# PRODUCTION AND TEST OF 352 MHz NIOBIUM SPUTTERED REDUCED BETA CAVITIES

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**Abstract:** Three types of 352 MHz single cell cavities foreseen for different particle speeds (v/c=0.8, 0.625 and 0.48) have been designed and built with the niobium sputtered on copper technique. We report on the results of the cold tests at 4.5 and 2.5 K and the actual status of the data analysis.

## 1. Introduction:

Until recently only two well distinct types of superconducting (sc.) accelerating cavities have been used, the 'spherical' type (ß=1) in electron accelerators and storage rings and low-ß cavities used for heavy ions, having completely different shapes (e.g. $\lambda/4$ resonators). Recent proposals for an energy amplifier and nuclear waste incinerator [1] or for spallation sources [2] make use of a powerful proton beam and rely on a high efficiency between wall-plug power and beam power. For these applications low frequency sc. cavities would be well suited; they offer also a large iris aperture, particularly welcome to minimize the beam losses along the machine. However, the energy (velocity) range over which protons have to be accelerated cannot be completely covered neither by low-β cavities nor by ß=1 cavities[1]. Therefore different cavities have to be designed and tested for such applications.

## 2. Design of Cavities:

Computer modeling has been done [3][4] which shows that one can 'shorten' spherical ß=1 cavities and obtain what we call 'reduced-ß cavities'. One can reach about ß=0.5 (T≈150 MeV) without violating the reasonable design criteria which had been applied for spherical cavities.

[1] The LEP2 sc. cavities do not accelerate any more for β=0.65 (T≈300 MeV ) and are more than 50% efficient (with respect to β=1) only for β>0.82 (T≈700MeV)

A precise machine optimization can only be done when the performance of cavities at different ß is exactly known but preliminary scenarios [5] propose 3 types of cavities for ß =0.48, ß=0.625 and ß=0.8 - and possibly classical ß=1 cavities at the high energy end. In any case once such a covering set of cavities has been explored, interpolations to similar designs can be made.

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 [6] can have particular advantages here.

• The advantage of low frequency (wide iris aperture against beam losses, lower number of cavities, couplers, ...) 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 complicate the mechanical construction and hinders temperature mapping of cavities. The use of the Nb/Cu technique offers the possibility to increase the material thickness without increasing the cost significantly, compared to the solid Nb case.

• The large power transferred towards the beam makes the power coupler the limiting element and 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 niobium cavities 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 2 Gauss [7], therefore a complicated magnetic shielding is not necessary.

Three types of reduced-ß cavities have been designed [4] following CERN's experience with spherical cavities, see drawings in fig. 1. To keep the efficiency as high as possible, the beam pipe diameter was reduced to 200 mm still allowing the existing LEP2 fabrication tools for sputtering to be used. A further decrease of the beam pipe would further lower the cell to cell coupling and provoke field flatness problems in multicell cavities as finally required. The 'side-wall' inclination was chosen at least 8° to withstand vacuum forces

