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THERMAL ANALYSIS OF ROTATING SINGLE SLICE GRAPHITE TARGET SYSTEM FOR FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is a high power heavy ion accelerator facility at Michigan State University completed in 2022. Its driver linac is designed to accelerate all stable ions to energies above 200 MeV/u with beam power of up to 400 kW. Currently FRIB is operating at 10 kW delivering various primary beams. The target absorbs roughly 25% of the primary beam power and the rest is dissipated in the beam dump. This paper presents a brief overview of the current production target system and details the thermal analysis ANSYS ® simulations utilized for temperature and stress prediction. The existing single-slice rotating graphite target can accommodate up to 40 kW for lighter beams, with a planned transition to a multi-slice concept.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), a major nuclear physics facility for research with fast, stopped, and reaccelerated rare isotope beams, has adopted an incremental approach toward the ultimate design beam power of 400kW by safe operation and avoiding any possible damage to the machine. Currently, FRIB routinely delivers 10 kW primary beams on target, producing rare isotopes that are separated and analyzed in the Advanced Rare Isotope Separator (ARIS) [1] shown in Fig. 1.

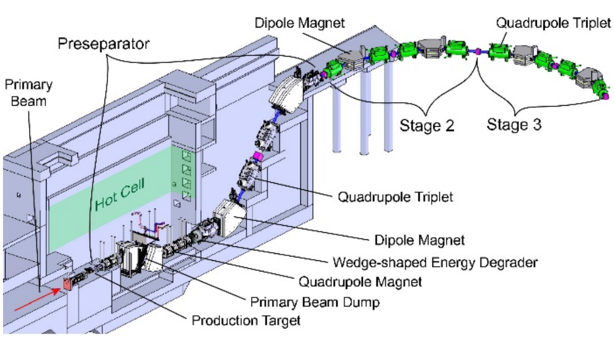

Figure 1: Overview of the design of the Advanced Rare Isotope Separator (ARIS) at FRIB [1]. The primary beam from the driver linac reaches the production target from the bottom left in the figure, as indicated by a red arrow. The first part of the preseparator is located inside of a hot cell that is part of the production target facility. The extent of the hot cell is indicated schematically.

The FRIB target system as shown in Fig. 3 consists of a 30 cm rotating graphite disk of known thickness. The graphite grade is 2360 with 5 μm grain size procured from MERSEN USA ® [2]. The thickness of the graphite disk is governed by the type of primary beam. During 10kW operations so far, the thinnest disk used is 2.1 mm and the thickest being 8mm. This graphite disk is held in place on an YSZ (YTTRIA STABILIZED ZIRCONIA) ceramic [3] hub with graphite spacers and a remote handling compatible spring loaded lock nut. The ceramic hub/spacers/target assembly gets mounted on the invar shaft. Invar was chosen for its low thermal expansion. Current system uses low temperature (~150-200C) bearings to support the shaft, hub, spacers and target with a modest 500 rpm operational speed. These bearings have 52100 bearing steel races and balls with a phenolic cage. The primary cooling mechanism for the target is radiation cooling. A water cooled copper heat exchanger with a swivel door (for remote handling operations) encases the entire target assembly. This cylindrical copper heat exchanger has water cooling on its three faces. Water flow rate through the cooling line for the door and rear is about 0.375 GPM and 7 GPM for the side of HX. In order to enhance the radiative cooling at power at 10kW power and beyond, the internal surfaces of the Heat exchanger were coated with a high emissivity paint remotely. The door could only be coated up to 50% as shown in Fig. 2

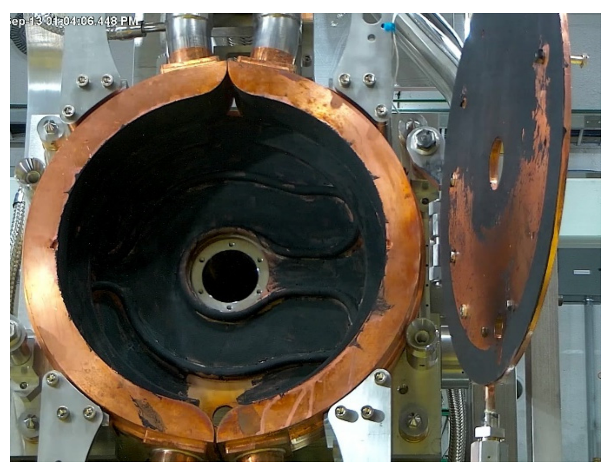

Figure 2: FRIB Target Heat Exchanger (HX) coated with high emissivity paint

In order to minimize the emittance of the rare isotope beams, the primary beam at FRIB is focused into a 1 mm diameter beam spot size (90% of the beam inside the 1 mm diameter) on the FRIB production target.

