MODEL MEASUREMENTS AND PRELIMINARY DESIGN OF THE R.F. CAVITIES FOR THE EULIMA CYCLOTRON CONCEPT

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Abstract: A preliminary study of the radio-frequency cavities for the EULIMA separated-sector cyclotron is presented. A symmetrical cavity scheme with a multi-stem delta-shaped electrode has been studied. Numerical computations and model measurements have shown that a cavity with the desired frequency and peak voltages of 100 and 200 kV at injection and extraction is feasible. The preliminary design of the cooling system and of the mechanical assembly of the cavity is briefly presented.

Introduction:

Efficient radio-frequency cavities must be designed and are expected to be a reliable part of the whole accelerator of which characteristics are presented extensively in ref. [1,2] . The proposed radio-frequency system for the EULIMA separated-sector, superconducting isochronous cyclotron consists of two resonant cavities located in opposite valleys, operating at a fixed frequency and providing 100 and 200 kV peak voltages at injection and extraction. Designs for two possible final beam energies (340 and 430 MeV/n, z/A=0.5) and two operation harmonics (h=4,6) that correspond to 69.6 and 104.4 MHz have been investigated.

The required final beam energies, the high operating frequencies and the strong beam focusing (spiral-shaped magnet sectors) result in geometrical and mechanical constraints that make the achievement of a reliable cavity a difficult task. Due to the strong dee expansion and operating frequency , the cavity design involves several coaxial resonators normal to the dee and symmetrically located with respect to the beam reference plane.

In this paper, we present the studies accomplished so far for the 430 MeV/n EULIMA cyclotron R.F. cavities. A preliminary optimization of the cavity shape has been obtained with a compuational method that derives from transmission line theory and a model has been built to check the validity of the method. Results are commented in a following section. Other possibilities (lower energy (340 MeV/n "carbon" machine) and sixth harmonic operation) have also been under study and are briefly presented as well as the design of the cooling system and mechanical assembly of the cavities.

Numerical model of the R.F. cavities:

Due to the complex geometry of the cavity (spiral-shaped dee and liner), it is very difficult to use existing three-dimensional computer codes such as MAFIA since they require a tremendous number of grid points to obtain a satisfactory representation of the cavity geometry. Therefore, a computational method following a classical approach in modern cyclotron cavity design [3] and adapted from the coaxial line theory has been used. It must be noted that this method is applicable only if a TEM-like mode is expected.

The cavity is subdivided into a suitable number of line elements as shown in Fig.1, each of them being characterized by a constant characteristic impedance. The actual contours of the line segments are obtained by estimating the current and "equipotential" lines under assumed resonance conditions. The characteristic impedance is computed with the bidimensional computer code POISSON from the "average" section geometry of the corresponding line segment. Three-dimensional distortion due to the spiral shape of the dee and liner must be suitably accounted for . Capacitive terminations are added to take into account the effects encountered at the line ends.

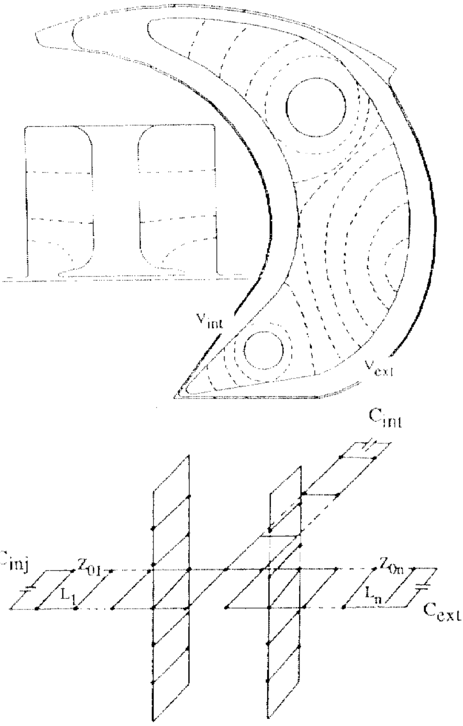

Fig. 1 : Cavity subdivision into line segments and corresponding schematical model. The dashed lines correspond to the estimated equipotential lines on the dee.

Based on this representation of the cavity, a program using elementary transmission line equations , calculates (for a given cavity geometry i.e. from the distribution of characteristic impedances) the voltages along the gaps, the short-circuit current density, the currents flowing through each segment, the quality factor Q and the required R.F. power. Once these steps are performed, refined calculations are carried out in order to compute more accurately the current density and heat distribution in the whole cavity,which allows an optimization of the water-cooling system.

Clearly, the accuracy and the validity of the whole design method is critically dependent upon the estimate of the actual locations of the equipotential lines , which are typical of a TEM-like mode. An initial far-off guess may lead to an erroneous estimate of the R.F. parameters of the cavity. It must also be stressed that the uncertainties due to the method increase with the frequency and the number of stems. Furthermore, a fixed-frequency design imposes an accurate definition of the geometrical parameters of the cavity for short-range tuning systems are to be used. Since the operating frequencies are quite high, it is of utmost importance to check the computational results with measurements on a model.

