Proceedings of the 14th International Conference on Cyclotrons and their Applications, Cape Town, South Africa

DESIGN OF THE R.F. CAVITY FOR A 200 MeV PROTON SUPERCONDUCTING CYCLOTRON

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The 200 MeV superconducting cyclotron for cancer therapy with protons, under study at L.A.S.A. (Laboratory for Accelerators and Applied Superconductivity), is designed with compact and low-power RF cavity. This paper describes the proposed cavity, equipped with two stems and operating at 115.8 MHz, and presents the design studies by using a first approximation calculation in the trasmission line approach, a refined calculation using the MAFIA 3D code and measurements on a 1:1 scale model. Results on the resonance frequency, voltage distribution in the acceleration gap, and power dissipation are reported together with the main construction details.

1 Introduction

A superconducting cyclotron dedicated to protontherapy has been designed and presented at this conference[1]. Particular care was dedicated to the RF cavity study, which presents some peculiarities:

- the shape is quite unusual, due to the use of two stems in order to minimize the dissipated power, obtain a correct voltage distribution and assure a good mechanical stability;
- it works in 3rd harmonics (115.8 MHz): for this reason its vertical dimension is fairly small to permit a complete location in the valleys;
- the total span of the dee in the extraction region must be at least 12 cm in order to accomodate the electrostatic deflector;
- it works at fixed frequency and has a fixed geometry; its length must be defined with a good precision in order to assure the design frequency. The permitted error in the determination of this parameter should be less than 0.2 MHz;
- the voltage in the central region has to be fairly low, less than 50 kV, in order to allow the injection of the protons from an internal source;
- the voltage in the extraction region must increase until 75-85 kV in order to permit a rapid crossing of the dangerous resonances and obtain a good extraction efficiency;
- the voltage in the other regions is less critical, but must not be lower than 30 kV in order to maintain the phase displacement of the particles less than 10° RF, supposing a magnetic field localized error of a few tens of gauss[1, 2].

A first appoximation analysis has been carried out by studying the problem in the trasmission line approach. As a second step, the design of the RF system has been defined in a better approximation by using the MAFIA 3D code. Finally, the theoretical results have been verified using a 1:1 scale model and the comparison of the results is reported in this paper.

2 General design

Figs. 1 and 2 are respectively an upper and a lateral view of the cavity showing the dees with the 120° symmetry, the position of the stems and the part of the dees of greater thickness for the mounting of the electrostatic deflector.

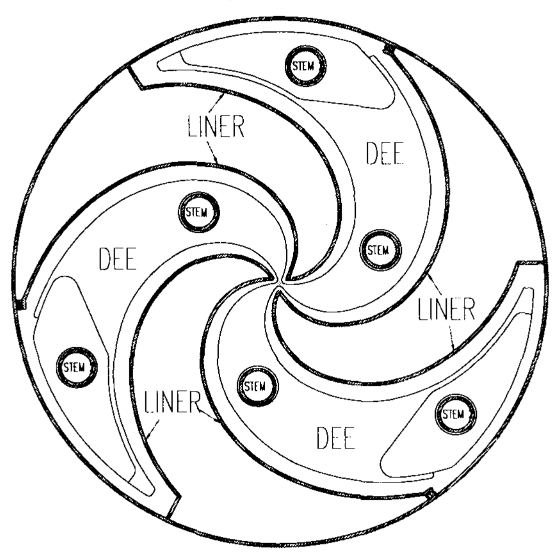

Fig. 1 : Upper view of the cavity

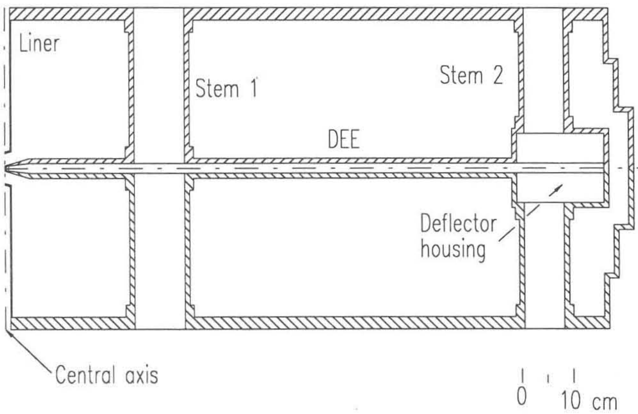

Fig. 2 : Lateral view of a third of cavity, along the median azimuth of the dee

The whole cavity consists of three identical λ/2 resonators, housed in the valleys of the cyclotron. Connected in the central region they realize an RF resonator with an azimuthal symmetry of 120°.

