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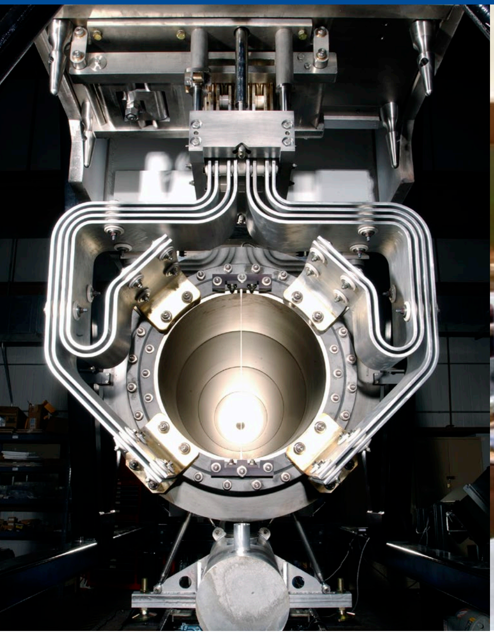


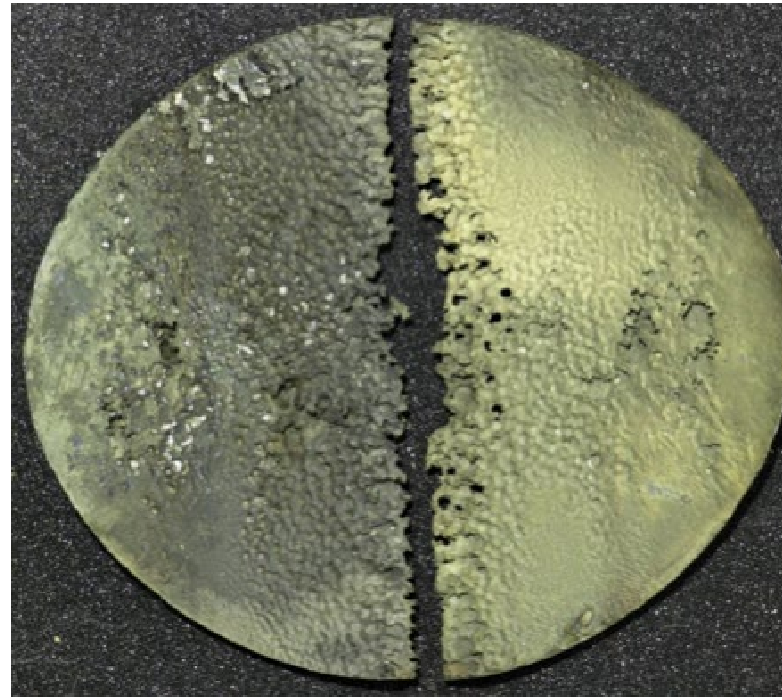
Targetry challenges for the next generation of high-intensity neutrino beams

