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Simulation, Design, and Testing of a High Power Collimator for the RDS-112 Cyclotron

Johanna L. Peeples^{a,*}, Matthew H. Stokely^a, Michael C. Poorman^a, Gerald T. Bida^b, and Bruce W. Wieland^a

^aBTI Targetry LLC (formerly Bruce Technologies Inc.), Cary, NC, USA

^bDepartment of Radiology, Duke University Medical Center, Durham, NC, USA

Abstract

A high power [F-18]fluoride target package for the RDS-112 cyclotron has been designed, tested, and commercially deployed. The upgrade includes the CF-1000 target, a 1.3 kW water target with an established commercial history on RDS-111/Eclipse cyclotrons, and a redesigned collimator with improved heat rejection capabilities. Conjugate heat transfer analyses were employed to both evaluate the existing collimator capabilities and design a suitable high current replacement.

Keywords

RDS-112; Cyclotron Targetry; Collimator; Fluorine-18; Batch Boiling Target; Positron Emission Tomography

1. Introduction

In 1986, CTI Cyclotron Systems in Berkeley, CA introduced the RDS-112 cyclotron, the first commercially available surface-shielded negative-ion cyclotron. In 1991, the RDS-112 was replaced by the next generation RDS-111/Eclipse, and in 1992 manufacturing moved from Berkeley, CA to Knoxville, TN (Nutt, 2002). The RDS-111/Eclipse has become one of the most widely used PET cyclotrons in the world, with more than 200 units in operation. RDS cyclotrons produce 11.3 MeV protons and can achieve single beam currents in excess of 120 μ A (IAEA, 2006).

Batch boiling water targets are commonly used to produce $^{18}\text{F}^-$ by proton bombardment of [O-18]enriched water through the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ reaction. Cyclotron produced $^{18}\text{F}^-$ can be synthesized into [F-18]fluorodeoxyglucose (FDG), which is widely used in clinical PET/CT for Medicare-approved diagnosis and therapy evaluation of many cancers, and for Alzheimer's.

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*Corresponding Author: (919) 677-9799, peeples@brucetech-targets.com, 1939 Evans Rd., Cary, NC, USA.

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The first [O-18]enriched water targets were developed in the 1980s, and were designed to operate at available cyclotron currents of 20–40 μA (Wieland et al., 1989). Over time, cyclotron beam output and target design thermal capacity have dramatically increased (Friesel and Antaya, 2009; Stokely et al., 2010). Due to a competitive marketplace, radiopharmacies must produce large amounts of $^{18}\text{F}^-$ and distribute across long distances. This has led to original equipment manufacturers (OEMs) offering ^{18}F targets capable of operating at much higher currents (60–100 μA) than in prior decades. Since many RDS-112 cyclotrons are still fully operational and capable of high beam currents, but no longer supported by the manufacturer, a high current retrofit target upgrade was deemed essential in order for them to remain competitive for commercial distribution of [F-18]labeled radiopharmaceuticals.

An enabling target technology has been developed that offers a means to fully utilize the production capacity of existing and future cyclotrons. This goal has been achieved for existing 11–18 MeV cyclotrons by retrofitting high power targets (Stokely et al., 2010; Stokely et al., 2012). These targets may double or triple the productivity of this class of cyclotrons. The relatively small investment to purchase a high performance retrofit target can significantly reduce operating costs, and in some cases negate or postpone the purchase of an additional cyclotron to meet increasing demand.

Along with the need for higher power cyclotron targets comes the need for improved supporting components. RDS-112 collimators have been observed to fail at higher beam currents, primarily due to overheating of collimator components. Failures have been observed for continuous currents greater than 10 μA on any individual 4-jaw segment, or transient currents of 15–20 μA per segment during tuning.

The OEM collimator, which is described in Section 3, consists of several graphite and copper components connected with screws, and employs a tantalum sheet explosion bonded to one of the copper pieces. Common failures included melted screws and weakening of the explosion bonding, often resulting in an electrical short circuit. The goal of this work was to design a new collimator for the RDS-112, capable of operation at higher beam currents without overheating the components.

The design strategy included the use of conjugate heat transfer modeling with the Solid Works Flow Simulation 2012 package (Matsson, 2012). This package integrates directly with computer-aided design and drafting (CAD) software to enable analysis of heat transfer and fluid flow problems. The Navier-Stokes equations are solved numerically using a finite volume approach on a Cartesian regular coordinate system. Proper benchmarking of the collimator model and Solid Works Flow Simulation package is important, and was accomplished experimentally. The same modeling techniques, which were validated experimentally, can also be used for design and optimization of new targets.

