A FLAT-TOPPING SYSTEM FOR THE NAC SEPARATED-SECTOR CYCLOTRON

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A fixed-frequency flat-topping resonator is described, which will fit into one of the existing valley vacuum chambers of the separated-sector cyclotron. The intensity and quality of the external beam current for isotope-production and neutron therapy will be improved significantly with the introduction of such a flat-topping system. Optimisation of the resonator dimensions and the results of orbit calculations with the additional resonator, are discussed.

1 Introduction

The NAC [1] operates a separated-sector cyclotron (SSC) and two solid-pole injector cyclotrons (SPC1 for light ions and SPC2 for heavy ions and polarized protons and deuterons). Beams are used for proton therapy (at 200 MeV for 4 days per week), neutron therapy (with 66 MeV protons for 3 days per week), radioisotope production (with 66 MeV protons for 4 nights per week) and nuclear physics research (over weekends). To accomplish this requires nine beam energy changes per week. Beam time is consequently limited and high beam currents have to be used for radioisotope production. The available beam intensity at 66 MeV is restricted to about 120 μA by beam losses (1 μA) at extraction in the SSC. Further improvement in beam intensity and quality before the SSC appears at present unlikely, since the 300 μA beam, extracted from SPC1, is limited by the longitudinal space-charge force. A flat-topping resonator is therefore envisaged for the SSC to improve the intensity and quality of the 66 MeV proton beam, which is produced at an RF frequency of 16.37 MHz. Figure 1 shows calculated beam widths due to energy spread as a function of radius in the SSC, for 66 MeV proton beams with and without flat-topping. The beam width due to energy spread at extraction can be decreased from 23 mm at present for a 20° long beam pulse without flat-topping to 5 mm for a 40° beam pulse with a flat-topping system. With this reduction in beam width it should be possible to extract beams of more than 200 μA from the SSC with a beam loss of 1μA.

2 Design considerations for a flat-topping system

Figure 2 shows the SSC layout. Less than one half of the injection valley vacuum chamber is available for a flat-topping resonator. The largest double-gap resonator that can be fitted into this space azimuthally has a dee angle equal to one-third of those of the main resonators and will therefore operate at three times the main RF frequency. A dee angle of 16.5° is required between the centrelines of the accelerating gaps, with a dee voltage of 50 kV at a frequency of 49.1 MHz. Since a new vacuum chamber would be too expensive and long down-times for

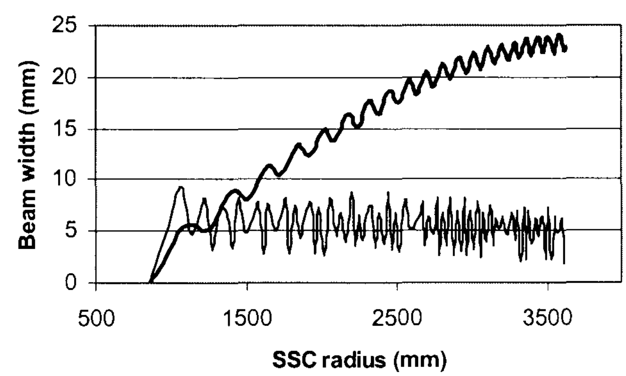

Figure 1: Beam width due to energy spread as a function of radius for a 20° long beam pulse without flat-topping (thick line) and for a 40° beam pulse with a flat-topping system, consisting of two dees in opposite valleys.

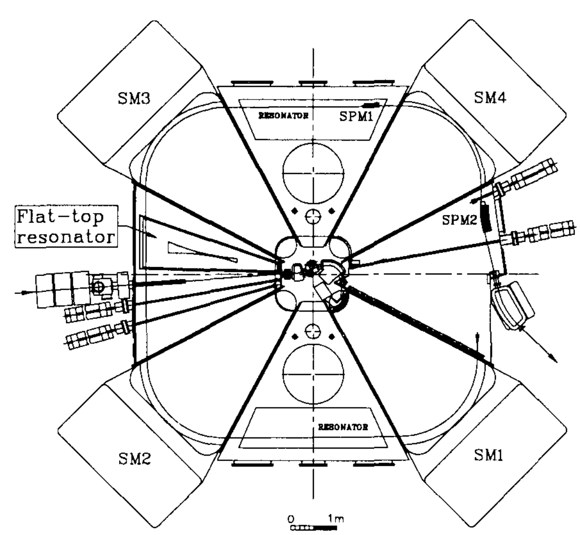

Figure 2: Layout of the SSC showing a flat-topping dee in the injection valley vacuum chamber.

