THE DESIGN AND PERFORMANCE OF THE BEAM INJECTION AND EXTRACTION SYSTEMS OF THE NAC SEPARATED-SECTOR CYCLOTRON

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Summary. The beam injection and extraction systems of the National Accelerator Centre separated-sector cyclotron (SSC), with a k-value of 200, have been manufactured, installed, tested and commissioned. The injection system consists of two bending magnets in the central region of the SSC and a magnetic inflection channel in the pole-tip of one of the sector magnets. The beam is extracted with the aid of an electrostatic extraction channel and two septum magnets, each in succeeding valleys. Specific design characteristics and the first operating experiences with proton beams accelerated up to the maximum design energy are discussed.

Introduction

During the design of the injection and extraction systems the wide range of specifications for the requirements of this multi-disciplinary accelerator facility had to be taken into account. These include variable-energy light and heavy ions with a 10:1 energy range and beam intensity variations from a few nA for heavy ions up to 100 μA for protons. With such high-intensity beams we had not only to make provision for beam power dissipations up to 10 kW, but also to ensure that very high injection and extraction efficiencies (virtually 100%) could be realised. This in turn requires an extensive beam diagnostic system for the SSC.[1] Furthermore, the SSC is not operated in constant orbit mode and we thus had to make provision for sufficient adjustment of the injection and extraction components (with large beam acceptances) to accommodate the various orbits. The number of revolutions may vary typically from about 32 for some heavy ions to 243 for protons accelerated to 200 MeV. One of the fundamental design characteristics of the SSC is a fairly large average orbit separation, typically 45 mm at injection and 7 mm at extraction for the highest energy protons. This is accomplished with a high rf accelerating voltage of up to 250 kV (resulting in a 1 MeV energy gain per turn at extraction) and a low sector magnet flux density of only 1.265 T (at a hill radius of 4427 mm). Consequently we do not have to make use of beam dynamical resonances to increase the orbit separation.

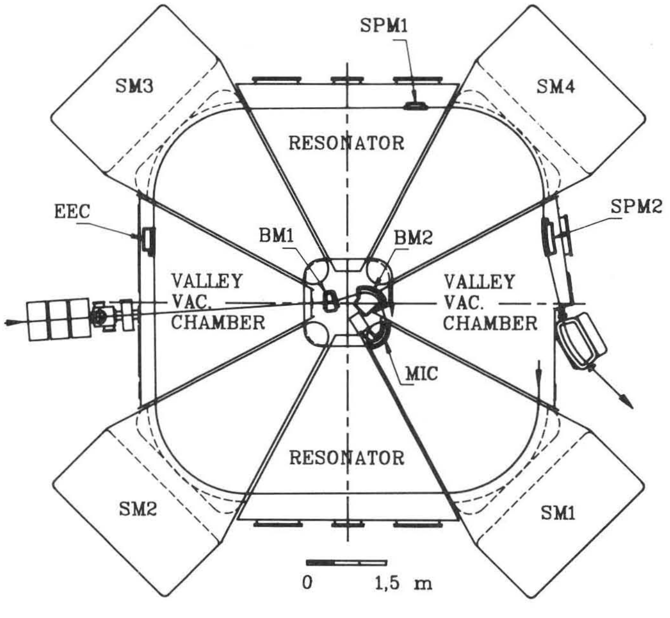

Fig. 1 The layout of the injection and extraction systems of the separated-sector cyclotron.

The Injection System

The beam is steered through the sector magnet stray-field with a strong steering magnet at the end of the transfer beamline, such that it enters the central region of the SSC along the valley centre line. The stray field deflects the beam by about 4 degrees. The basic layout of the injection system[2] is illustrated in Fig. 1. The two bending magnets in the central region direct the beam into the magnetic inflection channel (MIC) in the pole-tip of one of the sector magnets, as is shown more clearly in Fig. 2.

