MODEL STUDY OF THE RF CAVITY FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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Introduction

The RF system anticipated for the Milan superconducting cyclotron requires three independently excited cavities with spiral dees, tunable approximately over the 20 to 65 MHz frequency range, and providing 100 kV peak dee voltage at the extraction radius. Since details about the machine structure and rationale for a comprehensive model program are given in ref. (1), in this paper we shall present the RF studies carried out so far, both from the theoretical and experimental points of view. We will also discuss their implications for the design of a definitive RF system which will meet the above goals.

Because of well known geometrical and mechanical constraints, the only realistic scheme for a superconducting cyclotron RF cavity must involve a vertical coaxial resonator, or more likely two, connected to the dee. In our case two were preferred, because of axial electric field symmetry, short circuit current density and also mechanical stability. Given the rather large frequency range involved, the high peak dee voltage required and the peculiar spiral shape of the dee, a careful study of the cavity is necessary in order to minimize: i) the current density at the movable short circuit, ii) the RF power needed for the cavity.

A preliminary optimization of the cavity geometry was therefore attempted before we proceeded to build a model, according to the method described below.

Outline of the calculation method

In developing this method our goal was to calculate the major characteristics of the cavity, like the resonating range, the current density on the short circuits, etc., with an error possibly less than 10%. An approach similar to that used in coaxial transmission lines was therefore chosen.

Accordingly, the cavity has been subdivided into a number of line segments, each one with supposedly constant characteristic impedance, and then series and parallel connected as required. This subdivision is schematically shown in fig. 1, while the equivalent electric scheme used for the calculations is presented in fig. 2.

The actual geometrical contours of the line segments shown in fig. 1 have been derived by tracing the propagation surfaces of the electric field in the cavity, under supposedly resonance conditions. The impedance of each line segment has been calculated analytically only for those parts which do have a uniform coaxial geometry, i.e. along the resonators. For all other segments we had to rely on the simpler method of bidimensional electrostatic field tracing,[2] carried out on every single propagation surface.

This yields an immediate, although approximate, value of the characteristic impedance for each segment considered. It will be noted, from fig. 2, that we have added two capacities, namely C_{int} and C_{ext}, to the scheme. They represent the extremes of the dee, where the electric field has a strong component along the direction of propagation. By the same method of bidimensional electrostatic field tracing we have assigned values of 12 pF and 8 pF to C_{int} and C_{ext} respectively.

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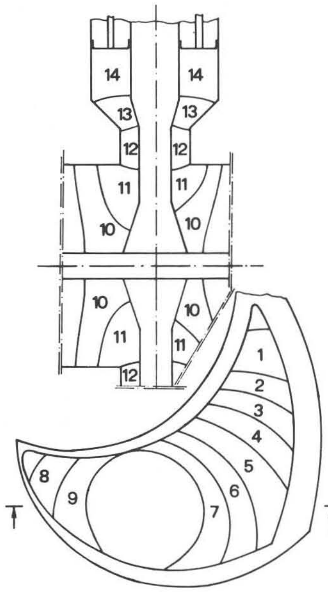

Fig. 1 - Schematic subdivision of the cavity in constant impedance line segments.

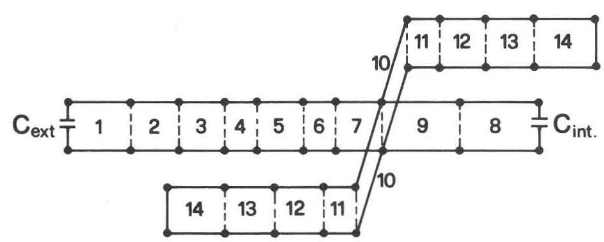

Fig. 2 - Electrical equivalent scheme of the cavity according to the subdivision of fig. 1.

Based on this representation of the cavity, a program, using the elementary equations of transmission lines, computes for every geometry of the cavity the resonant frequency and short circuit current. The error on these quantities should be around 10%, the main source being the evaluation of the correct shape of field propagation surfaces, and consequently the length and the characteristic impedance of each line segment. All the other quantities computed by the program are affected by an error of the same order or less, excepting the power dissipation and Q factor for which the error is about 20%-30%. This difference is due to the method of evaluating the current distribution on each line segment.[3]

Data from the 1:1 model

The 1:1 model geometry is schematically shown in fig. 3. The main parameters of the coaxial resonator, namely the inner radius of 150 mm and outer radius of 400 mm, have been chosen from an optimisation study based on the method just described. The tapering of the two coaxials down to respectively 100 mm and 210 mm diameter is required, to a large extent, by the need of inserting the RF stem through a valley. Dee dimensions are obviously dictated by the machine design.

