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# BEAM INJECTION AND EXTRACTION FOR THE SEPARATED-SECTOR CYCLOTRON OF THE NATIONAL ACCELERATOR CENTRE

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Abstract.- The injection and extraction systems proposed for the NAC separated-sector cyclotron (k=200 MeV) are described. A wide range of particles, including both light and heavy ions, with variable energy and beam intensities up to 100 μA have to be accommodated. Beam injection is accomplished with two bending magnets in the central region and an adjustable magnetic inflection channel in the pole-tip of one sector magnet to guide each beam onto its centred orbit. The extraction system consists of an electrostatic extraction channel and two septum magnets, one of which is mounted inside the resonator. Results of orbit computations and specific design principles of the injection and extraction components are discussed.

1. Introduction.- The design and construction of a multidisciplinary particle accelerator facility, centred around a separated-sector cyclotron (SSC) with a k-value of 200 MeV, has already reached an advanced stage[1-4]. The beams to be injected into the SSC will initially only be delivered by an 8 MeV solid-pole cyclotron for light ions. However a second injector cyclotron for heavier ions with beam intensities in the region of several hundred pnA is planned.

During the design of the injection and extraction systems for the SSC special account had to be taken of the fact that a wide range of ions with variable energy and beam intensities up to 100 μA are to be injected and extracted. The exact location of beam trajectories and centred orbits as well as beam profiles and sizes were determined with computer programs which took the acceleration of the beam into account. The orbits and beam properties for the most extreme cases were examined, i.e.:-

i) 8 to 200 MeV protons, the beam with the highest magnetic rigidity, the smallest orbit separation, the maximum number of revolutions, and the highest radial focussing frequency;

ii) 4.55 to 100 MeV protons, the beam with the highest intensity (up to 100 μA) and thus with the largest beam width and beam power (up to 10 kW);

iii) 0.47 to 8.96 MeV $^{14}N^{3+}$ ions, since this is one of the beams (although not the heaviest ion) with the least number of revolutions.

These factors were taken into account in the design of the injection and extraction components. Provision has also been made in these designs for increasing the field strength by at least 11% over that for the 8 to 200 MeV proton requirements. This allows for the possibility of accelerating $^3He^{2+}$ to 300 MeV for medical application at a later stage.

2. Injection.- The pre-accelerated beam from the injector cyclotron enters the virtually field-free central region of the SSC along a valley centre-line as illustrated in figure 1. The sector-magnet strayfield bends the beam through an angle of $4^o$ along this path. The installation of a flat-top resonator in this valley is envisaged as a future project.

In the central region an H-type bending magnet (BM1) without edge angles will deflect the beam by $18^o$ and

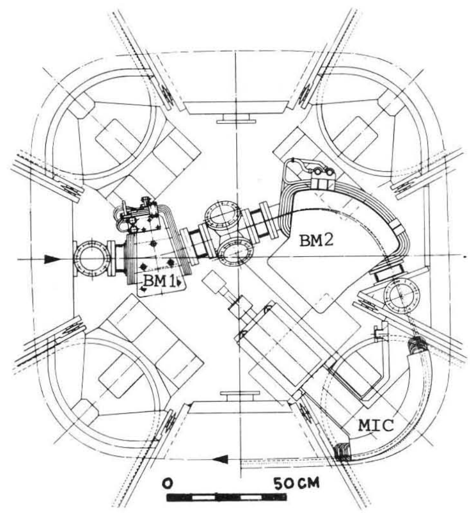


Fig.1: The central region lay-out of the SSC illustrating the two bending magnets and the MIC with its driving mechanism.

direct it into an $88^o$ C-type bending magnet (BM2); this magnet will guide the beam into the magnetic inflection channel (MIC) in the pole-tip of the first sector magnet. The MIC will then inject the beam onto its innermost centred orbit. The maximum flux densities generated by BM1, BM2 and the MIC for 8 MeV protons are 0.65 T, 1.35 T and 0.223 T, respectively. The MIC-field is superimposed on the sector-magnet field in the polegap resulting in a total flux density of 1.279 T. BM2 has edge angles of $24^o$ at the entrance and $0^o$ at the exit.

