HIGH-Q, HIGH GRADIENT NIOBIUM-COATED CAVITIES AT CERN

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Abstract

Superconducting cavities made by sputter-deposition of a thin niobium film onto copper have proven over the years to be a viable alternative to bulk niobium, the best example being the very successful operation of LEP at 200 GeV. It will be shown that this technology, investigated at 1.5 GHz by a dedicated R&D effort at CERN, can be developed to unprecedented performance, proving that no fundamental limitation prevent high quality factors to be maintained over a broad range of accelerating field.

1 INTRODUCTION

Superconducting cavities based on the niobium film technology are being successfully used in LEP2 at CERN. As many as 272 cavities operated at 4.5 K are presently installed, transferring a total power of about 18 MW to the beams resulting in an energy of 101 GeV per beam [1]. The cavities are being operated at 7 MV/m on average, well above the design value, and the operating experience did not reveal any major difficulty. This success makes a strong case in favor of the use of niobium film cavities for future large-scale projects, if the required performance level is obtained. Extrapolation of LEP2 data erroneously led in the past to the conjecture that film technology is intrinsically limited compared to bulk niobium. In this paper, the outcome of an ongoing R&D effort at CERN, aimed at identifying the physical principles which determine the ultimate performance of niobium films, is presented. Most of the information regarding the experimental procedure, the RF characterization and the analysis of the data in terms of a reduced set of parameters can be found in [2]. We concentrate here on summarizing a few relevant results with the purpose of showing that no intrinsic limitation has been found and that very high Q-values can be maintained over a very broad range of accelerating field.

2 THIN FILM DEPOSITION

This study has been carried out using 1.5 GHz resonators operated in the TM_{010} mode. The cavities are made of Oxygen-Free Electronic grade (OFE) copper, which provides a substrate with a high thermal conductivity at liquid helium temperatures (one order of magnitude higher at 4.2 K than for RRR 300 niobium). The cavity construction technique has a profound effect on the structural properties of the copper substrate, which in turn affects the growth of the niobium film. Seamless cavities have been chosen, manufactured by spinning [3]. Other construction methods have been tested (namely hydroforming and electroforming) and found less performing, but not much effort could be devoted to optimizing these substrates.

It has been proven by material analysis that the inner surface of spun cavities is damaged after shaping with cracks at least 150 µm deep, in particular at the irises. A special procedure has been developed recently to remove these defects by electropolishing, at variance with the chemical polishing used in the past [4]. Electropolishing may produce mirror-like surfaces with an average roughness of the order of 0.2 µm, which are moreover completely free from macroscopic defects.

The coating method follows closely the sputtering procedure developed for LEP2 [5], based on a cylindrical magnetron configuration, and adapted to 1.5 GHz cavities, as illustrated in figure 1. The sputtering discharge is established in a noble gas atmosphere (argon in the case of standard LEP2 coatings) at a pressure of 1.5×10^{-3} mbar, between the central cathode and the grounded cavity. The electrical current of the glow discharge is stabilized at 3 A, resulting in a potential of approximately 360 V using a coaxial permanent magnet having a magnetic induction of about 100 G at the surface of the cathode. The coating takes place usually at 150 °C, and a thickness of 1.5 µm is obtained in 15 minutes of treatment. The cut-off tubes are coated first by displacing the permanent magnet, with slightly modified parameters: 10^{-2} mbar, 1 A, 320 V.

The niobium cathode is inserted in the cavity in a class 100 clean room, where it is always kept when not in use. High-pressure water rinsing with ultra-high-purity water at 100 bar is performed on each cavity before and after deposition. The rinsing installation has been upgraded recently for closed cycle operation, its cleanliness being qualified by a particle count in the output water lower than 500 particles/ml.

3 RF AND MATERIAL CHARACTERISATION

In the analysis of the RF results it is convenient to split the RF surface resistance in three terms, the BCS surface resistance, the fluxon-induced resistance and the residual resistance: $R_s=R_{BCS}+R_{fl}+R_{res}$.