Each element consists of two λ/4 resonators, symmetric respect to the median plane of the cyclotron, shaped as a cylindrical box, and a semi-dee connected to the horizonta wall of the box by means of two stems.

The material chosen for the construction of the whole cavity is OFHC copper, cooled by a forced flow of demineralized water. In the inner side of the dees, a sheet of graphite is inserted in order to decrease the nuclear activation of the copper.

3 Calculation

In the analysis carried out by the trasmission line approach, one λ/4 cavity was considered, which is schematized by a number of constant impedance trasmission lines, parallel and series connected.

In this approximation the length of the cavity and the total power dissipated was calculated, adopting for the dees a shape which allows to maintain exactly a difference of 180° RF between the dees entrance and exit phase, for the whole accelerating range. This was possible because the particular shape of the hill. Their angular width in the region close to the median plane is decreased by mean of lateral grooves (adopted for the fine correction of the magnetic field[1, 2]), allowing an increased angular width of the RF liners. The geometry of the cavity results to be a little more complicated but, as consequence of the low dee-to-liner capacity so obtained, an important reduction of the power dissipated in the cavity has been obtained.

With this approach a first approximation shape of the cavity was found, which minimizes the dissipation power and by which a correct voltage distribution was obtained.

In order to obtain a better approximation, MAFIA code[3] was employed. It is a 3D code which calculates the most important quantities as the resonant frequency, the quality factor, the current and power distribution, etc. when used in the frequency domain.

In Fig. 2 a sixth of the cavity as schematized by code MAFIA is shown. In this figure is possible to see the liner walls (as cut in the "brick"), an half dee with the increasing height in the extraction region, and the two stems. In this figure the upper wall of the cavity (short-circuit) is not represented, in order to allow the view of the dee.

In the final runs about 636000 mesh points were used, corresponding to an element dimension of 7.6×7.6×16 mm^3. The vertical dimension of the elements was reduced to 3.3 mm in the region between zero and 3 cm from the median plane; the two horizonthal dimensions were reduced to 4×4 mm^2 in the central region in order to describe more correctly the complicated shape of the dees and the liners. This large number of mesh points entails a CPU time of the order of 4-5 hours using the IBM RS6000/550 workstation of the CERN computer center.

The principal results obtained by the computation were:
–the resonant frequency versus the cavity height;
–the accelerating voltage versus the radius;
–the quality factor, the total power dissipated and the upper resonant modes.

These data are reported in Figs. 3, 4 and in the Table 1; a few of them are compared with the experimental values obtained with the 1:1 scale model.

