



Advanced Materials Studies for High Intensity Proton Production Targets and Windows

Frederique Pellemoine

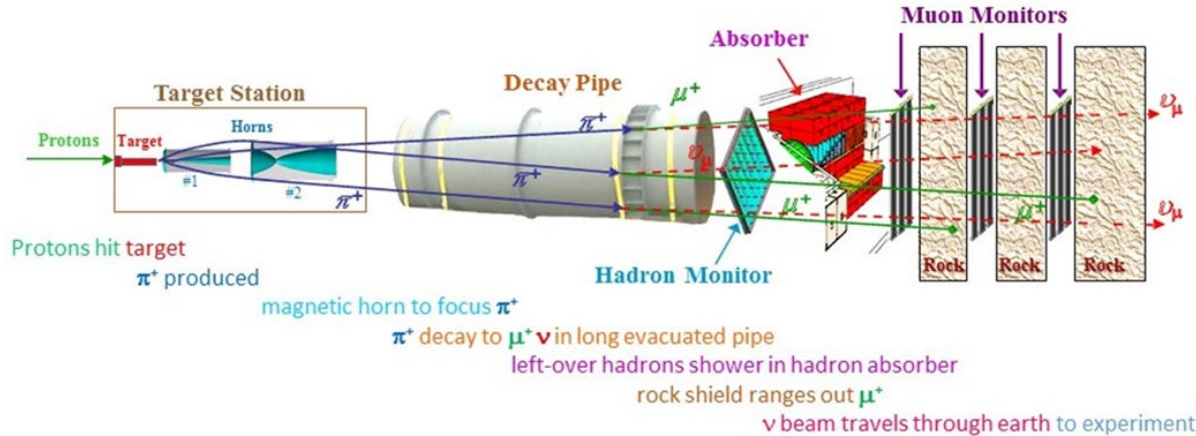
NuFACT 2022

August 4th , 2022

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

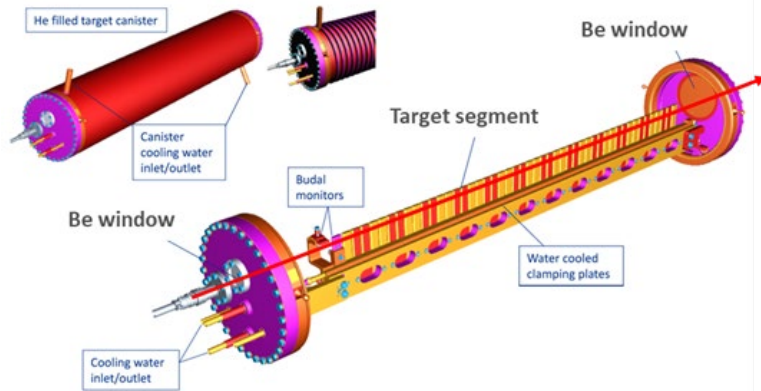
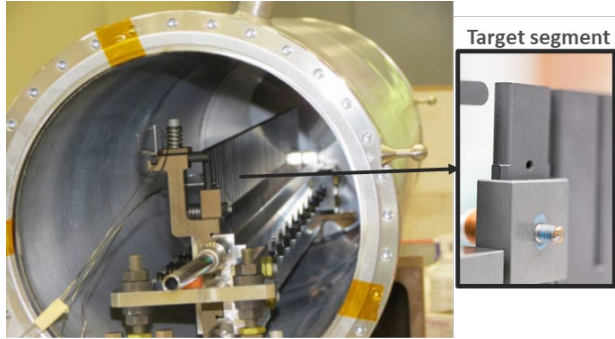
Neutrinos at the Main Injector (NuMI)



Target station able to operate with 1-MW proton beam since FY21

- 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.

