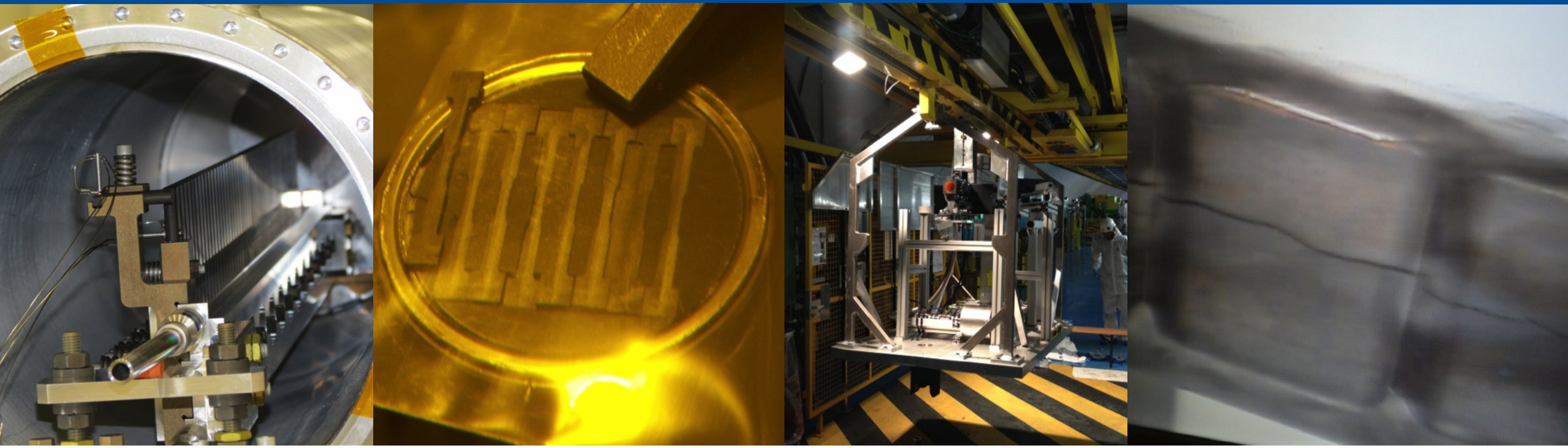


The Radiation Damage In Accelerator Target Environments (RaDIATE) Collaboration R&D Program – Status and Future Activities

Patrick Hurh (Fermilab)

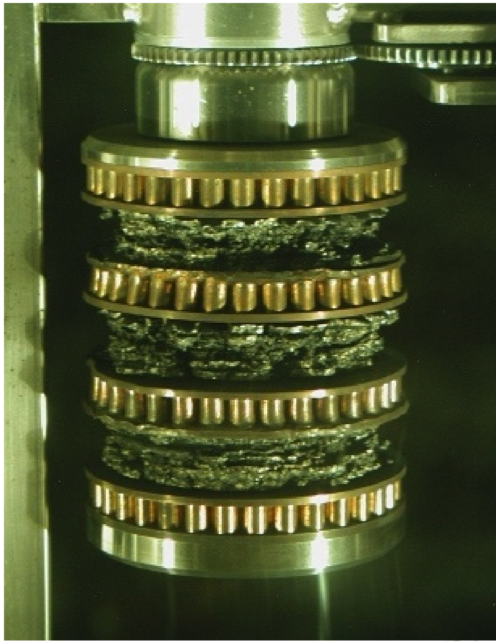
on behalf of the RaDIATE Collaboration

IPAC'17 – 17 May 2017

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 Challenges



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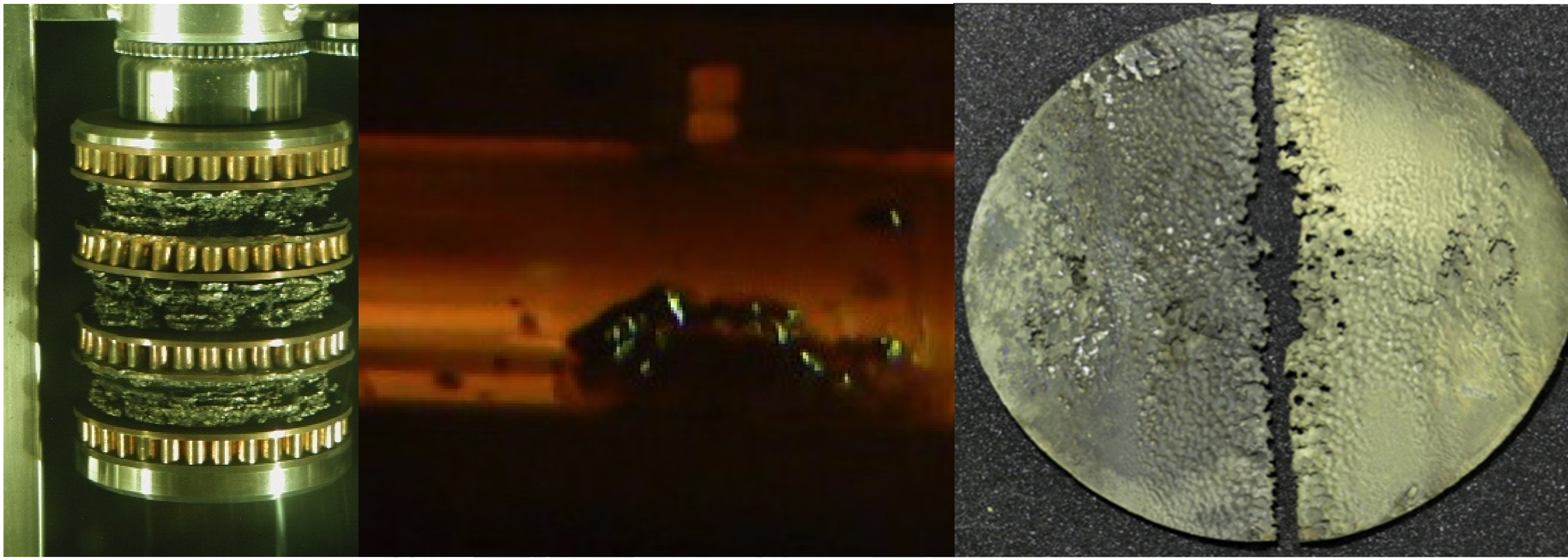

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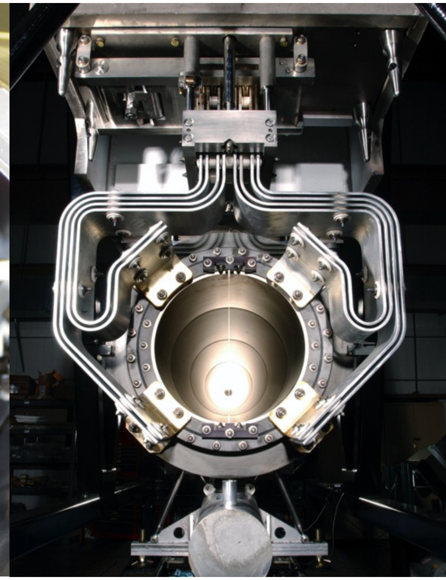
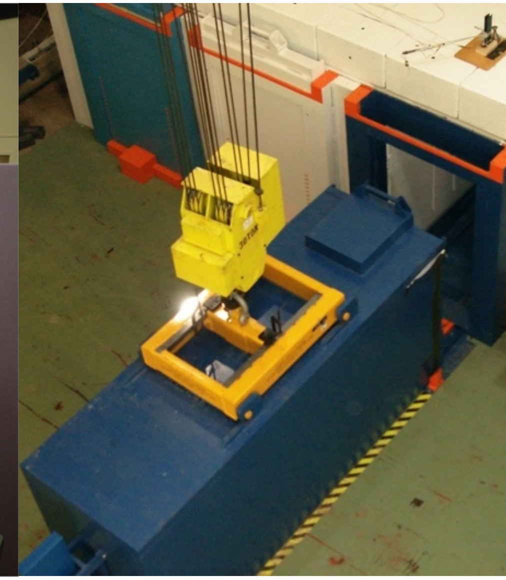
High Power Targetry Scope



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

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Subjects of the RaDIATE Collaboration

High Power/Intensity Targetry Challenges

- Material Behavior
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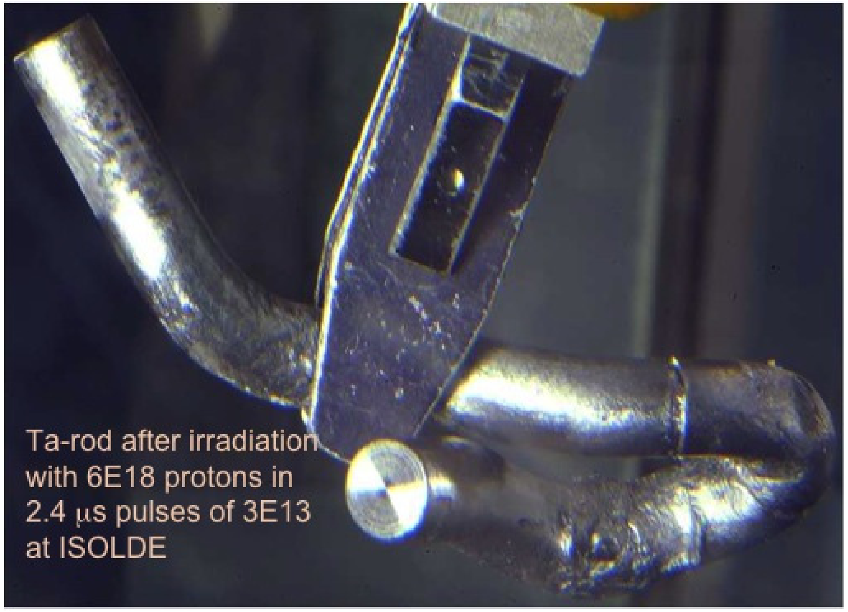
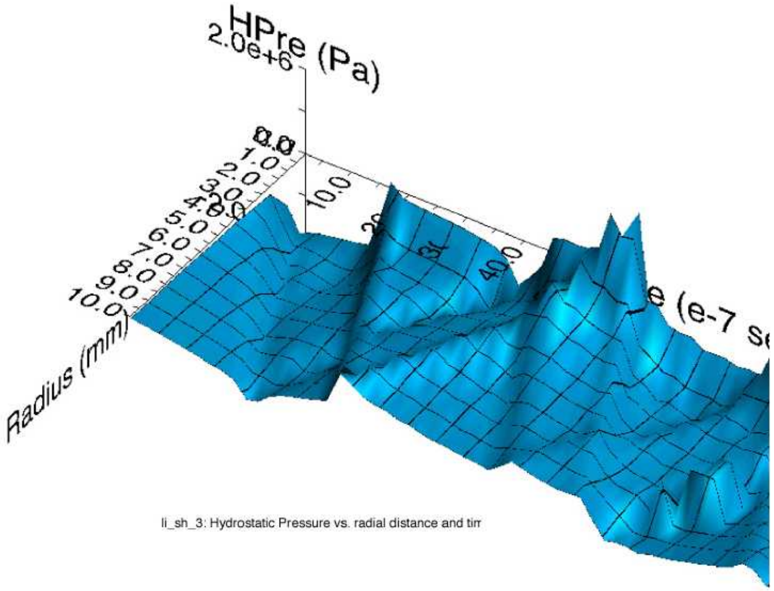
Subjects of the RaDIATE Collaboration

In 2012, at a Proton Accelerators for Science and Innovation Workshop (PASI), workshop participants from a range of high power accelerator facilities identified radiation damage to materials as the most cross-cutting challenge facing high power target facilities [1].

