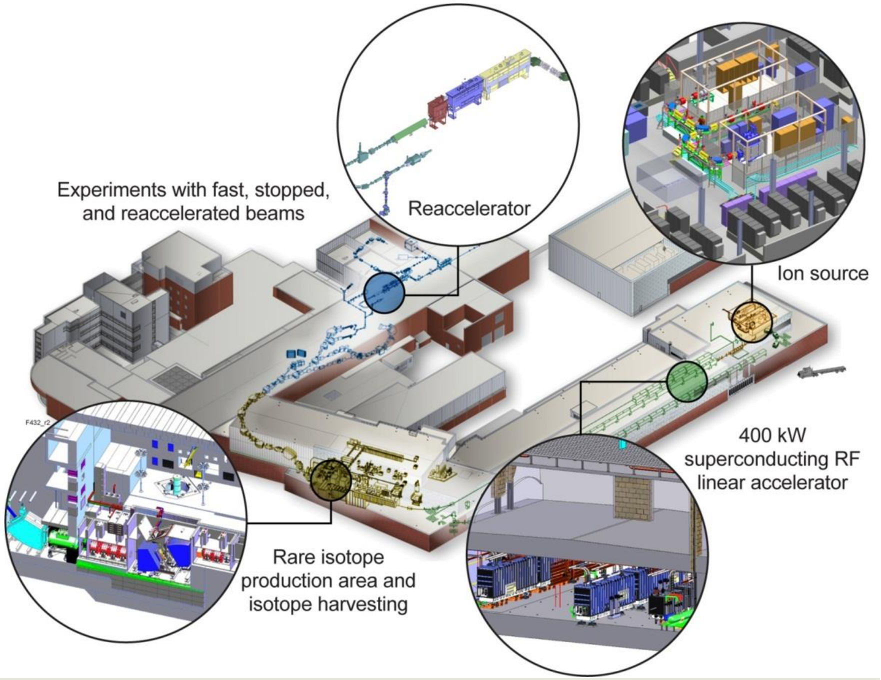
High Power Targetry at FRIB

F. Pellemoine
Target and Beam Dump Systems Group Leader

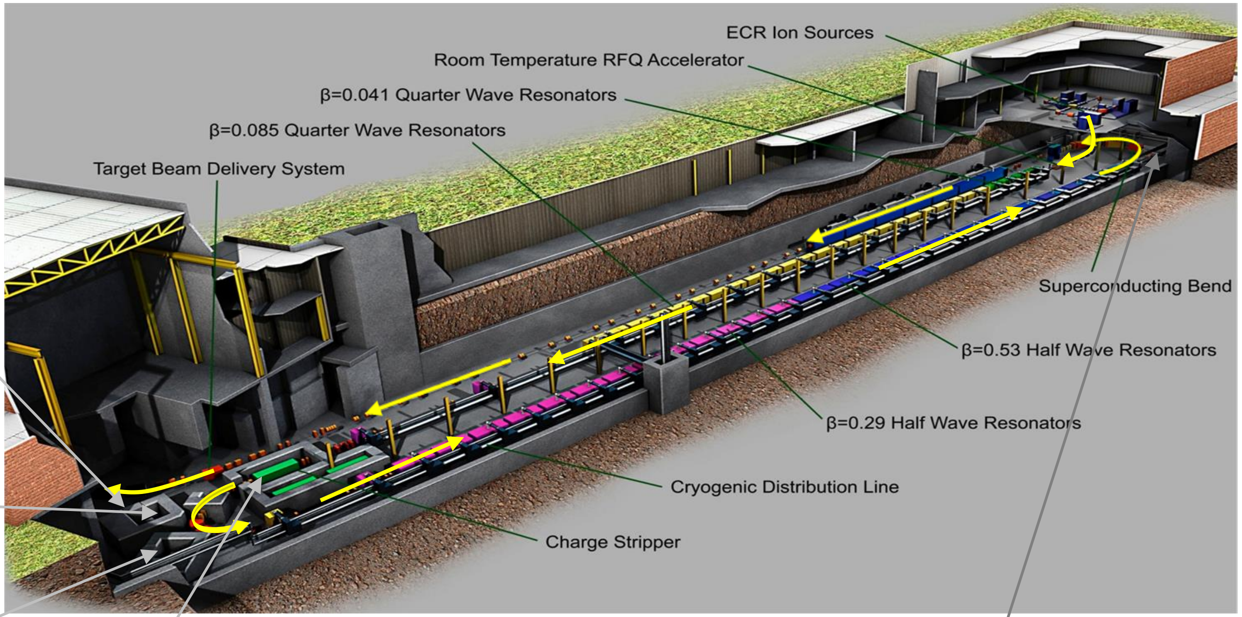
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Challenge in Accelerator System area
  - Lithium stripper
  - Folding segment dumps and beam delivery system dump
- Challenge in Experimental System area
  - Production target
  - Beam dump
- R&D and testing to support design
  - Production target
  - Beam dump
- Isotope harvesting
- Summary



Challenges in Accelerator System Area



Beam Delivery System Dump
- E = 150-300 MeV/u
- $P_{deposited}$ ~ 400 kW
- Duty factor = 0.03 %

Folding Segment 1-a
- E = 12-20 MeV/u
- $P_{deposited}$ ~ 42 kW
- Duty factor = 0.03 %

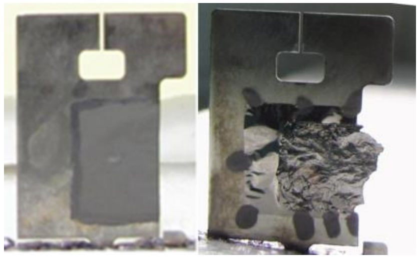
Folding Segment 1-b
- E = 12-20 MeV/u
- $P_{deposited}$ ~ 12 kW
- Duty factor = 1 %

Stripper (Lithium)
- E = 16-20 MeV/u
- P_{beam} = ~ 40 kW
- $P_{deposited}$ ~ 0.6 kW
- $\sigma_{x\ beam}$ = 0.75 mm
- $\sigma_{y\ beam}$ = 0.75 mm
- P =~ 30 MW/cm^3

Folding Segment 2 Dump
- E = 15-160 MeV/u
- $P_{deposited}$ ~ 300 kW
- Duty factor = 0.03 %

Accelerator System Area
Lithium Stripper

- Stripper challenges in FRIB
  - Solid carbon foils can be used only with low Z ions at low intensities
  - We need to utilize a stripping media that doesn't suffer radiation damage to the material lattice
  - Liquid lithium was selected as baseline for FRIB
    - » It has a relatively low melting point (181 C), low vapor pressure at that temperature (~10^{-7} Pa), high boiling point (1342 C), high heat capacity and low viscosity.
    - » The negative aspect is that it is reactive with air, safety concerns