Neutrino target – NOvA



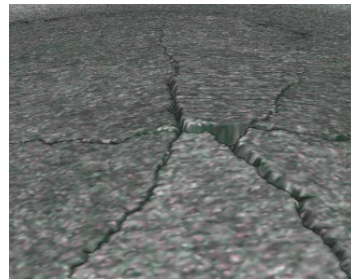
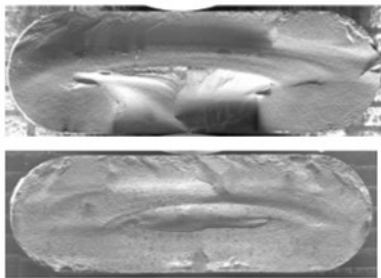
	NOvA	AIP
Graphite fins	50 x 24 mm x 7.4 mm	50 x 24 mm x 9 mm
Beam energy [GeV]	120	120
p/pulse	4.90E+13	6.50E+13
Power [kW]	700	1000
σ [mm]	1.3	1.5
Peak Temp. [°C]	670	1000
QS Temp [°C]	390	890
POT	1.10E+21	1.28E+21
Peak dpa	1.10	0.96
Peak He [appm]	5580	3600

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

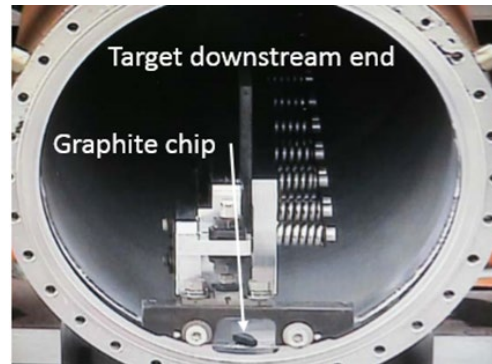
What we want to avoid...



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



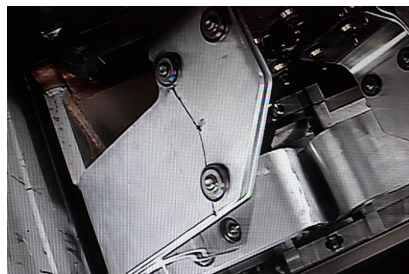
Be window embrittlement (FNAL)



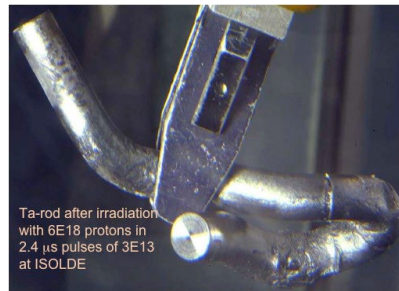
NOvA MET-01 target fin fracture (FNAL)



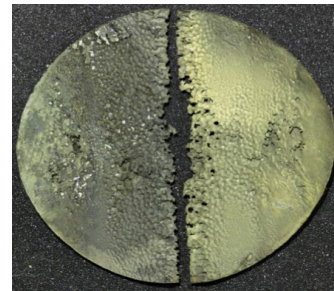
MINOS NT-01 target containment water leak (FNAL)



Horn stripline fatigue failure (FNAL)



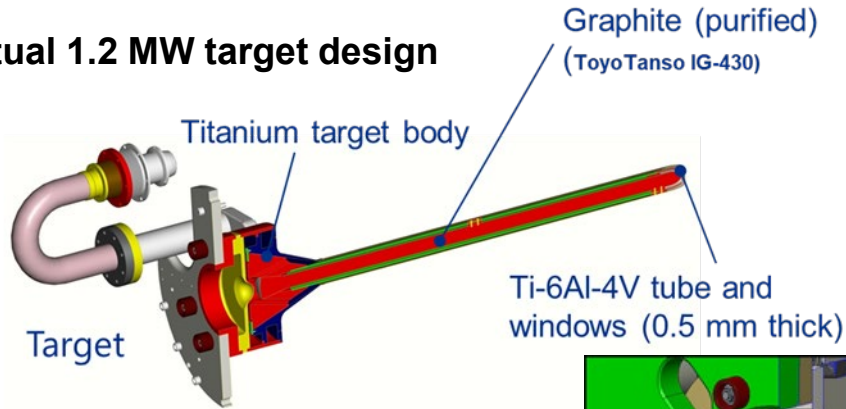
ISOLDE target (CERN)



