Advanced Materials Studies for High Intensity Proton Production Targets and Windows
Frederique Pellemoine
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Outline

- Introduction
  - Overview of Fermilab accelerator complex and neutrino beamline
  - Neutrino targets

- High Power Targetry (HPT) scope and challenges
  - Radiation damage and thermal shock
  - Autopsy and analysis of failed components

- HPT R&D program and collaborations
  - Current research approach and results
  - Development of alternative methods
  - Novel materials development
  - RaDIATE collaboration

- Summary
Neutrinos at the Main Injector (NuMI)

- Main injector proton beam (120 GeV/c) smashes into a 1.2 m long graphite target to create charged pions and kaon.
- The pions are focused by magnetic horns and decay into muons and muon neutrinos in a 700-m long decay pipe, allowing time for pions of various momenta to decay and produce the desired neutrinos.
- Beam detectors downstream of the decay pipe monitor the neutrinos produced and residual charged particles for the experiments.

Target station able to operate with 1-MW proton beam since FY21
Neutrino target – NOvA

• Helium atmosphere
• Beryllium windows
• Water cooled aluminum pressing plates
• Graphite core

<table>
<thead>
<tr>
<th></th>
<th>NOvA</th>
<th>AIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite fins</td>
<td>50 x 24 mm x 7.4 mm</td>
<td>50 x 24 mm x 9 mm</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>p/pulse</td>
<td>4.90E+13</td>
<td>6.50E+13</td>
</tr>
<tr>
<td>Power [kW]</td>
<td>700</td>
<td>1000</td>
</tr>
<tr>
<td>σ [mm]</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Peak Temp. [°C]</td>
<td>670</td>
<td>1000</td>
</tr>
<tr>
<td>QS Temp [°C]</td>
<td>390</td>
<td>890</td>
</tr>
<tr>
<td>POT</td>
<td>1.10E+21</td>
<td>1.28E+21</td>
</tr>
<tr>
<td>Peak dpa</td>
<td>1.10</td>
<td>0.96</td>
</tr>
<tr>
<td>Peak He [appm]</td>
<td>5580</td>
<td>3600</td>
</tr>
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</table>
What we want to avoid...

MINOS NT-02 target failure: radiation-induced swelling (FNAL)

MINOS NT-01 target containment water leak (FNAL)

Horn stripline fatigue failure (FNAL)

Be window embrittlement (FNAL)

NOvA MET-01 target fin fracture (FNAL)

ISOLDE target (CERN)

Target containment vessel cavitation (ORNL - SNS)
Future Neutrino Target – LBNF-DUNE (1.2 – 2.4 MW)

Conceptual 1.2 MW target design

- Helium atmosphere
- Titanium target containment windows
- Helium gas cooled graphite core

2.4 MW target will require significant R&D to guide design and material choice
High Power Targetry Challenges

Thermal Shock and Radiation Damage were always identified as the most cross-cutting challenges of high-power target facilities but need to consider target thermal fatigue as fatigue stress cycle amplitude $x2$ at 2.4 MW.
Radiation Damage & Thermal Shock

**Radiation Damage:** Displacements in crystal lattice expressed as Displacements Per Atom (DPA)
- Hardening and embrittlement
- Creep and swelling
- Fracture toughness reduction
- Thermal/electrical conductivity reduction
- Coefficient of thermal expansion
- Modulus of elasticity
- Transmutation products (H, He gas production can cause void formation and embrittlement)

**Thermal Shock:** Sudden energy deposition from pulsed beam
- Fast expansion of the material surrounded by cooler material generates localized area of compressive stress
  - 1 MW target: ~250 K in 10 µs pulse (2.5 x 10^7 K/s)
- Stress waves move through the material at sonic velocities
- Plastic deformation, cracking and fatigue failure can occur

**Thermal Fatigue:** Cycling loading environment
- Cycling loading progressively damage material’s microstructure such that it can ultimately fail at stress levels that are actually lower than its failure strength
  - Fatigue Stress Cycle Amplitude x2 at 2.4 MW
Radiation Damage in Accelerators

<table>
<thead>
<tr>
<th>Irradiation Source</th>
<th>DPA rate (DPA/s)</th>
<th>He gas production (appm/DPA)</th>
<th>Irradiation Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed spectrum fission reactor</td>
<td>$3 \times 10^{-7}$</td>
<td>$1 \times 10^{-1}$</td>
<td>200-600</td>
</tr>
<tr>
<td>Fusion reactor</td>
<td>$1 \times 10^{-6}$</td>
<td>$1 \times 10^{1}$</td>
<td>400-1000</td>
</tr>
<tr>
<td>High energy proton beam</td>
<td>$6 \times 10^{-3}$</td>
<td>$1 \times 10^{3}$</td>
<td>100-800</td>
</tr>
</tbody>
</table>