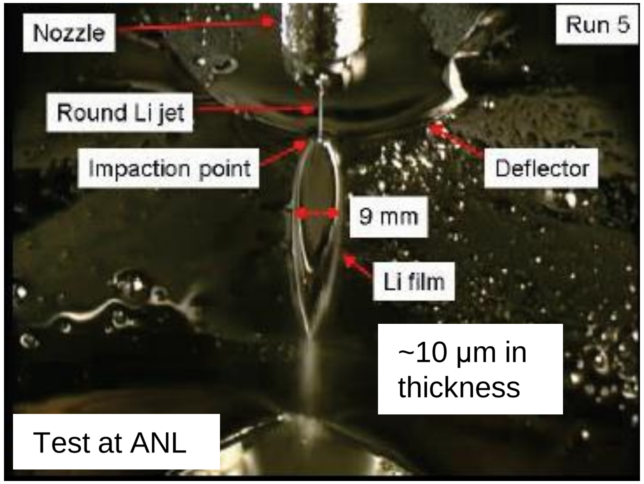


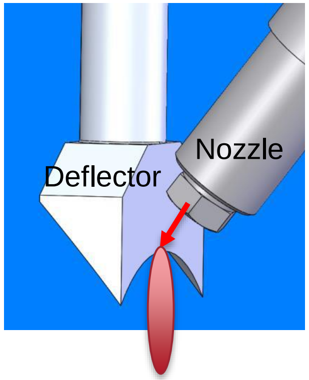
F. Marti et al., "A carbon foil stripper for FRIB", TUP 106, Proceedings of LINAC2010, Tsukuba, Japan, TUP105.

Accelerator System Area

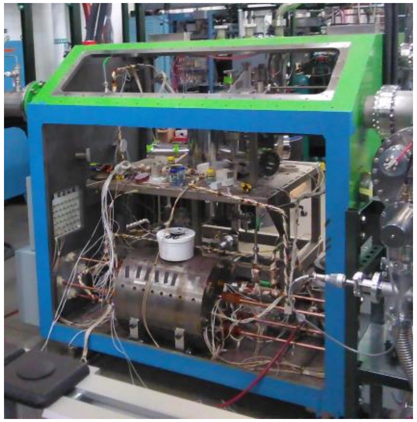
Lithium Stripper - R&D and Safety Issues

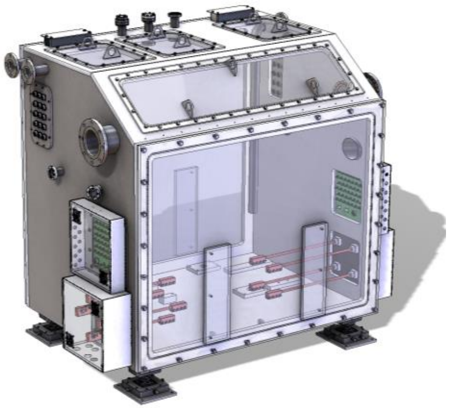
- R&D issues
  - Continuous operation for two weeks with electromagnetic pump.
  - Erosion/corrosion of nozzle / deflector
  - Improvement of film stability
  - Diagnostics for film thickness measurement





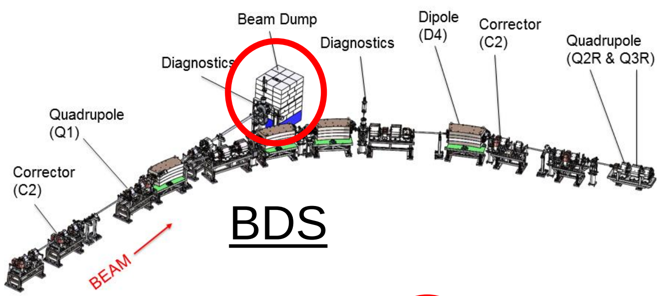
- Safety issues
  - Liquid lithium-air contacts resulting in a potential lithium fire
    - » Secondary containment vessel filled with argon
  - Activation of the lithium, and the argon gas in the secondary containment vessel as well as in the argon storage tank





Accelerator System Area Beam Dump

- Accelerator beam dumps have a common core design, air-cooled with location-specific local shielding
  - Folding Segment 1 (FS-1) beam dumps are low energy, the required shielding is for residual activation protection
  - Folding Segment 2 (FS-2) beam dumps are higher energy, the additional steel and concrete stack provides primarily prompt shielding



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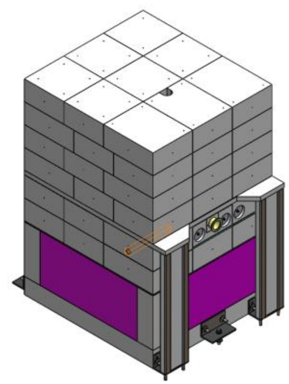
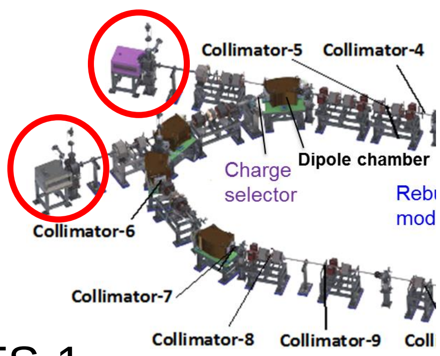
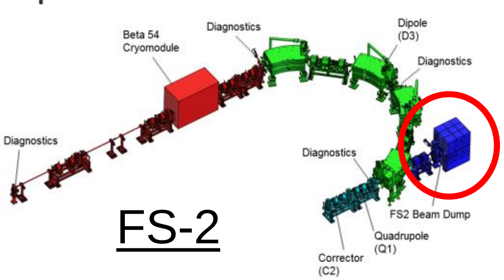


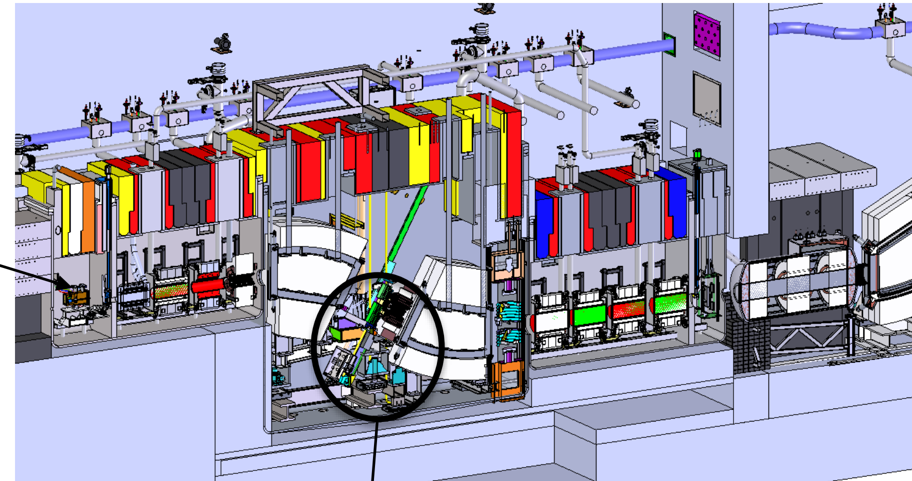


FS-1



FS-2

Challenges in Experimental System Area

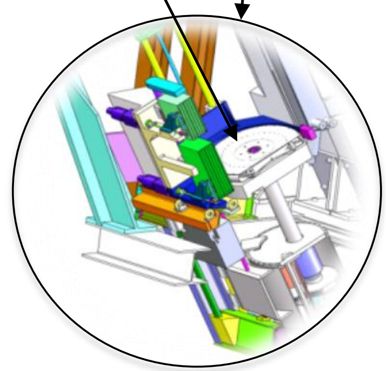


Production target (graphite)