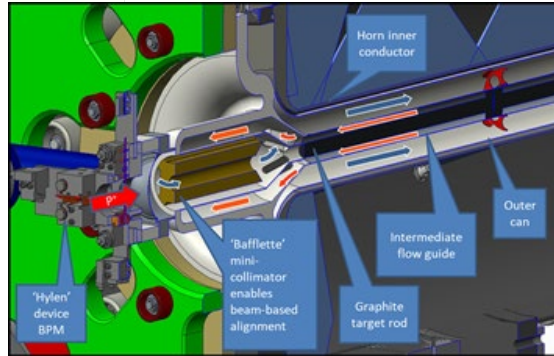
Target containment vessel cavitation (ORNL - SNS)

Future Neutrino Target – LBNF-DUNE (1.2 – 2.4 MW)

Conceptual 1.2 MW target design



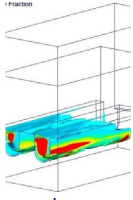
- Helium atmosphere
- Titanium target containment windows
- Helium gas cooled graphite core



DUNE	
Graphite fins	TBD
Beam energy [GeV]	60-120
p/pulse	7.50E+13
Power [kW]	1200-2400
σ [mm]	2.67
Peak Temp. [°C]	TBD
QS Temp [°C]	TBD
POT	2.54E+21
Peak dpa	0.73
Peak He [appm]	400

2.4 MW target will require significant R&D to guide design and material choice

High Power Targetry Challenges



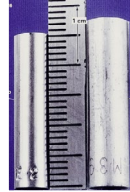
Heat removal



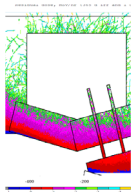
Thermal shock



Physics performance



Radiation damage



Operational safety



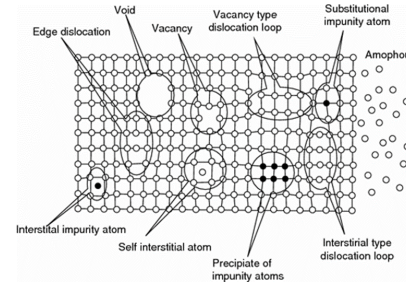
Storage and disposal

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)

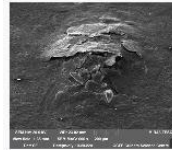
- Hardening and embrittlement
- Creep and swelling
- Fracture toughness reduction
- Thermal/electrical conductivity reduction
- Coefficient of thermal expansion
- Modulus of elasticity
- Transmutation products (H, He gas production can cause void formation and embrittlement)



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

Thermal Shock: Sudden energy deposition from pulsed beam

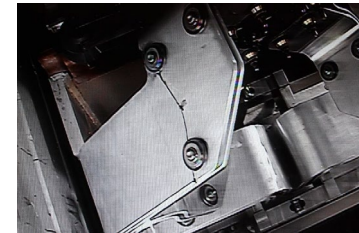
- Fast expansion of the material surrounded by cooler material generates localized area of compressive stress
 - 1 MW target: ~ 250 K in $10 \mu\text{s}$ pulse (2.5×10^7 K/s)
- Stress waves move through the material at sonic velocities
- Plastic deformation, cracking and fatigue failure can occur



Iridium (left) and Sigraflex (right) targets tested at CERN's HiRadMat facility

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



Horn stripline fatigue failure (FNAL)

Radiation Damage in Accelerators

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	6×10^{-3}	1×10^3	100-800

- 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

$n \neq p$
1-14 MeV 100+ MeV

DPA experiment at FTBF



- Beam window damage is evaluated with Displacement Per Atom

$$\text{DPA} = \sigma_d \phi$$

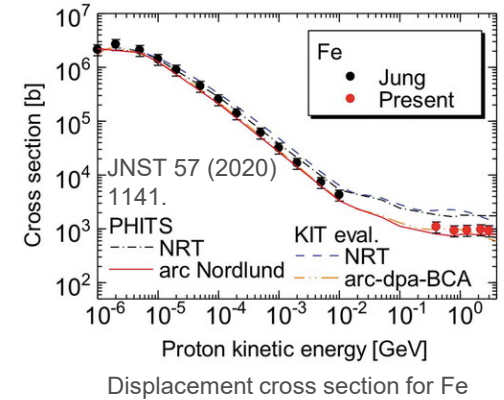
σ_d : displacement cross-section (m^2)
 ϕ : irradiation fluence (particles/ m^2)

