High Power Capability of the Primary Beam Dump for FRIB – Simulation and Experimental Study

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Facility for Rare Isotope Beams

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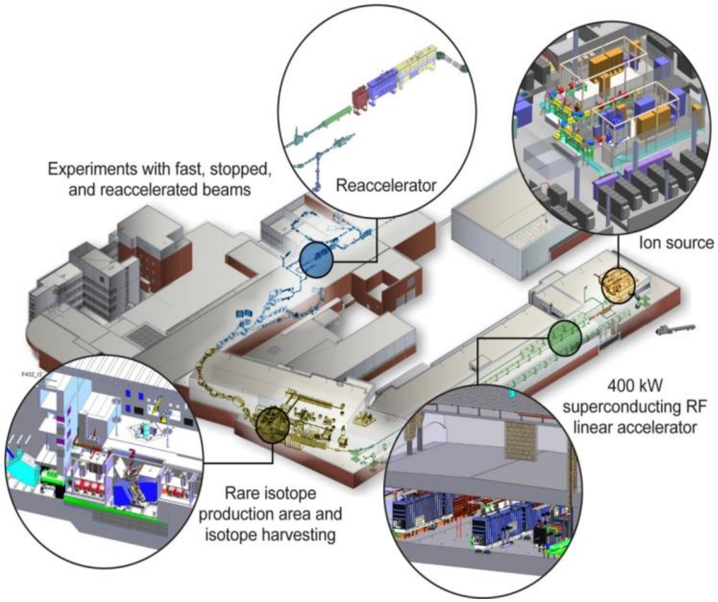
Outline

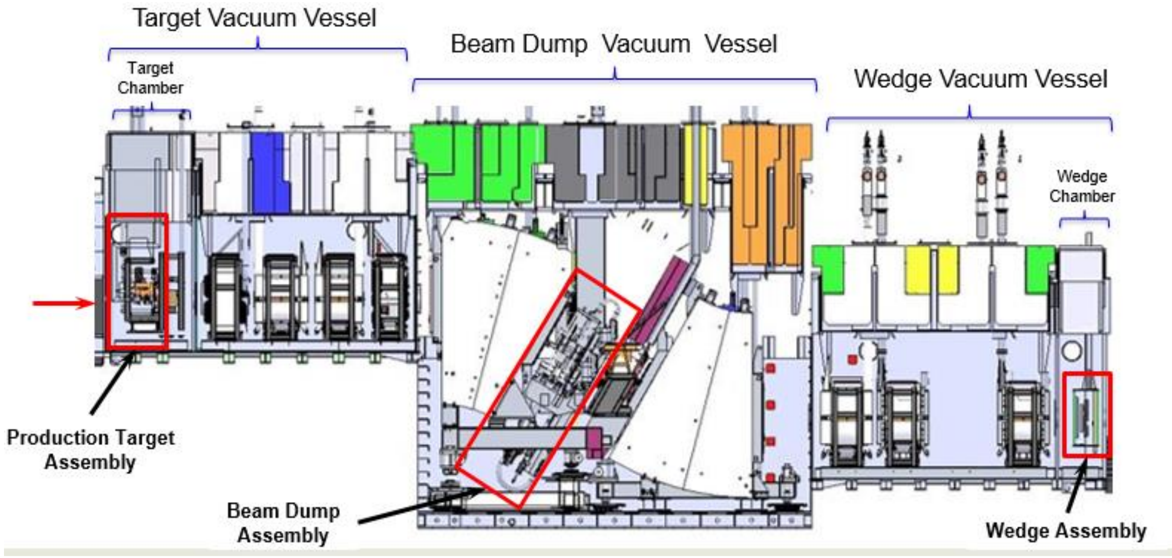
- FRIB High Power Beam Dump Concept
- Beam Dump Simulations
  - Thermo-mechanical Simulations in Support of the Beam Dump Design
  - Fluid Flow Simulations
- Beam Dump Prototype Testing
  - Flow Test at ORNL
  - Test of ¼ scale mockup with electron beam at BINP
- Current Status of Fabrication
- Summary
- Acknowledgements

Facility for Rare Isotope Beams

- World-leading heavy ion accelerator facility for rare isotope science
  - Nuclear Structure
  - Nuclear Astrophysics
  - Fundamental Interactions
  - Isotopes for Societal Needs

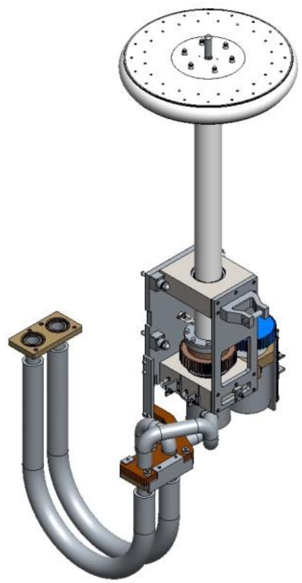
- Rare isotope production targets and beam dump compatible with beam power of 400 kW for ^{16}O to ^{238}U (200 MeV/u for ^{238}U and higher energies for lighter ions)



