Design study of 10 kW direct fission target for RISP project

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Abstract. We are developing Isotope Separation On-Line (ISOL) target system, which consists of 1.3 mm-thick uranium-carbide multi-disks and cylindrical tantalum heater, to be installed in new facility for Rare Isotope Science Project in Korea. The intense neutron-rich nuclei are produced via the fission process using the uranium carbide targets with a 70 MeV proton beam. The fission rate was estimated to be $\sim 1.5 \times 10^{13}/\text{sec}$ for 10 kW proton beam. The target system has been designed to be operated at a temperature of $\sim 2000^\circ\text{C}$ so as to improve the release efficiency.

Production and delivery of high purity intense of Rare Isotope Beam (RIB) have been a major concern for fundamental research fields such as astro- and nuclear-physics as well as applied research field such as material and bio-medical science. Rare Isotope Science Project (RISP) of Korea has proposed to construct Isotope Separation On-Line (ISOL) facility in order to provide the intense rare isotopes. The ISOL target enables us not only to produce the nuclei with the medium mass neutron-rich region but also to obtain their high production rates. A uniform 70 MeV proton beam with a maximum current of 500 μA , which is delivered from a cyclotron driver, will impinge on an uranium carbide target. The neutron-rich isotopes are produced via proton-induced fission. A singly charged ($1+$) RIB is produced and extracted from the target and the ion source, respectively, then the beam emittance is reduced by a RF-cooler to be 3 $\pi\text{mm mrad}$ before injecting to the high resolution mass separator (HRMS). The isotopes selected by the HRMS are delivered to an electron beam ion source (EBIS) or an electron cyclotron resonance (ECR) type charge breeder so as to breed the charge from the 1^+ charge state to a n^+ charge state for efficient and economical post-acceleration. An A/q separator is installed at the downstream of the charge breeder to purify the ion beam contaminated during charge breeding. Here, we report on the results of the ISOL target design for 10 kW proton beam.

The main issues concerning the design of the ISOL target can be divided into three categories; in-target fission rate, release time, and temperature of the target. Firstly, a total effective thickness of the target should be as thick as possible in order to maximize the in-target fission rate. This requires a large size of the target. Secondly, release time should be as short as possible so as to minimize the losses by the decay of isotopes. A small size of the target helps to reduce the release time by decreasing the flight length of the isotopes. However, it should be noted here that the small size can lead to melt down of the target due to the reduced radiant cooling. Lastly, the temperature of the target should be as high as possible to increase the thermal velocity of the isotopes, which leads to the reduction of the release time. Therefore, the correlations between the three points mentioned above should be investigated so as to find the optimum condition for the ISOL target.

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Figure 1. Schematic view of 10 kW-ISOL target being designed in RISP.

Figure 2. Temperature distributions of the Ta heater (a) and the UC_x disks (b) for the homogeneous incident proton beam of 50 mm diameter. The distributions in the beam direction are nearly flat in the effusion region.

Figure 1 shows the schematic view of 10 kW-ISOL target being designed in RISP. The 10 kW-ISOL target consists of two graphite windows at a front of the target, 19 UC_x disks of 1.3 mm thickness ($\rho = 2.5 \text{ g/cm}^3$, $\phi = 50 \text{ mm}$), a graphite container, a Ta-heater ($\phi_{\text{outer}} = 60.0 \text{ mm}$, thickness = 0.2 mm), graphite beam dumps located at an end of target, and a transfer line to transport the isotopes to an ionizer (hot-cavity). The design of the 10 kW-ISOL target of RISP is a scale-up version of that of SPES [1–6]. The rare isotopes are produced in the target grains by a 70 MeV proton beam incident on the uranium carbide (UC_x) target via the proton-induced fission. We employ the 70 MeV proton beam in order to use thicker target than that of SPES. The effective thickness of UC_x for RISP is much thicker than that for SPES [1] by a factor of ~ 2 – 3 . The isotopes produced in the UC_x grain diffuses out of the grain (diffusion), then effuses out of the UC_x disk (inter-grain effusion). After that, the isotopes move to an entrance of the hot-cavity by the thermal motion (free effusion).

A power deposition and a fission rate were calculated using the Monte Carlo radiation transport code MCNPX (ver. 2.6.0) [7]. Since the proton beam is spread out in space as it passes through the UC_x disks, which is due to the Coulomb multiple scattering, the proton flux in the rear disks become lower than those in the front disks. The power depositions in the 19 UC_x disks, the graphite container, and the dumps were calculated to be ~ 5 , ~ 3 , and $\sim 2 \text{ kW}$, respectively, for the homogeneous proton beam of 50 mm diameter. The distribution of the power deposition in the beam-direction (z -axis) mainly depends on the axial spacing of the UC_x disks and the proton beam size.