- 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.

$$\sigma_{\text{exp}} = \frac{1}{\rho_{\text{FP}}} \left[\frac{\Delta \rho_{\text{metal}}}{\phi} \right]$$

$\Delta \rho_{\text{metal}}$: Electrical resistivity change (Ωm)
 ϕ : Average Beam fluence ($1/\text{m}^2$)
 ρ_{FP} : Frenkel-pair resistivity (Ωm)

- The device and data taking system have been developed at J-PARC.
- The experiment at FTBF will be scheduled in **Jan. 2023**.



Sample assembly
Al, Cu, Nb, W wires



Irradiation chamber
with cryo cooler

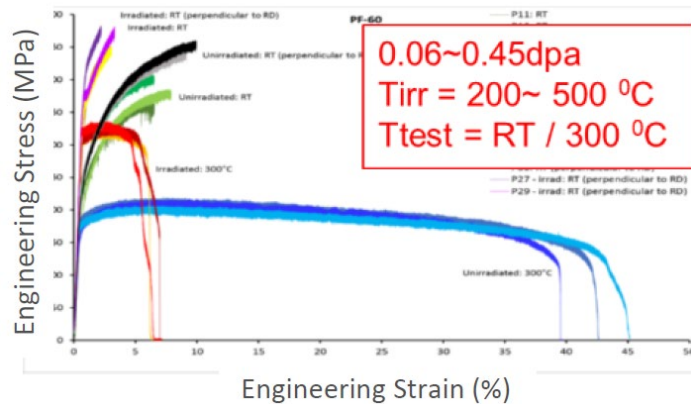
Research Approach - Prototypic irradiation to closely replicate material behavior in accelerator target facilities



- **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

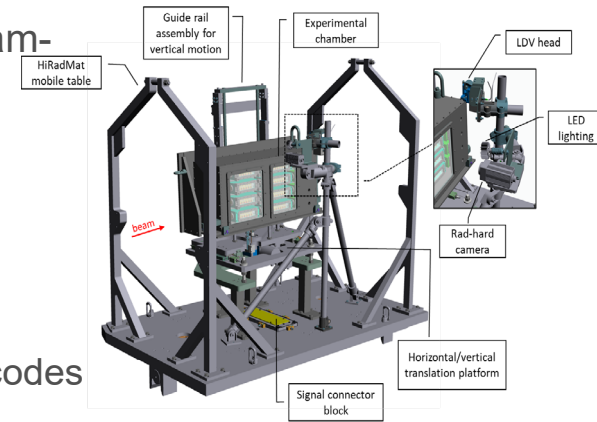
PIE of Proton-Irradiated Beryllium at PNNL

- 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



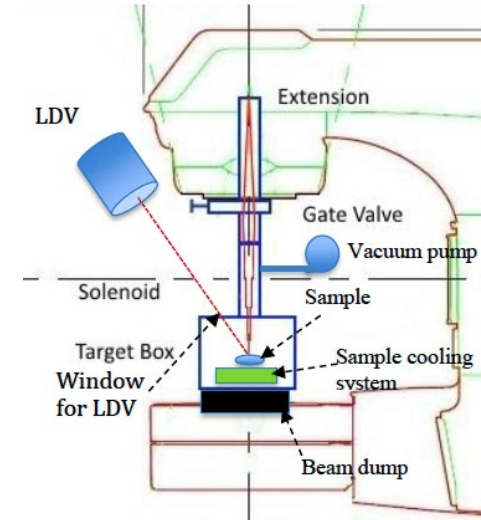
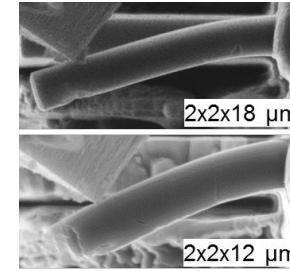
Thermal Shock Experiments at CERN's HiRadMat Facility

