The Design of Highly-Permeable, Fast-Diffusion-Release High-Power ISOL Targets

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Abstract. In this report, we provide results of simulation studies for the design of fast diffusion-release high-power targets for RIB generation at high energy ISOL based facilities. Processes that lead to target heating (e.g., primary beam energy deposition, energy release through nuclear reactions and beam scattering effects) are accounted for in the simulations. From these studies, we find that internal thermal radiation is an important mechanism for heat redistribution in the low-density, small-dimensioned fibrous targets used in viable target designs and therefore, must be carefully taken into account. Such fragile, low thermal conductivity targets must withstand irradiation with ≥ 100 kW beams for extended periods of time and therefore, care must be taken to avoid exceeding the limiting temperature of the target material while ensuring homogeneous temperature distribution over the volumes of these targets. Thermal radiation of high-temperature fibers to surrounding surfaces is an effective means for cooling targets subjected to high power beam irradiation, especially for materials with poor intrinsic thermal conductivities. Focus-through and scanning techniques, used in combination with additional heat shielding placed on the exit end of the target, are found to be effective means for reducing beam power deposition density to manageable levels, homogenizing the temperature distributions within such targets while avoiding devastating primary beam scattering losses during transit. Results derived from simulation studies of fibrous (e.g., ZrO_2 and HfO_2) and composite (e.g., BeO/W/RVCF, NbC/RVCF, Ta/RVCF and UC_2/RVCF) targets subjected to irradiation with 1 GeV proton beams with power levels up to 400 kW, are presented in this report.

1. INTRODUCTION

At Isotope Separator On-Line (ISOL) technology based radioactive ion beam (RIB) research facilities, maximum production rates are set by reaction cross sections for producing the species of interest, and the practical limits of the primary beam intensity in terms of maximum permissible power density-on-target that can be tolerated without compromising the efficiency of the ion source or the physical integrity of the target. In order to maintain a viable research program at such facilities, experimentally useful intensities of a broad range of isotopes with lifetimes as short as practically realizable must be provided to users. However, adequate intensities of very short-lived RIBs are difficult to realize since the species of interest must be diffused from either solid (or liquid) target materials, effusively transported to an ion source, ionized, and accelerated to research energies, in times commensurate with their lifetimes. Radioactive decay during diffusion-release from target matrices and effusive-flow through targets to the ion source account for most of the losses and therefore, delay times associated with these processes must be reduced to as low as practically achievable values. Short diffusion–length, highly refractory target materials must be chosen since the solid-state diffusion process depends exponentially on temperature; these fibrous target materials must then be formatted in open structures that are close-coupled to the ion source to ensure fast transport to the source following diffusion release from the target material. Targets with these properties are necessarily fragile and can be easily destroyed by deposition of excessively high amounts

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of production beam power and therefore, care must be taken to avoid exceeding the limiting temperature of the target material while ensuring homogeneous temperature distribution over the volumes of these targets. This is an especially challenging problem for next generation high power RIB facilities such as at the RIA [1,2], where such fragile, low thermal-conductivity targets, must withstand irradiation with 100 kW to 400 kW beams for extended periods of time.

One approach to avoiding the beam deposited heat problem is by using the two-step target concept [3,4] whereby the production beam interacts with a primary target that emits high fluxes of neutrons. The neutrons then react with a close-coupled secondary target made of a fissionable material such as UC_2 or ThC_2. The secondary target can then be independently heated to the desired, controllable temperature. However, the two-step concept can only be used to produce neutron-rich species. For the production of proton-rich species, targets must be designed that can withstand direct irradiation with high-energy, high-power, light ion beams. In this report, computational methods are utilized to assess the merits of a number of beam manipulation methods devised for more uniformly distributing primary beam deposited power over the volumes of low-density, fibrous, single-stage targets.

The successful target design philosophy, adopted at the Holifield Radioactive Ion Beam Facility [5-8], is predicated on the use of dimensional criteria that permit custom engineering of the thickness of deposits of the production material that will release the species of interest within its lifetime [8]. These criteria have been used in the design of highly successful, fast diffusion-release, highly permeable, low-density fibrous compound material [5], and composite targets, [7] that have been used on-line in important nuclear astrophysics [9] and nuclear structure physics research [10] at the Holifield Radioactive Ion Beam Facility [11]. This design philosophy has been incorporated in the target concepts considered in this report.

