate because of two reasons. Either one excites the same mode in two cavities of different size and similar shape, or one uses two different modes in the same cavity. In the first case, the results become the more reliable the more the parameters chosen for coating and processing are similar and well under control. In the second case, the RF field amplitude "sees" different regions of the cavity surface.

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[26] The RRR values are measured on samples coated inside a cavity.

[27] C. Benvenuti, N. Circelli, M. Hauer and W. Weingarten, Superconducting 500 MHz accelerating copper cavities sputter-coated with niobium films, IEEE Trans. Magn. MAG-21 (1985) 153.

Both methods have been studied [1, 23]. Results of the first one are presented in the histograms of Fig. 7 (which update the results from ref. [1] by the tests described in ref. [18]). A large number of date is available from the industrial production of LEP2 cavities at 352 MHz [3]. They are compared with results from 1500 MHz cavities studied in collaboration between CERN and Saclay [1, 14, 17, 18, 23, 28]. The criteria for the data analysis were (a) a linear fit between $B_p = 1$ and 5 mT, (b) the standard deviation of R_s' be smaller than 10 %.

The shape of the two distributions is similar, and the expectation values are 1.4 nΩ/mT for 352 MHz and 7.5 nΩ/mT for 1500 MHz, respectively, compatible with a linear frequency dependence of R_s'.

Whereas the early data were contradictory [17], there is now evidence for a linear frequency dependence of R_s'.

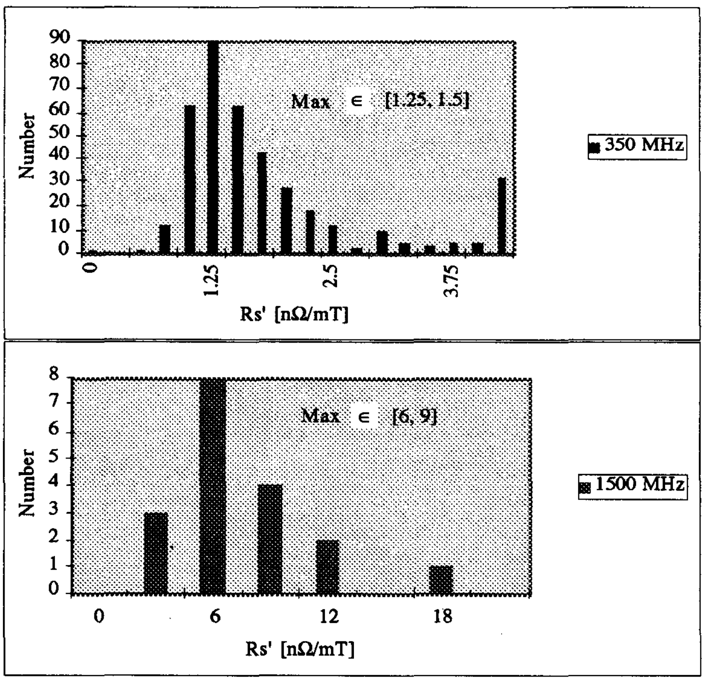

Fig. 7: Histogram of NQL parameter Rs' (4.2 K) for NbCu LEP2 cavities (350 MHz) from the industrial production (upper) and NbCu 1500 MHz cavities. Rs' is 1.375 nΩ/mT for the 350 MHz cavities, and 7.5 nΩ/mT for the 1500 MHz cavities. These numbers scale linearly with the frequency.

(viii) Surface treatment by water rinsing

It is known that NQL may be modified by water rinsing [14]. This observation indicates that NQL are affected by the surface conditions.

(ix) Temperature during coating

Another feature has been found during the production of the LEP2 cavities. Reducing the temperature during bakeout and coating from values above 200 °C to 150 - 170 °C

[28] Ph. Bernard, D. Bloess, E. Chiaveri, C. Hauviller, T. Schiller, M. Taufer and W. Weingarten, P. Bosland, A. Caruette, M. Fouaidy and T. Junquera, Superconducting hydroformed niobium sputter coated copper cavities at 1.5 GHz, ibid. ref. 2, 739.

significantly improved the acceptance ratio for the first coating [29]. These results are confirmed by experiments on 1500 MHz NbCu cavities 18.

(x) Behaviour at low RF magnetic field

The behaviour at low field allows to determine whether there is a threshold for the onset of NQL. Such a threshold was indeed observed near 9 mT [1], which is confirmed by more recent data from a 350 MHz LEP2 cavity (Fig. 8).

