TRANSFER BEAMLINES FOR ECR AND POLARIZED–ION SOURCES FOR A NEW INJECTOR CYCLOTRON AT NAC

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ABSTRACT

A second solid–pole injector cyclotron (SPC2) is under construction: this machine will be required to provide heavy ions and polarized protons and deuterons for injection into the separated–sector cyclotron (SSC) which is already operating. The proposed transfer beamlines from the new ECR ion source as well as from the new polarized–ion source to the injector cyclotron are described.

The line from the horizontal ECR source uses mirror–symmetric 90° dipoles with the second dipole twisted through 90° to direct the beam upwards into the axial injection system, using solenoids to achieve achromatic transport and to compensate for space–charge effects. The solenoid polarities are chosen to give precisely 90° rotation without affecting the mirror symmetry which minimizes second–order effects. A movable solenoid will control the initial waist size for various emittances.

For the horizontal polarized–ion source, a vertical mirror–symmetric achromatic system with two 45° bends and solenoids will produce a final double waist at the same point as that from the ECR source, so that the succeeding vertical section of beamline can operate in a similar way for either source. Rotation of the polarization axis from horizontal to vertical (required for both protons and deuterons) will be achieved by a combination of electrostatic and magnetic deflections to give the correct axial alignment.

1. INTRODUCTION

A second injector cyclotron, a k=11 MeV solid–pole machine, is being constructed to provide the k=220 MeV separated–sector cyclotron[1] at NAC with heavy ions and polarized ions. The heavy ions will be generated within an ECR source, and a separate polarized–ion source has also been ordered. The ECR source will permit the cyclotron facility to accelerate heavy ions with charge–to–mass ratios between 0.12 and 0.5 to between 3 and 55 MeV per nucleon. The ECR source is now assembled in a room adjacent to the SPC2 cyclotron vault basement, and shielded from the radiation which will exist below the cyclotron, thus permitting free access for servicing the source (see fig. 1.) The design of the 15 m beamline between this source and the cyclotron is discussed below.

For the polarized–ion source the beamline is fairly straightforward, but a brief description of the vertical 90° achromatic bend, using two 45° dipoles is also given.

2. ECR SOURCE BEAMLINE

We have taken as our starting point the assumption that the beam from the ECR source will have a maximum magnetic rigidity of 0.0646 T.m, an emittance of 200π mm.mrad (horizontal and vertical), and a momentum–spread of 0.1%. The line is divided functionally into sub–systems for (a) matching the beam to the beamline, (b) charge–state selection, (c) achromatic transfer via two 90° dipoles into the vertical direction, (d) emittance matching and (e) rotation around the vertical axis.

Each of these sections is described and the influence of second–order effects and space charge is also discussed.

2.1. Controlling Beam Divergence from ECR Source

The solenoid S1 (fig. 1) is used to focus the beam at the slit SL1, located at the double–focusing distance from the analysing magnet B1. The divergence of the beam extracted from the ECR source depends on several factors, including the size of the apertures in the extraction electrodes. Beam divergences greater than 50 mrad at the slit SL1 would mean that some of the beam intensity was lost owing to the beam striking the vacuum chamber within dipole B1. However, the solenoid S1 has been constructed so that it can be moved (up to 240 mm) along the beam pipe by remote control, and the divergence of the beam focused at SL1 can thus be varied from 0.61 to 1.63 times the divergence extracted from the source.

This matching can also be achieved by varying the puller electrode position at the source itself[2], but it has been established experimentally with our ECR source that this also has an undesirable influence on the intensities of the various charge states.

