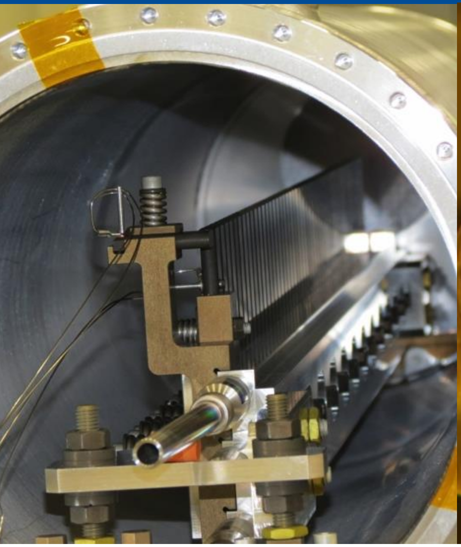
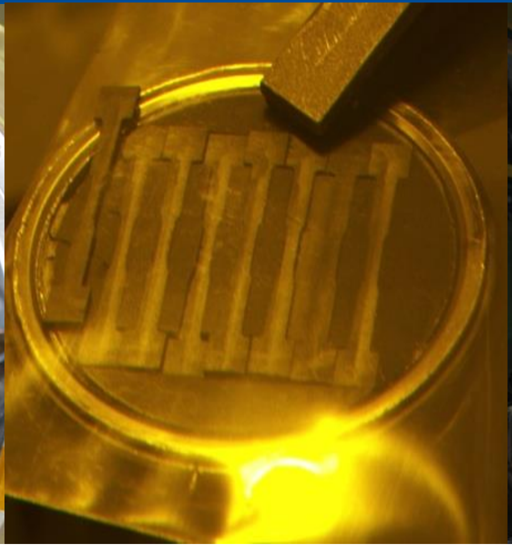
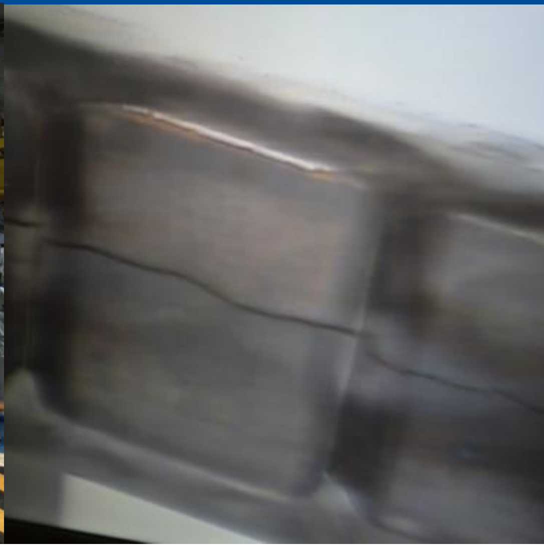



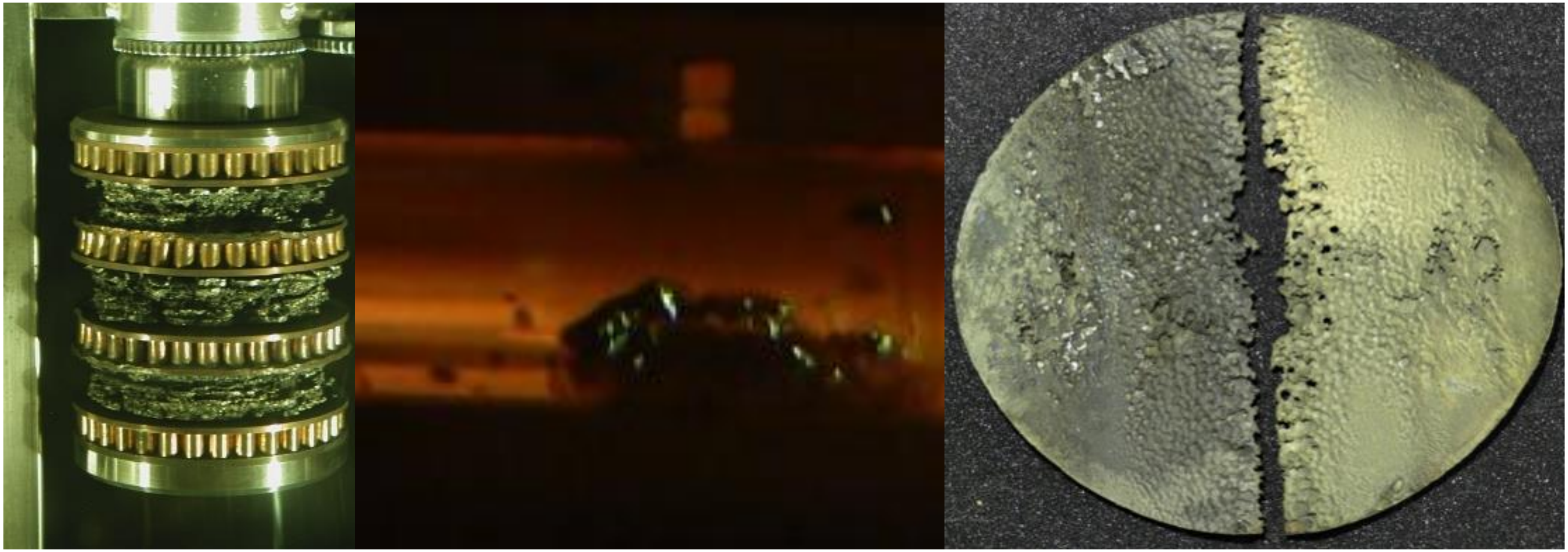


The Challenges of Next Generation Neutrino Beam Targetry and the RaDIATE Collaboration

Patrick Hurh (Fermilab)
on behalf of the RaDIATE Collaboration

ATS Seminar – CERN – 06 Feb 2018

High Power Targetry Challenges



- Recently major accelerator facilities have been limited in beam power not by their accelerators, but by their target facilities (SNS, NuMI/MINOS)
- Plans for future high power, high intensity target facilities will present even greater challenges
- To maximize the benefit of high power accelerators (physics/$), these challenges must be addressed in time to provide critical input to multi-MW target facility design

Neutrinos continue to make news

Fermilab Accelerator Complex

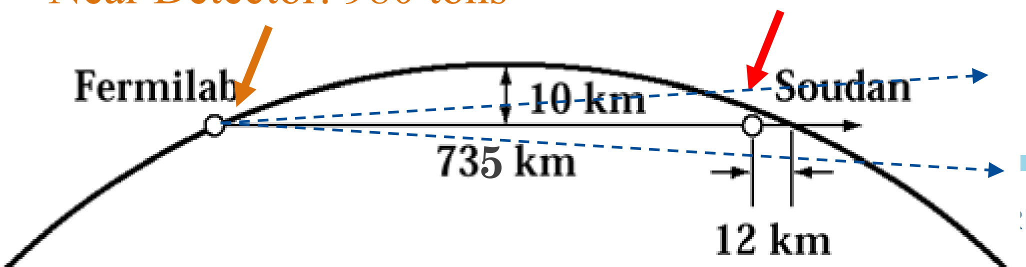
The NuMI Facility

“Neutrinos (ν – Nu) at the Main Injector”

- Intense muon-neutrino beam directed towards Minnesota
- Main Injector supplies 25 – 50 trillion 120GeV protons every 1.33 seconds
  - Operating regularly at 700 kW
- Each pulse produces about 10^{14} ν_{μ}
  - ~ 20,000,000 Pulses per year
- Direct beam 3^{o} down
- On-site and off-site experiments
- Different types of neutrino beams
- Beam is 10s of kilometers wide at exit

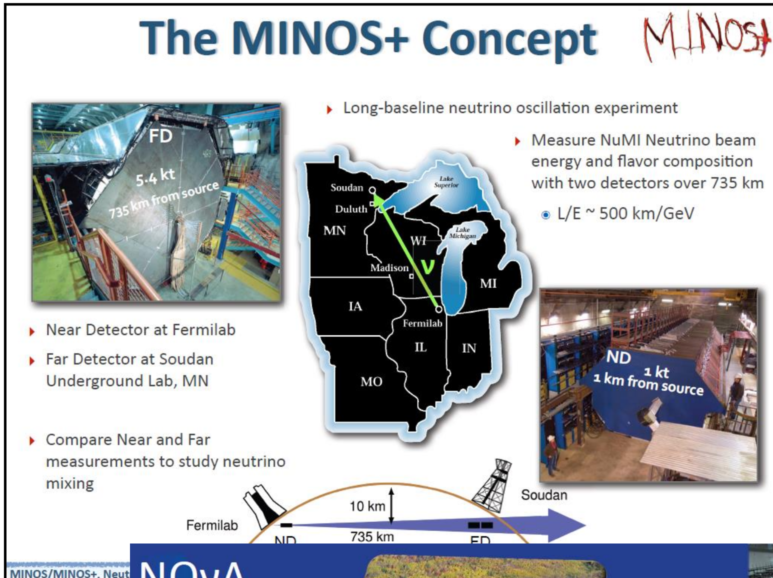
Near Detector: 980 tons

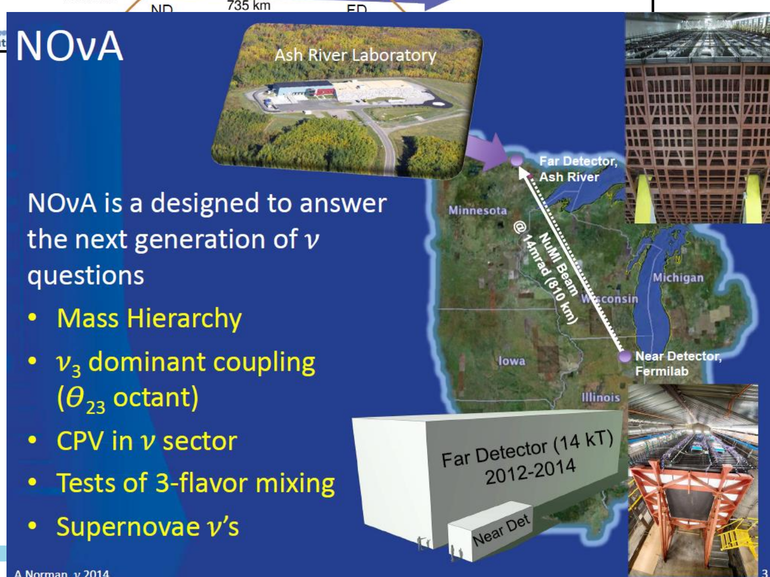
Far Detector: 5400 tons



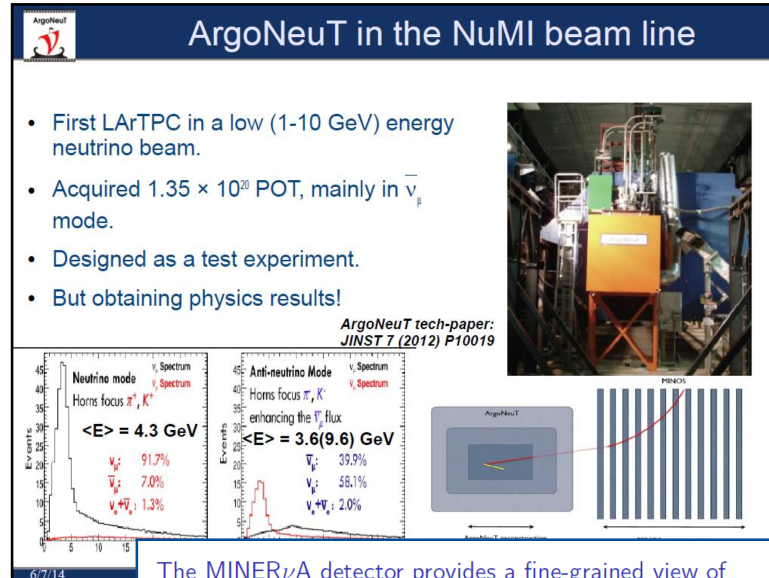
Multiple Experiments in the NuMI Beam

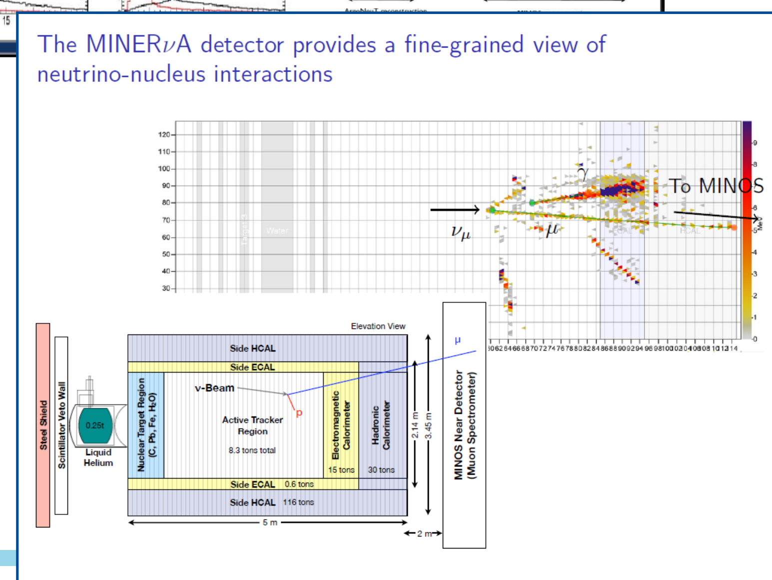
Long-baseline oscillation experiments





Neutrino scattering experiments





Why a Beam? – Controlled Laboratory Experiment

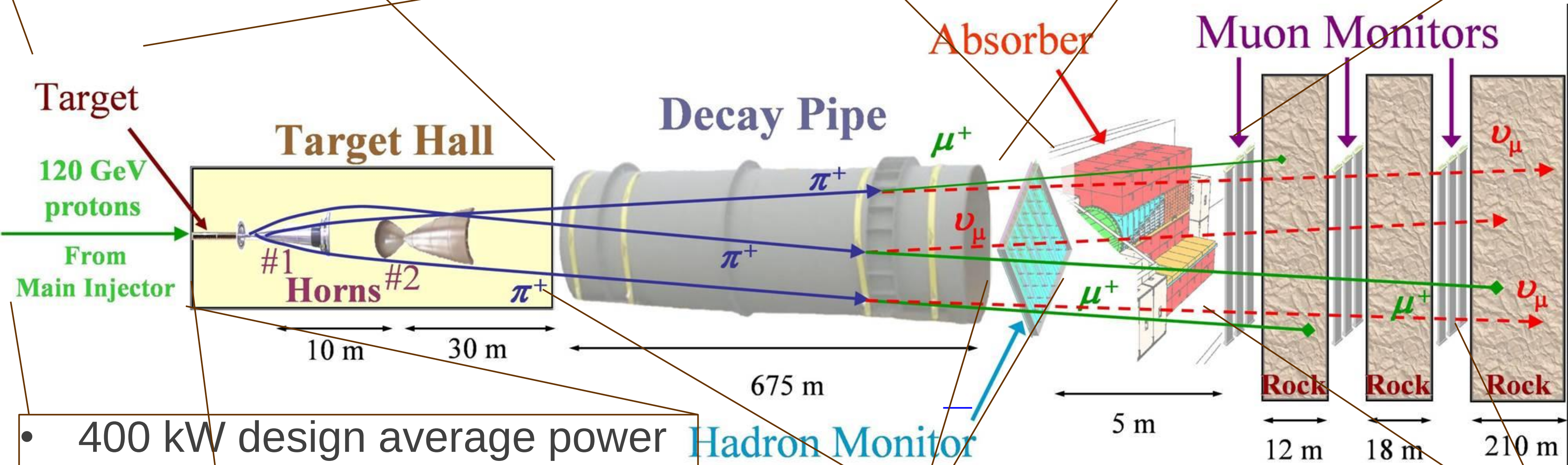
- Natural sources exist – but they are very weak and not necessarily well understood
  - Solar and atmospheric neutrinos only understood once oscillations were established and well understood
    - Moving from observation to experiment
  - Supernovae are hard to come by
- Artificial beams are controlled and intense
  - Decide when, where, and how the beam is generated
  - Detectors are placed strategically
  - Beams can be controlled with precision – vital as measurements approach 1%
- Applications:
  - Today neutrino oscillation is the first focus
  - Probe of nuclear structure
  - Observation of the neutral current
  - Demonstration of neutrino flavor (muon, tau)
  - Measurement of weak mixing angle

The NuMI Beam "Neutrinos at the Main Injector"

- 2 interaction length, C target
- Produces π^+, K^+ mesons

- 2 m diameter
- Roughly decay length for 10 GeV π^+
- He-filled

- Absorbs ~ 40 % of beam power
- Allows high-energy muons to penetrate



- 400 kW design average power
- 700 kW upgrade for NOvA
- $\sigma \sim 1$ mm

- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focus meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

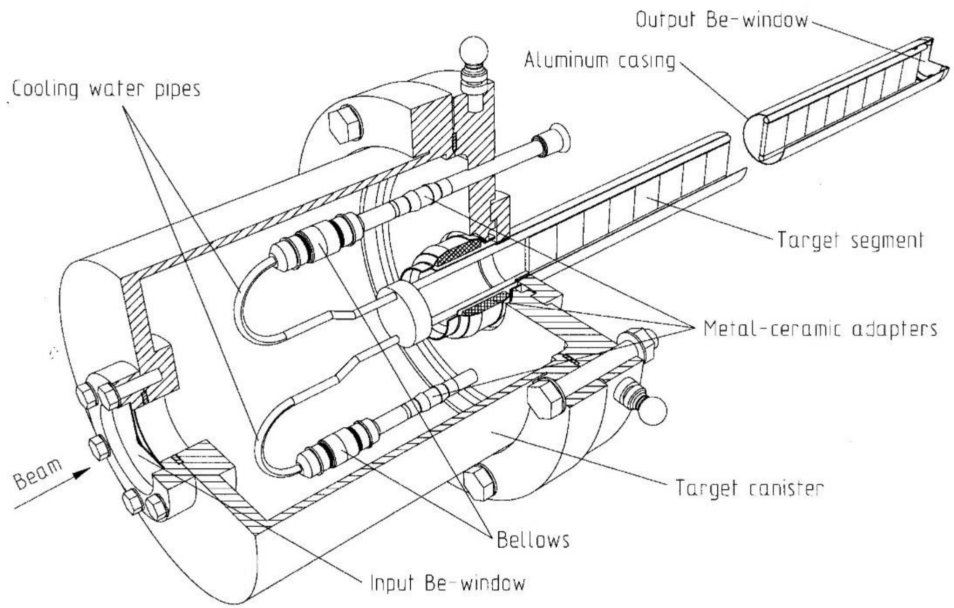
Fermilab

Defining Characteristics of Long Baseline Beams

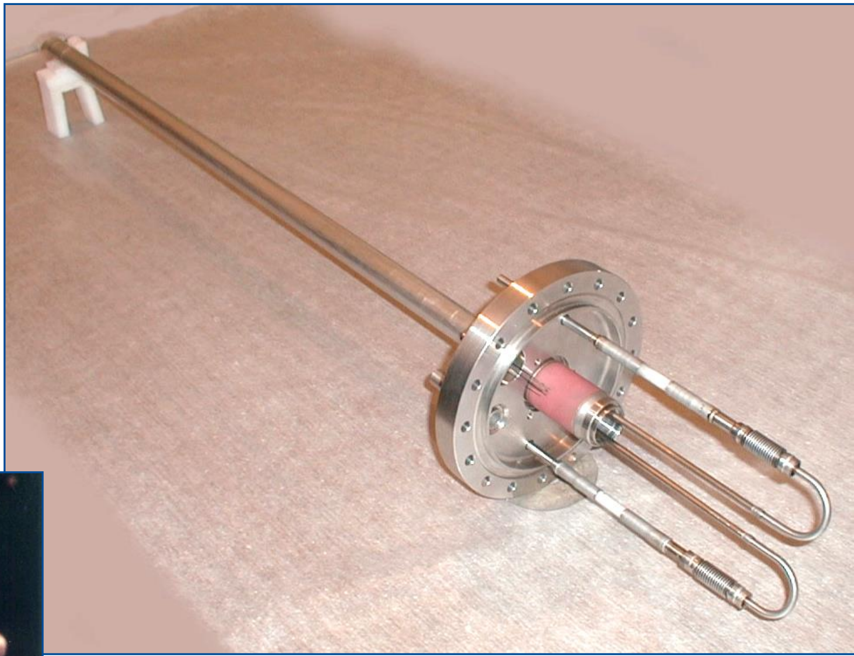
- Proton Beams: synchrotron based, nearing 1 MW
  - High Stored Energy: ~ 1 MJ
  - Small Beam Spot: 1 – few mm
  - High Proton Energy: 30-120 GeV
  - Single-turn extraction, long cycle time: 1 – few seconds
- Pion Focusing: Pulsed horns
  - Horns more efficient than quads
  - High currents: few hundred kA
- Large Decay volume
  - Meters in cross-section
  - 100s of meters in length
- Beam radiation dispersed over extended area

