FERMILAB-SLIDES-22-088-AD

R&D Program for HEP High-Power Targets at Fermilab

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Seminar at GANIL

July 5, 2022

Outline

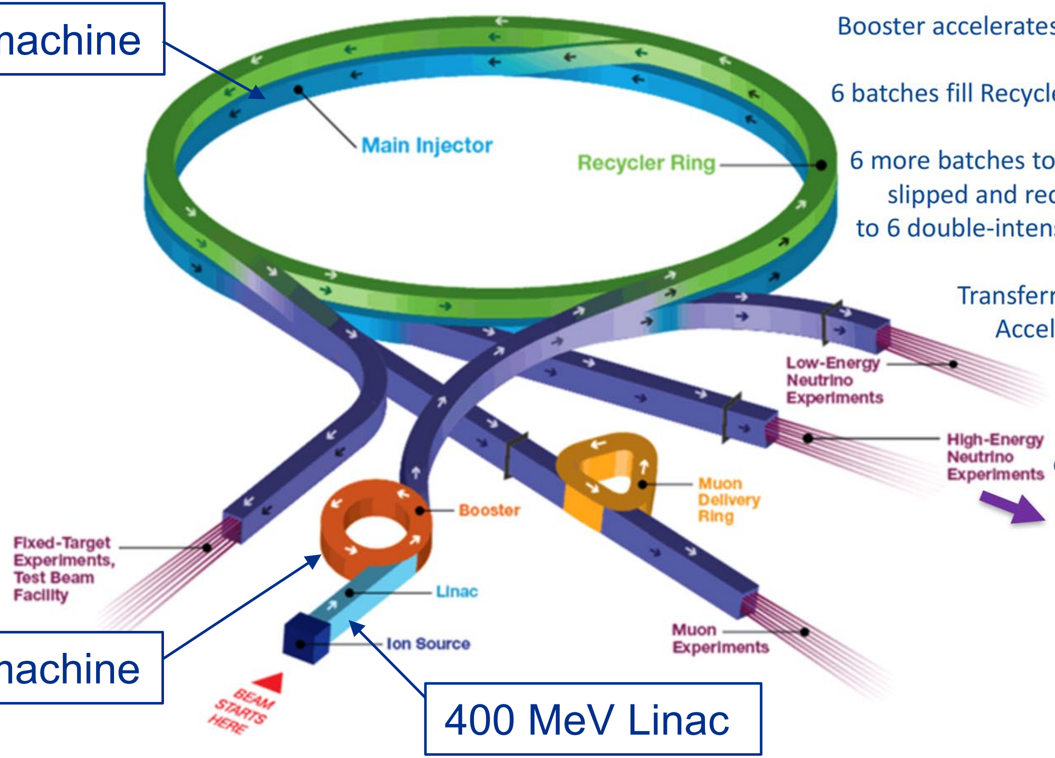
- Introduction
  - Overview of Fermilab accelerator complex and neutrino beamline
  - Neutrino targets

- High Power Targetry (HPT) scope and challenges
  - Radiation damage and thermal shock
  - Autopsy and analysis of failed components

- HPT R&D program and collaborations
  - RaDIATE collaboration
  - Current research approach and results
  - Development of alternative methods
  - Novel materials development

- Summary

Fermilab Accelerator Complex



120 GeV machine

8 GeV machine

400 MeV Linac

Booster accelerates a “batch”

6 batches fill Recycler circumference

6 more batches to Recycler
slipped and recaptured
to 6 double-intensity batches

Transferred to M.I.
Accelerated

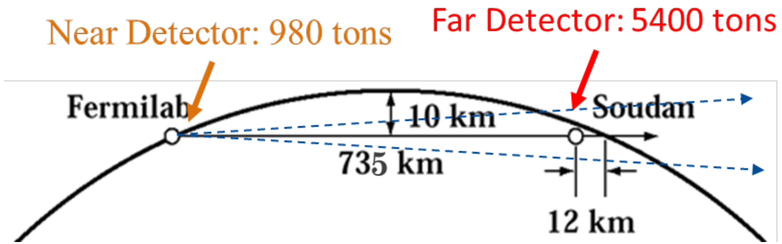
Single turn
extraction
to NuMI

NuMI

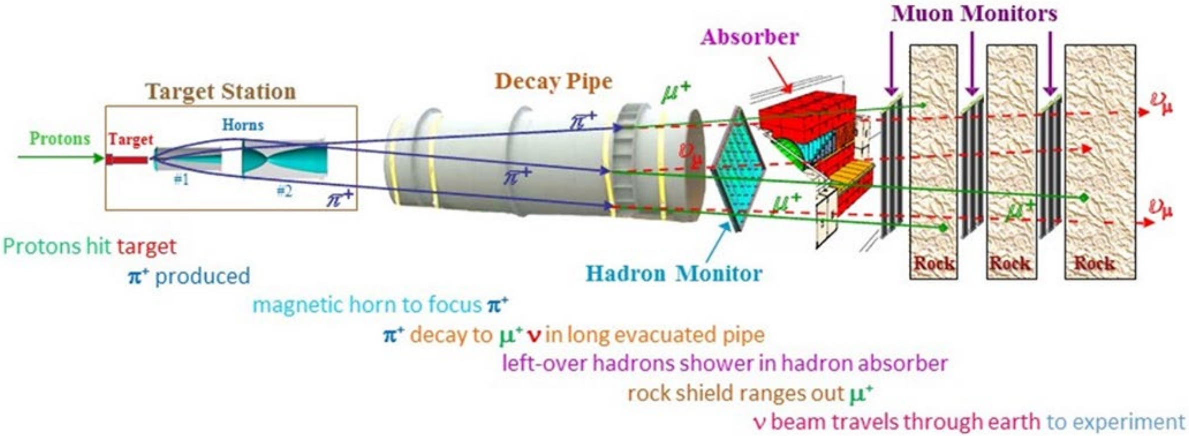
Accelerator Neutrino Program at Fermilab

- Scientists at Fermilab create a muon neutrino beam by slamming protons from the main injector accelerator into a graphite target. Several experiments (MINOS, NOvA, MINERvA) at the laboratory count on the high-intensity beam of neutrinos to unravel the mysterious properties of these ghost-like particles and their role in the evolution of the Universe

- Main injector supplies 25–50 trillion 120-GeV protons every 1.33 seconds (700 kW)



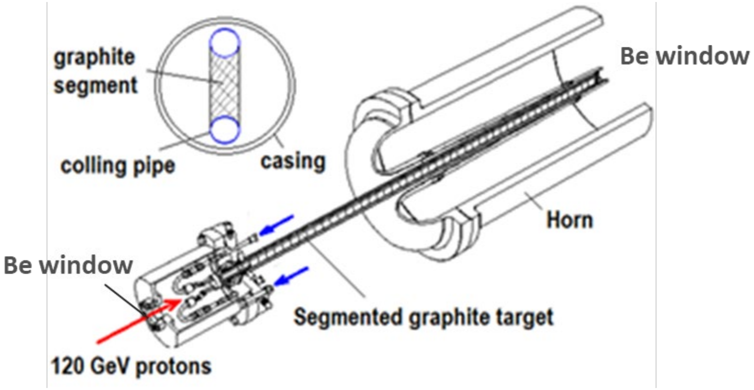
Neutrinos at the Main Injector (NuMI)



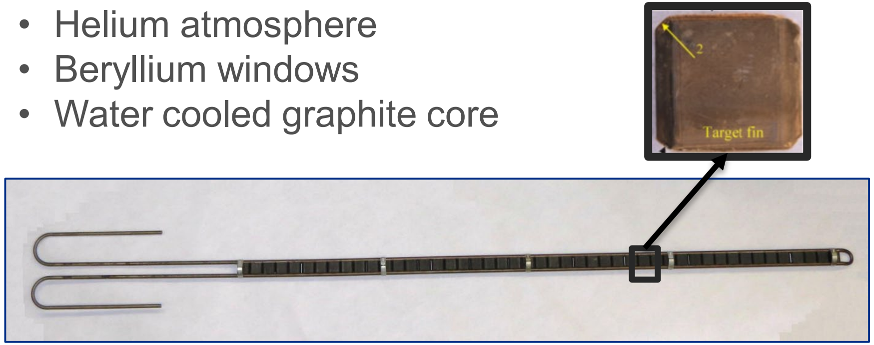
Target station able to operate with 1-MW proton beam since FY21

