OPERATING EXPERIENCE WITH THE LIGHT-ION INJECTOR OF THE NAC

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Summary. A k=8 MeV 4-sector cyclotron capable of accelerating particles ranging from protons to q/m=0.25 ions on harmonic numbers 2 and 6 was designed and built as injector for a 200 MeV separated-sector cyclotron. The central region was designed to accommodate three constant orbit geometries. Switching between these three geometries can be accomplished within minutes. Adjustable slits in the central region play a major role in obtaining good quality internal beams and an efficient extraction.

The completed injector cyclotron has now been in operation for about a year and has operated reliably at maximum level for more than 200 hours. On each of the three constant orbit geometries various particles have been accelerated successfully. Internal 8 MeV proton beams up to 100 μA in intensity were produced. For the maximum specified current of 10 μA, 100% extraction efficiency was obtained. The maximum external current recorded was 175 μA for 3.15 MeV protons. Deuterons were successfully accelerated on harmonic number 6.

Introduction

In 1978 the NAC started with the design of a suitable injector cyclotron for the 200 MeV separated sector cyclotron being designed at that stage.

The aim of this project was to provide a multi-disciplinary facility for nuclear research, isotope production and medical applications. The specifications for SPC1, the first of two injector cyclotrons, required good quality proton, deuteron, $^3He^{2+}$ and α-particle beams with intensities $\leqslant$ 10 μA and energies up to the maximum injection energy of the SSC (injection k-value = 8 MeV), as well as high intensity proton and deuteron beams ($\leqslant$ 100 μA) at energies up to about 4 MeV.[1] The injector for the heavier ions, SPC2, was to be designed and built once the first injector was operating.

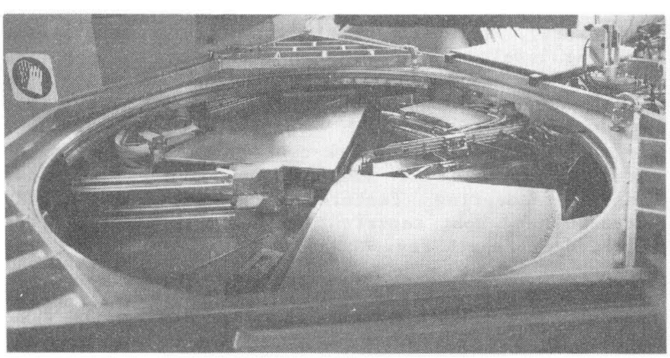

Fig. 1. The layout inside the vacuum chamber of SPC1. Components that can be seen are the first slit system, electrostatic- and first magnetic channel, ion source (slightly withdrawn) and, to the left of the dee in the foreground, the ionisation beam profile monitor.

During the design stage of SPC1, additional demands by the users-to-be, required the maximum energy for α-particles and $^3He^{2+}$-ions to be increased by about 35% and the extension of the range of ions, suitable for injection into the SSC, to a charge to mass ratio of ~0.25.

To fulfil all these diverse requirements the central region was designed to accommodate three different orbit geometries and operation on harmonic numbers 2 and 6. Adding to this the multi-disciplinary character of the facility, which necessitates several beam changes a week and the medical treatment of patients which puts a very high premium on reliability, it becomes clear that we were given an opportunity to design a rather special small injector cyclotron.

The final design was a k=8 MeV solid pole cyclotron with four 45° sectors, two 90° dees, an extraction energy ranging from ~0.1 MeV/nucleon for the heavier ions up to 8 MeV for protons and an rf-system covering a frequency range from 8.6 MHz to 26 MHz.[1,2] The resonator-dee assembly can be wheeled back on rails and all the other components in the vacuum chamber can easily be accessed by driving the upper yoke and pole assembly upwards through a distance of 550 mm (see Fig. 1).

The Central Region

The central region[3] was designed to require the minimum of adjustment and time when changing from one mode of operation to another. The first two constant orbit geometries (COG1 and COG2) are used exclusively for the acceleration of protons, deuterons and α-particles on the second harmonic number. The third one (COG3) is used for low energy α- and deuteron beams as well as for the heavier light ions such as nitrogen and neon, and acceleration takes place on the 6th harmonic.