Several ploys have been investigated for reducing the beam power density and homogenizing the temperature distribution over the entire volume of targets with the objective of arriving at designs that accommodate irradiation with primary beam power levels exceeding 100 kW, as required at the RIA, for example. Focus-through and scanning techniques, used in combination with additional heat shielding placed on the exit end of targets, are found to be effective means for reducing beam power deposition density to manageable levels while homogenizing the temperature distributions within such targets.

In the present studies, beam scattering effects and nuclear reaction contributions to target heating were simulated with the Monte Carlo particle simulation code, GEANT4 [12]. This code also tracks release and transport of fission products [13], a feature that is very useful when determining the heat distributions within fission targets. Simulation studies were performed with *"interaction length"* targets. However, by reducing target lengths, better uniformity in temperature over the entire volume of the target can be realized.

2. THERMAL CONDUCTIVITIES OF **FIBROUS MATEFUALS**

It is difficult to dissipate intense heat from the interior regions of low-density targets if only normal thermal conduction is considered, even for materials with the highest intrinsic bulk thermal conductivities. For example, the maximum acceptable power of a 1 GeV proton beam irradiating targets made of the most refractory material with the highest intrinsic bulk thermal conductivity, is less than 100 kW [14]. However, thermal radiation effects within the interior regions of low-density fibrous target matrices cannot be ignored. The low-density, small-dimensioned fibrous targets required for fast diffusion release, fast effusive-flow transport have open channels over the entire target volume that provide partially optically transparent paths for photons to travel so that thermal radiation can take place within the interior regions of such materials. We have demonstrated through computational methods, using the finite element code ANSYS [15], that internal radiation is an important heat transfer mechanism in low-density fibrous targets.

The accuracy of thermal computations strongly depends on the availability of target specific thermal conductivity versus temperature data. There is a dearth of thermal conductivity for fibrous materials,

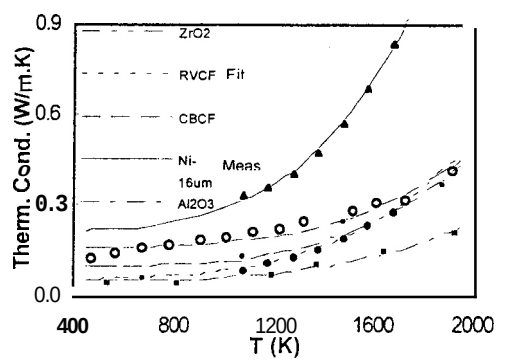

Figure 1. Measured thermal conductivity for a few low-density fibrous target materials

especially at the elevated temperatures (~2000°C), required for target applications. The lack of such data greatly complicates the ability to realize plausible results from such calculations. However, a few sets of data have been measured for low thermal conductivity commercially available fibrous materials or composite target materials [16,171. (See e.g., Fig. 1).

From Fig. 1, it is seen that the measured thermal conductivities increase with increasing temperature. This behavior is in complete contrast to the thermal conductivities of bulk materials that decrease with increasing temperature for most materials. The measured data, shown in Figure 1, are well represented by fitting with the following relation:

$$\sigma = A + B \cdot T^4 \qquad (1)$$

where A and B are constants that depend on the material and T is the absolute temperature. Since the second term is due to radiation, it is obvious that thermal radiation effects take place within such open structures. This is an important mechanism for heat redistribution, especially at the elevated temperatures where thermal radiation dominates the heat transport process. Simulation studies of low-density materials that do not include the proper thermal conductivity behavior with temperature are obviously incorrect.

3. SIMULATION OF INTERNAL TARGET RADIATION EFFECTS

All simulations were made for **4** cm diameter, 80 cm long targets, irradiated with 1 GeV proton beams. The lengths of targets, unless otherwise specified, were determined by calculating the amount of target material required to reduce the beam to *1/e* of its initial value through nuclear reactions. These targets are said to be *interaction-length* long. Of course, the target length, will vary depending on the density of the target material required to absorb 63% of the beam through nuclear reactions. When only normal thermal conduction is considered, the maximum intensity that materials with the highest intrinsic thermal conductivities (e.g., Ta/RVCF) can withstand without exceeding the limiting temperature of the particular material, is less than 100 μA for proton energies of 1 GeV. The intensity limitation is even more severe for fibrous materials with the lowest intrinsic thermal conductivities, (e.g., ZrO_2 and HfO_2). These materials can only withstand irradiation with ~10 μA, 1 GeV proton beams.

