Superconducting Niobium Sputter-Coated Copper Cavities at 1500 MHz

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Abstract

Tests of single-cell, hydroformed, 1500 MHz Nb sputter coated Cu cavities were continued. Emphasis was placed on techniques to reduce field emission electron loading, which is currently the principal obstacle to obtaining higher accelerating gradients in the superconducting cavities used in LEP. Q-values exceeding 10^{10} and accelerating gradients of 14 MV/m were obtained after high-pressure water rinsing. DC magnetic fields were used as a diagnostical tool to study features of the Nb coating.

1. INTRODUCTION

In this paper we will give a follow up of the work done conjointly at CERN and CEN-Saclay on Nb sputter-coated Cu (Nb/Cu) cavities at 1500 MHz. Details of the earlier work may be found in ref. 1. Other results on Nb/Cu cavities at CERN and Saclay are given elsewhere [2–5].

Here we have done work concentrated on two aspects of these cavities. First we report on high pressure water rinsing (HPWR), which is shown to improve cavity performance (electron-loading, residual resistance, and non quadratic magnetic RF losses, NQL). The second aspect concerns the problem of NQL. We have measured the dependence of these losses on temperature as well as on frequency.

2. EXPERIMENTAL

We performed RF tests on the same set of cavities as in ref. 1 (table 1).

Table 1 RF tests performed in the fundamental mode at 1.8 K.

Cavity #	$Q(E_a \to 0)[10^9]$	$Q(E_a \to 0)[10^9]$4.2K	E_{amax} [MV/m]	Onset e^- [MV/m]	$\alpha G/Q_0$[a] 4.2K [nΩ/mT]	$\alpha G/Q_0$ [nΩ/mT]	Remarks
A1	10	.7	5.8	4	24	2	e^-
HPWR[b]	20	.63	14	14	6.1	.7	
A2	2	.64	3.2	2	13	4	e^-, Q degraded
HPWR	5.3	.6	7.5	6	8.0	2.4	
B1	8	.6	5.5	–	30	8	Q-switch[c]
HPWR	2.8	.54	5.9	–	16	10	
B2	10	.64	2.4	–	70	54	Q-switch, e^-
HPWR	–	–	–	–	–	–	not tested
B3	6	.5	4.0	–	54	30	Q-switch
HPWR	2.5	.5	4.5	–	33	2.7	
B4	2	.52	3.7	–	53	25	(Accidental) Fe
HPWR	.4	.27	3.3	–	–	–	layer underneath Nb

a) $\alpha G/Q_0$ describes the non quadratic magnetic RF losses [2] from the parametrization $Q = Q_0 \exp(-\alpha B_p)$. G = 295 Ω. B_p is the peak magnetic RF field amplitude.
b) High-Pressure Water Rinsing.
c) A "Q-switch" is a sudden decrease of Q-value caused by a s.c. normal phase transition (by, for example, a Nb blister of poor thermal contact to the copper underneath).

After the first RF test (after rinsing with ultrapure 18 MΩcm deionized (DI) water under atmospheric pressure) the cavities were prepared for rinsing with ultrapure 18 MΩcm DI water under 100 bar (HPWR): in a class 100 clean room the sealed cavity (equipped with an all metal valve) is vented to air. The antennae for RF input and RF pickup are disconnected and the rinsing cane is mounted. It has eight cylindrically shaped orifices of 0.8 mm diameter to supply the water jet. The cavity is transported to the HPWR premises well sealed off from the outside atmosphere.

The HPWR installation is served by a sandwich PTFE membrane pump with hydraulic actuation (flow rate max. 30 ℓ/min) delivering a pressure of 100 bar. The water is passed through a filter (pore size 0.08 μm) at the point of use and where it enters the valve of the cane. During rinsing the flow is approximately 10 ℓ per hour per orifice, in total 80 ℓ per hour. Rinsing with water is performed for about half an hour upon which the water is replaced by ethanol for several minutes. Ethanol is used to avoid drying stains and to accelerate drying.

