Targetry challenges for the next generation of high-intensity neutrino beams

Robert Zwaska
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What we don’t want

Ta-rod after irradiation with 6E18 protons in 2.4 \( \mu \)s pulses of 3E13 at ISOLDE
High Power/Intensity Targetry Challenges

- Target Material Behavior
  - Radiation damage
  - Thermal “shock” response
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Remote handling
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection
  - Radiation accelerated corrosion
  - Manufacturing technologies

Additional Neutrino Beam Challenges:

- Primary beam handling and instrumentation
- Accuracy and consistency of all beam inputs, particularly alignment
- Focusing elements
- Beam-based alignment
- Secondary beam instrumentation
- Radiation transport modeling
- Hadron production

The high statistics from high-power beams require an emphasis on precision
Nu HPT R&D Materials Exploratory Map

Thermal Shock Severity (p/cm²/pulse)

Radiation Damage Severity
(damage equivalent fluence, p/cm²)

Uncharted Territory

Future Nu 4 MW

LBNF-2.4 MW Tau Nu

LBNF-2.4 MW (Ideal)

NT-01
NT-03
NT-04
NT-05
NT-06
NT-07

T2K First Target

LBNF-1.2 MW (CDR)

NuMI-MINOS Target NT-02 (damaged)

NuMI-NOvA Target TA-01 (survived)

NT-06 NT-05

SNS range for 1.4 MW operation for 1 year

Service

Future
Broad aims are threefold:

- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**
High Power Targetry: Materials R&D

**Multi-MW** Neutrino Targets & Beam Windows Materials:

- **Graphite** (target core material) studies:
  - Swelling/fracture studies
  - Preparing for HE proton irradiation at BLIP (2020) to confirm elevated temperature annealing

- **Beryllium** (beam window material) studies:
  - Examination of BLIP irradiated Be specimens underway
  - Helium implantation studies show bubble formation at irradiation temperatures above 360 °C

- **Titanium Alloys** (beam window material) studies:
  - Examination of BLIP irradiated specimens underway
  - World first high cycle fatigue testing of irradiated titanium underway at FNAL

Benefits to multi-MW targets e.g. LBNF):
- alloy/grade choice
- cooling system design
- tolerable beam intensities
- expected lifetimes

In-beam thermal shock testing of *BLIP irradiated* Be and Ti alloys at CERN
Background- Fractured NuMI target fin

Beam Parameters:
- Energy: 120 GeV
- Beam sigma: 1.1 mm
- Spill duration: 10μsec, 4x10^{13} protons/pulse
- Duty cycle: 1.87 sec
- Peak fluence: 8.6x10^{21} protons/cm²

Detailed PIE at PNNL

Bulk swelling of ~2%
Graphite Results – X-ray diffraction of NuMI graphite fin shows lattice growth and amorphization at beam center

Irradiation temperature ~150 °C
Modeling of graphite swelling predicts fracture

Sujit Bidhar (FNAL) – User defined material model in ANSYS

- **Elastic modulus** as a function of dose and temperature
- **Swelling (NSLS-II)** as a function of dose and temperature

Tensile strength of graphite:
- 79 MPa (0 DPA)
- 110 MPa (0.1 DPA)

No radiation damage effects

Stress

179 Mpa !!

Swelling

2 MPa

Thermal Response
High Energy Proton Irradiation

- 181 MeV p irradiation @ BNL's BLIP facility
  - Over 200 specimens from 6 RaDIATE collaborators
  - Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, FNAL
- Completed irradiation on March 9, 2018
  - 4.5E21 accumulated protons on target
  - 1.52 peak DPA on Ti alloy achieved

**Impact:** Will benefit many facilities including LBNF, T2K, BDF at CERN, FRIB, and even LHC-HiLumi (collimators)
Microstructural response:
- *creation of transmutation products;*
- *atomic displacements (cascades)*
  - average number of stable interstitial/vacancy pairs created = DPA (Displacements Per Atom)
- *Gas production (hydrogen / helium)*
Consisted of **9 capsules** from 6 RaDIATE institutions with **over 200 material specimens** relevant to beam intercepting devices in various current/future accelerator facilities

- **181 MeV** incoming protons used for RaDIATE irradiation
- Irradiation campaign executed in **3 phases** with different target box configurations
  - 6 capsules in target box during each irradiation phase
- Total protons on target: **4.57E21** (154 µA avg)