Thermal Shock (stress waves)



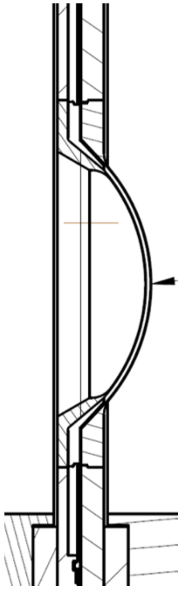
Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)

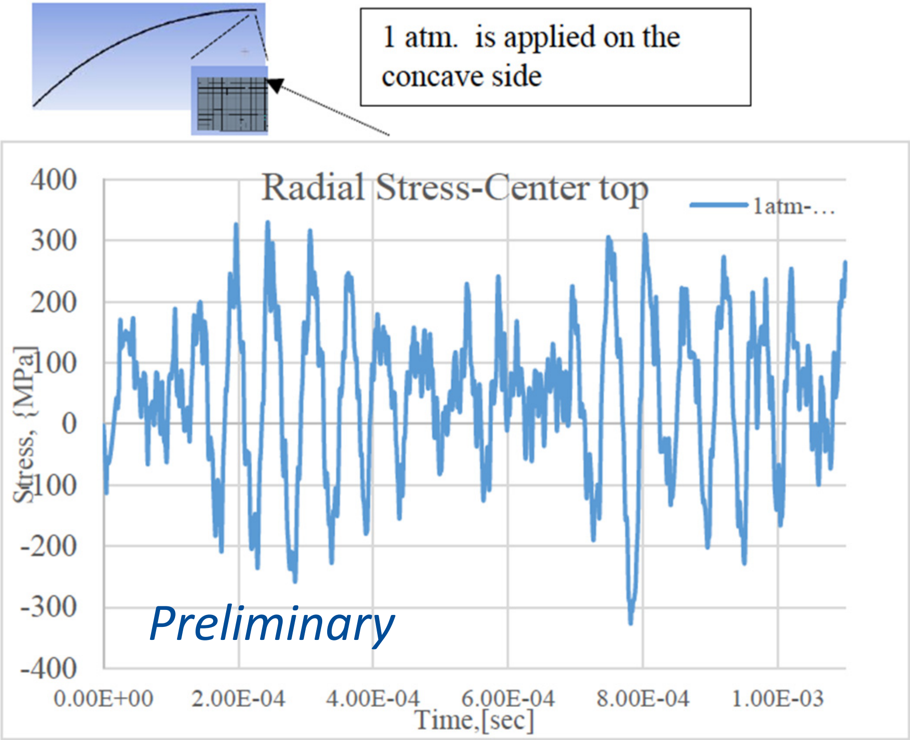


Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

- 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

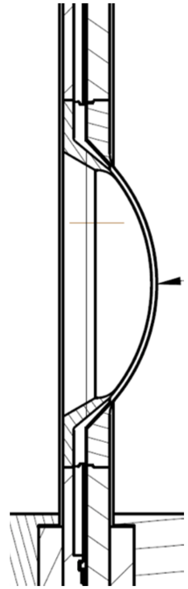


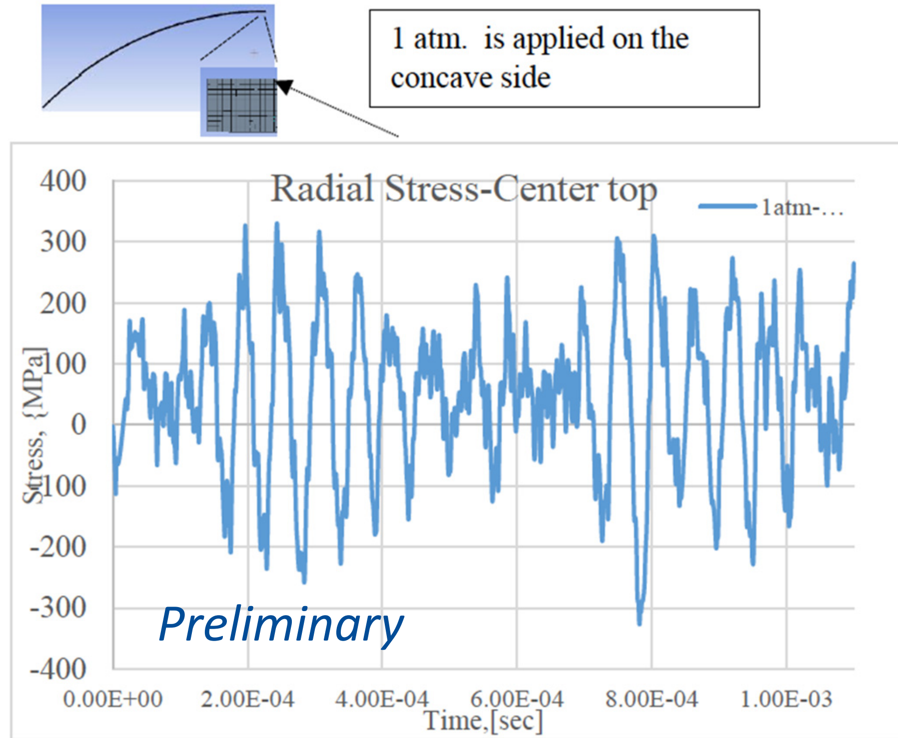


S. Bidhar, FNAL

- 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)

Stress wave example: T2K window





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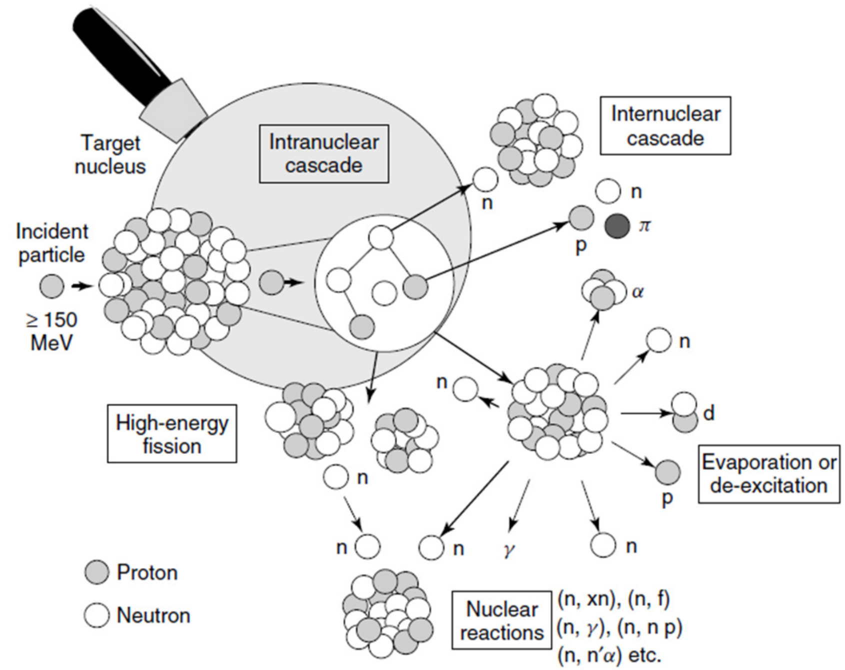
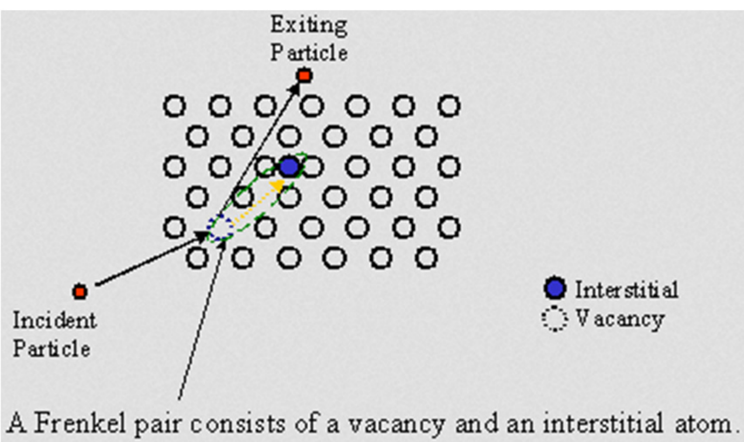
Heavy dependence upon material properties, but:
Material properties dependent upon Radiation Damage…

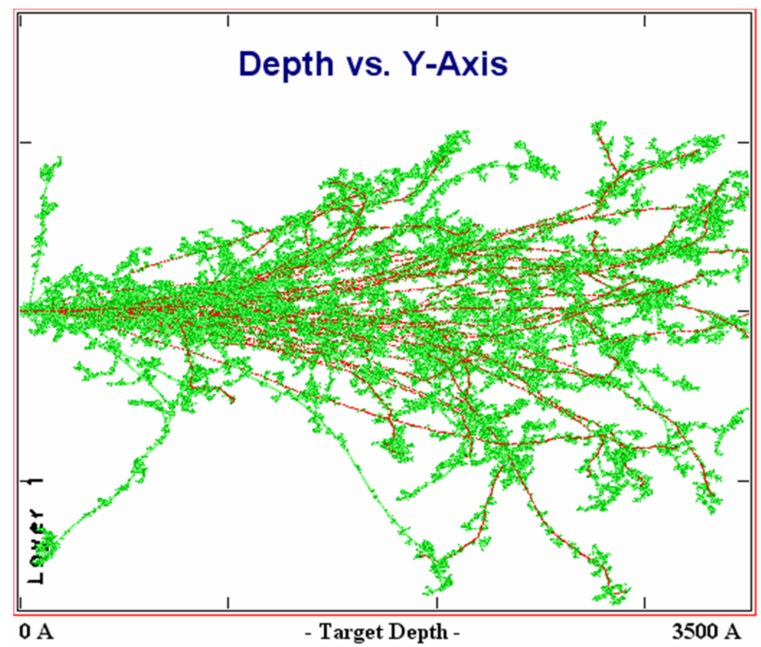
Radiation Damage Disorders Microstructure



Microstructural response:

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

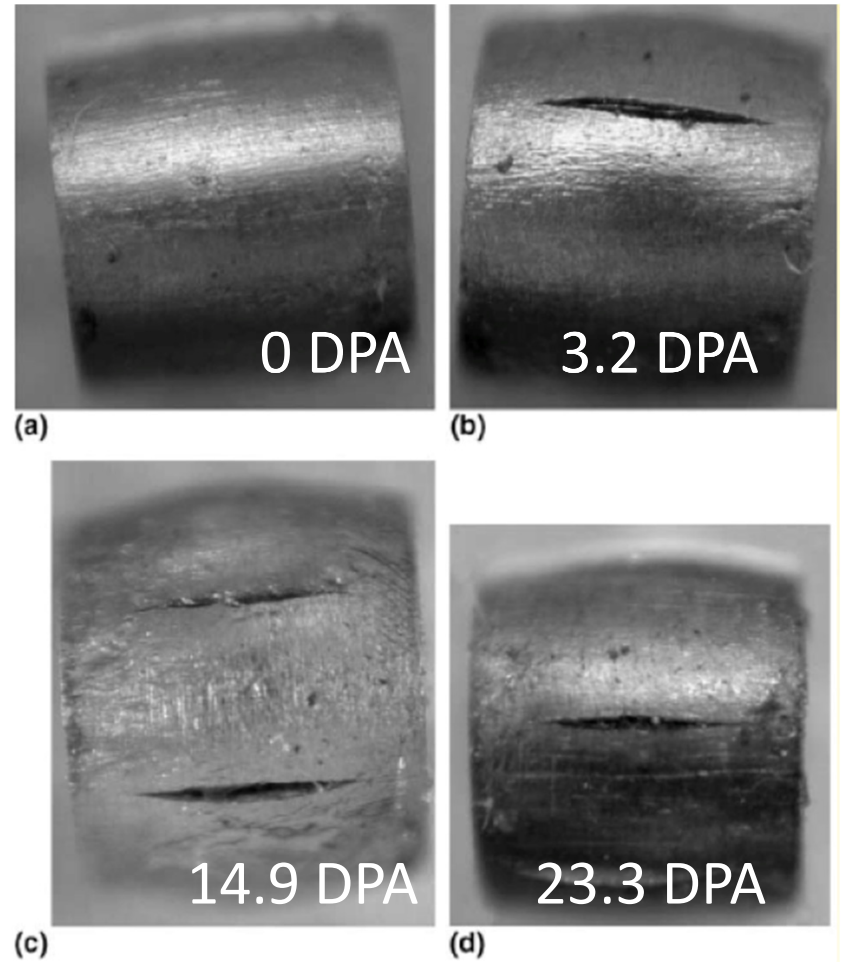




Slide prepared by V. Kuksenko (Oxford)