After rinsing, the cavity is dried under laminar air flow, the antennae are remounted, the cavity closed and ready for being assembled with the vacuum system for the RF test.

One cavity (#A1), after HPWR, was exposed to a DC magnetic field during cooldown. This field was generated by a solenoidal coil of 30 cm length and 20 cm outer diameter, the axis of which coincided with the cavity axis. For 3 A excitation current, the field was 6 mT (3 W power dissipation in leads and coil at 4.2 K) .

The upper critical magnetic field B_{c2} of sputter coated samples was measured as well. The experiment consists of two planar coils, with the sample in between, placed into a magnetic field B<3 T parallel to the sample. The conductivity of the sample is probed by measuring the mutual inductance (at low frequency).

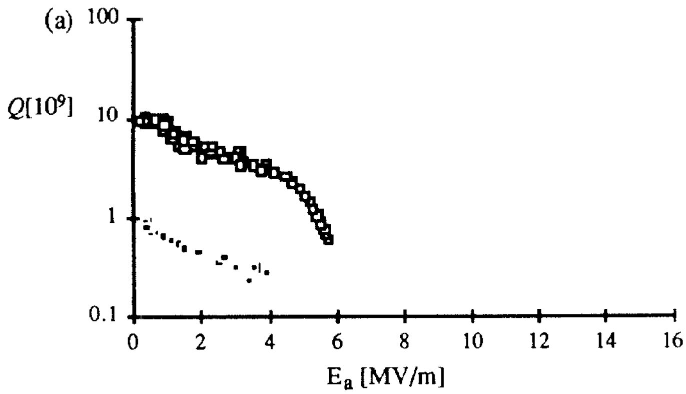

Figure 1. Q-value vs accelerating field for the fundamental mode at 4.2 K (lower) and 1.6 K (upper), a) before and b) after high-pressure water rinsing.

3. DISCUSSION

3.1 High-pressure water rinsing

HPWR is a method used for cleaning in the semiconductor industry [6]. As with ultrasonic cleaning, it loosens the forces between surface and contaminating layer, which is removed by the water. The Nb coating withstands the HPWR, which proves its good adhesion. We conclude from table 1, that whenever we applied HPWR, electron loading and NQL were reduced. The residual losses were reduced as well, if one takes into consideration only cavities without surface flaws (Q-switch). If not, it increased, probably uncovering the copper underneath (we saw Nb debris in the drain water). In a 500 MHz Nb/Cu cavity we observed a reduction of the residual losses from 20 to 5 nΩ as well after HPWR. However, as different water is used in the installations for rinsing, we still have to confirm that it is the high pressure and no other hidden quantity which improved the performance of the cavity.

3.2 DC magnetic field induced RF losses

A series of measurements were performed in which one of the six cavities was cooled in an axial DC external magnetic field B_{ext}, which ranged from 0.1 to 6.0 mT. The residual magnetic field in the absence of current is in the order of 3 μT and hence negligible. The results are plotted in fig. 2. This plot appears to present two roughly linear ranges with significantly different slopes. At 1.8 K, up to a field of approximately 0.3 mT, $R_s = (64\ n\Omega/mT)\cdot B_{ext} + R_{res}$, while for the higher applied fields $R_s = (130\ n\Omega/mT)\cdot B_{ext} + R_{res}$. These results should be compared with values reported for solid Nb cavities for which this slope is much larger, approximately 5000 nΩ/mT [2].

