FRIB Radiation Studies: Damage, Component Lifetimes, Hands-on Accessibility

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Facility for Rare Isotope Beams (FRIB)
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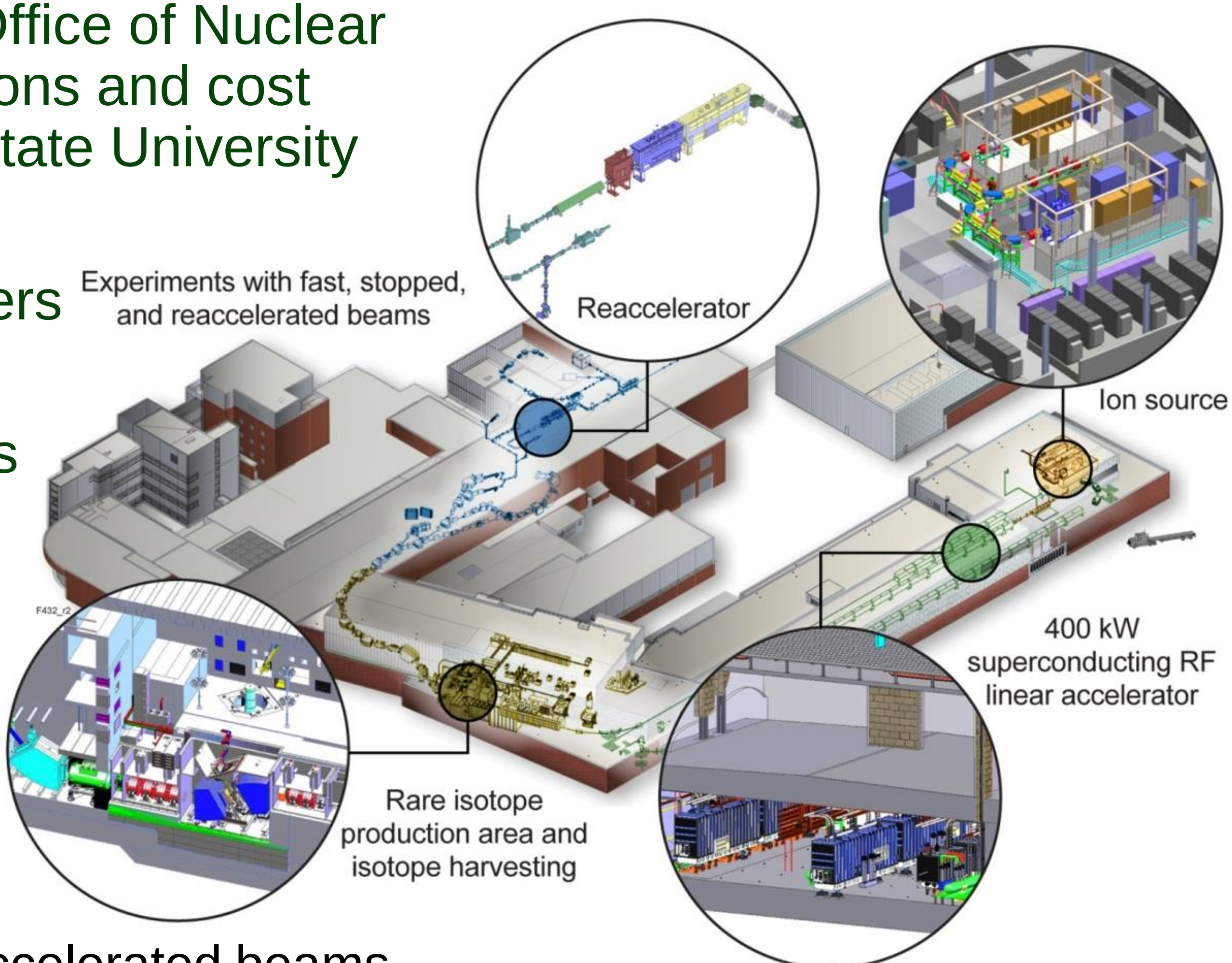
Outline

- Brief introduction to FRIB
  - Radiation transport scope within the project
- Radiation transport analysis of the target and beam dump modules
  - Power deposition into components calculated
  - Material damage studied
  - Component lifetimes assessed to facilitate material choice
  - Hands-on accessibility of the vessel shielding areas analyzed to support future operations
- Summary

