

Design of a high power solid target for ^{211}At

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Abstract. The new SPIRAL2 LINAC at GANIL delivers light beams (p, d, alpha,...) with very large intensities. In order to exploit these beams in an optimal way, high power target stations are requested. In this contribution, we present such an irradiation station designed to optimize the production of ^{211}At , an alpha emitter of interest for targeted alpha therapy. In order to dissipate at least 10 kW of beam power, a rotating, water-cooled system comprising twelve individual targets has been developed together with a fast and safe extraction mechanism.

1 Introduction

While the use of radionuclides for diagnostic purposes (Single Photon Emission Computed Tomography, SPECT, and Positron Emission Tomography, PET) is a mature field in nuclear medicine, the therapeutic use of alpha emitting radionuclides is still less evolved. Targeted Alpha Therapy aims at using locally highly cytotoxic properties of alpha particles by carrying the alpha decaying radionuclides to specific sites of cancerous cells. This would allow maximize the efficiency of the treatment while reducing damages done to healthy tissues.

^{211}At is considered as a promising candidate for such application thanks to its adequate half-life of 7.2 h and its alpha decay mode [1]. Currently, an efficient way to produce this radioisotope is the reaction $^{209}\text{Bi} (^4\text{He}, 2n) ^{211}\text{At}$. As the needs for ^{211}At for research or future medical applications are bound to strongly increase [2], up-to-date accelerators, including linear accelerators, able to deliver alpha beam at high intensities with precise energy and high quality bismuth (Bi) targets are mandatory.

To address this challenge, the REPARE (Research and developments for the Production of innovAtive RadioElements) project aims at improving ^{211}At availability by, amongst other ways, developing technologies to improve production capacities through dedicated facilities [3, 4]. One specific task of this project is the development of specific targetry able to sustain high intensity beams either considering liquid (cf T. Bigourdan et al in this proceeding) or solid target, developed in this paper.

2 ^{211}At production

The radioisotope of interest, ^{211}At , is produced by fusion-evaporation reaction using bismuth targets irradiated with an alpha beam at an energy higher than 20.7 MeV. The excitation function to produce ^{211}At has a maximum at about 30 MeV. However, this energy is above the threshold energy of reactions leading to cross-contaminants such as ^{210}Po , decay products of the three-neutron channel (^{210}At), which is problematic. Indeed, ^{210}At decays with a half-life of 8.1 h to ^{210}Po , which is highly cytotoxic because of its huge specific activity ($1.66 \cdot 10^{14}$ Bq/g) and long half-life (138.4 days). An efficient way to minimize the production of ^{210}At is to keep the alpha beam energy below the threshold of the $^{209}\text{Bi} (\alpha, 3n) ^{210}\text{Po}$ reaction, i.e. 28.6 MeV. Therefore, the effective beam energy window to produce ^{211}At ranges from 28.6 down to 20.7 MeV [5]. With an ^4He beam in the mA range delivered by GANIL-LINAC, an end-of-beam activity of the order of 10 GBq/hour is reached and the targets should thus sustain a beam power of at least 10 kW. This is the main design specification of the REPARE irradiation station, which is described in the following sections.

3 Overview

3.1 Main design specifications

The challenge for the design of the solid target station is therefore to dissipate in a very efficient way the incident beam power in order to maintain the Bi in its solid state all along the irradiation time. The Bi material is chosen as metallic, with a melting point of 271°C, instead of oxide or sulphur form to prevent any by-products and to make easier the extraction of astatine by dry process.

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These targets are made of a 70 μm evaporated Bi layer of 40*106 mm² area on a 3 mm thick substrate of aluminum nitride (AlN, area 50*120 mm²) for this study where the beam stops at 200 μm depth. The beam has a double-gaussian shape of 106 mm height and 2 mm wide. To reach the 10 kW dissipation goal, with 3 kW loss in Bi and 7 kW stopped in the substrate; the targets are mounted on a rotating water-cooled wheel hosting 12 targets. They are arranged in pairs on a structure, called a “racket”, in order to minimize radiological exposure in compliance with an ALARA approach during their extraction from the wheel. The dimensions of the target, have been designed in such a way that they cover the large beam spot and can be easily handled for the subsequently chemical process to extract ²¹¹At (Figure 1).

