High Power Targetry at FRIB

F. Pellemoine

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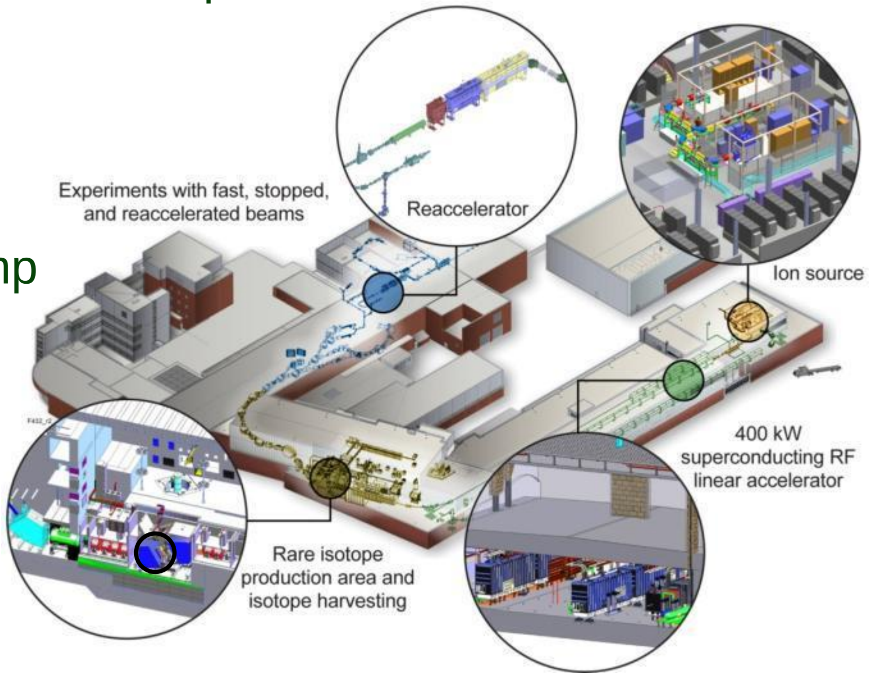
Outline

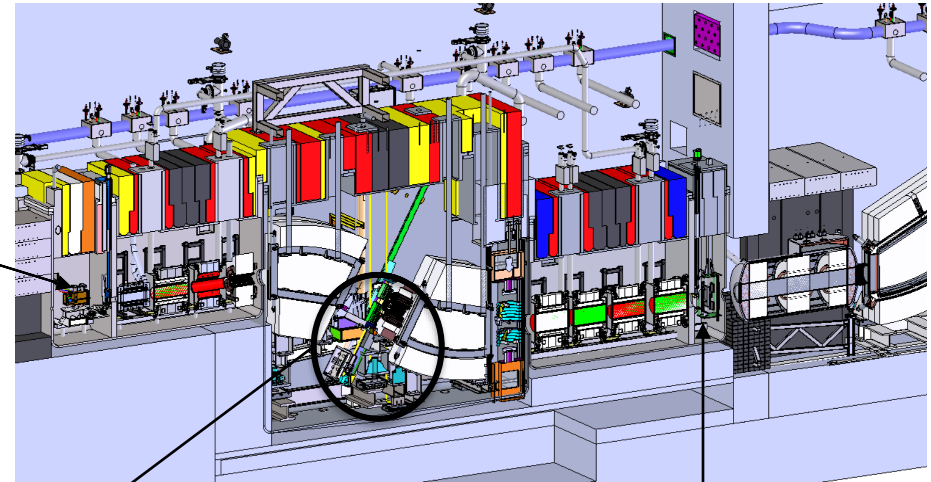
- FRIB overview
- Concept and challenges
  - Production Target
  - Primary Beam Dump
  - Fragment Catcher
  - Wedge
- R&D to mitigate issues
  - Extensive use of high energy electron beam
  - Heavy ion beam irradiations and material characterization

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 at 200 MeV/u for ^{238}U (>200 MeV/u for lighter ions)



Materiel Challenge in Experimental System Area

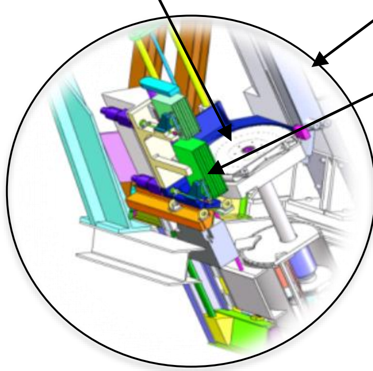


Production target (graphite)

- 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)

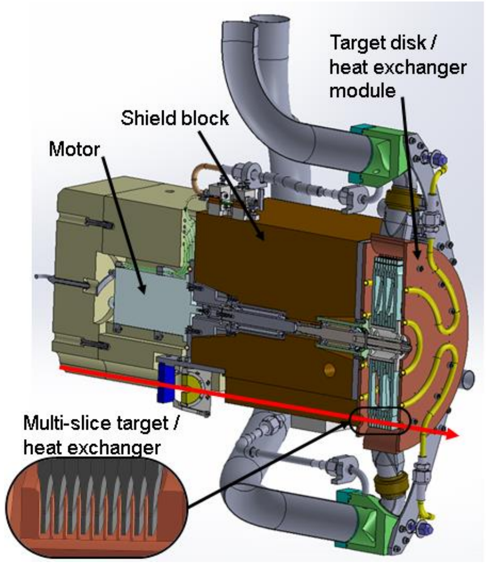
- E = 156 – 260 MeV/u
- $P_{deposited}$ < 10 kW
- $\sigma_{x\ beam}$ = up to 15 cm
- $\sigma_{y\ beam}$ = up to 5 cm
- P = 9 kW/cm³
- Dose ~ 2.5 dpa

