Thermal, mechanical and fluid flow aspects of the high power beam dump for FRIB

Mikhail Avilov, Adam Aaron, Aida Amroussia, Wladimir Bergez, Carl Boehlert, Thomas Burgess, Adam Carroll, Catherine Colin, Florent Durantel, Paride Ferrante, et al.

Thermal, mechanical and fluid flow aspects of the high power beam dump for FRIB

Mikhail Avilov [a,*], Adam Aaron [b], Aida Amroussia [c], Wladimir Bergez [d], Carl Boehlert [c], Thomas Burgess [b], Adam Carroll [b], Catherine Colin [d], Florent Durantel [e], Paride Ferrante [a], Tiffany Fourmeau [a], Van Graves [b], Clara Grygiel [e], Jacob Kramer [a], Wolfgang Mittig [f], Isabelle Monnet [e], Harsh Patel [a], Frederique Pellemoine [a], Reginald Ronningen [a], Mike Schein [a]

[a] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[b] *Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA*
[c] *Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, MI 48824, USA*
[d] *Institut de Mecanique des Fluides de Toulouse, Toulouse University, CNRS, Allée Camille Soula, 31400 Toulouse, France*
[e] *Centre des recherches sur les Ions, les Materiaux et la Photonique (CIMAP) CEA-CNRS-ENSICAEN-UCN, BP 5133, 14070 CAEN CEDEX 5, France*
[f] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*

Keywords:
FRIB
Beam dump
Titanium

ABSTRACT

The Facility for Rare Isotope Beams (FRIB) under construction at Michigan State University is based on a 400 kW heavy ion accelerator and uses in flight production and separation to generate rare isotope beams. The first section of the fragment separator houses the rare isotope production target, and the primary beam dump to stop the unreacted primary beam. The experimental program will use 400 kW ion beams from ^{16}O to ^{238}U. After interaction with the production target, over 300 kW in remaining beam power must be absorbed by the beam dump. A rotating water cooled thin shell metal drum was chosen as the basic concept for the beam dump. Extensive thermal, mechanical and fluid flow analyses were performed to evaluate the effects of the high power density in the beam dump shell and in the water. Many properties were optimized simultaneously, such as shell temperature, mechanical strength, fatigue strength, and radiation resistance. Results of the analyses of the beam dump performance with different design options will be discussed. For example, it was found that a design modification to the initial water flow pattern resulted in a substantial increase in the wall heat transfer coefficient. A detailed evaluation of materials for the shell is in progress. The widely used titanium alloy, Ti 6Al 4V (wt%), is presently considered as the best candidate, and is the subject of specific tests, such as studies of performance under heavy ion irradiation.

1. Introduction

The Facility for Rare Isotope Beams [1], which is presently under construction at Michigan State University, is a heavy ion accelerator based facility for rare isotope science that produces the radioactive isotopes for studies in nuclear structure, fundamental interactions, nuclear astrophysics, and for many other applications. For rare isotope production, FRIB will use primary ion beams from ^{16}O to ^{238}U having power up to 400 kW and specific energies of at least 200 MeV/u. During beam operations, only about a quarter of beam power will be used for isotope production, from interactions between the primary beam and the production target, while the power of the unreacted fraction of the primary beam (up to 325 kW) will be absorbed in a beam dump (BD) that is a part of a first stage of FRIB fragment separator ARIS [2]. FRIB beam operation conditions, in particular the record breaking power densities of a primary beam [3], result in variety of challenges for beam dump materials. In this paper, we present the BD concept developed to address these challenges, the results of numerical analyses performed in support of the BD design, as well as the recent progress in BD material study. The results of the BD mockup flow test and plans for testing with an electron beam will also be discussed.

* Corresponding author.

http://dx.doi.org/10.1016/j.nimb.2016.02.068

2. Beam dump concept

The overall concept of a BD has been developed within the framework of the FRIB beam dump R&D program. The basic requirement of the BD is the high power capability: it should absorb up to 325 kW of beam power reliably for at least 1 year (5500 h) of operation. The rotating water filled drum whose shell is made of a titanium alloy was selected as the baseline concept for the BD. The BD conceptual design, as shown in Fig. 1, implements a metal drum that is 70 cm in diameter and 8 cm in height, rotating at 600 rpm velocity, and filled with water flowing at 60 gallons per minute (gpm). The shell is designed to be as thin as 0.5 mm in order to reduce the power deposited in it. The alloy Ti 6Al 4V was selected as the material for that shell because of its excellent mechanical properties, for example low density, high strength, good corrosion resistance, and good fatigue performance. The unreacted primary beam penetrates the thin shell and must be stopped, and for this purpose the water was chosen for beam power dissipation and for cooling the drum wall. The high rotational velocity increases the water pressure inside the drum up to 5 bar, causing the water boiling temperature to increase up to 150 °C.