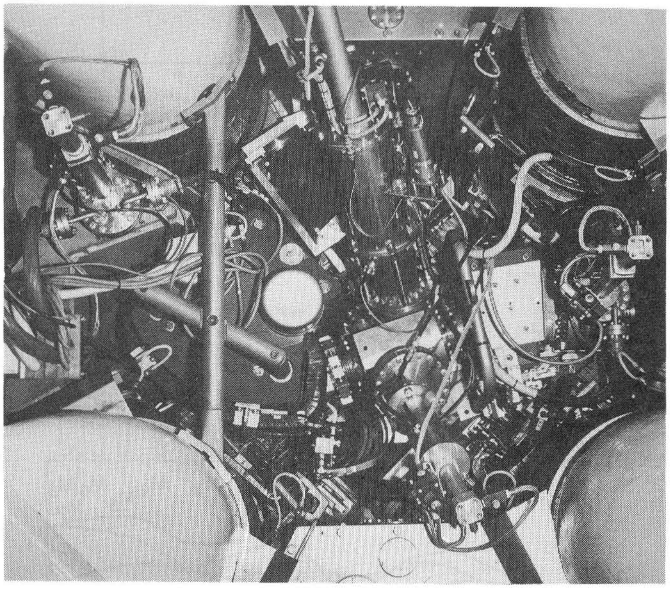

Fig. 2 Top view of the crowded central region of the SSC. The injected beam enters from the right and then passes through dipoles BM1 and BM2 before entering the MIC in the pole-gap of the upper left sector magnet.

The central region support structure

The injection and beam diagnostic components in the central region are supported by the structure shown in Fig. 3. This structure is in turn mounted on a stainless steel base, which is permanently grouted onto a concrete pillar. The whole central region is thus supported independently.

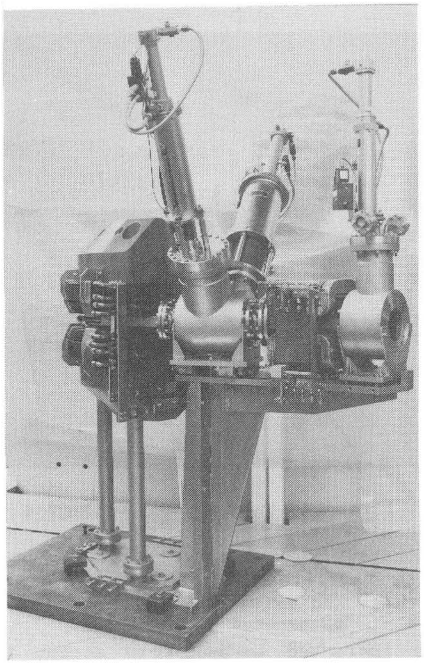

Fig. 3 The injection magnets BM1 (right) and BM2 (left) together with diagnostic components and their vacuum chambers, mounted on the central region support structure. The diagnostic components are (from the right) a harp, a scanner and a capacitive phase probe.

The bending magnets BM1 and BM2

BM1 is an H-type bending magnet, with zero degree edge angles and straight poles, deflecting the beam 18° to the left (into BM2) with a typical radius of curvature of 650 mm. BM2 is a C-shaped magnet with entrance and exit edge angles of 24° and 0° respectively, and deflects the beam by 88° to the right (into the MIC) with a typical radius of curvature of 304 mm. Both magnets have 100 mm wide poles with a usable gap-width (i.e. over which the field homogeneity is $\geqslant 99\%$) of 50 mm and a pole-gap height of 36 mm inside the vacuum duct. The flux densities for injecting the highest energy protons are 0.65 T (for an excitation current of about 450 A with 48 coil turns) and 1.35 T (for an excitation current of about 560 A with 80 coil turns) for BM1 and BM2 respectively. The magnets have been designed for a maximum power consumption of 9.3 and 20 kW.

Extensive sector-magnet field measurements with BM1 and BM2 in position have shown that their influence is negligible and thus the field compensation techniques contemplated initially were not necessary.