- User facility at CERN, designed to provide high-intensity pulsed beam to test materials and accelerator components
 - 440 GeV, $\sigma_r = 0.25 \sim 4$ mm (rms)
 - Up to 3.46×10^{13} ppp in 7.95 μ s
- **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

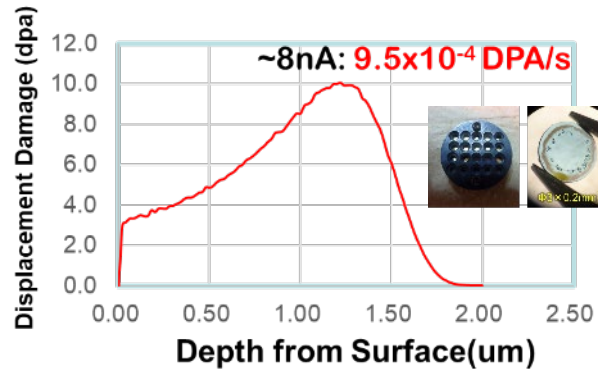
- High energy proton irradiation
 - Highly activated material \Rightarrow need hot cells and specific characterization equipment
 - High energy \Rightarrow Low dpa rate \Rightarrow long irradiation time (order of months) \Rightarrow Expensive
- Alternative radiation damage method
 - Low-energy ion irradiation
 - 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 \Rightarrow 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 Fe²⁺ ion beam irradiation at HIT Facility



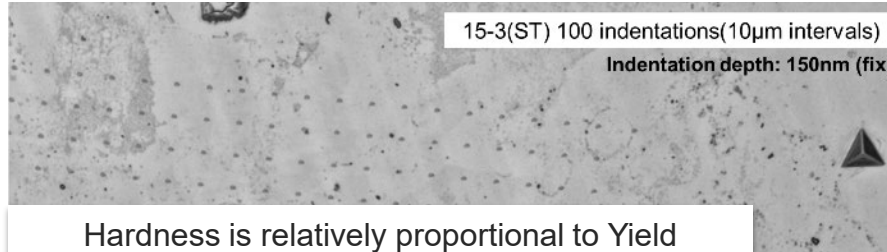
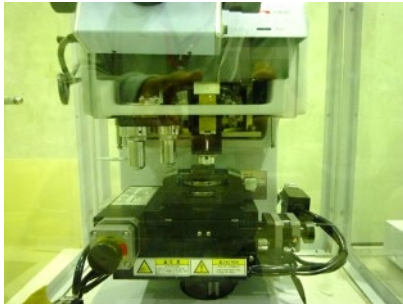
High Fluence Irradiation Facility at the University of Tokyo



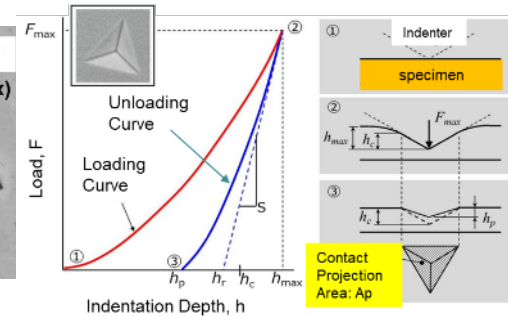
- Accelerated damage rate
 - up to 10 DPA in a few days
- Shorter irradiation time
- No specimen activation