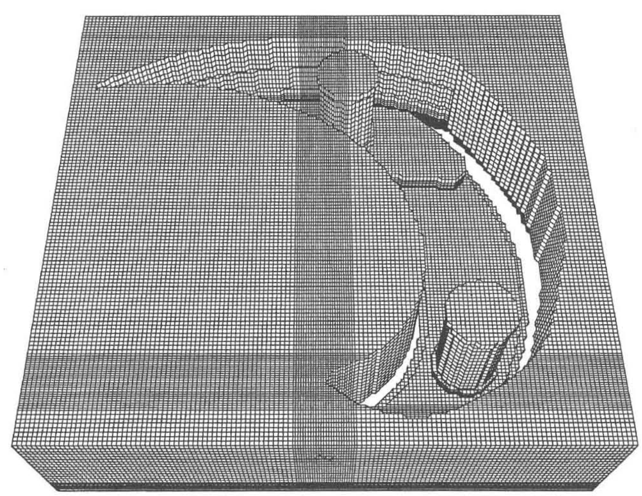

Fig. 2 : A sixth of the RF cavity schematized by code MAFIA

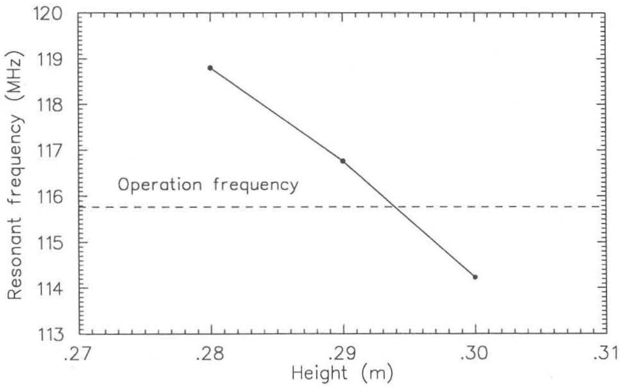

Fig. 3 : Resonant frequency vs. half cavity height

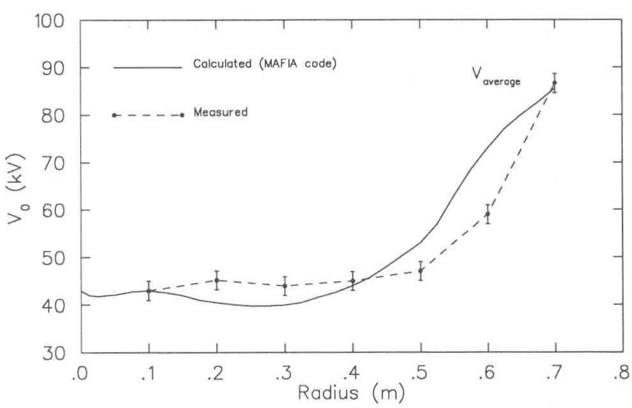

Fig. 4 : Accelerating dee voltage vs. radius

Table1 : Principal values obtained by MAFIA and 1:1 scale model

Values	*Calculated with MAFIA*	*Measured*
Quality factor (Q)	3790	3700
Total RF power	40 kW	-
First upper mode	152 MHz	120 MHz

4 Experimental measurements

A complete fiability of the design has been finally obtained by measurements on a 1:1 scale RF model. This model was realized with wood plates covered with a thin copper sheet. The central region of the dees and liner were machined from bulky copper and screwed to the rest of the cavity. The internal height of half cavity was chosen 29 cm, corrisponding to a calculated frequency of 116.8 MHz (see Fig. 3).

The model, realized and installed at the Cyclotron Laboratory of the Center A. Lacassagne in Nice, is shown in the picture of the Fig. 5. In this picture the three-fold structure of the cavity is clearly visible. The three dees assemble is lifted and is ready to be inserted in the lower liner. It is interesting to notice the shape of the dees with the increasing height in the extraction region and the couple of cylindrical stems for each dee. It is also possible to note the particular shape of the liner, with different steps which increase the angular width of the liner in order to minimize the dee-to-liner capacity.

With this model, measurements of resonant frequencies, quality factor and accelerating voltage were made.

Measurements of the resonant frequencies and quality factor were carried out by means of a network analyzer. The resonant frequency results to be 117.7 MHz, with an error of 0.8% respect to the calculated value.

The measured quality factor Q was about 3700, in good agreement with the teoretical one (see Table 1). In the same table the first upper mode is reported as calculated and measured. The upper mode of 120 MHz measured in the model is probably due to some asymmetry between the cavity. In any case this mode is not dangerous because it is far enough from the resonant frequency and the peak at the excitation frequency of 120 MHz is 15 times lower than the peak of the operating frequency. The voltage of this upper mode exitated at the operating frequency results to be about $5 \cdot 10^4$ times lower than the voltage of the resonant frequency.

