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High power density targets

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ABSTRACT

In the context of new generation rare isotope beam facilities based on high-power heavy-ion accelerators and in-flight separation of the reaction products, the design of the rare isotope production targets is a major challenge. In order to provide high-purity beams for science, high resolution is required in the rare isotope separation. This demands a small beam spot on the production target which, together with the short range of heavy ions in matter, leads to very high power densities inside the target material.

This paper gives an overview of the challenges associated with this high power density, discusses radiation damage issues in targets exposed to heavy ion beams, and presents recent developments to meet some of these challenges through different projects: FAIR, RIBF and FRIB which is the most challenging. Extensive use of Finite Element Analysis (FEA) has been made at all facilities to specify critical target parameters and R&D work at FRIB successfully retired two major risks related to high-power density and heavy-ion induced radiation damage.

1. Introduction

Next-generation high-power rare isotope beam facilities in the world using the in-flight method have been and are being built: the Rare Isotope Beam Factory (RIBF) at RIKEN in Japan [1] in operation and the Facility for Rare Isotope Beams (FRIB) at Michigan State University, USA [2], the Facility for Antiproton and Ion Research (FAIR) at GSI in Germany [3] are under construction. With beam powers at these facilities ranging from about 40 kW (FAIR) to 400 kW (FRIB), similar technical challenges exist. FRIB, with primary beam up to 400 kW and 200 MeV/u will be the world's top rare isotope beam facility for the next generation.

In order to provide high-purity beams for science the beam spot on the production target needs to be of the order of 1 mm diameter in order to achieve a good resolution of the fragment separator following the production target. Together with the short range of heavy ions in matter this creates a situation of very high power densities inside the target material which makes the realization of reliable high-power production targets for in-flight rare isotope production challenging. Static solid targets as used at low-power facilities (FRS at GSI or A1900 at NSCL) are no longer feasible and rotating targets are needed if solid material is used. The technical challenges to face include overheating and excessive thermo-mechanical stress load variations caused by the high beam intensity and target rotation that can lead to material fatigue and creep and can limit the target lifetime.

In addition to the high-power density challenge, irradiation of the target material with swift heavy ions will result in radiation damage of the material, leading to changes in the structure and of thermo-mechanical properties and also lead to a decrease in target lifetime.

2. High power target technology

Rare isotope production at RIBF [1], FRIB [2], and FAIR [3] relies on fast heavy ion beams impinging on high-power production targets. Table 1 summarizes beam and target parameters for these facilities.

An important aspect in high-power target design is to limit the maximal temperature due to the beam energy loss in the material. The control of this absorbed power is proving to be one of the key challenges. One step towards limiting the heating is mounting the targets on a rotating wheel in order to spread the power deposition into a larger volume and area. Such a rotating target concept has been adopted by all three facilities.

Different primary beams (up to U beam) are needed to do the science. They have a wide range of specific energy loss in target material with Uranium having the largest loss. Depending on the primary beam, targets with different thicknesses are necessary for most efficient rare isotope production and high resolution mass separation.

At the rare isotope beam separators BigRIPS [1] at RIBF and Super-FRS at FAIR [3] single-slice targets are used uranium beam powers well below 100 kW. The Advanced Rare Isotope Separator

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Table 1
Primary beam and target parameters for Super-FRS (FAIR), BigRIPS (RIBF) and ARIS (FRIB) production target system.

Parameters	Super-FRS FAIR at GSI	BigRIPS RIBF at RIKEN	ARIS FRIB at MSU
Primary Beam Energy [MeV/A]	Up to 2700	Up to 350	Up to 266
Max. Primary Beam Power [kW]	36	100	400
Max. Power for Uranium Beam [kW]	28	86	400
U Beam Power density in target [MW/cm^3]	0.6	5.7	60
Target material	Graphite	Be, Graphite, W	Graphite
Total target thickness [g/cm^2]	1–8	1–6	0.3–8
Slice thickness [mm]	–	–	0.2–20
Target operation time	1 year	2–4 weeks	2 weeks
Target diameter [cm]	45	30	30
Rotational speed [rpm]	60	100–300	5000
Average temperature T_{avg} ± variation T [°C]	750 ± 25	1550	1900 ± 200

ARIS at FRIB [5] will use a multi-slice rotating target in order to cope with the 400 kW power that will be available at this facility.

2.1. Single slice targets

For BigRIPS a water-cooled target was developed [6]. The disk made of graphite, beryllium or tungsten has a diameter of 30 cm and thicknesses from 1 to 6 g/cm^2 depending on the atomic number (Z) of the projectile and the selected energy. The thickness of the target is stepped in order to be able to adjust the target thickness without a target change. The aluminum disk is cooled by water through a double-piped shaft, as shown in Fig. 1. A ferromagnetic rotary feed-through provides the mechanical transition from atmospheric pressure to the inside of the vacuum chamber [7]. The rotation of the target inside the vacuum chamber is achieved using a motor located outside the vacuum chamber. The power density in the target from the continuous beam provided by the RIBF cyclotron complex can reach values up to 5.7 MW/cm^3 if the target is not rotated.

