# THE 870 KEV HIGH INTENSITY PROTON BEAM TRANSFER LINE FOR THE INJECTOR II CYCLOTRON OF SIN

C. Markovits

SIN, Swiss Institute for Nuclear Research
CH - 5234 Villigen, Switzerland

## Summary

The 870keV high intensity proton beam transfer line couples the Cockcroft-Walton preinjector to the 72MeV Injector II isochronous cyclotron. It starts horizontally and injects the beam at the end of a 3m long vertical section into the cyclotron center. The design criteria and beam optics of this line are described. The main parameters of the magnets are given and the vacuum and diagnostics systems are outlined. Space charge effects are not negligible in this transfer line: calculated beam envelopes for different beam intensities are shown, and the operating experience of three years is summarized.

## Introduction

The SIN accelerator complex originally consisted of a 72MeV- and of a 590MeV Ring- proton isochronous cyclotron. As part of an updating program leading to higher beam intensities, a second injector system was added. Injector II is a two stage machine. A 870keV Cockcroft-Walton preinjector is followed by a 72MeV four sector isochronous ring cyclotron (Fig.1).
The design, commissioning and performance of the preinjector [1,2,3] and of the injector cyclotron [4,5,6,7] were discussed in previous reports.

The coupling line between the two parts of the new injector system was built without any modification as proposed in an earlier beam optical study [8]. Commissioning of the beam line started in December 1983. In March 1984, the first 870keV beam was injected correctly into the cyclotron and stopped at the end of the 5th turn. In June, the first beam could be extracted from the cyclotron and since the end of the same year, Injector II is serving regularly for the production of the high energy beams.

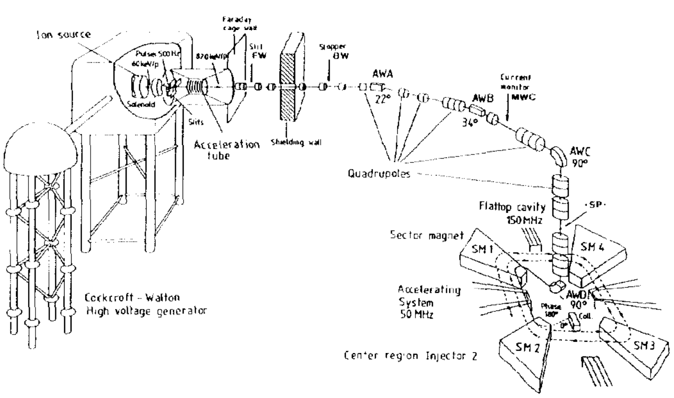


***Fig. 1:*** *Schematic view of the Cockcroft-Walton preinjector, the 870 keV transfer line and the injection into the center region of the cyclotron.*

## Beam optics

Since the beam optical solution was described in Ref.8 in considerable detail, we will present here only the concept and its main characteristics.

The optics of the transfer line was designed to:
1. Transport an intense (up to 30mA) 870keV dc proton beam over a distance of about 19m with only minor losses along the beam line.
2. Match the beam emittance at the acceleration tube exit to the acceptance of the cyclotron at injection.
3. Provide for at least one emittance measurement, preferably at the beginning of the beam line.
4. Meet the design criteria for fully neutralized as well as for fully unneutralized beams. The degree of neutralization was expected to lie somewhere between these two extremes.

The beam emerging from the acceleration tube arrives above the cyclotron center after a horizontal beam path of about 15m with two bends of total 56°. It is then bent vertically by 90° and after a 3m long vertical section and a second 90° bend is injected horizontally by means of the specially shaped cone of the first sector magnet with a bend of 135° into the first cyclotron orbit (Fig.1). To avoid the deterioration of the monoenergetic beam quality, no buncher was planned in the transfer line. At least 90 percent of the beam with the wrong phase must therefore be stopped on a collimator in the first turn. This means that the injection parameters have to be adjusted very carefully, taking the respectable power of the dc beam into account. However, there is very little room for the installation of diagnostic devices needed to ensure good matching. It was therefore decided to do the matching outside the crowded central region at the end of the horizontal part of the beam line, and to build the vertical section in a symmetrical manner, arranging the two 90° bends and the eight quadrupoles around a "symmetry point" SP in the middle of the section. The matched beam can be then transported without distortion to its "image" in the cyclotron.