- 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 – MINOS (400 kW)

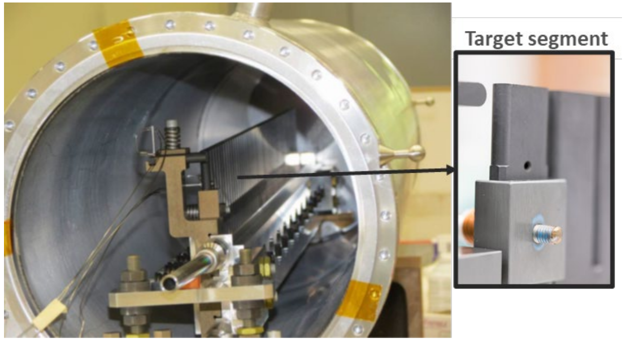


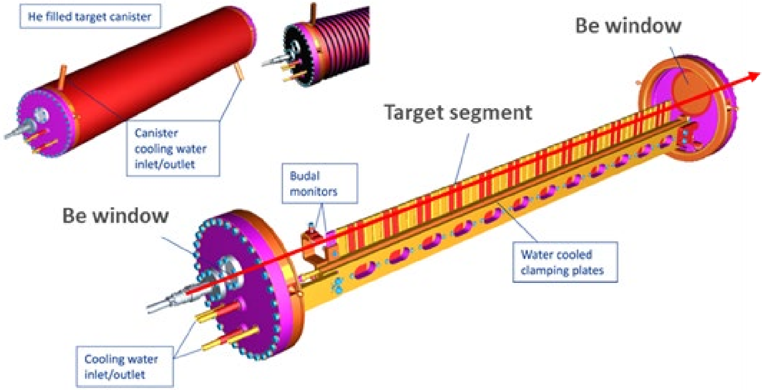
- Helium atmosphere
- Beryllium windows
- Water cooled graphite core



	MINOS
Graphite fins	47 x 20 mm x 6.6 mm
Beam energy [GeV]	120
p/pulse	3.37E+13
Power [kW]	340
σ [mm]	1.1
Peak Temp. [°C]	330
QS Temp [°C]	60
POT	6.55E+20
Peak dpa	0.63
Peak He [appm]	2270

Neutrino target – NOvA AIP (0.7 – 1 MW)

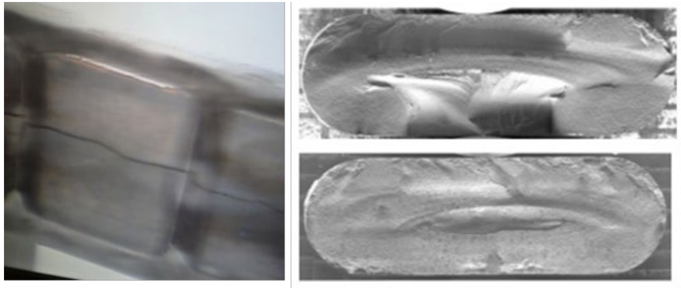




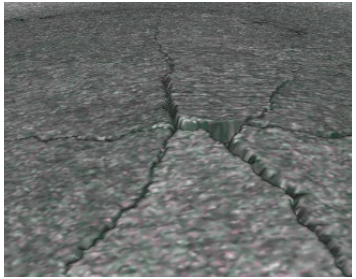
	NOvA	AIP
Graphite fins	50 x 24 mm x 7.4 mm	50 x 24 mm x 9 mm
Beam energy [GeV]	120	120
p/pulse	4.90E+13	6.50E+13
Power [kW]	700	1000
σ [mm]	1.3	1.5
Peak Temp. [°C]	670	1000
QS Temp [°C]	390	890
POT	1.10E+21	1.28E+21
Peak dpa	1.10	0.96
Peak He [appm]	5580	3600

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

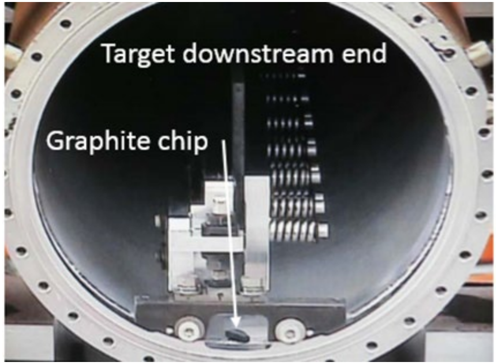
What we want to avoid…



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

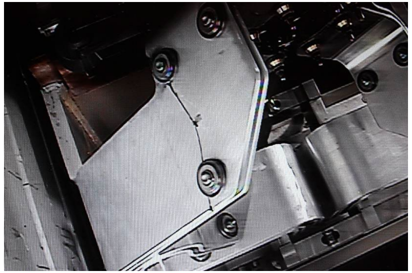


Be window embrittlement (FNAL)

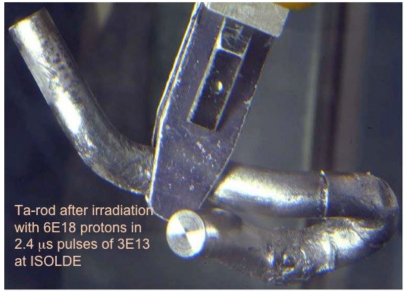


NOvA MET-01 target fin fracture (FNAL)

MINOS NT-01 target containment water leak (FNAL)

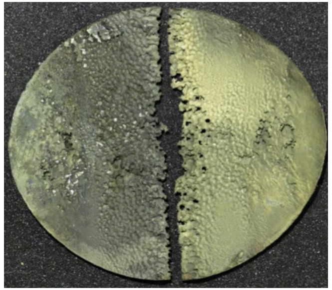


Horn stripline fatigue failure (FNAL)



Ta-rod after irradiation with 6E18 protons in 2.4 µs pulses of 3E13 at ISOLDE

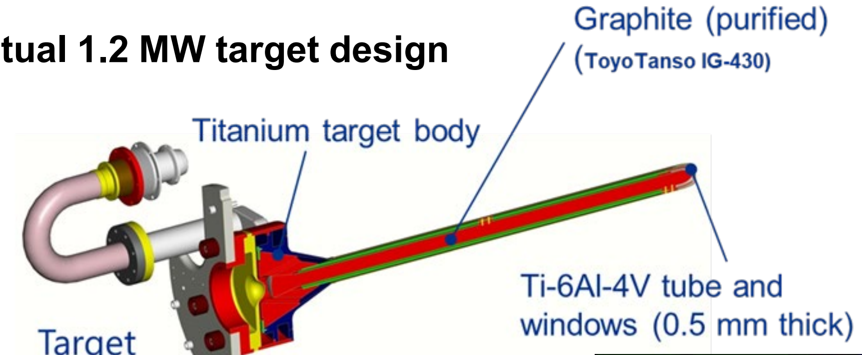
ISOLDE target (CERN)



Target containment vessel cavitation (ORNL - SNS)

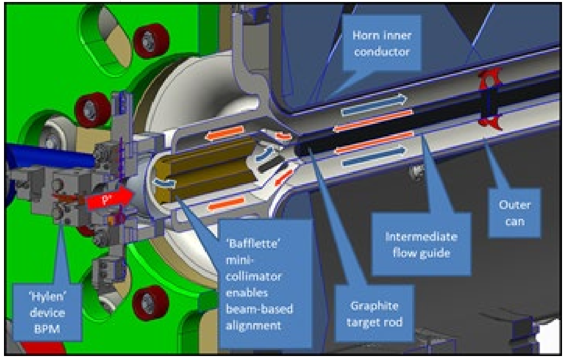
Future Neutrino Target – LBNF-DUNE (1.2 – 2.4 MW)

Conceptual 1.2 MW target design



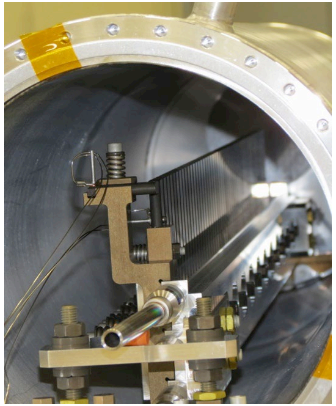
	DUNE
Graphite fins	TBD
Beam energy [GeV]	60-120
p/pulse	7.50E+13
Power [kW]	1200-2400
σ [mm]	2.67
Peak Temp. [°C]	TBD
QS Temp [°C]	TBD
POT	2.54E+21
Peak dpa	0.73
Peak He [appm]	400