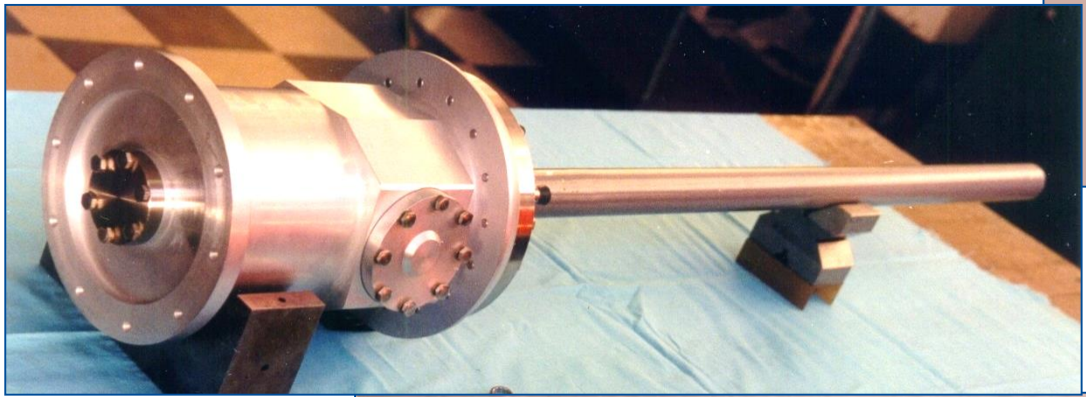
  Tritium, activation, corrosion, cooling

The MINOS Target



~ 4 kW beam power deposited in target

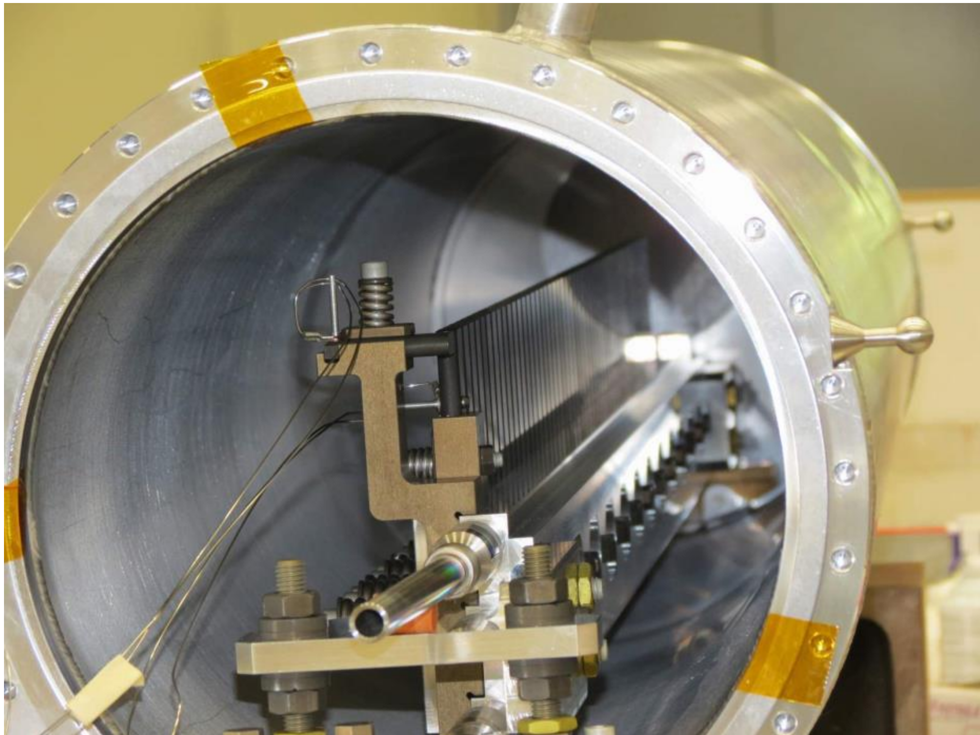




Encased in vacuum / helium can with beryllium windows

Water cooled graphite core

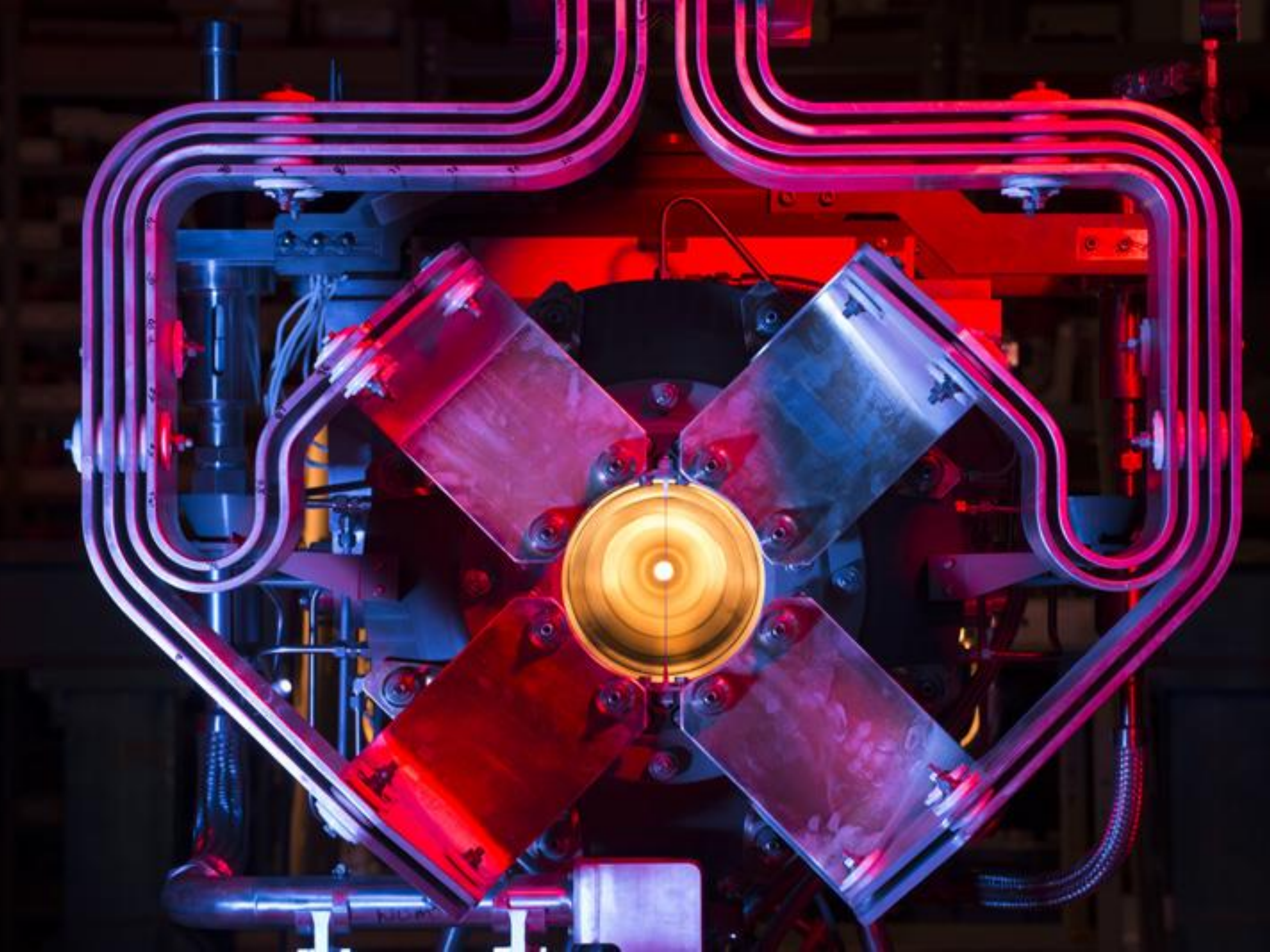
NOvA Target



- Graphite fins: 50 x 24 mm; 7.4mm wide
- Helium atmosphere
- Beryllium windows
- Water cooled aluminum pressing plates
- fins not brazed to cooling (cf. NT-series)
- Water cooled outer vessel

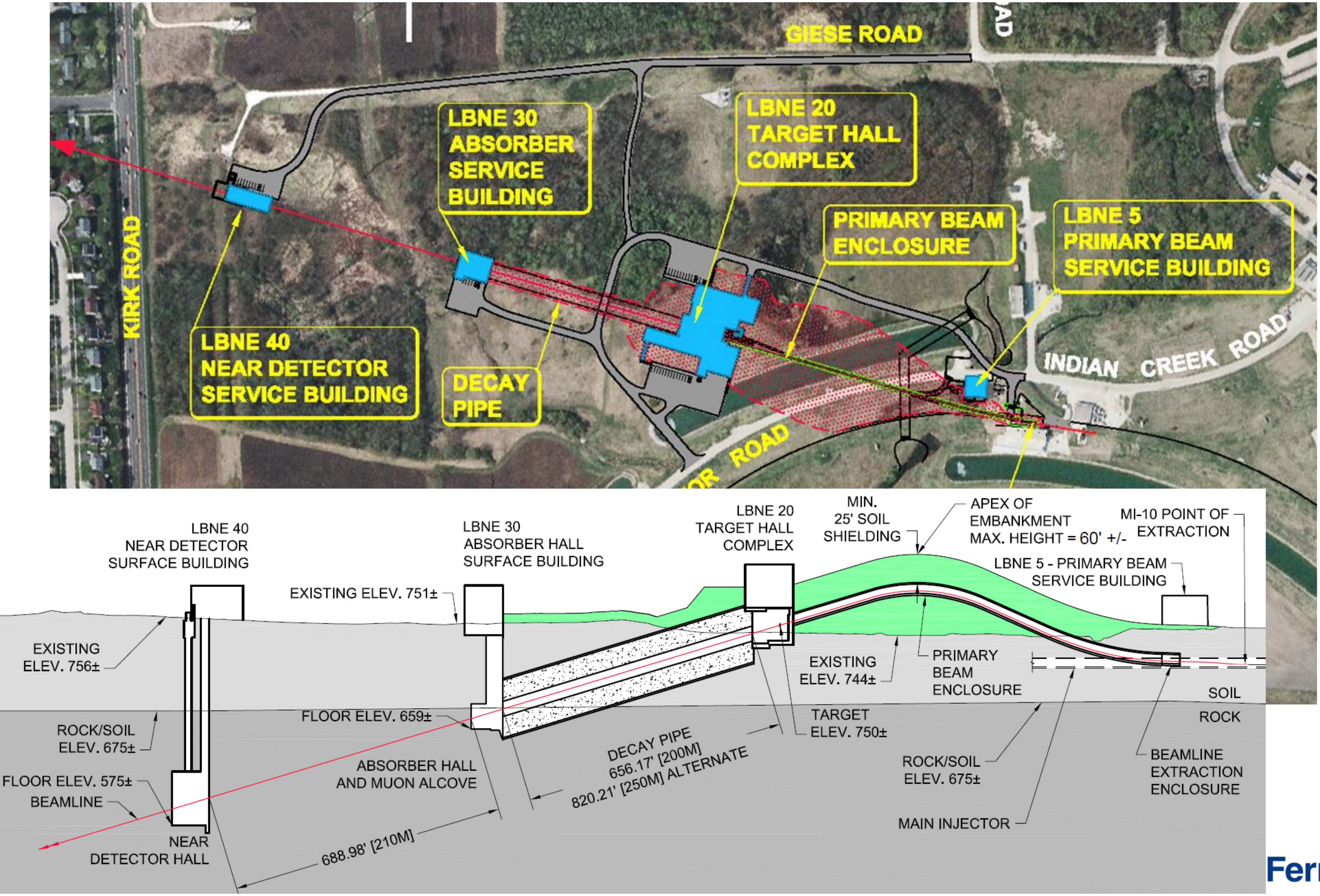
IHEP Protvino (Russia) initial design

STFC-RAL / FNAL final design and construction



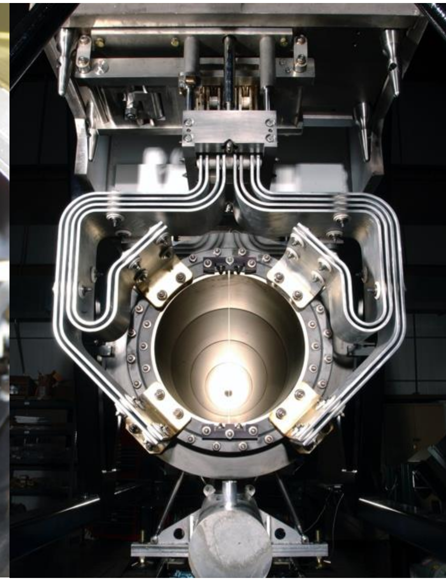
Horn Fabrication

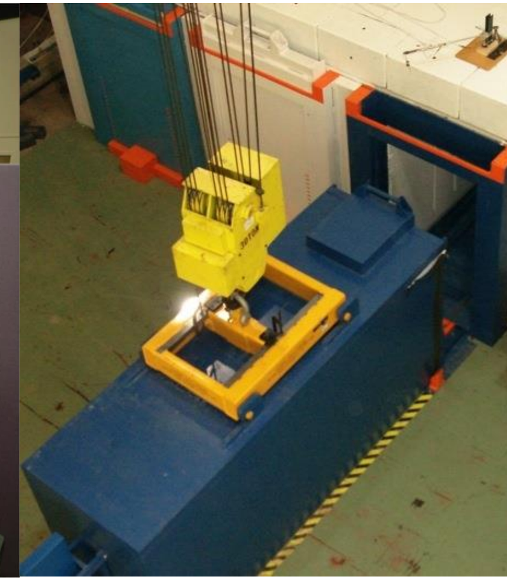
DUNE: Deep Underground Neutrino Experiment
LBNF: Long-Baseline Neutrino Facility



Fermilab

High Power Targetry Scope





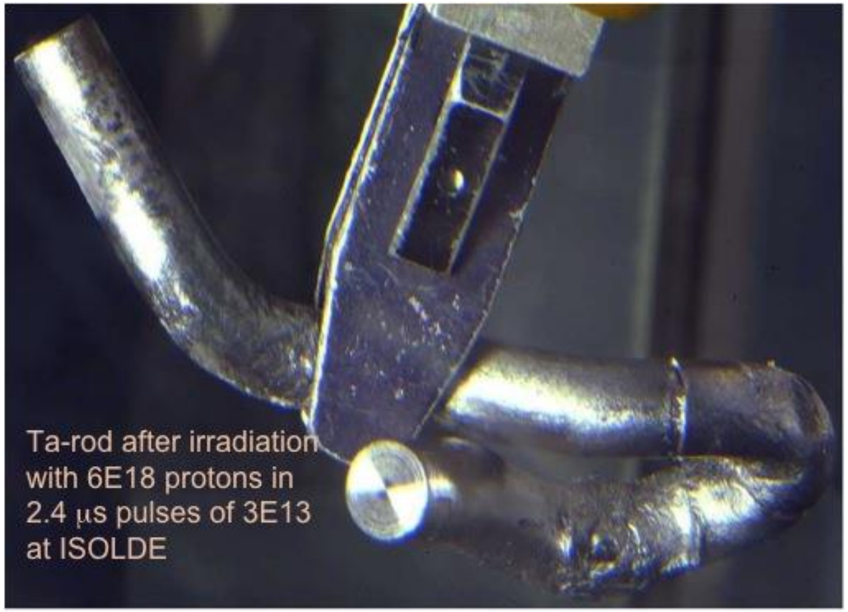
R&D Needed to Support:

- Target
  - Solid, Liquid, Rotating, Rastered
- Other production devices:
  - Collection optics (horns, solenoids)
  - Monitors & Instrumentation
  - Beam windows
  - Absorbers
- Collimators (e.g. 100 TeV pp collimators)
- Facility Requirements:
  - Remote Handling
  - Shielding & Radiation Transport
  - Air Handling
  - Cooling System

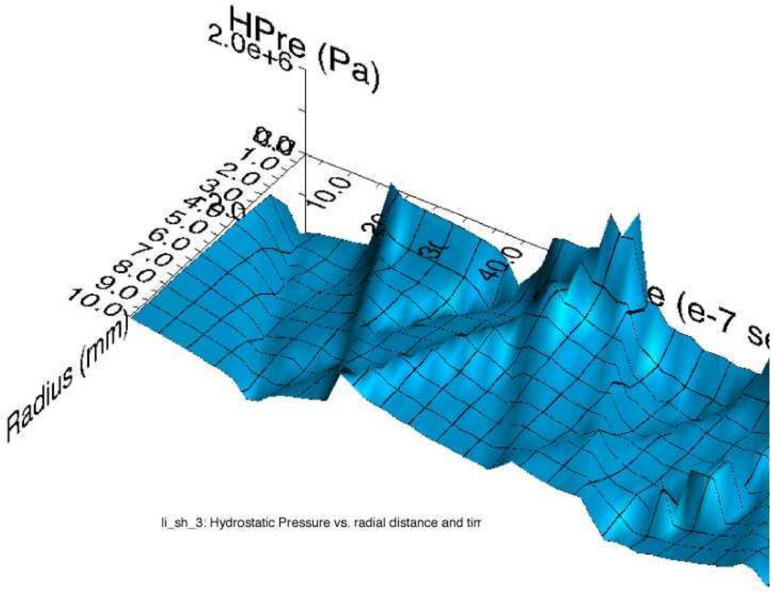
High Power/Intensity Targetry Challenges

