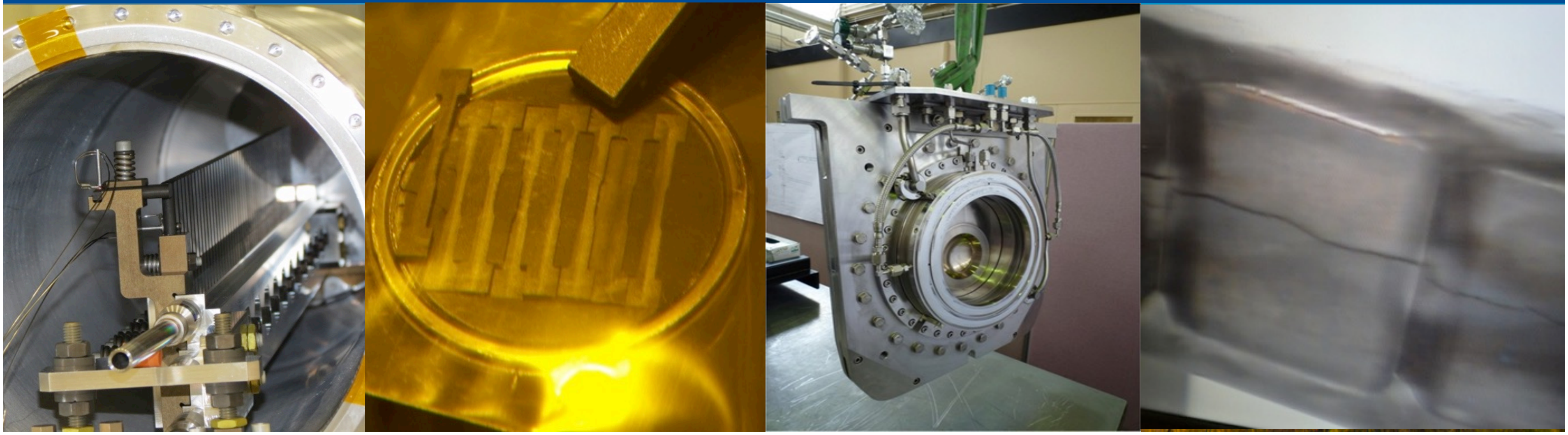


Recent studies of radiation damage effects in high-power accelerator target materials

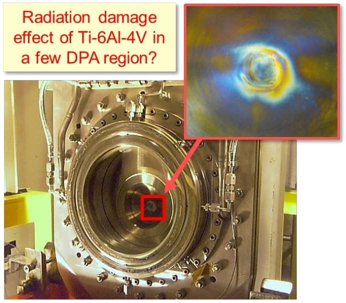
Kavin Ammigan (on behalf of HPT R&D group and RaDIATE Collaboration)

Joint Experimental-Theoretical Physics Seminar

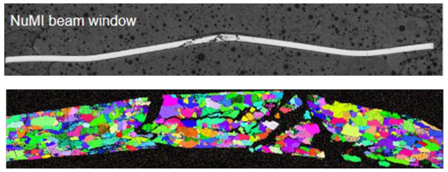
18 December 2020

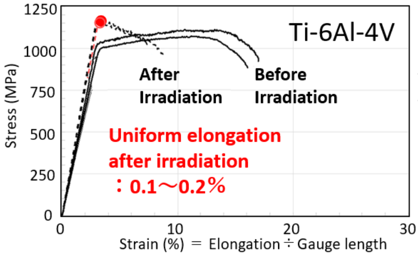
Overview

Radiation damage effects in beam-intercepting materials (windows/targets)

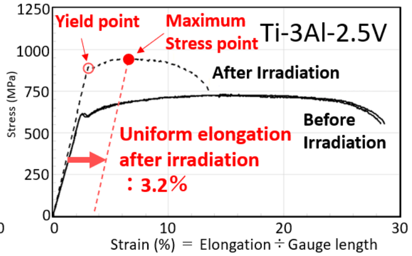

Radiation damage effect of Ti-6Al-4V in a few DPA region?


Fracture near beam spot region of Be window (0.5 DPA)





Uniform elongation after irradiation ：0.1～0.2%

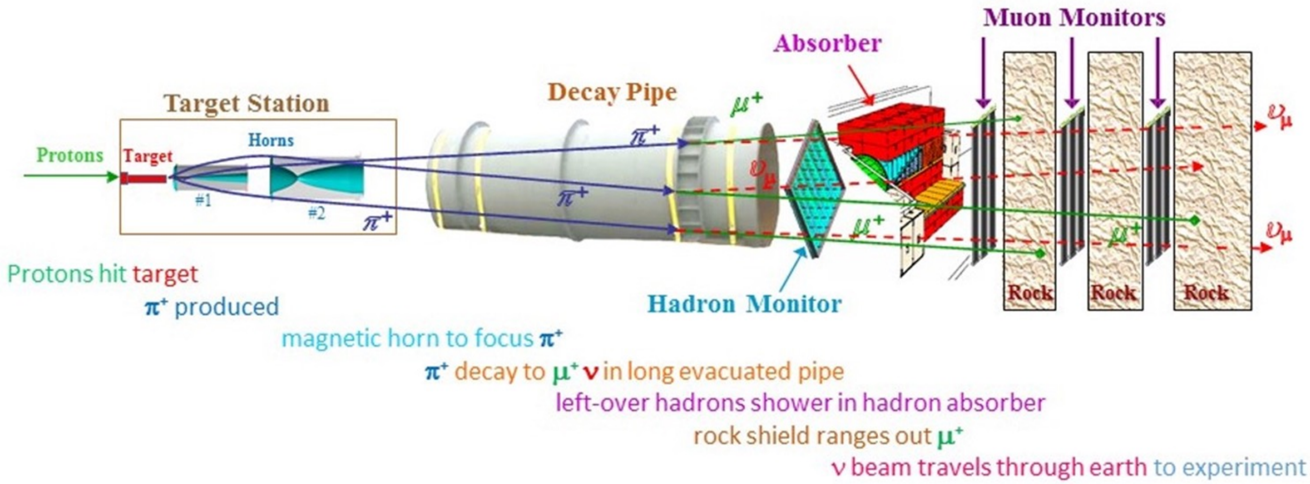


Uniform elongation after irradiation ：3.2%

- Challenges of high-power target facilities
- Need for material research to support future accelerator upgrades and facilities
- Approach to studying radiation damage in materials
- Recent results that will inform material selection and future research

High-Power Targetry Challenges

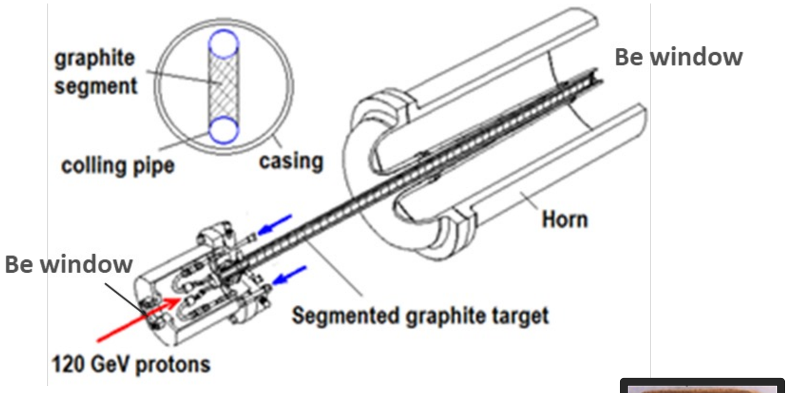
The NuMI Beamline



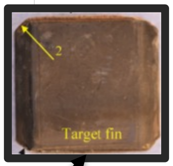
- **Current target facilities (2004 - ~2025)**
  - NuMI-MINOS target (400 kW)
  - NuMI-NOvA target (700 kW)
  - NuMI-NOvA AIP target (1000 kW)
  - Beryllium primary beam window
- **Future target facilities: LBNF-DUNE (2028–)**
  - Beam power: 1.2 – 2.4 MW
  - Beryllium primary beam window
  - Titanium target containment window

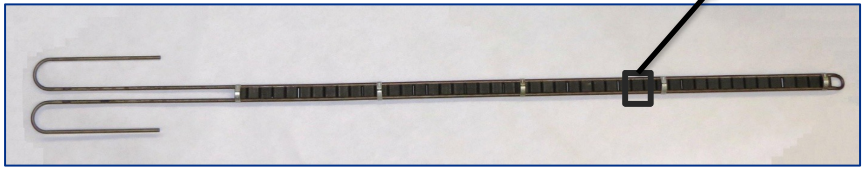
Neutrino targets - MINOS

MINOS Target (400 kW)



- Helium atmosphere
- Beryllium windows
- Water cooled graphite core

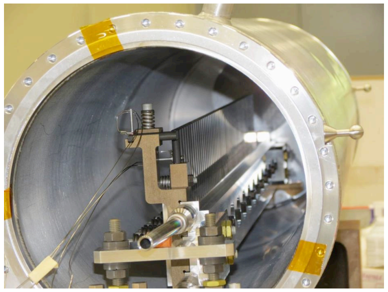




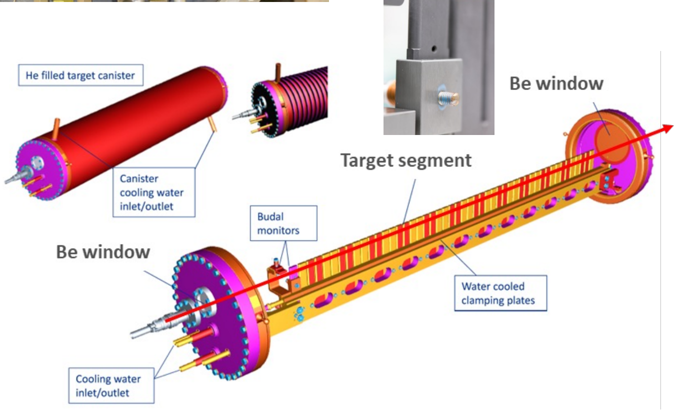
	MINOS
Graphite fins	47 x 20 mm x 6.6 mm
Beam energy [GeV]	120
p/pulse	3.37E+13
Power [kW]	340
σ [mm]	1.1
Peak Temp. [°C]	330
QS Temp [°C]	60
POT	6.55E+20
Peak dpa	0.63
Peak He [appm]	2270

Neutrino targets – NOvA AIP

NOvA AIP Target (1 MW)



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

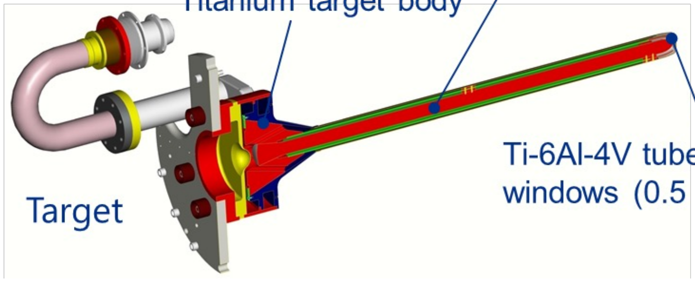


	NoVA	AIP
Graphite fins	50 x 24 mm x 7.4 mm	50 x 24 mm x 9 mm
Beam energy [GeV]	120	120
p/pulse	4.90E+13	6.50E+13
Power [kW]	700	1000
σ [mm]	1.3	1.5
Peak Temp. [°C]	670	1000
QS Temp [°C]	390	890
POT	1.10E+21	1.28E+21
Peak dpa	1.10	0.96
Peak He [appm]	5580	3600

Future Neutrino Target

LBNF-DUNE (1.2 MW)

Conceptual target design



Graphite (purified)
(**ToyoTanso IG-430**)

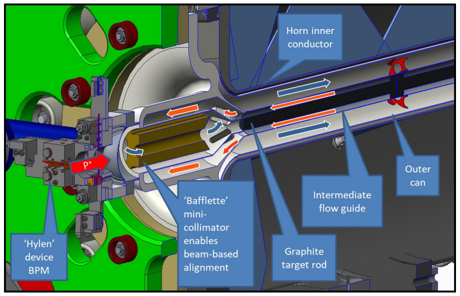
Titanium target body

Target

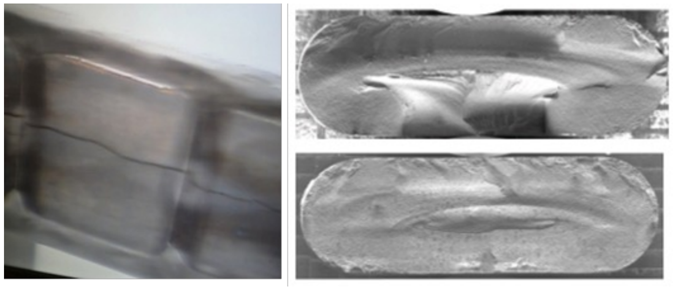
Ti-6Al-4V tube and windows (0.5 mm thick)

	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

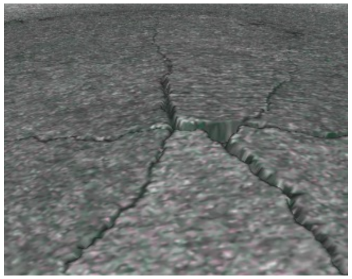
- Helium atmosphere
- Titanium target containment windows
- Helium gas cooled graphite core



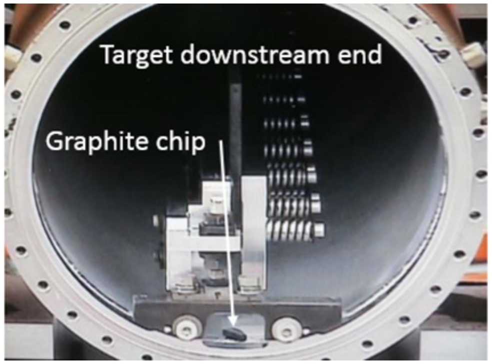
Beam-intercepting device failures we do not want…



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

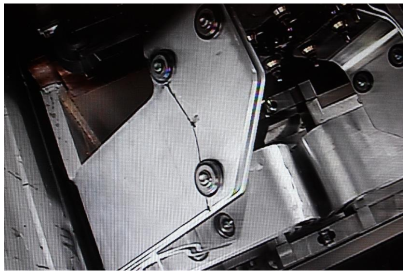


Be window embrittlement (FNAL)

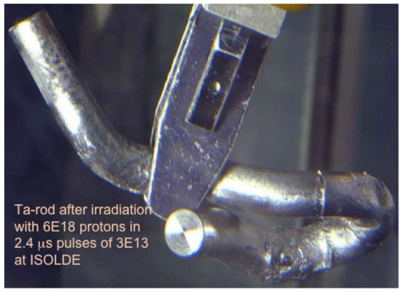


NOvA MET-01 target fin fracture (FNAL)