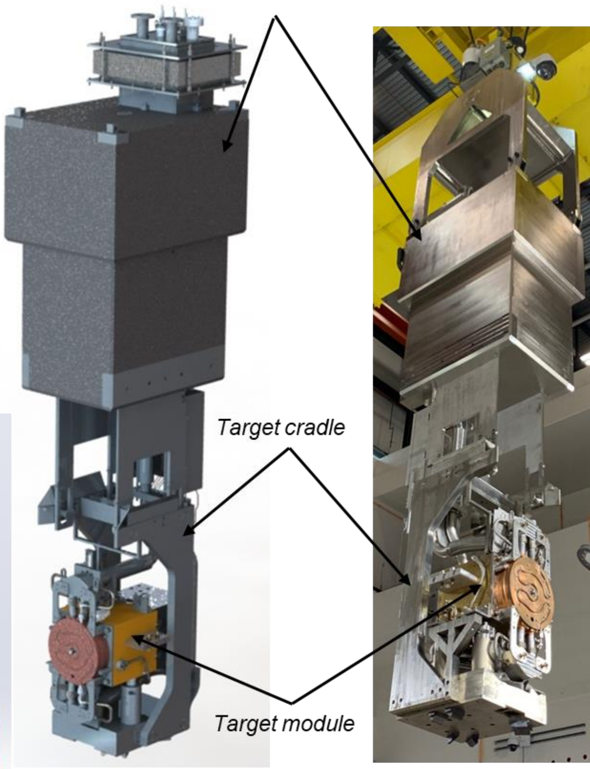
Wedge (Al-alloy)

- 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

FRIB Production Target
Rotating Multi-slice Graphite Target Design

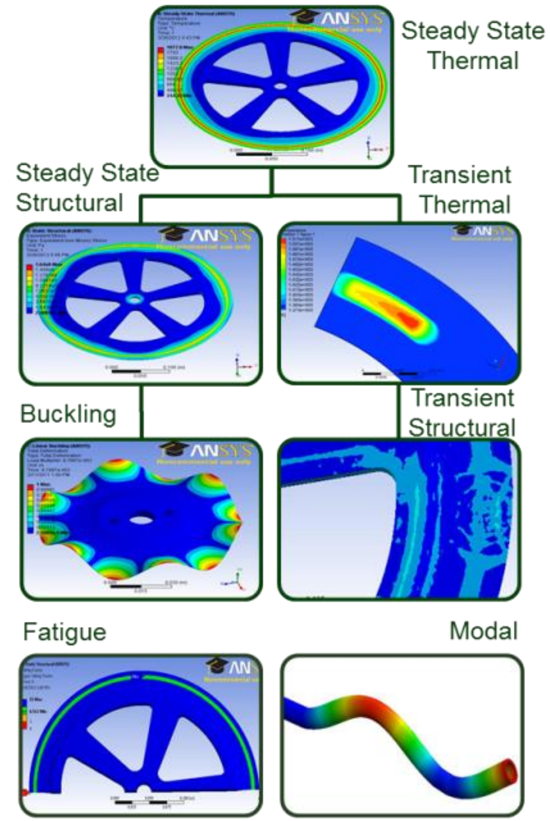
- Rotating multi-slice graphite target chosen for FRIB baseline
  - Increased radiating area and reduced total power per slice by using multi-slice target
  - Use graphite as high temperature material
  - Radiation cooling
- Design parameters
  - Remote replacement and maintenance
  - Optimum target thickness is ~ ⅓ of ion range
    - » 0.15 mm to several mm
  - 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





FRIB Production Target
Challenges Overview

- Thermo-mechanical challenges
  - High power density: ~ 20 - 60 MW/cm^3
    - » 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
    - » Property changes: thermal conductivity, tensile and flexural strength, electrical resistivity, microstructure and dimensional changes, …
  - Swift heavy ions (SHI) damage not well-known
  - $5 \cdot 10^{13}$ U ions/s at 203 MeV/u may limit target lifetime
    - » Fluence of ~$9.4 \cdot 10^{18}$ $ions/cm^2$ and 8 dpa estimated for 2 weeks of operation
- Similar challenges at
  - Facility for Antiproton and Ion Research (FAIR) at GSI
  - Radioactive Ion Beam Factory (RIBF) at RIKEN

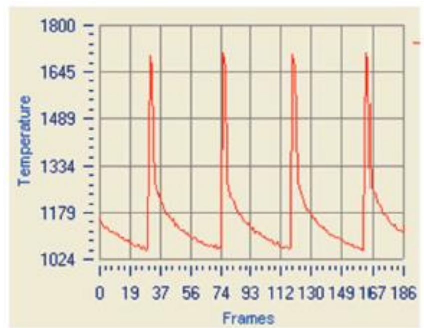


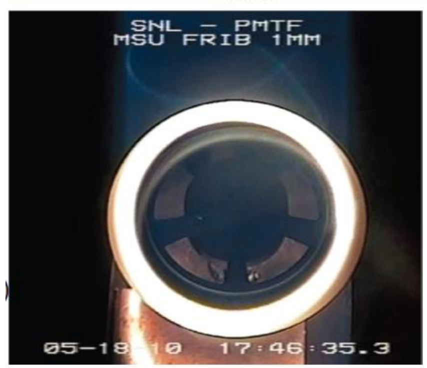
F. Pellemoine et al., JRNC 299 (2014) 933-939

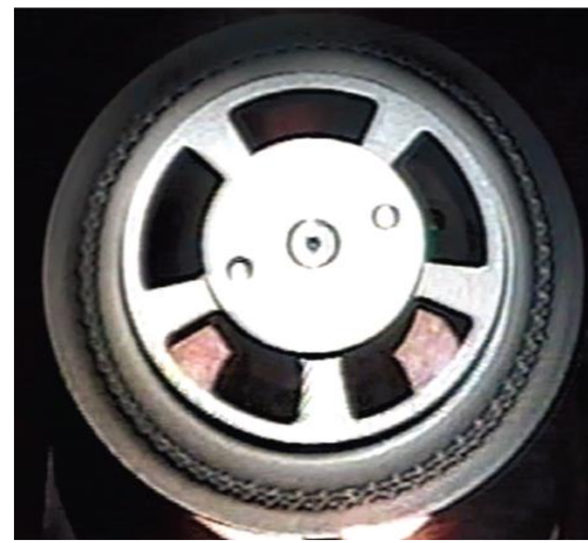
R&D to mitigate issues
Single-slice 20 kW Target Prototype

- Electron beams used to simulate similar power density close to FRIB conditions without the activation of the target due to nuclear reaction
- 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