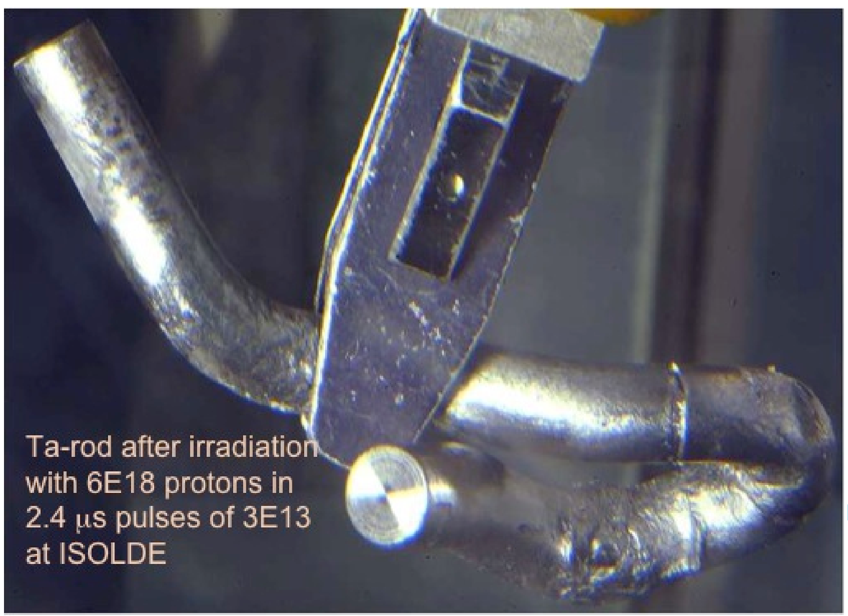
Robert Zwaska

Neutrino 2020 Conference

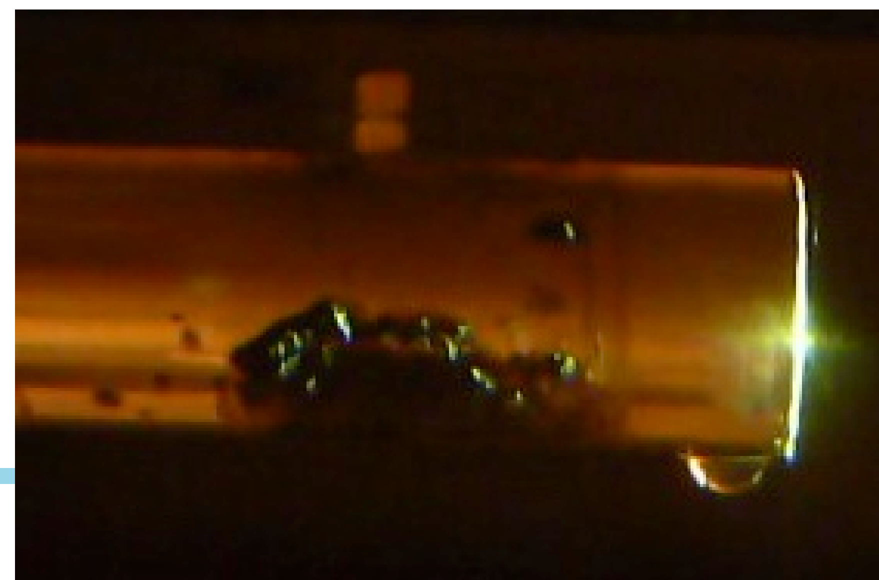
29 June 2020

What we don’t want





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



High Power/Intensity Targetry Challenges

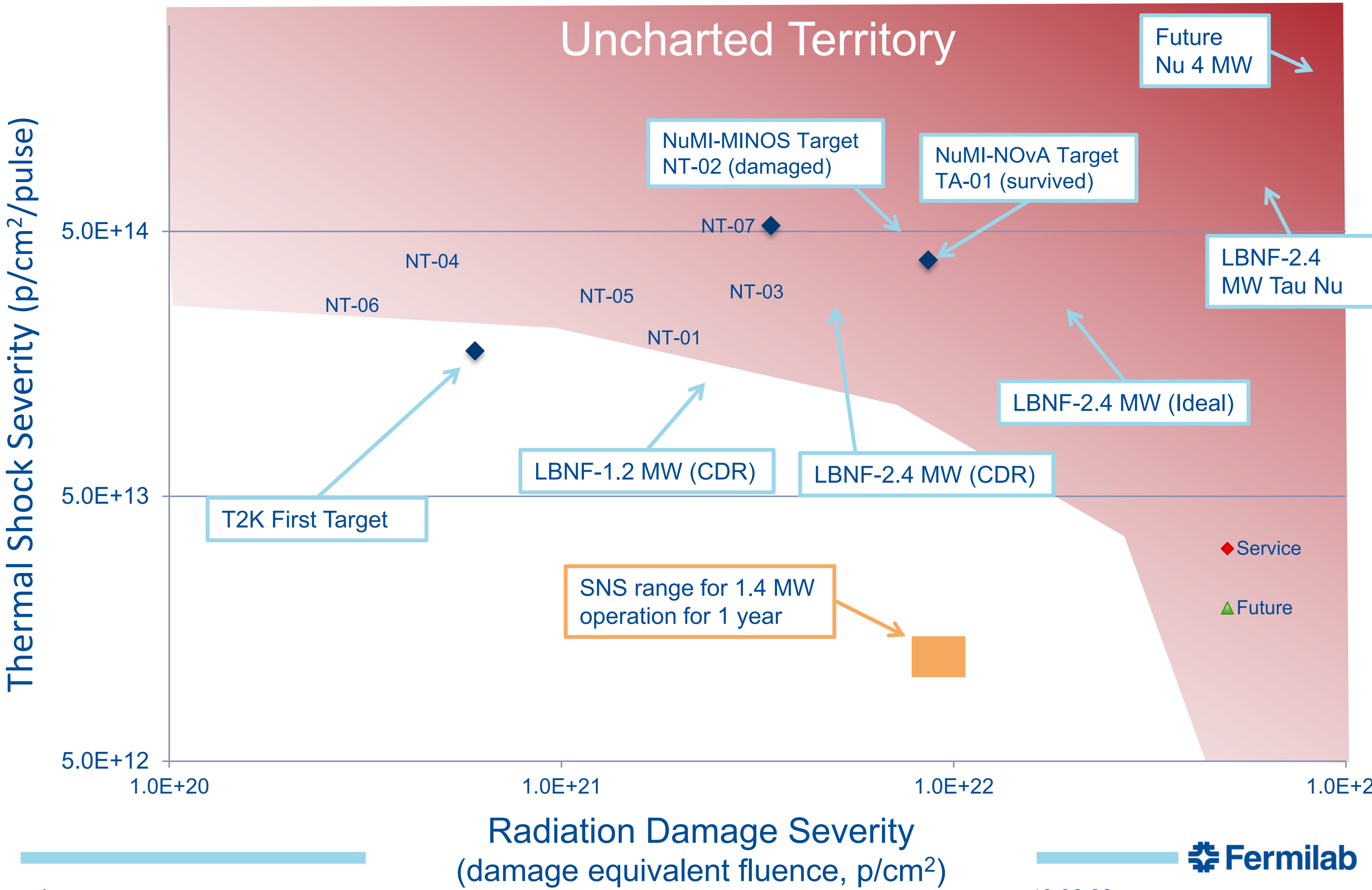
- Target Material Behavior
  - **Radiation damage**
  - **Thermal “shock” response**
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Remote handling
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection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

Additional Neutrino Beam Challenges:

- Primary beam handling and instrumentation
- Accuracy and consistency of all beam inputs, particularly alignment
- Focusing elements
- Beam-based alignment
- Secondary beam instrumentation
- Radiation transport modeling
- Hadron production

The high statistics from high-power beams require an emphasis on ***precision***

Nu HPT R&D Materials Exploratory Map



RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

www-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**

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

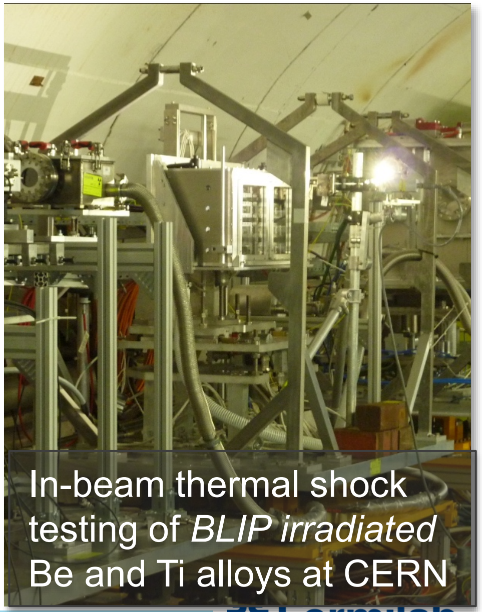
High Power Targetry: Materials R&D

Multi-MW Neutrino Targets & Beam Windows Materials:

- Graphite (target core material) studies:
  - Swelling/fracture studies
  - Preparing for HE proton irradiation at BLIP (2020) to confirm elevated temperature annealing
- Beryllium (beam window material) studies:
  - Examination of BLIP irradiated Be specimens underway
  - Helium implantation studies show bubble formation at irradiation temperatures above 360 ˚C
- Titanium Alloys (beam window material) studies:
  - Examination of BLIP irradiated specimens underway
  - World first high cycle fatigue testing of irradiated titanium underway at FNAL

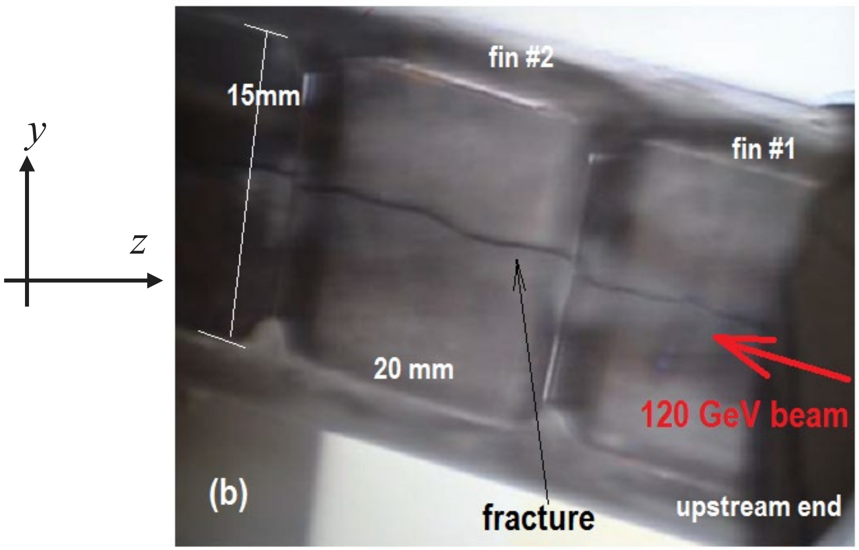
Benefits to multi-MW targets e.g. LBNF):
- alloy/grade choice
- cooling system design
- tolerable beam intensities
- expected lifetimes

RaDIATE

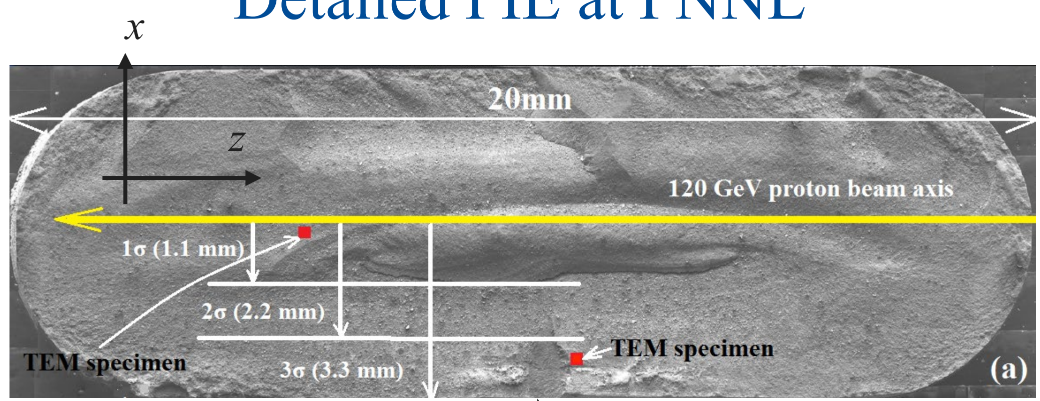


In-beam thermal shock testing of *BLIP irradiated* Be and Ti alloys at CERN

Background- Fractured NuMI target fin



Detailed PIE at PNNL



Bulk swelling of ~2%

Beam Parameters:

