SUPERCONDUCTING NIOBIUM FILMS FOR RF CAVITIES

P. Darriulat, CERN, 1211 Genève 23, Switzerland

1. INTRODUCTION

The present report is based on a paper submitted for publication elsewhere [1] and is presented here on behalf of its authors. Lack of space prevents me from giving a detailed presentation. Instead I have made a selection of the most important results without going into the details of how they were obtained.

The aim of the study is a better understanding of the mechanisms of RF losses in niobium film cavities, such as the 350 MHz cavities in current use at LEP2 [2], hereafter referred to as "standard films". The hope is to gain sufficient understanding to overcome the difficulties inherent to the film technology, and thus to take full advantage of its assets which make it a most serious competitor to the bulk technology.

For reasons of convenience the study is conducted on 1.5 GHz cavities operated in their TM_{010} mode. In nearly three years over a hundred different cavities have been produced and studied, including: bulk niobium (heat treated or not); films (1.5 μm thick) grown by magnetron sputtering in xenon, krypton, argon or argon-neon mixtures of various proportions; films grown on copper or on niobium substrates; films grown on pre-layers of various kinds (copper, titanium, gold, tin and aluminium); films grown on oxide free or oxidised copper; films grown under different sputtering conditions (bake-out and coating temperatures, discharge voltage, etc…); hydrogen loaded films.

The measurements performed on each cavity include: the critical temperature T_c ; the penetration depth λ; the surface resistance R_s and its dependence on temperature T, on RF magnetic field H_{rf}, and on the external magnetic field H_{ext} applied in the cavity volume as it is cooled down across T_c ; the penetration field H_p , measured at 1.7K from outside the cavity at the equator, and providing information on the lower critical field and on the critical current. In addition measurements performed on samples include the residual resistivity ratio RRR, the upper critical field H_{c2}, microscopic analyses of various resolutions, X-ray diffraction analyses, etc…

The cavity performance is characterised by its surface resistance (or equivalently by the quality factor $Q=295\Omega/R_s$) and by the maximal RF energy which can be stored in it. In the present phase of the study we did not attempt to optimise these variables.

2. THE MAIN RESULTS

2.1 Penetration depth and mean free path

The penetration depth is measured from the temperature dependence of the cavity frequency when approaching T_c. Its dependence on $t=T/T_c$ (Figure 1) is close to the Gorter-Casimir form $(1-t^4)^{-1/2}$, in agreement with BCS theory. A measurement of the London penetration depth at T=0 is obtained from these data, $\lambda_L(0)=33\pm4$nm. Also, from the relation $\lambda \propto \lambda_{clean} (1+\pi\xi_0/2l)^{1/2}$ the measurement of λ provides an estimate of the ratio ξ_0/l between BCS coherence length and mean free path. As shown in Figure 2, such estimates (circles) are in reasonable agreement with the values deduced from RRR measurements (triangles) when available.

