DEVELOPMENT OF THE NAC ACCELERATOR FACILITIES

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ABSTRACT

Improvements to the injection and extraction systems of the separated-sector cyclotron are in progress. A flat-top acceleration system, making use of the existing dees, for the light-ion injector cyclotron, is being tested. A bi-directional beam sweeping system for the isotope production targets has been designed and built.

1. INTRODUCTION

The 200 MeV separated-sector cyclotron[1)] and the 8 MeV light ion injector cyclotron at the NAC have been in operation since the beginning of 1987. Beam time is allocated to physical sciences (49%), neutron therapy (14%), radiobiology and biophysics (8%) and isotope production (26%). An injector cyclotron for polarized and heavy ions is scheduled for completion in December 1993. The ECR and polarized ion sources are operational. A beamline and facilities for proton therapy are under construction and will be completed later this year. The K600 spectrometer has been commissioned. The final detector is now being constructed. A number of improvements to the existing facilities are discussed below.

2. BEAM CENTERING IN THE SEPARATED-SECTOR CYCLOTRON

To center a beam the change in the centering error for increments in the currents of each of the injection elements is measured at a given turn. By using linear combinations of these increments for any pair of injection elements, the centering error can be adjusted to the required value. With this procedure the centering error is typically reduced by a factor of six in a single step.

Owing to the lower than expected dee voltage at injection in the 200 MeV separated-sector cyclotron, proton beams with energies above 120 MeV could not be centered with the injection system as it was originally designed. During beam centering studies it was noticed that when the injection system is set up for total transmission through the magnetic inflection channel, the centering error can be adjusted to only an angular error on the third or fourth turn, depending on the injection energy. To center the beam at energies above 120 MeV, it is therefore only necessary to change the beam angle, on the third or fourth turn, with a short electrostatic injection channel (EIC). The available space in the cyclotron allows a maximum channel length of 190 mm. The maximum angular error on the third turn is 25 mrad. The maximum required field strength in the channel is 23.5 kV/cm. A cross-sectional view of the EIC is shown in Fig. 1. A grounded shield screens the first few orbits from the electrical field around the deflector. Figure 2 shows the orbit pattern for 200 MeV protons at injection. On the first two turns the beam is not centered but from the third turn onward the centering error is only 3 mm. In practice the beam is centered by first obtaining only an angular centering error at the EIC, through adjustment of the first few injection elements. The beam angle is then corrected by applying the calculated voltage for a properly centered beam to the channel. During operation the beam center is adjusted to give the maximum orbit

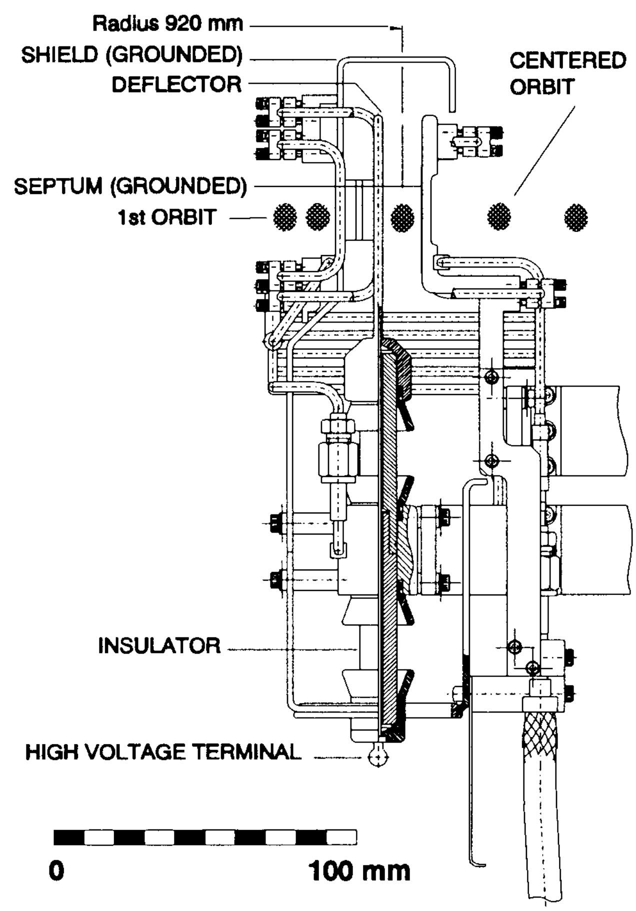

Fig. 1. A cross-sectional view of the EIC.

