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# Design of the gas cell for the IGISOL facility at ELI-NP

P. Constantin [a,*], D.L. Balabanski [a], L.T. Anh [a,b], P.V. Cuong [a,c], B. Mei [a]

[a] Extreme Light Infrastructure – Nuclear Physics, "Horia Hulubei" National Institute for Physics and Nuclear Engineering, Str. Reactorului 30, 077125 Bucharest Magurele, Romania
[b] Graduate University of Science and Technology, Vietnam Academy of Science and Technology, Hanoi, Vietnam
[c] Centre of Nuclear Physics, Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam

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ABSTRACT

One of the experimental programs that will be carried out at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility is the production of exotic neutron-rich ion beams in an IGISOL facility via photofission in a stack of actinide targets placed at the center of a cell filled with He gas. Simulations with the Geant4 toolkit were done for the optimization of the target configuration that maximizes the rate of released photofission fragments. The cell geometry is established based on the stopping properties of these fragments. Studies, based on simulations with Geant4 and SIMION 8.1, of the space charge effect and its induced electric field in the gas cell are presented. Estimates of the extraction time and efficiency of the photofission fragments are derived.



## 1. Introduction

Radioactive ion beams (RIBs) are formed by either the isotope separation on-line (ISOL) technique or the in-flight separation technique [1]. Conceptually, the main difference between them is the type of primary beam and target used. ISOL facilities use particle primary beams, *e.g.* electrons, protons, neutrons, or photons, as suggested at ELI-NP, usually on thick and hot targets to produce exotic isotopes that diffuse out due to the high temperature of the target. The isotopes of interest are separated and sent to experimental stations, or post-accelerated. In-flight facilities use heavy-ion primary beams on thin targets to produce exotic isotopes that are separated by a fragment separator. For some applications, the isotopes are slowed down by a gas cell, also called a gas catcher, and passed to electromagnetic devices for beam formation. It should be noted that modern facilities are more complex and often cross the simple lines drawn above.

The standard ISOL facilities have the disadvantage that isotopes of refractory elements do not diffuse out of the thick targets used. One solution has been developed at the JYFL facility in Jyväskylä [2] with the ion-guide ISOL (IGISOL) technique, where a 30 MeV proton beam impinges on a thin $^{238}$U target placed in a He gas cell. The IGISOL gas cells, like the one used at JYFL, have small volumes and can extract ions only by using the gas flow.

Refractory isotopes will also be produced at the CARIBU facility at the Argonne National Laboratory [3]. The isotopes resulting from the spontaneous fission of an 1 Ci $^{252}$Cf source are slowed down in a gas catcher and further processed by an isotope separator. The volume has to be large due to the significant energies and straggling of the released fragments. Efficient extraction from large cells can be done only by applying electric fields to drift out the fragments in time scales of the order of milliseconds. A combination of DC and RF (radio frequency) fields is used for ion extraction.

Another facility with an experimental program for the study of refractory elements, which will come online in the near future, is the SLOWRI beamline at RIKEN. Exotic nuclei are produced by using RIBs of the BigRIPS fragment separator and an ion catcher based on the RF-carpet ion-guide technique [4].

Low energy beams of refractory elements are produced also at the FRS Ion Catcher facility at GSI [5] and at the FRIB facility at Michigan State University [6] via in-flight separation followed by stopping in gas catchers.

The development of high-brilliance gamma beams at the ELI-NP facility, produced via Compton back-scattering of a high power laser off an intense electron beam, will open a rich experimental program dedicated to studies of actinide photofission [7,8]. An important part of this program is the production of refractory neutron-rich isotopes in the Zr-Mo-Rh light fragment region and in the rare-earth heavy fragment region. These isotopes will be handled with the IGISOL technique. The gamma beam will generate photofission fragments in a thick actinide target placed in the

* Corresponding author.
*E-mail address:* paul.constantin@eli-np.ro (P. Constantin).

