Injection System Design and Tests for the TR13 Cyclotron

M. Dehnel[1], K. Erdman
EBCO TECHNOLOGIES/U.B.C.
T. Kuo, L. Root
TRIUMF

Abstract

The design, testing and selection of a compact modular injection system for the TR13 cyclotron's externally injected 2 mA H^- ion beam is presented in this paper. Concurrent design techniques, and proto-type evaluation on a 1 MeV test cyclotron are discussed. Key results include comparisons of simulated and measured parameters, beam transmission as a function of injection system rotation angle, and full beam scintillator images in the vicinity of the inflector exit.

1. INTRODUCTION

The TR13 is an automated compact 100 μA H^- cyclotron built for radioisotope production in a hospital environment [1]. One of the features of the system is the ion source and injection system (I.S.I.S.). It was our design goal to produce a compact, modular and cost-effective I.S.I.S. capable of supplying a matched 2 mA H^- direct current (DC) beam to the center region of the TR13 cyclotron. An adequate match between the ion source emittances and the center region acceptances is required to keep beam losses and emittance growth due to mis-matching to within acceptable limits.

As with any system of this complexity, there are trade-offs between performance, cost, ease of operation, and maintenance etc.. The approach we took to arrive at the preferred system was to computationally determine candidate injection systems, and to then utilize the 1 MeV TR type test cyclotron [2] to empirically select the best one.

2. DESIGN

2.1 General

Once the decision was made to go ahead with the TR13, the design of the various sub-systems proceeded in parallel to facilitate the expeditious completion of the project. This meant the design of the injection system had to proceed prior to full knowledge of the TR13 phase space acceptance ellipses. But since the highly effective TR30 center region was specified for the TR13, beam matching calculations could be done using the TR30 models as a first step.

In an effort to take advantage of efficiencies of manufacture, identical (modular) focusing elements were specified for the injection system. Solenoid magnets were too bulky and expensive, and electrostatic quadrupoles were prone to sparking and to beam space charge problems due to inadequate space charge neutralization [3]. Therefore, magnetic quadrupoles were used. In order for the TR13 to be sufficiently compact for the hospital environment, the injection system length needed to be at least 0.3 m shorter than the 1.8 m long solenoid and two quadrupole (SQQ) injection system [4] of the TR30.

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2.2 Calculations

The original SQQ system was designed [4] using a beam matching technique [5] which is approximate in nature, but useful for concurrently designing the injection system with the cyclotron. It is also useful for constraining the cross-plane coupling [6] portion of the emittance growth which is introduced primarily by the inflector.

In the technique of [5] the cyclotron focusing is assumed to be smooth and uniform producing upright acceptance ellipses. This approximation yields a very simple expression for the normalized cyclotron circulating emittance

$$\varepsilon_{cn\rho} = \frac{\beta\gamma(\nu_\rho \rho^2_{max})}{R_{cyc}} \tag{1}$$

where R_{cyc} is the cyclotron radius, β and γ are the usual relativistic parameters, ν_ρ is the radial cyclotron tune and the quantity ρ_{max} refers to the largest radial beam half-size seen over one betatron oscillation. The equation is also valid if z, the axial beam half-size, is substituted for ρ. With the normalized circulating emittance described in this manner, it can be minimized in each phase plane by simply minimizing the maximum displacements over a betatron oscillation. This is easily accomplished using TRANSOPTR [7].

The original SQQ injection line design had an initial drift of 120 cm and a source waist radius of 4 mm. Under these conditions the circulating emittances were reasonably balanced with a sum total $\varepsilon_{cn\rho}+\varepsilon_{cnz}$ of 1.4 mm-mrad for initial source emittances of 0.365 mm-mrad in each phase plane. The best $\varepsilon_{cn\rho}+\varepsilon_{cnz}$ results for quadruplet (4Q) and triplet (3Q) injection systems with an initial drift of 50 cm and an initial source waist radius of 2.0 mm were between 1.4 and 1.8 mm-mrad depending on magnet polarities and the magnet axial orientation. Again the emittances were reasonably balanced. The doublet (2Q) based injection system could only manage $\varepsilon_{cn\rho}+\varepsilon_{cnz}$ of about 3.0 mm-mrad.