As the movements of the ion source, puller, one axial and two radial slits as well as the two adjustable extraction channels are controlled by microprocessors communicating via mail boxes to the mini-computers, switching from one orbit geometry to another is in principle initiated by one instruction. The only exception is the removal/fixing of the winglike protuberances, (about 20 x 20 x 15 mm in size) to the ion-source head. These protuberances are in fact small dummy dee extentions, required only for the high energy mode COG1. The total time required for this last operation is less than 15 minutes. At present the ion-source-puller configuration is selected by means of a function key, the slit and extraction element positions are still entered at the console. A change from COG2 (h=2) to COG3 (h=6) can be accomplished in about 5 minutes. These times are negligible compared to the times required for the stabilization of the magnetic field (~45 minutes) and for setting up the rf-system when a major energy change is involved (~1 hour).

The design of the central region required the

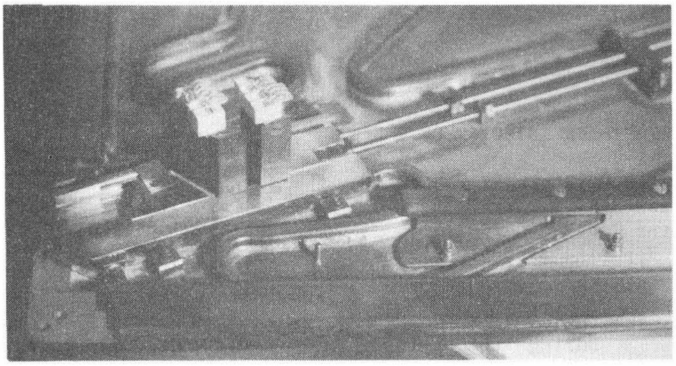

Fig. 2 Lower dee-plate with radial slit installed on a water-cooled track. The contact fingers on top of the slit jaws take the current and temperature measurements to busbars attached to the top dee-plate.

radial momentum selection slit to be installed inside a dee. Limited space precludes direct water cooling of the movable jaws. The three different orbit geometries necessitate a travel of about 40 mm. The driving mechanism, cooling water and all the electrical leads enter through the 5 meter long dee stem. After initial heat transfer studies, using electron-gun heating of prototype slit jaws, we succeeded in designing a compact slit system consisting of two 30 mm high pillars sliding on a water cooled track where good thermal contact is always maintained (Fig. 2). As no lubrication is used, phosphor-bronze and gold-plated copper are used for the sliding surfaces to prevent seizure. Double face metallised beryllium-oxide plates are silver-soldered between each jaw and its base, thus providing not only a solid path for heat transfer, but also the necessary electrical insulation for current measurements on the slit jaws. The temperature of each jaw is monitored by means of platinum resistors. Measurements showed that a temperature rise of 1.5°C/Watt input power is obtained, thus limiting the maximum temperature to 600°K for the maximum design value of 400 watts. Since its final installation in the cyclotron, the unit has performed satisfactorily for more than 700 hours giving no sign of deterioration of its characteristics.

The beam defining slits (1 axial and 2 radial slits) are positioned on the first turn for COG2 and COG3 and, due to lack of space, on the second turn for COG1. Beam intensities measured in the region between the last slit in the central region and the first extraction element showed that no beam is lost on COG1 (measured current at extraction ~80 μA) and about 10% lost on COG2 and COG3, measured for currents of 140 μA and 10 μA respectively. The orbit plots shown in Fig. 5 and Fig. 6 give an indication of the general quality of the beams produced.

The quality of the beams produced on COG1 is found to be better than those produced on COG2 and COG3. This is due to the fact that COG1 was optimised for good beam quality by making use of pillars on the first turn to obtain good electrical focussing at the first few gap crossings as well as to assist in phase selection. For COG2 and COG3, being on the outside of COG1, we were forced to use a more open geometry. At first, the phase acceptance on COG2 was too big and this led to a poor orbit pattern and extraction efficiency. Narrowing the puller channel and widening the inner jaw of the first radial slit improved this situation.

Rf-system

The rf-system[2] has already operated reliably at maximum level (56 kV peak, at 26 MHz with 16 kW per resonator) for 200 hours. Some improvements on the original design were required before this became possible.

A few stainless steel screws of the short-circuiting plate, which were situated in a position where their heads were exposed to the rf-field, became loose due to temperature cycling and two were melted before it was noticed. The problem was solved by using bronze screws which are secured by locknuts and spring-washers.

