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The CERN Nb/Cu Programme for the LHC and Reduced-β Superconducting Cavities

E. Chiaveri

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The niobium/copper (Nb/Cu) sputter technology, successfully used on a large scale for LEP2, has been applied to the LHC and reduced-β superconducting (SC) cavities. For the LHC RF system the SC cavities were chosen, not only because of their high accelerating field leading to a small contribution to the machine impedance, but also because of their high stored energy which minimizes the effects of periodic transient beam loading associated with the high beam intensity (0.5 A). There will be eight single-cell cavities per beam, each delivering 2 MV (5.3 MV/m) at 400 MHz. In this paper the results of the industrial production of 21 cavities will be presented, and high-power test results on the prototype cryomodule reported. For the reduced-beta application an R&D programme at CERN was started in 1996. The goal is to demonstrate both the feasibility of such cavities and the possibility of producing them by low-cost modifications of LEP2 cavities (once LEP is decommissioned. Four different geometries were extensively tested (β = 0.48, 0.62, 0.66 and 0.8). In the present paper results obtained with single and multicell cavities will be presented, and a possible scenario for a superconducting proton linac will be reported.

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1 INTRODUCTION

For the LHC project cavities having a large stored energy (low R/Q, high voltage) are best suited in order to minimize the effects of transient beam loading due to the long gaps (up to 3 μs) in the high intensity (0.56 A) proton beams [1]. This leads naturally to single-cell SC cavities with large beam tubes very similar to those designed for the high current e^+e^- factories. There will be eight 400 MHz cavities per beam, grouped by four in two cryomodules. Each cavity is connected inside a cryomodule to its neighbours by wide (∅ = 300 mm) beam pipes and (unshielded) bellows. The operating voltage of the cavities (2 MV during storage, i.e. 5.3 MV/m) is quite low by to-day's standards but leaves ample margin for boosting the LHC RF voltage and reducing bunch length in the future if necessary.

In 1996 an R&D programme was launched at CERN to study the feasibility of reduced-β Nb/Cu SC cavities. Its motivation came from various proposals for high-intensity proton linacs to be used for different purposes (e.g. as the drive beam of an energy amplifier, transmutation of radioactive waste, neutron and muon sources etc.) [2,3,4]. The 352 MHz SC RF system for LEP was considered for reconversion, after LEP decommissioning in the year 2000, into the medium-β (0.5 ÷ 0.8) and high-β (~1) part of some of these linacs. One reason for this is of course economical but there are also other important points in favour of this option:

- The reliability of the system during operation has already been demonstrated in LEP, where only about 10% of the downtime was due to faults of the RF system
- The large aperture of the irises (over 200 mm), which results from the choice of the operation frequency (352 MHz), should prevent the activation of the cavities by the beam halo.

Each LEP "module" is made up of four cavities and delivers on average between 40 and 54 MV to the beam. Considering the variation of the transit time from cavity to cavity due to acceleration, an SC machine going from ~200 MeV to ~ 2 GeV would need between 50 and 60 such modules, with several stages optimized for growing betas. Unmodified LEP cavities, which are designed for β = 1, have a reasonable efficiency for β = 0.9 only (1 GeV). This corresponds to half the linac.

Our study showed that for values of β ranging from 0.66 to 0.8, the reconversion of the LEP cavities into reduced-β cavities is feasible and could be very interesting from the economical point of view. For lower values of β (0.48, 0.625), on the other hand, the RF performance of the cavities produced with the Nb/Cu technology is not so satisfactory, so that there is little incentive to modify LEP cavities so as to become β ~ 0.5 cavities.

2 LHC CAVITIES

2.1 LHC Cavity Manufacture

The cavity technology is similar to that used on a large scale for LEP2 [5]; it is based on niobium film on copper cavities operating at 4.5 K and on a modular cryostat with easy lateral access. Bare cavities (Fig. 1) are produced by spinning and electron-beam welding and are coated with a thin (1 to 2μm thickness) film of niobium by magnetron sputtering. We have chosen a beam tube diameter of 30 cm which gives R/Q = 44 Ω and a nominal voltage of 2 MV/cell for 11.8 MV/m peak electric field and 27.3 mT peak magnetic field on the surface. In terms of a cavity length of λ/2 (as used for multicell cavities), this corresponds to an accelerating field of 5.3 MV/m. There will be eight single-cell cavities per beam in order to produce the nominal voltage of 16 MV during storage. The beam separation of 420 mm is large enough to accommodate the vacuum tank radius of 360 mm, but not to bring the other beam outside the cryostat. Consequently the second beam tube is also cold.