- $E = 202 – 260$ MeV/u
- $P_{beam} = 400$ kW
- $P_{deposited} \sim 100$ kW
- $\sigma_{x\ beam} = 0.24$ mm
- $\sigma_{y\ beam} = 0.29$ mm
- $P = 60$ MW/cm^3
- Dose ~ 8 dpa

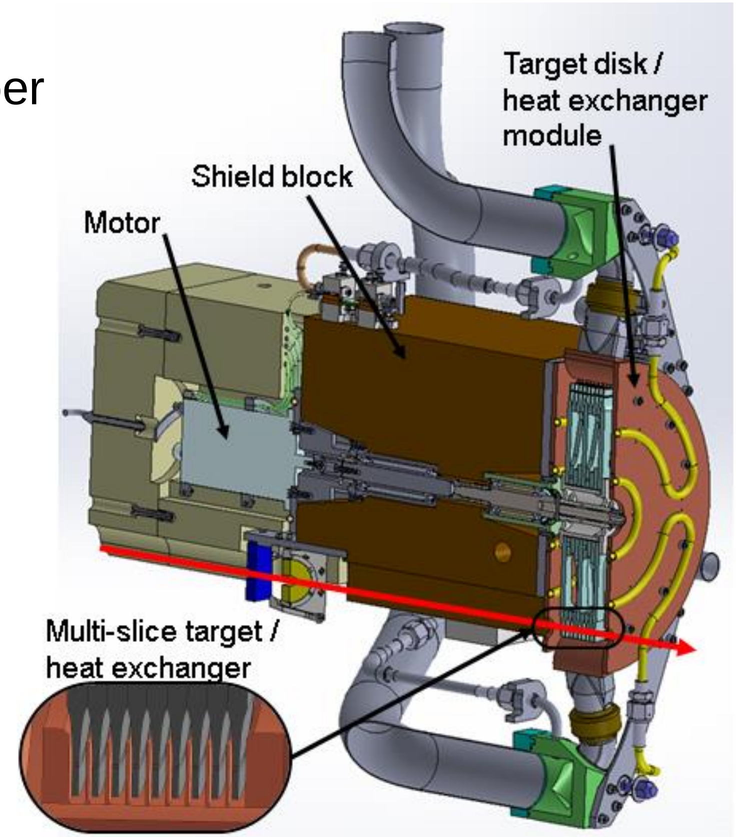
Beam dump drum (Ti-alloy)

- $E = 156 – 260$ MeV/u
- $P_{deposited} \sim 300$ kW
- $\sigma_{x\ beam} = 1\text{-}10$ mm
- $\sigma_{y\ beam} = 2\text{-}50$ mm
- $P = 30$ MW/cm^3
- Dose ~ 7 dpa



FRIB Production Target
Rotating Multi-slice Graphite Target Design

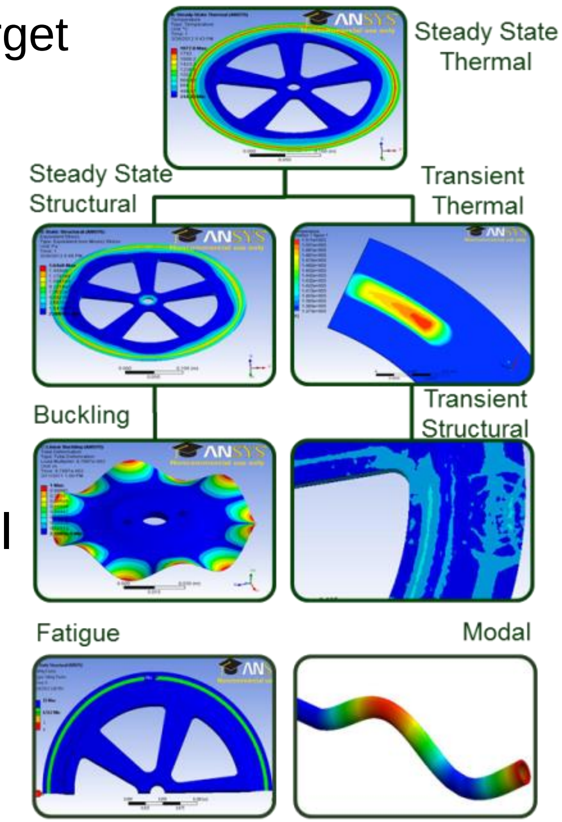
- Rotating multi-slice graphite target chosen for FRIB baseline
  - Increased radiating area and reduced total power per slice by using multi-slice target
  - Use graphite as high temperature material
  - Radiation cooling
- Beam Dump requirements
  - High power capability up to 100 kW
  - 2 weeks
  - Remote replacement and maintenance
- Design parameters
  - Remote replacement and maintenance
  - Optimum target thickness is ~ ⅓ of ion range
  - Maximum extension of 50 mm in beam direction including slice thickness and cooling fins to meet optics requirements
  - 5000 rpm and 30 cm diameter to limit maximum temperature and amplitude of temperature changes



Session #4
Session #5

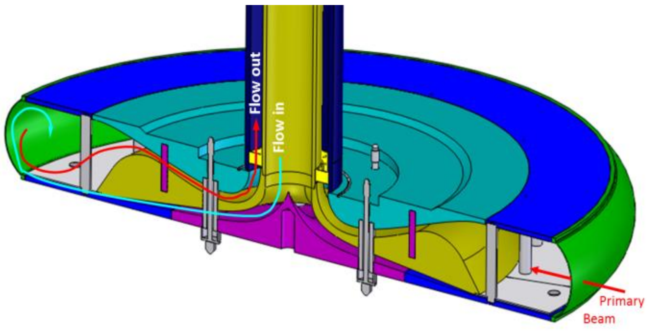
FRIB Production Target
Challenges Overview

