Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Status and Update of the RaDIATE Collaboration R&D Program

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on behalf of the RaDIATE Collaboration

13th International Topical Meeting on Nuclear Application of Accelerators

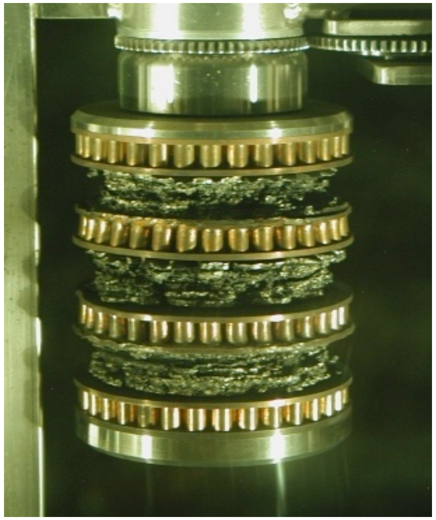
3rd August 2017

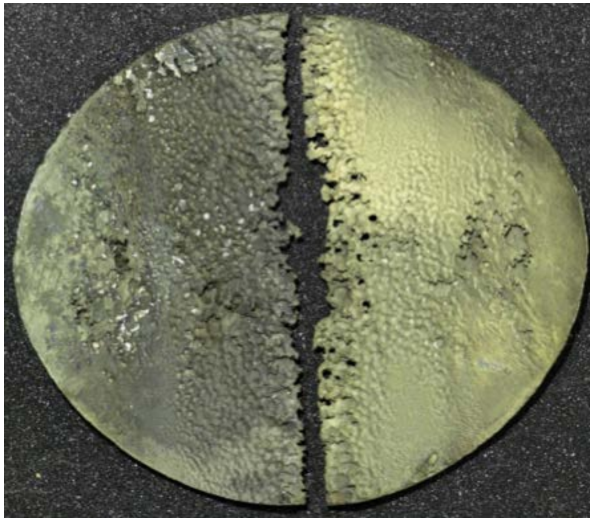
Outline

- High power targets: scope and challenges
- Research focus of the RaDIATE collaboration
- Ongoing and future R&D activities of RaDIATE
- Summary

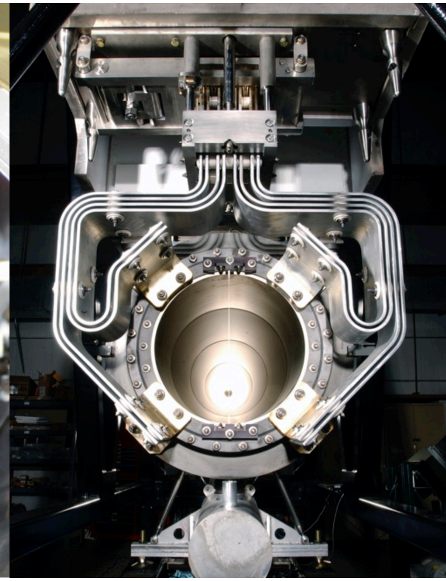
High Power Targetry Challenges

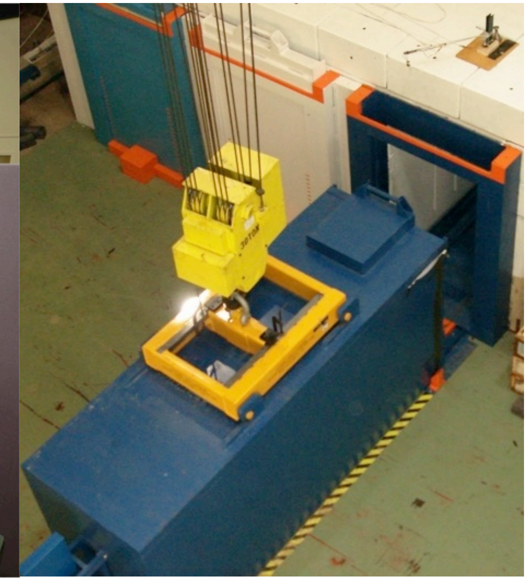
- Major accelerator facilities have recently been limited in beam power not by their accelerators, but by their target facilities (SNS, NuMI/MINOS)
- Even greater challenges are present for future high power and high intensity target facilities
- To maximize the benefit of high power accelerators (physics/$), challenges must be addressed in time to provide critical input to multi-MW target facility designs





High Power Targetry Scope

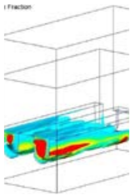





R&D needed to support:

- Targets
  - Solid, Liquid, Rotating, Rastered
- Other production devices
  - Collection optics (horns, solenoids)
  - Monitors & Instrumentation
  - Beam windows
  - Absorbers
- Collimators (eg. 100 TeV pp collimators)
- Facility requirements
  - Remote handling
  - Shielding and Radiation Transport
  - Air Handling
  - Cooling System

