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TECHNICAL NOTE

Production of [^{18}F] fluoride with a high-current two layer spherical gold target

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Abstract A new automated target for high yield production of aqueous [^{18}F] fluoride at high beam currents has been constructed for a cyclotron at NRCAM in Karaj (Cyclone 30). It consists of one small golden sphere inside another target chamber, mounted into a special holder, which provides rapid cooling by water flow around and inside the sphere. The target is irradiated with 28 MeV protons. The incident energy on the target chamber is 18 MeV. This target is operated without external over-pressure and has been tested for beam currents up to 60 μA. The measured target yield is 80% of the theoretically calculated yield of ^{18}F, which is used for the synthesis of [^{18}F] 2-fluoro-2-deoxy-D-glucose.

Key words water target • [^{18}F] fluorine • FDG • PET • high current

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Introduction

The proton irradiation of oxygen-18 is one of the most effective nuclear reaction for producing fluorine-18. Increasing demand for the glucose analogue 2 [^{18}F]-2-deoxy-D-glucose (FDG) for positron emission tomography (PET) continues to challenge investigators to develop more efficient high and low pressure target systems for production of tens Giga Bq quantities of [^{18}F] fluoride ion [2–6, 8–22]. Many factors should be considered for a reliable target design. They include thickness of the window and cooling fluid layer for optimum beam degradation, efficient cooling fluid for a target chamber and window, and a selection of suitable geometry and material for the target body. Most considerations have to be given to the heat transfer and chemical properties of the target body material.

The possible materials for the mentioned target chamber are silver, titanium, niobium and gold. Silver shows the highest thermal conductivity of the elements, however, under the beam conditions it often forms colloids, which contaminates solutions and causes trapping of fluoride ions [22] and causes decreasing the target yield. Table 1 shows a comparison of important physical properties of gold, titanium and niobium. Gold, being the second best in respect to thermal conductivity, under beam conditions stays inert, so that it can be used in corrosive environment and conditions.

The sphere is a construction of choice to bear elevated pressure and to obtain maximum pressure stability for a given wall thickness [1]. The pressure stability P_{max} (bar) of an ideal spherical shell can be estimated using equation [1, 22]:

$$P_{max} = 4h \cdot \sigma / d \qquad (1)$$

where h is the wall thickness (mm), d is the diameter (mm) of the sphere chamber, and σ is the tensile strength (bar).

Table 1. Selected physical properties of gold, titanium, and niobium.

Metal		Au	Ti	Nb
Atomic number		79	22	41
Density	($g\,cm^{-3}$)	19.3	4.5	8.6
Melting point	(K)	1337	1944	2468
Thermal conductivity	($W\,m^{-1}\,K^{-1}$)	317	21.9	53.7
Tensile strength	(MPa)	110	230	330

According to our calculations with SRIM code [23], proton energy of about 28 MeV is required to permit reasonable production of [^{18}F] fluorine due to approximately 10 MeV degradation of the cyclotron beam in the following layers: an aluminum window (on the vacuum side), a gold window (on the target side), a cooling fluid, and the target body (Table 2).

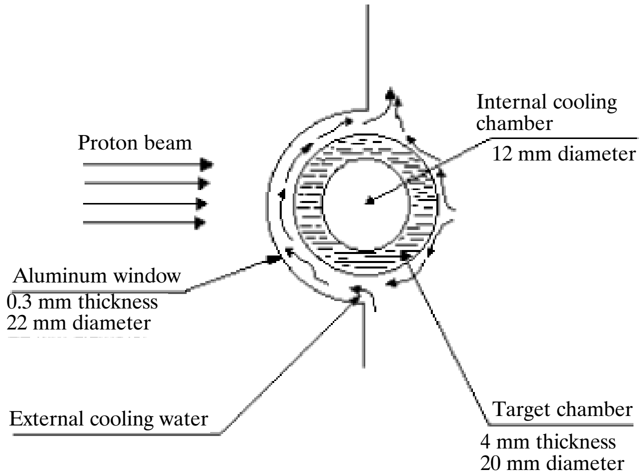

Fig. 1. Simplified schematic drawing of the target system.