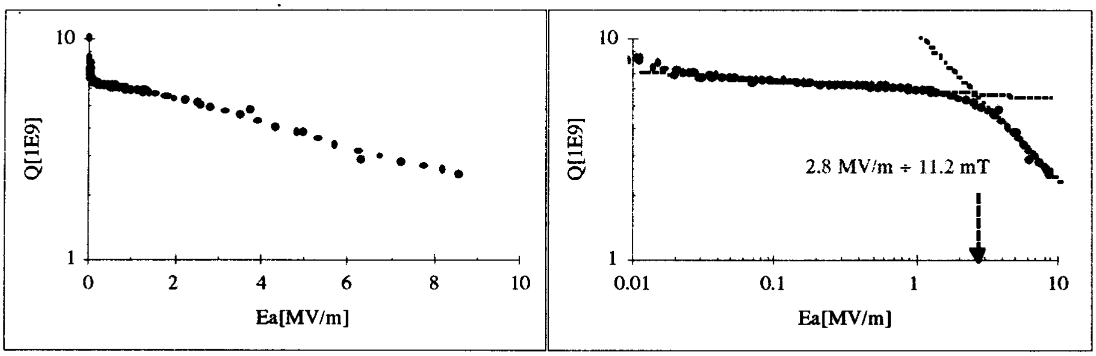

Fig. 8: Q(E_a) plot in common semi-logarithmic and in double logarithmic way. The latter reveals the onset of NQL between 6 and 15 mT.

2.3 Sample measurements

The first measurements on NbCu samples were aimed at determining RRR, T_c and B_{c2} of the diode sputtered layers. RRR measurements were performed by DC current methods and RF methods [16 27 30]. Because of the small RRR values observed (~ 10) and the large B_{C2} values observed (> 1.5 T), SNMS tests were initiated, which revealed interstitial impurities (C, O, N) in the 10^{-3} range [16]. The observation obtained from the bath temperature dependence of NQL, T* ≈ 7 K (see chapter 2.2), led to the hypothesis of weak sc spots contaminated by oxygen with a depressed T_c ≈ 7 K, probably located near the grain boundaries. TEM measurements, however, which allowed a spatial and elemental resolution on an atomic scale, did not confirm this [1, 23]. The grain boundaries in particular were carefully investigated, and no contamination was found. Instead, very small grains (5 nm) with an average grain size near 40 nm, and defect agglomerates within grains were detected. Therefore, the underlying idea for explaining NQL changed towards structural defects, by the presence of which the coherence length is drastically decreased.

Laser annealing [31], presently being prepared at CERN, could be an interesting method for the understanding the physics of the layer and for improvement of the cavity performance.

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[29] G. Cavallari, E. Chiaveri, J. Tückmantel and W. Weingarten, Acceptance tests of superconducting cavities and modules for LEP from industry, ibid. ref. 23, 2042.

[30] C. Benvenuti, D. Bloess, E. Chiaveri, N. Hilleret, M. Minestrini, and W. Weingarten, Superconducting cavities produced by magnetron sputtering of niobium on copper, ibid. ref. 4, 445.

[31] E. Radiconi. C. Benvenuti, M. Bianconi, L. Correra, Laser annealing of Nb coatings for superconducting RF accelerating cavities, CERN LEP2 Note 95 - 33, 17 May 1995.

Treatments of samples have shown that the grain size increased, the surface gets smoother, and the annealing in Ar atmosphere is not detrimental.

IV. DISCUSSION

From the experimental data described so far, two regimes can be distinguished (cf. Fig. 8). In the first one for $B_p \leq 10$ mT the BCS and residual losses are dominant. In the second one for $B_p \geq 10$ mT the NQL are dominant.

In the first regime the residual losses are (as the BCS losses) proportional to the frequency squared. As outlined in ref. [14], this is expected from resistive losses in a superconductor (for example a thin nc surface layer or grain boundaries [32]).