High Power/Intensity Targetry Challenges

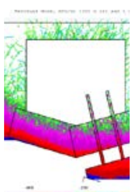


Heat removal

Thermal shock

Physics performance

Radiation damage



Operational safety

Storage and disposal

Subjects of the RaDIATE Collaboration

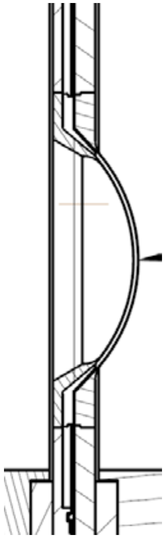
RaDIATE Collaboration

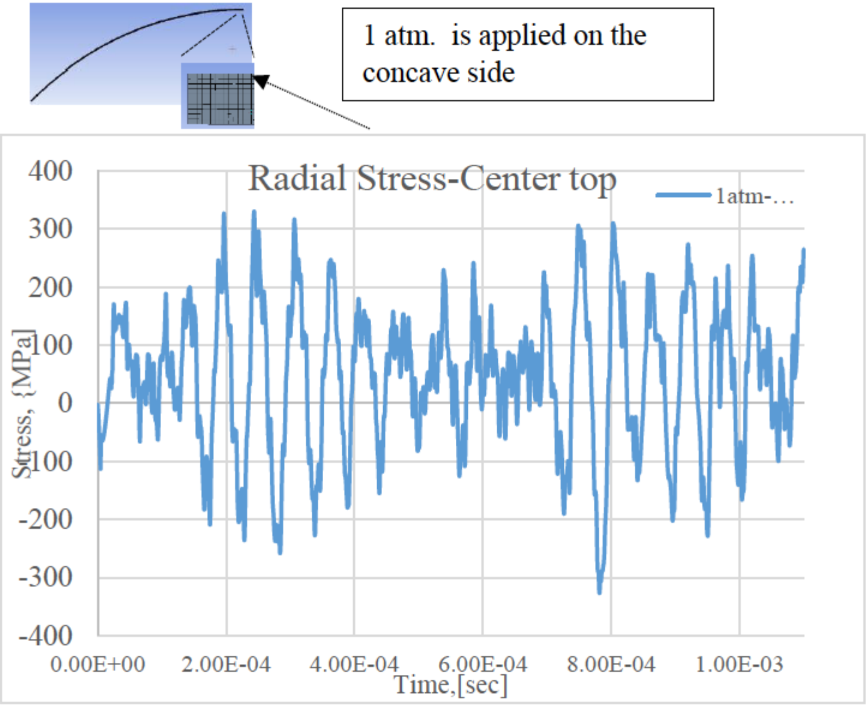
Radiation Damage In Accelerator Target Environments

At the Proton Accelerators for Science and Innovation Workshop (PASI 2012), workshop participants from a range of high power accelerator facilities identified ***radiation damage*** and ***thermal shock*** as the most cross-cutting challenges facing high power target facilities

Thermal Shock (Stress Waves)

Example: T2K beam window





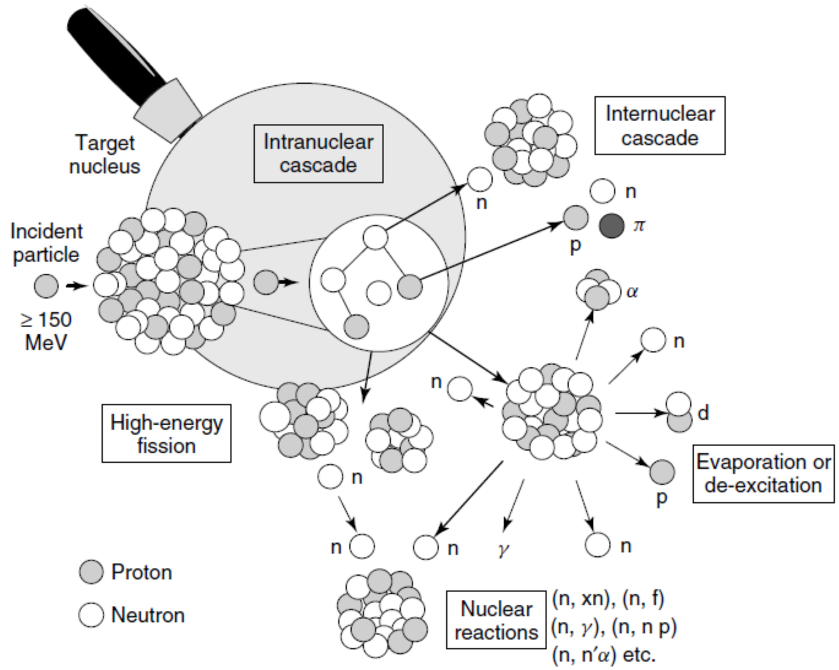
Material response dependent on:

- Specific heat (temperature jump)
- Coefficient of thermal expansion (induced strain)
- Modulus of elasticity (associated stress)
- Flow stress behavior (plastic deformation)
- Strength limits (yield, fatigue, fracture toughness)

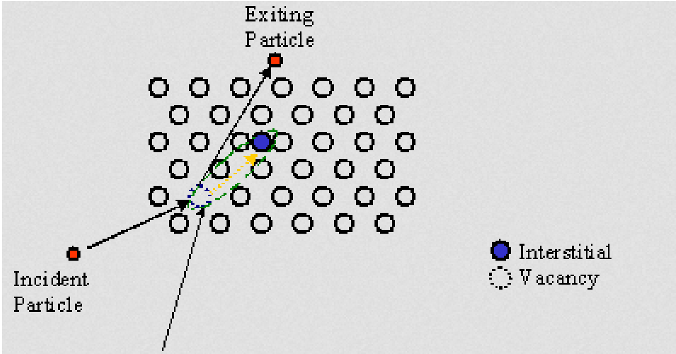
- Dynamic stress waves may result in plastic deformation, cracking, and fatigue

Heavy dependence on material properties, but:
material properties dependent upon Radiation Damage