Materials and methods

Target design

The target was constructed with two gold chambers, one inside another. For manufacturing of two different diameters of gold hemispheres, a special two-piece stamping die (male–female) was supplied.

The hemispheres were deep drawn (deep drawn is an expression used to define the way our hemisphere is formed and shaped by forcing a circular foil into a semi-hemisphere die) from circular gold foil (0.220 mm thickness, 28.3 mm and 17 mm in diameter for the outer and inner hemisphere, respectively). The circular pieces of foil were cut from available sheets (gold alloy > 95% gold, < 5% silver) using a manual press.

A hole was drilled into the center of each hemisphere and a small-bore silver tube of 80 mm length was inserted (1.5 mm o.d., 0.8 mm i.d. and 4 mm o.d., 3 mm i.d. for outer and in inner spheres, respectively).

The tubes were welded into the hemispheres and then the two pairs of hemispheres were welded together. Thus, the target body consists of two chambers, the internal chamber (a sphere with 12 mm in diameter) and the external chamber (a sphere with 20 mm in diameter). In fact, the internal chamber is an internal cooling system. In the target-cooling chamber the water flow rate is 1.2 l/min at 2°C. The gap between the two spheres is 4 mm, which is sufficient to stop the 18 MeV proton beam inside the enriched water layer (Table 2). The volume of the target chamber is approximately 2.8 ml. The external cooling water provides a rapid cooling by water flow of rate about 3 l/min at 2°C around the target chamber. The aluminum window (placed on the vacuum side, 0.3 mm thick and about 22 mm in diameter) is designed in the form of a hemisphere so that a half of the spherical chamber is placed inside the window, and has a 1.3-mm gap for passing the cooling water between the window and the target chamber. Figure 1 shows a simplified schematic drawing of the target system.

Figures 2 and 3 show pictures of the bare target and of the target chamber with a brass support and Swagelok™ fittings attached (respectively). A schematic drawing of the developed target system is shown in Fig. 4.

Target operation

The two-layer gold sphere target is clamped on to the window holder by a brass support piece, onto which the target water-cooling assembly (internal and external cooling) is connected. Before loading the target with enriched water, helium is purged through the target body and the delivery line for about 10 min. This is done by rotating a Rheodyne™ valve to dispense position and opening the helium supply valve. Then the target chamber is rinsed with 20 ml of absolute ethanol and after that with 20 ml of distilled water.

The measurement of the target pressure is one of the key factors for the assessment of the correct target filling and irradiation conditions. A Kulite [7] pressure transducer of XTM-190 was used to measure the target pressure. The target is filled with 2.8 ml of ^{18}O-water (95%-^{18}O) by means of an automated double three-way rheodyne valve, which

Table 2. Calculated estimate of energy loss in different parts of target assembly.

Energy (MeV)	Al window thickness	Cooling water thickness	Wall thickness of the target chamber	Target thickness
	0.3 mm	1.5 mm	0.25 mm	4 mm
E_{in}	27.8	26.5	23.0	18.0
E_{out}	26.5	23.0	18.0	1.0
Energy loss (ΔE)	1.5	3.5	5.0	17.0

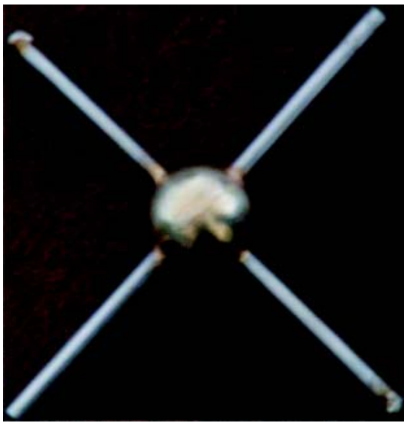

Fig. 2. Picture of the bare two layer target.

