DESIGN OF A HIGH INTENSITY 860 KEV PROTON BEAM TRANSPORT LINE FOR THE NEW SIN INJECTOR

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Abstract. The 860 keV beam line starts at the exit of the accelerator tube of the Cockcroft-Walton pre-injector and leads first horizontally, then vertically into the centre of the new injector cyclotron. The design criteria and the proposed optical solutions are desribed. In the calculations, space charge effects have to be taken into account. One has to look for solutions in which the excitation of the quadrupoles varies smoothly with beam intensity. The layout of the transfer line is given together with the expected beam envelopes for intensities of 0 and 40 mA.

1. Introduction. The main characteristics of the new SIN injector are described elsewhere in this conference [1]. It is a two-stage proton machine consisting of an 860 keV DC preaccelerator of the Cockcroft-Walton type together with a 72 MeV separated sector isochronous cyclotron. A perspective representation of the beam guiding system between these two stages is shown schematically in fig.1.

2. Design criteria. The beam transfer line between the pre-injector and the injector cyclotron has to perform several tasks:

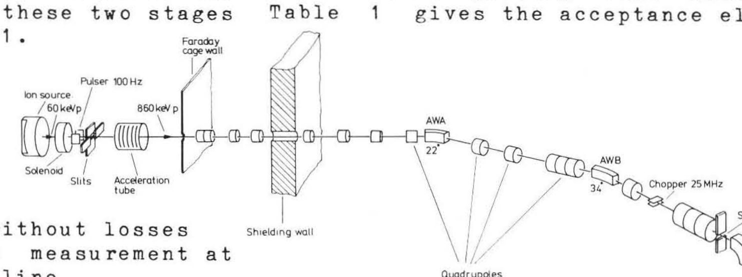
(1) Transport the beam over a distance of about 20 m without losses
(2) Provide for an emittance measurement at the beginning of the beam line
(3) Match the beam to the cyclotron.

In addition to these requirements, which are common to similar beam transfer lines between accelerators, we have a further, very important, condition:

(4) The beam should be able to perform the foregoing tasks with space charges up to 40 ma taken into account, and this solely by varying the excitation current of the quadrupoles.

This last condition arises from the fact that the degree of neutralization in the beam is not yet known; it may even vary along the beam line. 40 mA DC current corresponds to about 4 mA accelerated beam in the cyclotron, the rest of the beam with incorrect phase being stopped by collimators on the first turn.

Two important boundary conditions for the beam optical solution for this transfer line are the expected beam emittance at the end of the acceleration tube [2] and the acceptance of the cyclotron at injection. The size of the accepted phase space area is assumed not to vary with beam intensity and was taken as 1.3πcm mr for both transverse phase spaces x and y [3]. However, because of the space charge blow-up at higher beam currents, the shape of these phase space areas will change, the waists becoming thicker and the slope of the beam divergence flatter with growing beam intensities [4]. Table 1 gives the acceptance ellipses of the



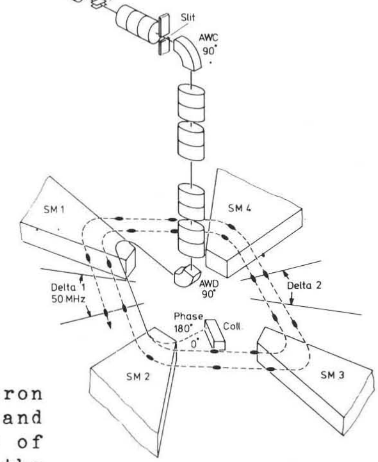


Fig. 1: Layout of the 860 keV proton beam transfer line in perspective representation.

Starting from the accelerator tube exit of the pre-injector, the beam crosses the shielding wall between the Cockcroft-Walton vault and the cyclotron vault horizontally and arrives after a bend of total 56^{0}3 m above the cyclotron machine centre. The beam will then be bent vertically by a 90^{0} dipole to enter the axial part of the transfer line at the end of which it will be injected by a second 90^{0} magnet, identical to the first, into the gap of a cyclotron sector magnet resp. by its specially shaped cone into the first cyclotron orbit.

cyclotron calculated for different beam intensities according to ref.4 together with the corresponding dispersion values [3].