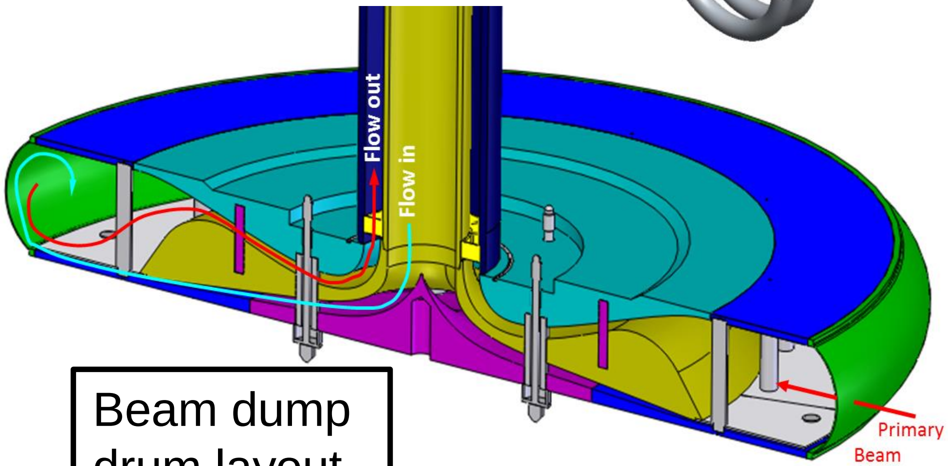


FRIB Baseline Beam Dump Concept
Water-Filled Rotating Drum

- Water-filled rotating drum concept chosen for FRIB baseline
  - High power capability up to 325 kW
  - 1 year (5500 hours) desired lifetime
- Ti-6Al-4V alloy selected for the beam dump shell
  - Low density
  - High strength
  - Excellent fatigue properties
  - Good corrosion and radiation resistance
- Design parameters
  - Ti-alloy shell thickness 0.5 mm to reduce power deposition in the shell
  - 600 rpm and 70 cm diameter to limit maximum temperature and amplitude of temperature changes
  - 60 gpm water flow to provide cooling



Beam dump assembly



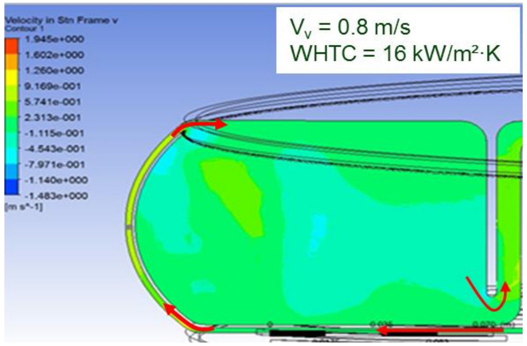
Beam dump drum layout

Beam Dump Drum Approach for Full Power Operation for all Beams

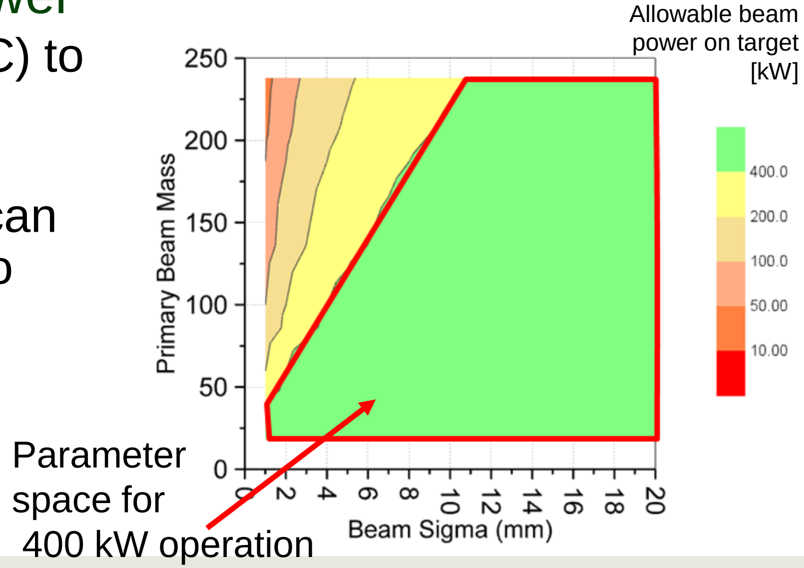
Heat Removal by Forced Convection

- Beam dump drum is a technical challenge
  - High Wall Heat Transfer Coefficient (WHTC) with high turbulent water flow needed to remove heat from beam dump shell
  - Effects of high power density, presence of water, rotation, heavy ion beams need to be considered
- Beam dump with double shell geometry and forced convection with single-phase fluid flow is expected to be suitable for all primary beams at full power
  - Increases Wall Heat Transfer Coefficient (WHTC) to absorb full power for all beams
    - » WHTC up to 23 kW/m²·K with forced convection
  - Beam physics simulations show that separator can operate with beam sizes up to sigma = 10 mm to reduce heat flux on the drum shell
- Heat transfer assumption validated in electron beam test in Novosibirsk

