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# THE IUCF TRANSFER BEAMLINE

D.W. Devins, R.E. Pollock, J.W. Hicks and C.C. Foster
Indiana University Cyclotron Facility*,
Bloomington, Indiana 47401

## Abstract

The transfer beamline between the injector stage and main stage cyclotrons has been designed, constructed and is under test. The beamline provides a good match between the calculated extracted phase space ellipses in the injector and the inflection requirements of the main stage over a wide range of particle types, emittances and energies. Energy dispersion of 0.07% FWHM for 16 MeV protons is available at a waist. Attempts were made to minimize time dispersion; as a result the time spread through the transfer system is negligible for light ions. For $^{12}C(4+)$ the time spread will cause an energy spread in the main stage at 200 MeV of about 100 KeV, under normal operating conditions.

## Introduction

The transfer beamline between the injector cyclotron and the main stage of the Indiana University Cyclotron Facility must satisfy several requirements. The foremost is that the phase-space ellipses of the beam at the extractor of the injector stage should be transformed at all energies for all particles by the beamline into the optimum ellipses required for 100% acceptance at the inflector of the main stage. At the same time provision should be made for energy analysis in the beamline to insure that fluctuations in injector cyclotron parameters resulting in a beam energy shift will not cause beam loss in the main stage leading to activation but rather will cause only intensity fluctuations before entering the main stage. Energy analysis requires at least one dispersive element in the beamline. For a beam of finite size momentum dispersion also introduces an increase in the length of the beam bursts. It is desirable to reduce this increase in burst length as much as possible in order to minimize energy spread in the main machine caused by RF phase mismatching.

It is important to make available in the injector vault a target location which can be used not only for bombardment purposes but also for diagnostic studies on beam properties such as emittance and time structure. It should be possible to divert the beam to this target location without mechanical changes in the beamline elements.

The tune-up procedure for the beam transport system should be as simple as possible. Intermediate waists, where necessary, should be well-defined. A sufficient number of horizontal and vertical steering magnets should be available at appropriate locations to facilitate maintaining the beam on-axis while compensating for misalignment of magnetic elements. Vacuum pumping and valving to segment the beamline appropriately should be provided.

The beamline should have a phase-space acceptance at least equal to the maximum emittance with which a beam can be extracted from the injector stage. Beam loss should not occur in the beam line elements, other than when planned at slits. Finally, this transfer beam line must be designed and constructed in a manner which will allow injection into the main stage from another device, such as a tandem, should that prospect become desireable at some future date.

We have designed a transfer beamline which comes quite close to satisfying all these requirements. This report will examine the physical layout of the beam line and the calculated properties of transferred beams in detail.

## Physical Layout

The physical layout of the transfer beamline is shown in Fig. 1. For the purpose of calculation we consider the beam to enter the transfer system at the downstream end of the electrostatic deflector in the west valley of the injector cyclotron. The extractor magnet, TBM1, is the first magnetic element of the system. This magnet has a 19" radius of curvature for the central ray, bends 52.84° and has a 0.36" gap.

Energy analysis is done at the position of TMS1 with the magnetic system composed of TQ1A, TBM2 and TQ1B providing a waist in both planes along with the appropriate dispersion. The quadrupole system, TQ2A, B and C, forms effectively a triplet which is adjusted to provide the match required at the main stage inflector. There are no accessible intermediate waists in this section (the horizontal beam has a waist inside the inflector magnet, TBM4, near the downstream end.)

For injection operation TBM2 bends 45° to the right (+45°). For diagnostic purposes the current in this magnet can be reversed and adjusted to provide a -30° bend. TQ3A and B form a double waist at the diagnostic position. A quadrupole doublet is required here rather than a singlet because with the left-hand band the beam emergent from TBM2 is roughly parallel in both planes.

## Emittances

The maximum phase-space acceptance of the transfer beam line is determined by the extraction magnet, TBM1. Because of proximity to the circulating beam, the magnet gap was made particularly small. This is the limiting factor in the vertical plane acceptance. Computer calculations simulating the acceleration of a beam with the largest possible phase-space areas indicate the maximum possible phase-space ellipses of a 16 MeV proton beam which will pass through the electrostatic extractor are 1.5 mm x 2.4 mr horizontally and 45 mm x 6.1 mr vertically, where these numbers represent the maximum tangents to the ellipses.

