COMMISSIONING OF THE INJECTOR CYCLOTRON FOR POLARISED AND HEAVY IONS AT NAC

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The final assembly of the injector cyclotron (SPC2) for polarised and heavy ions, with the concomitant transfer beamlines, was completed in mid 1994. The first beams were accelerated in June 1994 and beam development was continued up to August when the first production beams were delivered to the separated sector cyclotron. Beams of polarised protons have been produced. High intensity proton beams from the ECR source as well as beams of $^{12}C^{3+,4+,5+}$, and $^{40}Ar^{8+}$ have been produced. The best transmissions through SPC2 obtained thus far were 7%, 21%, and 6% for the three orbit patterns (34, 17 and 8 turns) respectively. Development and optimization of the ion sources, beamlines, and SPC2 is moving ahead.

1 Introduction

The k=11 MeV second solid pole injector cyclotron (SPC2) at the NAC has been designed[1] to utilise three constant orbit patterns in order to accelerate beams of light and medium heavy ions from an ECR source and an atomic beam source (ISI) for polarised protons and deuterons. The cyclotron has now been in operation for one year, and a number of beams were developed and delivered to the 200 MeV separated sector cyclotron (SSC).

In Figure 1 SPC2 is shown as viewed from between the two rf-resonators. The inflector insertion and positioning mechanism housing can clearly be seen on top of the cyclotron.

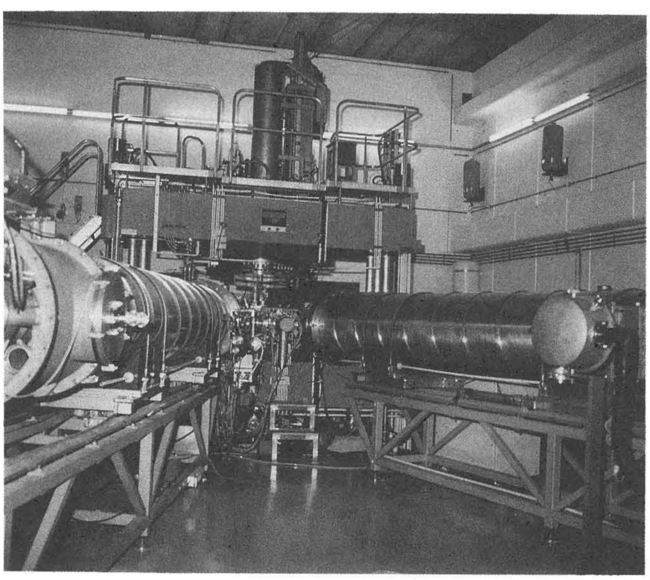

Figure 1: Photograph of SPC2.

2 First Year in Operation

The beams produced in the first year of operation are summarised in Figure 2.

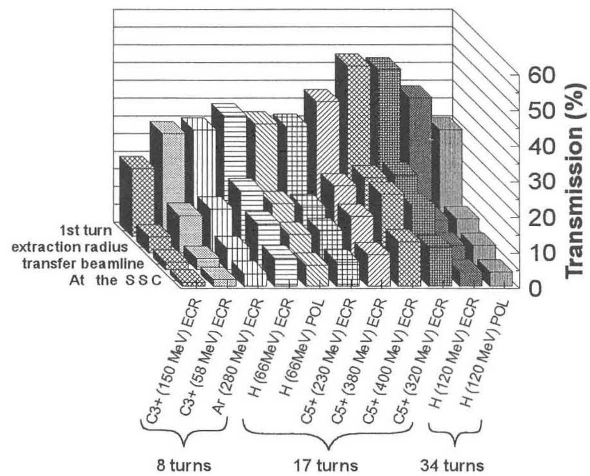

Figure 2: Summary of beam transmissions achieved for SPC2.

Transmissions up to the various positions indicated are relative to the last Faraday cup before the beam enters the yoke of SPC2. The best transmission obtained thus far was 21% for a 400 nA 20 MeV $^{12}C^{5+}$ beam extracted from SPC2. From the data it can be seen that the transmissions obtained for the ECR and the ISI are of the same order for the 34-turn and 17-turn orbits respectively. The transmission using the 17 turn orbit is about 3 times that of the 34-turn orbit. This can be attributed to the fact that the 34-turn orbit has to pass through the central inflector shield for a second time and thus is limited by two more slits that have to be as small as possible for shielding purposes.