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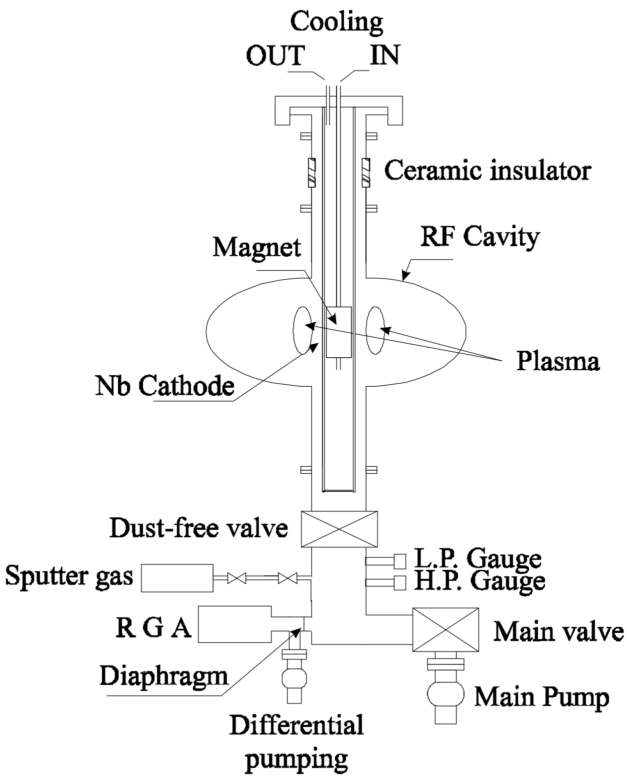

Figure 1: The sputtering apparatus

Extensive studies have been carried out on films produced with various sputter gases and on different substrates to investigate their superconducting properties. Changing the sputter gas allows in particular to change the electron mean free path of the films. The sputter gas is implanted in the films because of two-body back scattering from the cathode. Its amount ranges from a few ppm for Xe and Kr, up to a few hundred ppm for Ar and a few percent for Ne.

The dependence of the BCS surface resistance on the mean free path has been found to be in agreement with theoretical predictions, with a minimum for $l \sim \xi_0$. The main features of the data are in fact well described by the BCS theory using standard literature values of coherence length, London penetration depth, and strong coupling parameter.

A phenomenon that is often overlooked is the dependence of R_{BCS} on the RF field amplitude. It has been found that this dependence is the same for bulk niobium and niobium coated cavities, as illustrated in figure 2. This can be expressed by a global field-dependent term that multiplies the usual expression for R_{BCS}. A quadratic term can usually fit the experimental data, and an increase of the surface resistance of 50% is typically reached at a RF amplitude of 32±5 mT. This behavior is of course enhanced at 4.2 K, where it overshadows the residual resistance, and is negligible at 1.7 K. Since LEP is the only accelerator not operating at 1.7 K, this contributed to the impression that the surface resistance of films has a stronger RF amplitude dependence than for bulk cavities. Even for cavities operating at 1.7 K, this term might be one of the main intrinsic limitations of the surface resistance at very high fields. Extrapolation of the present data indicates that the BCS surface resistance for films could be as high as 20 nΩ at 160 mT (Q_{BCS} of 1.5×10^{10} at 35 MV/m).

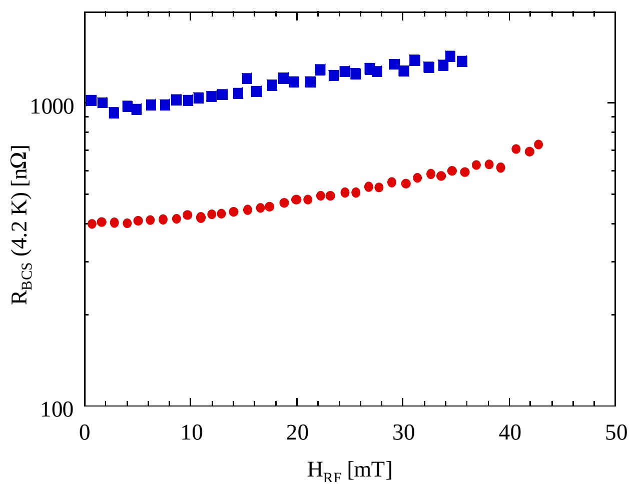

Figure 2: Dependence of R_{BCS} on H_{RF} for niobium film (dots) and for niobium bulk cavities (squares).

