Thermal, Mechanical and Fluid Flow Challenges of the FRIB Primary Beam Dump

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Facility for Rare Isotope Beams

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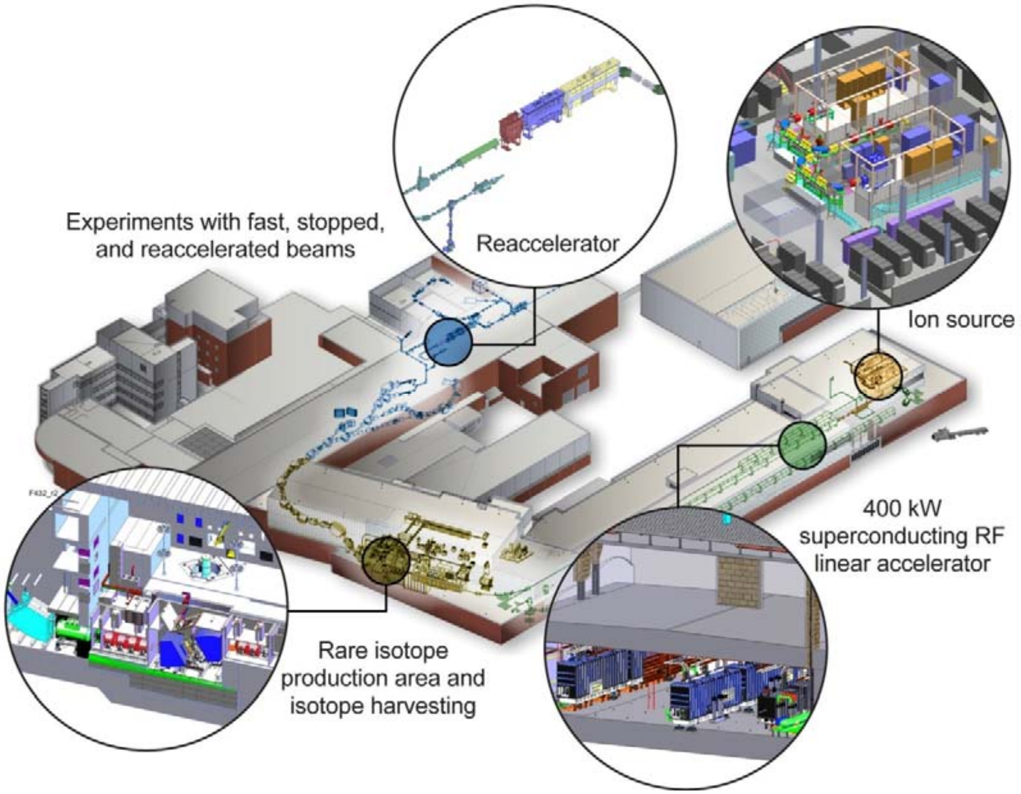
Outline

- FRIB primary Beam Dump Concept and Technical Requirements
- Overview of Challenges for the Beam Dump
- Mechanical Challenges
- Thermal and Thermo-mechanical Challenges
- Fluid Challenges
- Chemical Challenges
- Radiation Challenges
- Summary

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



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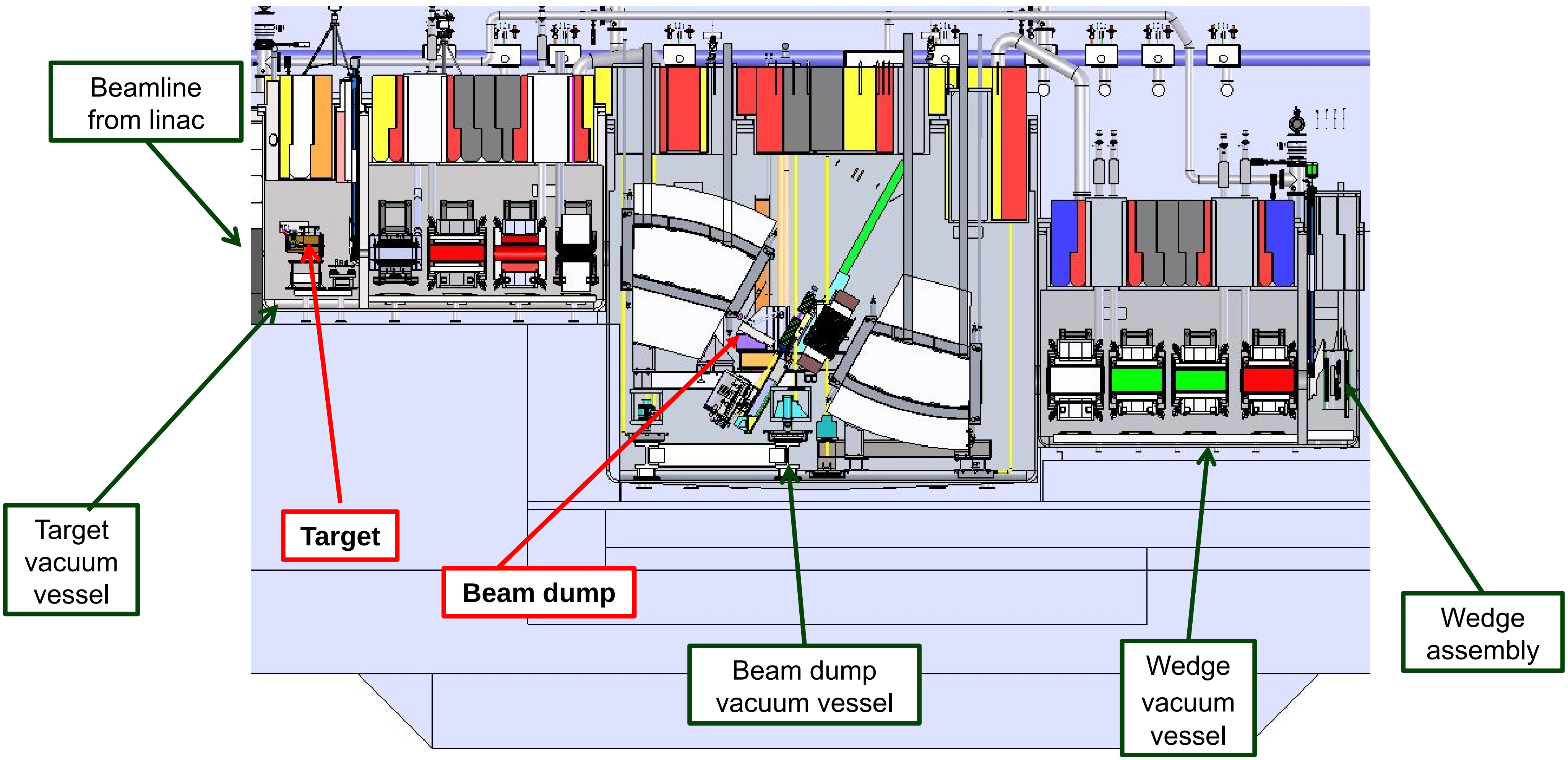
Scope and Technical Requirements