Double shell with forced convection

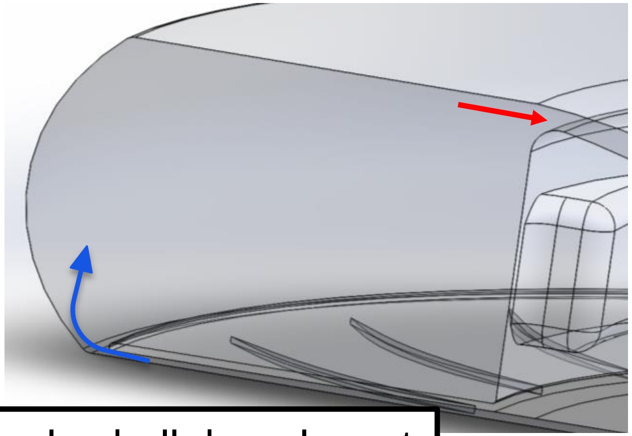


Double shell drum layout

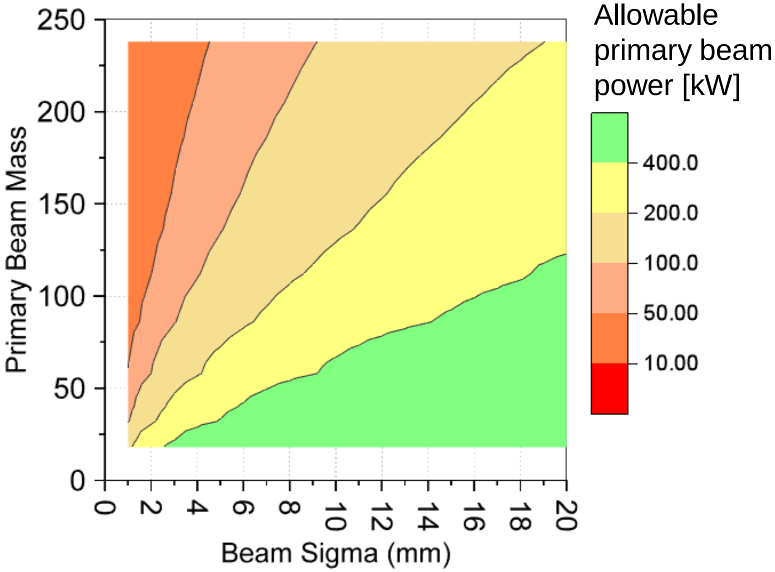


Beam Dump for First Years of Operation
Robust Solution with Single Shell Drum for Full Power Operation for Light Beams

- Robust single shell beam dump for first years
  - Nucleate boiling (NB) was considered as an option to improve the wall heat transfer, but maintaining the NB regime is challenging → single shell geometry with single-phase fluid flow selected as the baseline option
  - Full power (325 kW) for light beams, up to 100 kW for the heaviest ^{238}U beam
- Get operational experience during first years, assess heat removal from drum shell, learn about material behavior under heavy-ion irradiation at FRIB beam conditions, corrosion effects
- Take experience into account in development of beam dump drum for full power and all beams

