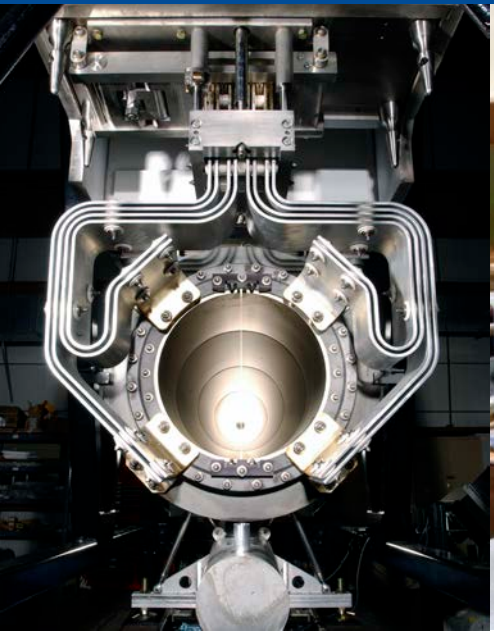
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science



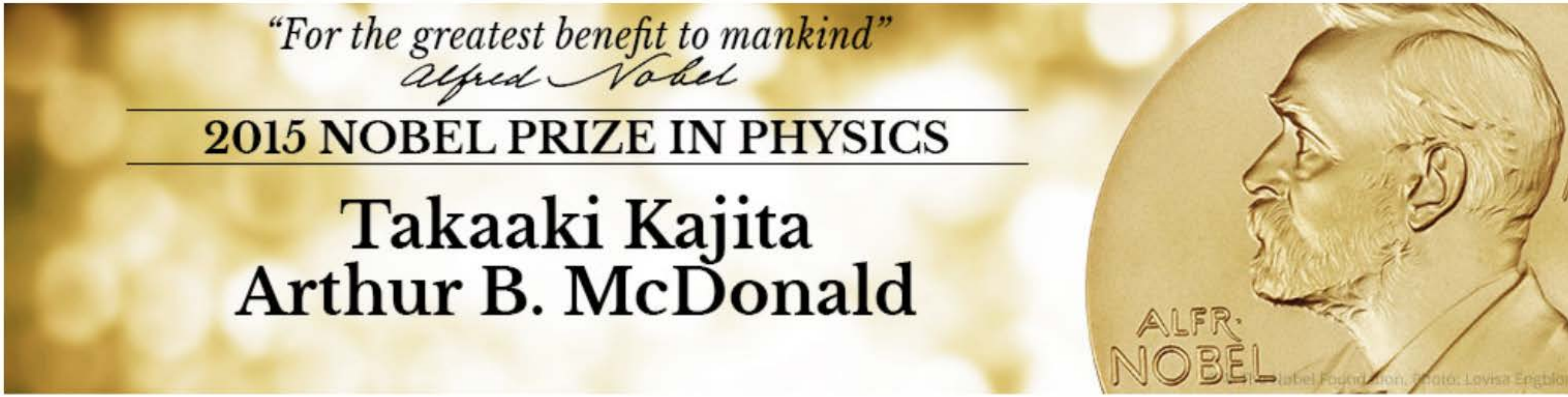
# The Challenges of Next Generation Neutrino Beam Targetry

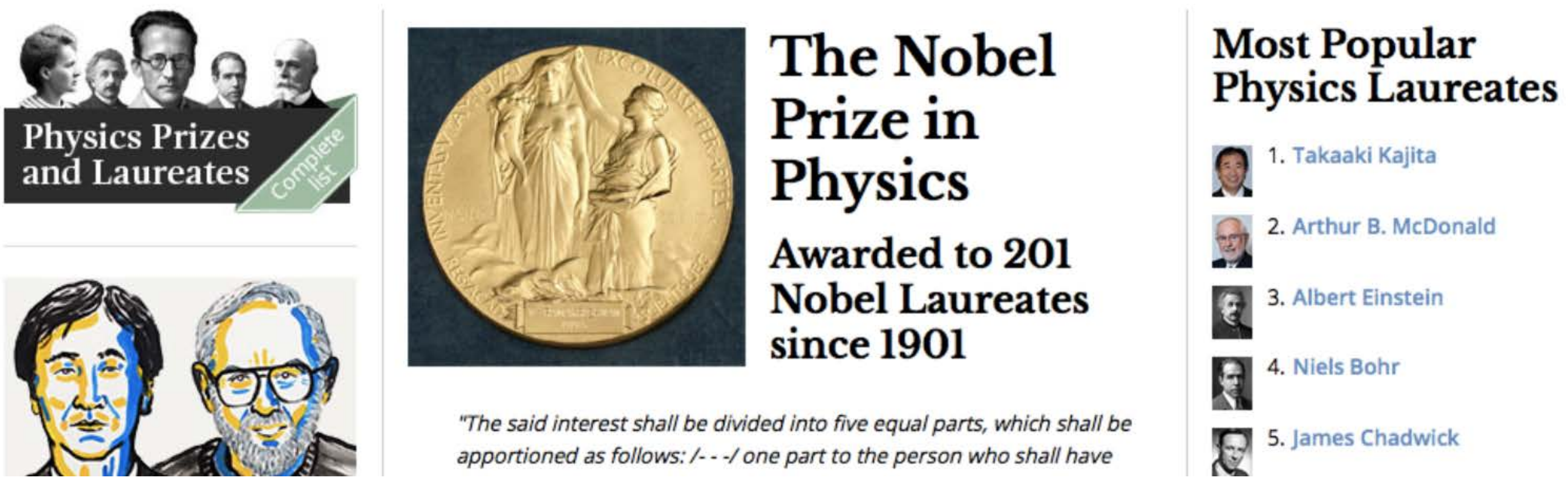
Robert Zwaska, Patrick Hurh

IIT Colloquium

23 March 2017

# Neutrinos continue to make news

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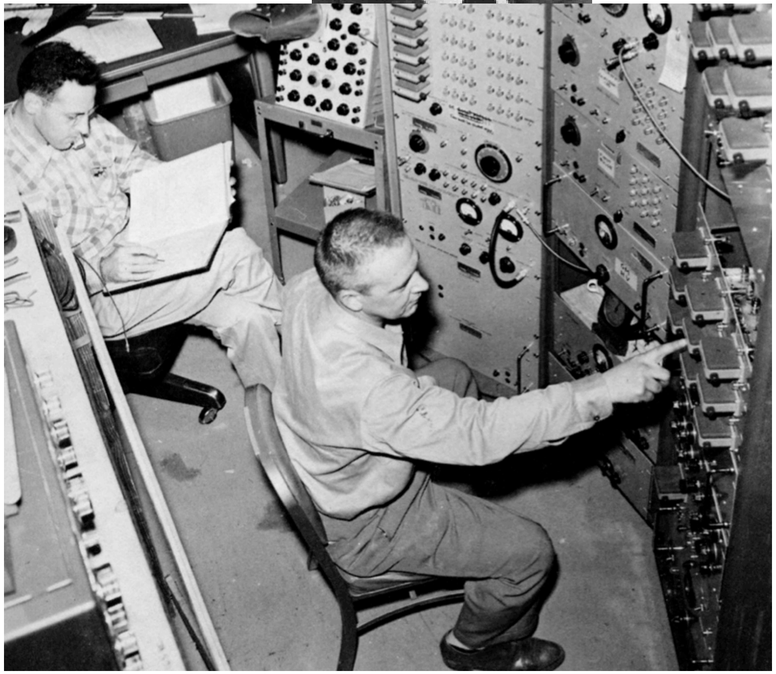
# The Nobel of Neutrinos

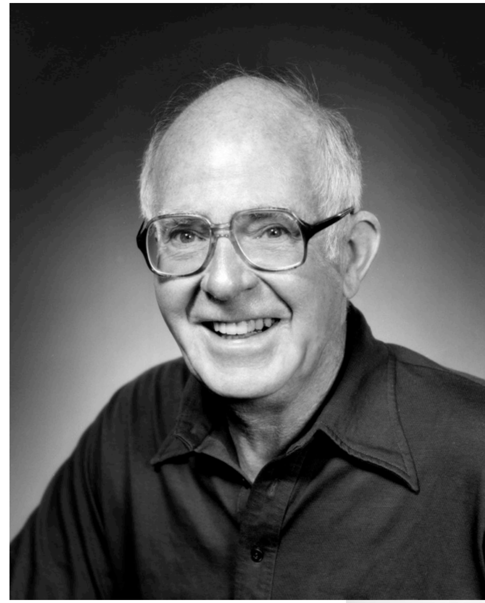
- Invented as a particle “impossible” to detect (Pauli, 1930)
  - Save conservation of energy and angular momentum

- Detected by Cowan & Reines in 1956 (Nobel 1995)

- Lederman, Schwartz, & Steinberger developed the **Neutrino Beam** in 1962 (Nobel 1988)



# The Nobel of Neutrinos



- Cosmic Neutrinos (solar, atmospheric, and supernovae) discovered over several decades, for Koshiba & Davis (Nobel 2002)

- Neutrino Oscillations (solar & in-beam) for Kajita & McDonald (Nobel 2015)

- What is left in store?

# Outline

- Introduction to Fermilab & Neutrino Beams
- Material Challenges to Neutrino Beams
- Radiation Damage
  - Mechanisms and experiments

# Fermilab Accelerator Complex

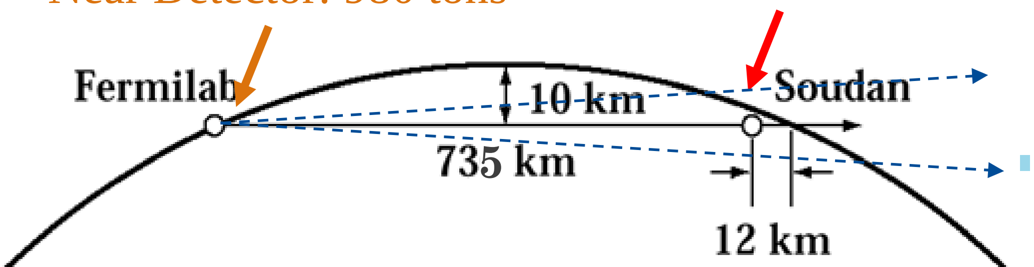
# The NuMI Facility

# “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 $10^{14}$ $\nu_\mu$
  - ~ 20,000,000 Pulses per year
- Direct beam 3º down
- On-site and off-site experiments
- Different types of neutrino beams
- Beam is 10s of kilometers wide at exit

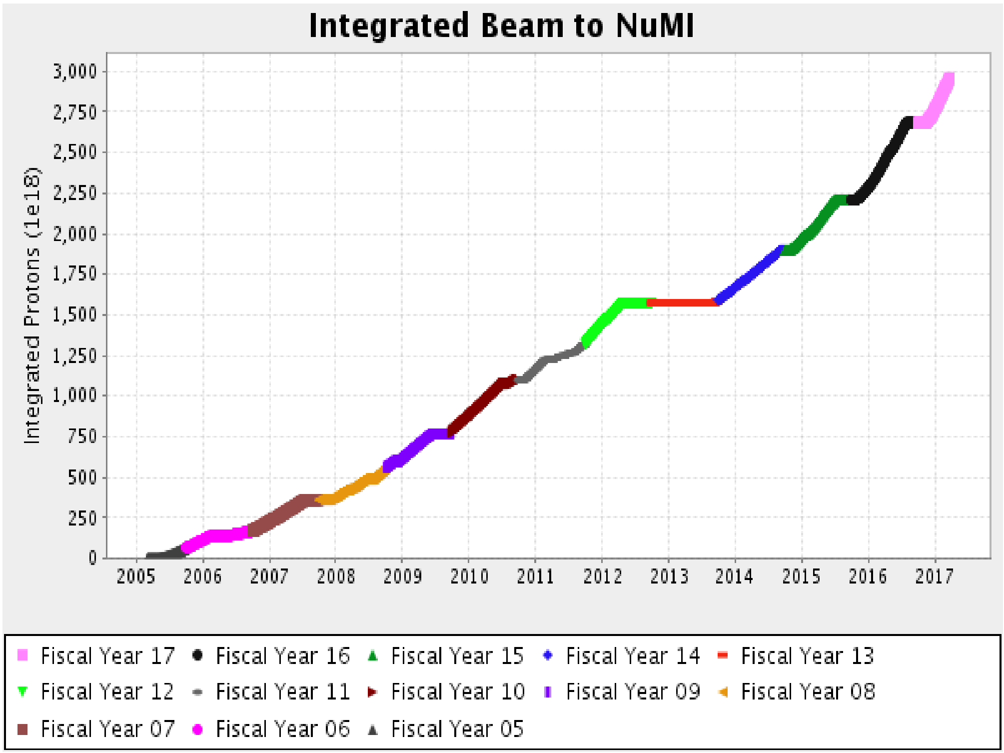

Near Detector: 980 tons

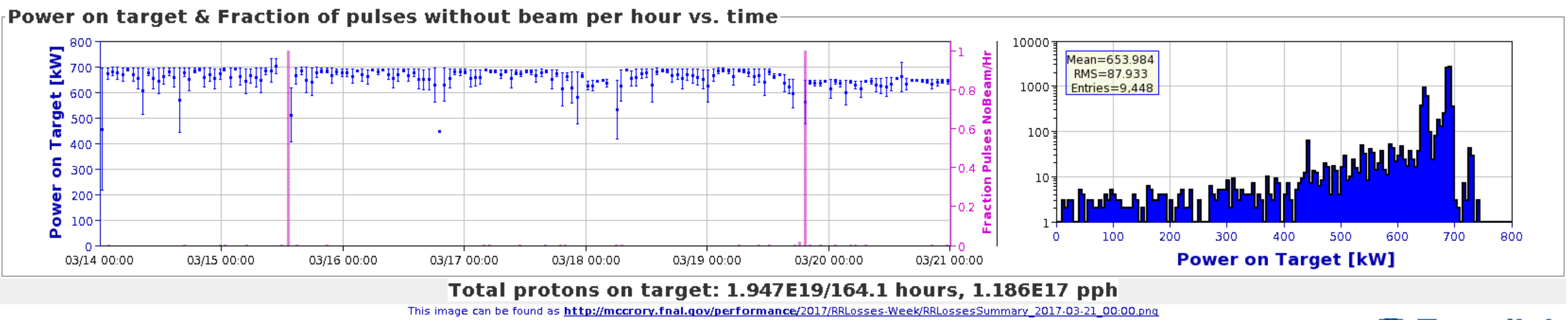
Far Detector: 5400 tons



# 700 kW – a reality

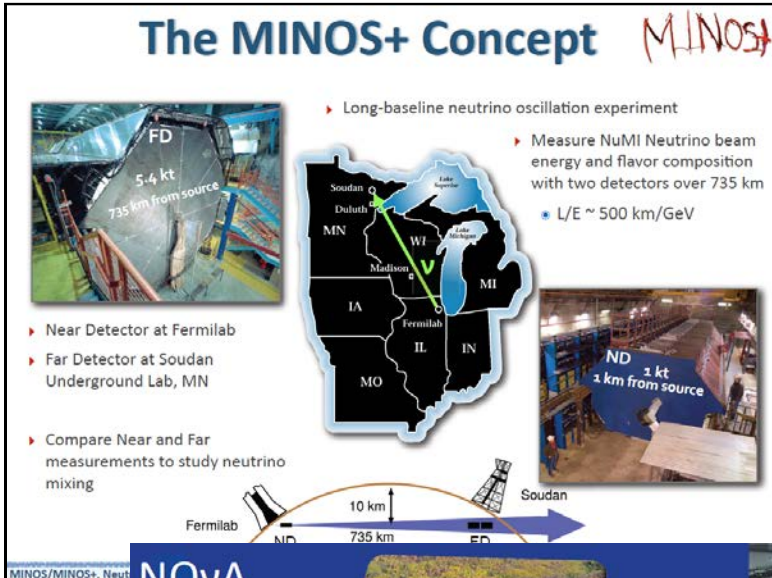
- Have achieved extended running above 700 kW
  - Up to 750 kW for short periods (7% above design)
  - Up to 53.9e12 protons (10% above design)
- Typical running is 650-700 kW (10% reduction for timeline sharing)
- Will approach a Megawatt in the next few years
  - Future beams will push into the Multi-MW regime

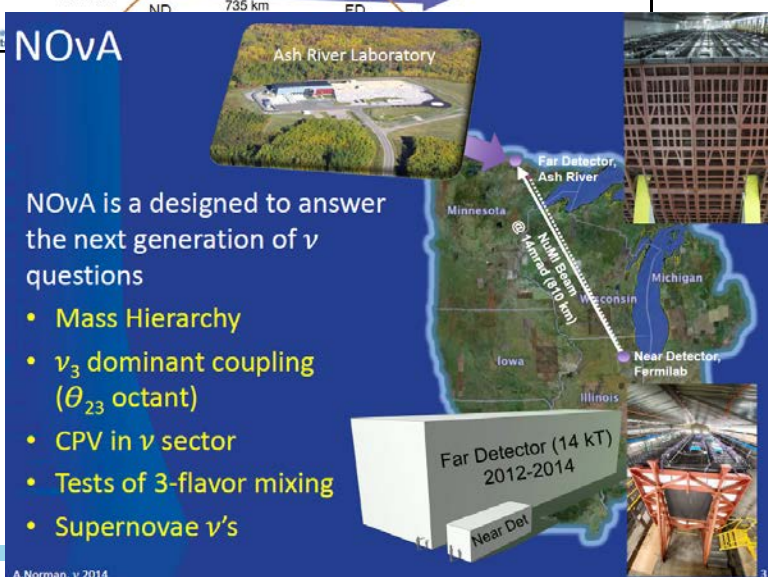


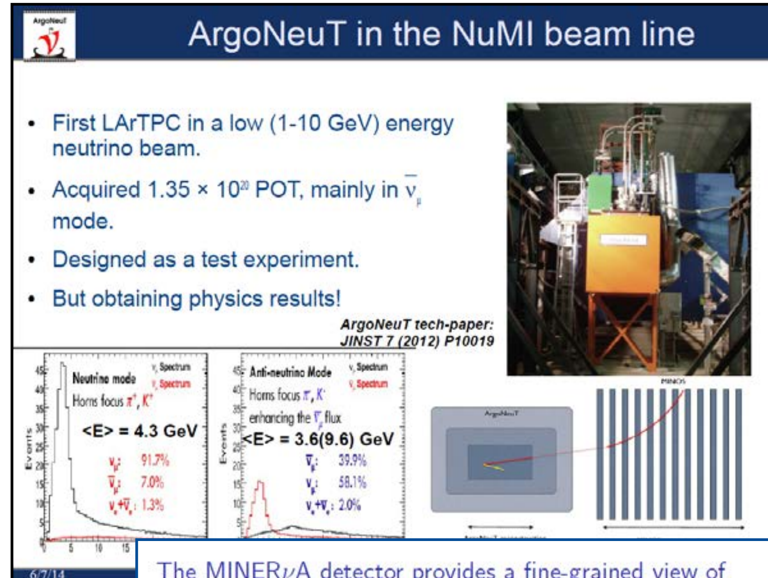
# Multiple Experiments in the NuMI Beam

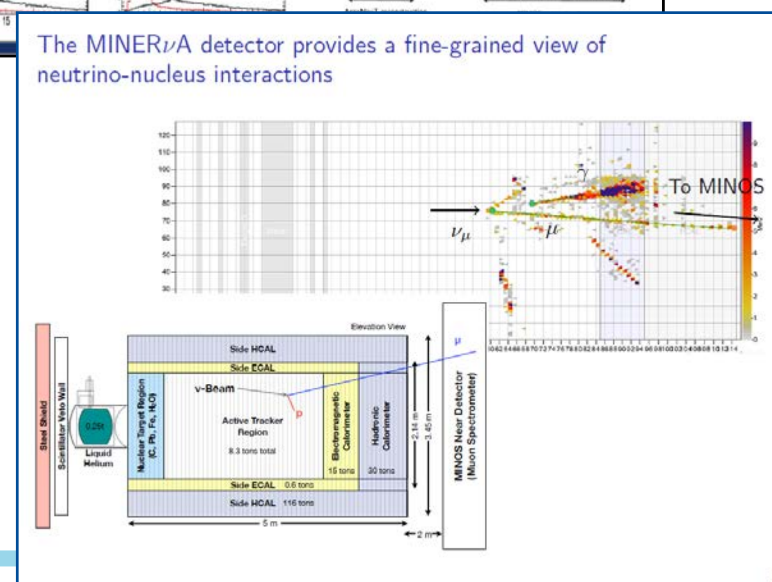
## Long-baseline oscillation experiments




## Neutrino scattering experiments



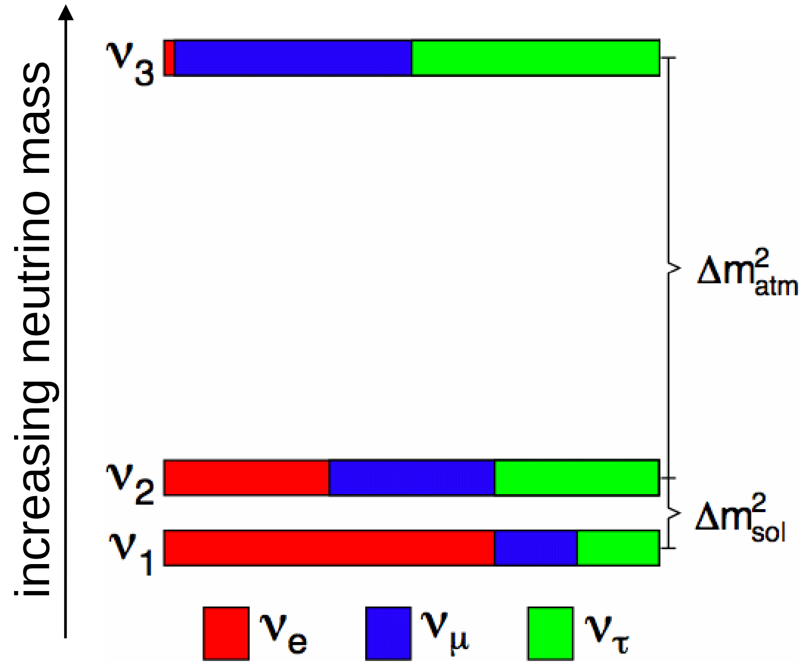



# Neutrino mixing drives the push to beams

→ Why is $\theta_{23}$ near maximal?
→ What is $\theta_{13}$ and why is it small?
→ Why so different than quark mixing?

$$U_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ 0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$U_{\mathrm{MNS}} \sim \begin{pmatrix} 0.8 & 0.6 & 0 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$




→ Is CP violation is present?
→ Are neutrinos Majorana?
→ What is the hierarchy of neutrino masses?

$$U=\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Accelerator/Atmospheric/Reactor   Solar sector   Majorana phase