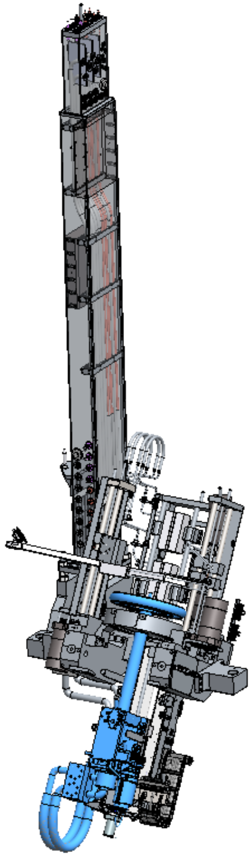
- Thermo-mechanical challenges
  - High power density: ~ 20 - 60 MW/cm³
    - » High temperature: ~ 1900 ºC: Evaporation of graphite, stress
  - Rotating target
    - » Temperature variation: Fatigue, Stress waves through target
- Swift Heavy Ion (SHI) effects on graphite
  - Radiation damage induce material changes
    - » Thermal and mechanical property changes
  - Swift heavy ions (SHI) damage not well-known
  - High fluence/dose may limit target lifetime
- Similar challenges at
  - Facility for Antiproton and Ion Research (FAIR) at GSI
  - Radioactive Ion Beam Factory (RIBF) at RIKEN



FRIB Primary Beam Dump
Water-filled Rotating Drum Concept

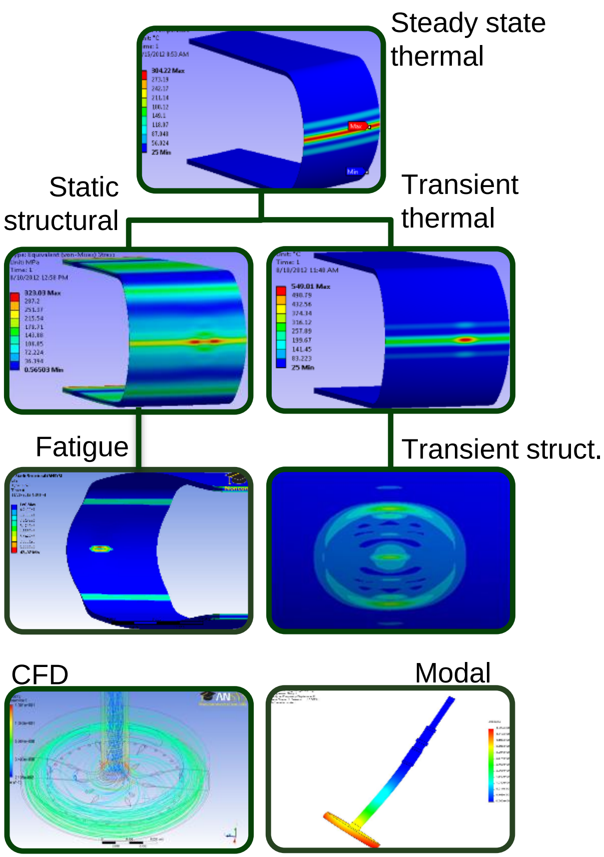
- Water-filled rotating drum concept chosen for FRIB baseline
  - Using water to stop the primary beam and absorb beam power
- Beam Dump requirements
  - High power capability up to 325 kW
  - 1 year (5500 h) lifetime desirable
  - Remote replacement and maintenance
- Design parameters
  - Ti-alloy shell thickness 0.5 mm to minimize power deposition in shell
  - 600 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
  - 8 bar pressure inside the drum increases water boiling point to 170ºC
- Ti-6Al-4V was chosen as candidate material for the beam dump shell





FRIB Primary Beam Dump
Challenges Overview

- Thermo-mechanical challenges
  - High power – up to 60 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
- Water
  - Corrosion, Cavitation
- Swift heavy ions
  - Radiation damage in material
  - Sputtering
  - Radiolysis (gas production)



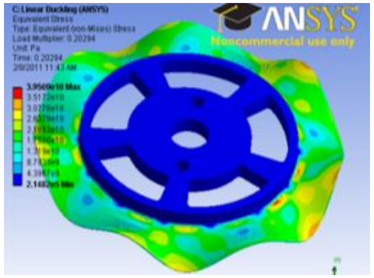
R&D to support design

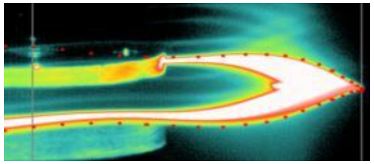
- Thermo-mechanical behavior and radiation damage of material during operation could limit the lifetime of each equipment
  - Thermo-mechanical stress, fatigue, corrosion, physical property change of material under irradiation, ….
- FRIB will provide a wide range of swift heavy ion beams
  - Equipment needs to be reliable for each single beam configuration
  - Radiation Transport analysis done for each component to support design

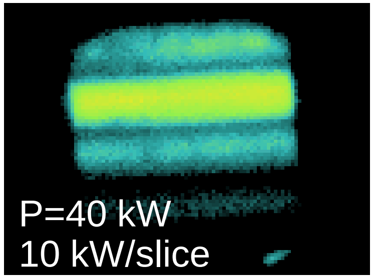
R&D to support design

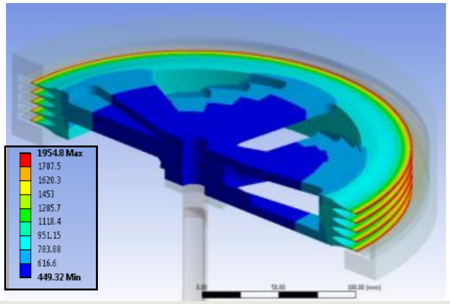
Target Testing with High Energy Electron Beam

- Electron beams used to simulate similar power density close to FRIB conditions without the activation of the target due to nuclear reaction
- Successful low energy electron beam tests at Sandia National Laboratories (2010) and SOREQ (2010)
  - Demonstrated that FRIB power densities can be achieved
- Prototype for FRIB production target successfully tested with electron beam at BINP-Novosibirsk (2012)
  - 5 slices – 0.3 mm - 5000 rpm - 30 cm diameter
  - Demonstrated that FRIB power densities can be achieved
  - Valuable information on further design improvements of heat exchanger and targets themselves. Input for final design of FRIB production target









Sandia National Laboratories

SOREQ

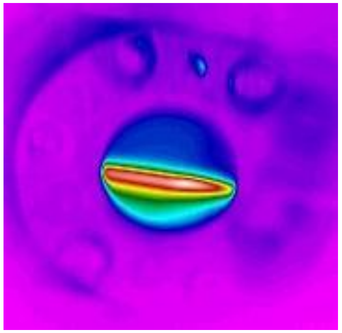
Budker Institute of Nuclear Physics

R&D to support design

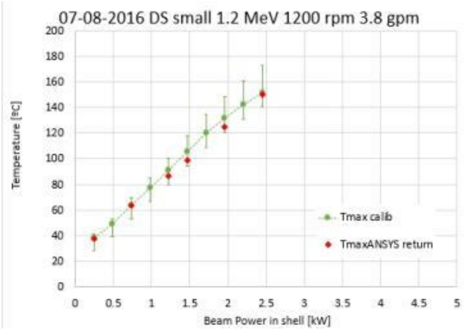
Beam Dump Testing with High Energy Electron Beam