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center of a He gas cell used as ion guide. In order to avoid the long extraction times characteristic for diffusion and to increase release efficiency, the target is sliced into thin foils. As discussed in the next section, due to the total photofission cross section $\sigma_{\gamma f}(^{238}\mathrm{U}) \sim 1$ b [9], many such foils are needed to obtain significant fragment yields. This results in a rather long gas cell and, to keep the extraction fast, imposes an ion drift direction orthogonal to the $\gamma$ beam direction. A strong DC field drifts the ions out in the orthogonal direction and, when they reach the area close to the cell wall with the exit nozzle, resonant RF fields prevent their adhesion to the wall and push them towards the exit nozzle where the gas flow takes them out in a supersonic jet. The cell will operate at low temperatures, around 70 K, for increased gas density, hence stopping power, and purity.

Such a Cryogenic Stopping Cell (CSC) will be built for the Super-FRS facility at GSI [10] as an upgrade of the current design, which is operating successfully at the FRS Ion Catcher Facility [5,11]. The current design, with extraction along the heavy ion beam, has demonstrated fast (25 ms) and efficient (50%) ion extraction [12]. The new design, with extraction orthogonal to the beam, is expected to allow even faster (around 5 ms) and more efficient extraction, at the much higher rate of the Super-FRS primary beam of about $10^7$ ions/s at the entrance of the CSC. This upgrade will lead to an increase by four orders of magnitude in the maximum ionization rate, above which space-charge creation drastically affects ion extraction.

At ELI-NP, the development of a similar CSC is considered. The main differences are the primary beam type and the target placement inside the gas cell. They imply smaller backgrounds and different trajectories of the stopped ions, resulting in some variation of the cell configuration.

The work presented here continues the study of Ref. [7] for the particular case of the CSC at the ELI-NP IGISOL facility. The first goal is to find the optimal target and cell configurations. The second goal is to address the issue of space charge effects and to estimate the extraction time and efficiency of the CSC.

To avoid repetitive references to the previous work [7], its main results are briefly listed. First, the method to control the $\gamma$ beam maximal energy $E_\gamma^{max}$ with the electron beam energy $T_e$ is demonstrated. Then, it is described how to set the $\gamma$ beam threshold energy, $E_{th}$, via beam collimation, by using the energy-angle correlation of the $\gamma$ beam. Also, various parameterizations of the ion charge state $q$ of ions produced in photofission are introduced. They are used to get the parameters of the photofission fragments released from the target, such as kinetic energy, charge and velocity. Finally, the fragment release efficiency is estimated. All these results are used in the present study.

Within this paper, the Geant4 simulation toolkit [13] and the SIMION 8.1 software package [14] are used to deduce baseline parameters for the future development of a CSC prototype. The work is organized as follows: Section 2 presents the optimization of the target geometry for a maximum rate of released photofission fragments; Section 3 establishes the dimensions of the gas cell by analyzing the stopping properties of these fragments in its gas; Section 4 studies the space charge effect and its implications on the functioning of the CSC.

All the particle rates are normalized to a conservative value for the gamma beam rate of $5{\cdot}10^{10}$ $\gamma$/s. This value is significantly lower than the expected optimal rate of $10^{12}$ $\gamma$/s of the ELI-NP beam, and it is used for rate estimates of day-one experiments at ELI-NP.

## 2. Target geometry optimization

Two possible locations of the CSC, at distances $D = 7$ m and 40 m from the $\gamma$ beam origin, *i.e.* the ELI-NP gamma beam system (GBS) high-energy interaction point (IP) of the electron and laser beams [15], are considered. The first location, closer to the IP, offers a smaller beam spot leading to a more compact target assembly inside the gas cell. However, the existing free space of the experimental hall at this location limits the dimensions of the CSC to less than 1.5 m along the $\gamma$ beam. Also, the space available for the IGISOL beamline components and supporting equipment is limited, making the experimental hall rather crowded. The second location has no space constraints, but has a larger beam spot.