MINOS NT-01 target containment water leak (FNAL)

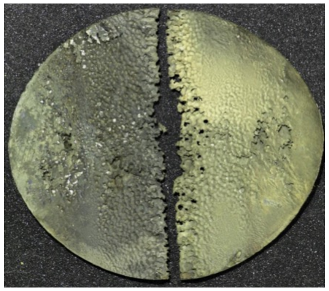


Horn strip line fatigue failure (FNAL)



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

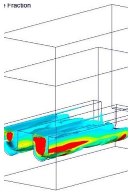
ISOLDE target (CERN)



Target containment vessel cavitation (ORNL - SNS)

High Power/Intensity Targetry Challenges

Material behavior and targetry technologies

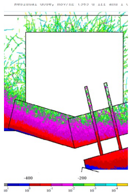


Heat removal

Thermal shock

Physics performance

Radiation damage



Operational safety

Storage and disposal

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

Thermal Shock and Radiation Damage most cross-cutting challenges facing high power target facilities

Motivation for Material R&D

Motivation for Target Materials R&D

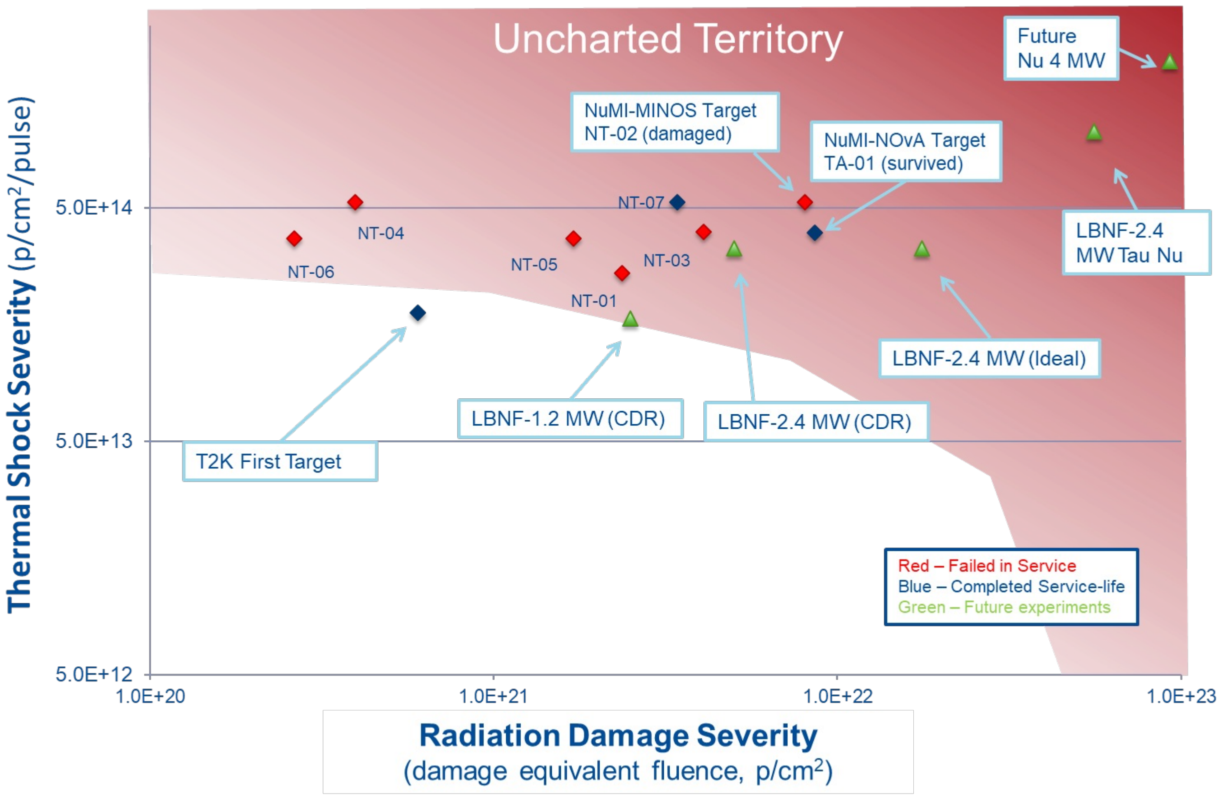
- In recent past, major accelerators facilities have been limited in beam power by target and window survivability (J-PARC MLF, NuMI/MINOS)

- Next generation multi-MW accelerator target facilities will present even greater challenges (LBNF 1.2/2.4 MW, proposed Neutrino Factory 4 MW)

- Develop robust beam-intercepting devices to maximize physics benefits of future experiments.
  - Avoid compromising particle production efficiency by limiting beam parameters
  - Accurate component lifetime prediction and reliable operation

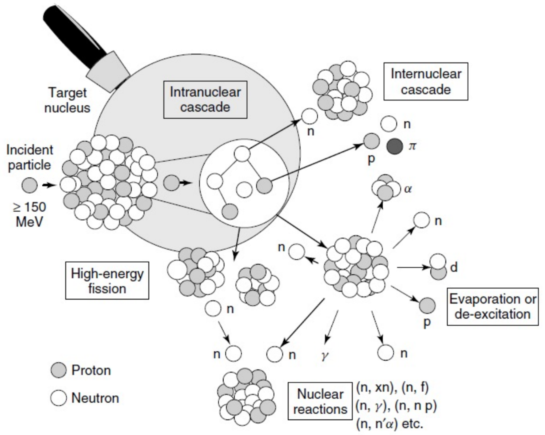
"Realizing a multi-MW proton source to provide neutrino beam intensities at Fermilab beyond PIP-II project will require significant further R&D on targets and focusing systems, concentrated on tolerance of materials to radiation effects of intense beams", HEPAP report, 2015.

Nu HPT R&D Materials Exploratory Map



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

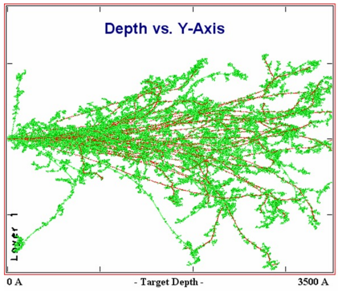
Radiation Damage Disorders Microstructure

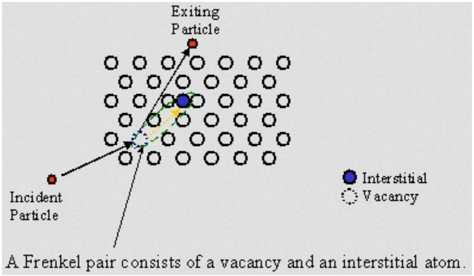


From D. Filges, F. Goldenbaum, in:, Handb. Spallation Res., Wiley-VCH Verlag GmbH & Co. KGaA, 2010, pp. 1–61.

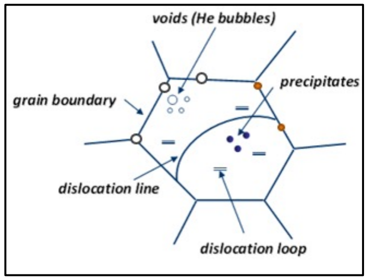
Microstructural response:

- ○ Creation of transmutation products
- ○ Creation and agglomeration of point defects
- ○ Segregation (precipitation) or depletion of point defect sinks
- ○ Atomic displacements (cascades): **Displacements Per Atom (DPA)** = Average number of stable interstitial/vacancy pairs created



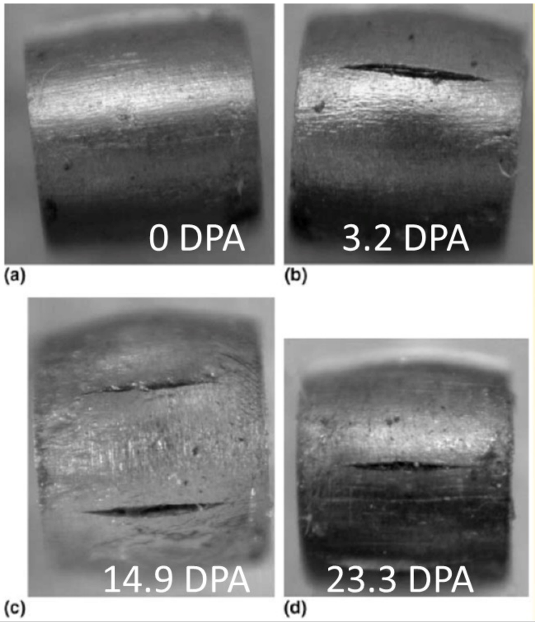


A Frenkel pair consists of a vacancy and an interstitial atom.



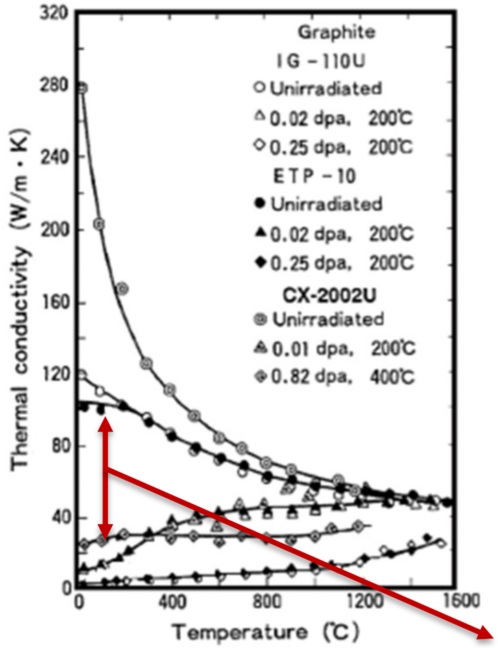
Radiation Damage Effects

- **Displacement in crystal lattice**
  (expressed as Displacements Per Atom, DPA)
  - 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
- **Very dependent upon material and irradiation conditions (temperature, dose rate, particle energy/type)**



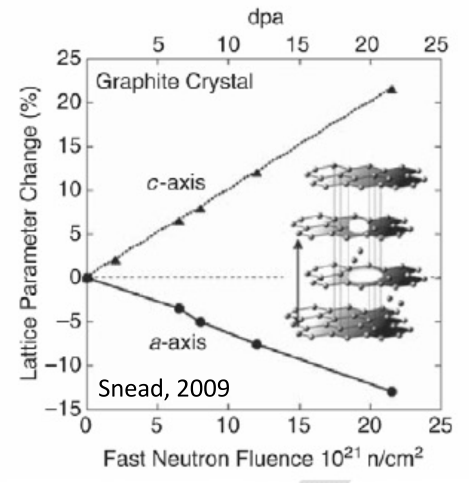
S. A. Malloy, et al., Journal of Nuclear Material, 2005.
(LANSCE irradiations)

Radiation Damage Effects



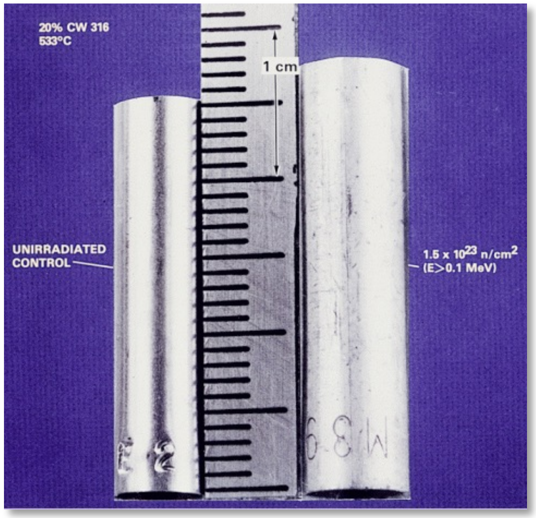
N. Maruyama and M. Harayama, Journal of Nuclear Materials, 195, 44-50 (1992)

Complex lattice swelling in graphite



Snead, 2009

Factor of 10 reduction in thermal conductivity at 0.02 DPA



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 1.5E23 n/cm^2

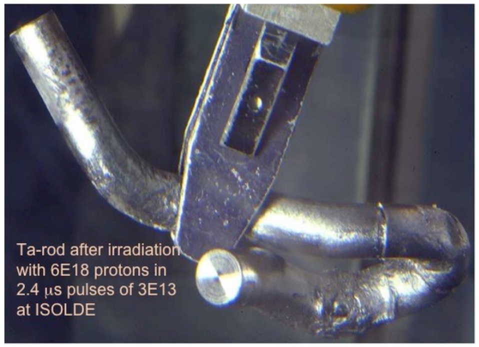
Thermal shock (stress waves)

- Localized area of compressive stress generated due to fast expansion of material surrounded by cooler material
    - 1 MW target: 250 K in 10 µs (2.5 x 10^7 K/s)

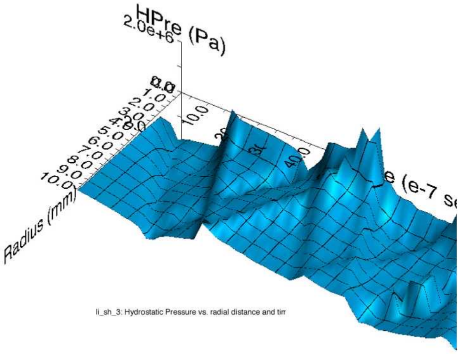
- Stress waves move through the target at sonic velocities

- Plastic deformation, cracking and fatigue failure can occur


Iridium target tested at CERN’s HiRadMat facility



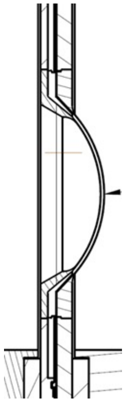
Ta-rod after irradiation with 6E18 protons in 2.4 µs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)

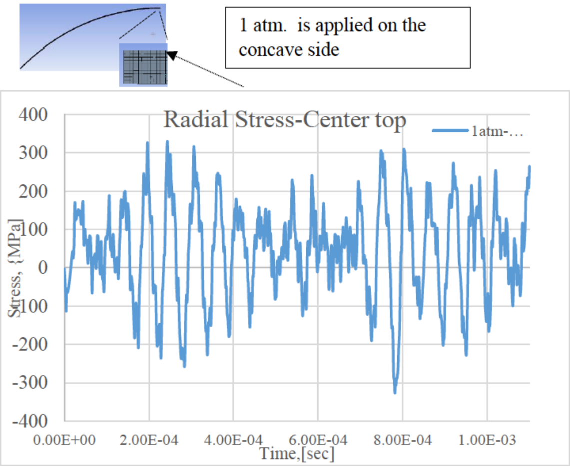


Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

Stress wave example: T2K window

Example: T2K Ti beam window





Material response dependent 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)

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

Initial stress wave amplitude

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

Elastic wave speed

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

Radiation Damage in accelerators

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

Effects from low energy neutron irradiations do not equal effects from high energy proton irradiations. Table compares typical irradiation parameters.