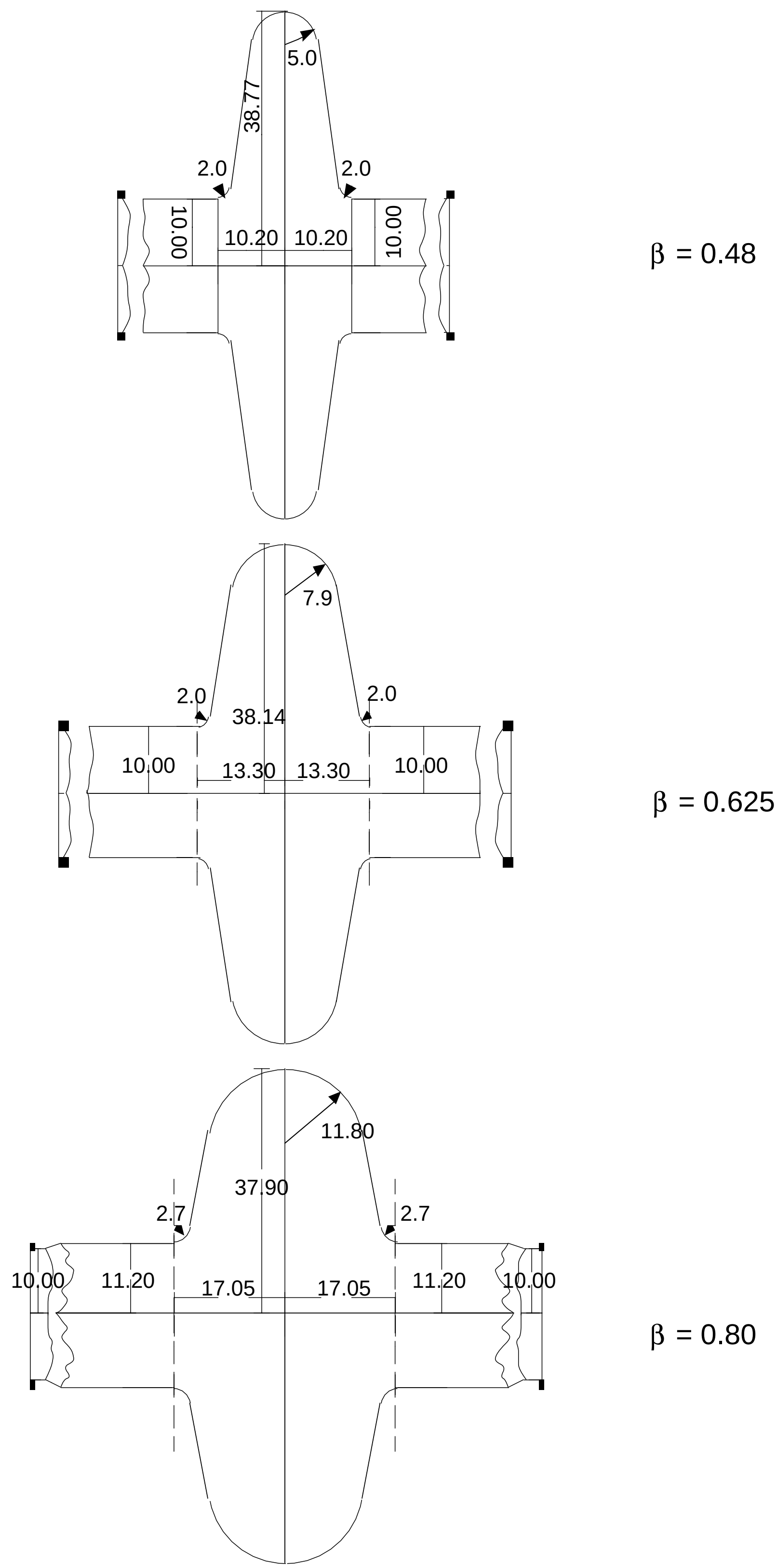


Fig. 1: Drawings of reduced-β-cavities (dimensions in cm)

without stiffeners with a 5 mm copper wall thickness. Estimates using the magnetic fields and tangential electric field gradients in the upper cell region gave a good indication for the unlikeliness of a dangerous multipacting level in the design.

## 3. Expectations for reduced-β cavities:

To get an idea of the expected performance of reduced-β cavities we have based ourselves on the LEP2 cavities data (same frequency) assuming *the same surface quality* of the Nb film, i.e. the same surface resistance $R_s$ and field emission conditions. Specifications for bare LEP2 cavities at 4.5 K were:

- a minimum field of 6 MV/m
- a quality factor Q=8 $10^9$ at very low field
- a quality factor Q=3.4 $10^9$ at 6 MV/m

These specifications were achieved on practically all cavities.

The field in sputtered cavities is limited by the onset of field emission which depends in general on the peak electric surface field - emitters located at the peak field location are the most active ones. Therefore the maximum accelerating field values for reduced-ß cavities should be scaled according to the ratios of peak field to accelerating field. These electric field limits are never sharp, so we have given rounded expectations for the accelerating field values $E_{spec}$ in table 1. Since the reduced-ß cavities are shorter (the path length for electrons to pick up energy is shorter), the expectation figures are certainly pessimistic.

The cryogenic power consumption of a cavity is inversely proportional to the shunt impedance $R_{shunt}$ of the cavity ($P_{diss} = V^2/2R_{shunt}$). $R_{shunt}$ can be understood as the product of the cavity Q value by the geometrical constant R/Q, independent of the surface quality. Reduced-ß cavities have an *unavoidable intrinsic* drawback with respect to ß=1 cavities for both factors.

