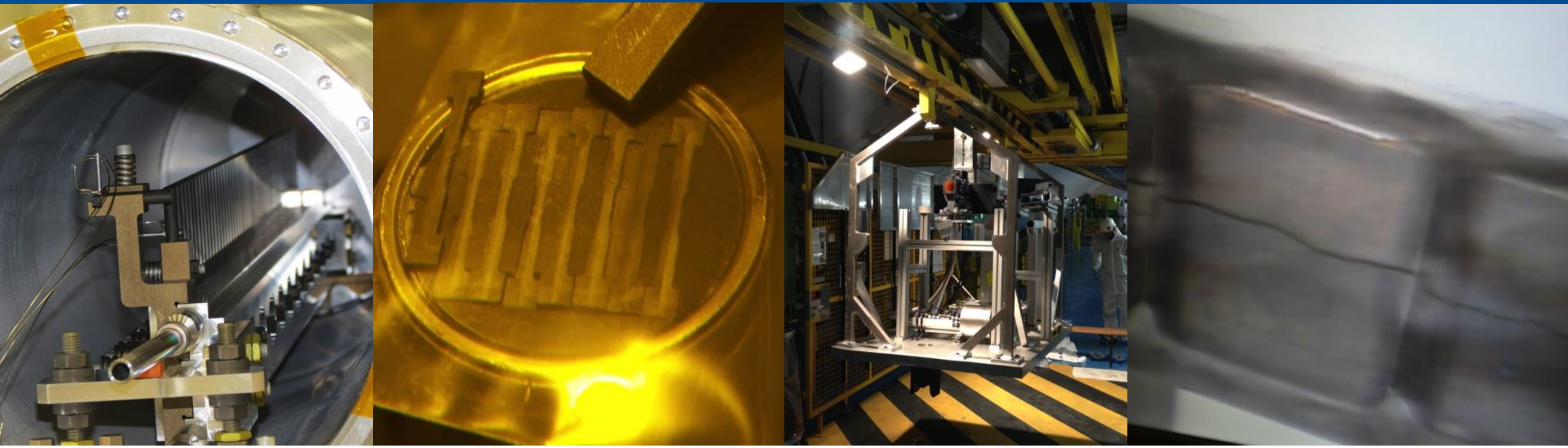
Fermilab
U.S. DEPARTMENT OF ENERGY
Office of Science



Challenges of Neutrino Targets and the Role of the HiRadMat Facility

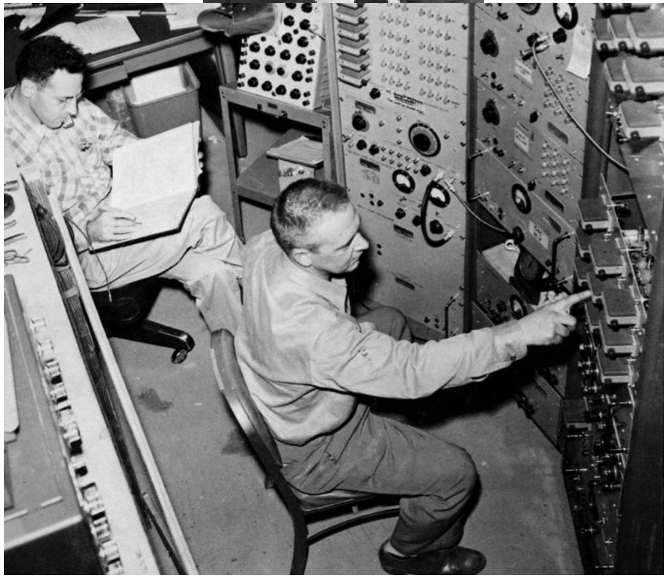
Patrick Hurh

International HiRadMat Workshop 2019 (CERN)
11 July 2019

hurh@fnal.gov

The Nobel of Neutrinos

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

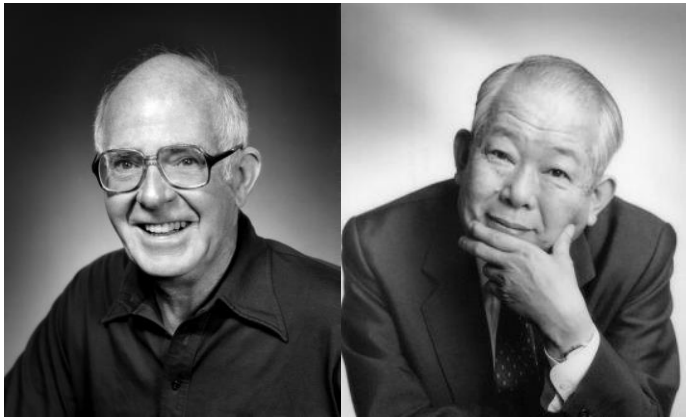


- Detected electron neutrino by Cowan & Reines in 1956 (Nobel 1995)