Radiation Damage Disorders Microstructure



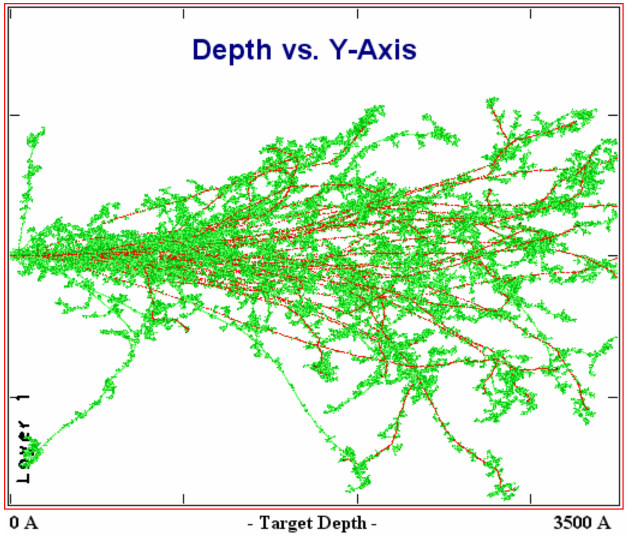
From D. Filges, F. Goldenbaum, in:, Handb. Spallation Res., Wiley-VCH Verlag GmbH & Co. KGaA, 2010, pp. 1–61.



A Frenkel pair consists of a vacancy and an interstitial atom.

Microstructural response:

- o Creation of transmutation products
- o Atomic displacements (cascades)
  - o Displacements Per Atom (DPA) = Average number of stable interstitial/vacancy pairs created



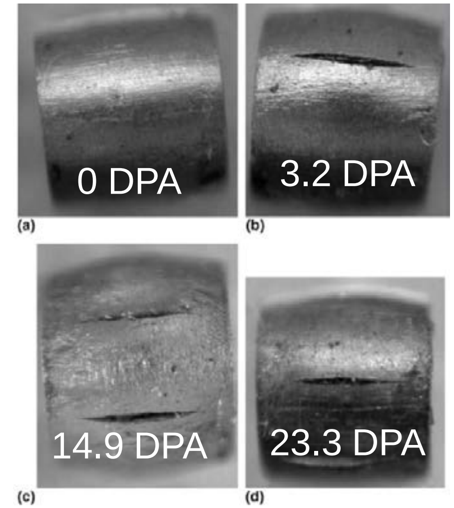
Radiation Damage Effects

Displacements in crystal lattice
(expressed as Displacement Per Atom, DPA)

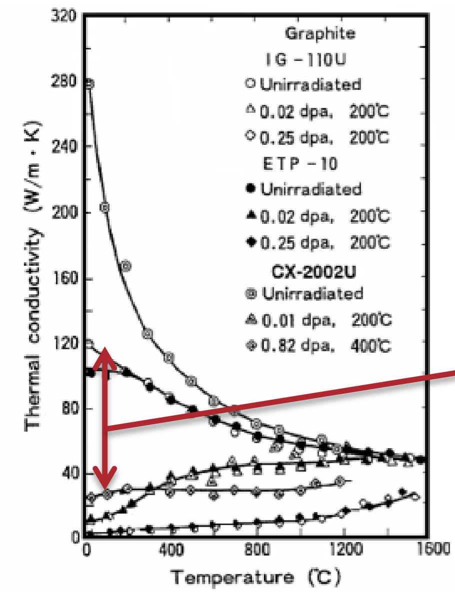
- o Embrittlement
- o Creep
- o Swelling
- o Fracture toughness reduction
- o Thermal/electrical conductivity reduction
- o Coefficient of thermal expansion
- o Modulus of Elasticity
- o Accelerated corrosion
- o Transmutation products
    - o He, H gas production can cause void formation and embrittlement (appm/DPA)

Very dependent upon material and irradiation conditions (eg. temperature, dose rate)

D.J. Porter and F.A. Garner, J. Nuclear Materials, 159, p. 114,1988



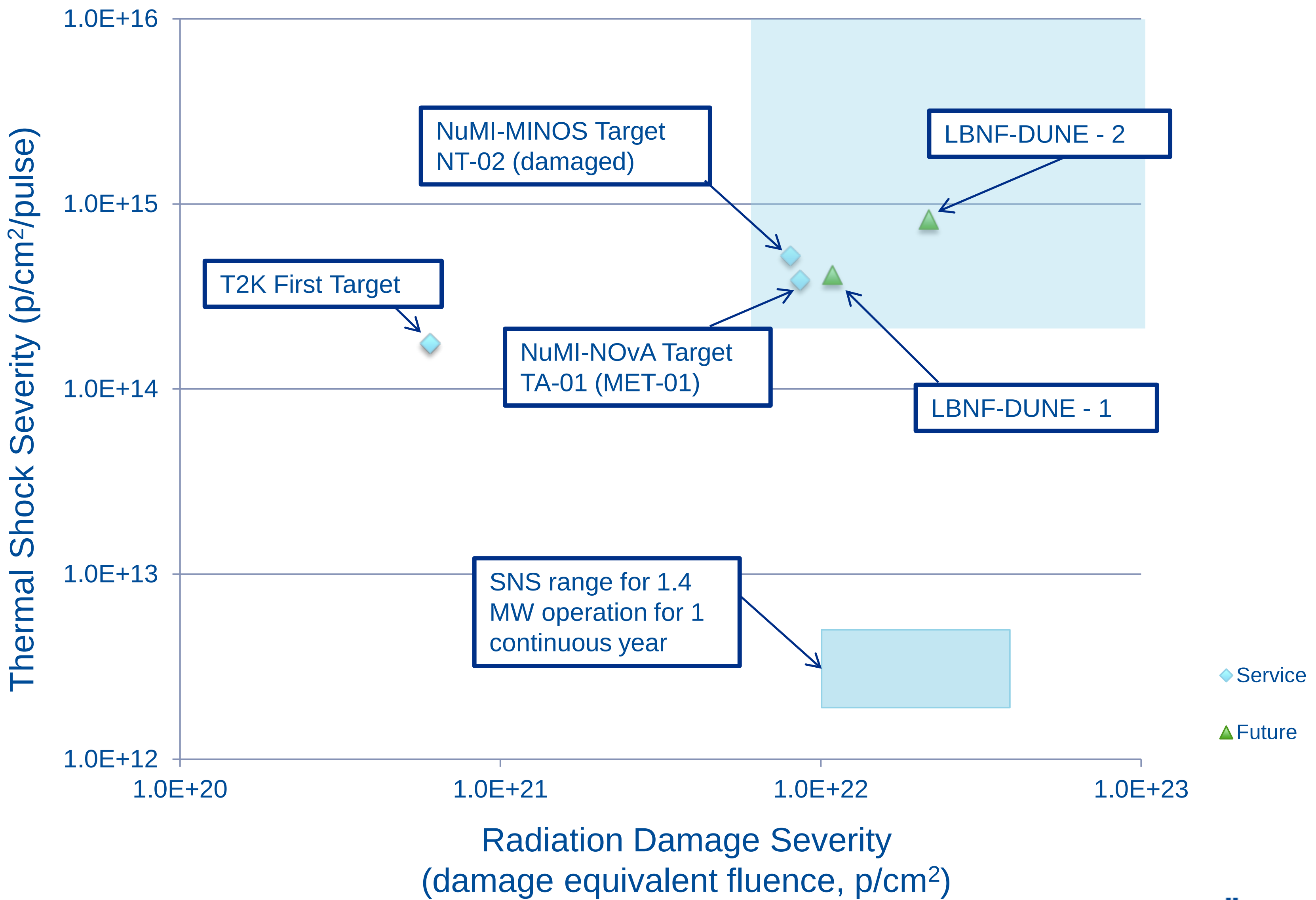
S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)