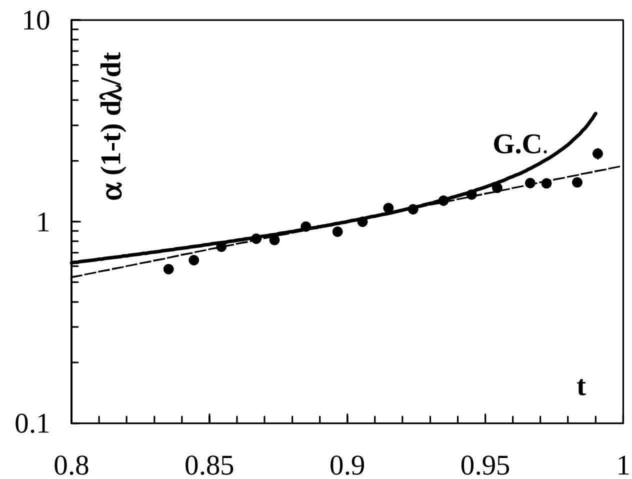

Figure 1

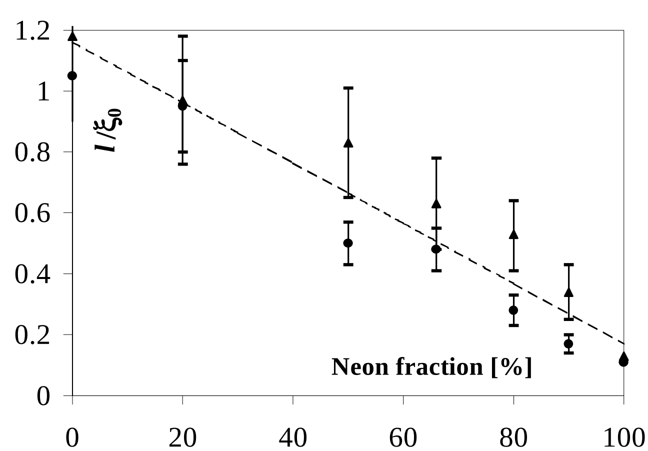

Figure 2. Films grown in Ne/Ar mixtures.

2.2 BCS resistance

The surface resistance is the sum of three terms, $R_s=R_{BCS}+R_{fl}+R_{res}$. Each term will be discussed separately.

The BCS resistance, $R_{BCS} \propto \exp(-\Delta/T)/T$, where Δ is the energy gap, results from photon absorption causing transitions between quasiparticle states, and therefore vanishes at T=0 (note that it is negligible at CEBAF and TESLA but significant at LEP2). Its dependence on mean free path displays a minimum (Figure 3) in the l region below $l=\xi_0$, in good agreement with BCS theory [3]. It is remarkable that such a subtle effect be experimentally verified. The BCS resistance is more than twice as large for heat-treated bulk cavities as it is for standard films. The minimum value provides an estimate of $\lambda_L(0)=27\pm2$nm, which, combined with the earlier estimate, gives $\lambda_L(0)=29\pm3$nm. Using published values of the Ginzburg-Landau parameter, one obtains an estimate of the BCS coherence length, $\xi_0=33$nm. Both the $\lambda_L(0)$ and ξ_0 values are in good agreement with earlier estimates from bulk data.

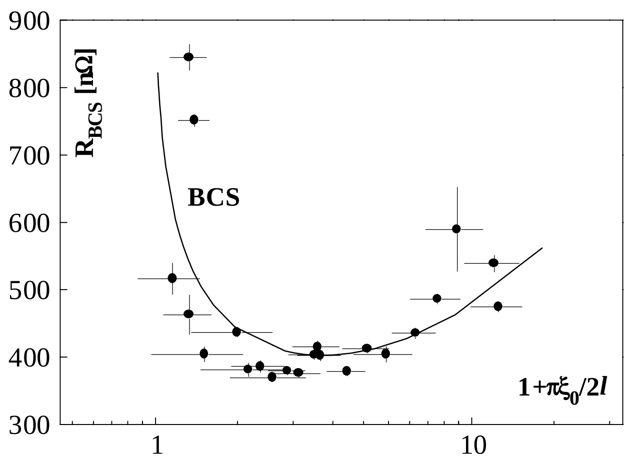

Figure 3. The BCS resistance at T=4.2K.

Within errors, the ratio $\alpha=\Delta/T_c$, where the energy gap Δ is obtained from the temperature dependence of the BCS resistance (Figure 4), is measured to be $\alpha=1.87\pm0.04$, independently from the value of l and in agreement with published values. Its departure from the BCS value, 1.75, is the result of strong coupling corrections. As shown in Figure 5 for standard films at 4.2K, the BCS resistance increases with H_{rf}, typically by 50% between 0 and 30±5mT. This result is valid independently from the value of the mean free path and applies to the bulk case as well as to the case of dirty films. Note that this increase contributes to the "slope" of the LEP2 Q curves and that its scale is commensurate with the value of the critical field, $H_c\cong200$mT.