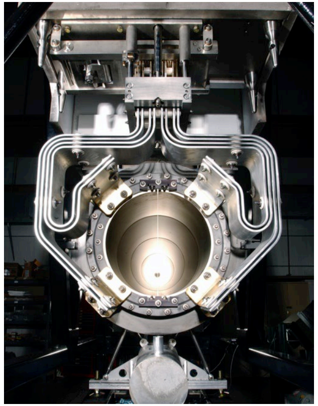
- Helium atmosphere
- Titanium target containment windows
- Helium gas cooled graphite core

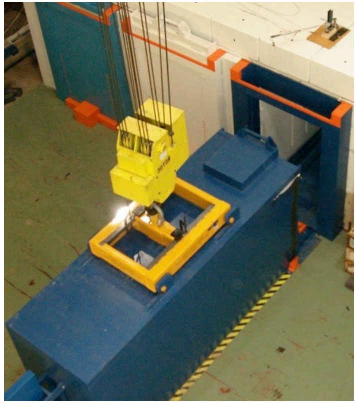


2.4 MW target will require significant R&D to guide design and material choice

High Power Targetry Scope



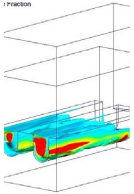




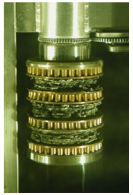
- Target
  - Solid, Liquid, Fixed, Rotating
- Facility requirements for safe operation
  - Remote Handling
  - Shielding & Radiation Transport
  - Air Handling
  - Cooling System

- Other beam-intercepting devices
  - Collimators
  - Collection optics (horns, solenoids)
  - Monitors & Instrumentation
  - Beam windows
  - Absorbers

High Power Targetry Challenges



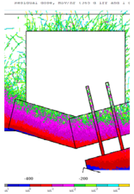
Heat removal



Thermal shock

Physics performance

Radiation damage



Operational safety

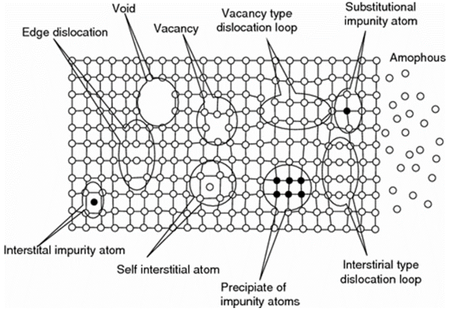
Storage and disposal

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

Radiation Damage & Thermal Shock

Radiation Damage: Displacements in crystal lattice expressed as Displacements Per Atom (DPA)

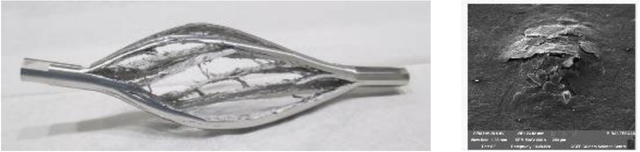
- Hardening and embrittlement
- Creep and swelling
- Fracture toughness reduction
- Thermal/electrical conductivity reduction
- Coefficient of thermal expansion
- Modulus of elasticity
- Transmutation products (H, He gas production can cause void formation and embrittlement)



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

Thermal Shock: Sudden energy deposition from pulsed beam

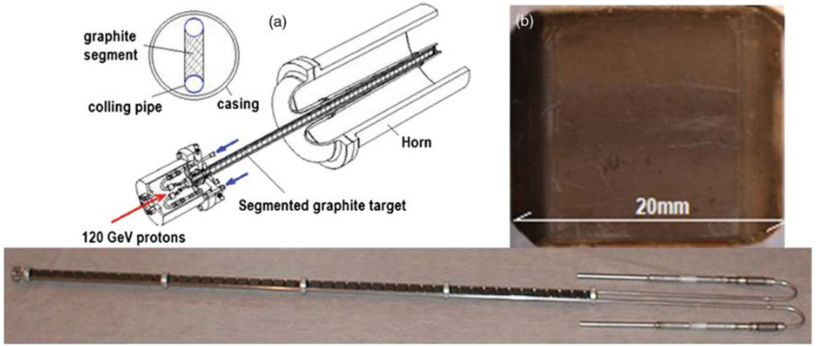
- Fast expansion of the material surrounded by cooler material generates localized area of compressive stress
  - 1 MW target: ~250 K in 10 μs pulse (2.5 x 10^7 K/s)
- Stress waves move through the material at sonic velocities
- Plastic deformation, cracking and fatigue failure can occur



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

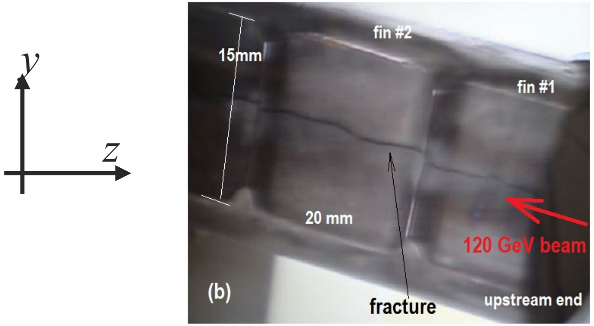
First Approach to Study Targets and Windows Failed in Service

Observation of gradual decline in neutrino yield towards the end of the target’s life – attributed to radiation damage

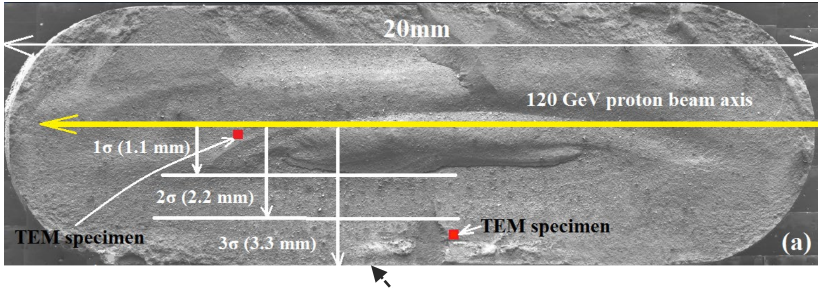


NuMI target (NT-02) autopsy and examination

- Estimated peak DPA: 0.63
- Detailed Post Irradiation Examinations at PNNL show bulk swelling leading to dimensional changes, and build up of internal stresses in graphite