With this concept, the transfer line can be divided clearly into three parts (Fig.2):
1. Horizontal section, first part:emittance measurement by means of a vertical and a horizontal waist (separated to avoid thermal damage to the monitors).
2. Horizontal section, second part: transport and matching. To compensate for space charge blow-up, the distance between two quadrupoles is nowhere greater than 1.2m. The accepted phase space in the cyclotron was assumed not to vary with the intensity and was defined as A(x)=A(y)=13pimmmrad [9]. However, the shape of the ellipses was assumed to vary with the proton current and this was taken into account. The matching itself is discussed in Ref.8.
3. Vertical section: transport of the matched beam to the cyclotron, as explained above. To accomplish the task of the "imaging", at the symmetry point SP the conditions $r21=r43=r26=r46=0$ for the double waist and for zero slope dispersion trajectories have to be fulfilled and all elements have to be excited symmetrically in respect to SP.

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The optics calculations were done with the SIN-version of the TRANSPORT code, in which the linear part of the space charge forces is included [10,11,12]. The effect of these forces is simulated here by virtual defocusing lenses, the spacing of which can be varied. The calculations were performed starting at the end of the second turn in the cyclotron and working backwards towards the acceleration tube because it is much easier to find a stable solution this way.

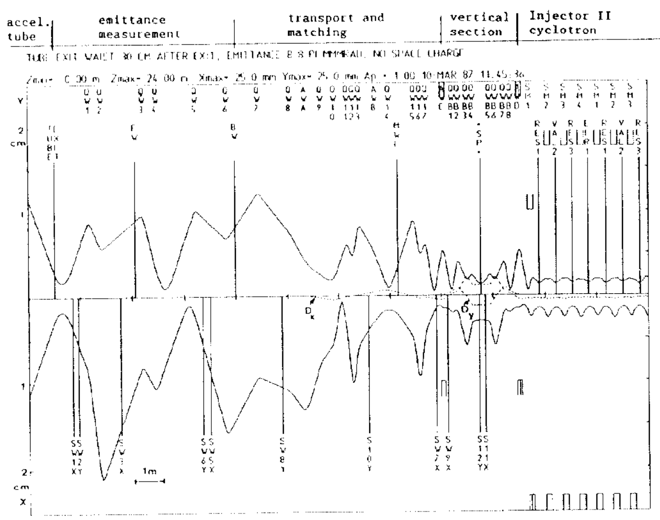


*Fig. 2: The optics of the transfer line: envelope calculated with zero space charge.*

## Magnets

The beam transfer line consists of 25 quadrupoles, including two triplets in the horizontal and four doublets in the vertical section,two horizontal and two vertical dipoles and eleven steering magnets. The magnets are of conventional design [13] and are water cooled, except the steering magnets. All the bending and quadrupole magnets are furnished with mirror plates. The main parameters are given in Table 1.

In the vertical section, the parameters, including the physical dimensions of the magnets,were dictated by the cyclotron itself: the 90° magnets AWC and AWD have to be double-focusing and must have a field index comparable to that of the cone of the first sector magnet SM1. Their bending radius is only 12.5cm. Because of their small dimensions, the entire AWC and AWD were put in large vacuum chambers. Their coils are protected from beam spill by water cooled, insulated copper collimators, which are continuously monitored in the control room. The doublets QWB have to fit in a thick steel tube of 30cm diameter, shielding them from the stray field of the sector magnets. The steering magnets in the vertical section are mounted in the large cylindrical vacuum chambers between the doublets.

| Bending magnets | Gap cm | Leff cm | Bmax kG | Imax Amp | Bending angle | Wedge angle | Field index |
|---|---|---|---|---|---|---|---|
| AWA | 6.0 | 26.3 | 1.97 | 40 | 22° | -10.5° | - |
| AWB | 6.0 | 32.8 | 2.44 | 50 | 34° | 16.8° | - |
| AWC AWD | 2.0 | 18.2 | 11.64 | 1300 | 90° | 3.2° | 0.415 |
| **Quadru-poles** | **Rpol cm** | **Leff cm** | **Gmax kG/cm** | **Imax Amp** | **Steering magnets** | **Max. mrad** | **Imax Amp** |
| QWA | 4.0 | 13.5 | 3.57 | 80 | SWA | 13.3 | 10 |
| | | | | | SWB | 11.4 | 5 |
| QWB | 4.0 | 13.2 | 3.26 | 100 | SWT | 15.3 | 5 |
| | | | | | SWV | 9.8 | 5 |