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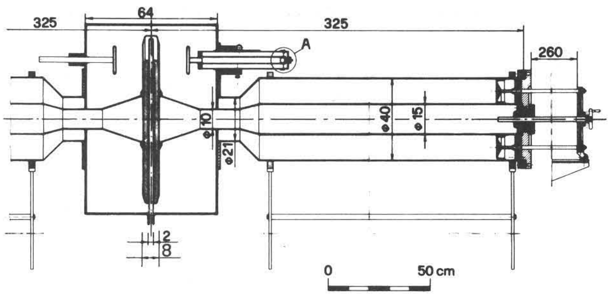

Fig. 3 - Scheme of the 1:1 cavity model.

The model has been entirely built out of copper and is supported horizontally. Adjustment, and corresponding readout, of the positions of the short circuits, coupling capacity and trimming capacitor is manual. A close-up view of the dee in the resonator box, also showing the inner coaxial and coupling capacitor, is given in fig. 4.

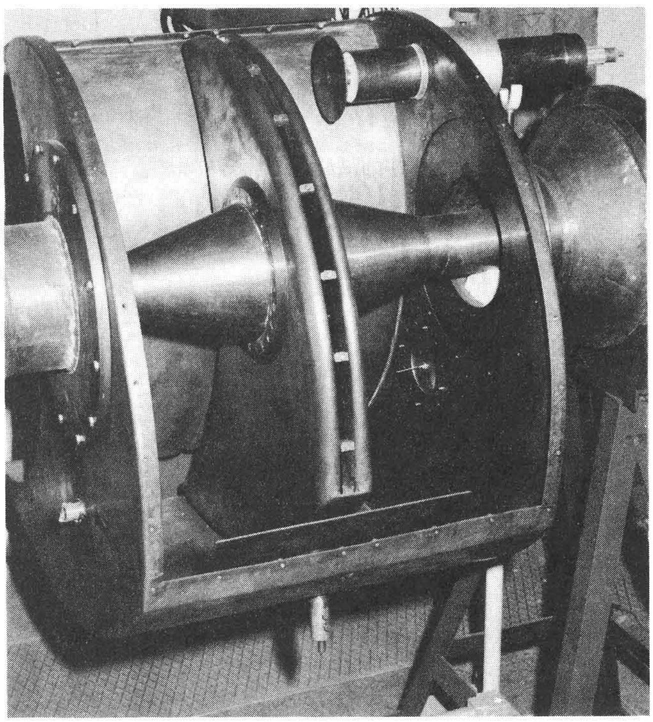

Fig. 4 - Close-up view of the dee and cavity in the model.

The model has allowed us to carry out an extensive check of the macroscopic properties of the cavity, as well as of the validity of our calculations.

The experimental and calculated short circuit position is shown in fig. 5 as a function of the resonating frequency. As might have been expected, the two curves coincide at the low frequency limit, while they disagree by about 8% at high frequencies. This shows that it may be impractical to build this cavity for frequencies much in excess of 60 MHz, and that if these frequencies are needed it is advantageous to shift to the second harmonic of the particle orbital frequency.

From the model measurements one can then derive the power needed in the cavity, as a function of the frequency. This is shown by the points in fig. 6, the solid line being drawn merely to guide the eye.

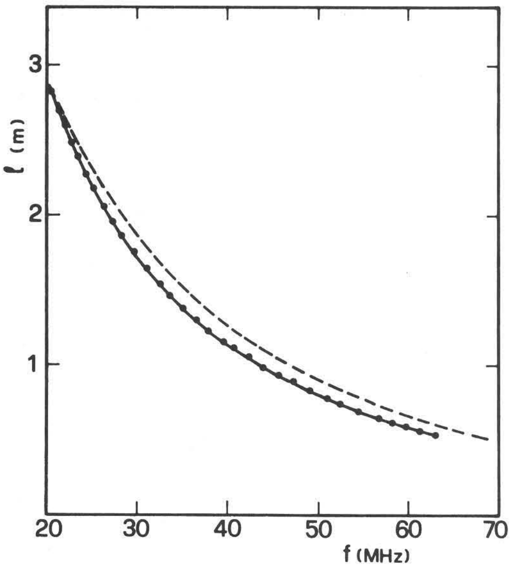

Fig. 5 - Short circuit position as a function of the resonating frequency for the 1:1 model. Dashed line refers to calculated values, points to experimental ones.