Half-scale model measurements:

In a first approach, it was decided to build a half-scale model of the 69.6 MHz cavities of the 430 MeV/n cyclotron with two symmetrically located stems. As compared to cavities with a larger number of stems, they require smaller R.F. power . Considering the dee dimensions and the short quarter-wave length of the design frequency, it appeared that two stems expanding symmetrically along the dee were needed. This kind of two-stem cavity has been designed for the SIN 72 MeV new injector [4] with similar dimensions and frequency but with a straight dee (no spiral shape).

Measurements on the half-scale model showed that the expected TEM-like mode was not present, which was not easy to predict without checking on a model. Consequently, the gap voltage distribution did not correspond to our expectations. It could be inferred that the excessive horizontal expansion of the stems along the dee and the reduction of the cavity height resulted in an impossibility for the magnetic field lines to circle around the stem as expected. It can be noted that superconducting cyclotrons such as AGOR or the Milan K-800 have cavities operating in a TEM-like mode at slightly lower frequencies and with a similar spiral geometry, but the stem expansion is not so inportant since the external radius of the machine is much smaller (about one half) [3,5] .

A solution with four stems instead of two can still be envisaged if the stem expansion along the dee is not excessive. Cylindrical stems were used since they are easy to build. Following design calculations, the two-stem half-scale wooden model covered with copper sheets that are electrically connected together by tin soldering was modified to include four stems as can be seen in Fig. 2.

Fig. 2 : View of the half-scale model.

So as to double-check the agreement between computations and experimental results, the frequency and gap voltage distribution were measured with two different devices. Firstly, a network analyzer HP8753B was used for both frequency and voltage measurements. Alternatively, a vector-voltmeter for voltage measurements was combined with a R.F. generator. This latter method has been used extensively at GSI, SIN and TRIUMF for similar measurements on cavities with long gaps [6,7] . The R.F. signal is generated either by the network analyzer internal source or by the Rhode und Schwarz SMS generator. It propagates through the cavity and output signals are measured with two different probes. One of them remains at a given location (for instance near the extraction radius) and is used as a reference. The other probe is moved along the gaps. The difference between the two signals gives a direct indication of the relative voltage distribution.The results obtained with both measuring apparati were in good agreement (within a few percents).

For a given geometry of the dee and liner, the frequency and gap voltage distribution depend on the diameter and position of the stems with respect to the dee and on the cavity height (short-circuit). By adjusting properly these parameters, one is able to tailor the gap voltage distribution and compensate the effects of dissymmetry due to the spiral shape of the dee. With a fundamental frequency of 134 MHz, which corresponds to 67 MHz at full scale, a suitable gap voltage distribution was obtained and is shown in Fig.3. An estimate of the equipotential lines is given in Fig. 1 where they correspond to the dashed lines. The reproducibility of the measurements was within two percents. Other modes were also observed on the spectrum analyzer display as shown in Fig.4. In particular, a higher mode resonated at 154 MHz, with opposite voltages near the injection and extraction regions and a zero voltage at an intermediate radius. This mode and the upper ones are obviously not desirable for acceleration purposes. Precautions must be taken to damp them.

A preliminary study of the frequency tuning mechanism was made on the model in order to evaluate the disturbation induced by cylindrical trimming boxes on the voltage distribution. Several positions with respect to the stems were investigated. It appeared that a variation of the frequency of two percent could be tolerated without excessive disturbance of the voltage distribution.

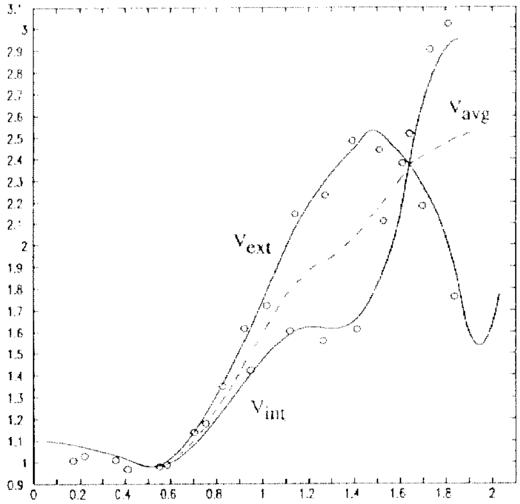

Fig. 3 : Measured and computed gap voltage distribution for the 430 MeV/n cyclotron cavity (fourth harmonic).