modifications to the existing chamber are not desirable, the resonator will have to be installed through the 600 mm high and 1200 mm wide port at the back of the chamber. The inner height of the vacuum chamber is 1035 mm.

Because of the relatively low injection energy of 3.15 MeV and the high flat-topping dee voltage, it would have been better (depending on the radial voltage distribution of the flat-topping resonator) to use two flat-topping dees in opposite valleys in order to keep centering errors small and to obtain better beam quality. The improvement in beam quality that can be obtained with only one resonator is, however, still significant, as is shown in figure 3. For a 40° beam pulse the beam width due to energy spread at extraction will be 9 mm with only one flat-topping resonator, compared to 5 mm with two flat-topping dees.

The radial voltage distribution of the flat-topping resonator will, in general, differ from those of the main

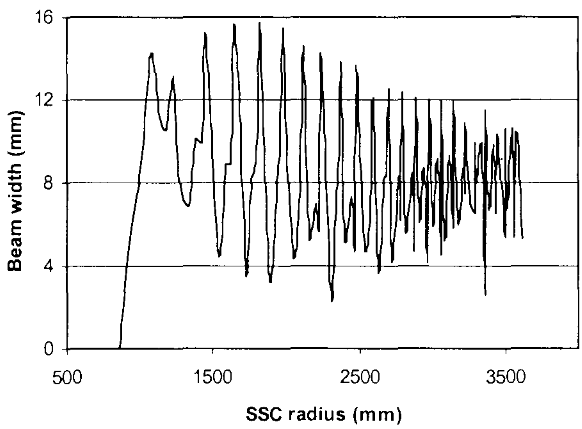

Figure 3: Beam width due to energy spread as a function of radius for a 40° long beam pulse with one flat-topping resonator and a voltage distribution identical to those of the main resonators.

resonators and the average value has to be adjusted for minimum energy spread and beam width at extraction. With different voltage distributions the radial beam width increases with radius from injection before it decreases again to a minimum at extraction. Since the beam passes twice over many turns through the $\nu_z = \nu_x$–resonance the beam width has to be kept within limits. Another aspect of the voltage distribution that has to be taken into account is that the flat-topping resonator will reduce the orbit separation at injection and extraction. The voltage distributions in the different resonator types considered below is therefore of importance in the selection and design of a suitable resonator.

As aids in the optimization of the resonator dimensions the computer programs SOPRANO version 1.4 and OPERA-3d version 2.6 from Vector Fields [2] have been used for the calculation of resonance frequencies, field distributions, power dissipation and Q-values. Using these results field integrals were calculated to obtain the voltage distribution along the accelerating gaps. To ensure proper understanding and use of these programs, calculations were done for resonators of which these characteristics are known - either from measurements on existing resonators at NAC or from calculations using simple analytical expressions, such as for a cylindrical co-axial line resonator, before work on the new resonator commenced. Wherever feasible results obtained with SOPRANO were verified with calculations using transmission-line models for the resonators.

3 Vertical half-wavelength resonator

This resonator, shown in figure 4, is similar to the one described by Schmid [2]. It consists of a triangular dee and two flat vertical stems that extend over a wide radial range of the dee. For a qualitative understanding of the changes in voltage distribution resulting from alterations in the resonator dimensions, it was found useful to consider the resonator as consisting of lumped parameters, as shown in the circuit diagram in figure 4.