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

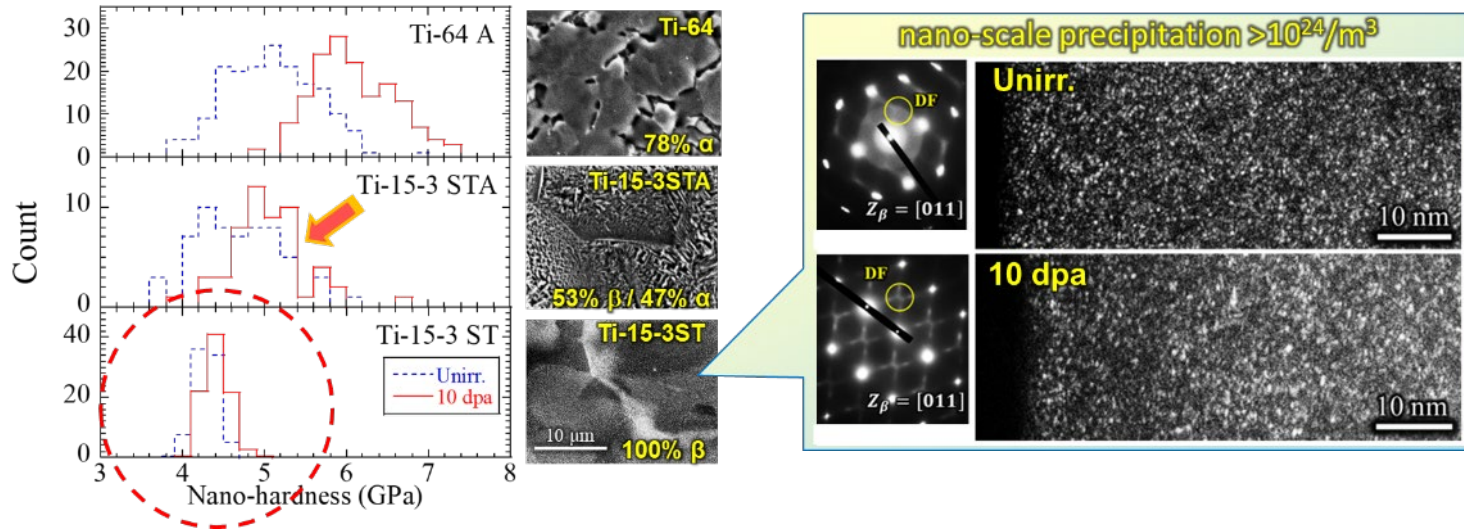
Nano-indentation hardness test



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



Ion Beam Irradiation to High DPA

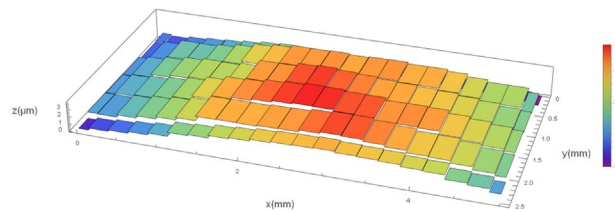
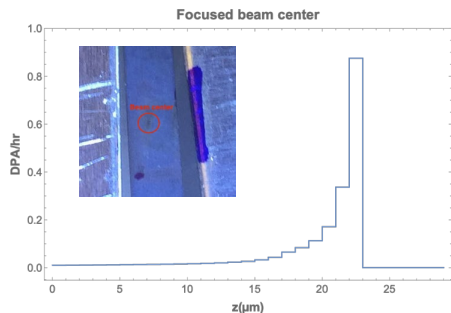


- The single metastable β phase Ti-15-3 alloy exhibits high radiation damage tolerance, that does not undergo irradiation hardening **up to 10 dpa at room temperature**
 - Dense nano-scale precipitates (precursors of the athermal ω -phase) that act as effective “sink sites” to absorb irradiation defects
- Ti-15-3 is typically aged at $\sim 500^\circ\text{C}$ 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)**

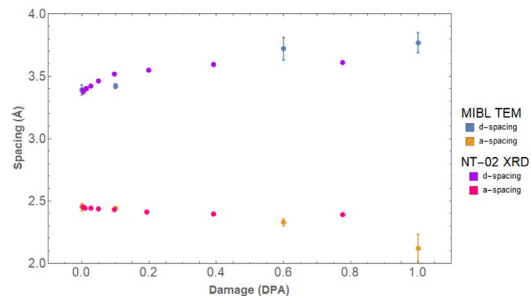
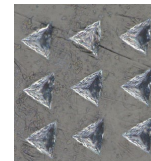
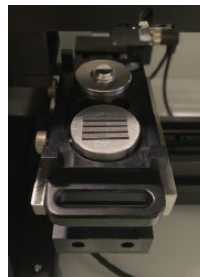
Graphite Irradiation Studies with Heavy Ions