We present here a simple model which we believe explains these results. If a fraction f of the flux is trapped (f is near unity [2]) into n vortices per unit area each containing one flux quantum $\Phi_0 = 2\cdot 10^{-15}$ Tm^2,

$$f \cdot B_{ext} = n\Phi_0. \tag{1}$$

The flux quantum has a normal conducting core of radius equal to the coherence length ξ. The average surface resistance $\langle R_s{}^m \rangle$ is then the product of the number n of flux quanta per unit area, their area $\pi\xi^2$, and the normal conducting surface resistance $R_s{}^n$,

$$\langle R_s{}^m \rangle \approx n(\pi\xi^2)R_s{}^n \approx (f \cdot B_{ext}/\Phi_0)(\pi\xi^2)R_s{}^n. \tag{2}$$

With the penetration depth λ and the Ginzburg-Landau parameter $\kappa = \lambda/\xi$,

$$\langle R_s{}^m \rangle \approx (f \cdot B_{ext}/\Phi_0)(\pi\lambda^2(T)/\kappa^2)R_s{}^n. \tag{3}$$

The temperature dependence ($\xi \ll \lambda$) [7] is given by ($T<T_c$)

$$\lambda^2(T) = \lambda_0{}^2/(1 - (T/T_c)),\ \lambda(0) = \lambda_0. \tag{4}$$

We used equation (3) to estimate κ in the two different linear ranges at 1.8K. With $\lambda \approx 32$ nm [8], $R_s{}^n \approx 7$ mΩ (10 K), we obtain $\kappa \approx 20$ for $B_{ext} < 0.3$ mT, and $\kappa \approx 10$ for $B_{ext} > 0.3$ mT.

For Nb bulk, we obtain $\kappa \approx 1.6$ (demonstrating the validity of our approach, as we would expect $\kappa \approx 0.9 - 1.6$ [9]). The corresponding coherence lengths are $\xi \approx 1.7$, $\xi \approx 3.5$ and $\xi \approx 20$ nm for bulk Nb, respectively.

The critical magnetic field at 4.2 K for the sputter-coated samples is $B_{c2} \approx 1.5$ T, much larger than for bulk Nb ($B_{c2} \approx B_c \approx 0.2$T) with a transition width of 1 T. This is another argument in favour of $\kappa \approx 10$, as $B_{c2} \approx \kappa B_c$.

We can estimate the coverage c of the surface corresponding to the largest $\kappa \approx 20$. We expect that at the transition ($B_1 = 0.3$ mT) the corresponding surface is normal conducting and exposed to $B_{c2} \approx \kappa B_c \approx 4$ T. Hence, $c = B_1/B_{c2} \approx 0.3$ mT/4 T $\approx 10^{-4}$, and islands with $\kappa \approx 20$ are embedded in Nb with lower κ.

This is consistent with the observation that the surface resistance in the normalconducting state at low temperature (7 mΩ) as well as the residual resistivity ratio RRR (15) are equal to that of commercial reactor grade Nb.

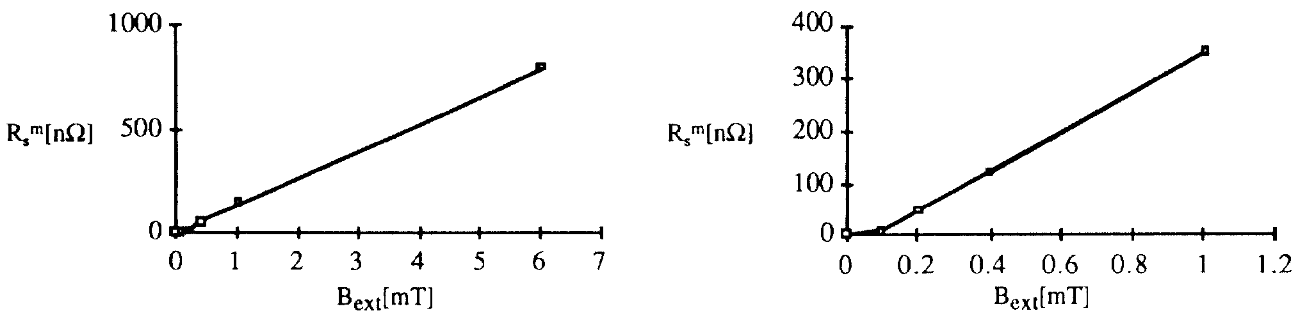

Figure 2. $\langle R_s^m \rangle$ is the difference of the surface resistance with nonzero and with zero DC magnetic field to which the cavity is exposed during cooldown, (a) 1.8 K and (b) 4.2 K.