I(p) mA	x mm	x' mrad	y mm	y' mrad	Dx mm/o/oo	Dx' mr/o/oo
0	1.73	7.5	1.88	6.9	0.40	0.0
10	1.86	7.0	2.00	6.5	0.48	0.0
20	2.00	6.5	2.11	6.2	0.58	0.0
30	2.11	6.2	2.22	5.9	0.70	0.0
40	2.24	5.8	2.34	5.6	0.84	0.0

Table 1. Acceptance ellipses and dispersion displacement values according to periodic solutions in the cyclotron for different beam intensities.

The other boundary conditions are given by the geometry of the layout, that means the height difference and the distance resp. angle between the pre-injector exit and the cyclotron injection. The division of the total angle of 56° to 22 + 34 degrees is the result of a search for optimal geometry.

3.Beam optics: general remarks. The beam optics calculations were made with the well known program TRANSPORT [5] to which space-charge calculation routines were added at SIN [6]. These routines are based on the equations of Kapchinsky-Vladimirsky [7] and include the linear part of the space-charge forces [8,9]; they were written originally at CERN [10]. An on-line version of the program adapted at SIN [11] for the VAX computer was a very helpful tool for the design of the beam line.

The transport calculations always started from upright phase ellipses of a matched beam inside the cyclotron and proceeded backwards in the direction of the ion source. Our design aim was to find solutions in which the three principal criteria described above are fulfilled in three different parts of the transfer system. Such a solution would simplify the operation of the beam line. A further advantage would be to find solutions whereby a magnetic element would influence one beam quality only. An example for such an element is a quadrupole with a double waist and a big dispersion displacement at its centre: because of the small beam amplitudes, this quadrupole has practically no influence on the envelopes but a very great effect on the dispersion trajectory, thus acting as a 'dispersion knob'. A beam line made of such 'decoupled' elements would be much easier to tune but is not always possible to design. In practice, the space charge is taken into account by simulating it using dispersive lenses [10], the spacing of which can be varied. Calculating with space charge being very time consuming, one is forced to make sacrifices on accuracy by using small steps at 'critical' places only. We were using steps between 1 and 5 cm long.

4.Proposed solutions. The first part of the 860 keV beam line (fig.2) includes 4 quadrupoles and is mainly an emittance measuring section. The beam of the pre-injector is expected to be symmetrical and convergent, building a double waist in a distance of about 80 cm downstream from the acceleration tube exit [2]. A quadrupole doublet QW1/2 placed outside the Faraday-cage of the pre- injector will focus the doubly divergent beam and transport it to the quadrupole singlets QW3 and QW4, with the help of which a vertical (y) resp. horizontal (x) waist will be produced. The emittance can be measured in each direction by three profile monitors put in the waist and on both sides of it. A peculiarity of this line is that on one side the beam divergence cannot be measured on a free drift length since a quadrupole has to be included

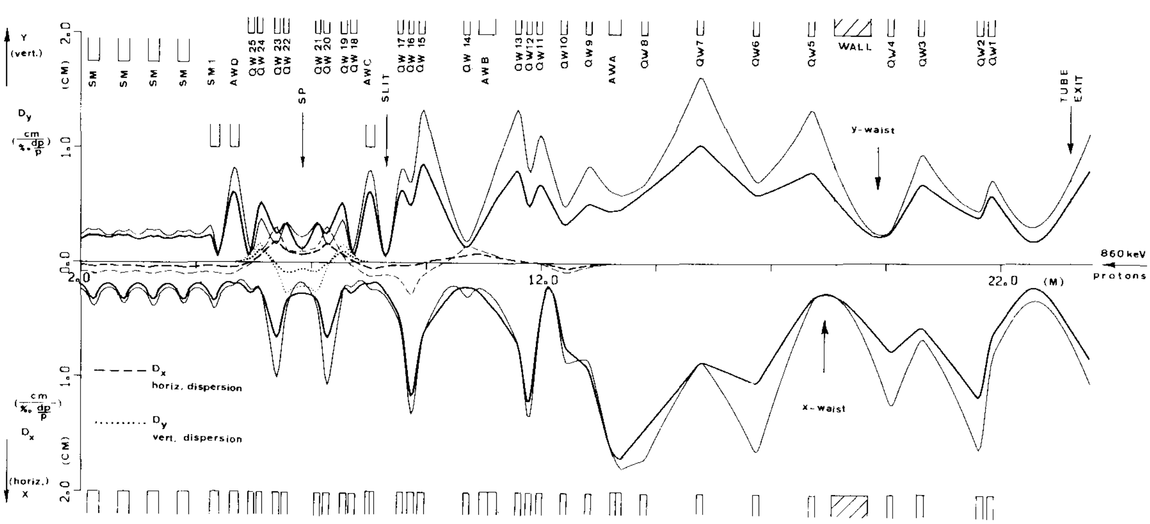


Fig.2: Beam envelopes and dispersion trajectories in TRANSPORT notation for a beam without space charge (thick line) resp. for a beam with 40 mA intensity (thin line).

because of the space-charge blow-up which prevents the use of drift spaces longer than about 1.5 m. A pair of slits for another emittance measurement will also be installed immediately after the doublet QW1/2 with a Faraday-cup behind. This measurement cannot be made on-line as the doublet must be turned off.