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



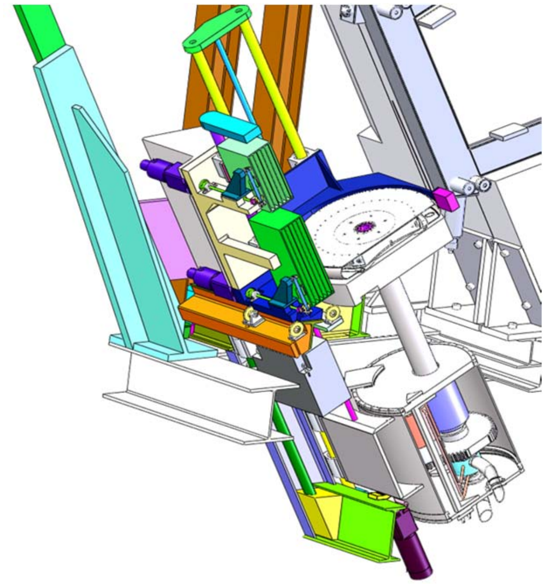
Slide 4

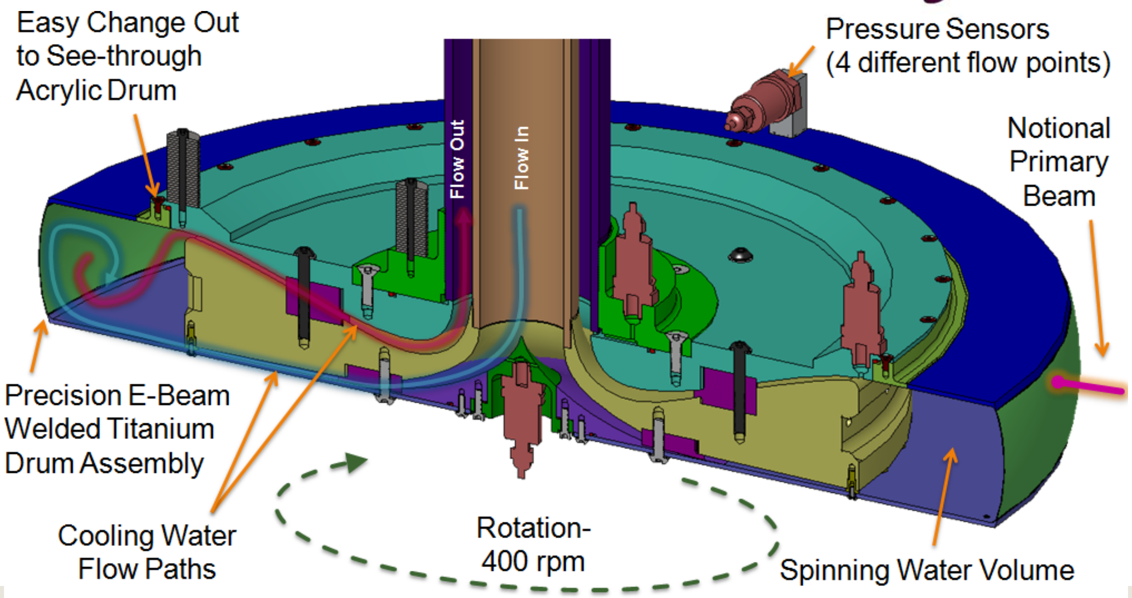
PF1 Pellemoine, Frederique, 5/5/2014

Primary Beam Dump
Water-filled Rotating Drum Concept

- Beam Dump requirements
  - High power capability up to 325 kW
  - 1 year (5500 h) lifetime desirable
  - Remote replacement and maintenance
- Water-filled rotating drum concept chosen for FRIB baseline
  - Using water to stop the primary beam and absorb beam power
- Design parameters
  - Ti-alloy shell thickness 0.5 mm to minimize power deposition in shell
  - 400 rpm and 70 cm diameter to limit maximum temperature and amplitude of temperature changes
  - 60 gpm water flow to provide cooling and gas bubble removal

Beam Dump schematic layout





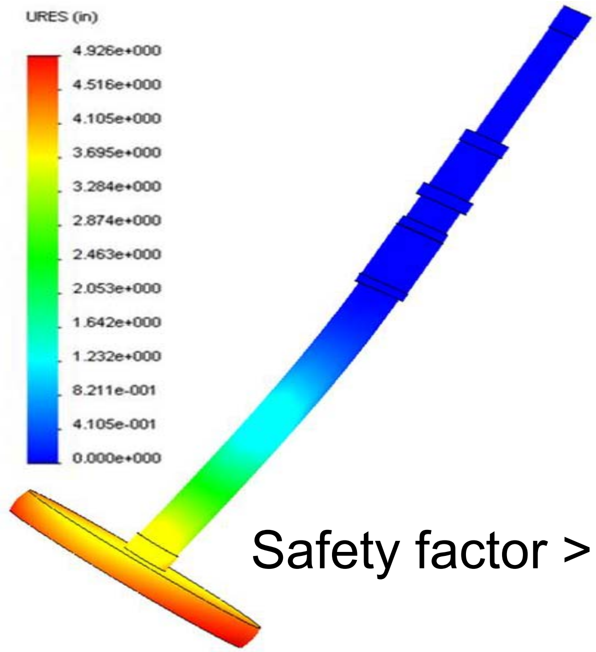
Beam Dump Challenges Overview

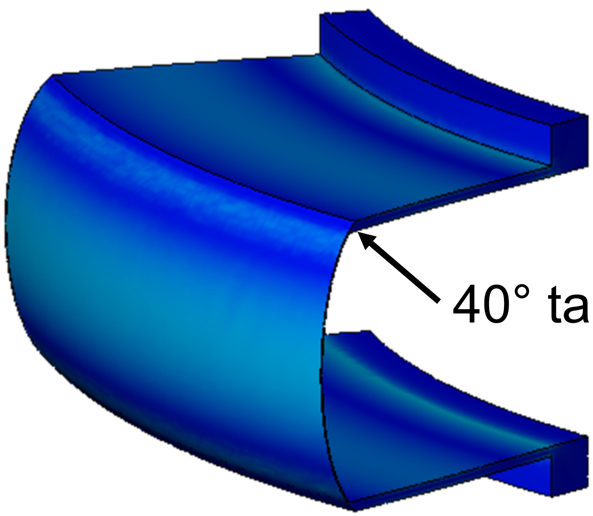
Challenge	Challenge
Mechanical	**Chemical**
vibration	corrosion
mechanical resonances	radiolysis
pressure-induced stress	**Radiation**
Thermal and thermo-mechanical	radiation damage of materials
thermal stress	sputtering
fatigue	radiation creep
stress wave	
thermal creep	
Fluid	
bubble formation: nucleate boiling	
bubble formation: cavitation	
wall heat transfer	

- Some effects may be enhanced by the presence of the other
- Up to now no facility exists to study the combination of all these effects => perform studies that combine some challenges using existing facilities

Mechanical Challenges
Vibration, Mechanical Resonances, Internal Pressure

- Stress induced by internal pressure
  - Studied numerically
  - The optimization of the BD shell geometry performed in order to better withstand the increased pressure level due to BD rotation
  - Safety factor of 5 calculated
  - Verified by the mockup tests

