ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG36

MECHANICAL DESIGN OF THE THERMAL IMAGING SYSTEM FOR THE FRIB TARGET*

S. Rodriguez†, S. Lidia, I. Nesterenko, M. Hausmann, M. Patil,
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

As the Facility for Rare Isotope Beams (FRIB) ramps up to 400 kW, a thermal imaging system (TIS) is essential to monitor the beam spot on the production target. The TIS is an array of mirrors and a telescope in the target vacuum chamber; this relays the image through a window to the camera module outside the chamber. The design presented many challenges from alignment, to remote installation of the TIS and integrated shielding, and repeatable re-installation of the mirror array and optics module.

The target TIS has been in operation since 2021 and supports FRIB operations for secondary beam production, with incident power up to 10 kW. The temperatures seen validate the expected temperatures from analysis. The mechanical design of the FRIB target TIS is presented here as well as initial performance.

INTRODUCTION

The target at the Facility for Rare Isotope Beams (FRIB), in its current configuration, is a 30 cm diameter rotating graphite disk used in the production of rare isotopes by absorbing approximately 25% of the delivered primary beam power (10 kW). As FRIB ramps up power to an eventual 400 kW, thermal diagnostics of the target becomes more and more important to ensure it does not reach a temperatures that prohibit its use. The way FRIB monitors the temperature at the beam spot is with the Thermal Imaging System (TIS). The TIS is a mirror array designed to relay the image of the target up to a camera module outside the target vessel. Figure 1 shows an overview of the target module, TIS, and the camera module. For scale, the vessel that these reside in (the target vessel) is ~4 m deep. These reside in the Target Hall alongside the Beam Dump and energy degrading Wedge assembly.

Some of the challenges in making this design work are the long image path from the object plane at the target and the image plane at the cameras, thermal expansion of the system due to the proximity to the target, radiation transport challenge through the optical path, and initial alignment. These challenges are augmented by the lack of accessibility in the target vessel and the expected and experienced radiation levels in the target hall resulting in the need for remote manipulation and installation.

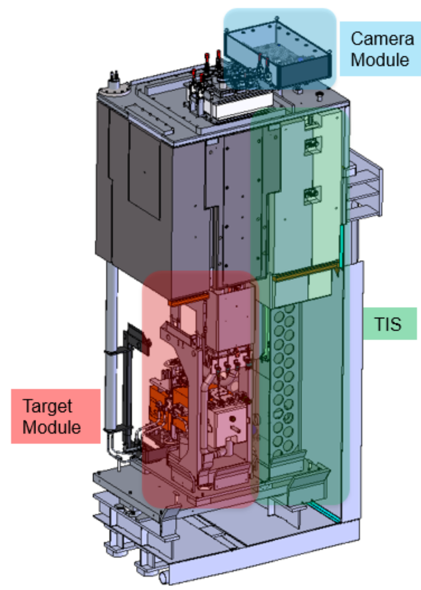

Figure 1: Target and TIS.

MECHANICAL DESIGN

Optical Design

The mechanical design is first anchored to the optical path of the system.   shows the optical design; this is comprised of five flat mirrors and a pair of Cassegrain telescopes. The Cassegrain telescopes are comprised of four spherical mirrors. Mirror #1 is made entirely of copper as this is in very close proximity to the target. All the other mirrors, including those of the telescope, are fused silica (quartz) with a silver coating on the reflective face.

The purpose of the telescope here is to focus the image and reduce the size of the viewport. Also, as the system requires shielding in the vacuum chamber, this allows the size of the shielding opening to be smaller. As the target image is relayed through the mirrors, the size of the mirrors required is larger and larger; the telescope takes in the diverging image and focuses it at an equal focal distance as the target; hence, the telescope is mid-way in the optical path. Using this telescope allows us to use the same size mirrors for #2 & #5 (4 in) as well as the same mirrors for #3 & #4 (6 in). The resulting clear aperture requirements for the viewport is 2.75 in for which a 3 in viewport is used on a 4.5 in conflat. The telescope spherical mirrors are 7 in & 2.9 in in diameter for the primary and secondary mirrors respectively. These have a spherical surface with radii of 160 cm for the primary mirror & 320 cm for the secondary

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
†rodrigus@frib.msu.edu

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG36

mirror. The development of the optical system was designed in part using Zemax software and Monte-Carlo simulations; more details of this design can be found in [1].