N. Maruyama and M. Harayama, “Neutron irradiation effect on … graphite materials,” Journal of Nuclear Materials, 195, 44-50 (1992)

Factor of 10 reduction in thermal conductivity at 0.02 DPA

Neutrino HPT R&D Materials Exploratory Map



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Radiation Damage In Accelerator Target Environments

radiate.fnal.gov

Broad aims are threefold:

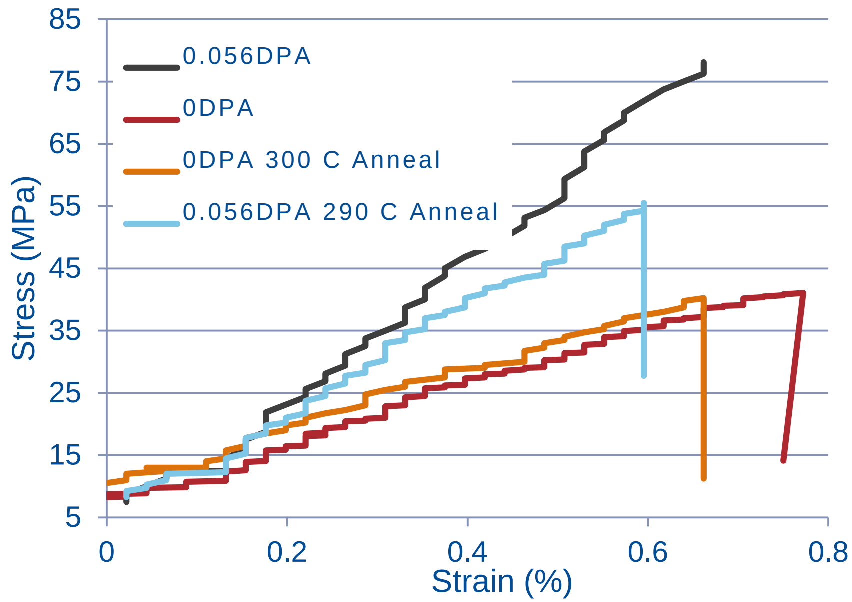
- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between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

Currently adding CERN and J-PARC to the MOU

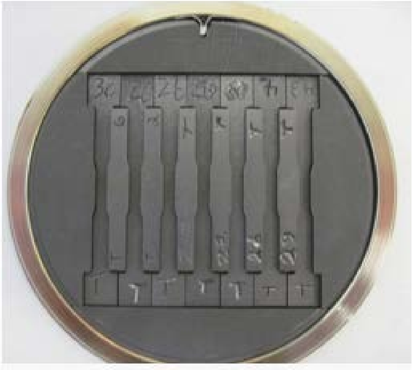
HE proton irradiations to explore candidate target/window materials

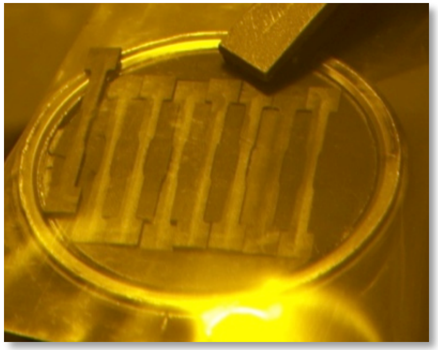
BNL BLIP Irradiation 1 (2010)

- **181 MeV** proton irradiation
- 4 graphite grades exposed to 6e20 p/cm^2
- Changes in material properties (30-50%)
- Annealing (> 150 °C) achieves partial recovery
- Confirmed choice of POCO ZXF-5Q (least change in critical properties)



- Irradiation at higher temperatures may be beneficial. However,
  - Diffusion assisted effects are increased (swelling from He bubble formation, creep)
  - Increased oxidation rate
  - Degraded thermal shock resistance