- Material Behavior
  - **Thermal “shock” response**
  - **Radiation damage**
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection
  - Remote handling
  - Radiation accelerated corrosion
  - Manufacturing technologies

Thermal Shock (stress waves)



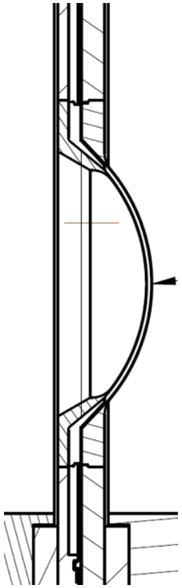
Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)

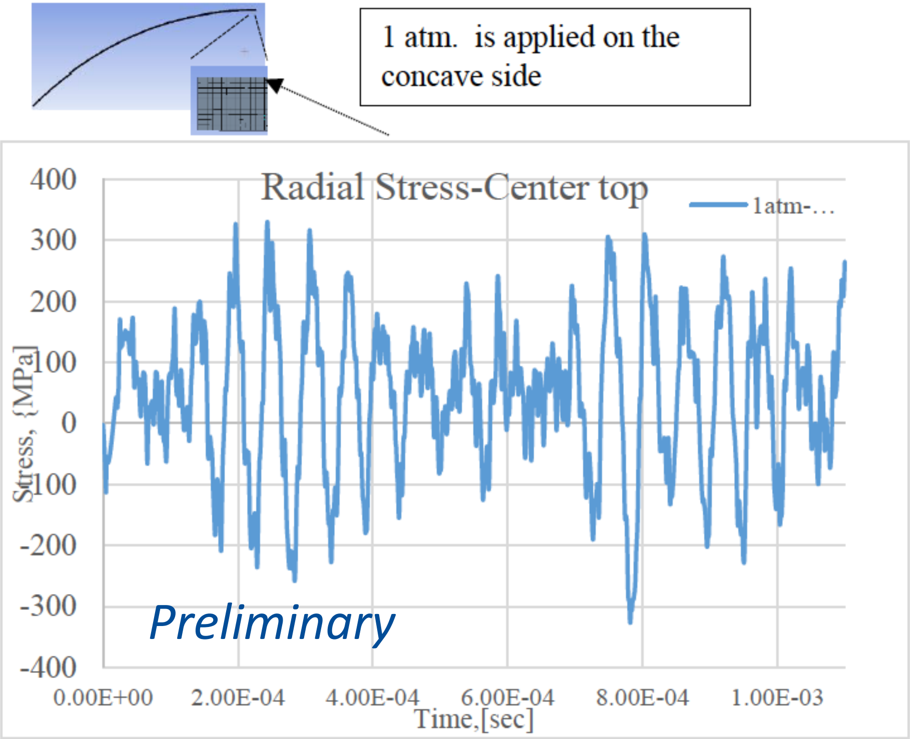


Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

- Fast expansion of material surrounded by cooler material creates a sudden local area of compressive stress
- Stress waves (not shock waves) move through the target
- Plastic deformation, cracking, and fatigue can occur

Stress wave example: T2K window



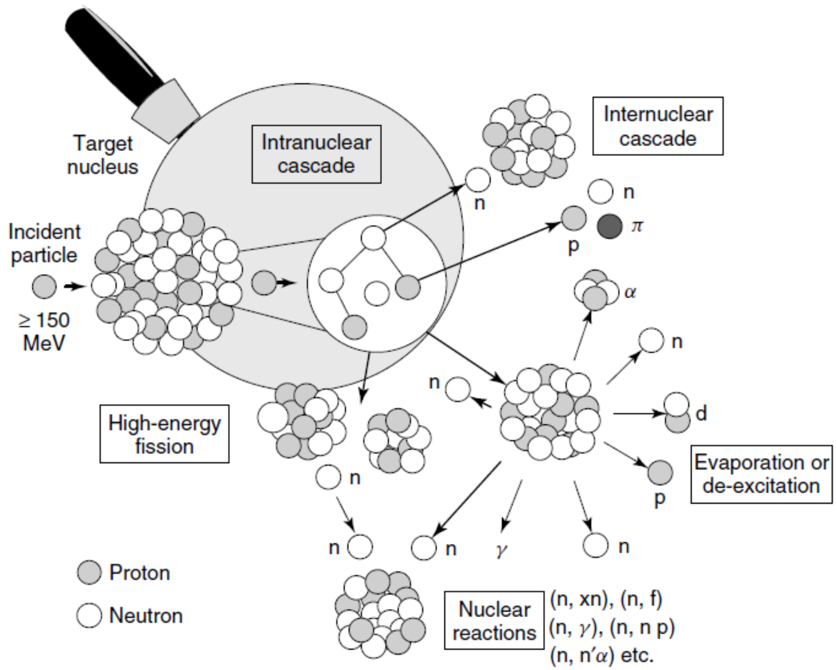


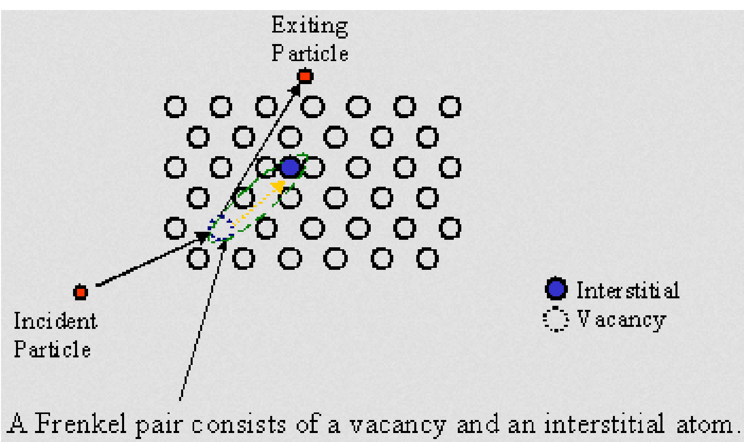
S. Bidhar, FNAL

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

Heavy dependence upon material properties, but:
Material properties dependent upon Radiation Damage…

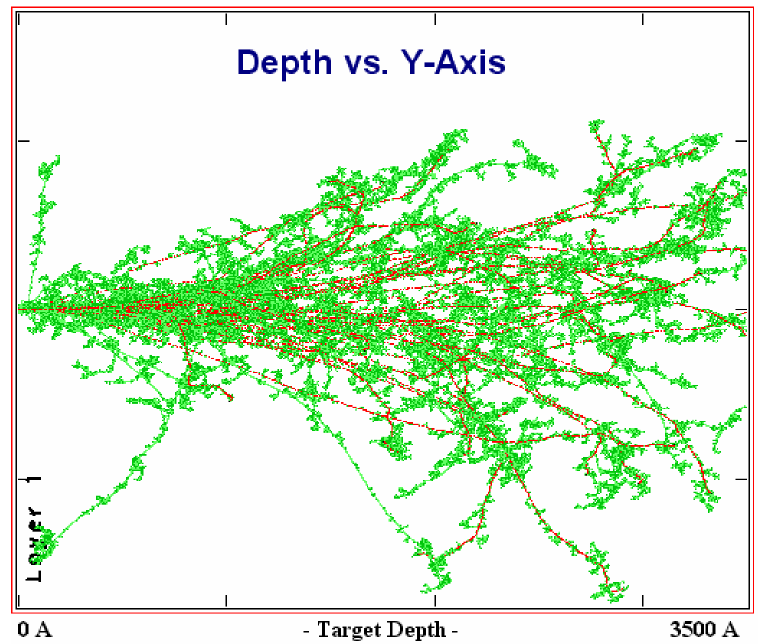
Radiation Damage Disorders Microstructure





Microstructural response:

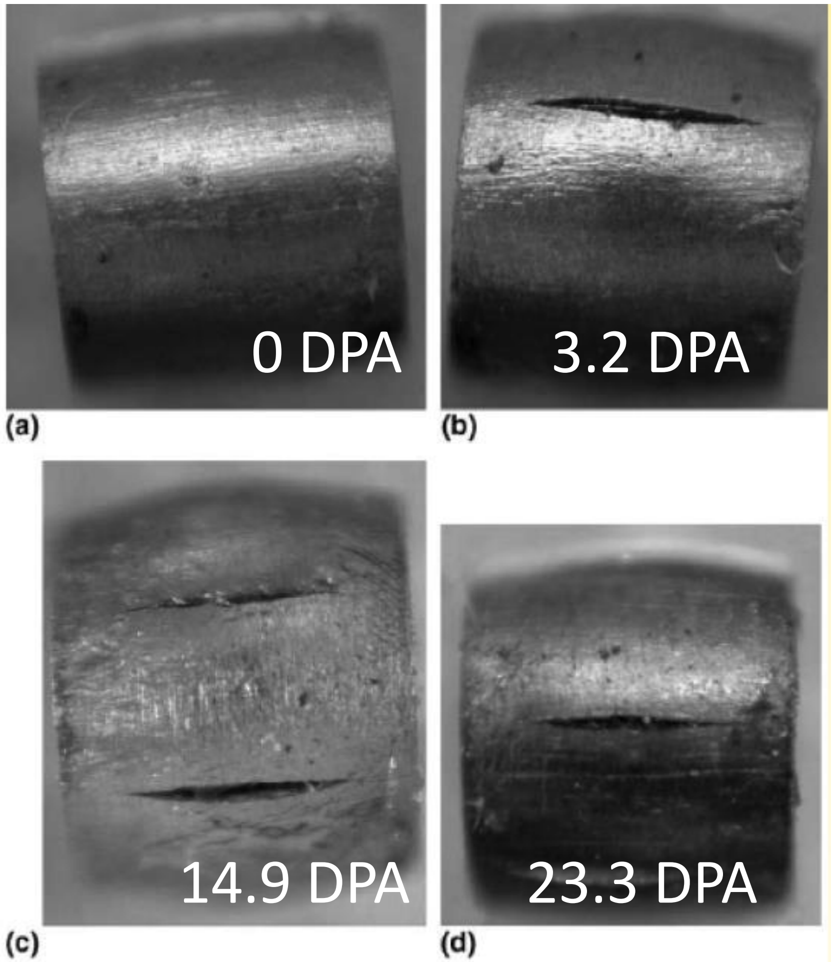
- *creation of transmutation products;*
- *atomic displacements (cascades)*
  - *average number of stable interstitial/vacancy pairs created = DPA (Displacements Per Atom)*



Slide prepared by V. Kuksenko (Oxford)

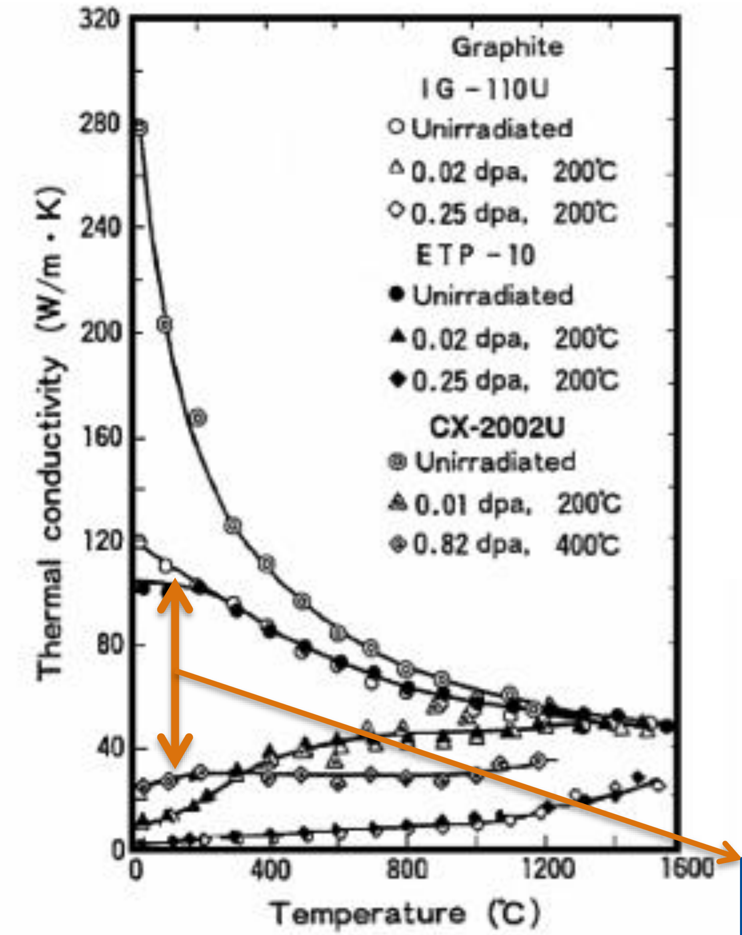
Radiation Damage Effects

- Displacements 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
  - Fatigue response
  - Accelerated corrosion
  - Transmutation products
    - H, He gas production can cause void formation and embrittlement (expressed as atomic parts per million per DPA, appm/DPA)
- Very dependent upon material condition and irradiation conditions (e.g. temp, dose rate)



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

Radiation damage effects can be significant



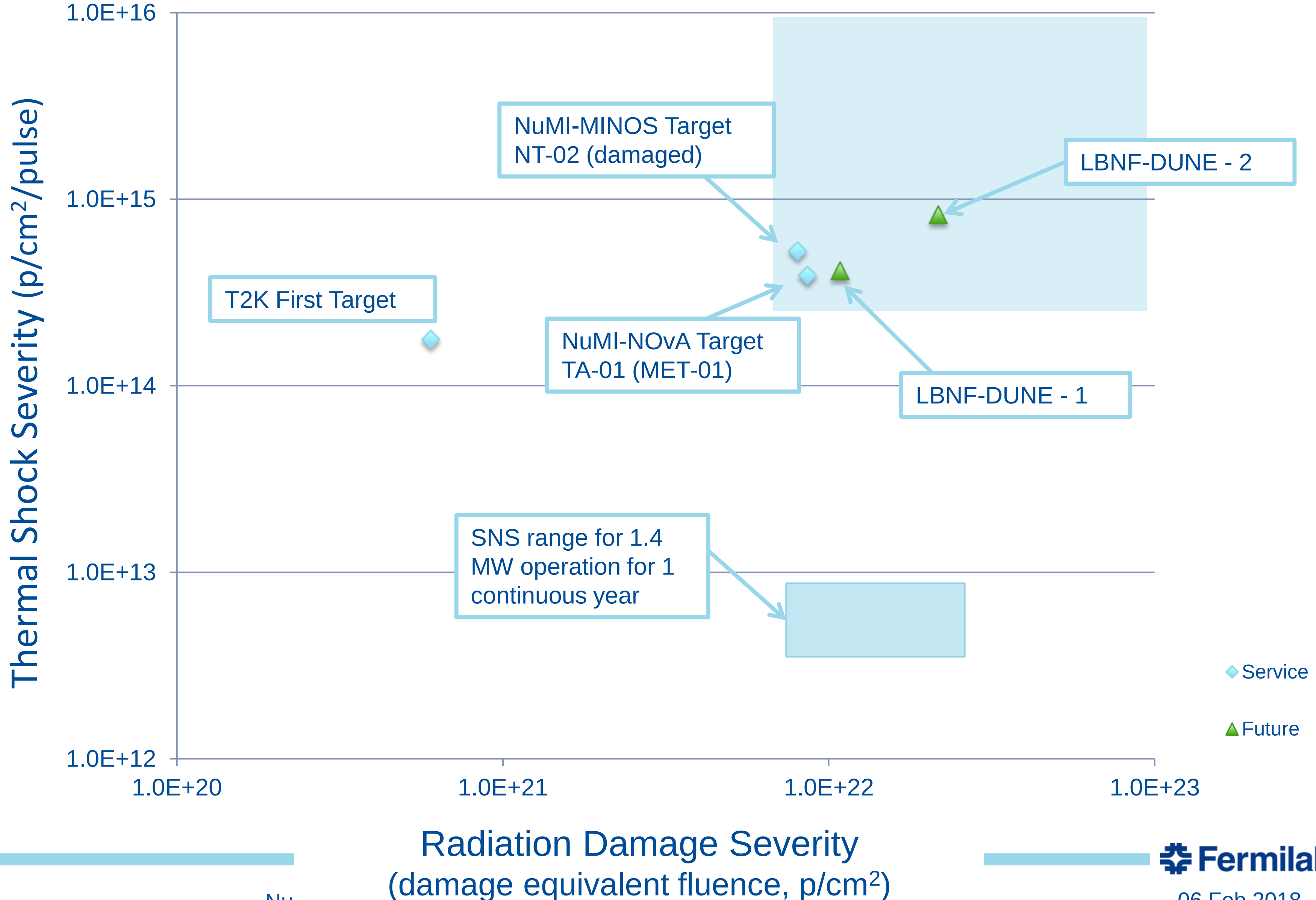
N. Maruyama and M. Harayama, "Neutron irradiation effect on … graphite materials," Journal of Nuclear Materials, 195, 44-50 (1992)

Factor of 10 reduction in 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 (on right) exposed to reactor dose of 1.5E23 n/cm^2

Nu HPT R&D Materials Exploratory Map



R a D I A T E
Collaboration

***Ra**diation **D**amage **In** **A**ccelerator **T**arget **E**nvironments*

Broad aims are threefold: radiate.fnal.gov

- 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**

Ferm[ilab]   Science & Tec[hnology] Facilities Coun[cil]   FRIB   Argonne NATIONAL LABORATORY   Ciemat Centro de Investigaciones [En]ergéticas, Medioambientales y Tecnológicas

Just added CERN and J-PARC to the MOU in Dec 2017

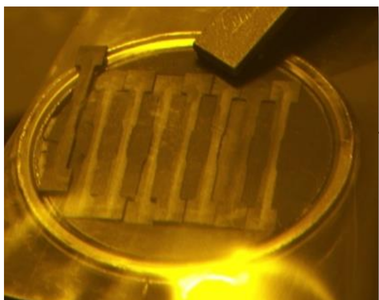
CERN

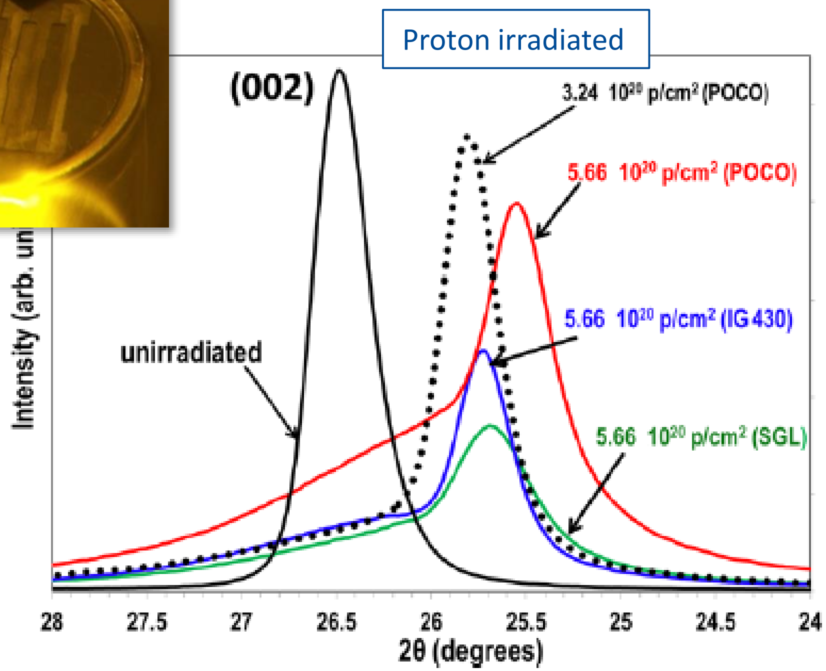
Fermilab HPT R&D Program – Status of Activities