2. Benchmark Experiment

Efficient design of new collimators and targets relies heavily on the use of conjugate heat transfer models. It is important to verify the accuracy of these models for the given application. A benchmark experiment was designed to determine temperature distribution in

an inexpensive, yet accurately representative, test assembly to be directly compared to temperatures predicted by the computer models. One option for experimental determination of temperature is the use of thermocouples. This method is undesirable because it is expensive, and the accuracy of the thermocouples must be verified. Another way to determine temperature experimentally is to visually observe when a material, with known melting temperature, begins to melt. This method can be employed at relatively low cost by embedding small metal pins at multiple locations within the assembly.

Graphite was selected as the primary material for the new RDS-112 collimator due to its low activation properties, and the design was simplified to eliminate resistances to heat transfer. A geometrically representative test assembly was constructed for the benchmark experiment. The test assembly included a graphite heat sink that was designed to resemble a 4-jaw collimator in terms of basic geometry, materials, and fastenings. The heat sink is range thick for the entire incident beam (12.0 mm diameter in the test case) except for a 2.0 mm diameter hole in the center that passes that portion of the beam through to a Faraday cup. This allows the beam to be tuned to a maximum and centered. Seven aluminum 6061-T6 pins were placed at evenly spaced radial locations in blind holes on the back side of the one-quarter section of the graphite heat sink, as shown in Figure 1(b). For simplicity, the other three quadrants were replaced by a monolithic piece of graphite.

The test apparatus provided for transmission of the center 2.0 mm diameter of the beam to a Faraday cup (rather than the 10.0 mm collimation diameter of the deployed system), while the rest of the beam was used to maximize heating of the test assembly. The aluminum 6061-T6 pins have a solidus melting temperature of 855°K (1080°F). The experiment was designed to result in melting of some pins at achievable beam currents. Pin melting is an indicator of maximum temperature in excess of the melting point, and it can be used to determine the range of temperature in the heat sink achieved during irradiation. Comparison of the experimental result to the modeling predictions for several beam powers can be used to validate the conjugate heat transfer models. The experiment was performed at the Duke University CS-30 cyclotron, which has a maximum available proton beam energy of 26 MeV.

A notch was cut into the melting quadrant, in order to restrict the flow of heat, increase the maximum temperature, and achieve pin melting at available beam currents. To provide the best available spatial accuracy, the pin diameter was 0.79 mm (0.03125 in), the pin length was 3.2 mm (0.125 in), and the pin center-to-center spacing was 1.6 mm (0.0625 in). The maximum range of 26 MeV protons in graphite was determined using SRIM-2008.04 to be 4.31 mm (0.17 in). The total thickness of the graphite heat sink in the beam path was selected to be 7.9 mm (0.3125 in) to insure that all protons were stopped in the graphite with no direct heating of the pins by the beam, even if the pins are fully inserted. The solid model of the test assembly and one-quarter section are shown in Figure 1.

When the experiment was performed on the CS-30 cyclotron, the beam was degraded to incident energy of 20 MeV. For each experimental condition, total micro-amps on the one-quarter melting section, the three-quarter section, and the target were recorded. Although the assembly can accommodate fully inserted pins, the pins were inserted to approximately half

their length (1.5 mm) to facilitate viewing. After each experimental condition, the test assembly was visually inspected to determine which pins reached melting temperatures. During the experiment, it became necessary to shift the beam slightly off-center to result in increased heating of the one-quarter section. Results of the pin melt experiment are presented in Table 1 and Figure 2.

A discrete approximation to a volumetric Gaussian heat flux distribution was applied to the heated regions of the test assembly. A standard deviation of 2.785 mm was selected, corresponding to 80% beam transmission in a 10 mm diameter. Radial increments of 0.25 mm were used with four equal-energy axial slices. The thickness of each axial slice was chosen, using SRIM, to correspond to 5 MeV of beam attenuation. Total heat transfer into the one-quarter section corresponds to the product of beam energy, 20 MeV, and beam current on the section.

Applied contact resistance values of 2050 W/m²-K between the BeO washers and aluminum housing and 1700 W/m²-K between the stainless-steel screws and stainless-steel washers were selected based on the literature (Mills, 1999). Average temperature on the top surface of each of the seven pins was predicted using Solid Works Flow Simulation. Predicted temperatures above the 855°K (1080°F) melting temperature are shown in Figure 3, and can be compared to experimental observations of melting.

The Solid Works Flow Simulation model correctly predicted the observed experimental conditions. For currents below 6 μ A on the one-quarter section, no melting is predicted or observed. For a beam current of 6.5 μ A on the one-quarter section, the model correctly predicts melting of the first four pins. Melting of all seven pins was both predicted and observed for a 10 μ A beam current on the one-quarter section.

