A HIGH CURRENT PET TARGET AND COMPACT BEAMLINE

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Abstract

Many of today's PET cyclotrons are delivered from the factory for fully automated operation in a hospital based clinical program. Simplicity and ease of operation by non-specialists is desired, and this is achieved in part through relatively low current targets attached to the PET cyclotron's main vacuum tank. However, commercial scale production of short-lived radiopharmaceuticals is becoming increasingly prevalent where substantially higher current target operation [1] requiring greater optimization of beam parameters through compact external beamlines [2,3,4] is necessary to meet ever more demanding production schedules and delivery commitments. This paper describes a system which incorporates high performance Bruce Technologies PET water targets and a short well instrumented beamline [2,4] designed by D-Pace for beam centering, focusing and maximum productivity.

INTRODUCTION

Low cost cyclotrons with vacuum tank mounted targets have become an extremely effective solution for production of PET radionuclides over the past decades. As the ^{18}FDG market continues to grow, the prevailing strategy to meet demand includes both the enhancement of system capabilities and the installation of new production sites. In the future, it is likely that much higher capacity single cyclotron production (20-50 Ci of $^{18}F^{-}$ per target per irradiation) will have limited commercial viability. Multi-kilowatt water target designs would be better suited to beamline rather than tank-side operation due to beam steering and focusing for optimized radioisotope production and reduced dose to personnel from local target shielding. Collaboration between D-Pace and Bruce Technologies has resulted in an intermediate solution capable of producing 10-20 Ci of $^{18}F^{-}$ per irradiation per target station.

CF-1000 TARGET

The CF-1000 1 kilowatt water target platform was produced alongside the TS-1650 (1.65 kW) to fill the gap between existing conventional OEM target systems and the multi-kilowatt Thermosyphon series targets developed by Bruce Technologies [5,6,7]. Development and testing was performed primarily on a GE PETtrace cyclotron. Design specifications are included in Table 1. As is the case in any ion beam target system, the production capacity is limited by the rate at which heat is removed from the target medium. The thermal limit may be predicted using computational methods employing characterization of coupled radiation transport and thermal hydraulic phenomena within the target chamber. This approach greatly expedites the traditionally empirical prototyping process.

Table 1: CF-1000 Parameters

Fill Volume	2200 µL
Incident Proton Energy	14 – 16.5 MeV
Current Limit at 16.5 MeV	85 µA
Current Limit at 14 MeV	> 100 µA
Window Material	Havar
Window Thickness	0.001 in
Chamber Material	Tantalum or Niobium
Maintenance Interval	15000 µA-hr

Generalized Heat Transfer Strategy

The overall target heat transfer capability of a liquid target is dictated by, principally, three thermal resistances:

- Boiling condensing process which transfers heat from the target medium to the chamber wall.
- Conduction within the target body between the chamber wall and the cooled surface.
- Forced convection in the cooling water circuit.

The relative contribution of each component depends on design specific geometry. A robust method for sensitivity analysis of the geometry has been developed in previous work [6].

The boiling and condensing process within the target chamber has proven to be the most difficult aspect of design and modeling. Strong coupling between radiation transport, energy deposition and void formation in addition to relatively high power densities and significant wall effects from small chamber volumes places this application beyond the current capabilities of commercially available computational fluid dynamics (CFD) methods. Bulk property models assuming homogenous equilibrium conditions and utilizing traditional engineering correlations have proven extremely useful in predicting total heat transfer for a variety of different chamber designs and operational boundary conditions. Since these models utilize volume averaged parameters, design margin must be included for sources of inhomogeneity in the system, the most significant being local peaking in the beam intensity distribution.