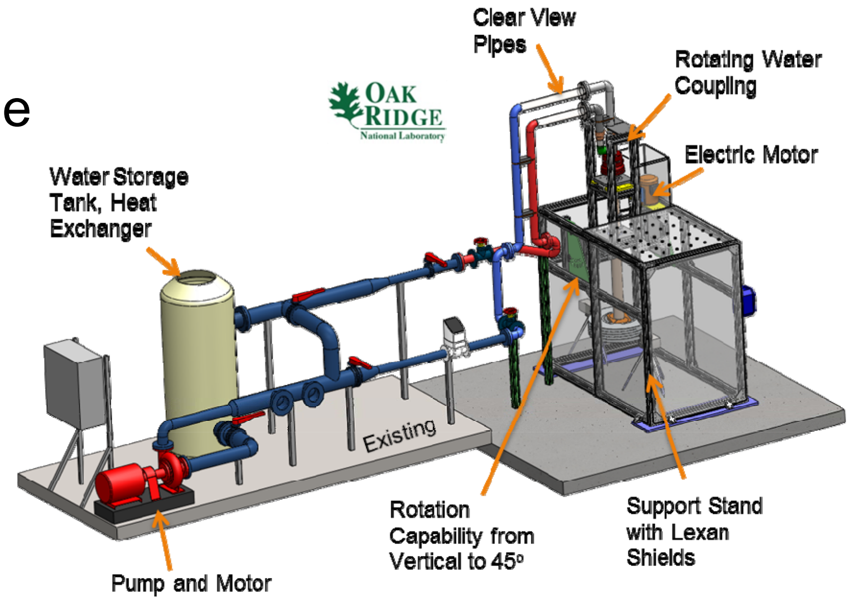


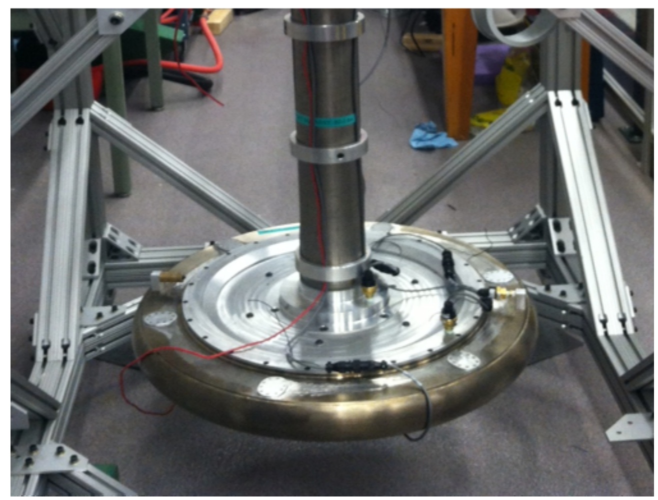


- Mechanical resonances
  - Studied numerically, the operation rotating frequency range found to be far below the first resonance peak.
  - Safety factor of > 90 calculated
  - Mechanical test of mockup did not reveal major issues

Mechanical Challenges
Mockup Tests to Confirm Mechanical Design

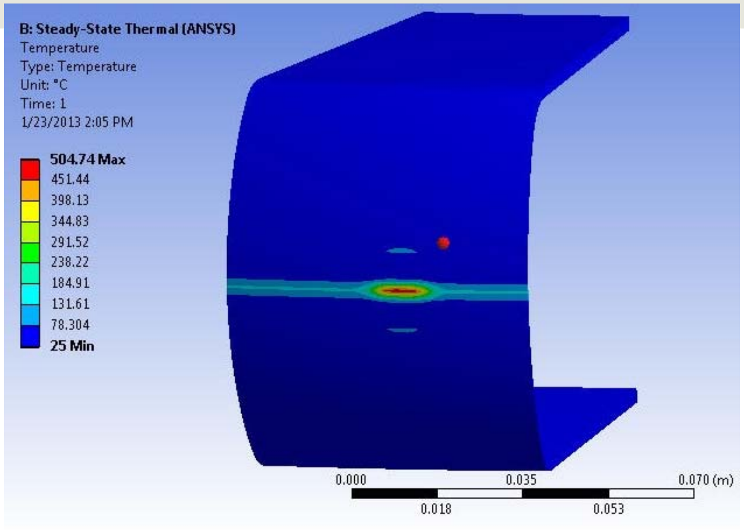
- Beam dump mock-up tests at ORNL performed to evaluate mechanical and flow design
  - Parametric study over flow parameter range
    - » Rotation speed, flow rates, pressures, angle
    - » Evaluation of pressure drops
- Additional prototypic operation verified
  - Mechanical balance
  - Fill and drain tests
  - Reliability



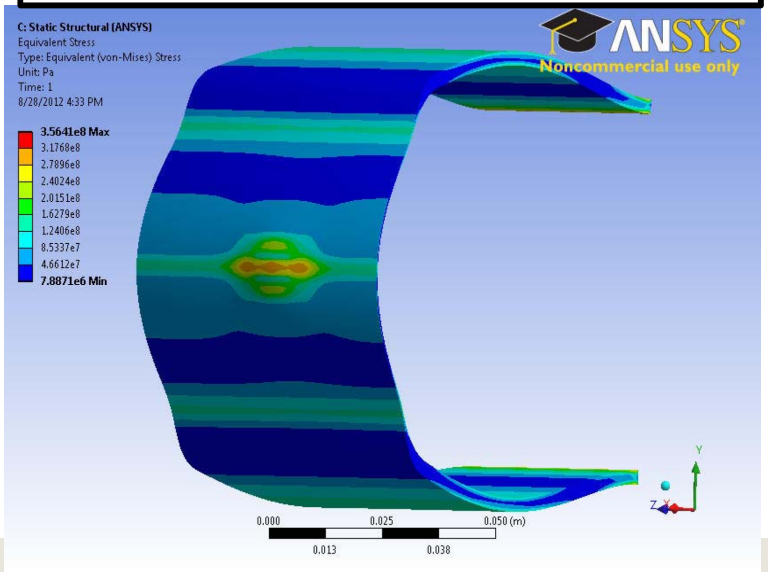


Thermal and Thermo-mechanical Challenges
Thermal Stress in the BD Shell

- High power beam induces high level of thermal stress in the BD shell
  - Thermal and mechanical conditions are numerically simulated for different primary beams and different rigidities
- In the most severe case with U beam:
  - Temperature: 350 ± 150 ºC (limited by 500 ºC to prevent corrosion)
  - Thermal stress: 250 ± 150 MPa
- Far below the stress limit for Ti-6Al-4V alloy
  - 800 – 900 MPa



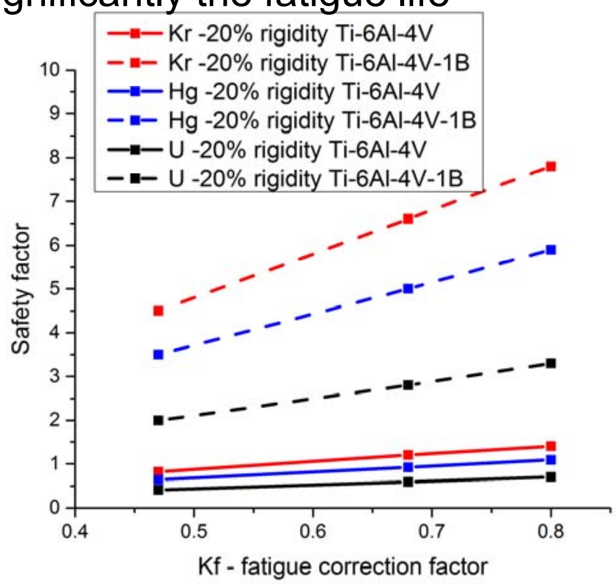
Calculated temperature profile in the Beam Dump shell