# Why a Beam? – Controlled Laboratory Experiment

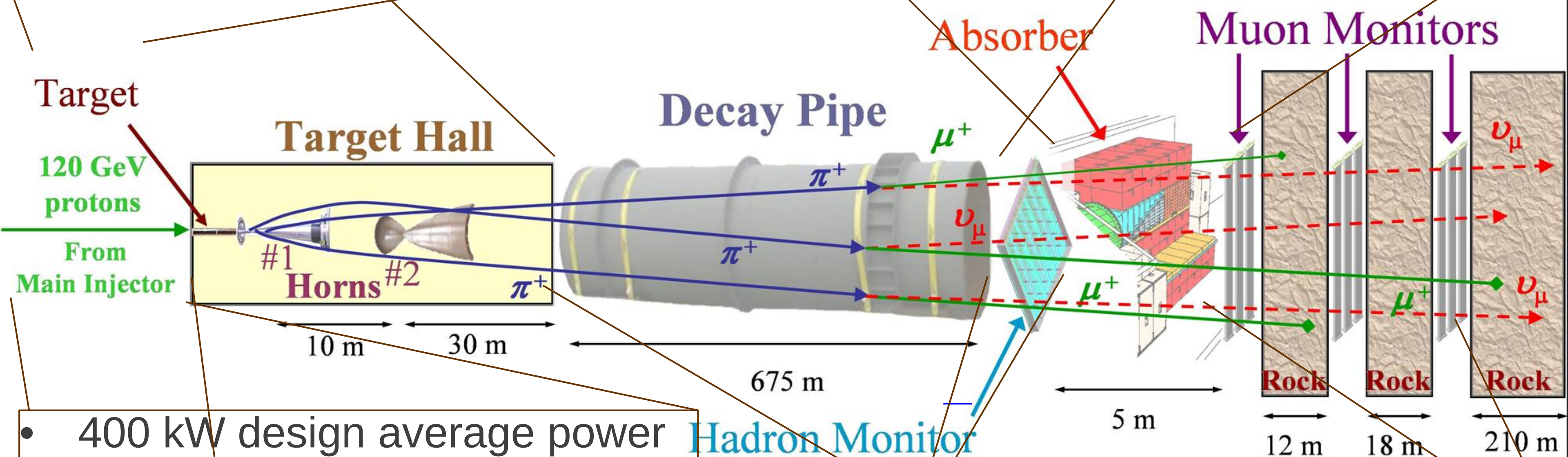
- Natural sources exist – but they are very weak and not necessarily well understood
  - Solar and atmospheric neutrinos only understood once oscillations were established and well understood
    - Moving from observation to experiment
  - Supernovae are hard to come by
- Artificial beams are controlled and intense ⇨ Precise!
  - 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 $\pi^+$, $K^+$ mesons

- 2 m diameter
- Roughly decay length for 10 GeV $\pi^+$
- 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

# Pion Decay

$$\pi^+ \to \mu^+ \nu_\mu$$

- Neutrinos produced at random direction in pion rest frame
  - Boosted in the direction of the beam
  - Ultimate energy determined by the decay angle with respect to the boost, in the lab:

$$E_\nu \approx E_\pi \frac{1 - m_\mu^2 / m_\pi^2}{1 + \gamma^2 \theta^2} \approx \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

  - Muon carries the balance of the energy
- Flux is also affected such that the beam is strongly directed in the direction of the pion velocity:

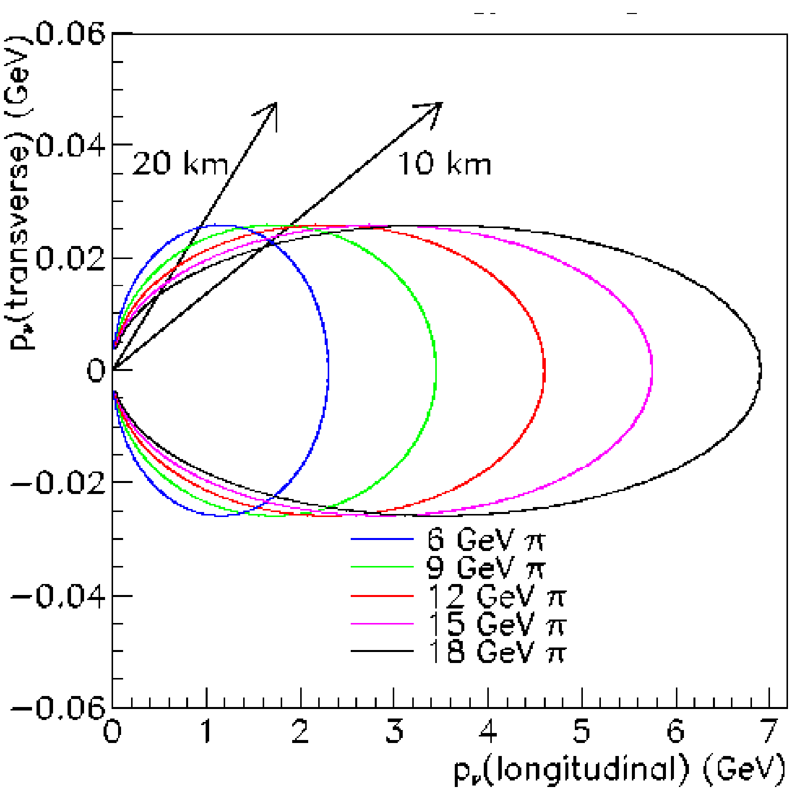
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi} \left( \frac{2\gamma}{1 + \gamma^2 \theta^2} \right)^2$$

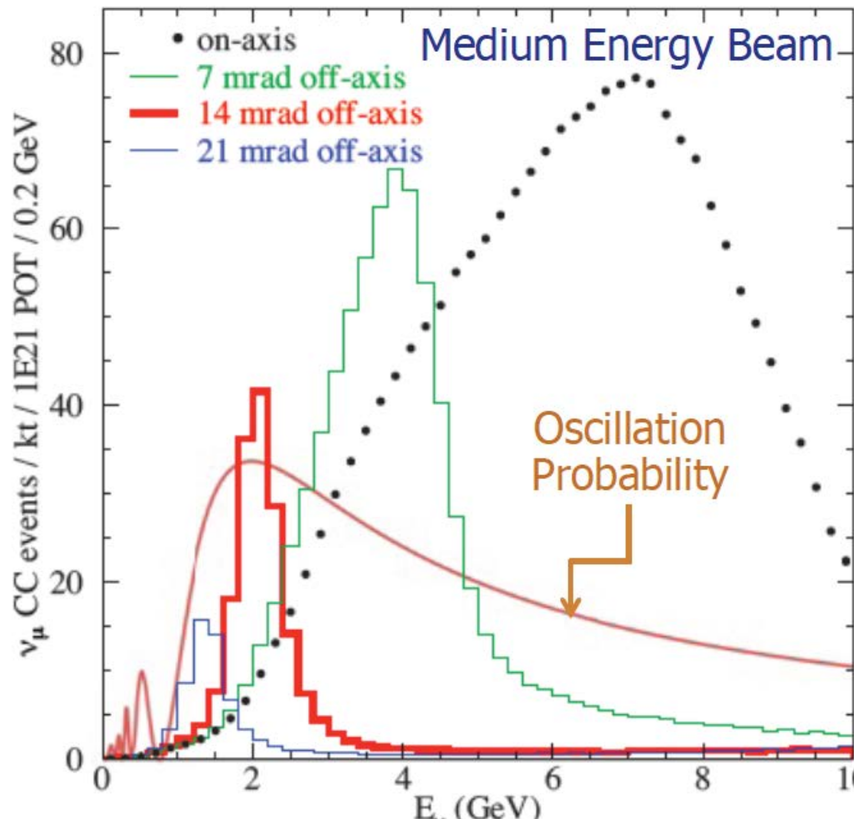
- All two-body decays have this functional form. Three body-decays are boosted in the same way, but are complicated by the decay kinematics

# Off-Axis Beam

$$E_\nu \approx E_\pi \frac{1-m_\mu^2/m_\pi^2}{1+\gamma^2\theta^2} \approx \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

- Technique used by T2K in Japan & NOvA at Fermilab
  - First proposed by BNL
  - Fewer total number of neutrino events
  - More at one narrow region of energy, tuned to oscillation probability
  - For $\nu_\mu$ to $\nu_e$ oscillation searches, backgrounds spread over broad energies



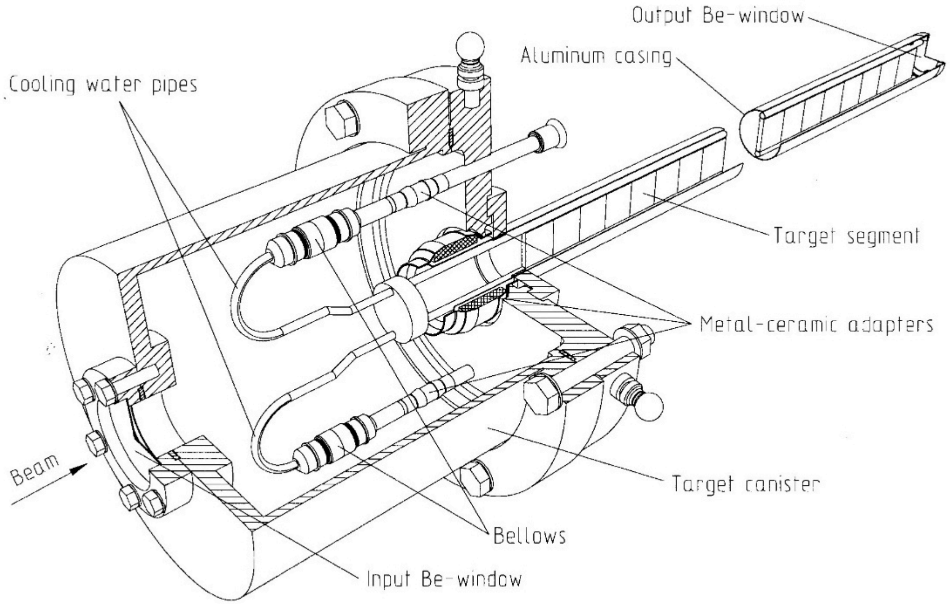



# Defining Characteristics of Long Baseline Beams

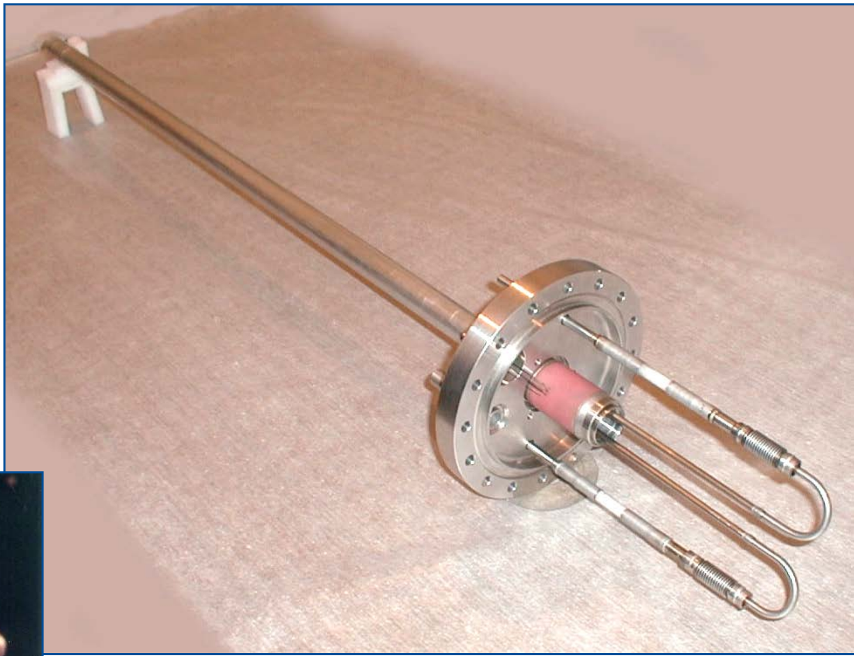
- Proton Beams: synchrotron based, nearing 1 MW
  - High Stored Energy: ~ 1 MJ
  - Small Beam Spot: 1 – few mm
  - High Proton Energy: 30-120 MJ
  - Single-turn extraction, long cycle time: 1 – few seconds
- Pion Focusing: Pulsed horns
  - Horns more efficient than quads
  - High currents: few hundred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

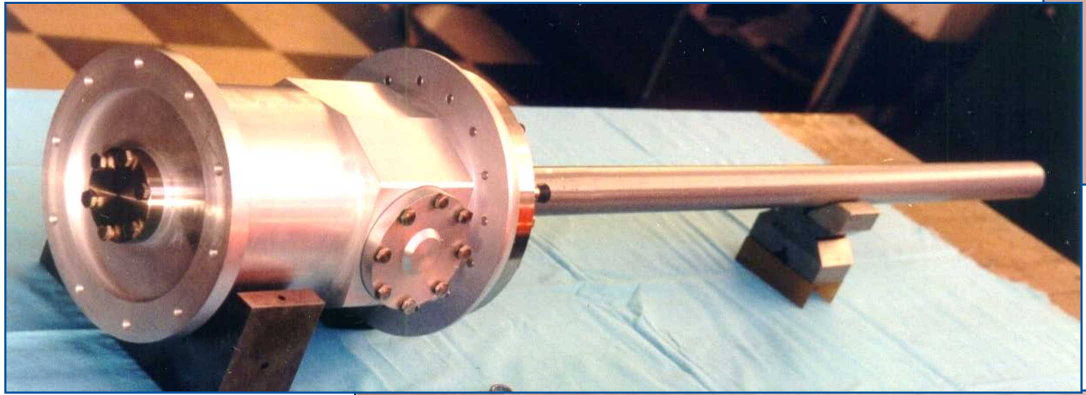
  Tritium, activation, corrosion, cooling

# The MINOS Target




~ 4 kW beam power
deposited in target

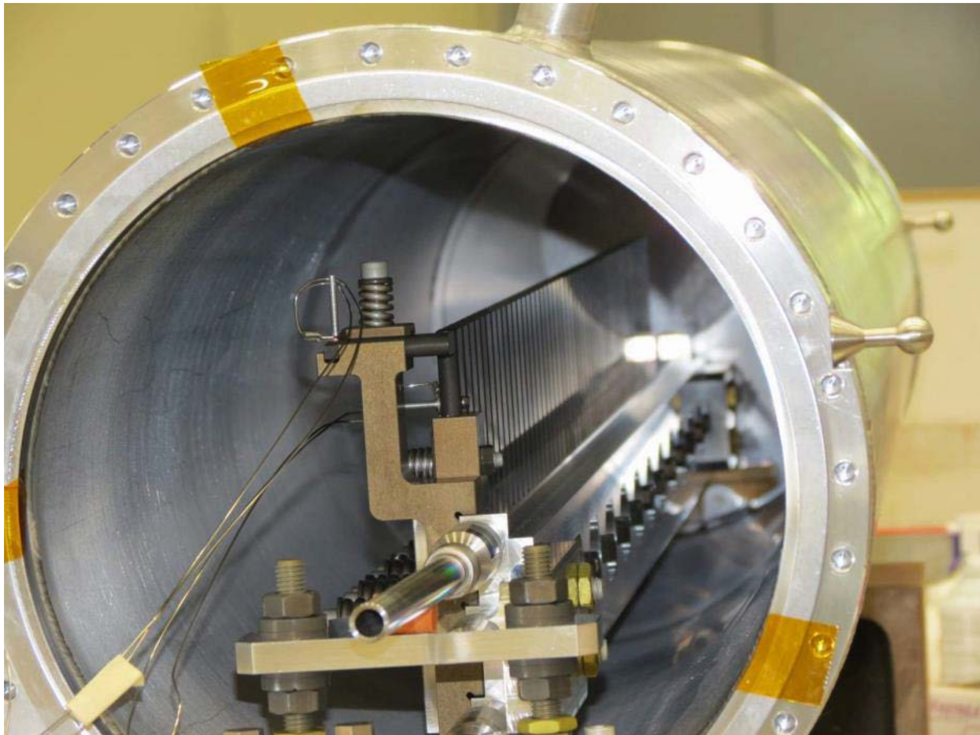




Encased in
vacuum / helium can
with beryllium windows

Water cooled
graphite core

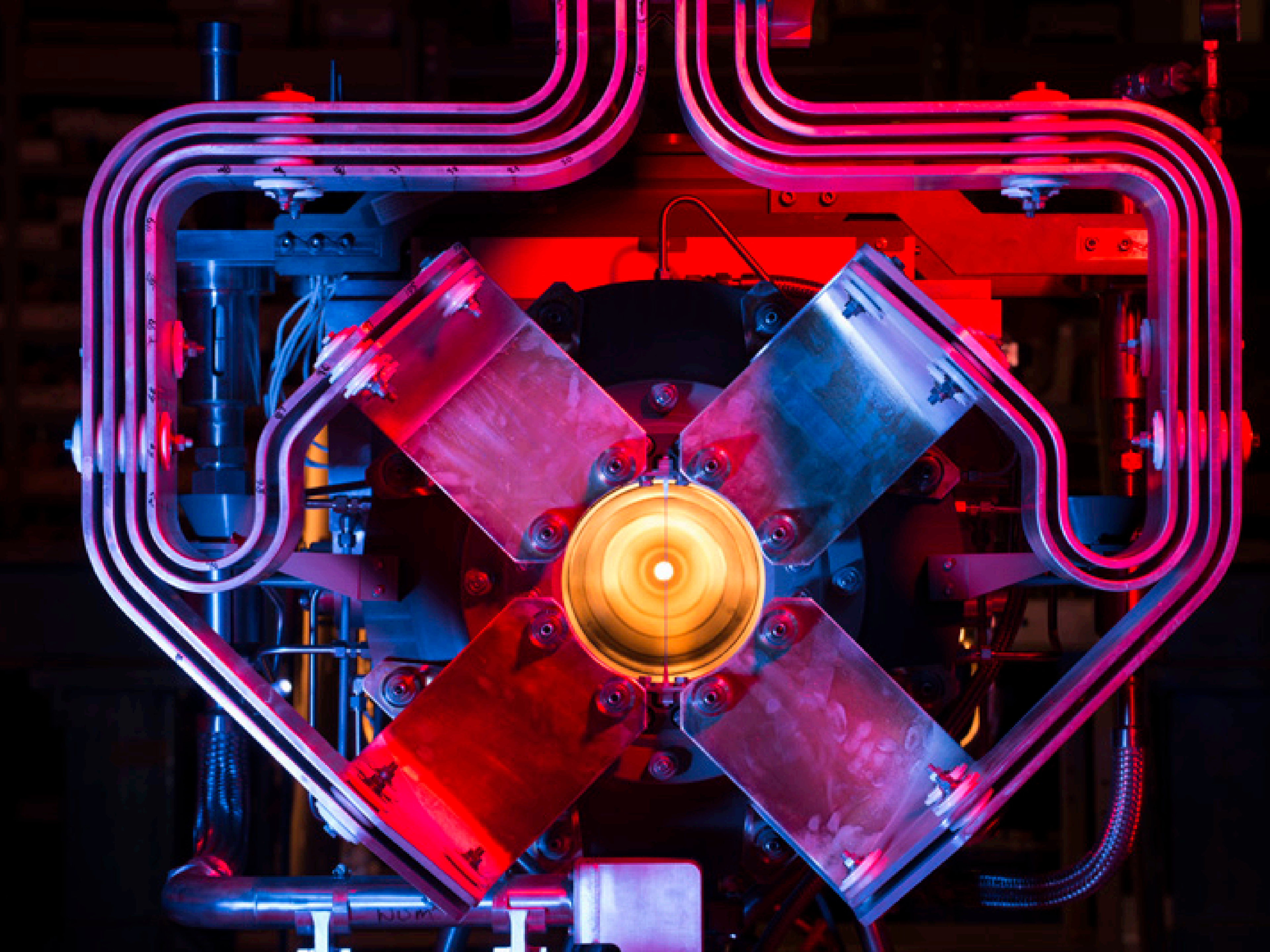
# NOvA Target



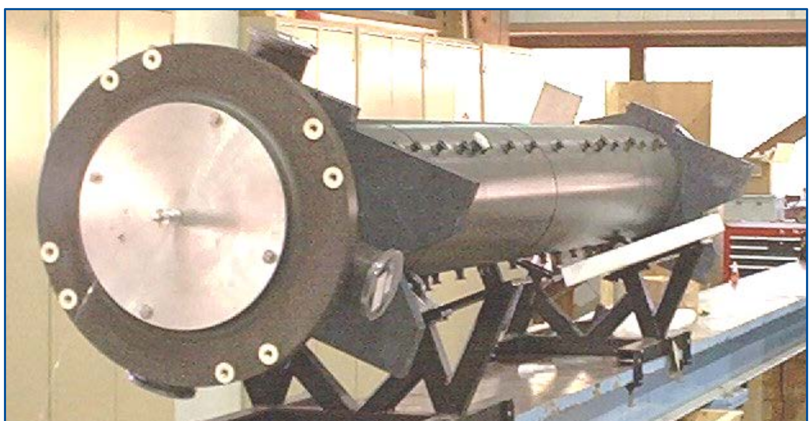
- Graphite fins: 50 x 24 mm; 7.4mm wide
- Helium atmosphere
- Beryllium windows
- Water cooled aluminum pressing plates
- fins not brazed to cooling (cf. NT-series)
- Water cooled outer vessel


IHEP Protvino (Russia) initial design

STFC-RAL / FNAL final design and construction

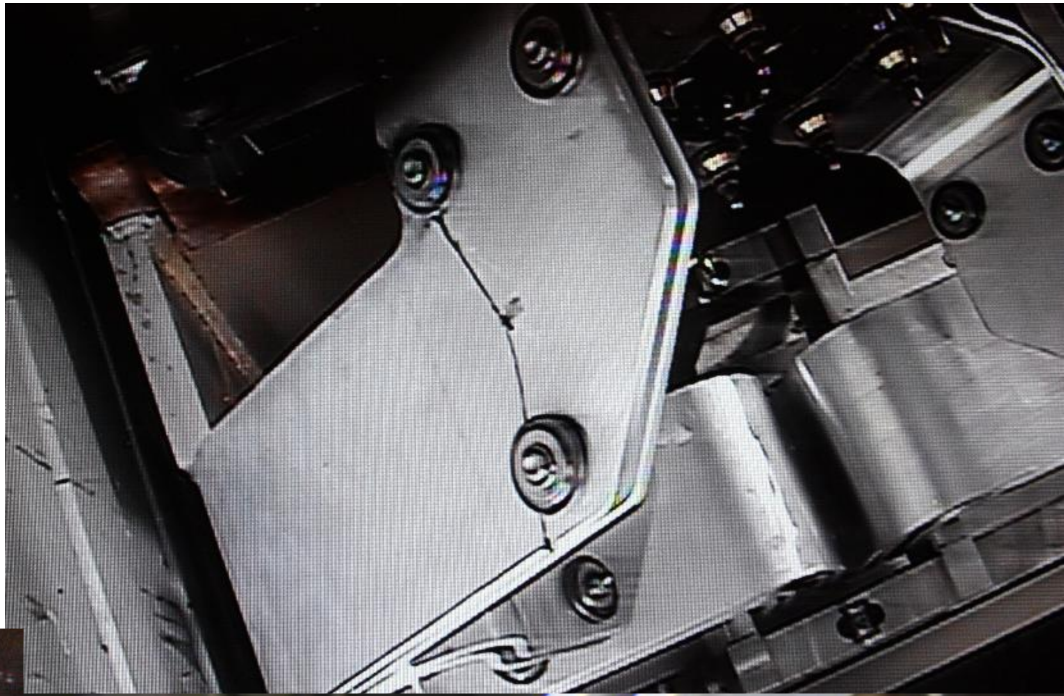


# Horn Fabrication

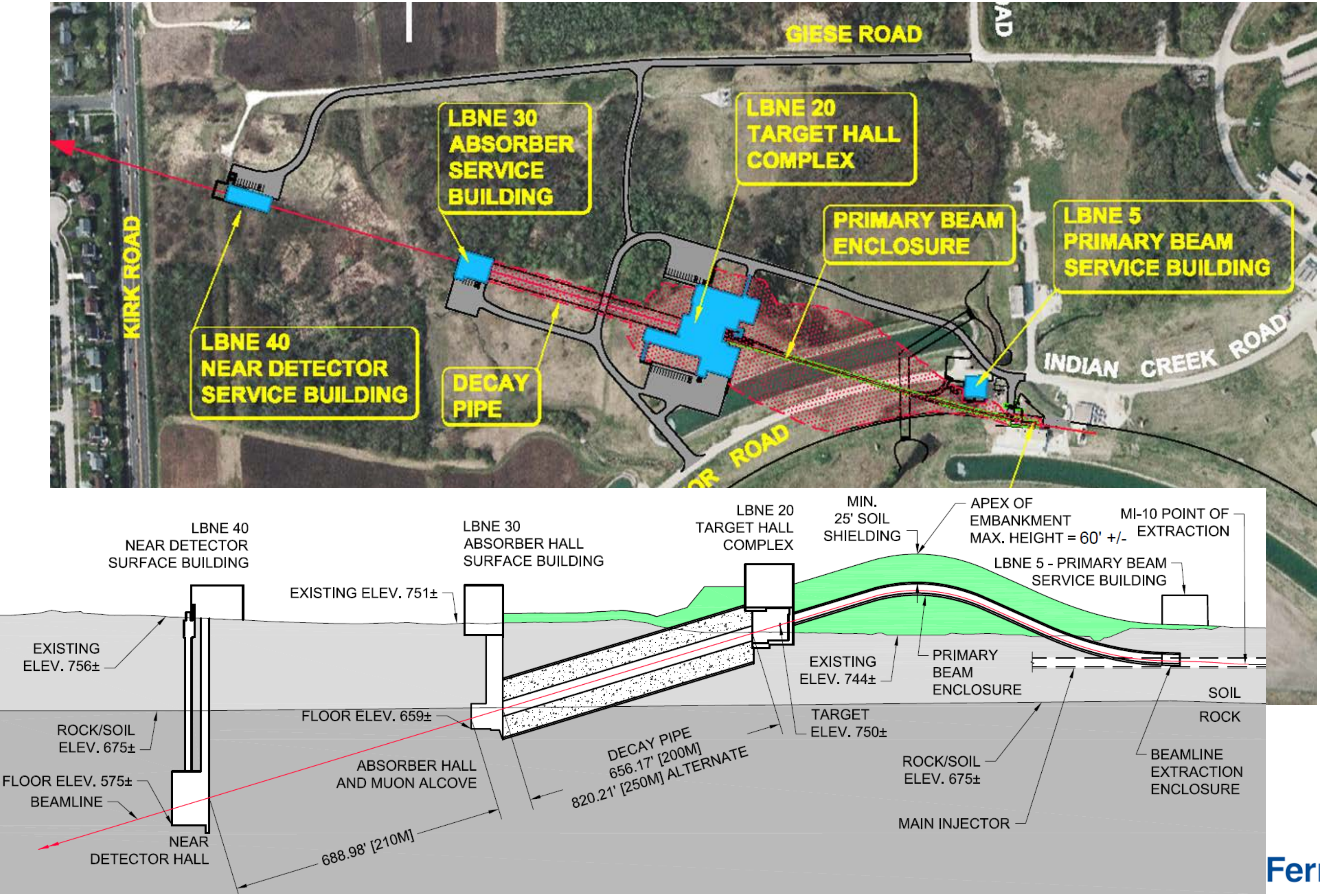


# Challenging Environments

- Replaced NuMI Horn summer 2015 due to failed stripline
  - First 700 kW capable horn, in service since Sept. 2013, accumulated ~ 27 million pulses
- Failure was due to fatigue, likely enhance by vibrations

