RELIABLE FLUORINE-18 [$^{18}F^-$] PRODUCTION AT HIGH BEAM POWER

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Abstract

Demand for ^{18}F for the synthesis of the glucose analog Fluorodeoxyglucose ^{18}F[FDG] and other radiopharmaceuticals for Positron Emission Tomography (PET) has been increasing very rapidly over the past few years. Small volume (< 5 ml) liquid targets are routinely used for production of ^{18}F and other radiotracers. Among other considerations, power dissipation is a key concept in the design of these targets to be able to accommodate over two kilowatts of beam power. In addition, plumbing, instrumentation and control of target operations have to be properly selected to perform well under harsh temperature, pressure and radiation conditions.

An automated liquid transfer system for this type of targets was developed and has been in daily operations for more than three years at our facility. System reliability resulted in improved production, minimum maintenance and reduced radiation exposure to the personnel. A description of this system, its components, materials, instrumentation and software will be presented in this paper. Furthermore, reliability issues of previously existing components due to radiation damage will be discussed.

INTRODUCTION

Cyclotrons capable of delivering beam power in the 2 kW range are becoming available for commercial production of PET radiopharmaceuticals. New targets capable to accommodate this and higher beam power are also being developed. Their capacity to sustain high beam power is strongly dependent on heat exchange with the environment as a consequence of target materials and water cooling design. In the past, the high cost of target material (^{18}O-enriched water) prompted cyclotron manufacturers to keep target volume around 1 ml or lower. At high beam power, target heat load increases evaporation and voids formation while reducing ^{18}O-enriched water density. These limitations are forcing designers to increase target volume. Fortunately, this need has been followed by a substantial reduction in the cost of ^{18}O-enriched water.

Our self-shielded ACSI TR-19/9 cyclotron is capable to deliver up to 350 µA external proton beam (6.7 kW). Two variable energy extractor arms permit single or dual beam extraction in the 13.5 to 19 MeV range in proton mode. On port #1, a combination dipole magnet serves to select between two beam transport lines. The top beam line is horizontal and has a four target selector at its end, while the bottom one has a solid target station. Extraction port #2 has a short beam line where the beam exits at a 25º angle with the horizontal. A second four target selector is installed at its end.

High production capacity to accommodate the ever increasing number of patient scans requires a powerful, reliable and robust system. Our goal is to meet these requirements, taking maximum advantage of the cyclotron power to operate up to two simultaneous targets at 2.5 kW each. The system design has to include minimal maintenance, production downtime and personnel exposure. In order to achieve this goal, we designed an ^{18}F targetry system to replace the one provided by the cyclotron manufacturer.

TARGETS DESIGN

ACSI, formerly EBCO Technologies, introduced the first commercial ^{18}F targets where beam incidence angle on the water chamber is not perpendicular. The beam spreads over a larger area than in the perpendicular case reducing power density and required water depth. Disadvantages of this type of design over traditional perpendicular target chambers are higher power deposited on the water foil and increased window area, requiring thicker foils. The higher energy loss on these thicker foils makes this design unsuitable for low energy cyclotrons (<15 MeV). Since 2004, we've been operating two ACSI targets, one for each extraction port, which are based on this design concept [1]. To differentiate them, we labeled SA1 the one designed for the horizontal beam target selector and SA2 the one designed to run on the 25º beam line. Table 1 shows specifications for these targets.

Table 1. Targets specifications

	ACSI			Cyclotope
Target Model	SA1		SA2	CY2
	Original	Modified	Original	
Material	Nb	Nb	Nb	Nb
Beam Angle	Horiz.	Horiz.	25º	25º
Load vol.	2.0 ml	3.5 ml	2.7 ml	1.5–4.0ml
Energy*	18 MeV			
Max. I	60 µA	100 µA	60 µA	135 µA
Max. Power†	1.0 kW	1.7 kW	1.0 kW	2.3 kW
Base pressure	~330 psi			
Pressure incr. rate	0.2 psi/µA	0.2 psi/µA	0.2 psi/µA	0.5 psi/µA
Avg. ^{18}F - SY‡	7.77 GBq /µA	8.73 GBq/µA	7.92 GBq /µA	9.62 GBq /µA

* Nominal energy (energy on target water is ~17MeV).
† Calculated power on target water.
‡ Yields measured without any further target rinse, 97%+ ^{18}O-enriched water.