Cannot directly utilize data from nuclear materials studies!

$n \neq p$

1-14 MeV

100+ MeV

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

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

radiate.fnal.gov

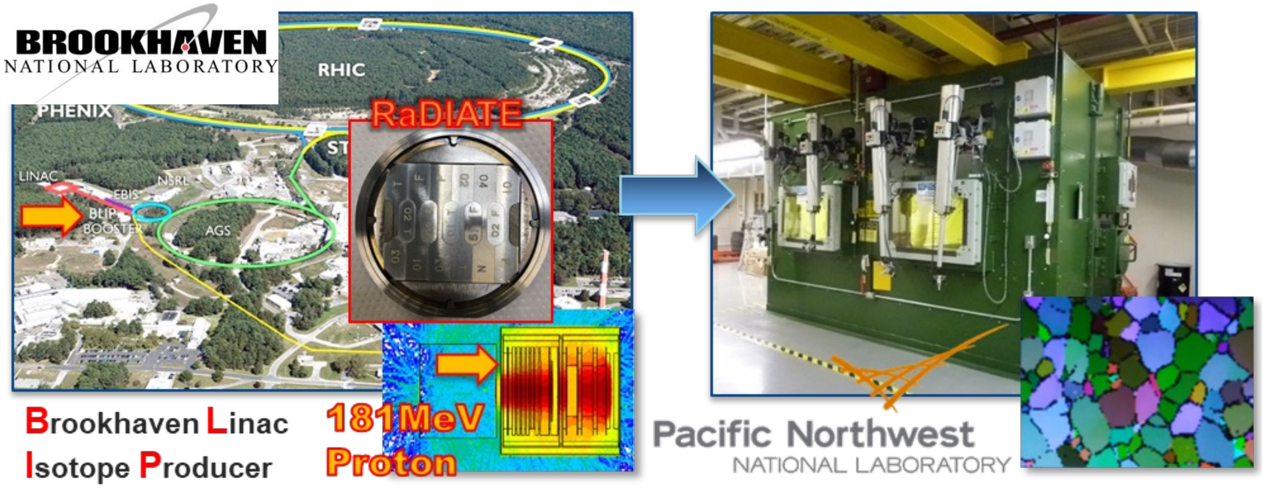
@J-PARC, Sep.20, 2017

Fermilab
BROOKHAVEN NATIONAL LABORATORY
OAK RIDGE National Laboratory
EUROPEAN SPALLATION SOURCE
UNIVERSITY OF OXFORD
CERN
Argonne NATIONAL LABORATORY
FRIB
Pacific Northwest NATIONAL LABORATORY
Los Alamos NATIONAL LABORATORY EST.1943
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Science & Technology Facilities Council

Radiation Damage Studies

High Energy Proton Irradiation

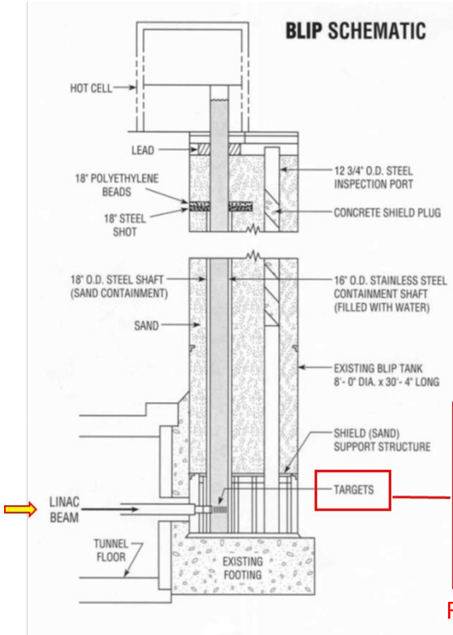
High energy proton irradiation of candidate materials

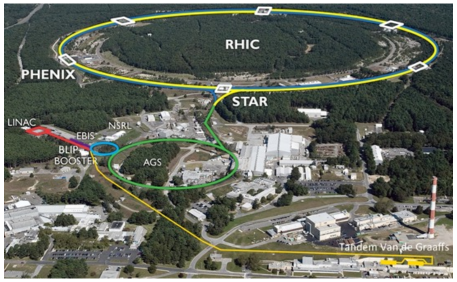


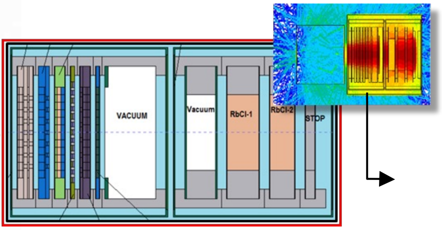
- Multi-material irradiation campaign at BNL’s BLIP facility organized by RaDIATE collaboration
- Post-Irradiation Examination (PIE) conducted at participating institutions with ‘hot cell’ facilities

BNL’s BLIP facility

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



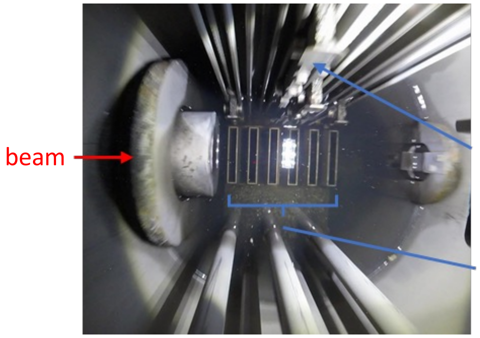




RaDIATE targets Isotope targets

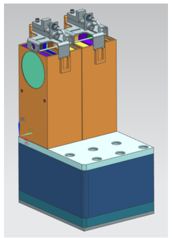
Upstream material layers optimized in order to deliver precise proton energy/flux for optimal isotope yield

View from top of water containment shaft



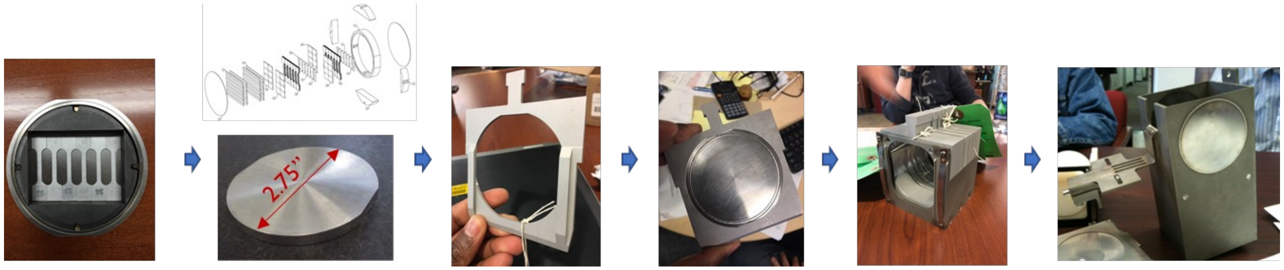
Drive chain mechanism for target box insertion/removal

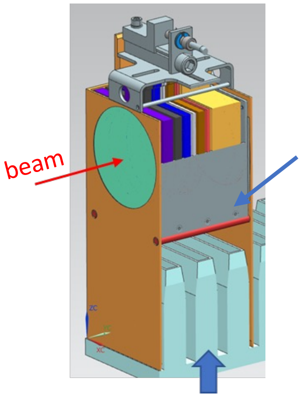
Water nozzles



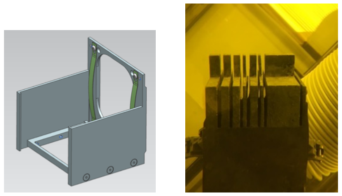
Targets under 30 ft of water

BLIP experimental set-up

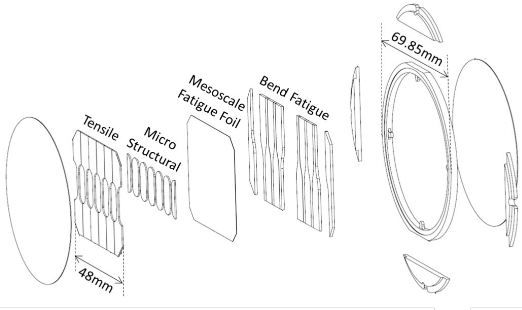




Water from nozzles flows in channels between capsules



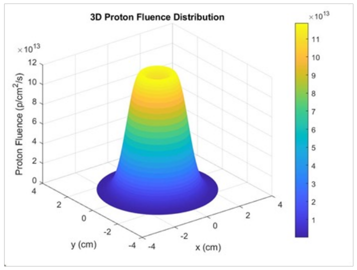
Basket sits on support rods in target box

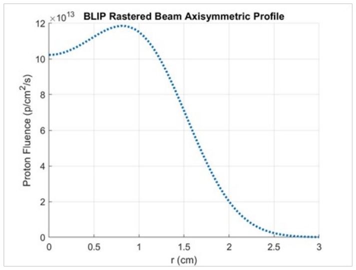


- No instrumentation and online diagnostics to monitor capsules during irradiation

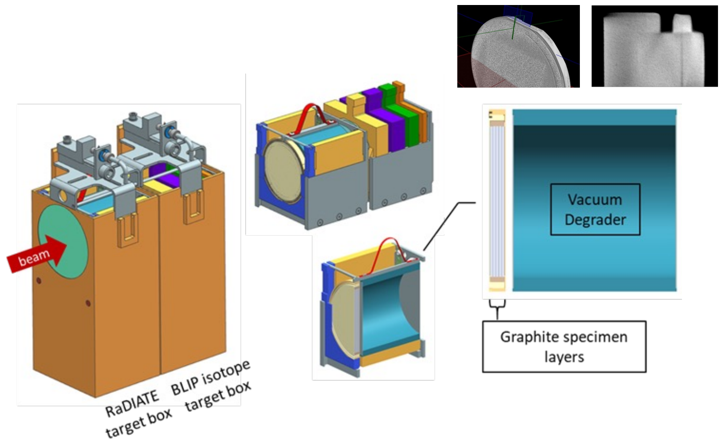
Rastered beam on targets

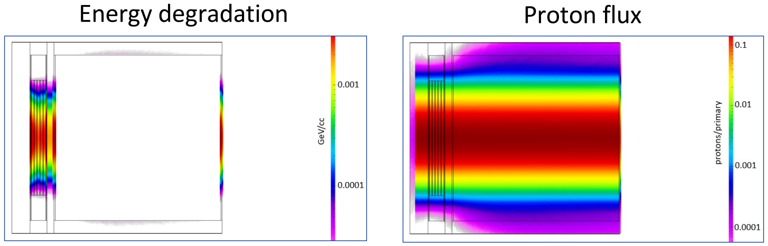
Peak current: 165 μA
Pulse frequency: 6.67 Hz
1 inner sweep at r: 0.55 cm
4 outer sweeps at r: 1.2 cm
σ: 0.51 cm





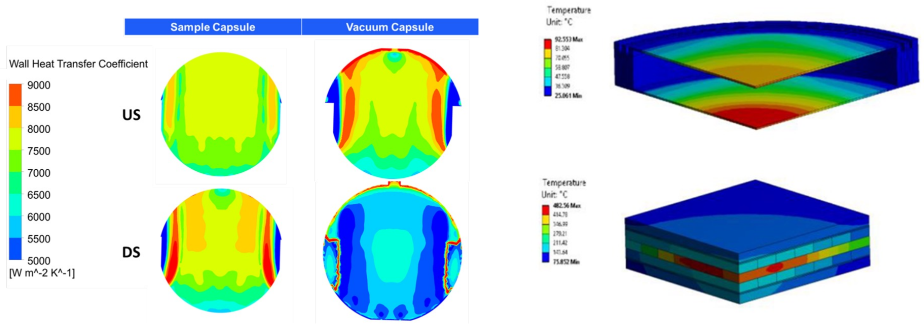
Complex experimental design for BLIP irradiation



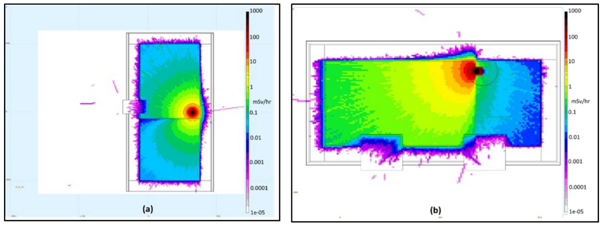


Capsule optimized to deliver precise proton energy/flux for downstream isotope production

Computational Fluid Dynamics and Finite Element Analysis to accurately evaluate cooling heat transfer coefficient, irradiation temperature and structural integrity of capsule during irradiation



Dose rate evaluation for post-irradiation handling and shipment

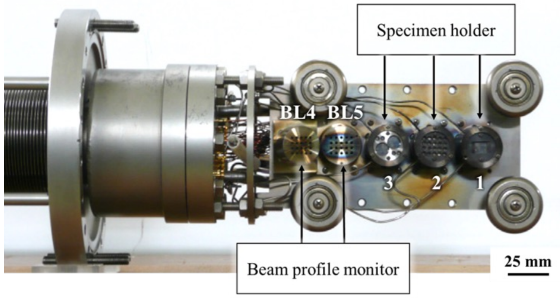


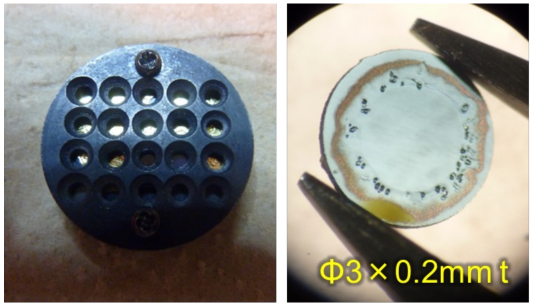
RaDIATE Collaboration

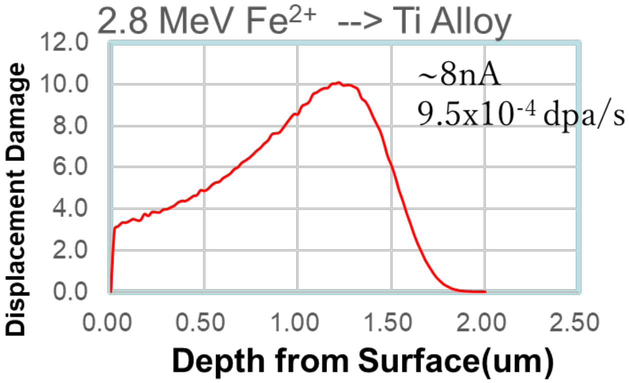
Radiation Damage In Accelerator Target Environments

