DESIGN OF AN RF SYSTEM FOR AN OPEN-SECTOR CYCLOTRON

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Abstract

An open-sector cyclotron with a K-factor of 200 which will accelerate light and heavy ions has been proposed as a national accelerator facility for South Africa. An RF system for this accelerator is presented. The design aim is for a 1 MeV energy gain per revolution and a frequency range from 8.6 to 26 MHz. Different types of resonators were investigated and a half-wave resonator with a delta-shaped accelerating electrode was found most suitable. A computer program for calculating the characteristics of this type of resonator was developed. Scaled models of delta resonators of different designs were constructed to measure the resonator characteristics and to compare it with calculations. Power loss, voltage distributions, current densities and fundamental and higher resonance frequencies were measured. The design of the power amplifier and the coupling to the resonator were also investigated.

1. Introduction

The proposed open-sector cyclotron (OSC) will be capable of accelerating protons to 200 MeV and heavy ions to an energy of about 18 MeV/nucleon for Argon. Solid-pole cyclotrons will be used as injectors for this four-sector machine. The main resonators of the OSC will occupy two opposite valleys thereby leaving sufficient space for the components of the inflection and deflection systems as well as for two flat-topping cavities in the remaining two valleys. Each resonator will be driven from a common frequency synthesizer through a phase and amplitude stabilizer, a driver stage and a power amplifier. Since many of the components operating at a low power level are commercially available, only the proposed resonators and power amplifiers will be discussed in this paper. In the past cavities[1] and various types of delta resonators[2][3][4] have been proposed as resonators for the OSC. The characteristics of these resonators have been studied and compared in order to select a suitable type of resonator for the OSC. A half-wave resonator with a delta-shaped accelerating electrode was chosen. This type of resonator was also studied by measurements on models. Two amplifier designs and impedance matching schemes are discussed.

2. Considerations for the Choice of a Resonator

Some of these considerations as dictated by the design of the injector, the magnets of the OSC, the beam quality and the inflection and deflection systems are discussed below.

2.1 Available Space

A magnet angle of 34^{0} was chosen in order to prevent serious resonances in the betatron oscillations and to have the OSC compatible with the injector machines. The space available for each main resonator and its vacuum chamber is therefore limited to a segment which subtends an angle of 56° at the centre of the machine. Depending on the injection energy, the space in the vicinity of the first orbit is particularly crowded.

2.2 Frequency Range and Harmonic number

The magnetic flux density in the OSC is again determined by compatibility with the injector. This leads to a maximum orbital frequency of 6.5 MHz. The lowest orbital frequency will occur with acceleration of heavy ions and will be approximately 0.5 MHz. In order to maintain the same ratio between the harmonic numbers of the injector and the OSC for light ions a 3-to-1 frequency range is required for the resonators of the OSC. Operation with a variable ratio between the harmonic numbers requires either a variable deflection system in the injector or a variable injection system in the OSC. If the OSC is operated with delta resonators at harmonic numbers different from those at which peak energy gain occurs the beam pulses are either compressed or expanded in the azimuthal direction[5]. A 3-to-1 frequency range is a prerequisite for obtaining peak energy gain per revolution over a wide energy range with this type of resonator.

A further restriction on the harmonic number is due to the transit-time effect[6]. This phenomena limits the effective energy gain per revolution which can be obtained. For an accelerating gap size of 10 cm the harmonic number is limited to 30 to ensure that the beam will never be retarded.

2.3 Energy Gain per Revolution

In order to obtain sufficient orbit separation for extraction an energy gain of at least 1 MeV per revolution is aimed for. A large energy gain per revolution will also reduce the tight tolerances on the magnets.

2.4 Voltage Distribution

Depending on the voltage distribution in the resonators the RF magnetic field will either compress or expand the beam pulses[7]. A constant or radially increasing voltage will therefore mostly be desirable.

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3. Comparison of Different Types of Resonators

Both cavity and delta resonators are used in open-sector cyclotrons. The delta resonators are connected either as a part of a quarter or a half-wave system.

