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High Power Targets

Challenges for next-generation high-intensity neutrino beams

Kavin Ammigan

The 22nd International Workshop on Neutrinos from Accelerators (NuFact 2021)

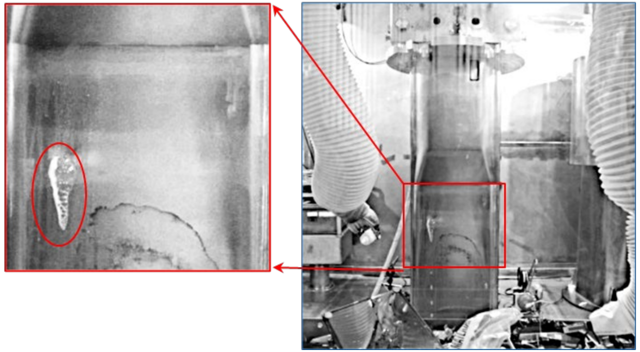
10 September 2021

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

MINOS NT-01 target (FNAL)



SNS target vessel (ORNL)

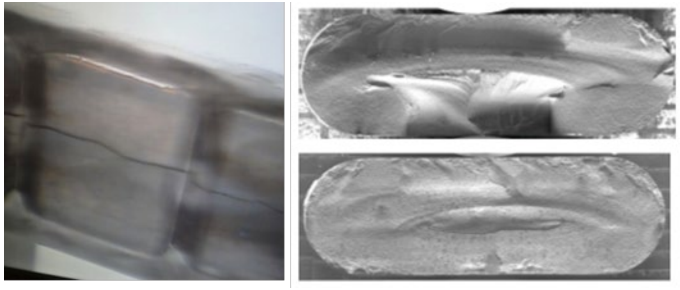
Next-generation multi-MW accelerator target facilities present even greater challenges

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

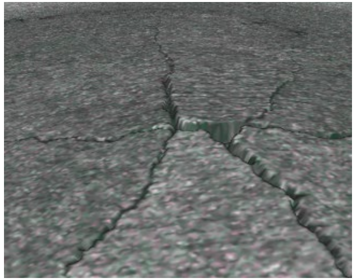
Target R&D essential to:

- Avoid compromising particle production efficiency by limiting beam parameters
- Maintain reliable operation and accurately predict component lifetime

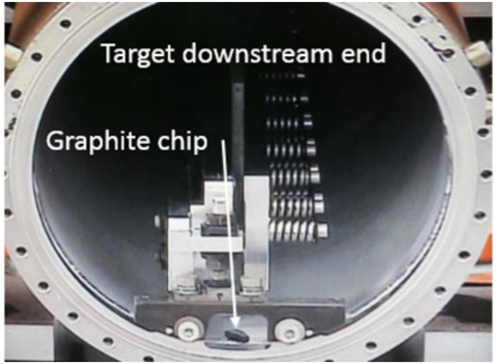
What we want to avoid…



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

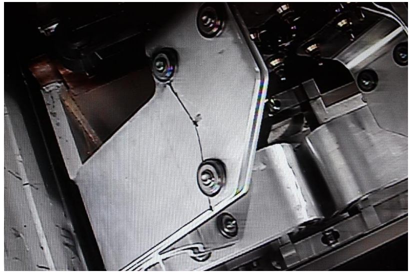


Be window embrittlement (FNAL)

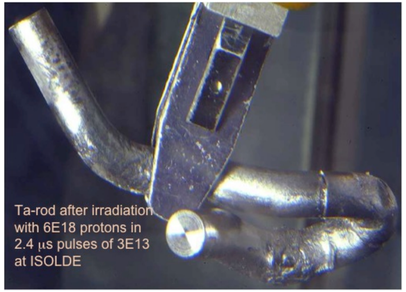


NOvA MET-01 target fin fracture (FNAL)

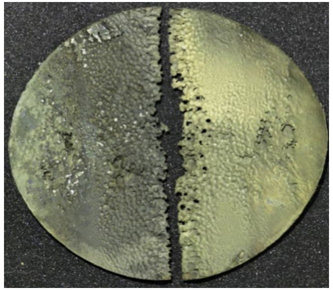
MINOS NT-01 target containment water leak (FNAL)



Horn stripline fatigue failure (FNAL)

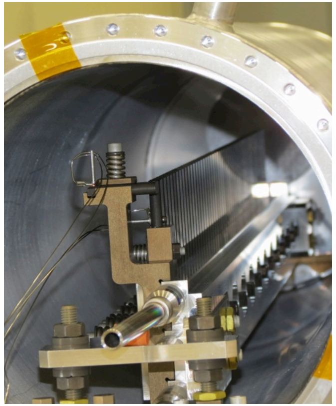


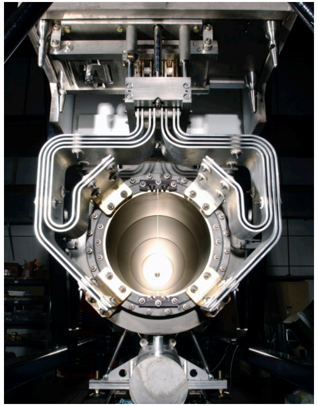
ISOLDE target (CERN)

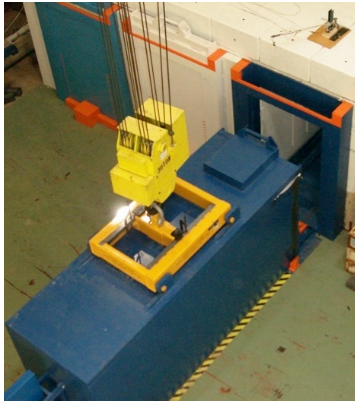


Target containment vessel cavitation (ORNL - SNS)

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

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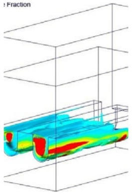
High Power/Intensity Targetry Challenges

