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# THERMAL-FLUID ANALYSIS AND OPERATION OF A LOW POWER WATER-COOLED TILTED BEAM DUMP AT FACILITY FOR RARE ISOTOPE BEAMS (FRIB)*

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*Abstract*

The Facility for Rare Isotope Beams is a high power heavy ion accelerator completed in April 2022. The FRIB accelerator was commissioned with acceleration of heavy ions to energies above 200 MeV/nucleon (MeV/u) that collide onto a rotating single-disk graphite target. The remaining beam is absorbed by a water-cooled static beam dump that is oriented at a 6 degrees angle with respect to the beam. The beam dump consists of the beam stopper made of machined Aluminum 2219 block, and 3D-printed inlet and outlet parts made of Aluminum 6061 that deliver the cooling water from utilities to the beam stopper and its return. This low power beam dump is designed for up to 10 kW beam power. This paper presents a discussion on the thermal-fluid behavior of the beam dump for various beam species and beam power.

## INTRODUCTION

The Facility for Rare Isotope Beams was completed in April 2022, on scope and cost, and ahead of the baseline schedule planned in 2012 [1-2]. The ramp-up plan considers a gradual power increase to the ultimate design beam power of 400 kW. In the delivery beam system, the beam dump is designed to absorb approximately 75% of the primary beam power, and Fig. 1 shows the location of the Beam Dump in the Target Hall.

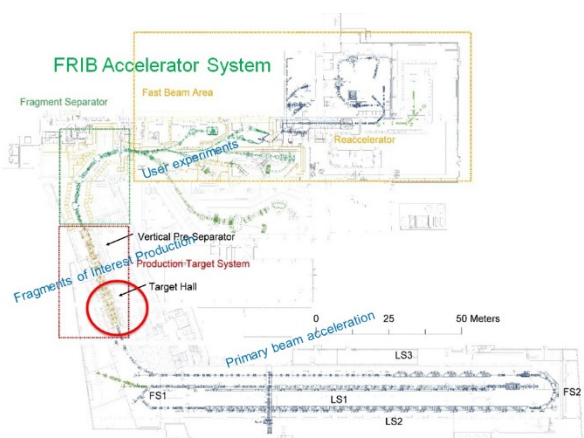


Figure 1: Location of the beam dump (Target Hall) in the FRIB Accelerator System.

Since the start of FRIB commissioning and operations, a first version of the beam dump has been in operation, oriented 20 degrees with respect to the incoming beam (Fig. 2), with 1 kW maximum power on-target and beam dump [3]. With the ramp-up plan, the facility runs beam power up to 10 kW.

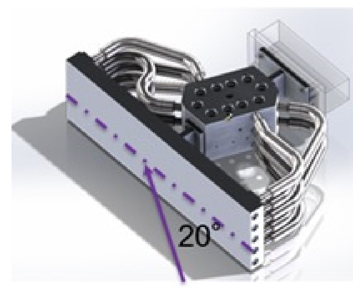


Figure 2: 20° Static beam dump.

## THE CURRENT STATIC BEAM DUMP

The current beam dump is a water-cooled static beam dump oriented at a 6-degree angle to the beam. Eight cylindrical channels of 0.625 inches diameter goes through the absorber providing the cooling effect. The absorber's inclined surface in the beam direction increases the power deposition area on the stopping material, which decreases the power density. Thus, more power can be deposited on the absorber.

The beam dump consists of the beam stopper (absorber) made of machined Aluminum 2219 block and 3D-printed inlet and outlet parts made of Aluminum 6061 that deliver the cooling water from utilities to the beam stopper and its return (Fig. 3). Cooper alloy was not chosen because Cu is vulnerable to oxidation that is enhanced by chemical reactions with oxygen produced by secondary particles interacting with the water (oxidation may result in pitting of the material).

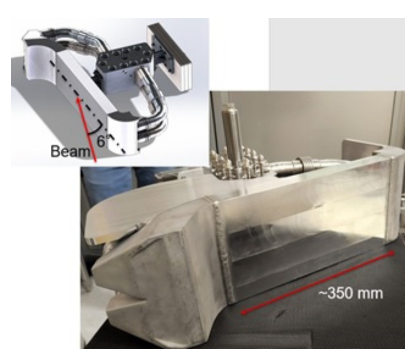


Figure 3: 6° Static beam dump.

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## THERMAL-FLUID MODEL

To analyze the thermal-fluid behavior of the device, a 3D Solidworks® model is exported to Ansys Fluent® - Release 22.0, a commercial code using the finite volume method [4]. The absorber region uses a structured mesh (hexahedral), and areas where the shape of the beam dump is complex use unstructured mesh. The structured mesh has a 0.5 mm grid size to capture thermal effects appropriately according to the beam sizes.