Calculated stress profile in the Beam Dump shell

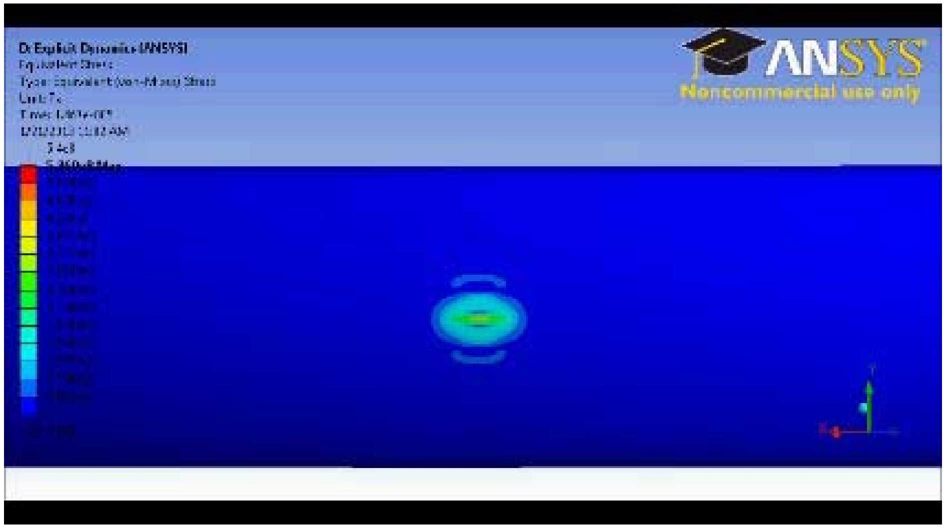
Thermal and Thermo-mechanical Challenges
Fatigue and Stress Wave

- Fatigue
  - BD rotation -> cyclic thermal load from the beam -> possible fatigue issues
  - BD must survive 1.e8 cycles
  - Adding 1% of B to Ti-6Al-4V alloy could improve significantly fatigue properties of the shell, increasing the safety factor for all primary beams and rigidities
  - **<u>Validation tests required</u>** as simulation gives large dispersion in results with respect to the input parameters
  - Corrosion and radiation damage may affect significantly the fatigue life



Fatigue safety factor comparison for Ti-6Al-4V and Ti-6Al-4V-1B alloys

- Stress wave
  - Is a result of the beam impact to the rotating surface. Contributes to the total stress in the BD shell
  - Simulation performed revealed stress wave contribution ~ 10% of the total stress

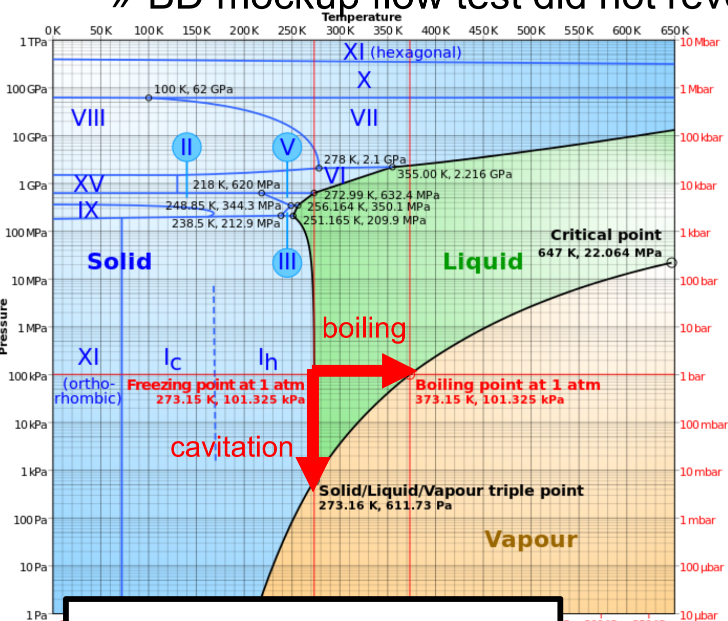


Stress wave propagation in the BD shell

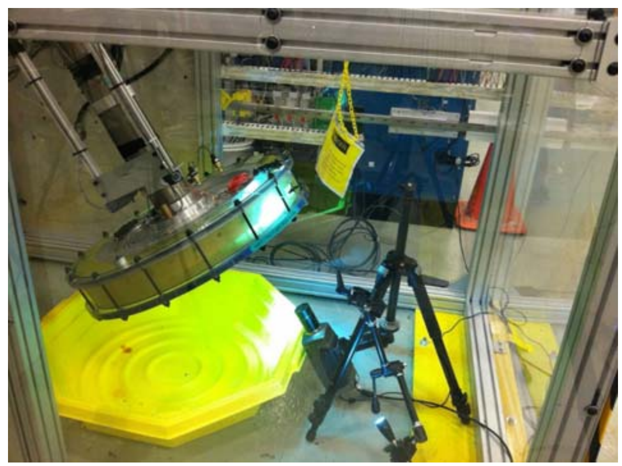
Fluid Challenges
Bubble Formation: Boiling and Cavitation

- Boiling – bubble formation due to high power deposition in water and in the shell
- Cavitation – bubble formation due to rapid change of pressure
- Bubble formation -> bubble collapse -> shockwave -> possible BD shell damage
  - Study of bubble formation on the shell is in progress
  - Cavitation study – simulation and test
    - » Simulation showed no critical pressure changes
    - » BD mockup flow test did not reveal cavitation