The horizontal scanners in front of BM1 and the MIC and the profile monitor in front of BM2 aid in locating the beam and in determining its size. This facilitates the beam transportation through the injection system. Collimators are to be installed at the MIC entrance, and the MIC walls are to be lined with sections of tungsten foil, from which intercepted beam currents can be measured to minimise beam losses. A capacitive pick-up probe is to be installed in the diagnostic chamber between BM1 and BM2 to monitor the phase of the injected beam pulses with respect to the rf system and to aid in ensuring a bunch length focus (due to the buncher in the low-energy beamline) at the first valley centre-line.

The two bending magnets and the diagnostic chamber between them are to be mounted on a supporting structure which can be installed as a unit in the central region.

The SSC is not operated in a constant orbit mode and therefore each beam has to be injected onto its respective centred orbit. The number of revolutions in the SSC varies from about 32 (for heavier ions) to 240 (for 8 to 200 MeV protons). To allow for this variation in orbit positions BM1 and BM2 have been designed with wide poles (a usable gap width of about 50 mm); furthermore the radii of curvature of the orbits through the MIC vary slightly and for this reason a 50 mm wide magnetic channel, remotely adjustable over a linear range of 70 mm, was chosen. The 100 mm wide vacuum chamber ducts in the pole-gaps of the two bending magnets have a usable gap height of 36 mm.

Since the MIC position has to be adjustable it was found to be more practical to mount the MIC inside the magnet vacuum chamber in the 66 mm pole-gap of the sector magnet. It was made possible to increase the MIC height by removing the first three trim-coils and bending the upper and lower vacuum chamber walls against the pole face in this region. The total vertical MIC height is 45 mm and it is to be installed through the valley vacuum chamber. Its primary field is realised with a 40 mm high coil. However the field shape is optimised with 1.1 mm thick floating shims to be installed symmetrically above and below the median plane over the whole MIC width and length[5]. At the ends the coil conductors are bent up against the magnet vacuum chamber walls yielding a vertical aperture of 27 mm. Both the coil and the shims are enclosed in a stainless steel shroud flanged to an arm providing the necessary rigidity to support and position the MIC. It has been designed for a maximum current of 1250 A with a power dissipation of 22.5 kW. The proposed driving mechanism is powered with a hydrospindle accurately adjusted with a stepping motor. The vertical displacement of the MIC from its symmetrical position in the pole-gap should not exceed 0.5 mm.

For symmetry reasons the same trim-coils deleted in the first sector magnet will also be deleted in the third (opposite) sector magnet, where they might be replaced by coils aiding in centring the beam and permitting final adjustments. The trim-coils in the remaining two sectors must compensate for the shift in orbit position over this region.

The maximum accelerating voltage amplitude at injection (~ 207 kV) was chosen such that the smallest orbit separation (for 8 MeV protons) at the MIC exit is still about 43 mm, enough to insert the 15 mm wide MIC septum with sufficient beam clearance. For most of the other beams the orbit separation is however large enough so that the beam traverses the MIC close to its centreline. Beam widths up to 15 mm are expected for 4.55 MeV protons with a beam emittance of $38\pi$ mm.mrad for a beam intensity of 100 $\mu$A.

A resonator angle (between accelerating gaps) of $51^{\circ}$ was chosen. This implies symmetric acceleration at less than maximum voltage. For 8 MeV protons (with harmonic number $h = 4$) the beam bunch has to be injected such that it crosses the accelerating gaps at $18.5^{\circ}$ from the maximum accelerating voltage. With orbit calculations it became clear that it would be difficult to centre beams with less than about 30 revolutions due to the large radial gain per turn and sensitive accelerating voltage changes experienced with $h = 12$ and a starting phase near $60^{\circ}$. For 0.47 MeV $^{14}N^{3+}$ with the least number of revolutions the accelerating voltage will have to be limited to 23 kV at injection implying a lower limit of 32 revolutions with a starting phase of $58.8^{\circ}$ to ensure well-defined injection conditions.