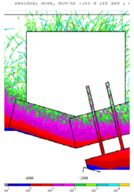


Heat removal

Thermal shock

Physics performance

Radiation damage



Operational safety

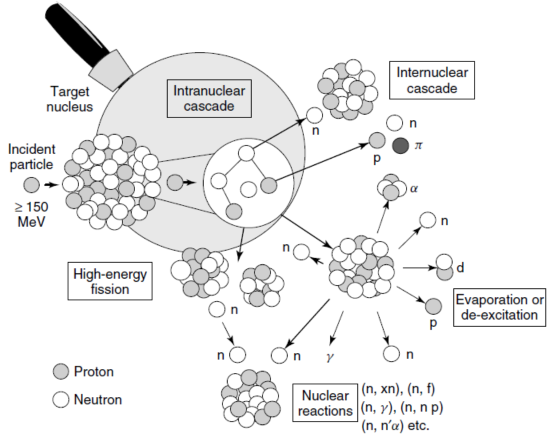
Storage and disposal

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

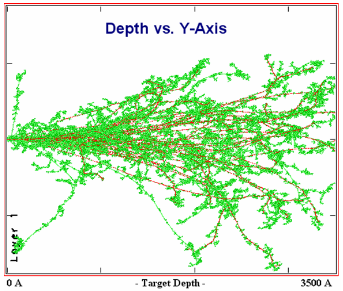
Radiation Damage in Materials

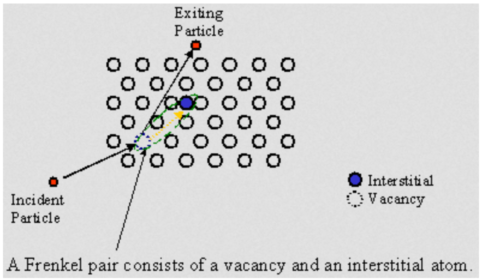


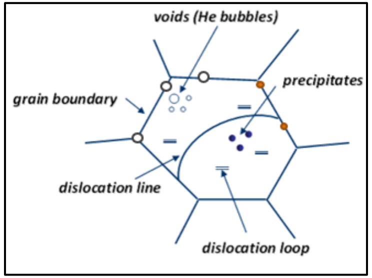
From D. Filges, F. Goldenbaum, in:, Handb. Spallation Res., Wiley-VCH Verlag GmbH & Co. KGaA, 2010, pp. 1–61.

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)



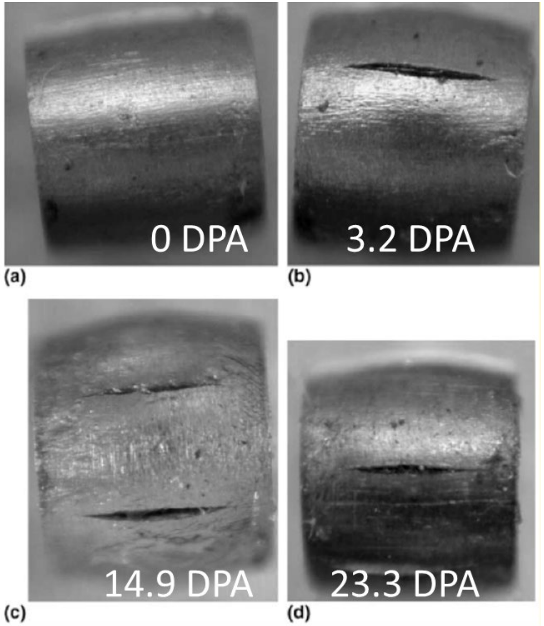




Radiation Damage Effects

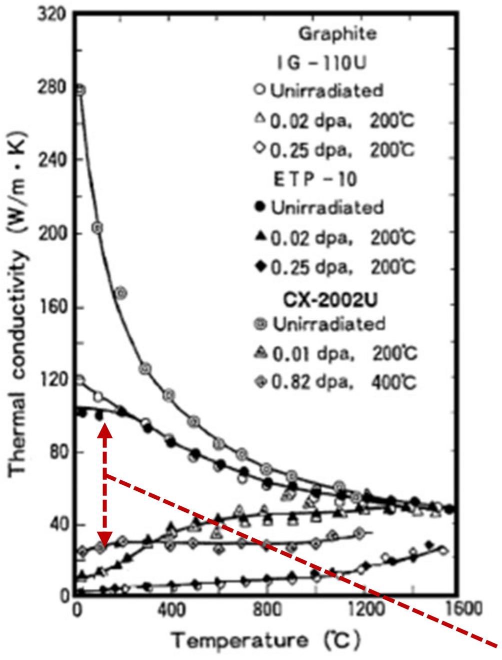
- Atomic displacements in crystal lattice (DPA) cause bulk property changes
  - Embrittlement
  - Creep
  - Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Coefficient of thermal expansion
  - Modulus of Elasticity
  - Accelerated corrosion
- Transmutation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

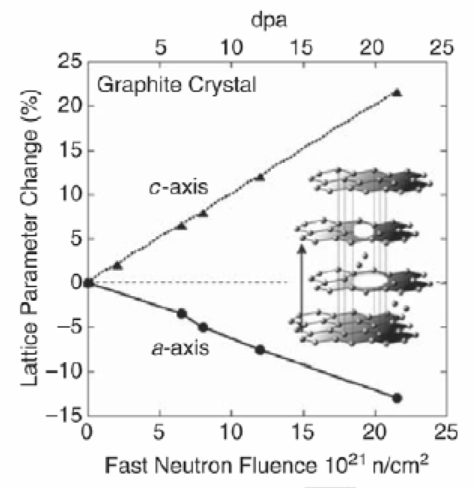
Radiation Damage Effects

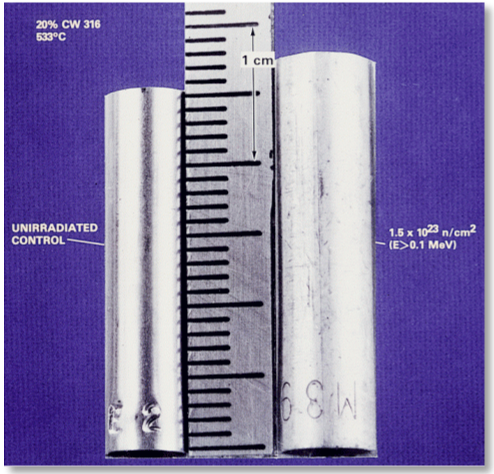


N. Maruyama and M. Harayama, Journal of Nuclear Materials, 195, 44-50 (1992)

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

Complex lattice swelling in graphite





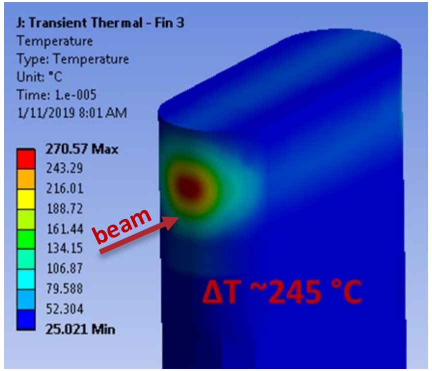
D.L. Porter and F. A. Garner, J. Nuclear Materials, **159**, p. 114 (1988)