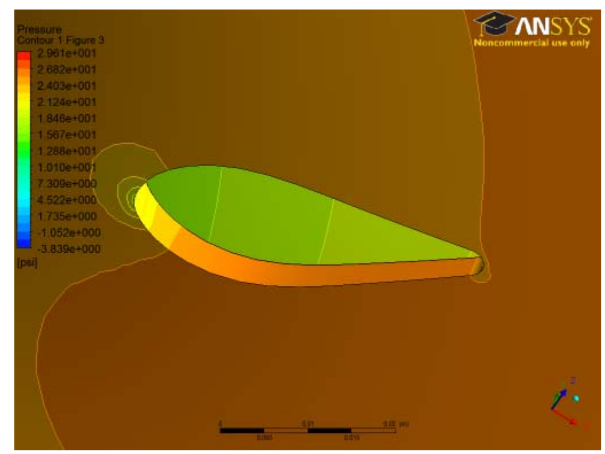
A movie from the test



Water phase diagram



Flow test with transparent (acrylic) beam dump



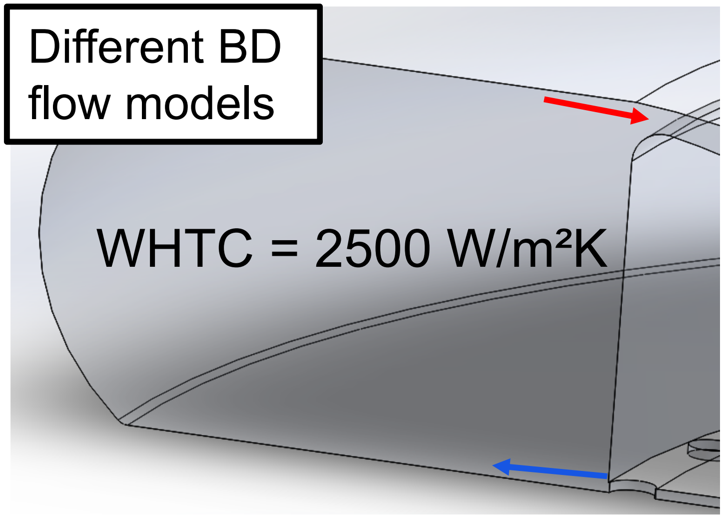
Pressure drop simulation

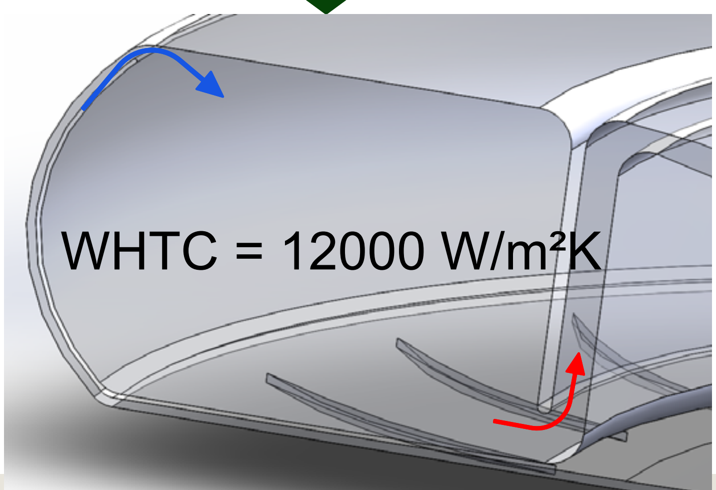
Fluid Challenges

Wall Heat Transfer [1]

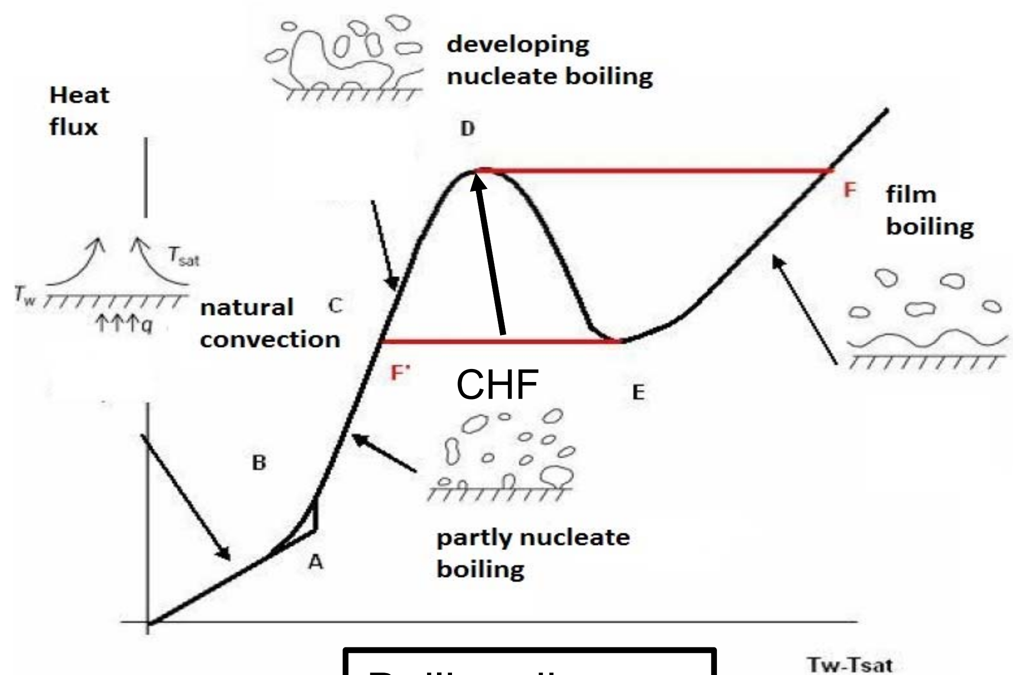
- Good heat transfer is essential for heat removal from the shell => highly turbulent water flow required. CFD simulation – wall heat transfer improved by introducing the turbine and insert

Different BD flow models





- **<u>Nucleate boiling</u>** allows to obtain an order of magnitude larger heat transfer
  - Critical heat flux is one of the most essential parameters: exceeding it will result in transition to the film boiling -> failure