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

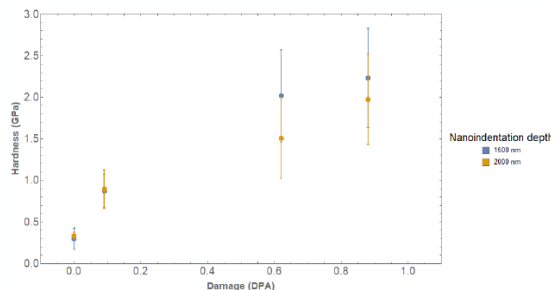
- 4.5 MeV He⁺⁺ ions at MIBL
- 1 MeV/A ³⁶Ar¹⁰⁺ at IRRSUD



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

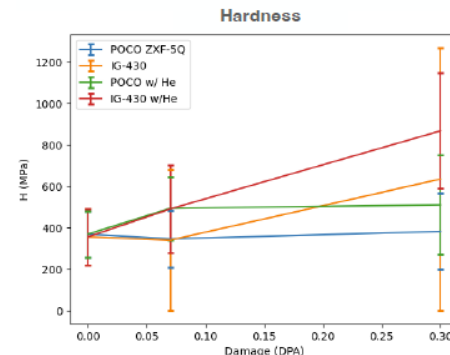


TEM: similar behavior of HI irradiated graphite compared to failed NT-02 target



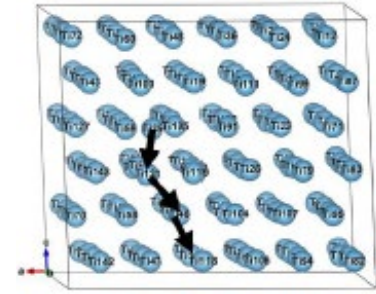
Nano-indentation of graphite irradiated up to 0.9 DPA at MIBL

Preliminary results

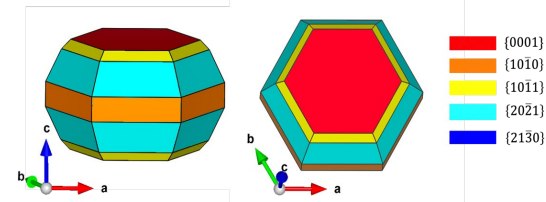


Ab Initio and Molecular Dynamics Material Modeling

- 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



Pacific Northwest
NATIONAL LABORATORY



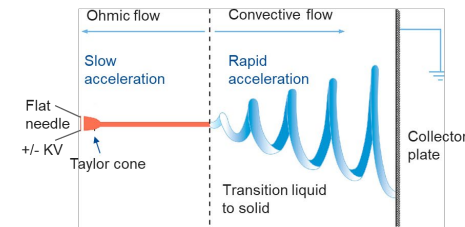
Equilibrium Wulff shape

Department of
Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

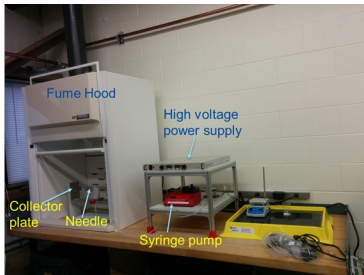
Novel Targetry Materials: Electrospun Nanofibers and HEAs