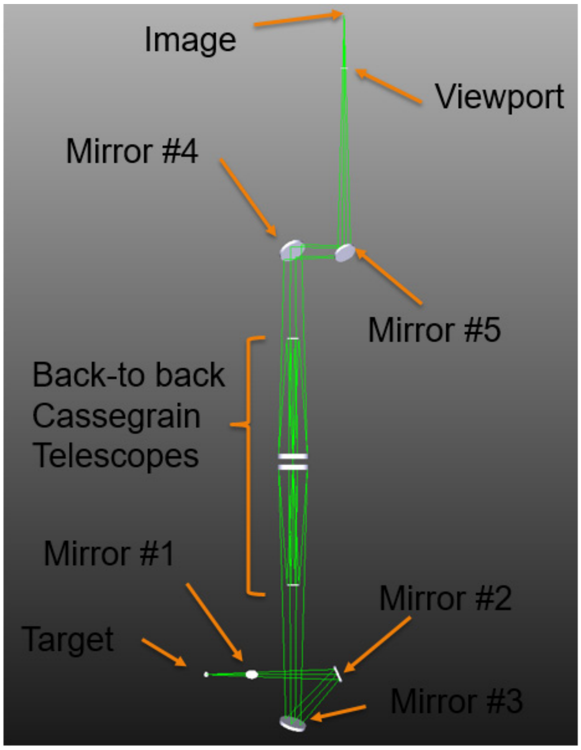

Figure 2: TIS Optical Design.

Frame Thermal Design

As the target is expected to heat-up from the beam, the environment is also expected to heat-up due to some conduction and radiated heat transfer. To address this factor, the TIS frame and the individual mirror mounts are designed out of Invar 36. Invar has a very low coefficient of thermal expansion (1.3 µm/m-C°) compared to other structural materials such as stainless steel (18 µm/m-C°). With the Invar frame, and a maximum temperature of 66°C, less than 0.5mm of displacement to the mirrors is expected.

Table 1 shows the displacement of each mirror expected from thermal expansion of the frame and mirror mounts.

Table 1: Mirror Displacement from Heat

Mirror	Transverse Displacement [mm]
Flat #2	0.11
Flat #3	0.04
1st primary	0.08
1st secondary	0.03
2nd secondary	0.16
2nd primary	0.08
Flat #4	0.47
Flat #5	0.46

Shielding Design

Radiation transport was another major concern to be addressed by the TIS design. Figure 1 shows a layer of shielding blocks integrated to the target module and the TIS. To avoid a direct line of sight through which radiation could pass through the shielding, a dog-leg was built into the optical path; this is the bend with mirrors #4 & #5 as seen on . To make this passage through the shielding, this had to be designed as two pieces that fit around the TIS frame and magnets. Additionally, the shielding blocks are held together in a manner that is able to be assembled and disassembled remotely. Also, this is done in a manner that decouples the TIS frame from the shielding blocks, allowing it to settle in kinematic mounts prior to the shielding blocks settling in their place.

Alignment

Aligning the TIS was particularly challenging, as there is no hands-on access to the mirrors or telescope once installed in the target vessel. To achieve this, the target module and the TIS module are designed to mount on kinematic mounts which enables installation with a measured repeatability of ~ 0.05mm. The resulting highly repeatable spatial relationship allowed to perform the actual alignment of the TIS to the target off-line in the following stages. 1) The telescope mirrors are aligned to themselves. 2) The flat mirrors are aligned to each other with a laser. 3) The telescope is aligned as a unit to the mirrors. 4) The TIS is mounted on the target module to verify mirror alignment. 5) The camera module is aligned and focused to see a mock target on the test setup [1]. Figure 3 shows the test set up used to align the camera. The use of kinematic mounts allows us to maintain the alignment through target changes, which has been demonstrated in FRIB operations.

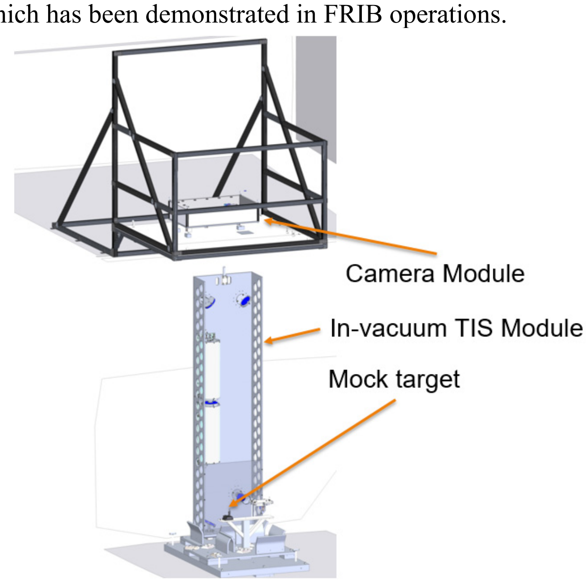

Figure 3: TIS test setup.

Assembly & Installation

Assembly and installation of the TIS requires the use of remote manipulators and a remotely controlled crane. To achieve this, the clam-shell shielding is held together with

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG36

"remote handling" fasteners, which can be fasten using through-the-wall manipulators. Additionally, the TIS module, as well as each shielding block, is equipped with a lifting stud that can be picked up remotely with a crane. Assembly of the TIS with the shielding is done on a maintenance stand that allows the shielding to be assembled around the TIS without damaging it. Figure 4 shows the TIS partially assembled in its maintenance stand. Once fully assembled, as the shielding is lifted with crane, the TIS is carried with it. As this is installed in the target vessel, on the kinematic mounts, the TIS settles in place before the shielding settles.