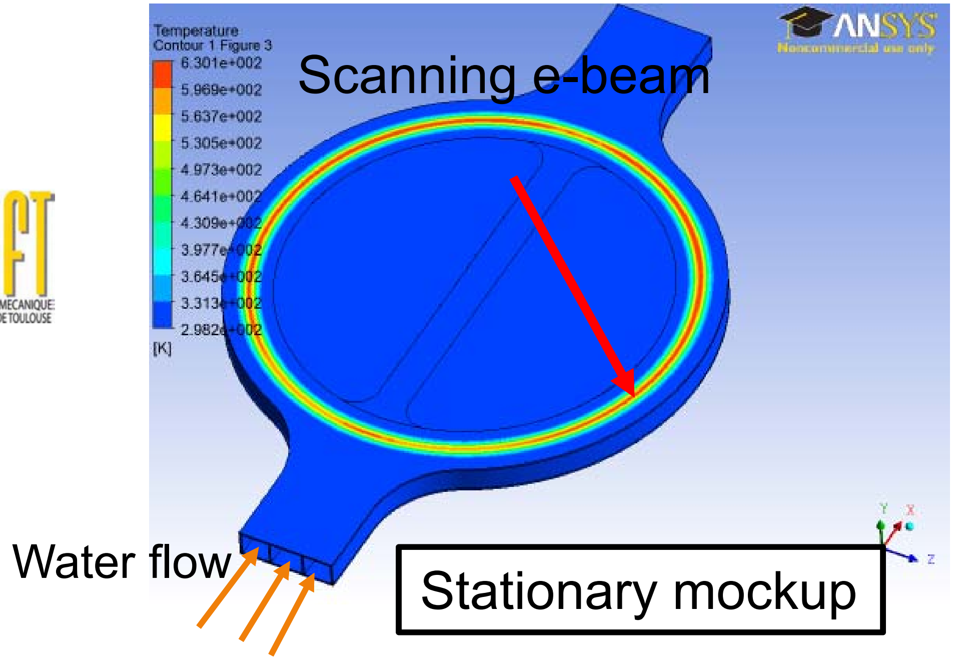
Boiling diagram

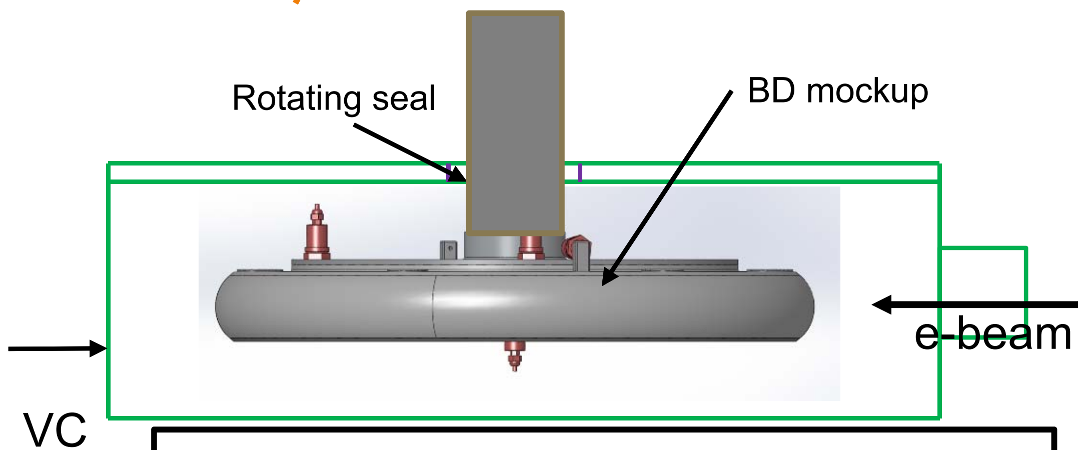
Fluid Challenges

Wall Heat Transfer [2]

- Study:
  - Collaboration with Fluid Mechanic Institute of Toulouse established (expertise in transitory boiling problem in nuclear power plant)
  - Simulation of the BD fluid and thermal conditions with NEPTUNE code
  - **<u>Q:</u>** How can fast rotation help in bubble removal from the BD shell thus improving the heat transfer?
- Tests:
  - Tests intended to evaluate the heat flux transfer through the shell
  - Electron beam will be used to heat the mockup
  - Other issues (like fatigue or bubble formation) are possible to study

IMFT INSTITUT DE MECANIQUE DES FLUIDES DE TOULOUSE



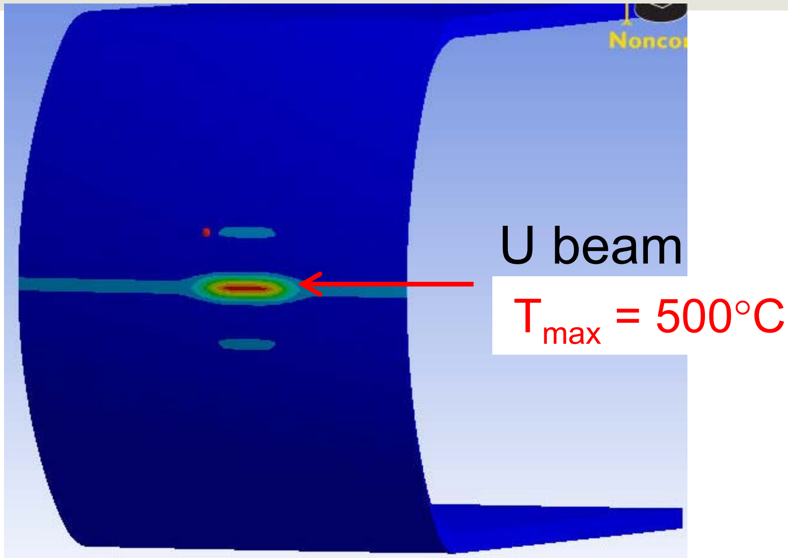


BINP, rotating quarter-scale mockup

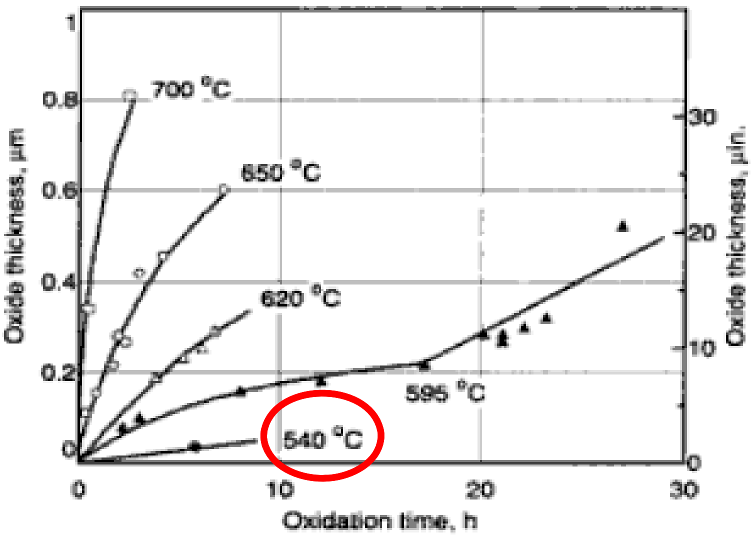
Budker Institute of Nuclear Physics

Chemical challenges

Corrosion, radiolysis



Beam spot on the BD shell



- Corrosion
  - Ti-6Al-4V temperature must be limited by 500 ºC to avoid strong corrosion in water
  - Reduced power densities for few ion beams at few rigidities could be used
  - Nanoscale corrosion studies during SHI irradiation at Sandia Lab
- Radiolysis
  - Liberates hydrogen and oxygen gas and produces hydrogen peroxide that may impact the BD shell
  - Gas production estimates did not reveal substantial quantities of H, O and HO2
  - Water circulation helps to prevent the gas accumulation
  - Adding H2 (3 ppm) mitigates radiolysis

Radiation challenges

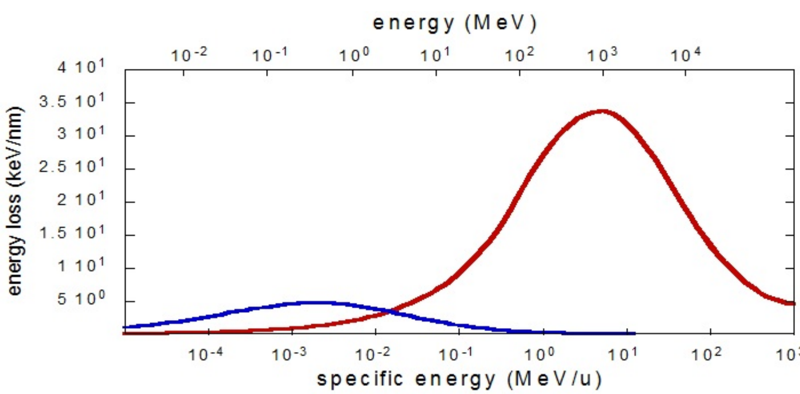
Radiation damage of Ti alloy and Sputtering

- Irradiation test with Ti-6Al-4V and Ti-6Al-4V-1B alloys
  - Irradiation tests were performed at IRRSUD (GANIL, Caen, France)
  - No evidence of Phase transformation and ion track was shown at 3 irradiations (^{82}Kr at 25 and 45 MeV and ^{131}Xe at 92 MeV)
  - More tests ongoing at IRRSUD
  - Samples of Ti-6Al-4V-1B were irradiated at NSCL with ^{40}Ca beam at 50 MeV/u

<u>Talk of F. Pellemoine, this workshop</u>

- Sputtering
  - A process of surface erosion due to bombardment by the ions
  - Sputtering is stronger in insulators (TiO2)
  - Sputtering evaluation for Ti and TiO2 (M. Toulemonde, GANIL): U beam at 160 MeV/u
  - Thickness of sputtered layers were estimated to be 0.2 nm/year for Ti, 1 micron/year for TiO2 – should not be an issue