Facility for Rare Isotope Beams
A Future DOE-SC National User Facility

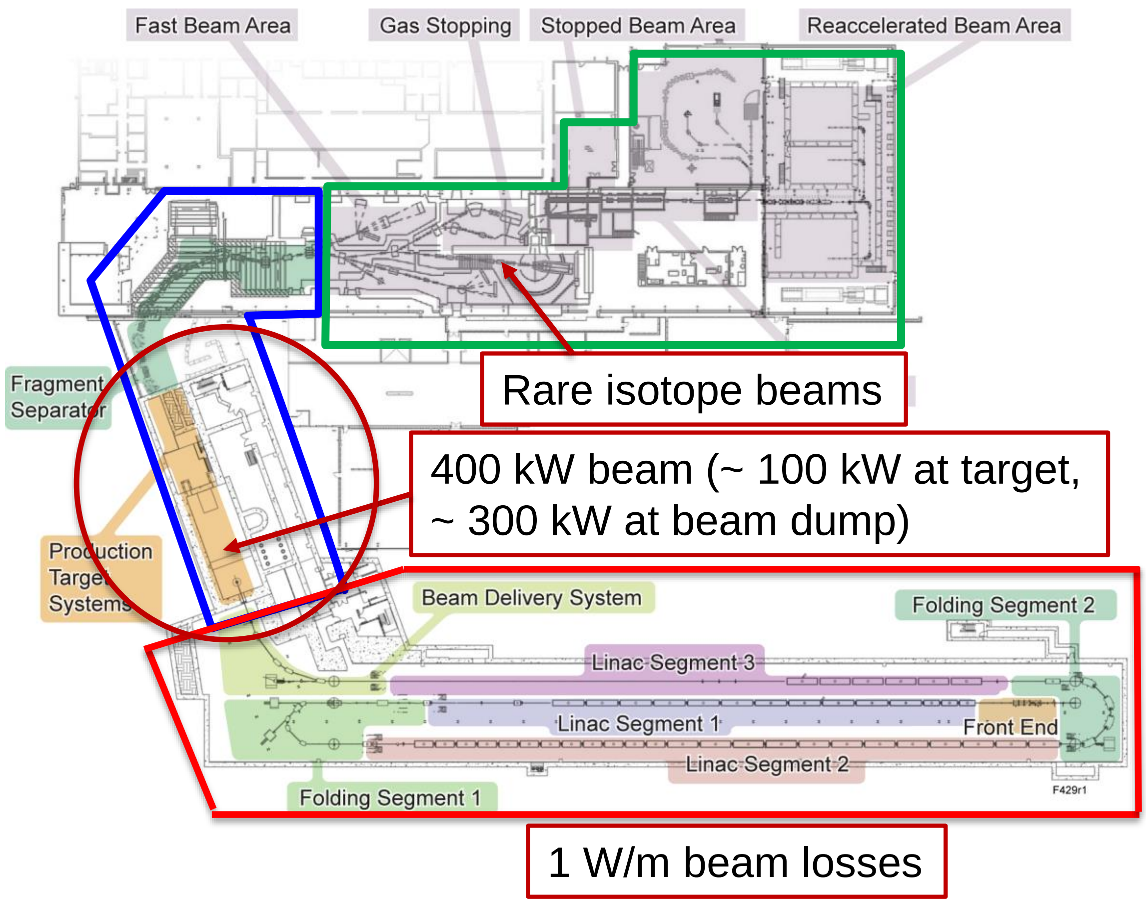
- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University and State of Michigan
- Serving over 1,300 users
- Key feature is 400 kW beam power for all ions ($5x10^{13}$ $^{238}U/s$)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Radiation Transport Scope

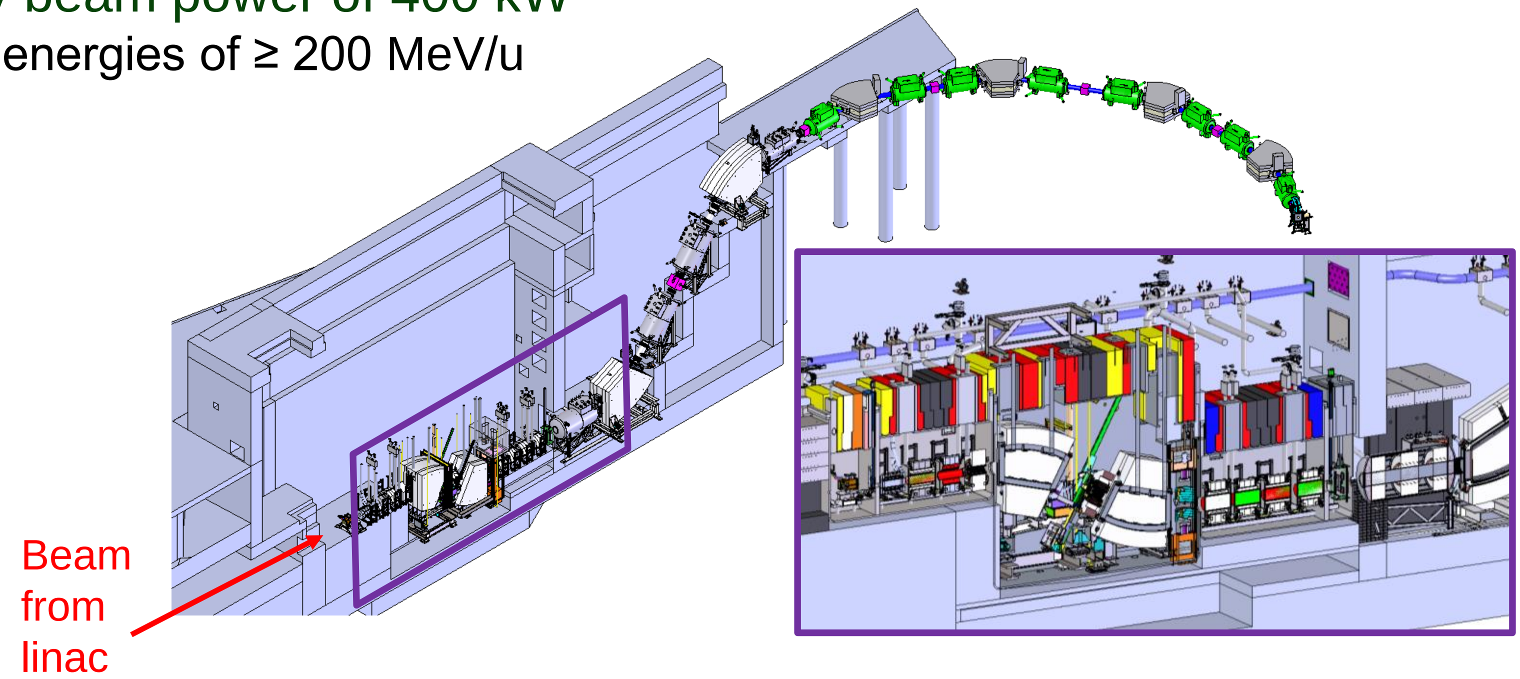
Technical Design and Safe Operation of Entire Project is Supported by Radiation Calculations

- FRIB facility
  - Accelerator Systems
  - Experimental Systems
  - Experimental areas
- Technical scope
  - Bulk, local shielding
  - Component and material choices
  - Hands-on, remote handling
  - Personnel, public doses



Fragment Separator

- Fragment separator for production and delivery of rare isotopes with high rates and high purities to maximize FRIB science reach
- Primary beam power of 400 kW
  - Beam energies of ≥ 200 MeV/u

