DESIGN AND CHARACTERIZATION OF HIGH POWER TARGETS FOR RIB GENERATION

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Abstract

In this article, thermal modeling techniques are used to simulate ISOL targets irradiated with high power proton beams. Beam scattering effects, nuclear reactions and beam power deposition distributions in the target were computed with the Monte Carlo simulation code, GEANT4. The power density information was subsequently used as input to the finite element thermal analysis code, ANSYS, for extracting temperature distribution information for a variety of target materials. The principal objective of the studies was to evaluate techniques for more uniformly distributing beam deposited heat over the volumes of targets to levels compatible with their irradiation with the highest practical primary-beam power, and to use the preferred technique to design high power ISOL targets. The results suggest that radiation cooling, in combination, with primary beam manipulation, can be used to control temperatures in practically sized targets, to levels commensurate with irradiation with 1 GeV, 100 kW proton beams.

1 INTRODUCTION

Radioactive ion beams (RIBs) offer unique opportunities to study nuclear processes inaccessible with stable projectile/target combinations. Their availability permits examining reactions important in furthering our knowledge about the structure of the nucleus, the nucleosynthesis processes responsible for heavy element formation and the stellar processes that power the universe. Worldwide interest in these opportunities has motivated the construction of several facilities dedicated to research with RIBs, including the Holifield Radioactive Ion Beam Facility at the Oak Ridge National Laboratory [1]. High power targets will be required for use at next generation facilities such as the proposed Rare Isotope Accelerator (RIA) Facility [2,3]. The RIA will incorporate traditional Isotope Separator On-Line (ISOL) as well as projectile fragmentation techniques for generation of RIBs. The beam quality of RIBs generated with the ISOL method is quite good, while intensities of short-lived species are seriously compromised by decay losses during diffusion-release from the production target material and effusive transport to the ion source. In order to produce useful intensities of species with sub-second lifetimes, a high power ISOL facilities such as the RIA, targets must be developed that incorporate short diffusion lengths and high permeability properties required for fast diffusion release and expedient transport to the ion source. These requirements connote that targets must be highly permeable, low density, with micron-scale dimensions, since both diffusion and effusion times decrease exponentially with increasing temperature. The fragility of targets with these prescriptions presents serious challenges that must be overcome in order to design targets that withstand irradiation with beams of the power levels available at RIA.

High-efficiency-release ISOL targets have been successfully developed for the generation of useful radioactive ion beam intensities for nuclear physics and nuclear astrophysics research at the HRIBF [4,5] as well at other ISOL facilities (see, e.g., Ref. 6). Short diffusion lengths are achieved either by using thin fibrous materials as targets or by coating thin layers of selected target materials onto low-density carbon fibers such as reticulated vitreous carbon fiber (RVCF) to form highly permeable composite targets. In this report, we present the results of simulation studies of the temperature distributions in new concepts targets for potential use at high-power, ISOL-based RIB facilities such as the RIA.

2 SELECTION OF TARGET MATERIAL

The intensity of RIBs produced by the ISOL method depends on the production rate and the efficiency with which the radioactive species can be released from the target material and transported to the ion source. Maximum production rates are set by reaction cross sections for producing the species of interest and the practical limits of the primary beam intensity that can be used on-target without compromising the efficiency of the ion source or vaporization of the target material itself. Since diffusion in solid-state materials depends exponentially on temperature, it is desired to select refractory target materials that can be heated to temperatures as high as practical and have small dimensions and highly permeable structure required for fast diffusion release and effusive-flow transport to the ion source. The limit of target temperature is set by the vapor pressure, above which the ionization efficiency of the source begins to deteriorate [4].

Table 1 provides examples of candidate target materials for the production of proton-rich and neutron-rich radioactive species through spallation or fission reactions.

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Table 1. Example candidate materials for ISOL targets

Material	T_{max} (°C)	Material	T_{max} (°C)
C	1975	WC	2480
W	2863	ThC_2	2650
Ta	2650	UC_2	2100
Re	2600	BeO	2230
Zr	2030	ZrO_2	2050
ZrC	2375	HfO_2	2300
NbC	2220	ThS_2	2000

3 TARGET DESIGN

Efforts are presently being directed toward the design and fabrication of new concept targets with short diffusion length, high permeability, and high refractory properties required for RIA applications. These concepts include the use of low-density fibrous targets or low-density target matrices, such as RVCF foam, which can be used as the plating matrix for deposition of target materials and serve as the thermal conduit for transport of heat deposited in the target matrix by the production beam. Fig. 1 displays examples of SEM images of small diameter HfO_2 fibrous material and UC_2 coated on RVCF composite targets that have proved to be fast and efficient release targets during on-line use at the HRIBF.

