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Design and test of a graphite target system for in-flight fragment separator

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ABSTRACT

A graphite target system to produce rare isotope beams using in-flight fragmentation method has been designed for the rare isotope science project in Korea. A main primary beam to bombard the target is ^{238}U in the energy of 200 MeV/u with a maximum power of 400 kW, in which the beam power deposit on the target amounts up to 100 kW. A multi-slice target concept was adopted to enhance radiation cooling effect. A finite element program ANSYS was used to analyze thermo-mechanical behavior of a single and multi-slice targets. To validate the design, an electron beam at the energy of 50 keV was used to test a single slice target. A good agreement of the hot spot temperature was achieved between the simulation and measurement. For multi-slice targets a series of ANSYS analysis was performed in search of the optimal design. Target design parameters for the isotope beam production, which can sustain an incident 400-kW ^{238}U beam, have been found.

1. Introduction

In-flight fragmentation is a method to produce high-energy rare isotope beams by nuclear reactions such as projectile fragmentation or in-flight fission with use of a thin target [1]. An isotope beam of interest is selected by in-flight fragment separator composed of an array of magnets and energy degraders while unreacted primary and unwanted isotope beams are removed at the beam dump located downstream of the first dipole magnet. Fig. 1 shows a layout of the separator's front end, where the target and the beam dump are indicated. The layout of the entire separator can be found in Ref. [2]. The rare isotope science project (RISP) is underway in Korea to facilitate various isotope beams produced by in-flight fragmentation and ISOL methods for nuclear science users [3].

The target is made of low atomic number materials to efficiently induce fragmentation reactions of the primary beam. Graphite and liquid lithium have been considered [4,5], and the graphite target was chosen for the baseline design.

A representative isotope to be produced by ^{238}U fission is ^{132}Sn, which is a double-magic nucleus. An optimized thickness of the graphite target is then around 1.7 mm for the energy of 200 MeV/u, which corresponds to 20–30% of the U beam range inside the graphite, and the total power dissipation is estimated to be roughly 86 kW. Removal of this amount of heat in a single-slice target is technically difficult, so the use of multi-slice target with radiation cooling enhanced has been studied [6]. The energy loss was calculated as a function of the depth in target as shown in Fig. 2 with PHITS [7], which is a heavy-ion radiation transport code to evaluate the generation of heat and radiation.

The spot size of the primary beam is 1 mm on the target, which contains more than 90% of the beam, in order to maintain high momentum resolution to separate an isotope beam of interest from other nuclei. The maximum power density inside the target on the beam spot is around 60 MW/cm^3. The power deposit is assumed to be uniform in the area of beam bombardment, and target rotation is not considered.

Since the beam power deposit is high, optimal dimensions of the target were studied in thermo-mechanical aspect using ANSYS [8]. Thickness of a single slice was determined by considering the mechanical strength as well as radiation cooling. The maximum hot-spot temperature allowed is set to be 2000 °C considering sublimation rate of graphite in vacuum [9].

Single-slice graphite targets were tested with an electron beam at the energy of 50 keV to study thermo-mechanical properties of a rotating graphite disk. In the beginning, a single-slice target of uniform thickness with a diameter of 13 cm was used, which is shown in Fig. 3. After electron beam irradiation, cracks were found adjacent to the area grabbed by an aluminum frame for rotation. Rigidity of the single slice was reinforced by tapering at the radius of 4 cm to be thicker in the inner region as shown also in Fig. 3.

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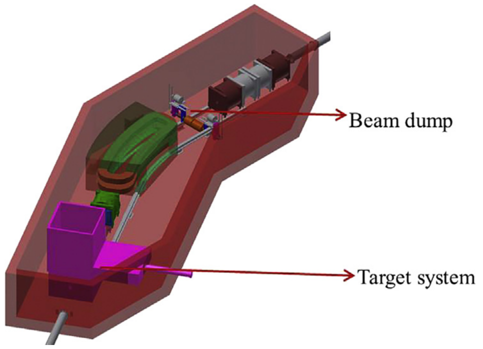

Fig. 1. Layout of the front end of the pre-separator. The locations of the target and the beam dump are indicated.

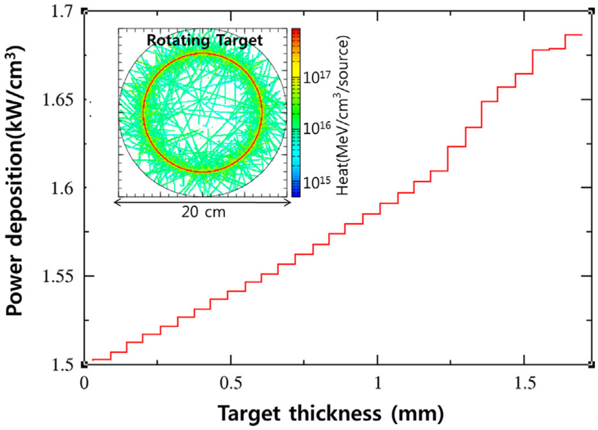

Fig. 2. Beam energy deposit estimated by PHITS calculation for a graphite target of 1.7 mm thick. Heat deposit is assumed to be uniform at the radius of beam bombardment as shown as a red circle in the insert graph. The target is fixed. PHITS does not compute the heat transport so that heat deposits by the primary and secondary ions are indicated as their tracks.

