High Power Targets
Challenges for next-generation high-intensity neutrino beams

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The 22nd International Workshop on Neutrinos from Accelerators (NuFact 2021)
10 September 2021
Robust High-Power Targets Critical in Maximizing the Efficiency of Neutrino Production

Recently, major accelerator facilities have been limited in beam power not by their accelerators, but by target survivability concerns:

- **NuMI-MINOS, FNAL (2010-11)**
  - Reduced beam power (-10% to -40%)
  - Target failures attributed to faulty welds
- **MLF, J-PARC (2015-16)**
  - Early replacement of target
  - Limited to 200 kW when resuming ops
- **SNS, ORNL**
  - Reduced beam power (-15%) frequently in 2013-14
  - Target vessel failures attributed to faulty welds and dynamic stresses

**Next-generation multi-MW accelerator target facilities present even greater challenges**

LBNF DUNE 1.2-2.4 MW, Hyper-K 1.3 MW, Future neutrino facilities 4 MW+

**Target R&D essential to:**

- Avoid compromising particle production efficiency by limiting beam parameters
- Maintain reliable operation and accurately predict component lifetime
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)
High Power Targetry Scope

- **Target**
  - Solid, Liquid, Fixed, Rotating

- **Facility Requirements**
  - Remote Handling
  - Shielding & Radiation Transport
  - Air Handling
  - Cooling System

- **Other beam-intercepting devices**
  - Collimators
  - Collection optics (horns, solenoids)
  - Monitors & Instrumentation
  - Beam windows
  - Absorbers
High Power/Intensity Targetry Challenges

Thermal Shock and Radiation Damage identified as most cross-cutting challenges of high-power target facilities

Additional neutrino beams challenges
- Primary beam handling and instrumentation
- Accuracy and consistency of beam inputs
- Focusing elements
- Beam-based alignment
- Secondary beam instrumentation
- Hadron production
Beam-induced damage to the microstructure

- Atomic displacements (cascades)
  - **Displacement Per Atom (DPA)** = Average number of stable interstitial/vacancy pairs created
- Creation and agglomeration of point defects
- Segregation (precipitation) or depletion of point defect sinks
- Creation of transmutation products (H and He production)
Radiation Damage Effects

- Atomic displacements in crystal lattice (DPA) cause bulk property changes
  - Embrittlement
  - Creep
  - Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Coefficient of thermal expansion
  - Modulus of Elasticity
  - Accelerated corrosion

- Transmutation products
  - H, He gas production causes void formation and embrittlement

- Radiation damage effects very dependent upon material and irradiation conditions
  - Temperature, dose rate, particle energy/type

S.A. Maloy et al., J. Nuclear Materials, 343, pp. 219-226, 2005
Radiation Damage Effects

Factor of 10 reduction in thermal conductivity of graphite after 0.02 DPA

Complex lattice swelling in graphite

Void swelling in 316 Stainless Steel tube exposed to reactor dose of $1.5 \times 10^{23} \text{n/cm}^2$


Thermal Shock Effects (stress waves)

- High-intensity pulsed beam creates localized area of compressive stress, generated due to fast expansion of material surrounded by cooler material
  - NuMI 1-MW graphite target: $\Delta T \approx 250$ K in 10 $\mu$s ($2.5 \times 10^7$ K/s)

- Dynamic stress waves travel through the target at sonic velocities
- Thermal shock can induce plastic deformation, cracking and fatigue failure

Temperature rise during 10 $\mu$s pulse in NuMI 1-MW graphite target (FNAL)

Ta-rod after irradiation with $6 \times 10^{18}$ protons in 2.4 $\mu$s pulses of $3 \times 10^{13}$ at ISOLDE (photo: J. Letry)

Ta-rod after irradiation with $6 \times 10^{18}$ protons in 2.4 $\mu$s pulses of $3 \times 10^{13}$ at ISOLDE (photo: J. Letry)

Iridium target tested at CERN’s HiRadMat facility

Temperature rise during 10 $\mu$s pulse in NuMI 1-MW graphite target (FNAL)
Stress Wave Example: T2K Window

