AN INTEGRATED SELF-SUPPORTING MINI-BEAMLINE FOR PET CYCLOTRONS

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Abstract

A commercial Fluorine-18 water-target can now handle 150 micro-amperes of 10-19 MeV proton current [1,2,3,4,5]. The days of a few tens of micro-amperes bombarding a PET target with low residual activity on a self-shielded cyclotron are over. Now an integrated self-supporting mini-beamline is essential for safe, optimized and reliable operation of PET cyclotrons especially with high power liquid or solid targets. The high levels of prompt/residual radiation are moved (~1 m) away from the cyclotron so local-shielding can be placed around the target/selector assembly, which minimizes cyclotron component damage due to prompt neutrons/gammas, and ensures the high residual target radiation is attenuated, so maintenance personnel can work on the cyclotron in a "cool" environment. Beam diagnostic readbacks from baffles/collimators provide steering and focusing control of the beam. This "plug-n-play" beamline is an integrated self-supporting unit cantilevered from the cyclotron. The single aluminum sub-structure acts as mounting flange, support structure, beampipe, and magnet registration device. A cross-shaped vacuum envelope through the compound quadrupole/steering magnets result in maximum beam throughput and optimization.

MINI-BEAMLINE DESCRIPTION

The mini-Beamline is an evolution of the D-Pace Compact Beamline for PET [6,7,8], which was short yet used large elements (radially), and was more expensive. The mini-Beamline is a light-weight integrated unit with options. It is intended for any cyclotron used for Positron Emission Tomography (PET) radioisotope production. IBA has facilitated a first installation opportunity and this paper shall illustrate the system's performance and set-up for the case of a Cyclone® 18.

Ion-Optics

IBA provided the Twiss parameters (α,β,γ) describing the 18 MeV proton beam at each of the four extraction ports with unnormalized emittance 15 πmm·mrad (90% of the beam intensity) in both phase planes. A conservative momentum dispersion of 0.35% was utilized. Ion-optics were undertaken with Beamline Simulator [9] to confirm high transmission from each of the main tank ports to a target (ϕ = 10 mm) at ~1.4 m from the main tank (~ 1 m from cyclotron yoke). Table 1 gives the mini-Beamline element parameters, Figure 1 shows a cross-section of the largest beam envelope which is in the X plane at the centre of the horizontally focusing quadrupole magnet. Note the unique shape of the extruded aluminum vacuum tube. It increases the beamline acceptance and is a stronger mechanical section as compared to a round pipe. Figure 2 gives the X & Y beam profiles for extracted beams from each of the four ports to target. This establishes the mini-Beamline's efficacy on any port.

Table 1: Mini-Beamline Ion-Optical Parameters

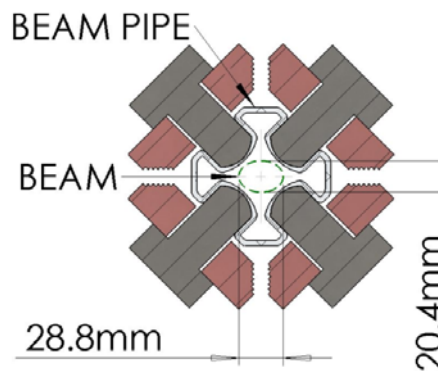| Parameter	Value	Unit
Drift 1	489	mm
VQ: L, ϕ_{bore}, B_{max}	150, 33, 0.3	mm, mm, T
Drift 2	50	mm
HQ: L, ϕ_{bore}, B_{max}	150, 33, 0.3	mm, mm, T
Drift 3	600	mm

Figure 1: Cross-Section at Widest Beam Envelope.

Features

Figure 3 shows the 3D layout of the mini-Beamline. The light-weight integrated aluminum sub-structure provides several functions. It is a low residual activity vacuum vessel with specialized interior shape for high transmission, and large-section exterior for strength. It self-supports the entire beamline and is cantilevered from the magnet yoke by way of an adjustable foot. It has precision machined features for tightly toleranced magnet registration. The upstream flange mates to the cyclotron main tank, and houses an aluminum entrance collimator electrically isolated with VESPEL™ stand-offs and has beam current readback to the control system (bnc).