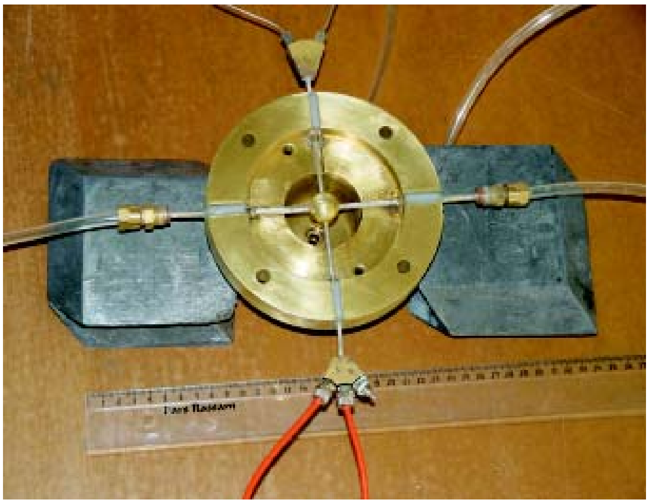

Fig. 3. Picture of the spherical gold target with a brass holder and tubes for cooling and loading the target.

is powered by the compressed air at about 6 bars (Fig. 5). The target chamber and rheodyne valve are connected by PEEK tubes (200 mm in length, 1.6 mm o.d., 0.8 mm i.d.).

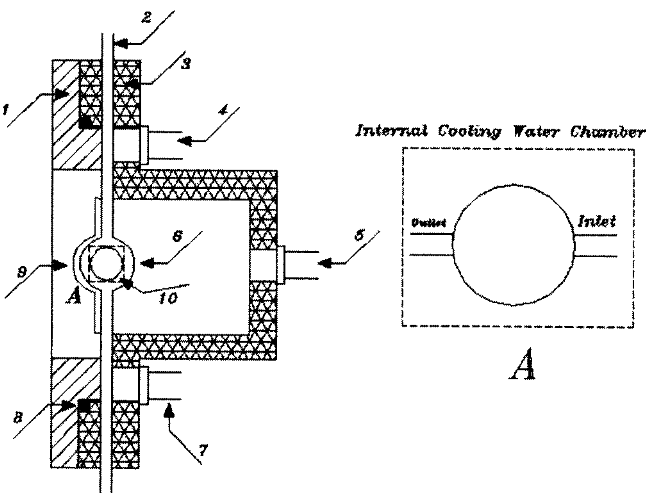

Fig. 4. Schematic technical drawing of the target system. *1* – window holder (aluminum), *2* – silver rod, *3* – target holder (brass), *4* – cooling water outlet, *5* – cooling water inlet, *6* – target chamber (gold), *7* – cooling water inlet, *8* – O-rings (Viton), *9* – vacuum window (aluminum, 0.3 mm), *10* – internal cooling chamber (gold).

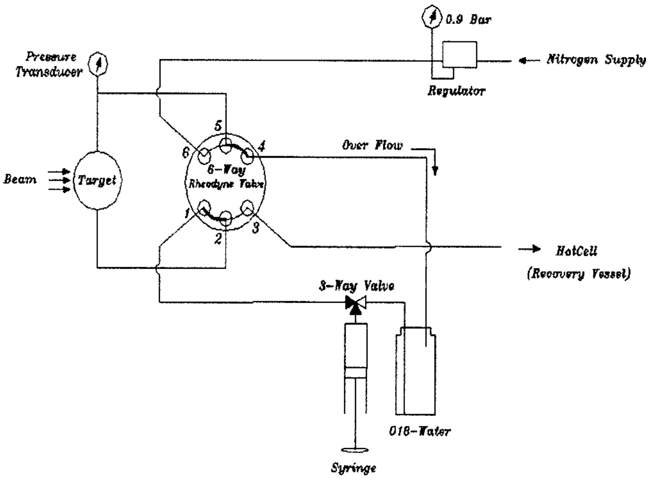

Fig. 5. Schematic representation of the unit for remotely filling the ^{18}O-enriched water target at the NRCAM cyclotron unit.