***TABLE I:*** *Magnet parameters*

In the horizontal section, the two bends AWA (22°) and AWB (34°) were a present from the preinjector, when it was decided to switch over to solenoids instead of bends. Some modifications were necessary according to the demands of the optics calculations: e.g. the large negative wedge angles in AWA for the horizontal dispersion matching. AWB is a parallel edge magnet. Both AWA and AWB have water cooled insulated copper collimators inside their vacuum chambers. The vacuum chamber of the triplet QWA15/16/17 is water cooled. The use of different types of steering magnets was determined by space limitations: for example, the type SWT is inside a vacuum bellows of 8cm diameter.

## Mechanical design and vacuum

The elements of the horizontal line are mounted on individual supports fastened to a large iron girder. The magnet units and profile monitor boxes are supported on adjustable feet. The magnets are fitted with surveying marks. By means of a procedure developed at SIN [14], a very reliable positioning of the beam line elements can be achieved.

Outside the magnets, the entire vacuum system of the transfer line is made of steel for magnetic shielding against the stray field of the sector magnets. The inner diameter of the beam pipes is 72mm.

A pressure of 10**-5 mbar is maintained by four 50 l/s turbomolecular pumps distributed along the beam line. Each of the four pumping stations has its own microprocessor control. The gaskets used are either aluminium or ethylene propylene O-rings, the flanges being compatible for both.

## Diagnostics

The diagnostics equipment [15] consists of:

**1.** 30 SIN-type profile monitors MWP, each with one 0.1mm thick, 3mm wide molybdenum finger driven by a dc-motor. A pair of these scanners, one for the horizontal and one for the vertical direction, are assembled together in a steel box or in the axial section in a cylindrical vacuum chamber. For beam currents greater than 2mA,the beam must be chopped by a kicker magnet built in the 60kV beam line of the preinjector, with a repetition rate of 500Hz and variable duty cycle. Special effort was necessary to synchronize the scanner movement with the kicker [16].

**2.** One residual gas profile monitor MWL, a prototype which can be used also for high intensity dc beams. We plan to replace the finger monitors as soon as possible with this new type.

**3.** 24 fixed aperture, water cooled insulated copper collimators KWI, distributed on "strategic" locations along the beam line to protect the vacuum gaskets and magnet coils, control the beam losses and serve as security elements in the interlock system. The openings of the collimators are round or rectangular and of different sizes, depending on the beam size.

**4.** One beam current monitor MWC at a location with small beam size, using a toroidal core for the measurement of the beam intensity [17].

**5.** One beam stopper BW at the end of the emittance measurement section, an insulated copper block with a V-shape hole built for high power consumption, which can be moved pneumatically into and out of the beam.