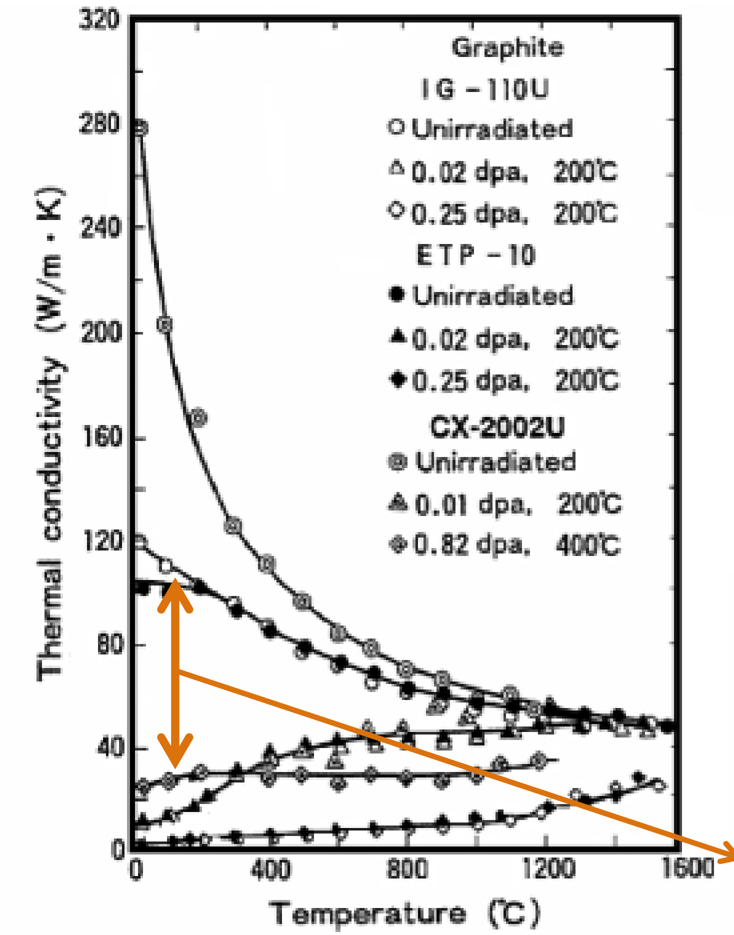
Radiation Damage Effects

- 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)



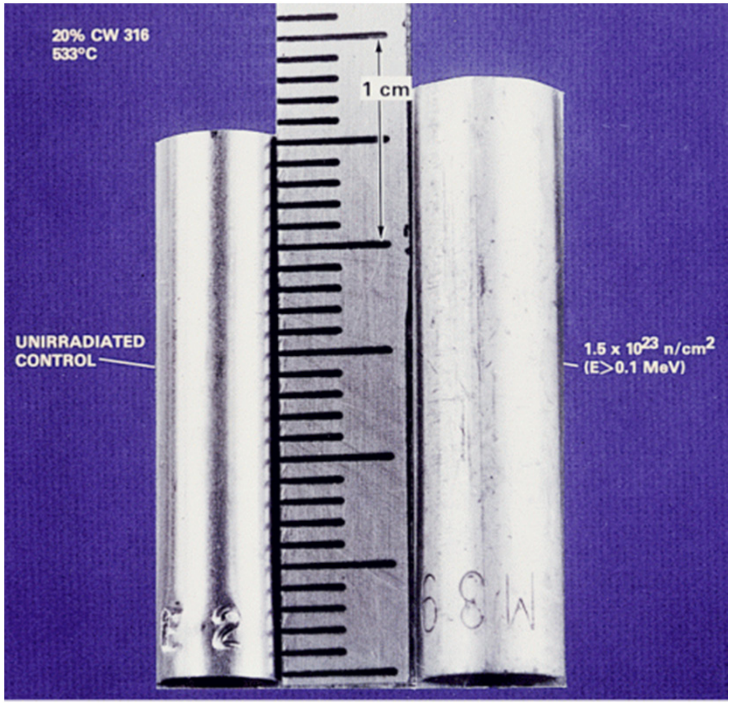
S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)

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)

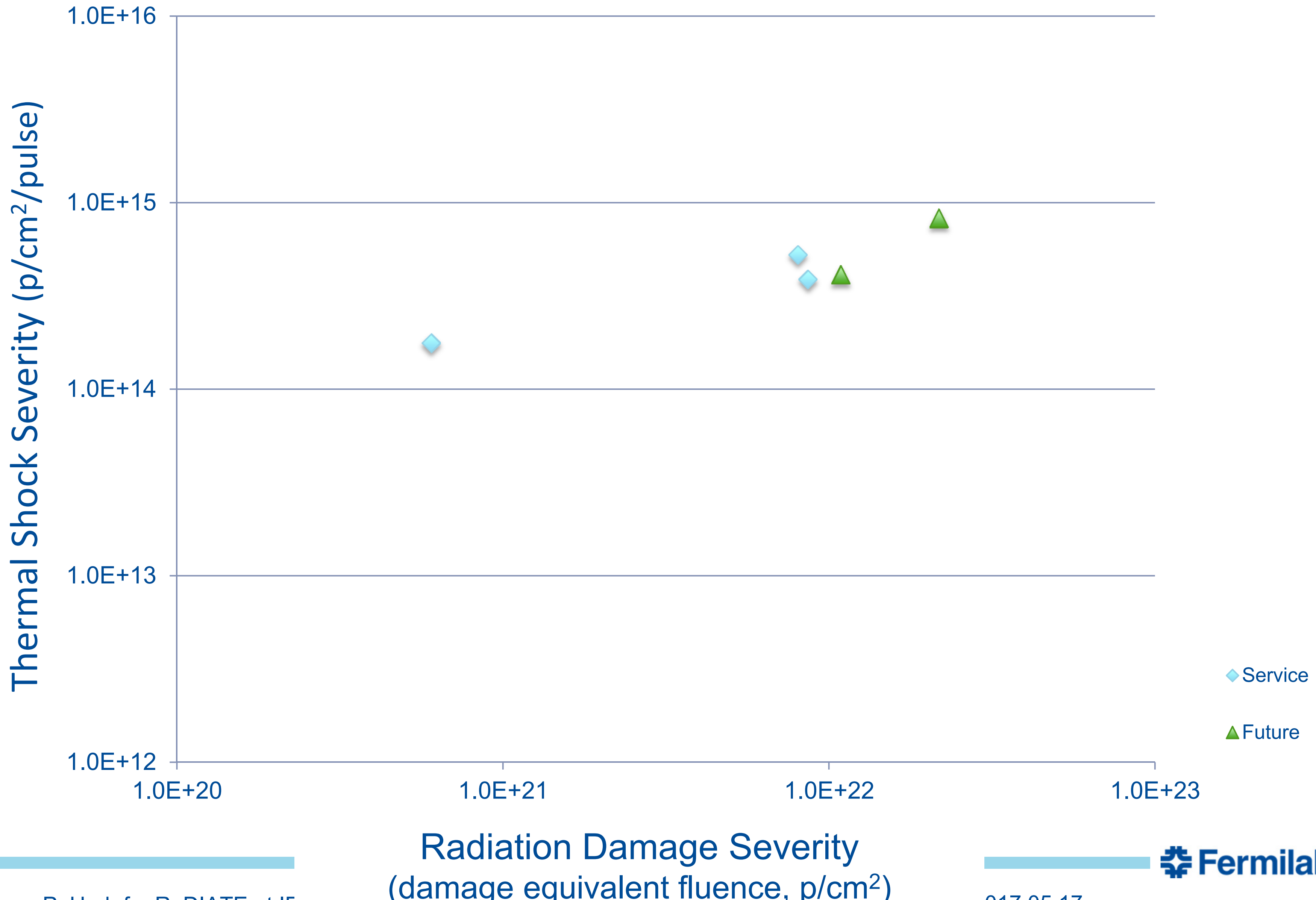
Factor of 10 reduction in conductivity at 0.02 DPA



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



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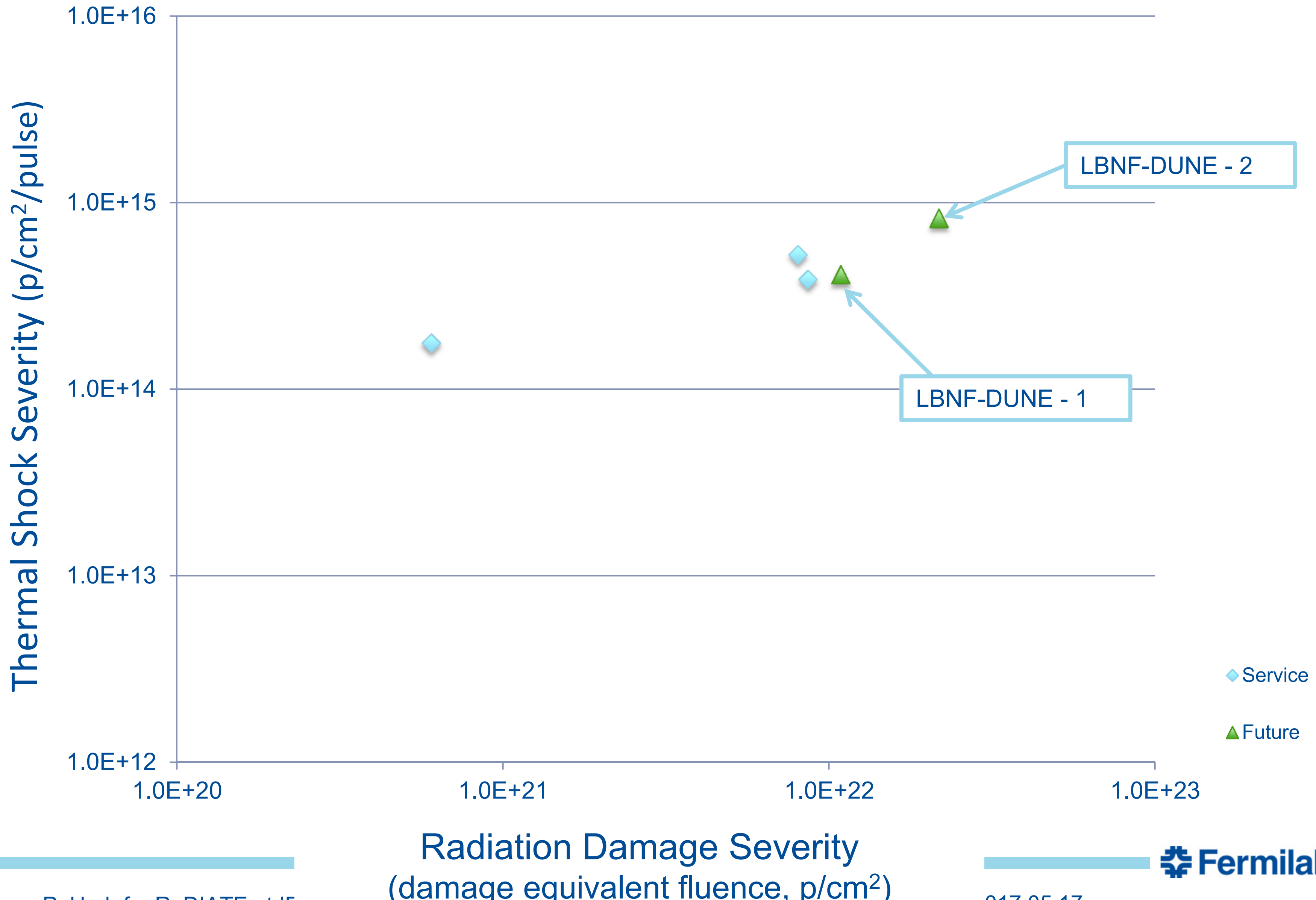