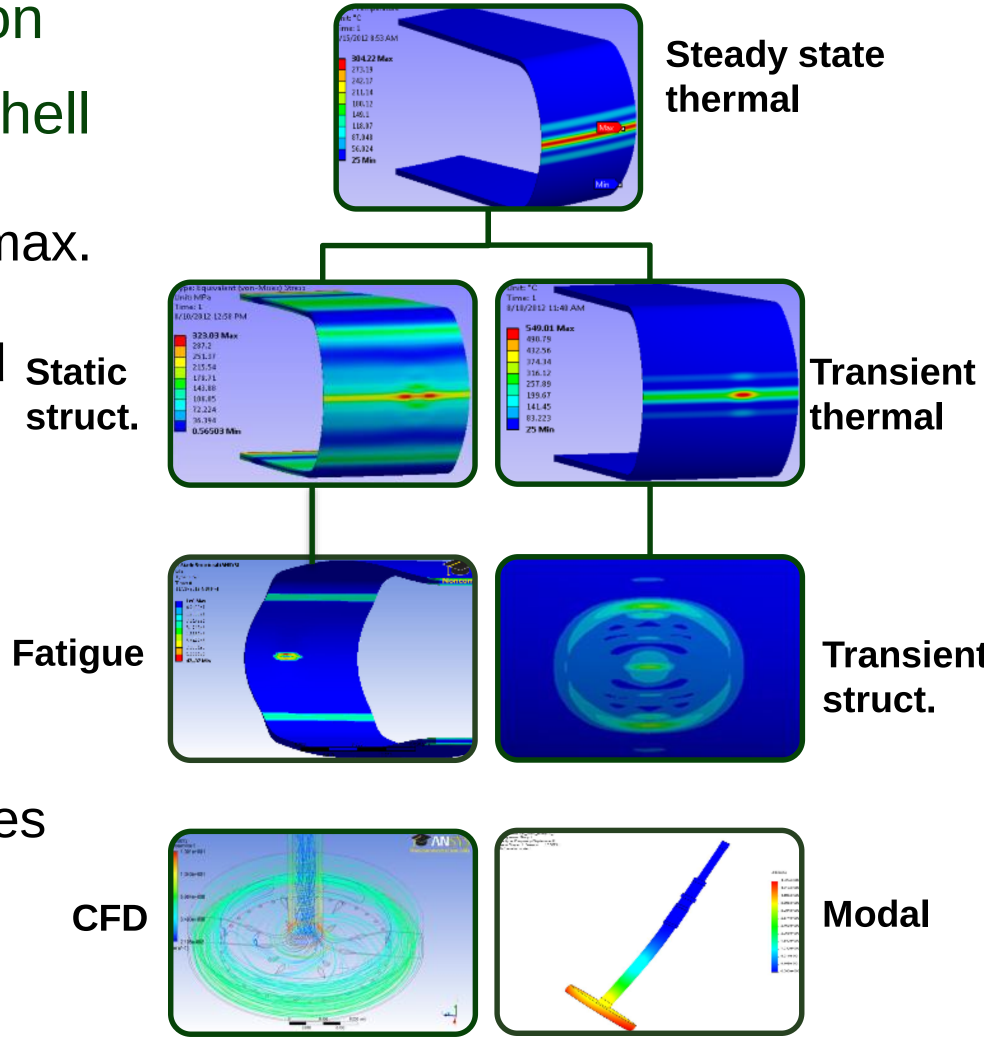


Single shell drum layout



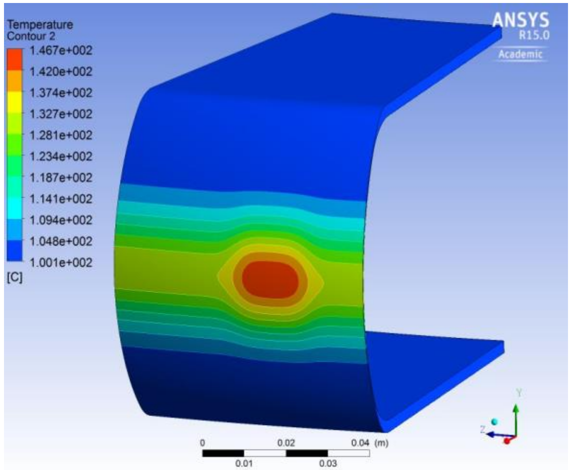
BD Thermal, Mechanical and Fluid Flow Challenges
Simulation Overview

- Challenges addressed in simulation
- High power – up to 18 kW in the shell
  - Thermal stress
  - Water near the boiling point (limits max. temperature of the shell)
  - Sufficient wall heat transfer required
- Rotating drum - 600 rpm
  - Temperature variation
    - » Fatigue
    - » Stress wave through the drum shell
  - Elevated mechanical stress due to internal pressure
  - Vibration and mechanical resonances
  - Cavitation



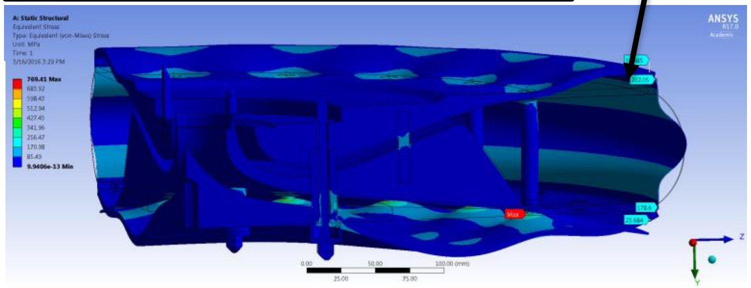
Thermal, Structural and Modal Analyses
BD Shell Stress Far Below the Stress Limit

- Thermal analysis
  - Max temperature of the shell should not exceed 150 ºC as determined by 8 bar water pressure
- Mechanical stress in the shell due to water pressure around 200 MPa in the shell
  - Shell profile optimized to withstand high stress level
  - Min safety factor of ~ 4 at 8 bar water pressure near the shell
- Thermo-mechanical stress induced by the beam
  - Significantly lower than from pressure (~ 80 MPa)
- Modal analysis
  - First natural frequency 15.2 Hz found – far above the operational rotation frequency of 10 Hz