A modified SA1 target with a 30% deeper chamber has shown a significant capacity increase to tolerate higher beam currents. Average saturated yields measured for the modified SA1 at 100 µA, 18 MeV, 97%+ ^{18}O-enriched water, were 8.73 GBq/µA (84%, corrected for enrichment, of IAEA published experimental saturated yield of 10.74 GBq/µA [2]). As we can see from Table 1, 30% increase on SA1 water chamber depth produced a 70% higher beam capability. As the 25º extraction port is not optimal for traditional liquid targets designs, a similar modification to SA2 may not yield comparable results, unless the volume is increased in a higher proportion.

We focused our attention on a new target design for port # 2, taking advantage of the 25º beam angle. For this design, the beam has a grazing incident angle, as in the ACSI targets, but in this case this angle is in the same rotation axis as the 25º beam line. In this way, both angles are added, resulting in an almost horizontal water foil, instead of vertical as in traditional targets. The beam enters the target from the bottom and traverses the water diagonally. This geometry allows for variable water load volume depending on the amount of current planned for the production. This is an advantage over traditional target designs, where the maximum beam path length through the water is fixed and limited by the water chamber depth. Conduction cooling is not available on the upper surface of the target water. Cooling is performed primarily by target water evaporation and condensation cycle on the top portion of the water chamber. Two different Cyclotope target models, CY1 and CY2, based on this design concept, are shown in Figure 2. Average saturated yields measured at 100 µA, 97%+ ^{18}O-enriched water, 18 MeV, were 9.95 GBq/µA. At higher beam currents saturated yields decreased to 9.25 GBq/µA at 120 µA and 8.14 GBq/µA at 135 µA respectively, possibly due to limitations in cooling capacity.

Figure 1. Cyclotope targets. Top, disassembled prototype. Bottom, final target in irradiation position.

TARGETS INSTRUMENTATION

In 2004, we replaced the original ^{18}F target system control and instrumentation with a new one, designed to operate up to four targets, two on each target selector. On the new system, the only component left from the original one was the syringe pump used for ^{18}O-enriched water target loading. Target loading and transfer are performed through the target bottom port by a low pressure port selection solenoid valve and a 4-ports pneumatic load / inject valve. The later one is shared between two ^{18}F targets in such a way that, when one target is in load / run position, the other target is in transfer position. A PEEK check valve installed between the solenoid and the load/injection valves serves to hold the target pressure during the irradiation and to reduce the target load dead volume. The top port of each target is connected through a long stainless steel line to a pressure transducer and to a high pressure pneumatic valve (1500 psi max.) used for pressurization and venting. These components are located outside the cyclotron shielding were radiation damage and component size are not an issue. This design is duplicated for each cyclotron target selector. The liquid transfer to the hot cell is performed at 100 psi through two multi-position stream selector valves for ^{18}F distribution.

The targets are pressurized with helium at ~330 psi before the run, to increase the water boiling point and reduce pressure bursts. On a typical 18 MeV beam run, the average pressure increment due to the beam power is between 0.2 and 0.5 psi/µA depending on the target model. Figure 2 shows the effect of two different target materials and various load volumes on the pressure increment due to beam power on target CY2.

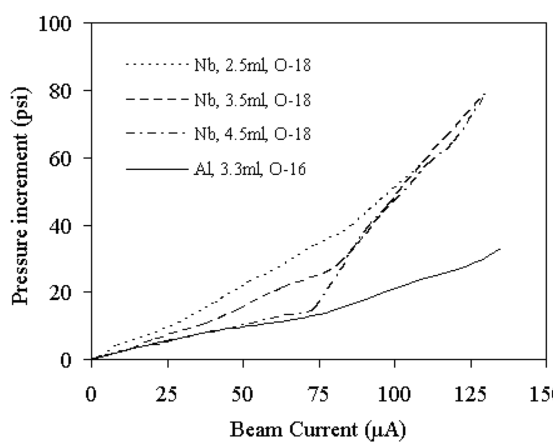

Figure 2. CY2 target pressure increment vs. beam current for various load volumes and different body materials.

Tubings and fittings

Stainless steel tubing is used for the ^{18}O-enriched water loading circuit and the target top venting and pressurization port. PEEK tubing is used for the target end to provide flexibility and electrical insulation. Fluoropolymer fittings and tubing, initially installed, had to be replaced because their lifetime was too short under the combination of high radiation fields and high pressure. Even PEEK fittings have shown signs of shrinkage under this harsh environment after more than three years of operation. We are currently testing Polyketone, PK, fittings which are suited for temperatures up to 200 ºC.

Valves

The original hardware supplied by the cyclotron manufacturer was replaced, mainly due to reliability issues induced by valves materials susceptible to radiation damage. The new hardware, a 4-ports pneumatic load/injection valve, a check valve and a high pressure pneumatic valve already described performs very reliably.