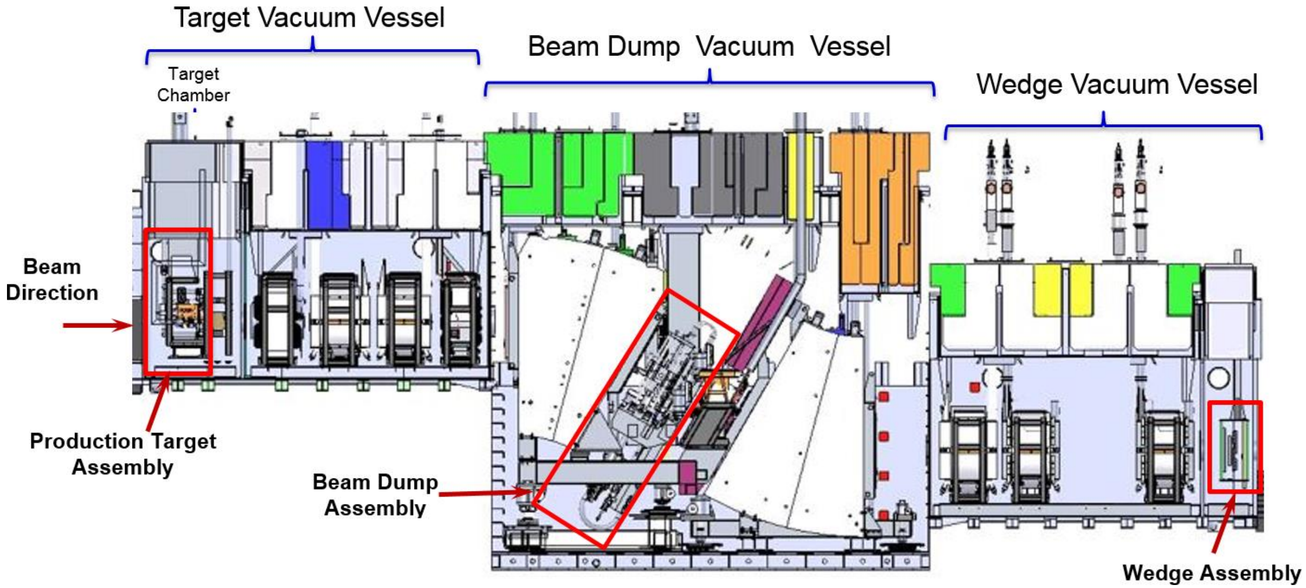


Target hall is high radiation environment

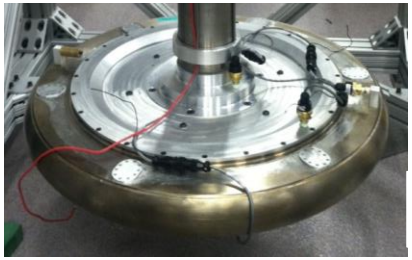
- Heavy ion beam on target (<100 kW) and on beam dump (<325 kW) are major radiation sources

Fragment Separator Front-End Accommodates Target and Beam Dump

- Target and beam dump interact directly with heavy ion beam and are strongest radiation sources
- Hands-on access above shielding during beam off-time required