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

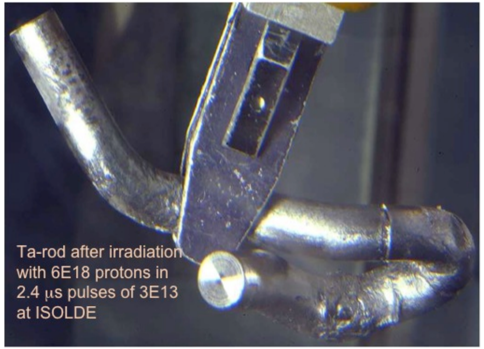
Thermal Shock Effects (stress waves)

- 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: ΔT~250 K in 10 μs (2.5 x 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 μs pulse in NuMI 1-MW graphite target (FNAL)

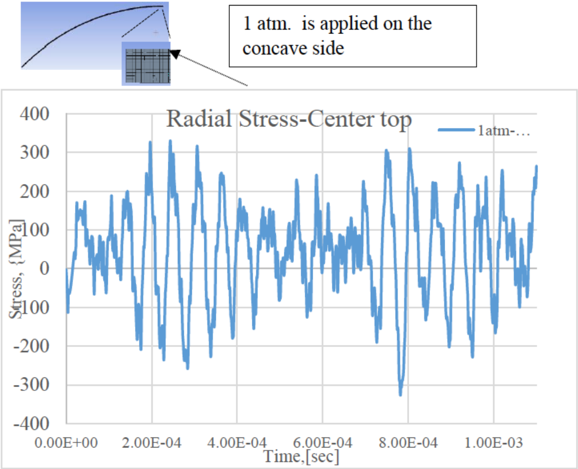


Ta-rod after irradiation with 6 x 10^{18} protons in 2.4 μs pulses of 3 x 10^{13} at ISOLDE (photo: J. Lettry)

Iridium target tested at CERN's HiRadMat facility

Stress Wave Example: T2K Window

T2K Titanium beam window



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)

$$\sigma = \sqrt{\rho E} \cdot \alpha \cdot L \cdot \frac{\Delta T}{\Delta t}$$

Initial stress wave amplitude

$$c = \sqrt{\frac{E}{\rho}}$$

Elastic wave speed

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

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Radiation Damage Data

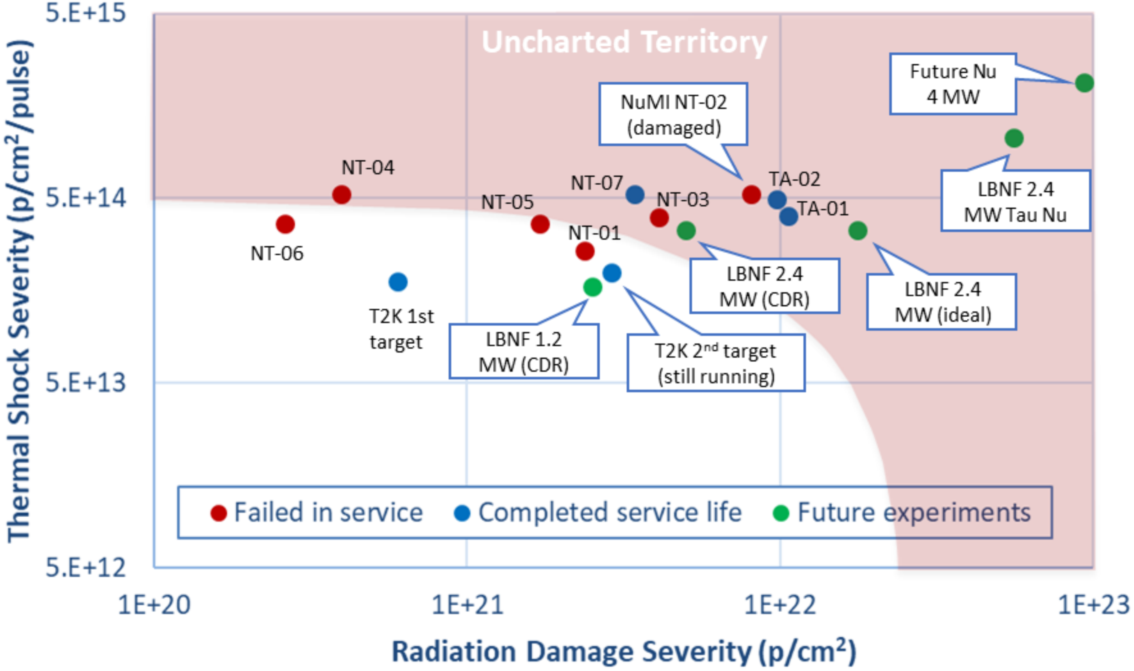
- Use of data from nuclear materials research is limited and cannot be directly utilized
- Effects from low-energy neutron irradiations do not equal effects from high-energy proton irradiations

$n \neq p$

1-14 MeV 100+ MeV

Irradiation Source	DPA rate (DPA/s)	He gas production (appm/DPA)	Irradiation Temp (˚C)
Mixed spectrum fission reactor	3×10^{-7}	1×10^{-1}	200-600
Fusion reactor	1×10^{-6}	1×10^{1}	400-1000
High energy proton beam	$\mathbf{6 \times 10^{-3}}$	$\mathbf{1 \times 10^{3}}$	**100-800**