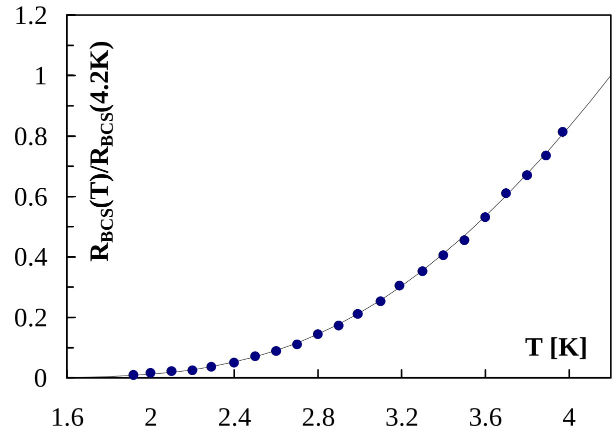

Figure 4. Standard films.

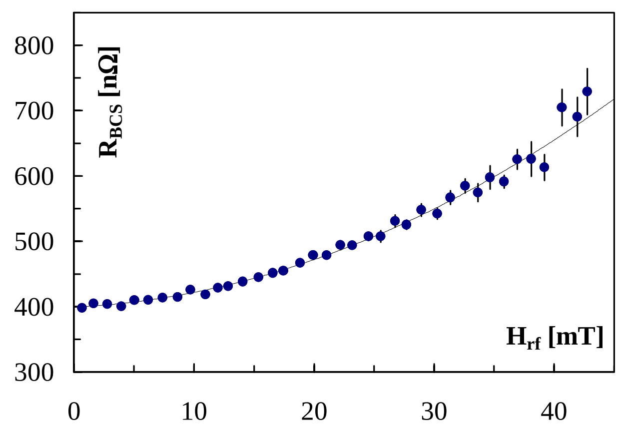

Figure 5. Standard films.

2.3 Fluxon induced losses

When the cavity is cooled down in the presence of a uniform external field H_{ext} parallel to its axis, the magnetic flux is usually trapped in its superconducting walls (the trapping efficiency is measured to exceed 99.8% for standard films), the only exception being heat treated bulk cavities where incomplete trapping is observed. The flux is trapped in the form of a lattice of elementary fluxons. For a uniform lattice an average spacing of 5 μm per Gauss of H_{ext} is expected between neighbour fluxons.

The viscous movement of the fluxons and their normal conducting cores generate losses which are described by an extra component of the surface resistance parameterised in the form $R_{fl}=(R_{fl}^0+R_{fl}^1\, H_{rf})\, H_{ext}$. Such a simple form ignores the occasional presence of a threshold in H_{ext}, typically 0.1 (resp. 0.3) Gauss for films grown on oxide free (resp. oxidised) copper. It also ignores the possible occurrence of a kink in the H_{rf} distribution, usually observed with films grown on oxidised copper, R_{fl}^1 doubling abruptly at a cavity dependent H_{rf} value. The following analysis is restricted to the range of variables for which the above simple parameterisation applies.

Figure 6 displays the dependence of R_{fl}^{0} and R_{fl}^{1} on mean free path. In this and the two following figures bulk data are labelled with triangles, films on oxide free copper with circles and films on oxidised copper with squares. As for R_{BCS} a minimum is observed in the region of l just below $l=\xi_0$, but this time much steeper, reflecting different pinning conditions as l is varied (and not an anomalous l dependence of H_{c2} as is sometimes stated). However, for pinning to produce structure on such a scale, the pinning centres cannot be uniformly distributed but must cluster, for example, at the grain boundaries.