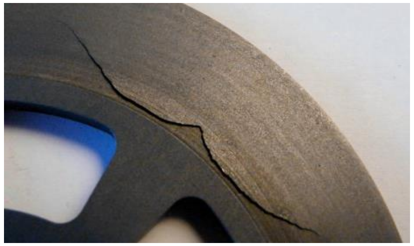


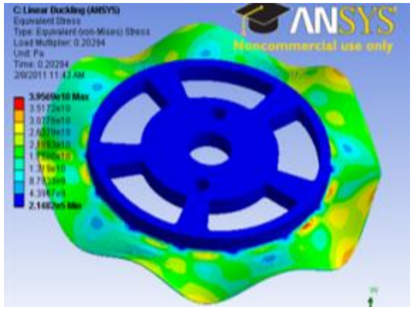
W. Mittig, F. Pellemoine and Sandia Team

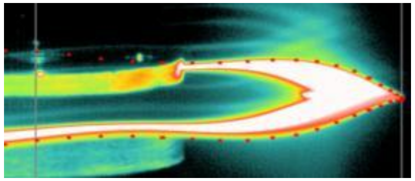
R&D to mitigate issues

Thermo-mechanical studies with high energy electron beam

- 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





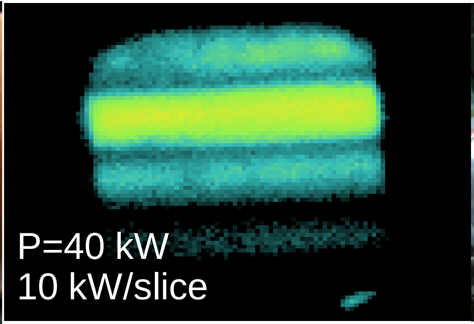


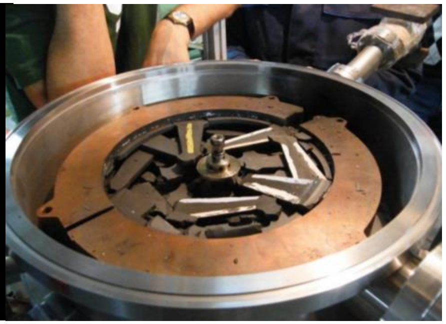
M. Avilov et al., JNRC 305 (2015) 817-823
F. Pellemoine et al., NIMA 655 (2011) 3-9

Sandia National Laboratories

Budker Institute of Nuclear Physics

SOREQ





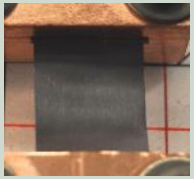
R&D to mitigate issues
Radiation Damage Studies– Au beam @ 8.6 MeV/u

1 A - 350°C
10^{14} cm^{-2}

11 A - 750°C
10^{14} cm^{-2}

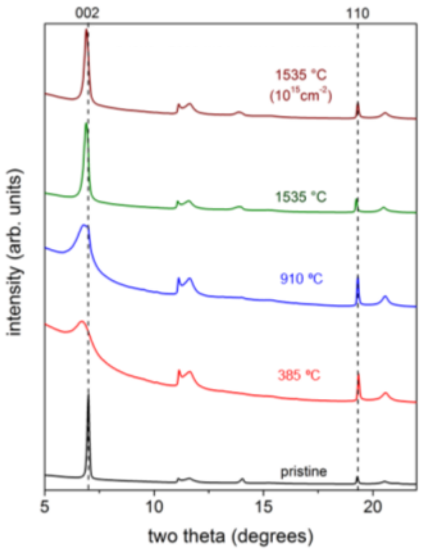
25 A - 1205°C
10^{14} cm^{-2}

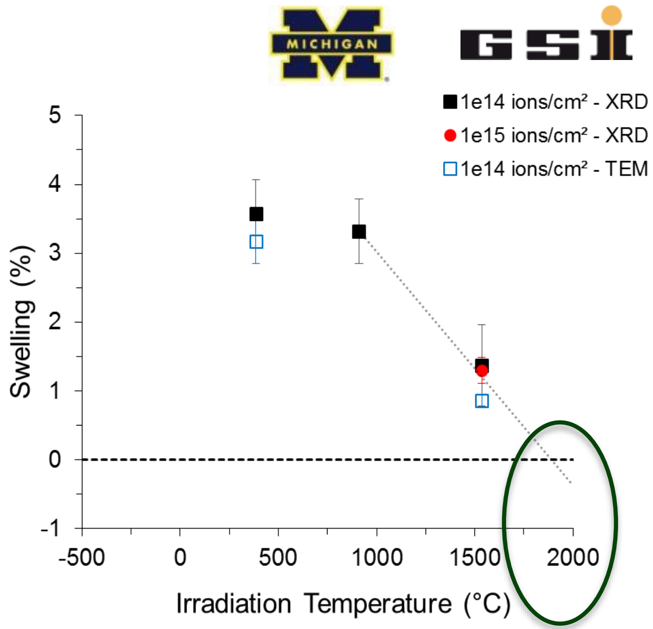
35 A - 1635°C
10^{15} cm^{-2}



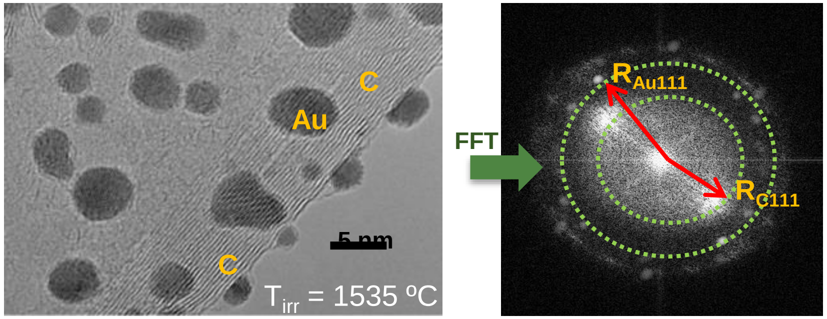
Annealing of Damage in graphite at High Temperature (> 1300ºC)