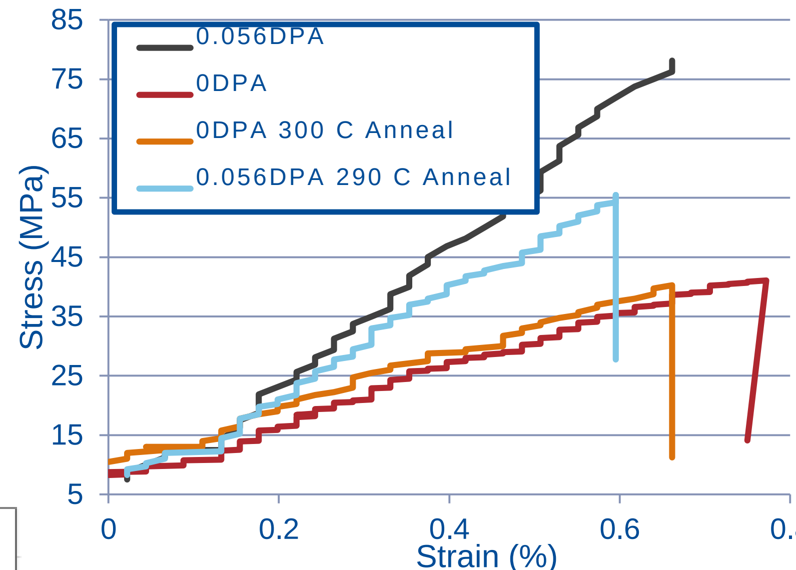
- Outline
  - Radiation Damage Separate Effects Studies
    - High energy proton irradiations
    - Low energy ion irradiations/implantations
  - Thermal Shock Separate Effects Studies
  - Combined Effects Studies
    - Autopsies
    - Experiment

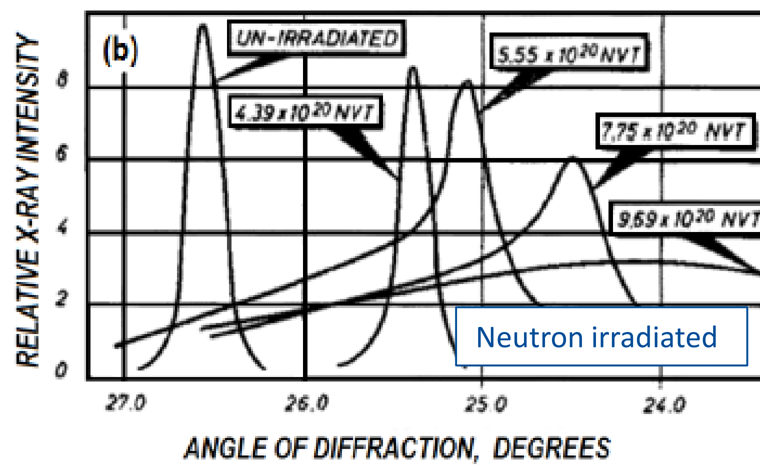
High-Energy Proton Irradiations (Radiation Damage Separate Effects)

- 181 MeV p irradiation @ BNL's BLIP facility
  - 4 graphites & h-BN exposed to 6.7E20 p/cm^2
  - Changes in material properties (30-50%)
  - Annealing (>150 ˚C) achieves partial recovery
  - POCO-ZXF-5Q (least change in critical properties)
  - XRD at NSLS indicates lattice changes at ~5E20 p/cm^2 similar to neutron irradiation studies









Future HE Proton Irradiations (Radiation Damage Separate Effects)

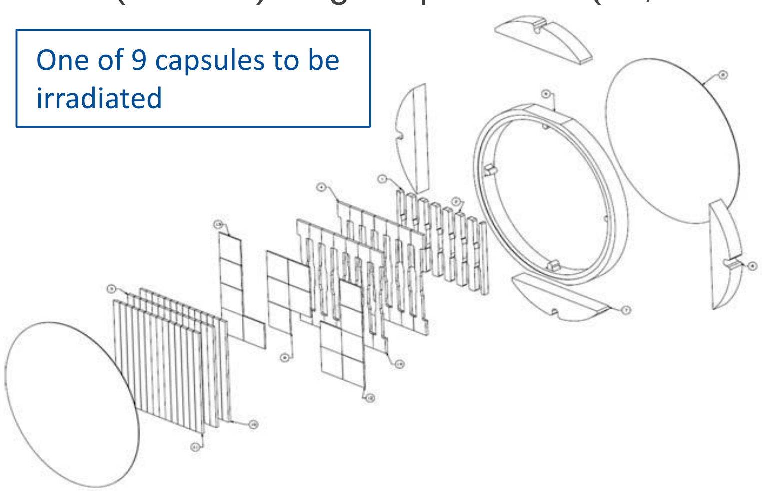
Future work includes 2017-18 BLIP irradiation

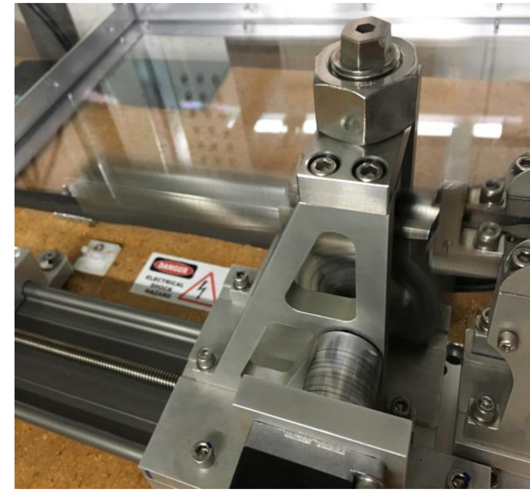
- Graphite at various temp (up to ~1,000 ˚C) to explore annealing of radiation damage
- Also Beryllium, Ti alloys, Si, TZM, Al, & Ir
- Post-Irradiation Examination (2018) includes mechanical, thermal, micro-structural, etc.
- Participants: FNAL, BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, LANL

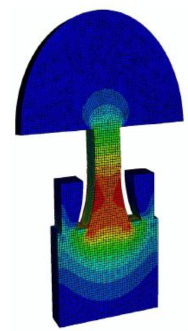
Fatigue evaluation of irradiated Ti alloys (US-JP)

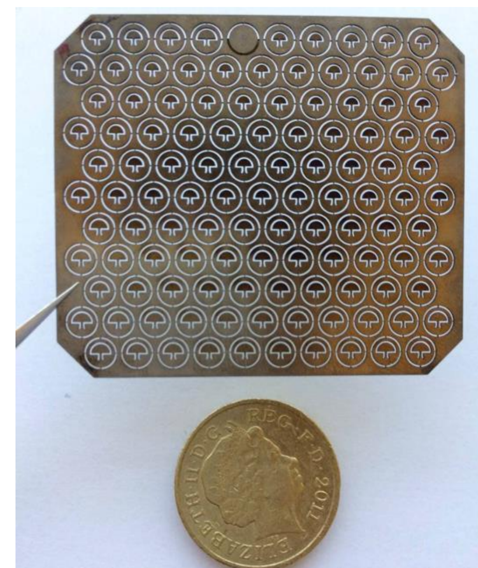
- World's first HE proton irradiated Ti high cycle fatigue study
- Miniature bending fatigue specimens (20 Hz)
- Meso-scale (few mm) fatigue specimens (20,000 Hz)

One of 9 capsules to be irradiated









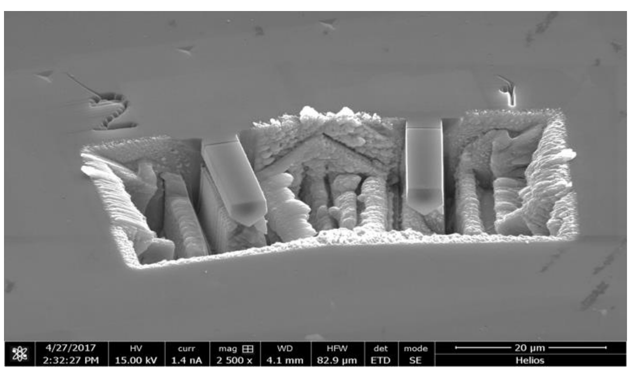
Ion implantation (Radiation Damage Separate Effects)

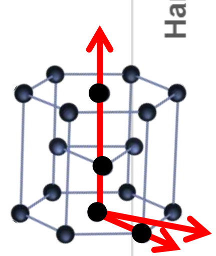
He implantation into Be study at Surrey/Oxford

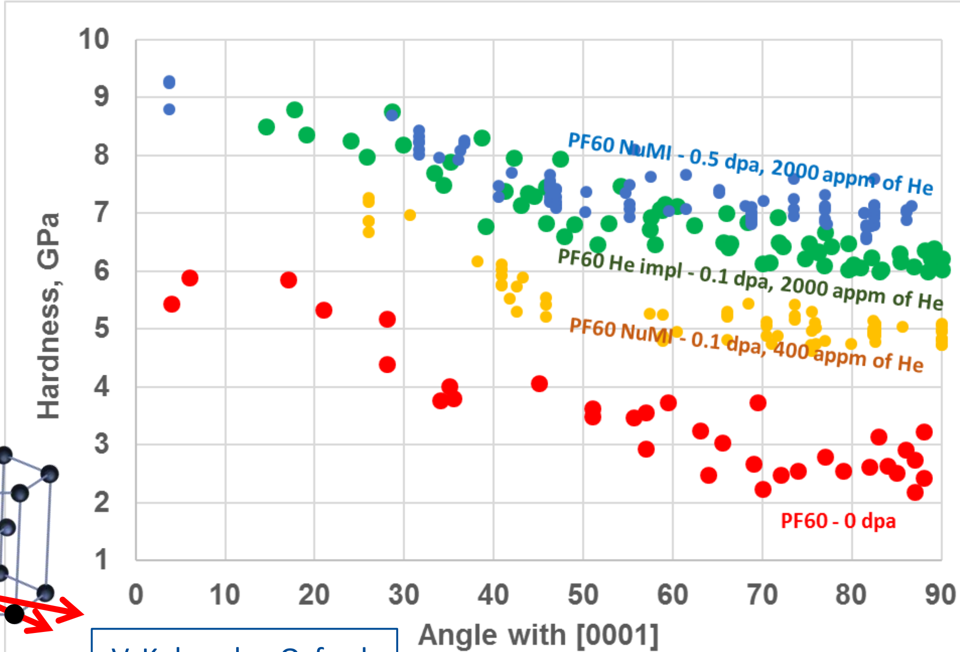
- Maximum beam energy: 2 MeV => 7.5µm implantation depth (SRIM)
- Dose: up to 0.1 dpa currently
- Temperature: 50ºC and 200ºC
- Nano-indentation indicates **significant hardening dominated by 2000 appm He** production (DPA is lower order effect)
- **Irradiation at 200˚C results in less hardening**

Ongoing Work with ion irradiation (2017-18)

- Beryllium micro-cantilever testing indicates 2x increase in fracture strength after irradiation
- Graphite C implantation at Surrey (D. Liu) TEM and micro-cantilever to compare with NuMI target and BLIP irradiated specimens





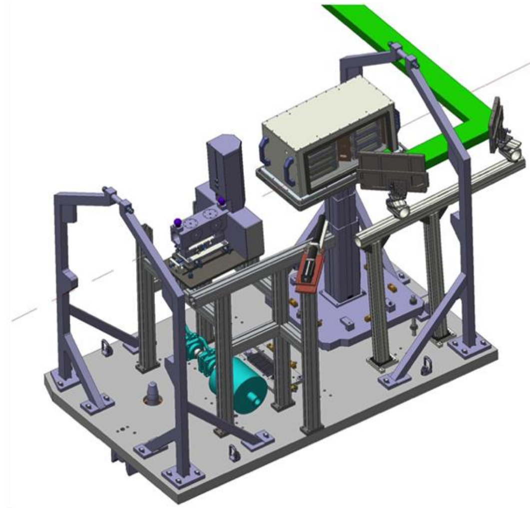


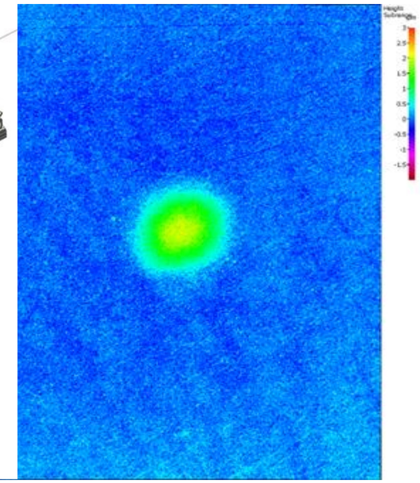
V. Kuksenko, Oxford

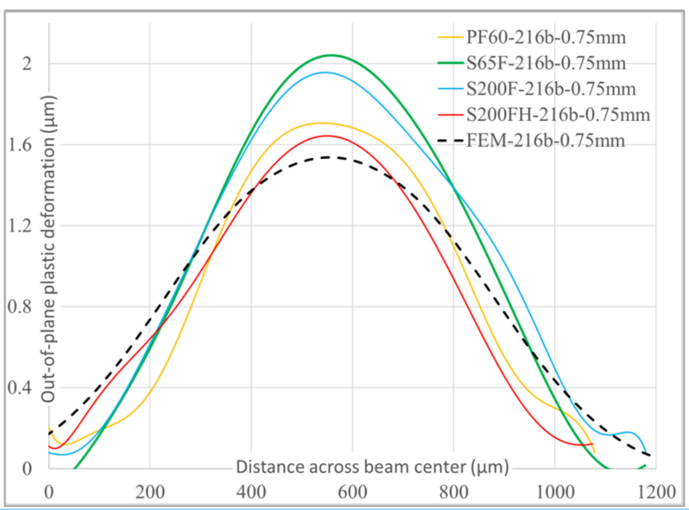
In-beam Thermal Shock Tests (Thermal Shock Separate Effects)

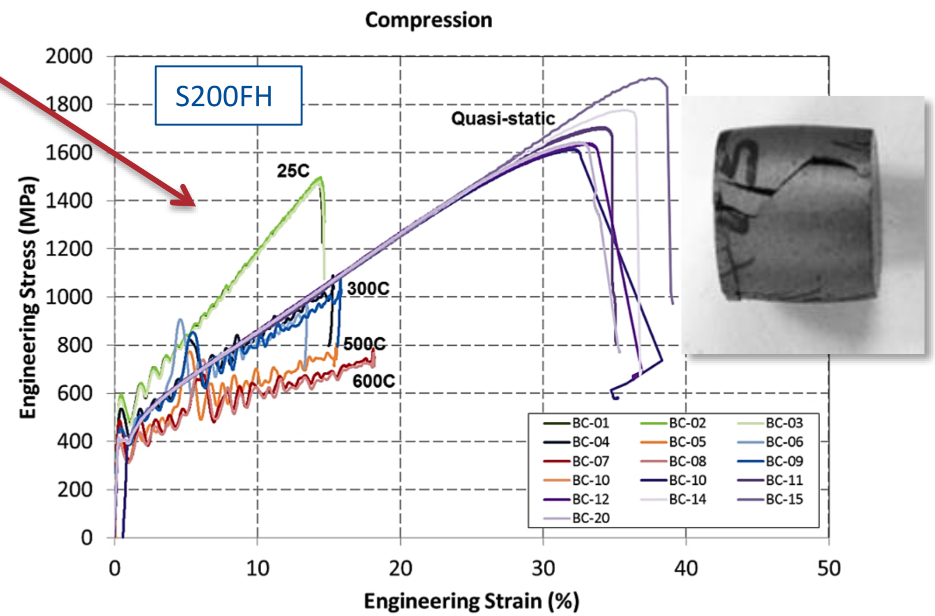
In-beam thermal shock test of Be at CERN's HiRadMat (FNAL, RAL, Oxford, CERN)

- All 4 Be grades showed less plastic deformation than predicted by generic strength models
- S200FH showed least plastic deformation and agreed with empirical strength model
- Glassy Carbon windows survived without signs of degradation
- Multiple pulses showed diminishing ratcheting in plastic deformation
- Work almost complete on data analysis
  - Johnson-Cook strength model developed at SwRI through SHB high strain-rate testing (elevated temp)





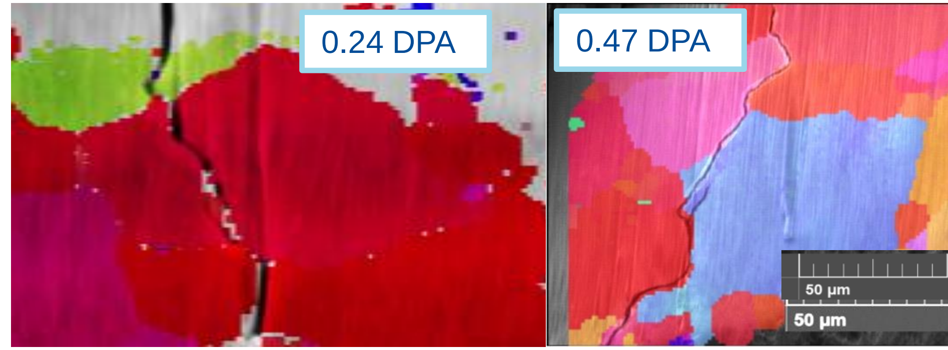


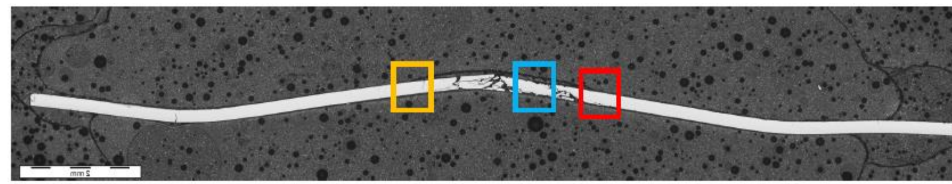


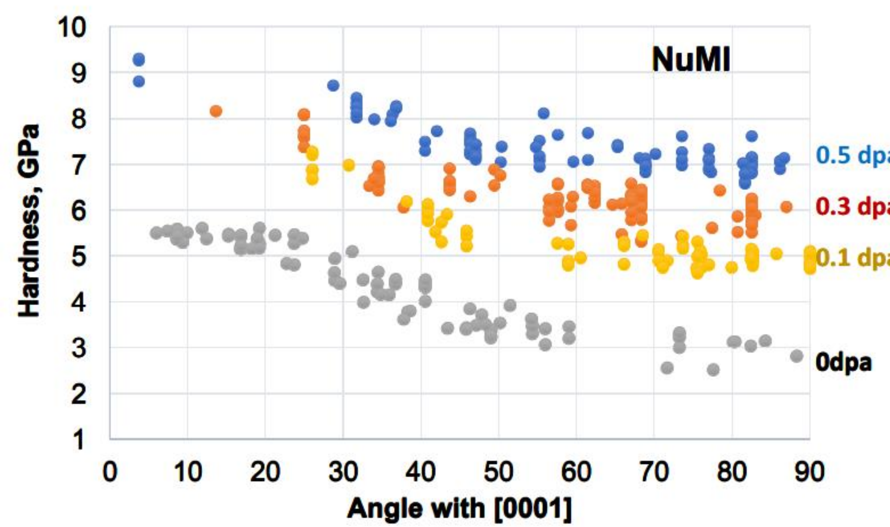
Autopsy of NuMI Be Window (Combined Effects)