Multi-slice rotating graphite target

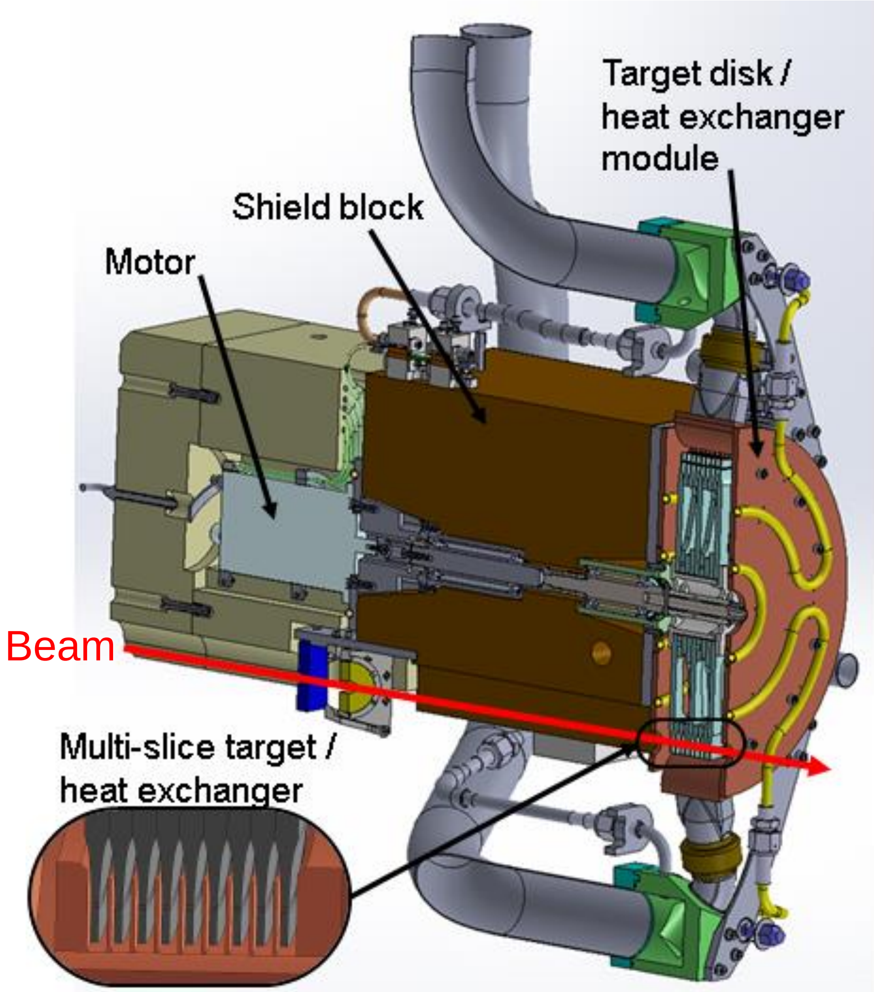


Water-filled rotating titanium alloy beam dump drum

Production Target Module
Up to 100 kW Beam Power Dissipated

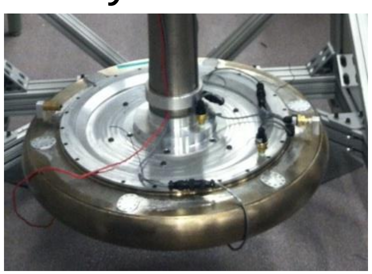
- Multi-slice rotating carbon disk target
  - Absorbs ~100 kW of beam power in 1 mm diameter beam spot
  - 30 cm diameter; rotation at 5000 rpm
  - Target thickness is 30% of ion range
    - » Total thickness varies from several mm to several cm
    - » Maximum extent along the beam 5 cm to meet optics requirements
  - Graphite withstands high temperatures
  - Several slices reduce deposited beam power per slice
  - Target is planned to be changed as frequently as every 2 weeks (duration of experiment)

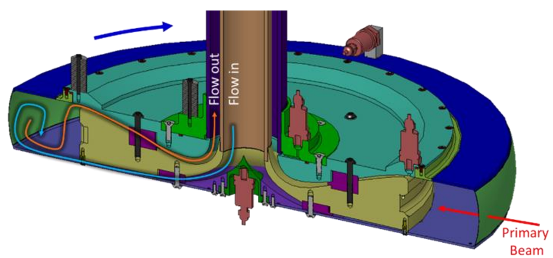
Target prototype



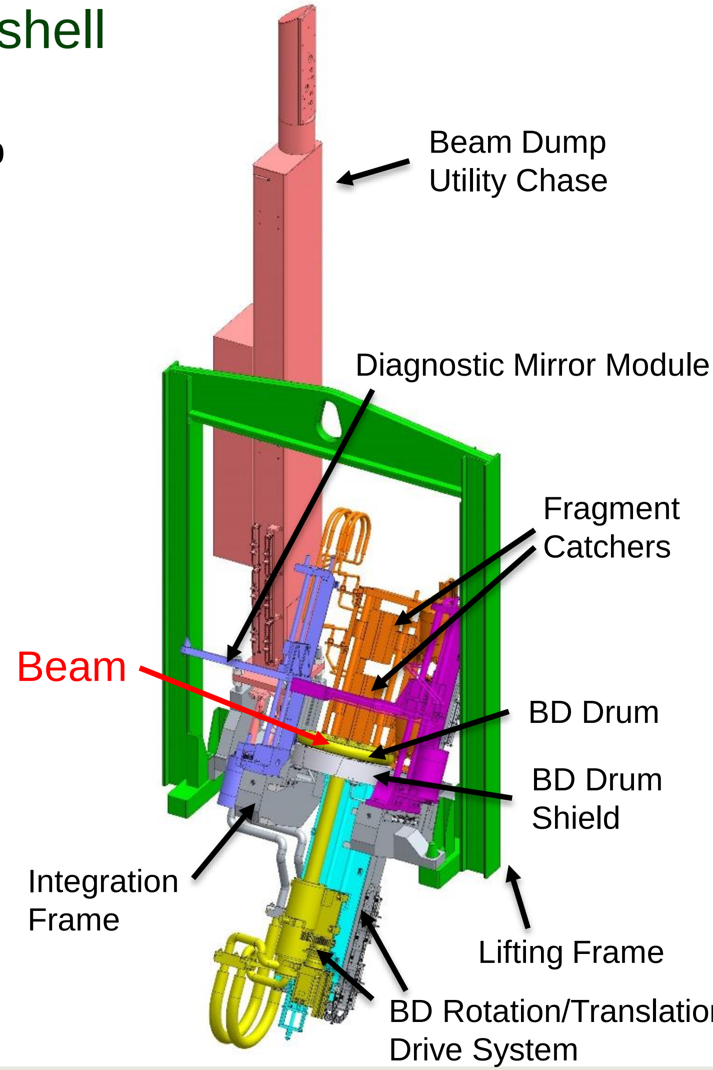
Beam Dump Module
Up to 325 kW Beam Power Dissipated

- Water filled rotating (600 rpm) drum with metal shell
  - Will intercept up to 325 kW primary beam
  - Primary beam specific energy is reduced by ~ 20% after passing through target
  - System design supports radiation levels at 400 kW operation
  - Drum is 0.5 mm thick, 70 cm in diameter, titanium alloy (Ti6Al4V) shell filled with water
    - » Thin shell to minimize power deposition
    - » Water inside the shell stops the primary beam
    - » Fragment catchers intercept unwanted isotopes
  - Beam dump drum is planned to be changed annually