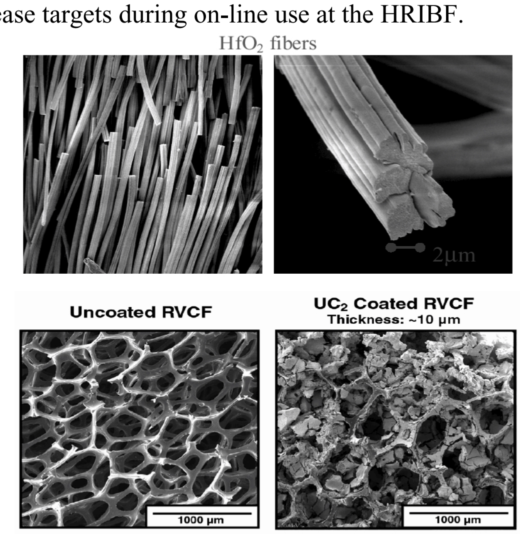

Fig. 1: SEMs of HfO_2 (upper) and UC_2 (lower) targets

4 SIMULATIONS STUDIES

Control and maintenance of the target temperature at a desired value is very important for optimizing the production of RIBs. Higher temperatures significantly decrease diffusion release times of particles from targets. Thus, in order to optimize radioactive species release, it is desirable to operate the target to the temperature limit set by the vapor pressure of the target material that does not compromise ion source efficiency. It is also important to provide means for removal of beam deposited heat from the target at controlled rates so that, as high as practically, primary beam intensities can be used to produce the species of interest.

We have conducted beam-target interaction studies for 1 GeV protons incident on various low density, highly permeable targets, using the Monte Carlo code GEANT4 [7]. In the simulations, the primary beam and all secondary particles released in nuclear events (electrons, γ-rays, neutrons, protons, alpha particles, and other light and heavy fragments) are traced until they leave the target or are absorbed, and their contributions to target heating are accounted for. Fig. 2 shows the beam power deposition profile in an UC_2/RVCF composite target. As shown, the beam power deposition is not uniform, and consequently, the temperature distribution profile is non-uniform, both radially and axially.

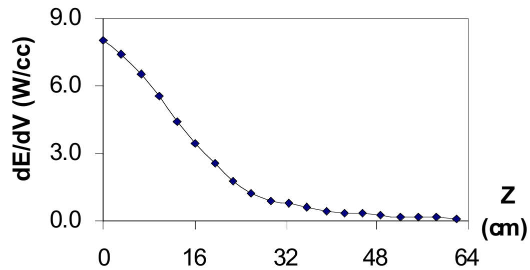

Fig. 2: Beam power density deposited by a parallel incidence, 1 GeV, 1 μA proton beam, along the beam axis of a UC_2 target. Density: 2.5 g/cc; Length: 65 cm; Beam Diameter: 0.5 cm.

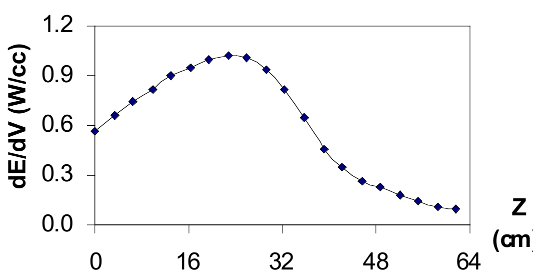

Fig. 3: Beam power density deposited by a converging incidence, 1 GeV, 1 μA proton beam along the axis of a UC_2 target. Density: 2.5 g/cc; Length: 65 cm; Incident beam spot diameter: 2 cm.

It is desirable to distribute the beam deposited power more uniformly over the volume of the target. One approach for achieving this effect is to illuminate the target at entrance with a large diameter, proton beam with convergent angle chosen so as to maximize transmission of the primary beam through the target. However, the beam deposited power density drops off quickly toward the center of the target due to primary beam losses attributable to nuclear reactions, as shown in Fig. 3. As a complement to this approach, the beam power deposition can be made more uniform by increasing the target material density toward the exit of the target. This combination produces a more uniform beam power deposition density profile along the beam axis, as illustrated in Fig. 4. To achieve this result, the composite UC_2/RVCF target was made in four sections with different densities. We are presently conducting further studies on the effects of manipulation of the driver beam at the production targets (beam size, convergence angle, time and spatial modulation, etc.) as well as investigating the feasibility of providing supplemental heat applied non-linearly at the rear of targets to produce more uniform temperature distributions.