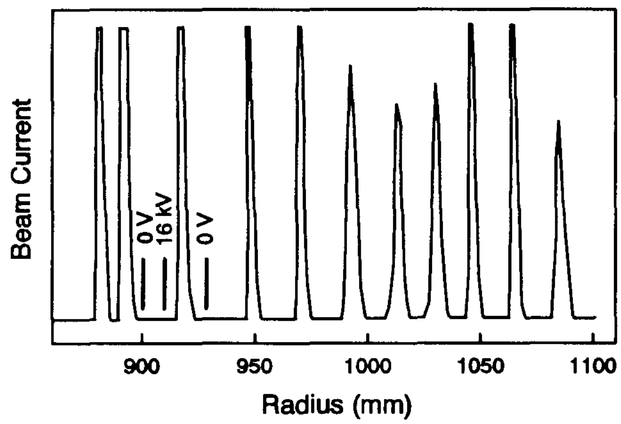

Fig. 2. Beam centering in the separated-sector cyclotron with an additional electrostatic inflection channel (EIC) at injection for 200 MeV protons. The EIC electrodes at the third turn are indicated. From the third turn onward the centering error is 3 mm.

separation at the first extraction element, for a given centering error. It is now possible to work with a much smaller centering error at 200 MeV and still get the same orbit separation at extraction.

At present the extraction system consists of an electrostatic channel (EEC) and two septum magnets (SPM1 and SPM2), as shown in Fig. 3. When the beam is centered and the EEC is used, the orbit separation at SPM1 is 12 mm. Because $v_x = 1.5$ at extraction for 200 MeV protons, it is possible to obtain double the normal orbit separation of 6 mm at the septum magnet SPM1, by making use of a centering error. Under these conditions the EEC cannot be

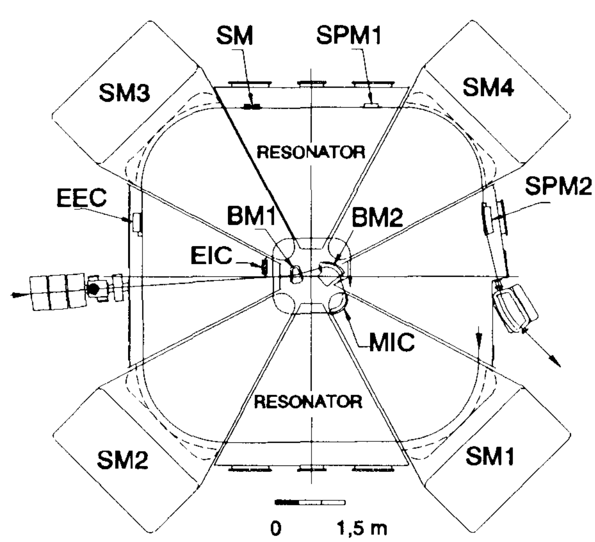

Fig. 3. Layout of the separated-sector cyclotron showing the positions of the the new electrostatic channel (EIC) at injection and the magnetic channel (SM) at extraction.

used because the outer orbit at the EEC swings in to pass SPM1 on the inside due to radial focusing in sector magnet three. To improve the extraction efficiency for 200 MeV protons, a further septum magnet SM is required at the position shown in Fig. 3, in which the position of the EIC is also indicated. At the entrance of the new septum magnet the orbit separation is 24 mm with a field strength of 60 kV/cm in the EEC and with a centering error of 6 mm. Due to the centering error the orbit separation at the EEC is 10 mm. The new septum magnet which is presently being planned will be similar to SPM1.

