CERN/AT–RF 91–26
16 October 1991

SUPERCONDUCTING NIOBIUM SPUTTER-COATED COPPER CAVITIES AT 1500 MHz

Ph. Bernard, D. Bloess, W. Hartung(*), C. Hauviller and W. Weingarten
CERN, Geneva, Switzerland

P. Bosland and J. Martignac
CEN Saclay, Gif-sur-Yvette, France

Abstract

A series of copper single-cell cavities were fabricated by hydroforming and sputter coated with Nb. The cavity could be excited both in the fundamental mode at 1500 MHz and in higher-order-modes at 2.5 GHz and 2.8 GHz (quadrupole modes) with low losses in the end flanges. The first results are the following: the lowest residual surface resistance at 1500 MHz was 10 nΩ. It increased quadratically with the frequency. The fundamental low field Q value at 1.8 K was 3×10^{10} decreasing to 1×10^{9} at the accelerating gradient of 14 MV/m, the maximum gradient obtained.

Presented at the 5th Workshop on RF Superconductivity,
19–23 August 1991, DESY, Hamburg.

(*) On leave of absence from the Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853, USA.

1. INTRODUCTION

The CERN LEP collider is being upgraded to 200 GeV center-of-mass energy by the installation of additional superconducting (s.c.) cavities (LEP 200 [1]). The majority of these (160) will be made of Cu-sheet sputter-coated with Nb (Nb/Cu cavities). Sufficient experience with the fabrication of such cavities and their operation in an accelerator has been gathered for performance up to gradients of 5 to 6 MV/m [2, 3], but the potential for improvement is a strong incentive for further research.

A prerequisite to further improvement is a detailed understanding of the radio-frequency (RF) properties of the coating. It is certainly true that extending the parameter space, for example to higher frequencies, may give more and deeper insight. We have extended data on Nb/Cu cavities available at CERN at 350 and 500 MHz [4] to higher frequencies, 1.5 GHz, 2.5 GHz and 2.8 GHz, by using experience and existing equipment for sputter deposition at Saclay [5]. An additional reason for choosing higher frequencies is that the smaller cavities and cryostats allow a faster turnover for RF measurements. Furthermore, cavities in the 1–3 GHz frequency range have attained increased attention for very high energy superconducting linear colliders. At the first TESLA Workshop [6], a principal aim was to study hydroforming of copper cavities (low cost mass production) with a thin layer of Nb (offering potential for high fields at high Q values thanks to the high thermal conductivity of Cu). Apart from Saclay, too, other laboratories have studied Nb/Cu cavities at 1.5 GHz [7, 8].

The questions we have asked and started to attack concerning Nb/Cu cavities are:

- Is hydroforming a feasible method for cavity mass production?
- How does the residual surface resistance depend on frequency?
- Why are these cavities insensitive to small static magnetic fields [9]?
- How can electron loading be suppressed or reduced (high-pressure water rinsing, very thin metallic layers on top the Nb metal)?
- Can high-accelerating gradients be reproducibly obtained in a multicell Nb/Cu structure at 1.5 GHz?

In this paper we give a status report on the work done so far.

2. FABRICATION OF CAVITIES

2.1 Hydroforming

The cavities were hydroformed, which avoids welds and allows low-cost production of large quantities. The starting material was a 86 mm external diameter OFE (oxygen free electrolytic) copper tube of a wall thickness varying between 2.5 and 3 mm and a length of ~ 500 mm. The cavity was produced by a series of expansion phases with intermediate annealing at a temperature between 500°C and 600°C. The final cavity shape is shown in fig. 1. Details may be found elsewhere [10]. The resulting wall thicknesses after the process are 1.05 mm at the equator and 2 mm at the iris.