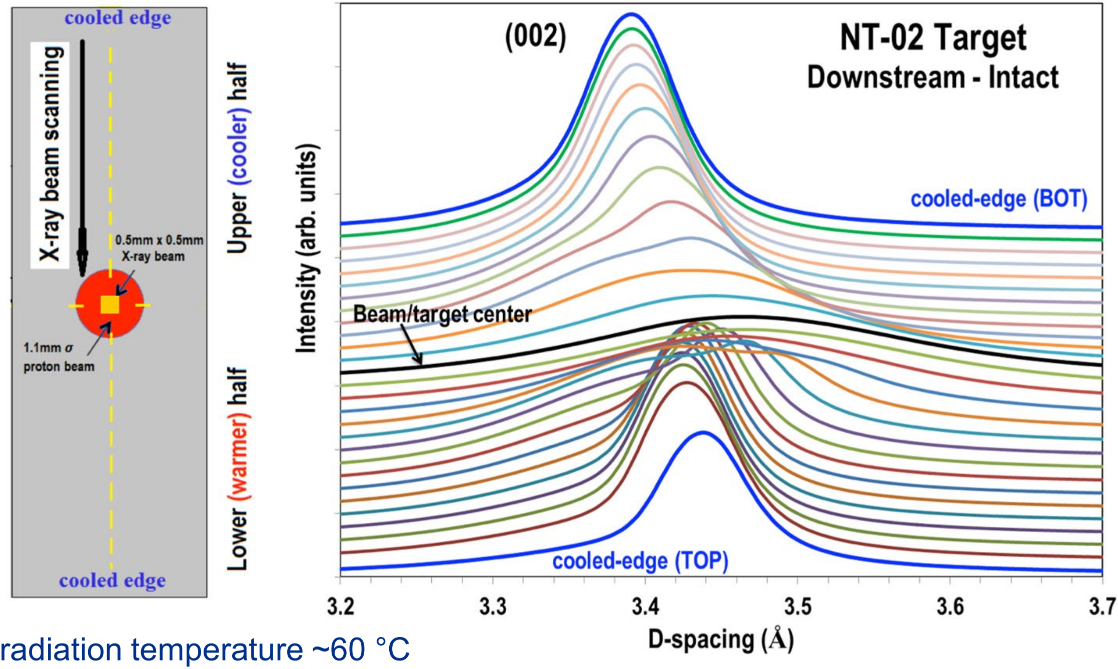


Detailed PIE at PNNL



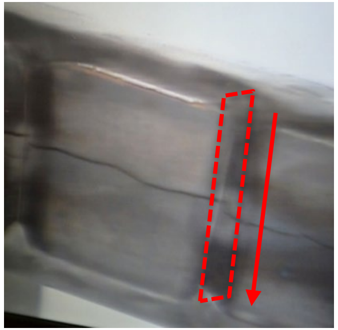
Bulk swelling of ~4%

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



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

Brookhaven National Laboratory



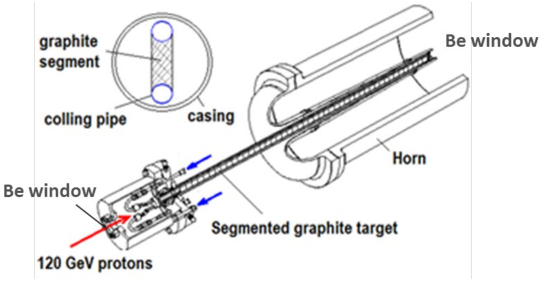
XRD shows lattice growth (swelling) and amorphization at the beam center

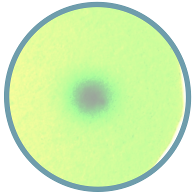
Irradiation temperature ~60 °C
(330 °C during pulse)

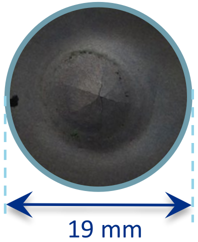
Additional simulation work together with these findings shows that radiation damage was indeed the cause of failure for the NT-02 target

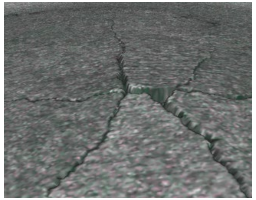
NuMI Beryllium Window Analysis

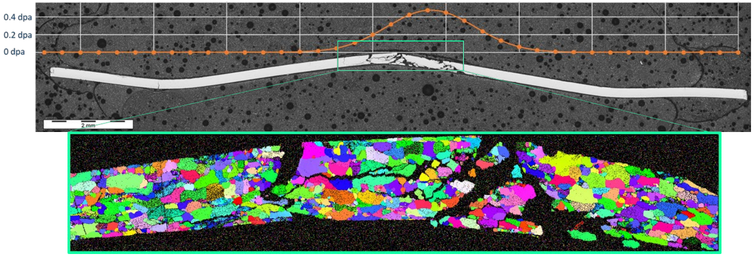
- 120 GeV proton beam
- 1.54 x 10^{21} POT (0.5 peak DPA)
- T ~ 50 °C





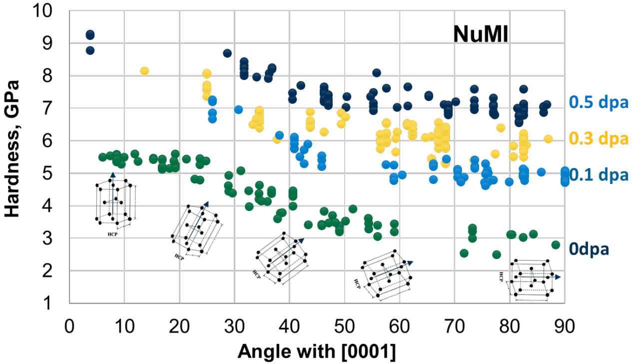






- Observed transition from transgranular fracture to grain boundary/mixed mode fracture in irradiated Be

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



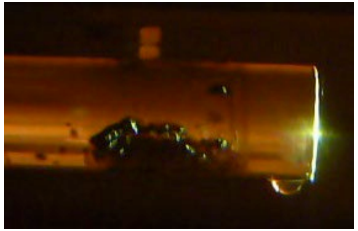
UK Atomic Energy Authority

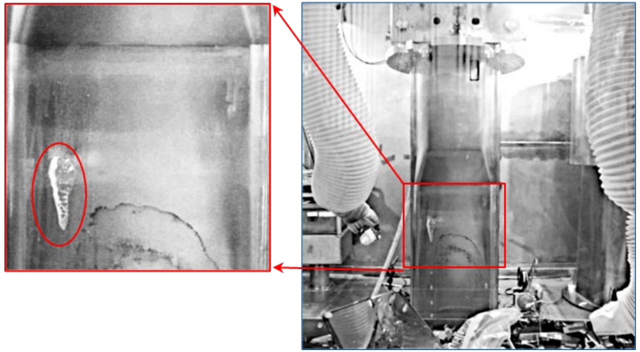
- Significant hardening even at 0.1 DPA
- Hardness of irradiated Be less anisotropic
- Increased hardness means less ductility (more brittle)

Robust High-Power Targets Critical in Maximizing the Efficiency of Secondary Particle 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

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 ≠ p

1-14 MeV

100+ MeV

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE collaboration created in 2012, with Fermilab as the leading institution

@J-PARC, Sep.20, 2017

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)

Fermilab
Oak Ridge National Laboratory
European Spallation Source
University of Oxford
CERN
Argonne National Laboratory
Brookhaven National Laboratory
Pacific Northwest National Laboratory
FRIB
Los Alamos National Laboratory EST. 1943
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
UKRI Science and Technology Facilities Council
J-PARC

Future Collaborators

CIMAP
CNRS
Department of Engineering Physics University of Wisconsin-Madison
UK Atomic Energy Authority
University of Bristol
TRIUMF
University of Birmingham

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

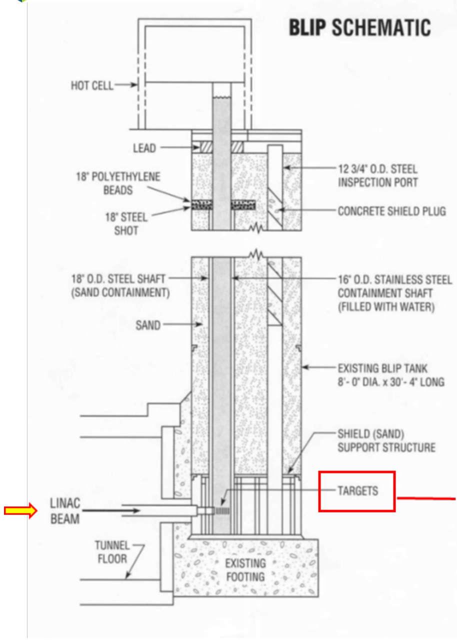
Research Approach - Prototypic irradiation to closely replicate material behavior in accelerator target facilities

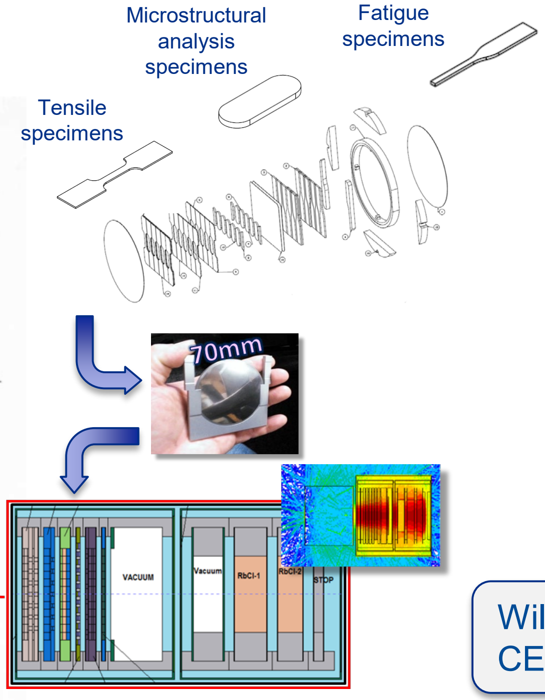
- High-energy proton irradiation of material specimens at BNL-BLIP facility in partnership with the RaDIATE collaboration
  - 1st irradiation campaign completed in 2017/2018, 2nd irradiation planned in 2024-2025
- Post-Irradiation Examination (PIE) conducted at participating institution equipped with 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