Energy :120 GeV

Beam sigma : 1.1mm

Spill duration : 10μsec, $4x10^{13}$ protons/pulse

Duty cycle :1.87sec

Peak fluence : $8.6x10^{21}$ protons/cm^2

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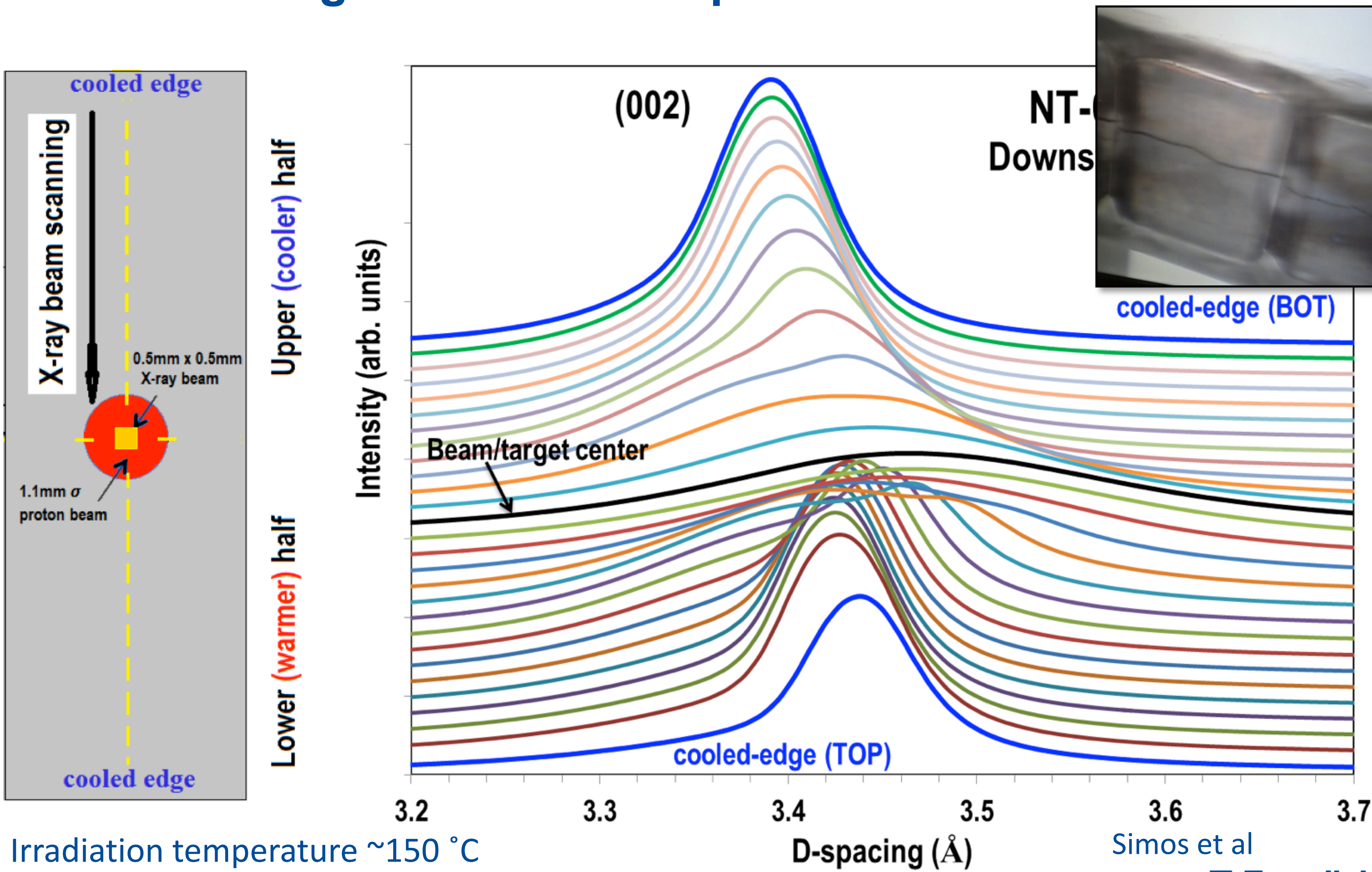
Graphite Results – X-ray diffraction of NuMI graphite fin shows lattice growth and amorphization at beam center



Irradiation temperature ~150 ˚C

Simos et al

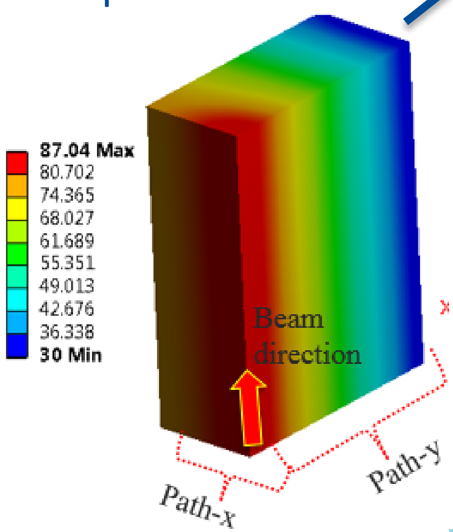
Modeling of graphite swelling predicts fracture

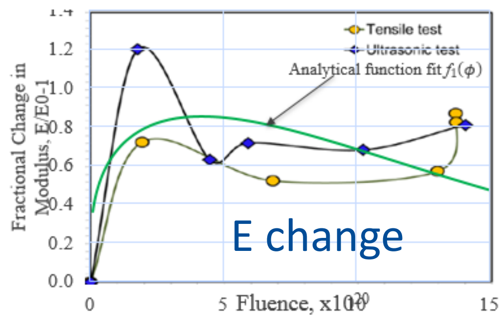
Sujit Bidhar (FNAL) – User defined material model in ANSYS

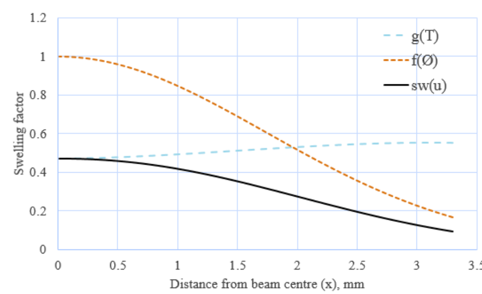
- **Elastic modulus** as a function of dose and temperature
- **Swelling (NSLS-II)** as a function of dose and temperature