3.1 Cavity Resonators

Experience in the design, construction and use of such resonators have been accumulated at the Swiss Institute for Nuclear Research[7]. High accelerating voltages can be obtained in these resonators at moderate RF power consumption. The centre particle in a beam pulse can always cross the gap at peak voltage for all harmonic numbers and except for the transit time effect, the energy gain per revolution is not influenced by the dimensions of the resonator. Phase compression will therefore only occur due to the voltage distribution which increases with the radius of the cyclotron for the part of the resonator used. The frequency of the cavity resonators can be changed by adjusting the top and bottom plates. However, the frequency range is limited and a 3-to-1 ratio cannot be obtained with practical dimensions. It is therefore impossible to operate an OSC with cavity resonators together with a solid pole cyclotron as injector, over a wide frequency range, without changing the ratio between the harmonic numbers frequently. To reduce the effect of transit time, small accelerating gaps will be necessary because the lowest frequency (40 MHz) obtainable with practical dimensions is about seventy times higher than the lowest orbital freqency for heavy ions in the proposed OSC. With such small gaps it will be difficult to prevent sparkover with the high voltages required for the acceleration of light ions to high energies. Mainly due to these reasons it was decided not to use cavity resonators for the proposed OSC.

3.2 Delta Resonator connected in a Quarter-Wave Configuration

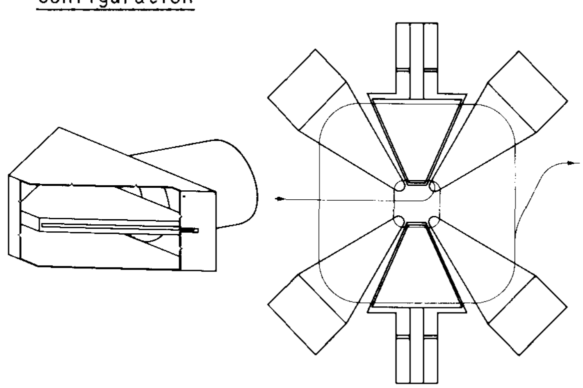

Figure 1. A quarter-wave delta resonator and the positioning of two of them in the OSC.

To allow space for the injection and extraction systems and possible flat-topping resonators, only two delta resonators can be used. The peak voltage is half of that required with cavity resonators for the same energy gain per revolution because each resonator has two accelerating gaps. A 3-to-1 frequency range can be obtained by adjustment of shorting plates and capacitive tuning of the delta. The accelerating voltage decreases with the radius of the cyclotron and the maximum obtainable frequency is limited to a value at which sufficient orbit separation can still be achieved for extraction. This maximum for the proposed OSC is between 15 and 20 MHz. This is too low for the fourth harmonic of the maximum orbital frequency. If lower harmonic numbers are used, it results in a lower energy gain per revolution for the same RF voltage and also results in phase compression of the beam, because the delta angle cannot be increased. For these reasons this type of resonator is not suitable for the proposed OSC.

3.3 Delta Resonator Connected in a Half-Wave Configuration

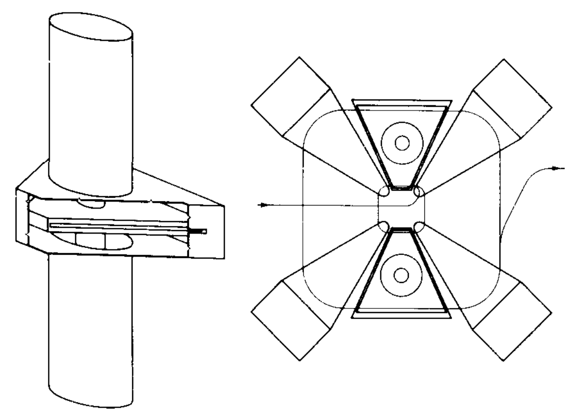

Figure 2. A half-wave delta resonator and the positioning of two of them in the OSC.

The accelerating electrode is the same as in figure 1, but the transmission lines are different, resulting in a doubling of the maximum frequency. Variation in the voltage distribution can be obtained by varying the position where the two vertical lines are connected and by varying their diameters. In this way maximum voltage can be obtained at extraction radius. The RF power consumption for this type of resonator is favourable compared to cavity resonators for the same energy gain per revolution. The same limitation of delta angle and harmonic number as with the quarter-wave delta applies but because of the higher frequencies possible and the suitable voltage distribution this type of resonator was selected, using the fourth harmonic number.

4. Design of a Delta Resonator Connected in a Half-Wave Configuration

Because of the complicated boundary conditions it is difficult to determine the characteristics of this type of resonator analytically. An approximation, in which circuit theory and the theory of uniform transmission lines are used, is therefore made. It is used for the prediction of most of the resonator characteristics and for the design of models. The final resonator design is obtained both from calculations and measurements on models.

4.1 Calculation of Resonator Characteristics

The delta is considered to consist of ten uniform reactangular co-axial lines, all of equal length, but each with a different cross-section as shown in figure 3.