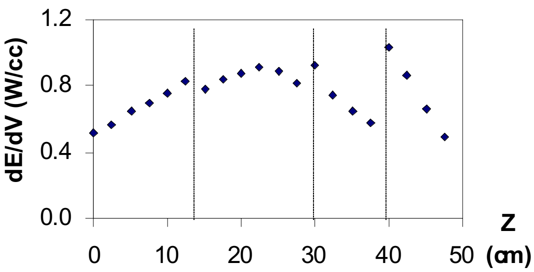

Fig. 4: Beam power density for a 1 GeV convergent proton beam along the axis of a UC_2 target with 4 different densities (2.49 g/cc, 2.0 g/cc, 2.52 g/cc, and 6.0 g/cc) ordered from beam entrance to exit in four sections, as indicated. Incident beam: spot size ~ 2.2 cm; Intensity: 1 μA.

5 TEMPERATURE DISTRIBUTIONS

In the design of high power ISOL targets, the radiation cooling technique is appealing because of its efficiency for cooling at high temperatures. The finite element thermal analysis code, ANSYS [8] was used to model thermal distributions in targets. The results show that high power ISOL targets made up of materials with good thermal conductivities such as tantalum and carbon can withstand irradiation of 1 GeV proton beams with power levels up to ~ 100 kW. Other materials, such as UC_2, that have lower thermal conductivities and lower limiting temperatures, can only withstand 20 kW (parallel incidence) and 30 kW (convergent incidence), as noted in Fig. 5.

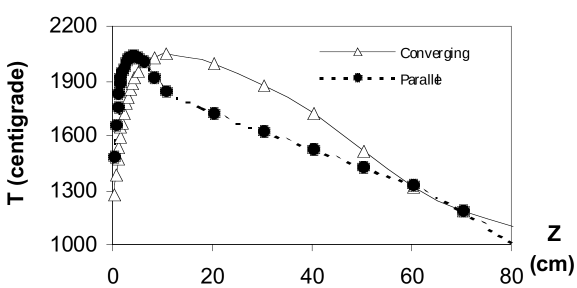

Fig. 5: Temperature distributions in UC_2 targets irradiated with 1 GeV, 20 kW parallel and, 30 kW converging incidence proton beams. Density: 2 g/cc; Length: 85 cm; Diameter 4 cm.

In order to maximize RIB production rates, ISOL targets must be operated at high beam power levels. It is clear from these studies that an effective method can be devised to distribute beam power more uniformly over the target volume. For example, thin fibrous targets made of thin disks, separated in space to take advantage of the radiation cooling effect, can significantly increase the total beam power deposited in these targets to acceptably high levels and thereby, greatly increase the RIB production rates, as shown in Fig. 6.

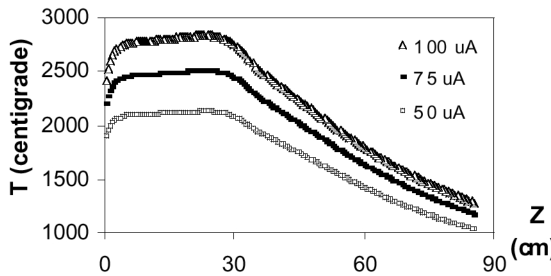

Fig. 6: Temperature in a tantalum target irradiated with 1 GeV, 50 kW, 75 kW, and 100 kW, converging proton beams. Density: 2.1 g/cc; Length 85 cm; Diameter 4 cm.

6 CONCLUSIONS

Computational studies reveal that nuclear reactions cannot be ignored in the design of thick ISOL targets, especially when most of the beam is adsorbed through these processes. This produces asymmetric beam heating effects and thus complicates target design. The power density falls off sharply from about the center to the exit of the target. This problem can be solved by manipulating the beam at entrance to the target while adding heat in a non-linear manner to the end of the target or varying the target density along the beam axis to achieve more evenly distributed heat and taking advantage of the radiation cooling effect.

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