First, the Q-value is necessarily lower. Since reduced-ß cavities have shorter cells with about the same diameter, they present a smaller volume but practically the same surface per cell. This is equivalent to a decrease of the stored energy (about proportional to the cell volume) for nearly the same surface losses. The cavity Q-value becomes lower accordingly. This effect is demonstrated in the column Q(Cu) of table 1, containing the calculated Q-values of cavities made from copper (same surface resistance), where Q decreases about linearly with ß.

| ß | R/Q $V^2/(2\omega U)$ | Q(Cu) | $R_{shunt}$ [MΩ] | $E_{pk}/E_{acc}$ | $B_{pk}/E_{acc}$ [G/(MV/m] | $E_{spec}$ [MV/m] | $Q_o(0)$ [$10^9$] | $Q_o(E_{spec})$ [$10^9$] |
|---|---|---|---|---|---|---|---|---|
| 0.48 | 13 | 27700 | 0.36 | 3.4 | 62 | 4.0 | 3.8 | 1.6 |
| 0.625 | 27 | 37400 | 1.01 | 2.7 | 52 | 5.0 | 5.2 | 2.0 |
| 0.8 | 42.5 | 47200 | 2.01 | 2.3 | 44 | 6.0 | 6.5 | 2.5 |
| 1 (LEP) | 232/4 | 57700 | 3.35 | 2.2 | 39 | 6.0 | 8.0 | 3.4 |

Tab. 1: Expectations for reduced-β cavities
made of ‘LEP2 quality’ Nb film

Second, there is a more than linear decrease of R/Q with decreasing ß. A linear decrease could be understood by the argument that a cell scaled with ß in length having about the same diameter produces an accelerating voltage V proportional to its length, and a stored energy U (about proportional to the cell volume) also scaled with ß. As a result the geometric factor $R/Q=V^2/(2\omega U)$ should also scale with ß. In addition, for the same RF-fields on the wall surface of the cells we have a reduction of the useful accelerating field on the axis when shortening the cells. If we approach the ‘side-walls’ of the cells to reduce the cell length keeping the iris diameter constant, the ‘stray electric field’ on axis - which in fact represents the useful accelerating field $E_z$ - diminishes. Consequently, the accelerating voltage (the integral over $E_z$ along the cell length) loses both in field strength and in length; this is a stronger than linear decrease with ß. This effect is represented in the column of R/Q for different ß.

We have scaled the expected Q-value at very low field (column $Q_o(0)$) according to the Q-values calculated for copper cavities with the classical RF programs, which integrate the above mentioned arguments.

Things are slightly more complicated for the Q-value at the specified accelerating field. At this field we have to determine the peak magnetic field of the cavity and take into account the degradation of the superconducting properties of the film corresponding to this magnetic surface field. Interpolation is done for a linear relation between log(Q) and $E_{acc}$, demonstrated many times for the LEP2 cavities. Since a reduced-β cavity has intrinsically a lower Q-value than a LEP cavity - see table 1 - we have to scale the result again as is done for the very low field case. Results are in table 1, column $Q_o(E_{spec})$. To scale with the peak magnetic field and not with a correctly weighted surface integral taking the Q(E) slope of the LEP2 cavities into account is of course a simplification, but the error is certainly sufficiently small to get a good idea of the potentialities of these cavities.

## 4. Construction and Warm Test of the Copper Cavities:

Mechanical stability calculations [8] showed that 5 mm (OFHC-) copper sheet is sufficient. Two copper single cell cavities were realized for β=0.48 - one was cut later for surface analysis - and one for β =0.625 and β=0.8 each. Welding, chemical treatment and rinsing were done following the LEP2 recipes, only minor technical details were adapted .

*Without* cut off tubes the measured mechanical stiffness (ß=0.48) was 0.19 μm/N and the longitudinal tuning sensitivity[2] -190 kHz/mm. This is not incompatible with the theoretical expectations for a cell *with* cut-off tubes[3] from mechanical and RF calculations which predicted -380 kHz/mm.

For the first Nb layers only the duration of the sputtering was adapted to the new geometry, there was no change in the sputtering configuration; in subsequent tests the parameters were varied to modify the production of the Nb layer.

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[2] A cell of a LEP2 cavity has about 160 kHz/mm tuning sensitivity
[3] The slope at the iris is fixed and the mechanical deformation is somewhat different

Photo: Copper cavity β=0.48 ready for sputtering

# 5. Cold Tests

## 5.1 ß=0.48 cavities

The first ß=0.48 cavity was measured twice with equivalent results: a low field Q about a factor 2.5 below the expectations. A Q-switch at very low field could be excluded. Furthermore, the slope of the logarithmic Q(E) curve was much steeper than expected.