3. Numerical analysis in support of the beam dump design

In order to determine the BD operational conditions and evaluate its performance with the high power density primary beams, extensive thermal, mechanical and fluid dynamic simulations were performed using the physics and engineering code suite ANSYS [4]. Thermal analysis (Fig. 2, left) was used to determine the maximum limit of absorbed power density, above which the water begins to boil at a given pressure. For that analysis, the unreacted primary beam after the production target was modeled by approximating its spatial distribution with a Gaussian function. Two primary beams were considered, representing the range of FRIB primary beam mass numbers: the heaviest being ^{238}U and the lightest, ^{16}O. To determine the beam spot size on a drum, a calculation was performed using Monte Carlo beam transport code MOCADI [5] that took into account the beam interaction with the target and the beam optics from the target to the beam dump. The metal drum's mechanical stability was evaluated in a mechanical stress analysis whereby the drum shape was optimized to effectively withstand the mechanical stress induced by the rotation and by the internal water pressure. Here, the beam power deposition was not taken into account. For the maximum stress value, a safety factor of over 5 was used. Thermo mechanical analysis then estimated the values of the thermal stress and the deformation induced by the beam power deposition in the shell. The values of 85 90 MPa found for the thermal stress are far below the ultimate stress for Ti 6Al 4V, which is over 900 MPa [6]. The drum wall may be subject to significant fatigue since the rotating unit experiences a periodic thermal load from the deposited primary beam power. The wall fatigue behavior was studied numerically, using the stress vs. number of cycles to failure (S N) curves obtained for Ti 6Al 4V [6]. Calculations showed that, for all primary beams, a designed fatigue life of 10^8 cycles can be reached with the fatigue safety factor of 8.5 or higher (Fig. 2, right).

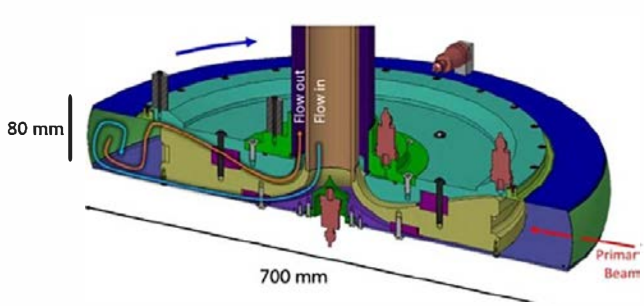

Fig. 1. FRIB primary beam dump concept.

4. Beam dump prototype mechanical test

A full scale prototype of the BD with the shell made of Ti 6Al 4V (Fig. 3, left) was designed and manufactured to validate the chosen concept. It comprised the full scale mockup of the BD with the shell made of Ti 6Al 4V. The mechanical test of the prototype was performed at Oak Ridge National Laboratory, where a loop containing 1300 l of water was available and capable of delivering in excess of 240 gpm. During the testing, the water flow rate and the rotation speed were controlled. The pressure was recorded for each individual test at six different locations that allowed us to obtain the pressure profile inside the drum for different values of flow rate and rotation speed. The obtained results showed good agreement with the simulation, confirming a maximum pressure on the wall of about 2 bar at 400 rpm rotational speed and 60 gpm flow rate. Additional prototypic operations, such as mechanical balance and fill and drain procedures, were also verified during the tests. Overall, the prototype performance demonstrated the feasibility of the chosen concept.

5. Heat transfer through the drum wall

During the BD operation, part of the primary beam power will be absorbed by the drum wall and must be dissipated to prevent unit failure. The power deposition in the BD was calculated with the use of fragment separator simulation code LISE^{++} [7]. Depending on the primary beam, the power deposited in the metal shell will be between 4 and 70 kW, which requires an excessive and highly turbulent flow for efficient wall cooling. Understanding of the water flow behavior therefore becomes crucial for the BD operation. A dedicated test was performed at ORNL with the BD prototype whereby to monitor the water flow inside the BD, the titanium drum was replaced by a transparent acrylic one. One millimeter diameter polystyrene beads having density (ρ = 1.05 g/cm^3) close to water were inserted into the water, and their motion was monitored by a high speed video camera. The beads' trajectories were tracked at a 255 rpm rotational speed and a 60 gpm water flow rate. Results of the tracking were compared with those obtained from computational fluid dynamics (CFD) simulations, and good agreement was found (Fig. 3, right).