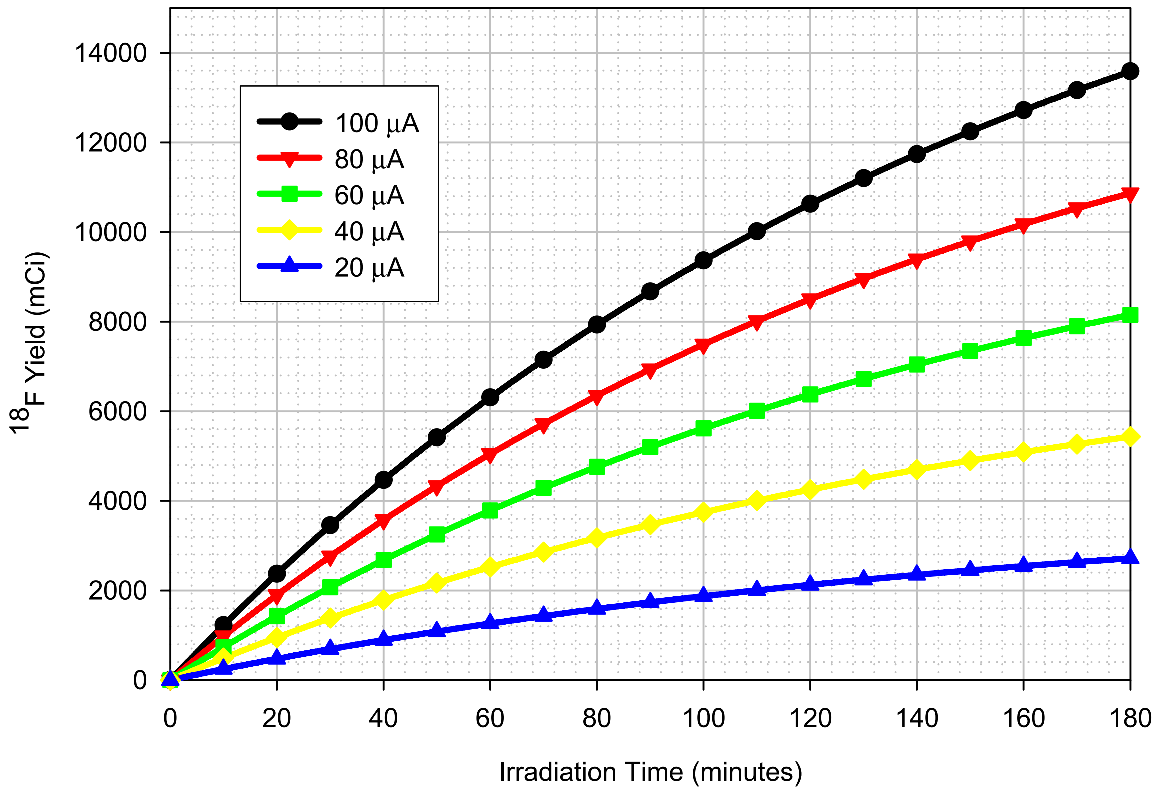

Figure 1: Production yield curves for the Bruce Technologies Inc. CF-1000 Target.

Optimization of the conduction was performed using traditional nodal methods. The conduction path from the chamber wall to cooling channel wall is extremely short (< 0.5 mm) to mitigate the modest thermal conductivity of modern chamber materials. In this design, an identical insert machined from silver (with thermal conductivity 7.5 times greater than tantalum) would equate to an increase in thermal performance of only 20 percent.

The cooling water flow path is the final ingredient for high power operation. In many OEM designs, more than 50 percent of the pressure drop in the cooling water circuit occurs outside of the target. Very generally, it is desirable to have a large Reynolds number in the region to be cooled and a small Reynolds number in the associated plumbing. This can be accomplished by using supply and return lines of sufficient diameter and implementing a large surface to cross sectional flow area ratio in the immediate vicinity of the surfaces to be cooled. Traditional fluid dynamics correlations are typically sufficient to characterize the water cooling circuit. A detailed example of this procedure is included in previous work [6].

Initial Prototyping and Testing

The basic design was tested using a GE PETtrace cyclotron fitted with an external D-Pace four-segment collimator and target port [3]. The collimator aperture could be changed by replacement of the graphite segments. The bulk of the testing was performed using a 12 mm aperture. Saturation yield tests using both natural abundance and [^{18}O]enriched target medium showed near theoretical results up to 80 µA, the maximum current available with the 12 mm configuration. A second prototype was developed for routine production which demonstrated a practical limit of 85 µA (1400 W).

Product Deployment

The design was integrated into the compact beamline [2,4], and the TRIUMF licensed target changer platform, refer to Figures 2 & 3, and the final production model was deployed in late 2008 at the cyclotron in Clermont-Ferrand operated by Cyclopharma.

The expected performance limit for this system at 14 MeV is greater than 100 µA. Testing and routine production have shown typical saturation yield values of 200 mCi/µA for ^{18}O(p,n)^{18}F up to the maximum current capability of the Cyclopharma cyclotron in Clermont-Ferrand. A higher power version of the target will extend the system capability beyond 200 µA as improvements in the cyclotron continue.

