A Mini-PET Beamline for Optimized Proton Delivery to the ISOTRACE™ Target System

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Introduction

The ISOTRACE™ Super-Conducting Cyclotron is PMB-Alcen's re-developed and modernized version of Oxford Instrument's OSCAR™ super-conducting cyclotron [1]. Its extracted 80+ micro-amperes of 12 MeV protons are used for the production of PET radioisotopes. Following the philosophy of Dickie, Stevenson, Szlavik [2] for minimizing dose to personnel, and as developed by Dehnel *et al* [3,4], and Stokely *et al* [5], the ISOTRACE™ shall utilize D-Pace's innovative, light-weight, high-acceptance, low-activation, and integrated Mini-Beamline. This permits the relatively high residual radiation fields around PET targets to be moved ~1 metre away from the cyclotron, and facilitates the use of local shielding (around the targets) that limits prompt gammas and neutrons, but more importantly attenuates the residual target radiation, so that maintenance/research staff can work on the cyclotron in a relatively low activity environment. In addition, the mini-beamline for PET utilizes a compound quadrupole/steerer doublet that permits active and dynamic focusing/steering of the extracted proton beam for optimized production and minimized losses [3], so it improves on the successful work of Theroux *et al* [6]. The integrated beamline unit is extremely small, so that it is very unlike bulky traditional PET and SPECT beamlines that require substantial support structures, such as described by Dehnel in [7,8].

Material and Methods

The ISOTRACE™ cyclotron is pictured in Figure 1. The exit port flange and gate valve to which the integrated mini-beamline for PET shall be mounted is shown. Immediately upstream of the exit port, hidden from view, is a 4 jaw collimator (called BPI for Beam Position Indicator) with spilled beam current readbacks to the control system.

Table 1 shows the nominal beam emittance and Twiss parameter values at the exit port flange location. This ion-optical information is necessary to simulate ion beam transport, develop the mini-beamline, and determine a nominal tune (i.e. magnet settings).

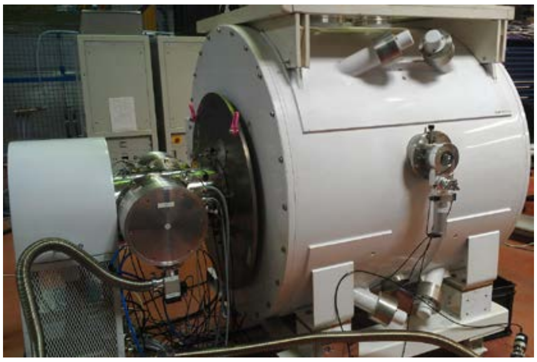

Figure 1: PMB-Alcen's ISOTRACE™ Super-Conducting Cyclotron for PET. The proton beam exit flange with gate valve is shown centre-right.

Twiss Parameters	*Horizontal*	*Vertical*
$4\cdot\varepsilon_{rms}$ (mm·mrad)	15	30
β (mm/mrad)	4.5	2.0
α	−3.8	−2.8
γ (mrad/mm)	3.5	4.5

TABLE 1. Extracted beam characteristics at exit port flange face of ISOTRACE™. Nominal momentum dispersion, $\delta = 0.5\%$.

Results and Conclusion

Table 2 shows the ion-optical system parameters. Figures 2 and 3 show the horizontal and vertical beam profiles. The Horizontally focusing Quadrupole magnet (HQ), and Vertically focusing Quadrupole magnet (VQ) aperture diameter, 33 mm, was chosen to give sufficient beam acceptance. The focusing strength is a function of BL, so the effective length, L = 150 mm, was chosen to ensure B_{max} less than 0.3 Tesla, while keeping overall magnet mass down. The quadrupole magnets are fitted with water-cooled compound coils in which the copper/mylar strip wound portion of each coil is a winding for the quadrupole focusing function, and the wire wound portion is for the steering function. To increase beam acceptance and provide additional section strength for the pipe support function, the internal aperture of the low-activation aluminium beam pipe and the external shape are in the shape of a cross. Figure 4 shows the beam cross-section at the mid-point of the downstream quadrupole magnet, and illustrates the additional acceptance as compared to a

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round beampipe. In order to machine the interior profile, the pipe is comprised of two pre-machined pieces that are friction stir-welded together. Figure 5 is an isometric of the mini-beamline for PET.

Parameters	*Value*	*Unit*
Drift 1	120	mm
HQ: L, ϕ_{bore}, B_{max}	150,33,0.18	mm,mm,T
Drift 2:	69	mm
VQ: L, ϕ_{bore}, B_{max}	150,33,0.212	mm,mm,T
Drift 3:	577	mm

TABLE 2. Mini-Beamline for PET ion-optical parameters for ISOTRACE™ extracted proton beam, and 10 mm beam spot on target.