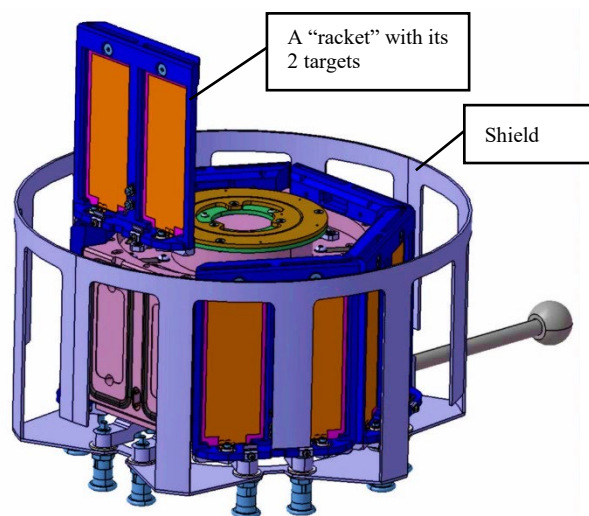


Fig. 1. Target wheel with one “racket” partially extracted

3.2 Target Station assembly

The REPARE irradiation station is composed of six main components listed in Figure 2. Its total weight and volume are 650 kg and 3x0.6x2.5 m³, respectively.

The assembly is positioned on a welded steel frame fixed on ground designed to withstand an earthquake, a compulsory requirement for each heavy component of the GANIL-SPIRAL2 facility.

The translation set composed of pneumatic actuators, supports the vacuum chamber, which can be placed either in alignment with the beam axis or out of it to enable irradiation of other targets placed upstream.

The motorisation set composed of a brushless motor, its encoder and dedicated mechanical reducer is connected to the perpendicular coaxial shaft of 50 mm diameter. To sustain the harsh radiation environments no electronic components are used.

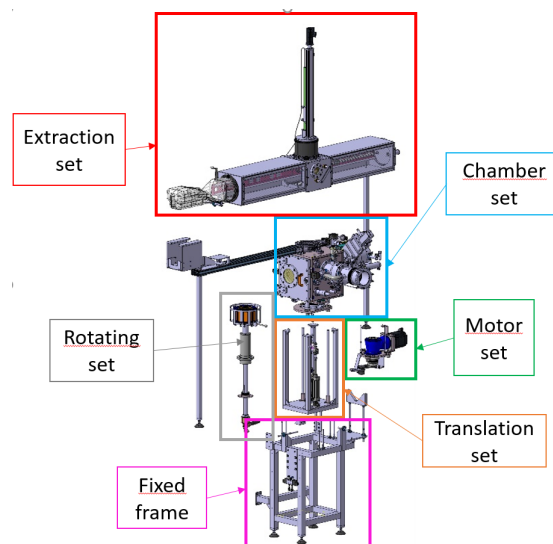


Fig. 2. REPARE irradiation station assembly showing the six main components

The rotating set includes a shield (s. 3.3.2), the wheel with its rackets, the above mentioned coaxial shaft, the rotating (ferrofluidic) vacuum-tight feedthrough and water cooling system (s. 3.3.1). This coaxial shaft drives the wheel and is made of a double tube for water inlet and outlet (Figure 3).

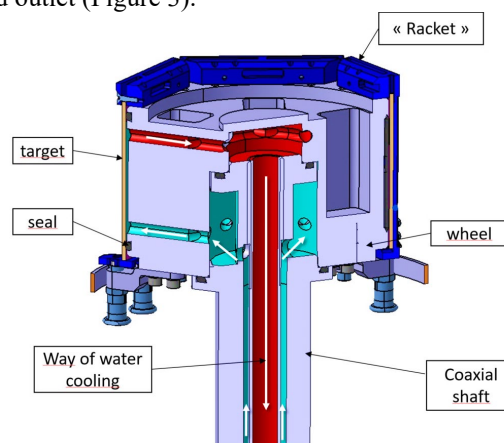


Fig. 3. Water cooling system: the cold water is cooling directly the rear surface of the target and is then extracted via the central part of the rotating axis.

The vacuum chamber is made of stainless steel with walls of 20 mm thick and opening of 30 mm thick to protect workers from radiations (below 45 μSv integrated dose) and is equipped with viewports and pumping systems to reach 10^{-6} mbar.

The extraction set connected above the chamber is acting as a glove box. The targets extraction system must be reliable as well as ensuring a protection of the personnel in charge of the station operation against radiological exposure. At the end of beam time, the rackets (i.e. two targets) are extracted from the wheel using a clamp, which grasps the racket out of the wheel and store them into an individual lead container. Six such lead containers are installed in a long box ensuring double confinement of the generated activity (Figure 4). The lead containers are extracted from the station in a vinyl bag and stored in a dedicated parcel for shipment.