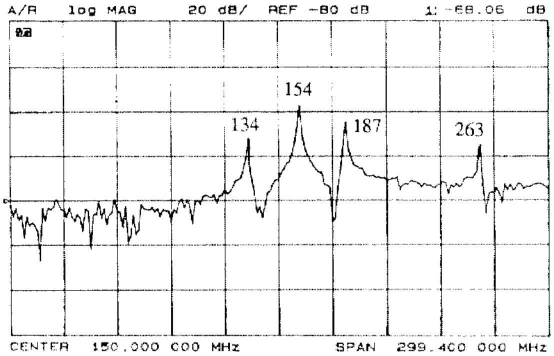

Fig. 4 : Frequency spectrum measured on the half-scale model for the 430 MeV/n cyclotron cavity (fourth harmonic).

Power loss estimates:

The wooden half-scale model is cheap and easy to build and modify but it has an inherently small quality factor Q and no realistic estimate of the cavity losses can be deduced from the present measurements. The data from the model were used to refine our computational scheme and obtain the main characteristics of the cavity for the 430 MeV/n cycotron operating at 69.6 MHz. They are summarized in Table 1. Computational investigation of the sixth harmonic operation of the same machine and the fourth harmonic operation of the 340 MeV/n cyclotron has also been done and the corresponding results are also visible in Table 1.However, no check has been made on a model yet. Uncertainties on the estimate of Q may be as large as 20%. Further optimization of the cavity geometry should lead to improved values of the quality factor and R.F. losses.

Table 1 : Main radio-frequency parameters for the various cyclotron versions.

Energy (MeV/n)	340	430	430
Harmonic Number	4	4	6
Frequency (MHz)	72	69.6	104.4
R.F. Power (kW)	140	155	95
Injection Voltage (kV)	110	110	110
Extraction Voltage (kV)	220	250	150
Quality Factor Q	8800	8500	6800
Cavity Height (m)	1.00	0.95	0.56
Number of stems	4	4	6
Beam Turns	1100	1100	2000

Thermal calculations and preliminary mechanical design:

Because of the high power dissipation in the R.F. cavities , an efficient water-cooling system must be designed in such a way that the temperature at any location should not exceed ten degrees above its value near the cooling pipes in order to minimize thermally-induced stresses in the copper walls and frequency drifts due to overheating.

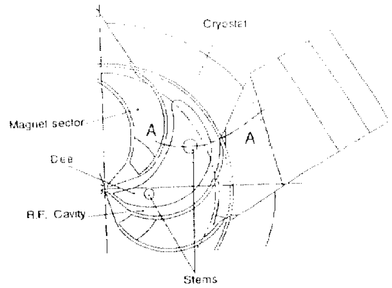

Fig 7.a : Top view of a quarter of the cyclotron

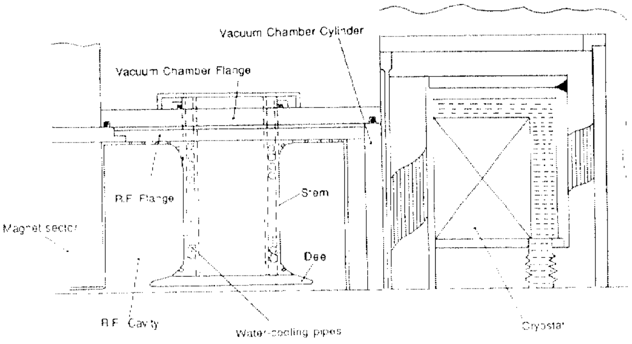

Fig 7.b : AA cross section of the R.F. cavity and cryostat

Two programs are used to compute the temperature distribution in the whole cavity. The three-dimensional finite-element package ANSYS allows to design the cooling sytem of the stems and R.F. contacts. The location of the cooling pipes was calculated with our program PIPE for a given heat distribution in the cavity liner walls, short-circuit plate and dee under the above-mentioned temperature constraint. A limit on the water flow velocity of less than 1m/s was imposed in order to avoid excessive mechanical vibrations in the dee and stem structures) .

A preliminary mechanical concept of the cavity is shown in Fig.5. Since the cavities are designed to operate at a fixed frequency, no complicated tuning mechanism with sliding short-circuit contacts is necessary. Furthermore, the vacuum chamber design is simple [1] since no alumina insulator is involved. A system that allow an accurate position of the dee with respect to the liner has to be designed as well as a structure that makes the whole assembly (dee and stem) sufficiently rigid.

Conclusions:

One of the important issues of the EULIMA feasibility study is the achievement of reliable and efficient radio-frequency cavities. Therefore, simple designs should be preferentially retained. Studies accomplished so far show that a simple design of the R.F. cavities for the required particle frequency in a 430 MeV/n cyclotron can be achieved and pursued towards more advanced stages once the features of the accelerator are completely determined. In the meantime, it is important to investigate various other solutions before a final decision is made. If one opts for a sixth harmonic operation, first computations indicate that the desired voltage ratio (2:1) may not be reached for the present cavity geometry. This might be verified with measurements on a refined model.

Acknowledgements:

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