Fermilab

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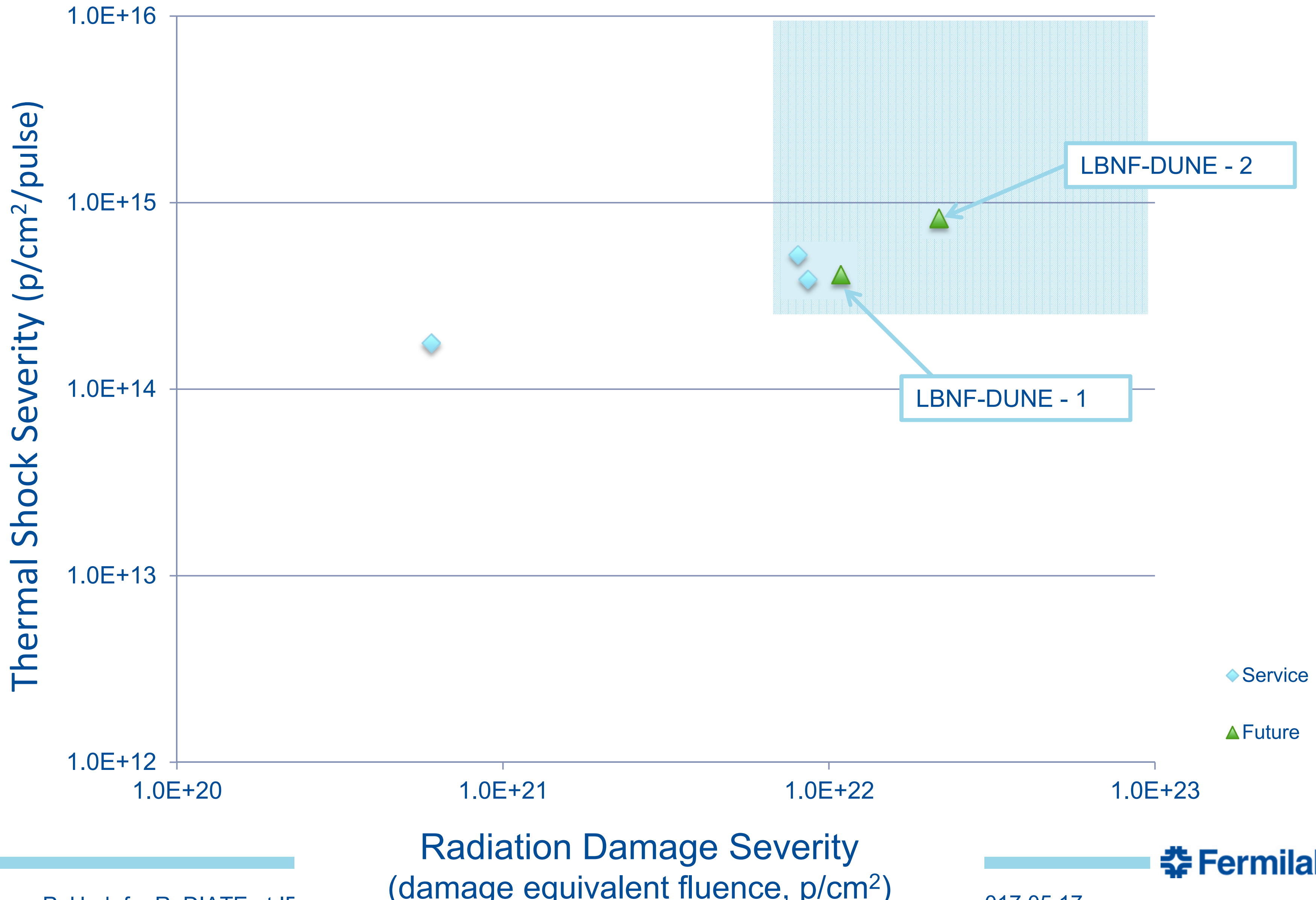

Fermilab

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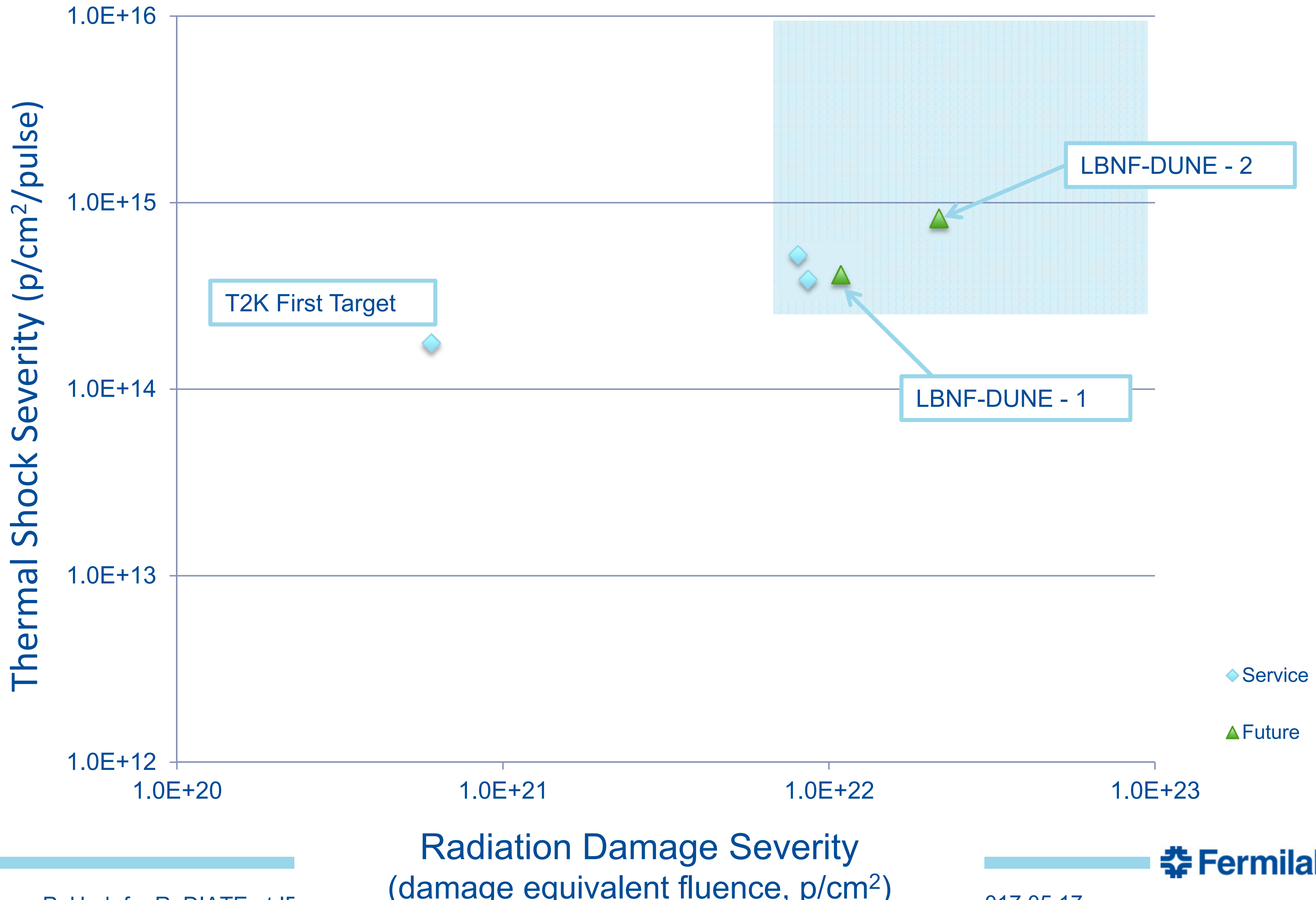

Fermilab

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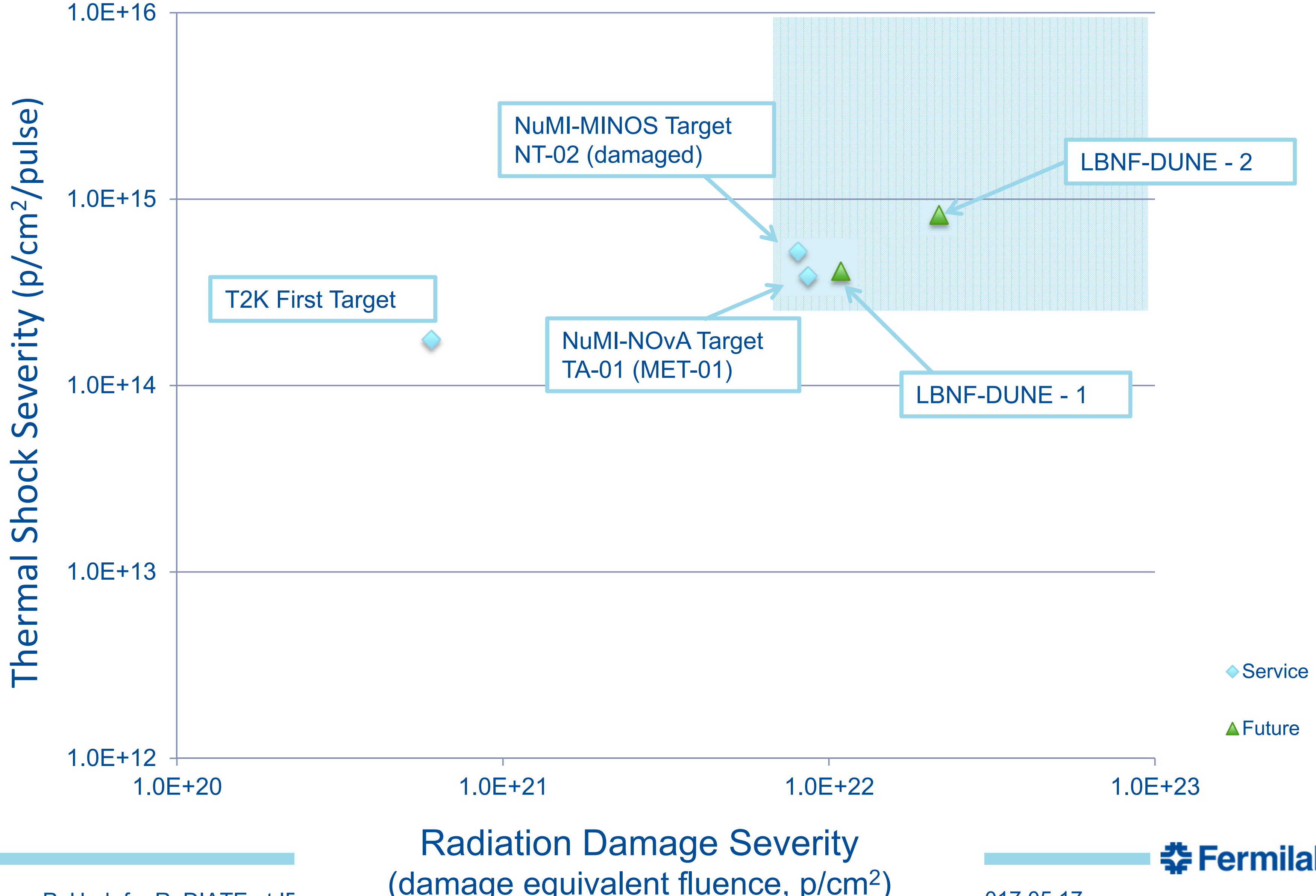

Fermilab

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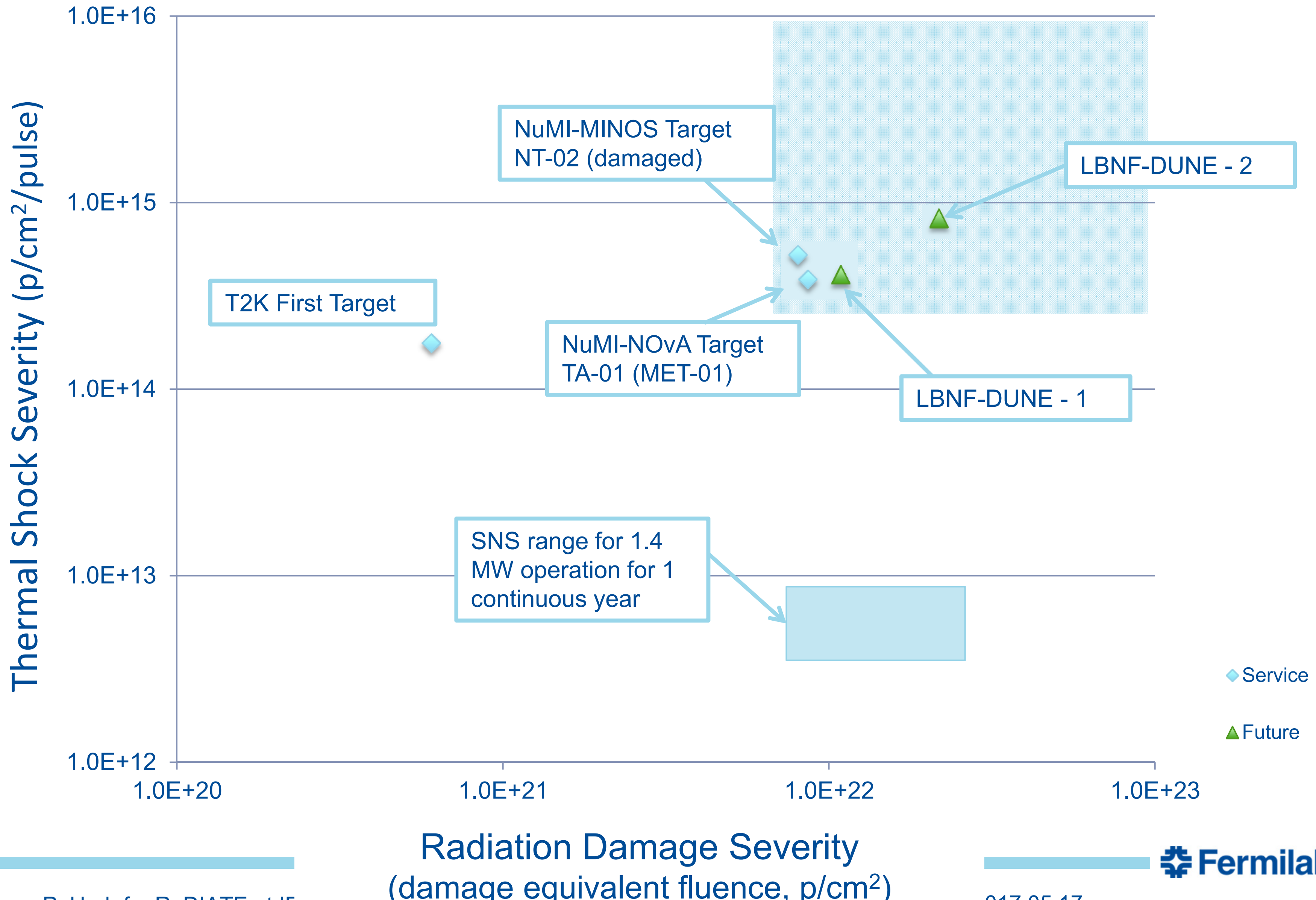