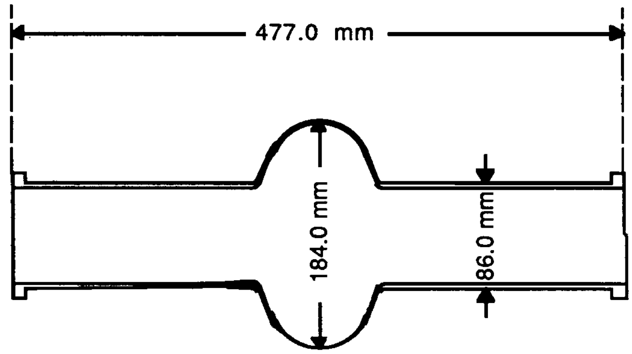

Fig. 1 Geometry of the 1500 MHz cavities. Outer diameters are indicated.

The mechanical reproducibility is good, the frequency dispersion $\Delta f/f$ at room temperature being 3×10^{-3}, 1×10^{-3} and 0.3×10^{-3} in the TE_{111}, TM_{110} and TM_{010} mode, respectively (in the TM_{010} mode at 1.8 K $\Delta f/f = 1.5 \times 10^{-3}$). Sometimes, tiny holes (a fraction of a millimetre diameter) opened up after chemical polishing (see below). Thereupon, the affected part of the surface was ground (emery paper), and the cavity was again chemically polished. The origin of these holes is presently not clear; it is suspected that they might be caused by the the segregation of hydrogen forming bubbles at the chosen annealing temperature of 500°C.

2.2 Processing of the cavity

The sequence of cavity processing after hydroforming is summarized in table 1.

Table 1 Sequence of cavity processing after hydroforming

1	EB-welding Cu beam tube flange, leak test.	9	Transport to Saclay.
2	Degreasing.	10	Sputter coating (see below).
3	CP (40 μm)[(a)] and rinsing (sulfamic acid).	11	Mounting[(b)] of flanges and valve for transport, evacuation and venting with filtered N_2.
4	Inspection and grinding of holes, if necessary.	12	Transport to CERN.
5	3 to 4 are repeated, if grinding was done.	13	Mounting of flanges, In joints, UHV valve, RF antenna and rod for rinsing.
6	Rinsing with ultrapure high-pressure water and ethanol.	14	Rinsing with ultrapure water [(c)].
7	Dustfree transport and drying[(b)].	15	Mounting[(b)] of RF antenna, pump drying (50°C).
8	Mounting[(b)] of flanges and valve for transport, evacuation and venting with filtered N_2.	16	Transport to lab with closed valve, assembling to cryostat insert and evacuation to ~ 10^{-7} mbar for RF test.

(a) CP = Chemical polishing (sulfamic acid, n-butanol, hydrogen peroxide, ammonium citrate).
(b) Under laminar air flow of class 100 or better.
(c) Resistivity 18 MΩcm at inlet, up till 17 MΩcm at outlet at the end of the rinsing, 100 ℓ, 0.2 μm dust filter at point of use, TOC ~ 5–20 ppb, < 5 particles (> .2 μm) per milliliter.

2.3 Sputter coating

Niobium films were deposited by DC magnetron sputtering using a cylindrical post cathode developed at Saclay, which is very similar to the cathode used at CERN for the LEP s.c. cavities [11].

The target, made of high purity Nb (*RRR* = 150), is 2 cm in diameter with 2 mm wall thickness. A permanent magnet, 4 cm long, cooled by flowing freon, produces a 20 mT magnetic field at the cathode surface. The sputtering facility is equipped with a turbomolecular pump (180 ℓ/s) and a primary pump (30 m^3/h). High purity (99.9995%) Ar gas flow is regulated with a mass flowmeter.

Prior to cavity coating we have investigated Nb films produced in a vacuum vessel, which was placed on the sputtering facility at the cavity's position. The critical temperature T_c and the residual resistivity ratio *RRR* were measured by the four-point resistive method. The best values obtained were $T_c = (9.2 \pm .1)$ [K] with *RRR* = 20. The thickness measurements were made with a Taly-step gauge. A typical deposition rate is ~ 7 Å/s for a power of 0.7 kW at the equatorial position of the cell. On the sides of the cell the deposition rate is ~ 15% lower. No measurements of the film thickness have been made at the iris position.