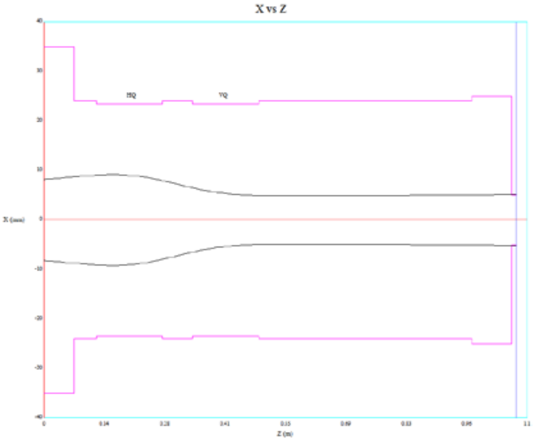

Figure 2: Horizontal beam profile for 12.63 MeV proton beam transported from ISOTRACE™ exit port flange to 10 mm beam spot at target location. HQ = 0.18 T, VQ = 0.212 T.

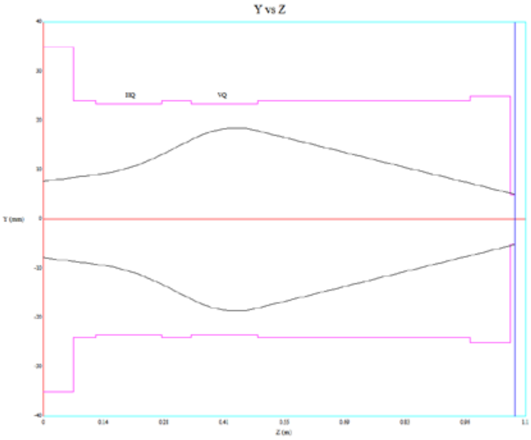

Figure 3: Vertical beam profile for 12.63 MeV proton beam transported from ISOTRACE™ exit port flange to 10 mm beam spot at target location. HQ = 0.18 T, VQ = 0.212 T.

The four upstream HQ compound coils are excited with a 75A power supply for the horizontally focusing quadrupole magnet function, and a ±10A power supply for a vertical steering function. The same power supplies are used for the four downstream VQ compound coils for the purpose of a vertically focusing quadrupole magnet function and horizontal steering function.

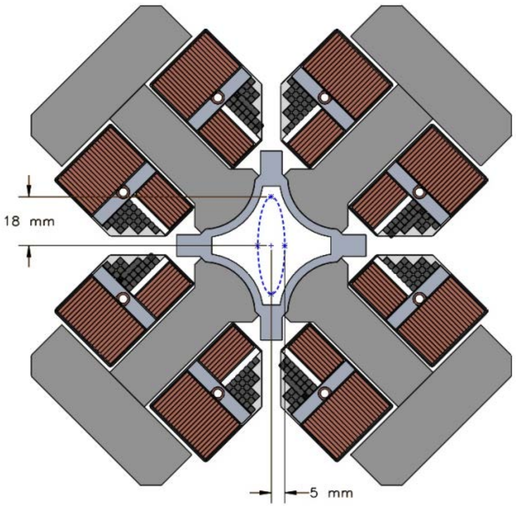

Figure 4: Cross-section of the downstream integrated Quadrupole/Steerer Magnet. Beam envelope, friction stir-welded aluminium beam pipe & support, and the water-cooled combined-function copper strip-wound and wire wound coil are shown.

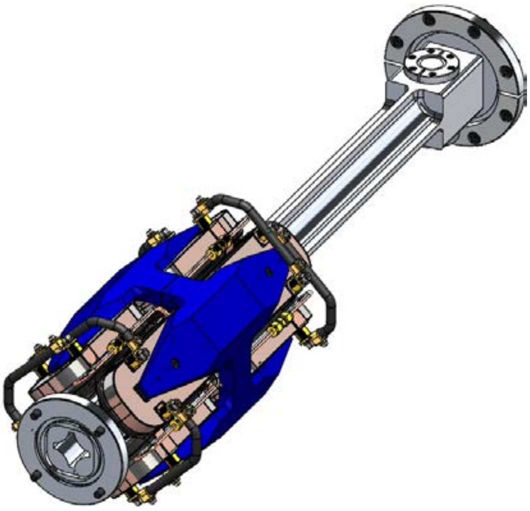

Figure 5: Integrated Quadrupole/Steerer Doublet Magnets on friction stir-welded aluminium beampipe/support/alignment component with roughing port. Total weight ~50 kilograms.

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