RaDIATE Collaboration

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**

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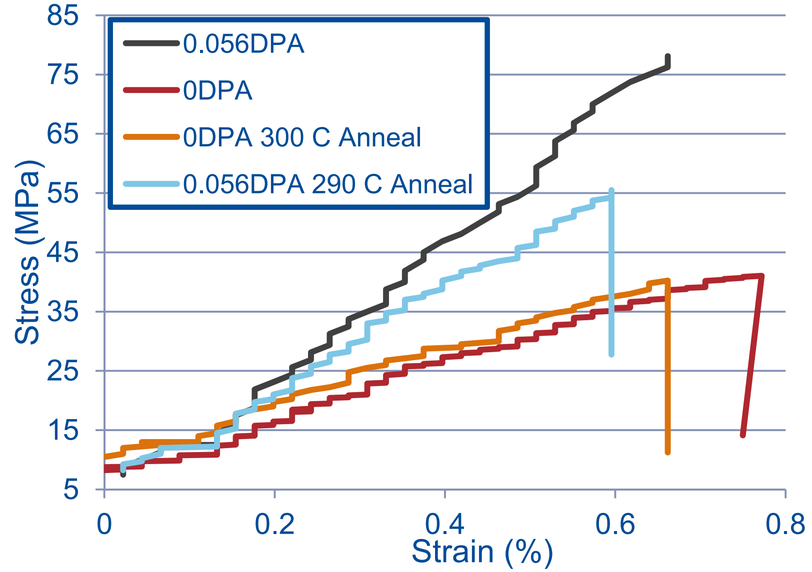
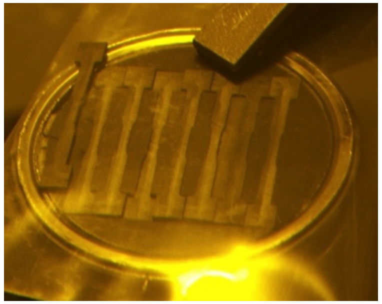
Currently adding CERN and J-PARC to the MOU

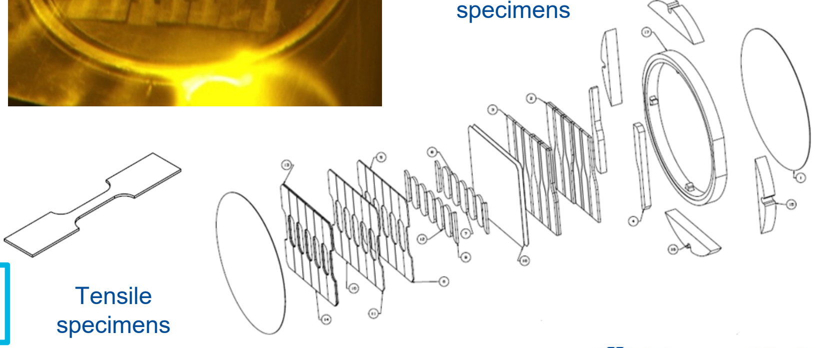
High Energy Proton Irradiations underway to explore candidate target/window materials

- 181 MeV p irradiation @ BNL's BLIP facility [2, 3]
  - 4 graphites & h-BN exposed to 6.7E20 p/cm^2
  - 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 [4]
  - 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

See Poster: K. Ammigan/P. Hurh WEPVA138



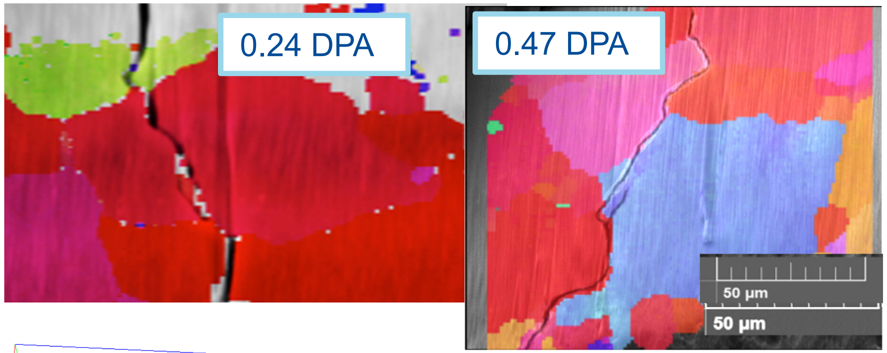


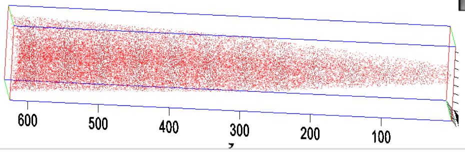


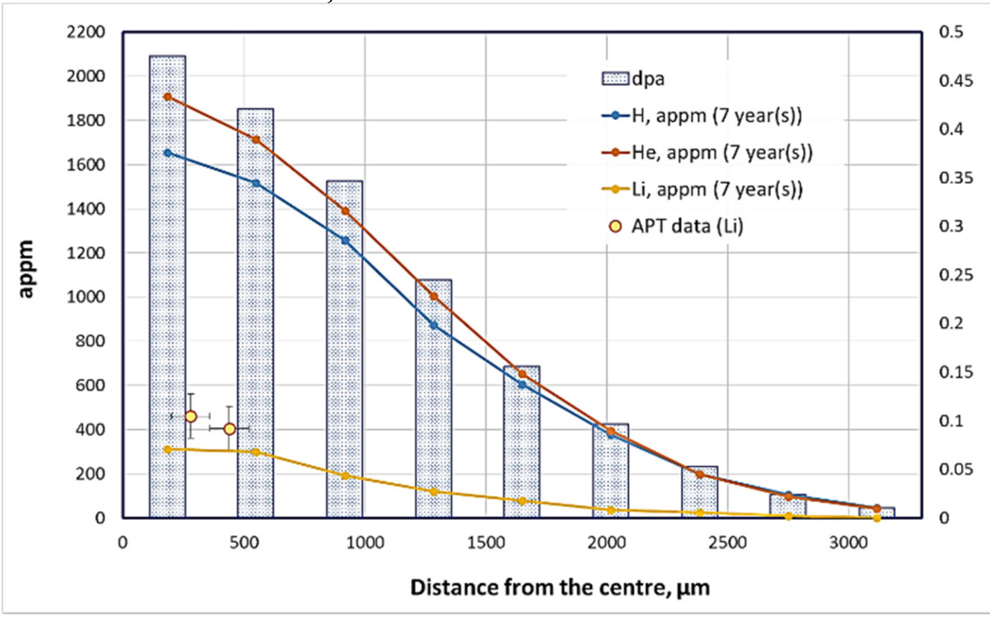
Fermilab

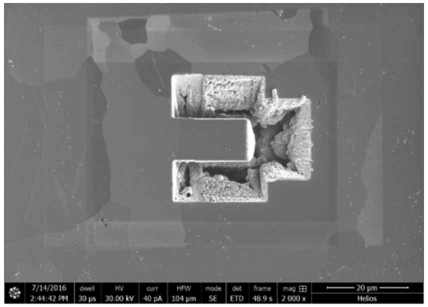
Examination of irradiated Beryllium beam window indicates fracture toughness changes under irradiation

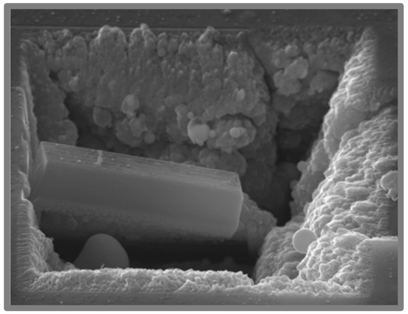
- NuMI Be window [5] (Kuksenko, Oxford)
  - Be window to 1.57E21 POT analyzed
  - Advanced microscopy techniques ongoing
  - Li matches MARS [6] predictions and remains homogeneously distributed at ~50 ˚C
  - Crack morphology changes at higher doses (transgranular to grain boundary fracture)
- Future Work with Be window (2017)
  - Micro-mechanics testing
    - Preliminary results indicate significant hardening and increase in effective elastic modulus
  - Annealing
    - He bubble coalescence and growth?
    - Recovery of properties?





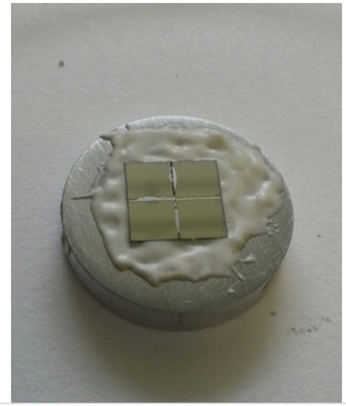


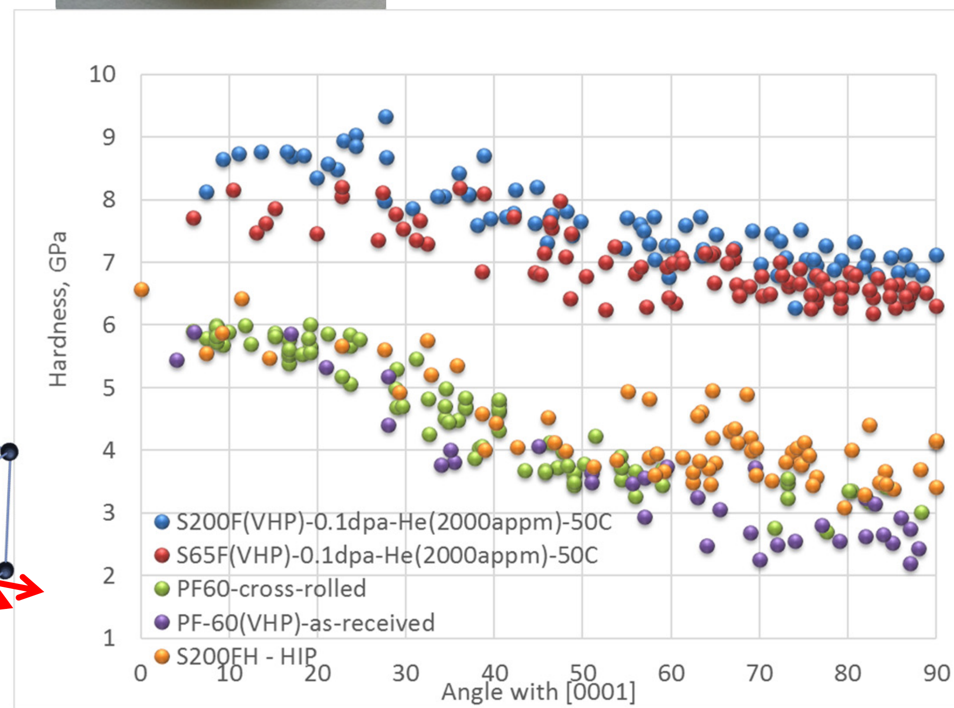


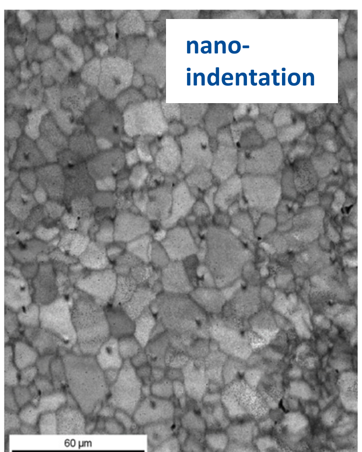


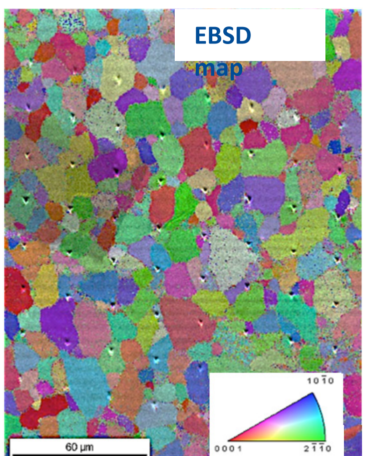
Ion implantation of Beryllium indicates significant hardening at low DPA