Beryllium-copper contact fingers between the copper pole liner and the copper plate of the vacuum chamber were destroyed over a length of 400 mm after the first 20 hours of operation at maximum power level. The problem was started by accidental damage to 50 mm of these 0.4 mm thick fingers during initial assembly, a fact which was not noticed at the time. The subsequent overcurrent on the adjacent fingers gradually destroyed more and more fingers until the overheating was noticed. Almost complete disassembly of the cyclotron was necessary to enable replacement of the faulty fingers. As a precaution an additional set of fingers, made from 0.4 mm thick dispersion-strengthened copper, was added over the silver-plated beryllium-copper fingers in the positions of high current density (more than 15 A/cm). This combination is very effective with the inner fingers producing the reliable spring pressure and with the outer fingers decreasing the temperature rise by at least a factor of three.

At the maximum operating voltage level of 56 kV at 26 MHz frequent sparking sometimes occurs owing to the close spacing between the ion source and puller electrode (6 mm). To enable the shortest possible interruption of the beam under such conditions, a monitoring and automatic restart program was developed for the microcomputer controlling the injector rf-systems. As soon as spark-over occurs the trip condition is recognized and after a delay of 0.5 seconds (to allow ionization to disappear) the drive signal is re-applied with a fast rise-time (100 nsec) using a double balanced mixer as a switch. The rise time is fast enough to drive the resonator through multipacting but the subsequent power level is kept low enough to avoid tripping of the 25 kW power amplifier which occurs when the reflected power exceeds 5 kW. When the automatic tuning system has tuned the resonators correctly (usually within 0.5 s and with the reflected power less than 500 watt) the drive power is increased step-wise until the correct operating level has been reached. Under normal conditions it requires approximately 2 seconds to restore the beam after spark-over has occurred. In some cases (less than 5% of spark-overs), repeated spark-over occurs before the operating level is reached. When this occurs the time taken before re-applying drive power and the time between successive power increments is lengthened progressively for each subsequent under-power spark-over. If 6 such spark-overs occur in succession power is switched off and the operator is notified. This self-adapting feature has proved extremely successful and most recurrent sparking is cleared after the third or fourth try.

As soon as power is removed from a resonator the resonant frequency starts changing owing to the temperature change. Within a minute it is not possible to restart in the previous "warm position". Two options are available in the program for restarting. With one the trimmers are first moved to the predefined position for "cold starting" prior to application of the drive signal. With the other option the signal is applied in the previous "warm position" but if it fails to produce resonator voltage, the trimmers are moved in the direction of the "cold position" in steps equal to 1% of the full range. Power is re-applied after each step and the process continues until voltage is obtained or the "cold position" is reached. In the latter case the program stops and notifies the operator. Under normal conditions both methods will result in a successful restart and the length of time the system has been off determines which method is quickest. If more than 10 spark-overs occur at full operating level during any 30 s period, power is switched off as a safety feature, and an error message reported. Possible causes are listed with each error message. With the aid of this program it has been possible to achieve many hours of unattended operation of both resonators, with a virtually continuous beam, even at maximum frequency and voltage, but with the knowledge that the system will stop safely and report the error if any malfunction should occur.

Extraction System

The extraction system of SPC1 consists of an electrostatic channel (EEC) a very compact active magnetic channel (MEC1), placed at a vertical waist of the extracted beam, to provide strong horizontal focussing for the fringe field crossing and a second active magnetic channel (MEC2) providing both focussing and steering of the beam. It is then followed by a mild steel pipe to reduce the stray field up to the exit port on the vacuum chamber. Some of these elements can be seen in Fig. 1.

The electrostatic channel is 360 mm long, has a minimum width of 4 mm and a maximum width of 15 mm. The high voltage electrode is fixed to a water-cooled copper support by means of four BeO insulators. It has now been working for more than 260 hours at E.V = 5600 $kV^2 cm^{-1}$, which is the maximum value required, and the only breakdown was due to damaged insulation material around the high voltage rod inside the vacuum chamber.

The first magnetic channel is about 100 mm long with a beam aperture 12.5 mm high and 30 mm wide. The field gradient can be varied from 12 Tm^{-1} to 24 Tm^{-1} (ni = 14620 At) in a field for 8 MeV protons. These measured values agree well with the design calculations.[1] The second magnetic channel provides a gradient of about 7 Tm^{-1} and the steering coils a field of about 0.15 T.

Four stepper motors are used to adjust the width, taper, radial position and rotation (with respect to beam direction) of the electrostatic channel. On the first magnetic channel (fixed beam aperture) two stepper motors are used for the radial movement and rotation. A microprocessor looks after these adjustments as well as the safety interlocking of the channels.