As a second approximation, the above calculations were refined by replacing the smooth focusing upright ellipses with the old TR30 acceptance ellipses [8] which were obtained by numerically tracking particles through realistic cyclotron fields. The ability of the Q based systems to match the source beam to these ellipses was then tested. In general, the value of $\varepsilon_{cn\rho}+\varepsilon_{cnz}$ increased by about 15% from those calculated using the previous method. In some configurations a substantial shifting of emittance from one phase plane to another, relative to the first set of calculations, was noted.

The 4Q and 3Q based injection systems were found to be comparable in matching capability to the SQQ system using TR30 models. This result was sufficient justification to initiate empirical testing. 4Q, 3Q and 2Q systems were constructed for testing using nominal quadrupole magnets of short length, large bore and low field (10 cm, 5 cm, 1 kG), as dictated by the simulations. In addition, the initial drift space was kept at 50 cm (minimum required for vacuum pumps), and the injection line was made to be rotatable to provide an extra degree of freedom to optimize performance [8].

3. TESTING

Since it was known that the ion source lens configuration and the initial drift space immediately downstream of the ion source would be experimentally adjusted during testing, it was found useful to generate reference plots which illustrated the matching capabilities of a range of possible Q based configurations using the matching technique of [8].

Figures 1 and 2 are examples of such plots for a 3Q system. Figure 1 helps one choose source radii and initial drifts which minimize $\varepsilon_{cn\rho}+\varepsilon_{cnz}$, and Figure 2 helps one decide whether the emittance sharing between phase planes is acceptable.

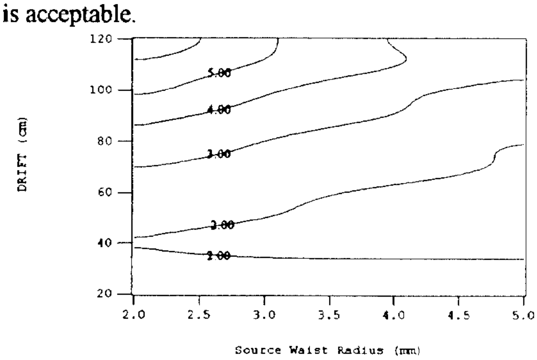

Figure 1. Contours of minimized $\varepsilon_{cn\rho}+\varepsilon_{cnz}$ (mm-mrad) at each source waist radius and initial drift length for fixed normalized source emittances of $\varepsilon_{snx}=\varepsilon_{sny}=0.365$ mm-mrad for a 3Q injection line.

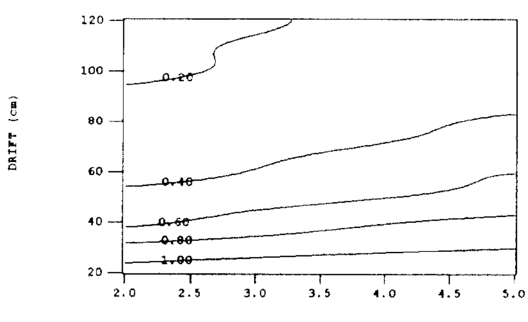

Figure 2. Contours of $\varepsilon_{cnz}/\varepsilon_{cn\rho}$ at each source waist radius and initial drift length for fixed normalized source emittances of $\varepsilon_{snx}=\varepsilon_{sny}=0.365$ mm-mrad for a 3Q injection line.

As the physical test system took shape and the final physically realizable drifts, ion source parameters, measured quadrupole characteristics, CASINO [9] calculated inflector characteristics, and test cyclotron tunes were determined a more accurate modeling of the system was undertaken.