**6.** One pair of slits FW, mounted vertically to cut the beam tails or to serve as a temporary beam stopper.

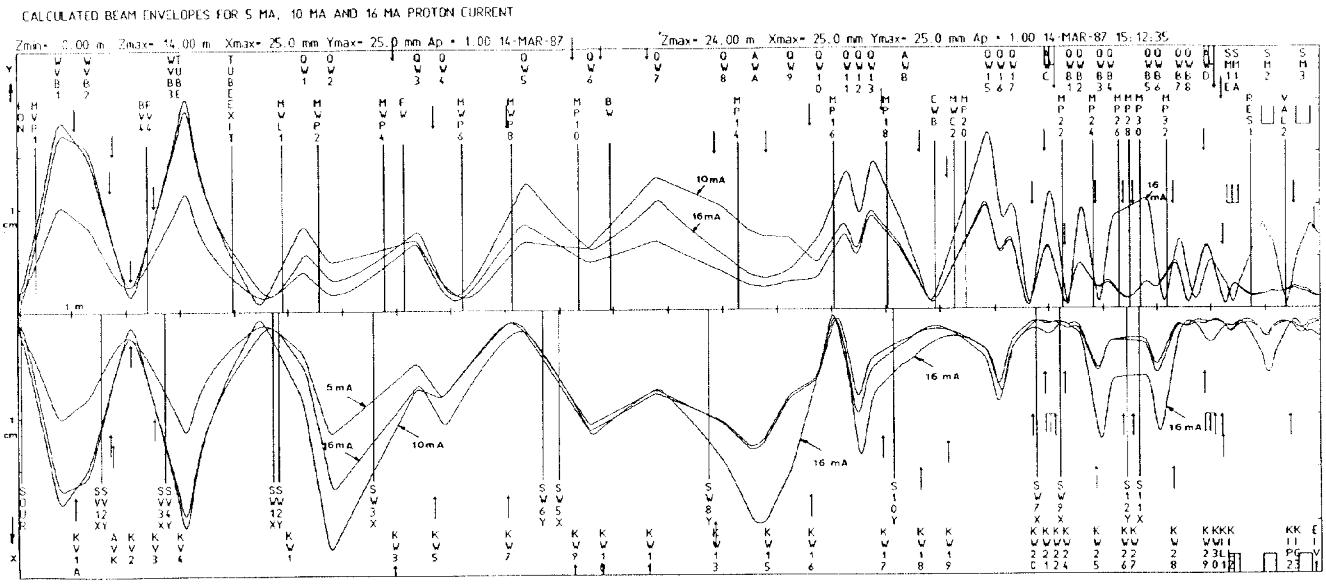


*Fig. 3: Beam envelopes calculated for different proton currents.*

## Operating experience

Commissioning of the beam line began in December 1983 with a 1mA dc beam. It came out divergent from the acceleration tube, with the waist 25cm behind the tube exit. Since then, the beam current was gradually raised, the space charge shifting the tube exit waist downstream. Depending also on the solenoid currents in the 60keV beam line, the waist moved as far as 1.5m to the first quadrupole QWA1. The position and divergence of the tube exit waist have a strong influence on the optics of the coupling line, especially for high current beams. For beams with an intensity up to about 6mA, corresponding to normal production runs, the agreement between the computed and measured values of this waist and the profiles along the beam line is very good. The required quadrupole tuning is minimal. In this region, the beam seems to be almost fully neutralized. However, with increased intensity this is no longer the case. Although the profiles look similar to those with low current, it is difficult to fit them with an envelope in accordance with the measured emittance of the acceleration tube, even with the full space charge taken into account. Furthermore, envelope fit calculations as well as measurements made with the tomographic method [18] indicate an emittance growth, observed at intensities of 14mA or higher possibly caused by filamentation. We intend to test a new "smooth" optics solution with smaller amplitudes which could be better for the high intensity beams. We also intend to shift the first two quadrupoles downstream.

Measurements of the effect of the brightness of the injected dc beam on the quality of the 72MeV beam extracted from the cyclotron are in progress. Nevertheless, we can deliver well matched 870keV beams to the cyclotron since, to produce 300 microamps of 590MeV protons, only 5 to 6mA of dc beam has to be injected and during beam development tests, 1mA 72MeV protons can be extracted from 10mA injected dc beam. The highest current injected so far was 16mA and the beam losses along the transfer line were less than 10 percent. To increase the intensity of the extracted beam from the cyclotron, a double gap buncher CWB was built in the transfer line. The best place found for it was that occupied by quadrupole QWA14, which had to be removed. QWA14 was installed to perform the horizontal dispersion matching, but the importance of this seems to have been overestimated [9]. Furthermore, the double waist in this position was ideal for the buncher. Fig.3 shows calculated envelopes for different beam intensities including the section ion source to acceleration tube exit [3].

## Acknowledgements

Very many people in SIN helped to build the 870keV beamline,whose contribution is gratefully acknowledged. We thank very much D. George for the magnets. We are indebted to G. Biemans, M. Dubs, R. Erne and M. Graf for their technical assistance and the control room crew, especially S. Drack, R. Kramer, A. Mezger and K. Zimmermann. We thank very much W. Joho, M. Olivo, L. Rezzonico, U. Schryber and T. Stammbach for helpful discussions and for their continuous interest and U. Rohrer for all of his useful computer codes.

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