High Power Targetry at FRIB

F. Pellemeoine
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
- $P_{\text{beam}} = 400$ kW
- $P_{\text{deposited}} \sim 100$ kW
- $\sigma_{x \text{ beam}} = 0.24$ mm
- $\sigma_{y \text{ beam}} = 0.29$ mm
- $P = 30$ MW/cm³
- Dose $\sim 8$ dpa

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

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

Wedge (Al-alloy)
- $E = 156 - 260$ MeV/u
- $P_{\text{deposited}} < 2$ kW
- $\sigma_{x \text{ beam}} = \text{up to 5 cm}$
- $\sigma_{y \text{ beam}} = \text{up to 5 cm}$
- $P = 13$ kW/cm³
- Dose $\sim 1$ dpa
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 \( \approx \frac{1}{3} \) 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
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
  - Property changes: thermal conductivity, tensile and flexural strength, electrical resistivity, microstructure and dimensional changes, …
- Swift heavy ions (SHI) damage not well-known
- $5 \times 10^{13}$ U ions/s at 203 MeV/u may limit target lifetime
  - Fluence of $\sim 9.4 \times 10^{18}$ ions/cm² 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
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)
- $P = 1.65 \text{ kW}, \Delta T = 640 ^\circ \text{C}$
- $P = 3.3 \text{ kW}, \Delta T = 1800 ^\circ \text{C} \Rightarrow \text{plasma effect}$

W. Mittig, F. Pellemeine 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

F. Pellemoine, May 2020 - Fermilab HPT Technical Meeting, Slide 8
R&D to mitigate issues
Radiation Damage Studies– Au beam @ 8.6 MeV/u

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

X-Ray Diffraction analyses

TEM analyses

Swelling is completely recovered at 1900°C

F. Pellemeoine et al., NIMB 365 (2015) 522-524
S. Fernandes et al., NIMB 314 92013) 125-129
Beam dump drum (Ti-alloy)
- \( E = 156 \text{ – } 260 \text{ MeV/u} \)
- \( P_{\text{beam}} = 400 \text{ kW} \)
- \( P_{\text{deposited}} \approx 300 \text{ kW} \)
- \( \sigma_{x \text{ beam}} = 1\text{-}10 \text{ mm} \)
- \( \sigma_{y \text{ beam}} = 2\text{-}50 \text{ mm} \)
- \( P = 30 \text{ MW/cm}^3 \)
- Dose \~ 7 \text{ dpa} 

Fragment catcher (Al-alloy)
- \( E = 156 \text{ – } 260 \text{ MeV/u} \)
- \( P_{\text{deposited}} < 10 \text{ kW} \)
- \( \sigma_{x \text{ beam}} = \text{up to } 15 \text{ cm} \)
- \( \sigma_{y \text{ beam}} = \text{up to } 5 \text{ cm} \)
- \( P = 9 \text{ kW/cm}^3 \)
- Dose \~ 2.5 \text{ dpa} 

Production target (graphite)
- \( E = 202 \text{ – } 260 \text{ MeV/u} \)
- \( P_{\text{beam}} = 400 \text{ kW} \)
- \( P_{\text{deposited}} \approx 100 \text{ kW} \)
- \( \sigma_{x \text{ beam}} = 0.24 \text{ mm} \)
- \( \sigma_{y \text{ beam}} = 0.29 \text{ mm} \)
- \( P = 60 \text{ MW/cm}^3 \)
- Dose \~ 8 \text{ dpa} 

Wedge (Al-alloy)
- \( E = 156 \text{ – } 260 \text{ MeV/u} \)
- \( P_{\text{deposited}} < 2 \text{ kW} \)
- \( \sigma_{x \text{ beam}} = \text{up to } 5 \text{ cm} \)
- \( \sigma_{y \text{ beam}} = \text{up to } 5 \text{ cm} \)
- \( P = 13 \text{ kW/cm}^3 \)
- Dose \~ 1 \text{ 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 \(\sim 10^{18}\) ion/cm\(^2\)
    » dpa (U beam) \(\sim 7\) (dpa/rate \(\sim 4 \cdot 10^{-7}\) 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 150\(^\circ\)C

- Ti-6Al-4V was chosen as candidate material for the beam dump shell
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 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

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

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (MeV)</th>
<th>Ion range (µm)</th>
<th>Se (keV/µm)</th>
<th>Flux (ions/cm².s⁻¹)</th>
<th>Fluence (ions/cm²)</th>
<th>T (°C)</th>
<th>Dose (dpa)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>³⁶Ar</td>
<td>36</td>
<td>6.8</td>
<td>7.5</td>
<td>2.10¹⁰</td>
<td>10¹⁵</td>
<td>30</td>
<td>0.08</td>
<td>Ti-6Al-4V PM</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>0.6</td>
<td>1.4</td>
<td>2.10¹⁰</td>
<td>10¹⁵</td>
<td>30</td>
<td>1.03</td>
<td>Ti-6Al-4V PM</td>
</tr>
<tr>
<td>³⁶Ar</td>
<td>36</td>
<td>6.8</td>
<td>7.5</td>
<td>4.10¹⁰</td>
<td>10¹⁵</td>
<td>350</td>
<td>0.08</td>
<td>Ti-6Al-4V PM</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>0.6</td>
<td>1.4</td>
<td>4.10¹⁰</td>
<td>10¹⁵</td>
<td>350</td>
<td>1.03</td>
<td>Ti-6Al-4V PM</td>
</tr>
<tr>
<td>⁴⁰Ar</td>
<td>4</td>
<td>3.8</td>
<td>3.16</td>
<td>2.18 .10¹³</td>
<td>4.8.10¹⁶</td>
<td>350</td>
<td>16</td>
<td>Ti-6Al-4V PM, Ti-6Al-4V AM, CP Ti</td>
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<tr>
<td></td>
<td>4</td>
<td>3.8</td>
<td>3.16</td>
<td>3.5 10¹³</td>
<td>2.5.10¹⁶</td>
<td>30</td>
<td>8.0</td>
<td>Ti-6Al-4V PM, Ti-6Al-4V AM, CP Ti</td>
</tr>
</tbody>
</table>

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.

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

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.

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

Aida Amroussia's Thesis - next RaDIATE Technical Meeting
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
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

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High Power Target Technology

Rotating single-slice targets

FRIB - 400 kW

Rotating multi-slice targets

Static targets

Liquid Li targets

Power Density [kW/cm²]

Beam Power Deposited [kW]

FRIB - 400 kW

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

FRIB

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University
F. Pellemeine, May 2020 - Fermilab HPT Technical Meeting, Slide 22