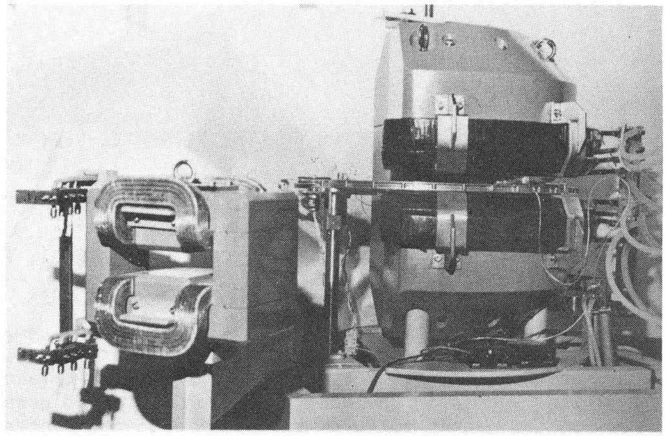

Fig.2: The two bending magnets of the injection system. BM2 on the right with the track of the field measuring system in the pole gap.

BM1 and BM2 have been delivered (see figure 2) and they are presently being tested. A prototype MIC coil has been tested under full power but magnetic field measurements have been postponed until the first sector magnet is assembled.

3. Extraction.- Beam extraction from the SSC is accomplished with an electrostatic extraction channel (EEC) and two septum magnets (SM1 and SM2) in successive valleys. The layout of the extraction system is illustrated in figure 3.

For the 200 MeV protons the orbit separation is still about 7 mm at the entrance of the EEC, due to the large energy gain per turn of 1 MeV and a relatively low sector-magnet field at extraction (i.e. 1.265 T in a hill). Consequently it is not envisaged to employ beam-dynamical resonances to enlarge the orbit separation. The orbit separation as a function of azimuthal position is illustrated in figure 4.

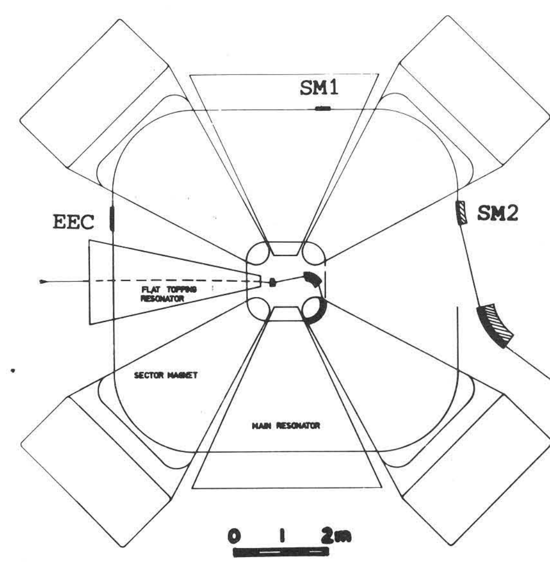


Fig.3: The extraction system lay-out of the SSC consisting of an electrostatic channel and two septum magnets.

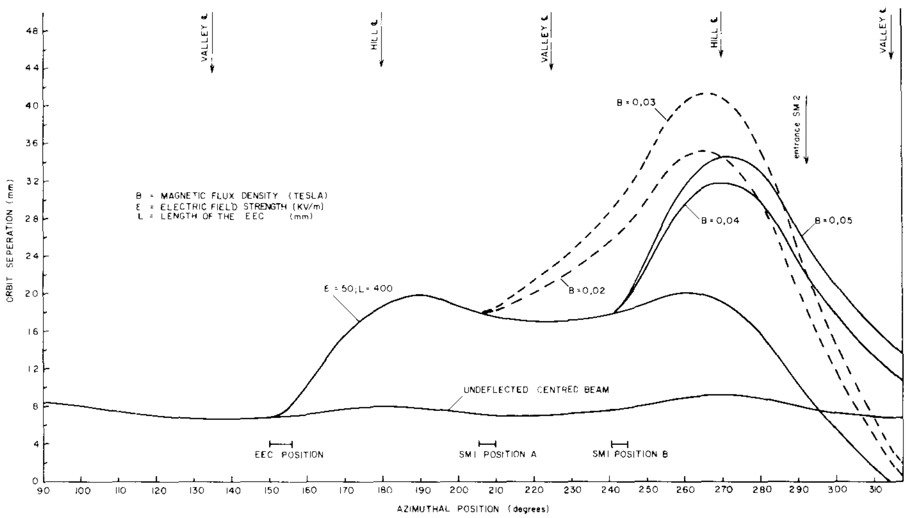


Fig.4: Orbit separation vs azimuthal position for the deflection of 200 MeV protons with the EEC and two septum magnets. The effects of various field strengths for SM1 are illustrated for two positions, A and B.