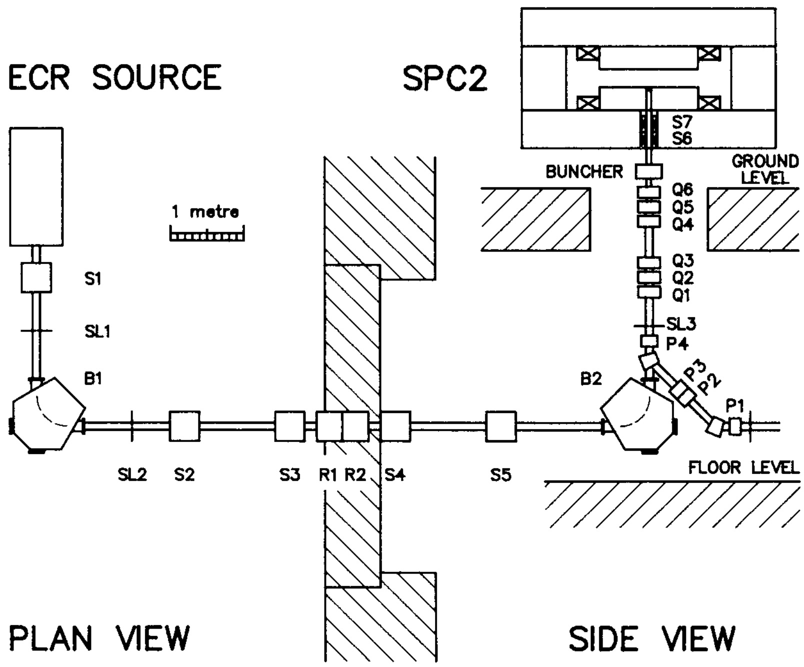

Fig. 1. Beamlines from the ECR source and polarized–ion source (not shown), leading to an axial injection system into SPC2.

2.2. Charge–State Selection

It is important that charge–state selection takes place as early as possible in the beamline, so as to eliminate the contribution of the unwanted charge states to space–charge effects. The solenoid S1 and the dipole B1 (with slits SL1 and SL2) both contribute to charge–state selection. Although the dipole is the primary selection device, some rejection of unwanted states occurs at the first slit.

The analysing magnet is a 90° double–focusing dipole, with a 400 mm radius and entrance and exit edge–angles of 29.8°, and a double–focusing distance of 900 mm from the effective edge. The fractional charge selection capability is given by:

$$\frac{dq}{q} = \frac{2\,w}{R_{16}},$$

where w is the width of the entrance and exit slits used, and R_{16} (the horizontal–dispersion element of the transfer matrix up to slit SL2) is 18.15 mm/% . For 20 mm slits, the charge selection is therefore 1 in 45. The second–order effects of a magnet similar to B1 have been thoroughly researched elsewhere[3] and lead to a broadening of the slit image at the analysing slit by 20%. The charge selection is then reduced to 1 in 37, which is more than enough for our requirements.

2.3. Twisted Achromat

A second 90° dipole B2 is needed to bend the beam into the vertical direction once it has been transported to a position beneath the cyclotron. Various types of focusing elements were considered for the horizontal section of beamline between the two 90° dipoles. However, after it occurred to us that this section could form a natural achromat, it became clear that solenoids were most suited to this application. The achromat is formed as a mirror–symmetric system of solenoids between two 90° dipoles.

Certain conditions must be met for the system to form a proper mirror–symmetric achromat. Firstly, the beam must be rotated by exactly 90° between the two dipole magnets, so that the dispersion path lies in the bend plane of each dipole. Secondly, the R_{16} and R_{26} matrix elements (in TRANSPORT[4] notation) must be zero at the end of the system. The first condition can be satisfied by using four identical unit cells, each comprising a solenoid with identical drift lengths on each side (solenoids S1 – S4 and their drift spaces). The solenoids are 400 mm long (nominally) and the drifts are 515 mm long.

For the first two of these unit cells (i.e. the first half of the solenoid system), the first–order transfer matrix is the identity matrix –I, with no nett rotation of the beam, because the solenoids have identical strengths but opposite polarities, and it is a double–telescopic system. For the second half of the system, the solenoids are identically powered, but this time with with the same polarity. The first–order transfer matrix is again –I, but the beam is rotated by 90°. The total transfer matrix of these two sub–systems is then +I, with 90° rotation, as required.

With all four solenoids having identical strengths (but with polarity of S3 reversed), TRANSPORT was used to vary the length of the unit cell until the 90° rotation was achieved exactly.

The complete system extends from slit SL1 to SL3, and the second condition for achromaticity can now be tackled. It has been shown[5] that for a mirror–symmetrical system with a transfer matrix **M** for the half–system, the transfer matrix **R** for the whole system has elements:

$$R_{16} = 2.M_{12}M_{26}$$

and

$$R_{26} = 2.M_{11}M_{26}.$$

Thus, if the angular dispersion at the symmetry plane of the system is zero ($M_{26} = 0$), then $R_{16} = R_{26} = 0$, and the system is achromatic. Only one parameter is needed to achieve this, and we use two identical solenoids, wired in series and with opposite polarities, placed at the symmetry plane. As the beam is focused to a fairly small waist at that point, this solenoid pair has very little effect on the focusing of the beam. There is also no nett rotation of the beam, because the polarities are opposed. The tuning of the whole system should be very simple, because there are only two variables, i.e. the excitation of the 4 identical solenoids S2 – S5, and the 2 identical solenoids R1 and R2. Fig. 2 shows the beam envelopes plotted for achromatic transport through this system.