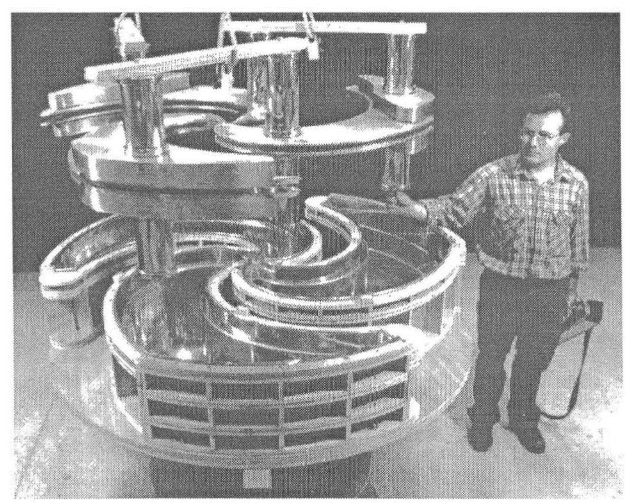

Fig. 5 : 1:1 scale RF model with the dees lifted

The accelerating voltage was calculated as $\int \mathbf{E} \cdot d\mathbf{l}$ along the gap between dee and liner. The value of the electric field **E** was obtained with resonant perturbation measurements. In this measurements a dielectric perturbing bead with a diameter of 12 mm was used and the value of the electric field was calculated from the relation[4]:

$$E \div \left(\frac{\Delta\omega}{\omega} \right)^{1/2}.$$

The perturbing bead was positioned at different radii, and for each radius 16 measurements were taken along the gap. The accelerating voltage, calculated as the average of the entrance and exit voltage, is reported in the Fig. 4. These values have been normalized to 42 kV in the central region, in order to comparate them with the calculated data.

The agreement is good until the radius of 50 cm, and in the region between 50 and 65 cm the differences seem to be bigger. This disagreement needs further investigation, but it is not very determining for the accelerating process.

Other measurements were done in order to verify the possibility to change the resonant frequency of the cavity, displacing the external stems.

In the Fig. 6 the resonant frequencies versus the stems displacement are reported, showing that it is possible to change the frequency of about 0.2 MHz with a displacement of only 2 mm. This result gives the possibility of obtaining very precisely the operating frequency of the real cavity varying in a simple way the geometry of the cavity, without changing its height.

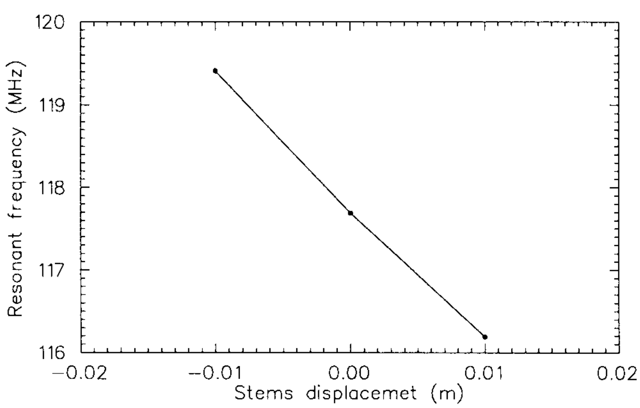

Fig. 6 : Resonant frequency vs. external stems displacement

5 Conclusions

The design of the λ/2 three-fold cavity for the 200 MeV superconducting proton cyclotron has been obtained. The design is based on a first approximation analytical calculation in the trasmission line approach, the use of the finite elements MAFIA 3D code and on RF measurements using a 1:1 scale model.

The peculiar characteristics of the cavity were tested and obtained in a good approximation. A methode to obtain the exact resonant frequency, by adjusting in a simple way the final position of the external stems in the real cavity, was tested.

Acknowledgments

The authors want to thank Mr. M. Bonezzi of the LASA Lab. (INFN - Sez. di Milano) for his contribution to the cavity design, Mr. G. M. Bergerot and J. F. Di Carlo of the Cyclotron Lab. of the Centre A. Lacassagne (Nice), for the construction of the cavity model and the execution of the measurements.

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