3. A FLAT-TOP SYSTEM FOR SPC1

The extraction efficiency of the separated-sector cyclotron for a 66 MeV proton beam, which is used for isotope production and neutron therapy, decreases sharply for beam currents above 120 µA. In order to increase the extraction efficiency for this beam and also for proton beams in the energy range 120 to 200 MeV, where the orbit separation is small, a flat-top acceleration system for the separated-sector cyclotron has been considered. Such a system is, however, at present too expensive. A flat-top system for SPC1 can be made more cheaply, especially if the existing resonators could be used for this purpose. It was thought that with such a system the energy spread in the beam extracted from SPC1 would be much lower and the beam could be bunched to shorter pulse lengths in the separated-sector cyclotron than before. The energy spread of beams in the separated-sector cyclotron will therefore be smaller and the extraction efficiency should improve. With shorter pulse lengths higher beam currents for a given beam loss in the separated-sector cyclotron will be available, and a larger percentage of the beam extracted from SPC1 could be injected into the separated-sector cyclotron. Longitudinal space charge forces in the separated-sector cyclotron, however, restrict the pulse lengths which can be used.

The next resonance frequency, above the main resonance frequency, of the SPC1 resonators does not occur at an harmonic of the main frequency. To adjust the second resonance frequency to coincide with an harmonic of the main frequency, two systems were considered. In the first case a loop, tuned to a frequency close to the desired harmonic frequency, is coupled inductively to a main resonator. In the second case an additional co-axial transmission line resonator, also tuned to a frequency close to the desired harmonic frequency, is coupled capacitively to a main resonator.

A computer program was developed to calculate the characteristics of the SPC1 resonators. Because of the calculated high power dissipation at the third harmonic in both the loops and additional resonators, it was decided to design the flat-top system to operate at the fifth harmonic

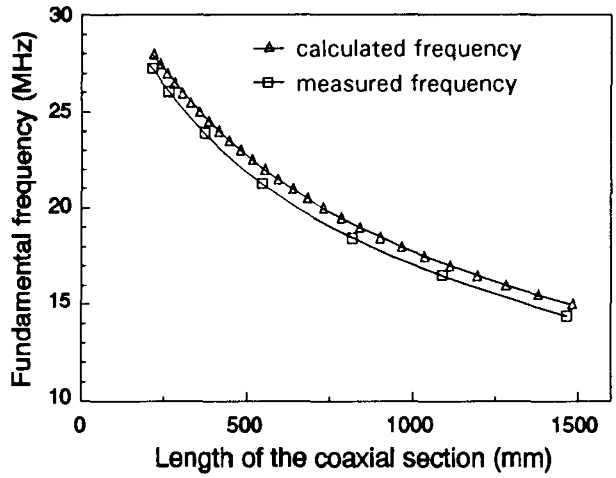

Fig. 4. Calculated and measured main resonance frequencies of an SPC1 resonator vs. the length of the co-axial section of the resonator.

of the main frequency. The calculated and measured main resonance frequencies, as a function of the length of the co-axial section of the SPC1 resonators, are shown in Fig. 4. The measured and calculated second resonance frequencies of the resonator, as a function of the main frequency, are shown in Fig. 5. Calculations have shown that the current in the loop and the voltage across the loop capacitor will be too high. The optimum position for the loop is also occupied by existing cyclotron components.

It was therefore decided to use the additional transmission line resonators with adjustable short-circuit plates to tune the main resonators to the fifth harmonic frequency. The additional resonators are coupled through series capacitors to the main resonators as shown in Fig. 6. The resonators are 1.2 m long and the diameters of the inner and outer conductors are 40 mm and 120 mm, respectively. The largest part of an additional resonator, including the