The magnetic inflection channel (MIC)

In order to direct the various particle beams onto their centred orbits we make use of a 50 mm wide inflection channel (in the pole-tip of the sector magnet) with an optimal radius of curvature of 325 mm, which deflects the beam by about 107°. The MIC can be positioned linearly over about 45 mm. The 12-turn coil and a 1 mm thick shim above and below the coil typically (for the injection of the highest energy protons) increase the sector magnet field in that region by 0.22 T to 1.29 T for an excitation current of about 1000 A. This channel has been designed for a maximum power dissipation of 26 kW. The two cooling circuits of the coil are fed from the high-pressure (i.e. 2 MPa) cooling-water system to ensure sufficient flow.

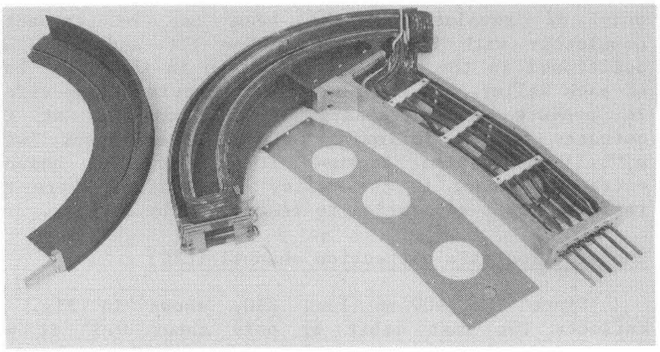

Fig. 4 The magnetic inflection channel. The upper half of the coil frame (left) and the lid on the supporting arm have been removed to expose the coil and the power and water feeds.

The MIC assembly is shown in Fig. 4. The coil is firmly clamped with a hard-anodized high-tensile-strength aluminium-alloy frame, which is held in position with a strong stainless steel arm housing all the supply leads and the vacuum feedthroughs. Owing to the very high magnetic and vacuum forces acting on the MIC (up to 5000 N) we opted for a compact hydraulic drive controlled with a stepping motor and position encoder.

For our sector magnets with 66 mm pole-gaps, the trim-coils are held in position against the pole-faces by the 8 mm thick sector magnet vacuum chamber walls. In order to increase the gap height available for the MIC to 49 mm, the first and part of the second trim-coil were omitted in this sector and the vacuum chamber walls were bent up against the pole-faces. This had to be done over a large area in order to make provision for the installation and removal of the MIC, which is carried out through a man-hole in the valley vacuum chamber.

The coil conductors have the function of a septum, thus increasing the field inside the coil without much field contribution at the first accelerated orbits. However, since the coil does not extend over the whole pole-gap height, shims are used to compensate for the stray field and the inhomogeneity of the field in the channel. The MIC decreases the field over the whole sector magnet pole area by less than initially anticipated, i.e. typically by a maximum of only 2 mT for a 1.25 T base field. In the initial beam injection trials and beam centering studies it was not necessary to implement any compensating techniques, e.g. with the booster-coils.

The MIC entrance is protected by a collimator, and 8 insulated water-cooled copper liners (inside and outside the channel) protect the coil and frame.

The Extraction System

The layout of the extraction system^2 is illustrated in Fig. 1. Single-turn extraction for 200 MeV protons, with an energy spread at injection of $\leqslant 10^{-3}$ and a typical radial emittance of 2.7π mm.mrad, is only envisaged for beam pulse lengths $\leqslant 8°$ of the rf phase. For this reason an electrostatic extraction channel (EEC) is used as the first extraction element, since it allows the use of a very thin septum. Once the orbit separation is increased sufficiently, magnetic deflection is used to extract the beam completely. To ensure large enough beam separation at the entrance to the second septum magnet (SPM2) for the radial focussing frequencies of all particle beams (i.e. $1.1 \leqslant \nu_r \leqslant 1.5$), a small septum magnet (SPM1) inside the resonator is indispensable. However, for large orbit separations at extraction (up to 60 mm for some heavy ion beams with only 32 revolutions) the beam can be extracted completely with SPM2 alone. The EEC and SPM1 are positioned in the second rather than in the first half of each valley, not only because it requires less effort to produce the necessary orbit separation at the entrance to the following extraction component (with ν_r~1.5) but also because it places the channel entrances closer to the valley centre-line, where the ratio of orbit separation to beam width is largest.