Table 1 gives the simulated and measured field settings and the orientation angle for the 4Q injection line installed on the 1 MeV test cyclotron. Simulations used the TRANSOPTR based approach with $\nu_\rho = 1.03$ and $\nu_z = 0.333$, $\varepsilon_{snx}=\varepsilon_{sny}=0.24$ mm-mrad, the source waist radius is 1.5 mm, $R_{cyc} = 19.6$ mm for an injected ion energy of 25 keV.

Table 1
Simulated and Measured System Settings

Parameter	Simulated	Measured
B1	214 Gauss	287 Gauss
B2	–476 Gauss	–510 Gauss
B3	600 Gauss	560 Gauss
B4	–463 Gauss	–530 Gauss
θ Orientation*	–18.9 °	–21.7 °

* This angle is measured with respect to the lab vertical axis which is at 14° counterclockwise with respect to the inflector entrance angle.

The measured quadrupole settings were those which peaked the beam transmission to 1 MeV for a 2 mA ion source current. The agreement between the measured and simulated results is fairly good. This verifies the usefulness of the matching algorithms described earlier.

3.1 *Transmission Comparisons on the 1 MeV Test Cyclotron*

In conjunction with the injection line tests, ion source optimizations were also carried out. It was evident early on in this combined testing that the 4Q system consistently produced the best transmission while the 3Q and 2Q systems produced slightly lower transmission. Table 2 illustrates the DC beam transmitted to a beamstop at the inflector exit (prior to RF acceleration) for a non-optimized ion source. The three runs correspond to source arc currents of 2.7, 4.8 and 6.4 amperes, respectively.

Table 2
Beam Transmitted to Inflector Exit Beamstop

Device	Run 1	Run 2	Run 3
Source Output	744 μA	1311 μA	1630 μA
4Q @ Beamstop	617 μA	963 μA	1210 μA
3Q @ Beamstop	502 μA	815 μA	1040 μA
2Q @ Beamstop	475 μA	840 μA	1091 μA

Thus, it became quite clear during the optimization process that the 4Q was of interest from the point of view of highest transmission, but that if the 2Q could provide sufficient transmission to meet the extracted beam requirements of the TR13, it would be the most interesting in terms of cost effectiveness.

Table 3 shows the 4Q and 2Q transmission results to the 1 MeV beamstop on the test cyclotron for the case where the source configuration was fully optimized in the low arc current regime. In this case the four runs correspond to source arc current settings of 2.7, 4.8, 6.4 and 7.3 amperes, respectively. The 4Q results from Run 4 correspond to the system tune in Table 1. The 4Q and 2Q transmissions to 1 MeV for the final ion source configuration were excellent at approximately 13% and 9%, respectively. As the calculated phase acceptance of the TR13's center region is ≈ ±20°, the transmissions are near their theoretical maximums.

Although the 2Q injection line did not produce the best

Table 3
Beam Transmitted to 1 MeV Beamstop

Device	Run 1	Run 2	Run 3	Run 4
Source Output	1103 μA	1598 μA	1925 μA	2075 μA
4Q @ 1 MeV	140 μA	212 μA	253 μA	275 μA
2Q @ 1 MeV	91 μA	149 μA	179 μA	-

transmission, it met all the requirements of the TR13, and it was the most cost effective solution. The 2Q line had the additional advantage that it was more stable than the 4Q line with respect to field perturbations. As a result, it is now the TR13 injection line, and it has successfully been used in the TR13 to accelerate over 100 μA of dual beam to target @ 13 MeV with a transmission of ≈10%.

3.2 *2Q & 4Q Injection Line Rotations*

Beam transmission as a function of the injection line axial orientation angle was investigated for both the 2Q and 4Q systems. The transmission variation with angle (Figure 3) was quite dramatic for the 2Q configuration, but not for the 4Q configuration. Unfortunately, mechanical limitations prevented testing rotations of greater extent than indicated.