Current diagnostics allows reading the maximum temperature on the target through the beamport and there are two RTD's on the cooper door. There is currently no temperature measurement for the shaft and the bearings. This makes the simulations all the more crucial. One of the weakest link in the system is the bearings with an estimated

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lower working temp limit of 150°C. Studies done in the past focused more on the target and speed optimization. Current study aims to encompass the whole model including the shaft and the bearings.

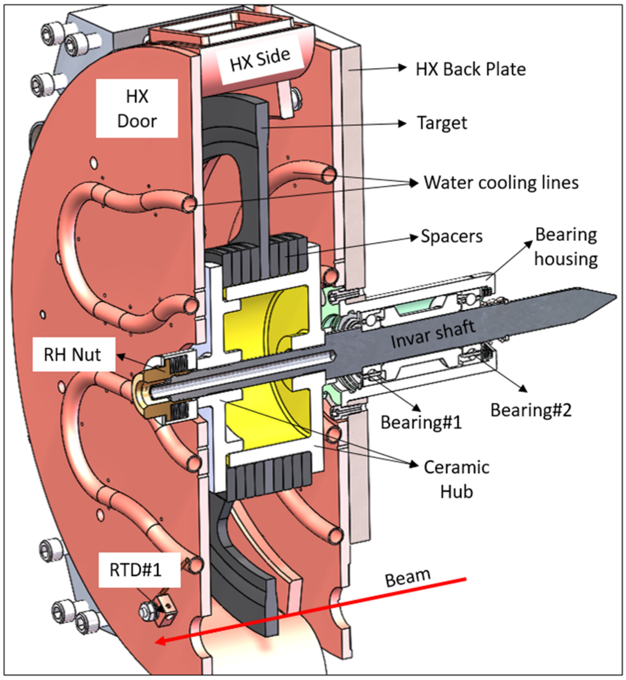

Figure 3: FRIB Target assembly with key components

ANALYSIS MODEL

The entire target assembly which was modeled in solidworks CAD software was imported to ANSYS WB. Due to the non-symmetrical nature of the target assembly, a reduced model was not possible. Some of the important material properties used in the analysis are tabulated in Table1.

Table 1: Material properties used for analysis

Material	Emissivity	Thermal Conductivity (W/m·°C)
Graphite	0.85	88
Ceramic	0.5	2.2
Invar	0.2	14.1
52100 Bearing Steel	-	45
Stainless Steel	-	15.3
Coated copper	0.8	386

The temperature of the hottest spot on the target is calculated in two steps:

Step 1: Calculation of the average steady state temperature assuming infinite RPM

Step 2: Calculation of the variation of temperature ΔT as a function of RPM

This is illustrated in Fig. 4. The R&D for the single and multislice target technology is discussed elsewhere [4]

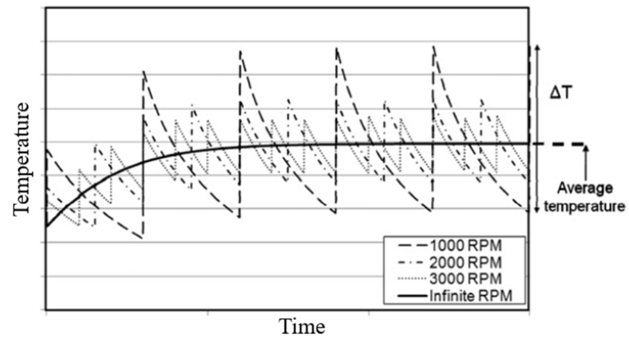

Figure 4: Temperature variation of the hottest spot on the rotating target. The continuous line corresponds to an infinite RPM and the 3 dotted line to a velocity from 1000 to 3000 RPM.

Step 1 target temperature is calculated from the global ANSYS steady state thermal model. Step 2 target ΔT is calculated from a simplified FLUENT ® model

For the steady state analysis, the power is deposited volumetrically into a 1mm diameter annular section and thickness equal to the target thickness. Actual power absorbed by the target depends on the type of beam run and the thickness of the target used. A convection coefficient is calculated based on the flow parameters. 3400 W/m^2.C for the HX door and HX back. 3700 W/m^2.C for the HX side. These are applied to the cooling water lines. An additional 500 W/m^2.C is applied to the back surface of the stainless steel HX back plate to mimic a large water cooled copper block which is used as a radiation shield for the motor.

Surface to surface radiation is modeled for all parts inside the HX. Separate enclosure is used for radiation transfer from the inside of the ceramic hubs to the invar shaft. The emissivity values utilized are shown in Table1. These are based on the measurements made in the lab.

All surface to surface contacts are modeled with estimated thermal contact conductance (TCC) values. TCC is based on material, surface finish and contact pressure. Graphite to graphite TCC is estimated based on literature [5]. To validate these assumed conductance values, in-situ temperature measurements with thermal paints and offline testing are planned. These paints change color when a certain temperature limit is reached. These paints can be applied to certain key areas like the hub and shaft before a beam run and color change analyzed at the next target change remote handling.