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

Thermal Response



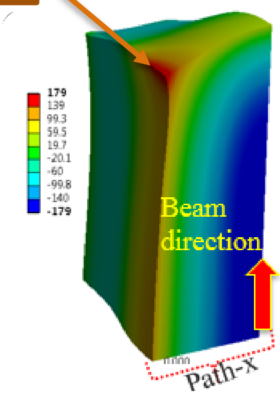




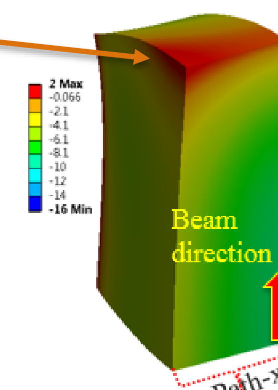
Swelling

179 Mpa !!

Stress



2 MPa



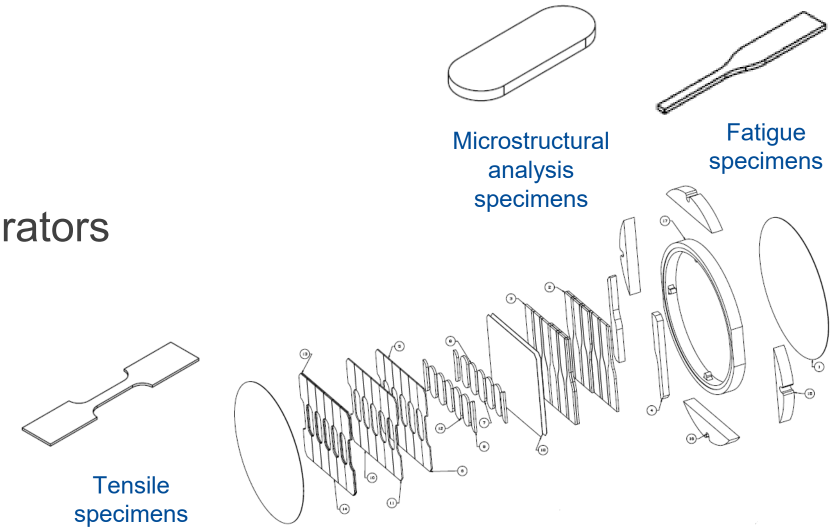
No radiation damage effects

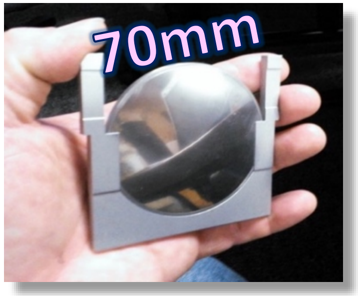
Stress

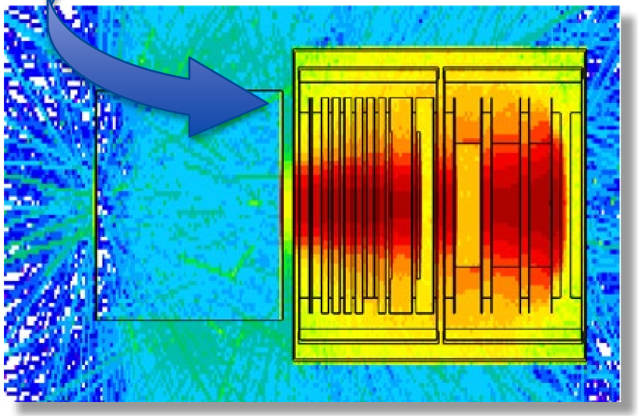
High Energy Proton Irradiation

- 181 MeV p irradiation @ BNL's BLIP facility
  - Over 200 specimens from 6 RaDIATE collaborators
  - Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, FNAL
- Completed irradiation on March 9, 2018
  - 4.5E21 accumulated protons on target
  - 1.52 peak DPA on Ti alloy achieved

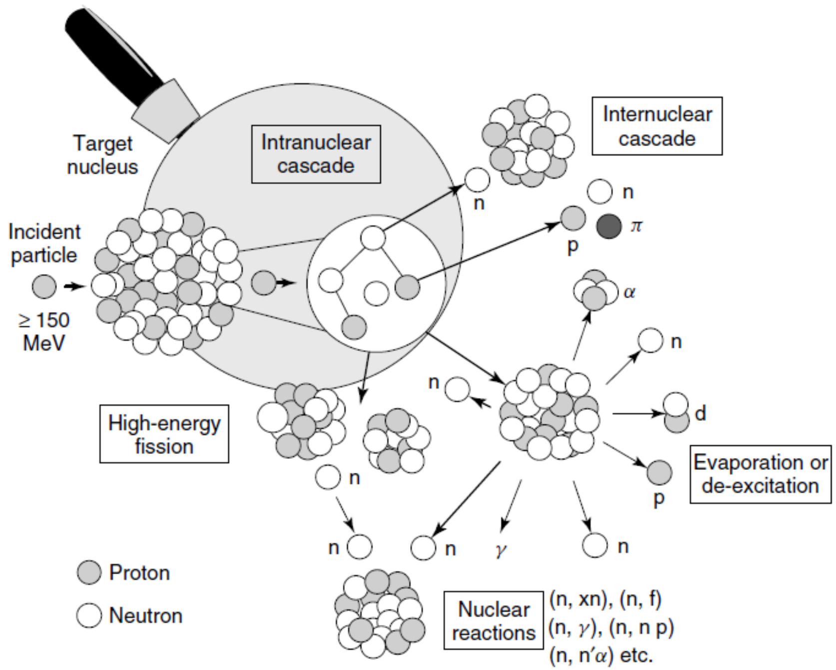
Impact: Will benefit many facilities including LBNF, T2K, BDF at CERN, FRIB, and even LHC-HiLumi (collimators)

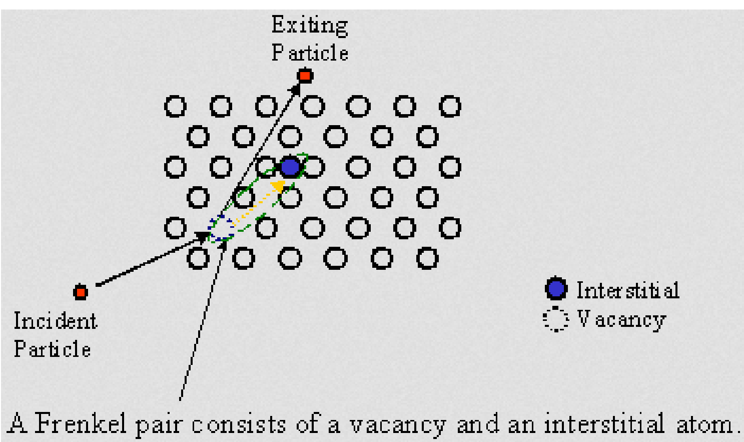






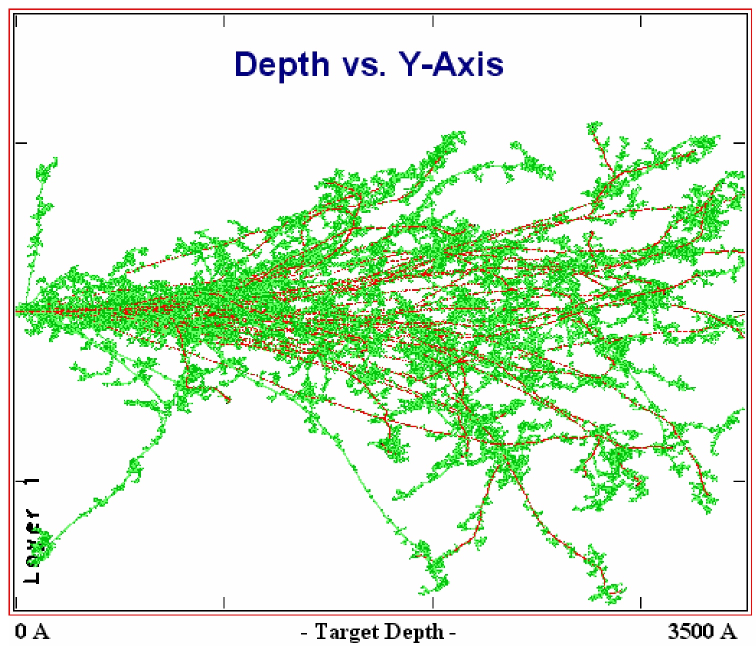
Radiation Damage Disorders Microstructure