The main stage acceptance was calculated by time-reversing a maximum-emittance beam back through the electrostatic inflector and through the measured magnetic field between the inflector magnet and the main magnet. These calculated phase-space ellipses, 1.2 mm x 4.9 mr horizontally and 4.4. mm x 5.5 mr vertically, exceed the injector-stage deflector capability in the horizontal plane only. The limiting factor in the transfer capability is still the injector-stage extraction-magnet gap.

Note that the values quoted above are the values for the tangents to the ellipses at the match points; they do not represent the major and minor axes of phase-space ellipses except at a waist. They were determined by the beam deceleration procedure which was terminated at the measured field boundary.

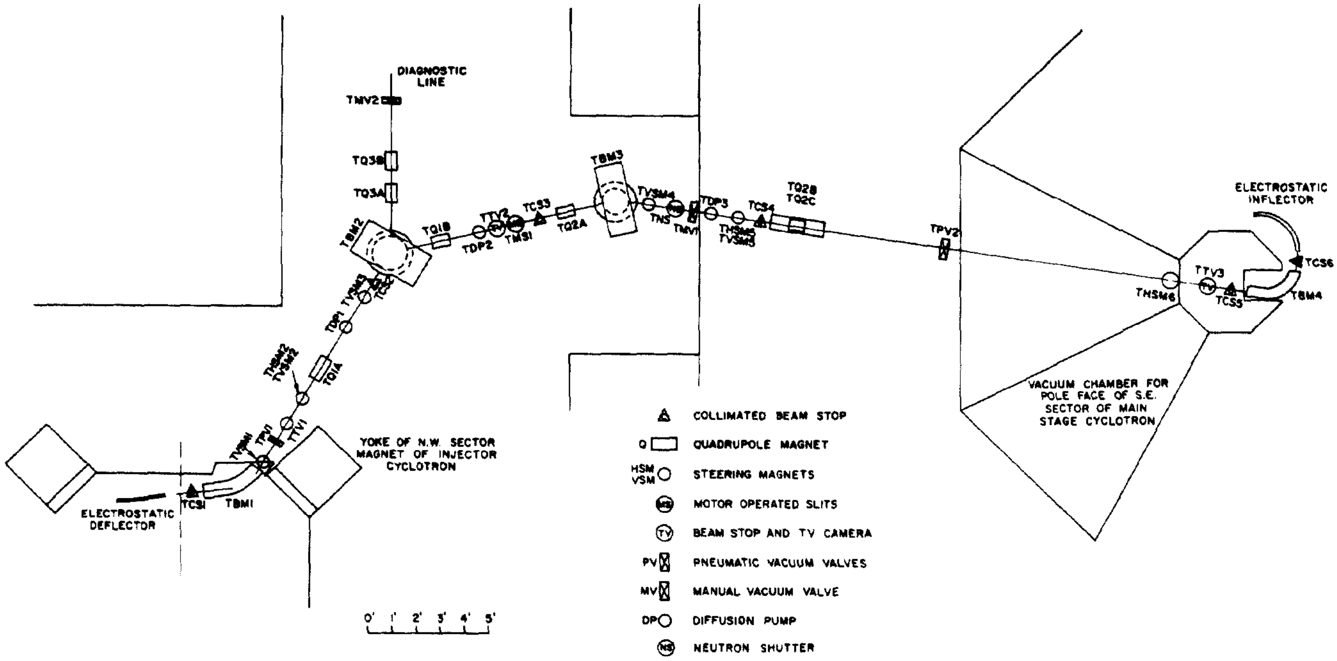


Figure 1. The Physical Layout of the IUCF Transfer Beamline

## Calculations

Beam transport calculations were made using the program TRANSPORT[1] as modified for use at IUCF.[2] The first task was to establish that sufficient energy resolution could be obtained at the location of the movable slits, TMS1, using the existing switching magnet, TBM2.

In order to provide a total energy resolution near 40 keV at 200 MeV for a 1 μamp beam the inflected beam at the appropriate energy should have a resolution of the order of 20 keV or ~.01% at the maximum inflection energy. The beam transport system should provide at least the means of fixing the range of energies which will be passed on to the main machine, if not also the means to measure this energy spread directly.

The procedure used to determine the layout was as follows. The inflector extraction and main-stage inflection trajectories were laid out on a large-scale drawing. The first bending magnet TBM2, was tentatively located on the extraction trajectory, a bending angle was assumed and the location of the double-waist (TMS1) established. Then the position of the two quads, TQ1A & B, their fields strengths and the angle of bend of TBM2 were allowed to vary to attempt to fit four constraints: a waist in each plane, a particular horizontal spot size and a particular value for the dispersion element of the transfer matrix, $R_{16}$.