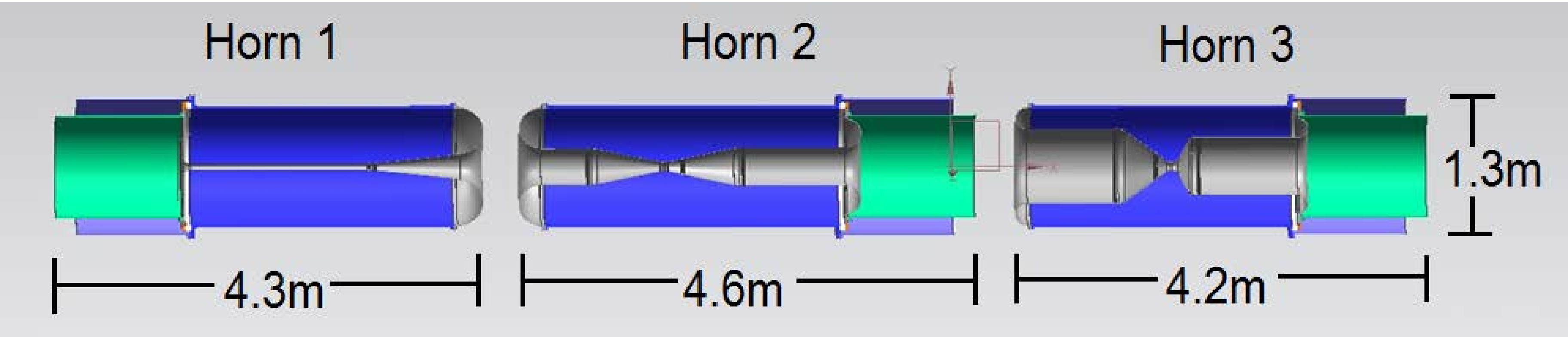


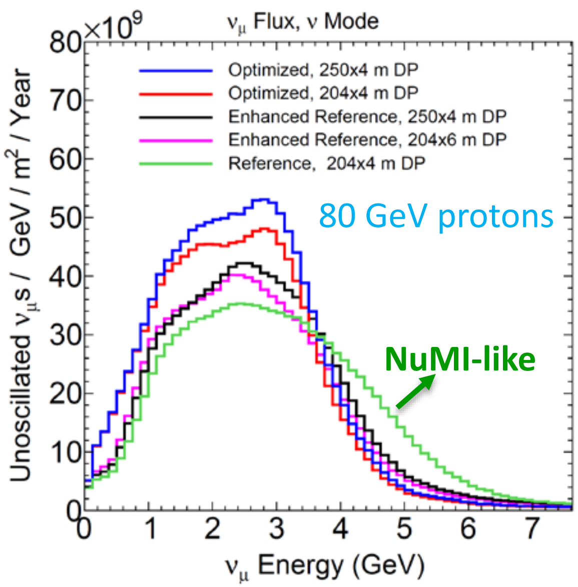
# DUNE: Deep Underground Neutrino Experiment
# LBNF: Long-Baseline Neutrino Facility

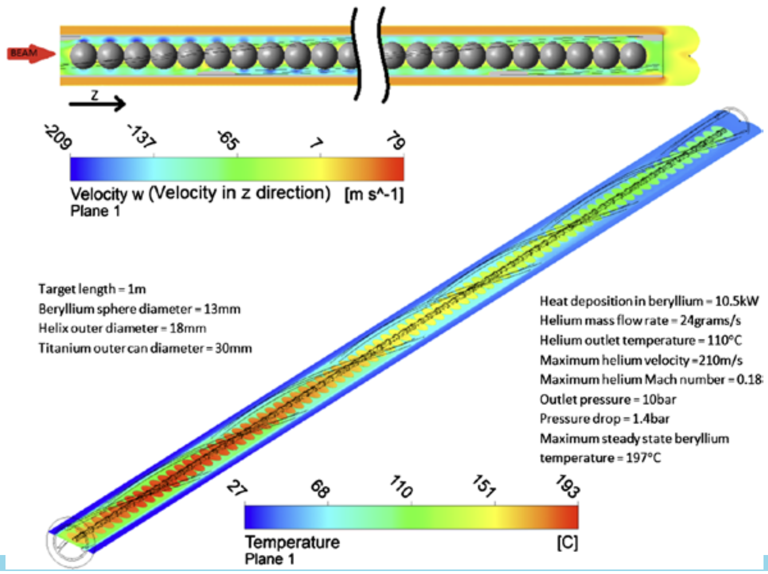


# DUNE optimizing the focusing system

Automated optimizations yielding 2m target and 3 large horns




Optimized target & horns push the envelope of technology, particularly with a 1.2 MW beam

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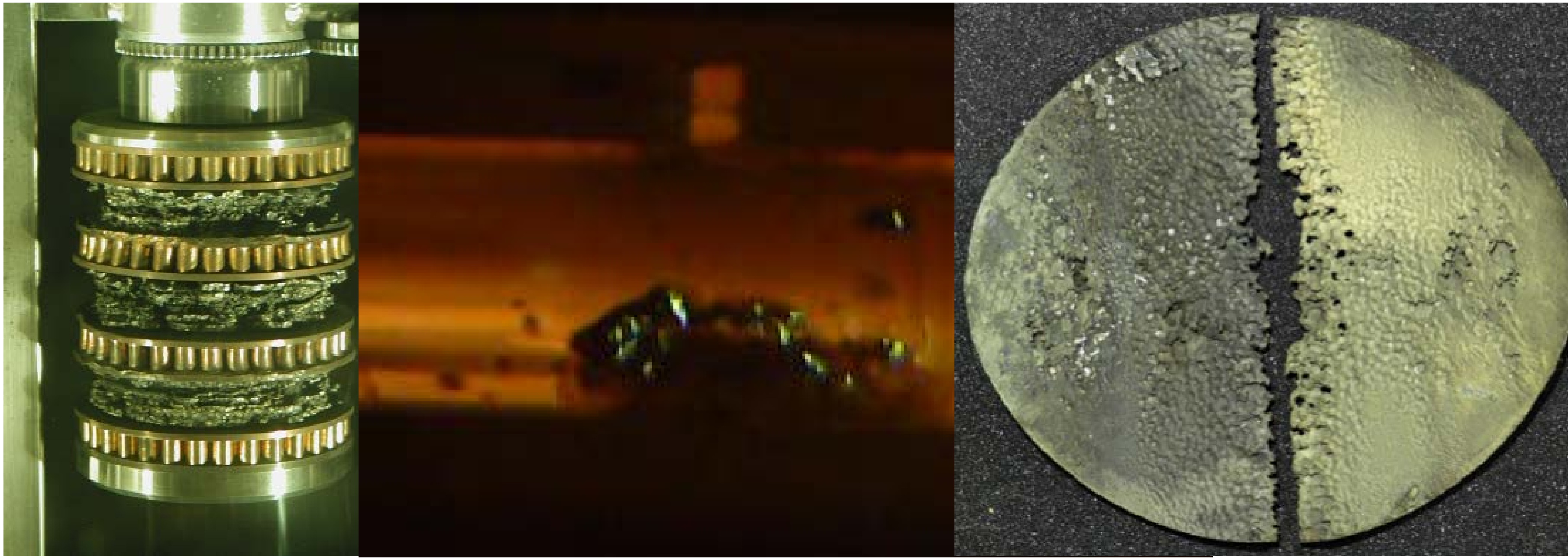
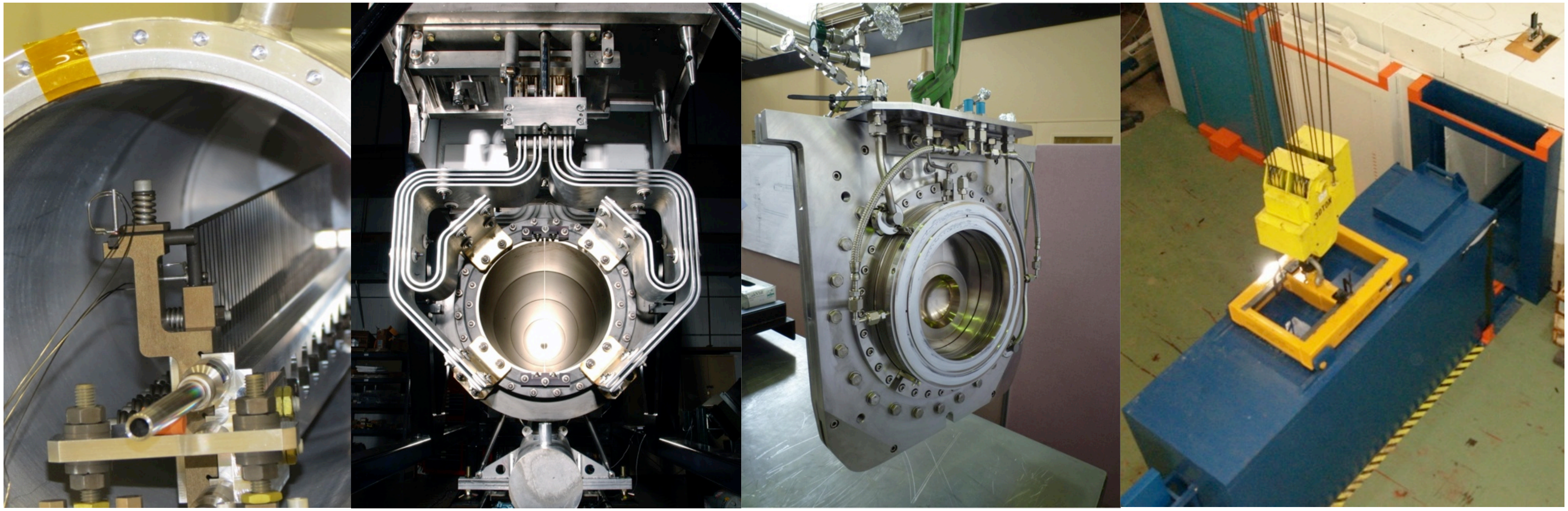
# High Power Targetry Challenges



- 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

# High Power Targetry Scope



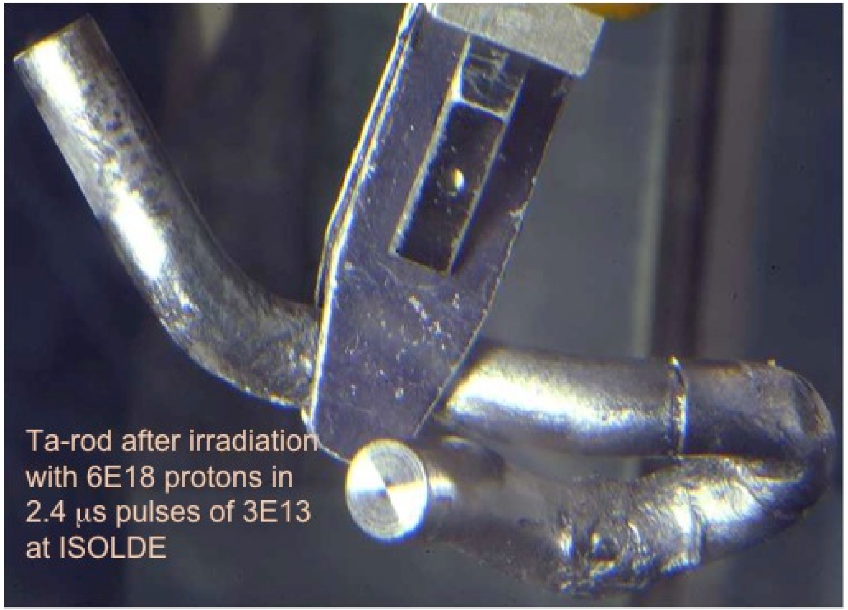
## R&D Needed to Support:

- 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

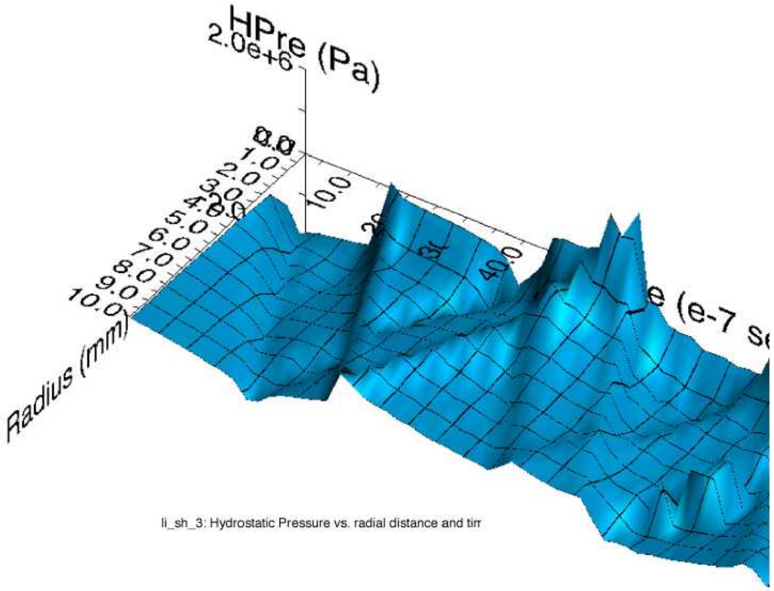
# High Power/Intensity Targetry Challenges

- 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)



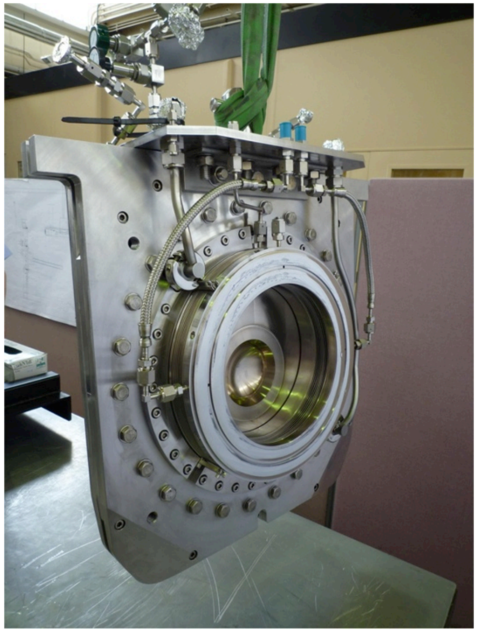

Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)

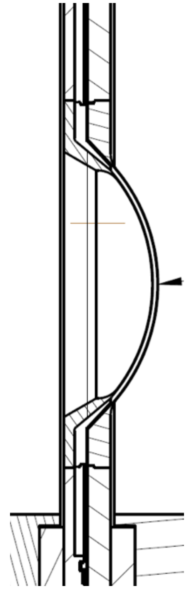


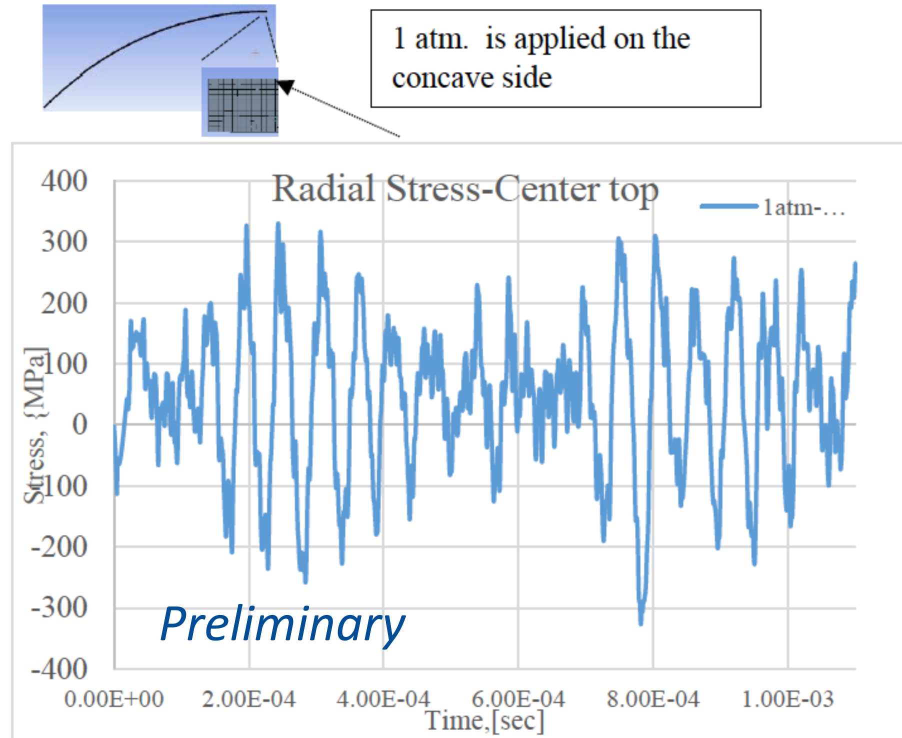

Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

- 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





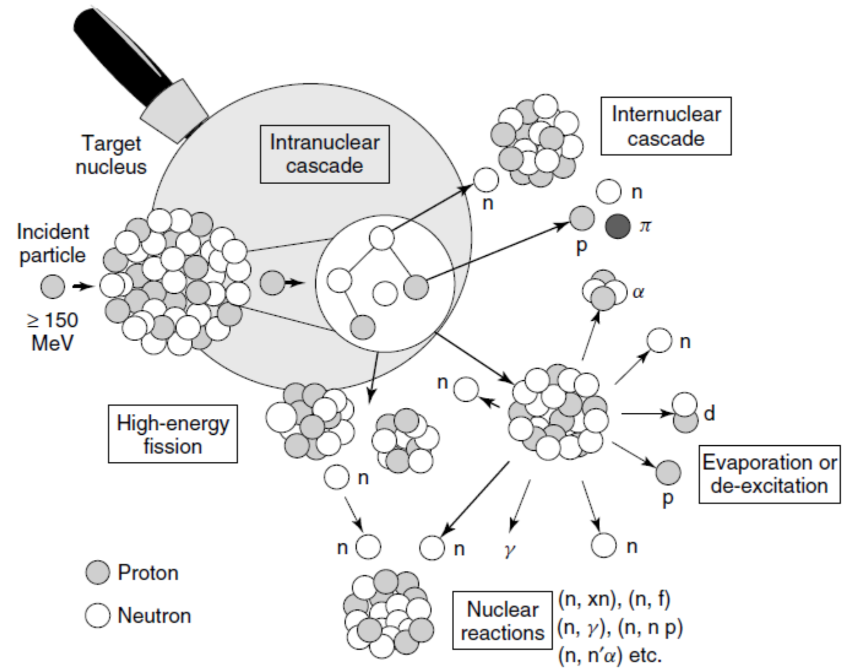



*S. Bidhar, FNAL*

- 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)

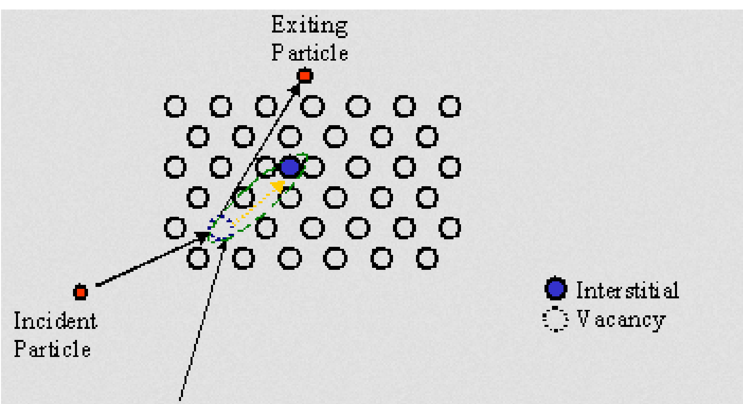
***Heavy dependence upon material properties, but:***
***Material properties dependent upon Radiation Damage…***

# Radiation Damage Disorders Microstructure

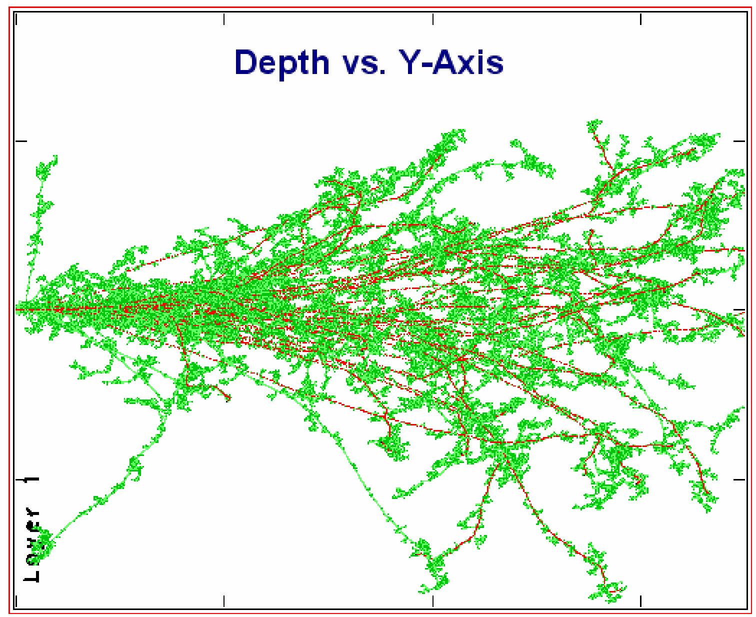



**Microstructural response:**

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



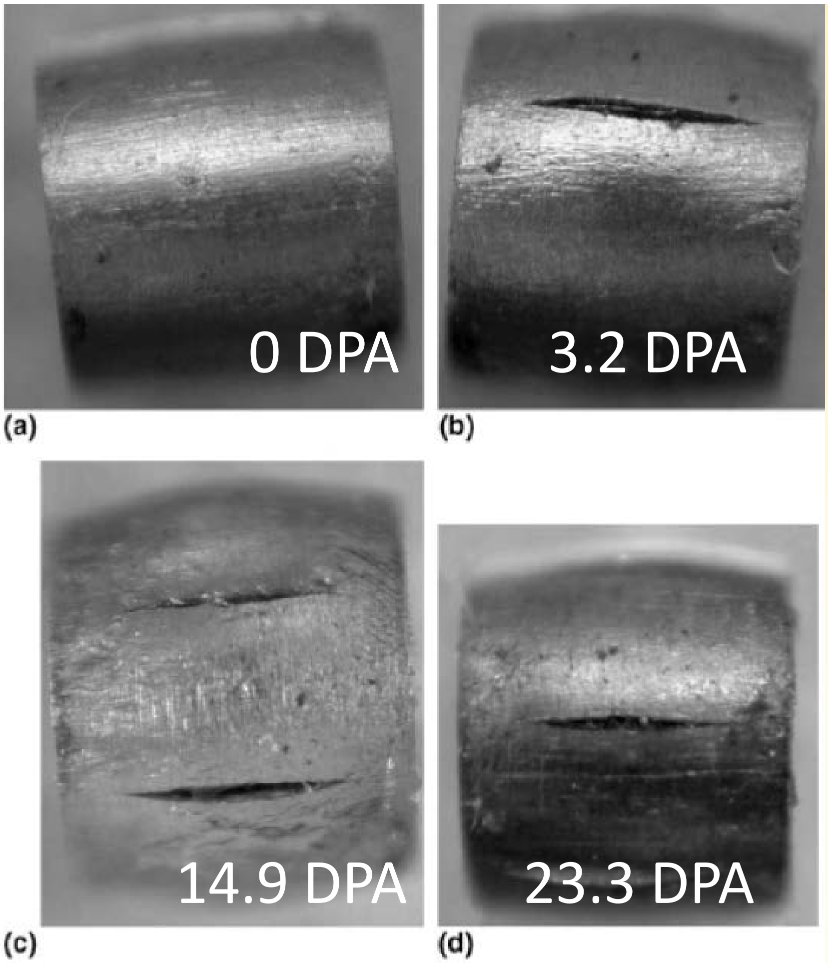

A Frenkel pair consists of a vacancy and an interstitial atom.