Microstructural response:

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



Slide prepared by V. Kuksenko (Oxford)

RaDIATE BLIP irradiation summary

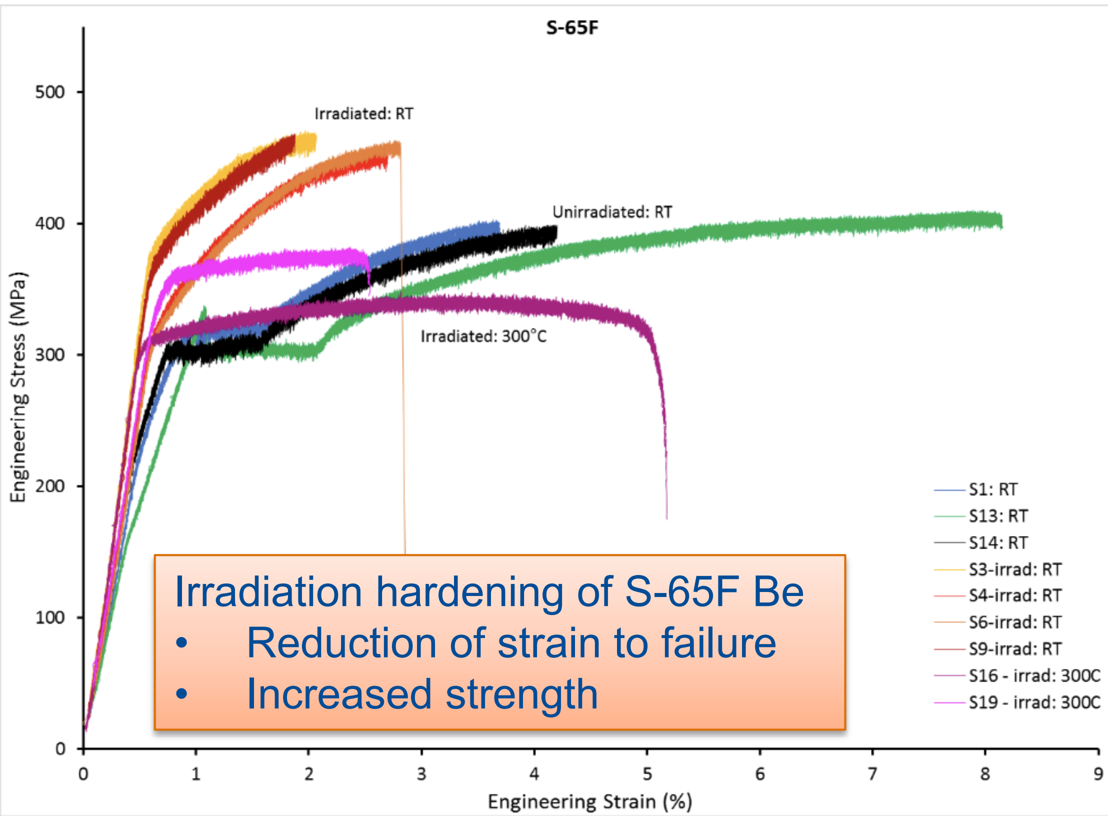
Consisted of **9 capsules** from 6 RaDIATE institutions with **over 200 material specimens** relevant to beam intercepting devices in various current/future accelerator facilities

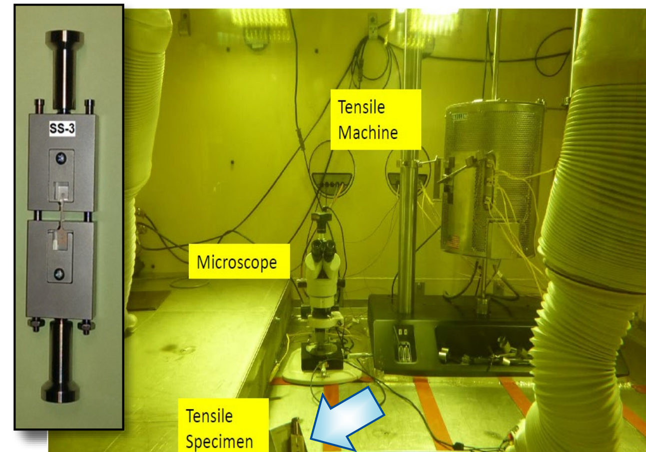
- **181 MeV** incoming protons used for RaDIATE irradiation
- Irradiation campaign executed in **3 phases** with different target box configurations
  - 6 capsules in target box during each irradiation phase
- Total protons on target: **4.57E21** (154 µA avg)

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

BLIP Irradiation Examinations Underway

- Significant hardening at low dose in Be and Ti
  - Less hardening in higher temperature specimens
- First ever fatigue study on irradiated Ti alloys begun
  - Indicates about 10% reduction in fatigue strength
- Microstructural examinations underway



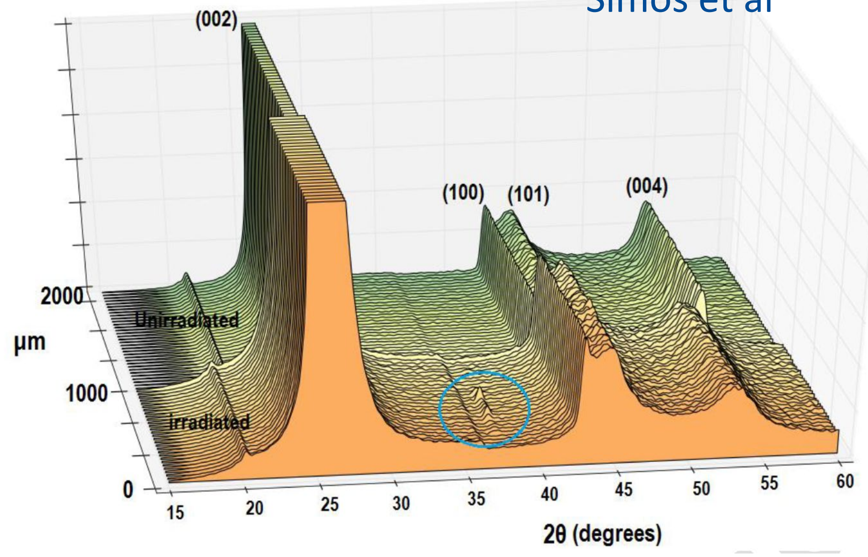


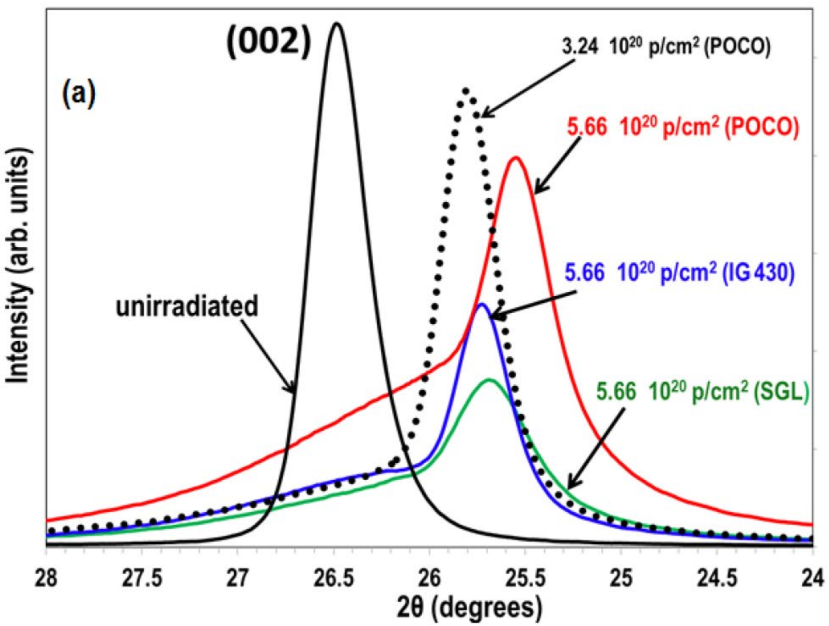

Custom Fatigue Testing Machine for Irradiated Materials (FNAL)