The steady state CFD analysis revealed a wall heat transfer coefficient to be about 5000 W/m^2 K, which enables full power operation (400 kW) for the light beams and the deposition of up to 100 kW of the heaviest ^{238}U beam (up to 18 kW deposition in the shell). In the early years of operation, the baseline BD single shell design (Fig. 4, left) will provide the information needed to optimize the design of the a replacement drum. Ways to improve the heat transfer through the drum wall were also considered, and BD operation in a nucleate boiling regime is one of the options. It appears that the formation of bubbles and their subsequent departure from the drum wall's internal surface yields an order of magnitude larger heat transfer when the heat flux is below the critical value. The nucleate boiling operation mode was studied in collaboration with IMFT, Toulouse, France. Simulations of the heat transfer for both static and transitory heat flux revealed serious challenges in maintaining the nucleate boiling regime at the nominal heat flux. The single phase fluid flow was thus chosen for the basic mode of BD operation. Another way to improve heat transfer is by using a

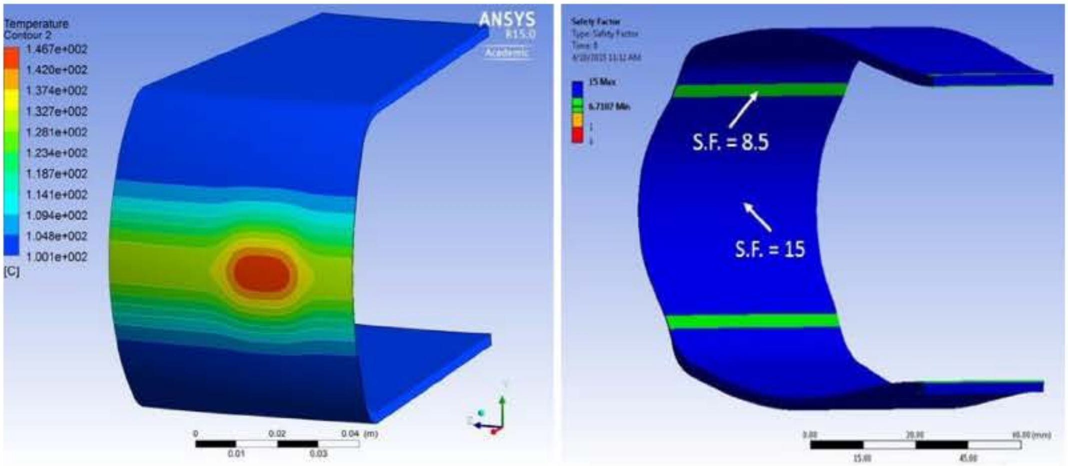

Fig. 2. Simulated temperature profile (left) and fatigue safety factor (right) for the BD shell.

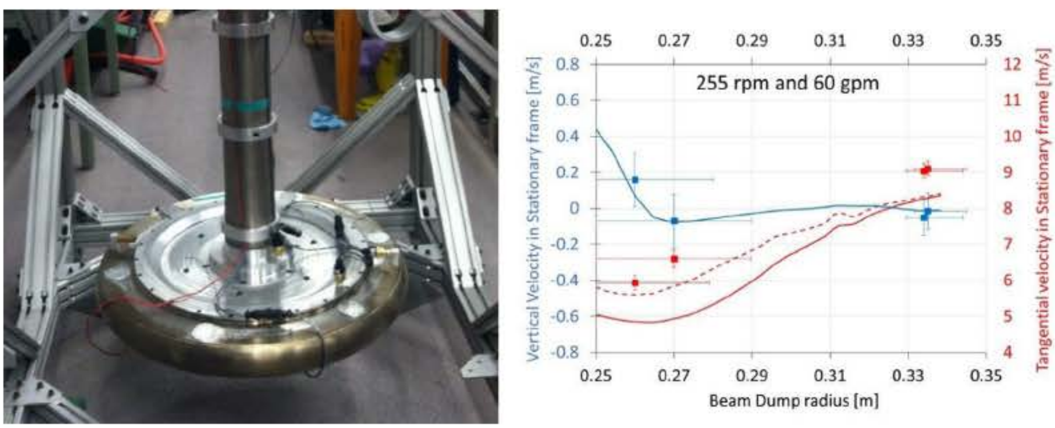

Fig. 3. Left – beam dump prototype for the mechanical testing; right – simulation results (lines) vs. the experimental data (dots). Blue – vertical, red – tangential flow velocities, averaged over the points having the same radius. The dashed line shows the tangential velocity when the wall surface roughness 0.1 mm is taken into account. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