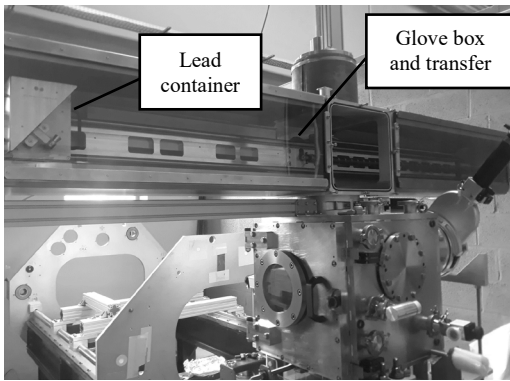


Fig. 4. Rackets extraction system

3.3 Modeling and functional parameters setting

To distribute the deposited beam power over large surfaces, the parameters of the cooling water (flux, and pressure) have to be quantified properly to prevent any risk of material melting and leakage. Moreover, precise measurements of beam intensity had to be developed in order to optimize the beam size and to synchronize it with the wheel rotation. These aspects are discussed below.

3.3.1 Fluidic simulations

For high power thick targets, the most efficient cooling method is thermal convection. Indeed the energy deposited by the beam inside the target and the substrate is transferred to the fluid flowing along the rear face of the later (AlN). However, the substrate has to sustain the water pressure while maintaining the sealing to prevent any leakage. In addition, the water flow has to be uniform over the rear face and all targets in order to guarantee a uniform surface cooling without any air bubbles. CFD (Computational Fluid Dynamics) simulations, taking into account rotation and cooling circuit conditions have been performed to evaluate the range of acceptable water pressure, its flux and rotation velocity. The cooling system (Figure 3) is modelled with ANSYS Workbench and FLUENT [6].

With a loading of 10 kW beam and a water pressure of 2 bars, the temperature of the target was calculated as a function of time. As is illustrated in Figure 5 for a rotation of the wheel at 100 rpm, the temperature is increasing in few seconds and stabilized to about 41°C. The temperature gradient is less than one degree at each beam impact. A simulation with a 400 rpm velocity indicates a final temperature of 31°C. This result is very conservative and makes possible to decrease the rotation velocity or the flow rate.

In addition, the velocity distribution of water along distributed inlets and rear face of the substrate was simulated at 200 rpm and 2 bars conditions. As shown in Figure 6, the water velocity is higher than 1m/s everywhere, sufficient to fulfill the design specification.

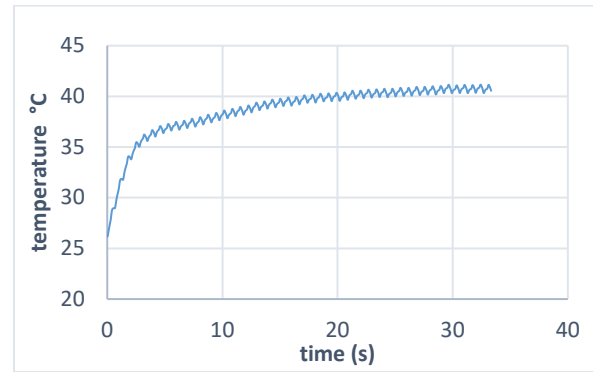


Fig. 5. Temperature evolution at 10 kW, 100 rpm, 2 bars

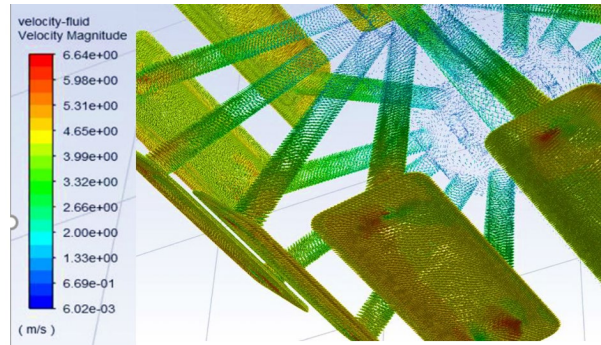


Fig. 6. Water velocity simulations at 10 kW, 200 rpm, 2 bars

3.3.2 Current measurements and beam setting

As mentioned earlier, it is crucial to minimize beam power deposition outside the effective target material (Bi), to measure precisely the beam current on target and to synchronize the time structure of the beam with the rotation of the wheel. Therefore, we designed a shield around the targets' wheel and developed an electronic system for current measurements.

Considering the aperture of the 12 targets of 20° each, a shielding structure was designed to protect the remaining 10° between two rackets from irradiation with stainless steel rolled sheets as depicted in Figure 7.