CIMAP



Energy loss vs. specific energy for nuclear (blue) and electronic (red) sputtering

Conclusions

- Water-filled rotating drum concept of the beam dump is chosen for the FRIB baseline
- No show-stoppers but challenges exists and being addressed
- Some effects may be enhanced by the presence of the other (e.g. – corrosion in presence of radiation, stress limit in the presence of radiation)
  - Up to now no facility exists to study an impact from all the effects combined
  - All challenges were studied case-by-case experimentally and in simulation
- Solutions found for most issues that could negatively impact on the BD operation
- Some studies (in particular, BD fluid flow/boiling/shell heat transfer) ongoing

Acknowledgements

FRIB-MSU:
Frederique Pellemoine
Wolfgang Mittig
Mike Schein
Tiffany Fourmeau
Reginald Ronningen

ORNL:
Adam Aaron
Adam Carroll
Van Graves
Tom Burgess

MSU Department of Chemical Engineering and Material Science:
Carl Boehlert
Aida Amroussia

Institute of Fluid Mechanics (Toulouse, France):
Catherine Colin
Wladimir Bergez

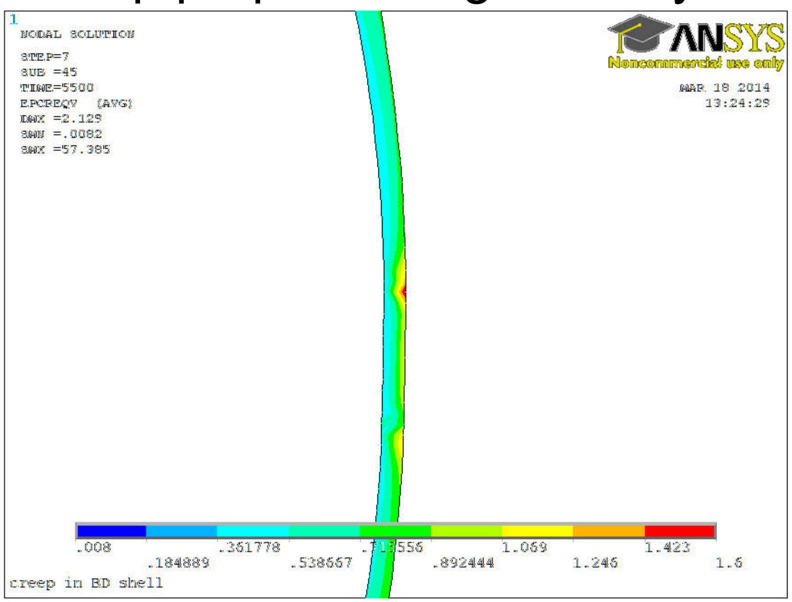
GANIL:
Marcel Toulemonde

Thanks for your attention!

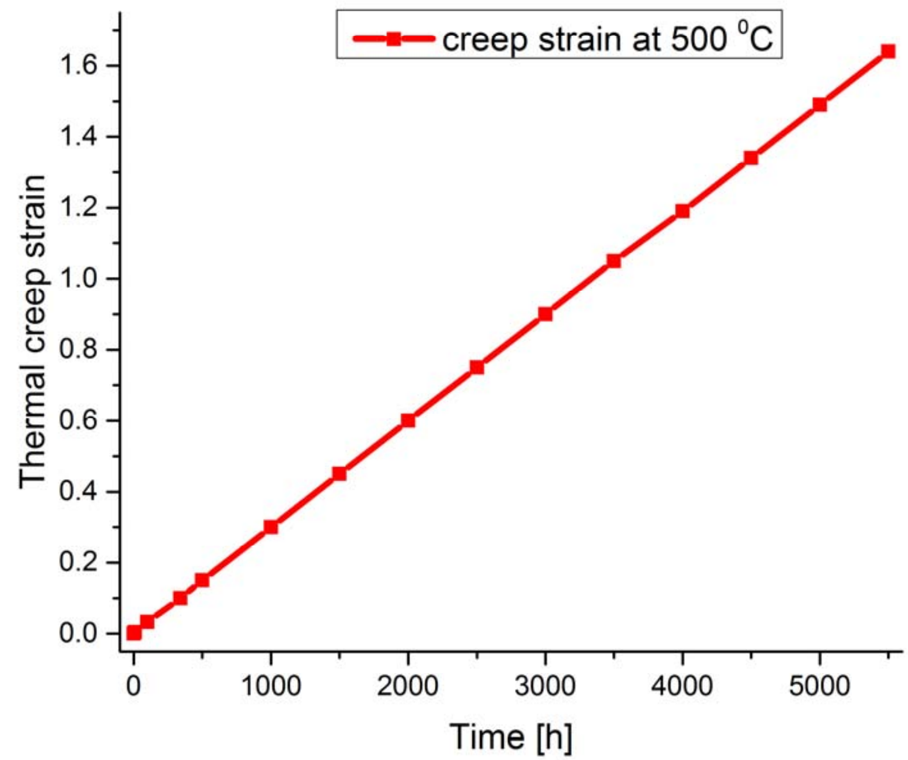
Backup slides

- Thermal creep evaluation

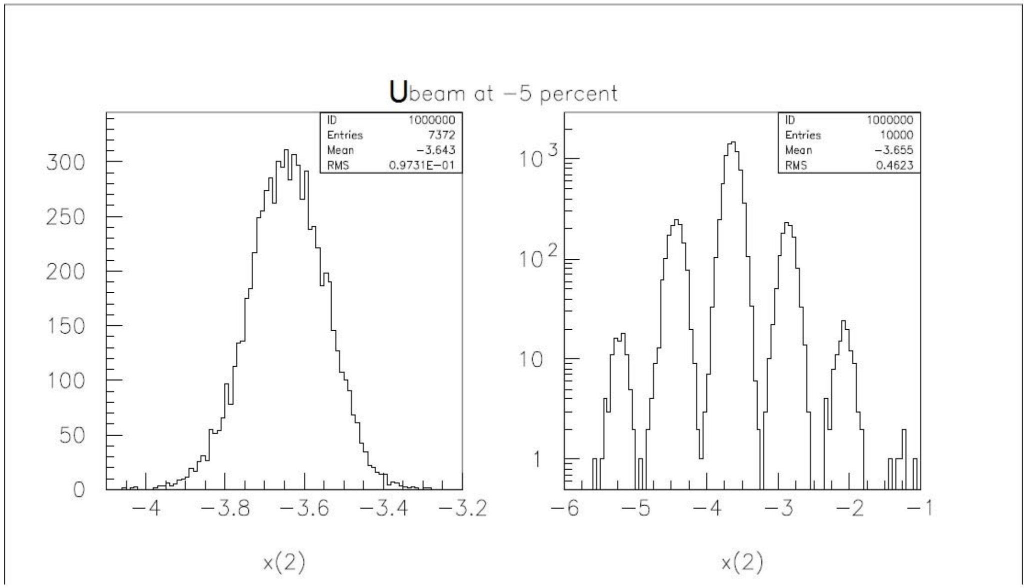
  Creep strain at failure: 0.32
  Corresponds to >1000 h of operation.
  Creep strain after 2 weeks = 0.1
  Creep strain after 5500 hours = 1.6
  Using Ti-6Al-4V-1B alloy improves creep properties significantly