Alternative irradiation method: low energy ion irradiation

HIT: **H**igh Fluence **I**rradiation Facility of the University of **T**okyo







Other ion irradiation facilities include:

- Michigan Ion Beam Laboratory (MIBL)
- Notre Dame Nuclear Science Laboratory (5U)
- IRRSUD facility (France)

HE proton irradiation

- **High energy, high fluence, large volume irradiations** ☺
- **Closely replicate HEP target environment and provide ‘bulk’ samples for analysis** ☺
- **Long irradiation times (mor**
  - HE irradiations (100 – 1000
    current and time to reach re
    (>1 DPA)
- **Difficulties of Post-Irradiation Examination** 😐
  - Activated samples requires remote handling techniques
  - Dedicated microscopy and testing equipment modified for use in ‘hot cells’

LE ion irradiation

- **Greatly accelerated damage rates (several DPA in hours)** ☺
  - Efficient way to screen candidate materials
- **Significantly lower irradiation cost** ☺
- **ation (PIE in ‘normal’ lab)** ☺
- **etration (0.5 – 100 μm)** 😐
  - Needs advanced micro-mechanics and meso-scale testing
- **Does not reproduce gas (H and He) production** 😐
  - Requires advanced triple-beam irradiation

Still need HE proton irradiations to correlate and validate results and irradiation techniques

Recent Results – Titanium Alloys

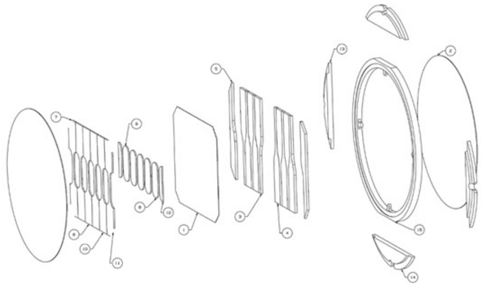
Titanium alloy studies

- Key beam-intercepting material at J-PARC/FNAL to realize high power (1.2 MW+) operation
  - J-PARC: primary beam window, Optical Transition Radiation (OTR) foil material
  - FNAL: LBNF target containment windows

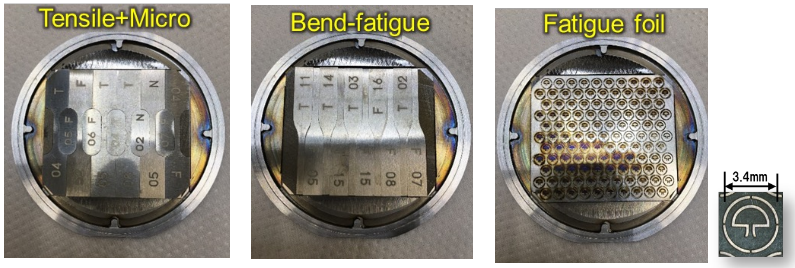
T2K Titanium beam window

BLIP 2017-2018 irradiation

Phase	Grade	Heat Treatment
α + β	Ti-6Al-4V Gr-5	Ultrafine grain
α	Ti-3Al-2.5Sn Gr-6	Annealed
β	Ti-15V-3Al-3Cr-3Sn	Solution Treated Aged
α	Pure Ti – Gr-2	Annealed
α + β	Ti-3Al-2.5V Gr-9	Annealed
α + β	Ti-6Al-4V Gr-23 ELI	Solution Treated Aged
α + β	Ti-6Al-4V Gr-23 ELI	Annealed



Titanium capsules



BLIP 2017/2018 Irradiation Summary

- BNL BLIP irradiation executed in 3 phases with different target box configurations
  - Over 200 specimens in 9 capsules
  - 3 capsules containing Titanium specimens

	2017		2018	Total
	Phase 1	Phase 2	Phase 3	
Total µA-hr	32464.49	45614.58	124979.89	203058.96
Total hr	226.27	302.94	789.09	1318.30
Total days	9.43	12.62	32.88	54.93
Total weeks	1.35	1.80	4.70	7.85
Avg. current (µA)	143.48	150.57	158.38	154.03
POT	7.30E+20	1.03E+21	2.81E+21	**4.57E+21**

181 MeV rastered beam
3 cm diameter footprint with
154 µA avg. current x 55 days
4.6×10^{21} POT

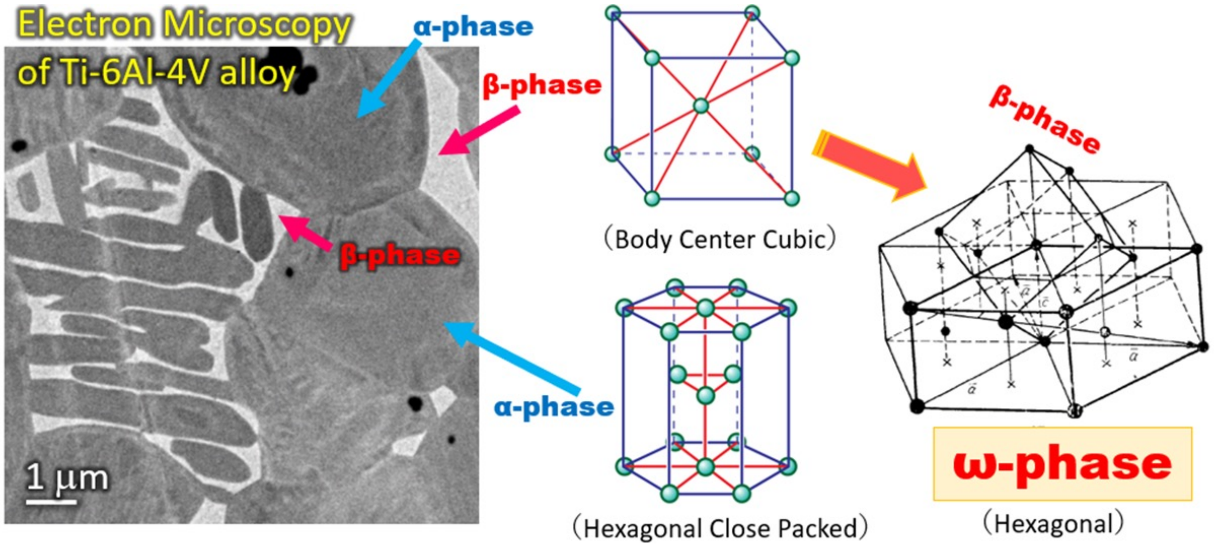
Comparable to MW facility operation

Capsule	Capsule position	Material	Irrad. Phases	Peak DPA/p (NRT)	POT	Total DPA
DS Ti1 (KEK)	6	Titanium	1	3.38E-22	7.30E+20	**0.25**
DS Ti2 (KEK)	6	Titanium	3	3.38E-22	2.81E+21	**0.95**
US Ti (KEK)	5	Titanium	1, 2, 3	3.34E-22	4.57E+21	~~1.53~~
Si (CERN)	3	SiC	1, 2	7.03E-23	1.76E+21	**0.12**
		Graphite	1, 2	2.52E-23	1.76E+21	**0.04**

Damaged

Past tensile data on proton-irradiated Titanium alloys only up to 0.3 DPA

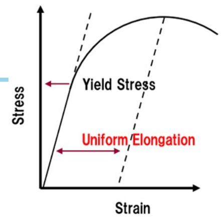
Electron Microscopy of Ti-6Al-4V

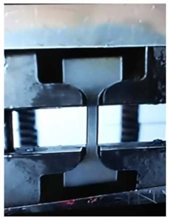


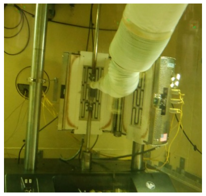
Ishida, T. et al., Journal of Nuclear Materials, 541, 2020.

- α-phase and β-phase with different crystal structures co-exist.
- The ω-phase is a very fine precipitate within the β-phase, with a specific relationship to the β-phase orientation.

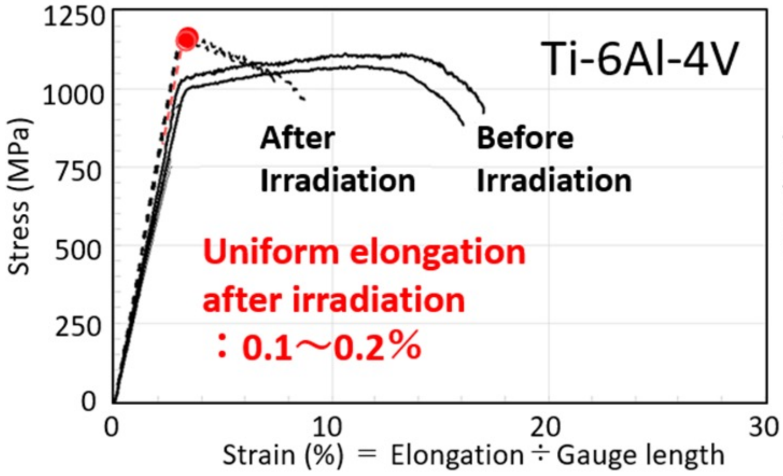
Ti alloy tensile testing (DS Ti1)

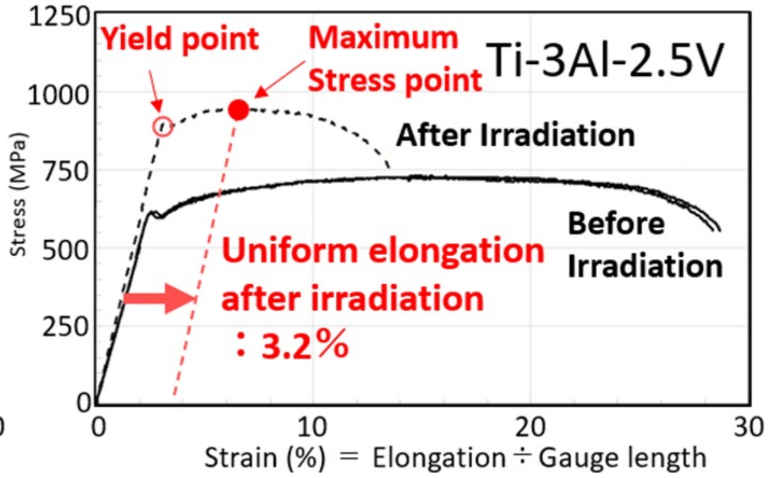






Stress-strain curves for Ti-6Al-4V (left) and Ti-3Al-2.5V (right)





Ti-6Al-4V large loss of ductility

- Uniform elongation after irradiation (~0.1%)

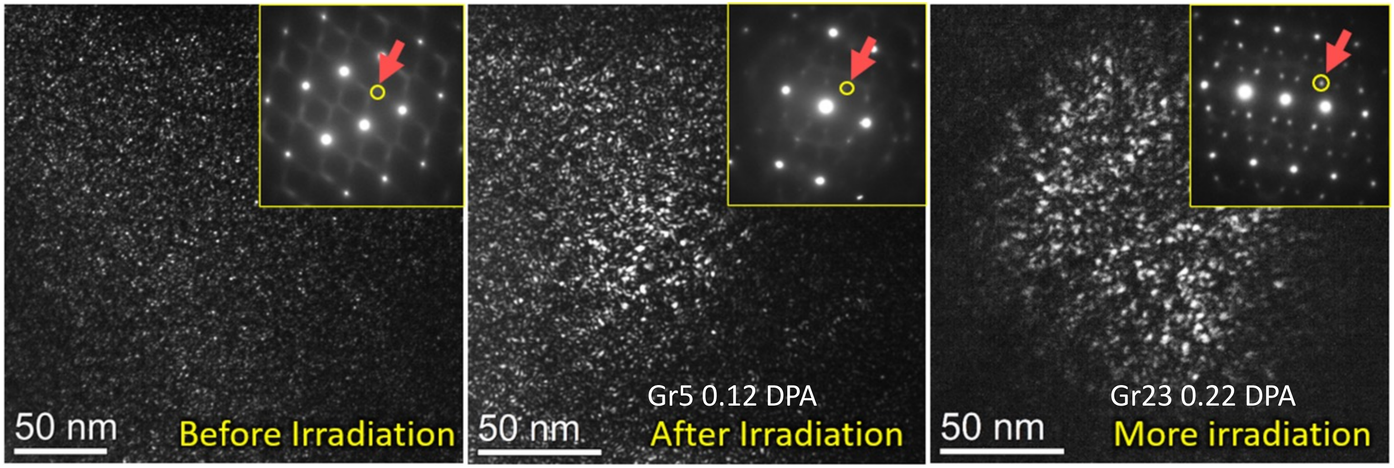
Ti-3Al-2.5V smaller loss of ductility

- Uniform elongation after irradiation (~3%)
- Near-α phase alloy seems more radiation tolerant (but lower non-irradiated strength)

Ishida, T. et al., Journal of Nuclear Materials, 541, 2020.