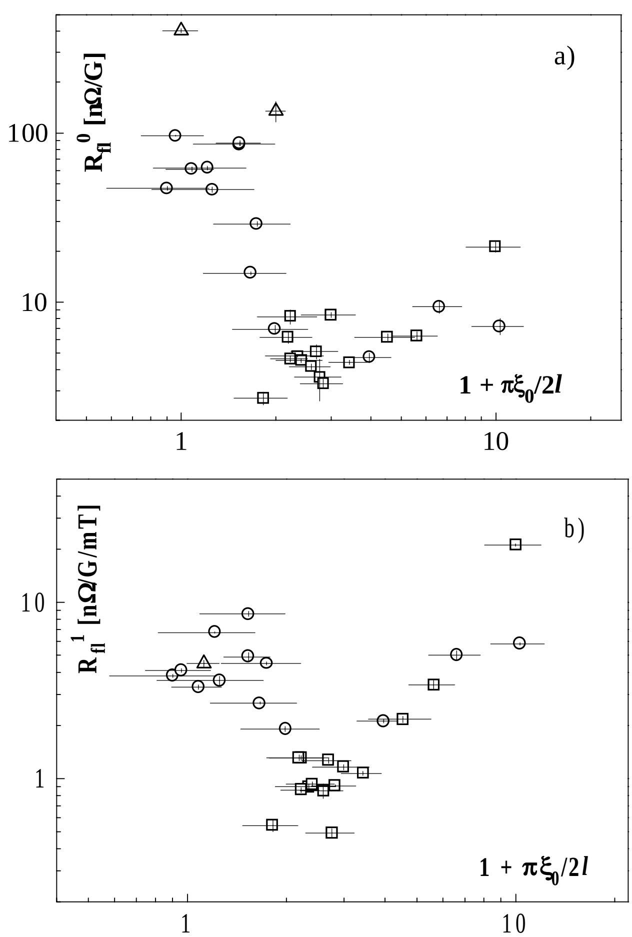

Figure 6

2.4 The niobium/substrate interface

The nature of the interface between the niobium film and its substrate plays an essential role. In particular ξ_0/l is nearly one unit lower, and T_c 0.2K lower, for films grown on oxide free copper than for films grown on oxidised copper (Figure 7). Sample analyses indeed reveal important differences between the textures of the two kinds of films and between their RRR values. Moreover films grown on oxidised copper have a higher penetration field, suggesting a stronger pinning at the interface. Figure 8 displays H_p^{-2} as a function of λ^2, where both quantities have been normalised to their clean limit values. A detailed understanding of the exact role played by the presence of oxide at the interface requires additional study.

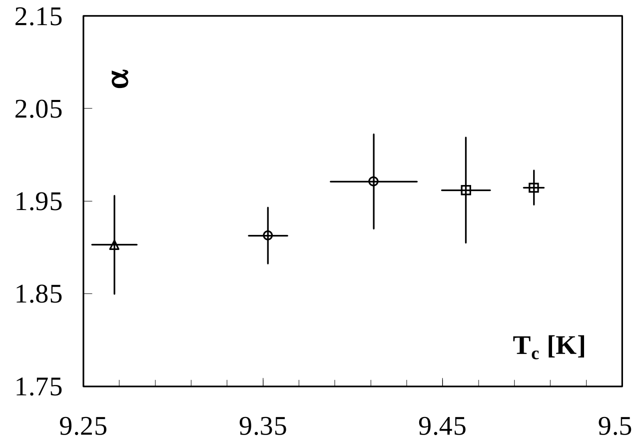

Figure 7

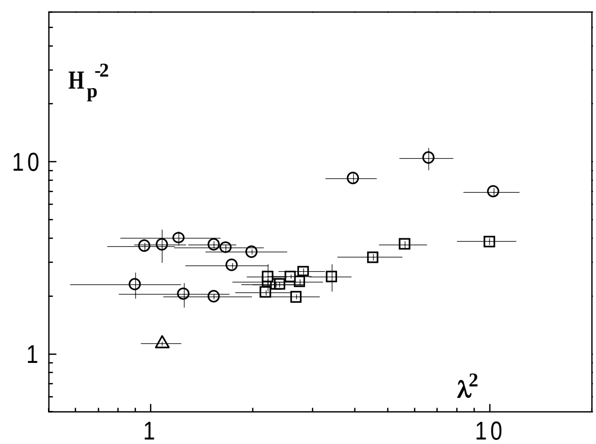

Figure 8

2.5 Residual resistances

The residual resistance is the only component of the surface resistance which survives at $T=H_{ext}=0$, and therefore the only serious enemy to be fought against. It is also, as in the bulk case, the least well understood. It may display a significant dependence upon H_{rf} but is virtually temperature independent.