3. Collimator Upgrade

The RDS-112 target system previously featured a 4-jaw collimator, and a single quadrant is illustrated in Figure 4. Each quadrant of the original collimator consisted of a tantalum sheet explosion bonded to a copper heat sink. A graphite sheet was attached to the copper heat sink using two SS-316 screws, with incident beam striking the tantalum before reaching the graphite. The copper heat sink was attached to the aluminum housing using three SS-316 screws with SS-316 spring form washers and ceramic BeO washers. The copper heat sink was composed of two separate pieces of copper, adding additional contact resistance to heat transfer. The collimator assembly was cooled by a non-optimized water flow through the aluminum housing. In older collimator versions, the explosion bonding between the tantalum and copper pieces has been observed to loosen, causing the tantalum piece to slide, and often resulted in electrical shorting. With newer versions, screws attaching the graphite segments have been observed to melt. These failures have been observed for continuous currents greater than 10 μ A per segment or transient currents of 15–20 μ A per segment during tune up.

A new collimator design was desired to support the use of higher power targets. The number of pieces, and corresponding resistances to heat transfer, were reduced in order to increase the thermal limits of the new collimator. Copper components, which remain activated long

after irradiation, were eliminated in favor of graphite. Graphite has previously been demonstrated to perform well in cyclotron collimators (Stokely et al., 2010; Ramsey and Carroll, 2003; Dehnel et al., 2005; Theroux et al., 2007).

An intermediate collimator design was evaluated with a new heat sink composed of a single piece of graphite with a tapered face exposed to the beam. This graphite heat sink replaces multiple separate pieces of the old collimator, including the graphite sheet, the copper heat sink, the copper bottom, the tantalum film, the two screws joining the graphite to the copper, and the two screws joining the copper heat sink to the copper bottom. The new graphite heat sink has an aperture 11 mm in diameter, assuring complete transmission through the 13 mm window frame on the water target. The old collimator model is shown in Figure 5(a), and the intermediate collimator model is shown in Figure 5(b).

A new collimator design was also evaluated where all of the BeO washers and spacers were removed from the design. The motivations for removing the BeO from the design are that the BeO washers from the original design are no longer being manufactured and that the material itself poses a potential health hazard (Kreiss et al., 1997). In the new design, the BeO washers separating the heat sink from the aluminum housing have been replaced with a hard anodized (type III) aluminum ring, which can be seen in Figure 5(c). This substitution makes the collimator much easier to assemble. However, the melting temperature of the Al 6061-T6 is much lower than that of the BeO. The remaining BeO washers and spacers isolating the heat sink from the screws have been replaced with Macor, a machinable glass-ceramic material. The maximum use temperature for Macor, 1000°C, is lower than BeO but higher than Al 6061-T6.

Each of the three collimator assemblies was modeled using the Solid Works Flow Simulation package for a cooling water flow rate of 1 LPM (0.26 GPM) with incident temperature of 15.5°C (60°F). Appropriate contact resistance values were applied between each part (Mills, 1999). A Gaussian-distributed surface heat generation rate was applied to the exposed face of the tantalum sheet for the original collimator and to the tapered surface of the graphite heat sink for the new collimator designs. The maximum temperature in each part was determined for various beam currents. The maximum current that could be applied to a single quadrant and remain below the limiting temperature for each part of each collimator assembly was estimated and is shown in Table 2.

For the original collimator, the copper heat sink is predicted to fail above 16 μA . For the intermediate design, the SS-316 spring washers are expected to fail above 55 μA . For the new design, the anodized aluminum ring and Macor insulators are predicted to fail at roughly the same time for beam currents above 47 μA . Use of the new graphite heat sink is predicted to increase the thermal capacity of the collimator by more than a factor of 3. When the BeO is eliminated from the system, the capacity is still almost 3 times more for the new design.

Two new collimators were installed at a single site in the fall of 2011. These collimators have been operated with continuous current of 15 μA and transient current up to 25 μA with no problems. It was observed that the anodizing on the aluminum ring can be scratched, if

not handled carefully, leading to intermittent shorting. This issue was corrected by increasing the minimum anodizing layer thickness to 0.028 mm (0.0011 in).