TEM Studies

Transmission Electron Microscopy observation of the β-phase in the Ti-6Al-4V alloy

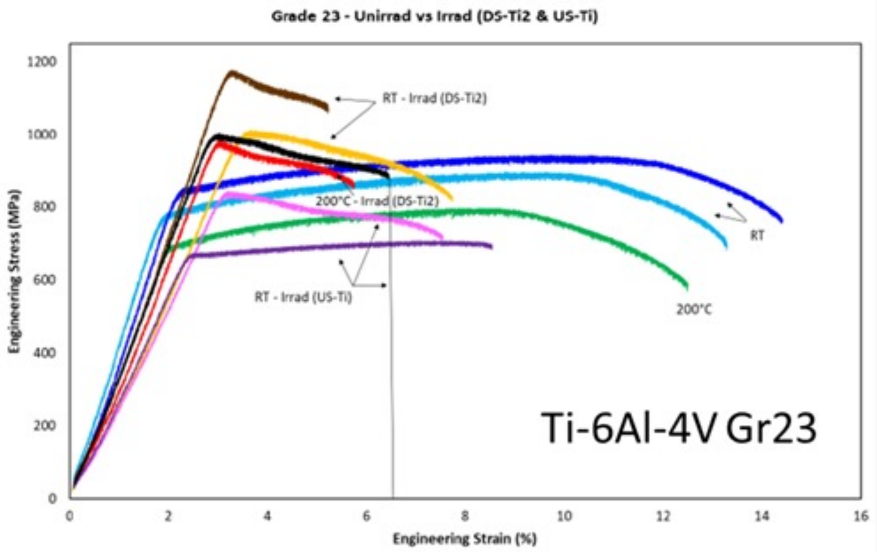


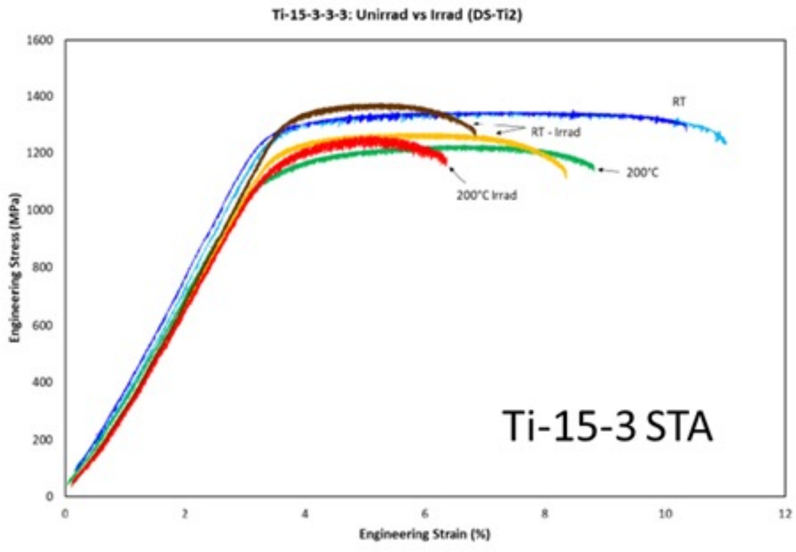
Ishida, T. et al., Journal of Nuclear Materials, 541, 2020.

- In the electron beam diffraction pattern shown in the inset, distinct spots appear and grow in size with increasing proton beam exposure as indicated by the red arrows
- This is the ω-phase that evolved upon proton beam exposure → **embrittlement**

Ti alloy tensile testing (DS Ti2)

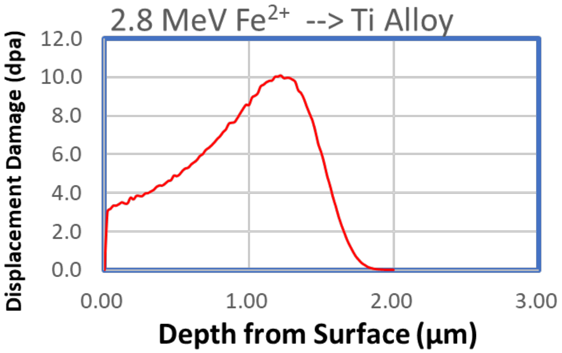
Preliminary results





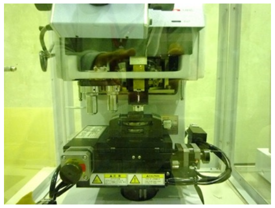
- After 0.95 DPA, radiation-induced hardening in Ti-6Al-4V Gr23 is significantly higher than in Ti-15-3 STA

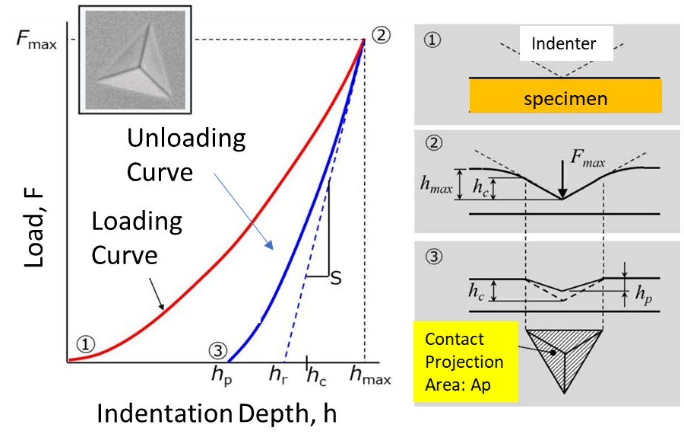
LE ion irradiations and nano-indentations at HIT



Current: ~8 nA
Dose rate: 9.5 x 10^{-4} DPA/s

Shimazu-DUH-211S type
Indenter : Berkovich (115°)





$$h_c = h_{max} - \epsilon(h_{max} - h_r)$$

$$\boxed{H_{IT} = \frac{F_{max}}{A_p(\boldsymbol{h_c})}}$$

Er : Elastic modulus of composite of indenter and specimen

$$E_r = \frac{S\sqrt{\pi}}{2\sqrt{A_p(h_c)}}$$

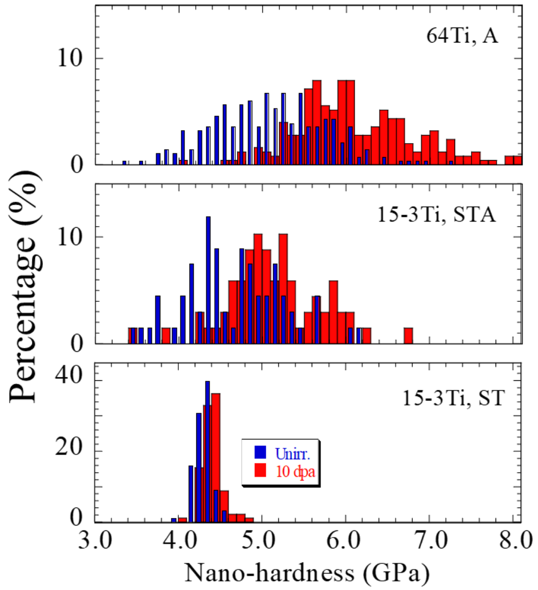
The indentation modulus E_{IT} of the specimen material is related to the reduced elastic modulus Er and the intender modulus Ei:

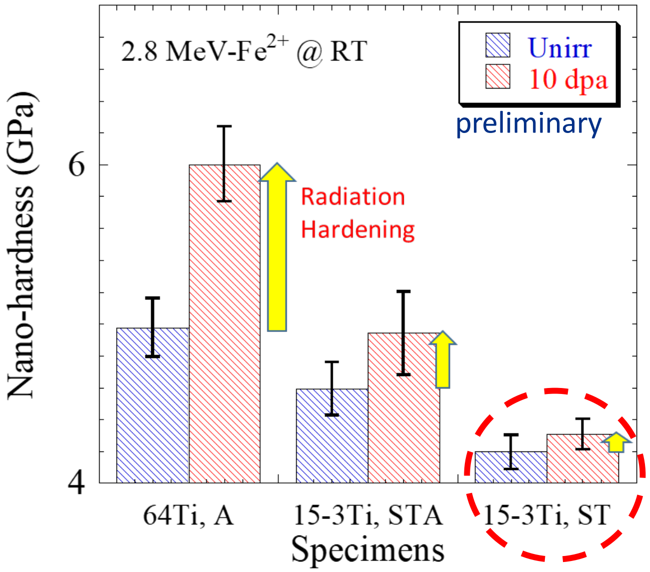
$$E_{IT} = \frac{1-(v_s)^2}{\frac{1}{E_r} - \frac{1-(v_i)^2}{E_i}}$$

Ei , νi : Elastic modulus, Poisson's ratio of indenter
Vs: Poisson's ratio of specimen,

Ti-6Al-4V and Ti-15-3 nano-indentation results

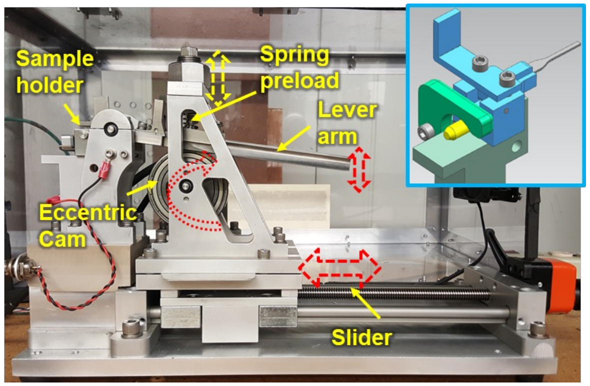
Preliminary results



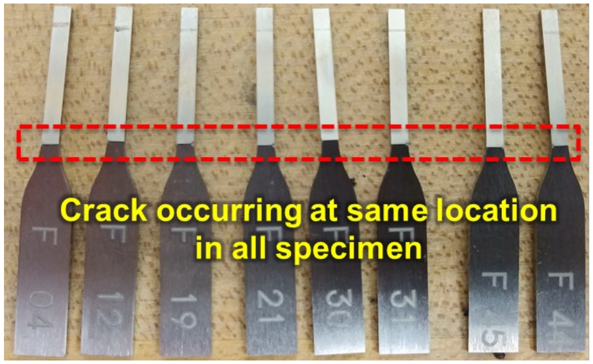


- Radiation hardening of Ti-15-3 was significantly smaller than that of Ti-6Al-4V
- Hardness of Ti-15-3 (Solution Treatment, w/o Aging) stays the same within the statistical effort after the irradiation to 10 DPA

Fatigue Performance of Proton-Irradiated Ti-6Al-4V



- Unique fatigue testing machine for irradiated specimen testing
- Cyclic load frequency 15 Hz
- Stress range: 375 MPa – 1,250 MPa
- Automatically shuts off when sample fails
- Designed for operation in ‘hot cell’



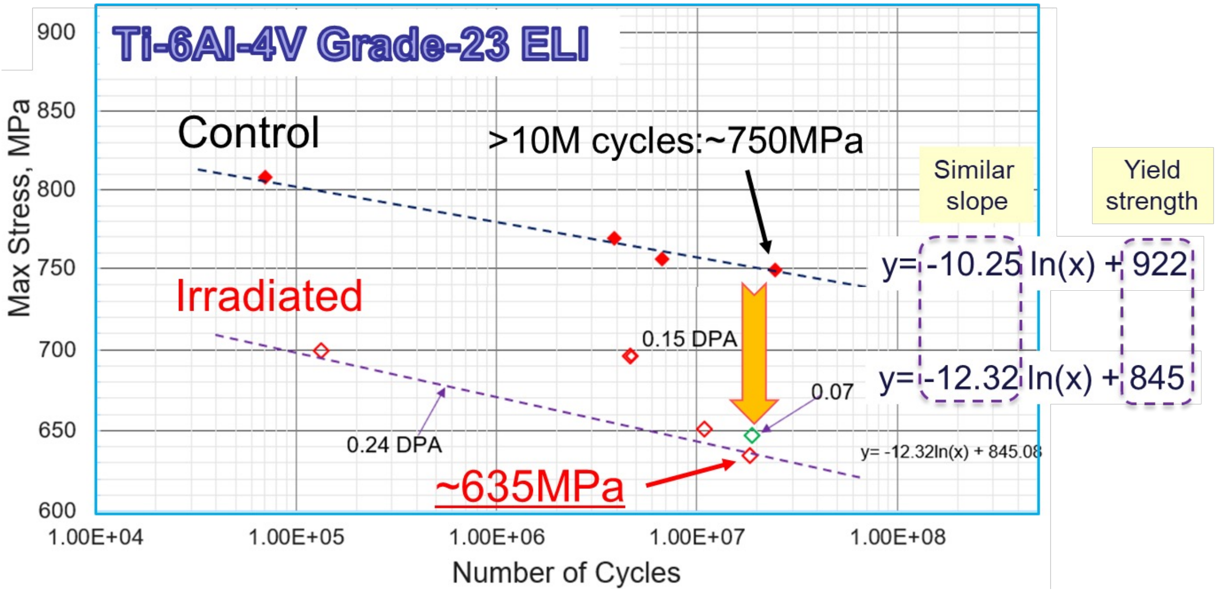
Crack occurring at same location in all specimen

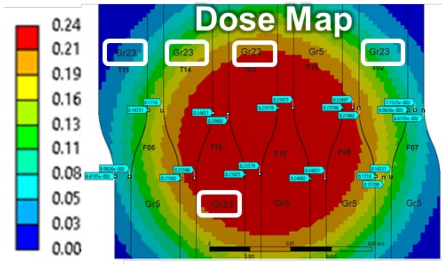
955MPa

Sharp edge stress concentration leads to fatigue crack

S.Bidhar et al., RaDIATE2019

Ti-6Al-4V Fatigue Performance





- 1st High Cycle Fatigue data on irradiated Ti-6Al-4V has been obtained
- Fatigue strength at 10 million cycles reduced from 750 MPa to 635 MPa at RT for 0.24 DPA
    - ~8M pulses/year for 1.16 s repetition cycle

S.Bidhar et al: https://meetings.triumf.ca/indico/event/81/session/6/contribution/18

Ti alloy key findings

- Prominent embrittlement of dual-phase Ti-6Al-4V due to radiation-induced ω-phase production in β-phase

- Precipitation-strengthened metastable β-phase Ti alloy Ti-15-3 with ST condition is radiation damage tolerant up to 10 DPA or more, though not stable for temperature between 250 – 400 °C (ω-embrittlement)
  - Confirmed by both HE and LE irradiations

- Ti-15-3 alloy with two-step ageing (ST2A) show promise for operation up to 300 C
  - Acceptable for 1.3 MW beam window with max. temp ~250 °C

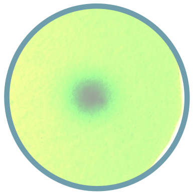
- 1st high cycle fatigue data obtained for irradiated Ti-6Al-4V

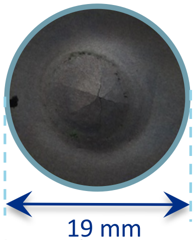
Ishida, T. et al., "Tensile behavior of dual-phase titanium alloys under high-intensity proton beam exposure: Radiation-induced omega phase transformation in Ti-6Al-4V", Journal of Nuclear Materials, 541, 2020.
"Why does Titanium Alloy Beam Window Become Brittle After Proton Beam Exposure", Press Release, November 6, 2020