The measurements were extended in temperature down to about 2.5 K (the pressure sensitivity of -275 Hz/mbar was measured during this test) and the residual resistance was found much larger than in LEP2 cavities ($Q_{BCS}$ = 2.1-2.4 $10^9$ at 4.2 K and $Q_{res}$ 2.4 $10^9$ for both layers).

The transmitted signal was carefully scanned and not the slightest indication for multipacting up to the maximum obtained field level (about 2.5 MV/m) was observed.

The first cavity was cut for Nb film analysis. Electron microscopy showed an inclined columnar structure of the film at the side wall as expected when the angle of incidence of the Nb atoms on the copper surface is very small.

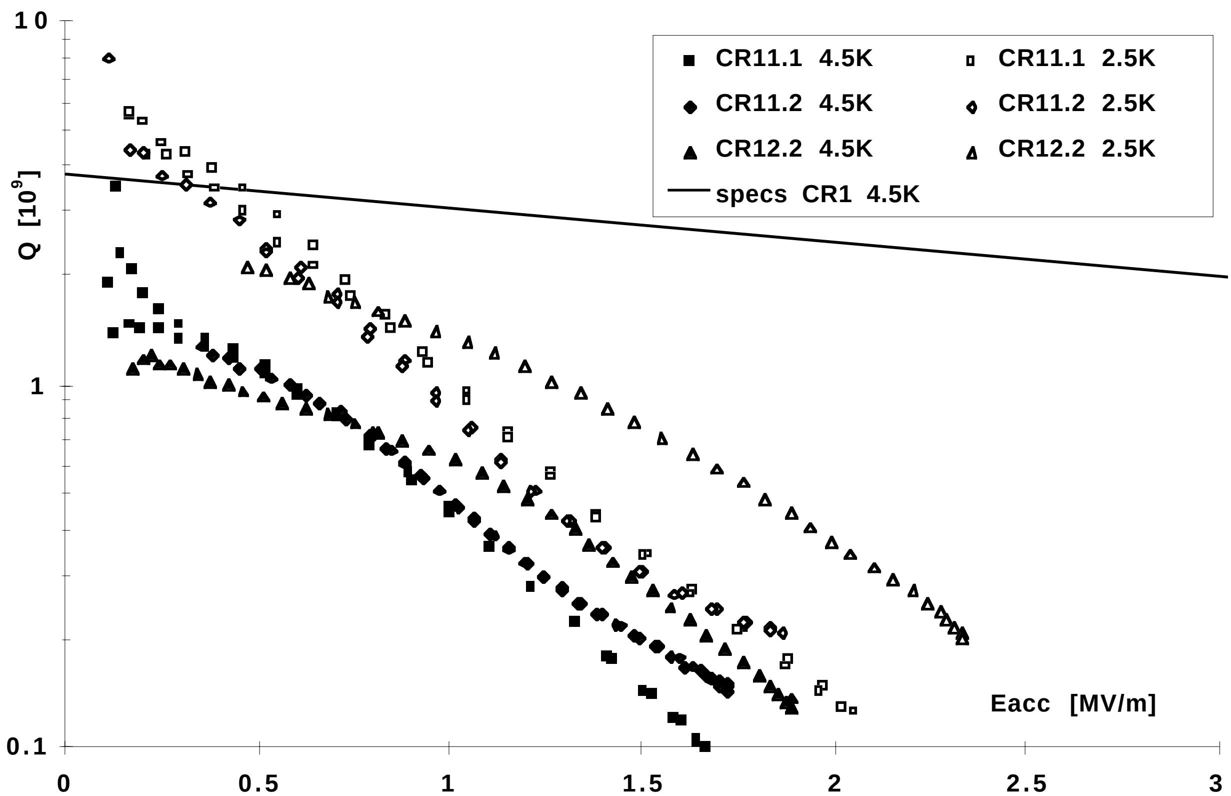


Fig. 2: Q(E) of the *two* ß=0.48 cavities at 4.5 K (full) and 2.5 K (open)

The second cavity was deposited with reduced thickness (with bad result) and with standard thickness again (CR12.2). The resulting Q-values were not significantly different from the tests with the first cavity.