Beam dump drum

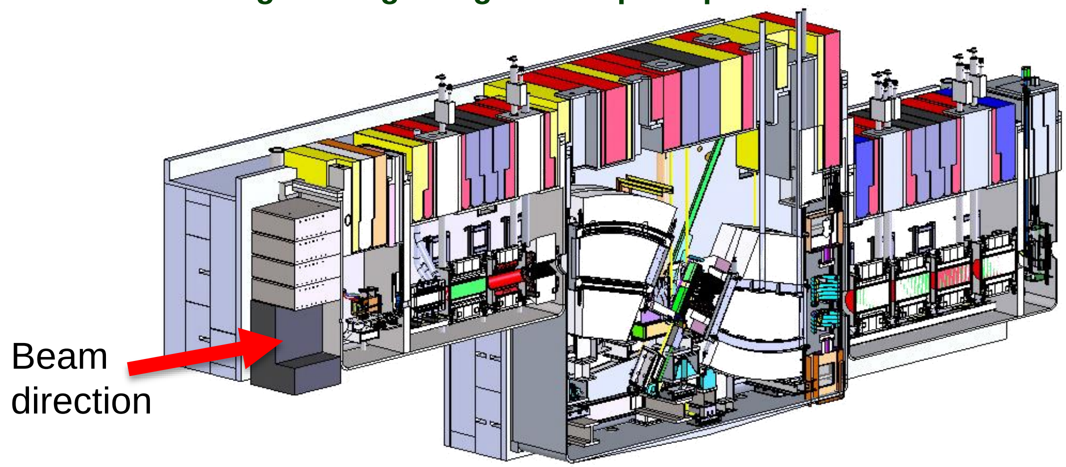


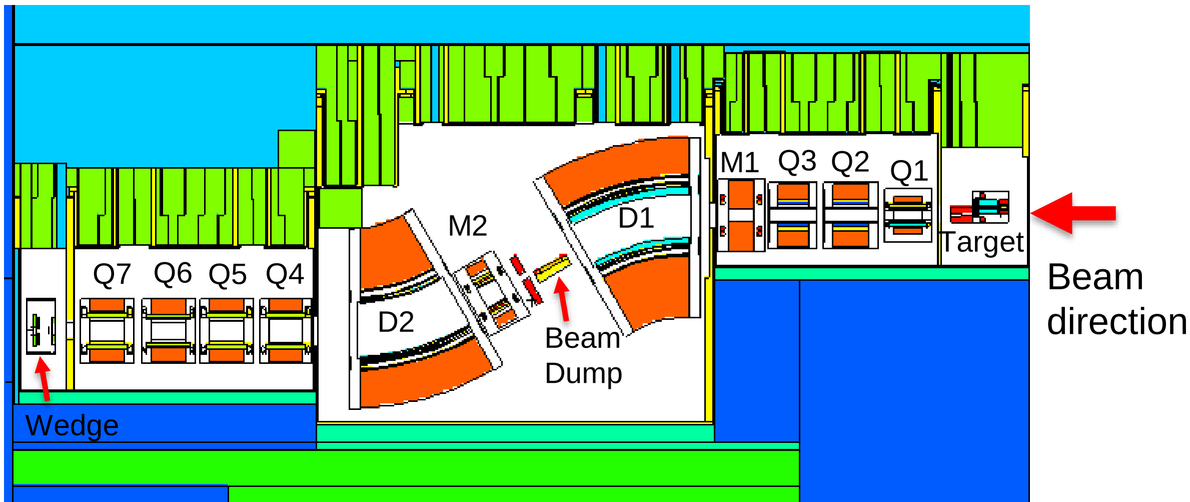
Radiation Transport Model

High Level of Detail Supports Construction and Future Operations

- Calculations are based on models developed from mechanical and facility design
- Monte-Carlo radiation transport codes are used
  - PHITS, MCNPX, MARS
- Capability of the models to transport ions in magnetic fields is important
  - Magnetic fields correspond to those needed for beam optics and are provided by fragment separator group

3D engineering design of the preseparator vacuum vessels

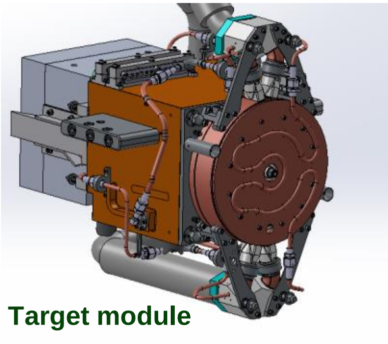


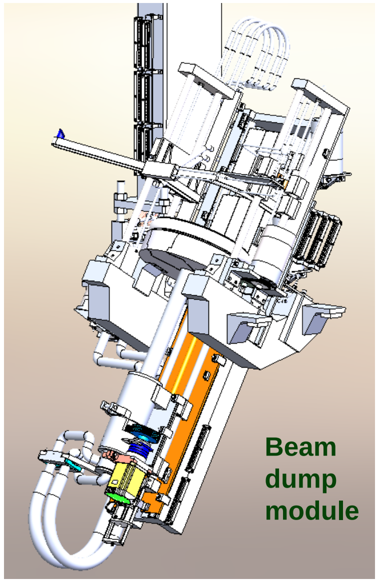


Radiation transport model of the preseparator vacuum vessels

Radiation Transport Analysis Examples
Focus on Target and Beam Dump Modules

- Radiation transport analysis of the target and beam dump modules: Several examples presented in the following slides
  - Power deposition into target module calculated
  - Material damage assessed - titanium alloy beam dump drum shell analyzed and lifetime estimated
  - Component absorbed doses calculated
    - » Component lifetimes are assessed based on absorbed doses
    - » Radiation tolerant materials chosen adequately to ensure component survival
  - Hands-on accessibility of above-shielding components analyzed to support future operations
    - » Target and beam dump modules are the most activated, often moved components
    - » Doses for utility disconnects/reconnects and component maintenance evaluated

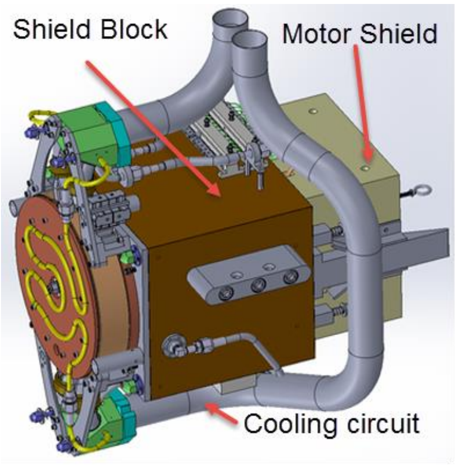

Target module


Beam dump module

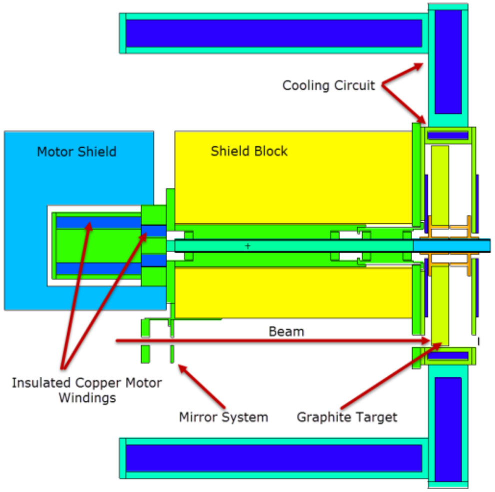
Radiation Power Deposition Analysis
Example: Target Module Components