Neutrino HPT R&D Materials Exploratory Map



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

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

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

radiate.fnal.gov

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)

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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

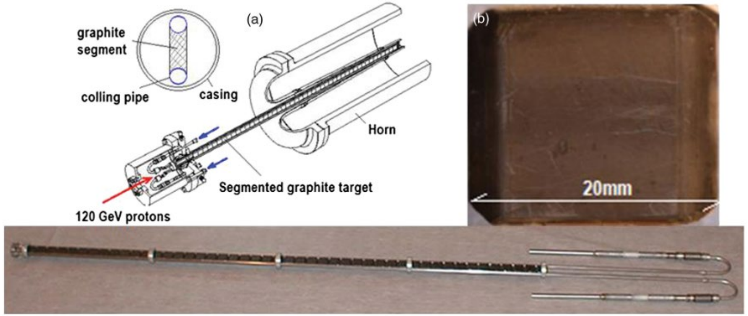
Benefits to multi-MW targets

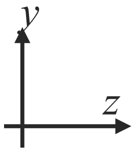
- Alloy/grade and heat treatment choice
- Identify novel candidate materials
- Cooling system design and operating temperature
- Tolerable beam intensities
- Expected lifetimes

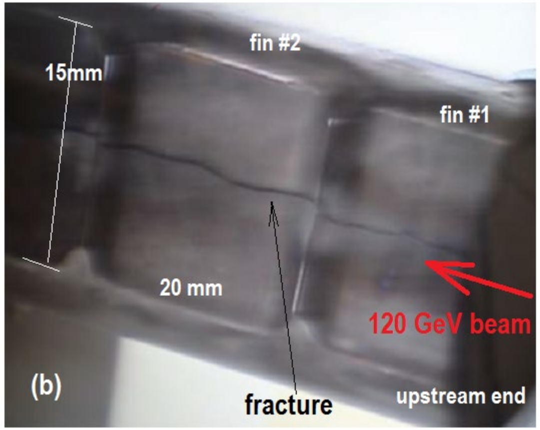
Analysis of Fractured NuMI Target Fin

NuMI target (NT-02) autopsy and examination

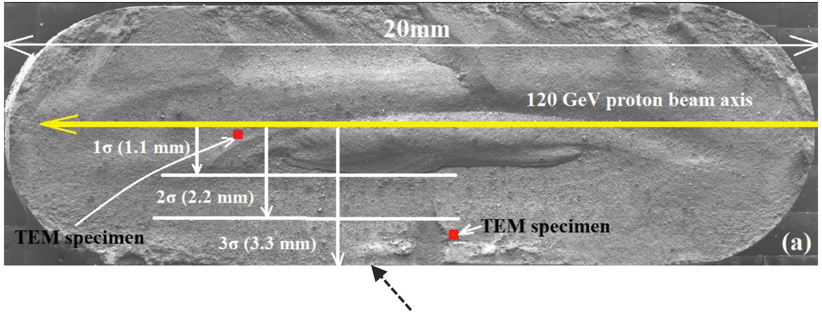
- Peak fluence: 8 x 10^{21} p/cm^2
- Beam energy: 120 GeV
- Spill duration: 10 μs, 4 x 10^{13} protons/pulse
- Duty cycle: 1.87 s
- Estimated peak DPA: 0.63







Detailed PIE at PNNL



Bulk swelling of ~4%

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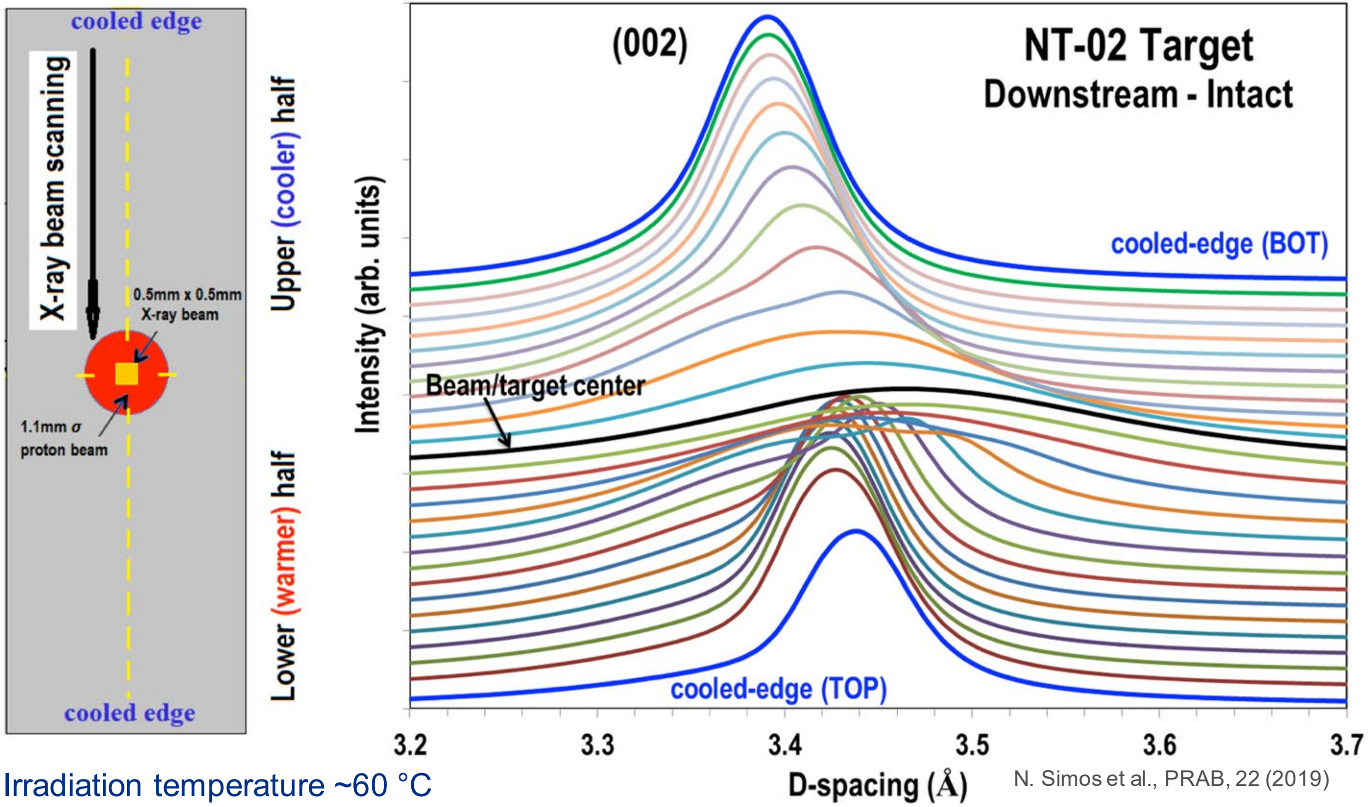
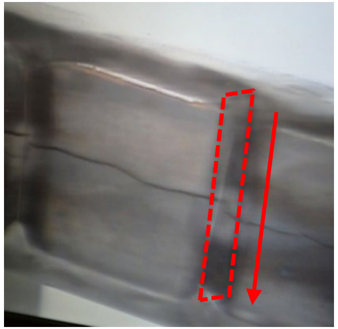
X-Ray Diffraction of NuMI Graphite Fin at NSLS-II