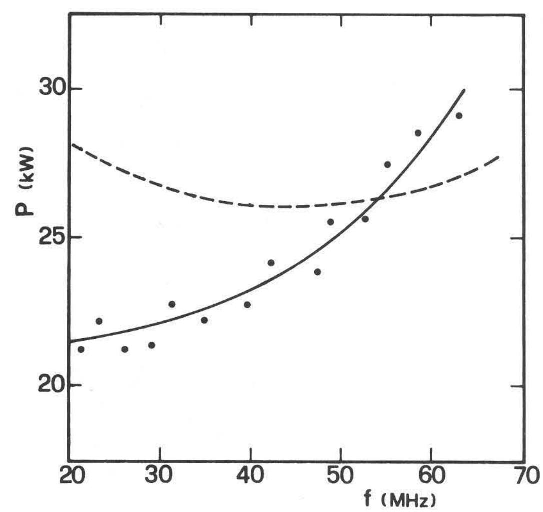

Fig. 6 - Power needed in the cavity, as a function of frequency. Solid line: derived from model measurements. Dashed line: theoretical prediction.

The dashed curve represents the anticipated values. The disagreement between calculated values and experimental ones has been already discussed.

Current density values at the short circuit are presented in fig. 7, again as derived from model measurements (solid line) and calculations (dashed line). The values refer obviously to 100 kV peak dee voltage at the extraction radius. We may note again that the discrepancy is minimal at low frequencies, while it gets larger at higher frequencies.

Voltage distribution along the dee radius was also measured at a number of resonating frequencies. Its knowledge is important for two reasons: i) peak voltage variations with radius can play a significant role in determining the accelerated beam dynamics, ii) from these measurements one can establish, with substantially better confidence, the contours of

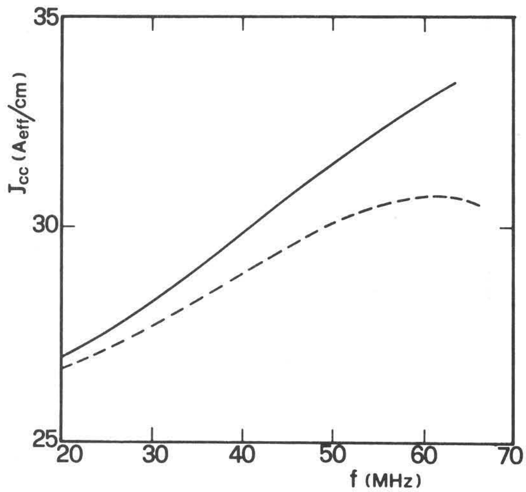

Fig. 7 - Current density at the short circuit, as a function of frequency. Solid line: derived from model measurements. Dashed line: theoretical prediction.

propagation surfaces on the dee. This in turn enables refinement of the theoretical model, in order to predict cavity properties.

These measurements were carried out with a passive probe having a high input impedance and low reactance, to minimize perturbations of the cavity itself. The measurement reproducibility has been better than 1%. The RF signal is rectified by two series diodes, close to the probe edge, while the distributed capacity of the 50 ohms coaxial cable and the input impedance of a dc digital voltmeter are the filter. A picture of two of the very simple probes used is presented in fig. 8.

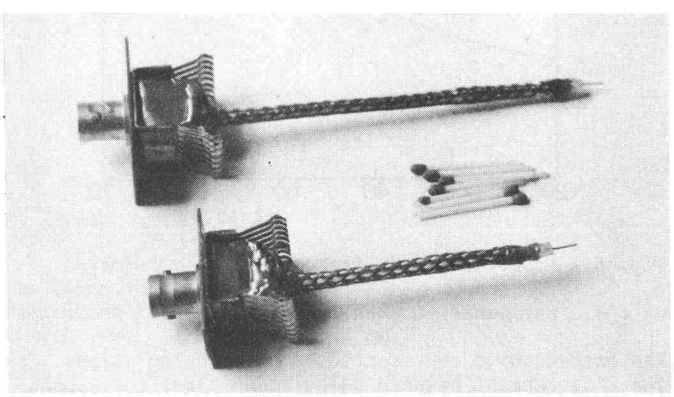

Fig. 8 - Picture of two probes used for voltage distribution measurements along the dee gaps.

