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PROPOSED TRANSFER BEAMLINE FOR THE NAC

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Abstract

A preliminary design of the transfer beamline between the solid-pole injector cyclotron (SPC1) and the separated-sector cyclotron (SSC) is described. Separate sections of this beamline match the momentum dispersion, the bunch length, and the horizontal and vertical beam extent to the requirements of the SSC, which have been determined with eigen-ellipse calculations.

Introduction

The NAC cyclotron facility$^{1)}$ which is at present under construction, will initially consist of a 200 MeV separated-sector cyclotron (SSC) and an 8 MeV solid-pole injector cyclotron (SPC1). This paper describes the transfer beamline between these two cyclotrons. This beamline must be able to accept whatever beam properties are delivered by the injector, and match these as closely as possible to those required for efficient acceleration in the SSC.

Parameters of the beam from SPC1

At this stage the properties of the beam extracted from SPC1 are uncertain, and we have made the assumption that the emittances of a 100 μA, 4 MeV proton beam in the horizontal (x,x') and vertical (y,y') planes are identical and equal to 38 π mm.mrad. For calculation purposes, however, we have used an 8 MeV proton beam with these emittances, as all the beamline elements must also be able to handle the higher energy particles. In practice the 8 MeV proton beam will be limited to approximately 10 μA, with correspondingly smaller emittances.

We began by considering the representative particles distributed round the relevant eigen-ellipse at the deflection radius of SPC1. These particles, placed on a centred, accelerated orbit, were followed through a possible set of deflection elements$^{2)}$ and out into the fringing field by means of the ray-tracing computer program GOBLIN. A momentum-spread of 0.5% half-width was assumed, and particles with the central momentum ±0.5% were displaced from the central orbit and similarly followed out of the injector. This enabled us to construct the phase-ellipsoid of a fairly realistic beam in 6-dimensional phase space, for input into the program TRANSPORT$^{3)}$. The resulting beam has rather alarming divergences and angular dispersion, but we regard this as a worst-case condition which provides a good test of our transfer system: if it can handle this beam, it can cope with any beam with better properties. (The deflection and extraction systems of SPC1 are under review, and improved beam properties are expected.)

Matching requirements

For optimal acceleration with minimum beam loss, the beam must be injected into the SSC on the correct centred orbit. The requisite shape of the beam ellipsoid in 6-dimensional phase space should be determined by tracking the beam through accelerated orbits to extraction. At injection, however, it will be similar to an eigen-ellipse, i.e., the phase ellipse for an equilibrium orbit (without acceleration) which reproduces exactly after each 90° sector. Thus in TRANSPORT matrix notation:

$$\sigma_E = R\,\sigma_E\,R^T \qquad (1)$$

where σ_E represents the 6-dimensional matrix of the eigen ellipse and R is the transfer matrix of one quadrant of the SSC at injection radius.

We have written a computer program STRAY which tracks a particle through a sector magnet and its associated fringing fields. The program replaces the magnetic field along the resulting path by a series of small dipole magnets, the parameters of which are read by the program TRANSPORT. Typically about 300 dipoles are used to represent one 90° sector. This process results in a single overall transfer matrix for any given path through the field. For an 8 MeV proton beam with an emittance of 38 π mm.mrad and an assumed momentum-spread of 0.5% we then find the eigen-ellipse parameters at the valley midline from equation (1).

The transfer system from SPC1 to the SSC must then be able to deliver any beam on an orbit at the SSC valley midline with parameters determined in this way. A further requirement is that of ease of operation, in that the controlling element(s) for one parameter should ideally not alter any other parameters. The proposed system for this transfer and matching is shown in figure 1, and is discussed below.

The first dipole m1 and quadrupoles q1 - q3 shape the beam from SPC1 to a double waist at slit s1 and ensure that x is not too large. (A large x at this stage would make the operation of s2 less effective.) This triplet should be able to focus any reasonable beam emerging from SPC1, and to control the horizontal beam size. The section from s1 to the buncher b1 is used for momentum selection and forming an achromatic beam, while the quadrupoles q10 - q15 control x, x', y and y', and the buncher matches the bunch length. The dipole m4 steers the beam through the stray field, and together with quadrupoles of q16 - q19, matches the dispersion to the required value. The final dipoles (m5 and m6) direct the beam into the movable magnetic inflection channel (MIC) and the injection orbit.