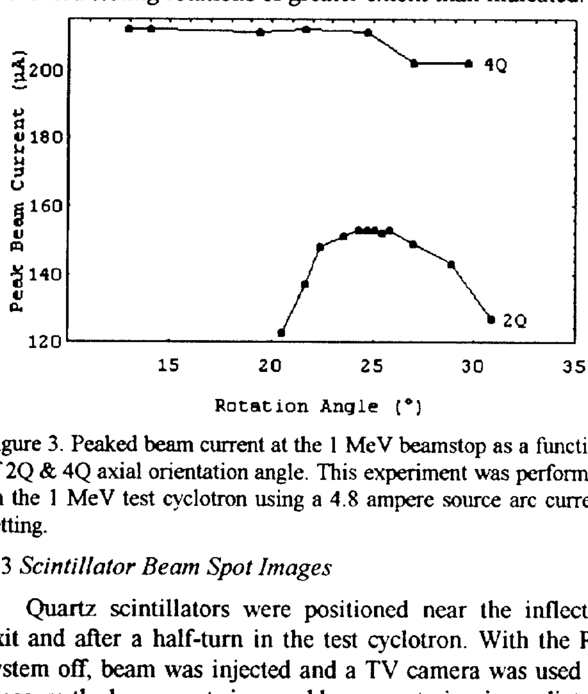

Figure 3. Peaked beam current at the 1 MeV beamstop as a function of 2Q & 4Q axial orientation angle. This experiment was performed on the 1 MeV test cyclotron using a 4.8 ampere source arc current setting.

3.3 *Scintillator Beam Spot Images*

Quartz scintillators were positioned near the inflector exit and after a half-turn in the test cyclotron. With the RF system off, beam was injected and a TV camera was used to measure the beam spot sizes and beam centering immediately downstream of the inflector. Figure 4 shows a typical beam spot image. Note that the ruler on the right hand side is scribed in mm. It is apparent that the image is saturated at this current (1.1 mA), however, it is clear the exit spot is comfortably smaller than the 6 mm exit gap of the inflector. The (x, y) coupling of the beam is obvious, as well.

It can be seen that the two beam spots do not have the same vertical centering. This information was useful for correcting the axial positioning of the inflector for improved transmission.

4. CONCLUSION

This paper describes useful techniques for designing an injection system for a compact 100 μA H^- cyclotron concurrently with the cyclotron design. The effectiveness of these techniques are borne out by the successful implementation of the final injection system in the full scale cyclotron. As well, a useful technique for illustrating emittance growth as a function of system parameters was presented. This technique is particularly useful for quick reference during system testing.

The 2Q injection system was found to be the most cost effective compact modular injection system which met all the design criteria.

The beam transmission as a function of the 2Q and 4Q injection line axial orientation angles was also reported.

Lastly, full beam scintillator images were presented to illustrate a useful technique for determining the beam size and centering in the first half-turn of a cyclotron.

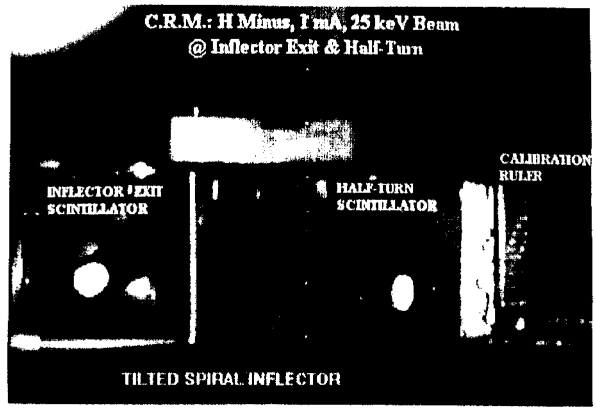

Figure 4. Beam spot images in the first half-turn of the 1 MeV test cyclotron for the Run 1 4Q system of Table 3.

5. REFERENCES

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