Cavities prepared under identical conditions yield mutually consistent values of T_c , Δ , R_{BCS} , R_{fl} and H_p , but often inconsistent values of R_{res} . However large differences between measured values of R_{res} do not affect the other parameters, suggesting that the residual resistance is the result of extragranular dissipation (intergranular or superficial, uniformly distributed or localised). Occasionally very low R_{res} values are maintained over a broad H_{rf} range (Figure 9), providing clear evidence against a common belief that niobium coated cavities would suffer from a fundamental limitation in this domain. While grain boundaries are obvious candidates for hosting the impurities or defects responsible for non zero residual resistances, the weak link Josephson junction models [4], which describe correctly high T_c cuprates, are found improper at giving a sensible description of reality. The surface quality of the substrate is an essential element (R_{res} is observed to increase with substrate roughness), suggesting the possible importance of macroscopic defects. Hydrogen loaded cavities show symptoms reminiscent of the bulk situation where the precipitation of hydride is known to generate large residual resistances, increasing with H_{rf} . However, as in the bulk case, several important details are not well understood.

More studies are required in order to better identify what exactly causes R_{res} to deviate from zero and to devise appropriate cures.

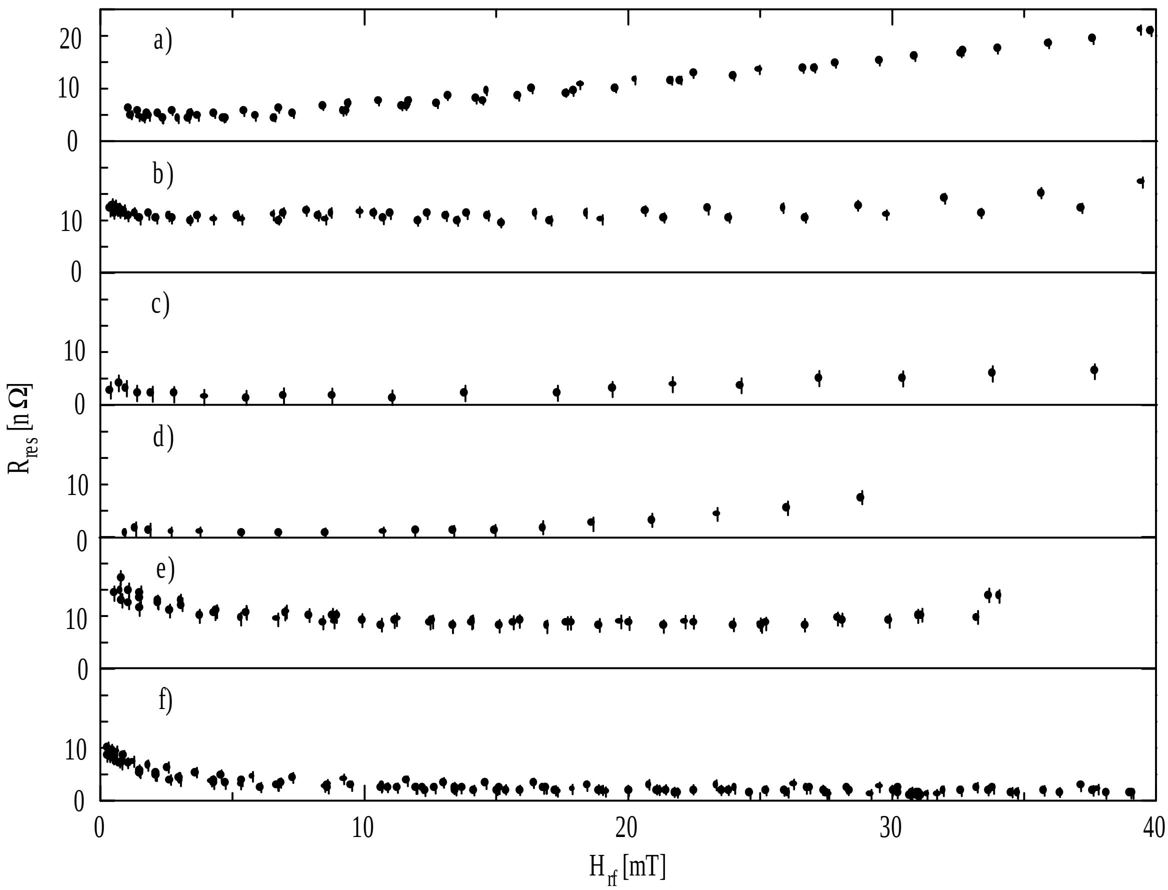

Figure 9. Residual resistances of film (a to d) and bulk (e to f) cavities.