For the cavity coating, the cathode is mounted inside the cavity under clean air of a class better than 100 (except for the first two coatings). This ensemble is then mounted on the sputtering facility and baked at 150–200°C during the pump down. The residual pressure before deposition was ~ 3×10^{-7} mbar. In order to obtain a homogeneous thickness of the Nb film, the cavities were coated in 9 steps: the first discharges were done in the two beam tubes of the cavity. Contaminating gas is thus preferentially gettered in that region, which is exposed to small RF fields, and is hence less harmful (residual pressure after the complete deposition is lower than 10^{-8} mbar). For this procedure, the magnet was moved inside the fixed Nb cathode to displace the dense region of the glow discharge.

The sputtering parameters used for each cavity (discharge in the cell) are presented in table 2. The thickness of the deposit at the equator of the cell is ~ 5 μm for all cavities.

Table 2 Coating parameters

	p [mTorr]	–V [V]	I [A]	T of cavity during coating [°C]
Cavity A1	6×10^{-3}	360	1.5	150
Cavity A2	6×10^{-3}	350	1.5	150
Cavity B1	6×10^{-3}	320	2.5	200
Cavity B2	3×10^{-3}	390	1.5	150
Cavity B3	3×10^{-3}	390	1.5	150
Cavity B4	3×10^{-3}	380	1.5	150

3. RADIO-FREQUENCY TESTS

The computer codes SUPERFISH [12] and URMEL [13] were used to compute the characteristic RF properties of the cavity (table 3). For the monopole modes the result from SUPERFISH is quoted.

Table 3 Radio-frequency properties of the cavity

Mode	f [MHz]	Decay length [mm](a)	$E_p^2/(\omega U)$ [10^3 Ω/m^2]	H_p/E_p [mT/(MV/m)]	G [Ω]
TM_{010}	1499	19.5	31.2	2.41	295
TM_{011}	2660	44.5	10.2	4.29	456
TM_{110}	2038	58.4	58.6	4.17	297
TE_{111}	1755	36.1	38.3	6.63	333
TM_{210}	2782	20.3	30.5	3.75	442
TE_{211}	2492	18.0	11.5	6.60	481

(a) The decay length is the geometric length in beam tube upon which the field decays to 1/e (calculated analytically). $R/Q = 82\ \Omega$, $E_p/E_a = 1.95$ (fundamental mode), E_p (H_p) = peak surface electric (magnetic) field, E_a = accelerating field, G = geometry factor and U = stored energy.

As can be seen from table 3, the TM_{210} and the TE_{211} modes are good candidates to probe the surface resistance at higher frequencies than the fundamental mode. The RF losses in the end flanges made from Cu are virtually the same as in the fundamental mode, because the decay length in the beam tube is the same. For a beam tube length of 17 cm, the Q-values equivalent to these losses are estimated to be 3×10^{11} for the two modes.

Each cavity test was started with a measurement of the Q value at 4.2 K with increasing accelerating field (fig. 2(a)). Then, the He temperature was lowered by pumping on the He bath, and the Q value (average surface resistance, respectively) at low RF field was measured in the fundamental mode (figs 3 and 4).

Upon obtaining the lowest possible temperature (1.5 to 1.8 K), the Q-value was measured again with increasing accelerating field (fig. 2(a)). Then, the He bath was heated up to 4.2 K, the cryostat filled up again with liquid He, and a similar sequence was performed for one or several higher-order-modes (fig. 4).

We applied high-pressure water rinsing after the coating, too. Before, the cavity (A1) had exhibited electron loading (fig. 2(a)). We did not try to do hard processing, but rinsed the cavity with 100 bar ultrapure high-pressure water. The residual Q value and the maximum accelerating gradient went up by a factor 2 (fig. 2(b)), and the slope of the Q vs E_a curve became significantly lower. The RF tests conducted up till now are summarized in table 4.