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HE proton irradiations to explore candidate target/window materials

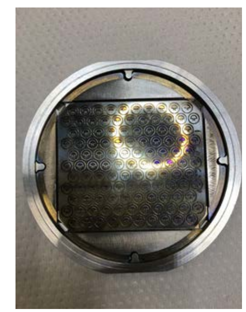
BNL BLIP Irradiation 2 (2017-2018)

- Phase 1 completed, Phase 2 to start in early 2018
- Total of 8-week irradiation
- Includes various grades of different materials:
  - Be & C (FNAL)
  - Ti & Si (FRIB, KEK, FNAL, U. of Oxford, STFC)
  - Al (ESS)
  - Ir, TZM, CuCrZr (CERN)
- Most PIE work will be performed at PNNL

Tensile & Microstructural specimens

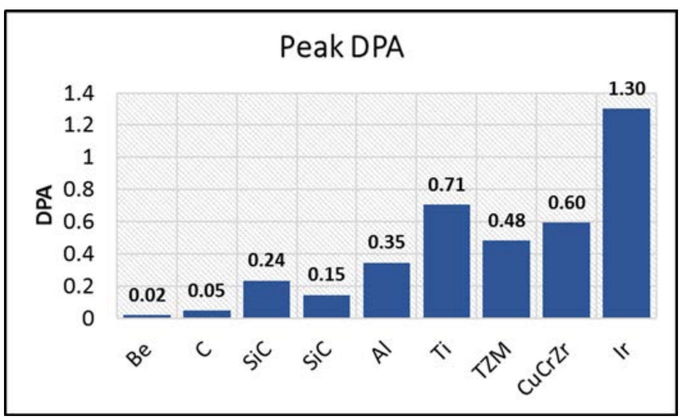
Bend specimens

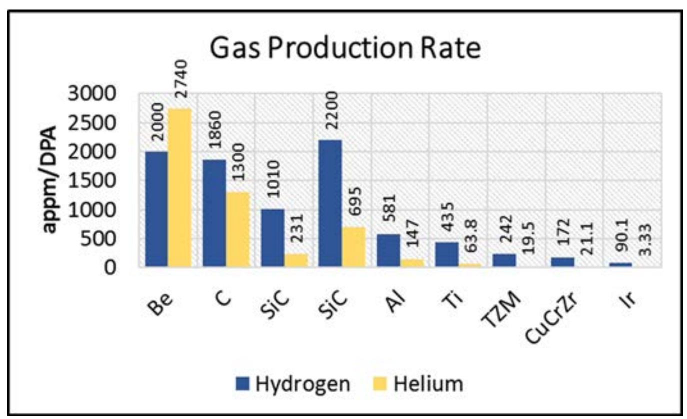
Fatigue specimens



Mesoscale fatigue specimens

HiRadMat specimens





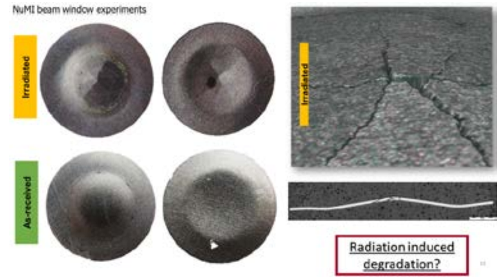
Examination of irradiated Be beam window indicates fracture toughness changes under irradiation

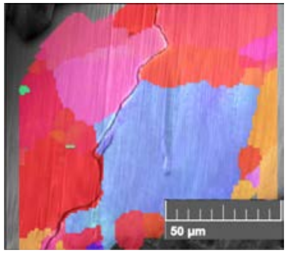
NuMI Be window (Kuksenko, Oxford)

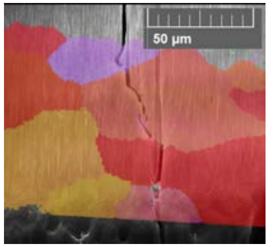
- PIE of Be window exposed to 1.57e21 protons
- Advanced microscopy techniques ongoing
- Li matches MARS predictions and remains homogeneously distributed at ~50 °C
- Crack morphology changes at higher dose
  - Transgranular to grain boundary fracture

Recent and future work with Be (2017)

- Micro-mechanical testing
  - Micro-cantilever
  - Nano-indentation
- Preliminary results indicate significant hardening and increase in effective elastic modulus