X-Ray Diffraction analyses





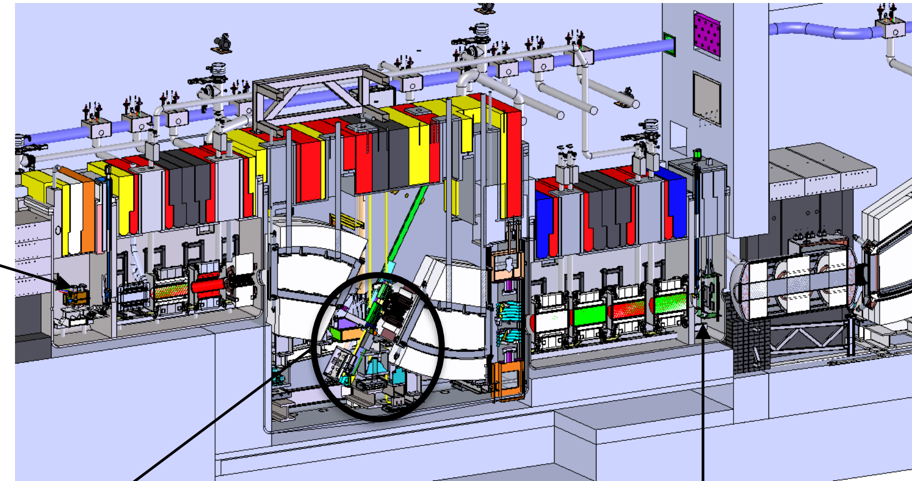
TEM analyses



Swelling is completely recovered at 1900ºC

F. Pellemoine et al.,NIMB 365 (2015) 522-524
S. Fernandes et al., NIMB 314 92013) 125-129

Materiel Challenge in Experimental System Area



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- $P = 60\ MW/cm^3$
- 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
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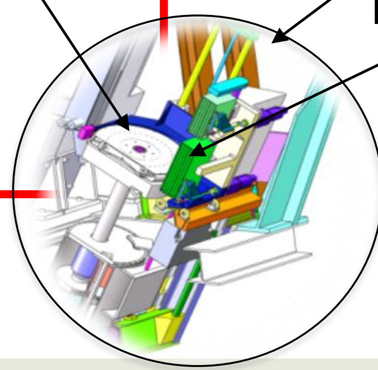

Fragment catcher (Al-alloy)
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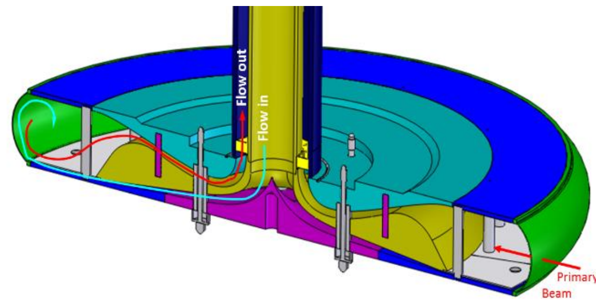
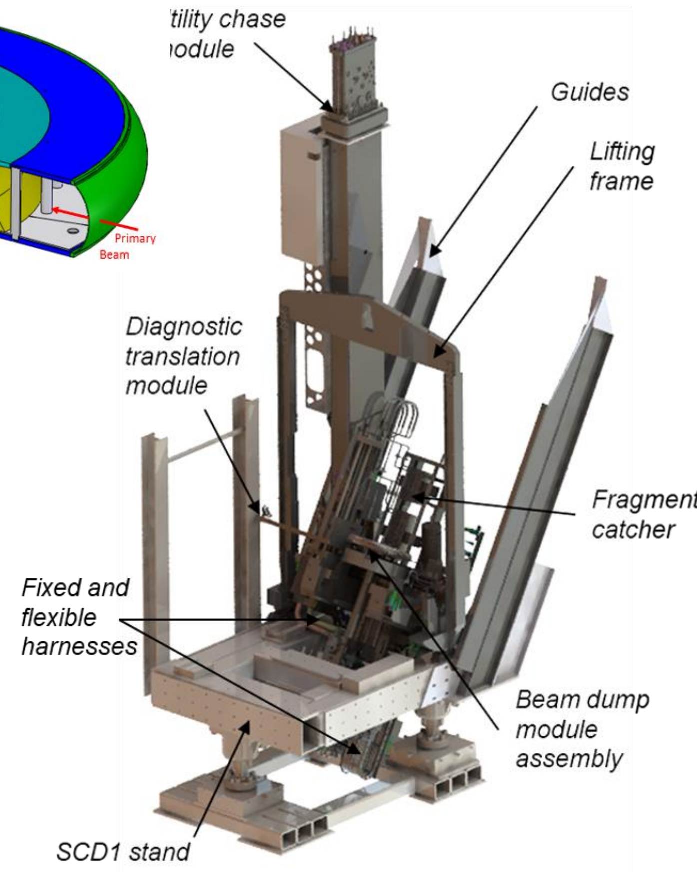
Wedge (Al-alloy)
- $E = 156 – 260$ MeV/u
- $P_{deposited} < 2$ kW
- $\sigma_{x\ beam}$ = up to 5 cm
- $\sigma_{y\ beam}$ = up to 5 cm
- $P = 13\ kW/cm^3$
- Dose ~ 1 dpa