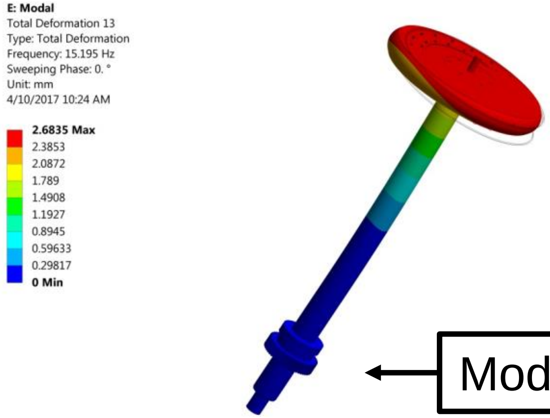


Shell temperature profile

200 MPa



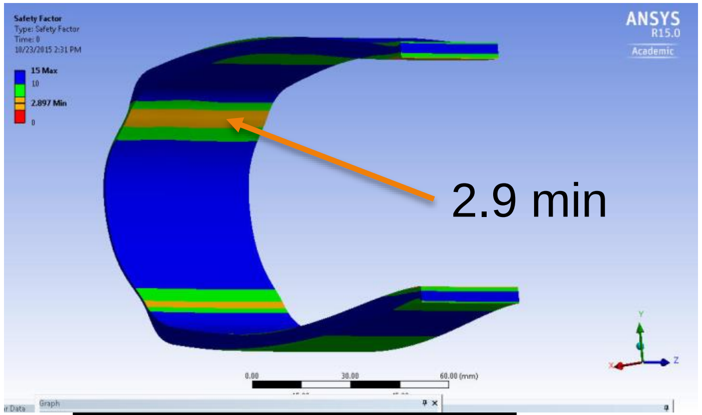
Mechanical stress in the drum



Modal analysis

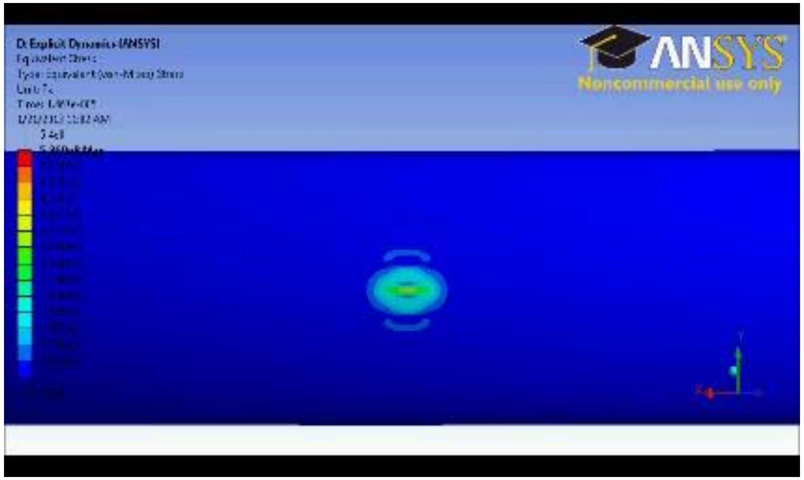
Fatigue and Stress Wave
No Issues Found

- Fatigue
  - BD rotation -> cyclic thermal load from the beam -> possible fatigue issues
  - BD must survive 1.e8 cycles
  - Numeric analysis has been performed to estimate fatigue life and safety factor, based on the thermal load allowable for the shell normal operation
  - Design fatigue life was found with safety factor about 3 for 8 bar pressure
- 3D printing technology is likely the best approach for full power beam dump fabrication
  - Expect better results with 3D-printed Ti alloy shell



Fatigue safety factor

- Stress wave
  - Is a result of the beam impact to the rotating surface. Contributes to the total stress in the BD shell
  - Simulation performed under conservative assumption of 350 ºC shell temperature. <200 ºC expected
  - Simulation performed revealed stress wave contribution less than 10% of the total stress

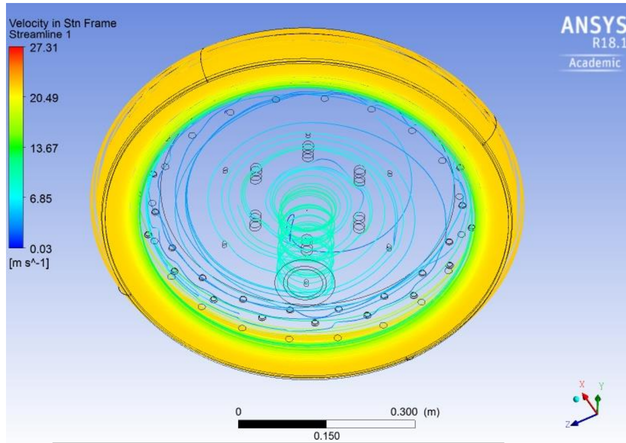


Stress wave propagation in the BD shell

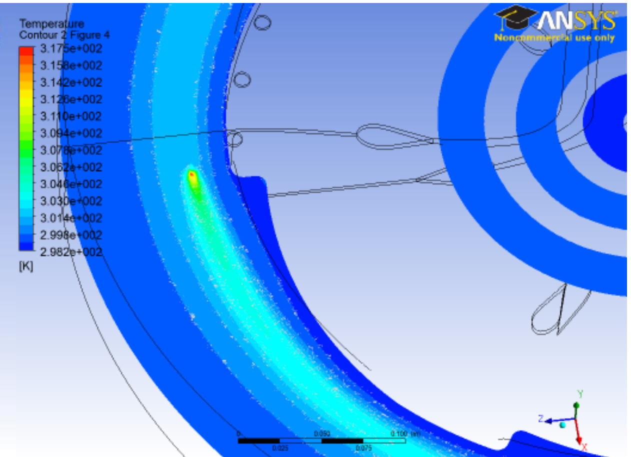
CFD Simulation with Deposited Beam

400 kW for light ions and up to 100 kW of U beam allowed for single shell design

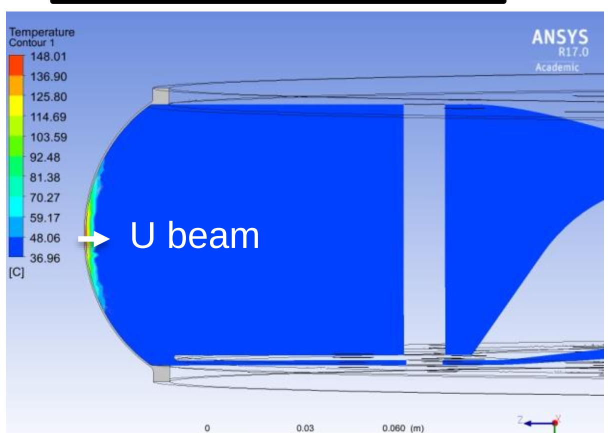
- ANSYS CFX simulations take into account the power deposition both in the shell and in the water
  - Larger contribution from the shell heating
  - Max. water temperature of 148 ºC found for 100 kW ^{238}U beam
  - Lower temperature for 400 kW ^{16}O beam
- Simulations confirm the operational capability for the single shell



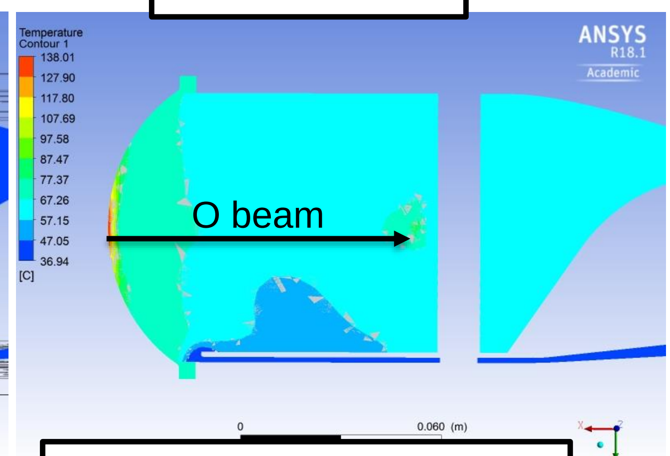
BD fluid flow streamlines



O beam in water



100 kW – U beam σ = 10 mm
Temperature profile



400 kW – O beam σ = 4 mm
Temperature profile

Mechanical/Flow Test at ORNL
Confirmed the BD Mechanical Design

- Beam dump mock-up tests at ORNL performed to evaluate mechanical and flow design
  - Parametric study over flow parameter range
    - » Rotation speed, flow rates, pressures, angle
    - » Evaluation of pressure drops