Should a stripper be required in the SPC1 transfer line, it could be positioned at s1. This would be convenient because of the double waist there, and because the buncher could then correct the extra longitudinal spreading introduced by the stripper. The increased momentum-spread and any disturbance of the dispersion would also be corrected by the subsequent section of beamline.

Making the beam achromatic

In figure 1 the system between the slit s1 and the buncher b1 consists of two dipoles m2 and m3 and the six quadrupoles q4 to q9, in a mirror-symmetric arrangement. A waist in x is formed at the symmetry plane, and as the first half of the system is dispersive, the slit s2 can be used to control the energy spread of the transmitted beam. The quadrupoles q6 and q7 control the dispersed ray, so that the beam becomes achromatic after the buncher. This may readily be seen from figure 2. For a beam with less angular dispersion at s1, this system becomes closer to a truly mirror-symmetric achromat, with a subsequent improvement in transfer properties. If a heavy-ion injector (SPC2) is installed at a later stage as planned, a similar system could be used, linking with the present system by direct transmission through dipole m3 (de-energised).

Buncher

If a flat-topping resonator is not installed in the SSC initially, then a fairly short bunch length (of less

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than 4^o phase half-width) will be needed at injection if single-turn extraction from the SSC is required.

The buncher can be considered as a thin lens acting in longitudinal phase-space which focusses the bunch length to a minimum ($r_{56} = 0$ in TRANSPORT) at the valley midline. For a minimum strength the buncher should be located midway between the two accelerators: in our system this is nearly so. The buncher is placed at an x,y waist so that the horizontal and vertical beam parameters are least perturbed by the bunching action. It is important that the buncher should be placed in an achromatic section of beamline, as the buncher changes the momentum of the particles and in effect changes the dispersion path of any non-achromatic beam. This would imply an undesirable interdependence between dispersion handling and buncher settings.

Beam shaping

The quadrupoles q10 - q15 are used to form a versatile system for independent horizontal and vertical beam control, i.e., an "orthogonal quadrupole" system$^{4)}$. In principle, a minimum of four quadrupoles is needed to control the beam parameters x, x', y and y'. However, by adding another two quadrupoles, the shaping in x and y can be controlled independently by arranging that horizontally focussing quadrupoles are located at vertical waists, and vice versa. The quadrupoles controlling x shaping are then "orthogonal" to those controlling y. This greatly improves the ease with which fine tuning of the system can be done. We have calculated the positioning of the quadrupoles for minimum apertures using modified thin-lens optics. The optimum positioning is dependent on the ratio of horizontal to vertical divergence at either end of the system. As the shaping is done when the beam is achromatic, it is independent of the momentum-spread of the beam, and does not affect the subsequent dispersion matching. In the system illustrated here, the quadrupole q10 serves to put x and y into an "orthogonal" mode, by focussing the beam to a vertical waist at the centre of q11. Quadrupoles q11 and q13 control x and x' at injection, while q12 and q14 control y and y'. The quadrupole q15 acts analagously to q10 in reverse. The independence of control of horizontal and vertical beam parameters which results is remarkably good, despite the worst-case beam considered.

Dispersion matching

Theoretically we need a dipole and only two quadrupoles to match both the dispersion (r_{16}) and the angular dispersion (r_{26}) required at the SSC valley midline. However, the dipole m4, which introduces the dispersion, bends the beam through only 9^o in the present design. As a result the dispersion immediately after the dipole is small, and the quadrupole strengths would therefore need to be very high. In addition, very large edge angles in m4 would be needed for vertical focussing. Four quadrupoles (q16 - q19) are therefore used in transporting the beam up to the SSC valley and into the central region, as shown in figure 1. The path of the dispersed ray is indicated in figure 2.

Injection path

The beam passes through the valley between two sector magnets to reach the central region of the SSC. The magnetic field in the valley is not zero, and this causes the beam to follow a curved path calculated using the program STRAY mentioned earlier.

The dipoles m5 and m6 bend the beam in opposite directions, as this facilitates a better placing of m6 in the restricted area of the central region, so that a lower field strength may be used for the magnetic inflection channel (MIC). This arrangement also makes the dispersion easier to handle. (The MIC is designed to move in the horizontal plane so as to inject heavy ions onto orbits different from those for protons.)