Recent Results – Beryllium

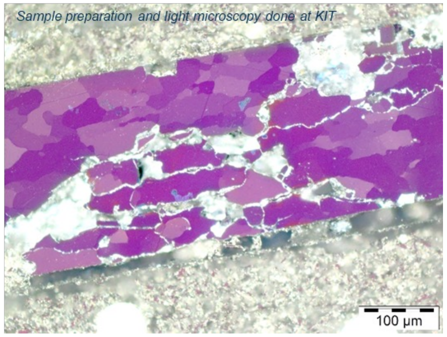
Radiation Damage Studies of Beryllium

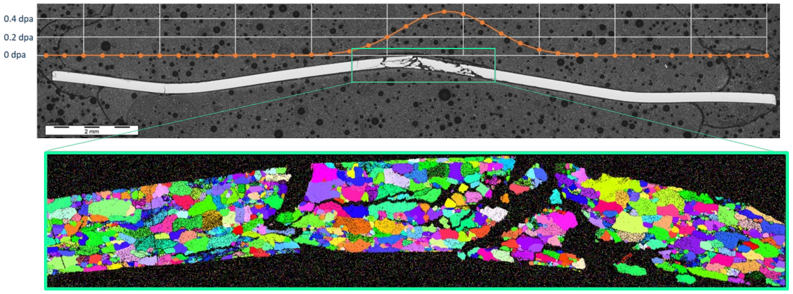
NuMI Be window

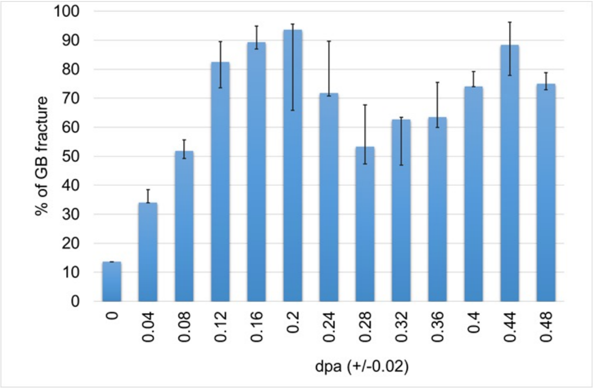




120 GeV proton beam
1.54 x 10^{21} POT
Up to 0.5 DPA
T ~ 50 °C





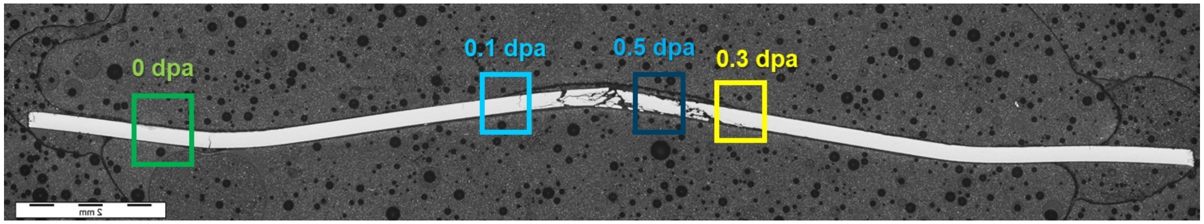


Kuksenko et al., J. of Nuclear Materials, 490, pp. 260-271, 2017
S. Kuksenko, RaDIATE Collaboration Meeting, 2019

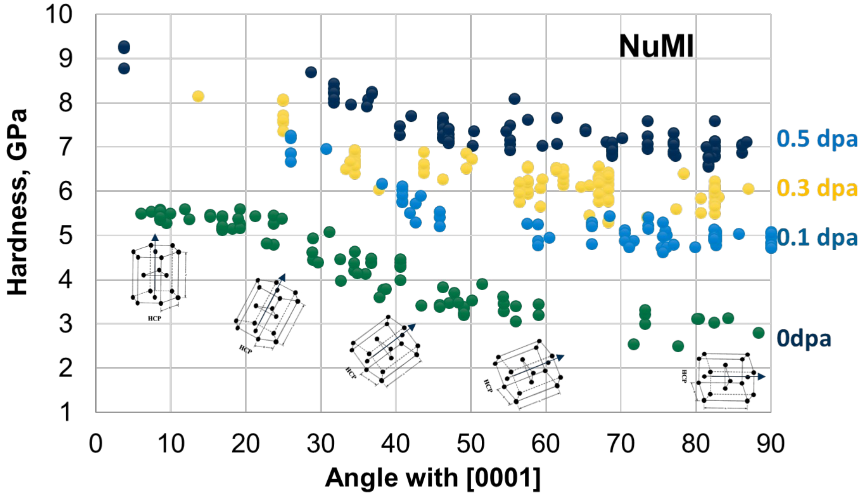
Transition from transgranular to grain boundary/mixed mode fracture

- Non-irradiated beryllium – mainly transgranular cleavage
- Grain-boundary fracture may be caused by strengthening of the matrix or “weakening” of GB

NuMI Be Window Hardness Measurements

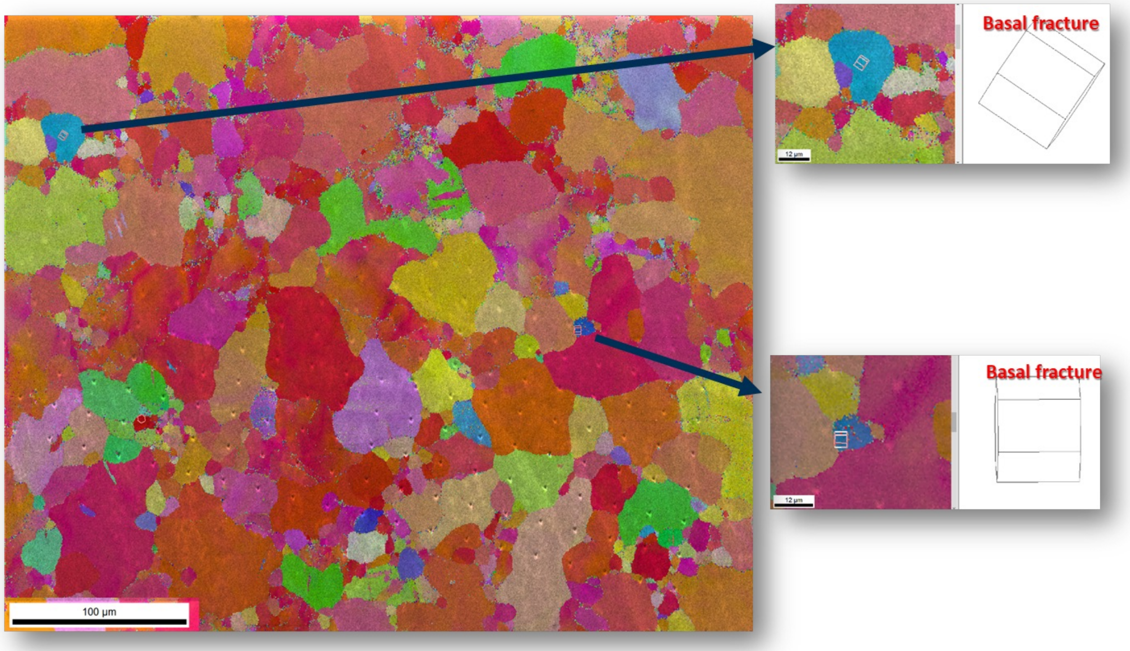


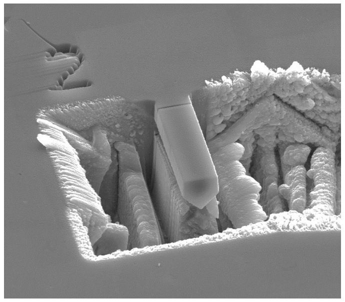
S. Kuksenko, RaDIATE Collaboration Meeting, 2019

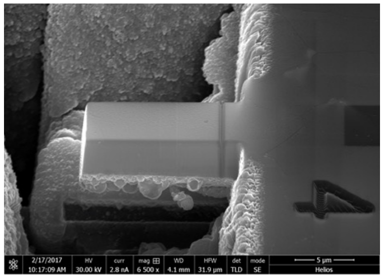


- **Significant hardening is observed in the proton-irradiated Be even at 0.1 DPA**
- **Hardening increases with irradiation to higher doses (at least up to 0.5 DPA)**
- **Hardness of the irradiated Be is less anisotropic**

Be Micro-cantilevers fracture tests

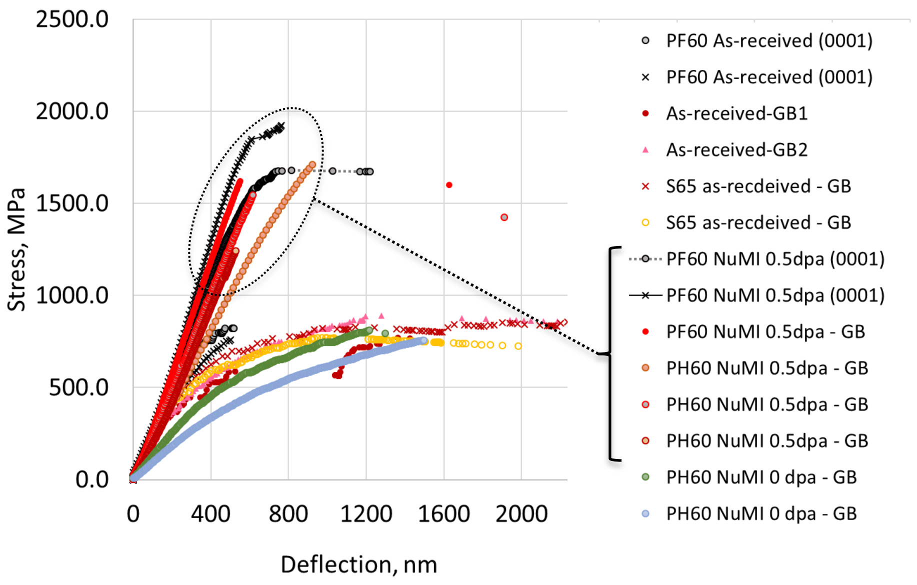


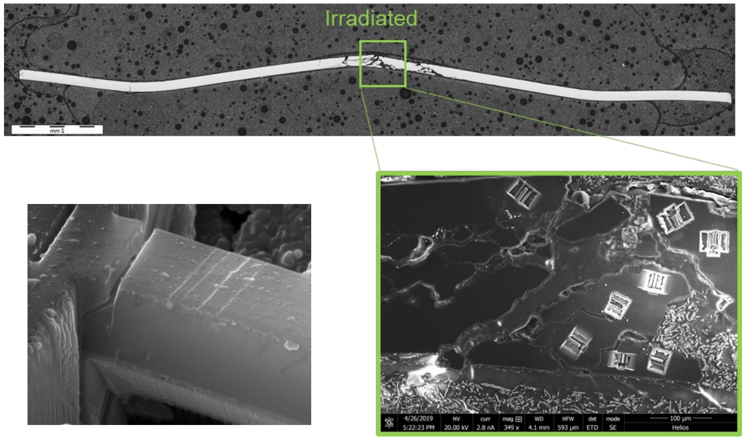




Micro-cantilevers were fabricated by Focused Ion Beam. Cantilevers were pre-notched so that the fracture properties of grain boundaries and basal cleavage plane, in both as-received and irradiated states, can be compared.

Be Micro-cantilevers fracture tests

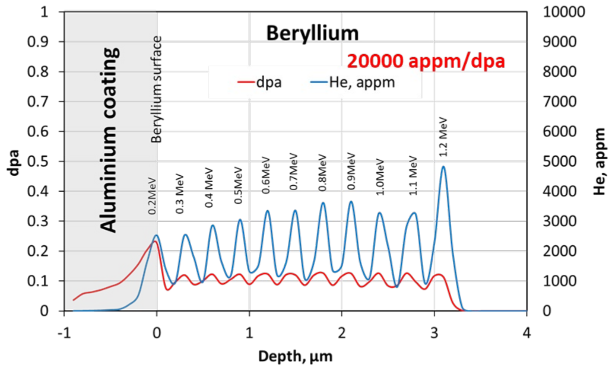


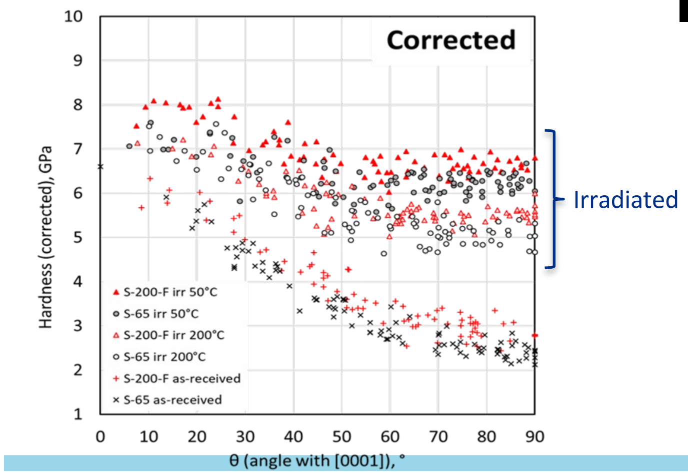


S. Kuksenko, RaDIATE Collaboration Meeting, 2019

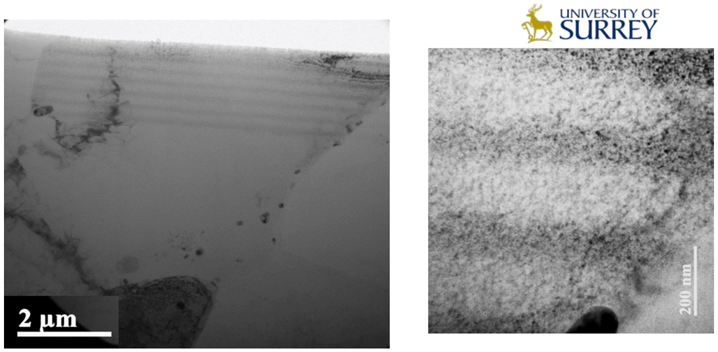
- More plastic deformation in as-received cantilevers oriented for GB fracture
- Almost no plasticity in cantilevers after irradiation in both GB and (0001) cleavage cantilevers
- Fracture load of both grain boundary and cleavage cantilevers increased significantly after irradiation