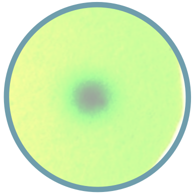
N. Simos et al., PRAB, 22 (2019)

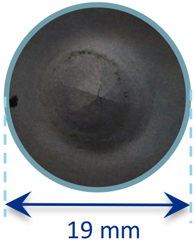


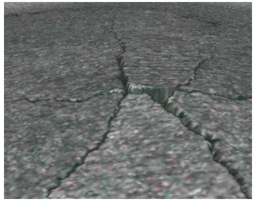
XRD shows lattice growth and amorphization at the beam center

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

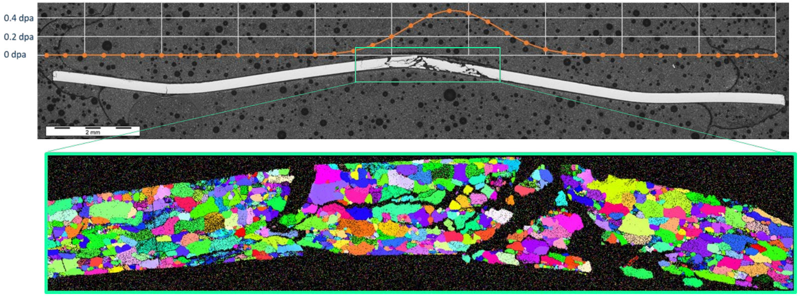
NuMI Beryllium Window Analysis

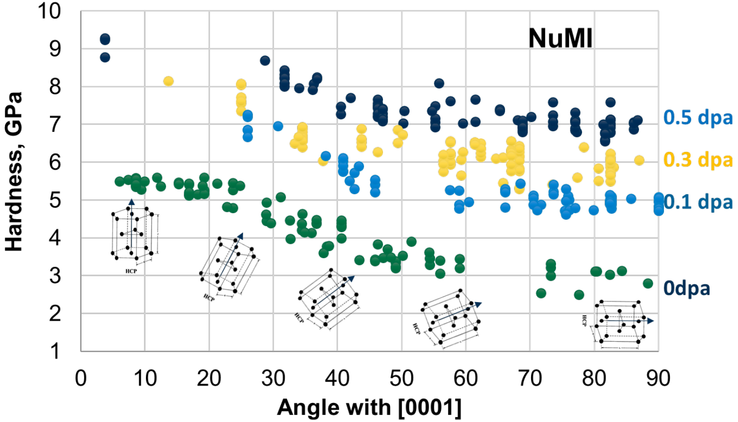






- 120 GeV proton beam
- 1.54×10^{21} POT (0.5 peak DPA)
- T ~ 50 °C





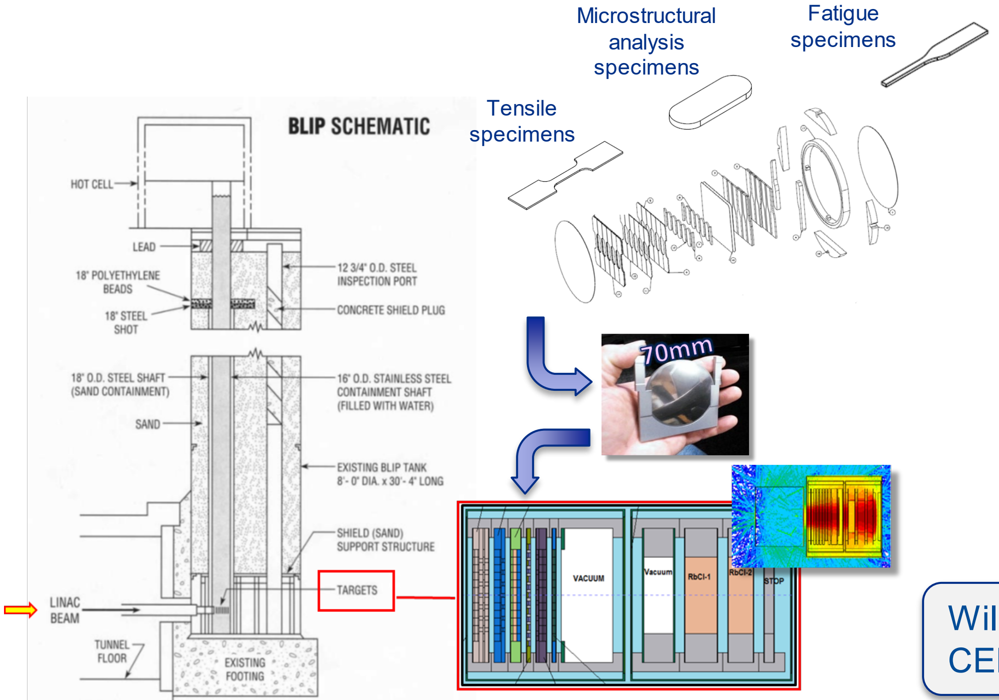
- Observed transition from transgranular fracture to grain boundary/mixed mode fracture in irradiated Be