The unique quadrupole doublet is divided into ambient air-cooled quadrants with the yokes primarily in the longitudinal direction. For asymmetric focusing and XY Steering a circumferential yoke is used for differential flux. The X & Y compound magnets utilize one small power supply per thermally-interlocked coil (Total = 8).
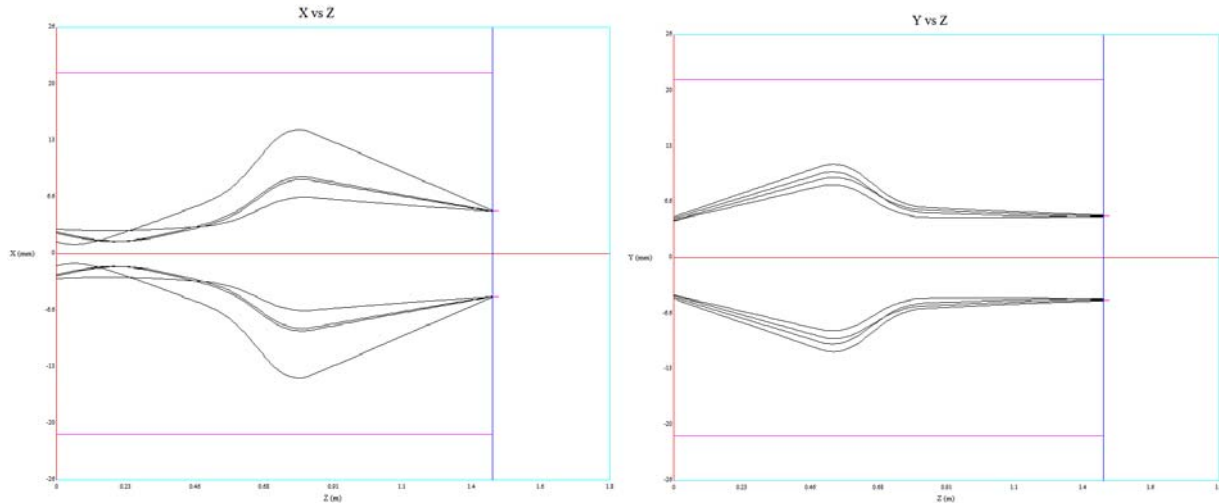
Figure 2: Horizontal and vertical 18 MeV proton beam envelopes for each of the four Cyclone® 18 extraction ports transported through the mini-Beamline and deposited on a target with 10 mm beamspot diameter.

Independent supplies for each coil provide the compound function of focusing and XY steering in each magnet. A controller in the electronics rack algorithmically adjusts the current settings in each coil to provide vertical focusing, and horizontal/vertical steering for the upstream magnet, and horizontal focusing and horizontal/vertical steering in the downstream magnet.

Downstream of the magnets is a low-profile 50 mm inner diameter VAT™ valve followed by a very short T-section which includes ports for vacuum gauges, and a connection to the cyclotron roughing pump.

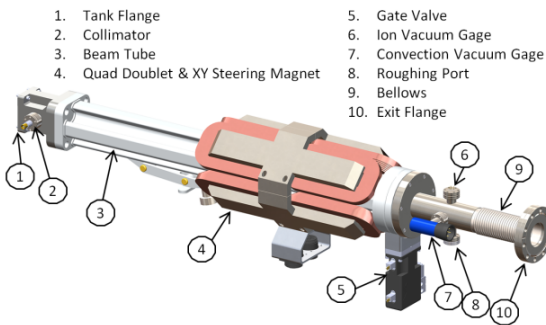| 1. Tank Flange | 5. Gate Valve |
2. Collimator	6. Ion Vacuum Gage
3. Beam Tube	7. Convection Vacuum Gage
4. Quad Doublet & XY Steering Magnet	8. Roughing Port
	9. Bellows
	10. Exit Flange

Figure 3: Layout of the mini-Beamline for PET.

Figure 4 gives a schematic view of the 3U rack-mountable electronics chassis. It contains a controller to interface with the cyclotron control system, or the customer can interface directly to the box equipment, and beamline readback signals. The box and signals are: (a) four low-wattage power supplies for compound control of the upstream vertical quadrupole magnet with XY steering, (b) four low-wattage power supplies for compound control of the downstream horizontal quadrupole magnet with XY steering, (c) an interlock signal for coil thermal switches (serial connect), (d) an entrance collimator beam current readback, (e) vacuum gauge controller, (f) gate valve solenoid signals.
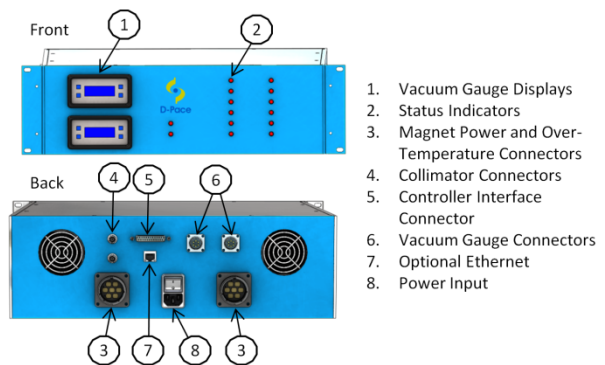