- Testing with high energy electron beam at Novosibirsk with ¼ scale mock-up: a 0.5 mm thick shell made of DMLS Ti-6Al-4V – July 2016
  - Validate the maximum heat flux in the beam dump shell
  - Wall Heat Transfer Coefficient (WHTC) determination in rotating system
  - Single-phase fluid flow and point of entering nucleate boiling regime limit
- Good agreement between experimental data and simulation results for single shell geometry (independent of the beam size) and for double shell geometry (small beam)

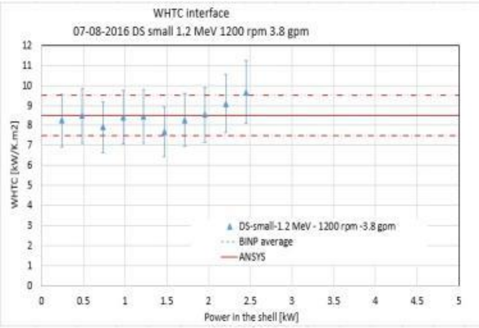
Budker Institute of Nuclear Physics

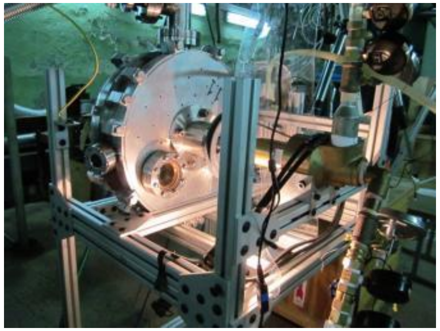


Small beam – Double shell



Small beam – Double shell





S1-Ishida

Poster-Amroussia

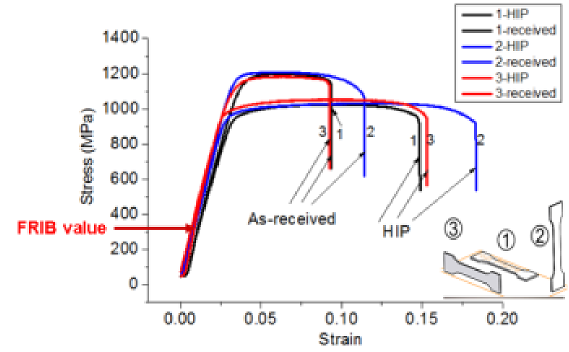
R&D to Support Design

Session #2

Session #4

Material Study to Assess Beam Dump Lifetime

- Material study of Ti-6Al-4V alloys under irradiation to assess beam dump shell lifetime
- Low energy heavy ion irradiation at University Notre Dame and GANIL-IRRSUD facilities performed to study mechanical property changes of Ti-alloys with radiation damages
  - Reach high dose (up to 10-20 dpa/day) without activation of the samples
  - Low range limits the analysis to few characterization (SEM, TEM, Nano-indentation,…)
- Test at BNL-BLIP facility started in April 2017 with RaDIATE collaborators
  - Irradiation with high energy protons (up to 1 dpa in Ti samples) – sample activation
  - characterize property changes due to proton induced damage
- Mechanical tests at MSU-College of Engineering
  - Fatigue test, porosity measurement and tensile test



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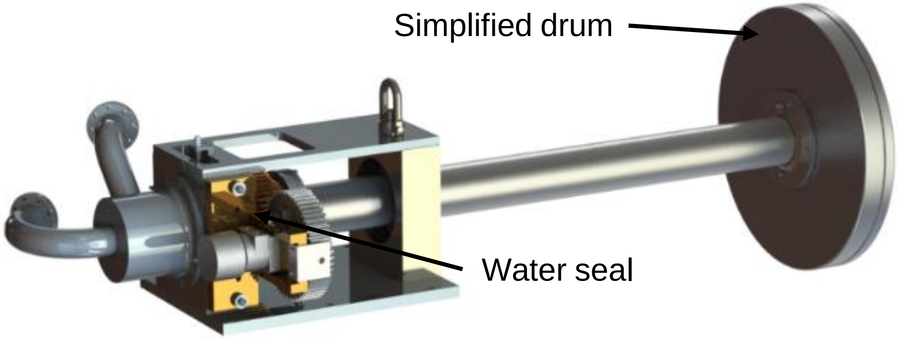
CiMap

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Test to validate concept
Beam Dump Rotating Seal Testing

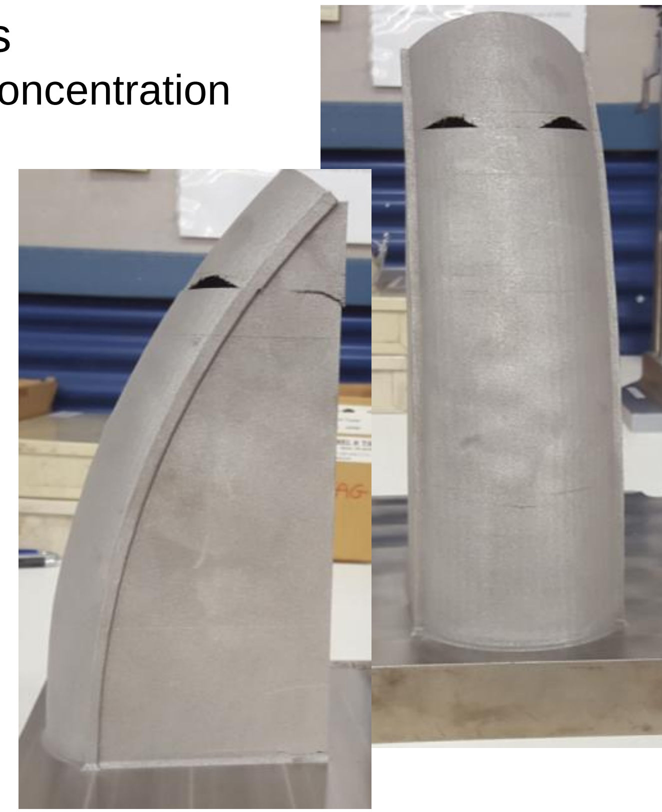
- Beam dump rotating seal test on going
  » Validate the concept
  » Estimate outgassing rate