Here L_1 and L_2 represent, respectively, the dee sections in front (near injection) and behind (near extraction) the

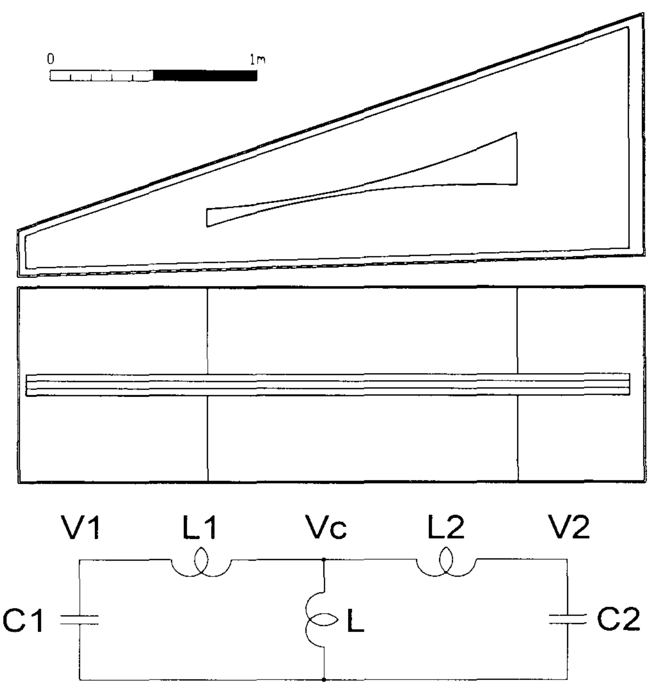

Figure 4: Top and side views of the resonator and the circuit diagram used to explain its characteristics.

vertical dee stems, which are indicated by the inductance L in the diagram. C_1 and C_2 simulate the capacitances at the front and back ends of the dee. The circuit has two resonance frequencies. At the lower frequency the voltages across L, C_1 and C_2 are all in phase, whereas at the higher of the two frequencies the voltage across either C_1 or C_2 is out of phase with the voltage across L. These frequencies (and many others at higher values), as well as the corresponding phase variation of the dee voltage, are also obtained with OPERA-3d. The voltages V_1 and V_2, at nodes 1 and 2, respectively, in terms of the voltage V_c, at the central node c, are at any frequency $f = \omega/(2\pi)$ given by: $V_1/V_c = 1/(1-\omega^2 L_1 C_1)$ and $V_2/V_c = 1/(1-\omega^2 L_2 C_2)$. These equations not only show that the voltages at the three nodes are in phase at frequencies below both resonance frequencies $f_1=1/(2\pi(L_1C_1)^{1/2})$ and $f_2 = 1/(2\pi(L_2C_2)^{1/2})$ but also that V_1 and V_2 are under these conditions larger than V_c and that an increase in the capacitance in one of the two legs in the circuit will result in an increase in voltage at the node at which the capacitance has been increased. The condition for resonance, with all three voltages in phase, can be written in terms of the inductances and the voltages V_1, V_c and V_2: i.e. $L_2 (V_1 - V_c)+L_1 (V_2 - V_c) = (L_1 L_2)/L$. This equation shows that for an increase in a node voltage, resulting from an increase in the capacitance at that node, the voltage at the node in the opposite leg of the circuit will decrease and that in order to flatten the voltage distribution, for fixed dee dimensions, the inductance of the vertical stems has to be increased.

Since the dee length amounts to about half a wavelength at 49.1 MHz, the radial extent of the dee stems has to be large to prevent the dee voltage from increasing too much from the centre towards injection and extraction. Apart from adjusting the gaps between the dee endpoints and the outer conductor (at injection and extraction) to control the end capacitances, radial positioning of the stems and modulation of the stem widths as well as the radial extent of the stems have been used to obtain a voltage distribution similar to those of the main resonators, as is shown in figure