FRIB Primary Beam Dump
Water-filled Rotating Drum Concept

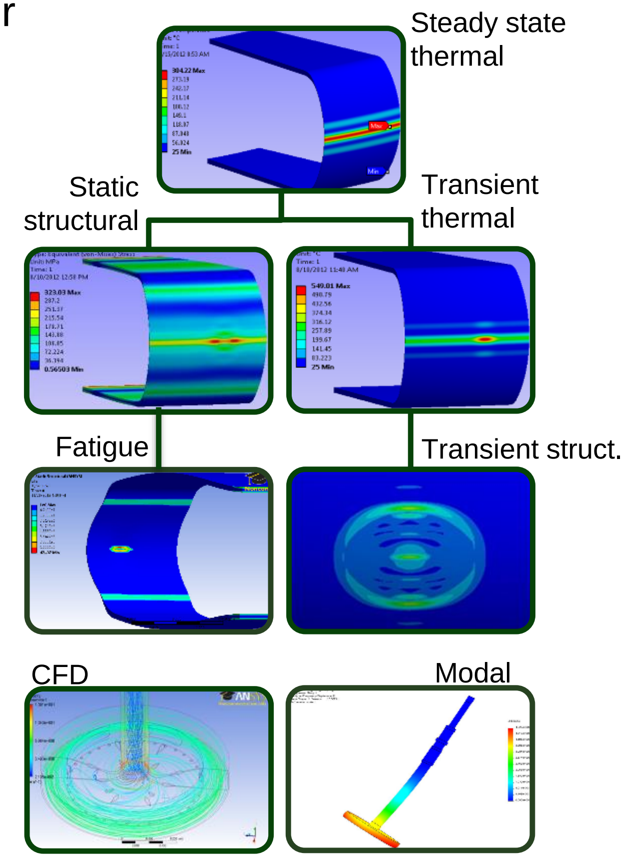
- Beam Dump requirements
  - High power capability up to 325 kW
  - 1 year (5500 h) lifetime desirable
    - » fluence ~10^{18} ion/cm²
    - » dpa (U beam) ~ 7 (dpa/rate ~ $4 \cdot 10^{-7}$ dpa/s)
  - Remote replacement and maintenance
- Water-filled rotating drum concept chosen for FRIB baseline
  - 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
  - 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 150ºC
- Ti-6Al-4V was chosen as candidate material for the beam dump shell





FRIB Primary Beam Dump
Challenges Overview

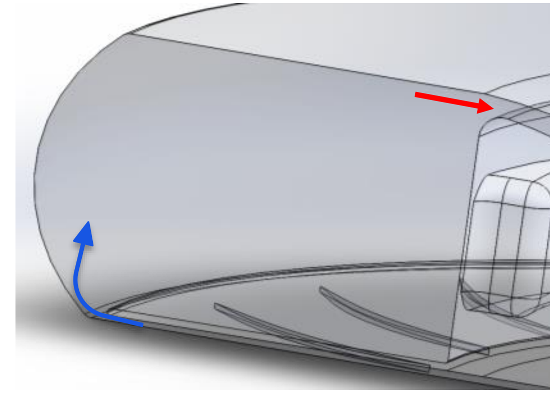
- Extreme conditions due to heavy ion beams
  - Energy loss of U beam at 156 MeV/u in Ti-alloy shell is 4 order of magnitude higher compare to proton beam at 1 GeV
- Challenges addressed in simulation
  - High power – up to 60 kW in the shell
    - » Thermal stress
    - » Water near the boiling point 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)

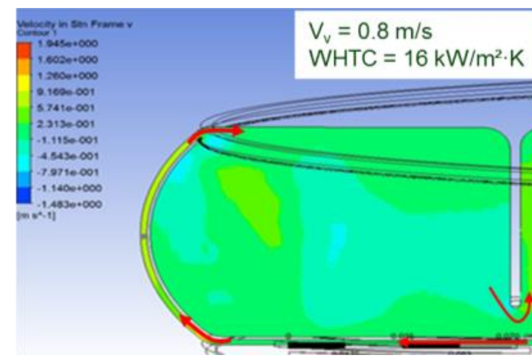


M. Avilov et al., NIMB 376 (2016) 24-27

Beam Dump Drum Design
Staged Approach for Full Power

- Beam dump drum remains a challenging technical system
  - High Wall Heat Transfer Coefficient (WHTC) with high turbulent water flow needed to remove heat from beam dump shell
- Robust single shell beam dump with 1mm-thick machined wall
  - Single shell geometry with single-phase fluid flow
    - » Suitable for full power for light beams (mass < 36) and up to 50 kW for ^{238}U beam
- In parallel: development of 0.5 mm shell drum using 3D printing Ti-6Al-4V
  - Single shell suitable for full power for light beams (mass < 64), up to 100 kW for ^{238}U beam
  - Double shell for all primary beams at full power
    - » Build double-shell drum based on experience with single-shell drum during power ramp-up





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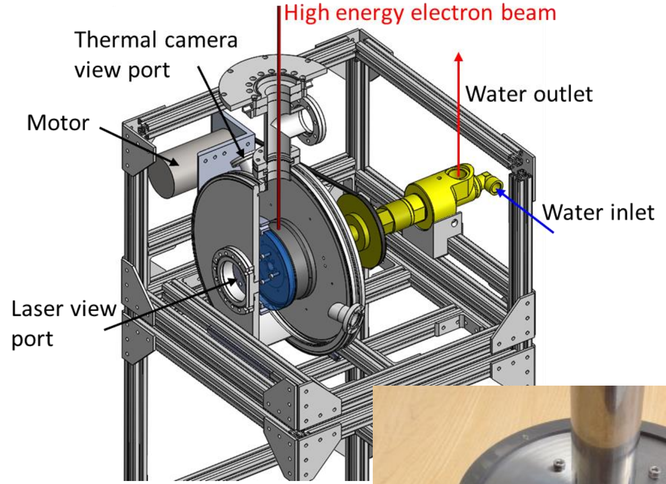
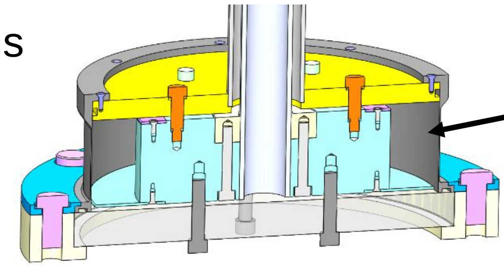
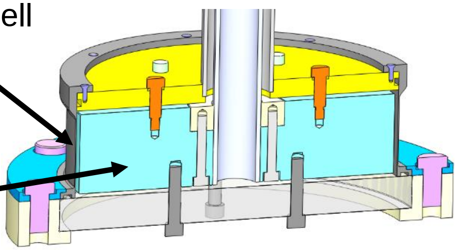
R&D to mitigate issues
Electron Beam Test to Validate Heat Removal Assumptions

- 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
  - ¼-scale beam dump mockup made of 3D printed Ti-alloy was used with 0.5 mm thick shell
  - Electron beam test was used to heat the mockup 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