4. RDS-112 Target Upgrade

Over the last decade, significant advances have been made in material selection for wetted components in ^{18}F targets. Refractory metals, specifically tantalum (Satyamurthy et al., 2002; Alvord et al., 2005) and niobium (Zeisler et al., 2000; Nye et al., 2006), are the current standard for target chamber materials. This is principally due to improved fluoride reactivity (Satyamurthy et al., 2002) and a significant reduction in ionic and colloidal contaminants when compared to silver targets (Alvord, 1993; Zeisler et al., 2000; Nye et al., 2006; Ferguson et al., 2011). The CF-1000 target was developed to meet the growing need for high power cyclotron targets on RDS systems (Stokely et al., 2010), and it has been implemented in both niobium and tantalum. The authors have observed no significant difference in performance, difficulty of fabrication, or cost. Although tantalum stock is significantly more expensive, the raw stock is a small percentage of total fabrication cost. The target window is 0.038 mm (0.0015 inch) thick Havar, and does not require a grid support or helium cooling. Sputtered tantalum coatings on Havar have shown excellent results in other work (Gagnon et al., 2010; Gagnon et al., 2011) but have not yet been evaluated in this specific target package.

The maximum beam current of the target is limited by its heat rejection capability. As a result, the design must mitigate the additional resistance to heat transfer resulting from use of relatively low thermal conductivity refractory metals. This design optimization process, as well as the characterization of the heat transfer coefficients at the target medium to chamber wall interface, has been presented in previous work (Peeples, 2008; Stokely, 2008; Peeples et al., 2011). Other design features, including considerations specific to operation on an RDS-111/Eclipse, have been presented in previous work (Stokely et al., 2010).

Conjugate heat transfer modeling of the target was performed using Solid Works Flow Simulation. An exploded view of the target assembly is shown in Figure 6. For a cooling water flow rate of 11.4 LPM (3 GPM), as measured at several sites, with incident temperature of 15.5°C (60°F), the expected thermal capacity of the target was estimated to be 1.3 kW.

Two RDS-112 cyclotrons have been retrofitted with this high current target and collimator system. Typical saturation yields of 120 mCi/ μA (4.4 GBq/ μA) have been observed at beam currents up to 100 μA . These RDS-112 targets are part of the CF (Conventional Fluoride) family of targets, that includes RDS-111, RDS-112, THC-14, MINItace, and others, currently used at 16 cyclotron sites worldwide and operated with currents as high as 120 μA .

5. Conclusions

With the demand for higher power targets for RDS-112 cyclotrons comes an additional need for higher power support components, including collimators. Conjugate heat transfer models were developed to facilitate the design process and were experimentally benchmarked. Collimators developed from these efforts have been installed and successfully operated at

two RDS-112 sites. This work demonstrates the value of modeling in the design process, and the installed products demonstrate that extended service of RDS-112 cyclotrons is a viable option with a high current target upgrade.

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Highlights

- An experiment is performed to benchmark conjugate heat transfer models.
- Modeling results for three RDS-112 collimator designs are compared.
- New RDS-112 collimators are deployed and tested at two sites.

Figure 1.
Solid Works views of (a) the test assembly from the target-side and (b) the one-quarter section used for pin melting

Figure 2.
Photographs of pins showing (a) zero melted pins before irradiation, (b) four melted pins following 6.5 μA irradiation and (c) seven melted pins following 10 μA irradiation

Figure 3. Average temperature on the top surface of each pin was predicted using Solid Works Flow Simulation for each of the four experimental conditions. Melting temperature of the Al 6061-T6 pins is indicated by the dashed line.

Figure 4.
Illustration of a single quadrant of the original OEM 4-Jaw Collimator

Figure 5. Solid Works assembly and assembly with single quadrant removed of (a) old collimator, (b) intermediate collimator and (c) new collimator. (d) Illustration of beam on collimator

Figure 6.
Exploded view of RDS-112 target assembly

Table 1

Experimental results

Experimental Condition	Current on One-Quarter Section (μA)	Current on Three-Quarter Section (μA)	Current on Target (μA)	Melted Pins
1	4	6	1.5	None
2	6	12	3.0	None
3	6.5	12	2.5	1–4
4	10	16	0.75	1–7

Table 2

Maximum current on a single quadrant at limiting temperature

Part	Limiting Temperature (°K)	Maximum Current on Original Collimator (μA)	Maximum Current on Intermediate Collimator (μA)	Maximum Current on New Collimator (μA)
Copper Heat Sink	1356	16	-	-
SS-316 Top Screws	1673	27	-	-
Tantalum Sheet	3273	34	-	-
Al 6061-T6 Ring	855	-	-	47
Macor Insulators	1273	-	-	48
SS-316 Washers	1673	47	55	101
SS-316 Base Screws	1673	61	72	128
BeO Washers	2780	67	74	-
Graphite Sheet	3922	72	-	-
Graphite Heat Sink	3922	-	83	126
Limiting Current		16	55	47