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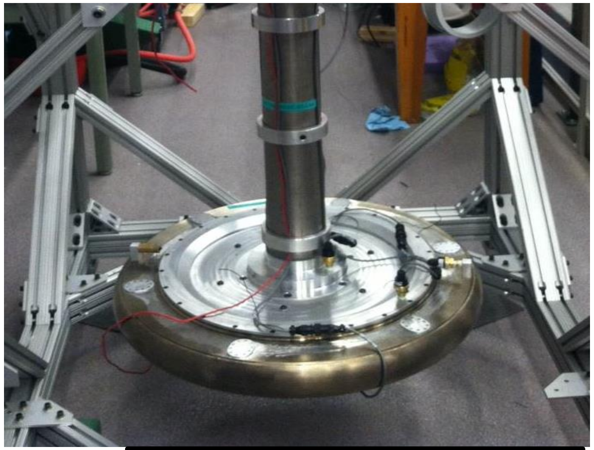
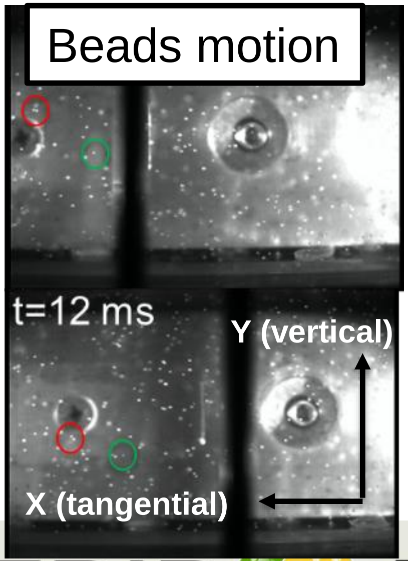


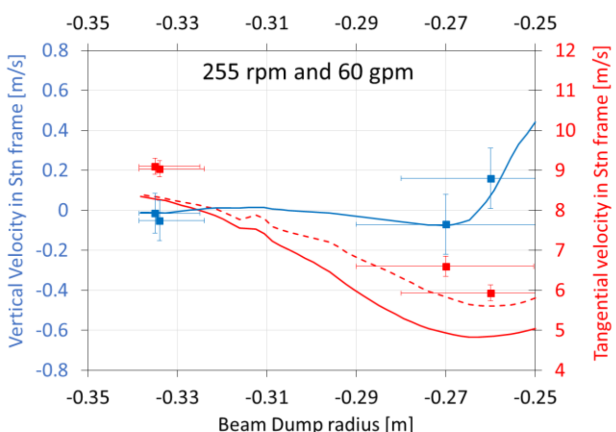
Ti alloy BD mockup

- Test with rotating transparent drum
  - Plastic beads (ρ = 1.05 g/cm³, 1 mm diameter) inserted
  - High speed camera used
  - Estimated velocity profile validated by experimental data,

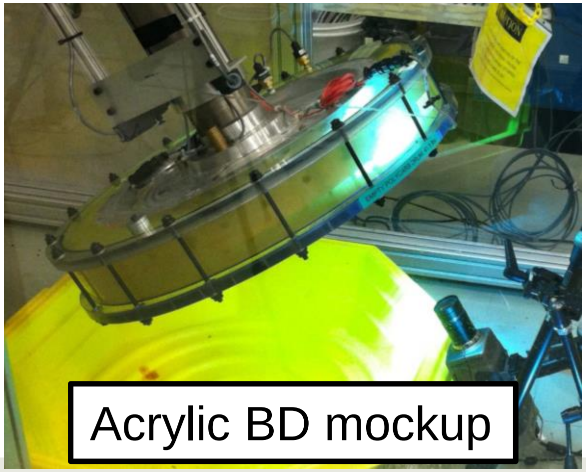
by using polystyrene beads – good agreement with simulation



Beads motion



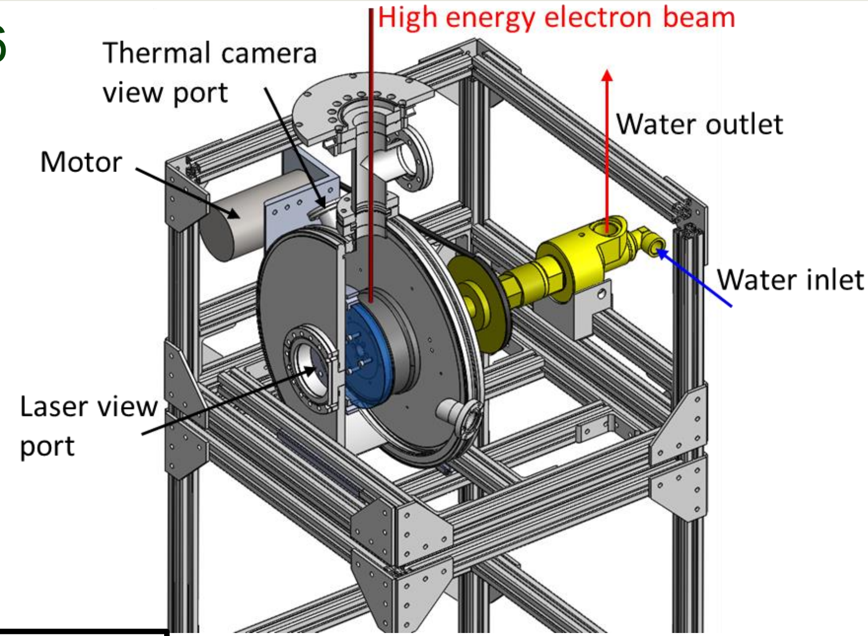
Vertical and tangential flow velocities vs BD radius