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



Electro-spinning set-up at Fermilab

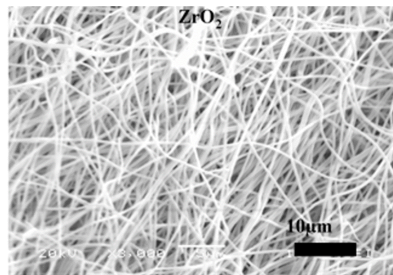


Electrostatically driven electrospinning process

Taylor cone

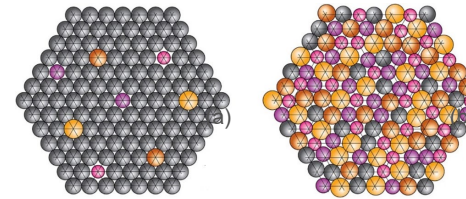


SEM image of Zirconia nanofibers

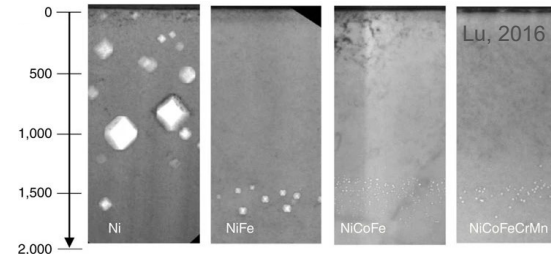


High-Entropy Alloy (HEA) development at UW-M

- 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)



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



RaDIATE Collaboration

Radiation **D**amage **I**n **A**ccelerator **T**arget **E**nvironments

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)



Department of
Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON



University of
BRISTOL



UK Atomic
Energy
Authority



UNIVERSITY OF
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Science and
Technology
Facilities Council



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

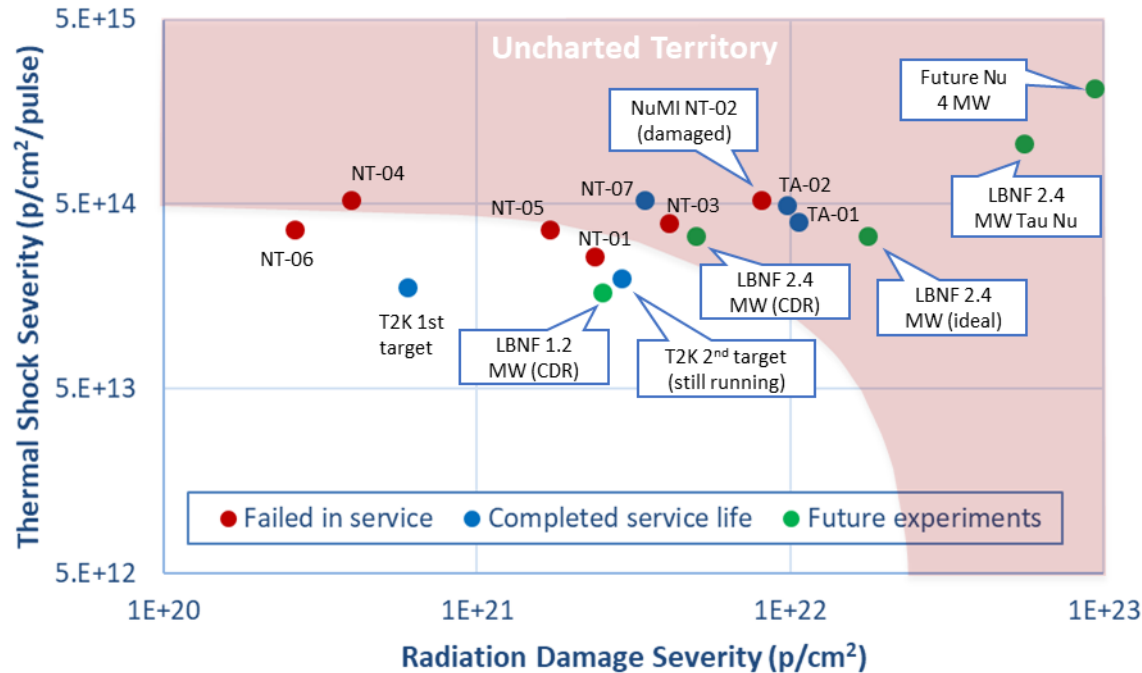


R a D I A T E Collaboration

Radiation Damage In Accelerator Target Environments



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.