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

The Nobel of Neutrinos

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



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

GETTY/REUTERS

- What is left in store?

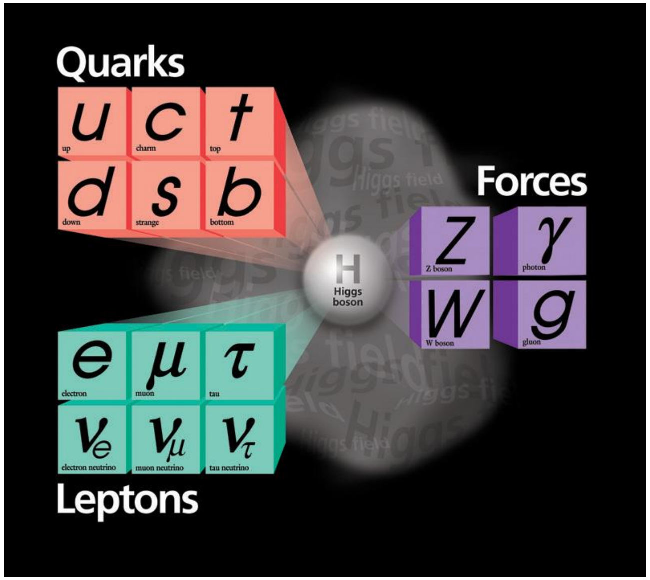
Neutrinos are fundamental (-ly weird)

Neutrinos come in 3 flavors:

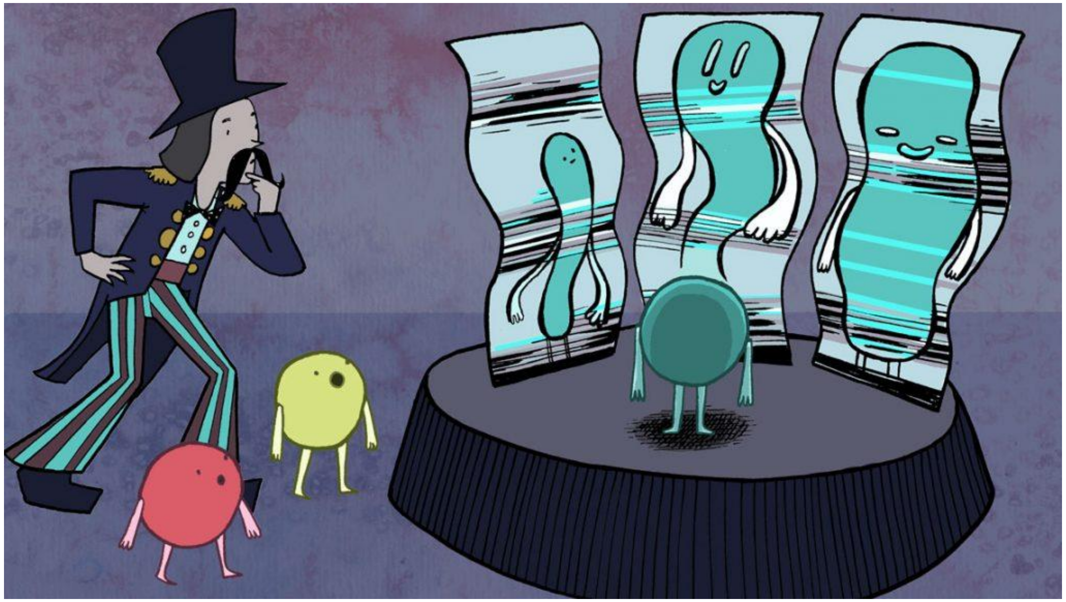
- electron
- muon
- tau

And in 3 masses (v1, v2, v3)