In the second regime R_s is linear to the frequency ω. As discussed in refs. [1, 23], such losses are expected from intrinsic defects (weak links) switching into the nc state in nanoseconds. Per RF half cycle the RF field does the work needed to break the Cooper pairs within the defects, which re-condense again when the RF field becomes small again. Evidently, these losses increase linearly with the frequency. The conventional formalism of type II superconductivity is sufficient to calculate characteristic parameters. The calculation is based on the small coherence length of several nm [17]. The onset magnetic field (10 mT) is interpreted as the lower critical field B_{c1}. The upper critical field B_{c2} is relatively large (12 T at 4.2 K) but neither in contradiction with the experimental results described above nor in contradiction with experience for extreme type II superconductors. In the particular case considered [1], the NQL are given by a formula which except for a numerical factor near unity equals

$$R_s' = \frac{4}{3} \cdot \frac{\omega}{2\pi} \cdot \frac{\mu_0 \lambda}{B_{c2}(T)}. \tag{6}$$

This relation describes according to Bean the losses by an alternating current due to magnetic flux penetration [33]. For the frequency of the LEP cavities (352 MHz) and with reasonable values for the penetration depth, $\lambda = 50$ nm, B_{c2} (4.2 K) = 12 T, one obtains R_s' = 2.4 nΩ/mT, which is the observed value (1 - 3 nΩ/mT, cf. Fig. 7).

As is outlined further [23], a temperature dependence of the NQL as observed can be expected if the defects are SNS or SIS junctions. The $B_{c2}/(\lambda \cdot \mu_0)$ term in eq. 6 describes essentially a current density. According to de Gennes [34] the maximum super current density which crosses a SNS or SIS junction is proportional to $(1-T/T_c)^2$ or $(1-T/T_c)$, respectively.

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[32] J. Carini, A. M. Awasthi, W. Beyermann, G. Grüner, T. Hylton, K. Char, M. R. Beasley, A. Kapitulnik, Millimeter-wave surface resistance measurements in highly oriented $YBa_2Cu_3O_{7-\delta}$ thin films, Phys. Rev. B37 (1988) 9726.

[33] C. P. Bean, Magnetization of High-Field Superconductors, Rev. Mod. Phys. 36 (1964) 31.

[34] P. G. de Gennes, Boundary Effects in Superconductors, Rev. Mod. Phys. 36 (1964), 225.

Hence one would expect that RF losses caused by flux penetration into a SNS or SIS junction, as hypothesized in ref. [35], are described by eq. 6.

In addition, the correlation between R_{res} and R_s' could be naturally explained by the assumption, that both are proportional to the number of defects, some of which are nc and some of which are weak superconductors.

One would expect the penetration of magnetic flux depends on the surface condition, which is indeed observed.

The critical temperature $T^* < T_C$ has not yet been satisfactorily explained. In ref. [23] some possible explanations are given, which are based on the granularity[36] of the layers (which implies very small grain sizes between 5 and 10 nm, which are indeed observed). The idea is that only for a temperature substantially lower than T_C (the critical temperature of the individual grains) the whole sample will become sc [37].

V. CONCLUSION

It was shown that thin film cavities bear a large potential for future accelerator application, because the features of the sc metal can in principle be independently optimized from those of the substrate structure. (Conventional) high T_c sc films promise low RF losses and large accelerating gradients. The prevailing disadvantage of thin film cavities is the decrease of the Q-value with the RF power (NQL). Evidence is given, that these losses are caused by magnetic flux penetration into weak sc junctions near the surface.

Laser annealing of the niobium surface, which is presently prepared at CERN, could show a way to improve cavity performance.

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[35] A. M. Portis, Microwaves and Superconductivity: Processes in the Intergranular Medium, Earlier and recent Aspects of Superconductivity, eds. J. G. Bednorz and K. A. Müller, Heidelberg 1990, p. 278.

[36] According to J. C. Garland, Granular properties of high Tc superconductors, Physica A 157 (1989) 111: Granular superconductors are modelled as islands of homogeneous sc material coupled to one another through Josephson-like links. The details of the coupling are material dependent, involving the true Josephson effect if the grains are separated by a thin insulating barrier, the proximity effect if grains are separated by regions of normal metal, or "weak-link" coupling if the grains are bridged by a sufficiently narrow sc channel.

[37] After the Workshop R. Vaglio suggested to me, that disordered niobium with very small RRR ≈ 1.5 has a lower $T_c \approx 7$ K and a larger $B_{c2} \approx 4$ T. T_c can decrease below 1 K, depending on the RRR value, but B_{c2} cannot exceed 4 T. The other sc parameters are calculated using standard formulas of type II superconductivity. More details can be found in C. Camerlingo, P. Scardi, C. Tosello, R. Vaglio, Disorder effects in ion-implanted thin films, Phys. Rev. B 31 (1985) 3121.