We superimpose a trapezoidal MIC field onto the base field of the sector magnet, and then calculate a trajectory backwards through the MIC using STRAY. In practice we calculate the entire system up to the buncher backwards, using TRANSPORT with matrix representation of the stray-field regions, so as to match to the beam transported to the buncher from s1. A run through the complete system from s1 to the SSC is then done. The TRANSPORT output is written to a file, which is then read by a plotting program BUNDLE: the resulting plot is that shown in figure 2. The final stage is switching on the buncher, represented in matrix form$^{5)}$, and correcting the small perturbations to the system which this introduces.

Conclusion

We have designed a transfer beamline capable of matching a wide range of beam parameters to those required for optimum beam transmission through a separated-sector cyclotron. The system should provide flexibility and ease of operation.

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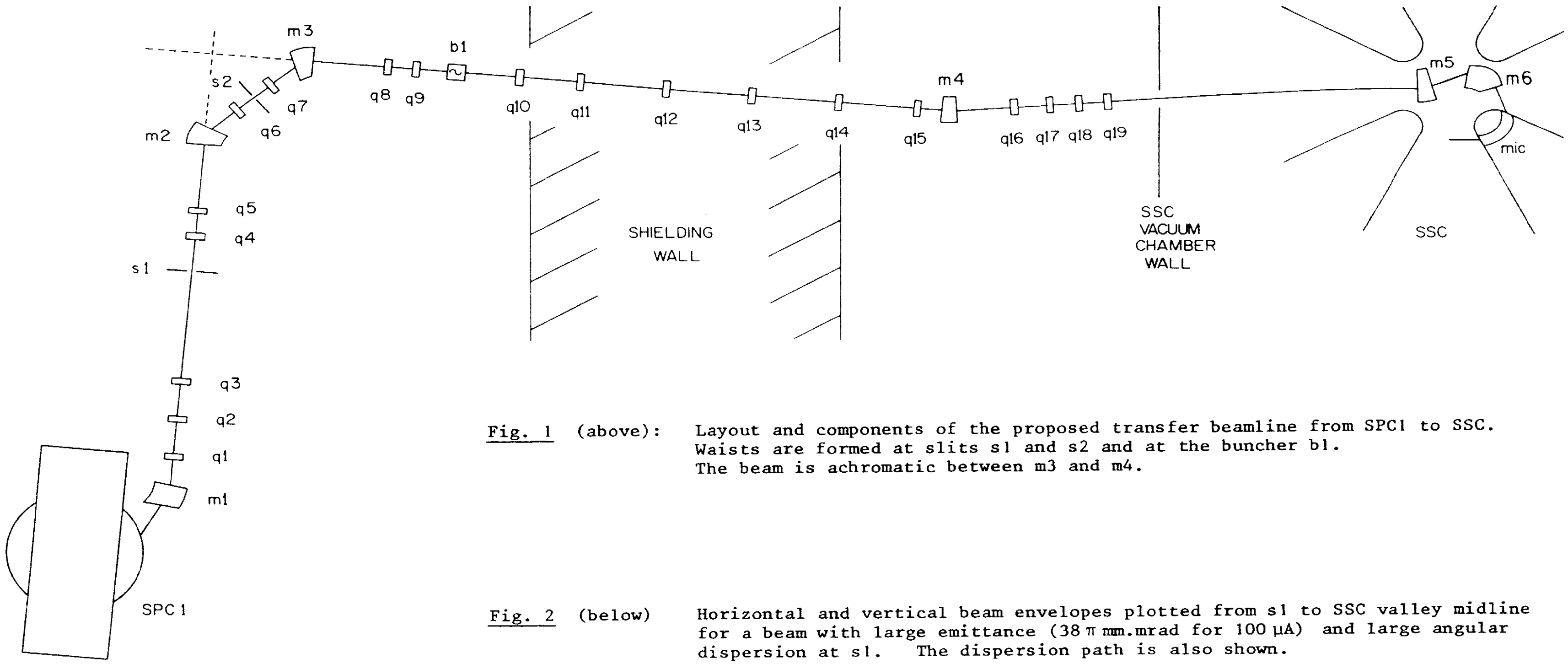

Fig. 1 (above): Layout and components of the proposed transfer beamline from SPC1 to SSC. Waists are formed at slits s1 and s2 and at the buncher b1. The beam is achromatic between m3 and m4.

Fig. 2 (below) Horizontal and vertical beam envelopes plotted from s1 to SSC valley midline for a beam with large emittance (38 π mm.mrad for 100 μA) and large angular dispersion at s1. The dispersion path is also shown.