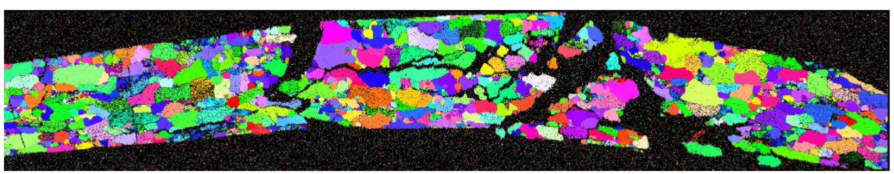
Examination of irradiated NuMI Beryllium beam window indicates hardening under irradiation (Kuksenko, Oxford)

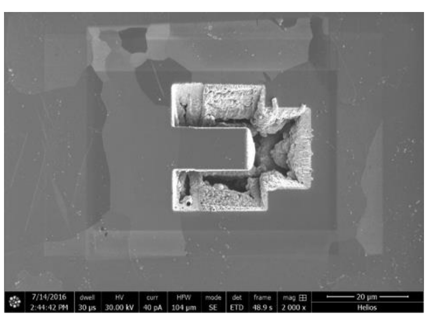
- Be window to 1.57E21 POT analyzed
- Advanced microscopy techniques (SEM, EBSD, APT, TEM)
- Li matches MARS [6] predictions and remains homogeneously distributed at ~50 ˚C
- Crack morphology changes at higher doses (transgranular to grain boundary fracture)
- Nano-indentation indicates significant hardening (doubling at 0.5 DPA)

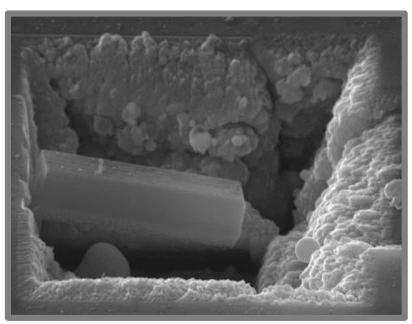






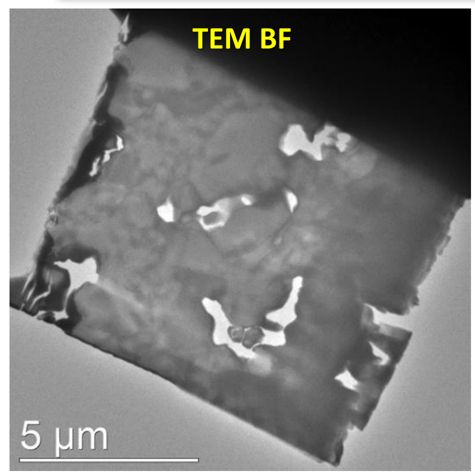


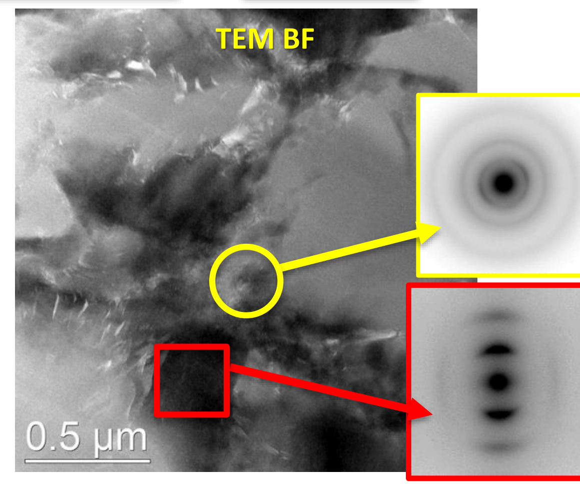




Autopsy of NuMI graphite target (Combined Effects)

- NuMI target (NT-02) autopsy and graphite PIE (FNAL, PNNL)
  - Graphite fins saw 8E21 p/cm^2 fluence
- Evidence of Bulk Swelling
  - The micrometer measurements indicate swelling did occur
    - More swelling in US fin locations
    - More swelling is associated with the fractured fins
- Evidence of fracture during operation
  - Symmetric fracture structure
  - Limited impurity transport into whole fins relative to fractured fins
- Evidence of limited radiation damage and material evolution
  - Surface discoloration appears to be mostly solder and flux material
  - Crystal structure & porosity consistent with non-irradiated state, perhaps explained by:
    - nano-crystalline features pinning defects
    - Extreme dose rate from pulsed beam

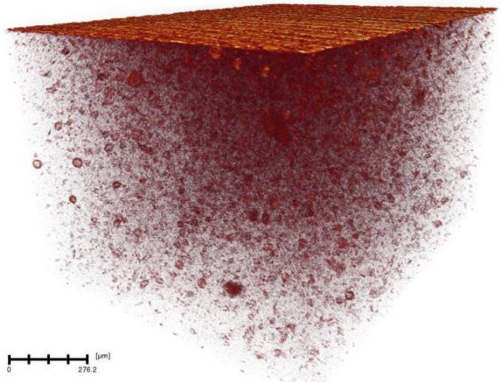




- Taken from fracture surface at the center where the beam was targeted
- Lamella has mixed regions of what appear to be amorphous (yellow insert diffraction pattern) and nanocrystalline microstructure (red square)
- Mrozowski cracks at the interfaces between these two regions

Future Autopsy-based Studies (Combined Effects)

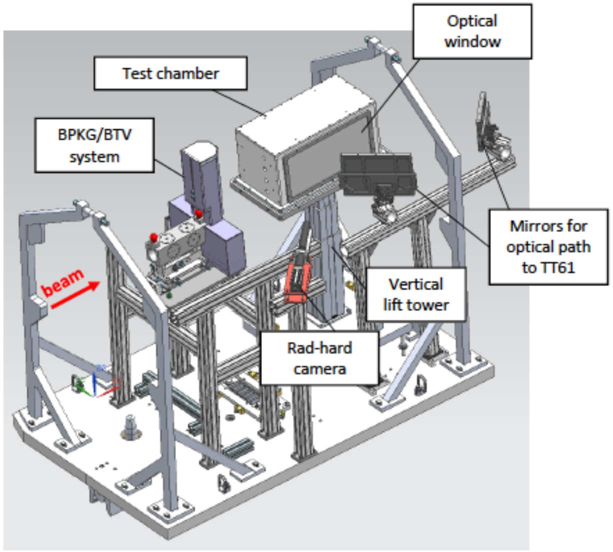
- Continued work with NuMI – MINOS target graphite (D. Liu, Oxford)
  - Nano-indentation and micro-cantilevers to extract mechanical properties
  - Comparison in ion irradiated and proton irradiated graphite
- NuMI - NOvA target graphite (TA-01)
  - Cooling down – fin recovery planned for early 2018
- NuMI - NOvA target graphite/beryllium fin comparison (TA-02)
  – In operation currently
- T2K first titanium alloy beam window
  – Cooling down at J-PARC

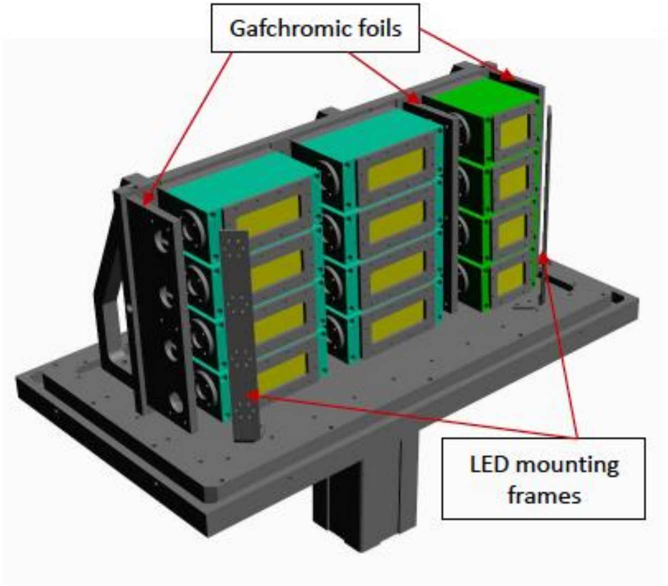


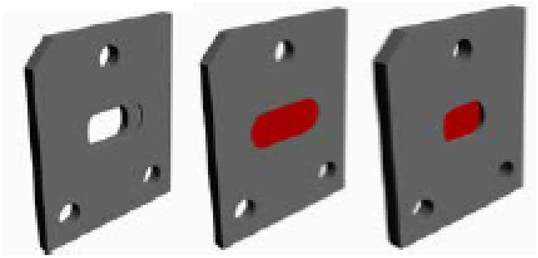
In-beam Thermal Shock of Irradiated Mat'ls (Combined effects)

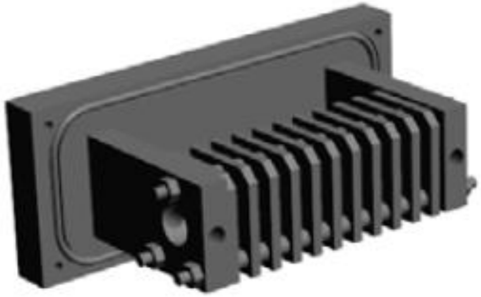
BeGrid2 Experiment at HiRadMat (CERN):

- Testing of irradiated materials at BLIP
  - Beryllium grades
  - Graphite grades
  - Glassy Carbon
  - Silicon
- First time for irradiated materials at HiRadMat
- Higher p beam intensities than BeGrid1
- Non-irradiated novel materials (nano-fiber mats)
- Non-irradiated high-Z materials for CERN's Beam Dump Facility (SHiP)
- Experiment scheduled for October 2018

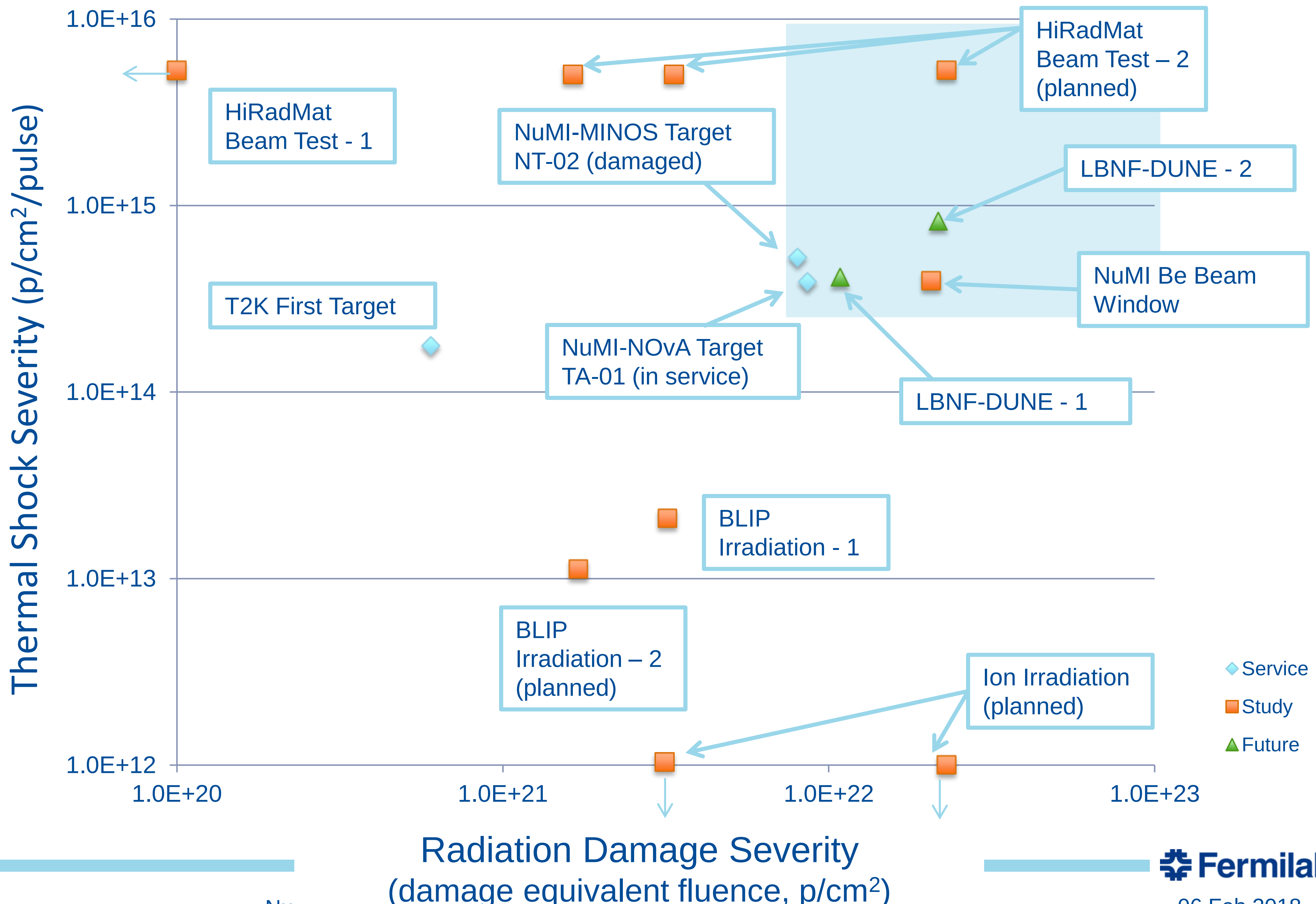








Nu HPT R&D Materials Exploratory Map



Summary

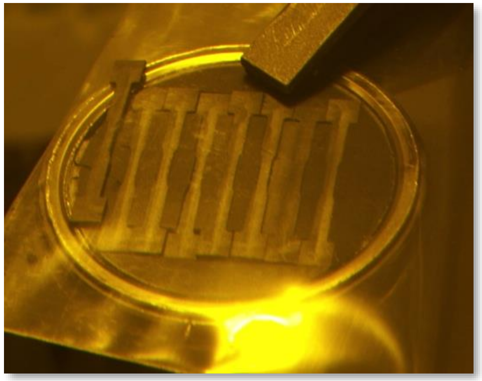
- High power accelerators require beam interaction components (targets, beam-windows, collimators, absorber/dumps) that are capable of stable operation under challenging conditions.
  - Currently operating accelerator facilities have been limited in beam power due to target survivability issues
  - Planned multi-MW accelerator upgrades and new facilities will present even greater challenges

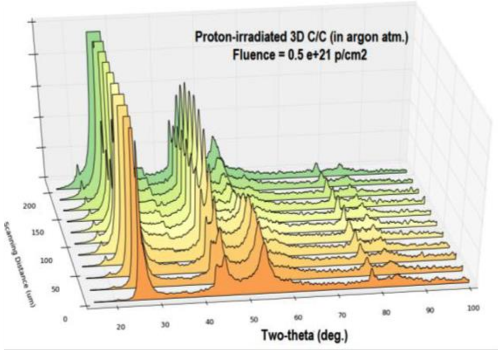
- Targets, beam windows, and other beam intercepting devices will experience extreme conditions
  - Lattice displacements & transmutation
  - Dynamic thermal stresses produced by pulsed beam

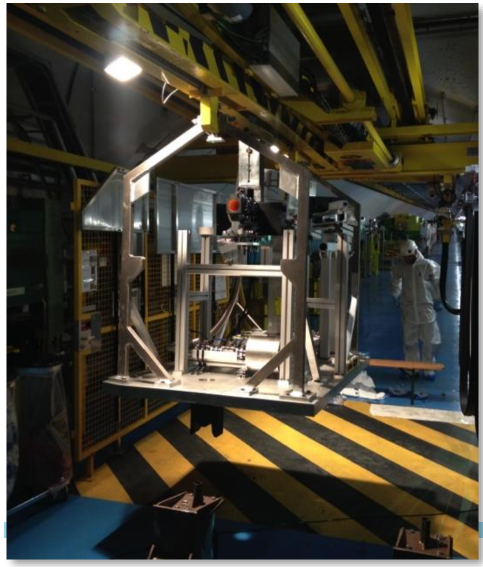
- R&D by the global accelerator targets community under the aegis of RaDIATE is underway to help meet these future challenges
  - High-energy proton irradiations and low-energy ion irradiations to study radiation-damage effects
  - In-beam thermal shock tests of irradiated material specimens brings together both major challenges of thermal shock and radiation damage into single experiments

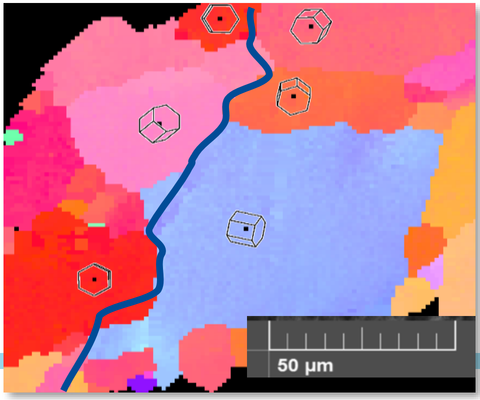
Some RaDIATE Current Opportunities

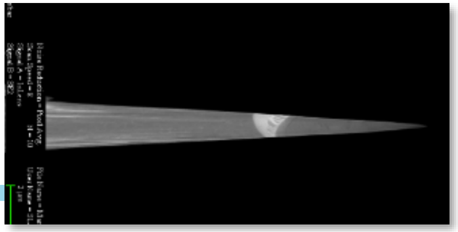
- **Graphite irradiation studies (correlation of effects from different energy regimes)**
- **PIE of in-beam thermal shock testing (comparison of response of irradiated vs non-irradiated materials)**
  - **Variety of materials from Be to Ti Alloys**
  - **Profilometry to look at permanent deformation**
  - **Crack detection techniques**
- **Fatigue testing (high frequency and conventional) of Ti alloys irradiated at variety of temperatures**
- **PIE of proton irradiated materials from BLIP irradiation run**
  - **Possibility of NSUF support for PIE at US laboratory**











Back-Up Slides Follow

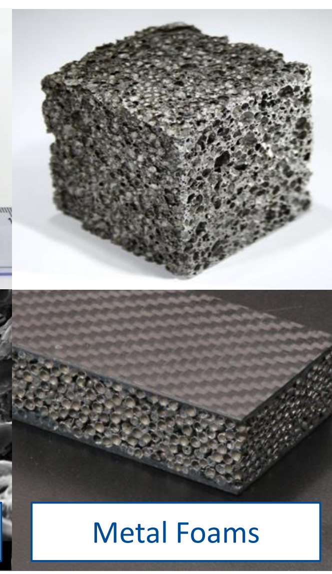
Development of New Targetry Materials

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.