Slide prepared by V. Kuksenko (Oxford)

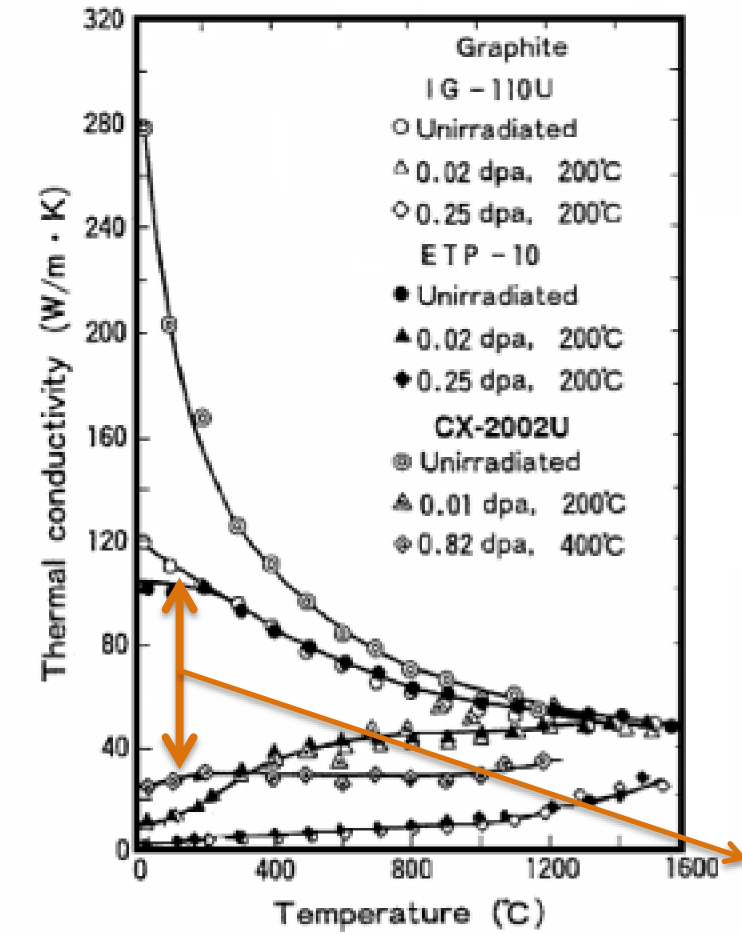
# Radiation Damage Effects

- 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$^2$



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# Reactor materials studies are limited in relevance to Targetry

$n \neq p$

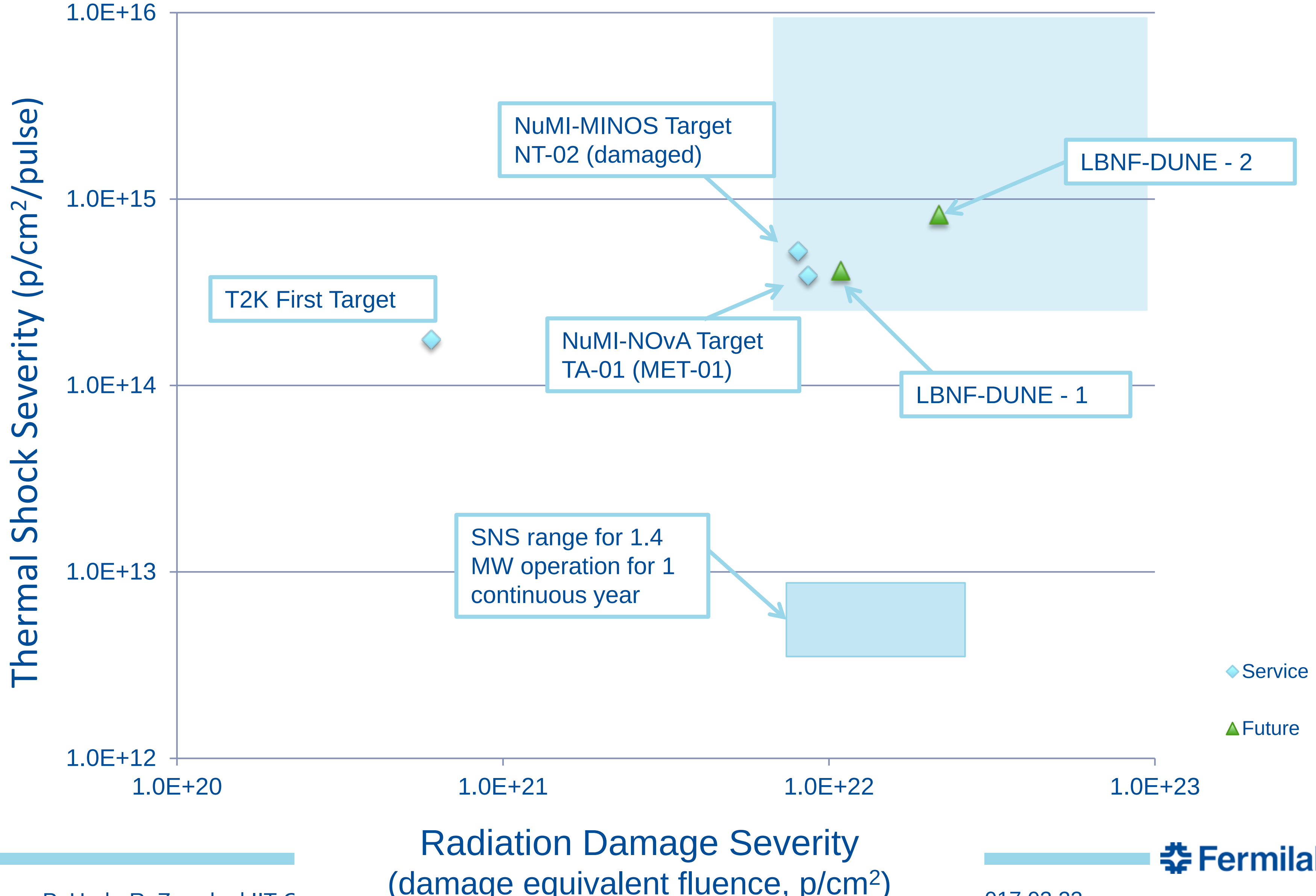
1-14 MeV    100+ MeV

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

# Nu HPT R&D Materials Exploratory Map



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# RaDIATE Collaboration

## *Radiation Damage In Accelerator Target Environments*

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**

Currently adding CERN and J-PARC to the MOU

Science & Techn
Facilities Council

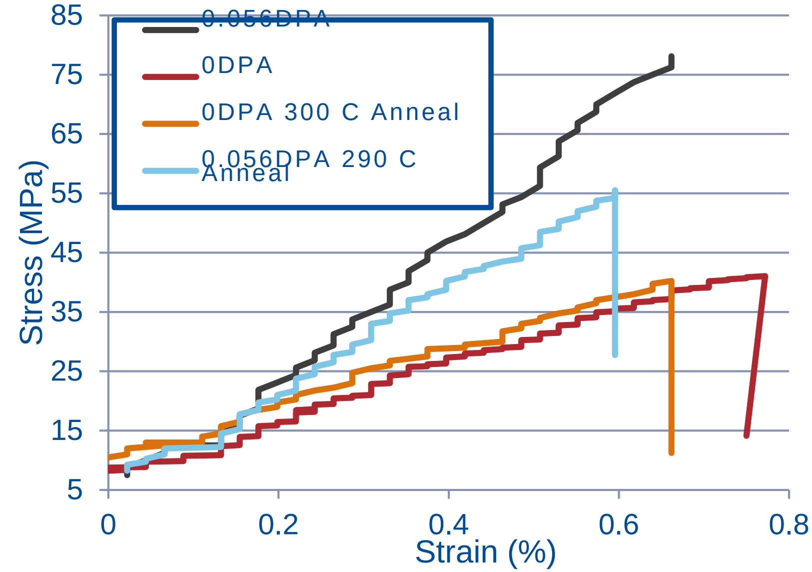
FRIB

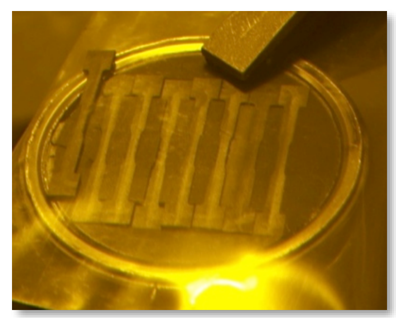
Argonne NATIONAL LABORATORY

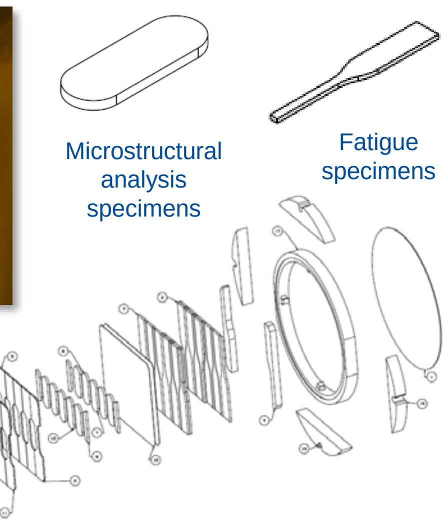
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

# High Energy Proton Irradiations underway to explore candidate target/window materials

- 181 MeV p irradiation @ BNL's BLIP facility
  - 4 graphites & h-BN exposed to 6.7E20 p/cm$^2$
  - h-BN structurally degraded beyond recovery
  - Changes in material properties (30-50%)
  - Annealing (>150 ˚C) achieves partial recovery
  - Confirmed choice of POCO-ZXF-5Q (least change in critical properties)
  - Irradiating at higher temp may be beneficial, however:
    - Diffusion assisted effects are increased (e.g. swelling from He bubble formation, creep)
    - Oxidation must be avoided
    - Elev. temp properties affecting thermal shock resistance are generally degraded
- Future work includes 2017 BLIP irradiation
  - Organized by RaDIATE collaboration
  - Includes graphite at various temp (up to ~1,000 ˚C)
  - Also Beryllium, Ti alloys, Si, TZM, Al, & Ir
  - Post-Irradiation Examination (2018) includes mechanical, thermal, micro-structural, and fatigue evaluation
  - Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, LANL

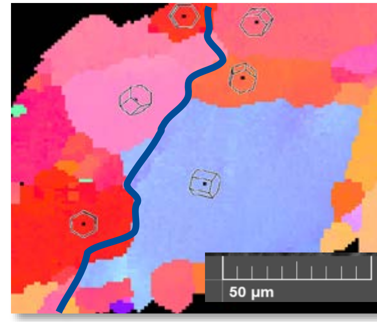


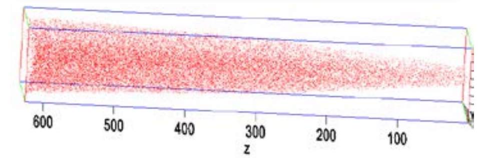



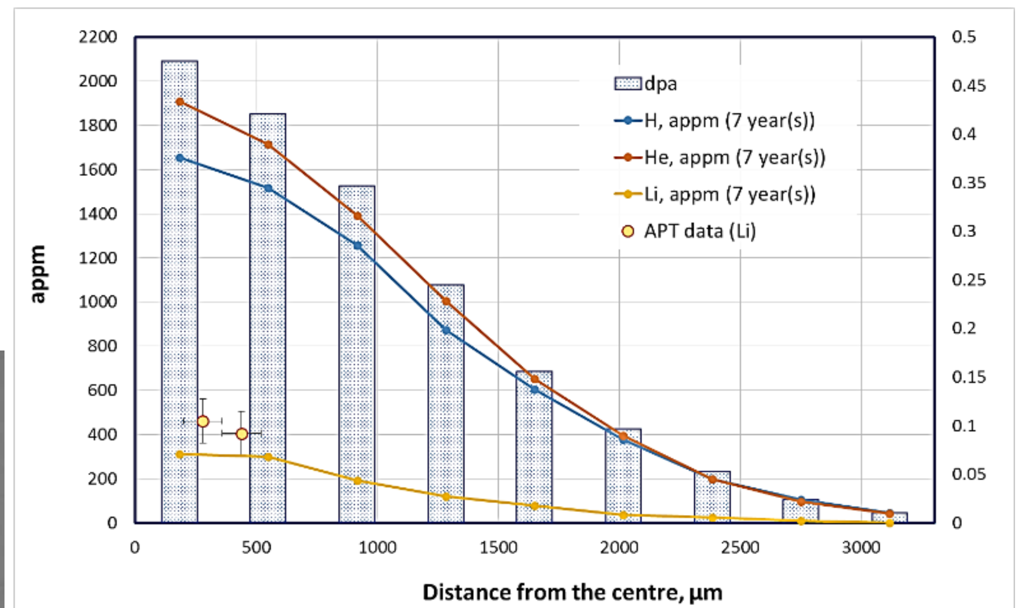


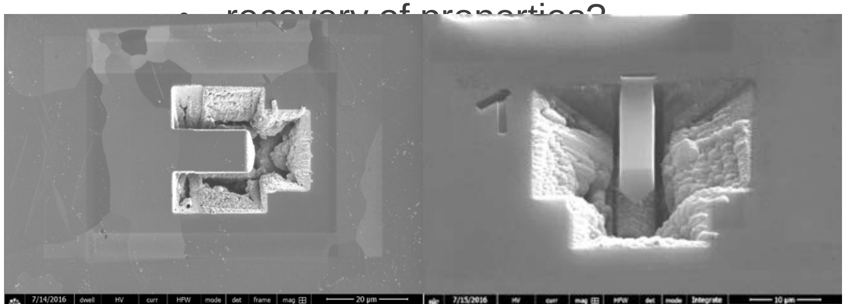
# Examination of irradiated Beryllium beam window indicates fracture toughness changes under irradiation

- NuMI Be window PIE (FNAL, Kuksenko,Oxford)
  - Be window to 1.57E21 POT analyzed
  - Advanced microscopy techniques ongoing
  - Li matches predictions and remains homogeneously distributed at ~50 ˚C
  - Crack morphology changes at higher doses (transgranular to grain boundary fracture)
- Future Work with Be window (2017)
  - Micro-mechanics testing
    - micro-cantilever
    - nano-indentation
  - Annealing
    - He bubble coalescence and growth?
    - recovery of properties?



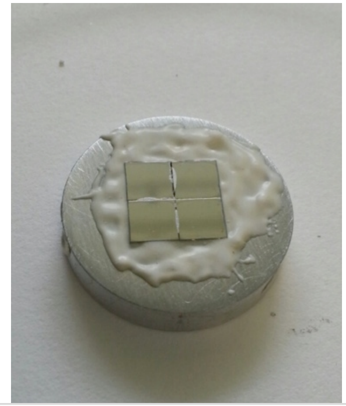



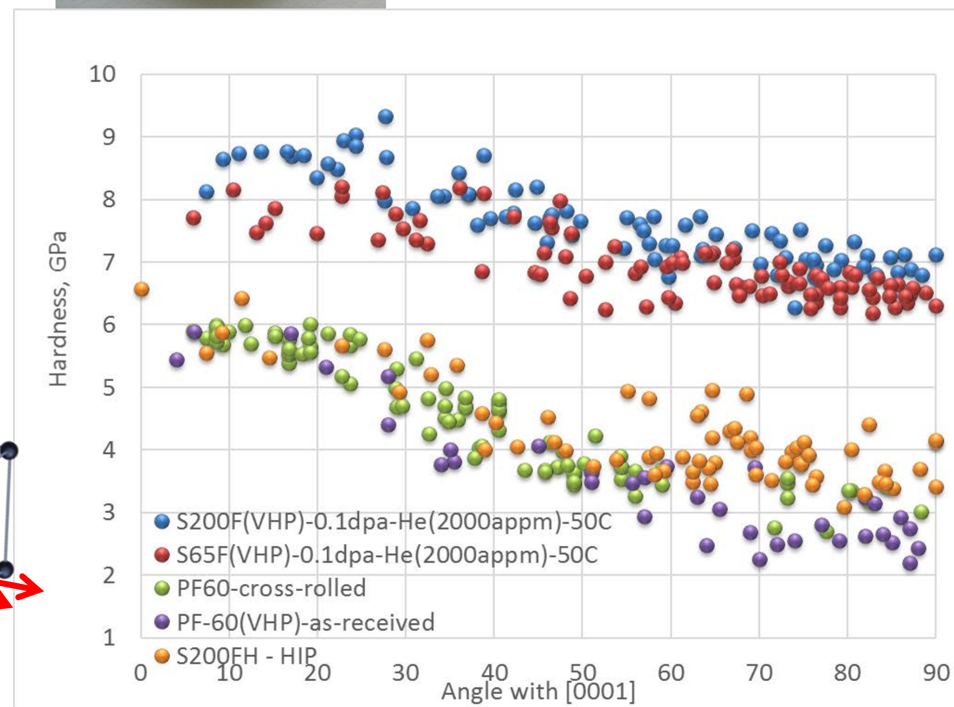



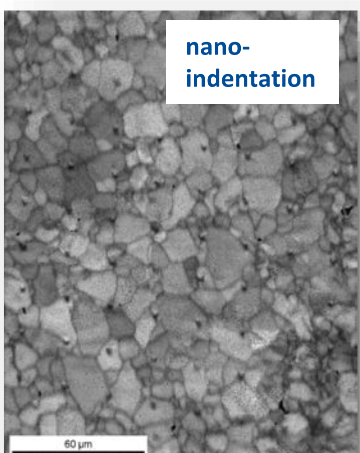



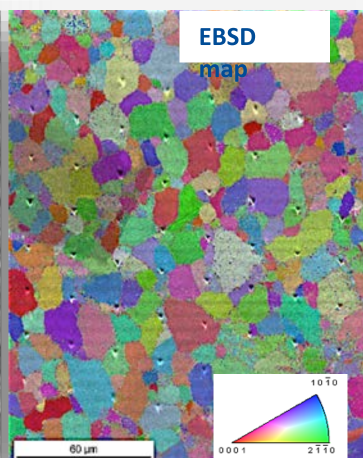
# Ion implantation of Beryllium indicates significant hardening at low DPA

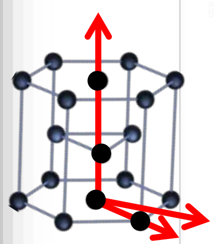
- Helium implantation study at Surrey/Oxford
  - Ions: He+
  - Maximum beam energy: 2 MeV => 7.5µm implantation depth (SRIM)
  - Dose: up to 0.1 dpa currently
  - Temperature: 50ºC and 200ºC
  - Nano-indentation indicates significant hardening at 0.1 DPA and 50 ˚C
  - Work of V. Kuksenko (Oxford)
- Future Work with He in Be (2016-17)
  - Micro-mechanics testing
    - micro-cantilever
  - Higher dose and temperature irradiations





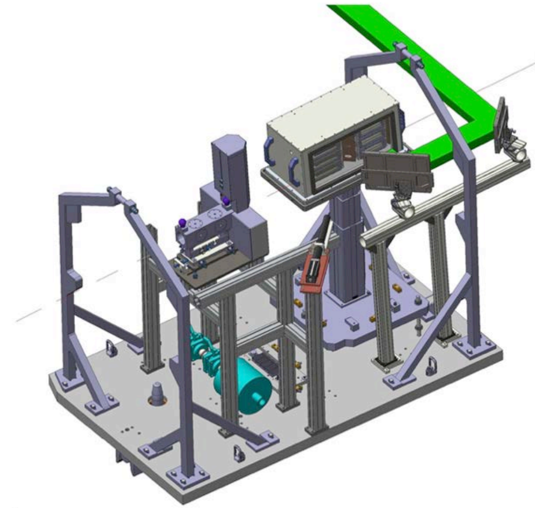



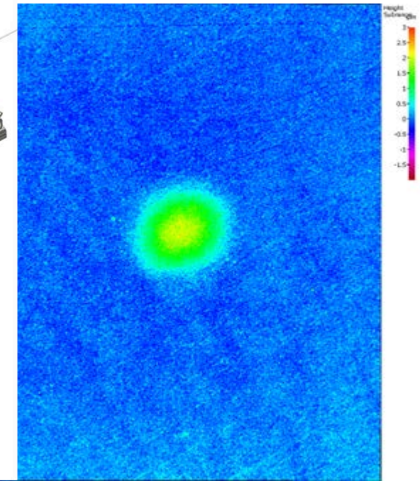


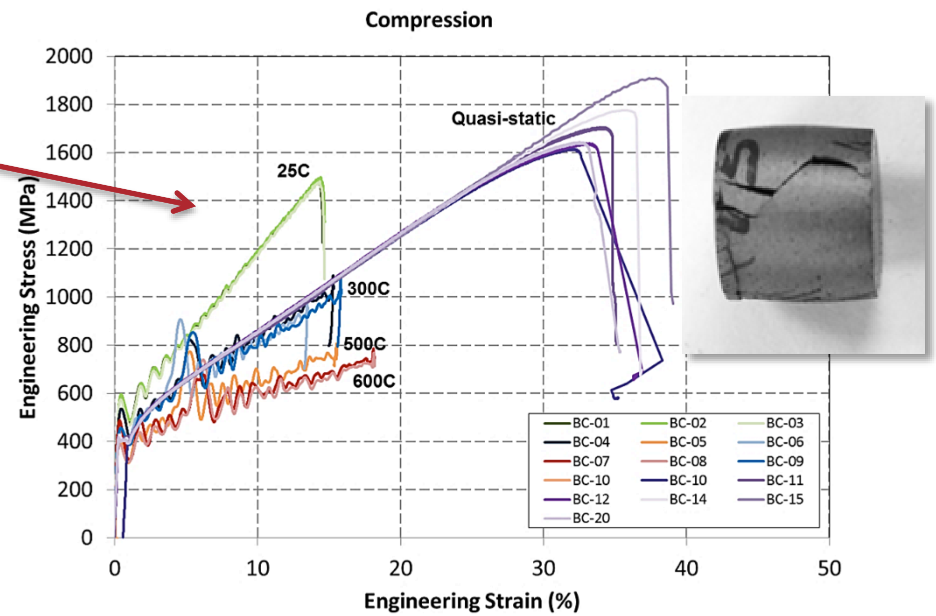
Fermilab

# Dynamic thermo-mechanical simulations of Beryllium validated by in-beam thermal shock experiments

- 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
  - Glassy Carbon windows survived without signs of degradation
  - Multiple pulses showed diminishing ratcheting in plastic deformation
  - Work continues on advanced strength model and data analysis
    - Johnson-Cook strength model developed at SwRI through SHB high strain-rate testing (elevated temp)
- Future work (2018) at HiRadMat includes:
  - Testing of irradiated materials (BLIP)
    - Beryllium grades
    - Graphite grades
    - Glassy Carbon
  - Higher p beam intensities
  - Development of J-C damage model for Be

