Superconducting Niobium Sputter-coated Copper Cavity Modules for the LEP Energy Upgrade

C. Benvenuti, P. Bernard, D. Bloess, G. Cavallari, E. Chiaveri, E. Haebel,
N. Hilleret, J. Tückmantel and W. Weingarten
CERN — European Organization for Nuclear Research
CH-1211 Geneva 23 (Switzerland)

Abstract

Experience from the construction, assembly, and tests of two superconducting (s.c.) cavity modules for LEP are given. Each module consists of four individual four-cell 352 MHz Nb sputter-coated Cu cavities equipped with an RF power coupler, higher-order-mode (HOM) dampers and frequency tuner, housed in a single cryostat. The demountable HOM dampers of a new type designed for sputter-coated cavities allow Q_{ext} of 9000 for the HOMs with the largest (R/Q). Q values are higher (4.5 to 11 • 10^9) than those for similar Nb sheet cavities up to the maximum accelerating fields obtained (6 to 9.5 MV/m). The field limitation is electron loading and never thermal breakdown. Results on vertical tests of individual cavities are reported (Q value, maximum accelerating fields, residual resistance). They are complemented by results on horizontal tests of individual cavities, and on the fully equipped klystron-driven four-cavity module.

I. INTRODUCTION

The first s.c. cavity module for the LEP energy upgrade [1] to centre of mass energies of 200 GeV "LEP 200" has been installed in the first shutdown of LEP in winter 1990 [2]. This module consists of four individual four-cell cavities mounted in one common cryostat. The cavities are made of "cavity grade" Nb sheet. However, for reasons of higher thermal conductivity and reduction of material costs an alternative solution has been pursued at CERN from the beginning: thin Nb films deposited on a Cu cavity body as substrate [3] (Nb/Cu cavities). This technology has been mastered, and in addition offers inherent advantages not anticipated. Thermal breakdown (quench) from tiny normal conducting defects is absent thanks to the large thermal conductivity of the OFHC–Cu used (400 to 500 W/(mK)). Shielding against static magnetic fields of the same order of magnitude as the earth's magnetic field is unnecessary [4], significantly alleviating the task to obtain high Q values in an accelerator environment. A twin module of two Nb/Cu cavities [5] has successfully been operated in the SPS accelerator. What remains to be shown is the feasibility of an industrial production of such cavities. Therefore, CERN has launched a series production of a small number of Nb/Cu cavities in house. Eight of them have been assembled into two modules to complement the first one from Nb sheet. One is already installed in LEP, the second one is due for installation in a short summer shutdown, raising the total installed s.c. RF voltage up to the designed 102 MV.

II. FABRICATION AND SURFACE PROCESSING

The beam tubes are rolled, longitudinally electron beam (EB) welded, ball extruded to give way to the power and HOM coupler holes. The cavity half cells are produced by lathe spinning. The beam tubes as well as the half cells are degreased, ground, if necessary, electropolished (40 µm, phosphoric acid, n-butanol), and rinsed with water. Conflat type flanges are brazed to the coupler and beam tube ports. All parts are joined by EB welding. The whole cavity is degreased, filled with sulfamic acid, chemically polished (20 µm, sulfamic acid, n-butanol, hydrogen peroxide, and ammonium citrate), rinsed with sulfamic acid, water, and alcohol, and dried under clean laminar air flow. The magnetron cathode is mounted in a class 100 clean room. This is what we call a standard process. The sputtering is performed by stepwise powering different electromagnets inside the cathode. Other details can be found elsewhere [6]. The magnetron is removed in the clean room, the cavity equipped with RF input and pick-up antennas, closed, and rinsed with ultrapure water (18 MΩ cm) from a moving PVC tube. The resistivities of the inlet and outlet water are recorded. Presently, we also monitor the TOC (total organic carbon), particle content (> .1 µm), and at regular intervals the bacteria content of the water plant. After drying by pumping, the cavity is vented with filtered (.2 µm pore size) dry nitrogen gas, mounted on the cover of the vertical cryostat, evacuated and cooled down for the RF tests (table 1).