The electrostatic extraction channel (EEC)

Since the 400 mm long EEC, shown in Fig. 5, deflects the last orbit by only about 0.3° it was feasible to design and manufacture a straight channel. The EEC basically consists of an 80 mm high chrome-plated copper cathode, which is indirectly water-cooled via four beryllium oxide insulators, and a septum consisting of 60 individually spring-tensioned 0.05 mm x 7 mm tungsten foil strips spaced at 1 mm intervals. Cooling calculations, carried out with a computer program taking the effective stopping power of particle beams into account, showed that most particles are scattered out of the thin foil before the maximum penetration depth is reached. For this reason a pre-septum, consisting of 3 such foils, has been mounted in front of the channel to throw a "shadow" onto the actual septum. This pre-septum forms part of the entrance collimator (see Fig. 5), which consists of water-cooled copper blocks capable of dissipating beam powers up to 10 kW (with a 5 mm beam diameter) and stopping even 200 MeV protons. The EEC has independent position and gap-width (between 5 and 15 mm) adjustments at both the entrance and exit.

For the extraction of 200 MeV protons we require a modest field of 50 kV/cm. The EEC has however been tested successfully up to its design voltage of 120 kV (i.e. 80 kV/cm) after 12 hours of conditioning. Typical leakage currents during operation are ⩽ 5 µA. A 5 MΩ damping resistor, for the protection of the EEC during spark-over, is positioned as close as possible outside the valley vacuum chamber.

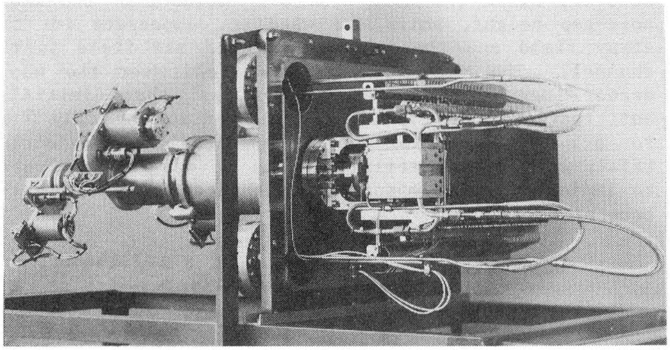

Fig. 5 The electrostatic extraction channel with the water-cooled collimator at its entrance. Part of the positioning mechanism is shown.

The first septum magnet (SPM1)

This 300 mm long extraction magnet with its driving mechanism is carried by a base-plate mounted onto a stiffening rib inside the inner delta of the west resonator (Fig. 6). Due to the relatively low flux densities required (typically 0.1 T for 200 MeV protons) it was feasible to design a straight channel. The magnet consists of a 10 mm thick C-shaped yoke and a water-cooled coil with 6 turns manufactured from 4 mm × 4 mm copper conductors. The total septum width is 6.5 mm. With the aid of a 50 kV/cm electrostatic field in the EEC the orbit separation for 200 MeV protons is increased to 16 mm to accept this septum. The usable gap size is 30 mm × 30 mm. The magnet was designed for 0.2 T in the pole-gap, with an excitation current of 1000 A, to allow for sufficient flexibility. The maximum power consumption of 11 kW is dissipated through 2 cooling circuits. Extensive two-dimensional field computations were carried out to optimize the septum magnet field properties. Measurements have confirmed that the field homogeneity is ⩾ 99% over the available gap width and that the stray field outside the septum could be limited to 0.5 mT over the whole excitation range, with the aid of a 1 mm thick permalloy shield.