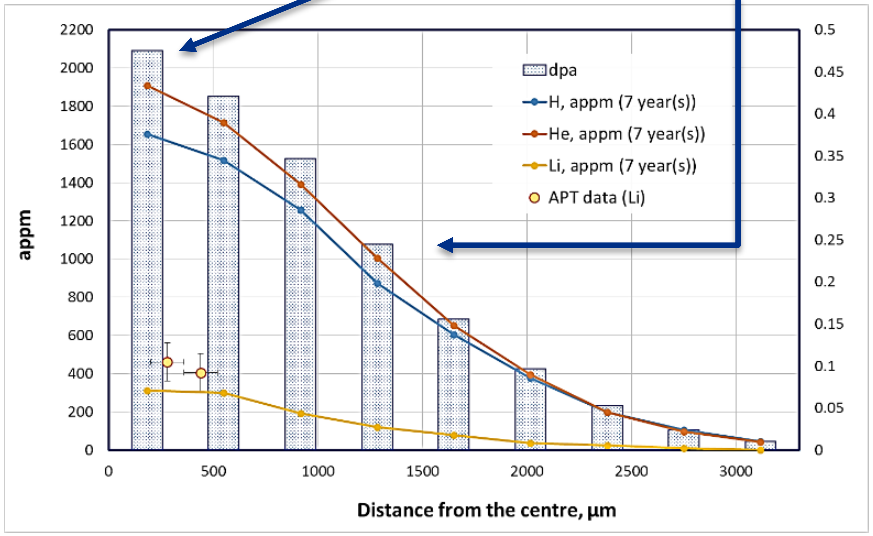


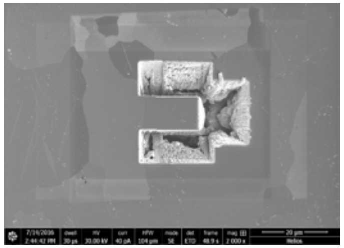


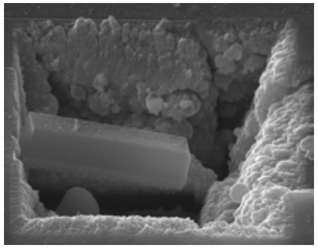


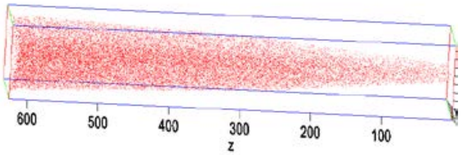
0.47 DPA

0.24 DPA







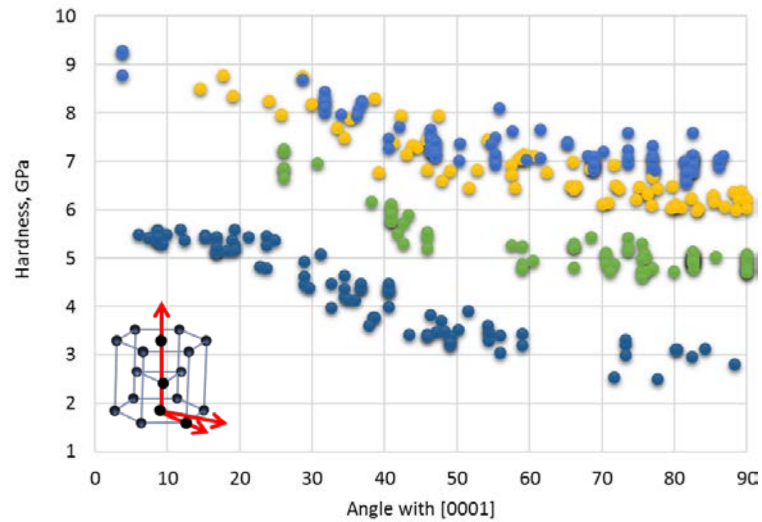


Ion implantation of Be indicates significant hardening at low DPA

He implantation at Surrey/Oxford

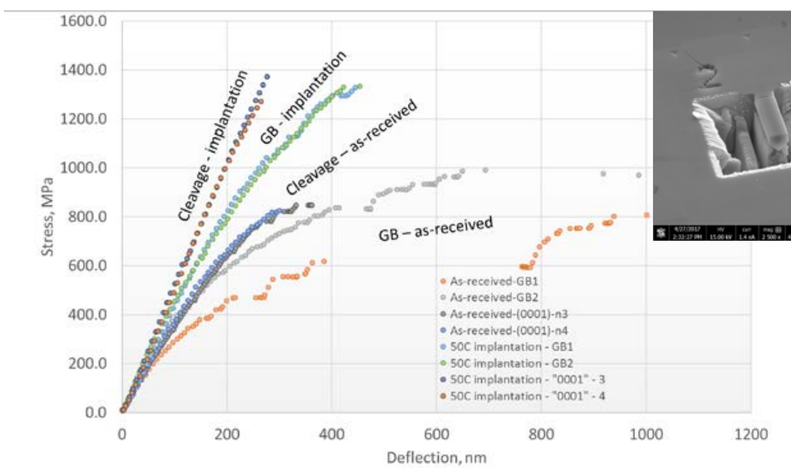
(Kuksenko, Oxford)

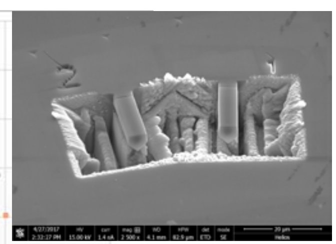
- 2 MeV He+ ions: 7.5 µm penetration depth
- Dose: up to 0.1 DPA
- Temperature: 50 °C and 200 °C
- Nano-indentation shows significant hardening at 0.1 DPA and 50 °C

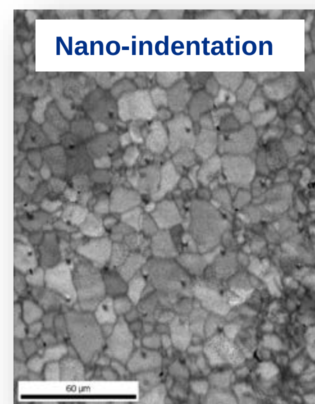


Future work with He in Be (2017-2018)