<table>
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<th>2017</th>
<th>2018</th>
<th>Total</th>
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<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
<td>Phase 3</td>
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<tr>
<td>Total µA-hr</td>
<td>32464.49</td>
<td>45614.58</td>
<td>124979.89</td>
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<tr>
<td>Total hr</td>
<td>226.27</td>
<td>302.94</td>
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<td>Total days</td>
<td>9.43</td>
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<td>32.88</td>
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<td>Total weeks</td>
<td>1.35</td>
<td>1.80</td>
<td>4.70</td>
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<tr>
<td>Avg. current (µA)</td>
<td>143.48</td>
<td>150.57</td>
<td>158.38</td>
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<tr>
<td>POT</td>
<td>7.30E+20</td>
<td>1.03E+21</td>
<td>2.81E+21</td>
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</table>
BLIP Irradiation Examinations Underway

- Significant hardening at low dose in Be and Ti
  - Less hardening in higher temperature specimens
- First ever fatigue study on irradiated Ti alloys begun
  - Indicates about 10% reduction in fatigue strength
- Microstructural examinations underway

Irradiation hardening of S-65F Be
- Reduction of strain to failure
- Increased strength
X-ray diffraction – Swelling in BLIP irradiated graphite

**Impact:** Allows confidence to use reactor data for lattice swelling of graphite in HE proton regime for future target facilities

Neutron irradiated graphite dimensional changes

- B.J. Marsden, “Irradiation Damage in Graphite due to fast neutrons in fission and fusion systems,” IAEA-TECDOC-1154, 2000

**Impact:** Correlation informs target choice of operating temperature (cooling system design)

Big change in c-axis growth

~250 °C
In-Beam Thermal Shock Test: BeGrid2 (HRMT43)


Primary Objectives:

- Compare thermal shock response between non-irradiated and previously irradiated material specimens from BNL BLIP (Be, C, Ti, Si)
  - First/unique test with activated materials at HiRadMat

- Explore novel materials such as metal foams (C, SiC) and electrospun fiber mats (Al$_2$O$_3$, ZrO$_2$) to evaluate their resistance to thermal shock and suitability as target materials
BeGrid2 (HRMT43) – 3-D printed specimen holders
MIMiC - Methods of Irradiated Material Characterization

Replicating proton beam interaction damage with minimal residual activity

The current routes for high-energy proton irradiations are expensive, long in duration, and lack control of testing conditions and schedule.

- **Low-energy ion irradiations** are attractive because they allow study of the evolution of the micro-structure during irradiation without activating the specimens, are relatively low cost, and can achieve high dose in very short durations.

- **Micro-mechanics** and meso-scale testing are potential enabling technologies to overcome some of the limitations of low-energy irradiations as well as to drastically reduce specimen size requirements (which also reduces activity of specimens).

- **Ion irradiations and micro-mechanics** have been used in the RaDIATE studies on beryllium.
Nu HPT R&D Materials Exploratory Map

Uncharted Territory

- HiRadMat Beam Test - 1
- HiRadMat Beam Test - 2
- Thermal Shock Test (planned) MIMiC
- Graphite Fin Studies

Thermal Shock Test Severity (p/cm²/pulse)

5.0E+14
5.0E+13

Radiation Damage Severity
(damage equivalent fluence, p/cm²)

5.0E+12
1.0E+20
1.0E+21
1.0E+22
1.0E+23

- HiRadMat Beam Test - 1
- HiRadMat Beam Test - 2
- Thermal Shock Test (planned) MIMiC
- Graphite Fin Studies
- BLIP Irradiation - 1
- BLIP Irradiation - 2
- Ion Irradiation (planned) MIMiC

- Future Nu 4 MW
- LBNF-2.4 MW Tau Nu
- NuMI Be Beam Window

NT-01, NT-02, NT-03, NT-04, NT-05, NT-06, NT-07, TA-01, NT-08, NT-09, NT-10, LBNF-1.2 MW CDR, LBNF-2.4 MW IDEAL

Service, Study, Future

R. Zwaska | Neutrino 2020

20.06.28
Overview of Strategy for HPT Material R&D

To Present (2010-2020) – Benefits ongoing neutrino program

• Measure irradiated material behavior of currently identified targetry materials
  • Be, graphite, Ti alloys
  • High-energy proton irradiations, thermal shock tests, autopsies
• Identify more effective Methods of Irradiated Material Characterization (MIMiC)
• Explore ab initio and molecular dynamics to model irradiated material behavior

Mid Term* (2021-2027) – Benefits LBNF 2.4 MW design & next-gen experiments

• Continue irradiated material studies on candidate targetry materials
  • Focus on reducing costs/risks of high-energy proton irradiations
• Develop MIMiC ideas into valid experimental techniques

Far Term* (2028 and beyond) – Benefits next-gen HPT Facilities

• Utilize the developed MIMiC techniques, ab initio/MD modeling, and previous experimental results to develop and select promising candidate targetry materials
• Qualify selected candidate targetry materials for next generation HPT facilities with a combination of high-energy proton and MIMiC techniques
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