To simulate the contributions to heat transport by thermal radiation within the interior regions of low-density fibrous target materials, two simple 2-D models were used to illustrate the effect. The 2-D models used to demonstrate internal radiation effects are schematically illustrated in Figure 2. More meaningful 3-D simulations could not be effected with computers available at the time of these studies because of the prohibitively large memory and CPU time required to solve a particular problem. The maximum target temperature that a particular target material can tolerate, as computed with the 2-D radiation models, is determined by the beam power, its distribution, the intrinsic thermal conductivity of the material and thermal radiation between the elements of

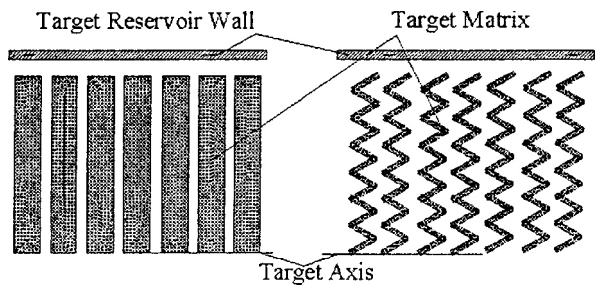

Figure 2. 2-D models used in illustrating the effect of internal thermal radiation for fibrous targets listed in Table I.

TABLE I. Proton Beam Intensity and Deposited Power: 2-D Model

Target	Without Radiation		Internal Radiation	
	I (μA)	dP (kW)	I (μA)	dP (kW)
Ta/RVCF	86	14.2	**245**	40.5
NbC/RVCF	**64**	11.7	120	21.6
BeO/W/RVCF	66	9.9	100	14.5
UC_2/RVCF	31	6.2	70	14.0
ZrO_2	9	1.3	82	11.8
HfO_2	7	**1.2**	80	13.4

The simulation results demonstrate that internal thermal radiation is the dominant means of dissipating heat within low-density fibrous target materials, especially at high temperatures. To enhance internal radiation cooling, highly permeable, low-density materials with 'open' structures such as RVCF are preferred for use as matrices for deposition of ISOL target materials.

4. SIMULATIONS OF BEAM POWER DISTRIBUTION

Since RIB intensities in an ISOL facility increase linearly with beam power for spallation and fission production reactions, they are limited by the maximum permissible power density-on-target that can be used without compromising the efficiency of the ion source or the physical integrity of the target. Therefore, to extend the range and intensities of short-lived RIBs, techniques must be developed that ensure that the beam power density never exceeds the limiting temperature of the target material.

The peak power depositional density depends on the size of the beam at entrance to the target, as seen in Figure 3. However, due to scattering, a large fraction of the primary beam may be lost during transit for parallel, divergent or convergent beams with less than optimum convergence angles. By focusing a large diameter beam to a convergence angle that optimizes transmission through the target, beam losses due to scattering can be minimized through reasonably sized diameter targets. This technique permits full or close to full utilization of the primary beam for producing radioactive species, since the beam will be confined within the diameter of the target (see Figure 4). The technique also reduces the beam power deposition density resulting in a more uniform temperature distribution over target volumes. The use of additional layers of heat shielding on the exit end of the target, in combination with the beam focus-through technique, are effective in achieving more homogeneous temperature distributions within such targets. Another, perhaps, less practical technique that can be used for this purpose is to linearly increase the target material density along the length of the target, as described in Ref. 18. However, since the target material density adversely affects the speed at which

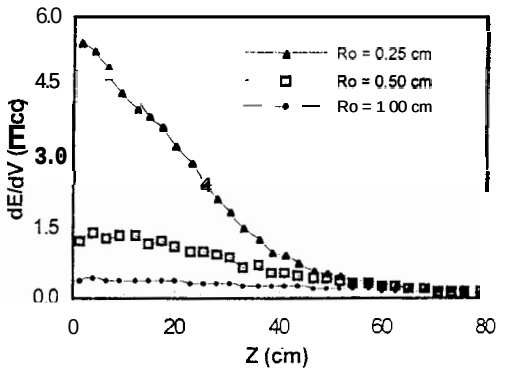

Figure 3. Beam power deposition density for parallel incidence, 1 GeV, 1 μA proton beams, with differing entrant beam sizes.along a 4.0 cm diameter, 80 cm long, 1.2 g/cc NbC/RVCF target.

the diffusion and effusive-flow processes can take place, the method may not be practically useful.