### 5.2 ß=0.625 cavities

The copper cavity was deposited twice - stripped after an initial test - with standard LEP2 parameters. The low field Q-values were about a factor 2 below expectations and a strong slope was observed. Lowering the temperature (-250 Hz/mbar frequency-pressure dependence) allowed to separate $Q_{res}$=2.4 $10^9$ and $Q_{BCS}$=4.0 $10^9$. No indication of multipacting was found (up to 5 MV/m)

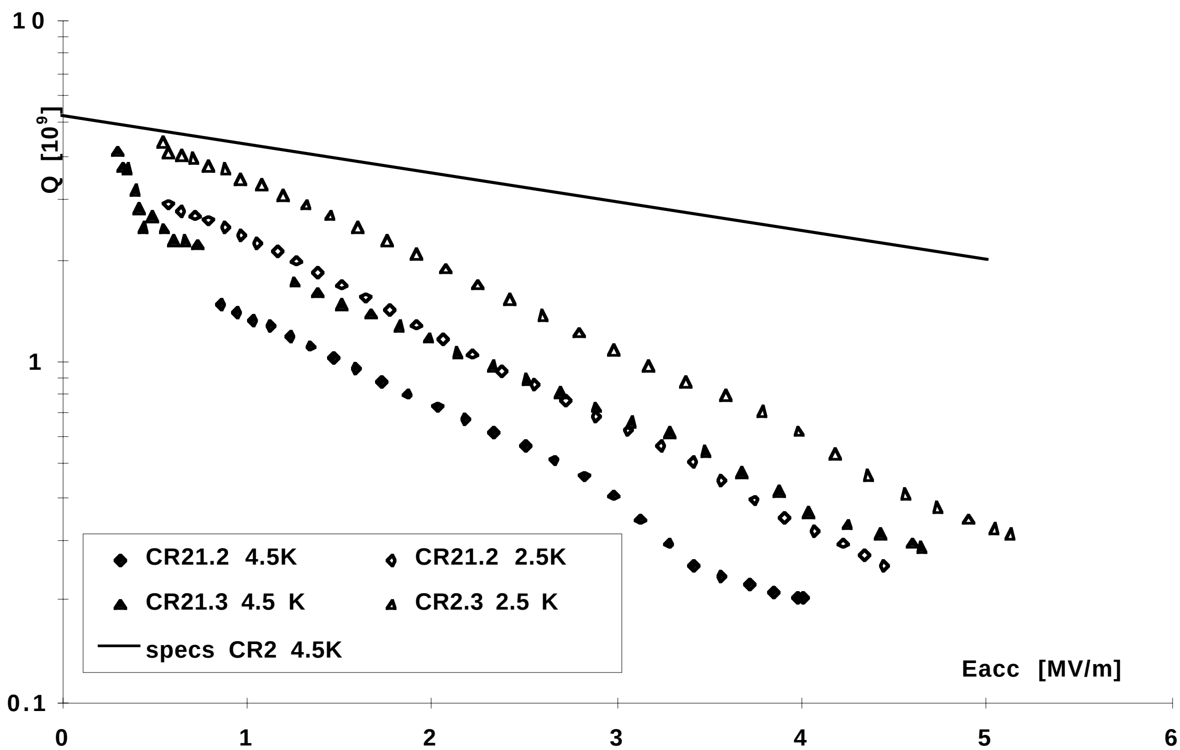


Fig. 3 : Q(E) of the ß=0.625 cavity at 4.5 (full) and 2.5 K (open)

Rinsing of the cavity improved the Q(E) curve (Fig. 3, CR21.3), $Q_{BCS}$=5.7 $10^9$ and $Q_{res}$=5.5 $10^9$ were found, both having increased. The then available T-map showed no particular features.

The cavity was cooled down with compensated earth magnetic field, since low quality layers in LEP2 cavities often were sensitive to small magnetic fields [9]. However, the result with and without were identical, both at 4.5 and 2.5 K.

### 5.3 ß=0.8 cavities

The first coating had an accidental defect and the second coating had an electron emitter which could not be processed away. The third provided a field of 9 MV/m at 2.5 K (-210 Hz/mbar frequency-pressure dependence was measured), $Q_{res}$ =13.9 $10^9$ and $Q_{BCS}$ =9.0 $10^9$. The curve of the logarithmic Q(E) (fig. 4, CR31.3) is about parallel to the expected curve.