The eight single-cell cavities of each beam are arranged in two identical cryomodules. The four cavities of a cryomodule have a cell-to-cell distance of 3λ/2 at 400 MHz (1122 mm) and are connected by the large diameter (∅ = 300 mm) beam pipes. The coupling between adjacent cells is negligible at the fundamental frequency and weak for the two lowest higher-order modes, but it is strong above the cut-off frequency of the 300 mm diameter pipe. Above 700 MHz the location and magnitude of the HOMs differ markedly in the case of the coupled cavities as compared to those of a single cell with identical conical tapers. Moreover the peak and average values of the corresponding R/Qs are significantly more favourable for the coupled cavities than for a set of four individual cavities. with conical tapers.

There is a so-called “trapped” mode at 1240 MHz which couples very weakly to the beam pipe modes and which can be potentially dangerous. Its Q_{ext} is critically dependent on the cell length ($Q_{ext} > 10^5$ for a cell length of 332 mm; $Q_{ext} = 300$ in the LHC case of a cell length of 320 mm).

The series production of 21 bare cavities has now been completed by industry. Their typical performance is indicated in Fig. 2.

The copper wall thickness is chosen as a compromise between tuning force and mechanical stability against buckling; for a thickness of 2.8 to 3 mm, the cavity axial spring constant is about 20 kN/mm and the tuning sensitivity 240 kHz/mm.

Figure 1: LHC single-cell cavity

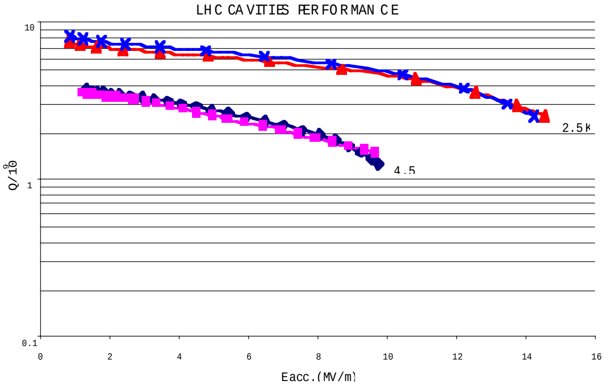

Figure 2: Typical LHC cavities performance (all limited by amplifier power)

2.2 Cryomodules

Each cryomodule contains four single-cell cavities, each having its own helium tank. A prototype version having only two cavities has been constructed (Fig. 3) and tested.

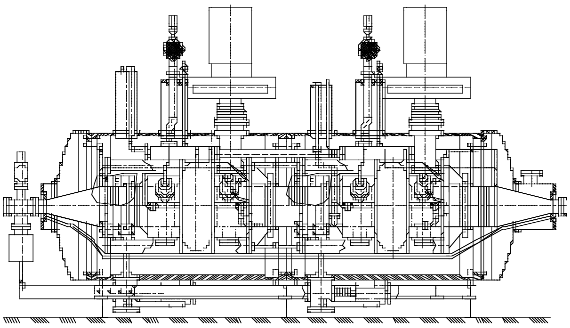

Figure 3: The prototype cryomodule with two cavities

A modular construction was adopted for the vacuum tank of the cryomodule. Each tank is a stainless steel cylinder, with no welds and with four large lateral openings to permit easy access to the cavity. These openings are sealed with aluminium panels with long rubber rings. Each tank is joined to its neighbours or to the end flanges with Helicoflex® metallic joints (combined with rubber rings to allow vacuum testing before cavity assembly).

The four cavities are connected to wide bellows in a clean room; this assembly is then rolled inside the complete vacuum tank. The main couplers are mounted last, again in a clean room. It is feasible to disassemble and reinstall a single cavity in the middle of a cryomodule without disassembling its neighbours. The helium tank of each cavity is made of 2 mm thick stainless steel. Its cross-section is cylindrical around the cavity cell and octagonal at the location of the ports.