The transmissions for the 8-turn orbit are much poorer than those for the other orbits. This may in part be due to lack of statistics at this stage, but is mainly ascribed to the existence of a coherent vertical oscillation of the beam that is particularly noticeable on this geometry. Plots from a three finger probe indicate that the amplitude of these oscillations could be up to 3 or 4 mm. This is in agreement with magnetic field measurements showing that the magnetic median plane is slightly conical, dropping towards larger radii with respect to the geometrical median plane. The highest intensity beam accelerated through SPC2 was a proton beam at the neutron therapy energy (3.15 MeV at injection to the SSC). The intensity measured in the transfer beamline from SPC2 to the SSC was 82 μA, with a transmission of 13% through SPC2.

3 Magnetic Median Plane Measurements

Some unexpected but persistent vertical beam oscillations observed in the light-ion injector cyclotron SPC1 gave us a strong motivation to measure the magnetic median plane in SPC2, in particular as axial injection and the much wider variety of ion species and energies to be accelerated by this machine will complicate beam development in any case. A special measuring instrument was developed for this purpose[2] and the measurements were carried out over a period of two weeks, just before the final cleaning and assembly of SPC2 in the first half of 1994. The instrument makes use of three orthogonally mounted Hall-generators and two electrolytic tilt sensors for measuring the radial, azimuthal and axial (defined by gravity) field components simultaneously, and must be extremely carefully calibrated. After calibration, the horizontal field components can be measured with an accuracy of better than 0.1 gauss in the presence of vertical fields up to 2 tesla.

The field components were measured 1.5 mm above and below the geometric median plane at 16 azimuthal positions distributed almost evenly around a circle, for two radius values, r = 0.1 m and r = 0.3 m, and at two different excitations (300A, 600A) of the main coils. The horizontal field values in the geometric median plane are then calculated by linear interpolation. The results obtained in this way for the radial field components B_r are shown in Figure 3. The azimuthal field components are similar in magnitude, but can be ignored here, due to their weak effect on the beam along equilibrium orbits.

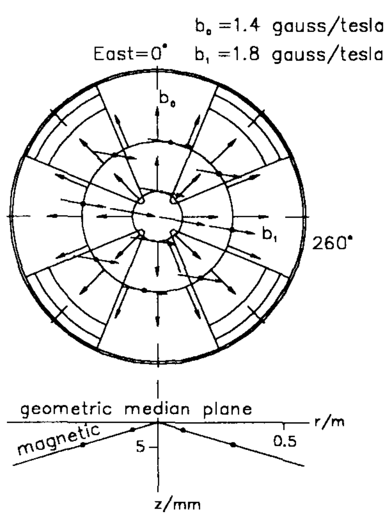

Figure 3: SPC2 median plane fields.

A Fourier analysis of the measured B_r values provides an indication of the two most important radial field terms, i.e. the constant term B_{r0} and the first harmonic B_{r1} with its phase angle θ_{r1}. The results show that both B_{r0} and B_{r1} are independent of R but proportional to the excitation, such that $B_{r0}/\langle B\rangle \sim 1.4 \times 10^{-4}$ and $B_{r1}/\langle B\rangle \sim 1.8 \times 10^{-4}$. The phase angle of B_{r1} is nearly constant and points in the direction θ_{r1} ~260° with east as reference for $\theta = 0$. B_{r0} can be related to a magnetic median plane deviation from the geometric median plane which increases linearly with radius such that $\Delta z_m/R \approx 15$ mm/m, independent of excitation. At extraction ($R \approx 0.5$ m), the magnetic median plane could be up to 7.5 mm below the geometric one. A likely cause for B_{r0} would be asymmetries in magnetic properties of bulk material used for the magnet, whereas B_{r1} is probably due to the excitation effects of uncompensated vertical conductor sections of the main coils.