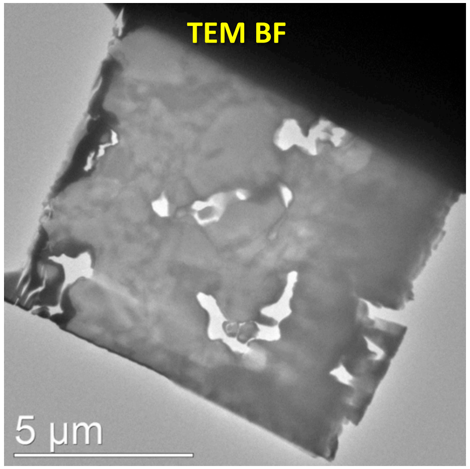


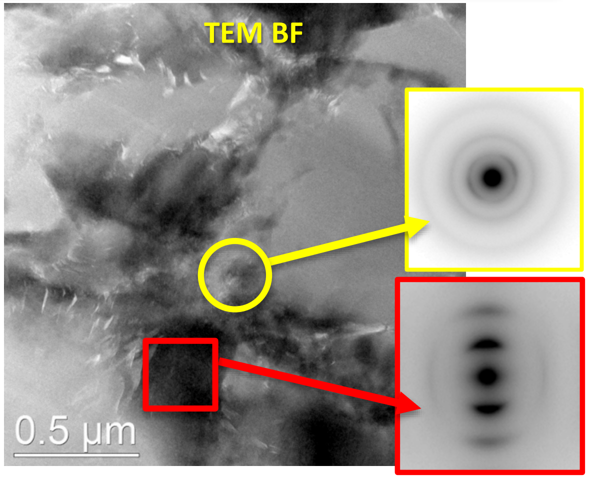




# Radiation-induced swelling as possible cause of failure of NuMI NT-02 graphite target

- NuMI target (NT-02) autopsy and graphite PIE [9] (FNAL, PNNL)
  - Graphite fins saw 8E21 p/cm$^2$ fluence
- Evidence of Bulk Swelling
  - The micrometer measurements indicate swelling did occur
    - More swelling is associated with US fin locations
    - More swelling is associated with the fractured fins
  - Absence or low occurrence rate of Mrozowski cracks
- 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 as-fabricated conditions



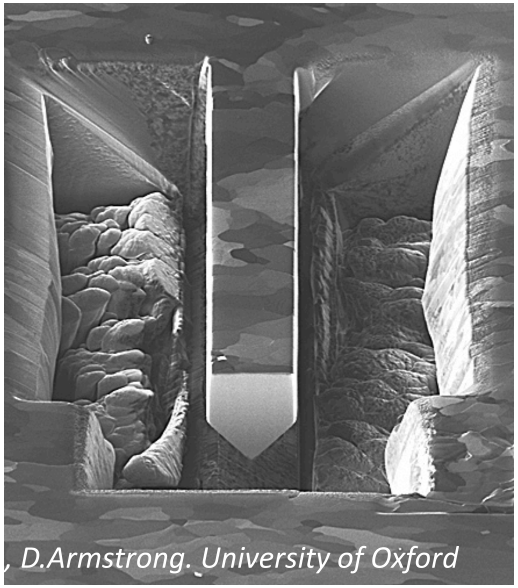

- Taken from fracture surface at the center where the beam was targeted
- Lamella has mixed regions of what appear to be amorphous (yellow insert diffraction pattern) and nanocrystalline microstructure (red square)
- Mrozowski cracks at the interfaces between these two regions

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

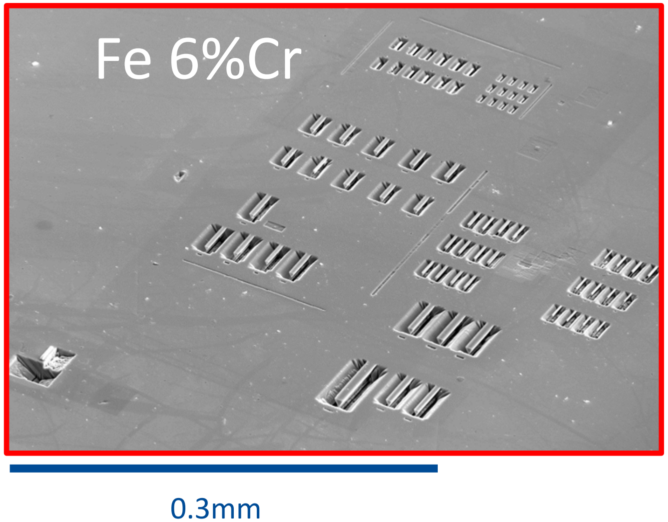
- **High energy**, high fluence, large volume **proton irradiations** are expensive and time consuming
  - Long irradiation beam times (months)
  - Difficulties of Post-Irradiation Examination (PIE) of highly activated samples
- **Low energy**, small volume **ion irradiations** are inexpensive and can 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**

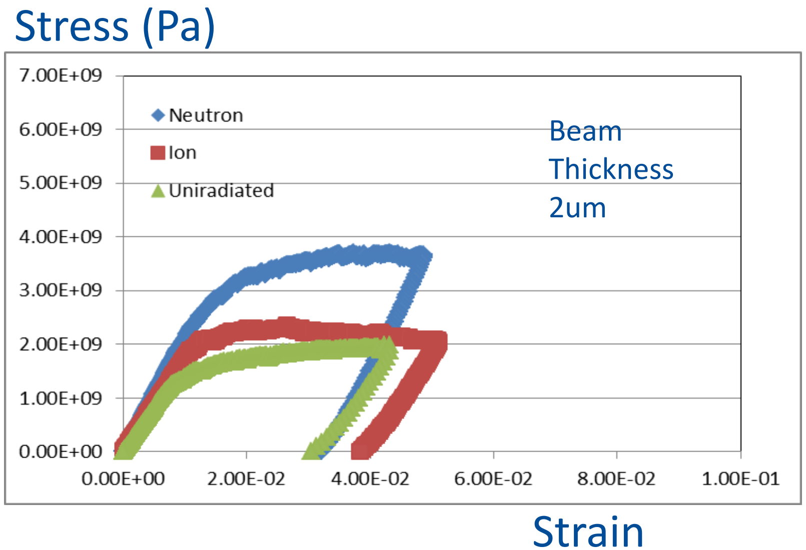
# Micro-mechanics can provide mechanical properties at the micro-scale

- 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



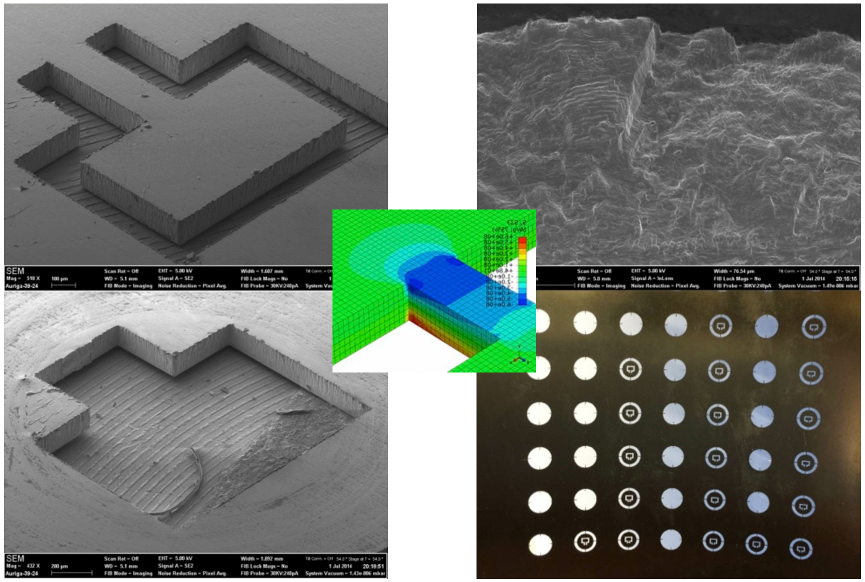

Chris Hardie, University of Oxford



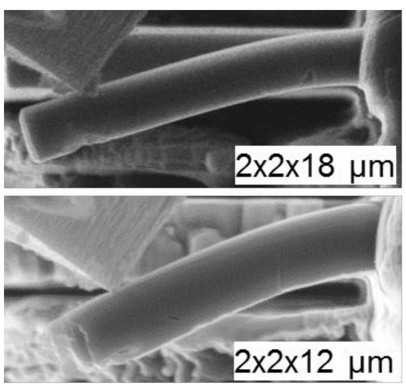



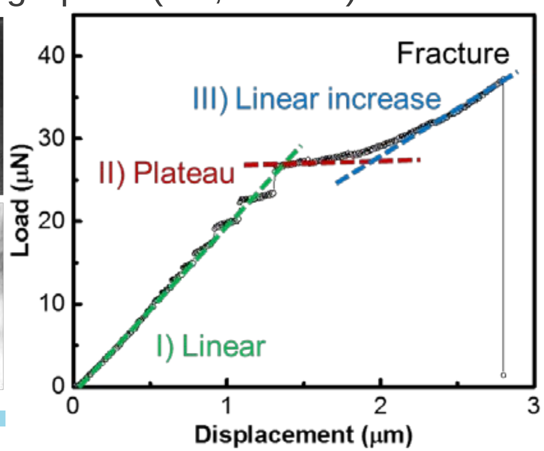
# New directions and techniques

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



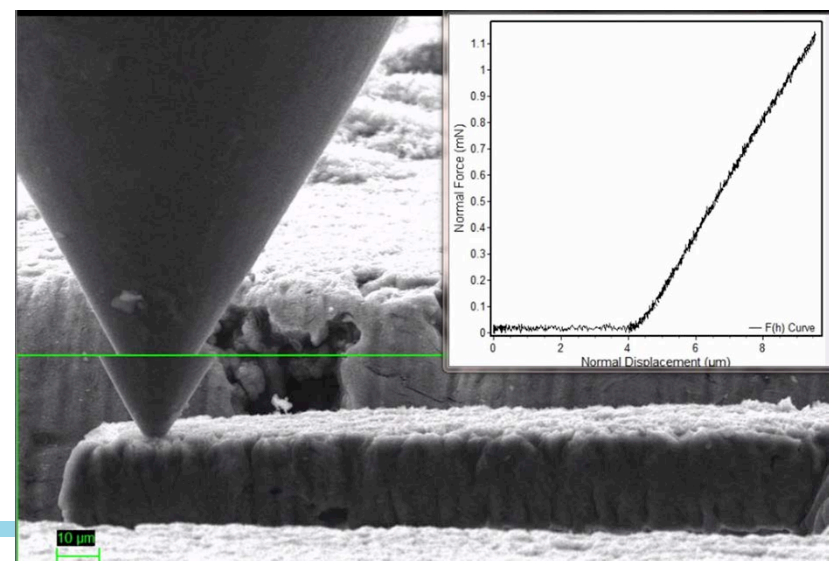
- Micro-mechanics on graphite (Liu, Oxford)



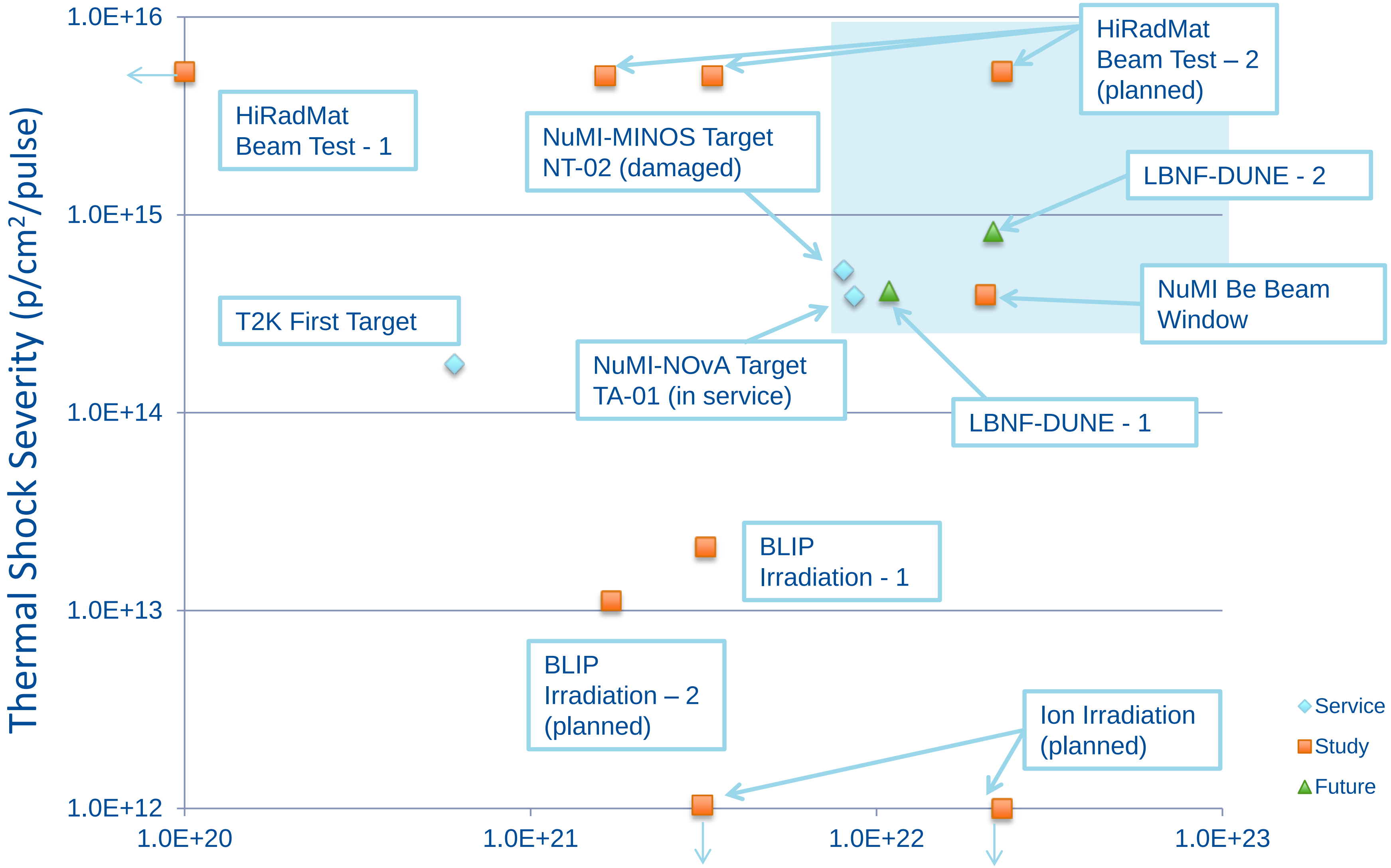




## Other planned work

- 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)



# Nu HPT R&D Materials Exploratory Map



# Summary

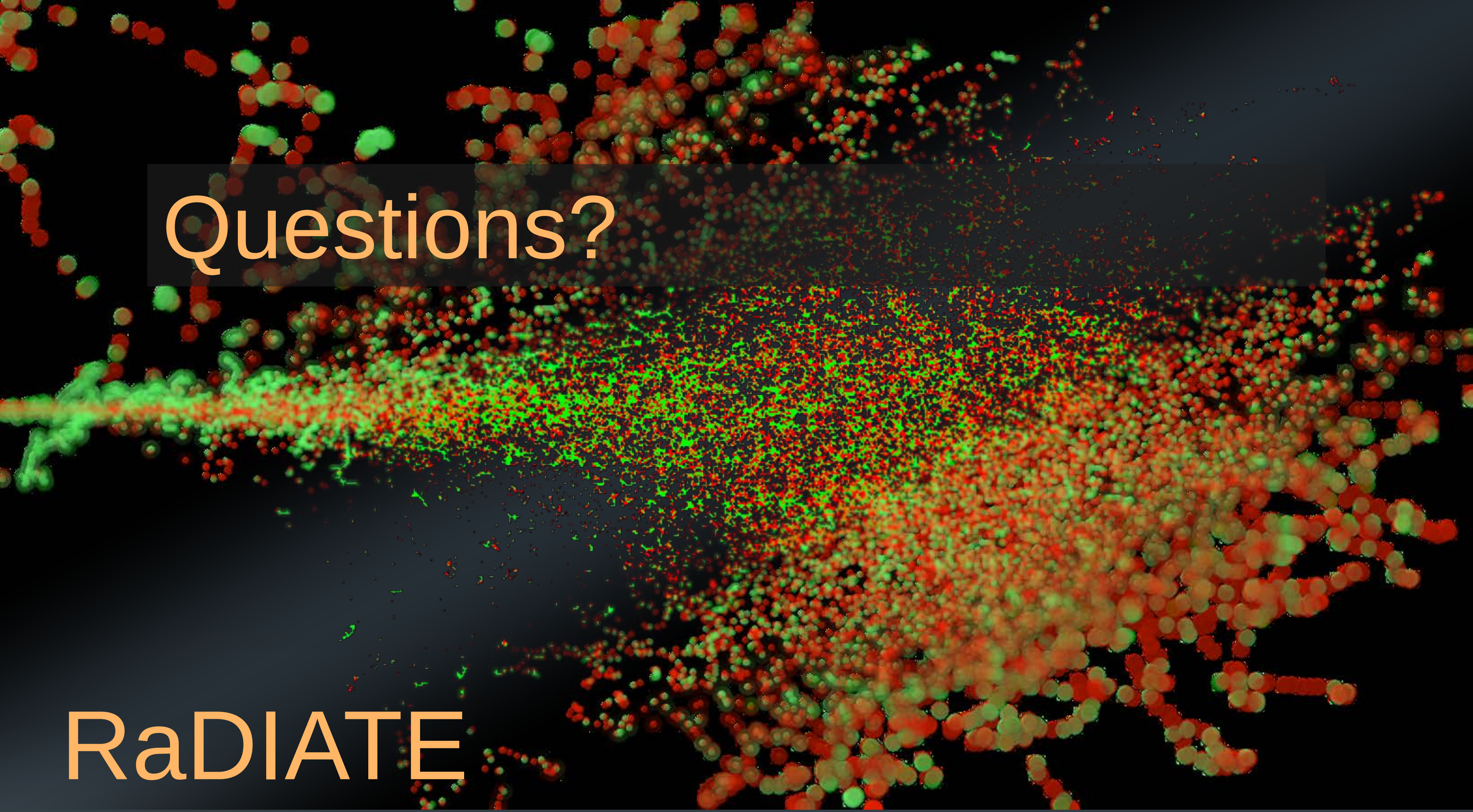
- Neutrino Science is live and healthy
  - Several discoveries within grasp

- Neutrino beam experiments place ever-greater challenges on materials
  - Low interaction cross sections require higher beam powers
  - Greater precision & reliability required for control of systematics

- Neutrino beam devices (targets/horns) are subjected to very high levels of radiations and pulsed energy deposition
  - Lattice displacements & transmutation
  - Dynamic thermal stresses produced by pulsed beam

- R&D by the global accelerator targets community under the aegis of RaDIATE
  - High-energy proton irradiations to study radiation-damage effects in candidate target and beam window materials
  - In-beam thermal shock tests of irradiated material specimens brings together both major challenges of thermal shock and radiation damage into single experiments

# Questions?



RaDIATE

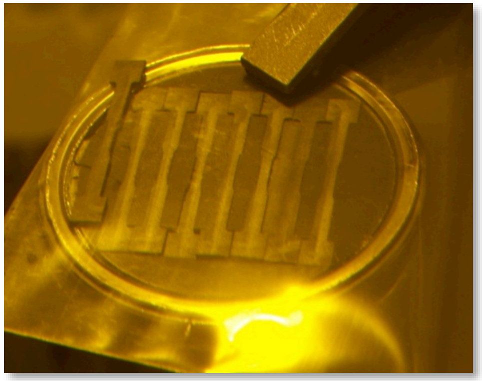
10 keV protons into Beryllium (simulated with SRIM 2008 and artistically rendered with Graphic Converter by P. Hurh)

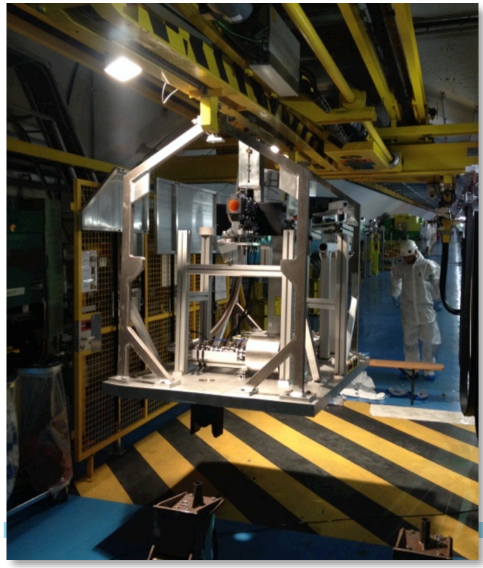
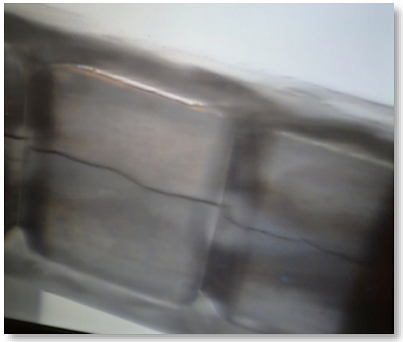
Radiation Damage In Accelerator Target Environments

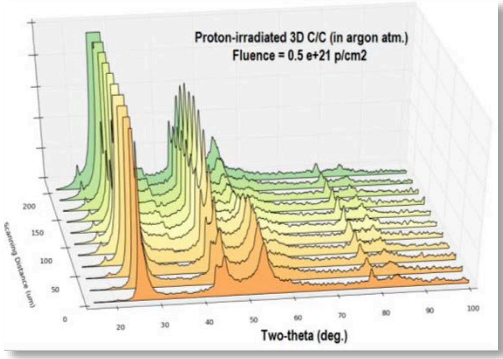
# Back-Up Slides Follow

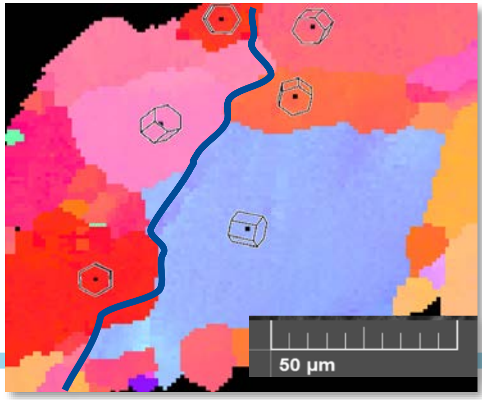
# RaDIATE Current Activities

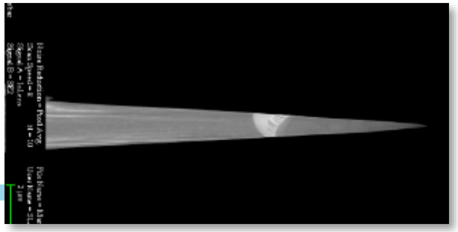
- **HE proton irradiations & Post-Irradiation Examinations (PIE)**
  - Many materials of interest from Be to Ir!
- **LE ion irradiations & PIE**
  - Utilize advanced techniques to correlate damage to HE proton regime
- **PIE of spent targets/windows**
- **Thermal Shock studies**