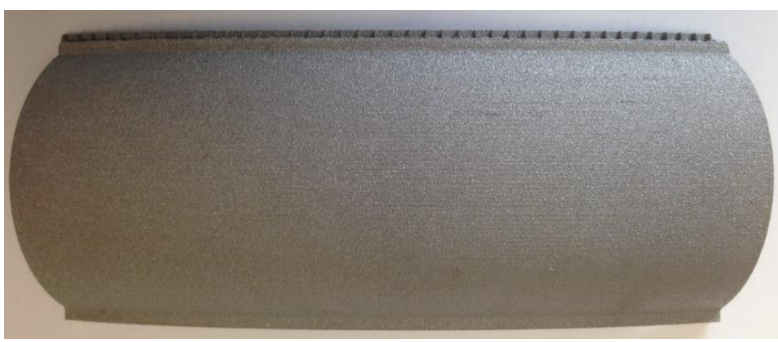


3D Printed Material for Beam Dump Drum

Fabrication Challenge

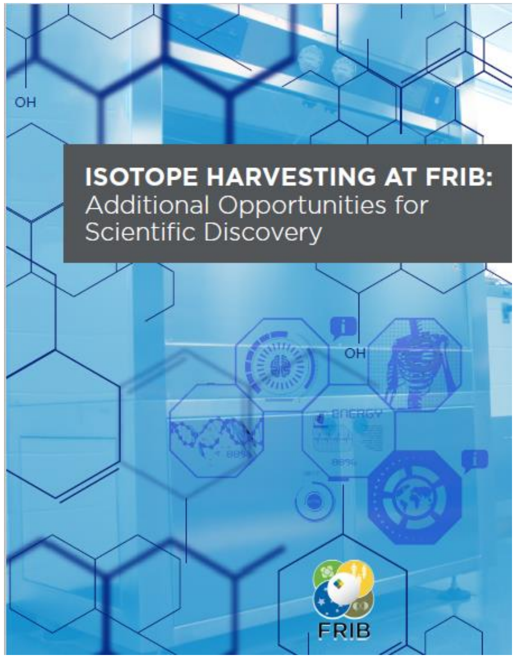
- 3D printer technology is needed for drum shell fabrication for high power
- Several technologies exist to support beam dump drum fabrication
  - Electron Beam Additive Manufacturing (EBAM) for 1 mm shell
  - Direct Metal Laser Sintering (DMLS) for 0.5 mm shells
    - » Failure (material show sinking and cracks) due to stress concentration
  - EBAM and DMLS work with cold environment
  - ARCAM EBM® (Electron Beam Melting)
    - » Arcam EBM® process takes place in vacuum and at high temperature, the components produced are free from residual stress and have material properties better than cast and comparable to wrought material.

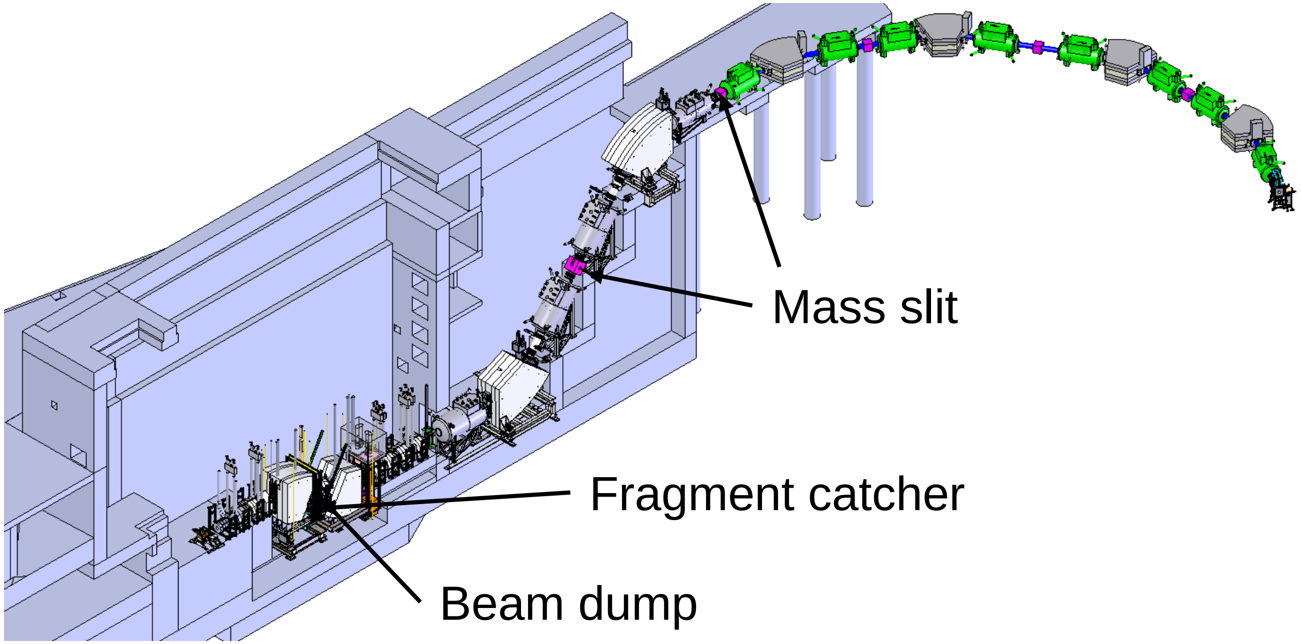




Isotope Harvesting

- "The normal operation of FRIB will produce a wide variety of useful … Many of these radioisotopes also have applications that serve societal needs, in fields ranging from diagnosis and treatment of cancer to national security."





Summary

- Lithium Stripper, production target and beam dump, are challenging equipment that need to be reliable for every single beam configuration
- Extensive R&D was performed to validate the concept for the Lithium stripper, production target and the beam dump
- Continue to improve understanding of material behavior under irradiation to assess lifetime of equipment during operation
- Continue to evaluate technical improvements that may be needed as facility ramps up to full power
- New generation facilities all around the world have or will have similar challenges to deal with
- The 7^{th} High Power Targetry Workshop will be a great source of discussion and sharing