A tolerance analysis in smooth approximation on the maximum vertical displacement of the beam which can be expected from B_{r0} and B_{r1} shows that such displacements should not exceed ~4 mm under normal conditions in SPC2. Hence the combined effect of B_{r0} and B_{r1} could lead to coherent vertical beam oscillations with an amplitude of up to 4 mm.

4 Performance of Sub Systems

4.1 Vacuum System

In order to avoid excessive beam losses due to the interactions of heavy ions with residual gas molecules, the vacuum requirements are typically more stringent by an order of magnitude in SPC2 and its associated beam lines than those for an equivalent light ion injector facility. Thus the vacuum system of SPC2 has been designed, and the equipment selected accordingly, to reach a pressure in the 10^{-5} Pa range[1], and that for the injection beam line from the ECR source in the low 10^{-6} Pa range. Before the first beam test the whole cyclotron was dismantled, especially for thorough cleaning of all accessible surfaces of the components exposed to vacuum, and then reassembled. This procedure seems to have had a considerable effect, because the ultimate vacuum pressure which up to now has been achieved in SPC2 under operational conditions with a 2.2 m^3/s turbomolecular pump and a 10 m^3/s cryopump was just below 1×10^{-4} Pa, about a factor 3 better than expected. The pressure should improve further to $<5 \times 10^{-5}$ Pa with the installation in the near future of two additional cryotraps, each with a pumping speed of 10 m^3/s for water vapour. Measurements confirmed that the beam lines associated with SPC2 also operate well within the pressure range of their vacuum design specifications.

In Figure 4 the predicted and measured pressure in the system from the ECR source up to SPC2 are compared. The separate crosses indicate the pressures as measured on the beamline. The circles indicate pressures measured on the

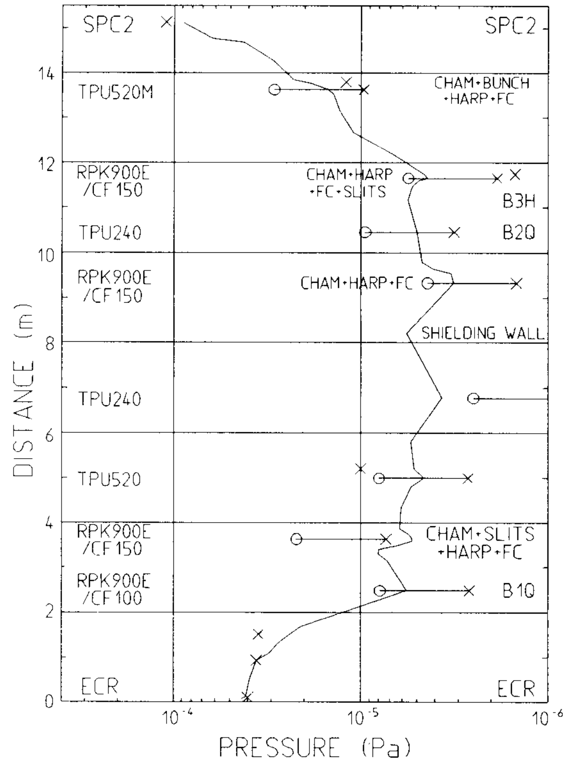

Figure 4: The pressure distribution in the beamline vacuum system from the ECR source to SPC2.

pump valves, and the connected crosses indicate the estimated 1/3 pressure at the corresponding pump ports.

4.2 Ion Sources

The 10 GHz Minimafios ECR ion source is outdated and intensity wise not competitive with modern ECR sources. It is however very reliable and performed well during test and production runs.

The first polarised beams were produced in August 1994. The transmission from the exit of the ISI source to the entrance to SPC2 was improved from the expected 50% to 80%. The lifetime of the ioniser filaments was increased from about 2 weeks to more than 6 weeks by decoupling the vibrations of the ioniser vacuum pump from the chamber. The required currents on target were in the range 100 to 300 nA. The intensity available for injection into the SSC is between 700 nA and 1000 nA. Typical losses in the SSC are about 30%. Losses in the high energy beam lines depend on to what extent the beam defining slits are used to limit the beam dimensions, but typical values range from 10% for experiments where beam definition is not very important to about 80% for very sharply defined beams. Until now, only vertical polarisation was used, and with fine tuning of the Wien filter in the beamline between the source and SPC2, polarisation values of over 70% and up to 76% have been measured on target.