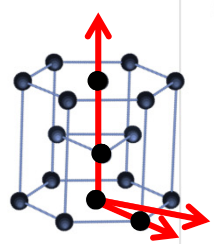
- He implantation study at Surrey/Oxford [7]
  - Ions: He+
  - Maximum beam energy: 2 MeV => 7.5µm implantation depth (SRIM)
  - Dose: up to 0.1 dpa currently
  - Temperature: 50ºC and 200ºC
  - Nano-indentation indicates significant hardening dominated by 2000 appm He production (DPA is lower order effect)
  - Work of V. Kuksenko (Oxford)
- Future Work with He in Be (2017)
  - Micro-cantilever testing
  - Higher dose and temperature irradiations





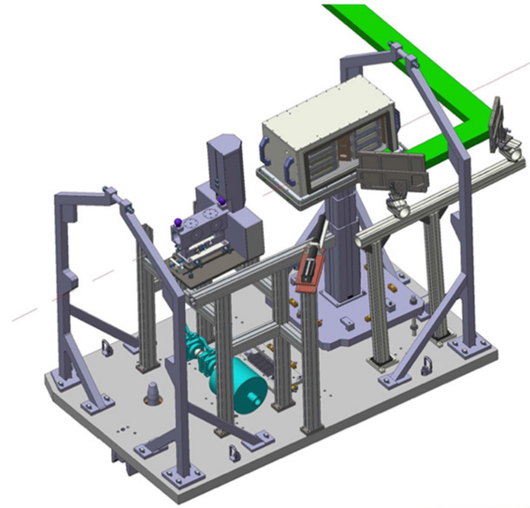


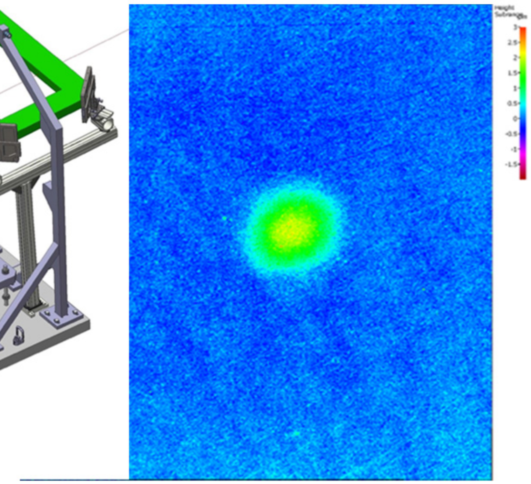


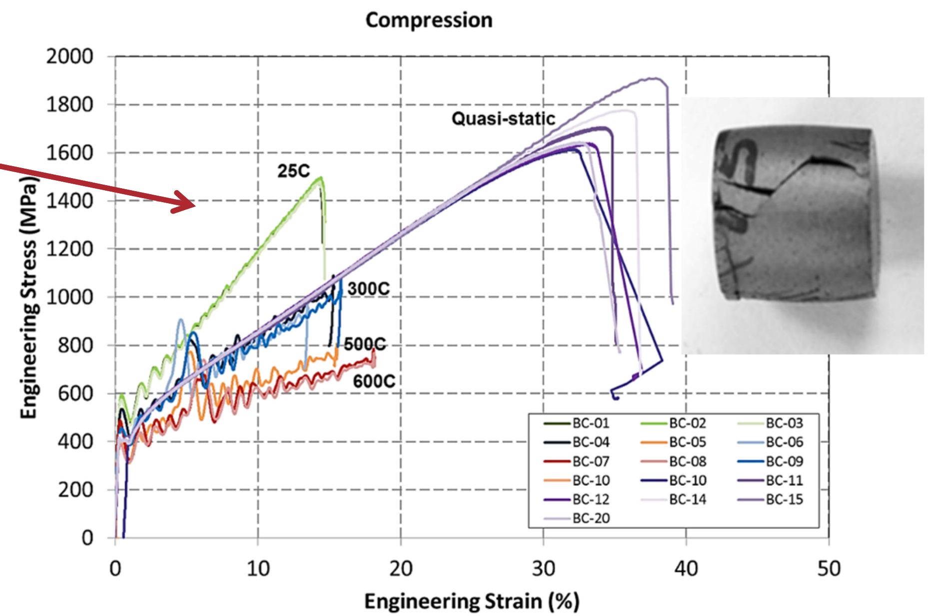


Dynamic thermo-mechanical simulations of Beryllium validated by in-beam thermal shock experiments

- In-beam thermal shock test of Be at CERN's HiRadMat [8, 9] (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
  - Testing of novel materials (nano-fiber mats)
  - Higher p beam intensities
  - Development of J-C damage model for Be

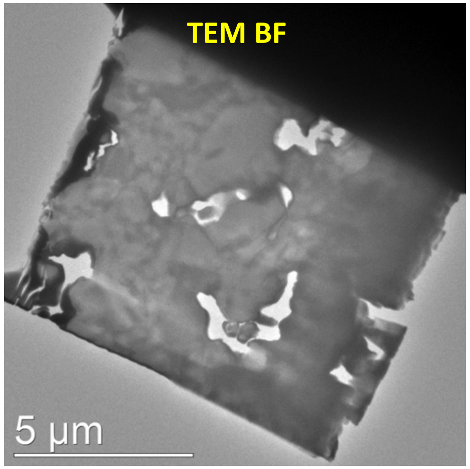


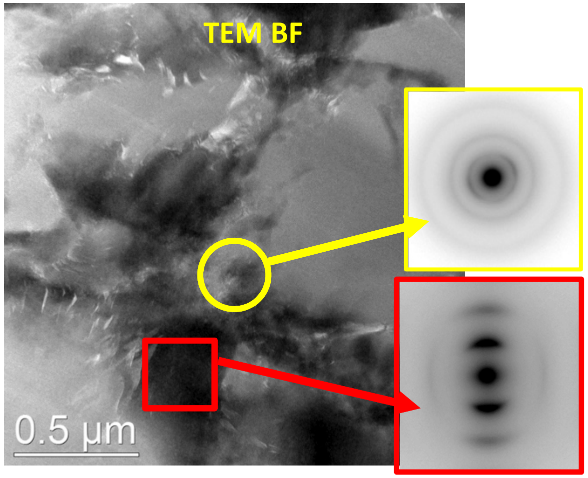




Radiation-induced swelling as possible cause of failure of NuMI NT-02 graphite target

- NuMI target (NT-02) autopsy and graphite PIE [10] (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



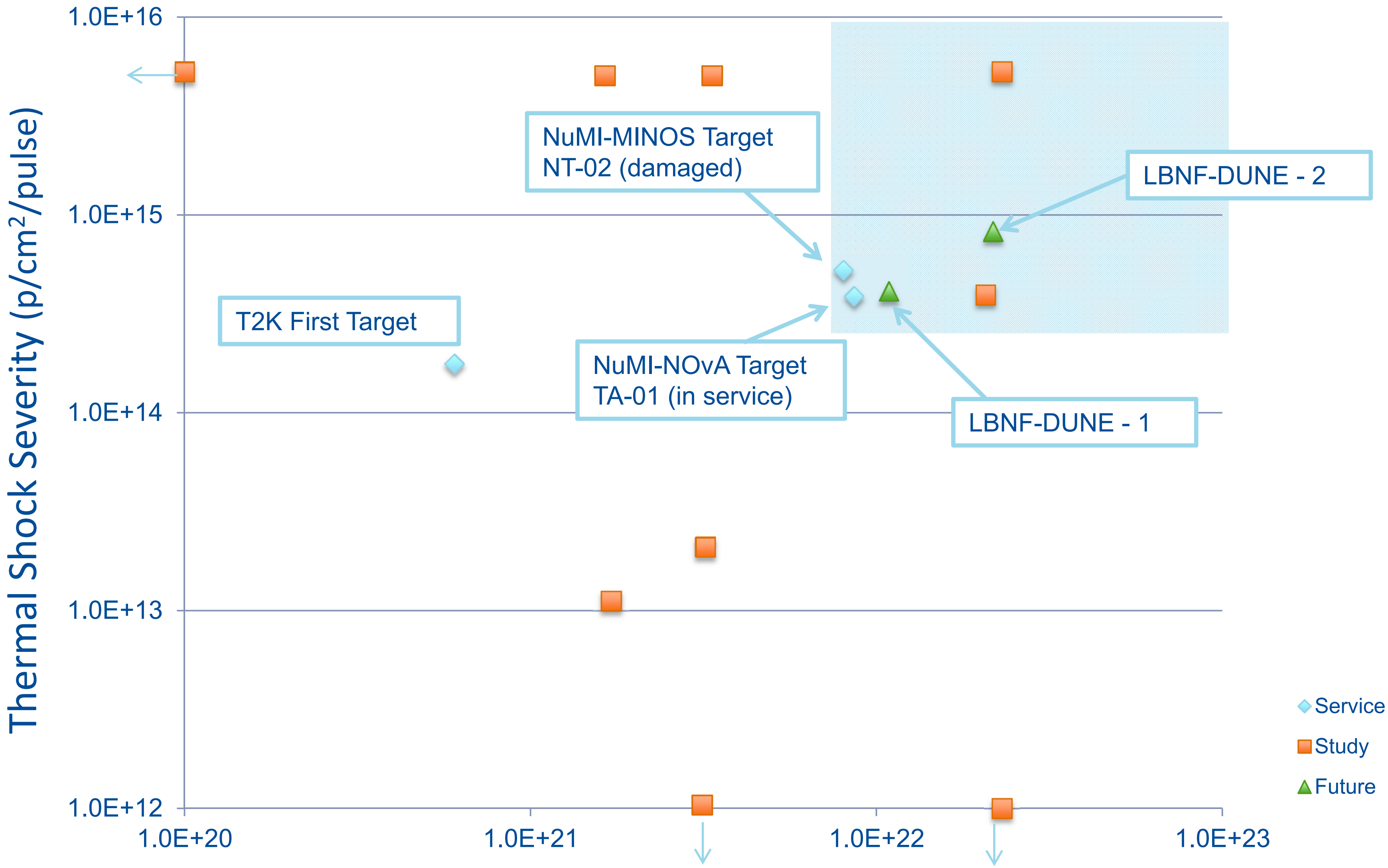


- Taken from fracture surface at the center where the beam was targeted
- Lamella has mixed regions of what appear to be amorphous (yellow insert diffraction pattern) and nanocrystalline microstructure (red square)
- Mrozowski cracks at the interfaces between these two regions