INDUSTRIAL BEAMLINE

The motivation for implementing compact beamlines is related to the commercial scale production of short-lived radiopharmaceuticals where substantially higher production of $^{18}F^{-}$ using high power (multi-kilowatt) water targets in which hundreds of microamperes of proton beam current will be required. In this mode of production, it is no longer appropriate to have little or no control over beam steering and focusing as is the case in older systems where targets are attached close to the cyclotron vacuum tank. At such high beam current levels, it is important to have the ability to optimize beam steering, and focusing. In particular, it is important to be able to broaden the intensity peak of the beam, so that the power delivered per unit area is below the design maximum for the target. Another very important feature of a compact beamline system with local shielding is related to minimizing dose to maintenance personnel. Traditional PET Cyclotron systems with high-powered targets will result in high residual radiation fields in close proximity to the cyclotron in locations that are difficult to access for maintenance. In the case of a compact beamline, the residual radiation source (i.e. the high-powered targets) are removed from the immediate vicinity of the cyclotron (1 metre), and surrounded by local lead/polyethylene shielding that cuts the residual radiation by a factor of 100. This is of great benefit to maintenance operations.

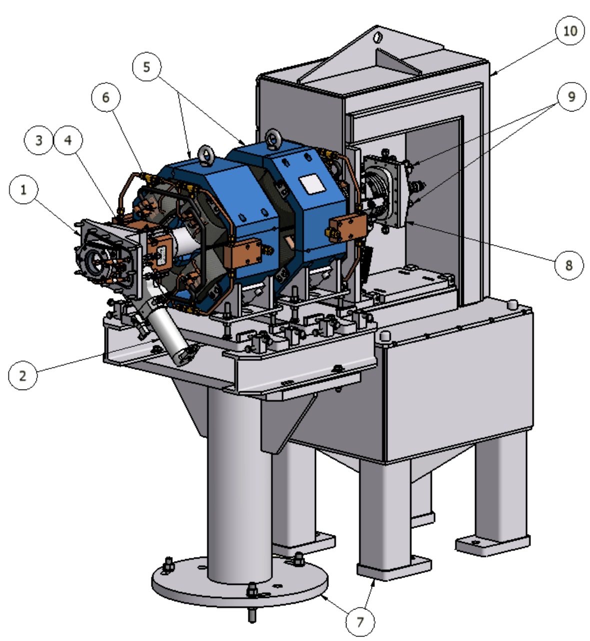

Figure 2: Compact 1.1 metre beamline designed by D-Pace for THC-14 PET Cyclotron [2,4]. (1) Graphite Exit Port Baffle with Beam Current Readback, (2) Gate Valve, (3) XY Steering Magnet, (4) Bellows, (5) Quadrupole Doublet, (6) Aluminium Beampipe, (7) Supports, (8) TRIUMF Target Selector, (9) CF-1000 Target, (10) Lead/Polyethylene Shielding.

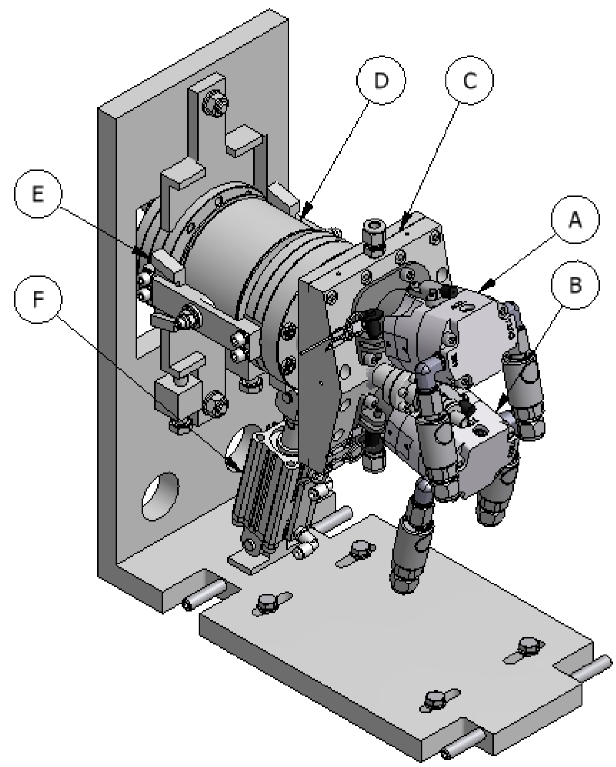

Figure 3: TRIUMF Licensed target Selector with (A, B) Bruce Tech CF-1000 water targets, (C) Housing with Graphite water-cooled baffle and 4-jaw collimators with beam current readbacks, (D) Bellows, (E) Angle Bracket Alignment Structures, (F) Piston.

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