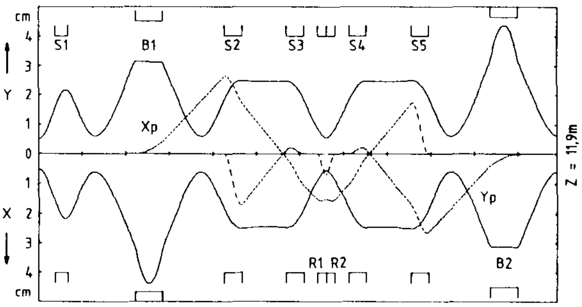

Fig. 2. First–order beam envelope calculation and 1% momentum dispersion paths X_p and Y_p, for the twisted achromat shown in fig. 1.

2.4. Second–Order Effects

Because dipoles B1 and B2 contribute greatly to second–order broadening of the beam, it is important to investigate second–order effects for the whole system. One advantage of symmetrical systems is that many second–order terms vanish. The program TRANSPORT was again used to calculate the second–order effects. With the solenoids R_1 and R_2 switched off, second–order effects cause the beam at the exit of the system to be broadened by 53% in the horizontal plane and by 73% in the vertical plane (using axes defined at the entrance to the system). With R_1 and R_2 set correctly for an achromatic system, the broadening is a mere 0.5% horizontally and 0.3% vertically! The second–order beam envelope plot is almost identical to the first–order plot, and it is clear that there will be negligible effect on the rest of the beamline as a result of this twisted achromat.

2.5. Double–Dispersive Transfer

The whole system can also be operated in a double–dispersive mode, by rotating the beam by –90° instead of by +90° between the two dipoles. For this mode the R_{16} element after the second dipole is doubled. However, because second–order effects cause significant beam broadening, one would have to use TURTLE[6] to calculate the true width of the beam in order to see whether this increased dispersion really contributes to a useful increase in resolving power, which could then be a useful tool in measuring the yield of particular ions from the ECR source which are difficult to resolve otherwise.

2.6. Emittance Matching System

For matching the emittance of the beam to the injection requirements of SPC2, we propose to use six quadrupoles, arranged as a 2–triplet telescope on the vertical section of beamline below the cyclotron. In practice, quadrupoles Q1 & Q3 will be connected in series, as will Q4 & Q6, giving just four parameters. The advantage of using triplets instead of doublets is that the beam is kept significantly smaller, and the triplet system is much easier to tune. These quadrupoles focus the beam to a double waist just below the cyclotron yoke, at a location suitable for the buncher.

The conditions to which the beam must be matched at injection must still be finalized by calculation backwards from the first acceleration gap through the proposed spiral inflector. For preliminary design of the beamline, we have assumed the requirements to be for a double waist with a half–widths of 3 mm for both x and y at the entrance to the base of the spiral inflector. The double waist will be formed by a pair of solenoids S6 and S7 inside the yoke of the cyclotron. Fig. 3 shows the beam profile in the vertical section of beamline up to the inflector.

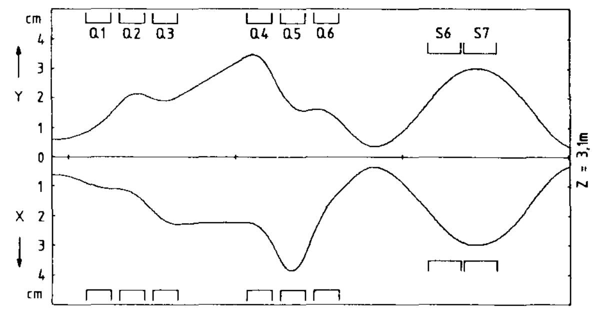

Fig. 3. Beam envelopes calculated for the vertical section of beamline up to the inflector.

2.7. Beam Rotator

Because of the coupling between the two transverse phase–spaces within the spiral inflector, there can be a considerable increase in the emittance of the beam[7], and this can be as much as 50%. The effect can be minimized by rotating the injected beam.

Systems which can be used as beam rotators have been described in the literature[7,8]. However, space does not permit us to install a system which is used solely for beam rotation. Because the beam from the ECR is (at least approximately) spherically symmetrical, and will be transported telescopically and achromatically into the vertical beamline, only the beam–matching pair of triplet quadrupoles are at our disposal for beam rotation. Rotating the 6 quadrupoles themselves as a unit (up to a maximum of ± 45°), together with a possible swapping of x and y phase spaces, is all that is needed to orient the beam ellipse in any direction with minimum change to the emittance matching.

2.8. Space–Charge Effects

We have used the SIN version[9] of TRANSPORT to calculate the effects of space charge on the beam profile. However, this program does not take charge neutralization into account, so the results will be a worst–case limit. We looked at a 20 keV H^+ beam with an intensity of 200 μA. This represents the case of the ECR source being used as a stand–by source for supplying particles for neutron radiotherapy.