At fixed beam maximum energy, the energy-angle correlation implies that using $\gamma$-rays with emission angle below $\theta_{max}$, for example by placing a target which covers the beam spot size $A$ at distance $D$, is equivalent to applying an energy threshold $E_{th}$. More specifically,

$$A = 2D\theta_{max} = 4D\sqrt{E_L/E_{th} - E_L/E_\gamma^{max}} \tag{1}$$

where $E_L = 2.4$ eV is the laser photon energy. In this equation, and in the rest of this work, the small angle approximation $tan(\theta) \approx sin(\theta) \approx \theta$ is used, which is safe for the ELI-NP range of $\gamma$-ray emission angles $\theta < 1$ mrad.

The beam transversal distributions at $D = 7$ m with red triangles and at $D = 40$ m with blue circles, for a beam with $E_\gamma^{max} = 18.5$ MeV and a threshold energy $E_{th} = 12$ MeV, are shown in Fig. 1. The distribution in black squares is at $D = 40$ m and for $E_{th} = 9$ MeV, $E_\gamma^{max} = 18.5$ MeV. There is a large difference between the two locations and a smaller variation with the energy range. The beam spot sizes calculated with Eq. (1) are shown with dashed lines.

The attenuation of a $\gamma$ beam with $E_{th} = 9$ MeV and $E_\gamma^{max} = 18.5$ MeV, in a bulk target of $^{238}$U with thickness $T = 5$ cm placed at $D = 40$ m, is shown in Fig. 2. The projection on the beam axis $z$ is very well described by exponential attenuation $exp(-\mu z)$, where $\mu \approx 1.1$ cm$^{-1}$ is the linear attenuation coefficient of photons in $^{238}$U in the 9–18 MeV range [16]. The photofission rate in such a target, with transversal size $A$ and thickness $T$, is then:

$$N_f(A,T) = \frac{n_t}{2D^2}\int_{E_{th}(A)}^{E_\gamma^{max}} dE \int_D^{D+T} dz \int_0^{\frac{A}{2D}} d\theta \cdot z^2\theta I_\gamma(\theta,E)\sigma_f(E)e^{-\mu z} \tag{2}$$

where $n_t$ is the target number density, $I_\gamma(\theta,E)$ is the $\gamma$ beam rate and $\sigma_f(E)$ is the photofission cross section [9]. The energy threshold $E_{th}(A)$ is obtained by inverting Eq. (1). The natural coordinate

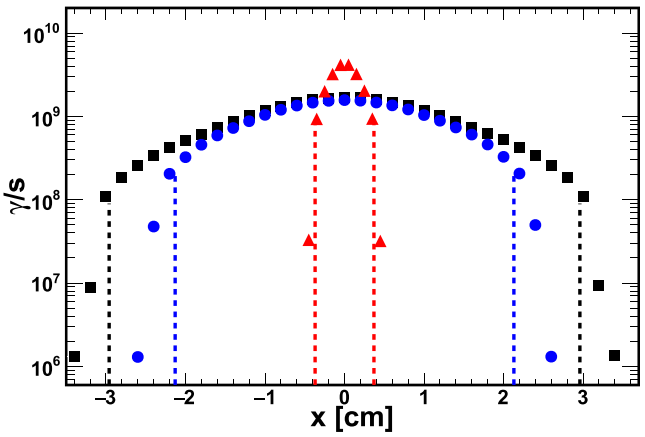


**Fig. 1.** Gamma beam transversal distribution at distance $D = 7$ m from the beam origin and $E_{th} = 12$ MeV (red triangles), at $D = 40$ m and $E_{th} = 12$ MeV (blue circles) and at $D = 40$ m and $E_{th} = 9$ MeV (black squares). The maximum beam energy is $E_\gamma^{max} = 18.5$ MeV. The corresponding dashed lines show the beam spot sizes $A$ calculated with Eq. (1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)