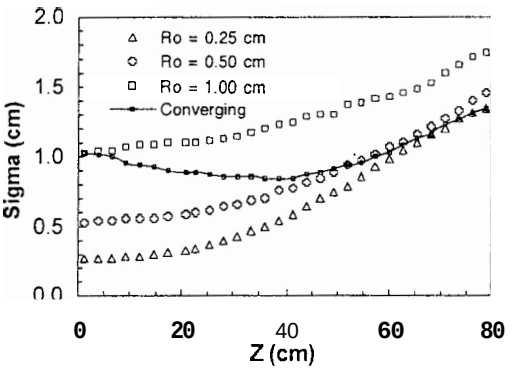

Figure 4. Radii (sigma) of parallel and convergent incident 1 GeV proton beams along a 4.0 cm diameter, 80 cm long, 1.2 g/cc NbC/RVCF target.

5. TIME-DOMAIN SIMULATION STUDIES

Time-domain converging incidence beam manipulation (scanning) techniques can be used to distribute the beam power over larger beam direction surface areas in order that these fragile targets withstand irradiation with ≥ 100 kW proton beams. This technique permits changing the time-scan period, variation of the scan speed, as well as the beam direction surface area to accommodate foreseeable power levels required at high energy facilities such as the RIA. For example, at the RIA beam power levels up to 400 kW will be available for target irradiation. By use of this technique, practically sized targets can be designed that **will** accommodate these power levels. Figure 5 shows a vertical (x-direction) scheme for scanning a 1 GeV, 400 kW, high-intensity proton beam over the entrance surface area of a 4 x 24 x 80cm^3, 1.2 g/cc NbC/RVCF composite target; the scan speed is varied to more homogeneously distribute beam heat in the target. The temperature versus time distributions for several positions, x, along the scan direction of the NbC/RVCF target are displayed in Figure 6. The data were taken at $z = 30$ cm and scan period of 13 s.

6. CONCLUSIONS

From these studies, we find that internal thermal radiation is an important mechanism for redistribution of production beam deposited heat in fibrous, low-density targets. This redistribution of heat moderates the local temperature and therefore, cools the low-density, small-dimensioned fibers and therefore, must

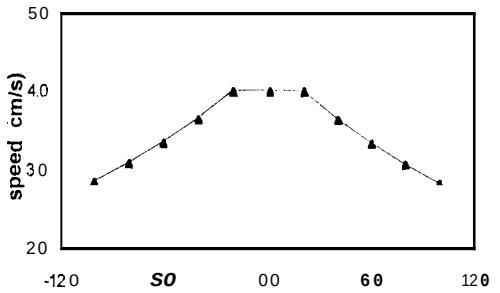

Figure 5. Beam scanning scheme for manipulating a convergent, 400 kW, 1 GeV proton beam over the beam entrant surface of an NbC/RVCF target. Scan length: ± 10 cm; scan period: τ = 13 s.

be carefully taken into account in computational simulation of thermal effects within such targets. Beam manipulating techniques can be used that permit irradiation of highly permeable, thin ligament fibrous targets with 1 GeV, 400 kW proton beams such as required at **RIA.** Since the beam deposited power varies both in the ***r***- and z-directions of a particular target, the temperature distribution also varies in each direction. The converging incidence beam technique can be used in combination with a target with increasing density along the axis, to improve the uniformity of the temperature distribution over the volume of the target material. However, the simplest and most effective approach for achieving uniform target temperature distribution is to elevate the temperature of the surrounding walls of the target so that the temperature will be uniformly distributed over the entire target volume. The approach is necessary for fast release of short-lived species produced by irradiating the target material with 1 GeV proton beams, at the sacrifice of reducing, somewhat, the maximum beam power that the target can withstand.

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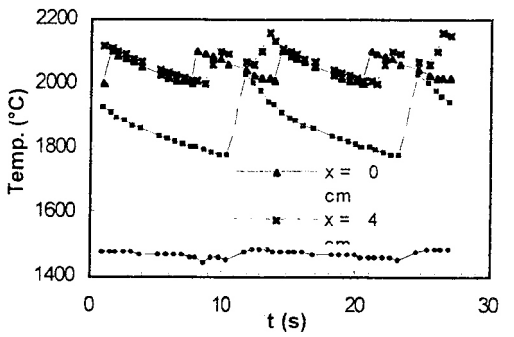

Figure 6. Temperature versus time fat various radial positions **x:** 1.2 g/cc, 4 x 24 x 80 cm^3, NbC/RNCF target; scanning proton beam: 1 GeV, 400 kW; range: **x** = ± 10 cm (target: ± 12 cm); τ = 13 s.

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