double shell design. In this design (Fig. 4, right), a second wall placed close to the main shell forming a narrow (2 mm wide) channel, resulting in significant increase in the flow velocity. CFD analysis performed for that design showed the wall heat transfer coefficient increases up to 23,000 W/m^2 K, which is sufficient to dissipate full expected power in the shell for any primary beam. The analysis performed, however, did not account for the fraction of the beam power deposited in the water. Comprehensive fluid flow and thermal analysis, which includes both of these fractions of the power, is currently in progress. To validate the CFD simulation, a test of the beam dump mockup with an electron beam is planned at the Budker Institute of Nuclear Physics, Novosibirsk, Russia. A ¼ scale mockup (Fig. 5) will have a 0.5 mm thick shell that was 3D printed from Ti 6Al 4V powder. During the planned test, the electron beam will heat the rotating water cooled mockup, and the wall temperature will be monitored by an infrared thermal camera. The temperature measurement performed for different mockup operation modes (beam power, beam spot size, flow rate, and rotation speed) will be sufficient to estimate the wall heat transfer for both single and double shell designs. Additionally, the temperature measurements will be used to evaluate the mockup performance under thermal loads close to that of the FRIB BD operational conditions.

6. Test of materials used in the beam dump

The BD metal shell will be irradiated by high intensity heavy ion beams. A good knowledge of shell material properties after irradiation is crucial for optimizing unit design and performance. Electronic energy loss was identified as the main damage process for high energy heavy ion beams [8], which can induce track formation and structural modification in metallic systems. Ti 6Al 4V samples were irradiated in the IRRSUD beamline at GANIL, France, with two beams having electronic energy losses representative of FRIB conditions: ^{36}Ar at an energy of 36 MeV and ^{131}Xe at 92 MeV, and at doses up to 2.8 dpa. The post irradiation study was performed at the MSU Department of Chemical Engineering and Material Science, and included Scanning Electron Microscopy, Electron Backscatter Diffraction analysis, and mechanical testing such as nano indentation and Vickers hardness analysis. The results [9] suggest a low sensitivity to high electronic excitation. The hardening observed was dependent on both the dose and the irradiation temperature, and it was more significant at irradiation temperatures over 350 °C. Further investigations are needed to study the combined effect of high irradiation dose, corrosion and fatigue on the BD shell to fully validate the material selection.