The possibility of varying the electron mean free path allowed also for the first time to show its influence on the fluxon-induced losses. Fluxon-induced losses are produced in RF if an external magnetic field H_{ext} is trapped in the superconductor when cooling down the cavity from above the critical temperature. The losses are parameterized as $R_{fl}(H_{rf},H_{ext})=(R_{fl}^0+R_{fl}^1 H_{rf})H_{ext}$. An additional surface resistance is produced even at zero RF amplitude H_{rf}. This effect is particularly strong in the case of bulk niobium, reaching up to 200 nΩ per Gauss of external magnetic field at 1.7K. The RF amplitude dependence of fluxon losses is characterized by R_{fl}^1, which has an average value of 3nΩ/G/mT in the case of the bulk. In figure 3a and 3b the values of R_{fl}^0 and R_{fl}^1 at 1.7 K are reported for a wide range of mean free path values, obtained using Xe, Kr, Ar, Ne and Ar-Ne mixtures as sputter gases on various substrates. The minimum takes place at $l \sim \xi_0$, an unexpected feature whose link to the corresponding minimum in R_{BCS} is possibly only fortuitous.

Earlier conjectures that the fluxon induced losses should depend on an anomalously high value of H_{c2} have been superseded by recent H_{c2} measurements on films, which simply confirm literature data obtained with the bulk [6]. The hypothesis that fluxon losses are governed by pinning appears more realistic. In particular, it is well known that rare gases in metals can segregate into clusters, and that such clusters are very efficient pinning centers, depending on their size. The density of pinning centers, and their possible superposition, may give rise to the behavior described in the figures.

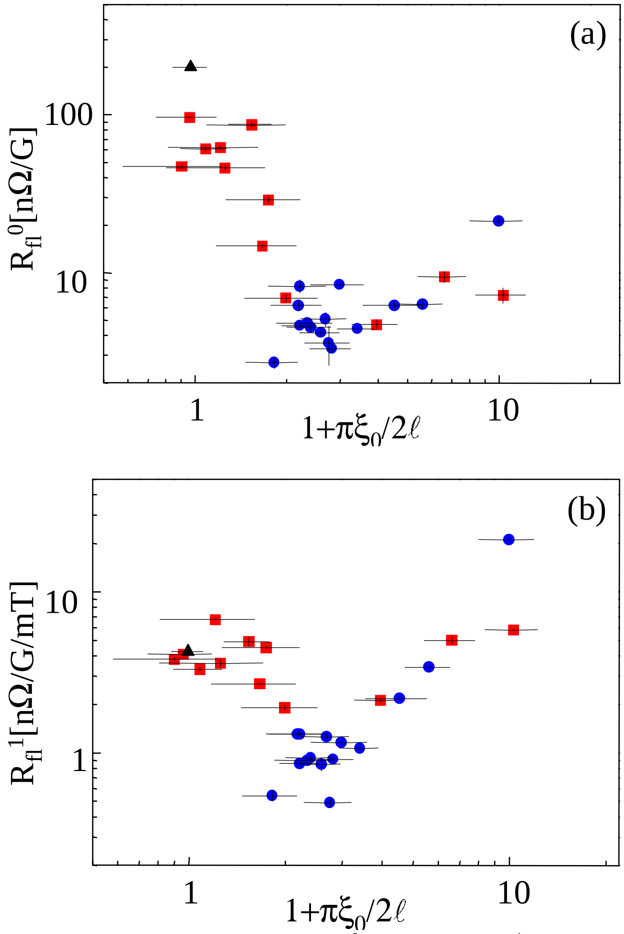

Figure 3: Dependence of R_{fl}^0 (a) and R_{fl}^1 (b) on $1+(\pi/2)(\xi_0/l)$ (obtained from the measured RF penetration depth). Triangles indicate bulk niobium used as a clean limit reference, rounds and squares indicate films deposited on copper with different preparation.