At the electrostatic channel beam current measurements are performed on a collimator protecting the copper high voltage electrode, a vertical tungsten wire (ϕ1 mm) in front of the copper septum and the septum itself. In front of each of the two magnetic channels and the screening pipe are left, right, top and bottom collimators for protection as well as diagnostic purposes. Inside the channels we have water-cooled copper liners for the protection of the coils. Unfortunately no provision was made for current measurements on different segments of these liners and only the total current on the liner can therefore be measured.

The extraction system is performing very satisfactorily. The working positions for the magnetic extraction channels MEC2 and MEC3 are identical with the calculated positions. MEC1 had to be adjusted slightly - in the case of the 8 MeV beam the shift amounts to

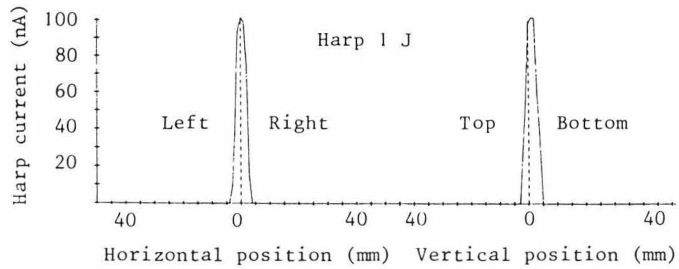

Fig. 3 Profile of a 3 μA, 8 MeV proton beam as recorded on a harp in the first diagnostic chamber.

about 3 mm. The voltage needed on the EEC was within 1% of the calculated value.

Exact comparison between calculated and operating excitation currents for MEC1 and MEC2 is difficult. A change in the focussing current of MEC1 not only changes the focussing but also has an influence on the direction of the extracted beam. Furthermore, a shift in the position of the channel also strongly influences these properties because the main field has a strong gradient in this region. At MEC2 a similar problem is encountered. Adjustment of the beam direction by means of the steering coils also changes the focusing power of the channel. Until now we have not had time to gather enough data to be able to make a thorough comparison between the calculated and optimised operating values. However, the extraction channels are functioning properly and we have good control over the extracted beam (Fig. 3). The maximum extracted proton current was 175 μA at 3.15 MeV and 100% extraction efficiency was achieved for a 12 μA 8 MeV proton beam.

A non-intercepting beam profile monitor

We have studied the feasibility of a non-destructive, internal beam position monitor for SPC1, the principle of which is based on the ionisation of residual gas by the beam, as suggested by Jongen.[4] The electrons released along the beam path are accelerated in a vertical electric field and collected on an array of tangential strips located off the cyclotron median plane.

Preliminary calculations based on typical operating pressure (10^{-6} mbar) and on relevant cross section data, yielded an electron current to beam current ratio, or efficiency, of the order of 10^{-4} in the case of a 10 mm long collector, which makes the method relatively insensitive though practical for large beam currents (>1 μA).

A prototype of this Ionisation Beam Position Monitor (IBPM) has been manufactured and installed in SPC1 (Fig. 1) and the response was observed during most of the beam tests (protons and deuterons). A typical plot of the beam position graph is shown on Fig. 4. The following conclusions may be drawn: the efficiency lies

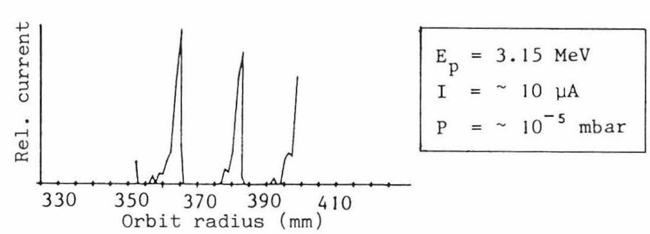

Fig. 4 Beam profile of an internal beam (orbits 12 and 13) as recorded on the ionisation beam profile monitor installed in the pole-gap of SPC1.

between 10^{-4} and 10^{-5} as predicted and a 10 µA beam could be located accurately. An optimum signal to noise ratio occurs at cathode voltage around -500 volts. The sparse information provided by the 50 mm long IBPM during these tests proved so helpful in setting up the beam that it was decided to go ahead with the development of larger IBPM's for permanent use in SPC1.

Beam Production

The completed injector cyclotron has now been in operation for about a year. During this time protons have been accelerated on COG1 (h=2, 37 turns), protons, deuterons and α-particles on COG2 (h=2, 17 turns) and deuterons on COG3 (h=6, 11 turns). Table 1 gives information on some of these runs.

Table 1. A few parameters of the proton and deuteron beams accelerated in SPC1.