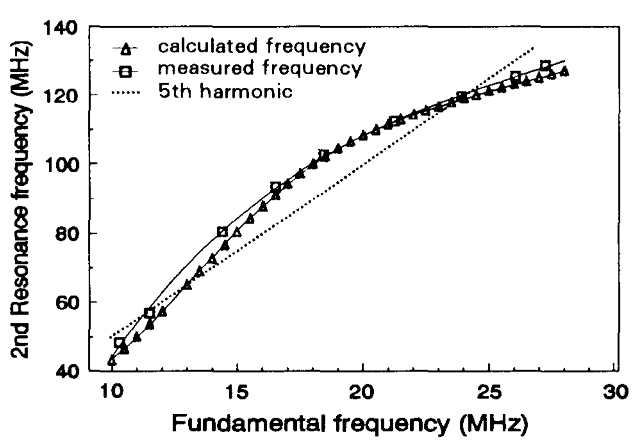

Fig. 5. Calculated and measured second resonance frequencies of an SPC1 resonator vs. the main resonance frequency.

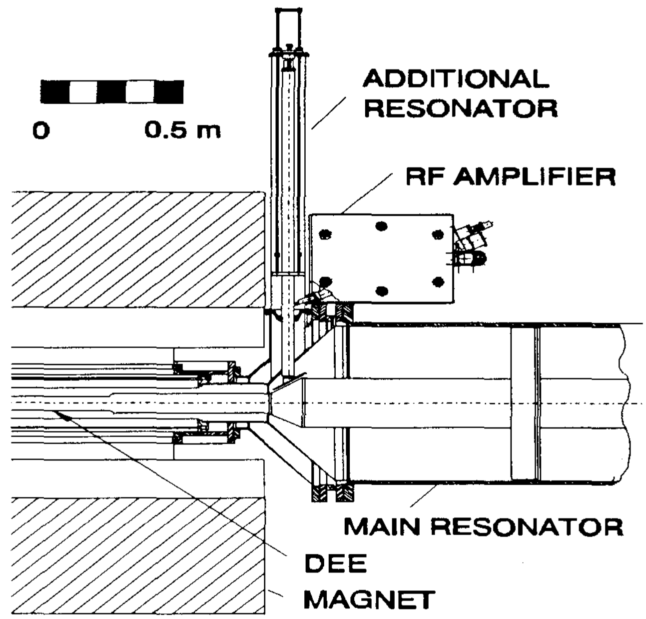

Fig. 6. An additional transmission line resonator coupled capacitively to an SPC1 main resonator to obtain a flat-top dee voltage.

short-circuit plate and the coupling system to the amplifier, is at atmospheric pressure and does not require vacuum feedthroughs. The series capacitor and the short-circuit plate have to be adjusted to obtain the harmonic frequency.

Calculations and measurements on the system have shown that the SPC1 main resonators can be tuned to the main and fifth harmonic frequencies over the main frequency range 10 MHz to 26 MHz. The maximum calculated power dissipation of 380 W at 130 MHz, i.e. the 5th harmonic of 26 MHz, is small compared to the maximum power dissipation at the main frequency. The harmonic voltage on the anode of the main amplifier is less than 1400 V, whereas the main voltage at the anode of the harmonic amplifier is 130 V. The tolerances on the amplitude and phase of the main dee voltage are 0.3% and 0.3°, respectively. For the harmonic voltage the corresponding tolerances are 7.5% and 1.5°, respectively.

To determine the influence of a flat-top system in SPC1 on the beam quality, an orbit code OCEM was used. This program was modified to take the harmonic dee voltage and its radial distribution into account. There is no noticeable change in the vertical focusing when the harmonic voltage is included in the calculation. With the flat-top system the beam separation increased from 1 mm to 8 mm at the extraction radius for a beam pulse length of 30°.

The two systems have been operated simultaneously at a main frequency of 16.3 MHz and a flat-top frequency of 81.5 MHz with beam.