The minimum values of fluxon losses, i.e. R_{fl}^0=3nΩ/G and R_{fl}^1=0.4nΩ/G/mT are obtained using krypton as sputter gas. In the hypothesis of the use of film cavities unshielded from the earth's magnetic field (~0.5 G) in a high gradient accelerator, this R_{fl}^1 term will alone limit the attainable surface resistance to 32 nΩ at 160 mT (Q value of about 9×10^9 at 35 MV/m). The use of argon as in the case of LEP coatings would double the surface resistance. Hence, the choice of using krypton as sputter gas for the films discussed in the next section.

4 OPTIMIZATION OF THE RESIDUAL RESISTANCE

The value of the residual resistance of a cavity is often obtained by simply taking the data measured at 1.7 K, temperature at which the BCS resistance is about 1.5 nΩ. When the residual resistance is also in the nΩ range this procedure is no longer valid, and it is necessary to fit with the BCS formalism an entire set of data measured at different temperatures to obtain reliable results. It is then observed that the residual resistance, for values of the RF amplitude sufficiently far from the field emission threshold, can be written as $R_{res}(H_{rf})=(R_{res}^0+R_{res}^1 H_{rf})$.

The experience gained in the course of this study allowed for the formulation of a few simple guidelines for obtaining films of a low residual resistance. The most important single parameter is the quality of the copper substrate. It has already been shown [7, 8] that the roughness of the copper can significantly influence both the R_{res}^0 and R_{res}^1 values of the niobium films. Smoothening of the copper surface is thus the best way for lowering the residual resistance. Electropolishing of the copper surface has been applied for this purpose, with the further advantage of obtaining virtually defect-free surfaces, both at the microscopic and at the macroscopic level, as discussed in [4]. Such defects are believed to be responsible for most of the RF amplitude dependence of the residual resistance, rather than the small grain size of films as earlier suggested [9]. These earlier conjectures can be discarded on the grounds of plain experimental evidence, as illustrated in figure 4. Here are reported values of R_{res}^0 and R_{res}^1 averaged over a high number of different cavities. For a same substrate, spun chemically polished copper in the example, the residual resistance does not depend within experimental errors on the nature of the gas used for the coating. Neon is an exception because of the huge amount of gas contained in the films, resulting in poor mechanical properties and adhesion. Hydroformed chemically polished copper cavities, having a higher roughness, result on average in higher residual resistances. Electropolished cavities, as expected, display much improved residual resistances that can be as low as those of bulk niobium cavities.

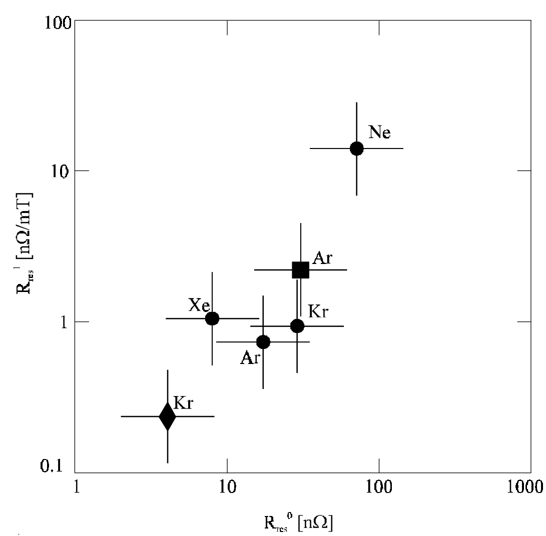

Figure 4: Residual resistances for electropolished spun copper cavities (diamond), chemically polished spun copper cavities (rounds) and chemically polished hydroformed copper cavities (square).