Use of this probe has been quite successful. From measurements with probes of different length we infer that the perturbation produced by the probe itself is well within $\Delta f/f \leq 5\cdot10^{-3}$.

An example of measured voltage distribution along the dee edges is shown in fig. 9 for the frequency of 63 MHz, and as a function of radius. Comparison with the theoretical values shows that, although the general trend is well reproduced, the actual difference between the voltage values for the two edges is much larger. This reflects the difficulty, already discussed, of correctly predicting propagation surface contours in such a geometry. The discrepancy is perhaps better

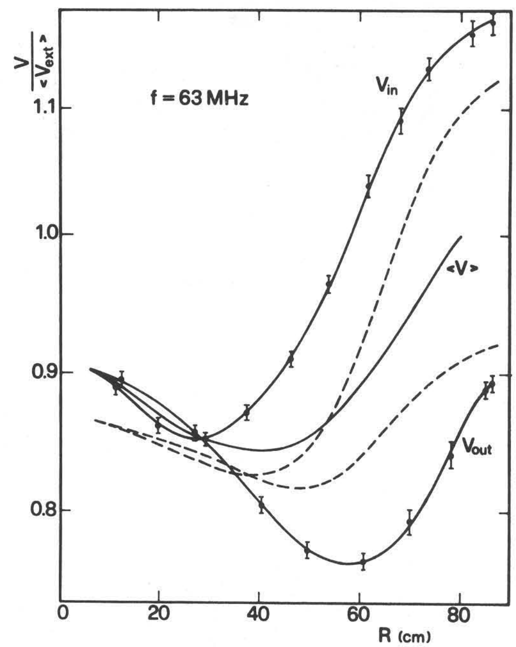

Fig. 9 - Voltage distribution along the dee radius, at 63 MHz. Experimental values (solid lines) and predicted ones (dashed lines) are shown.

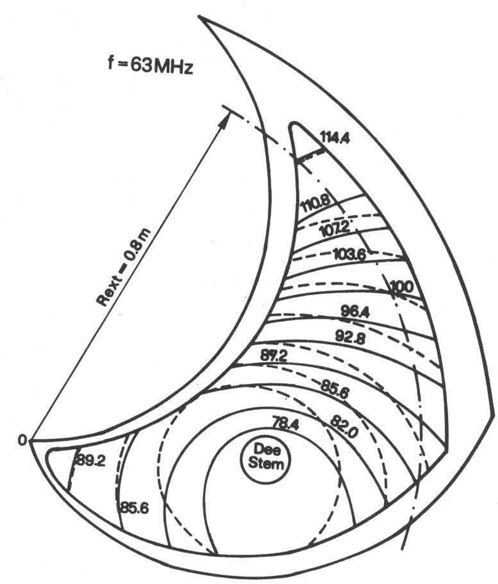

Fig. 10 - Propagation surfaces on the dee, at 63 MHz. Solid lines represent contours derived from model measurements, dashed lines predicted contours.

illustrated in fig. 10, where the actual and predicted equi-voltage contours on the dee are presented. It is indeed apparent from the figure that our calculations underestimated somewhat the effect of the dee spiral on field propagation surfaces.

Improved cavity design

The data, and their implications on the theoretical model used, have enabled us to produce a somewhat different and, we believe, optimized design of the cavity. This is shown in fig. 11. It can be noted