Table 1
RF tests on Nb/Cu LEP type cavities (only the last coating is listed)

Cavity #	Coating #	Treatment	$Q(E_a = 0)$ $[10^9]$	$E_{a\,max}$ [MV/m]	# Hot spots(a)
45	4	SV	7.5	4.6	0
46	3	SCV	7.0	5.4	0
		WRV	7.1	6.7	
		H	4.9	5.5	
47	2	SCV	12.	8.1	1
		H	7.0	2.8	
		H	8.5	6.1	
48	3	SCV	8.5	6.8	0
		V(b)	8.0	6.5	
49	3	SCV	10.	9.4	3
		H	6.4	7.1	
50	3	SCV	9.0	5.2	0
51	1	SV	8.0	7.7	5
		H	4.5	5.3	
		MH	4.6	6.1	
52	1	SV	8.1	9.7	0
		H	5.3	5.4	
53	2	SV	9.0	8.3	1
		H	5.9	8.0	
54	1	SV	10.	8.3	
		H	5.2	6.5	
55	1	SV	7.5	7.1	
		H	5.5	7.4	
56	2	S(c)V	9.0	1.5	0
		WRV	9.0	6.9	
57	1	SV	8.5	5.8	0
		H	2.7	5.1	
		H	2.8	5.3	
		MH	2.8	5.3	
		V	3.2	3.7	
		WR(d)V	8.5	6.4	
		(c)H	8.0	7.6	

Legend: S = standard treatment, C = chemical polishing of Cu instead of electropolishing, R = rinsing, W = water, H = horizontal test, V = vertical test without welded He tank, M = magnetic compensation coils mounted, (a) = "hot spot" is explained in the text, (b) = with He tank mounted, (c) = no WR, (d) = desinfected W.

0-7803-0135-8/91$01.00 ©IEEE

III. THE RF TESTS

A. *The tests of the individual cavities in a vertical cryostat*

The vertical test consists of the determination of the Q value vs accelerating gradient E_a at 4.2 K (fig. 1), RF and He processing (conditioning the cavity in a low partial pressure of He gas), if necessary, to eliminate electron loading and lowering the temperature by pumping on the He bath to determine the residual surface resistance R_{res}, the BCS surface resistance R_{BCS}, and performing temperature mapping [7].

Whenever the cavity has given unsatisfactory results, for instance stepwise Q decrease and/or persistent electron loading from defects of the Nb layer [3], the cavity is warmed up for repair which consists of removing the blister or stripping the Nb layer and recoating the cavity. The maximum accelerating gradient of an individual cavity is 9.7 MV/m (table 1), the maximum Q value (4.2 K) at 6 MV/m $4.8 \cdot 10^9$, the average Q value (4.2 K) at 6 MV/m $4.0 \cdot 10^9$.

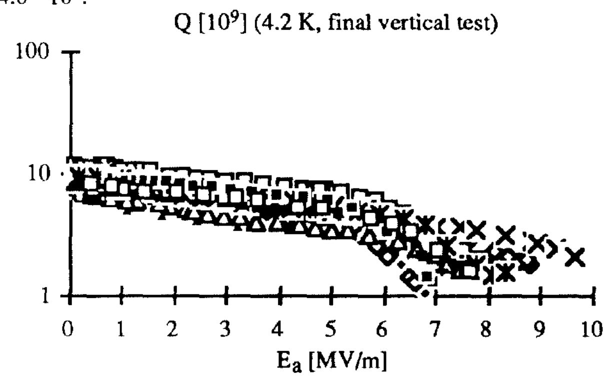

Fig. 1 Q value vs accelerating field for LEP type Nb/Cu cavities.

In order to study the long-term stability of the coating we have stored a cavity for two years under dry filtered N_2 gas. The RF performance was unchanged. A 500 MHz monocell cavity, when stored under laboratory air for one year, showed a slight decrease of Q. It has been much more pronounced after a bakeout at 200°C (factor 2 lower).

B. *The tests of the individual cavities in a horizontal cryostat*

When the vertical tests give satisfactory results, the He tank is welded around the cavity. It is again rinsed with ultrapure water, equipped with the final pick-up antennas, other fittings, and the tuners [8], assembled in the horizontal accelerator cryostat, evacuated to a pressure in the lower 10^{-7} mbar range, and cooled down to 4.5 K. Again, the Q value vs accelerating gradient E_a is determined.

In about half the cases, the results of the vertical and horizontal tests coincide within the measurement error (10%). In the other cases a decrease of the Q value to up to a factor of 2 has been encountered. One such cavity (# 57 in table 1) was remeasured vertically (same result as horizontally), rerinsed with ultrapure water from our clean water plant which before has been subject to disinfection from bacteria (< 10 colonies per 100 ml water). The Q went up to the one obtained before the degradation. The cavity was assembled for the horizontal test (no water rinsing) and the $Q(E_a)$ curve remained essentially the same as in the previous vertical test.

C. *Tests on the static magnetic field dependence*

The results of tests under different static magnetic fields confirm what has been observed in several previous tests. Up to twice the earth's magnetic field, no changes in Q value are seen.