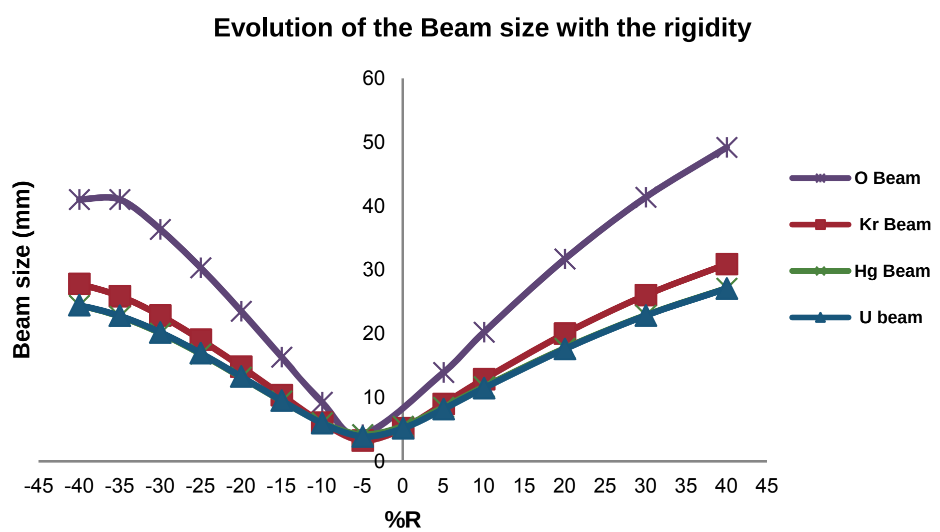


Barboza, Neto, Silva "Creep mechanism and physical modeling for Ti-6Al-4V"
Material Science and Engineering A369 (2004) 201-209



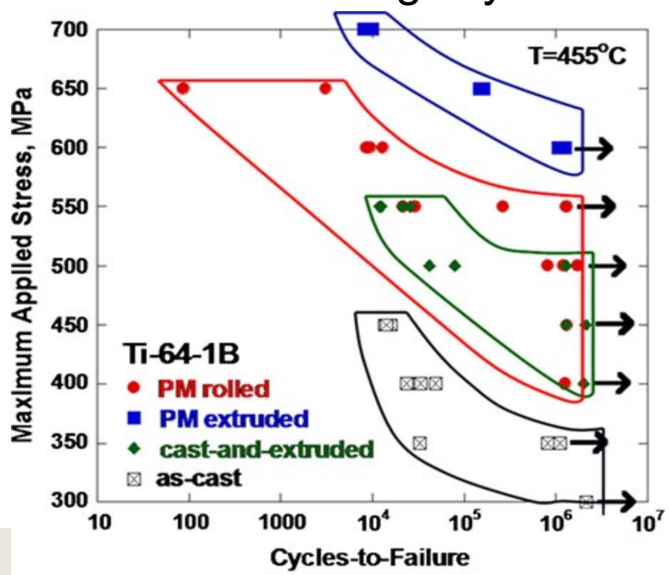
Backup slides





-5% Rigidity U beam profile on the BD shell (worst case)

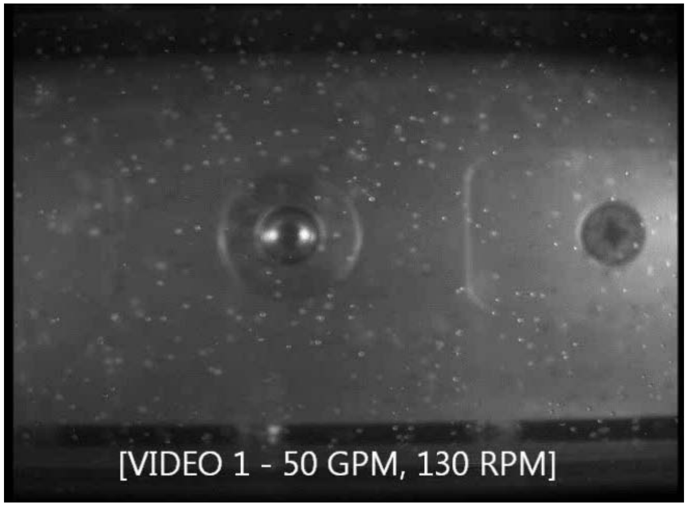
Beam size vs Rigidity

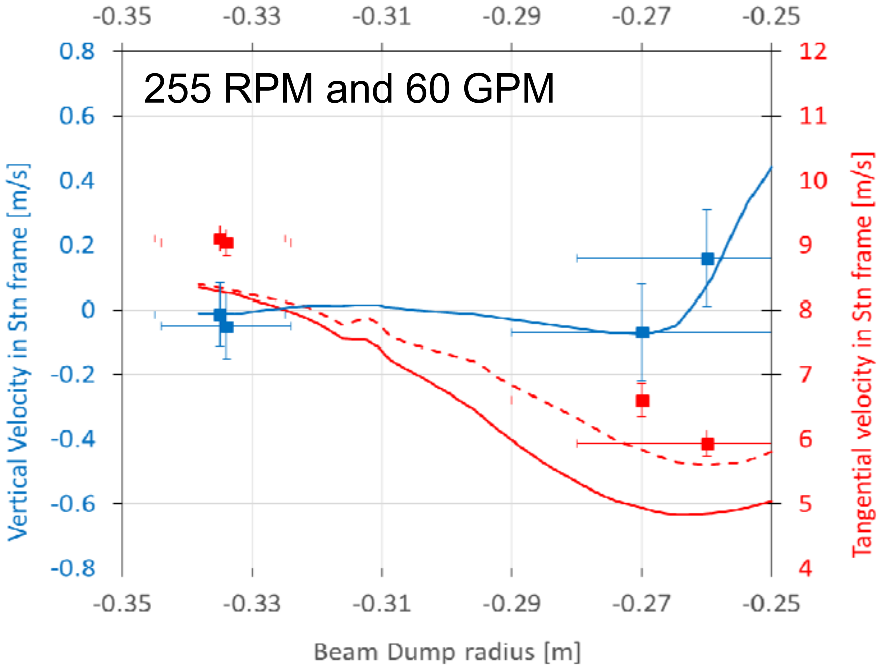


SN curves for various Ti alloys

Backup slides

- Flow velocity profile verified in flow test with polystyrene beads (ρ = 1.05 g/cm³)





Backup slides

- Chosen concept
  - Water-filled rotating drum
    - » Most deposition occurs in water, minimize radiation damage to drum
    - » Adequate cooling accomplished with water through convection
    - » Flexibility in material selection to accommodate different requirements
- Issues with other options
  - Graphite disk beam dump
    - » excessive sublimation rates
    - » Insufficient cooling of disk where maximum power deposition occurs (Bragg peak)
    - » Buildup of inventories
    - » Minimal flexibility in material selection
  - Liquid tin jet
    - » Significant instability of jet when rapidly heated
    - » Vaporization -> plating in beam line
    - » Size/complexity of molten metal loop required
    - » Few alternate materials for liquid metal jet