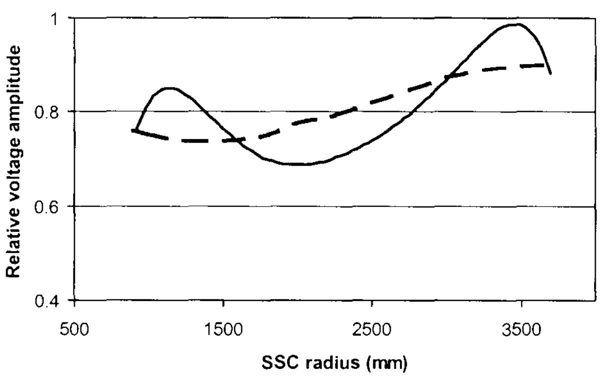

Figure 5: Dee voltage as a function of radius for the vertical half-wave resonator (solid line) and the SSC main resonators

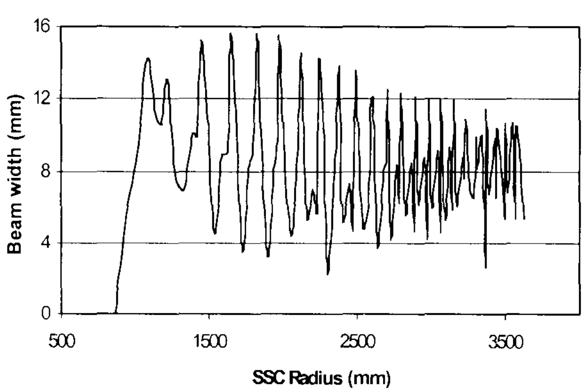

Figure 6: Beam width due to energy spread as a function of radius for a 40° long beam pulse and a vertical half-wave resonator.

5. The height of the dees has also been adjusted. The beam width due to energy spread as a function of radius for a 40° long beam pulse is shown in figure 6, which is almost identical to figure 3. The oscillation in the beam width, which is also present in the beam divergence, is due to the centering errors introduced by the flat-topping voltage. The maximum beam width at extraction is 9 mm.

The resonator characteristics are given in table 1. The resonator can, however, not be installed as an assembled unit through the existing port in the vacuum chamber. To obtain the voltage distribution shown in figure 5 the resonator height had to be increased to such an extent that it would have to be split in the median plane, installed in two separate sections, and assembled inside the vacuum chamber.

Table 1. Characteristics of the vertical half-wave resonator

Frequency	49.1 MHz
Maximum voltage	53 kV
Power dissipation	3.7 kW
Q-value	17500
Dee angle	16.5°
Height	940 mm
Width	1161 mm
Length	3024 mm
Accelerating gap	30 mm

4 Horizontal half-wavelength resonator

Figure 7 shows top and side views of a horizontal half-wave resonator, which can be assembled outside the vacuum chamber and installed as a single unit. The radial voltage distribution is shown in figure 8. Figure 9 shows the beam width due to energy spread as a function of radius. The resonator has a Q-value of 9500 and a power dissipation of 5.1 kW at the required dee voltage of 62 kV. The power dissipation can be reduced by further optimization of the resonator dimensions, for instance by increasing the accelerating gap width. With the present gap width of 30 mm the transit time factor is practically 1 at injection

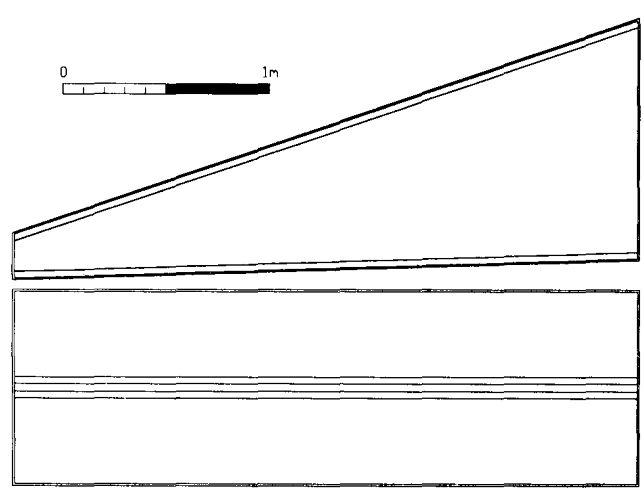

Figure 7: Top and side views of the horizontal half-wave resonator.