We also have applied larger static magnetic fields B_0 (up to 5.1 mT) perpendicular to the equatorial surface by mounting a coil of .45 m diameter 8 cm off the equator of one cell. After cool down we have determined $Q(E_a)$ in a convenient parametrization as, for instance, $Q(E_a) = Q_0 \exp(-\alpha E_a)$ [4], and have taken temperature maps (tables 2 and 3). From the absolute calibration of the resistors [9] we analyze the supplementary residual surface resistance. When the cavity is exposed to a static magnetic field of 5.1 mT, strong electron multipacting is observed.

Table 2
Parametrized Q curve ($Q(E_a) = Q_0 \exp(-\alpha E_a)$) at 4.2 K for different local static magnetic fields

B_0[mT]	Q_0	α [m/(MV)]	Q (6MV/m)
0	9.5	.141	4.1
2.5	8.9	.158	< .7
4.1	7.8	.197	< .52
5.1	8.0	.268	< .36
The relative error of Q_0 and α is 10%, [Q] = 10^9, [Ea] = MV/m.			

Table 3
Increase of local residual surface resistance at 3 K by static magnetic field of 2.5 mT

E_a [MV/m]	R_s^{local} [nΩ]
4.1	73 ± 30
5.3	178 ± 83
6.3	231 ± 56

D. *Test of the complete cryomodule and operation in LEP*

After the test of the individual cavities in their horizontal accelerator cryostat each cavity is equipped with two HOM couplers and a power coupler [8] (cryo-unit). Four cryo-units are joined together in a clean area into the common accelerator cryostat of 12 m length (cryomodule). Its total length is determined by the width of the access pits of LEP. The cryomodule is of modular construction. It has the maximum length that can pass through the LEP access pits. For the test in the laboratory with a 1 MW klystron, the average accelerating gradient has been 5 MV/m, in LEP, 3.7 MV/m, somewhat lower than the design value (5 MV/m). This is mainly due to an instability of the RF voltage of one individual cavity, being investigated right now. The total RF voltage from 2 cryomodules in LEP is 50 MV.

For the HOM couplers we have chosen a demountable geometry. The tubular coupling port needs a s.c. surface which is always sputter deposited with the cavity. The fundamental mode current is shunted away at the front end of the coupler, where all surfaces are s.c., such that no current flows across the joint [10]. In addition, this HOM coupler interacts electrically and magnetically, which improves the damping of the TE_{111} dipole modes at 460 MHz. The overall damping supplied is relatively high, Q_{ext} being 9000 for the TM_{011} mode with the largest (R/Q) value, 55 Ω. This coupler has sufficient damping to cope with 16 bunches in LEP.

IV. DISCUSSION

There are features which do not vary significantly between different cavities. The BCS surface resistance is constant (fig. 2), $\langle Q_{BCS}(4.2\ K)\rangle = (1.1 \pm .1) \cdot 10^{10}$. The lowest residual resistance is < 2 nΩ. We did not observe a quench due to excess heating at a defect. There are 7 coatings with no "hot spots" (table 1), defined as a peak on the temperature map exceeding 100 mK (500 mW at 2.5 K). Conditioning the cavity to cure against electron multipacting at $E_a \approx 5$ MV/m [11] is short (minutes). Whenever we have tested the Q value under the influence of static magnetic field up to about two times the earth's magnetic field, the result was null. Led by this encouraging experience, the cryomodule is operated in LEP, the performance of the cavities to be produced by industry has been specified as $Q_0 \geq 4 \cdot 10^9$ at $E_a = 6$ MV/m and 4.5 K.

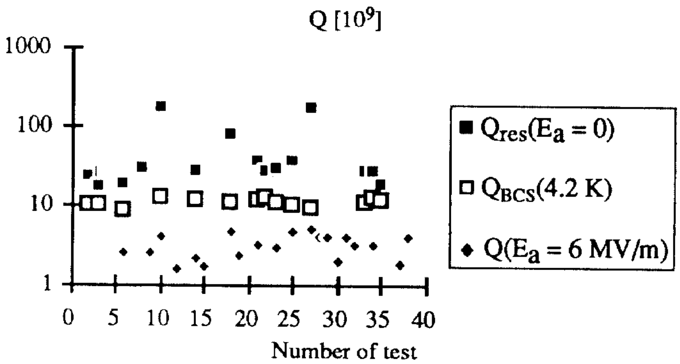

Fig. 2 Q values vs test number for all RF tests performed.

There are other features, however, which differ from one cavity to the other. For example, the number of hot spots varies between 0 and 5. There are cavities (about one half), the Q value and accelerating field of which are lower in the horizontal test than in the preceding vertical test. The residual Q value, $\langle Q_{res} \rangle = 5 \cdot 10^{10}$, and the Q value at 6 MV/m, $\langle Q(6MV/m) \rangle = 3 \cdot 10^9$, show a scatter (fig. 2). High resistivity of the drain water (> 10 MΩcm) is not a sufficient condition to guarantee short He processing (several hours) (fig. 3). But it is a necessary condition to avoid exceedingly long He processing times (> 25 h).