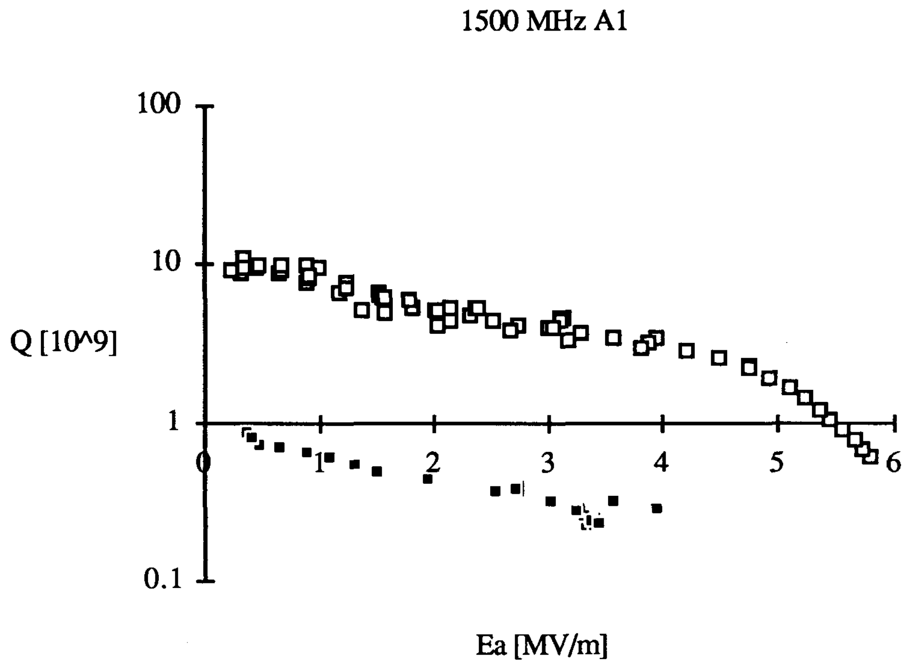

Fig. 2(a) Q value vs accelerating field for the fundamental mode at 4.2 K (lower) and 1.6 K (upper).

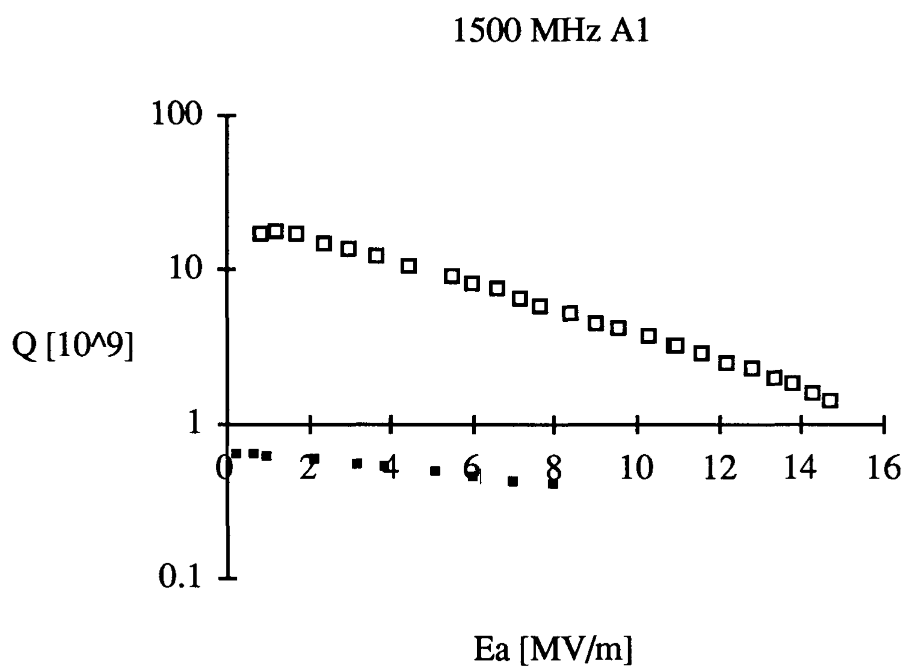

Fig. 2(b) Q value vs accelerating field for the fundamental mode at 1.6 K after high-pressure water rinsing at 4.2 K (lower) and 1.6 K (upper).