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**

Nu HPT R&D Materials Exploratory Map



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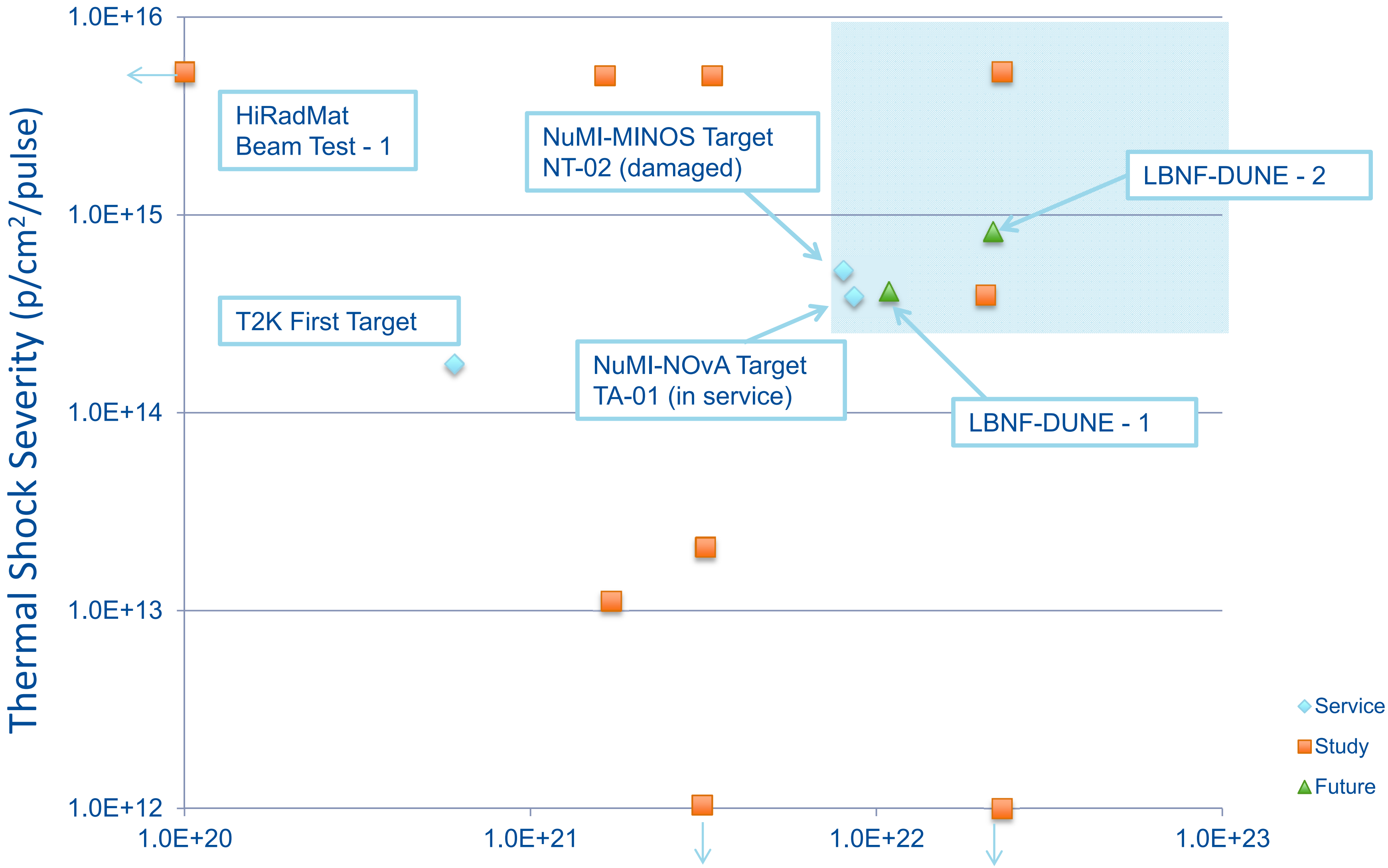

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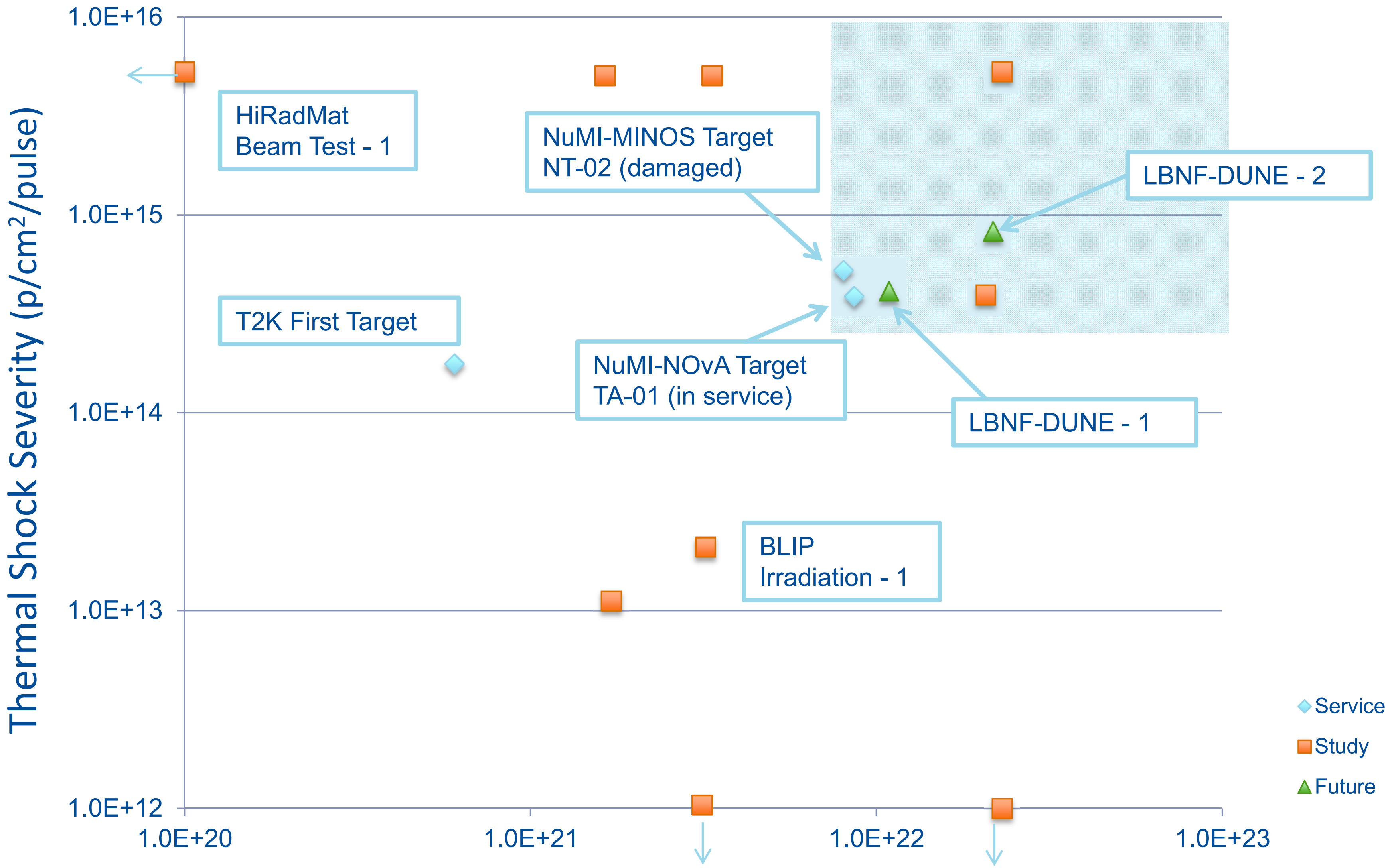
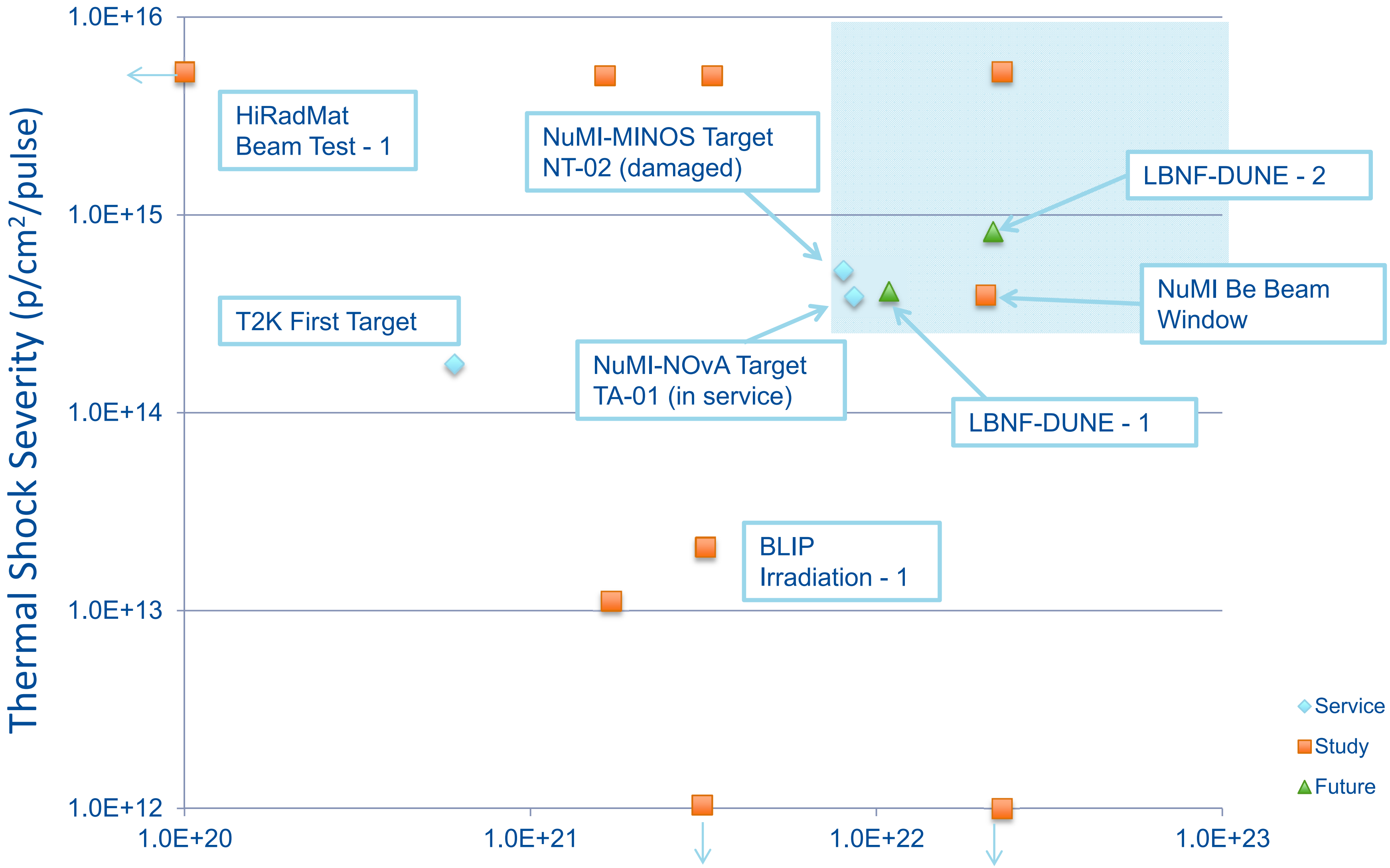
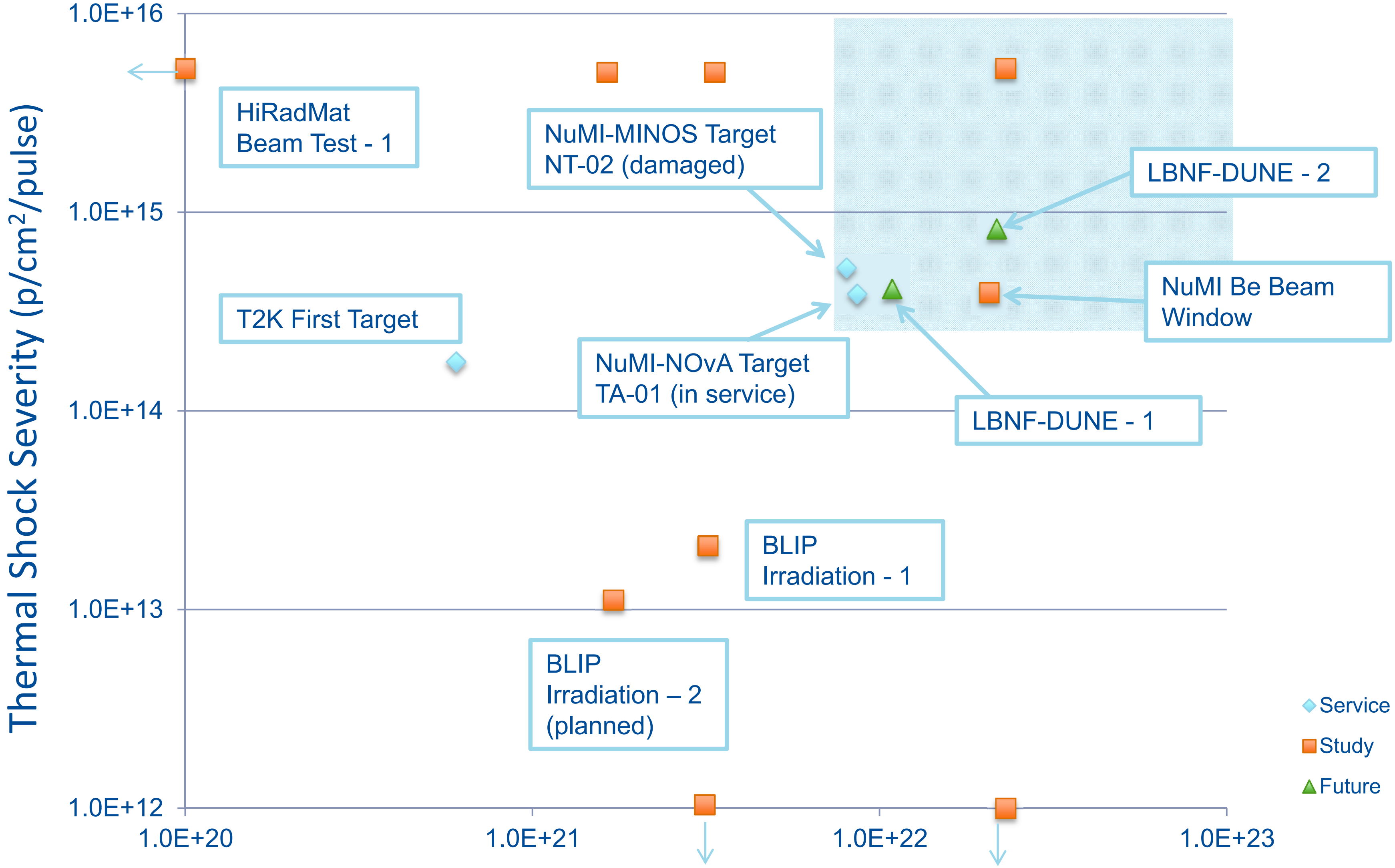