- Use of data from nuclear materials research is limited, cannot be directly utilized but give us some insight of radiation damage trends
- Could develop some methods to overcome issues and challenge to simulate protons with neutrons or other alternative methods
DPA experiment at FTBF

- Beam window damage is evaluated with Displacement Per Atom
  \[ \text{DPA} = \sigma_d \phi \]
  - \( \sigma_d \): displacement cross-section (m²)
  - \( \phi \): irradiation fluence (particles/m²)

- Models in FLUKA, MASR, and PHITS codes have not been validated due to lack of experimental data above 30 GeV.

- Measurements of displacement cross-section for metals (Au, Cu, Nb, W) with 120 GeV protons at FTBF.

- Experimental data: Damage rate at cryogenic temperature.
  - Recombination of Frenkel pairs by thermal motion is well suppressed.

- The device and data taking system have been developed at J-PARC.
- The experiment at FTBF will be scheduled in Jan. 2023.
Research Approach - Prototypic irradiation to closely replicate material behavior in accelerator target facilities

- High-energy proton irradiation of material specimens at BNL-BLIP facility in partnership with the RaDIATE collaboration
  - 1st irradiation campaign completed in 2017/2018, 2nd irradiation planned in 2024-2025
- Post-Irradiation Examination (PIE) conducted at participating institution equipped with hot-cell facilities (PNNL)
- In-beam thermal shock experiment at CERN’s HiRadMat facility that includes both pre-irradiated (BLIP) and non-irradiated specimens
  - Completed experiments in 2015 and 2018. Currently preparing for upcoming test in Oct. 2022
PIE of Proton-Irradiated Beryllium at PNNL

- Tensile tests performed on two varieties of proton-irradiated Be (PF60/S65F)
- Mechanical properties
  - Distinct radiation hardening observed at very low dose (<0.1 dpa)
  - Ductility reduced after irradiation, but some elongation still present even at room temperature
Thermal Shock Experiments at CERN’s HiRadMat Facility

• User facility at CERN, designed to provide high-intensity pulsed beam to test materials and accelerator components
  – 440 GeV, σr = 0.25 ~ 4 mm (rms)
  – Up to 3.46 x 10¹³ ppp in 7.95 µs

• HRMT-43, BeGrid2 experiment (2018) was the first and unique test with pre-irradiated material
  – First test on nanofiber electro-spun fiber mats and metal foam (SiC, ZrO₂, Al₂O₃, RVC)
  – Online dynamic thermomechanical measurements of graphite cylinders

• HRMT-60 (Oct 2022) will investigate the dynamic material limits of beam-intercepting devices in current and future multi-MW accelerator target facilities – 120 thin specimens, 4 instrumented cylinders
  – Understand single-shot thermal shock response and limits
  – Explore novel advanced materials
  – Assess the performance of various grades of conventional materials
  – Compare the behavior of non-irradiated to pre-irradiated materials
  – Directly measure beam-induced dynamic effects to validate simulation codes
Alternative to High Energy Proton Beam

- High energy proton irradiation
  - Highly activated material ⇒ need hot cells and specific characterization equipment
  - High energy ⇒ Low dpa rate ⇒ long irradiation time (order of months) ⇒ Expensive

- Alternative radiation damage method
  - Low-energy ion irradiation
    - Lower cost, high dose rate without activating the specimen
    - Narrow penetration depth
      - Micro-mechanics and meso-scale testing
    - Doesn’t reproduce the gas (H and He) production
      - He implantation in Graphite at Michigan Ion Beam Lab
  - Very few heavy ion irradiation facilities around the world ⇒ Need more development of such facilities

- Alternative thermal shock method
  - Use of electron beams, lasers, or other techniques could reduce the cost and length of R&D cycles compared to proton beam-line tests

- Ab initio and MD modeling could help to guide the development of alternative techniques
  - e.g. understanding the differences between radiation damage effects from HE protons vs. LE ions or other alternative methods
Low energy $\text{Fe}^{2+}$ ion beam irradiation at HIT Facility