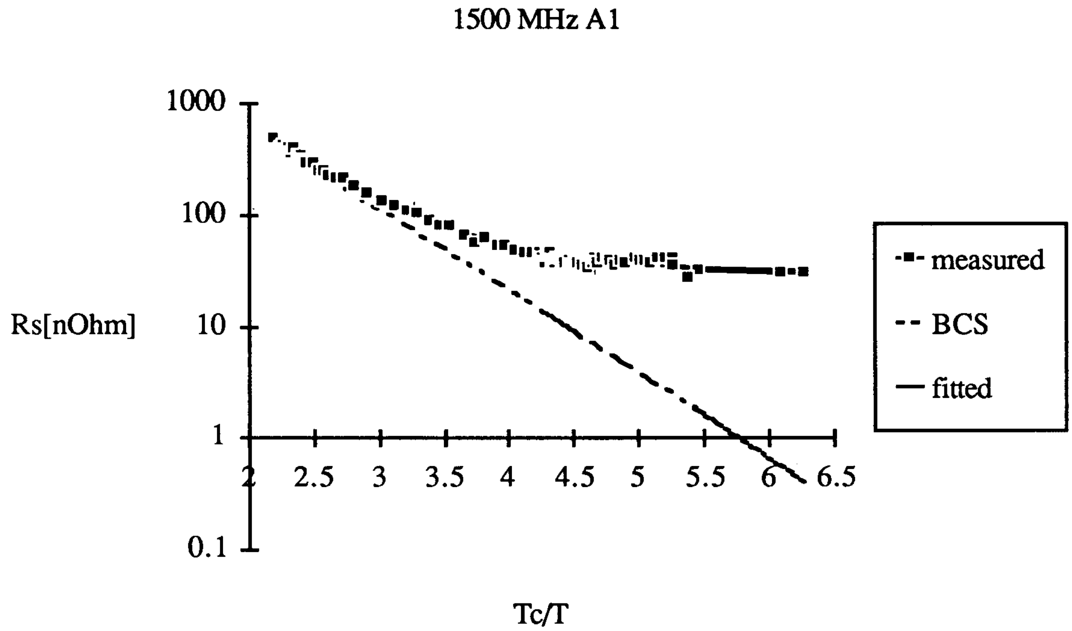

Fig. 3 The surface resistance R_S (cavity A1) vs T_c/T for the fundamental mode at 1504 MHz. T_c is assumed to be the same as measured for the samples (9.2 K). Also shown are a least square fit (A = 122 000 nΩK, Δ' = 1.94, R_{res} = 32 nΩ) and the BCS part of R_S.