Pressure transducers

The original miniature pressure transducers were sensitive to radiation. Furthermore, the mV range signal was very noisy and the transducers had to be constantly readjusted to compensate for offset drift. This kind of transducer was expensive and, on average, had to be replaced yearly. With the new configuration, the pressure transducers are mounted outside the high radiation fields where its size is not a limitation. The new pressure transducers are thin film stainless steel type with 0.4% BFSL accuracy. They do not require frequent offset corrections. Furthermore, we never had to replace a pressure transducer since their installation more than three years ago.

Helium and water cooling plumbing

The original target Helium and water cooling fittings were instant Polybutene type. Due to frequent leaks and material cracks, they had to be replaced by metal ones or by compression style fittings. Polyurethane tubing is used for water and helium cooling lines. The only sign of aging is a change of coloration. They are replaced yearly as part of our preventive maintenance program.

Manual three way valves were installed near the targets for the water cooling supply and return circuits to reduce line purging time during target servicing.

Target materials and maintenance

Niobium and titanium have shown good compatibility as target body materials for ^{18}F production. Occasionally the beam was not fully stopped by the ^{18}O-enriched water hitting the target body back wall. Niobium activation was negligible compared to Titanium activation in that case.

Target foils are Aluminum alloy for the vacuum foil and HAVAR for the water foil. All O-rings are Viton. Target preventive maintenance consists of quarterly foils and O-Rings replacement. Foil lifetime is only limited by a blackening on the water side causing a small yield reduction during its lifetime. With the purpose to further reduce the maintenance frequency, a study of foil materials with improved compatibility is underway.

CONTROL SYSTEM

The targets control application was created with National Instruments Lookout^{TM} 5.0. Distributed I/O modules with serial RS-485 interface were used for data acquisition and control. The target control system graphical interface is shown on Figure 3. The top panel serves to pressurize or vent the targets. A total of four target panels contain target parameters and pressure trends. The syringe pump shown on the bottom-left corner is used for target loading and is controlled via RS-232. Two stream-selector valves are used for transfer destination selection of the ^{18}F- (bottom-right). Additional pop-up windows help for hardware troubleshooting, pump configuration and target settings.

Each component can be controlled either on manual or automatic mode. Critical components are interlocked. Target and program are selected from an automatic control panel (top-right). Programming is performed by clicking on the elements that have to be operated for each step. Step termination is determined by time duration or other read back conditions. The load and transfer programs are stored in a worksheet. Target loading is performed on a closed volume and pressure increment is monitored to prevent runs on partially loaded targets in the event of a leak.

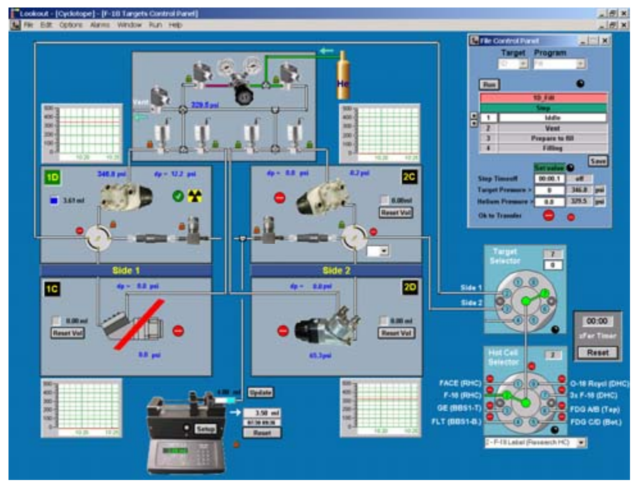

Figure 3. Control system schematic

CONCLUSIONS

A deeper target chamber for one of the ACSI targets showed improved yields at higher power. A new in-house target design is routinely being used for ^{18}F production at 18 MeV with average target yields of 9.62 GBq/µA (beam power $\leq$ 2 kW, 97%+ ^{18}O-enriched water), ~92%, corrected for enrichment, of IAEA published yields [2]. Further improvements have to be made to reach our 2.5 kW beam power goal for routine production. New target foil materials tests are underway to reduce buildup, extend maintenance frequency and reduce personnel exposure to radiation. The new targets instrumentation, plumbing and control system performed reliably and almost maintenance free since its installation, three years ago.

REFERENCES

[1] A. Zyuzin et al, “O-18 Water Target for High Current TR-PET Cyclotrons”, WTTC10, Madison, WI, 2006.

[2] IAEA-TECDOC-1211, IAEA, Vienna, (2001), http://www-nds.iaea.org/medical.