- Micro-cantilever testing
- Higher dose and temperature irradiations



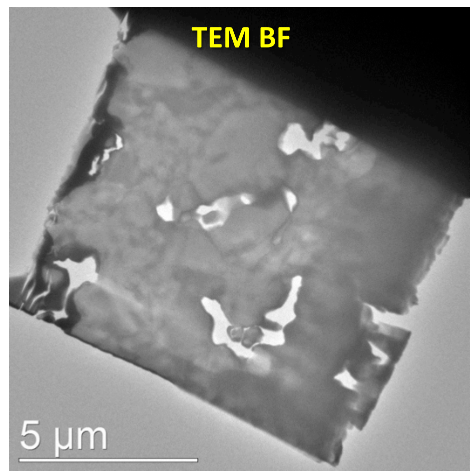


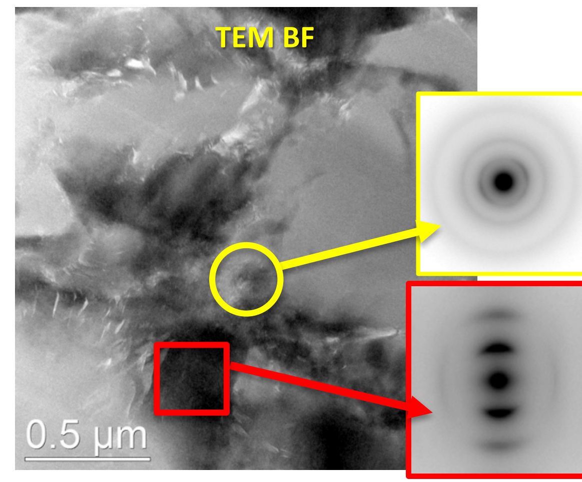


Radiation-induced swelling a possible cause of failure of NuMI NT-02 graphite target

NT-02 graphite target autopsy
(FNAL, PNNL)

- Graphite fin exposed to 8e21 p/cm^2
- **Evidence of bulk swelling from micrometer measurements of fins**
  - More swelling in US fin locations
  - More swelling in fractured fins
- **Evidence of fracture during operation**
  - Symmetric fracture structure
  - Limited impurity transport into whole fins relative to fractured fins
- **Evidence of limited radiation damage and material evolution**
  - Surface discoloration appears to be mostly solder and flux material
  - Crystal structure and porosity consistent with as-fabricated conditions





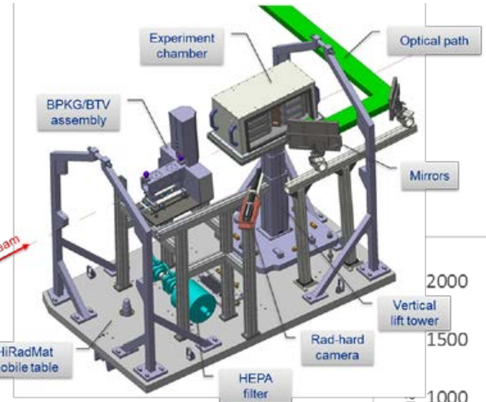
- Taken from fracture surface at the center where the beam was targeted
- Lamella has mixed regions of what appear to be amorphous (yellow insert diffraction pattern) and nanocrystalline microstructure (red square)
- Mrozowski cracks at the interfaces between these two regions

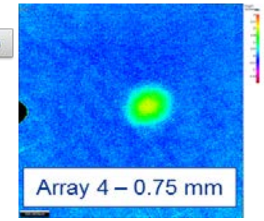
Dynamic thermo-mechanical simulations of Be validated by in-beam thermal shock experiments

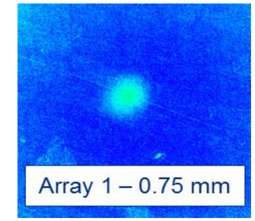
Thermal shock test at CERN’s HiRadMat

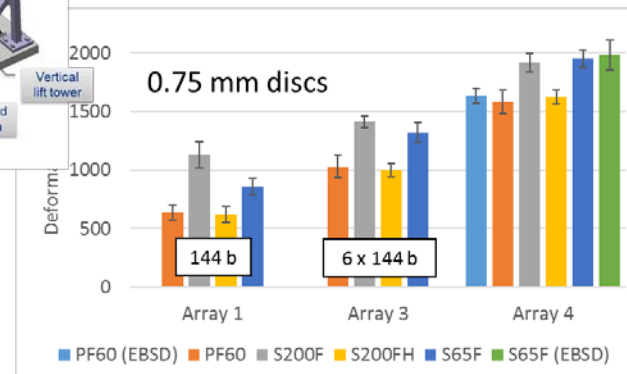
(FNAL, RAL, CERN, Oxford)

- All 4 Be grades showed less plastic deformation than predicted
- S200FH generally showed least plastic deformation
- Glassy carbon windows survived beam
- Multiple pulses showed diminishing ratcheting in plastic deformation
- Ongoing data analysis and validation of Johnson-Cook strength model validation - JC model recently developed at SwRI



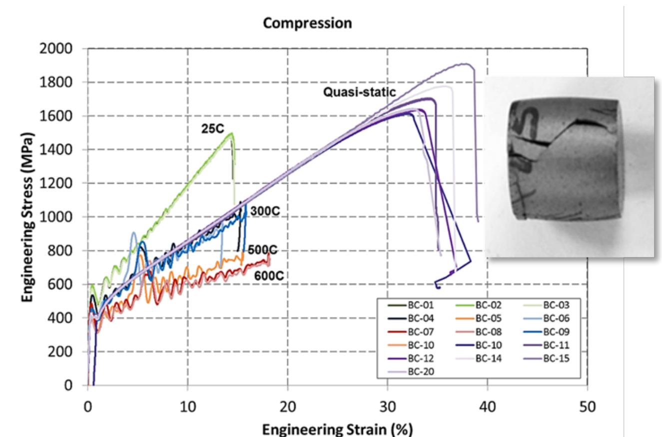






Future work (2018) at HiRadMat

- Thermal shock testing of proton-irradiated materials from BLIP
  - Beryllium, Graphite, Glassy Carbon, Titanium
- Testing of novel materials (nano-fiber mats)
- Test resonance effects on beam windows
- Higher proton beam intensity
- Development of JC damage model for Be