- Power deposition in beam line components estimated to support design and evaluate design features
  - Power density maps provide information on enhanced radiation field areas
  - Power density estimates in target module are shown as an example
  - Provide input for thermal analysis in mechanical design

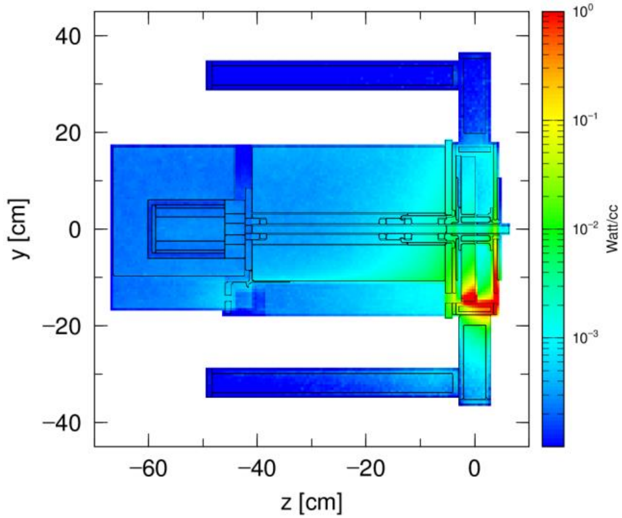
Mechanical design



Radiation transport model

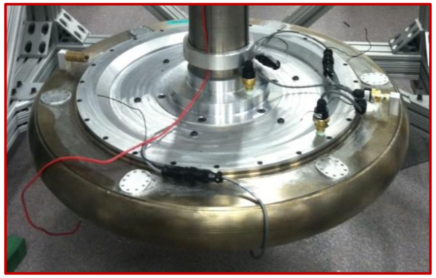


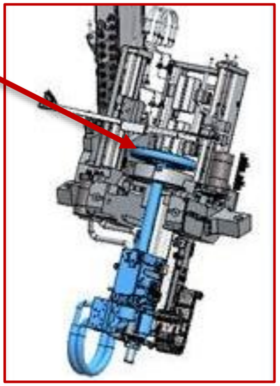
Power density map



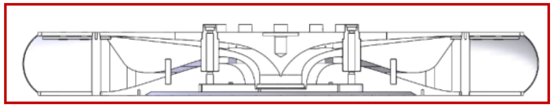
Material Radiation Tolerance Studies [1]
Example: Beam Dump Lifetime Study

- Analysis to assess radiation damage effects in beam dump metal shell
  - Primary beam interacts directly with shell
    - » Beam dump drum shell material – titanium alloy Ti6Al4V
    - » 0.5 mm thick shell with complex geometry, filled with water
  - Material damage (in Displacements Per Atom, or DPA) assessed
    - » Radiation transport codes PHITS, MARS, and SRIM were used
  - Results from different codes agree reasonably well
  - Results compared to 10 DPA limit
    - » Beam dump shell will survive for 3 years or more at full power operation
    - » Beam dump drum is planned to be changed every year





Water-filled, rotating beam dump drum

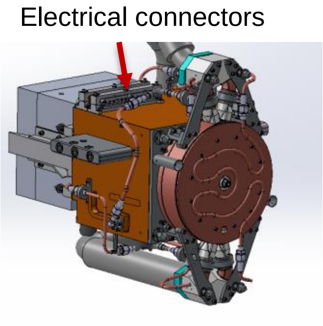


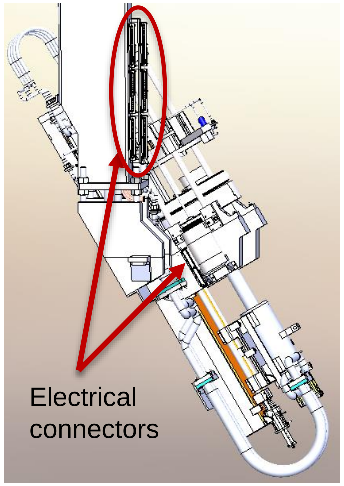
Beam dump shell damage in DPA for various beams

Beam	Annual Time, %	DPA per Operational Year		
		PHITS	MARS	SRIM
18O	5	0.3	0.2	0.24
48Ca	21	0.7	0.3	0.6
86Kr	27	1.5	0.5	1
136Xe	12	2.8	0.9	1.6
238U	35	5.9	1.8	3.1
Annual Time-Weighted DPA		3.0	0.9	1.7

Material Radiation Tolerance Studies [2]
Example: Alumina Insulator Swelling Assessment

- Materials used in target and beam dump module components studied
  - Alumina terminal holders in electrical connector assemblies
    - » Connectors are present in both target and beam dump modules
  - Radiation transport calculations performed
    - » Neutron fluxes, absorbed doses, DPA
    - » Absorbed doses lead to lifetime estimates
      - Alumina radiation tolerance is > 100 MGy (CERN)
  - Worst-case location results