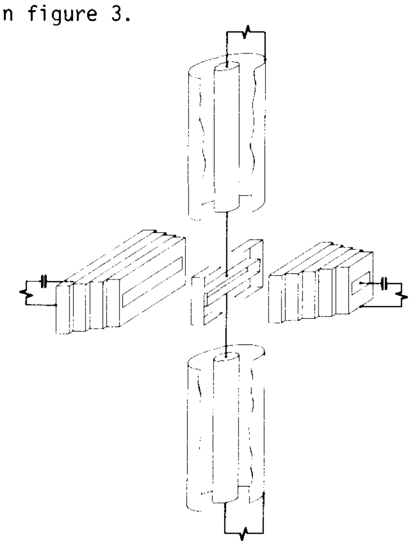

Figure 3. The model used for the calculation of the characteristics of a half-wave delta-resonator.

The resistances of the shorting plates and the capacitances between the end points of the delta and vacuum chamber are also shown. By means of a computer program based on this model the most important characteristics of the resonator i.e. resonance frequencies, power loss and voltage and current distributions can be calculated. Under certain conditions the delta can also be represented by an equivalent capacity for the calculation of some of the characteristics.

4.2 Method of Frequency Variation

The resonance frequency can be varied by changing the positions of the short-circuit plates and/or by adjusting the capacity between the delta and the chamber as shown in figure 4(a). Two possible ways of varying capacity are shown.

In the proposed resonator tuning will be done by means of short-circuit plates for high frequencies and variable capacitors for low frequencies. The variable capacitors are needed to obtain the low frequencies without using very long transmission lines as shown in figure 4(b). For this graph the delta was considered as a capacity (C), being the capacity between it and the chamber. The minimum value for the proposed resonator is approximately 500 pF. For a maximum length L of 2,5 meters the capacity will have to be varied between 500 and 1 000 pF to cover the frequency range down to 8,6 MHz. A large capacity results in high power loss and may cause spark-over problems if the distance to the delta becomes smaller than the accelerating gap. This occurs when C is larger than 1 000 pF. Lower frequencies can be obtained by a further increase of C but the maximum voltage will be reduced. The voltage distribution depends on the position of the lines at high frequencies but is practically constant at low frequencies.

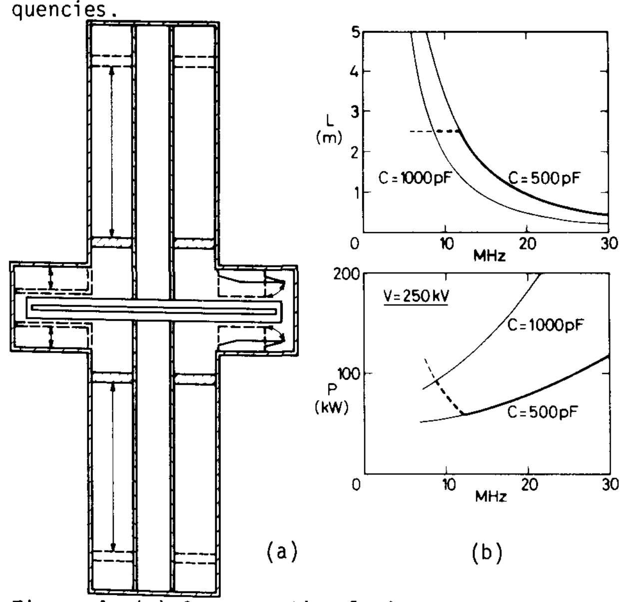

Figure 4. (a) Cross-sectional view of a resonator with movable short-circuit plates and two types of capacitance variation. (b) Variation of the length of each transmission line (L) and power loss (P) as a function of frequency for different values of delta capacity.

4.3 Resonator Dimensions

The angle between the centre lines of the accelerating gaps is determined by the magnet design and the choice of harmonic number. The size of the gap and the radii or curvature of the electrodes are obtained from considerations of spark-over and the transit-time effect. From the above radial and azimuthal dimensions of the delta can be determined. The height of the delta must be sufficient to accommodate the beam, the structure from which mechanical strength is derived and a possible flat-topping resonator which may be built inside the delta. The height of the vacuum chamber above and below the delta should be sufficient to prevent excessive power loss above 20 MHz but still allow the short-circuit plates to come close enough to the delta to obtain the required maximum frequency.