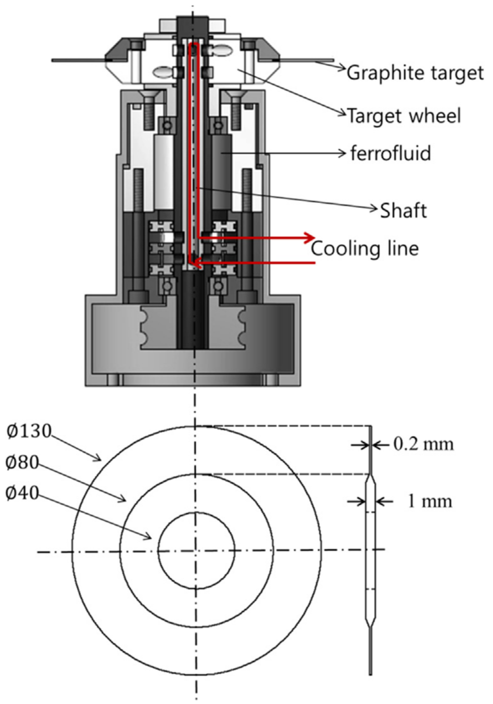

Fig. 3. Upper: a sectional view of the rotating graphite target system and lower: dimensions of the tapered target.

2. Graphite target design

Rotating graphite targets have been used for in-flight fragment separator and for muon production [10,11], in which power dissipation inside the target is very high. Cooling and thermo-mechanical aspects in the target have been analyzed using ANSYS considering the maximum power density of 60 MW/cm^3, which stems from the required beam size of 1 mm. Main input parameters for ANSYS simulations are listed in Table 1. Thickness of a single slice was chosen to be 0.2 mm and the power deposit per slice was up to 10 kW. Steady state solutions only were calculated assuming a fixed heat source on the beam hitting area of a ring-shape. Thus, temperature fluctuation due to finite rotational speeds was not calculated.

2.1. Thermal analysis

The hot spot temperature versus the beam power was calculated using ANSYS when the diameter of the target and the location of beam hitting from the edge of the target were varied as shown in Fig. 4, which includes radiation cooling with emissivity of 0.85 assumed for graphite. The peak temperature on the graphite did not change much with the ambient temperature varied from 26 °C to 100 °C in case that the hot spot temperature is well over 1000 °C. Dependence of the peak temperature on the beam hitting location is stronger for smaller diameter targets. When the emissivity differs from 0.85 by ± 0.5, the hot spot temperature varies by about ± 40 °C. The hot-spot temperature depends more noticeably on the size of the target, and simulation results are summarized in Table 2 for the two diameters of 30 cm and 40 cm as a function of beam power deposit in a single-slice target.

For a multi-slice target, the temperature distribution on each slice depends on the configuration of neighboring slices and the cooling panel structure. To investigate this effect, a simplified model employing three slices was used as shown in Fig. 5. Hot spot temperatures on the middle and outer slices were calculated as

Table 1
Input parameters for ANSYS simulations on the graphite target.

Parameter	Value
Power deposit per slice	4–10 kW
Emissivity of graphite	0.8–0.9
Ambient temp.	20–100 °C
Beam hit distance from outer edge	1.5–2.5 cm
Target thickness on beam spot	0.2 mm

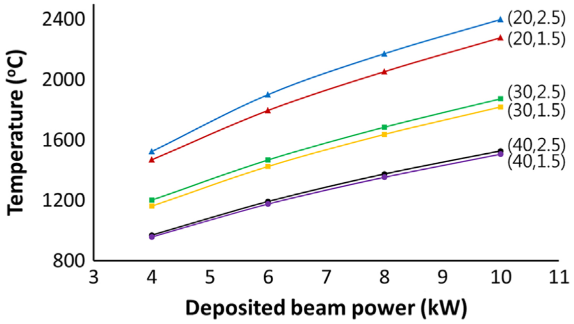

Fig. 4. The hot spot temperature versus the beam power deposit for different dimensions of a single slice target calculated with ANSYS assuming a fixed target. The target diameters and the locations of beam hitting are written in parenthesis, respectively, in unit of centimeter.