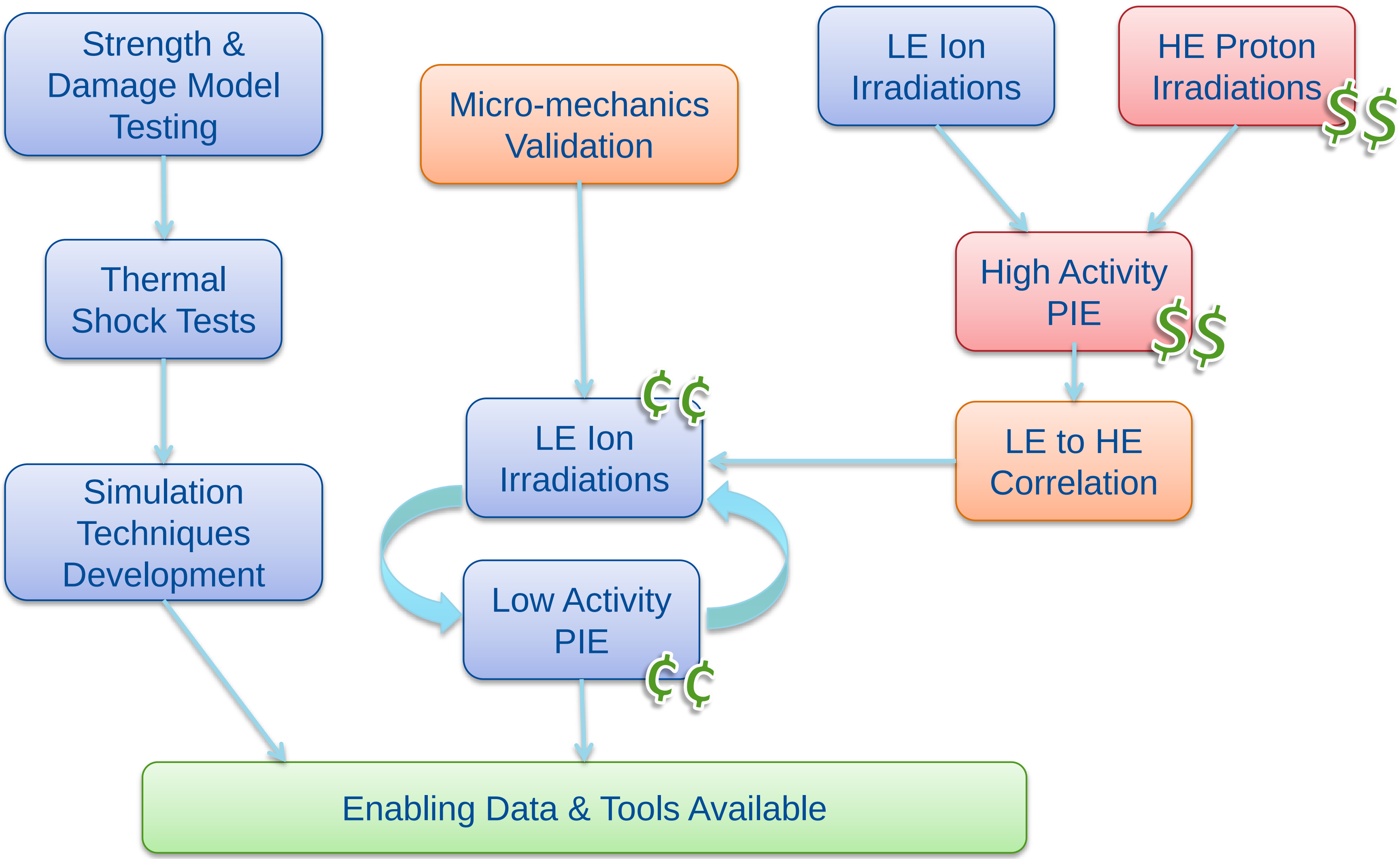







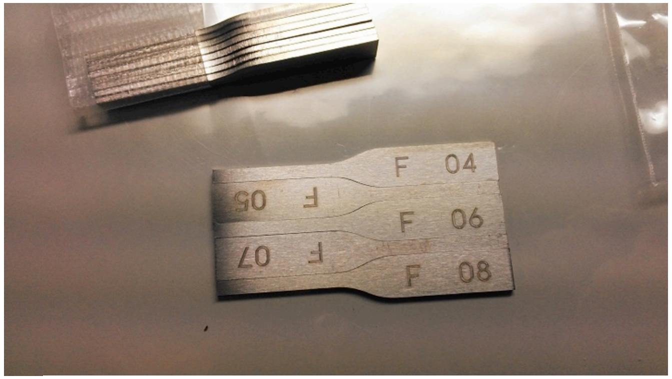
# Material Behavior Activities Overview

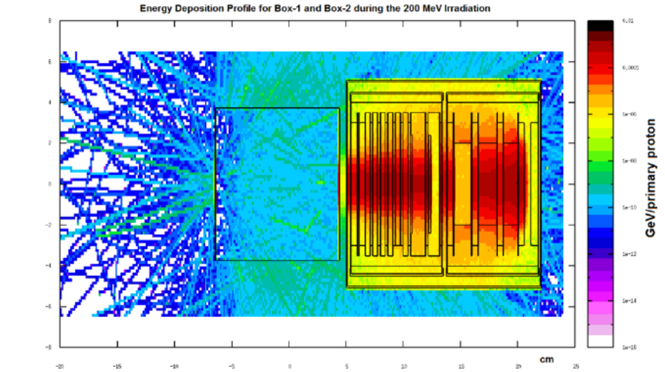


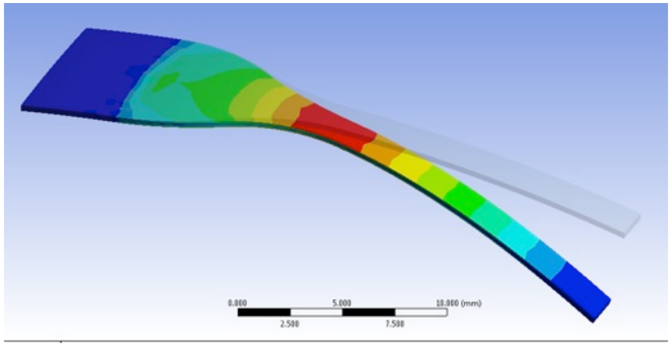
# RaDIATE R&D Progress

- 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

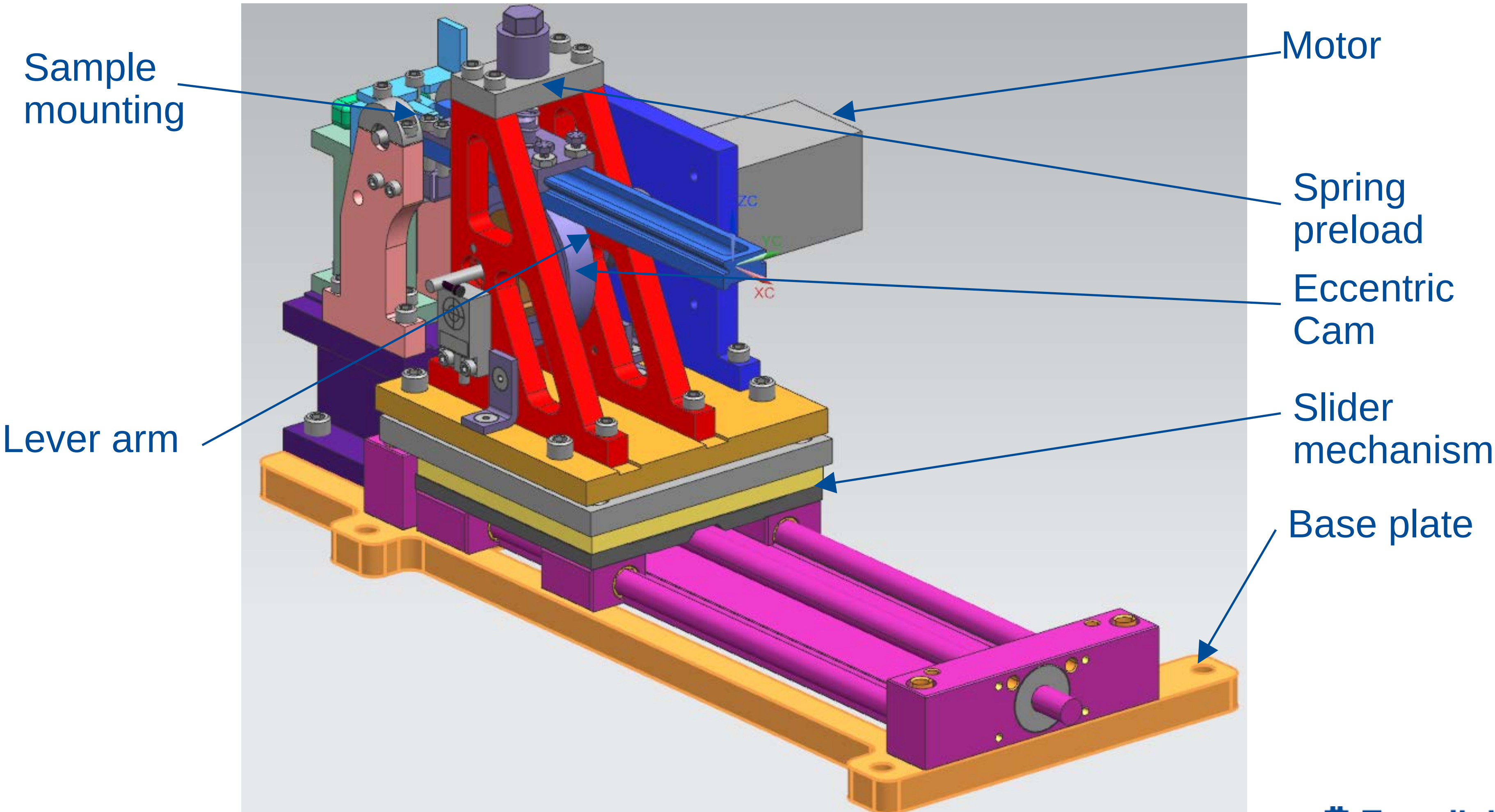


# RaDIATE R&D Progress

- Fatigue Testing Machine:



# Radiation Damage Research

1) Analyze spent components already irradiated with proton beam in operation
   - Targets & windows
   - Exposed to actual irradiation environment and all relevant irradiation processes
   - Long wait before component removal, autopsy and analysis

2) Dedicated proton-irradiation of material specimens
   - Costly
   - Long irradiation runs needed to achieve desired DPA

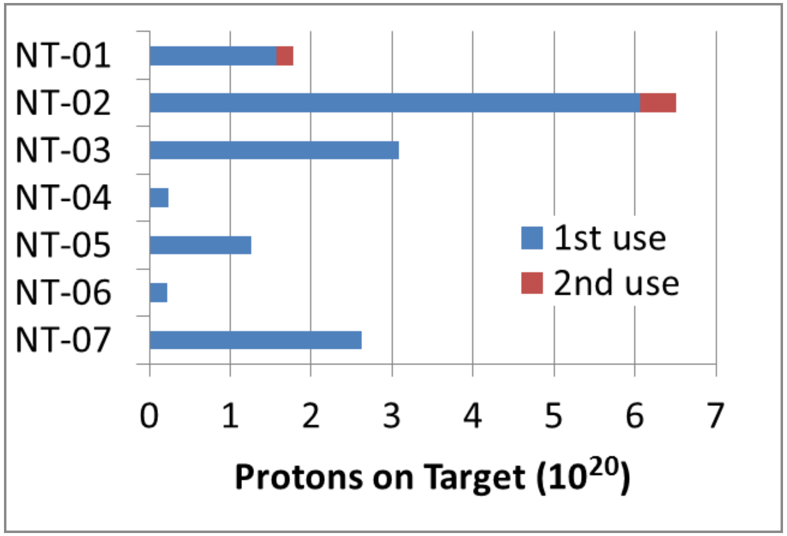
3) Low energy ion irradiation
   - Induce displacement damage at a faster rate in well-controlled environment
   - Goal: compare and correlate with proton irradiated data

# 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)

# 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

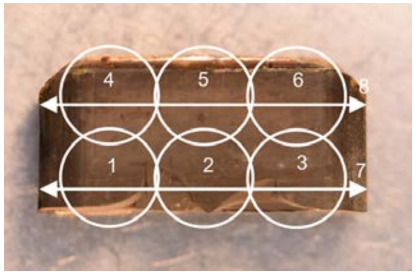
Cracks along centerline

# Post-Irradiation-Examination (PIE) of Target Fins

To determine whether neutrino degradation was a result of radiation damage

- Measure bulk swelling
- Evaluate fracture surfaces
- Evaluate microstructural conditions and extent of radiation damage

## Dimensional measurements





| | US Half Fin | US Full Fin | DS Half Fin | DS Full Fin |
|---|---|---|---|---|
| Avg. End Thickness (mm) | 6.54 | 6.57 | 6.55 | 6.55 |
| Avg. Middle Thickness (mm) | 6.67 | 6.64 | 6.60 | 6.57 |
| Relative Swelling (%) (Middle-to-end) | 2.0 | 1.1 | 0.7 | 0.2 |
| Absolute Swelling (%) (Middle-to-ref*) | 4.3 | 3.8 | 3.1 | 2.6 |

*Ref thickness = 6.4 mm

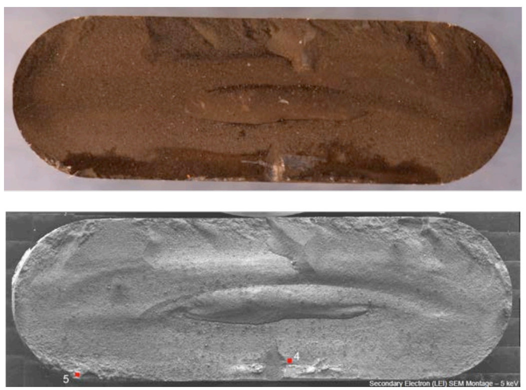
- Greater swelling in middle vs. ends
- Greater swelling upstream vs. downstream of target
- Greater swelling in half fins vs. full fins

**Results are self-consistent and provide indication of bulk swelling**

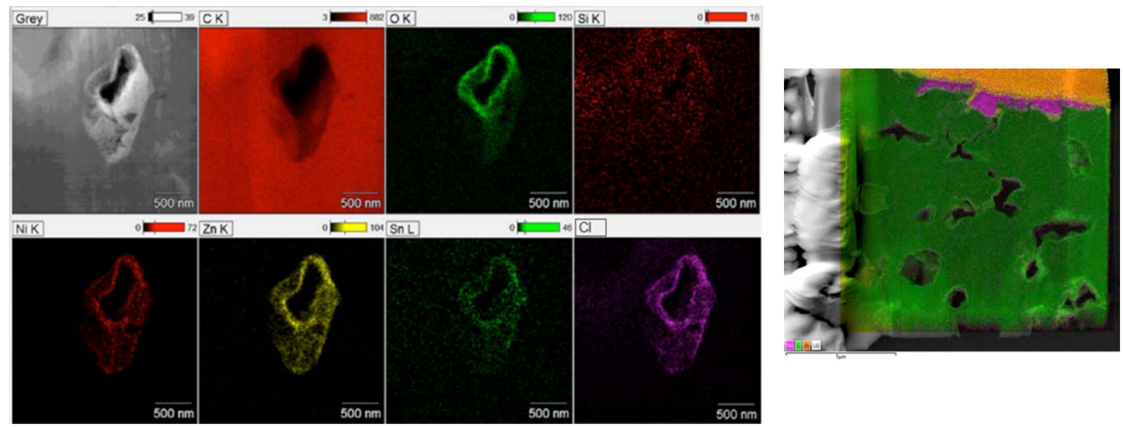
# Microstructural Analysis

Techniques used to identify and assess radiation damage features at different locations in graphite fins

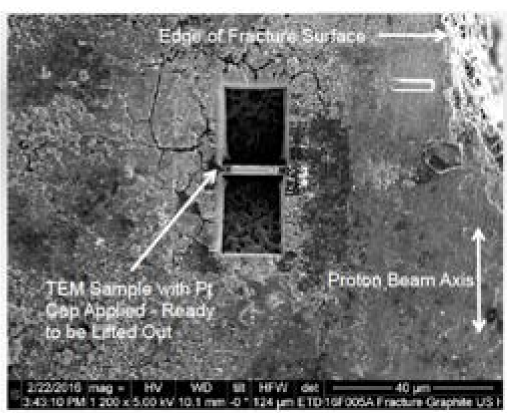
## Fractography

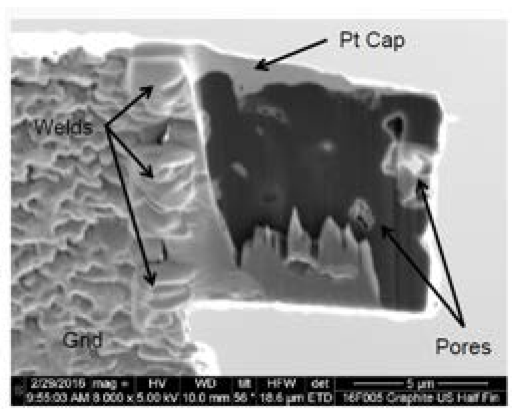


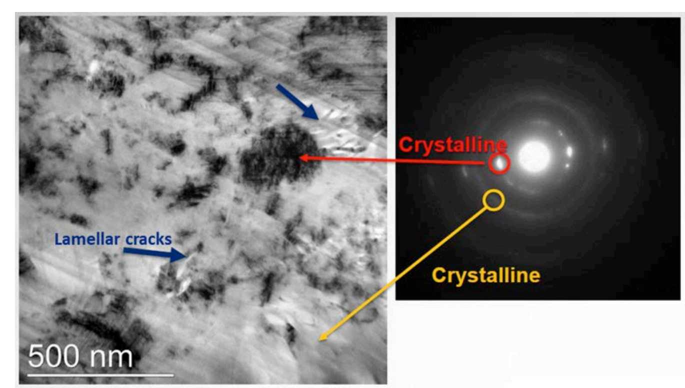
## Energy Dispersive Spectrometer (EDS)




## Transmission Electron Microscopy (TEM)



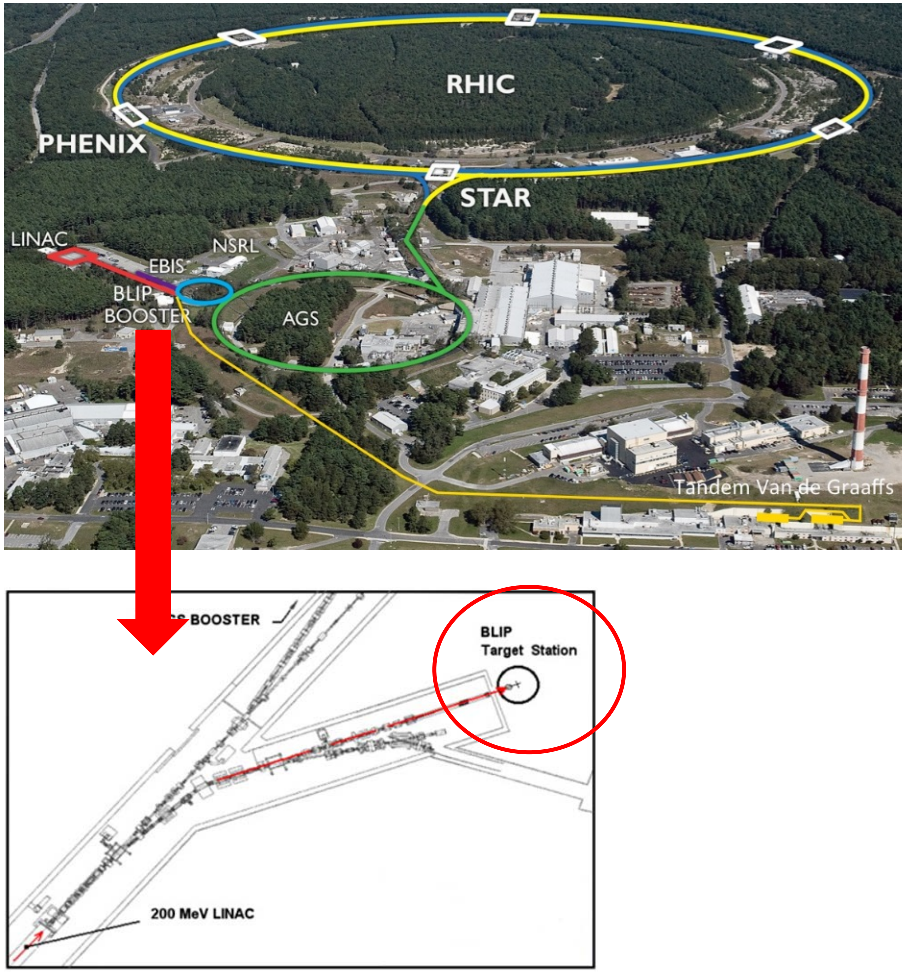



# Proton Irradiation Experiment

## 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*

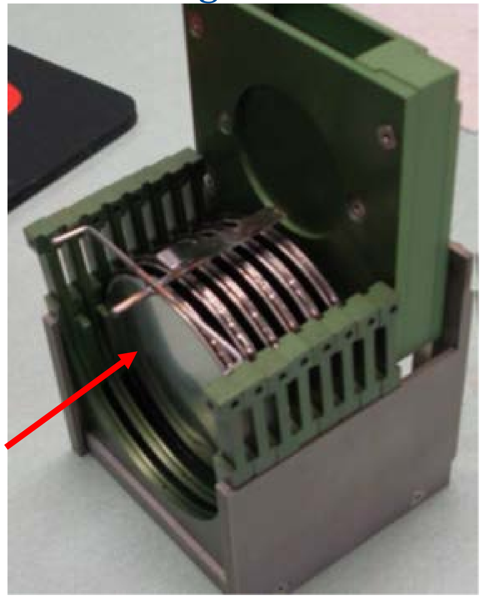
- Beam energy ~ 180 MeV
- Beam spot: $\sigma_x \sim 10$ mm, $\sigma_y \sim 7$ mm
- **Peak DPA: 0.1**
- Peak temperature: 200 ℃
- **Irradiation time: 9 weeks**

*Graphite specimens*

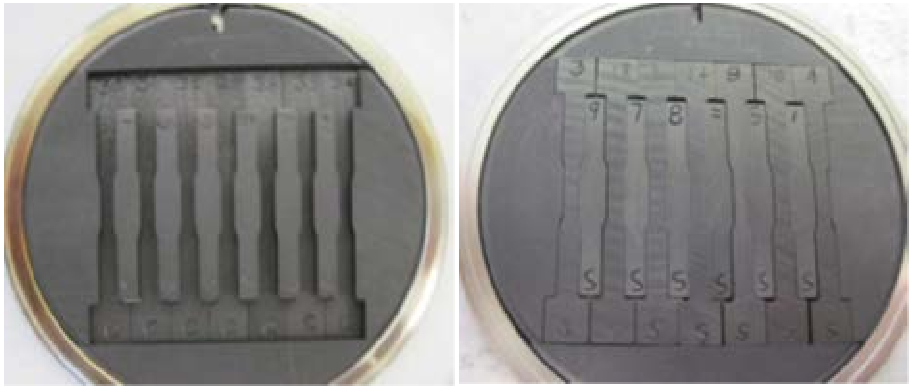
| | |
|---|---|
| • POCO ZXF-5Q | [27] |
| • IG-430 | [48] |
| • SGL R7650 | [27] |
| • C2020 | [27] |
| • 3D C/C composite | [18] |