The temperature of the target was calculated using the Finite Element model code ANSYS combined with the results of the code MCNPX. Thermophysical properties of graphite and tantalum taken from Refs. [8, 9] were used for thermal analysis. The thermal conductivity and the total hemispherical emissivity of UC_x disk were assumed to be $k = 10 \text{ W/m}^\circ\text{C}$ and $\epsilon = 0.80$, respectively, for 2000°C . Fig. 2 shows the temperature distributions of the Ta heater (a) and the UC_x disks (b) for homogeneous incident proton beam of 50 mm diameter. The target is located inside an Al-alloy vacuum chamber of 40°C . Both power deposition calculation and thermal analysis were performed by varying the axial spacing between the UC_x disks iteratively to achieve uniform distribution of the temperature

Figure 3. (a) Maximum normal stress in all of UC_x disks as a function of the homogeneous beam diameter. Radial (b) and circumferential (c) thermal stresses in front UC_x disk, which were calculated using the code ANSYS, for homogeneous incident proton beam of 45 mm diameter.

Figure 4. (a) A trajectory of a ¹³²Sn isotope from the UC_x disk to an entrance of hot-cavity, which was calculated using the Monte Carlo simulation code RIBO [11]. (b) Calculated release efficiencies as a function of the half live of ¹³²Sn. The black-square and the red-circle lines correspond to the results of release efficiencies for RISP and SPES [3], respectively.

in the beam-direction. A narrow spacing of the disks leads to temperature rising due to the reduction of view factor from the disk to the container.

While a smaller beam size gives us higher in-target fission rate due to the reduction of protons scattered to the container from the UC_x disks, it plays a role to increase a temperature difference between the center and the edge of disk, which may lead to a fracture by thermal stress. We optimized a diameter of homogeneous proton beam taking into account the thermal stress, adopting the elastic modulus ($E = 176$ GPa) and the coefficient of linear thermal expansion ($\alpha = 12.4 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$) of the UC_x disk reported in Ref. [10] for 2000 °C. The elastic modulus for 2000 °C is extrapolation value from that for 1500 °C. Figure 3(a) shows the maximum value of the normal stresses in all UC_x disks as a function of the homogeneous beam diameter. The fracture begins if the diameter of the beam is smaller than ~44 mm, which is represented by the blue-dashed line. We determined the appropriate beam diameter to be 45 mm in the present design. Figure 3(b) and (c) represent radial and circumferential thermal stresses in the front UC_x disk, which was calculated using the code ANSYS, where the negative and positive values correspond to the compression and tension stresses, respectively.

The release efficiencies of ^{132,133}Sn were calculated using the code RIBO [11], combining with the results of the in-target fission rate calculation and the thermal analysis. In the simulation, the ^{132,133}Sn isotopes were generated in all UC_x disks to reproduce the z -position distribution calculated by the code MCNPX. The random collision between the isotope and the grain was determined by the

mean free path. The possibility of re-absorption into the UC_x disk was taken into account. All of the collisions were described by the cosine law [12]. The velocity of the isotope was sampled from the Maxwell-Boltzmann distribution at a surface temperature. The sticking time (T_s), which corresponds to the mean time of retention of an atom on a surface, and the mean free path reported in Ref [11] were adopted in the calculation assuming the diffusion time (T_D) is 1 sec. The sticking time on the container (graphite) was assumed to be 10^{-6} sec which is same value with that on the UC_x for the Sn isotopes. The total mean number of collisions before ejecting from the transfer line was calculated to be $\sim 3.5 \times 10^5$.

Fig. 4(a) represents a trajectory of a ^{132}Sn isotope from the UC_x disk to the entrance of hot-cavity. Fig. 4(b) represents the calculated release efficiency at the exit of the transfer line as a function of the half live of ^{132}Sn , comparing with that of SPES [3]. The black-square and red-circle lines correspond to the results of the calculated release efficiencies for RISP and SPES, respectively. Although the release efficiency of the 10 kW-ISOL target for RISP is lower than that of SPES, we are expecting more higher (or comparable) release rate due to the higher in-target fission rate. The total in-target fission rate was calculated to be $\sim 1.5 \times 10^{13}$ particles/sec using the code MCNPX. The release rate of ^{132}Sn at the exit of the transfer line was deduced, using the ORNL model [13], to be $\sim 2 \times 10^9$ particles/sec which is comparable to the value of $\sim 10^9$ particles/sec for SPES [3].

Summary

In summary, we are developing ISOL target consisting of 1.3 mm-thick uranium-carbide multi-disks for Rare Isotope Science Project (RISP) in Korea. The in-target fission rate in the ISOL target was estimated to be $\sim 1.5 \times 10^{13}$ /sec for 10 kW proton beam at a beam energy of 70 MeV. The overall size of target and the disk spacing were optimized to maximize the release rate at a temperature of $\sim 2000^\circ\text{C}$ without ohmic heating. Release efficiency was calculated to be ~ 95 and $\sim 26\%$ for $^{132,133}\text{Sn}$ isotopes, respectively.

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