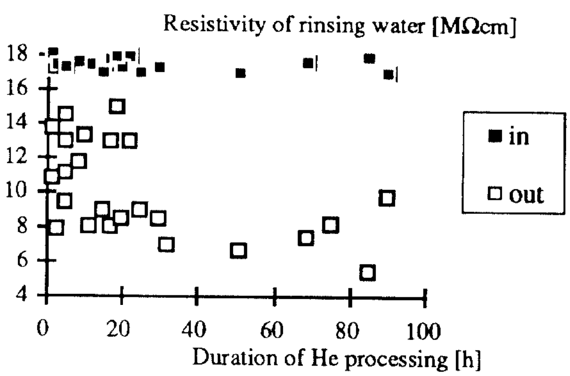

Fig. 3 Long duration of He processing is correlated with a low resistivity of the drain water (not correlated with the inlet water).

These observations indicate that the parameter set for cavity processing is not yet sufficient. In this respect our report gives the status on how to improve cavity performance and is not yet a final one.

We feel that the water quality is important, and we will not exclude the possibility that the assembly might have caused some problems (after displacing the cavity from the horizontal to the vertical test set-up, the electron loading increased). There is a correlation of the drain water resistivity and the time needed for "He-processing", which is applied to reduce electron loading by field emission. This is consistent with the results on Nb sheet cavities at KEK [12]. After having controlled the clean water parameters (TOC < 50 ppb, bacteria content < 10 colonies per 100 ml, resistivity > 17.5 MΩcm) and, if necessary, purged the clean water plant, the Q value has been high and the maximum accelerating field has been obtained rapidly without long conditioning. After a contamination we have been able to reestablish the performance of a cavity with clean water rinsing only (# 57 in table 1).

The insensitivity of the Nb/Cu cavities against small enough static magnetic fields is confirmed but does not survive up to fields of 3 mT and larger, which are in the order of stray fields of s.c. magnets (future LHC). When the cavity is exposed to a uniform static magnetic field the losses are certainly more than 4 times larger than the experimentally observed losses from the coil (which locally generates the same field). From that the upper bound of the Q value indicated in table 2 is derived.

V. CONCLUSION

The first cryomodule of four 352 MHz Nb-coated Cu four-cell cavities is being operated in LEP. The average gradient is 5.0 MV/m in the laboratory and 3.7 MV/m in LEP. The maximum accelerating field of an individual cavity is 9.7 MV/m. With 2 s.c. modules 50 MV has been obtained in LEP.

Acknowledgements

We thank E. Picasso for initiating and continuously pushing the project. Colleagues from machining, cleaning, chemical, heat treatment , electron beam welding, brazing and cryogenic facilities, have contributed to the success of the project. We thank them all for their untiring enthusiasm. The collaboration with the AT-Cryogenics and the SL-RF groups was indispensible and is gratefully acknowledged.

REFERENCES

[1] C. Wyss, this conference.

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

[3] C. Benvenuti et al., Appl. Phys. Lett. 45 (1984) 583; C. Benvenuti et al., IEEE Trans. Mag. MAG-21 (1985) 153.

[4] G. Arnolds-Mayer and W. Weingarten, IEEE Trans. Mag. MAG-23 (1987) 1620.

[5] C. Benvenuti et al., proc. 2nd Europ. Part. Acc. Conf., Nice eds P. Marin and P. Mandrillon (1990) 1079.

[6] C. Benvenuti et al., proc. 3rd Workshop on RF Superconductivity, Argonne, Ill., USA, ed. K.W. Shepard, ANL-PHY-88-1 (1987) 445.

[7] P. Bernard et al., Nucl. Instr. and Meth. 190 (1981) 257.

[8] G. Cavallari et al., proc. 3rd Workshop on RF Superconductivity, Argonne, Ill., USA, ed. K.W. Shepard, ANL-PHY-88-1 (1987) 565.

[9] R. Romijn et al., IEEE Trans. Mag. MAG-19 (1983) 1318.

[10] E. Haebel et al., in preparation.

[11] W. Weingarten, proc. 2nd Workshop on RF Superconductivity, CERN, Geneva, Switzerland, ed. H. Lengeler (1984) 551.

[12] K. Saito et al., proc. 4th Workshop on RF Superconductivity, KEK, Tsukuba, Japan, ed. Y. Kojima (1989) 635.