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

Brookhaven National Laboratory





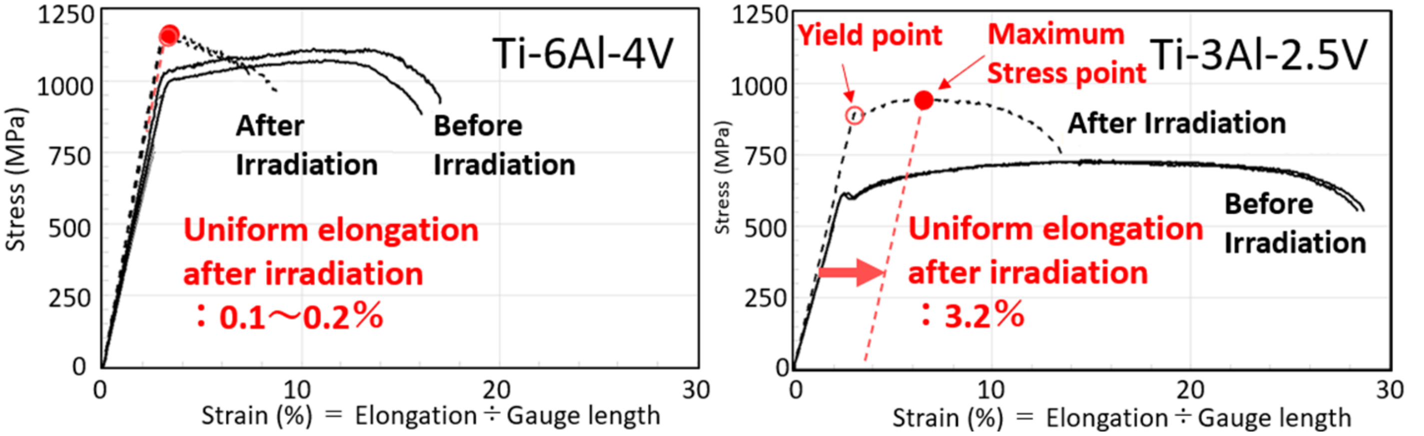
Material targets Isotope targets

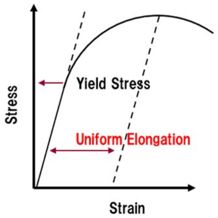
- RaDIATE multi-material irradiation campaign
- 181 MeV p irradiation for 8 weeks
  - Over 200 specimens from 6 RaDIATE collaborators
- Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, FNAL
- Completed irradiation in 2018
  - 4.5 x 10^{21} accumulated protons on target
  - Peak DPA: 0.95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

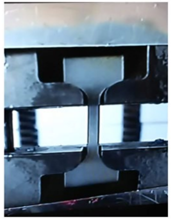
Will benefit many facilities including LBNF, T2K, BDF at CERN, FRIB, and HL-LHC collimators

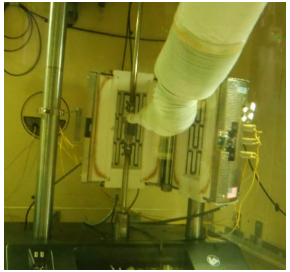
BLIP Ti Alloy Tensile Testing

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







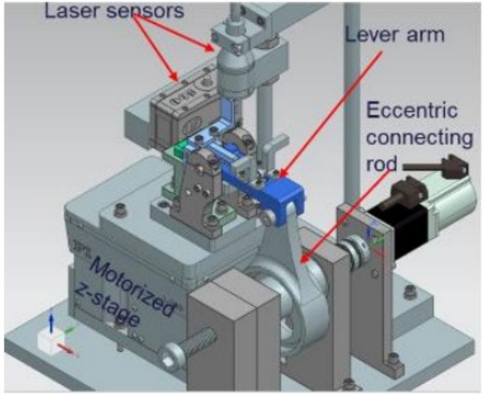


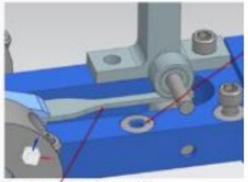
Testing done in hot cell

- 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

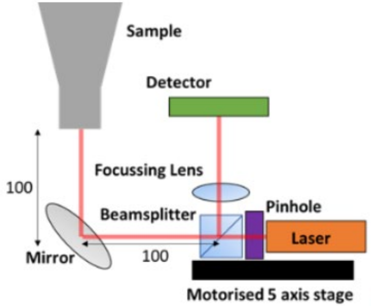
- Proton-irradiated fatigue life data crucial in evaluating component lifetime

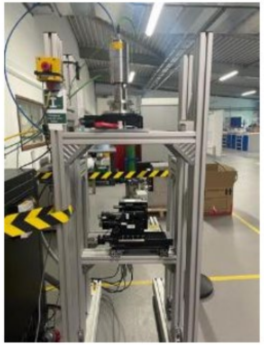



Sample thickness is 1mm+/-0.05

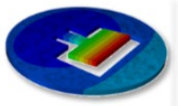
- World first high-cycle fatigue testing of irradiated titanium at FNAL
- Design of 3rd generation fatigue testing machine has been completed

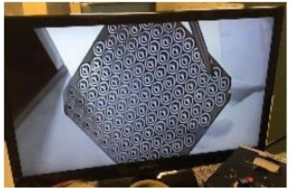
Ultrasonic mesoscale Fatigue Rig (UFR) at the UKAEA-MRF





20 kHz = 10^8 cycles in 1.5 h




Meso-fatigue foil during extraction in PNNL hot cell

UK Atomic Energy Authority

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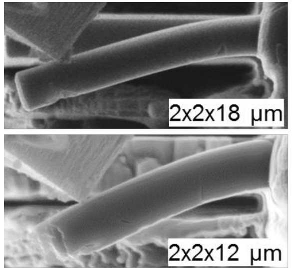
UKRI Science and Technology Facilities Council

Fermilab

Alternative to High Energy Proton Beam

- High energy proton irradiation
  - Highly activated material ⇨ need hot cells and specific characterization equipment
  - High energy ⇨ Low dpa rate ⇨ long irradiation time (order of months) ⇨ 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 ⇨ 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



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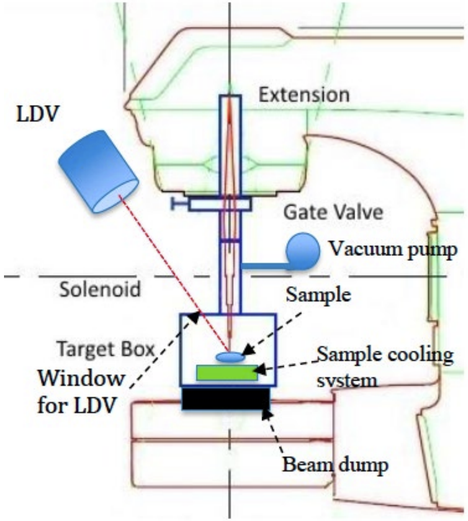
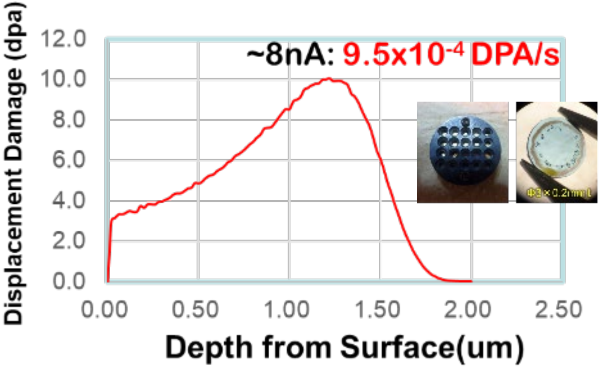