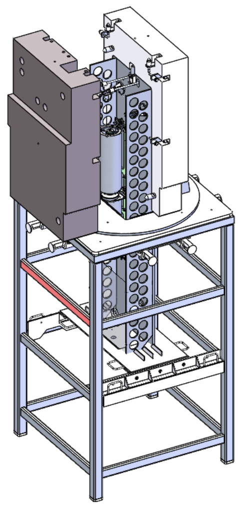

Figure 4: TIS on maintenance stand.

Camera Module

The camera module, as shown in Fig. 1, lives on the lid of the target vessel. This allows for it to be above the radiation shielding, which is favourable to longevity. The camera module consists of a mirror, three beam-splitting cubes, a photodiode, and two camera assemblies with lenses, filters, and focusers. The cameras used are not thermal cameras. In turn, two optical cameras are used, one of which has a long pass 780nm filter while the other has a wide band pass with 650nm central wavelength. These are calibrated using a black body source. This is a departure from other TIS setups that use a thermal camera with a dedicated thermal shielding box [2]. The camera module itself also rests on kinematic mounts which has allowed maintained alignment during target changes throughout operations. Figure 5 shows the FRIB TIS camera module.

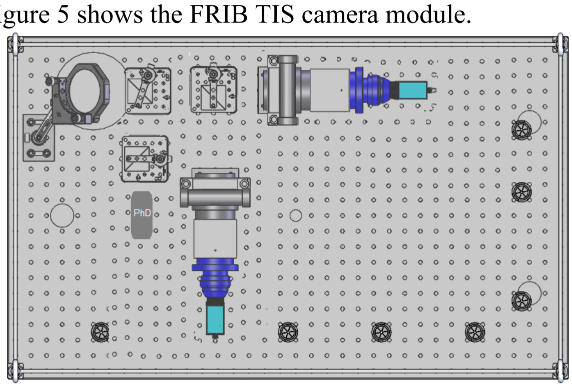

Figure 5: Camera module.

THERMAL ANALYSIS ON TARGET

Prior to running a particular beam into the target, analysis is conducted to predict the thermal effects on the target and its components. One such set of analysis focused on three types of beam, each for a different thickness of target at 10 kW [3]. Since the analyses were conducted, the facility has been able to run the beam at 10 kW to the target of those particular thicknesses. The facility has now, also, been able to take thermal images of the target during these runs, and are able to compare the simulated temperatures to the measured temperatures with the TIS.

Table 2 shows the measured and simulated results for the specific beam types. Figure 6 shows the thermal image of the target with 238U beam.

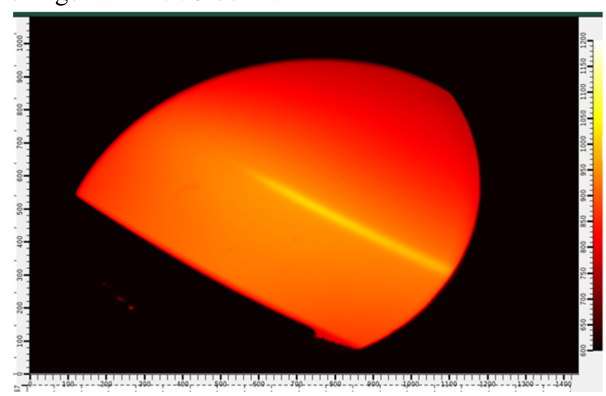

Figure 6: Thermal image of 238U beam on target.

Table 2: Measured and Simulated Data for 10 kW Operations

Primary Beam	Target Thickness	**Measured** Target Temp.	**Simulation** Target Temp.
	mm	°C	°C
28Si	8	887	865
238U	2.1	1004	1032
82Se	5	792	770

CONCLUSION

The design presented addresses the many challenges resulting particularly from the environment it lives in. Back-to-back Cassegrain telescopes were implemented to deal with the long optical path. The mirror mounts were designed and fabricated out of Invar 36 to reduce the effects of thermal expansion on the mirrors. A dog-leg was included in the optical path to deal with radiation transport through the shielding; this resulted in the shielding being constructed out of two clam-shell pieces. And lastly, the system is designed with kinematic mounts, and remote-handling provisions to allow for a remote hands-free assembly and installation of the TIS and its shielding.

FRIB has the ability to take thermal images of the target at 10 kW operation power and have been able to validate the thermal analyses conducted for multiple beam types on multiple target thicknesses.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG36

REFERENCES

[1] I. Nesterenko *et al*., Optical System for Observation of FRIB Target, NAPAC, 2019, `doi:10.18429/JACoW-NAPAC2019-TUPLE05`

[2] A. Yoshida *et al.,* "Beam-spot Temperature Monitoring on the Production Target at the BigRIPS Separator", *Nucl. Instrum. Methods Phys. Res.* vol. A655pg. 10-16, 2011 `doi:10.1016/j.nima.2011.06.011`

[3] M. Patil, J. Song, M. Reaume, M. Larmann, N. Bultman, and R. Quispe-Abad, "Thermal analysis of rotating single slice graphite target system for FRIB", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper THPS41, this conference.