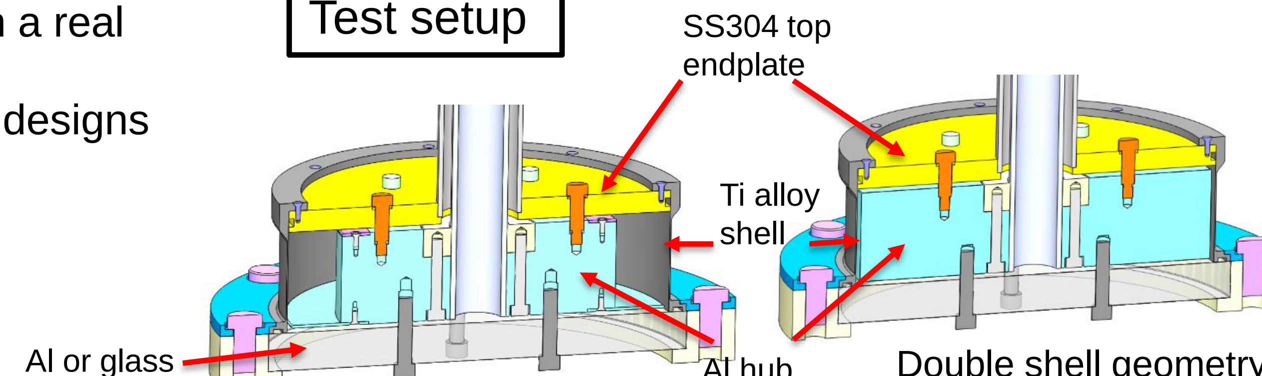
Acrylic BD mockup

Support for Beam Dump Drum Design
Test to Validate Heat Removal Assumptions

- Test with electron beam June – July 2016
  - Test intended to evaluate the heat flux to be removed from the shell, as well as transition to nucleate boiling
  - Electron beam test was used to heat the mockup shell
  - ¼-scale BD mockup was used with 0.5 mm thick shell
  - High energy electron beam 0.8 – 1.2 MeV, power up to 90 kW sufficient to represent the BD thermal conditions
  - Up to 6 gpm flow rate and up to 1200 rpm rotational velocity sufficient to simulate the fluid flow similar to that in a real beam dump
  - Both single and double shell designs were tested



Test setup



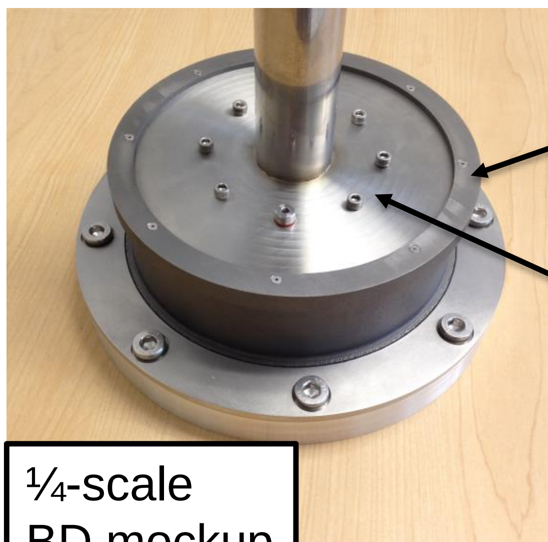
Single shell geometry

Double shell geometry

Budker Institute of Nuclear Physics

Test at BINP with a ¼-Scale Mockup
3D Printed Ti-6Al-4V Shell Used

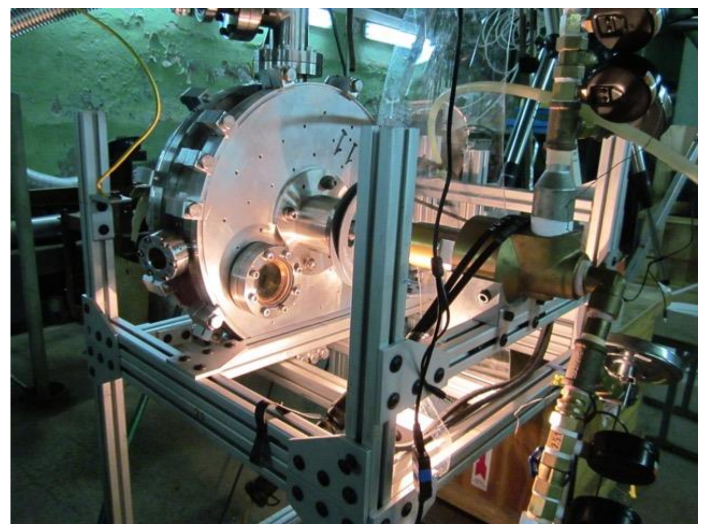
- ¼ scale mock-up made of Ti-6Al-4V was fabricated by 3D printing
  - Used to test this process for fabrication
    - Thickness inspection (0.48 ± 0.02 mm) reveals good homogeneity along the shell
  - Test in Novosibirsk also provided insight into mechanical performance