Low energy Fe^{2+} ion beam irradiation at HIT Facility

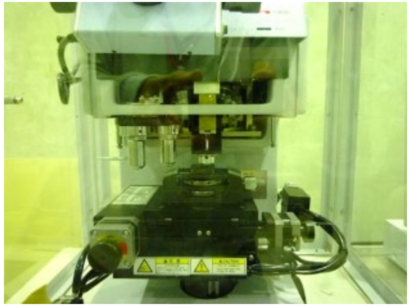
High Fluence Irradiation Facility at the University of Tokyo

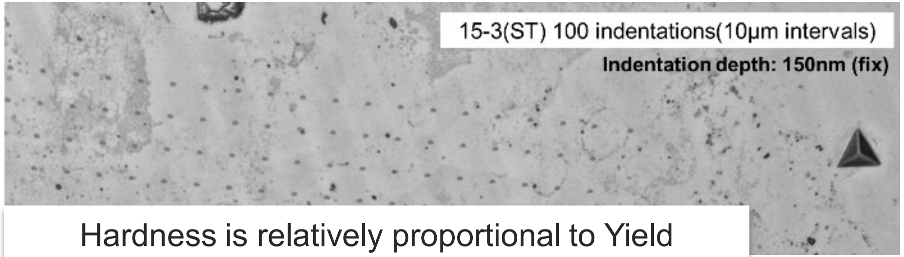


- Accelerated damage rate
  - up to 10 DPA in a few days
- Shorter irradiation time
- No specimen activation

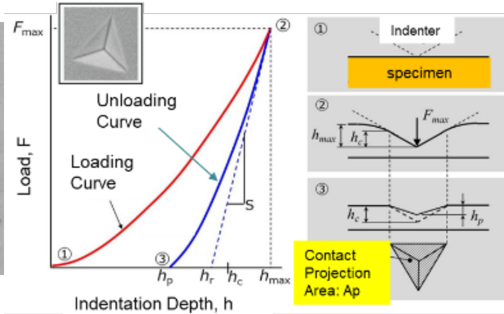
Effective and fast way to screen materials and to optimize heat treatment at high irradiation dose

Nano-indentation hardness test

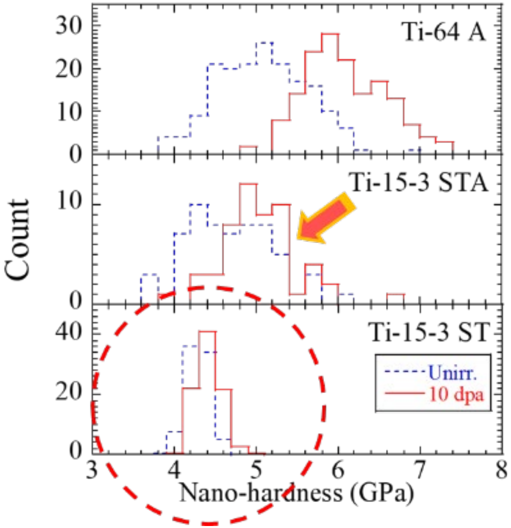


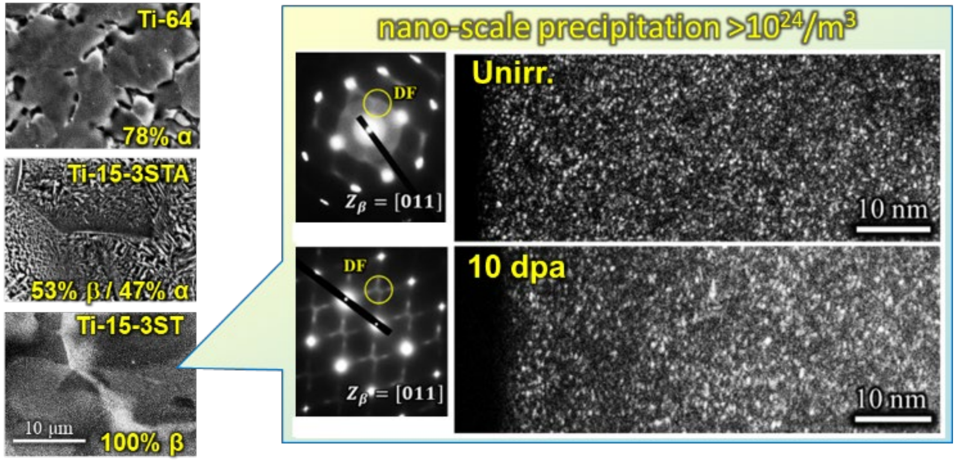


Hardness is relatively proportional to Yield Strength, but difficult to infer ductility (elongation)



Ion Beam Irradiation to High DPA



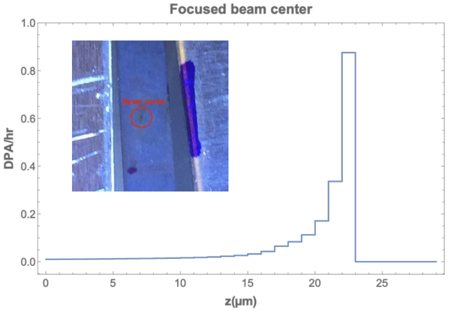


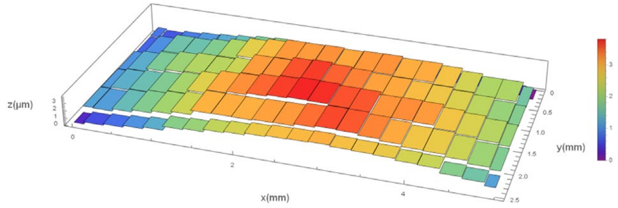
- The single metastable β phase Ti-15-3 alloy exhibits high radiation damage tolerance, that does not undergo irradiation hardening up to 10 dpa at room temperature
  - Dense nano-scale precipitates (precursors of the athermal ω-phase) that act as effective “sink sites” to absorb irradiation defects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

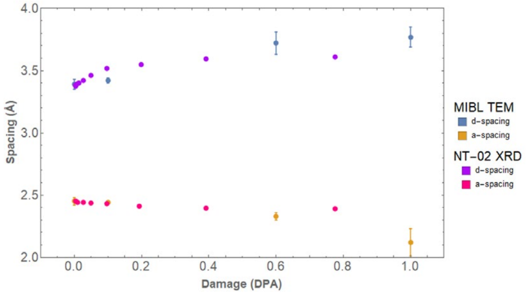
A. Burleigh and Prof. J. Terry (IIT)