The fluid region on the channels contains a first layer adjacent to the wall of 0.1 mm and four additional layers to capture the boundary layer (BL) region appropriately.

The Prandtl number is typically 3.55, indicating that the thermal BL is thinner than the velocity BL. CFD results confirm the expected boundary layers. The velocity BL thickness is about 2.2 mm in Fig. 4, and the thermal BL thickness is 0.8 mm according to Fig. 5.

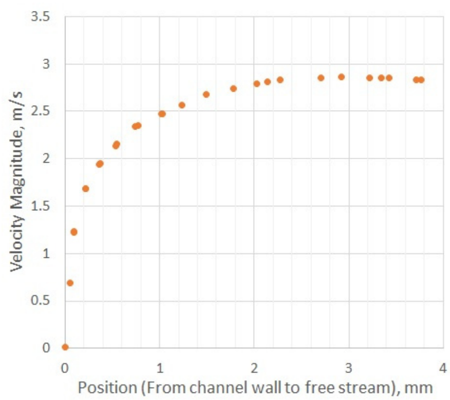


Figure 4: Velocity boundary layer at halfway along the water channel.

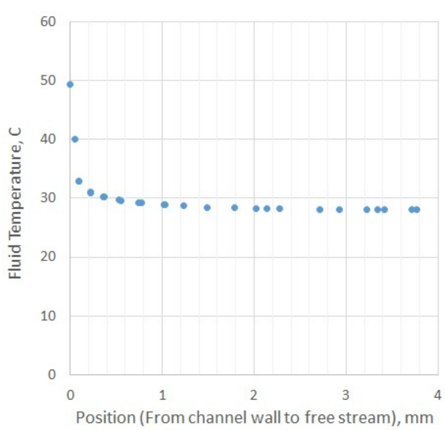


Figure 5: Thermal boundary layer at halfway along the water channel.

The viscous model used is the k-omega Shear-stress transport (SST) RANS model. The first layer in BL corresponds to a $y^+=18$ in the buffer layer. To resolve the flow field near the wall region, the k-omega SST model applies two approaches. The first method uses semi-empirical formulas called "wall functions" to bridge the viscosity-affected region between the wall and the fully turbulent region. In the second approach, the flow field is resolved with a mesh all the way to the wall that includes the viscous sublayer. The algorithm in the k-omega SST model determines the approach where required [5].

## OPERATION OF THE BEAM DUMP

The criteria for determining the maximum beam power during the operations:

- The Aluminum 2219 plate temperature must be less than 200 °C. This has been conservatively set as material properties degrade sharply after 200 °C, see Fig. 6.
- Water temperature must be less than 130 °C. The temperature is set not to exceed the boiling point of water at 3 bar.

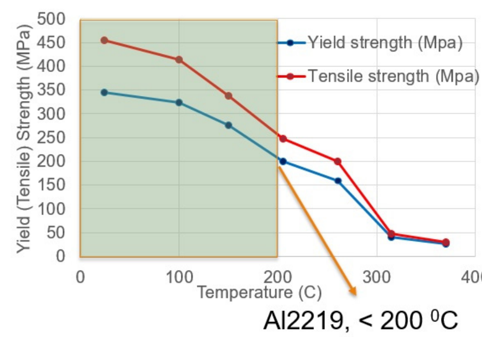


Figure 6: Yield strength limits at different temperatures.

The non-conventional unit system (NCU) provides the cooling water. The expected volume flow rate (VFR) is 60 GPM, and the pressure drop along the device is approximately 0.63 psi. The average water speed is 2.4 m/s, and the average calculated Convection Heat Transfer coefficient (CHTC) is 8,800 W/m$^2$-K.

28Si, 48Ca, 22Ne, 238U, 82Se, and 18O are some of the primary beams used in operations. Figure 7 illustrates the temperature contour plot for the 48Ca beam with beam sizes of $\sigma_x = 4.2\,mm$ and $\sigma_y = 6.3\,mm$ and deposited power of 3.6 kW on the absorber. Maximum temperature calculated was 151 °C. Results correspond to a normal beam operation; however, the CHTC can be impacted if VFR decreases. Fig. 8 depicts the apparently linear correlation between CHTC and VFR. As the VFR decreases, the CHTC decreases as well, impacting the device's cooling capacity. Therefore, VFR is monitored permanently during operations.

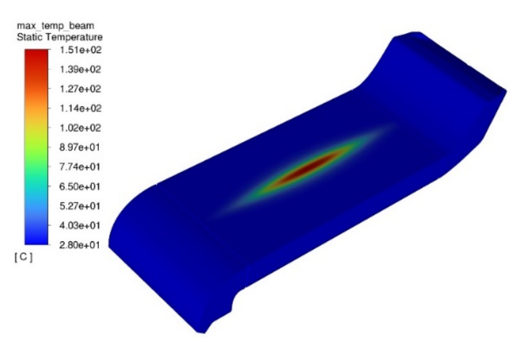


Figure 7: Temperature contour plot for 48Ca beam at 5 kW beam power.