The values of the spot size and $R_{16}$ were chosen to provide a momentum resolution, dp/p, as close to 0.1% as possible for the emittance assumed (initially 6.6 mm-mr horizontally). The procedure yielded an acceptable solution, after several iterations to make the distances between elements reasonable, the size of the beam inside elements appropriate and to attempt to force the bending angle of TBM2 to be one of those available with the existing vacuum chamber of the magnet. The system transfer matrix up to TMS2 has for $R_{16}$ a value of 18.9 mm/% . The momentum dispersion is given by the spot size (full width) divided by $R_{16}$.

The 24.25° bend from TBM3 is required to bring the beam onto the inflection trajectory. As pointed out earlier, the three quadrupoles TQ2A, B & C operate effectively as a triplet, even though the first element is some distance from the other two. In order to match to the inflection phase-space ellipses four variables were required, corresponding to the sizes and orientations of the ellipses (there

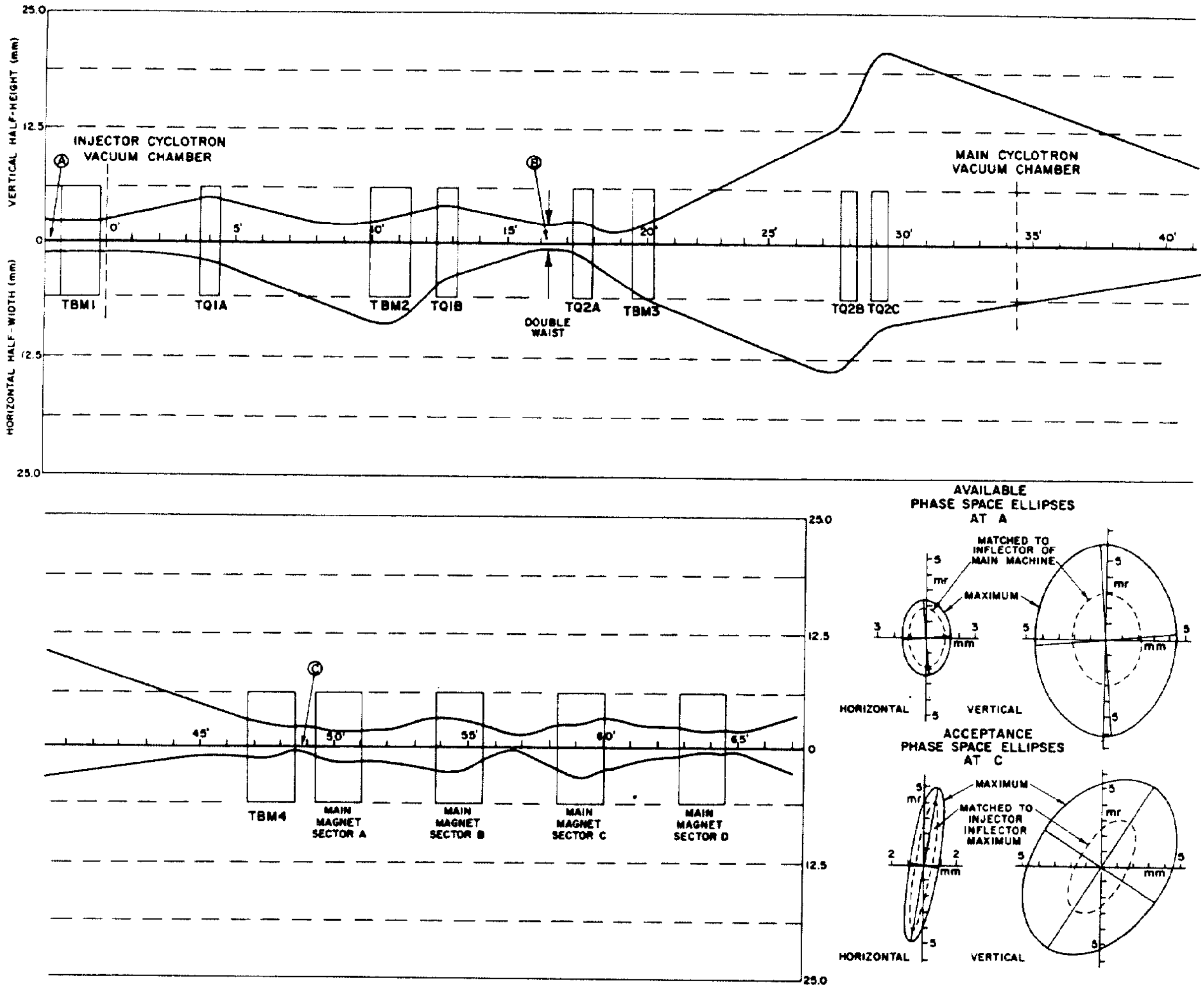


Figure 2. Results of a TRANSPORT Calculation for 16 MeV Protons Showing the Beam Envelopes in Both Planes and the Match Obtained at the Main Stage Inflector