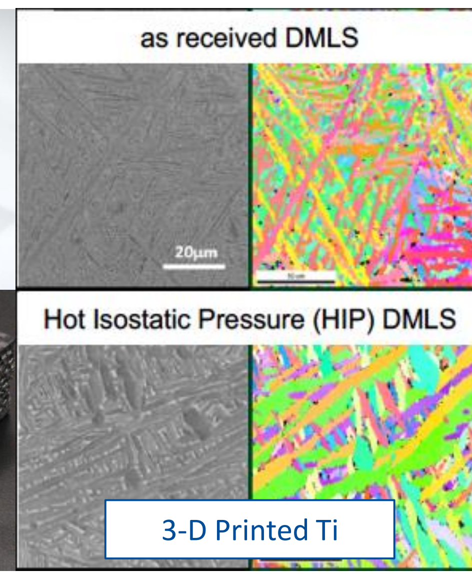
- Glassy carbon (RaDIATE BLIP run material, CERN/FNAL)
- Molybdenum graphite (RaDIATE BLIP run material, CERN)
- Metal foams (BeGrid2 material, FNAL)
- 3-D Printed Ti alloy (RaDIATE BLIP run material, FRIB)
- Nano-fiber mats (BeGrid2 material and subject of Sujit Bidhar's talk, FNAL)

Glassy Carbon

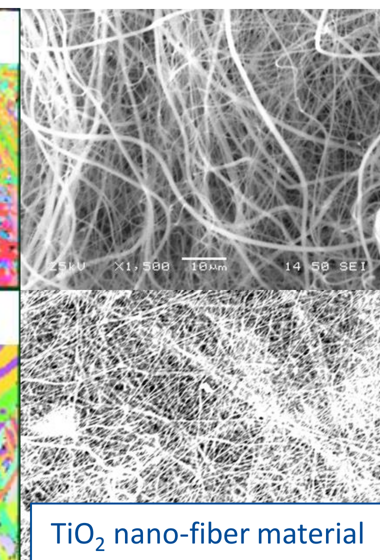
Moly Graphite



Metal Foams



3-D Printed Ti



TiO_2 nano-fiber material

Reactor materials studies are limited in relevance to Targetry

$n \neq p$

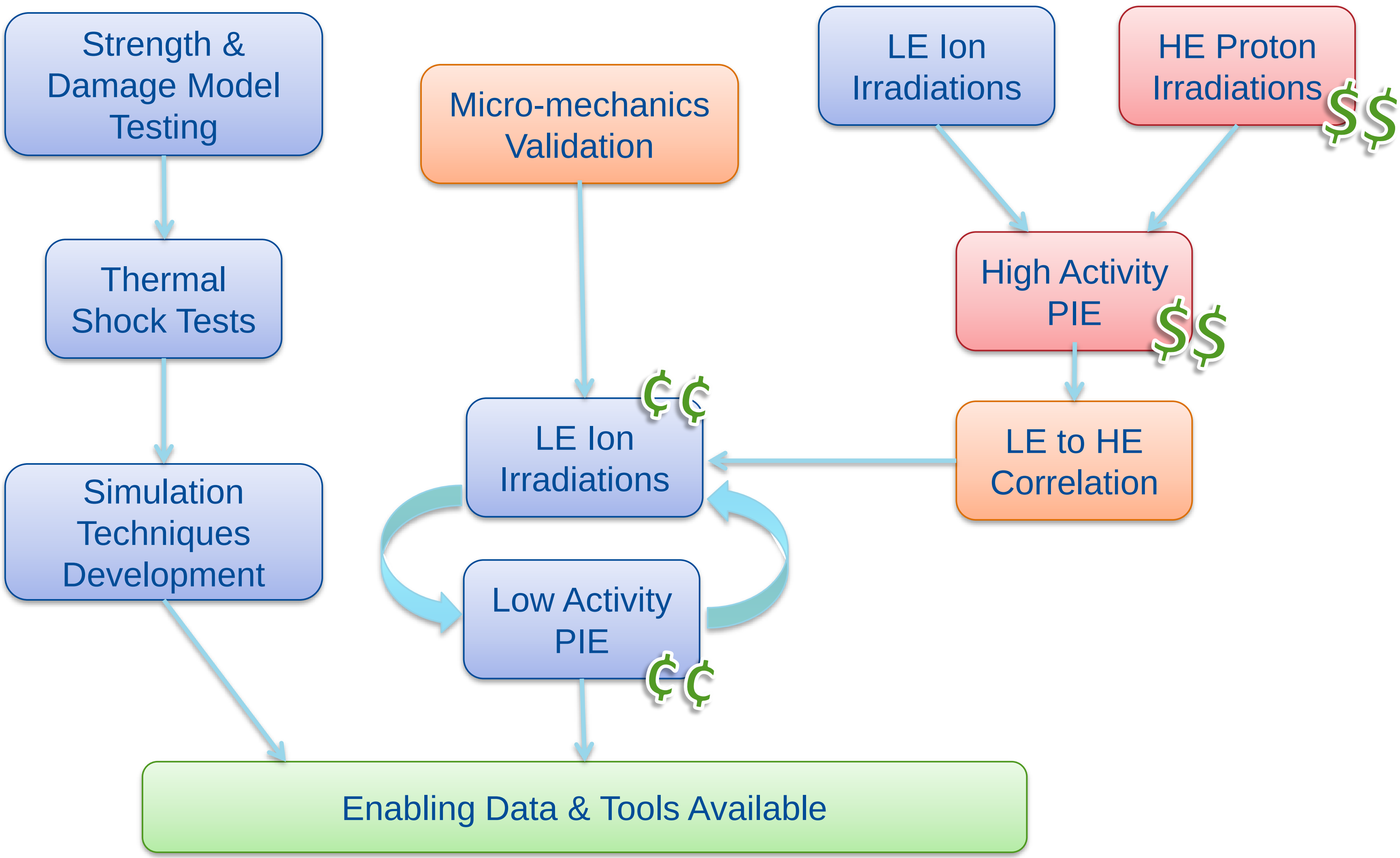
1-14 MeV   100+ MeV

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

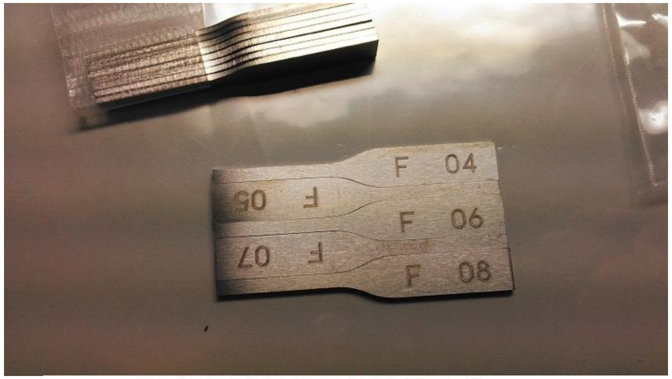
Material Behavior Activities Overview

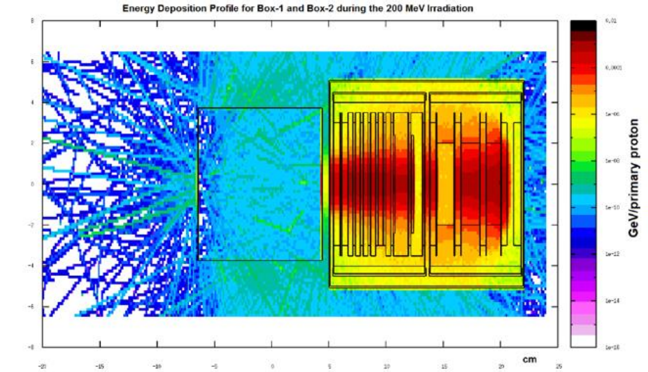


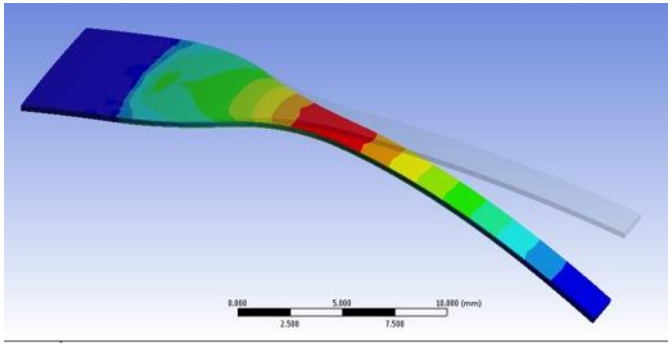
RaDIATE R&D Progress

- US/Japan Radiation Damage Studies on Titanium Alloys
  - 3 alloys studied: 6Al-4V, 6Al-4V ELI, 3Al-2.5V
  - Irradiated at BLIP in early 2017 to ~0.7 DPA
  - Fatigue testing, Tensile testing, Micro-structural evaluation
  - Also Tensile & Micro-structural evaluation of 3-D printed DMLS

- Roles & Responsibilities
  - Oversight and organization: FNAL, KEK
  - Materials Science Expertise: PNNL, JAEA, MSU, BNL
  - Specimens preparation: KEK, MSU
  - Irradiation: BNL, FNAL
  - Post-Irradiation Investigation (PIE): PNNL, BNL
  - Fatigue Testing Machine: FNAL



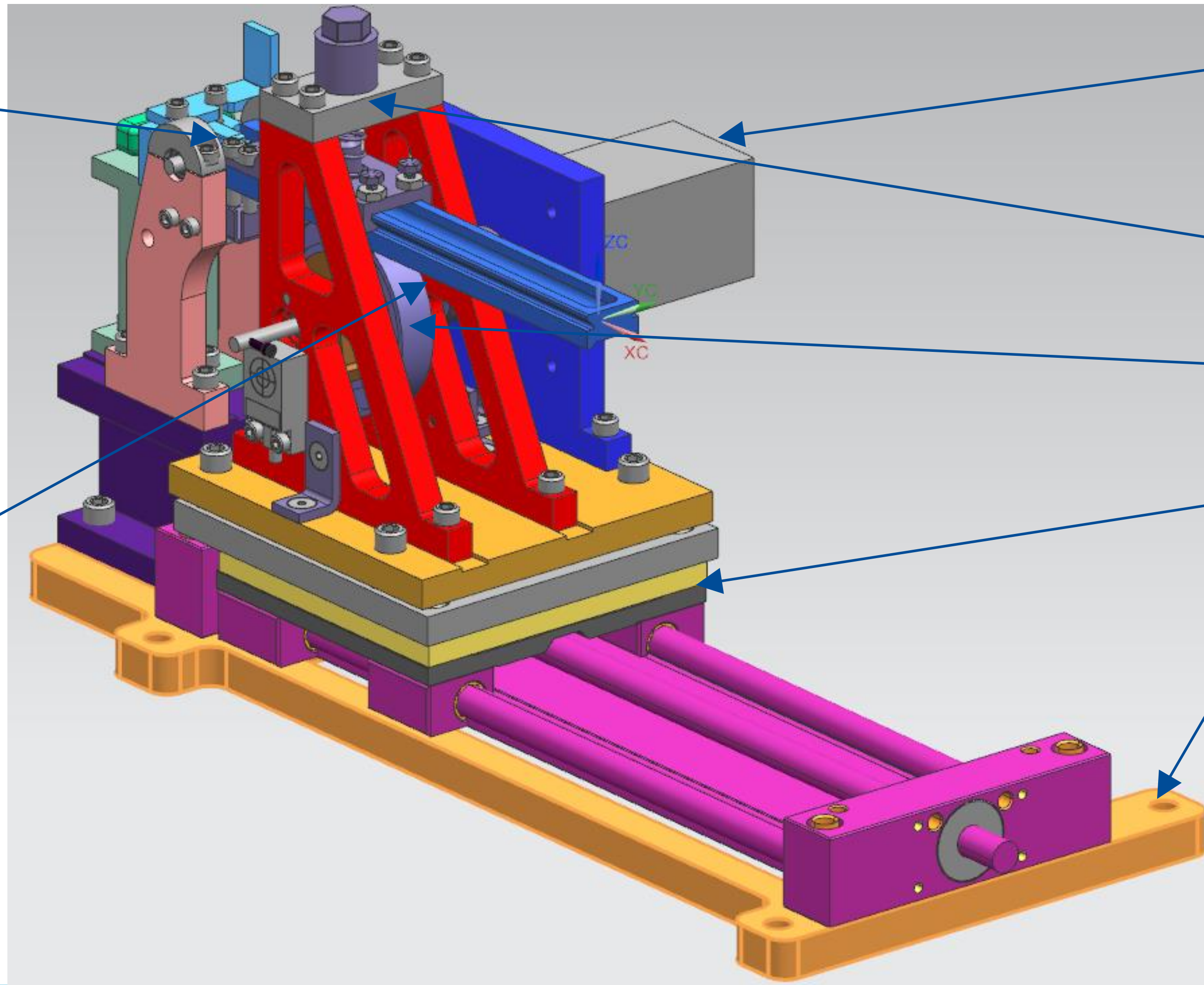




Slides courtesy of K. Ammigan, Fermilab

RaDIATE R&D Progress

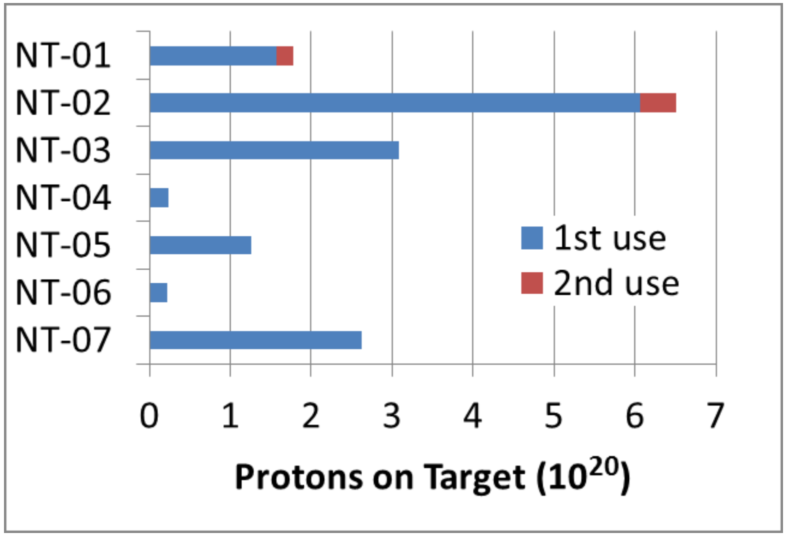
- Fatigue Testing Machine:



Slides courtesy of K. Ammigan, Fermilab

NT-02 Target Examination

- Operation between 2006 to 2009, and again in 2011
- Subjected to 120 GeV protons
  - Integrated POT ~ 6.1 x 10^{20}
  - Gaussian beam spot size (1σ): 1.1 mm
  - Peak fluence: 2.5 x 10^{22} p/cm^2
  - **Estimated DPA ~ 0.63**
- Peak temperature ~ **330° C**
  - Heat to 330 C in 10 μs, cool to 60 C before next pulse (1.85 s cycle time)



- Neutrino yield declined **10-15%** during life, **possibly due to radiation damage**
  - Yield reduction not observed in other NT targets
  - NT-02 lifetime significantly longer than any other NT targets (2x or more)

Slides courtesy of K. Ammigan, Fermilab

Fermilab

NT-02 Target

Proton beam

- Graphite fin core
- 47 fins – 6.4 mm x 15 mm x 20 mm segments
- Graphite fins soldered to water cooling tubes attached on top/bottom of fins

Target autopsy

- Performed in hot cell at FNAL
- Cracks observed along centerline
- Some fins broken in halves

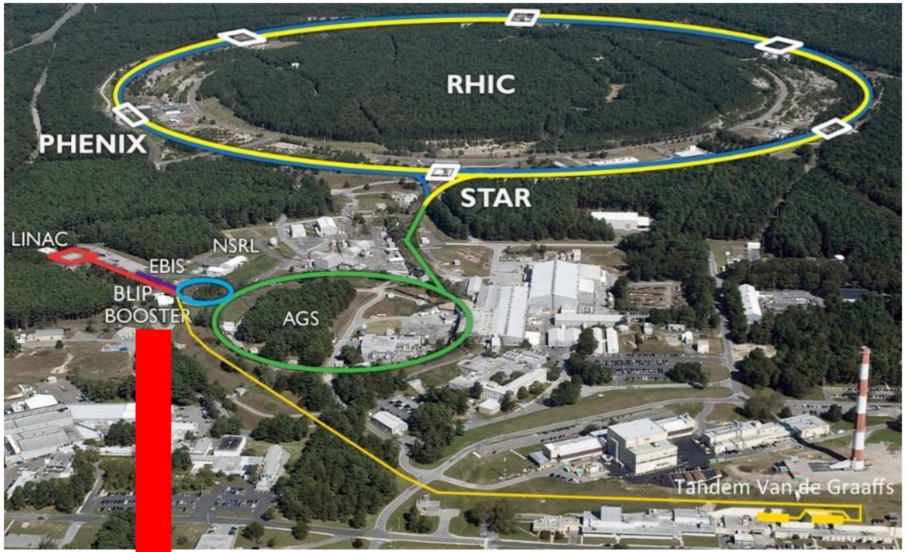
Cracks along centerline

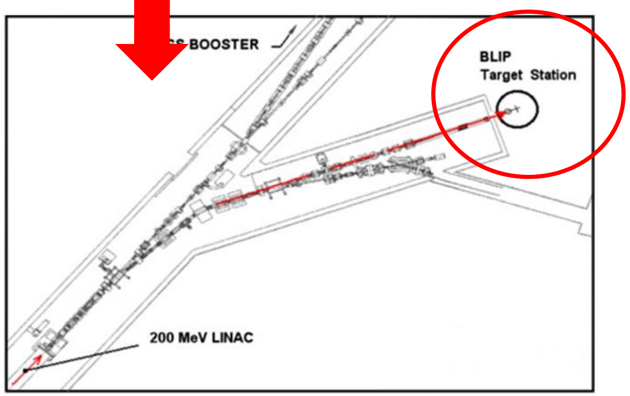
Proton Irradiation Experiment

Brookhaven National Laboratory

Brookhaven Linac Isotope Production (BLIP) facility - irradiation studies with high energy protons, up to 200 MeV