3. CONCLUSIONS

This brief overview of the main results of the studies developed in reference [1] has shown that niobium films grown on copper substrates are well behaved in terms of their superconducting properties. When grown on oxide free copper they reach RRR values in excess of 30, depending upon the noble gas used in the discharge (lighter gases resulting in stronger concentrations in the film) and upon the sputtering conditions. However, contrary to the bulk case, RRR is not an important variable as the large thermal conductivity is anyhow taken care of by the copper substrate. Non-magnetic impurities in concentrations not exceeding a few atomic permil are well known not to upset superconductivity and indeed standard films having RRR in the 10 to 20 range have minimal values of both R_{BCS} and R_{fl} with no detectable influence on R_{res} .

The important variable is the residual resistance. It is of extragranular origin and is influenced by the quality of the substrate and by possible hydride precipitates, as in the bulk case. Contrary to what is often stated, we know of no fundamental limitation to the production of low R_{res} films reaching large values of H_{rf}. We did occasionally reach RF fields as high as 75mT with Q values in excess of 10^{10}. However we do not know how to obtain such a performance in a reliable and reproducible way. More studies are necessary to improve our understanding of the relevant parameters and, hopefully, to demonstrate that practical limitations are not too severe.

The many assets of the film technology make it a very serious candidate for large new projects. They include: a better thermal protection against quenches; a lower niobium cost; no need for niobium chemistry; flexibility in the definition of the film parameters; no need to shield against the earth magnetic field; homogenisation of possible impurity clusters (such as tantalum); revamping possibility; excellent cleanliness conditions (at least potentially). The film technology obviously precludes any significant heat treatment of the niobium film and must cope with the mechanical fragility of a 1.5μm thick film, however none of which turns out to be a serious inconvenience.

Many difficult questions have not yet been properly answered. Progress implies a sustained R&D effort requiring high quality expertise in many different fields of material sciences and physical chemistry. To be successful such an effort must be free of the constraints imposed by the pressure of an engineering project and by the perspectives of a future implication of industry in the production phase. It must have as its first and only aim the understanding of the relevant physics phenomena. Only then one can hope for real progress.

4. ACKNOWLEDGEMENTS

We are indebted to V. Palmieri for having made available to us spun niobium cavities and spun copper substrates, to P. Kneisel for the loan of a very low surface resistance bulk niobium cavity, to E. Mahner for the measurement of the upper critical field of film samples and to S. Marsh and S. Sgobba for microscopic analyses. Technical support from the RF/SL, LHC/CR and EST/SM groups is gratefully acknowledged. We enjoyed many fruitful discussions with E. Haebel.

5. REFERENCES

1. C. Benvenuti, S. Calatroni, I.E. Campisi, P. Darriulat, M.A. Peck, R. Russo, A.-M. Valente, Study of the surface resistance of superconducting niobium films at 1.5 GHz, submitted for publication in Physica C.
2. K. Huebner, LEP2, present and future performance and limitations, these proceedings, and references therein.
3. D.C. Mattis and J. Bardeen, Phys. Rev. 111 (1958) 412; A.A. Abrikosov, L.P. Gor’kov and I.M. Khalatnikov, JETP 35 (1958) 265 (russian ed.) and 35 (1959) 182 (US ed.); J. Halbritter, Z. Phys. 266 (1974) 209 and Ext. Bericht 3/70-6, Kernforschungzentrum Karlsruhe, Germany, June 1970.
4. B. Bonin and H. Safa, Supercond. Sc. Techn. 4 (1991) 257; C. Attanasio, L. Maritato and R. Vaglio, Phys. Rev. B43 (1991) 6128 and IEEE Trans. Mag. 27 (1991) 1920