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Figure 8 shows that the maximum temperature on the absorber drastically increases as the VFR decreases for the same power deposited. Thermal-fluid simulations can help predict this maximum temperature corresponding to the power deposited and detect any need for the required VFR in the early stage.

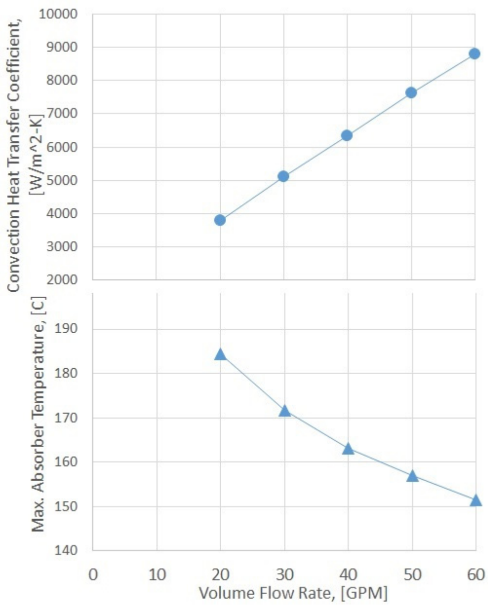


Figure 8: CHTC and maximum temperature on the beam absorber plots for 48Ca beam at beam power of 5 kW.

Figure 9 displays some footprints left by the beam on the absorber surface of the beam dump after one year of 3 – 5 kW beam operation. Footprints indicate that the beam was off-center in relation to the center of the absorber. Also, the picture shows that the beam corresponds to a long beam in which a portion of the power is deposited on the device's wings.

Figure 9: A photo of the beam dump in its current location.

The location of the beam dump is in the beam dump vessel, which is at high vacuum conditions, around $10^{-6}$ Torr. Any water leak from the cooling system can impact the amount of power the beam dump can absorb. Recently, a water leak was detected from one of the metal gaskets in the cooling system. The vacuum level decayed, and to remediate this condition, the water pressure and volume flow rate were the options to modulate for continuing operations. Table 1 shows the beams and power deposited into the beam dump during the event.

Table 1: Beam Features in the Operations

| Primary Beam | Power Deposited kW | $\sigma_x$ mm | $\sigma_y$ mm |
|---|---|---|---|
| 28Si | 7.86 | 4.6 | 13.5 |
| 48Ca | 9 | 4.7 | 16.9 |
| 22Ne | 10.17 | 6 | 15.8 |

Decreasing the VFR can lessen the water leak into the dump vessel, and so does the water pressure. Figure 10 and Figure 11 display the influence of these two parameters on the maximum temperature in the absorber and the wall temperature of the water channels. Decreasing the VFR to 30 GPM limits the operation with 28Si, 35 GPM with 48Ca beam, and 40 GPM with 22Ne. Water wall temperatures present similar threshold values of the VFRs. Decreasing the water pressure to the minimum absolute pressure allowable of 2 bars decreases the wall temperatures' temperature limit to 120 °C. The water pressure in the channels impacts the water's boiling temperature.

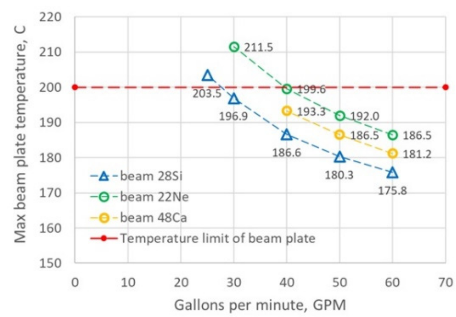


Figure 10: Maximum temperature on the absorber for the three beams in Table 1.

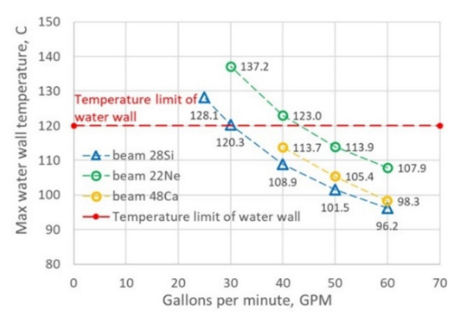


Figure 11: Maximum wall temperature of the channels for the three beams in Table 1.

## CONCLUSION

A discussion on the thermal-fluid behavior of the beam dump was presented using a sample 48Ca at 5 kW beam power. Also, a water leak event during operations and the solution to remediate the issue were discussed. It is expected to upgrade the current beam dump with the mini channel beam dump for power ramp-up from 10 kW to 20 kW in 2024.

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