Target box

Proton beam



Layered graphite specimens



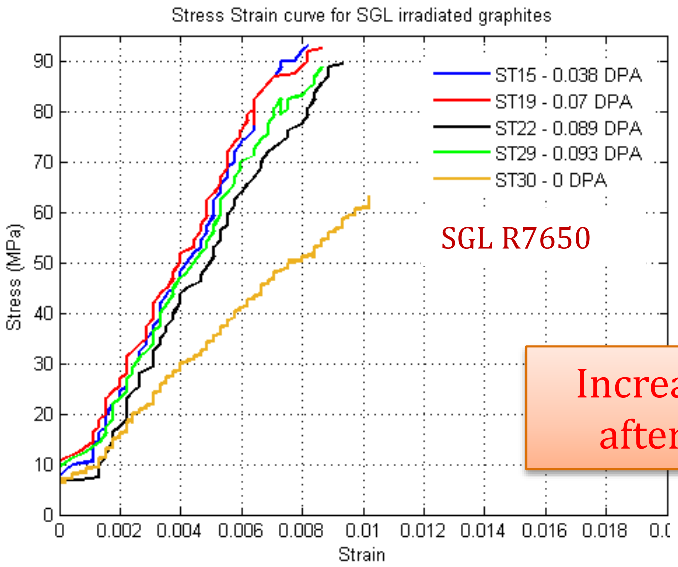
# PIE at BLIP

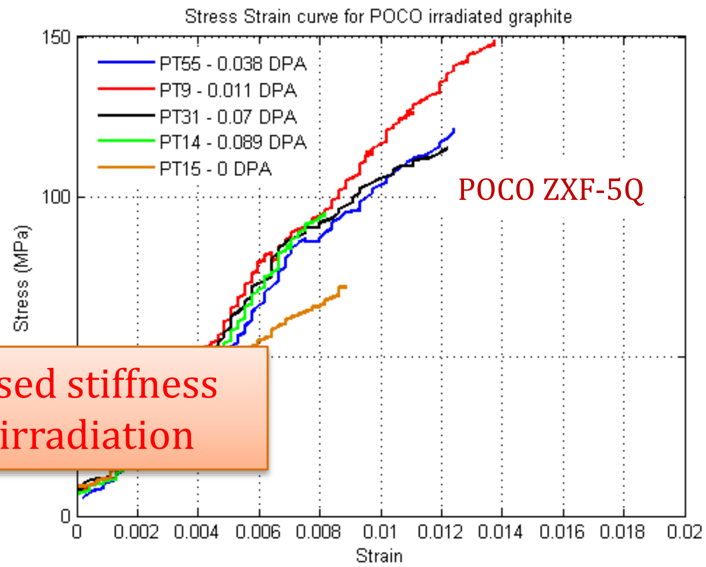
Evaluate macroscopic effects due to radiation damage

## Hot cell equipment

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

## Tensile test results




Increased stiffness after irradiation

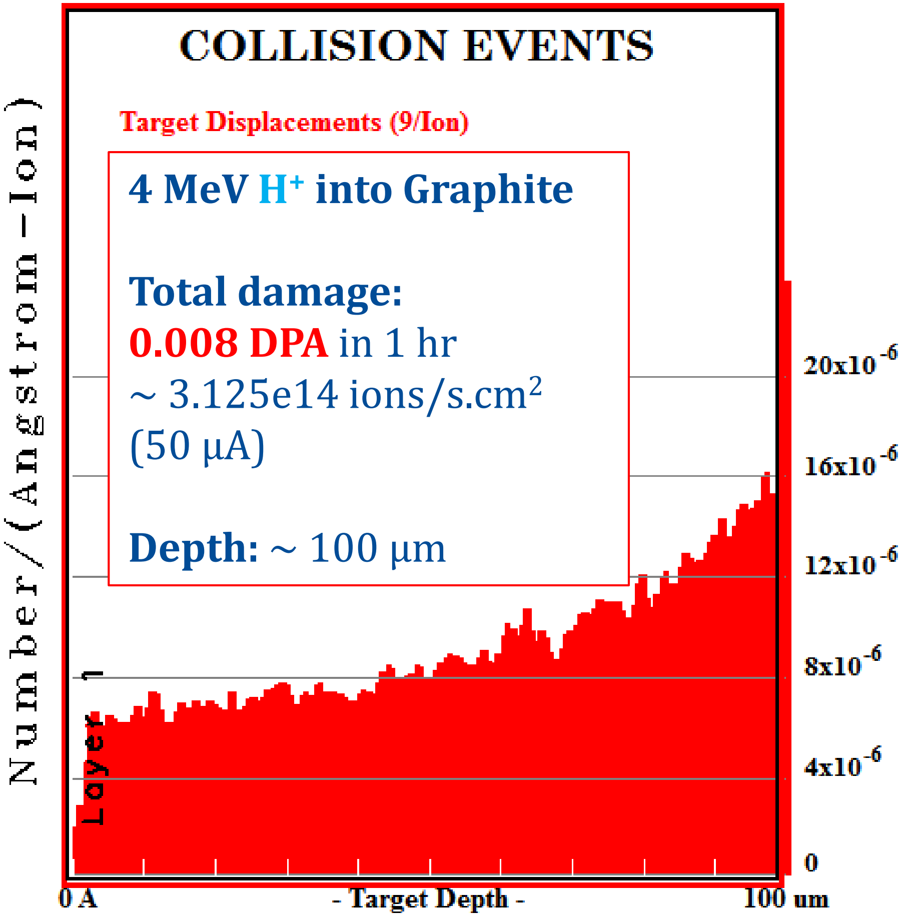
Next experiment planned in Spring 2017!

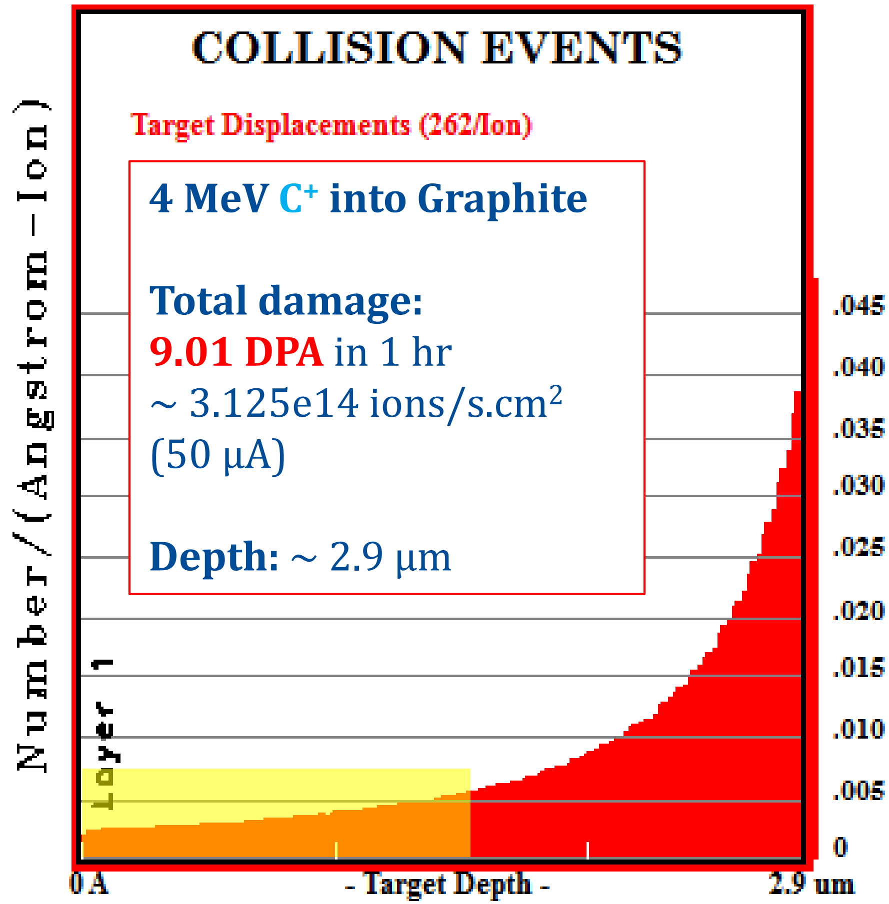
Materials
C, Be, TZM, Ir, Si, Ti, Al

# Proposed Ion Irradiation

- **Main motivation**: to induce displacement damage in material at an accelerated rate in a well-controlled irradiation environment
  - Irradiation temperature
  - Dose rate and total dose
  - Damage depth in material
  - Low sample activation, if any
- Compare and attempt to correlate damage effects between low energy ion irradiation and high energy proton irradiation
- **Drawbacks of ion irradiation**
  - Shallow depth of penetration and non-uniform damage profile
  - Ion interstitial ‘poisoning’
  - Dose rate effects on microstructure evolution
  - Absence of transmutation products

# Ion Irradiation of Graphite




- Faster displacement damage rate with $C^+$
- Shallower damage depth

# Ion Irradiation feasibility of graphite at NSL

NSL ion beam parameters

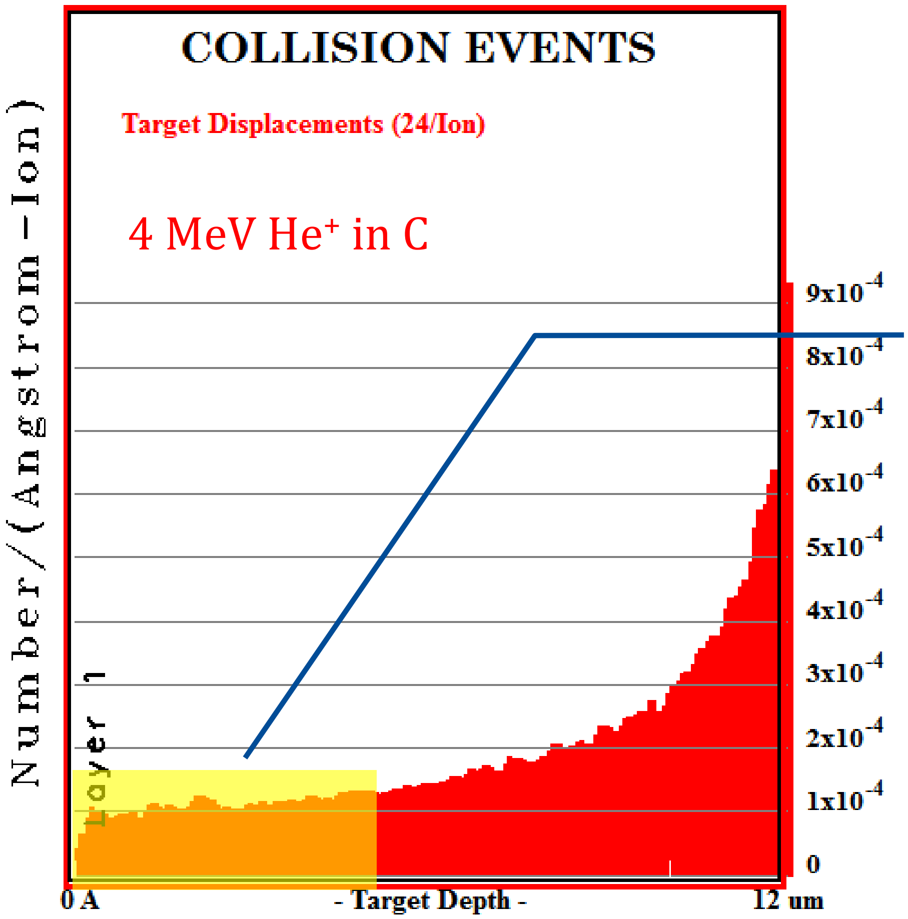
- Energy: 4 MeV
- Current: 50 μA

| Ion | Stopping range (μm) | Beam area ($cm^2$) | Target thickness (μm) | SRIM (disp/ion) | Irradiation time (hr) | Total DPA |
|---|---|---|---|---|---|---|
| H | 122 | 4 | 100 | 8.6 | 1 | 0.0021 |
| He | 14 | 4 | 12 | 23.2 | 1 | 0.0482 |
| C | 3 | 4 | 2.9 | 262 | 1 | 2.253 |
| Ar | 2 | 4 | 1.8 | 1621 | 1 | 24.356 |

Average DPA calculated with SRIM

# Addressing ion irradiation issues to emulate proton irradiation

## 1. Depth of penetration and non-uniform damage profile



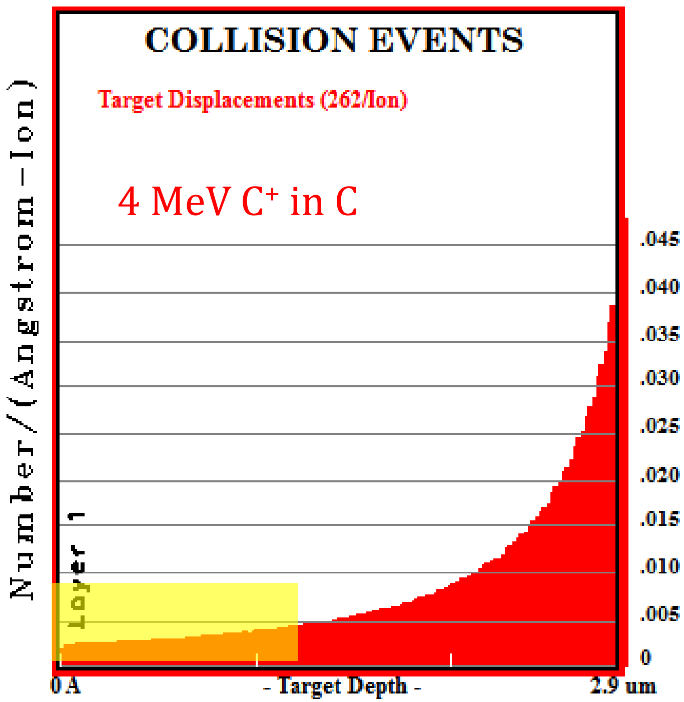

- Probe thin damage layer of specimen (TEM)
- Uniform damage levels within few μms

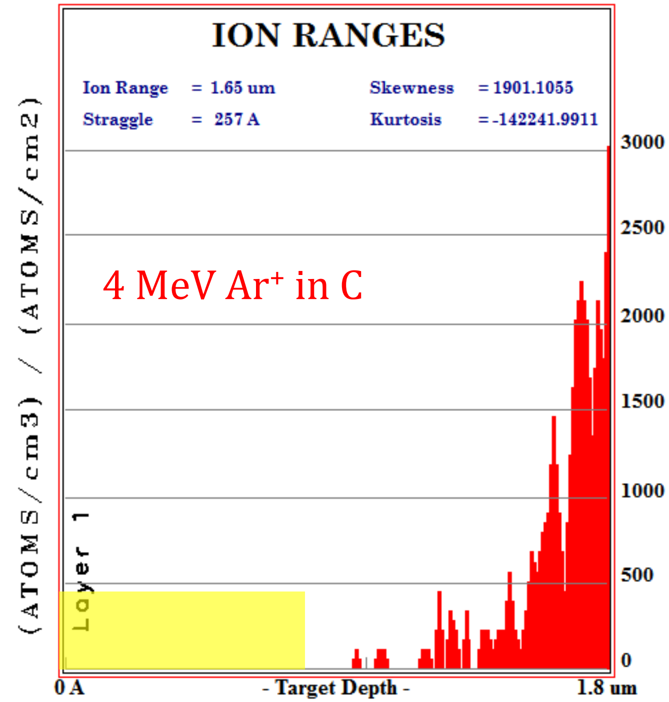
- Energy raster beam to spread energy and create more uniform damage profile

# 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



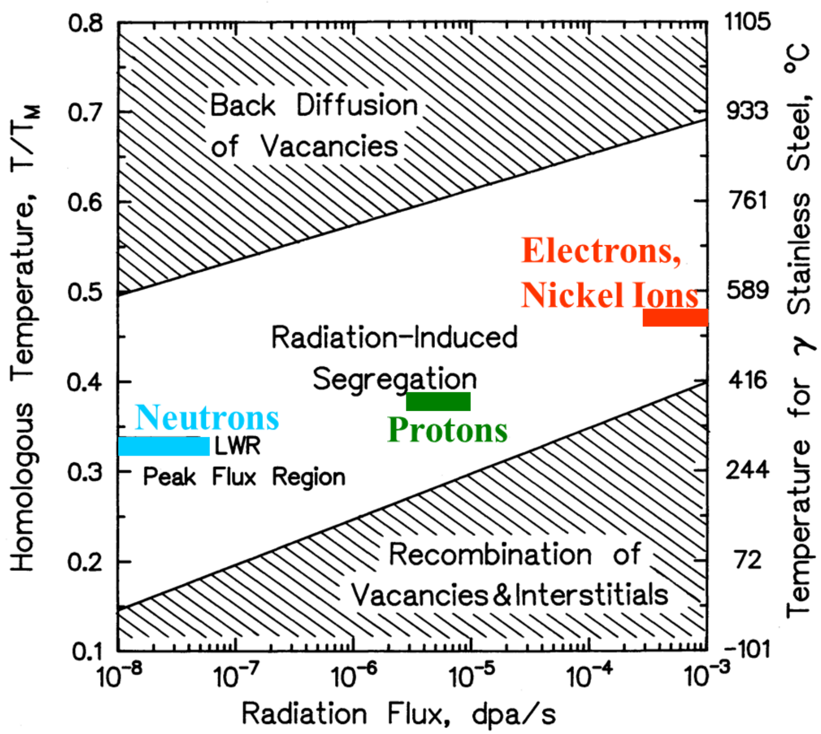

## 3. Transmutation products

- 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

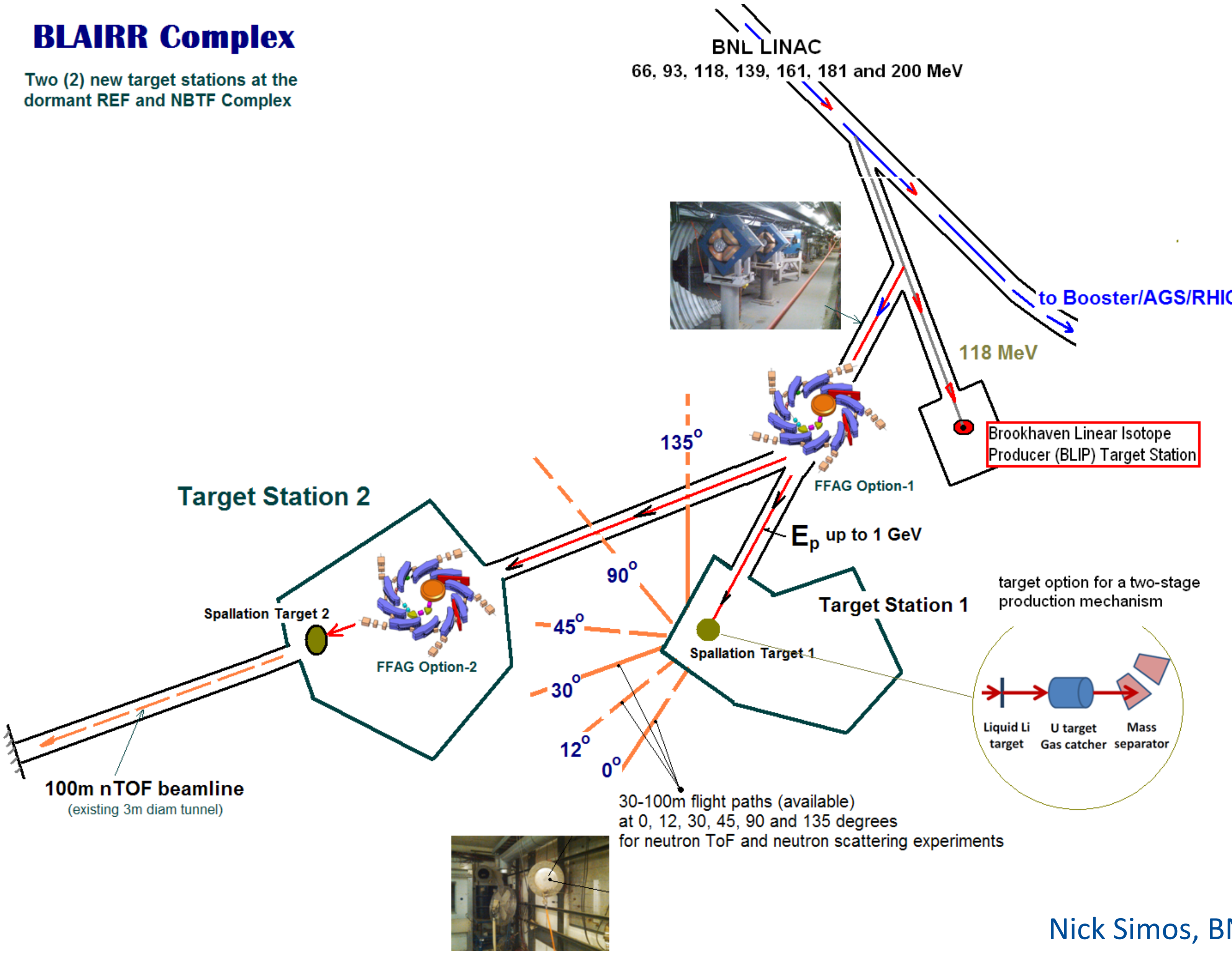
# HEP HPT Future Needs

| 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.