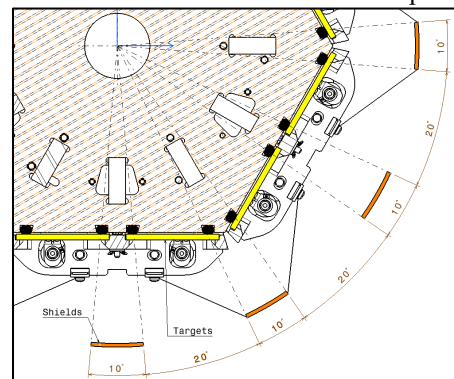


Fig. 7. Cross section of the rotating set across the targets (yellow) and the shield (orange)

This shield is electrically insulated from the wheel to enable current measurement of the eventually deposited beam, which is expected to range from 100 nA to 10 μ A. With this current measurement and a setting of a periodical signal (20% on /10% off) in accordance with the velocity of the wheel, a delay on this signal can be

adjusted and set to synchronize the beam with the targets.

To control the input intensity of the beam on the targets expected to range from 5 to 500 μA , current signals from the twelve targets are collected from a wire placed at the bottom of each to a connector placed in the middle of each “racket”, named “touch pens” (Figure 8).



Fig. 8. “Touch pen” of each “Racket”

The signals are then routed inside the wheel to its top on a copper ring. The signals from the shield also routed to another concentric copper ring (Figure 9). These rings are in contact with two fixed brushes out of graphite to collect both signals.

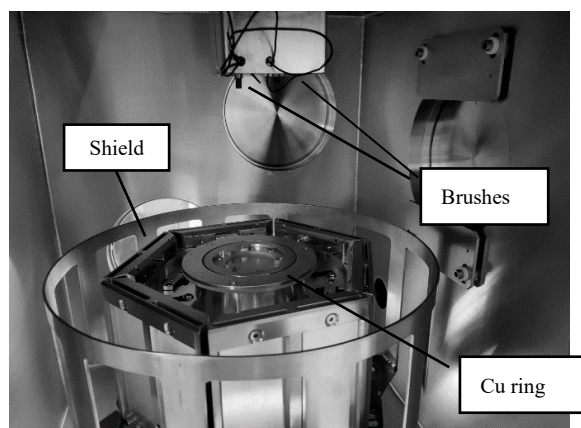


Fig. 9. Inside of the chamber (targets, measurement tools)

3.4 Off-beam tests

Following the detailed CFD simulations, the current measurement method and the reliability and reproducibility of the rackets extraction, several tests have been conducted. These tests consisted in:

- Controlling the absence of water leak at the level of the sealing of the targets with the wheel under 2 bars of water-cooling and 500 rpm of the wheel. The sealing is made of fluoroelastomers from Viton® [7] and is radiation hard [8].

- Testing the water cooling efficiency and measuring its flow. Actually, the heating of the targets was simulated with a heating system of 150 W covering the substrate and thermocouples. With an inlet water at 22°C, a water flow of 50 l/min (i.e. about 4.4 l/min for each target) and a pressure of 2 bars, less than 50°C was measured on the substrate. Moreover, after switching off the water cooling and heating the target up to 180°C, the cooling system has been switched on again and the temperature decreased down to 70°C in 4 minutes.

- Measuring currents under rotation, up to 500 rpm, by injecting a low current of 10 nA, generated by a

voltage and a resistance connected to the rotating copper ring. The collected current on the carbon brush was measured by an ammeter and visualized on an oscilloscope; it was stable and corresponds to the injected current with an accuracy of 1%.

- Validation of the extraction system and process handling, was revealed reliable, easy and robust.

4 Conclusion

A high power irradiation station has been designed in the context of the REPARE project, which aims at producing up to 100 GBq of ^{211}At in 8 hours of beam time using the very high beam intensity available at the GANIL SPIRAL2 facility. The target station is conceived to dissipate up to 10 kW of beam power. A cooling system combining direct water-cooling and target rotation has been developed. It has been tested offline and demonstrated to be very efficient. A dedicated current measurement method and beam synchronization with wheel rotation have been implemented. A reliable extraction system ensuring an easy and safe manipulation of the rackets has been designed. Detailed fluidic simulation calculations have been performed during the design process to ensure efficient cooling. Several offline tests focused on the absence of water leak during rotation, cooling efficiency, beam current reading and racket extraction mechanism have been conducted to confirm calculations and main functionalities. Currently, the REPARE irradiation station is assembled. The cooling efficiency, current measurements and beam synchronization will be tested under realistic conditions with beam in 2023. The first ^{211}At production run might be planned in fall 2023 provided the tests are all successful.

Acknowledgement

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