T2K Titanium beam window

- Cyclic stress loading environment can lead to fatigue failure
- Heavy dependence on material properties
  - But material properties dependent upon radiation damage

Material response depends on:
- Specific heat (temperature jump)
- Coefficient of thermal expansion (strain)
- Modulus of elasticity (stress)
- Flow stress behavior (plastic deformation)
- Strength limits (yield, fatigue, fracture toughness)

\[
\sigma = \sqrt{\rho E \cdot \alpha \cdot L \cdot \frac{\Delta T}{\Delta t}} \quad \text{Initial stress wave amplitude}
\]

\[
c = \sqrt{\frac{E}{\rho}} \quad \text{Elastic wave speed}
\]
Radiation Damage Data

- Use of data from nuclear materials research is limited and cannot be directly utilized
- Effects from low-energy neutron irradiations do not equal effects from high-energy proton irradiations

<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>
Neutrino HPT R&D Materials Exploratory Map

~10x increase in accumulated proton fluence expected in future multi-MW facilities
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)
High Power Target Materials R&D

Examine targets and beam window materials behavior under prototypic multi-MW proton beam conditions

- **Graphite** (target core) studies:
  - Beam-induced swelling and fracture studies
  - High-dose ion irradiation of graphite

- **Beryllium** (beam window) studies:
  - NuMI beam window analysis & Helium ion implantation
  - Post-irradiation examination of BLIP-irradiated specimens
  - In-beam thermal shock testing at CERN’s HiRadMat facility

- **Titanium** (beam window) studies:
  - Tensile testing of BLIP-irradiated specimens
  - Low-energy ion irradiation and nano-indentation
  - World first high-cycle fatigue testing of irradiated titanium at FNAL

- **Novel materials** studies:
  - Electro-spun nanofibers, high-entropy alloys, metal foams, MoGr, highly-ductile TFGR tungsten

**Benefits to multi-MW targets**
- Alloy/grade and heat treatment choice
- Identify novel candidate materials
- Cooling system design and operating temperature
- Tolerable beam intensities
- Expected lifetimes
Analysis of Fractured NuMI Target Fin

NuMI target (NT-02) autopsy and examination

- Peak fluence: $8 \times 10^{21}$ p/cm$^2$
- Beam energy: 120 GeV
- Spill duration: 10 µs, $4 \times 10^{13}$ protons/pulse
- Duty cycle: 1.87 s
- Estimated peak DPA: 0.63

Detailed PIE at PNNL

Bulk swelling of ~4%
X-Ray Diffraction of NuMI Graphite Fin at NSLS-II

XRD shows lattice growth and amorphization at the beam center

Irradiation temperature ~60 °C (330 °C during pulse)

N. Simos et al., PRAB, 22 (2019)
Observed transition from transgranular fracture to grain boundary/mixed mode fracture in irradiated Be

- Significant hardening even at 0.1 DPA
- Hardness of irradiated Be less anisotropic
- Increased hardness means less ductility (more brittle)

High Energy Proton Irradiation at BNL’s BLIP Facility

- Unique facility for material irradiation in tandem with medical isotope production
- High energy protons: 66 – 200 MeV with 165 µA peak current

- RaDIATE multi-material irradiation campaign
  - 181 MeV p irradiation for 8 weeks
    - Over 200 specimens from 6 RaDIATE collaborators
  - Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, FNAL
  - Completed irradiation in 2018
    - $4.5 \times 10^{21}$ accumulated protons on target
    - Peak DPA: 0.95 (Ti alloy)
  - Post-Irradiation Examination ongoing
    - Mechanical/Thermal testing
    - Microstructural analysis

Will benefit many facilities including LBNF, T2K, BDF at CERN, FRIB, and HL-LHC collimators
BLIP Ti Alloy Tensile Testing

Stress-strain curves for Ti-6Al-4V (left) and Ti-3Al-2.5V (right)

- Ti-6Al-4V loses almost all of its uniform elongation (UE) after irradiation
  - Important to retain UE in a target material as it allows for plastic deformation without rapid growth of cracks and sudden failure
- Evidence that Ti-3Al-2.5V alloy is more radiation-tolerant