Single shell geometry



Double shell geometry

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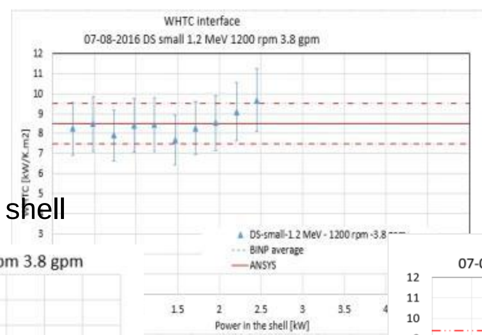
R&D to mitigate issues

Electron Beam Test to Validate Heat Removal Assumptions

- 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 016
  - 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)

Small beam – Double shell



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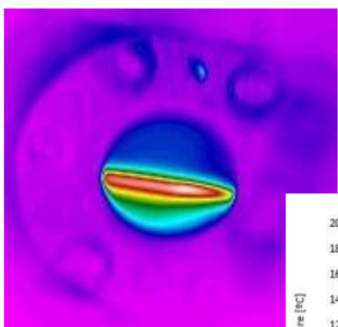
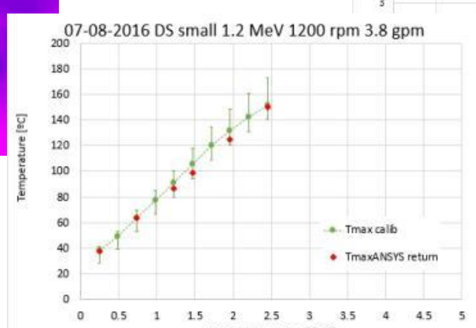
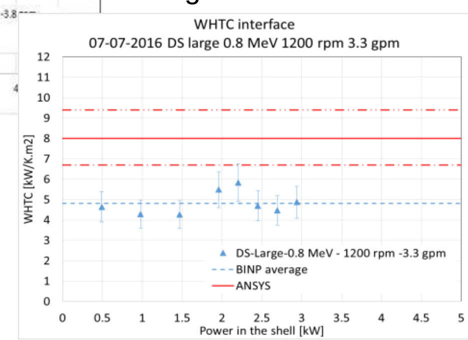
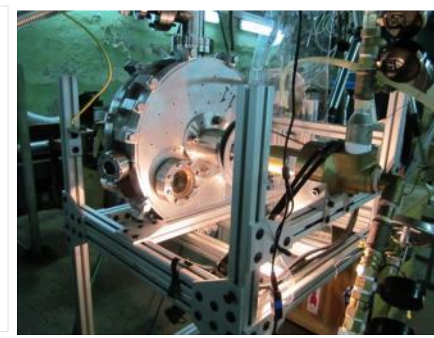


Small beam – Double shell



Large beam – Double shell





Beam Dump Design Support
3D Printed Material for Beam Dump Drum

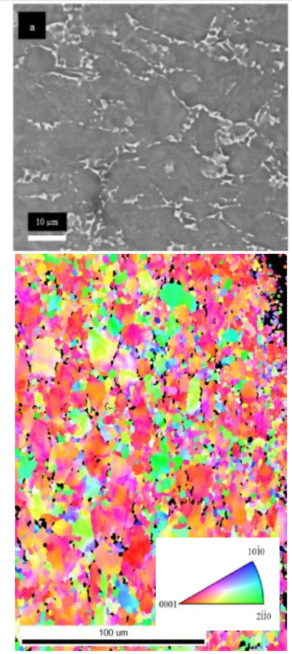
- 3D printer technology is needed for drum shell fabrication for high power
- Several technologies exist to support beam dump drum fabrication
  - Electron Beam Additive Manufacturing (EBAM) for 1 mm shell
  - Direct Metal Laser Sintering (DMLS) for 0.5 mm shells
    - » Failure (material show sinking 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.
    - » FRIB and Prof. Kwon (MSU-Department of Mechanical Engineering) collaboration to improve 3D process in the framework of the beam dump fabrication.

R&D to mitigate issues
Impact of the Post Process on Beam Dump Drum Lifetime

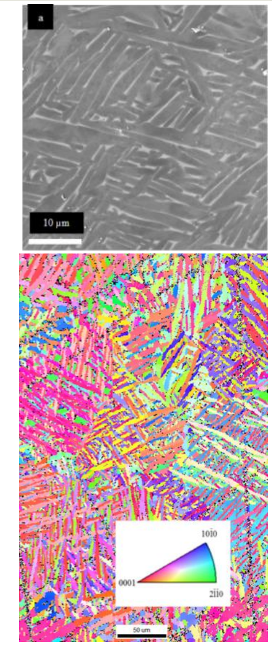
- Material study of Ti-6Al-4V alloys under irradiation to assess beam dump shell lifetime and understand the post process effect (machining, HIP) on 3D printed material behavior compare to the commercial Ti-6Al-4V

Table 10. Summary of the *ex situ* irradiation conditions. The irradiation dose indicated is the dose at the probed depth by nanoindentation.

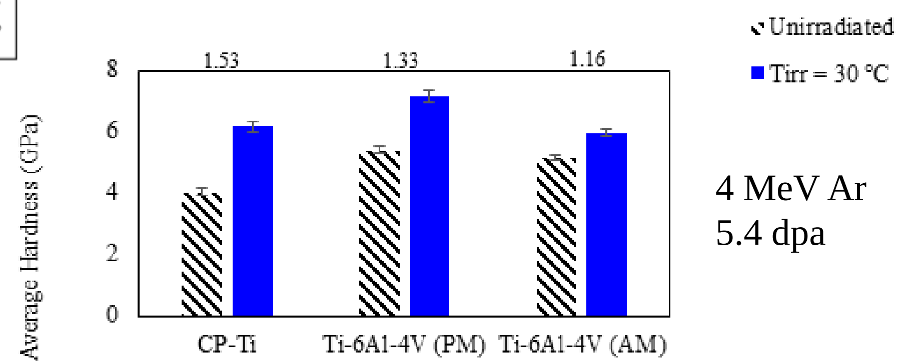
Beam	Energy (MeV)	Ion range (µm)	Se (keV/nm)	Flux (ions/cm^2.s^{-1})	Fluence (ions/cm^2)	T (°C)	Dose (dpa)	Material
^{36}Ar	36	6.8	7.5	2.10^{10}	10^{15}	30	0.08	Ti-6Al-4V PM
^{36}Ar	0.76	0.6	1.4	2.10^{10}	10^{15}	30	1.03	Ti-6Al-4V PM
^{36}Ar	36	6.8	7.5	4.10^{10}	10^{15}	350	0.08	Ti-6Al-4V PM
^{36}Ar	0.76	0.6	1.4	4.10^{10}	10^{15}	350	1.03	Ti-6Al-4V PM
^{40}Ar	4	3.8	3.16	2.18. 10^{13}	4.8.10^{16}	350	16	Ti-6Al-4V PM, Ti-6Al-4V AM, CP Ti
^{40}Ar	4	3.8	3.16	3.5 10^{13}	2.5.10^{16}	30	8.0	Ti-6Al-4V PM, Ti-6Al-4V AM, CP Ti