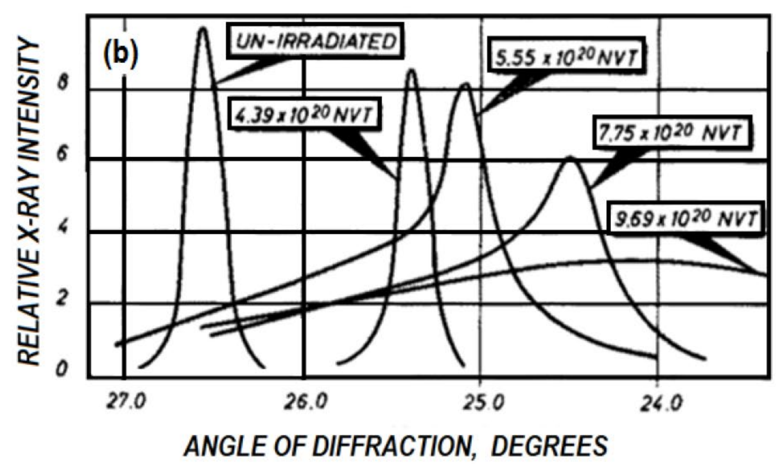
X-ray diffraction – Swelling in BLIP irradiated graphite

Simos et al

Impact: Allows confidence to use reactor data for lattice swelling of graphite in HE proton regime for future target facilities



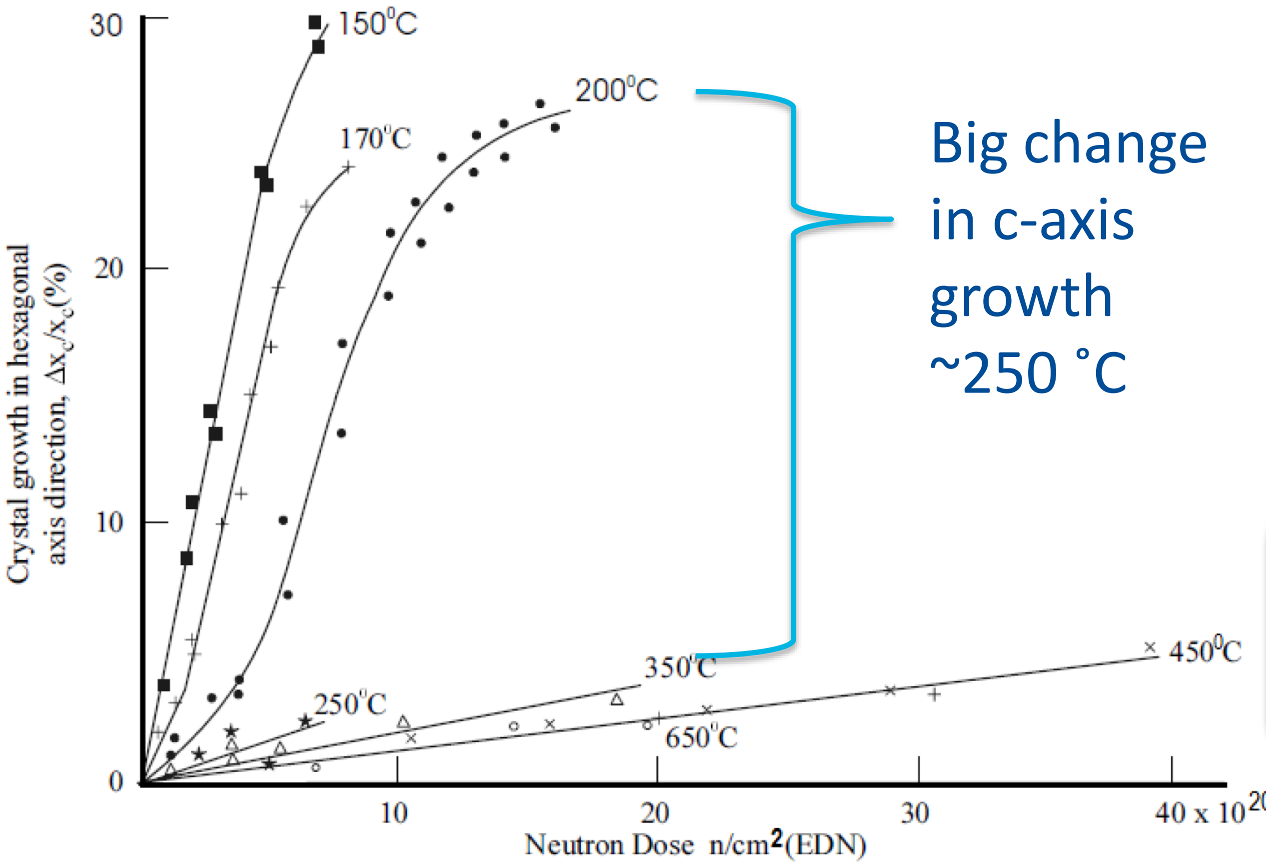




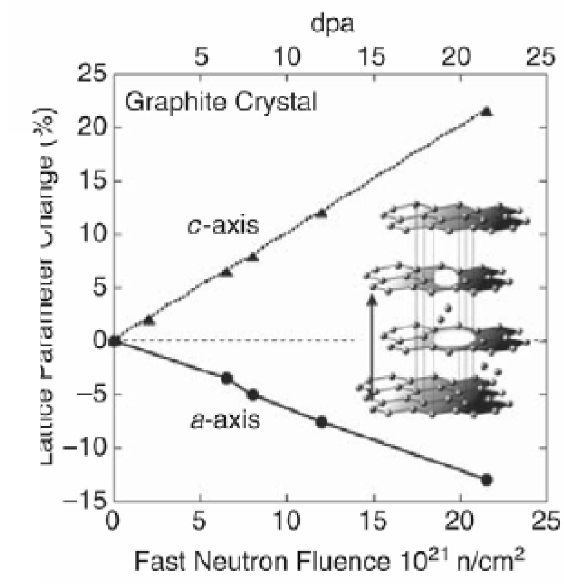
W. Bollmann. "Electron-microscopic observations on radiation damage in graphite" Phil. Mag., 5(54):621-624, June 1960.