High Fluence Irradiation Facility at the University of Tokyo

- Accelerated damage rate
  - up to 10 DPA in a few days
- Shorter irradiation time
- No specimen activation

Effective and fast way to screen materials and to optimize heat treatment at high irradiation dose

Nano-indentation hardness test

- Hardness is relatively proportional to Yield Strength, but difficult to infer ductility (elongation)

15-3(ST) 100 indentations (10µm intervals)

Indentation depth: 150nm (fix)
The single metastable β phase Ti-15-3 alloy exhibits high radiation damage tolerance, that does not undergo irradiation hardening up to 10 dpa at room temperature. Dense nano-scale precipitates (precursors of the athermal ω-phase) that act as effective “sink sites” to absorb irradiation defects.

Ti-15-3 is typically aged at ~500 °C to precipitate α-phase that enables higher temperature operation. α-phase precipitates are too coarse and can weaken sink strength and degrade radiation damage tolerance. Clear irradiation hardening (but less than Ti-64 A)
Graphite Irradiation Studies with Heavy Ions
A. Burleigh and Prof. J. Terry (IIT)

- 4.5 MeV He++ ions at MIBL
- 1 MeV/A $^{36}$Ar$^{10+}$ at IRRSUD

TEM: similar behavior of HI irradiated graphite compared to failed NT-02 target
AFM measurements show bulk swelling of ~3.8 µm in the irradiated region
Nano-indentation of graphite irradiated up to 0.9 DPA at MIBL

Preliminary results
Ab initio and molecular dynamics (MD) modeling are still not yet mature enough to model atomistic changes to micro-structural evolution to macro-properties of real-world materials.

- However: Prediction of fundamental response of various material classes to irradiation helps steer material choices and experiment design for future irradiation studies.

- Ti alloy Radiation Damage Modeling at PNNL ongoing
  - molecular dynamics simulations of pure α-Ti, with Ti-base alloy simulations
  - Simulated accumulation of interstitial-vacancy (Frenkel) pairs up to 0.4 dpa

- Collaboration with Computation Materials Group at University of Wisconsin
  - Modeling of He gas bubbles in Beryllium - ongoing
  - Modeling of radiation damage in HEAs – will start in Fall 2022
Novel Targetry Materials: Electrospun Nanofibers and HEAs

Nanofiber electro-spinning at Fermilab
- Nanofiber continuum is discretized at the microscale to allow fibers to absorb and dampen thermal shock, and discontinuity prevents stress wave propagation
- Evidence of radiation damage resistance due to nanopolycrystalline structure of the material

High-Entropy Alloy (HEA) development at UW-M
- Alloys consisting of 3 or more principal elements
- Excellent inherent properties including enhanced radiation damage resistance

Electrostatically driven electrospinning process
- Evidence of radiation damage resistance due to nanopolycrystalline structure of the material

Lu, 2016 Reduction in irradiation-induced void distribution in nickel and multi-component HEAs after 3-MeV Ni+ ion irradiation at 773 K

(a) Conventional alloy, (b) High-entropy alloy (Miracle & Senkov, 2016)
RaDIATE collaboration created in 2012, with Fermilab as the leading institution

Objective:
- Harness existing expertise in nuclear materials and accelerator targets
- Generate new and useful materials data for application within the accelerator and fission/fusion communities

Activities include:
- Analysis of materials taken from existing beamline as well as new irradiations of candidate target materials at low and high energy beam facilities
- In-beam thermal shock experiments

Program manager: Dr. Frederique Pellemoine (FNAL)
Summary

- Future high-power beams present critical target facility challenges
  - Understanding material behavior under intense multi-MW beams is high priority
    - Radiation damage effects from lattice disruptions and gas transmutations
    - Beam-induced thermal shock limit of materials

- Materials R&D essential to help design robust targetry components and maximize primary beam power on target and secondary particle production
  - Globally coordinated R&D activities are producing useful results
  - Alternative irradiation facilities, material testing and characterization methods essential to support R&D program
  - Explore Novel material to support future high-power Targetry components
Thank you for your attention

• Acknowledgements
Neutrino HPT R&D Materials Exploratory Map

10 x increase in accumulated proton fluence expected in future multi-MW facilities

Materials of interest
- **Graphite** (target)
- **Beryllium** (beam window and target)
- **Titanium alloys** (primary beam and target containment windows)
- **Novel materials**: electro-spun nanofibers, high-entropy alloys, metal foams, MoGr, glassy carbon, highly ductile TFGR tungsten, etc.