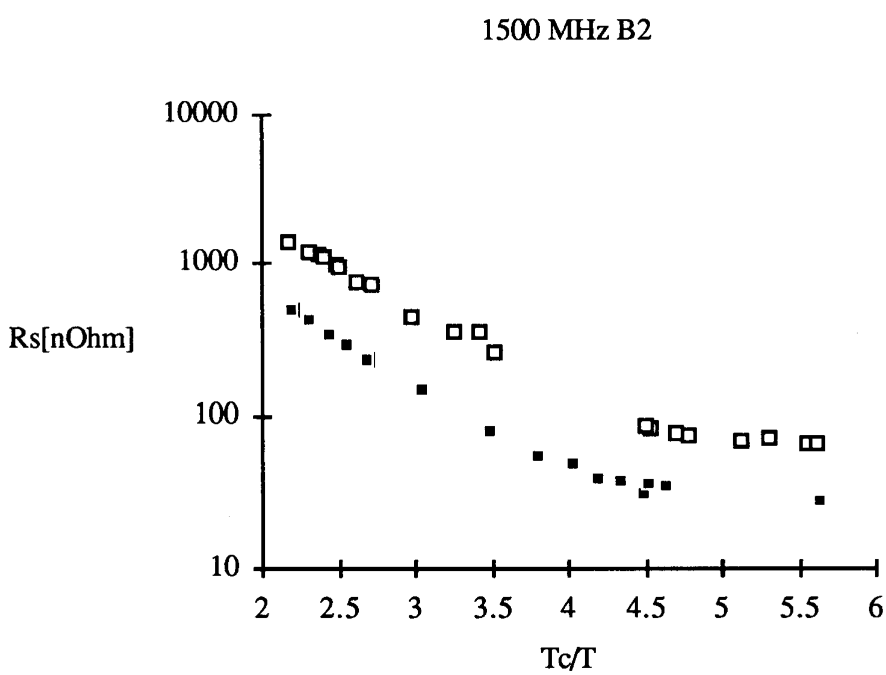

Fig. 4 The surface resistance vs T_c/T for the fundamental mode at 1504 MHz (lower) and the TE_{211} mode at 2490 MHz (upper). T_c is assumed to be the same as measured for the samples (9.2 K).

Table 4 Radio-frequency tests performed in the fundamental mode at 1.8 K

	f [MHz]	$Q(E_a \to 0)[10^9]$	Q(5 MV/m)$[10^9]$	E_{amax} [MV/m]	Remarks
Cavity A1	1503.385	10	2	5.8	e^-
dto.(HPWR)[(a)]		20	2	14	e^-
Cavity A2	1503.412	2		3.2	e^-, Q degraded
Cavity B1	1504.088	8	.5	5.5	Q switch[(b)]
Cavity B2	1503.996	10		2.4	Q switch, e^-
Cavity B3	1501.845	6		4.0	Q switch
Cavity B4	not yet tested				

(a) High-pressure water rinsing.
(b) 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).

4. DISCUSSION

The RF surface losses in a superconductor and hence the surface resistance consist of different contributions. These are, for example, the well-known BCS surface resistance $R_S^{BCS} = (A/T)\exp(-\Delta' \times T_c/T)$, the temperature-independent residual surface resistance R_{res}, and the RF field-dependent surface resistance, which may or may not be temperature dependent. The latter is observed with Nb/Cu cavities (but also in sputter-coated NbN, (NbTi)N [14] and high T_c materials [15], and, though less pronounced in Nb sheet metal) and prevents, among other mechanisms, to obtain high fields at high Q-values.

The data for the surface resistance R_S, measured in nΩ, as a function of the temperature T, measured in K, are fitted with the usual ansatz $R_S = (A/T)\exp(-\Delta' \times T_c/T) + R_{res}$, $T_c = 9.2$ K (fig. 3). The reduced energy gap Δ' is quite similar to that of Nb sheet metal, $\Delta' = 1.94$. The factor A was determined to $(1.3 \pm .1) \times 10^5$ [nΩK]. This is about a factor of 2 lower than for commercially available Nb of $RRR = 40$. That is what is expected, as A is proportional to the conductivity of the normal-conducting electrons, and hence the RRR, being lower by about a factor of 2 for the sputter-coated cavities.

We used Halbritter's program [16] to compute the BCS surface resistance. With the parameter set $\Delta' = 1.94$, λ (penetration depth) = 360 Å, ξ (coherence length) = 640 Å, and l (electron mean free path) = 250 Å, the BCS surface resistance at 1.6 K is 1 nΩ, which corresponds to the experimentally obtained value.

Up till now, the origin of the residual resistance R_{res} in s.c. cavities is only partially understood. One open question is how R_{res} depends on the frequency f. We have analyzed our data (table 5) under the hypothesis of a power law, $R_{res} \sim f^{\alpha}$, determined α for each coating by a linear fit of $\log R_{res}$ vs $\log f$, and calculated the average value. The result is $\langle\alpha\rangle = 2.0 \pm 0.3$. It is compatible with a quadratic power law $R_{res} \sim f^2$, which is expected for resistive losses in a superconductor [17] (for example a thin normal-metal surface layer or grain boundaries). A similar power law was also observed in bulk Nb cavities [18].