The four helium tanks within a cryomodule are interconnected at the liquid and gas levels in such a way that a common helium feed and a common gas return are sufficient. Individual safety exhaust pipes with rupture disks are, however, provided for each cavity.

As in LEP, each cavity cradle is suspended inside the cryostat to allow for contraction during cooldown. The longitudinal fixed point corresponds to the main coupler position to avoid stresses on the double-walled tube of the coupler. Neither a magnetic shield nor a heat shield is necessary. The vacuum tubes for the second beam are attached to the side of each cavity cradle and connected with standard shielded bellows. The measured static heat losses of the prototype cryomodule (having only two cavities and no second beam tube) amount to 50 W.

2.3 Tuner

A purely mechanical tuner was chosen to provide the large tuning range at full speed required to compensate beam loading and thus minimise power requirements at injection. The large spring constant of the cavity (20 kN/mm) requires a very rigid structure surrounding the cavity which can return forces with little deformation. The stainless-steel (type 304) cavity cradle, with its two thick end plates joined by four columns forms a very rigid (< 0.08 mm axial shrinkage at a force of 20 kN) structure free of harmful resonances. The cavity is always under tension, its end plate and the cradle end plate being pulled together via thin (1 mm thickness, 200 mm high) aluminum foils which also act as torsion shafts (Fig. 4). A high-performance aluminum alloy (2219 T851) was chosen for these critical elements because of its excellent fatigue properties and elastic limit at low temperature (better than stainless steel). The maximum constraint for a 1 mm displacement of the cavity (170 MPa) is far from the elastic limit (500 MPa). The two torsion shafts (foils and shaft are made from a single piece machined by electro-erosion) are driven by long arms which provide a lever action (ratio 14:1) outside the cryomodule via two thin-walled stainless-steel cylinders acting as counter-rotating torsion shafts The latter are driven by stainless-steel cables (∅ = 3 mm) providing again a transmission without friction or backlash.

Furthermore, this system allows displacement of the cradle during cooldown and provides low heat conductance.

In a hadron collider RF phase noise at the synchrotron frequency f_s is of great importance, as it may limit the beam lifetime. The contribution of the cavity microphonics, including the tuner, to the overall RF phase noise at the synchrotron frequency f_s (f_s = 24 Hz for the LHC) must be evaluated. Preliminary measurements on the LHC prototype cryomodule (without RF couplers) indicate a microphonics phase noise density which is adequate for the LHC. Note that the tuner in itself is too slow to compensate microphonics at f_s.

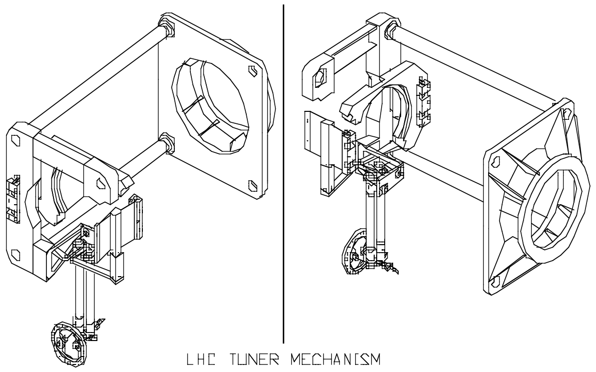

Figure: 4: Tuner mechanism

3 REDUCED-β DEVELOPMENT

3.1 Design of Cavities

Computer modelling [8] showed that spherical ß = 1 cavities can be “shortened” and what we call “reduced-ß cavities” obtained. About ß = 0.5 (E =150 MeV) can be reached without violating the reasonable design criteria which were applied for spherical cavities.

These cavities could be made from bulk niobium but the technique of niobium film on copper (Nb/Cu) as used for the LEP2 SC cavities [9] can have particular advantages here.