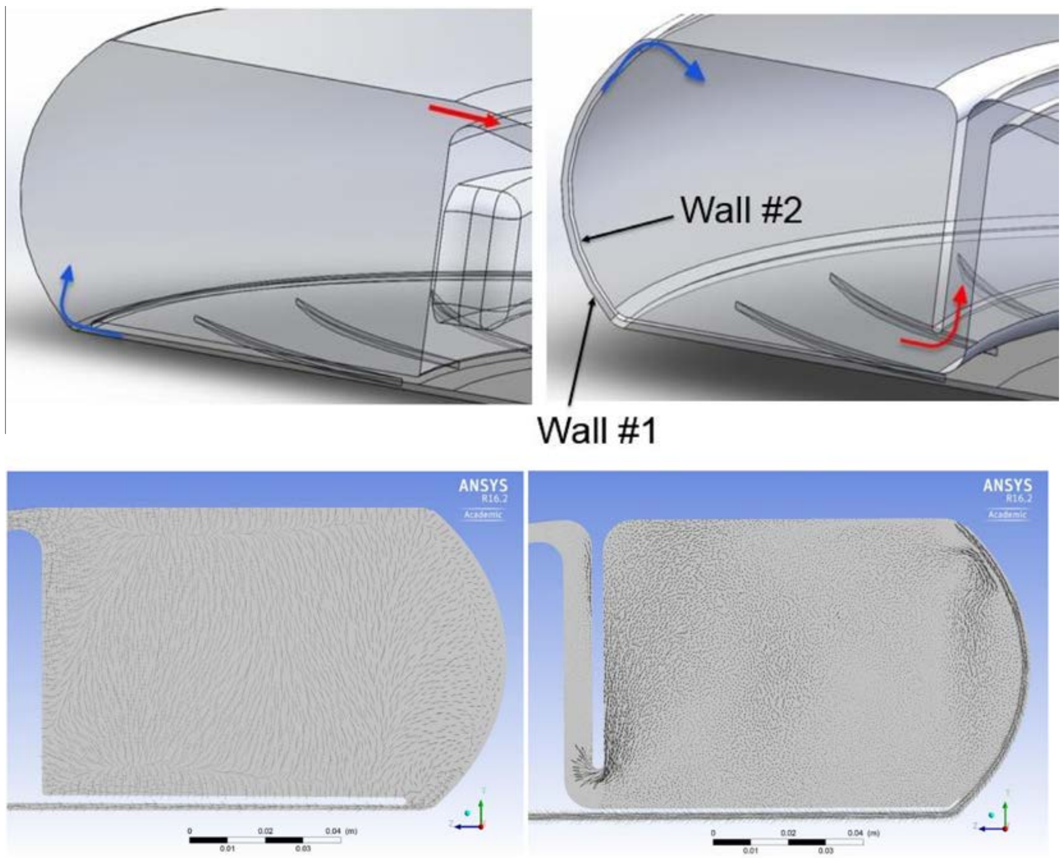

Fig. 4. Top – beam dump baseline designs for the single shell (left) and the double shell (right). Arrows indicate the direction of the water flow. Bottom – simulated flow vector in the beam dump baseline (left) and double shell (right) designs.

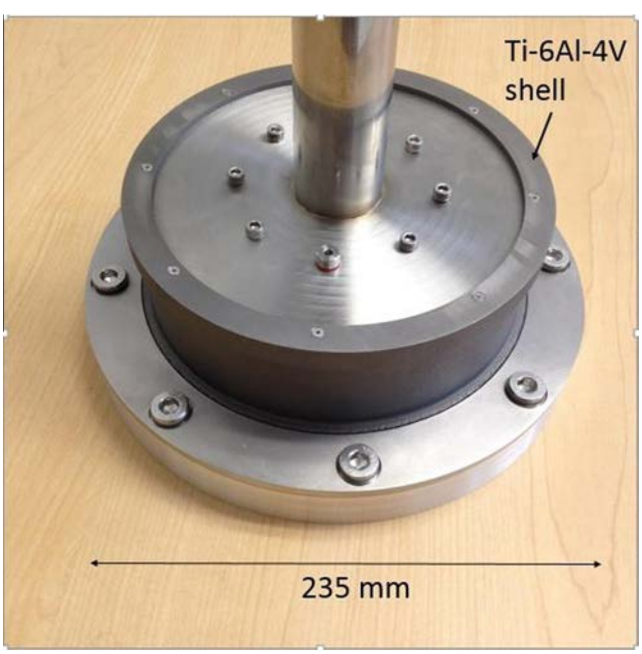

Fig. 5. A quarter scale mockup for the electron beam test.

7. Conclusions

A high power beam dump concept was developed for the FRIB beam operations. It is based on the rotating thin wall drum made of Ti 6Al 4V and filled with water. Extensive numerical analyses evaluated performance of the BD operation modes. Mechanical and fluid flow test performed without beam interaction with the BD validated the baseline concept chosen and confirmed the good mechanical stability of the design. Irradiation tests of the Ti 6Al 4V samples validated the selection of that alloy as a basic material for the BD metal shell. A possible shell design to improve the wall heat transfer is proposed. To validate the simulation, a dedicated test with an electron beam is planned in 2016.

Acknowledgements

This material is based upon work supported by the U.S. Depart ment of Energy Office of Science under Cooperative Agreement DE SC0000661, the State of Michigan and Michigan State University. This work was also partly supported by Michigan State University under the Strategic Partnership Grant “FRIB Materials in Extreme Environments”.

References

[1] D.J. Morrissey, J. Phys.: Conf. Ser. 267 (2011) 012001.
[2] M. Hausmann et al., Nucl. Instr. Meth. Phys. Res. B 317 (2013) 349–353.
[3] F. Pellemoine, Nucl. Instr. Meth. Phys. Res. B 317 (2013) 369–372.
[4] ANSYS, Inc. <www.ansys.com>.
[5] N. Iwasa et al., Nucl. Instr. Meth. Phys. Res. B 126 (1997) 284.
[6] Richard C. Rice, Jana L. Rubadue, Metallic Materials Properties Development and Standardization-MMPDS-01, January 2003.
[7] O. Tarasov, D. Bazin, Nucl. Instr. Meth. Phys. Res. B 266 (2008) 4657.
[8] M. Toulemonde et al., Nucl. Instr. Meth. Phys. Res. B 227 (2012) 28–39.
[9] A. Amroussia et al., Swift heavy ions irradiation damage in Ti–6Al–4V and Ti–6Al–4V–1B: study of the microstructure and mechanical properties, in: Proc. of Swift Heavy Ion in Matter Conference, Darmstadt, Germany, May 2015, in press.