- Primary purpose of BLIP is to produce medical isotopes
- Specimen irradiation occurs upstream and in tandem with isotope production
- Target boxed optimized in order to deliver desired beam energy/flux to isotope targets





BLIP Graphite Irradiation Run (2010)

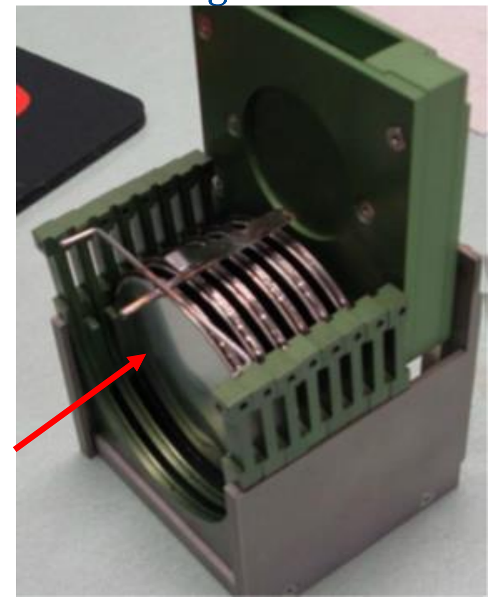
Specimen irradiation

- Beam energy ~ 180 MeV
- Beam spot: σ_x ~ 10 mm, σ_y ~ 7 mm
- **Peak DPA: 0.1**
- Peak temperature: 200 °C
- **Irradiation time: 9 weeks**

Graphite specimens

- POCO ZXF-5Q [27]
- IG-430 [48]
- SGL R7650 [27]
- C2020 [27]
- 3D C/C composite [18]

Target box



Proton beam

Layered graphite specimens

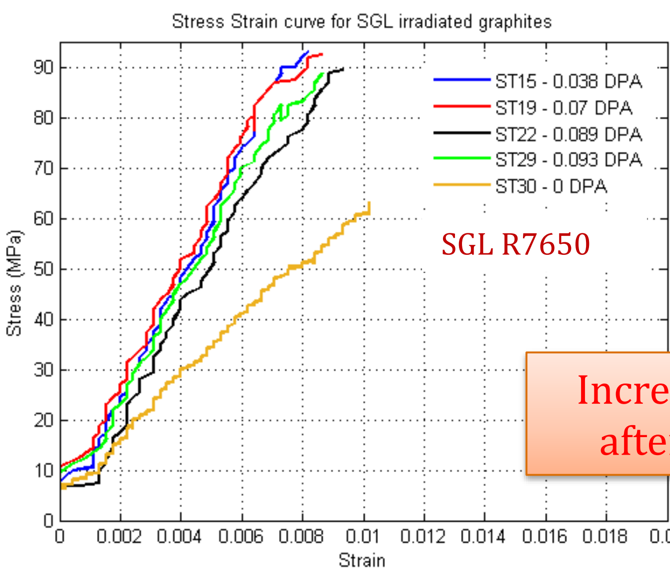
PIE at BLIP

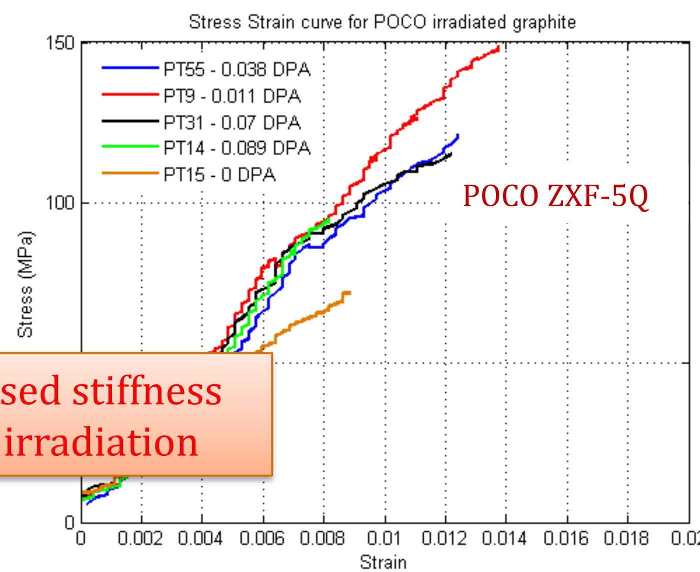
Evaluate macroscopic effects due to radiation damage

Hot cell equipment

- Dilatometer
- Tensile tester
- Ultrasonic system
- Electrical resistivity measurement system
- High temperature furnace

Tensile test results





Increased stiffness after irradiation

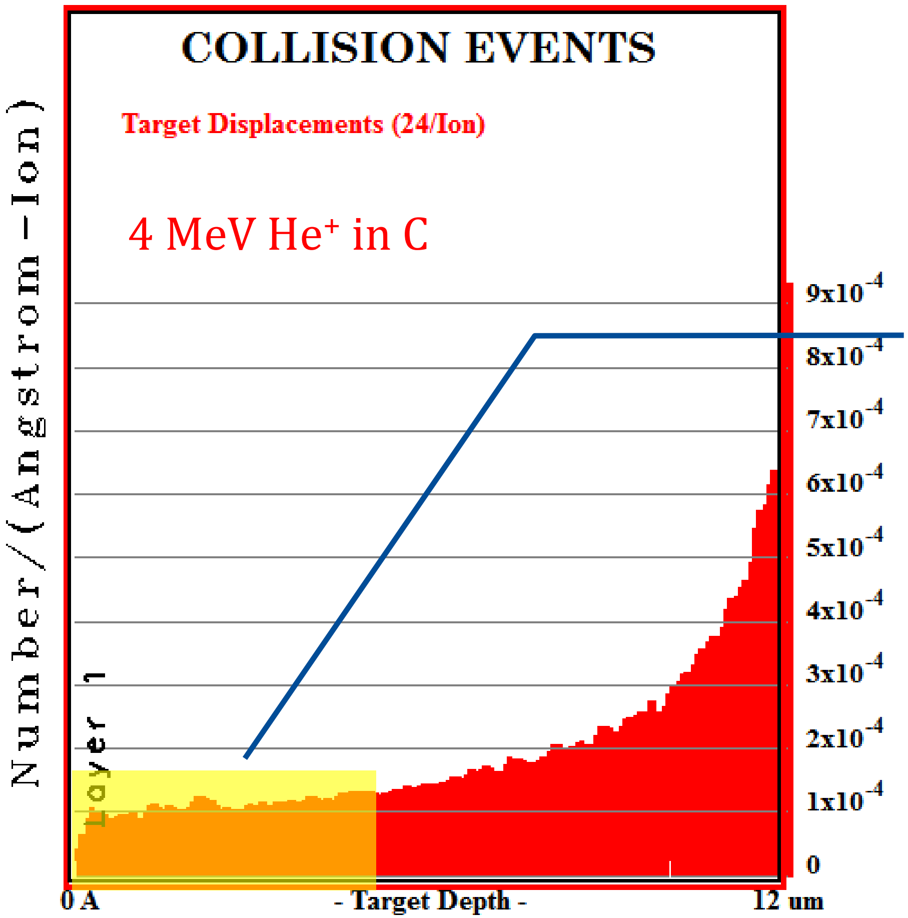
Next experiment planned in Spring 2017!

Materials
C, Be, TZM, Ir, Si, Ti, Al

Slides courtesy of K. Ammigan, Fermilab

Addressing ion irradiation issues to emulate proton irradiation

1. Depth of penetration and non-uniform damage profile



- Probe thin damage layer of specimen (TEM)
- Uniform damage levels within few μms

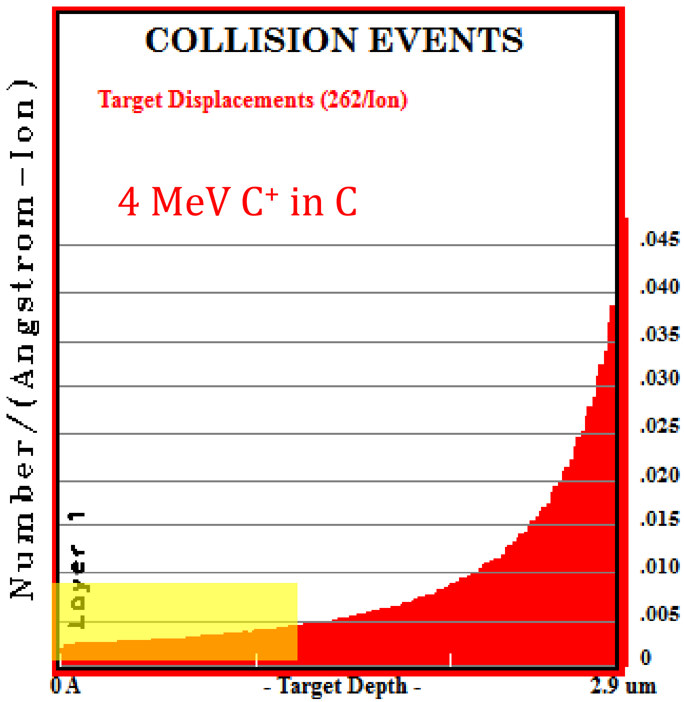
- Energy raster beam to spread energy and create more uniform damage profile

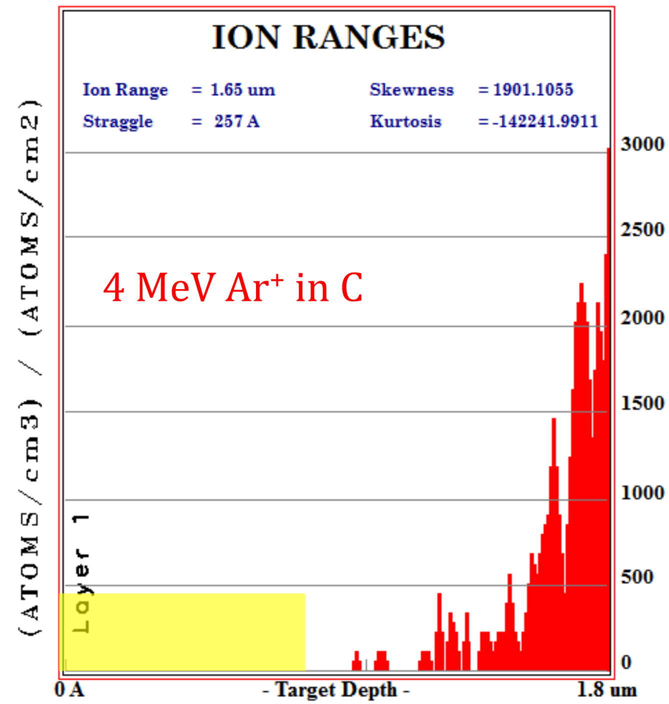
Slides courtesy of K. Ammigan, Fermilab

Addressing ion irradiation issues to emulate proton irradiation

2. Ion interstitial ‘poisoning’ when ions stop in specimen

- Self ions can be used
- Probe material in region before ions come to rest





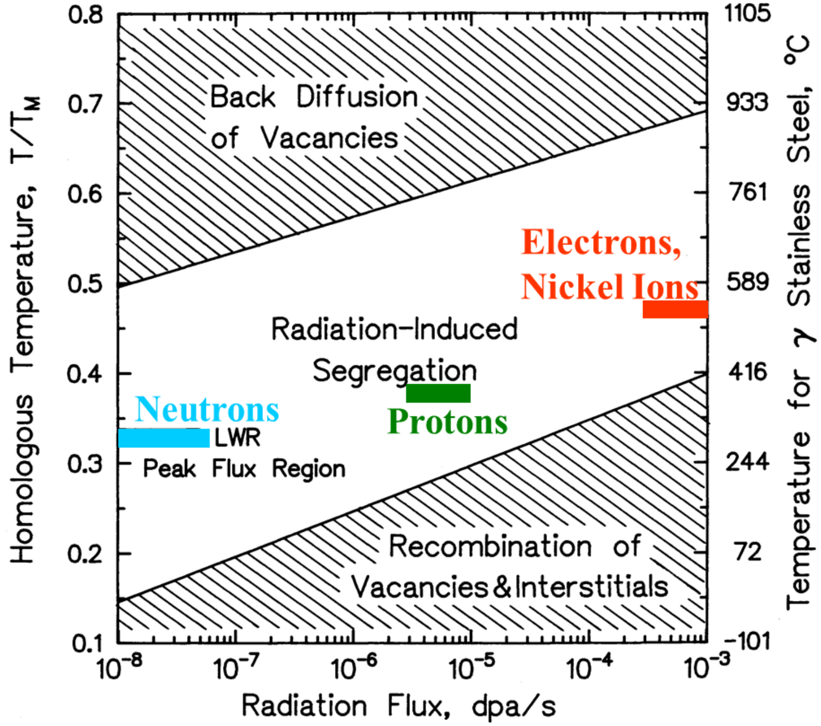
3. Transmutation products

- Inject H and He ions to replicate expected gas production rates

Addressing ion irradiation issues to emulate proton irradiation

4. Dose rate effects

- Damage effects not the same for cyclic irradiation and continuous irradiation
- Faster dose rates shown not to create same microstructure evolution as with slower rates



Was, G. & Jiao, Z., (2013)

- Shifting ion irradiation temperature has been suggested as a means to reproduce irradiated microstructure seen with protons or neutrons
- Higher ion irradiation temperature to match proton irradiation microstructural features

HEP HPT Future Needs

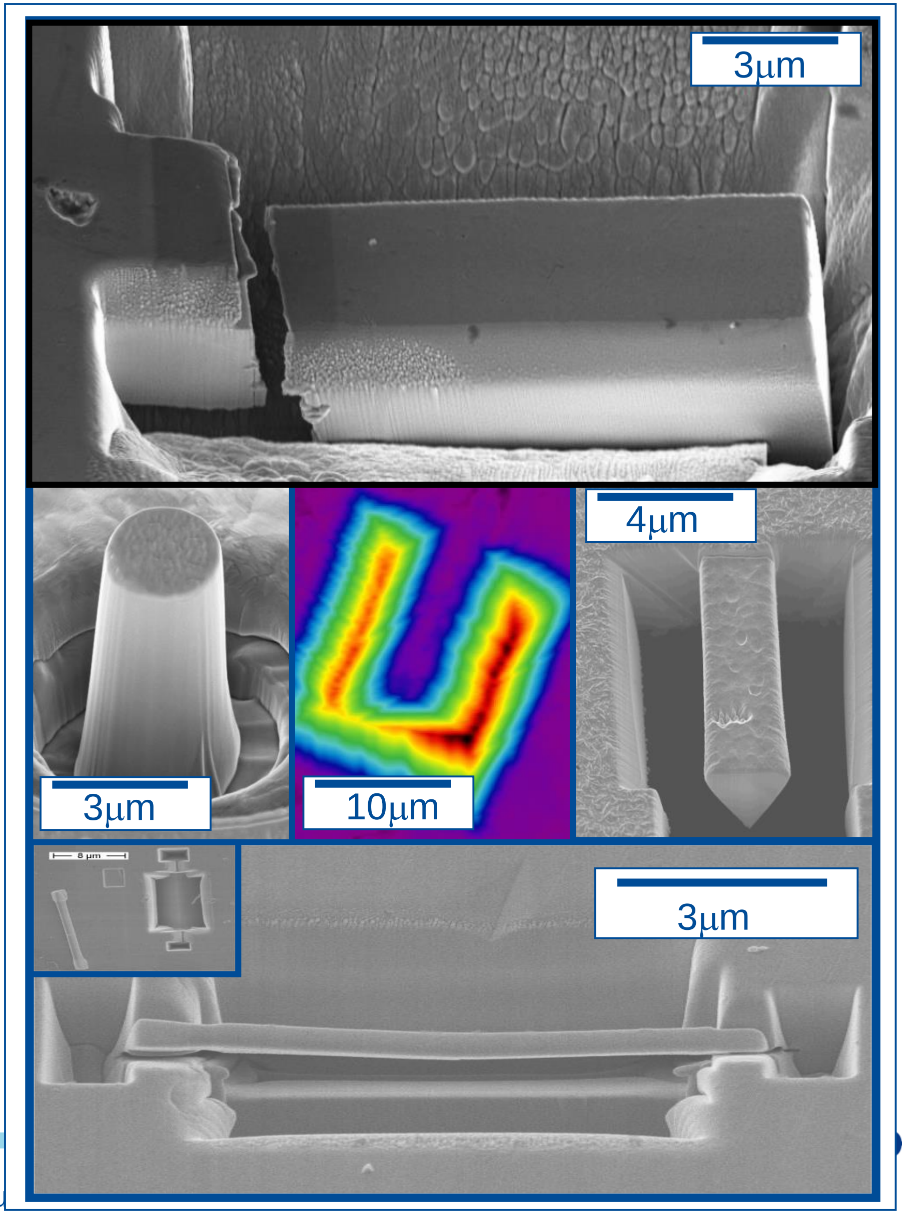
Exp/Facility	Laboratory	Time frame (yrs)	"On the books"?	Beam Power (kW)	Comments
ANU/NOvA	FNAL	0.5	Y	700	Ramping Up!
T2K	J-PARC	3	Y	750	Ramping Up!
CENF (SBL)	CERN	5?	?	300	Short baseline nu
LBNF-1.2 MW	FNAL	10	Y	1,200	PIP-II enabled
HyperK	J-PARC	10?	?	1,660+	2+ MW upgrade??
ILC	Japan?	15?	N	220	photons on Ti
Next-Gen Nu Facility –2.5 MW	FNAL	20?	N	2,500?	Mid-Term
Next-Gen Nu Facility - 5 MW	FNAL	30?	N	5,000?	Longer-term

Other low power (but high intensity) target facilities will also be needed. Notably follow-on experiments to Mu2e/COMET, g-2, etc… These are still challenging targets due to high-Z targets and small beam spots, but are not listed here.