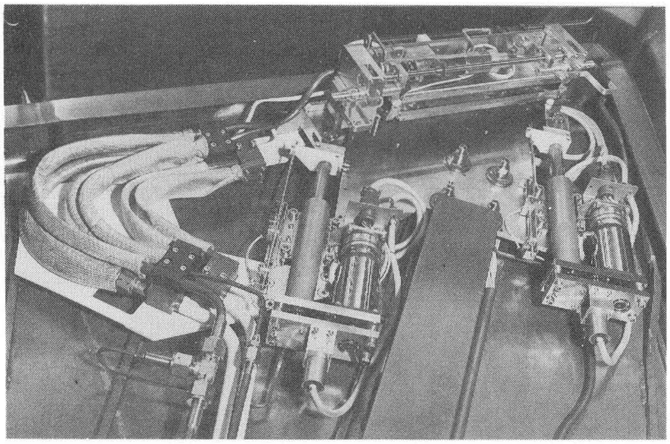

Fig. 6 The first septum magnet with its positioning mechanism mounted in the inner delta of a resonator. The scanner mechanism on top of the magnet permits the beam positions at both the entrance and exit to be determined.

Other special design features include: independent positioning of both entrance and exit with special (indirectly water-cooled) stepping motors designed for radiation conditions; an encoder to record these positions over the total stroke of 80 mm; all services (supply conductors, cooling-water, signal cables etc.) are supplied via the field-free inner transmission line; flexible supply leads (reaching temperatures up to 150°C for 800 A) and cooling pipes allow for the required movement; and a scanner, with a dc vacuum motor, potentiometer and tachogenerator, which scans two 0.5 mm thick molybdenum blades across the beam in front of and behind the magnet to permit the magnet position to be optimized relative to the orbits. Special care was taken to keep the flexible supply conductors as far away from the median plane as possible to avoid unacceptable coherent axial oscillations of the beam. The magnet and scanner can be removed as a unit through the pumping port at the rear of the resonator, leaving the base plate with drives and all services behind. If access is to be gained to the latter the upper half of the resonator must be raised, which requires that some roof beams have to be removed.

The second septum magnet (SPM2)

A narrow septum width and an acceptable power supply current were the main design criteria for SPM2. An adequate orbit separation of 38 mm is obtained for 200 MeV protons, with a 0.1 T SPM1 field, to accept a septum consisting of three 4 x 4 mm conductors next to each other. The total septum width of 15.5 mm is however also determined by the inner and outer copper liners and the magnetic shield to minimize the stray field outside the channel. The air-gap is 40 mm x 30 mm. This 600 mm long extraction magnet,

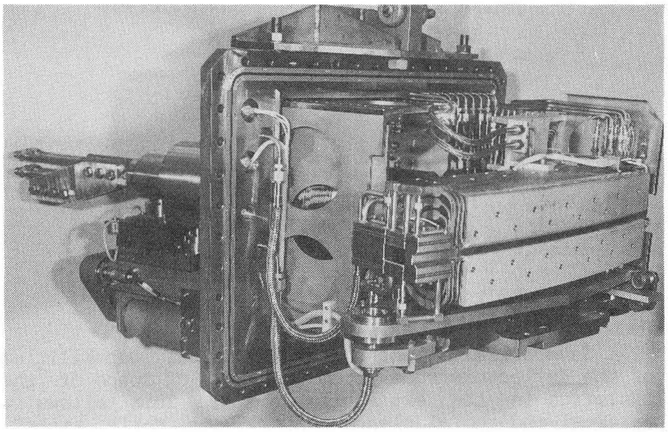

Fig. 7 The second septum magnet with the water-cooled collimator at the entrance. Part of the drive mechanism outside the vacuum can be seen.

shown in Fig. 7, deflects the beam through 15° into the high-energy beamline. A field of 0.94 T (designed for a supply current of 1460 A) is required for the deflection of 200 MeV protons. This magnet has been tested with an excitation current of up to 1800 A, corresponding to a high current density of 180 A/mm^2, a power consumption of 120 kW and a cooling-water temperature increase of 35°C. Each of the 18 turns of the coil is individually water-cooled. The inlet water manifolds are inside the vacuum enclosure while each cooling circuit outlet has a separate vacuum feedthrough (with bellows providing the necessary flexibility) for flow monitoring. Thermistors monitor the outlet water temperature. To reduce the power dissipation larger coil return conductors (i.e. 4 mm x 12 mm) were chosen despite the necessity for 2 additional soldering joints between each septum and return conductor.