Neutron irradiated graphite dimensional changes

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



Big change in c-axis growth ~250 °C



Impact: Correlation informs target choice of operating temperature (cooling system design)

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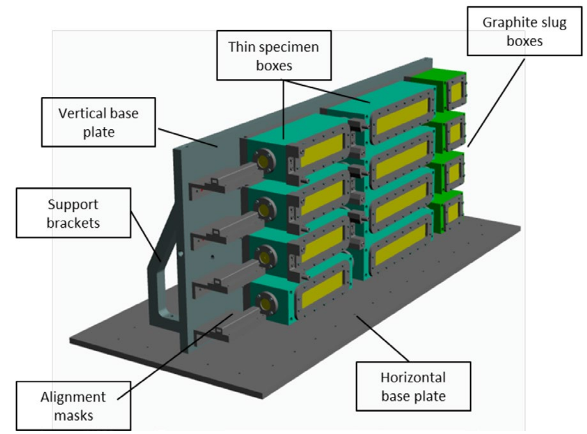
In-Beam Thermal Shock Test: BeGrid2 (HRMT43)

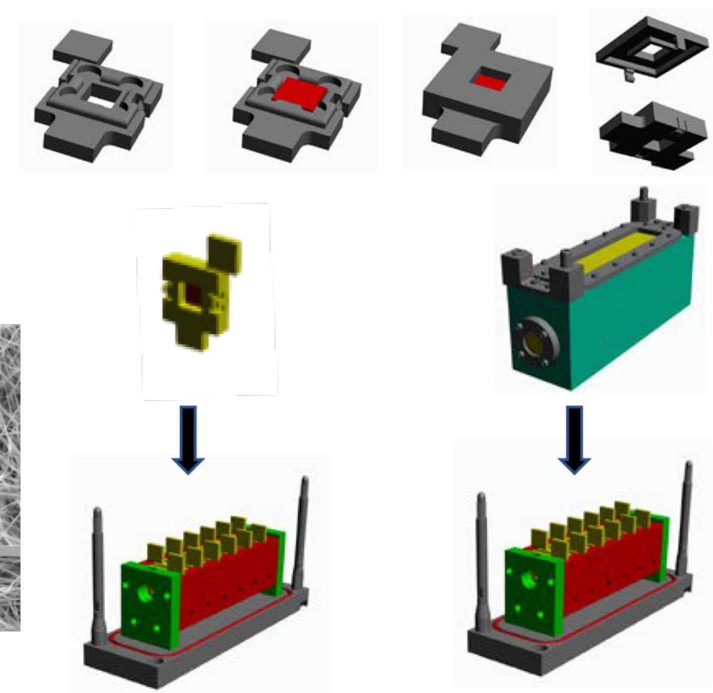
Beam taken on Oct. (2018)

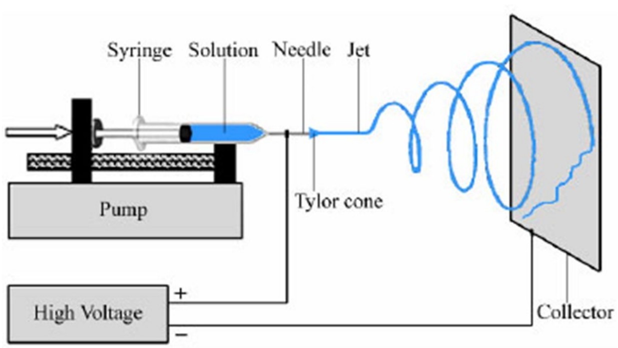
Primary Objectives:



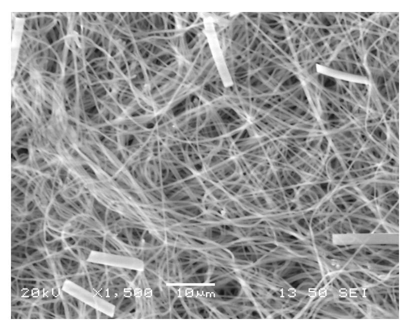
- Compare thermal shock response between non-irradiated and previously irradiated material specimens from BNL BLIP (Be, C, Ti, Si)
  - First/unique test with activated materials at HiRadMat

- Explore novel materials such as metal foams (C, SiC) and electrospun fiber mats (Al_2O_3, ZrO_2) to evaluate their resistance to thermal shock and suitability as target materials



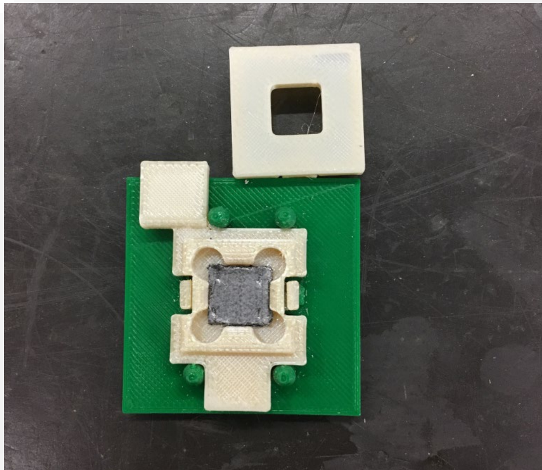


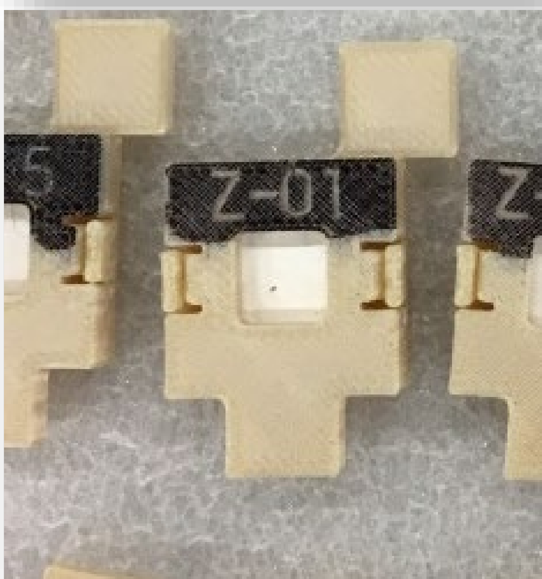
Electrospinning concept



SEM: as-spun Al_2O_3

BeGrid2 (HRMT43) – 3-D printed specimen holders



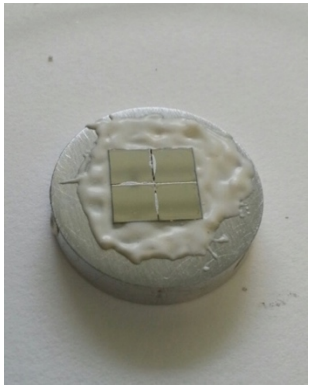


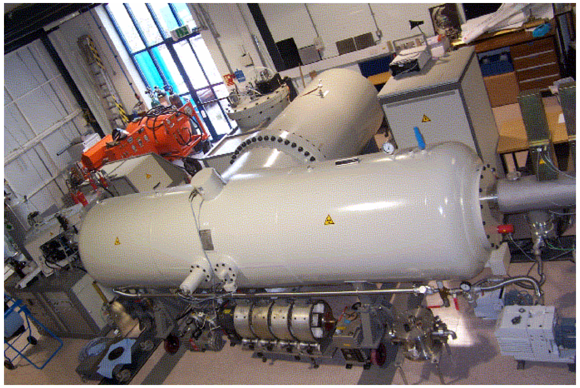
MIMiC - Methods of Irradiated Material Characterization

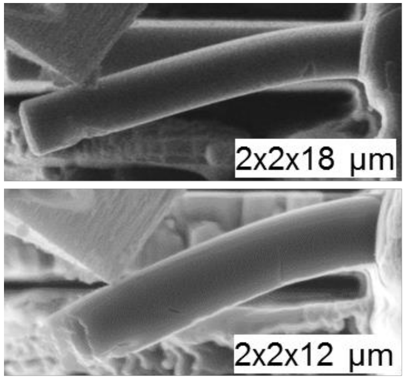
Replicating proton beam interaction damage ***with minimal residual activity***

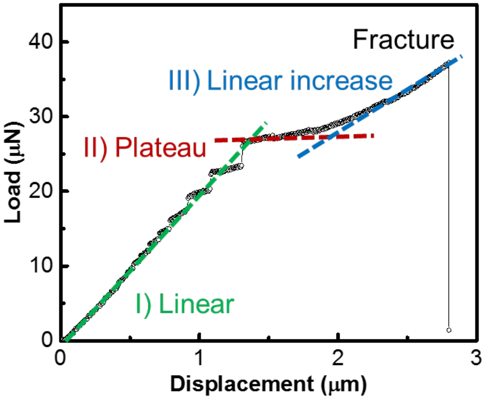
The current routes for **high-energy proton irradiations are expensive**, long in duration, and lack control of testing conditions and schedule.