The next section, a straight line mainly for beam transport, consists of 4 equidistant quadrupole singlets QW5 to QW8 put about 1 m apart. The beam here has still no dispersion.

The third, matching part of the beam line begins with the 22° dipole magnet AWA which introduces dispersion. AWA has edge angles of -11° on both sides for better horizontal focussing. The next two quadrupole singlets act mainly on the dispersion trajectory with the x- and y-amplitudes being kept as small as possible. QW9 makes the slope of the dispersion trajectory larger and QW10 produces a crossover in the following triplet QW11/12/13. This triplet has therefore no effect on the dispersion and will be used to build a double waist in the quadrupole singlet QW14 which in turn serves as a 'dispersion knob' described above producing a second crossover. The two crossovers are necessary so that the dispersion at injection is on the proper side. The 34° dipole AWB is a parallel edge magnet i.e. it has an additional vertical focussing property. The matching section and also the horizontal part of the beam line terminate with the triplet QW15/16/17. This triplet produces a sharp vertical waist on a slit in front of the entrance of the axial section and performs the final matching to the cyclotron by preparing the 6-dimensional phase ellipsoid for injection. This ellipsoid is expected to be the exact image of that at the slit, the axial section being built in a symmetrical manner not for matching but for undistorted transport of the matched beam to the injection point. In front of the triplet, a 25 MHz vertical chopper for the reduction of the beam intensity is foreseen, with the vertical slit mentioned above beeing used to stop the deflected part of the beam.

The axial part of the beam line consists of two identical 90° vertical bending magnets: AWC at the end of the horizontal line resp. AWD in the median plane of the cyclotron, together with 8 quadrupoles QW18 to QW25 between them arranged symmetrically in 4 doublets around the 'symmetry point' SP in the middle of the vertical section. Four quadrupoles are needed for building a double waist and zero slope (r26=r46=0) at SP for both dispersion trajectories, the latter being produced by the vertical bend. These four conditions have to be fulfilled for the imaging of the matched phase ellipsoid; with the excitation current of a quadrupole above and of a corresponding one below SP being identical, the lower half of the axial system is the exact duplicate of the upper one, making a veritable 'mirror' out of the virtual point SP.

The injection itself is done by the specially shaped cone of the first sector magnet SM1 together with the injection magnet AWD [12,13]. The beam will be bent in SM1 to about 134° and will be focussed in both directions by a field index lying between n=.55 and .68 and by wedge angles of between 15 and 22 degrees. The parameters of SM1 expressed in TRANSPORT code are the result of a careful fitting procedure [3], based upon the comparision of the TRANSPORT matrix elements with those obtained from the direct integration of the particle trajectory corresponding to the magnet measurement data and dividing SM1 into smaller sections with different pole field and field index values.

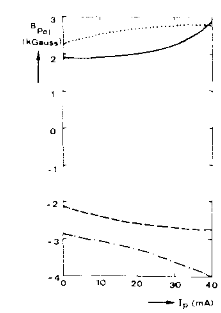
Dipoles	bend	l(eff)	gap	B(nom)	field	entr./ex.	
	°	cm	cm	kG	index	angle	°
AWA	22°	26.8	6.0	1.92	0.0	-11°	-11°
AWB	34°	32.7	6.0	2.43	0.0	17°	17°
AWC=AWD	90°	19.0	2.0	11.85	0.4	5°	5°

Quadrupoles	l(eff)	d(pol)	G(max)
	cm	cm	kG/cm
QW	13.3	8.0	1.30

Table 2. Magnet parameter values for the 860 keV beam transfer line.

The main parameter of the beam line magnets are summarized in Table 2. Fig.3 shows the variation of the quadrupole field with beam intensity for the axial part of the beam line.

Fig. 3: Variation of the quadrupole pole field with beam intensity for the axial section of the beam transfer line.



——— QW18 + QW25
—·—·– QW19 + QW24
········· QW20 + QW23
— — — QW21 + QW22

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