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

V.Kuksenko et al. J. Nuclear Materials, 490, pp.260-271 (2017)

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



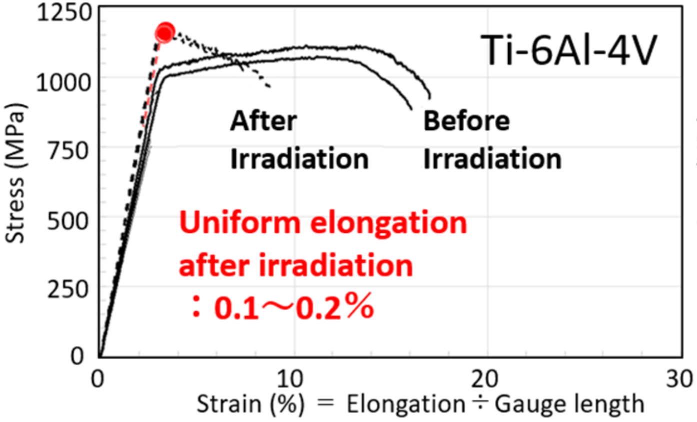
Material targets Isotope targets

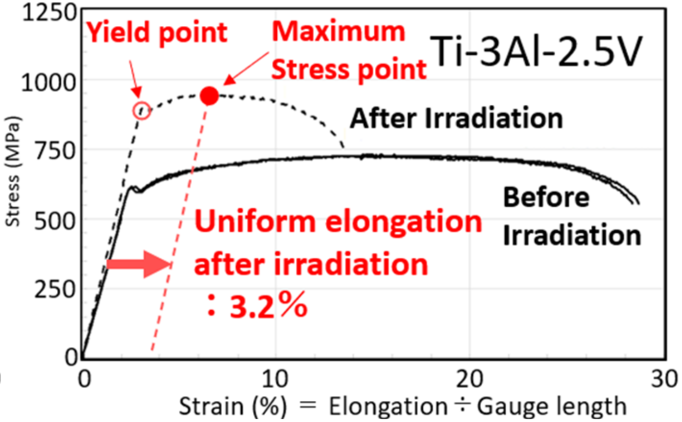
- RaDIATE multi-material irradiation campaign
- 181 MeV p irradiation for 8 weeks
  - Over 200 specimens from 6 RaDIATE collaborators
- Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, FNAL
- Completed irradiation in 2018
  - 4.5 x 10^{21} accumulated protons on target
  - Peak DPA: 0.95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

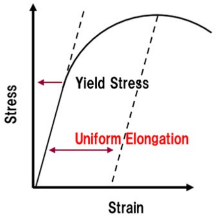
Will benefit many facilities including LBNF, T2K, BDF at CERN, FRIB, and HL-LHC collimators

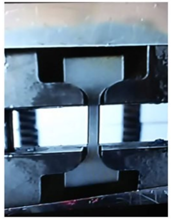
BLIP Ti Alloy Tensile Testing

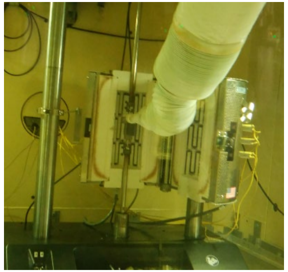
Stress-strain curves for Ti-6Al-4V (left) and Ti-3Al-2.5V (right)







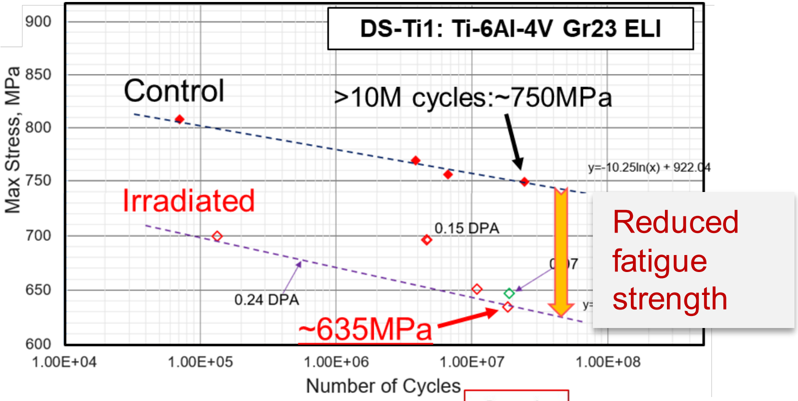


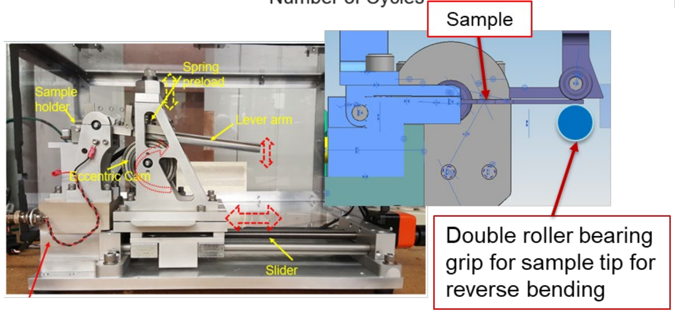


Testing done in hot cell

- 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

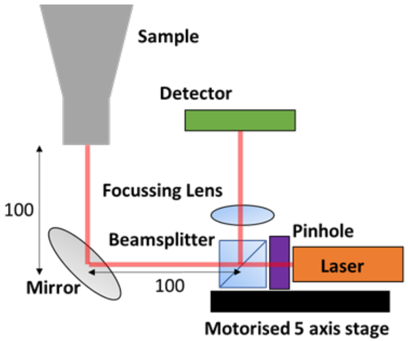
High-Cycle Fatigue Testing of Irradiated Ti Alloys



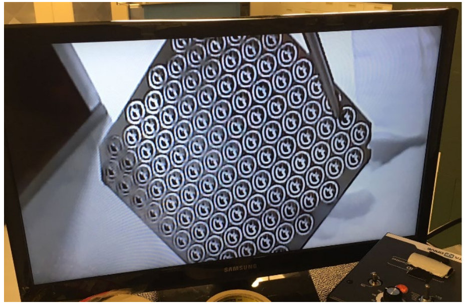


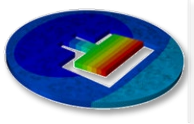
3rd Generation Fatigue Testing Machine (FTM) under development