The outer diameter of the line, which should be as large as possible, is limited by the available space on the vacuum chamber. For a given outer diameter an optimum inner diameter can be obtained from figure 5. This is for the proposed resonator without considering capacity variation. The maximum current density (maximum practical value about 70 peak A/cm) at the highest frequency is a limiting factor, giving a maximum characteristic impedance (Z) of 75 ohm (inner diameter 0,29 of outer diameter). If Z is decreased it results in longer lines, which becomes a problem at low frequencies. A value of 75 ohm is also close to the optimum when considering power loss.

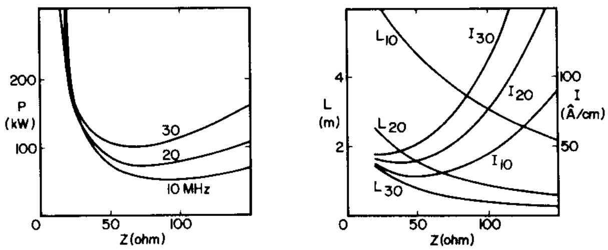

Figure 5. Variation of energy loss (P), peak current density (I) and length of each transmission line (L) as a function of the characteristic impedance (Z) of the lines, using a fixed outer diameter at three different frequencies (i.e. 10, 20, and 30 MHz).

From the above considerations the following dimensions for the resonator were obtained:

Size of accelerating gap	70 mm
Radius of curvature of electrodes	25 mm
Angle between centre lines of the gaps	49°
Radial length of delta	3,25 m
Height of delta	250 mm
Height of vacuum chamber	1,0 m
Length of each line	2,5 m
Outer diameter of line	1,75 m
Inner diameter of line	0,5 m

4.4 Electrical Characteristics of the Resonator as Determined by Measurements on a Model

The following characteristics were obtained, after conversion to full size, from measurements on a model one fifth full size. (L max. 1,5 m).

Frequency range	9 - 30 MHz
Power loss for 250 kV at 26 MHz	90 kW
Maximum current density in short-circuit plates	65 peak A/cm
Voltage minimum/voltage maximum at 26 MHz	0,8
Q-value	11 000

The higher order resonances R_2, R_3 and R_4 which were measured in the range up to 90 MHz are shown in figure 6. R_2 and R_3 are resonances due to the length of the delta itself and are practically independent of the position of the short-circuit plates.

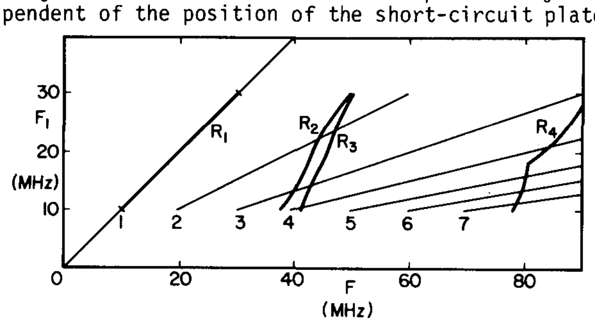

Figure 6. The relation between the required frequencies (F_1) and the resonance frequencies (R_n) obtained from the measurements on a model. The thin lines (2 to 7) represent harmonics of the required resonance frequencies (R_1).

5. The Power Amplifier and Coupling System

Two types of amplifier were considered. Commercial amplifiers for short-wave broadcasting are available and can be modified to cover a frequency range with a maximum of 30 MHz. For such an amplifier the impedance of the resonator and coupling system should be 50 ohm. Another type of amplifier in which the tube is directly coupled to the resonator through a capacitor inside the vacuum chamber, is shown in figure 7. In this case the impedance presented to the tube will be about 700 ohm.

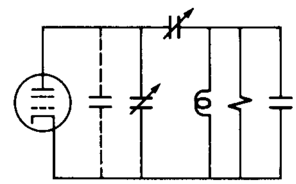

Figure 7. Simplified diagram of an amplifier directly coupled to a resonator.

The required impedances for both amplifier types can be achieved by adjustment of either the variable capacitor in parallel with the tube or the variable capacitor in series with the resonator over a 3-to-1 frequency range and for beam currents up to a few hundred µA. The parallel capacitor is outside the vacuum chamber and therefore easier to adjust.

6. Resonators for Flat-topping Systems

It is difficult to obtain flat-topping resonators capable of working up to the maximum required frequency of 52 MHz. Delta-resonators as proposed by Mosko [3] are suitable. Resonators similar to the half-wave delta-resonator described, with adjustable shorting plates, but with large triangular dimensions for the transmission lines can also operate up to these frequencies, as verified by measurements on a scaled model. Cavity resonators can also be used but it will be necessary to change the harmonic number if the main resonators are operated over a wide frequency range. The usable phase width changes with harmonic number.

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