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Need for low energy irradiation studies to explore radiation damage effects at high doses

High energy, high fluence, large volume proton irradiations are expensive and time consuming

- Long irradiation beam times required to achieve high dose (months)
- PIE on highly activated specimens is challenging

Low energy, small volume ion irradiations are inexpensive and can achieve high DPA rate

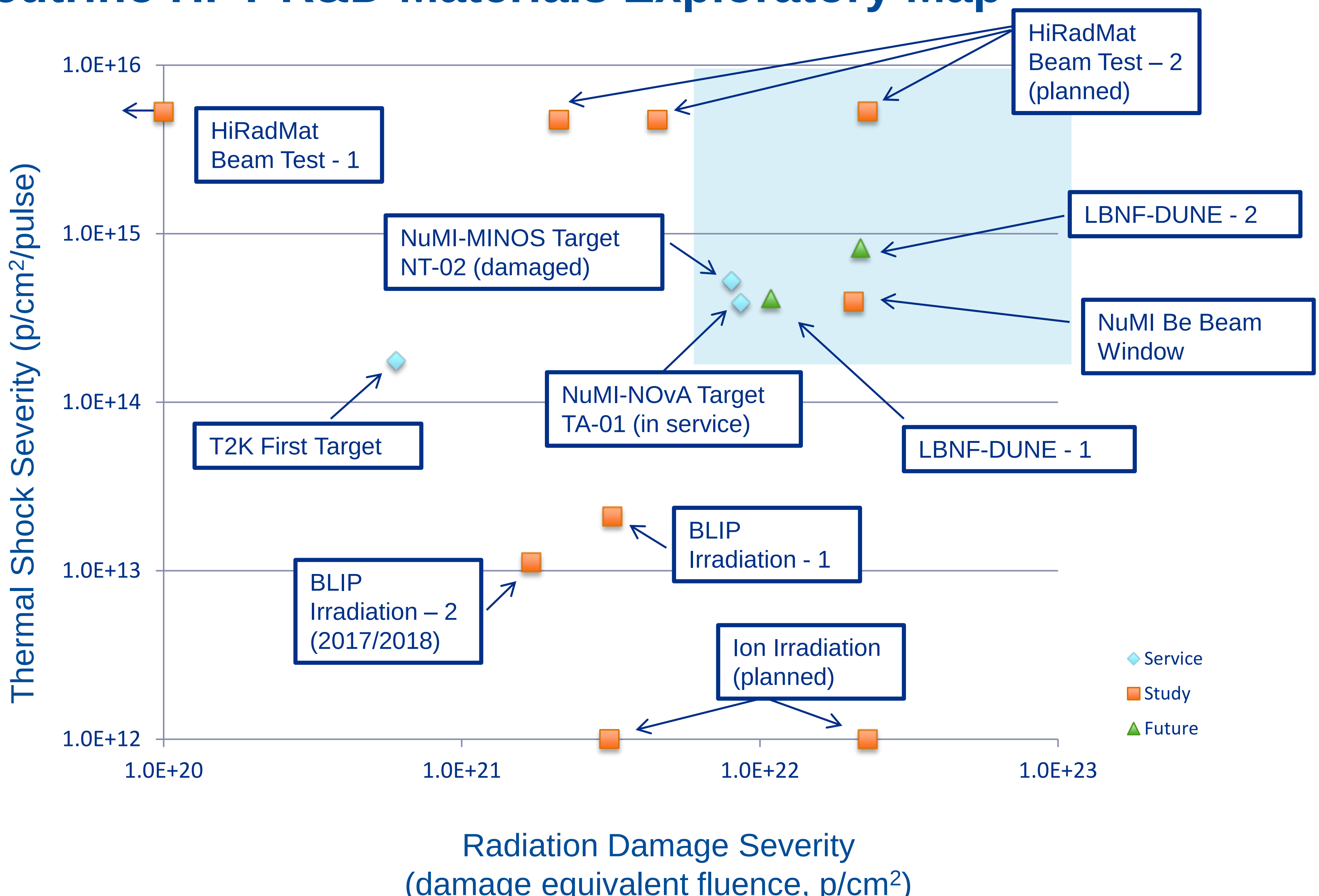
- Low to zero activation (PIE in ‘normal’ lab areas)
- Greatly accelerated damage rates (several DPAs in hours)
- **However**
  - Very shallow penetration depths (0.5 – 100 µm) and irradiation volume
  - Little gas production (transmutation) in specimens

Promising Solutions:

- **Micro-mechanics**: coupled with advanced microscopy techniques can enable evaluation of critical properties
- Simultaneous implantation of He and H ions (**triple-beam irradiation**) to mimic gas production

Still need HE proton irradiations to correlate and validate LE irradiation studies

Neutrino HPT R&D Materials Exploratory Map



Summary

- *Beam intercepting devices (targets, windows, collimators, absorbers/dumps) in high power accelerators require stable/safe operation under challenging conditions*
  - Current accelerator facilities limited in beam power due to target survivability issues
  - Future multi-MW accelerator upgrades/facilities pose even greater challenges

- *Beam intercepting devices will experience extreme operating conditions*
  - Increased rate of lattice displacements and transmutation gas production
  - Larger dynamic thermal stresses due to pulsed beam nature

- *R&D activities by the global accelerator targets community under the aegis of RaDIATE is on-going to help meet future challenges*
  - Material radiation damage studies with high-energy protons and low-energy ions
  - In-beam thermal shock tests to evaluate response of both non-irradiated and irradiated materials
    - Bring together both challenges of thermal shock and radiation damage into single experiments

Thank you for your attention

radiate.fnal.gov

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