- **4.5 MeV He++ ions at MIBL**

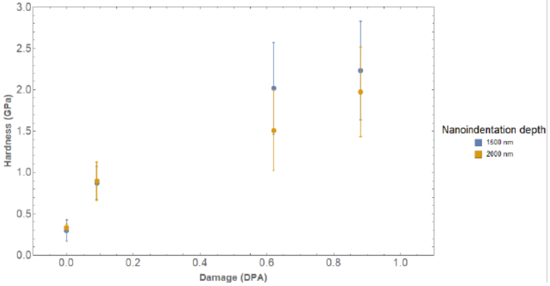




AFM measurements show bulk swelling of ~3.8 μm in the irradiated region

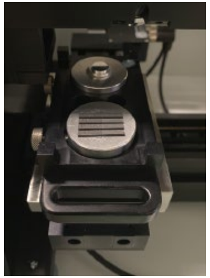


TEM: similar behavior of HI irradiated graphite compared to failed NT-02 target

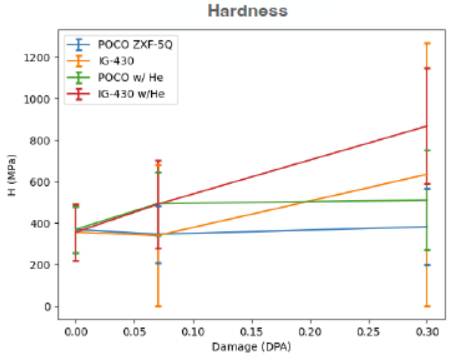


Nano-indentation of graphite irradiated up to 0.9 DPA at MIBL

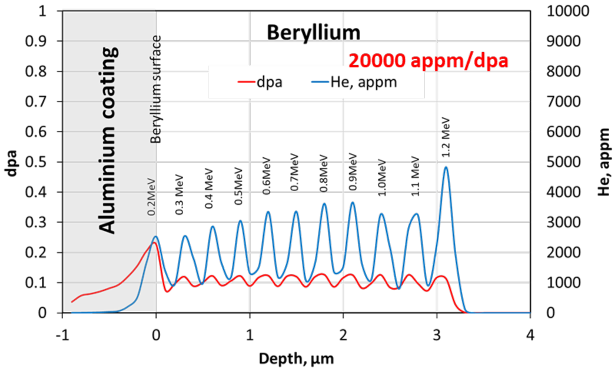
- **1 MeV/A $^{36}Ar^{10+}$ at IRRSUD**



Preliminary results

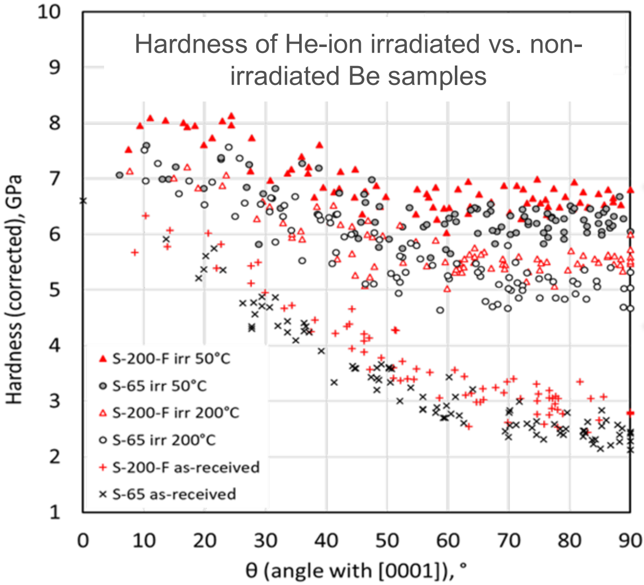


Helium Implantation in Beryllium



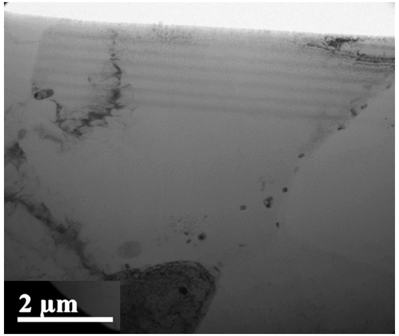
3 µm damage layer
T_{irrad}: 50 and 200 °C
0.1 DPA, 2000 appm He

S. Kuksenko et al., J. Nuclear Materials, vol. 555, 15130, 2021



Irradiated

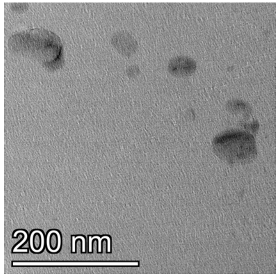
UK Atomic Energy Authority



He implantation peaks

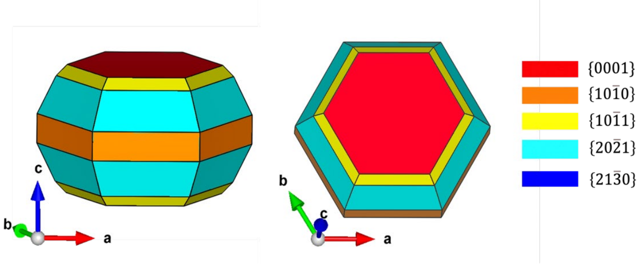
S. Kuksenko, RaDIATE Collaboration Meeting, 2019

- 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)



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
- Collaboration with Computation Materials Group at University of Wisconsin
  - Modeling of He gas bubbles in Beryllium
- Need experimental data from irradiation station (proton, Heavy ion, …) to validate our models



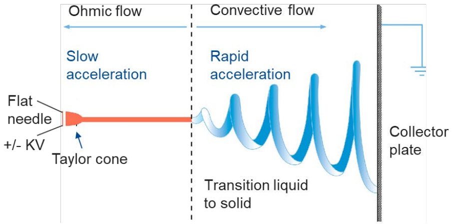
Equilibrium Wulff shape

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Novel Targetry Materials: Electrospun Nanofibers and HEAs

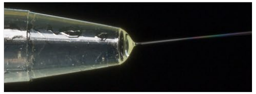
Nanofiber electro-spinning at Fermilab

- 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

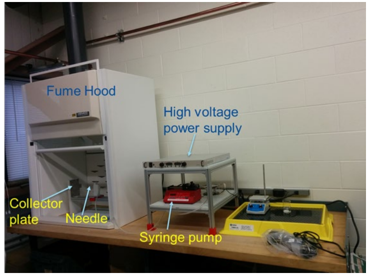


Electrostatically driven electrospinning process

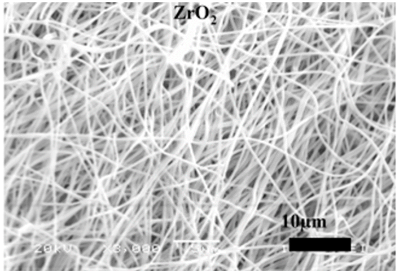
Taylor cone



Electro-spinning set-up at Fermilab

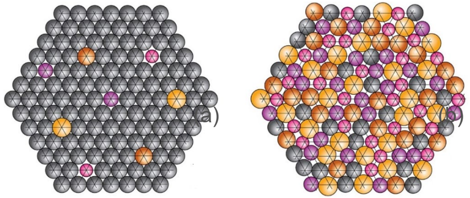


SEM image of Zirconia nanofibers

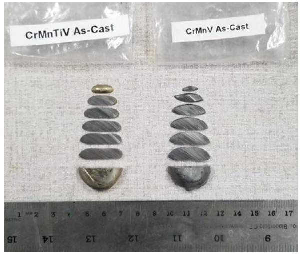


High-Entropy Alloy (HEA) development at UW-M

- 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)



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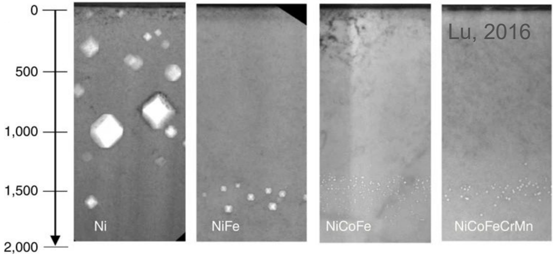