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



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





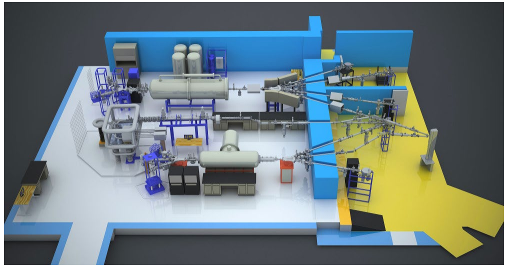
20 kHz = 10^8 cycles in 1.5 h

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

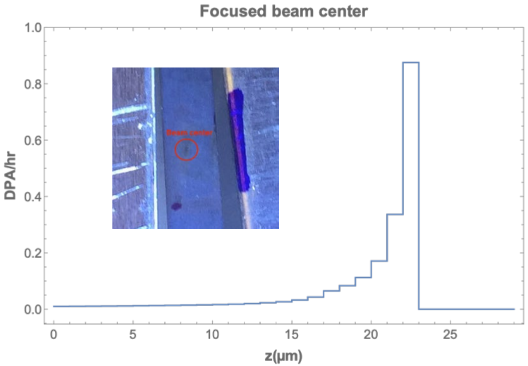
- High damage (DPA) accumulation in short time (without activation)
- Shallow damage depth (use of micro-mechanics and meso-scale testing)
- Dual/Triple beams irradiation needed to reproduce transmutation gas production



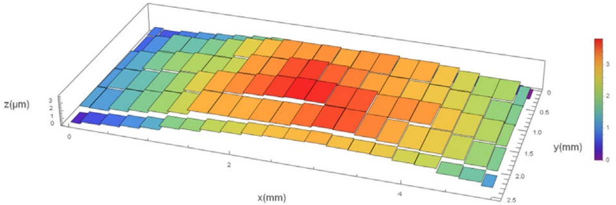
Michigan Ion Beam Laboratory

Graphite irradiation with 4.5 MeV He^{++} ions

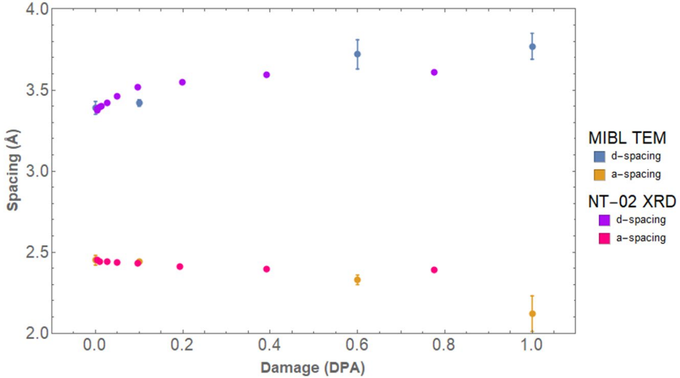
A. Burleigh and Prof. J. Terry (IIT)



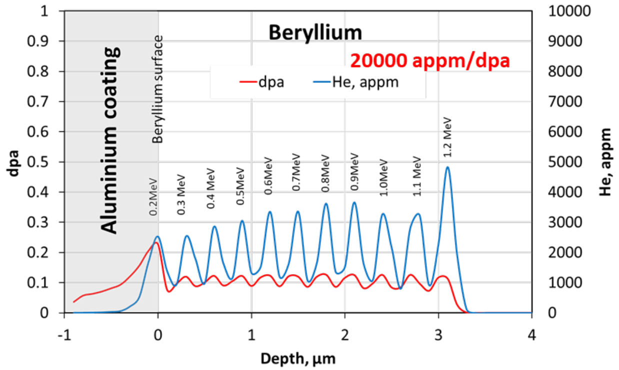
AFM measurements show bulk swelling of ~3.8 μm in the irradiated region



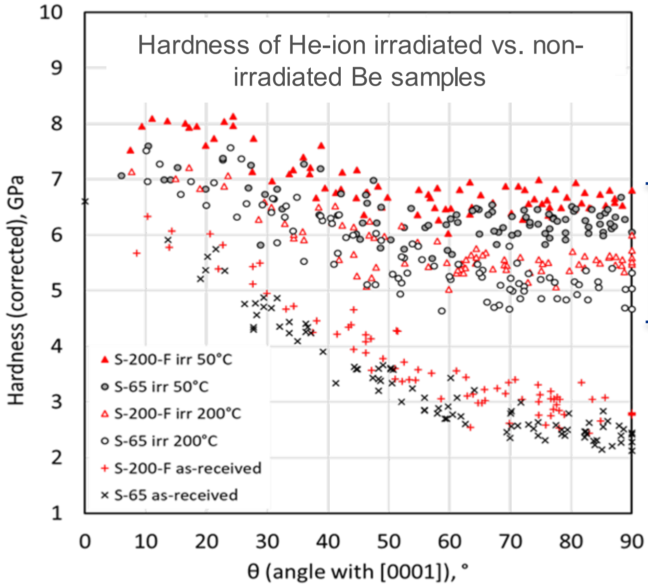
TEM: e- diffraction shows increase in d-spacing and decrease in a-spacing, similar to failed NT-02 target



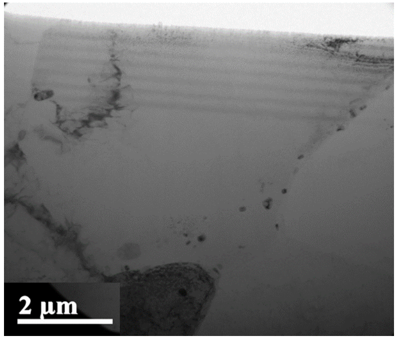
Helium Implantation in Beryllium



3 µm damage layer
T_{irrad}: 50 and 200 °C
0.1 DPA, 2000 appm He



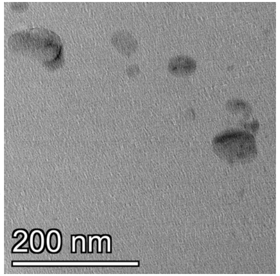
Irradiated



He implantation peaks

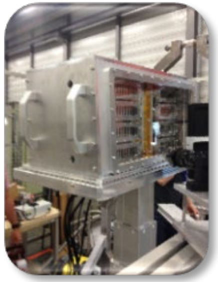
S. Kuksenko, RaDIATE Collaboration Meeting, 2019