The lowest residual surface resistance was obtained after high-pressure water rinsing (Cav. A1, $R_{res} = 10 \pm 3$ nΩ).

We did not do so far a detailed analysis of our data with regard to the field dependence of the surface resistance. We can state, nevertheless, that the surface resistance at the lowest temperatures (1.7 K) increases about linearly with RF amplitude, already observed for 500 and 350 MHz Nb/Cu cavities [9].

Table 5 The residual resistance [nΩ] in three distinct modes

	TM_{010} (1504 MHz)	TE_{211} (2490 MHz)(a)	TM_{210} (2790 MHz)(a)
Cavity A1	32 ± 8	140 ± 7(b) 155 ± 7(b)	65 ± 20
Cavity A2	170 ± 9	300 ± 15(b)	550 ± 25 580 ± 25
Cavity B1	55 ± 15	190 ± 10 160 ± 20(b)	
Cavity B2	26 ± 10	120 ± 30	65 ± 25
Cavity B3	50 ± 10	220 ± 11(b)	200 ± 20
Cavity B4	—	—	—

(a) Two polarizations.
(b) Measured at higher field.

5. CONCLUSION

Hydroforming is feasible at 1500 MHz. The origin of occasionally-created holes after chemical polishing needs to be understood in more detail.

Low field residual Q values of 2×10^{10} and maximum accelerating fields of 14 MV/m at a Q value of 1×10^9 can be obtained. We obtained a significant improvement of the Q value and accelerating field after high-pressure water rinsing, which needs to be confirmed by further experiments.

The residual surface resistance (at low RF field) of a a sputter-coated Nb layer was 10 ± 3 nΩ at 1500 MHz. Probing it in different higher-order cavity modes we found an increase as $R_{res} \sim f^{2.0 \pm 0.3}$.

Acknowledgements

We thank our colleagues from CERN, in particular E. Chiaveri for his untiring help, and C. Dalmas for his competent setting up of the RF system, M. Candolfi, G. Genest, A. Insomby, R. Jaggi, M. Kubly, A. Lasserre and H. Preis.

REFERENCES

[1] G. Cavallari et al., Laboratory report (this workshop).

[2] C. Arnaud et al., proc. 2nd Europ. Part. Acc. Conf., eds P. Marin and P. Mandrillon, Nice, France (1990) 152.

[3] C. Benvenuti et al., proc. IEEE Part. Acc. Conf., San Francisco, CA, USA (1991), to be published.

[4] C. Benvenuti (this workshop).

[5] B. Aune et al., proc. 4th Workshop on RF Superconductivity, KEK, Tsukuba, Japan, ed. Y. Kojima (1989) 97.

[6] J. Kirchgessner, proc. 1st TESLA Workshop, Cornell Univ., Ithaca, NY, USA, ed. H. Padamsee (1990) 369.

[7] G. Arnolds-Mayer et al., proc. 1st Europ. Part. Acc. Conf., Rome, Italy, ed. S. Tazzari (1988) 1187.

[8] G.C. Gualco et al., proc. IEEE Part. Acc. Conf., San Francisco, CA, USA (1991), to be published.

[9] G. Arnolds-Mayer and W. Weingarten, IEEE Trans. Magn. MAG–23 (1987) 1620.

[10] C. Hauviller, proc. IEEE Part. Acc. Conf., Chicago, Ill., USA (1989) 1485.

[11] C. Benvenuti et al., proc. 4th Workshop on RF Superconductivity, KEK, Tsukuba, Japan, ed. Y. Kojima (1989) 869.

[12] K. Halbach and R.F. Holsinger, Part. Accelerators 7 (1976) 213.

[13] T. Weiland, DESY 82–015 and DESY M–82–24.

[14] C. Benvenuti et al. (this workshop).

[15] S.M. Rezende and F.M. de Aguiar, Phys. Rev. B39 (1989) 9715.

[16] J. Halbritter, Zeitschr. für Physik C 238 (1970) 466.

[17] J.P. Carini et al., Phys. Rev. B37 (1988) 9726.

[18] P. Kneisel, private communication.