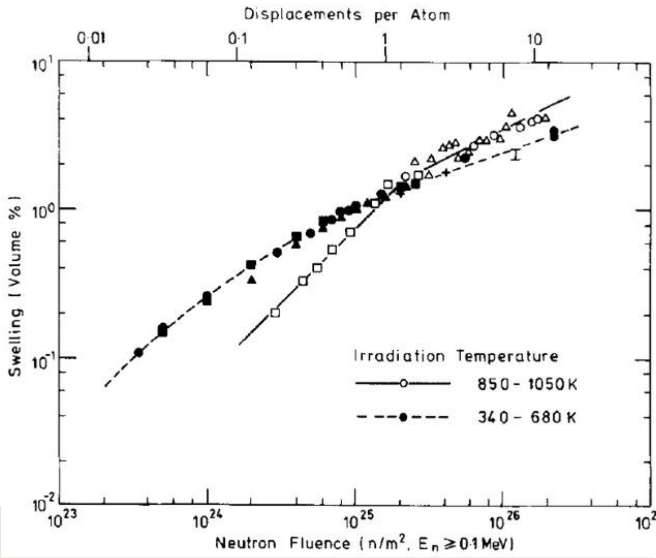




DPA, neutron fluence, and absorbed dose for 30 operational years

Displacements Per Atom	2.00E-03	**DPA**
Neutron Fluence (> 0.1 MeV)	1.7E+19	**n/cm2**
Absorbed Dose	237	**MGy**

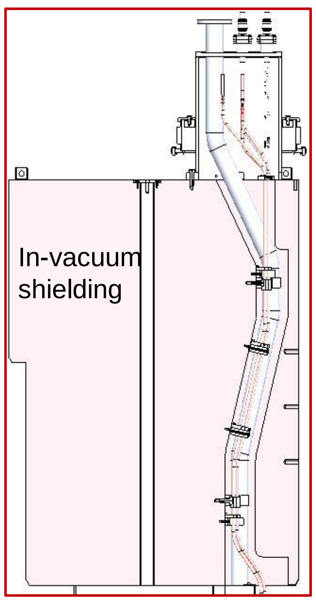
- No detectable swelling expected
- Estimated lifetime more than 10 years



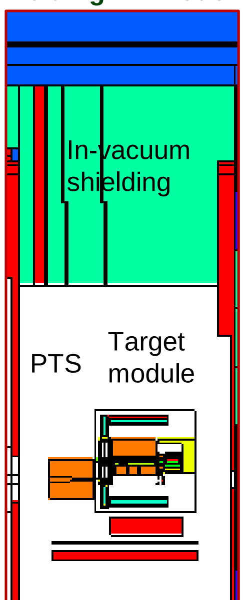
Hands-On Access During Beam-Off Times [1]
Access to Above Shielding Components Confirmed

- Requirement of target hall access during beam-off time periods with shielding in place – hands-on utility disconnects, maintenance
- Residual dose rates above the vessel shielding evaluated and hands-on access for component connection/disconnection and movement confirmed
  - Most often accessed locations; above most activated components
    - » Beam dump vessel utility chase (reentrant) shielding & target vessel in-vacuum shielding

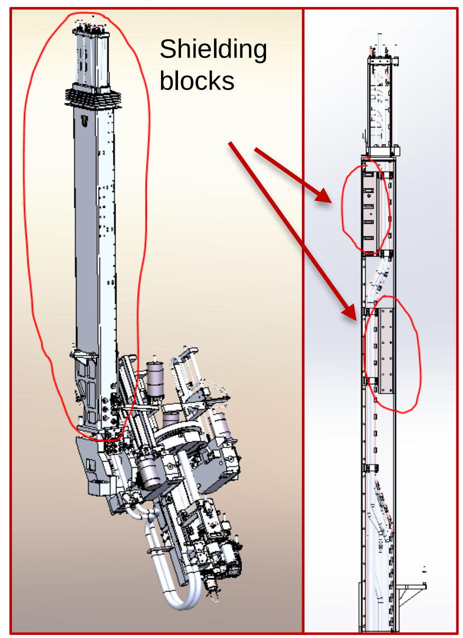
Target in-vacuum shielding ME model



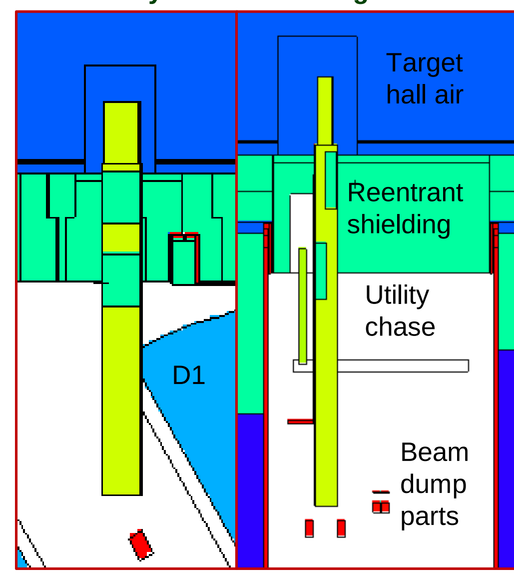
Target in-vacuum shielding RT model



BD utility chase ME model



BD utility chase shielding RT model



Hands-On Access During Beam-Off Times [2]

Access to Target Assembly Utility Confirmed

- Simple estimate based on scoping study
  - Residual dose rate estimates
    - » Beam/energy: ^{48}Ca, 240 MeV/u
    - » In-vacuum shielding thickness: 1.5 m
    - » Dose rate on top of shielding is 0.7 mrem/h →
      - Doglegs: Local increase up to 10 times
    - » Conservatively assumed dose rate 7 mrem/h
  - Hands-on access time estimates
    - » Disconnect – 1 h (cooling time 4 h)
    - » Reconnect – 1 h (cooling time 24 h)
    - » Target module residual dose rate ~10 times smaller after 24 h compared to 4 h

- Hands-on access on top of target in-vacuum shielding is possible
  - Estimated hands-on access time is 2 hours
  - Resulting total doses to a worker could be up to 8 mrem for a given conservative scenario
    - » <u>MSU ALARA goal for workers: 500 mrem/year</u>