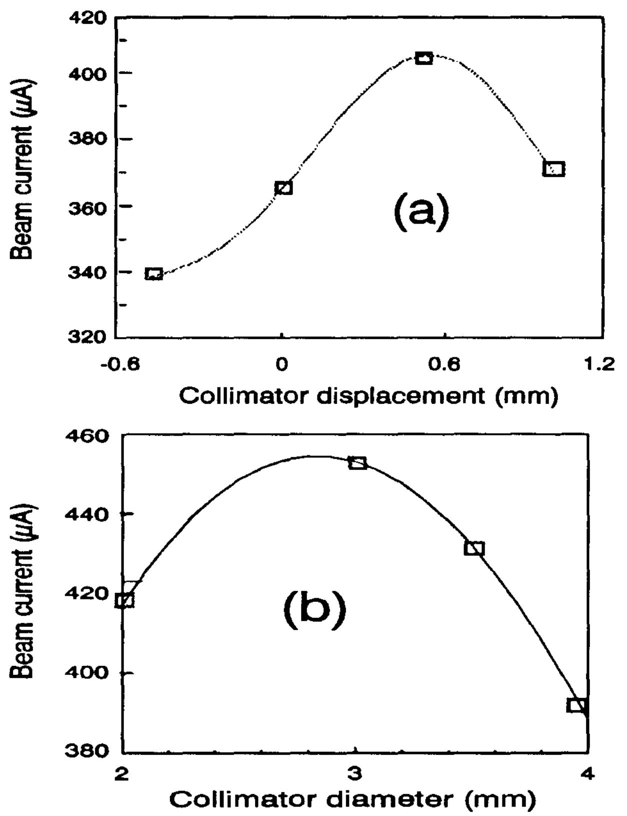

Fig. 7. Beam current vs. collimator position (a) and diameter (b) of the PIG ion source in the light-ion injector cyclotron.

4. OPTIMIZATION OF THE PIG ION SOURCE

A PIG ion source is used in the central region of the light-ion injector cyclotron. To optimize the source for high beam intensities, experiments in which the diameter and position of the collimators for the electron beam have been varied, were carried out. Figure 7 shows the internal beam intensity vs. these two parameters. Another parameter which was varied is the thickness of the extraction slit. The beam intensity has been increased by a factor of 2 by the optimization of these three parameters.

5. A BEAM SWEEPING SYSTEM

Radioisotopes are produced with a 65 μA proton beam of 66 MeV on a circular water-cooled target with a diameter of 18 mm. In order to limit the rise in the target temperature, a 450 Hz beam sweeper is used in the isotope production line. The sweeper consists of two 200 mm long dipole magnets, made from 0.3 mm thick laminations, mounted around the stainless steel beam pipe. Each magnet has two coils consisting of 640 turns each. The reactance of the two coils, which are connected in series, is 1261 ohm. The resistance is 2.7 ohm. To limit the voltage across the supply to the coils they are connected in series with a 280 nF capacitor to form a series resonance circuit. Two 400 W commercial audio power amplifiers are connected to the magnets through transformers to obtain a field strength of 6 mT. The currents through the coils of the two magnets are 90° out of phase, and can be varied independently to obtain circular or elliptical beam profiles with a maximum diameter of 10 mm.

6. ACCELERATOR OPERATION

Table 1 shows the beam statistics for the past three years of operation. More than 50% of the unscheduled interruptions for 1991 originated from the injector cyclotron and are mainly due to the ion source.

Table 1. Distribution of scheduled time

	1989	1990	1991
Scheduled time as % of calendar time	82.8%	85.1%	86.4%
Scheduled time (normalized to 100%)	7251h 100%	7453h 100%	7567h 100%
Interruptions	4.3%	6.9%	3.9%
Beam retuning after power dip or failure	2.5%	0.6%	0.8%
Beam development	4.7%	3.6%	2.2%
Energy change and beam tuning	7.8%	6.3%	6.3%
Beam time	80.6%	82.5%	86.8%
Average no of 8 hour shifts per month	61.0	64.1	68.4

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1) Botha, A.H., Conradie, J.L., et al., "Operation and Development of the NAC Accelerator Facilities", in **Proceedings of the Twelfth International Conference on Cyclotrons and their Applications** (World Scientific, Singapore, 1989) pp. 80-83.