Test irradiations were performed on the Cyclone 30 of the Nuclear Research Center for Agriculture and Medicine of Iran with 28 MeV protons and 60 μA of beam current.

The target was cooled at a total water flow rate of 4.2 l/min. After bombardment, the rheodyne valve was actuated and opened. Then, the target water was transferred through a 20-m teflon tube (PTFE, 1.6 mm o.d., 0.8 mm i.d.) to a hot cell by nitrogen pressure (0.8 bar).

Results and discussion

According to Eq. (1), in regard to the tensile strength of the soft gold (2200 bars) and the chamber dimensions specified above, the target can withstand an internal pressure of approximately 100 bars.

Although we know that the equation does not take into account any welded tubes or situations of the material at elevated temperatures, the predicted stability of the target chamber exceeds the regular operating pressure by more than one order of magnitude.

The pressure behavior of the target during the irradiation is shown in Fig. 6. At 60 μA, the observed pressure

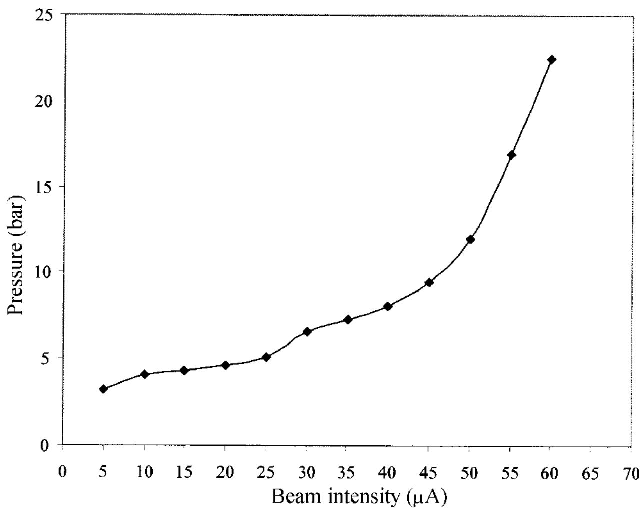

Fig. 6. Pressure in the target chamber *vs*. beam current (18 MeV protons).

Table 3. The result of pressure behavior in the target chamber *vs*. beam current variation.

Current (μA)	P1 (bar)	P2 (bar)	P3 (bar)	P4 (bar)	P5 (bar)	Standard deviation
5	3.2	1.5	4.3	2.2	3.5	0.99
10	4.1	2.1	5.0	3.5	4.3	0.98
15	4.3	3.0	5.3	4.3	4.7	0.75
20	4.6	5.0	6.1	4.8	5.5	0.54
25	5.1	5.6	6.6	5.3	6.0	0.53
30	6.6	6.5	7.4	6.4	7.7	0.53
35	7.3	7.4	8.8	8.2	8.9	0.67
40	8.1	8.9	9.2	9.4	9.7	0.55
45	9.5	9.7	10.1	10.5	10.9	0.51
50	12.0	11.0	11.5	13.0	12.3	0.68
55	16.9	15.4	16.5	17.0	16.5	0.57
60	22.5	21.6	20.0	22.0	22.4	0.91

was 22.5 bars. The experience with new target performed for five times in series (Table 3). Figure 7 shows cumulative energy deposition calculated using SRIM [23] as a function of depth for the 18 MeV proton incident on the ^{18}O-water. As shown in Fig. 7, almost 50% of the beam energy is deposited in the last 1 mm of the target using SRIM [23] calculations which is in accordance with the literature [12]. Since, the maximum heat is produced near the center of the spherical chamber, this is why we decided to design and construct an internal cooling system. High-pressure ^{18}O-water targets present an attractive alternative for the fast and reliable production of [^{18}F] fluoride in large amounts.