Ti-6Al-4V (PM)



Ti-6Al-4V (AM)



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Aida Amroussia's Thesis - next RaDIATE Technical Meeting

R&D to mitigate issues

Impact of the Post Process on Beam Dump Drum Lifetime

Table 11. Summary of the *in situ* irradiation conditions with 1 MeV ^{82}Kr ions.

Beam	Energy (MeV)	Range (um)	Se (keV/nm)	Flux (ions.cm^2.s^{-1})	Fluence (ions.cm^{-2})	T (°C)	Material	Dose (dpa)	Exp #
^{82}Kr^{+1}	1	0.4	2.3	3.8×10^{11}	5×10^{15}	30	CP-Ti	11.13	1
				3.8×10^{11}	1.7×10^{15}	350		3.79	2
				3.8×10^{11}	2.5×10^{15}	430		0.56	3
				6.3×10^{10}	2.5×10^{15}	450		0.06	4
				3.8×10^{11}	1.9×10^{15}	350	Ti-6Al-4V – (AM)	3.74	5
				3.8×10^{11}	2.5×10^{15}	430		0.56	6
				6.3×10^{10}	1×10^{15}	450		0.22	4

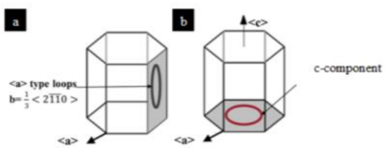


Figure 36 . Nucleation planes for (a) <a> and (b) c-component dislocation loops in hcp materials.

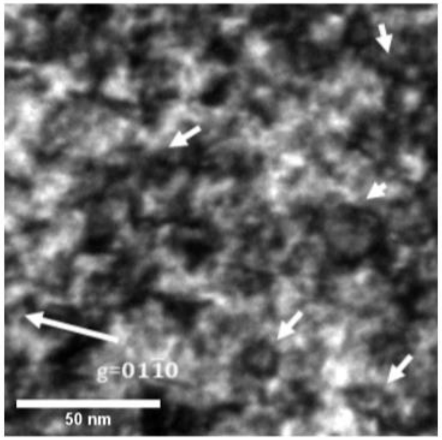


Figure 81. BF TEM photomicrograph showing the <a> loops observed in the sample irradiated up to 11 dpa at 30 °C with **g** = 01$\bar{1}$0. Some of the large <a> loops are indicated with white arrows.

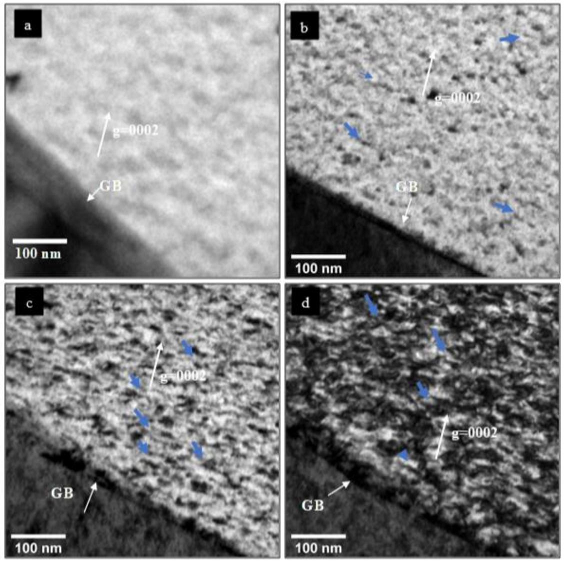
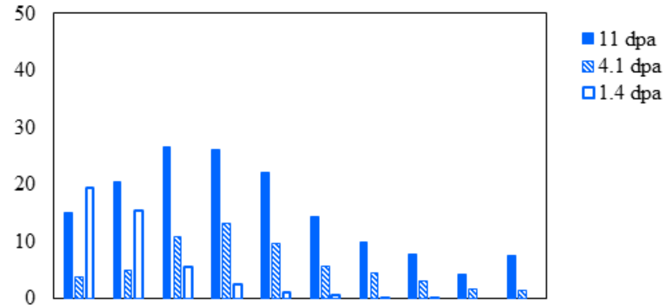


Figure 97. BF TEM photomicrographs showing the microstructural evolution in CP Ti irradiated with 1 MeV Kr at 30 °C at increasing doses in the same area: a) Area before irradiation; b) Area at a dose of 1.4 dpa; c) Area at a dose of 4.1 dpa d) Area at a dose of 11 dpa. Blue arrows point to some of the observed c-component loops in each micrograph. The grain boundary (GB) is indicated with a white arrow. Blue arrows indicate some of the observed c-component loops.