1. Vacuum Gauge Displays
2. Status Indicators
3. Magnet Power and Over-Temperature Connectors
4. Collimator Connectors
5. Controller Interface Connector
6. Vacuum Gauge Connectors
7. Optional Ethernet
8. Power Input

Figure 4: Schematic Layout of Electronics Crate.

FULL SET-UP: MINI-BEAMLINE – SELECTOR – TARGETS – SHIELDING

Figure 5 illustrates a full beam-handling and bombardment system that achieves the goals of: (i) optimizing radioisotope production by providing active beam focusing and steering, (ii) shifting the prompt neutron activation away from the cyclotron (reducing radiation damage and activation of cyclotron components), (iii) shifting the residual target activity away from the cyclotron, (iv) attenuating residual target activity (shielding achieves 1/100 attenuation), (v) reducing dose exposure to maintenance personnel (better health outcomes, and lower staffing costs). The full set-up includes: (a) The "plug-n-play" mini-Beamline described above, (b) a TRIUMF-licensed two-port target selector (optional) [2], (c) 50 mm lead radiation shield with stand, and (d) either: one IBA high-current F18 water-target [4,5] and a Faraday Cup, **or** one Bruce Technologies F18 water-target [1] and a Faraday Cup, **or** two targets set-up for back-up or a 150µA solid target system.
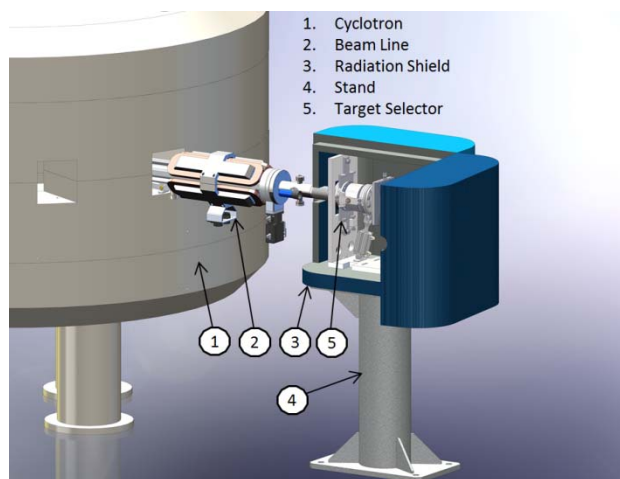
Figure 5: Full Beam Handling & Local-Shield for Optimized PET Radioisotope Production on IBA Cyclone®18.

UTILIZATION

Self-Shielded PET Cyclotrons

The trend is moving away from self-shielded cyclotrons as beam currents on target have more than tripled over the past decade. This is because multiple 150 µA (proton) targets within a cyclotron self-shield will trap the prompt neutron and gamma radiation, resulting from target bombardment, within the cyclotron itself. This reduces the lifetime of o-rings, cabling, tubing attached to the cyclotron and increases the frequency and duration of maintenance, and the level of dose-uptake by personnel. In addition, both routine and non-routine cyclotron maintenance tasks must take place proximate to an extremely high residual radiation field. For a self-shielded cyclotron a mini-PET beamline, target selector, target shield with stand could be used, however, the self-shielding would need to house the entire mini-Beamline and join to the target shielding and this seems impractical.

PET Cyclotrons in a Compact Vault

The mini-Beamline for PET concept is particularly useful for un-shielded cyclotrons and follows along with the trends established for 30 MeV SPECT cyclotrons about 20 years ago [10]. Essentially the message was to keep prompt and residual activity away from the cyclotron so it is in a "cool" environment, and the target maintenance and its associated personnel dose uptake risks can be undertaken separate from cyclotron maintenance. Also, all the benefits of optimized beam centering, focusing and collimator readback control can be utilized to maximize production.

In addition, the mini-Beamline provides a means for keeping the dimensions and concomitant cost of the shielded vaults low by keeping targets relatively close to the cyclotron, but far enough away to locally shield them. In terms, of facility planning, a small low-cost vault is very helpful especially in areas where real-estate costs are very high.

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