RESULTS

Comparison of measured temperatures with simulation is shown in Table 2. Three different beam scenarios with different target thickness are shown in the table. The measured hot spot temperature of the target matches closely with the simulated numbers. Results for the 238U run are discussed more in detail here.

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Table 2: Measured vs simulation data from 10kW Operations

Primary Beam	Target thick-ness	**Measured** Avg. ΔRTD	Target T	**Simulation** Avg. ΔRTD	Target T
	mm	C	C	C	C
28Si	8	4.5	887	6.5	865
238U	2.1	4.5	1004	7.1	1032
82Se	5	3.6	792	5.6	770

Figure 5 shows the beam thermal image on the target as seen by the camera though the window for 238U run. The power deposited into 2.1mm target disk for this case was 3.8kW. The measured hot spot target temperate was 1004°C. The simulated target temperature of 1032°C (T_∞ =902°C & ΔT_{500} = 130°C) matches closely with the measurement.

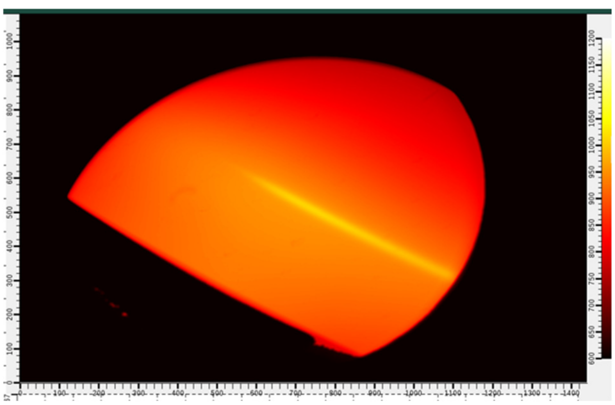

Figure 5: 238U beam thermal image on the target. Maximum recorded temperature was 1004°C

Estimated bearing temperature predicted was under the allowable limit of 150°C. The temperature profile of the Invar shaft is shown in Fig. 6. The location where the bearings are mounted on the shaft stay relatively cool. The radial expansion of the shaft at these locations is miniscule because of extremely low CTE of invar at those temperatures.

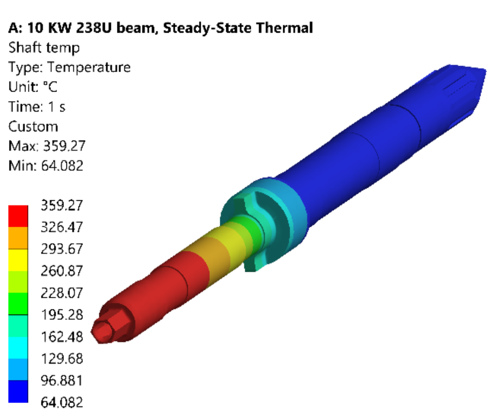

Figure 6: Predicted temperature profile of the Invar shaft for the 238U beam run

The temperature of the door measured with RTD's is slightly off from the simulated values. This can be due to various factors. The RTD's are mounted on a separated piece of metal and bolted to the door. There may be a slight temperature gradient though this. The high emissivity paint on the door is uneven which may cause variations in temperature. The water cooling convection coefficient may vary slightly from the calculated value.

Figure 7 shows the Maximum Principal stress for the 2.1mm target disk rotating at 500 rpm. 19.72 MPa of stress is found at the inner corner of the target disk cutout. The stress at the beam spot is about 9 MPa. These stresses are well below the tensile strength of 51 MPa for the graphite disk.

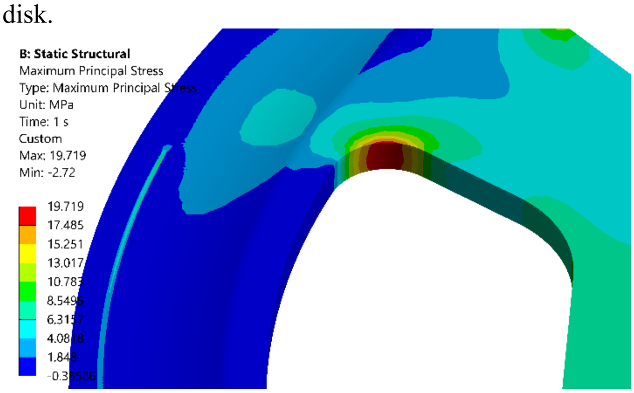

Figure 7: Max Principal stress in the 2.1mm graphite target for the 238U beam run. The line near the periphery shows the beam spot stress.

CONCLUSION

Current thermal analysis simulations can predict the maximum target temperature within reasonable limits. The simulations results can be used to predict the upper power limit of current system components and design for upgrades as FRIB ramps up to higher power. Analysis results show that the current setup with modest updates can operate up to 40-50kW depending on the beam type.

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