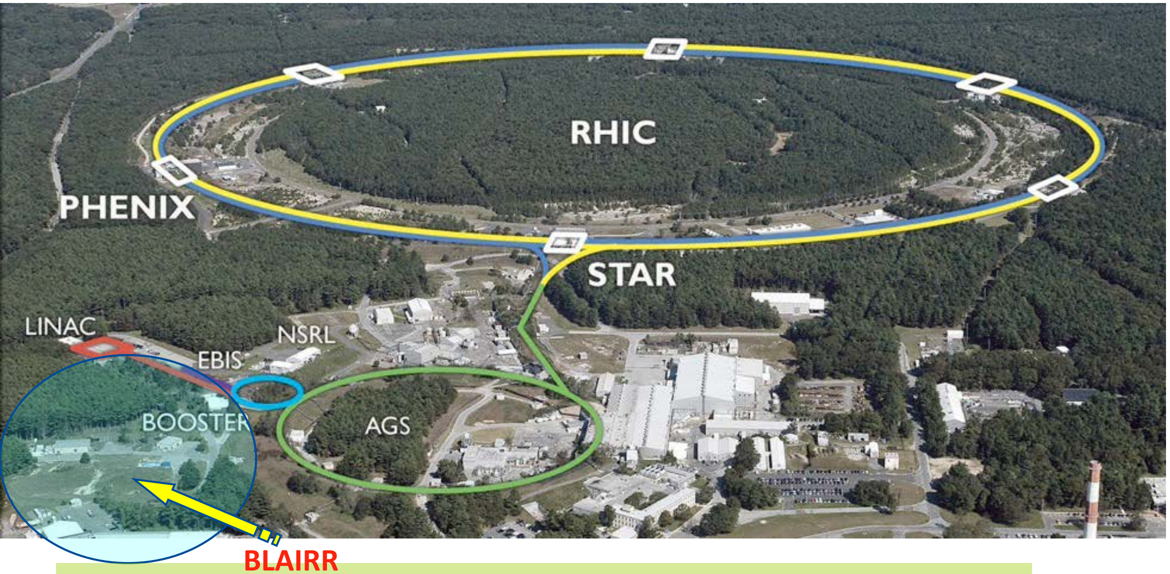
# BLAIRR Complex

Two (2) new target stations at the dormant REF and NBTF Complex




Nick Simos, BNL

# Brookhaven Linear Accelerator IRRadiation Test Facility (BLAIRR)




**Utilize currently dormant REF/NBTF beamline complex**

**BNL Linac can accelerate H+ or H- beams of 66, 92.6, 116.5, 139.0, 160.5, 181.0 and 200.3 MeV**

- Energy spread of ~140 keV at 200 MeV
- 6.67 Hz rep rate,
- 440µs pulse length
- 5ns micro-pulse
- 200.25 MHz micro-pulse structure
- Beam current reaching 130 µA (~26 kW power at 200 MeV)

## BLAIRR MOTIVATION

Neutron damage studies of materials for next generation fast neutron and fusion reactors

Proton radiation damage of materials for accelerator initiatives (as a function of energy)

Blanket, moderator, reflector concept validation/optimization

Nuclear cross-section data ➔ ADS-transmutation

Validating experiments of neutron flux/reaction rates for accelerator-driven systems

Nick Simos, BNL

# PNNL’s RPL

## Radiochemical Processing Laboratory

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

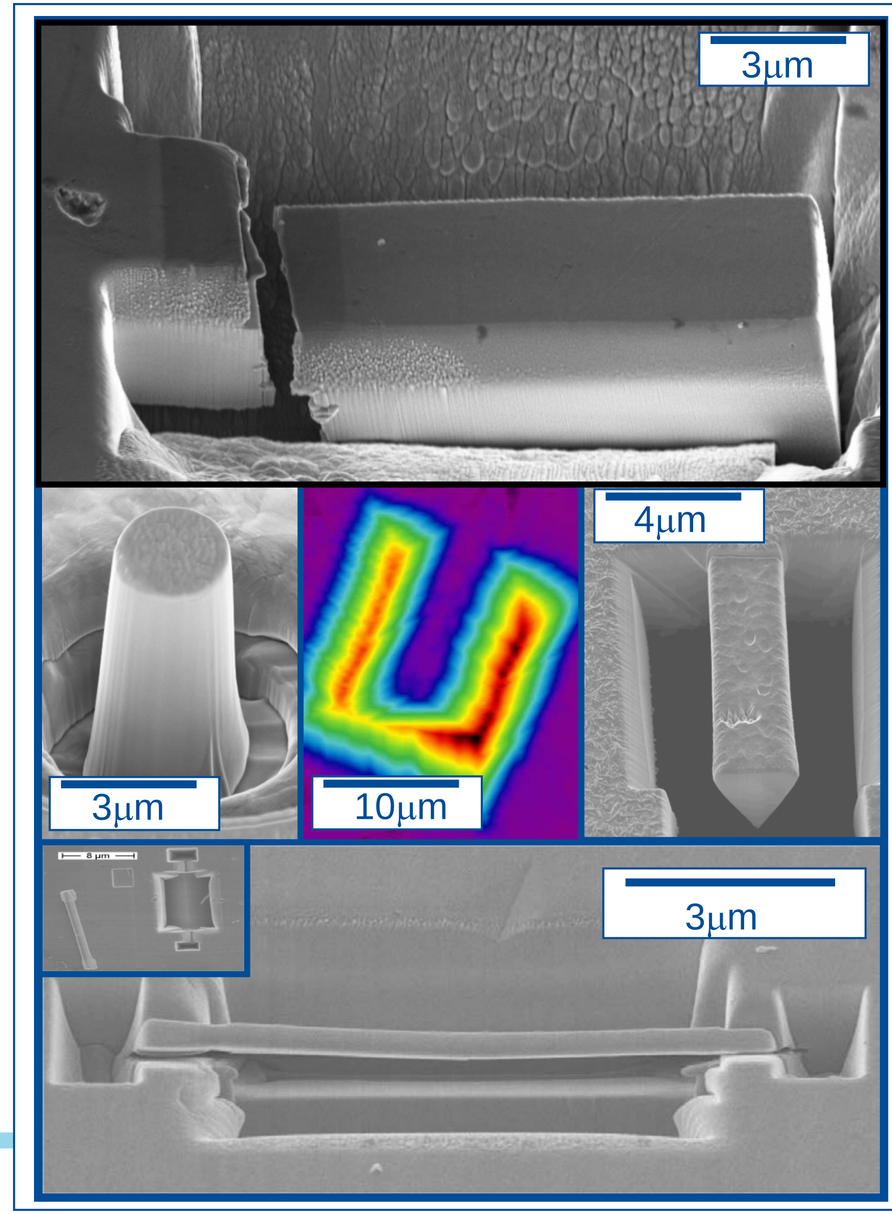
- DOE hazard category 2 facility for work with mg to kg of fissionable and non-fissionable radioactive materials
- 144,000 $ft^2$ building with 40,000 $ft^2$ of hot cell space (16 hot cells)
- Extensive wet laboratories, shielded glove boxes, wet radiochemistry fume hoods, and a modern analytical lab
- $40M in recent upgrades:
  - Seismic strengthening
  - 4 new hot cells
  - 3 new glove boxes
  - 2 new modular shielded storage units
  - High Level Radiation Facility C-cell cleanout and window replacement

D. Asner
PNNL

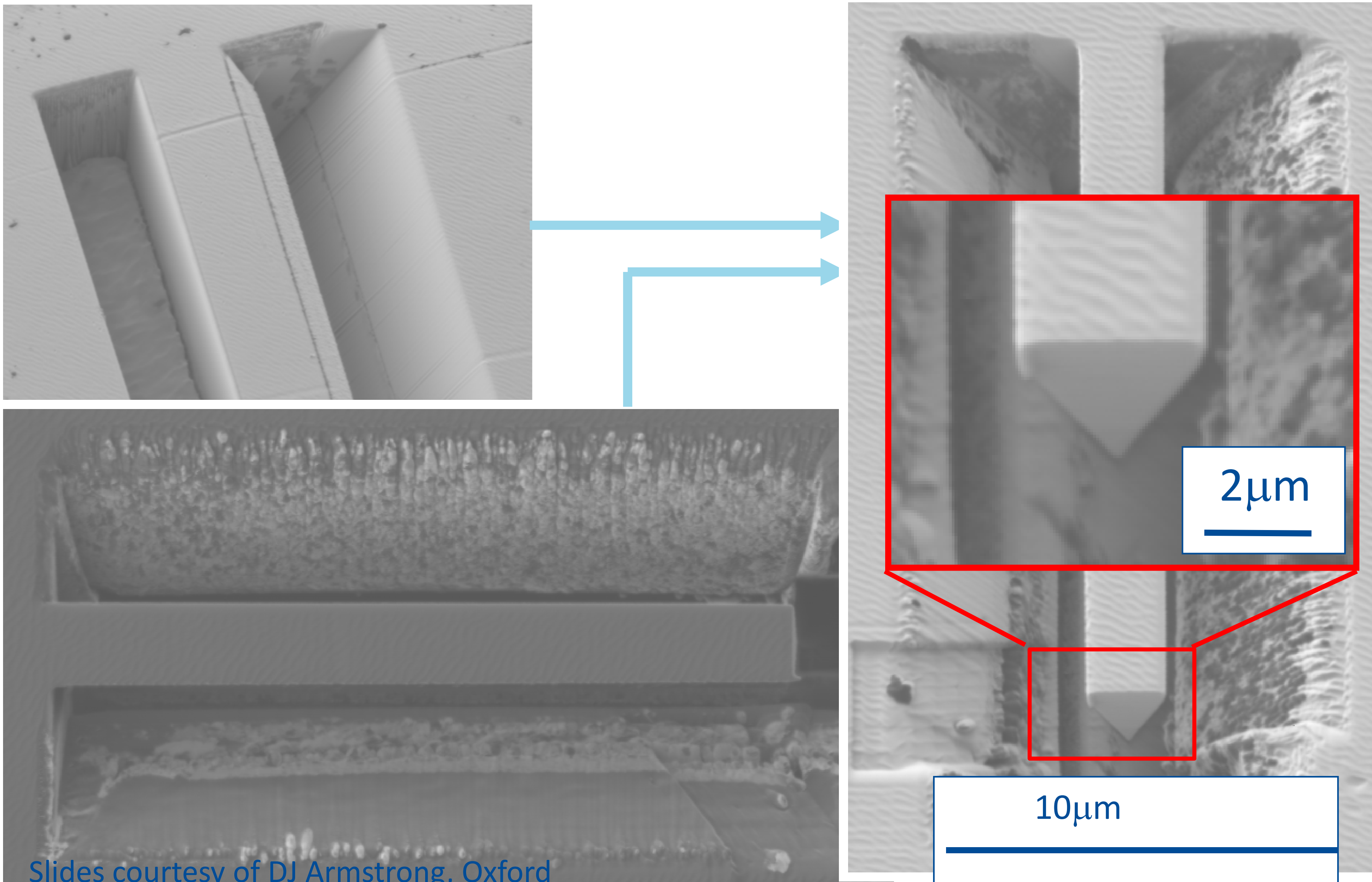
# Why use micro-mechanical testing?

- **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

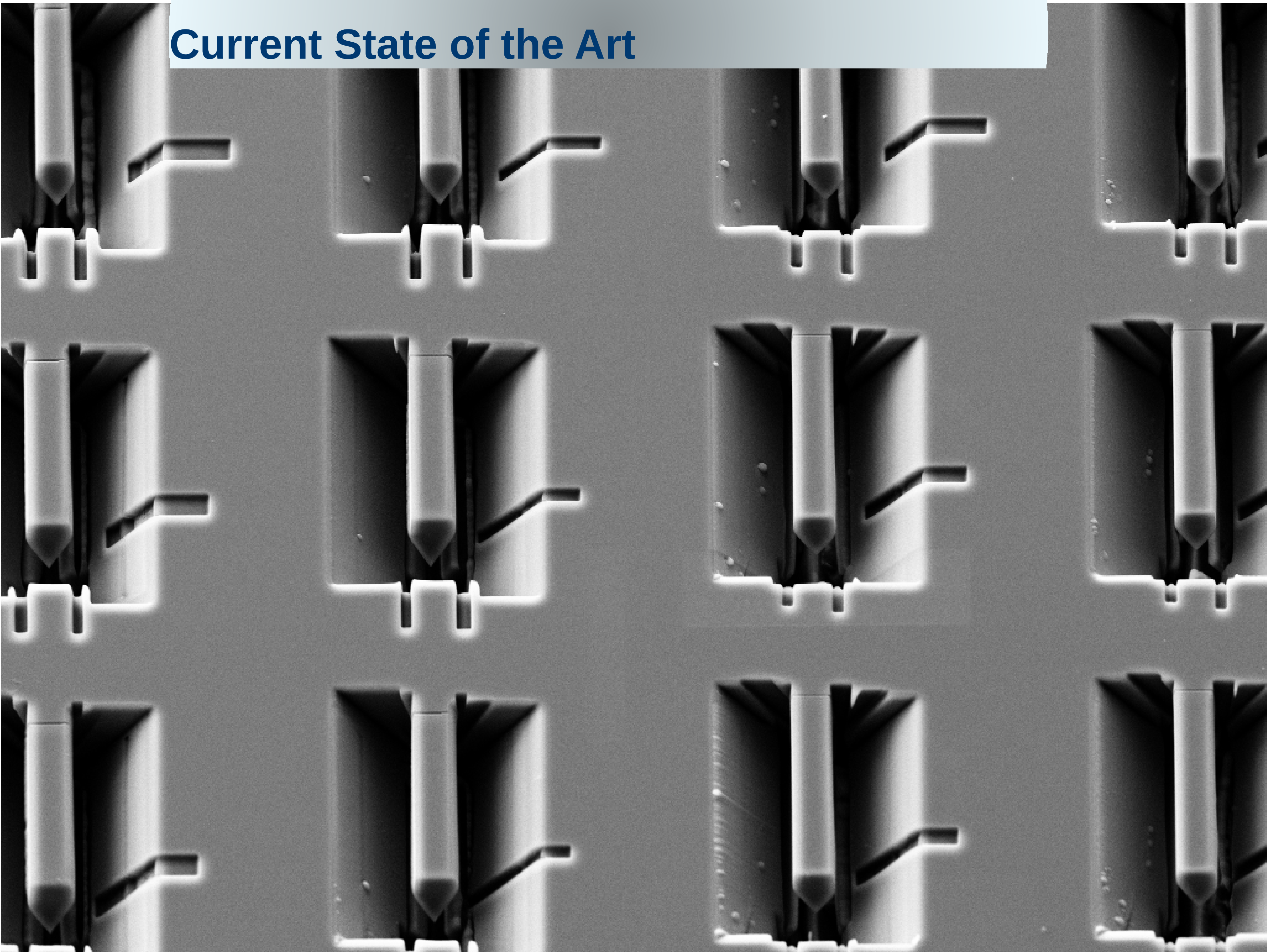


# Microcantilever Manufacture

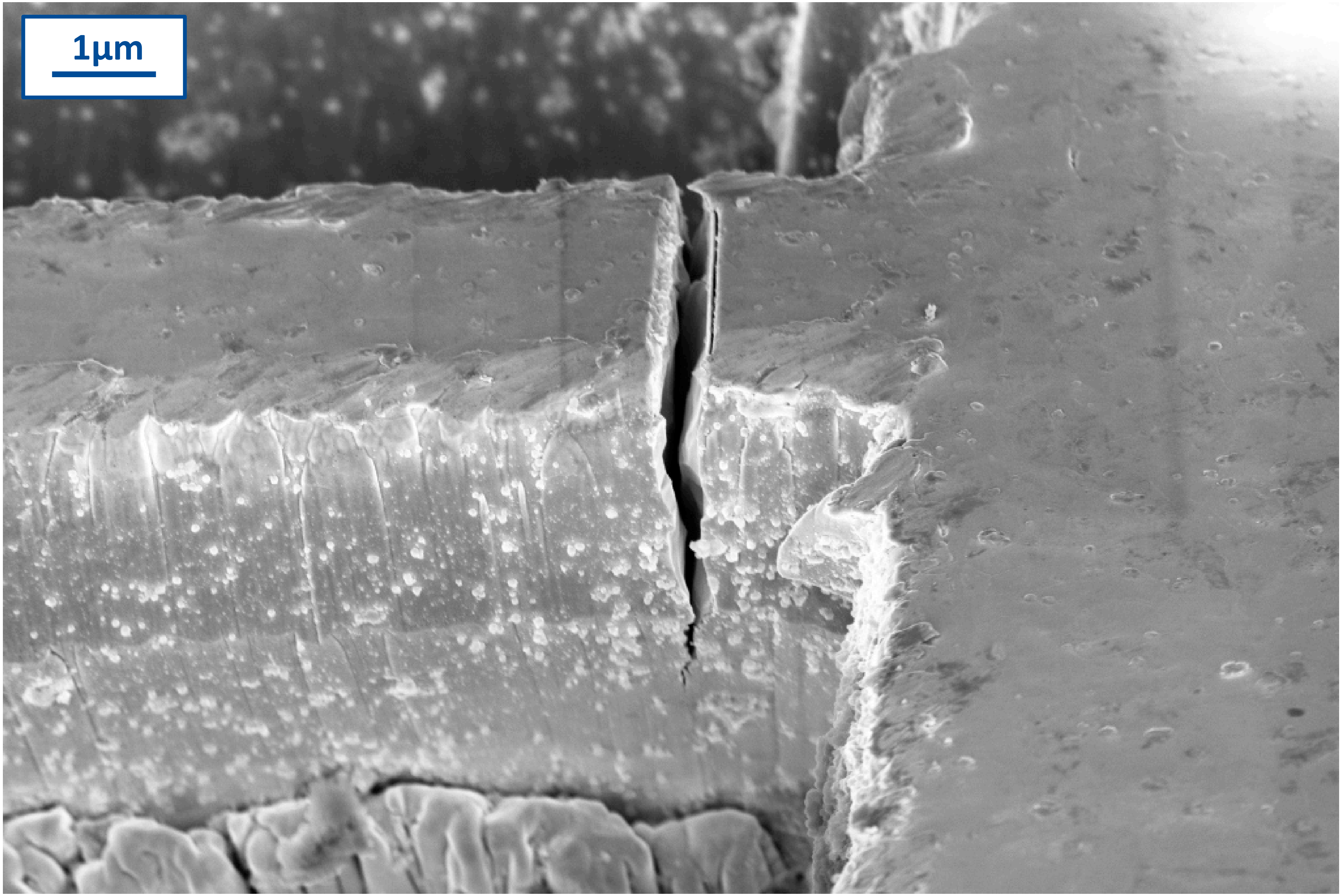



Slides courtesy of DJ Armstrong, Oxford

# Current State of the Art



# Fracture at 600ºC



# Operating Devices – No signs of trouble

| Device | Pulses (e6) | POT (e20) | Notes |
|---|---|---|---|
| TA-02 | 5 | 1.7 | Suspect window |
| PH1-03 | 18 | 6.4 | Retrofit 400 kW horn |
| PH2-02 | 87 | 22.6 | End-of-life ! |

FERMILAB
ACCELERATOR
DIVISION

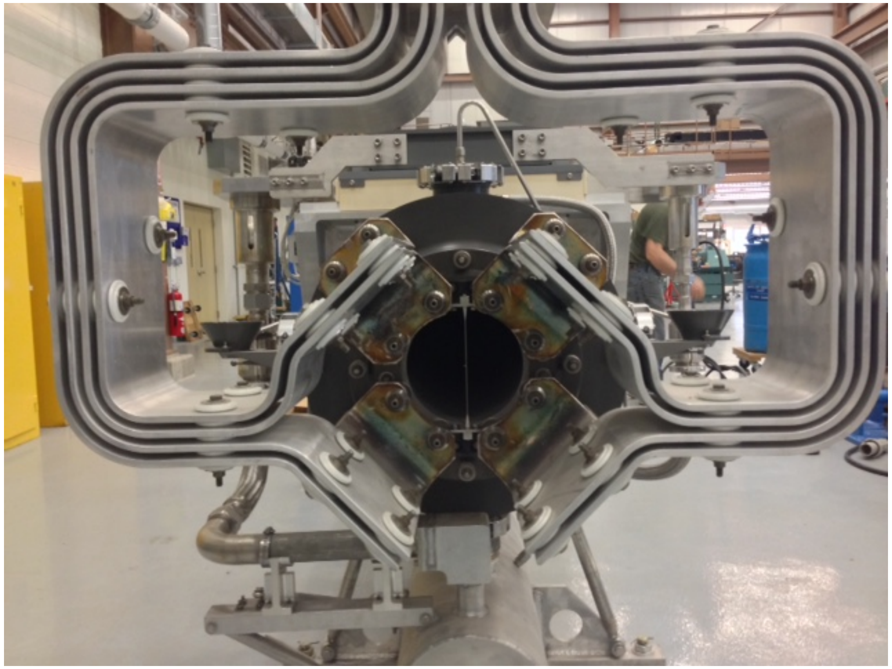
Helium leak was at edge of beryllium window


NUMI Target
MET 01 Beam Right

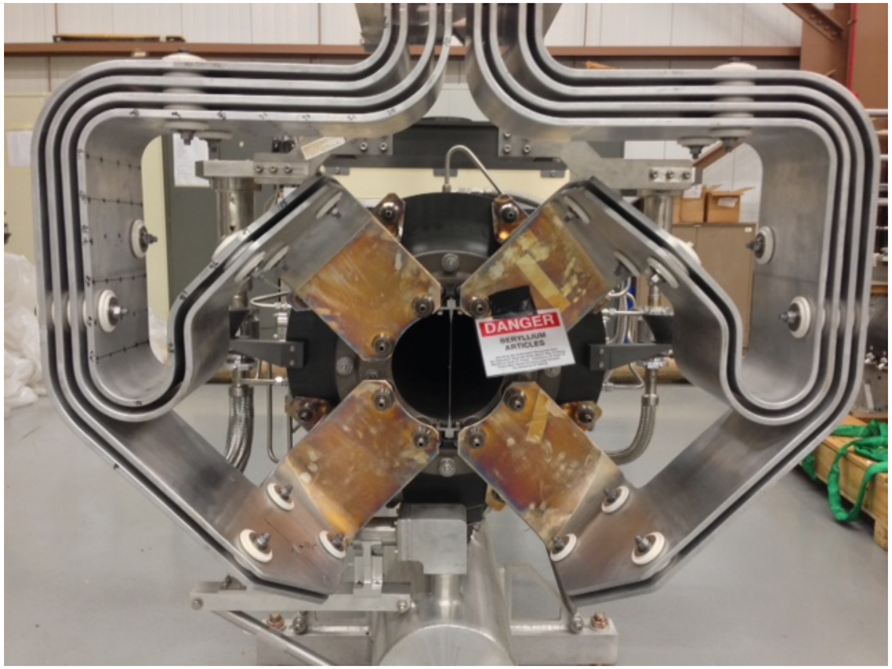
| Point | Doserate @ 1 foot (mr/hour) |
|---|---|
| 1 | 28000 |
| 2 | 15000 |
| 3 | 10000 |
| 4 | 3000 |

# Horn 1 Retrofit underway

**PH1-03**



**PH1-05**




- PH1-05 stripline being converted to more compact style
  - Extended style suffered fatigue failure
- Expect to complete later this year and use for future devices

# Expendable Inventory

| Device | Installed | Future |
|---|---|---|
| NuMI target | TA-02 | TA-03 ready to go<br>TA-04,05 70% complete<br>TA-06,07 in procurement<br>TA-08,09 planned |
| NuMI horn 1 | PH1-03 | PH1-05 retrofitting based on PH1-04 failure<br>PH1-06 waiting on welding<br>PH1-07 procuring parts |
| NuMI horn 2 | PH2-02 | PH2-03 ready to go<br>PH2-04 needs to complete test pulsing<br>PH2-05 in early procurement |

- Production schedule highly dependent on budget, priority, and events
  - Readying Muon campus / g-2 is a high priority within AD for the next few months
- NuMI priorities are
  - PH1-05 Retrofit
  - Redesign of downstream Beryllium window
  - Making progress on TA-04/05
  - Welding PH1-06/07
  - Procuring for TA-06/07
  - Preparing for PIP-I+ (See M. Convery talk)

# Horn 1 Misalignment

- Upstream end of horn 1 sunk ~ 3.8 mm
- Failure was caused by corrosion induced friction of drive components, causing excessive force on a Graphalloy bushing
- Bushings replaced with more robust design and horn moved to correct position
- Additional engineering controls and procedures to limit the likelihood and impact of another failure.
- Plan more regular exterior optical survey and beam scans
- Transverse motion mechanisms still stuck

# PH2-01 Disposal – Existence Proof!

- PH2-01, operated 2005-2008, retired to Nevada Oct. 2016
- First disposal of a highly radioactive component
  - Anticipate 1-2 shipments per year

# NuMI Targets Summary

| | Max. Proton/pulse | Max. Beam Power | Integrated Protons on Target |
|---|---|---|---|
| **MINOS Design Specification** | **4.0 e13 p.p.p. at 120 GeV** | **400 kW** | **3.7 e20 p.o.t. or 1yr minimum lifetime** |
| **NT-01** | 3.0 e13 | 270 kW | 1.6 e20 |
| **NT-02** | 4.0 e13 | 340 kW | 6.1 e20 |
| **NT-03** | 4.4 e13 | 375 kW | 3.1 e20 |
| **NT-04** | 4.3 e13 | 375 kW | 0.2 e20 |
| **NT-05** | 4.0 e13 | 337 kW | 1.3 e20 |
| **NT-06** | 3.5 e13 | 305 kW | 0.2 e20 |
| **NT-01 rerun** | 2.6 e13 | 228 kW | 0.2 e20 |
| **NT-02 rerun** | 3.8 e13 | 330 kW | 0.4 e20 |
| **NT-07** | 4.0 e13 | 345 kW | 2.5 e20 |
| **NOvA Design Specification** | **4.9 e13 p.p.p. at 120 GeV** | **700 kW** | **6 e20 p.o.t. or 1yr minimum lifetime** |
| **TA-01** | 4.4 e13 | 620 kW | 11.2 e20 |
| **TA-02** | 5.35 e13 | 750 kW | 2.3 e20 (+) |