3.3 Non-quadratic magnetic RF losses (NQL)

Non quadratic RF losses follow the RF amplitude with a power law larger than 2. They can have different origin, e.g. electron loading by field emission or multipactor, or of magnetic nature.

We concentrated on RF losses giving the approximate exponential decrease of *Q* vs RF field amplitude often observed in Nb/Cu cavities. It can be shown to be of magnetic origin [2]. We tacitely assume the same for the 1500 MHz cavity under study.

A convenient parameter to describe the NQL is the local surface resistance R_s at a given local magnetic field amplitude B. Experimentally, however, we determine the average surface resistance from the *Q*-value: $\langle R_s \rangle = G/Q$ (geometry factor G = 295 Ω). We convinced ourselves, that within the error of measurement (± 10%) the local surface resistance R_s where the magnetic field has its maximum value B_p (at the equator for the accelerating mode) is identical with the average surface resistance $\langle R_s \rangle$ at B_p.

The NQL (measured in nΩ/mT) were extracted from the slope (which we call R_s') of the linear range of the $\langle R_s \rangle$ vs B_p curve ($0 < B_p < 5 - 20$ mT). R_s' was measured for different modes at 1.5 GHz and 2.8 GHz (quadrupole mode) in the same cavity and in two different cavities at 0.5 [2] and 1.5 GHz vs the cavity wall temperature, fig. 3 (a) and (b).

The frequency dependence of R_s', if there is any, seems very small ($R_s' \sim \omega^n$, $n < 0.2$). R_s' appears to be proportional to $1/(1 - T_b/T^*)$ with $T^* = 7$ and 4 K, $T_b < T^*$. We conclude that NQL are sensitive to surface condition, as they are reduced by HPWR.

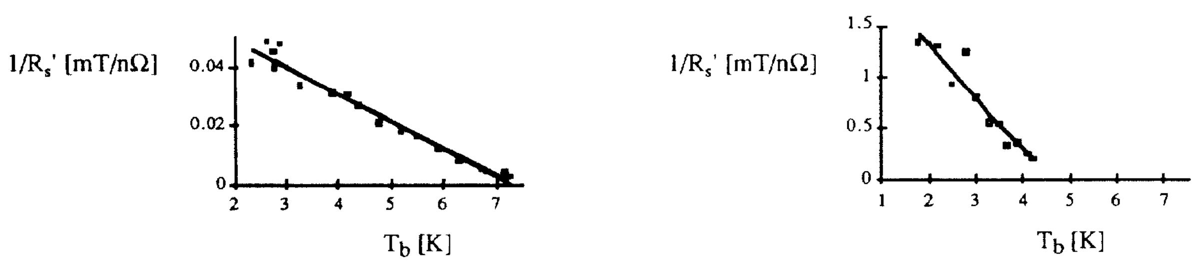

Figure 3. Inverse of non quadratic RF losses R_s' (measured in mT/nΩ) vs bath temperature T_b (or cavity wall temperature for $T_b > 4.2$ K) for (a) 500 MHz cavity and (b) 1500 MHz cavity (#A1).

4. CONCLUSION

We have obtained more documentary evidence that HPWR reduces residual losses, non quadratic magnetic RF losses and electron loading. We used a DC magnetic field as a diagnostical tool to probe the surface of Nb/Cu cavities. Their low sensitivity to trapped DC magnetic flux can be understood in terms of weak superconducting islands with increased Ginzburg-Landau parameter $\kappa > 20$, covering a fraction 10^{-4} of the surface. Non quadratic magnetic RF losses are sensitive to surface condition.

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