is no waist at the match point.) The strengths of the three quads plus the position of the doublet portion (TQ2B & C) were used as the four required variables. The doublet position, once determined for one type of beam, is fixed for all beams; only three variables can be used thereafter in practice. The position of this doublet was determined using the best-case emittance (maximum allowed by injector inflector); it was felt that all other beams could be adjusted with the triplet so that the phase-space ellipses would approximate the main-stage inflector acceptance ellipses, if not be oriented precisely. Rather better fits to the inflector constraints, even for the worst case beam, can be obtained but at the expense of requiring a very large beam vertically at TQ2C. To allow the largest beam possible at this location TQ2BC are together a doublet having a 4" clear aperture, while all others in the beam line are 3" in diameter. The best emittance beam was chosen to determine the location of TQ2B & C, because it was felt that the unique light-ion capability of the facility should be optimized.

TRANSPORT calculations for the best case beam are plotted in Fig. 2 along with the appropriate phase-space ellipses. This calculation is for 16 MeV protons. The match obtained at the main-stage inflector, point C, is excellent. The behavior of the beam coasting around the first turn of the machine is also indicated. This calculation assumes hard-edge magnets and so is useful, inside the main machine, only in a qualitative sense.

A calculation for a 19 MeV $^{12}C^{(4+)}$ beam, a heavy-ion beam typical of those which we will be able to accelerate after the first year or two of operation, provides a match which is not quite as good as in the best beam case, but the bulk of the beam will fit into the acceptance ellipse.

The problem of beam-burst length spreading through the transfer system was considered next. A beam burst of finite emittance and/or non-zero energy spread will in general increase in length as it passes through a dispersive system. It is possible to minimize this effect, but not to eliminate it altogether except for special symmetries which are not obtainable with the given cyclotron layout. In the 16 MeV proton case, assuming 2.4° of RF phase, acceleration on the 4th harmonic of the RF yields a particle phase of 0.575°. That is, the length of the beam burst along the orbit (z-direction) at the extraction radius of 40" is 0.575° x 40"/360°, or about one centimeter.

The TRANSPORT calculations enable this beam burst length and the effect of the various beam line elements on it to be calculated. For protons, the effect of the transport system is negligible since the burst is relatively long. The bending magnet TBM2, the main dispersive element, extends the burst length from 1.00 to 1.21 cm. But the combined effects of TBM3, TBM4 and the main stage Sector A magnet reduce the burst length to 1.04 cm as the burst crosses the first RF accelerating gap.

For the heavy ions the situation is rather different. For the 19 MeV $^{12}C^{(4+)}$ beam in the 12th harmonic mode, $2.4^{o}$ of RF phase corresponds to $0.20^{o}$ of particle phase or a burst length of 0.34 cm at extraction. This rather short beam burst, when coupled with the higher emittance of the beam, is significantly affected by dispersive elements. TBM2 increases the burst length from 0.34 to 0.96 cm; the remainder of the system reduces the burst length to 0.57 cm as the beam crosses the first accelerating gap. This increases the particle phase to $0.30^{o}$ and the RF phase to $3.8^{o}$. This phase width alone, if maintained throughout the acceleration process in the main stage, would produce an energy spread of 100 keV, at a final energy of 200 MeV. Finite emittance and other effects would make the total energy spread somewhat higher. Of course, this value can be reduced substantially by reducing the particle phase entering the injector cyclotron. Future additions to the transfer beam line system specifically dedicated to heavy ion injection should be designed with this problem in mind.

The diagnostic portion of the transfer beam line has been in operation about 5 months. Protons up to 11.0 MeV and $^{4}He^{(+)}$ to 5.5 MeV have been focused on experimenters' targets at the end of this line. This operation has verified satisfactorily the calculated properties of the beam line. The inflection section of the beam line will be placed in operation in the next few months.

References


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