The Super-FRS production target for slow-extracted beam [8,9] is based on a rotating single-slice target. The target assembly consists of a graphite wheel, with a radius of 22.6 cm and an optimum thickness between 1 and 8 g/cm^2. Graphite was chosen due to its low mass number which yields a high cross-section for production of fragments relative to the amount of energy deposited in the material. It can also operate at high temperatures, making it possible to cool the target wheel by radiation only. Similar to the BigRIPS targets the thickness is stepped. The target wheel is connected to a bearing housing at the axle by several spokes, as shown in Fig. 2. The power density inside the Super-FRS target, if not rotating, can reach values up to 1 MW/cm^3.

2.2. Multi slice target

In order to deal with the most challenging high beam power of 400 kW at FRIB, the production target [4] for the Advanced Rare Isotope Separator (ARIS) [5] is based on a novel concept similar to that for Super-FRS, except that a multi-slice approach has been chosen in order to provide an increased radiation area to more efficiently dissipate the large amount of heat deposited in the target. In its design, shown in Fig. 3, the ARIS graphite multi-slice target has a diameter of 30 cm with thicknesses from 0.3 to 8 g/cm^2. The target slices rotate between the fins of a water-cooled heat exchanger which absorbs the radiated heat from the target. The slices are not stepped and in order to provide different total target thicknesses the target module will have to be exchanged for different primary beams. The maximal extension of the target in the beam direction is limited to a maximum of 50 mm in order to preserve the resolving power of the fragment separator. This condition limits in a binding manner the space available between the slices to insert cooling fin (Fig. 3). The power density in the FRIB production target would reach values up to 60 MW/cm^3, if the target was not rotated.

3. Thermo-mechanical challenges

Many technical issues have to be faced in the development of rotating target systems for high-power primary beams. High temperature management is needed for avoiding material melting, minimizing evaporation, maximizing heat transfer and dealing with thermo-mechanical challenges such as fatigue, shock wave

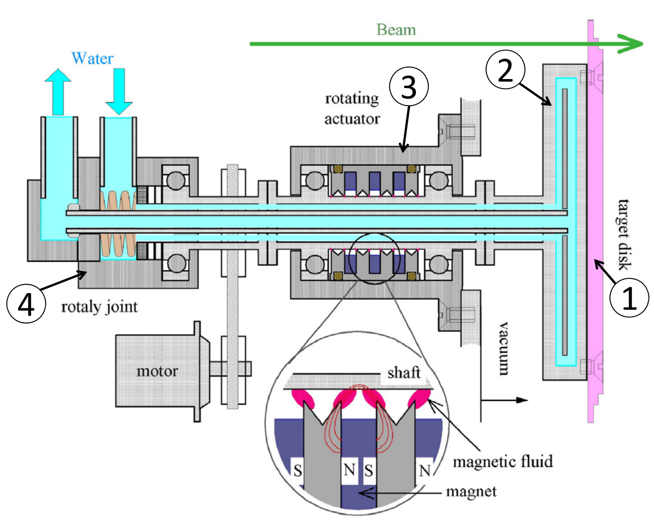

Fig. 1. Cross-section view of the BigRIPS production target [7] inside the target irradiation chamber: target disk (1), water-cooled disk (2), vacuum-tight rotating actuator (3), rotary-joint (4). In the actuator (3), drops of magnetic fluid are held by permanent magnets and play a role of liquid O-Ring. The beam axis is parallel to and offset from the axis of the rotating targets.

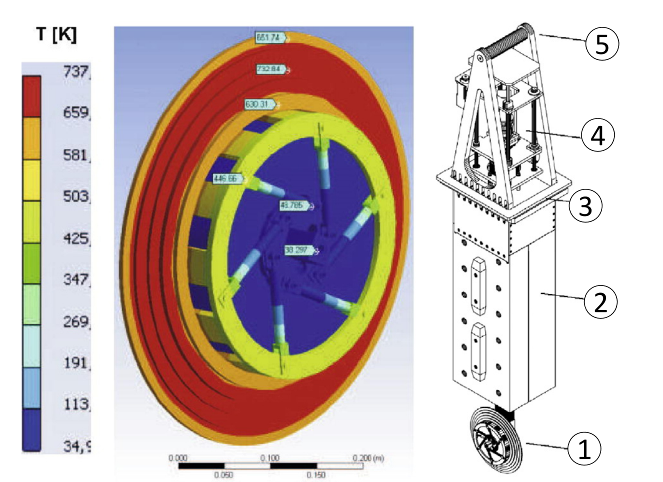

Fig. 2. Super-FRS production target. Left – Graphite target wheel with calculated surface temperature distribution [8]. The target is irradiated with a ^{238}U beam with 1 GeV/u and an intensity of 10^{12} ions/s. Right–Drawing of the target plug. The target wheel (1) is mounted at the bottom, drives (4) and a hook (5) for target removing are mounted above the vacuum seal (3) and shielding (2) [9].