Ion irradiation of Be





He implantation in Be through Al degrader

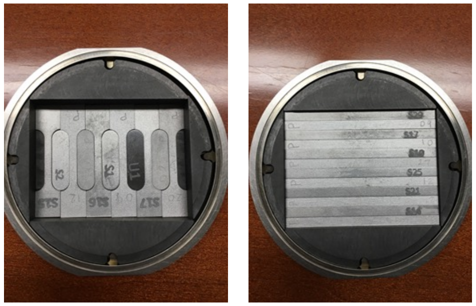


S. Kuksenko, RaDIATE Collaboration Meeting, 2019

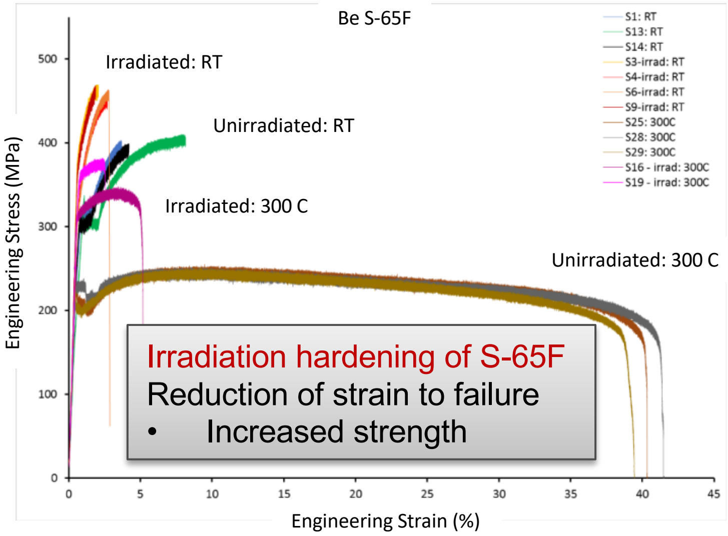
- S-65 and S-200-F were irradiated at 50 °C and 200 °C by He+ ions with eleven energies to create 3 µm wide damaged layer
- The calculated average damage is 0.1 DPA with the average He content in the damaged layer 2000 appm

Irradiated Be tensile testing (in progress)

- Various Be grade specimens irradiated at BLIP up to **0.06 DPA**
  - PF-60, S-65F, S-200F, S-200FH
- Tensile testing in hot-cells ongoing at PNNL at RT and 300 °C



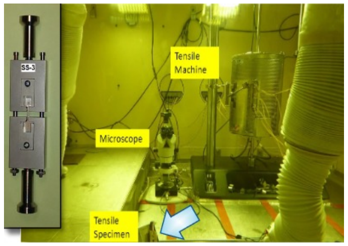
Be specimens assembled in BLIP capsule



Irradiation hardening of S-65F

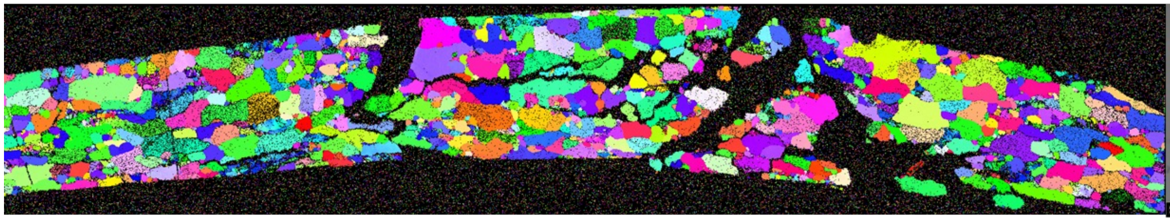
Reduction of strain to failure

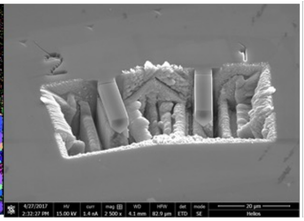
- Increased strength

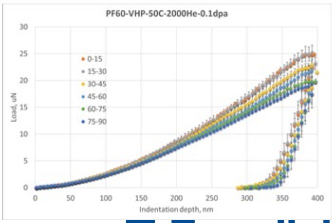


Beryllium Key Findings

- Radiation induces **significant hardening and fracture mechanism change** of beryllium even at **0.1 DPA**
- **Irradiation at 200°C shows less radiation-induced hardening**
- Preliminary tensile tests reveal **significant hardening** of S-65F grade at 0.06 DPA
- **Complete loss of ductility** in pre-notched cantilevers observed after proton and He ion irradiation at 50°C irradiation.



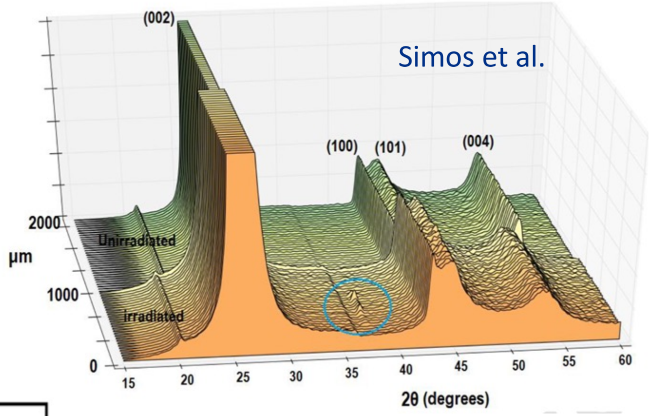


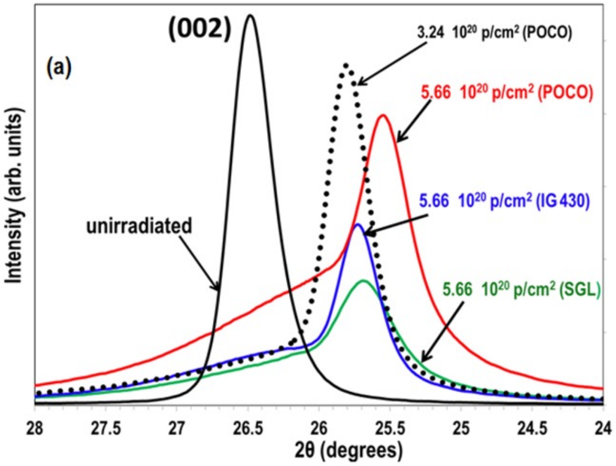


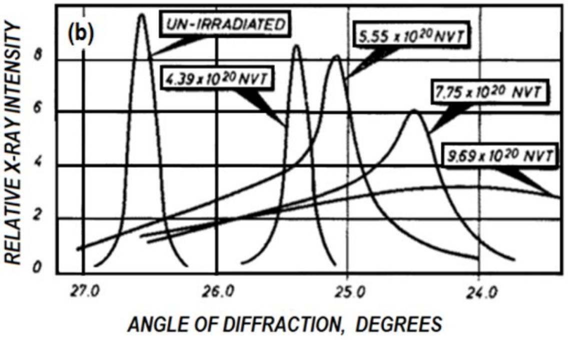
Recent Results – Graphite

X-ray Diffraction – Swelling in BLIP Irradiated Graphite

- X-ray diffraction at NSLS-II (BNL) on irradiated graphite shows lattice swelling
- Lattice swelling data from reactor studies agrees relatively well with data from HE proton irradiation!

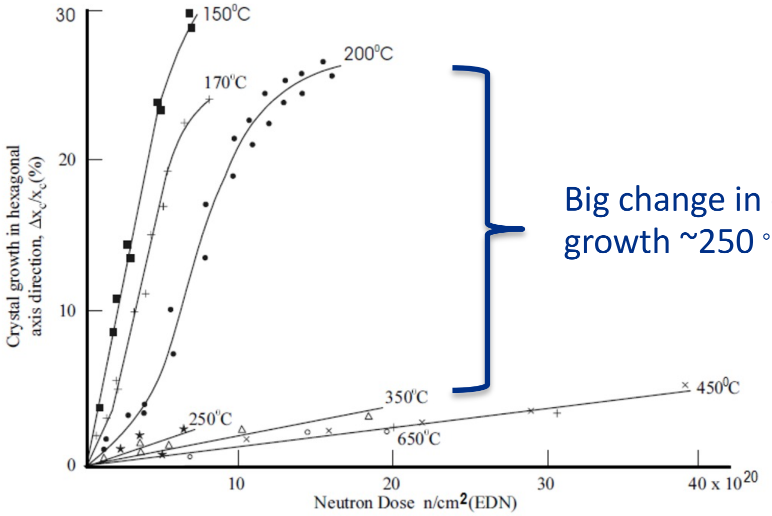

Simos et al.



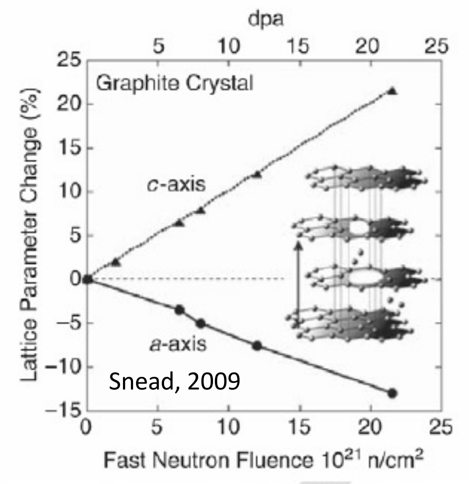


Neutron Irradiated Graphite Dimensional Changes

B.J. Marsden, “Irradiation Damage in Graphite due to fast neutrons in fission and fusion systems,” IAEA-TECDOC-1154, 2000



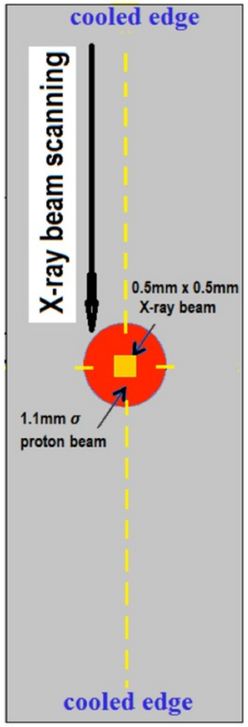
Big change in c-axis growth ~250 °C

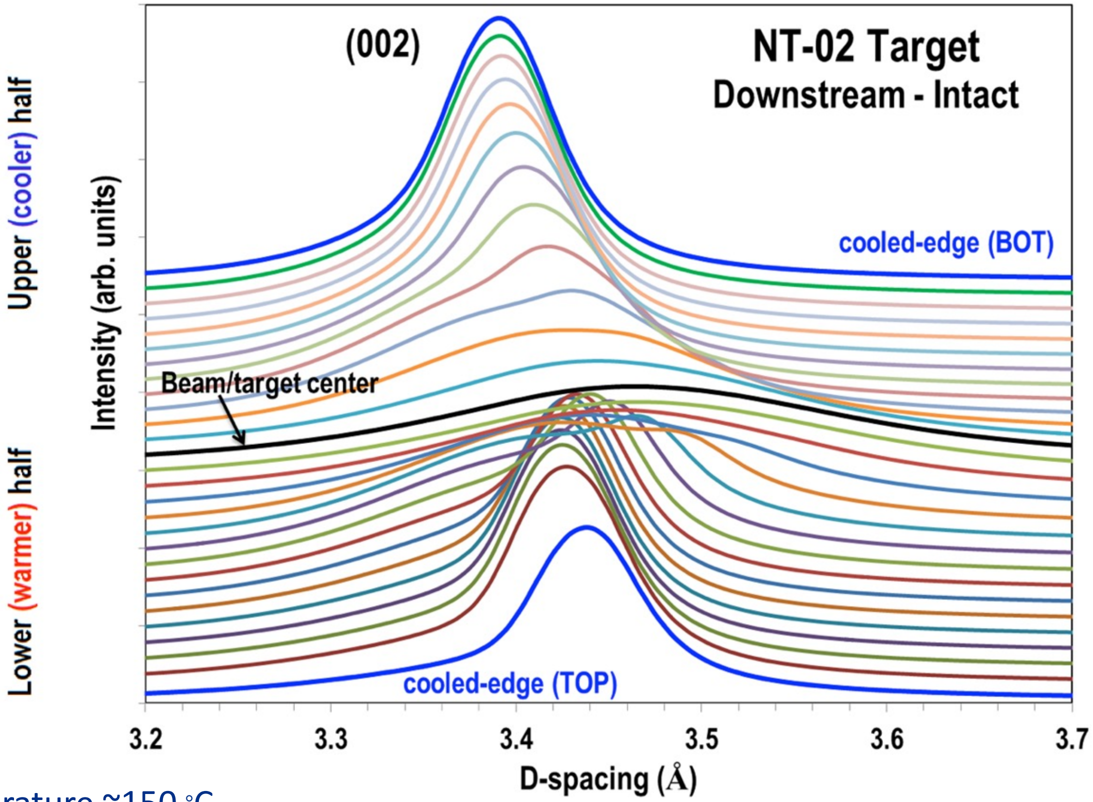


Snead, 2009

Correlation informed LBNF target choice of operating temperature (cooling system design)

X-Ray Diffraction of NuMI Graphite Fin





Shows lattice growth and amorphization at beam center

Irradiation temperature ~150 °C

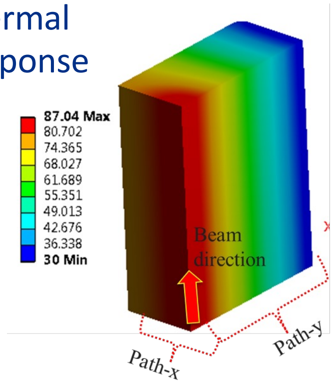
Modeling of graphite swelling predicts failure

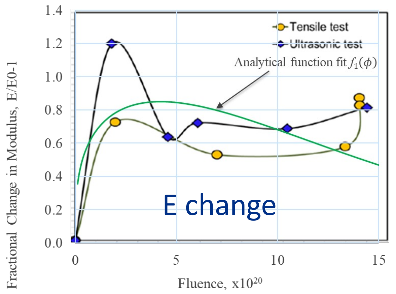
Sujit Bidhar (FNAL) – User defined material model in ANSYS

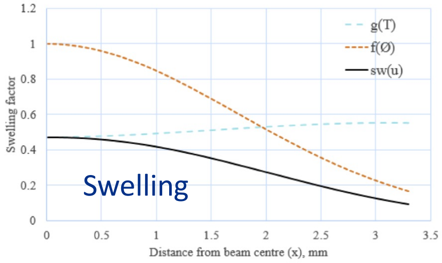
- **Elastic modulus** as a function of dose and temperature
- **Swelling (NSLS-II)** as a function of dose and temperature

Tensile strength of graphite:
- 79 MPa (0 DPA)
- 110 MPa (0.1 DPA)

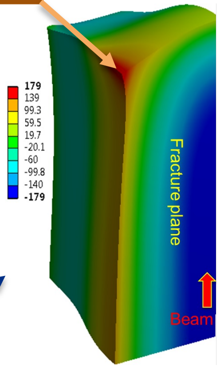
Thermal Response





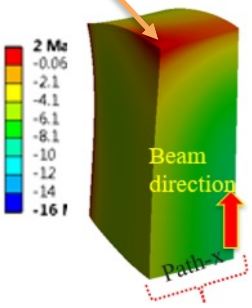


179 MPa!!



NT-02 fractured fin

2 MPa!!



Progress to date

- **Fermilab HPT R&D group and RaDIATE Collaboration grew to 14 institutions and over 70 participants**