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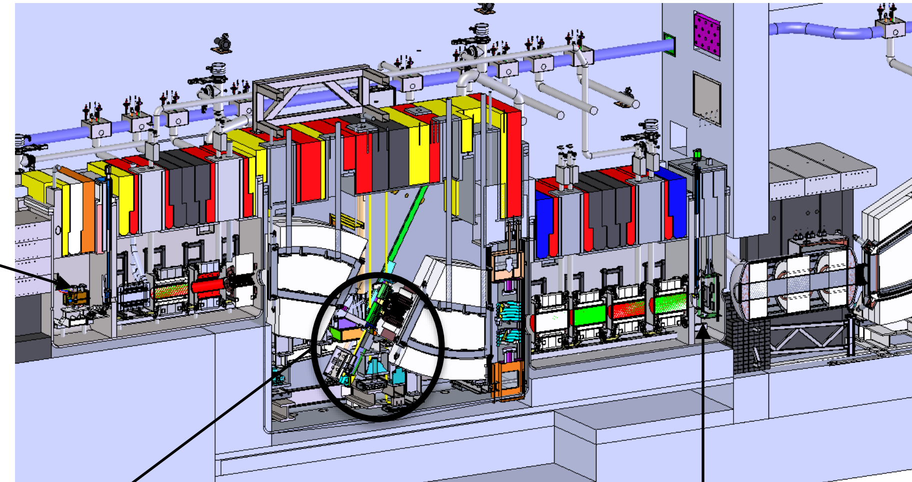
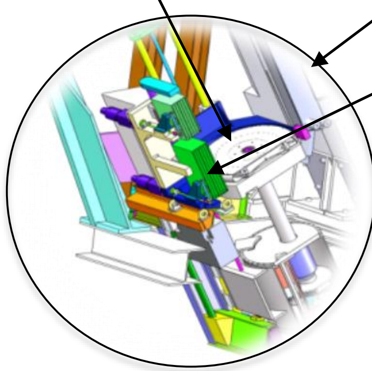
Backup Slides

Challenges in Experimental System Area



Production target (graphite)
- E = 202 – 260 MeV/u
- P_{beam} = 400 kW
- $P_{deposited}$ ~ 100 kW
- $\sigma_{x\ beam}$ = 0.24 mm
- $\sigma_{y\ beam}$ = 0.29 mm
- P = 60 MW/cm³
- Dose ~ 8 dpa

Beam dump drum (Ti-alloy)
- E = 156 – 260 MeV/u
- $P_{deposited}$ ~ 300 kW
- $\sigma_{x\ beam}$ = 1-10 mm
- $\sigma_{y\ beam}$ = 2-50 mm
- P = 30 MW/cm³
- Dose ~ 7 dpa



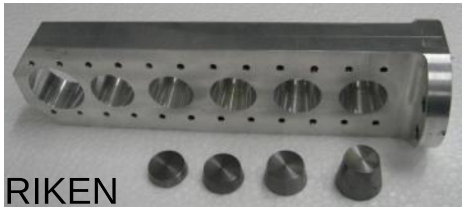
Fragment catcher (Al-alloy)
- E = 156 – 260 MeV/u
- $P_{deposited}$ < 10 kW
- $\sigma_{x\ beam}$ = up to 15 cm
- $\sigma_{y\ beam}$ = up to 5 cm
- P = 9 kW/cm³
- Dose ~ 2.5 dpa

Wedge (Al-alloy)
- E = 156 – 260 MeV/u
- $P_{deposited}$ < 2 kW
- $\sigma_{x\ beam}$ = up to 5 cm
- $\sigma_{y\ beam}$ = up to 5 cm
- P = 13 kW/cm³
- Dose ~ 1 dpa

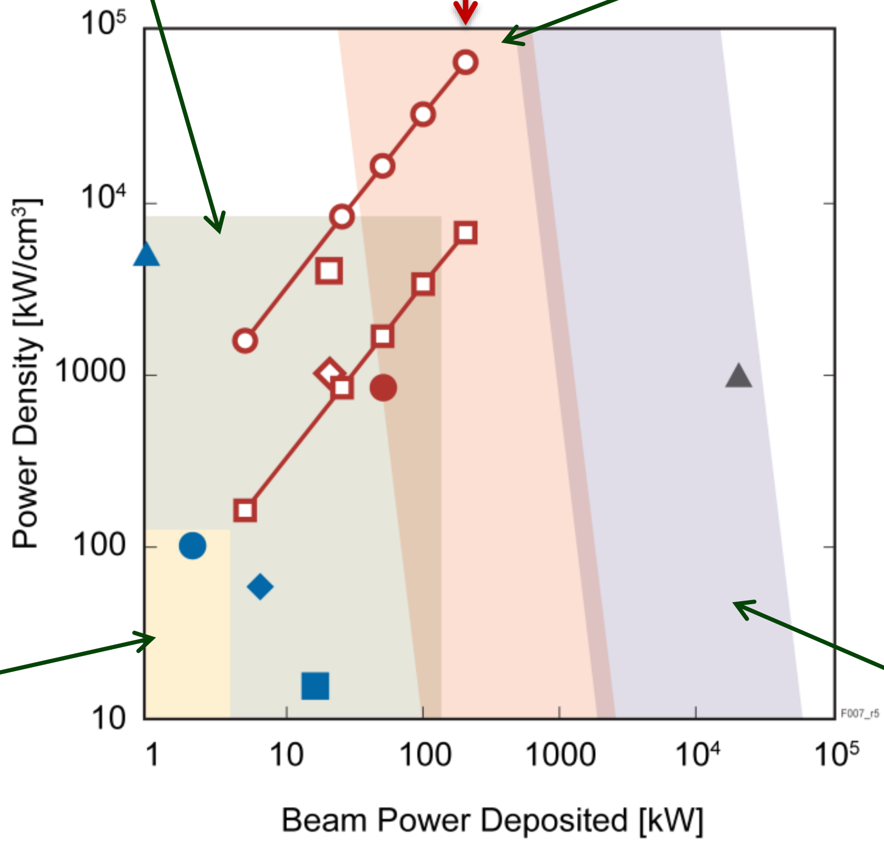
High Power Target Technology

Rotating single-slice targets

Static targets



FRIB - 400 kW



Rotating multi-slice targets

Running devices
- MSU - CCF
- SPIRAL - GANIL
- SISSI - GANIL
- LAMPF

Existing Prototypes
- GSI - FAIR
- RIKEN - RIBF
- FRIB - U
- FRIB - O
- SPIRAL2 - GANIL