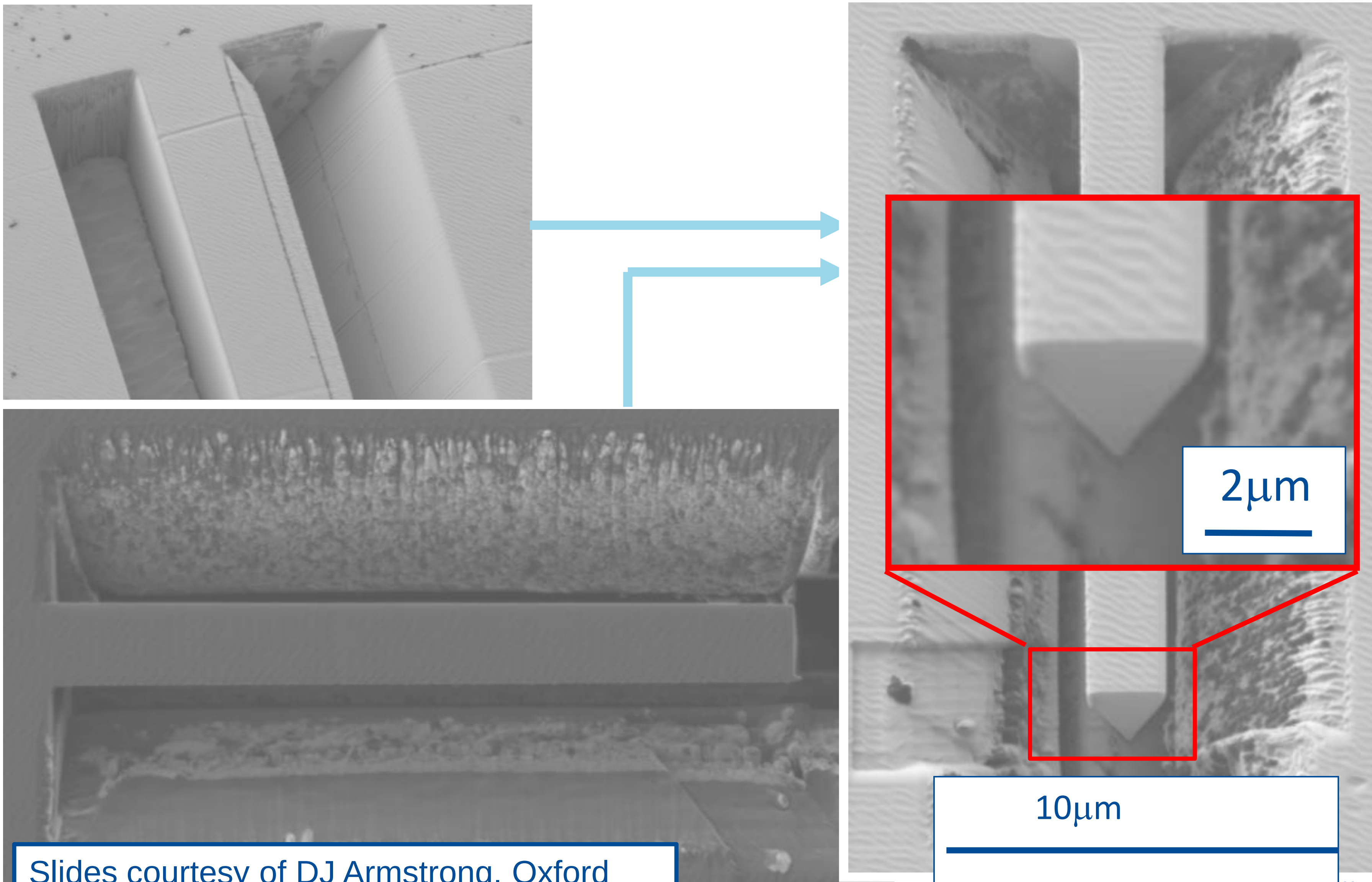
Why use micro-mechanical testing?

- **Useful where only small samples are available**
  - **Cost**
  - **Processing**
- **Need for a sample design that can be machined in surface of bulk samples**
- **Suitable for measuring individual microstructural features**
- **Samples that can be manufactured quickly and reproducibly**

Slides courtesy of DEJ Armstrong, Oxford

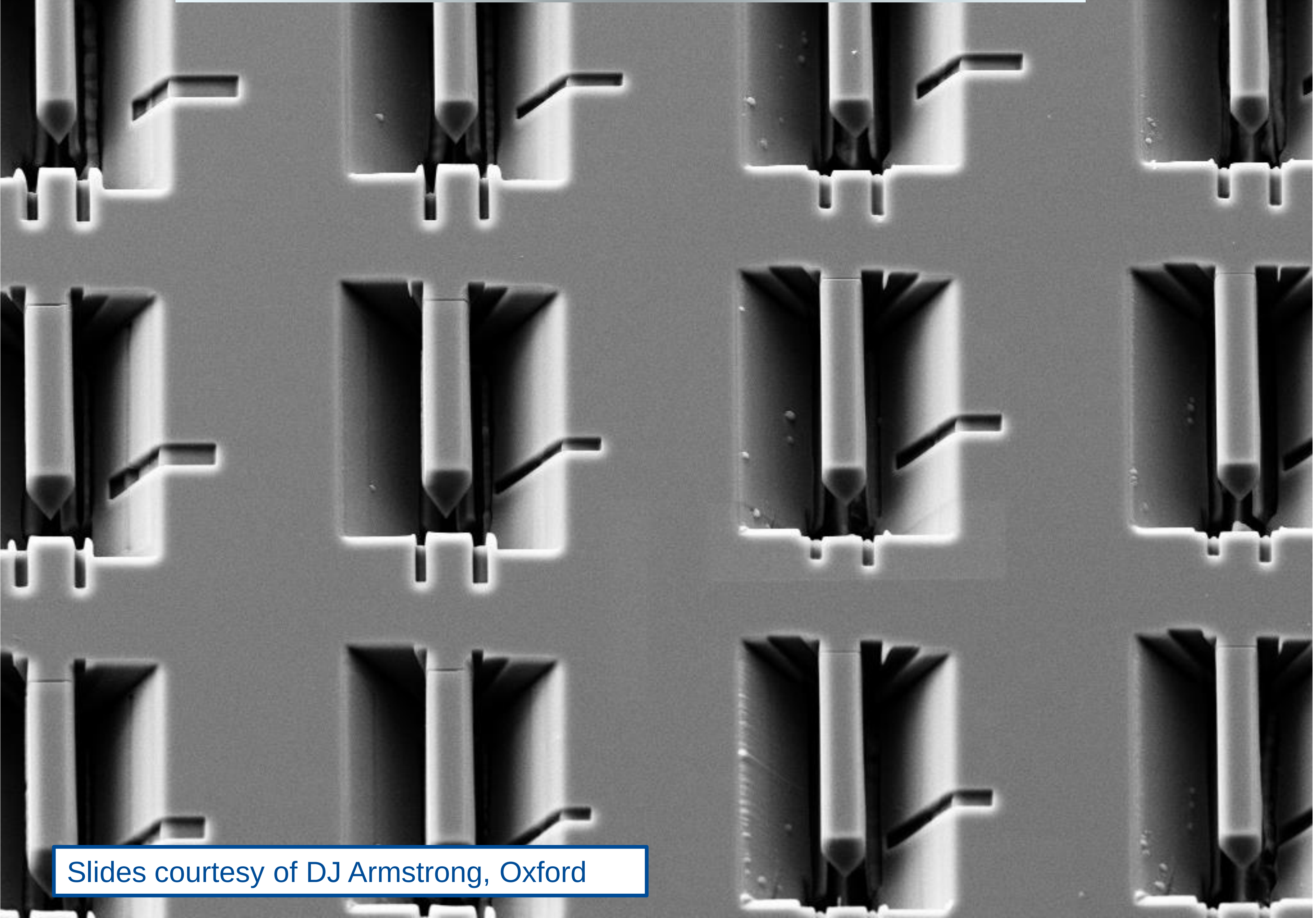


Microcantilever Manufacture



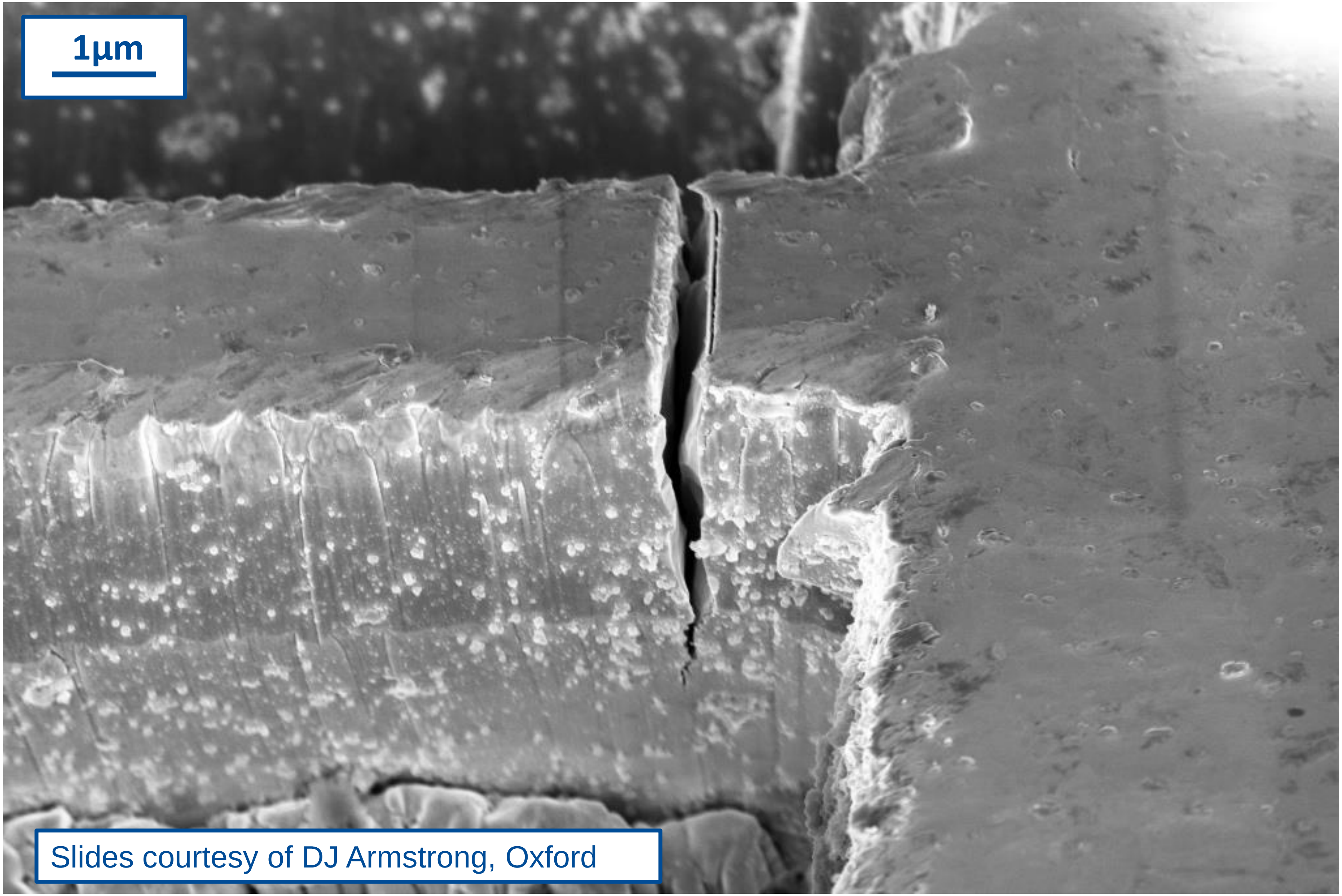
Slides courtesy of DJ Armstrong, Oxford

Current State of the Art



Slides courtesy of DJ Armstrong, Oxford

Fracture at 600ºC

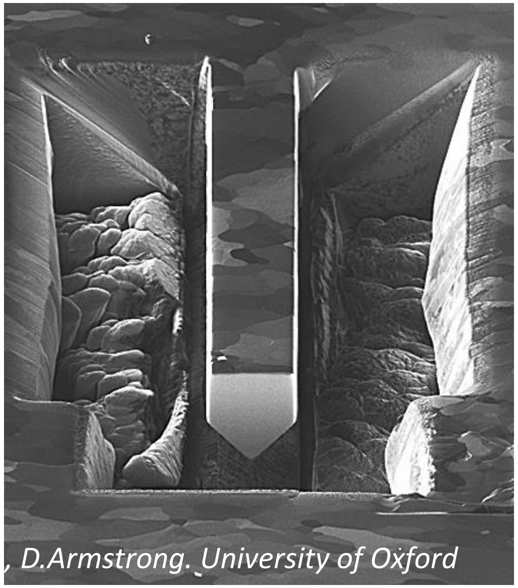


Exploration of Radiation Damage Effects to High Doses Likely Requires High and Low Energy Irradiation Studies

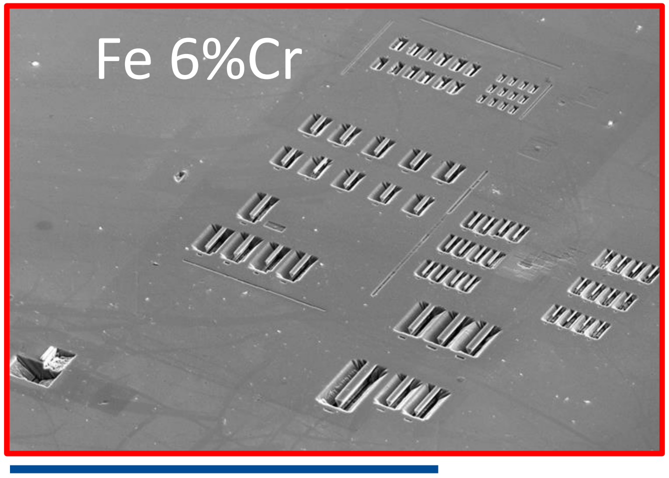
- **High energy**, high fluence, large volume **proton irradiations** are expensive and time consuming
  - Long irradiation beam times (months)
  - Difficulties of Post-Irradiation Examination (PIE) of highly activated samples
- **Low energy**, small volume **ion irradiations** are inexpensive and can achieve several DPA in an hour
  - Low to zero activation (PIE in “normal” lab areas)
  - Greatly accelerated damage rates (several DPA in hours)
- However **Low energy ion irradiations have drawbacks**:
  - Very shallow penetration (0.5-100 microns)
  - Little gas production (transmutation) in samples
- **Promising Solutions:**
  - **Micro-mechanics** (coupled with advanced microscopy techniques) may enable evaluation of critical properties
  - Simultaneous implantation of He and H ions (**triple-beam irradiation**)
- **But still need HE proton irradiations to correlate and validate techniques**

Micro-mechanics can provide mechanical properties at the micro-scale

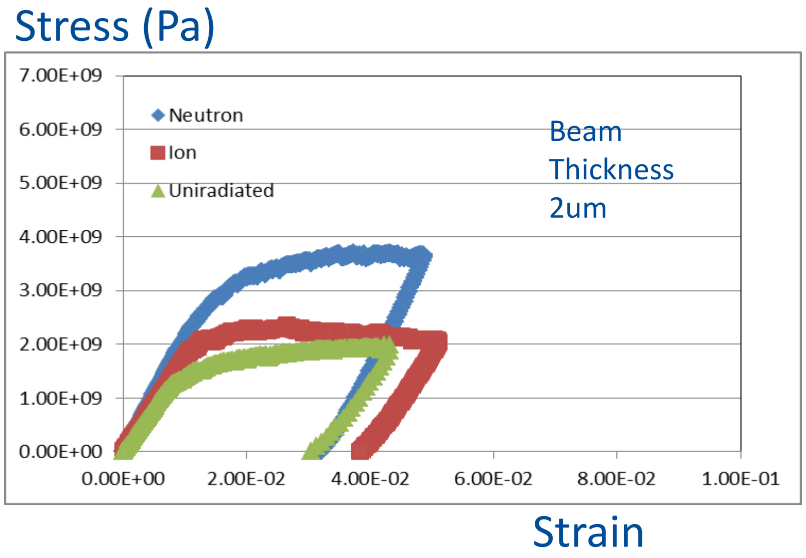
- Useful where only small samples are available (implanted layer)
- Need for a sample design that can be machined in surface of bulk samples
- Geometry that can be manufactured quickly and reproducibly



Chris Hardie, University of Oxford

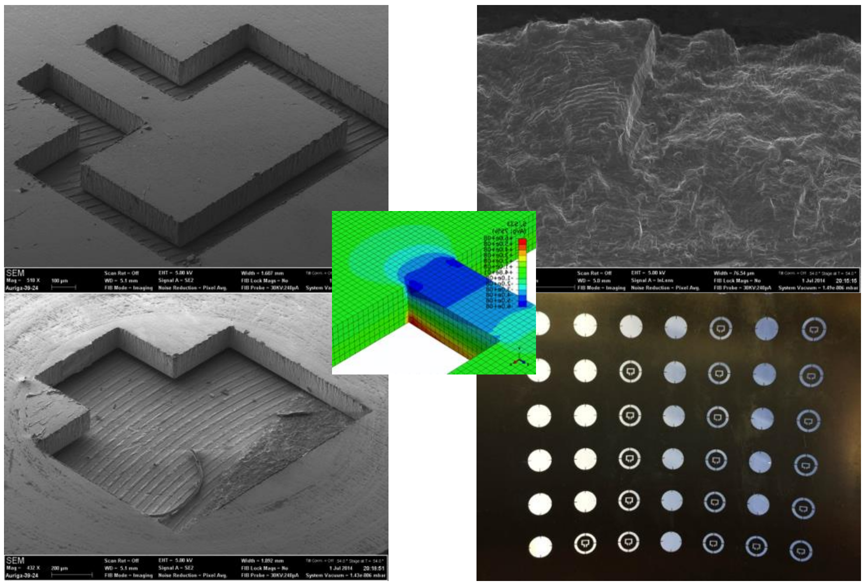


0.3mm

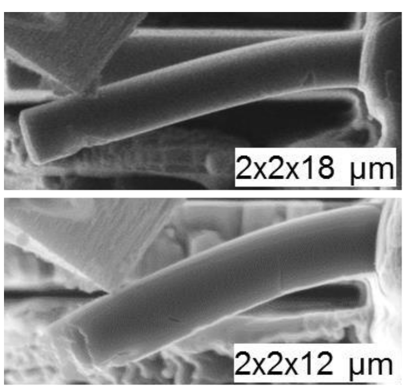


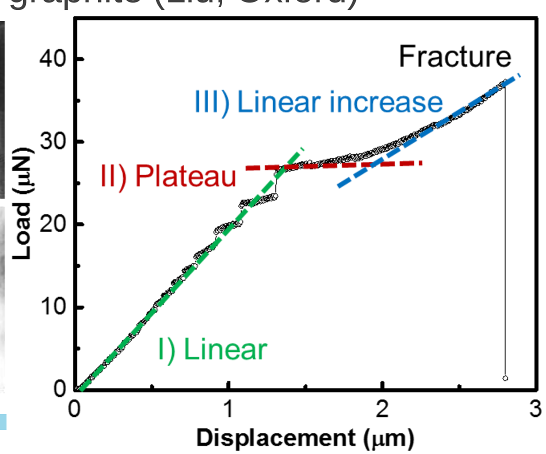
New directions and techniques

– High frequency meso-scale fatigue testing (20 kHz, 100 um foil) (Wilkenson/Gong, Oxford)



– Micro-mechanics on graphite (Liu, Oxford)





Other planned work

– Graphite
  - 2017-18 Low E ion irradiation studies (Notre Dame/Michigan/BNL?)
  - 2017 – Micro-mechanics (Liu @ Oxford)
  - 2018? - NOvA TA-01 target autopsy/PIE (PNNL)

– Beryllium
  - 2016-17 – Irradiation of Be fins in NOvA TA-02 target with PIE in 2018-19?

– Titanium 6Al-4V
  - 2018 - Macro-fatigue testing of BLIP specimens
    2018 - Meso-fatigue testing of BLIP specimens (20 kHz) (Oxford, Culham)