- The advantage of low frequency (wide iris aperture against beam losses, lower number of cavities, couplers etc.) is not mitigated by the cost increase of solid Nb cavities.
- The shortened cells lead to steep “side walls” which become mechanically unstable against vacuum pressure. One remedy is the use of stiffeners, which complicates the mechanical construction and hinders temperature mapping of cavities. The use of the Nb/Cu technique offers the possibility of increasing the material thickness without significantly increasing the cost, as compared to the solid Nb case.
- The large power transferred towards the beam makes the power coupler the limiting element (the cavity fields are rather modest). In this case the stronger “slope” of the Q(E) curve of Nb/Cu cavities does not play the dominant role but their generally higher Q-value at low field is certainly welcome.
- The higher thermal stability of the Nb/Cu cavities compared to solid Nb here offers the same advantages as for the LEP2 cavities. Also, the Nb/Cu cavities are insensitive to small stray magnetic fields (e.g. from focusing quadrupoles) up to about 0.2 mT; therefore complicated magnetic shielding is not necessary.

3.2 Results of single-cell cavities

From August 1996 four different types of niobium-plated single-cell copper cavity were produced at CERN: $\beta = 0.48$, $\beta = 0.625$, $\beta = 0.66$ and $\beta = 0.8$. The best performances obtained for each type are shown in Fig. 5 and Fig. 6. A typical performance of a LEP cavity is also shown in Fig. 6.

The $Q(E_{acc})$ curve of the $\beta = 0.8$ cavity fits the expectations (calculated by scaling the analogous LEP cavity curve with the geometry factor). For the others the results are lower than the scaling predicts, showing a degradation of the niobium film quality. This is probably due to the low impact angle of the Nb atoms on the surface of the cavity during the sputtering process for these geometries.

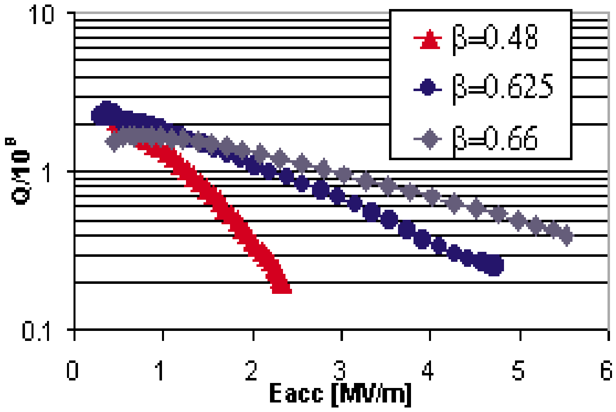

Fig. 5 Results for β=0.48,B=0.625,B=0.66

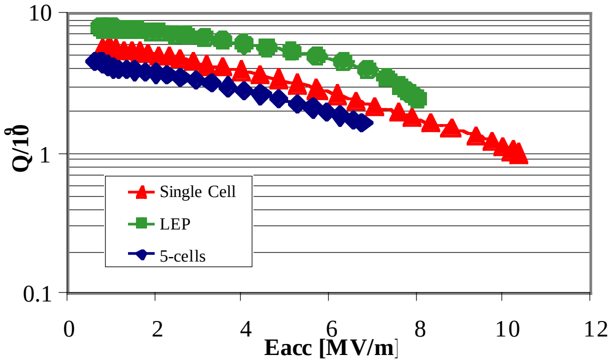

Fig. 6 Comparison of results B=0.8 and LEP
(all limited by amplifier power)

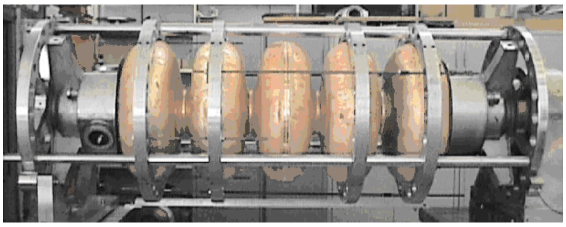

Fig. 7 Five-cell cavity B=0.8

3.3 The Five-cell β = 0.8 Cavity

The length of a cell is related to the β for which it is optimized. Since 5*0.8*l/2 = 4*1*l/2, a five-cell β = 0.8 cavity will have exactly the same length as a four-cell β = 1 one.

This consideration is the basis for a low-cost transformation of LEP cavities. In fact, as the lengths are the same, we can re-use almost all the ancillary equipment:

- *the thermal tuners*, which ensure coarse tuning and have a range of at least ± 25 kHz
- *the magnetostrictive tuners*, which provide fine and fast tuning and have a range of ±1 kHz
- *the two "cut-offs"*, which are the part of the cavity connecting the two end cells to the beam pipe (These are the most expensive mechanical parts of the whole copper cavity, because all the flanges for the different couplers have to be welded onto them.)
- some parts of the liquid helium circuit
- *the vacuum tank*, which ensures the thermal insulation between the helium tank and the atmosphere at 300 K
- *the main coupler and the Higher Order Modes (HOM) couplers*, after some minor modifications to adjust the coupling factors.