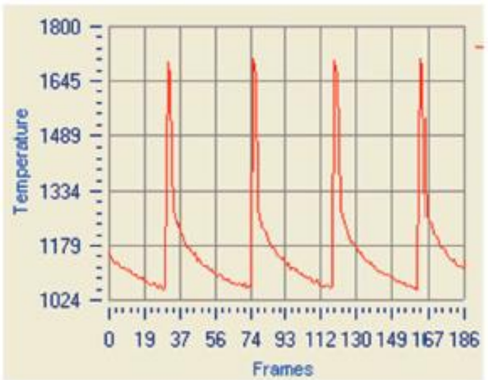
To be developed
- IFMIF

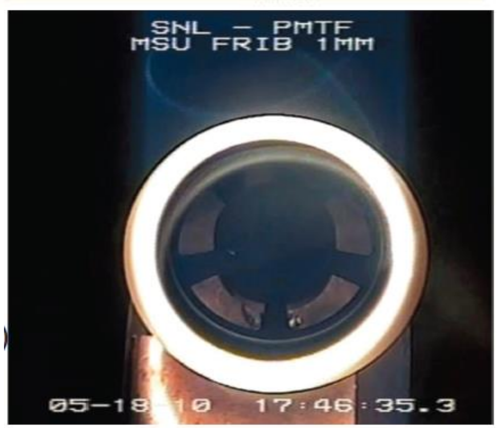
Liquid Li targets

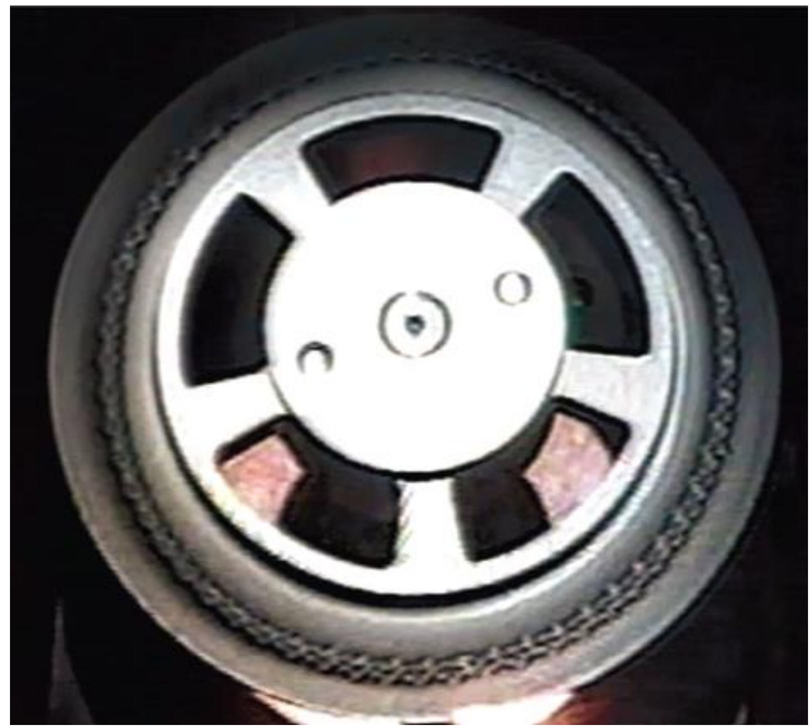
Prototype Target
Single-slice 20 kW Target Prototype

- Destructive tests with 20 keV electron beam at Sandia Laboratories (NM, USA)
  - Extreme conditions at 1 Hz (target 10 cm, 1 mm)
  - P = 1.65 kW , ΔT = 640 ºC
  - P = 3.3 kW, ΔT = 1800 ºC ⇨ plasma effect

Sandia National Laboratories



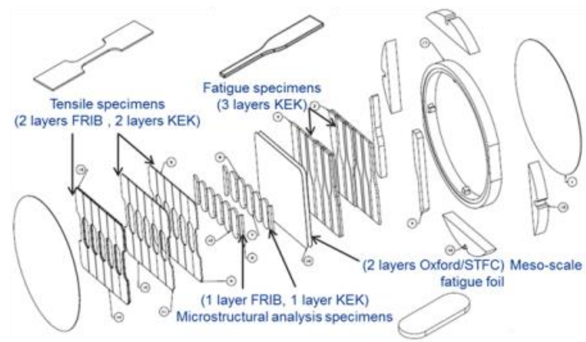




W. Mittig, F. Pellemoine and Sandia Team

Beam Dump Design Support Progress
Build Orientation and Radiation Damage Effect

- Test at BNL-BLIP facility started in April 2017 with RaDIATE collaborators
  - 4 days of irradiation with high energy protons, more in June.
  - Restart irradiation early 2018 to reach 8 weeks (up to 1 dpa in Ti samples) and characterize property changes due to proton induced damage
  - FRIB and KEK will irradiate DMLS and conventional Ti-alloy (Grade 5 and 23), compare and share results

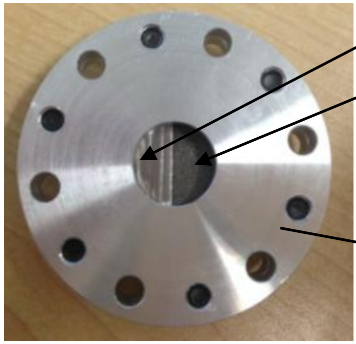


RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

- IRRSUD experiment planned in July (18-24) including Al-alloys (wedge and fragment catcher material) and 3D printed Ti-alloy
  - Build Orientation and Radiation Damage Effect with Low Energy Heavy Ion Irradiation (possible test with ARCAM samples)

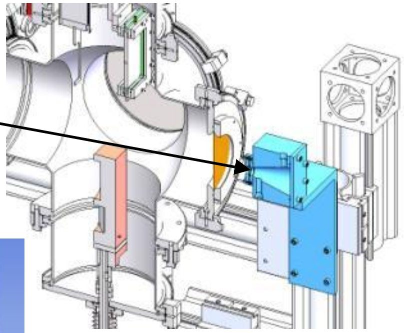
Beam Dump Design Support Progress
Corrosion Test for a Better Understanding of Lifetime

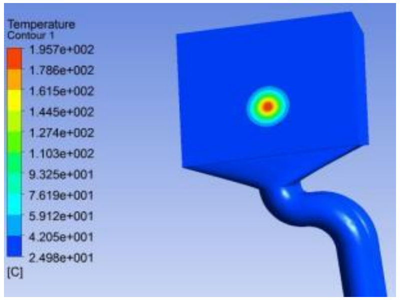
- Short irradiation at NSCL with high energy heavy ion beam
  - Windows made of 3D printed Ti-6Al-4V
  - Water cell fabricated
  - Benchmark gas production in water
  - Study first stage of corrosion on Ti-6Al-4V
- Long irradiation with new NSCL beam stopper
  - 3D printed beam stopper made of Ti-6Al-4V
  - Benchmark gas production in water
  - Study corrosion on Ti-6Al-4V with beam configuration close to FRIB operation
- H2 embrittlement
  - No significant change at low stress value even for high concentration of H



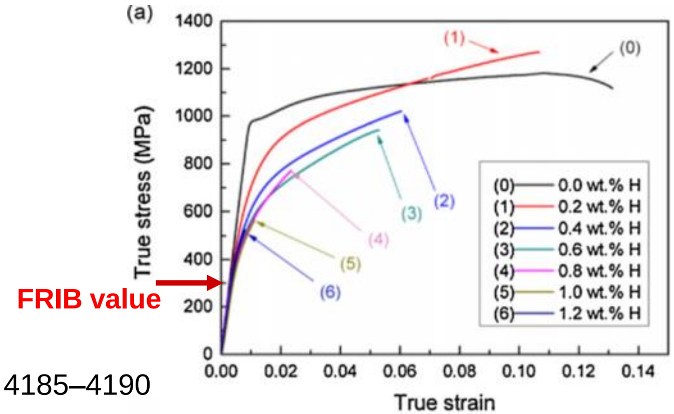
Polished surface

As-received surface





Tmax overall = 195 °C
Tmax water = 75 °C



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