- **Low-energy ion irradiations** are attractive because they allow study of the evolution of the micro-structure during irradiation without activating the specimens, are relatively low cost, and can achieve high dose in very short durations.
- **Micro-mechanics** and meso-scale testing are potential enabling technologies to overcome some of the limitations of low-energy irradiations as well as to drastically reduce specimen size requirements (which also reduces activity of specimens).
- **Ion irradiations and micro-mechanics have been used in the RaDIATE studies on beryllium.**

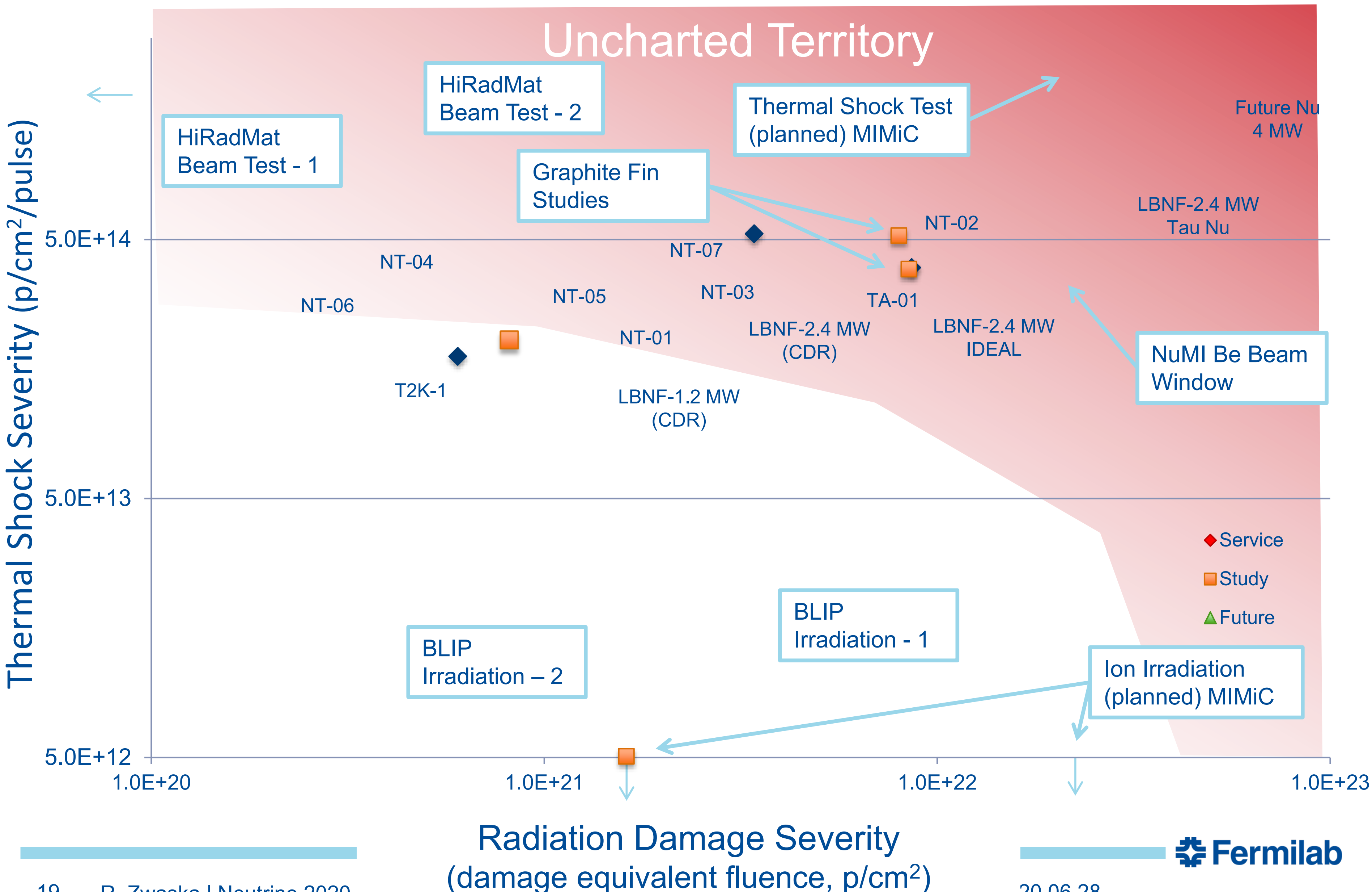








Nu HPT R&D Materials Exploratory Map



Overview of Strategy for HPT Material R&D

To Present (2010-2020) – *Benefits ongoing neutrino program*

- Measure irradiated material behavior of currently identified targetry materials
  - Be, graphite, Ti alloys
  - High-energy proton irradiations, thermal shock tests, autopsies
- Identify more effective Methods of Irradiated Material Characterization (MIMiC)
- Explore ab initio and molecular dynamics to model irradiated material behavior

Mid Term* (2021-2027) – *Benefits LBNF 2.4 MW design & next-gen experiments*

- Continue irradiated material studies on candidate targetry materials
  - Focus on reducing costs/risks of high-energy proton irradiations
- Develop MIMiC ideas into valid experimental techniques

Far Term* (2028 and beyond) – *Benefits next-gen HPT Facilities*

- Utilize the developed MIMiC techniques, ab initio/MD modeling, and previous experimental results to develop and select promising candidate targetry materials
- Qualify selected candidate targetry materials for next generation HPT facilities with a combination of high-energy proton and MIMiC techniques

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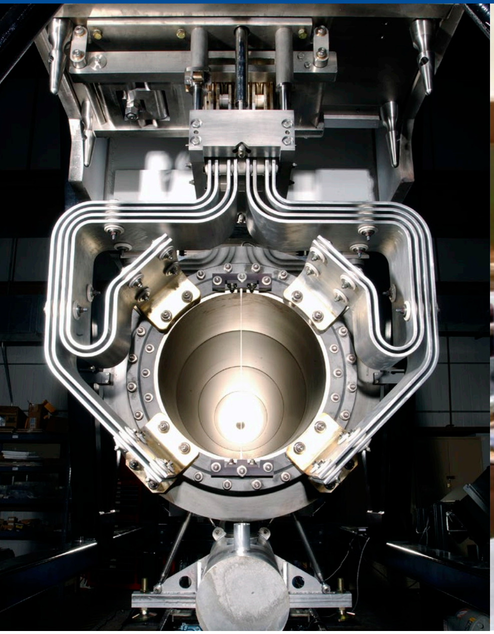

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