Because of the half-sinusoidal voltage distribution, the beam width due to energy spread, for a 40° long beam pulse, increases to 20 mm before the final width of 7 mm is reached at extraction. Because of the low dee voltage at injection, smaller centring errors are induced than with the vertical half-wave resonator, and a sharper beam can be obtained at extraction. Advantages of this type of resonator are that the orbit separation is not reduced at injection and extraction and the dee can extend radially to the vacuum chamber walls, since no gaps are required, thereby leaving more space for the beam on the first and last orbits.

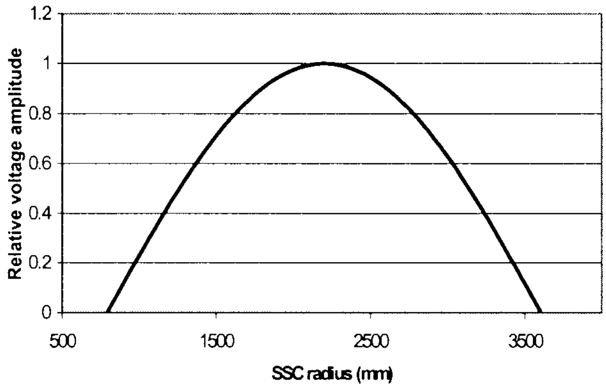

Figure 8: Dee voltage as a function of radius for the horizontal half-wave resonator.

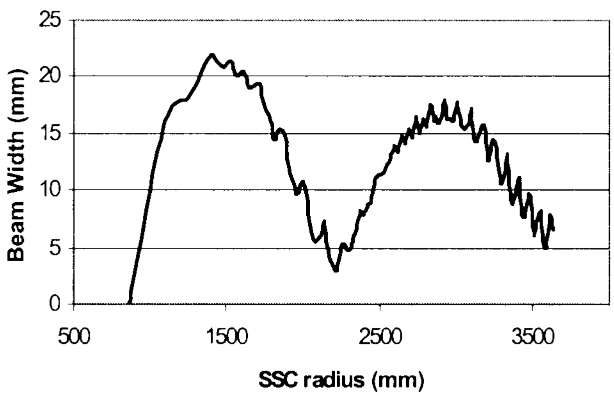

Figure 9: Beam width due to energy spread as a function of radius for a 40° long beam pulse and the horizontal half-wave resonator.

5 Quarter-wavelength resonator

The quarter-wave resonator, which can be assembled outside the vacuum chamber and installed as a single unit, is similar to the half-wave resonator discussed above, except that it extends only over a limited radial range – from 2300 mm (where the dee voltage is zero) to 3600 mm (where the dee voltage has its maximum value). A relatively high dee voltage of 115 kV is therefore required. The resonator has a Q-value of 10200 and a power dissipation of 9.2 kW. Because of the limited radial extent of the resonator and the voltage distribution, the beam width due to energy spread, for 40° long beam pulse, increases from injection to 120 mm before it is reduced to 18 mm at extraction. A disadvantage of this type of resonator is that the orbit separation at extraction is reduced from 22 mm to 16 mm.

6 Single-gap resonator

A single-gap resonator of the type described by Saito [4] was also investigated. The resonator stretches over the full radial range and has a half-sinusoidal voltage distribution similar to that of the horizontal half-wave resonator. The resonator has a Q-value of 6900 and a power dissipation of 341 kW, which is much higher than for the horizontal half-wave resonator, at the required dee voltage of 124 kV. The beam width due to energy spread varies with radius in the same way as it does for the horizontal half-wave resonator.

7 Conclusions

With further reduction in the power dissipation of the horizontal half-wave resonator it would be the most suitable resonator for a flat-topping system. It can be fully assembled outside the vacuum chamber and installed as a single unit, and would also not reduce the orbit separation at injection and extraction. Better beam quality can be obtained than with any of the other types of resonators studied.

References

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