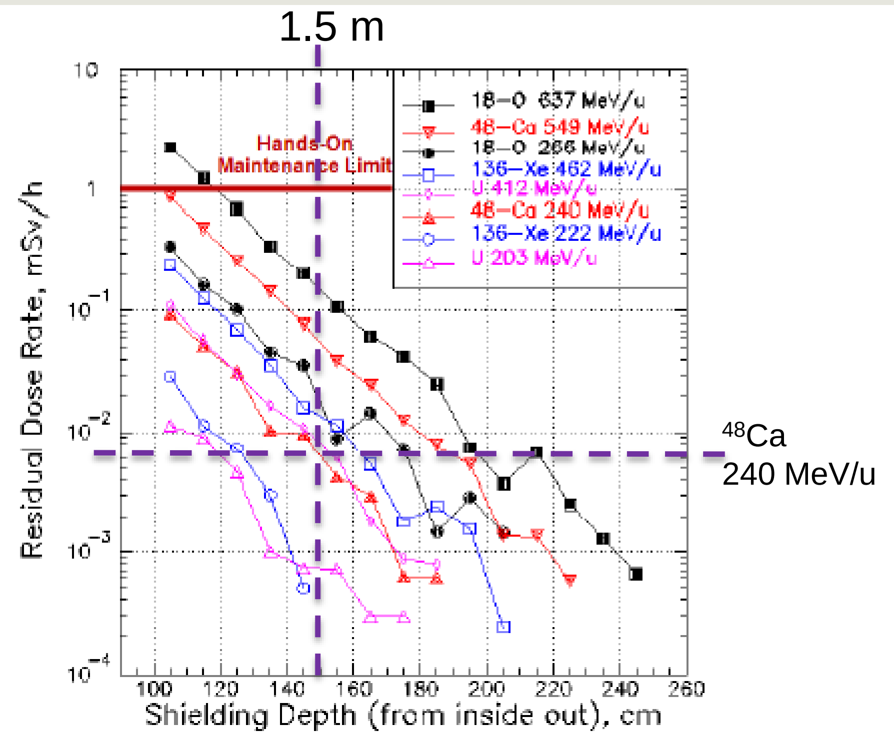


Figure 24 Activation of module shielding above the target.

Hands-On Access During Beam-Off Times [3]

Access to Beam Dump Utility Chase Confirmed

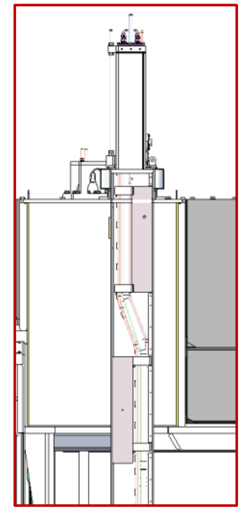
- Annual dose to worker less than 10% of ALARA goal
  - Top part of the utility chase needs to be accessed for connection/disconnection of components for the beam dump module change-out during beam-off
- Detailed analysis using realistic RT model
  - Conservative beam/energy: ^{48}Ca, 261 MeV/u, 400 kW
  - Irradiation time 1 year
    - » Planned interval between beam dump module change-outs
  - Cooling times
    - » 4 hours – minimum planned access time to target hall
    - » 24 hours – assumed time when beam dump utility chase would need to be accessed

Residual dose rates above BD utility chase

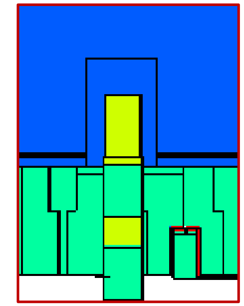
Beam Position	High	
Cooling Time, hours	4	24
Dose Rates, mrem/h	5	1.3

  - Estimated time spent for removal and installation of beam dump module is 16 hours (conservative assumption)
- Conservatively assuming an average exposure of 3 mrem/h would lead to a total dose to worker < 50 mrem
  - » MSU ALARA goal for workers is 500 mrem/year

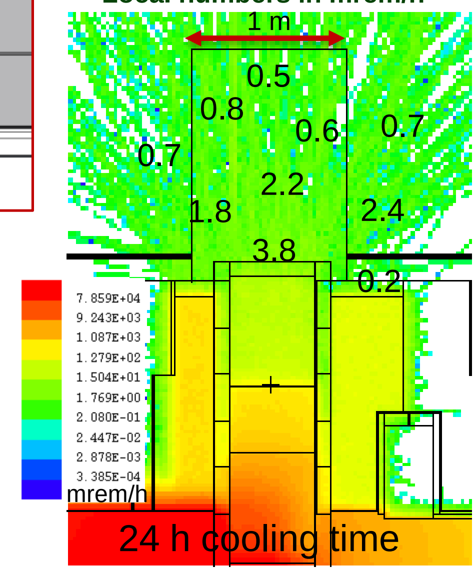
Beam dump utility chase ME model



RT model



Residual dose rate map: Local numbers in mrem/h



Beam direction

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

Summary

- FRIB is designed and established at MSU as a national user facility to provide fast, stopped, and reaccelerated beams of rare isotopes
- High radiation environment in the project target facility with fragment separator demands detailed analysis of radiation environment and its effect on beam line components
- Studies of the target and beam dump modules performed
  - Material damage, component lifetimes, and hands-on access capabilities assessed
- Calculations presented are part of a multi-step process to validate detailed beam line component designs and support future facility operation

Acknowledgements

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- …To my colleagues at FRIB for all their help and support, particularly my collaborators – Mikhail Kostin, Georg Bollen, and Reg Ronningen…
- …And to fellow participants for their attention!

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References

- Monte Carlo particle transport codes PHITS, MCNPX, and MARS, visualization software VISED, and conversion software MCAM used

  - PHITS: T. Sato, K. Niita, N. Matsuda, S. Hashimoto, Y. Iwamoto, S. Noda, T. Ogawa, H. Iwase, H. Nakashima, T. Fukahori, K. Okumura, T. Kai, S. Chiba, T. Furuta and L. Sihver, Particle and Heavy Ion Transport Code System PHITS, Version 2.52, J. Nucl. Sci. Technol. 50:9, 913-923 (2013)
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