Aida Amroussia's Thesis - next RaDIATE Technical Meeting

Beam Dump Design Support
Build Orientation and Radiation Damage Effect

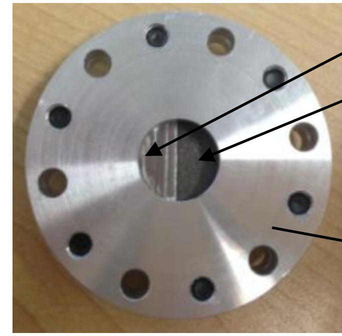
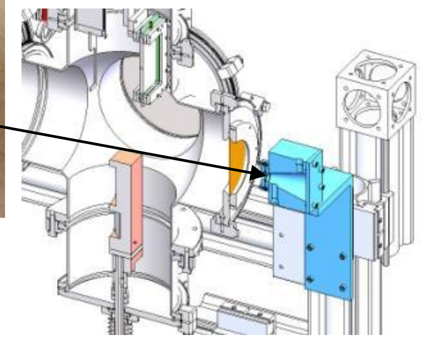
- Test at BNL-BLIP facility started in April 2017 with RaDIATE collaborators
  - 4 days of irradiation with high energy protons, more in June.
  - Restart irradiation early 2018 to reach 8 weeks (up to 1 dpa in Ti samples) and characterize property changes due to proton induced damage
  - FRIB and KEK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

RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

Before

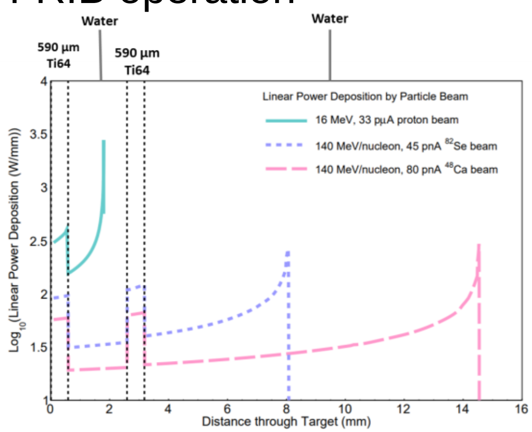
After

Material Study with High Energy Heavy Ions
Corrosion Test for a Better Understanding of Lifetime

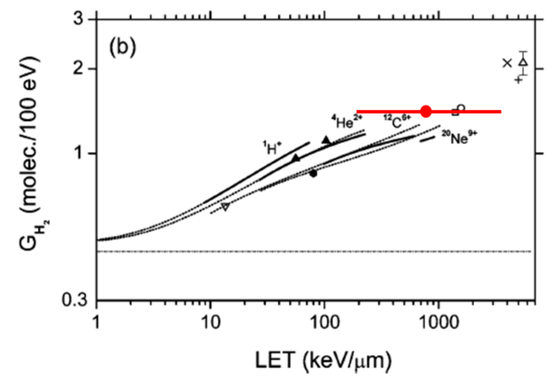



- Short irradiation at NSCL with high energy heavy ion beam
  - 4 different beams, energy and intensity were used
  - Cumulated dose ~ 4e-2 dpa in the window
  - Observed corrosion rate appears to be lower than expected (preliminary result)
  - Benchmark gas production in water
- Long irradiation with 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

See RaDIATE Collaboration Meeting at TRIUMF in Dec 2019
Emily Abel
Katharina DOMNANICH



3D printed NSCL beam dump



*G factor (gas production): NSCL result compared to results from Meesungnoen, J.; Jay-Gerin, J. P. J. Phys. Chem. A., **2005**, 109, 6406 – 6419*

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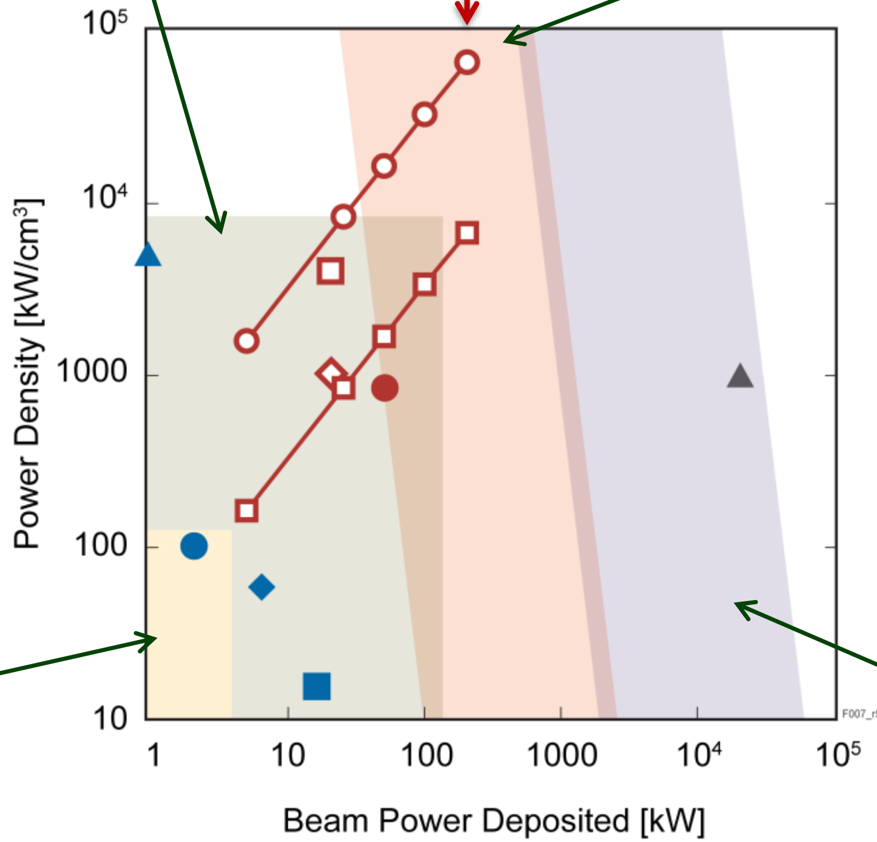
High Power Target Technology

Rotating single-slice targets

FRIB - 400 kW

Rotating multi-slice targets

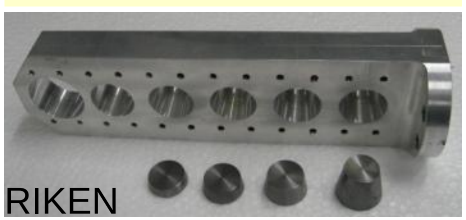


Running devices
- MSU - CCF
- SPIRAL - GANIL
- SISSI - GANIL
- LAMPF

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

To be developed
- IFMIF

Static targets



Liquid Li targets