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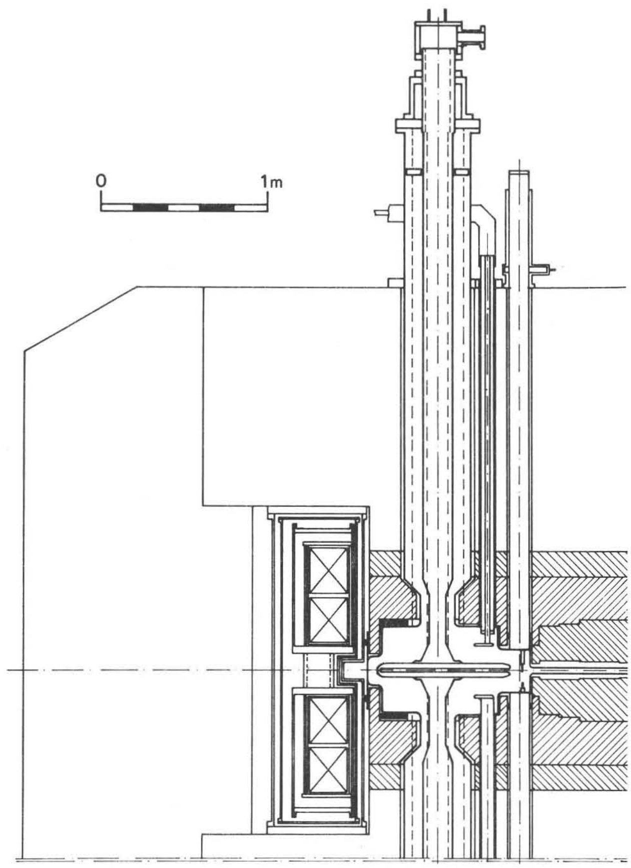

Fig. 11 - Possible improved design of the RF cavity. (see text for details)

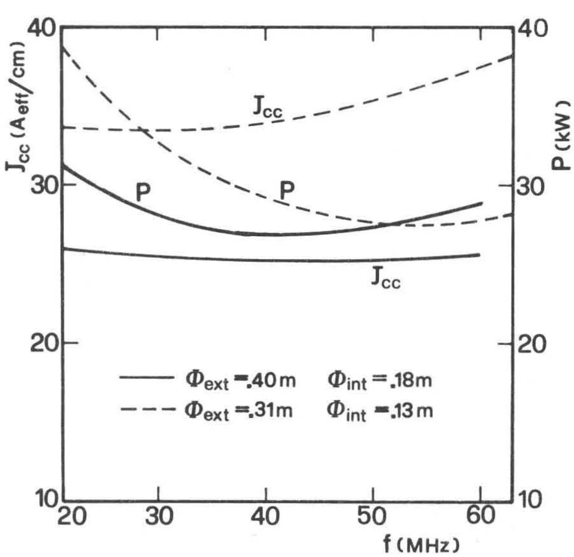

Fig. 12 - Solid lines: short circuit current density and total power in the cavity for the design of fig. 11, with tapering of the coaxial line. Dashed lines: short circuit current density and total power in the cavity for the design of fig. 11, with uniform diameter of the coaxial line (dashed lines in fig. 11).

that the internal diameter of the coaxial line has been increased to 180 mm from the original 150 mm diameter. On the other hand, the tapering down of both the inner and outer coaxial has been retained (also the latter diameter of 400 mm) since these features are really dictated, as stated before, by magnetic field constraints. This cavity should behave, as far as short circuit current density and total power are concerned, in the way shown in fig. 12 (solid lines). A peak dee voltage of 100 kV is of course assumed. It is apparent that over the whole frequency range the current density remains roughly constant at a remarkably low value of about 25-27 A/cm, while the power is in the neighbourhood of 30 kW.

A somewhat different geometry, which employs no tapering of the coaxial line, but smaller inner and outer diameters, of 130 mm and 310 mm respectively, has also been investigated. This is indicated by the dashed lines in fig. 11, and its corresponding properties are presented in fig. 12 (dashed lines). While the elimination of the coaxial line tapering would indeed provide some sensible mechanical simplifications, the comparison of solid and dashed lines of fig. 12 shows that the former should obviously be preferred, particularly in considering that, in the non-tapered resonator, the current distribution on the short circuit at high frequency is strongly non-uniform.

Conclusions

The overall comparison of experimental data and calculations shows that indeed a model is quite helpful, and in fact necessary, if the performance of the cavity has to be anticipated to better than 10%-20%. This is particularly true for the high frequency domain, where it is very difficult, and perhaps impractical, to further refine theoretical calculations.

A consequence of primary importance of the model study is that, with the present geometrical constraints, resonating frequencies above 60 MHz are difficult to reach and therefore a second harmonic mode should be used instead.

The data also show, as discussed above, that no large problems will arise, as far as current density and power are concerned, once the cavity is properly optimized.

To summarize, we believe that the information gathered so far is quite sufficient to proceed to a detailed design of the RF system with no unknowns left. A reduced scale model of the ensemble of the three cavities (perhaps 1:4) might, however, be built in order to study in some detail the coupling effects between the cavities.

References

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