In practice we need to build only the five copper cells and the helium tank. The necessary steps for the transformation are then the following:

1) dismounting the cavity from its vacuum tank
2) chemical etching of the niobium layer on the whole cavity, to clean the cut-offs
3) cutting the helium tank and the copper cavity at the cut-off level
4) production of the new copper cells
5) welding of the cells to the old cut-offs
6) coating with a new Nb layer
7) welding the new helium tank
8) remounting the cavity in the old vacuum tank.

All these steps were performed on an spare LEP cavity. The cut-offs were laser-cut from the stainless steel helium tank to ensure good surface quality for the subsequent welding. The four cells were separated by plasma cutting. We built a helium tank which was much simpler (and cheaper) than the LEP one, one which should however lead to a slightly bigger consumption of liquid helium. All the other operations are quite standard.

The bare reconstructed cavity (without helium tank) was measuredand the result is reported in Fig. 6. It is interesting to note that the degradation of the performance from the single- to the five-cell cavity is less than 25%. The maximum field achieved was limited only by the power of the amplifier.

The cavity was mounted on the vacuum tank and tested with a LEP power coupler. The result is equivalent to the bare cavity showing no degradation during the horizontal assembly.

The cost of the whole operation amounts to approximately 20% of the price of one new LEP cavity.

3.4 A Tentative Scheme for a Linac

An SC linac working at 352 MHz accelerates a beam of protons from 250 MeV to 2 GeV. By using three stages with cavity lengths matched to particles with β = 0.7, 0.8 and 1, the length of the RF part of this linac would be around 500 m, half of which would be made up of unmodified LEP cavities. The layout would consist of 36 four-cell β = 0.7 cavities, to be built completely from scratch, 76 five-cell β = 0.8 cavities that could be built by modifying LEP cavities and 104 four-cell β = 1 (LEP) cavities. The peak gradients assumed in the calculations are 5 MV/m for β = 0.7, 6 MV/m for β = 0.8 and 7 MV/m for β = 1.

This possible scheme is supported by the RF results from both single- and multi-cell cavities. Given the RF results obtained for β = 0.8 in a horizontal cryostat equipped with the power coupler, an accelerating field between 8 and 9 MV/m could be expected for a future application.

At present there are in the LEP machine many β = 1 cavities which could run at more than 8 MV/m without any major problems. Reducing β, using the standard LEP technique, results in a lowering of the maximum achievable field. We believe that down to β=0.7 it is still interesting to consider modified LEP cavities. The β = 0.7 cavity is the compromise between the minimum value of β and the requirements for the Nb sputtering technique used for LEP cavities.

4 CONCLUSION

The large-scale application of SC RF technology in LEP has demonstrated the soundness of SC cavities and in particular the Nb/Cu sputtering technique approach. The LHC and reduced-β applications are the natural follow-up of this technique. We have at CERN accumulated during the years a high level of competence in the field of SC RF cavities. The reduced-β programme is the correct way to use the knowhow and the present RF equipment for a linac application.

It has also to be emphasized that using LEP equipment, which includes not only the SC RF cavities, as described above, but also the RF power system (klystrons and their power supplies, circulators, waveguides etc.), part of the RF components, such as cavities and RF ancillary equipment (power couplers, HOM couplers, tuners etc), is certainly competitive from the budget point of view. We have shown in producing single- and multi-cell cavities for different betas that between 240 MeV and ~2 GeV we could build a proton linac at 352 MHz at 4.5 K.

As far as the LHC single-cell cavities (400 MHz) produced by industry are concerned, the final performance obtained in the final configuration with RF components in a horizontal cryostat is at least a factor 2 higher than expected.

Finally, we would like to stress that the Nb/Cu technology has demonstrated its validity on a very large scale and is certainly very competitive for a number of applications. We strongly believe that it has to be seriously considered as a possible solution for future projects.

5 ACKNOWLEDGEMENTS

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