Stronger focusing is required where space–charge effects are large, causing additional rotation of the beam in the horizontal section of the beamline: to compensate for this, it becomes necessary to install an additional solenoid R3 between the solenoids R1 & R2. This is used to correct the rotation at the symmetry plane. Fig. 4 indicates the calculated influence of space–charge on the beam, which causes the beam to become successively broader along the line. Fig. 5 shows the compensated version, achieved by recalculating the solenoid settings. (Remember that charge–state neutralization has not been taken into account.)

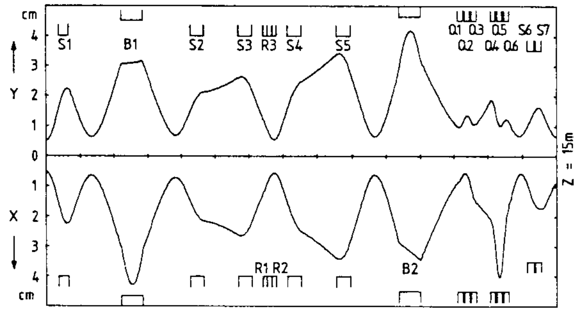

Fig. 4. Effect of space–charge on the beam size.

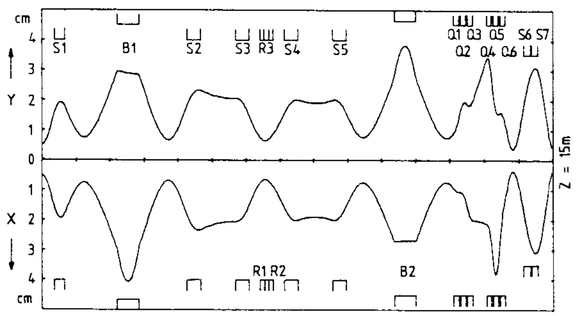

Fig. 5. The beam profile after recalculating solenoid settings to correct for space–charge.

3. POLARIZED–ION SOURCE

A polarized–ion source, which uses the atomic beam method to produce polarized protons and deuterons has been ordered, and is due to be delivered this year. The maximum energy has been set at 20 keV, and an intensity of 90 μA within an emittance of 135π mm.mrad after a 90° deflection has been offered. This ion source is being developed as a horizontal source, with its components on an optical bench, for ease of separation and maintenance.

3.1. Beam Transport

The beamline from this ion source will join the vertical section of the beamline from the ECR source discussed above, at a point just beyond the vertical 90° bend. In fact, both beamlines are intended to bring the beam to a focus at the same point, i.e. the exit slit of the twisted achromat described above. Fig. 1 shows the junction between these two lines.

The horizontal section of the polarized–ion line has not been designed in any detail, but will use straight telescopic sections, (with a horizontal analysing magnet to bend the beam into a test line for tuning the source). The vertical bend to bring the beam onto the axis of the cyclotron will consist of two 45° dipole magnets, each with 13° entrance and exit edge–angles. Two solenoids P1 & P4 connected in series but with opposite polarities, will be placed outside of the dipole pair and used for focusing. A further two solenoids P2 & P3, again wired in series with opposite polarities, will be located at the symmetry plane of the achromat to achieve dispersion matching. The transfer matrix for the achromat is –I, and there is no nett rotation of the beam around the beam axis. Fig. 6 shows the beam transported around this achromat.

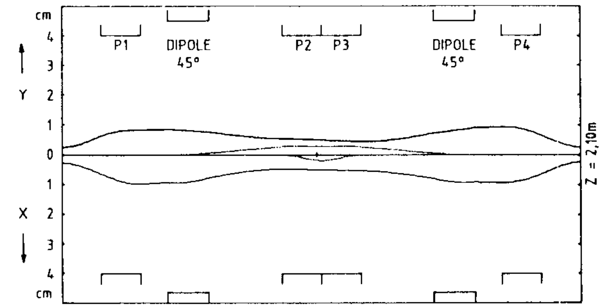

Fig. 6. Calculated beam envelope for an achromat with two 45° dipoles and solenoids

3.2. Direction of Polarization

Because these are polarized particle beams, care must be taken to ensure that the direction of polarization is correctly rotated from horizontal (at the ion source) to vertical (up or down) on the vertical section of beamline, ready for axial injection (without rotation of polarization) into the cyclotron. The two 45° bends will rotate the polarization axis of the protons and deuterons by 251.4° and 77.2° respectively in the bend–plane of the magnets. We therefore plan to use a crossed–field system (a "Wien filter") to rotate the polarization axis by a further 18.6° and 12.8° respectively. The filter introduces a small degree of dispersion, but this should be quite acceptable.

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