Ion	Energy (MeV)	V_D (kV)	N_t (turns)	I(int) (µA)	I(ext) (µA)	ε (%)
p	8.00	56	36(h=2)	12	12	100
p	3.15	47.25	17(h=2)	58	45	78
				260	175	67
d	1.76	48.9	11(h=6)	50	-	
				6	3	50

In each case well-centred orbits were obtained (Fig. 5 and Fig. 6). Optimum ion-source and slit settings were in good agreement with the calculated values. Typical differences varied from fractions of a millimeter to about 2 mm.

Sharply defined intense beams were produced on COG1. A current of 35 µA was recorded for 8 MeV protons at extraction with the dimensions of the two radial and one axial slit in the central region respectively 1.0 mm; 4.5 mm and 2.0 mm. By increasing the gap of the axial slit, beam currents up to 100 µA could be obtained. The specified 10 µA 8 MeV beam can easily be extracted with a 100% efficiency and we are confident that this current could be increased to 50 µA, should it be necessary.

Much of the injector's running time was devoted to the production of 3.15 MeV proton beams. This is the injection energy required by the SSC for the production of 66 MeV beams intended for the therapy vaults. The extraction efficiency was poor at first, but the modifications in the central region, described in a previous paragraph, improved this to almost 80%. The maximum external current of 175 µA was recorded at this energy with the first radial slit 10 mm wide and both the axial and second radial slits 6 mm wide.

During an unscheduled shutdown of the SSC we got the opportunity to try acceleration on the 6th harmonic. As the rf-system was already tuned for 26 MHz (8 MeV protons on COG1), a 1.757 MeV deuteron beam was decided on for this trial. Producing this beam was much easier than expected. Within a day 3 µA was extracted with a 50% extraction efficiency, but then we had to switch back to 8 MeV proton beams for the SSC. Orbit patterns obtained with a 3-finger differential probe showed a coherent vertical oscillation of the beam. At the entrance of the EEC it reached a maximum of about 4 mm below the median plane, was forced back in the fringe field and struck the upper collimator of the second magnetic channel where 50% was lost, thus the poor extraction efficiency.

These vertical oscillations have been observed before, but caused no concern as we had enough control

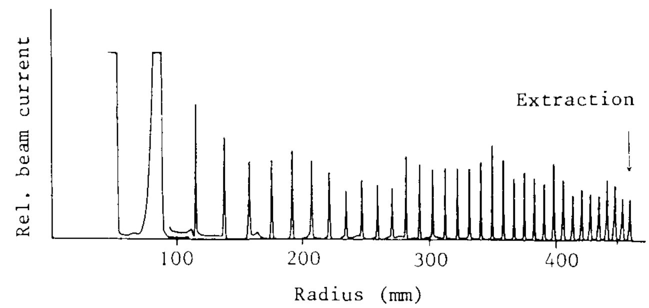

Fig. 5 Orbit pattern of an internal 80 µA proton beam accelerated on the 37-turn constant orbit geometry (COG1; h=2)

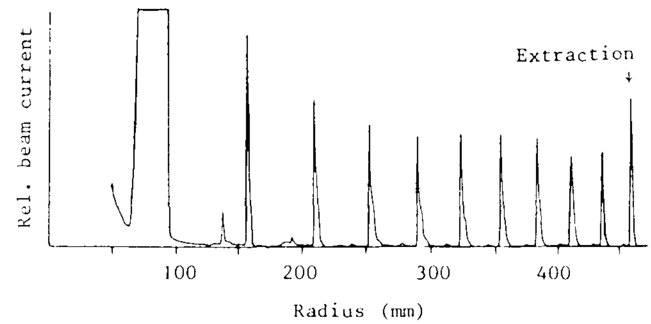

Fig. 6 Orbit pattern of an internal 50 µA deuteron beam accelerated to 1.75 MeV on the 11-turn constant orbit geometry (COG3; h=6).

over the beam. The beam loss which occurred in this case, however, will require further investigation. We suspect that these problems may be due to a change in the alignment of the dees.

Vacuum System

The main components of the vacuum system are one 4.8 m^3s^{-1} turbo and two 3.5 m^3s^{-1} cryogenic pumps.[5] It has been performing very well since its installation 3 years ago, and renders reliable service.

The pump-down time from atmospheric pressure to working pressure is approximately 2.5 hours. Typically the working pressure is about 1.5 × 10^{-4}Pa without gas from the ion-source. The lowest pressure reached in SPC1 was 8 x 10^{-5}Pa.

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