Testing done in hot cell
High-Cycle Fatigue Testing of Irradiated Ti Alloys

Reduced fatigue strength

Ultrasonic mesoscale Fatigue Rig (UFR) at the UKAEA-MRF

Extraction of meso-fatigue foil from BLIP capsule in PNNL hot cell

20 kHz = $10^8$ cycles in 1.5 h

3rd Generation Fatigue Testing Machine (FTM) under development

BLIP 2017-2018 Ti foils have been shipped from PNNL to MRF for testing over the coming months
Low-Energy Ion Irradiation

Alternative method to mimic high-energy proton-induced radiation damage

- High damage (DPA) accumulation in short time (without activation)
- Shallow damage depth (use of micro-mechanics and meso-scale testing)
- Dual/Triple beams irradiation needed to reproduce transmutation gas production

Graphite irradiation with 4.5 MeV He\textsuperscript{++} ions

A. Burleigh and Prof. J. Terry (IIT)

TEM: e- diffraction shows increase in d-spacing and decrease in a-spacing, similar to failed NT-02 target

AFM measurements show bulk swelling of \(~3.8 \ \mu m\) in the irradiated region
Helium Implantation in Beryllium

- Helium produced at high rates in Be with high energy proton beams (~3000 appm/DPA)
- At low temperatures, He atoms do not diffuse while at high temperatures, He atoms become mobile and can fill vacancy clusters to form damaging He bubbles
- He bubbles observed in NuMI Be window after annealing at 360 °C
- However, higher temperatures are generally desired to anneal displacement damage (see hardness plot above)
Thermal Shock Experiments at CERN’s HiRadMat Facility

HRMT24 – BeGrid (2015)

- Observed distinctive thermal shock response for various beryllium grades
  - 2.8E13 ppp, $\sigma$: 0.3 x 0.28 mm
- Detected plastic strain ratcheting from multiple beam pulses
- Successful validation of Be S200FH

Johnson-Cook strength model

Profilometry to measure plastic out-of-plane deformations

Confidence in modeling beam-induced thermomechanical response

HRMT43 - BeGrid2 (2018)

- First and unique test with pre-irradiated material specimens (Be, C, Ti, Si)
  - 3.5E13 ppp, $\sigma$: 0.27 x 0.22 mm
- First test on nanofiber electro-spun fiber mats and metal foam (SiC, ZrO, Al$_2$O$_3$)
- Dynamic online measurements of graphite cylinders

Online measurements and benchmarking of graphite cylinders

Johnson-Cook model validation

$\sigma_T = \left[ A + B(\epsilon_{eff})^n \right] \left[ 1 + C\ln(\epsilon^*) \right] \left[ 1 - T_H^n \right]$

Confidence in modeling beam-induced thermomechanical response

Sigraflex specimens

- Numerical simulation benchmarking in progress
- Profilometry and PIE work ongoing at UKAEA MRF, UK
- Damage observed in Sigraflex (LHC dump material) prompted further investigation

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

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

Lu, 2016

(a) Conventional alloy, (b) High-entropy alloy (Miracle & Senkov, 2016)
Ongoing and Future Target R&D Activities

- Complete PIE of BLIP irradiated materials and HiRadMat specimens
- Execute the next HiRadMat experiment in 2022 and ensuing PIE and data analysis
- Ion irradiation studies to correlate with HE-proton (at higher doses and elevated temperatures at MIBL and IRRSUD facility)
- Plan next multi-material HE-proton irradiation within the RaDIATE collaboration framework
- Develop more effective and alternative testing methods to reduce cost and duration of R&D cycles
  - Low-energy ion and electron beam for irradiations, pulsed electron beam for fatigue and thermal shock studies
- Radiation damage modeling: Ab initio and molecular dynamics material modeling (UW-M, PNNL)
- Develop and qualify novel materials for next-generation target facilities (HEAs, nanofibers, etc.)
- Explore novel targetry concepts: flowing powder, pebble bed, He-cooled spherical array targets
Future neutrino 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 testing methods essential to support R&D program
- Several novel target concepts and materials are being explored and developed
Thank you