Ti alloy shell

SS304

¼-scale BD mockup

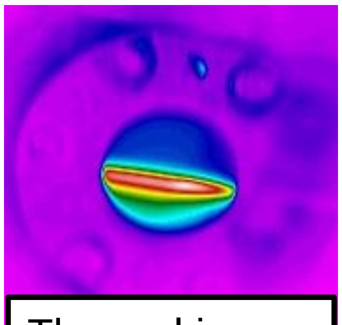


Test pictures

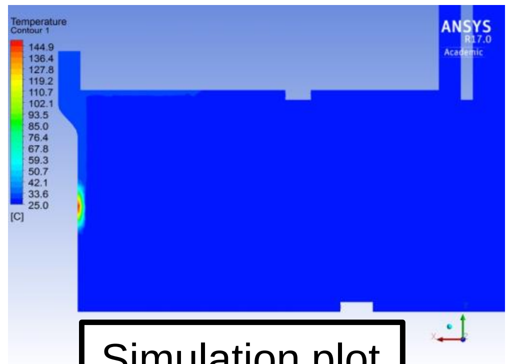
¼ Scale Mockup Test – Experimental Data vs Simulation
Electron Beam Test Validates Heat Removal Assumptions

- Good agreement between experimental data and simulation results for single shell geometry (regardless the beam size) and for double shell geometry (small beam)

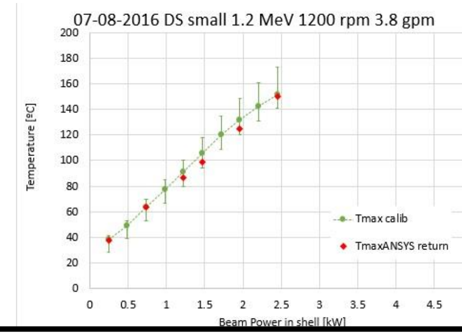
Small beam – Double shell



Thermal image



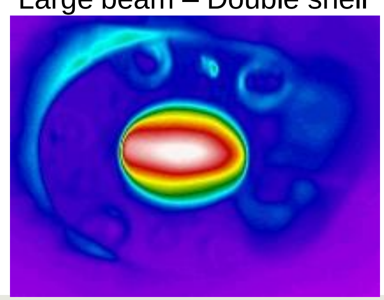
Simulation plot

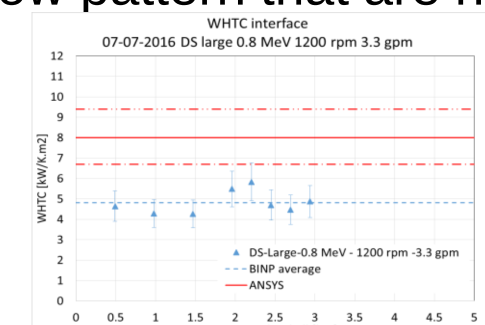


T shell vs power – ANSYS vs experiment

- Analysis revealed the WHTC factor of 1.6 higher compared to experimental data for double shell - large beam
  - Difference is likely due to some complex water flow pattern that are not taken into account in ANSYS

Large beam – Double shell

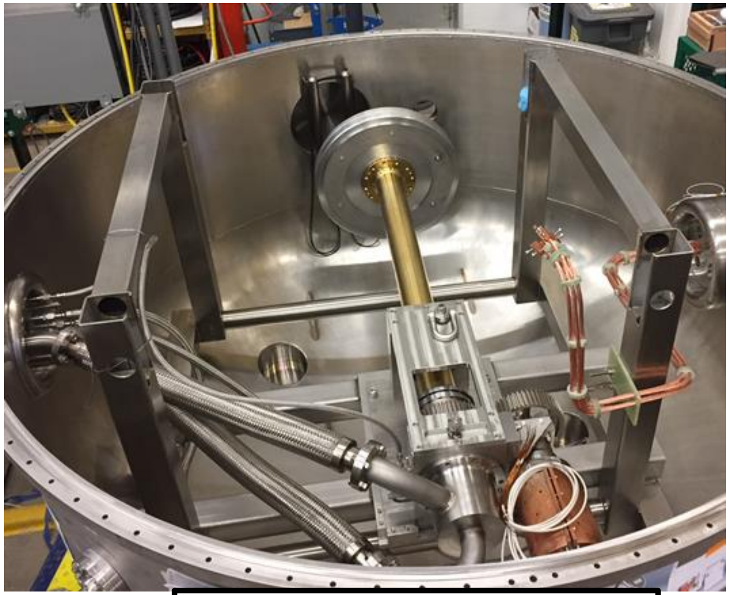




WHTC plots

Beam Dump Drum Testing and Fabrication Underway

- BD Drum fabrication near complete
  - 1-mm drum fabrication by conventional machining
- Mechanical test of the drum rotation module prototype ongoing



BD prototype set for mechanical test

Al drum prototype

Ti shell

Summary

- A high power beam dump concept was developed for FRIB and is being realized.
  - It is based on the rotating thin wall drum made of Ti-6Al-4V filled with water
- Robustness of single-shell beam dump drum sufficient for first years confirmed in simulation and prototype testing
- Possible double shell design to improve the wall heat transfer proposed
- Mechanical testing of drum assembly and fabrication of Ti-alloy drum underway

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Thanks for your attention!