Lu, 2016

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

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

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Fermilab

OAK RIDGE
National Laboratory

UNIVERSITY OF OXFORD

CERN

CIMAP

cnrs

Department of Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

Brookhaven National Laboratory

EUROPEAN SPALLATION SOURCE

University of BRISTOL

TRIUMF

Argonne NATIONAL LABORATORY

FRIB

Los Alamos NATIONAL LABORATORY
EST. 1943

UKRI

Science and Technology Facilities Council

J-PARC

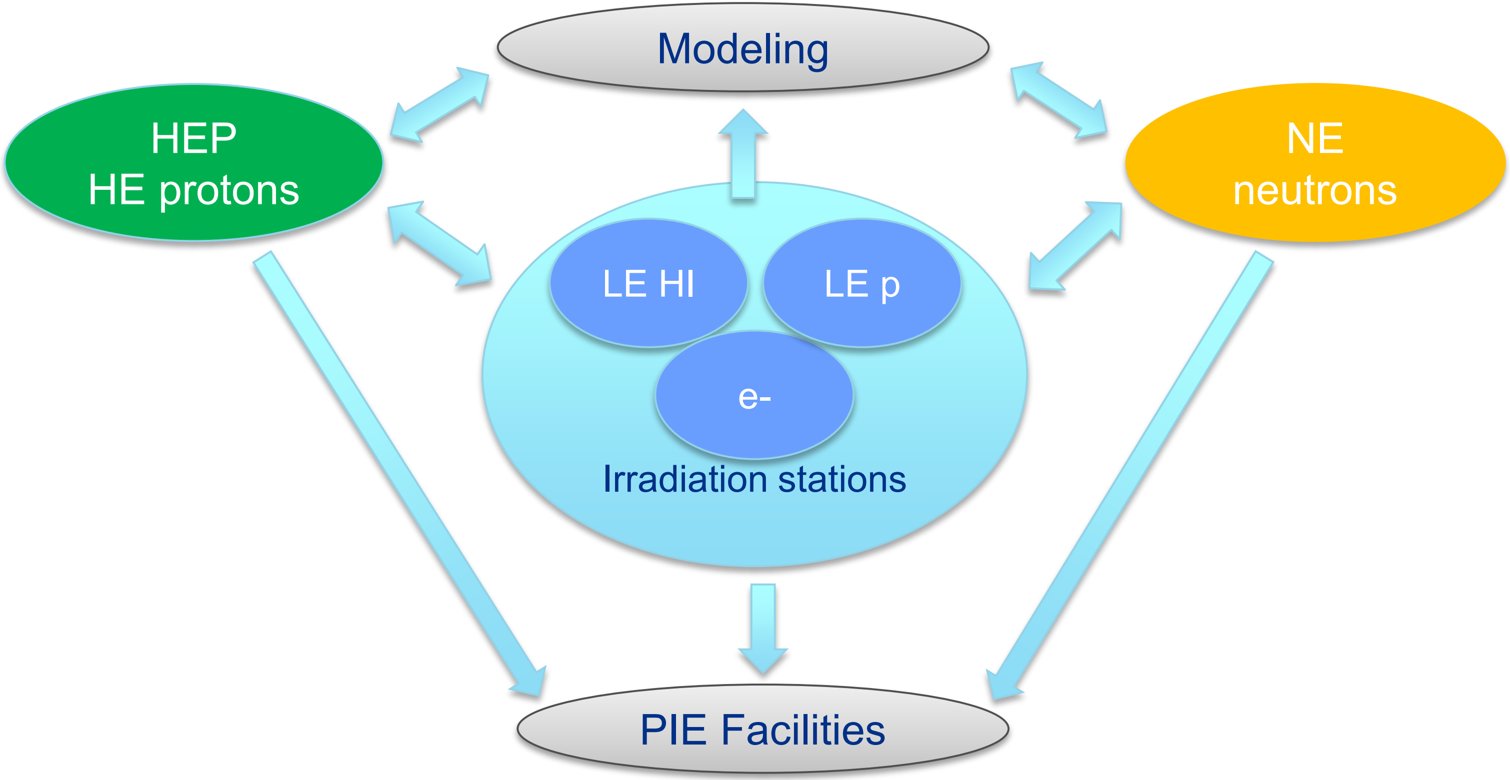
Pacific Northwest NATIONAL LABORATORY

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

UK Atomic Energy Authority

UNIVERSITY OF BIRMINGHAM

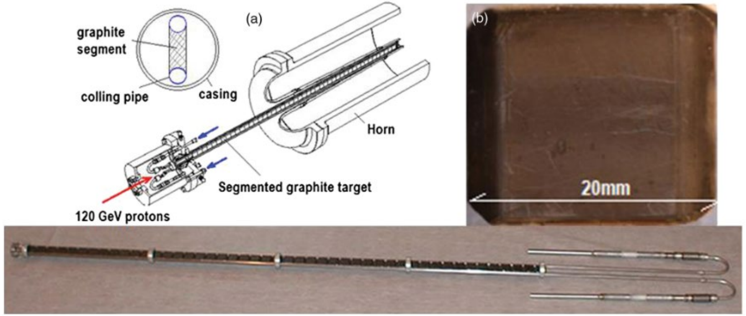
Use Alternative to Understand Radiation Damage

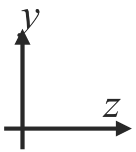


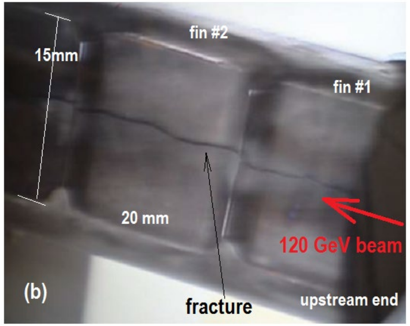
First Approach to Study Targets and Windows Failed in Service

NuMI target (NT-02) autopsy and examination

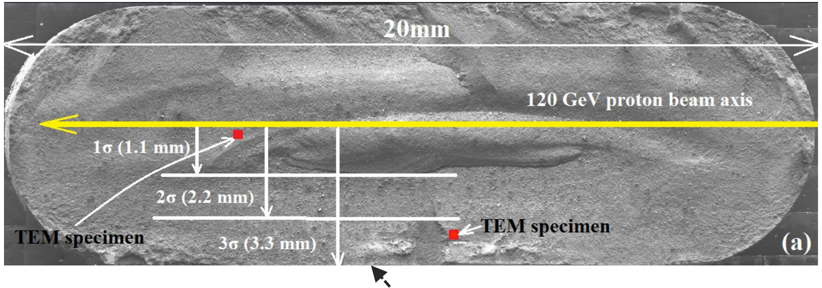
- Peak fluence: 8 x 10^{21} p/cm^2
- Beam energy: 120 GeV
- Spill duration: 10 µs, 4 x 10^{13} protons/pulse
- Duty cycle: 1.87 s
- Estimated peak DPA: 0.63





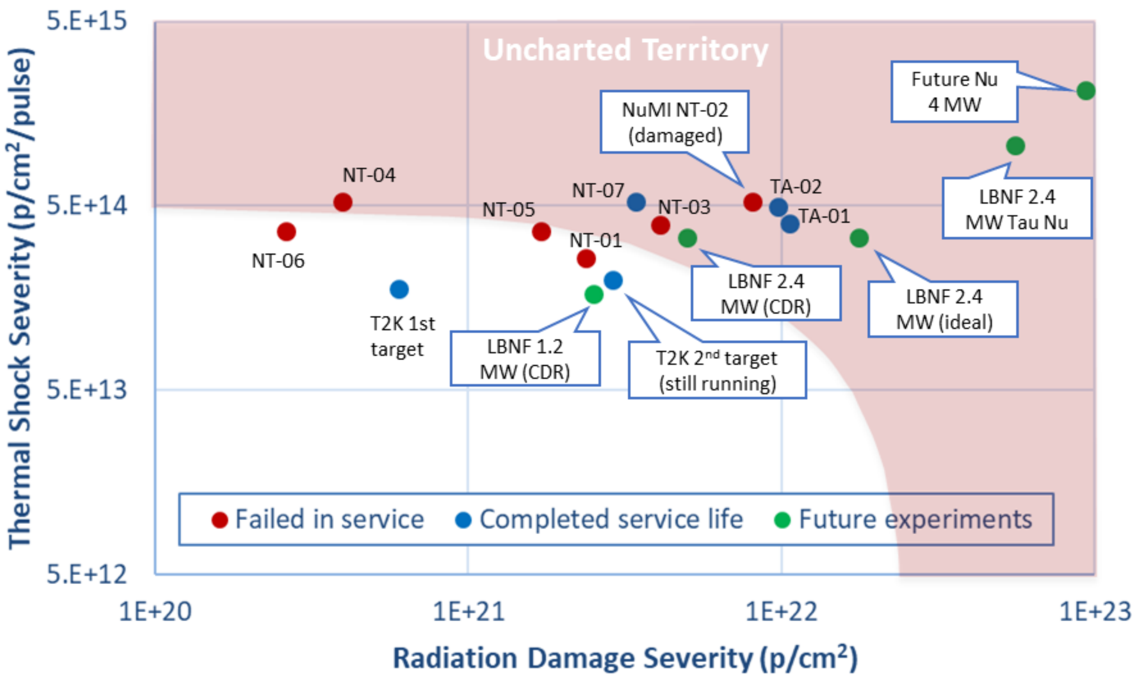


Detailed PIE at PNNL



Bulk swelling of ~4%

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.

NSUF Facilities of Interest

- 48 NSUF Partner Facilities offer world-class capabilities to researchers for investigating research aligned with the DOE-NE mission and its programmatic interests
- 18 NSUF Partner Institutions. At least 11 are of interest for HPT R&D
  - Idaho National Laboratory
  - Argonne National Laboratory (IVEM-Tandem Facility)
  - Brookhaven National Laboratory (National Synchrotron Light Source II)
  - Los Alamos National Laboratory (Tarik Saleh for RUS, Resonant Ultrasound Spectroscopy)
  - Massachusetts Institute of Technology (Pr. Short, Transient Grating Spectroscopy)
  - Oak Ridge National Laboratory (LAMDA)
  - Pacific Northwest National Laboratory (D. Senor)
  - Sandia National Laboratories (Khalid Hattar, Ion Beam Laboratory)
  - Westinghouse
  - University of Wisconsin (Adrien Couet)
  - University of Michigan (Gary Was, MIBL)