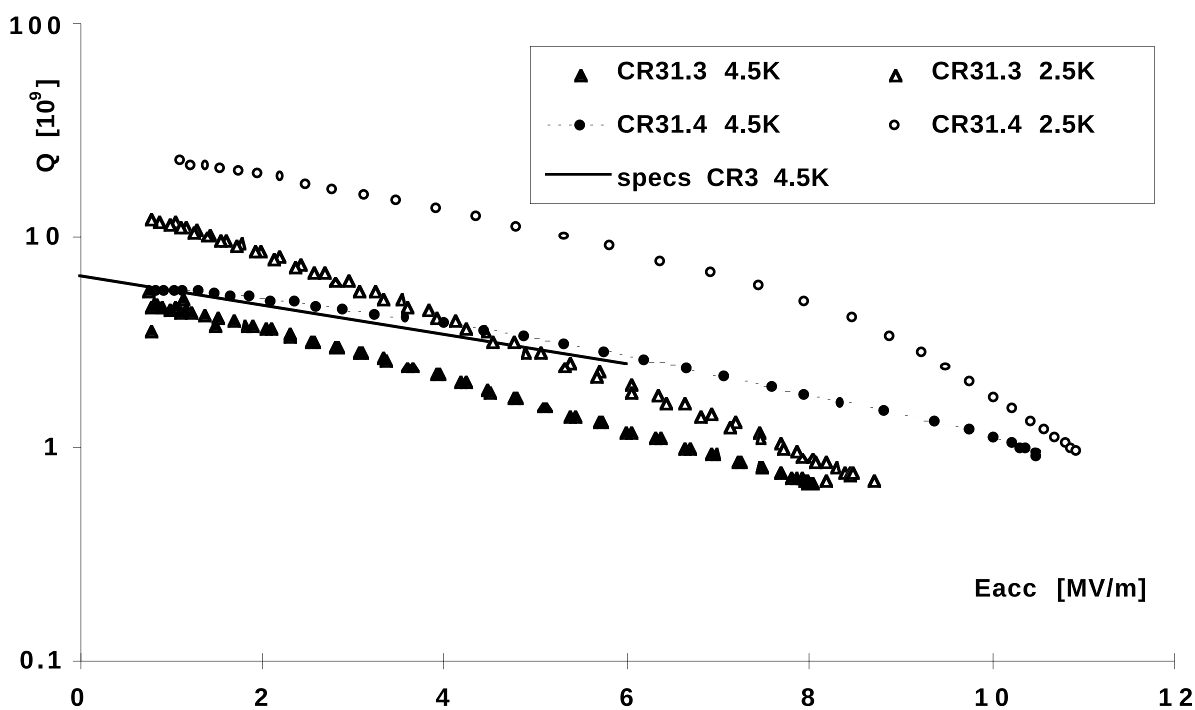


Fig. 4 : Q(E) of the ß=0.8 cavity at 4.5 (full) and 2.5 K (hollow)

It was realized that the magnets used to coat the cut off tubes were not optimally positioned, resulting in a grazing angle incidence on the cavity side wall. This has been corrected in the fourth coating. The cold test showed a Q(E) curve at 4.5 K clearly above the estimated performance, thus showing that a surface layer of the LEP2 quality was obtained (fig. 4, CR31.4). Values of $Q_{res}$

=36. $10^9$ and $Q_{BCS}$ =8.2 $10^9$ were found (at 1 MV/m), indicating a slightly higher BCS resistance but a significantly reduced residual resistance. The Q(E) curve at 2.5 K is largely above the 4.5 K curve as usually the case for the LEP2 cavities. 11 MV/m were reached (amplifier power limit) with no indication of multipacting.

## 6. CONCLUSIONS

We have demonstrated experimentally that a β=0.8 cavity at 352 MHz can be produced with the LEP2 niobium on copper technology. The niobium film is of the LEP2 quality standard and the maximum accelerating field reached more than 10 MV/m at 4.5 K. There are strong indications that the incidence angle of the sputtered niobium atoms on the copper surface is a particularly critical parameter for the reduced-β cavities. We are convinced that this difficulty can be overcome by modifying the sputtering configuration.

No quenches were observed on the cavities, the fields were always limited by the RF power available. All worries about multipacting were not founded, no indication at all was detected.

A fully equipped 5-cell β=0.8 cavity inside a LEP2 type cryostat is under preparation to evaluate also the technical feasibility of a multicell unit.

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