Values of R_{res}^0 and R_{res}^1 lower than respectively 1.5 nΩ and 0.1 nΩ/mT have repeatedly been obtained. A contribution of grain boundary weak links cannot of course be excluded at this level.

Only a fraction of the cavities displayed in figure 4 was produced using the upgraded rinsing installation described in paragraph 2. Improved rinsing has no effect on the values of residual resistance, but allows reaching accelerating fields in excess of 20 MV/m, while the data collected earlier were usually limited by field emission at accelerating fields barely exceeding 10 MV/m. A few of these cavities, coated using krypton as sputter gas, are illustrated in figure 5, where the Q curves as a function of the accelerating field measured at 1.7 K are reported. The experience has shown that extending the operating range results merely in a linear prolongation of the $R_{res}(H_{rf})$ behavior, up to a higher field emission threshold. This situation is reminiscent of what happened with bulk niobium and there is no reason to suspect the existence of any fundamental limitation of the operating range if a cleaner production process can be achieved.

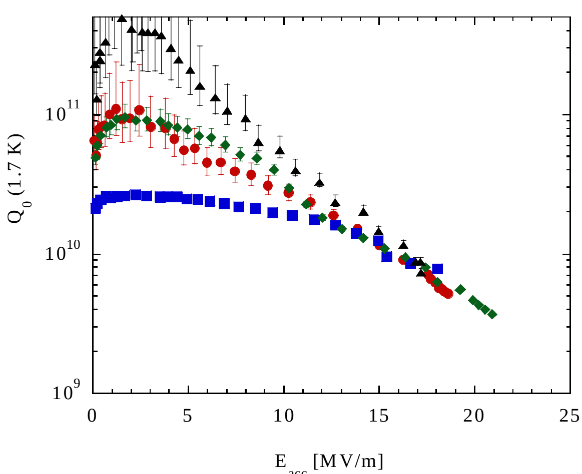

Figure 5: Q value as a function of the accelerating RF field for some of the best performing cavities obtained.

5 CONCLUSION

Niobium film technology has been known for a long time to provide considerable benefits over bulk niobium, in particular because of the inherent better thermal stability of cavities and the possibility of avoiding costly construction material and magnetic shielding. The use of film cavity for accelerators operating at 1.7 K was not however contemplated because of the supposedly intrinsic limitations of films which could prevent operation at high RF amplitudes while maintaining high Q values. We report in this paper that these limitations are experimentally not confirmed, and that Q values in excess of $1x10^{10}$ at 15MV/m and $4x10^9$ at 20 MV/m can be obtained. The operating range can probably be further extended by improving the manufacturing process.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] S. Myers, “High Energy Operation of LEP2” (CERN-SL-99-012-DI), Proceedings of the 1999 Particle Accelerator Conference - PAC '99 New York City, NY, USA.

[2] C. Benvenuti, S. Calatroni, I.E. Campisi, P. Darriulat, M.A. Peck, R. Russo and A.-M. Valente, Physica C 316 (1999) 153.

[3] V. Palmieri, Part. Accel. 53 (1996) 217.

[4] C. Benvenuti, S. Calatroni, P. Darriulat, M.A. Peck, A.-M. Valente and C.A. Van’t Hof, “Study of the Residual Resistance of Superconducting Niobium Films at 1.5 GHz”, Proceedings of this Workshop.

[5] C. Benvenuti, “Superconducting coatings for accelerating RF cavities: past, present, future”, (DESY M-92-01), Proceedings of the 5th Workshop on RF superconductivity.

[6] C. Benvenuti, S. Calatroni, P. Darriulat, M.A. Peck and A.-M. Valente, “Fluxon Pinning in Niobium Films”, unpublished results.

[7] G. Arnolds-Mayer et al., CERN/EF/RF 86-1, unpublished.

[8] C. Benvenuti, S. Calatroni, I.E. Campisi, P. Darriulat, M.A. Peck, R. Russo and A.-M. Valente, IEEE Trans. Appl. Supercond. 9, 2 (1999) 900.

[9] B. Bonin and H. Safa, Supercond Sci. Technol. 4 (1991) 257.