The "three gradients" method was used to measure the emittance of the beam from the ECR source and polarised source. The basic idea of this method is to determine the horizontal and vertical beam width as a function of the strength of an upstream quadrupole or quadrupoles. Three different quadrupole strengths are sufficient to calculate the emittance, but to increase the accuracy, a series of profile measurements are acquired and a least-squares fit to the data is done to obtained the emittance. The beam width is measured at 20% of the height of the profile (for a Gaussian distribution 93% of the beam is enclosed). The emittance for the ECR ion source and polarised source are summarised in table 1 below.

Table 1: The emittance for the ECR and polarised ion sources.

Normalised emittances	Beam from ECR source π mm mrad		Beam from polarized source π mm mrad
Ion type	H^+	$^{12}C^{5+}$	H^+
$\varepsilon_{horizontal}$	0.15	0.21	0.38
$\varepsilon_{vertical}$	0.14	0.1	0.35
Beam current	26 μA	1.8 μA	28 μA

4.3 Inflectors

Three inflectors, one for each of the orbit patterns, were manufactured and tested for the various beams. It was found that the design voltages were at optimum, and that the design zero position was very near the optimum values, needing only minor adjustment during optimisation of the transmission of the beam into SPC2. Vertical adjustment was found to be particularly useful to compensate for beam losses in the central region due to the coherent vertical oscillations.

4.4 RF System

Progress in reaching the required RF voltages in SPC2 was slow at times due to a prolonged and difficult process of conditioning, which generally followed any retuning of the resonators. This is now thought to be due to the inner conductors of the resonators not being properly cleaned before installation. The problem has now virtually disappeared. Power loss in the resonators was found to be of the order of 50% higher than expected at the higher frequencies. The cause is not yet clear, but the answer may be found in the surface finish of the dees or taper sections of the resonators. This, together with a manufacturing fault in the mains transformers of the power amplifiers' anode supplies, has meant that the power amplifiers are barely able to supply sufficient RF power at maximum frequency. New transformers are being acquired to rectify this problem. Another noteworthy difference between SPC2 and SPC1 is in the characteristic effects of temperature on the resonant frequency, which necessitated a new trimmer capacitor positioning algorithm.

5 Improving Intensity

5.1 Vertical Oscillations

As a first step to increase beam intensity, the vertical oscillations will be studied. If it can not be easily eliminated, we will have to consider installing one or two electrostatic vertical steerers in SPC2 to guide the beam through the extraction system. Almost 50% of the intensity losses occurs in the extraction stage, mainly on the vertical collimators of the magnetic extraction channels. Without these losses, the beam transmission through SPC2 is expected to improve to between 20% and 25% for the 8- and 17 turn orbit patterns, but only to between 7% and 10% for the 34-turn orbit.

5.2 Installation of a Second Buncher

A double-drift beam bunching system consisting of two bunchers, separated in space and independently driven but phase-locked together, is now being investigated to further enhance the beam current from SPC2. Because of the limited space in the injection beamline, the two bunchers cannot be placed anywhere at will. In our case a system with the first buncher driven at twice the frequency of the second gives the best theoretical results and an improvement of about 30 % in the beam current from SPC2 can be expected.

5.3 Increasing the Size of an Inflector

An inflector of greater physical dimensions is proposed in order to inject a high intensity beam on to the 17 turn orbit pattern for isotope production and neutron therapy.

6 References

1. Z B du Toit *et al.*, “Progress with the NAC injector cyclotron for heavy and polarized ions”, in *Proc. 13th Int. Conf. on Cyclotrons and their Applications* (World Scientific, Singapore 1992) p. 361.
2. L K O Schülein and H N Jungwirth, “A Precise Method to Measure Horizontal Field Components in Dipole Magnets”, *NAC-Report* (in preparation).

Figure 5: View of the interior of the injector cyclotron for polarised and heavy ions. Two of the slits, axial on the left and radial/axial on the right are visible. On the left the diagnostic harp and one differential probe can be seen. On the outer circumference some of the extraction elements, a magnetic channel on the left and the electrostatic channel on the right, can also be seen.