The proton incident energy of 28 MeV is degraded to 18 MeV in the target external layers, resulting in the production rate of 2770 MBq/μ_A·h (74.9 mCi/μ_A·h). The samples were irradiated for five times in series. It was found that the saturation yield is 8800 MBq/μ_A which shows 80% of the theoretical yield. Gamma spectroscopy of a water sample, after E.O.B, showed that the quantities of ^{197m}Hg detected were extremely low compared to the production of ^{18}F (Fig. 8).

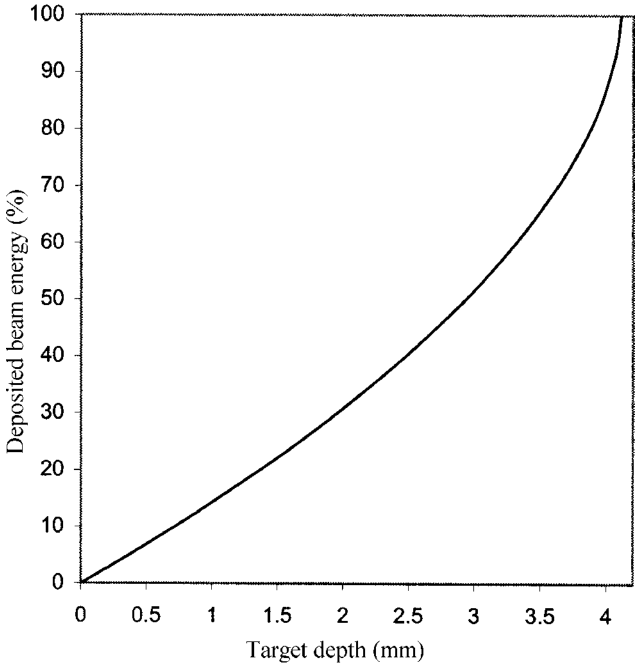

Fig. 7. Calculated estimate of energy deposited by the beam as percentage of total for 18 MeV proton incident on the ^{18}O-water target.

Conclusions

We have observed that the target designed by us (Figs. 2 and 3) can easily withstand 60 μA proton beams. Although, the maximum current incident on our target was 60 μA, we expect that it can surely withstand a current of up to 80 μA. This, as compared with the previously designed targets that could withstand about 50 μA proton beam, is considered as a break through.

With employing our design instead of the routinely used target (the target, designed and manufactured by I.B.A. Company–Belgium is available in 1.7 ml real volume) we succeeded to increase our productions up to 5 times as

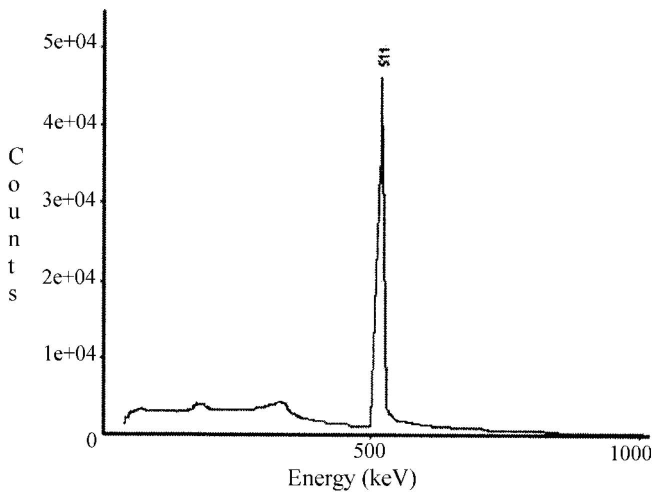

Fig. 8. Gamma spectroscopy of a water target after E.O.B.

much, which in turn reduced our irradiation time up to 5 times. In fact this means the reduction of production costs. Our design is not feasible for baby cyclotrons or other low energy accelerators.

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