With an energy spread of $\leq 0,1\%$ and an expected beam emittance of $2.7\pi$ mm.mrad at injection, the onset of multi-turn extraction for 200 MeV protons (10μA) occurs for a total beam pulse width of about $8^{\circ}$. However, with the installation of a flat-top resonator it is expected that the total pulse width can be increased by a factor 5 before the beam separation vanishes.

For efficient extraction it is therefore essential that the orbit separation be initially increased. This will be done by deflecting the beam outwards with a 400 mm long electrostatic channel with a very thin septum, consisting of 0.1 mm thick spring-tensioned molybdenum-foil strips. This channel will be operated at up to 75 kV across the 15 mm gap. The channel entrance and exit will be independently and remotely adjustable. To ensure a large enough beam separation at the entrance to the second septum magnet (SM2) for the entire range of radial focusing frequencies ($1.17 \leq \nu_r \leq 1.51$) a small septum magnet (SM1) will be placed inside the inner delta of the resonator. The EEC and SM1 are to be installed in the second rather than in the first half of the valleys. This not only deflects the beam into less of the sector-magnet fringe field (to obtain any given required beam separation at the entrance to the following extraction channel), but also places the entrance of these channels closer to the valley centre-line, where the ratio of orbit separation to beam width is largest. For an electric field strength of 50 kV/cm the orbit separation for 200 MeV protons is increased to 18 mm at the entrance of SM1 (see figure 4) with a clearance between beams of about 12 mm. This is sufficient to insert the straight 300 mm long septum of SM1. Its maximum power consumption is $\leq 1$ kW. This magnetic channel is mounted on a table with a remote radial position adjustment of about 100 mm. Furthermore the entrance of the magnet is pivoted below the front diagnostic finger and the magnet can be swivelled around this point by about $10^{\circ}$. Diagnostic scanning wires will be mounted at the front and rear of the magnet to determine its optimum position. A local structural design modification of the inner delta was necessary to accommodate the magnet and its table as a unit. This will be mounted via the vacuum pumping port through the louvres on the rear of the inner delta. The integral power and water conductors and signal cables are to be installed within the inner transmission line. Provision for possible future installation of an additional identical septum magnet in the first half of the same resonator has been incorporated in the resonator design.

A SM1 flux density of 0.05 T yields the required orbit separation of 26 mm for 200 MeV protons at the entrance to SM2. The orbit separation decreases rapidly after the sector-magnet and the beam should thus enter SM2 as soon as possible. With this 500 mm long magnetic channel, designed for a maximum flux density of 1.3 T (implying a supply current of 2500A), the beam is finally deflected out of the cyclotron vacuum chamber into the high-energy beamline. The maximum power consumption for extracting 200 MeV protons with this magnet is about 95 kW of which 85 kW will be dissipated in the septum alone. Each septum conductor will be soldered to a thicker return path conductor with separate cooling of each turn. The position of both entrance and exit of SM2 will be independently adjustable. The stray field to the outside of both septa is minimized with a thin magnetic shield (permalloy plate) on the outside of the septum[6].

The orbit structure in front of the EEC and SM2 will be monitored with radial differential probes for optimum positioning of these channels.

For those beams with a large enough orbit separation, the EEC could be omitted and beam extraction could be accomplished only with the magnetic channels.

Conceptual designs have been made of the extraction components and a prototype coil has been manufactured for SM1.

4. Conclusion.- Beam injection and extraction systems have been designed for the range of light and heavy ions to be accelerated by the SSC. Some injection components have already been delivered and detail designs of the extraction components will soon commence.

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