Thick water-cooled copper collimators, capable of dissipating 10 kW beam power and stopping all particle beams, protect the magnet entrance and coil. The intercepted beam current can be measured from each of these collimators as well as from the water cooled copper liners protecting the coil. The whole magnet can be positioned radially over 127 mm and pivoted about the front edge of the septum collimator with independent stepping motor drives. Magnetic field measurements have shown that the field homogeneity over the available pole-gap width is $\geqslant 99\%$; this and a stray field of $\leqslant 5$ mT correspond to the initial design values computed with the program VEPO2.[3]

The First Operating Experiences

The first evidence of successfully injecting a beam into the SSC was recorded on the 1st October 1985, when a 3.15 MeV 1 μA proton beam was measured on the beam stop in its innermost position. Eight days later a 2 μA proton beam was accelerated out to the extraction radius to an energy of 66 MeV. This historic event took place only 14 days after the first pump-down of the SSC ring.[4]

During these initial beam acceleration trials the rf voltage was limited to about 70 kV, and we had to make use of precessional injection to clear the MIC on the first turn. During the first proton beam injection (for acceleration to 200 MeV) the maximum rf voltage of 250 kV at extraction was available, and this allowed us to obtain the required 43 mm orbit separation at the MIC exit.

Beam injection is aided by the injection collimator (with 10 individual current measurements) and the facility of to measuring the beam position and intensity distribution (with harps or scanners) in front of each injection component. The capacitive phase probe in the central region was invaluable in determining and optimizing the injected bunch length. Valuable information is also obtained by measuring the intercepted beam current from the MIC collimators and inner and outer liner sections, i.e. 12 independent current measurements.[1]

Optimization of the beam centering has been carried out for 3.15 and 8 MeV protons. The technique used to optimize the injection phase is described elsewhere.[4]

Our concept of having only a limited number of injection components with a large acceptance (contrary to other SSC injection systems) for the injection of particle beams with a wide range of specifications proved to be a good solution. Without much optimization a 100% beam transmission through the injection system is achieved regularly. We are very pleased with the day-to-day and long-term stability, repeatability and ease of operation.

The first beam, i.e. 3 μA 66 MeV protons, was extracted from the SSC on the 25th July 1986. Much attention was paid to obtaining well-centered orbits. Optimization of the rf phase to an accuracy of 0.5° is essential for optimum beam separation at extraction. Without much energy selection in the transfer beamline and with a 12° injected bunch length, separated orbits were still obtained at extraction (with an orbit separation of about 17 mm) for an rf voltage of 190 kV. Extraction efficiencies $> 95\%$ were obtained from the outset without difficulty for 66 MeV protons. After positioning and setting all three extraction components to their calculated values for the first beam extraction trial run, the beam stop was driven beyond the extraction radius and the beam was deflected out of the valley vacuum chamber.

During the first 200 MeV proton beam extraction run, a well defined orbit separation could not be obtained at the extraction radius for an 18° bunch length and a maximum rf voltage of 200 kV. The beam had a large vertical oscillation amplitude (due to a sector magnet misalignment) as well as a large energy spread and beam width resulting in a significant beam loss in the extraction elements. A 200 nA beam was extracted. We are confident that this can be improved with a better sector magnet alignment and with the installation of the buncher at the end of this year to reduce the bunch length to an acceptable 8° for single-turn extraction.

The beam intensities were kept deliberately low to avoid unnecessary activation of the machine. The injection and extraction of much higher intensity beams will soon be required.

References

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