- 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)



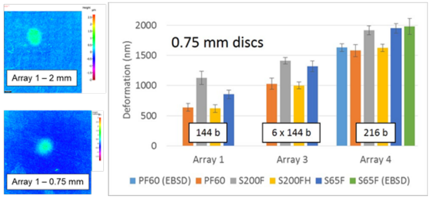
Thermal Shock Experiments at CERN's HiRadMat Facility

HRMT24 – BeGrid (2015)



- Observed distinctive thermal shock response for various beryllium grades
  - **2.8E13 ppp, σ: 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

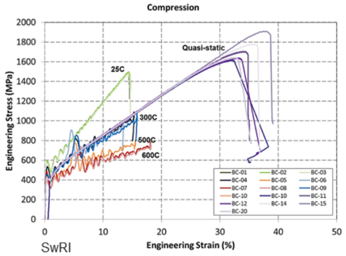


V. Kuksenko, Oxford

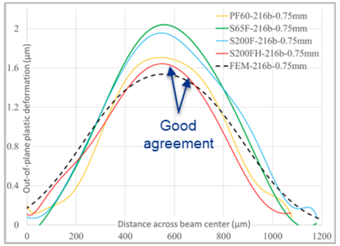
Confidence in modeling beam-induced thermomechanical response

Johnson-Cook model validation

$$\sigma_Y = \left[A + B(\varepsilon_{eff}^{p})^{n}\right][1 + C\ln\dot{\varepsilon}^{*}][1 - T_H^{m}]$$



SwRI

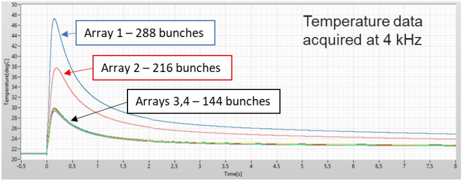


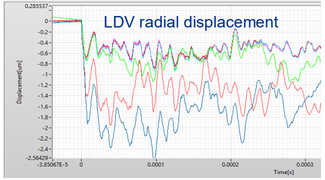
K. Ammigan et al., [Phys. Rev. Accel. Beams 22, 044501](#).

HRMT43 - BeGrid2 (2018)

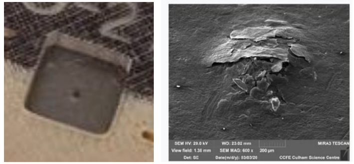
- First and unique test with pre-irradiated material specimens (Be, C, Ti, Si)
  - **3.5E13 ppp, σ: 0.27 x 0.22 mm**
- First test on nanofiber electro-spun fiber mats and metal foam (SiC, ZrO, Al_2O_3)
- Dynamic online measurements of graphite cylinders

Online measurements and benchmarking of graphite cylinders

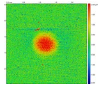




Sigraflex specimens



F. Nuiry, CERN

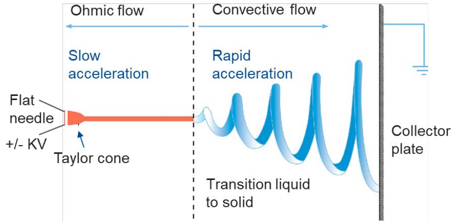


- Numerical simulation benchmarking in progress
- Profilometry and PIE work ongoing at UKAEA MRF, UK
- Damage observed in Sigraflex (LHC dump material) prompted further investigation

Novel Targetry Materials: Electrospun Nanofibers and HEAs

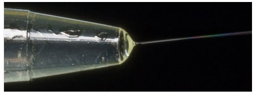
Nanofiber electro-spinning at Fermilab

- 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

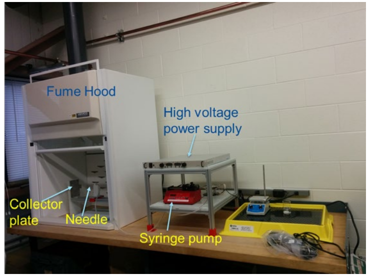


Electrostatically driven electrospinning process

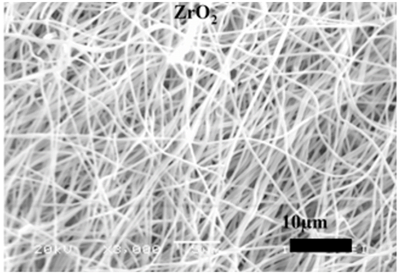
Taylor cone



Electro-spinning set-up at Fermilab

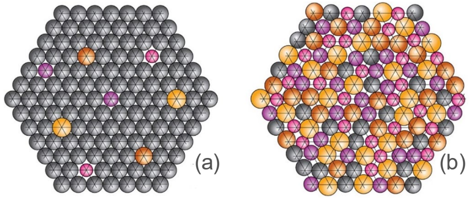


SEM image of Zirconia nanofibers

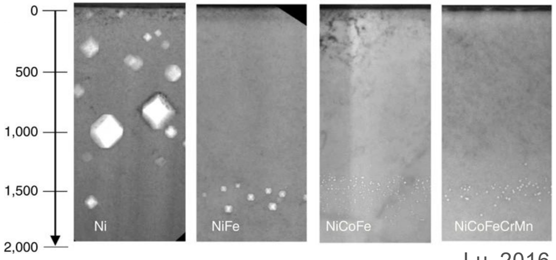


High-Entropy Alloy (HEA) development at UW-M

- Alloys consisting of 3 or more principal elements
- Excellent inherent properties including enhanced radiation damage resistance



(a) Conventional alloy, (b) High-entropy alloy
(Miracle & Senkov, 2016)



Lu, 2016

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

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

Summary

- 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