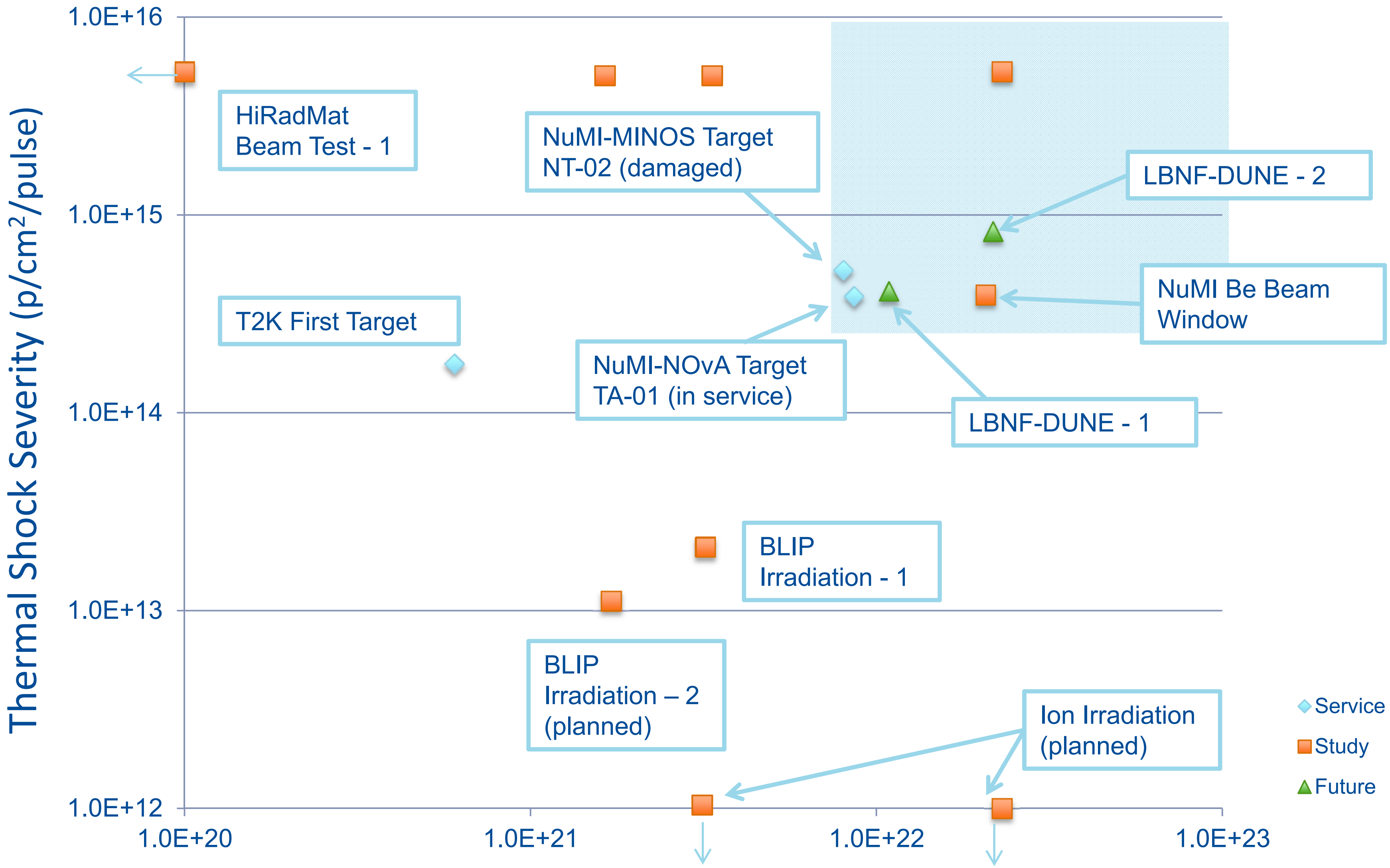
Nu HPT R&D Materials Exploratory Map



Nu HPT R&D Materials Exploratory Map



Nu HPT R&D Materials Exploratory Map



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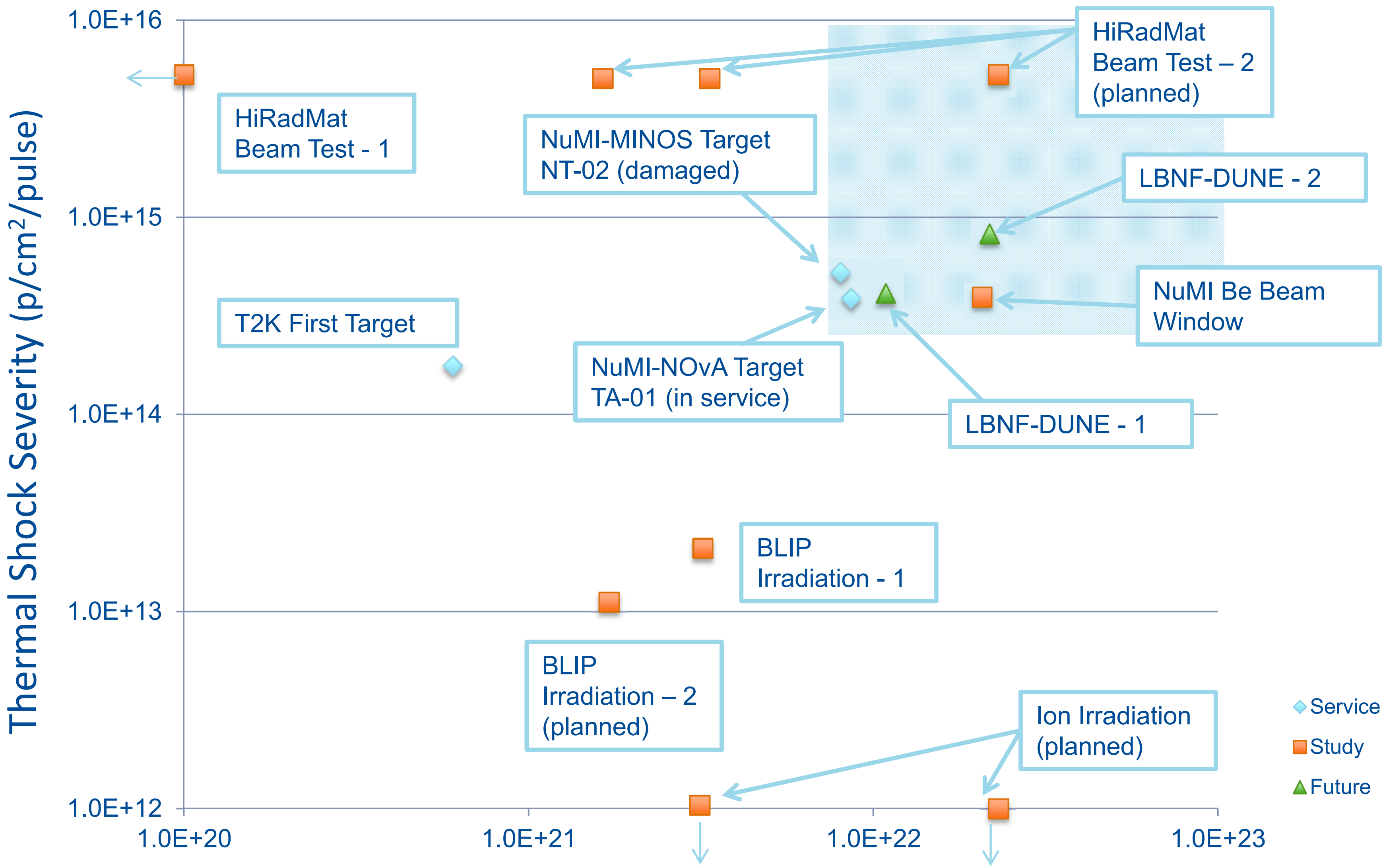

Fermilab

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

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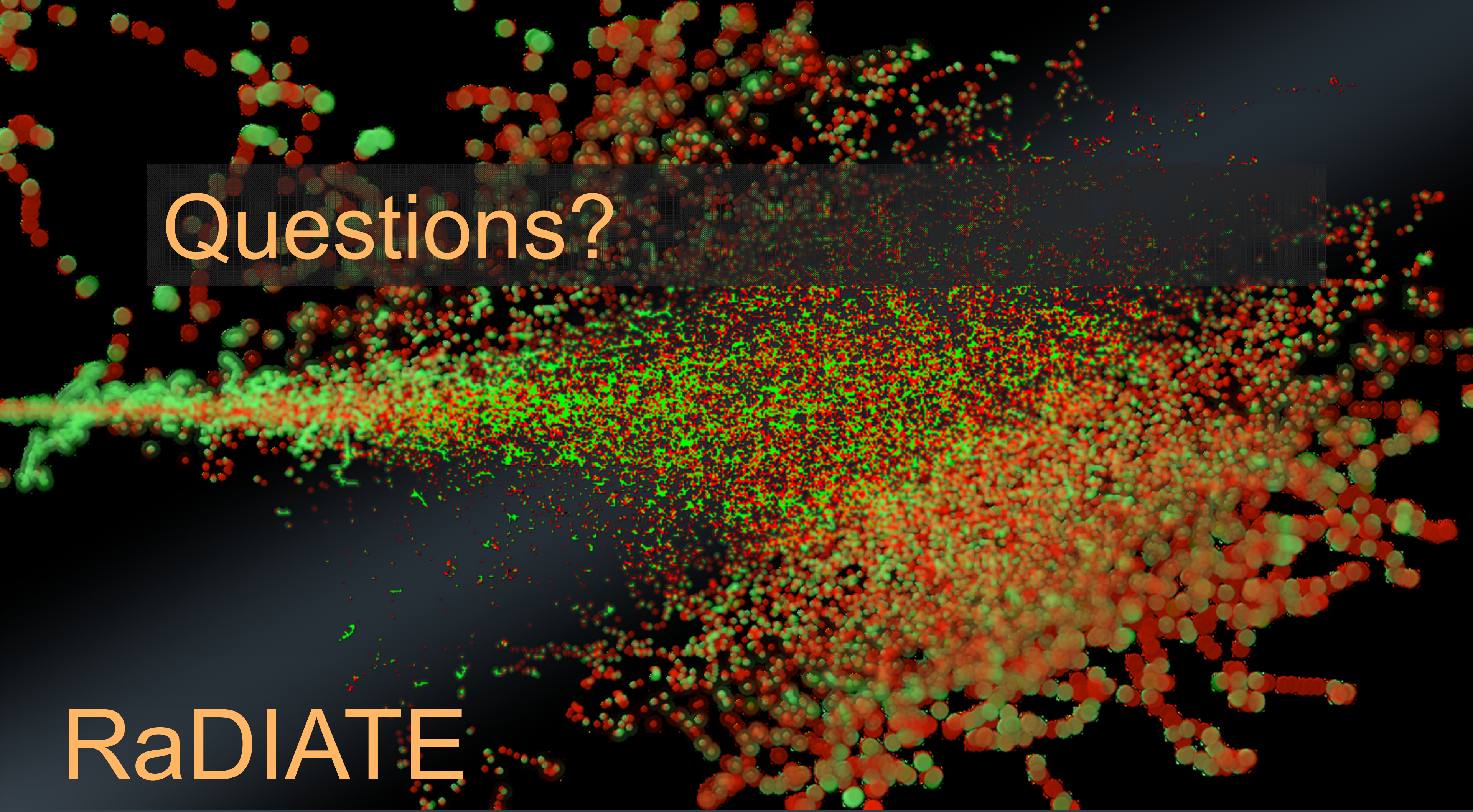
Questions?



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