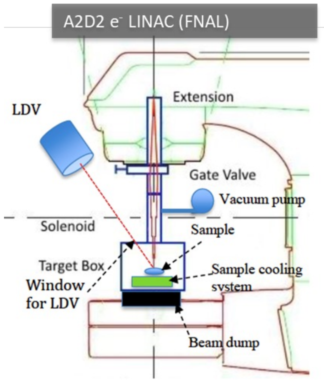
- **Completed Proton Irradiation Studies on Graphite, Beryllium and Titanium**
  - Informed design of LBNF target cooling system and graphite grade
  - Will inform design of Be beam windows for LBNF
  - Will inform design and grade of Ti windows for both LBNF and T2K
  - Benefits many facilities including LBNF, T2K, BDF at CERN, FRIB and HL-LHC

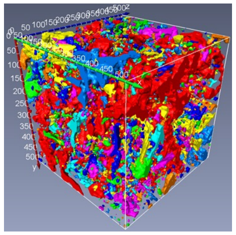
- **Using low energy ion irradiation for informing designs at much higher DPA for future facilities**
  - Fast screening to down-select material grades/alloys
  - Correlation and validation of results with HE proton irradiations

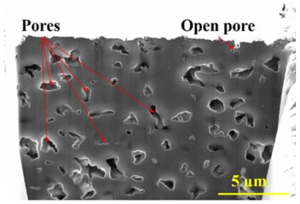
- **Completed two thermal shock experiments at CERN's HiRadMat facility**
  - Enabled prediction of stress and deformation of Be beam windows or targets
  - Brings together radiation damage and thermal shock on Be, Graphite and Ti alloys

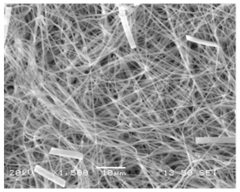
Ongoing & Future Work

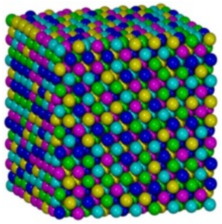
- Completing **Post-Irradiation Examination** of BLIP 2017/2018 HE proton irradiation
- Planning next **RaDIATE multi-material irradiation** at BLIP in 2024
- Continue **examination of retired targets and windows** (NOvA graphite target)
- **Ion irradiation** at even higher doses and elevated temperatures
- Develop **alternative thermal shock and radiation damage methods**
    - Reduce cost and duration of R&D cycles
- Planning next **thermal shock experiment** at CERN's HiRadMat facility in 2022
- **Modeling of He bubble** nucleation and growth in irradiation Beryllium
- Continue **opportunities with students** (4 PhD students and 1 post-doc)
- Develop **novel targetry materials**: nanofiber mats and high-entropy alloys











Summary

- **High power accelerators require beam-intercepting components that are capable of stable operation under challenging conditions.**
    - Currently operating accelerator facilities have been limited in beam power due to target survivability issues
    - Planned multi-MW accelerator upgrades and new facilities will present even greater challenges

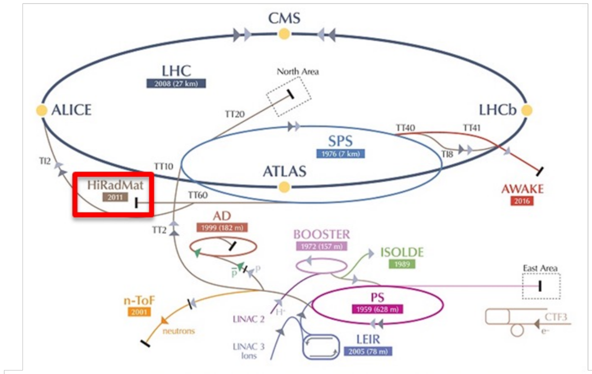
- **Targets, beam windows, and other beam intercepting devices will experience extreme conditions in next generation multi-MW facilities**
    - Lattice displacements & transmutation
    - Dynamic thermal stresses produced by pulsed beam

- **R&D by the global targets community via RaDIATE is progressing well**
    - High-energy proton irradiations and low-energy ion irradiations to study radiation-damage effects
    - In-beam thermal shock tests of irradiated material specimens tests both thermal shock and radiation damage in single experiments

Back-up slides

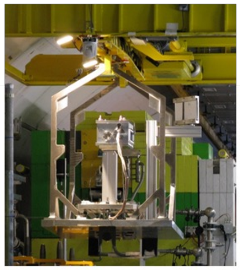
World First: Response of Irradiated Materials to Thermal Shock Induced By High Intensity Proton Beam

- **HRMT43-BeGrid2 :**Expose irradiated & non-irradiated specimens to high intensity beam pulses to compare thermal shock response
  - Irradiated specimens included Beryllium, Graphite, Silicon, Titanium, SiC-coated Graphite, Glassy Carbon specimens from BLIP
  - First unique test with radiation damaged materials with actual high-intensity proton beam-loading condition

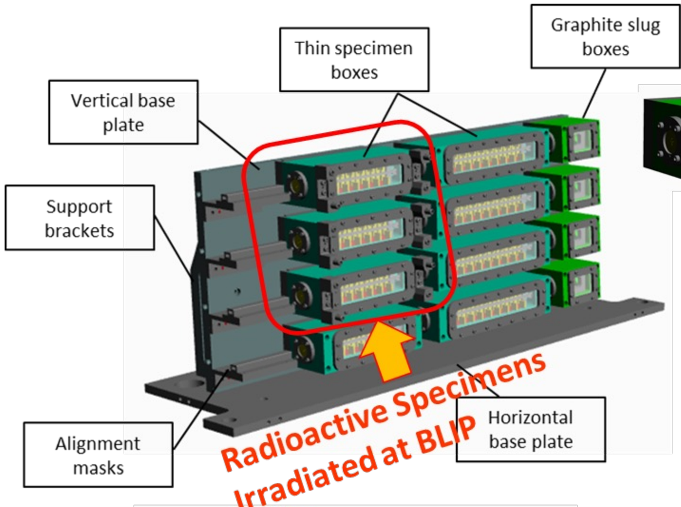


Beam Parameters	
Beam energy	440 GeV
Max. bunch intensity	1.2 x 10^{11}
No. of bunches	1 – 288
Max. pulse intensity	3.5 x 10^{13} ppp
Max. pulse length	7.2 μs
Gaussian beam size	1σ: 0.1 – 2 mm

Iridium rod in HRMT27 exploded with single shot 1.27x10^{12} ppp



HRMT-43 Experiment Set-up



Thin specimen boxes

Graphite slug boxes

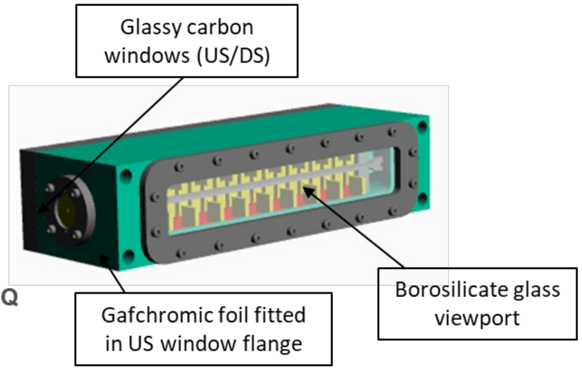
Vertical base plate

Support brackets

Alignment masks

Horizontal base plate

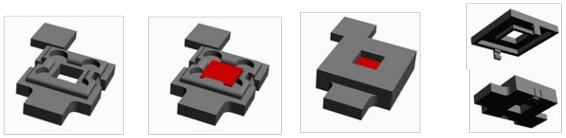
POCO ZXF-5Q
graphite slug

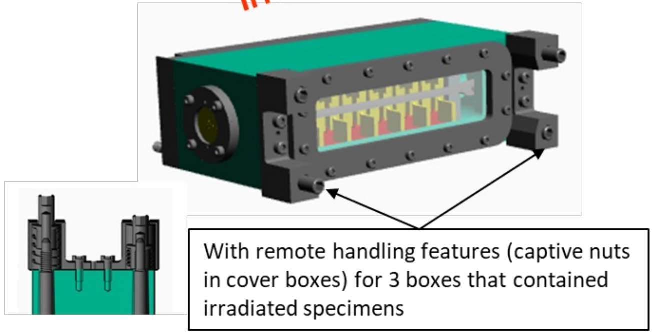


Glassy carbon windows (US/DS)

Gafchromic foil fitted in US window flange

Borosilicate glass viewport



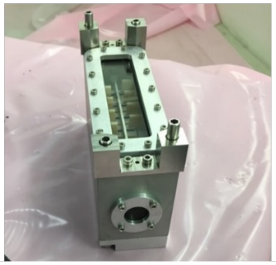


With remote handling features (captive nuts in cover boxes) for 3 boxes that contained irradiated specimens

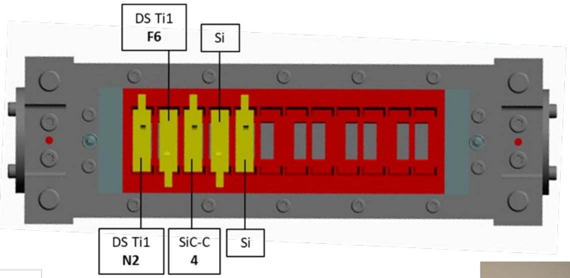
- Hermetically-sealed in air to fully contain specimens and avoid contamination release

- Irradiated specimens were shipped from BNL to PNNL
  - Assembled specimens in holders and inner containment boxes
- Irradiated boxes were shipped from PNNL to CERN for final assembly to vertical base plate

Successful Beam Exposure at CERN

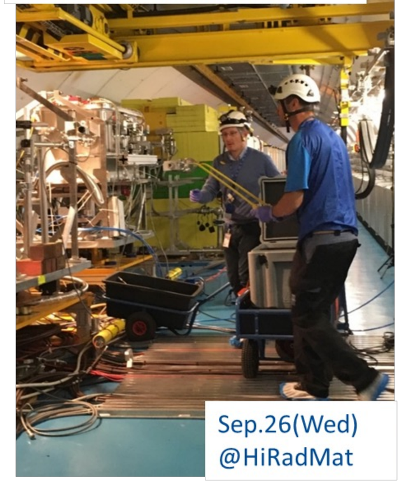


3 boxes with irradiated-specimens assembled at PNNL hot-cell

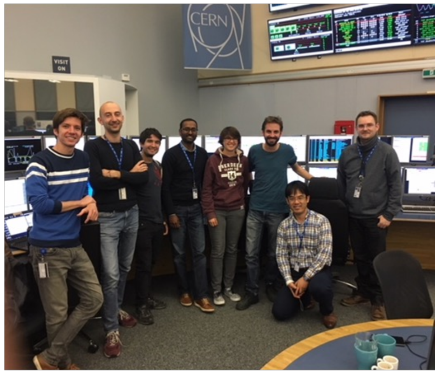


K.Ammigan, RaDIATE2018

BOX-3
Ti-6Al-4V Gr5
Ti-3Al-2.5V Gr9
SiC-coated Graphite
IG-630U



Sep.26(Wed)
@HiRadMat

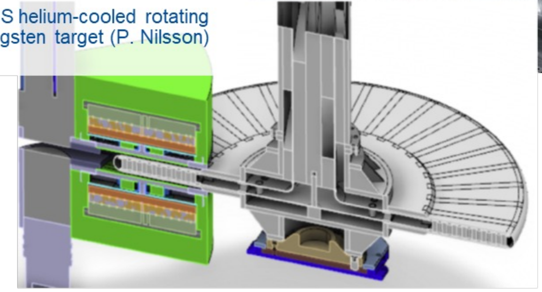


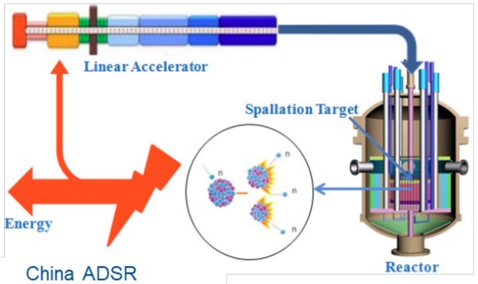
October 1 – 2, 2018 4:00am
BeGrid2 Exposure has been
completed !
PIE to begin in July 2019

Accelerator Targets Beyond High Energy Physics

- Spallation Neutron Sources
  - SNS at ORNL (1.4+ MW)
  - ESS in Sweden (4 MW)
  - ISIS in UK (0.16 MW)
  - MLF at J-PARC (1+ MW)
  - SINQ at PSI, Switzerland
- Rare Isotope Beams
  - FRIB at MSU
  - ISAC at TRIUMF (Canada)
  - ISOLDE at CERN
  - RIKEN in Japan
  - RAON in S. Korea
- Medical Isotope Production
  - Several facilities around the world
- Accelerator Driven Sub-critical Reactors


SNS mercury target


ESS helium-cooled rotating tungsten target (P. Nilsson)



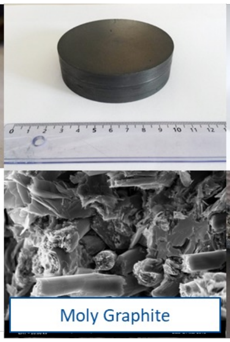
China ADSR

Development of New Targetry Materials

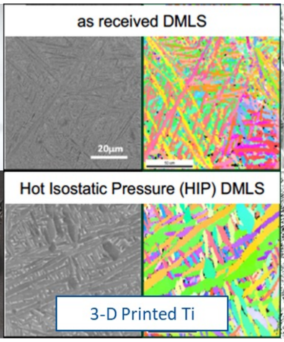
An ultimate objective is to develop new materials specifically addressing the requirements of future target facilities. Some progress is being made in exploring some of the newer materials and forms of material that have been developed.

- Glassy carbon (BeGrid2 material, CERN/FNAL)
- Molybdenum graphite (RaDIATE BLIP run material, CERN)
- Metal foams (BeGrid2 material, FNAL)
- 3-D Printed Ti alloy (RaDIATE BLIP run material, FRIB)
- Nano-fiber mats (BeGrid2 material, FNAL LDRD)
- High-Entropy Alloys (UW-M collaboration)

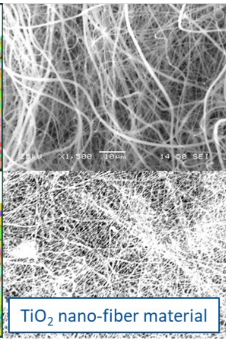

Glassy Carbon

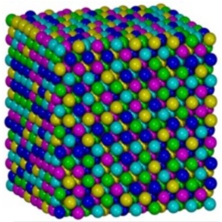

Moly Graphite


Metal Foams



3-D Printed Ti


TiO_2 nano-fiber material


High-Entropy Alloy