But the masses do not correlate with specific flavors

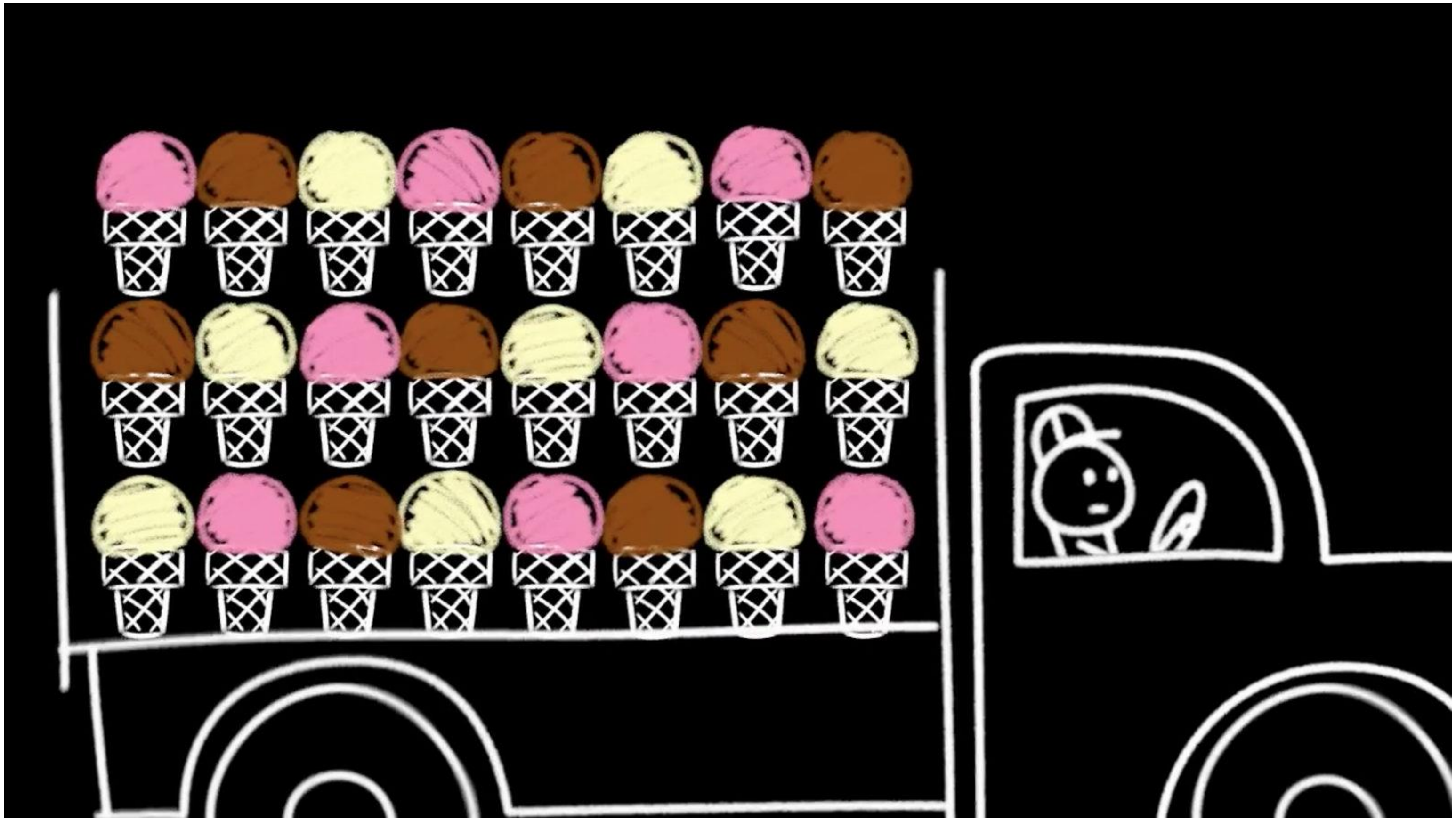


A neutrino of a particular flavor is made of a combination of masses (1, 2, and 3), and a neutrino of a certain mass (such as the lightest neutrino) has a certain probability of interacting in a detector to make a certain flavored charged particle (electron, muon, or tau).



Credit: Symmetry Magazine/Sandbox Studio, Chicago

If you don’t like the flavor of your neutrino, just wait

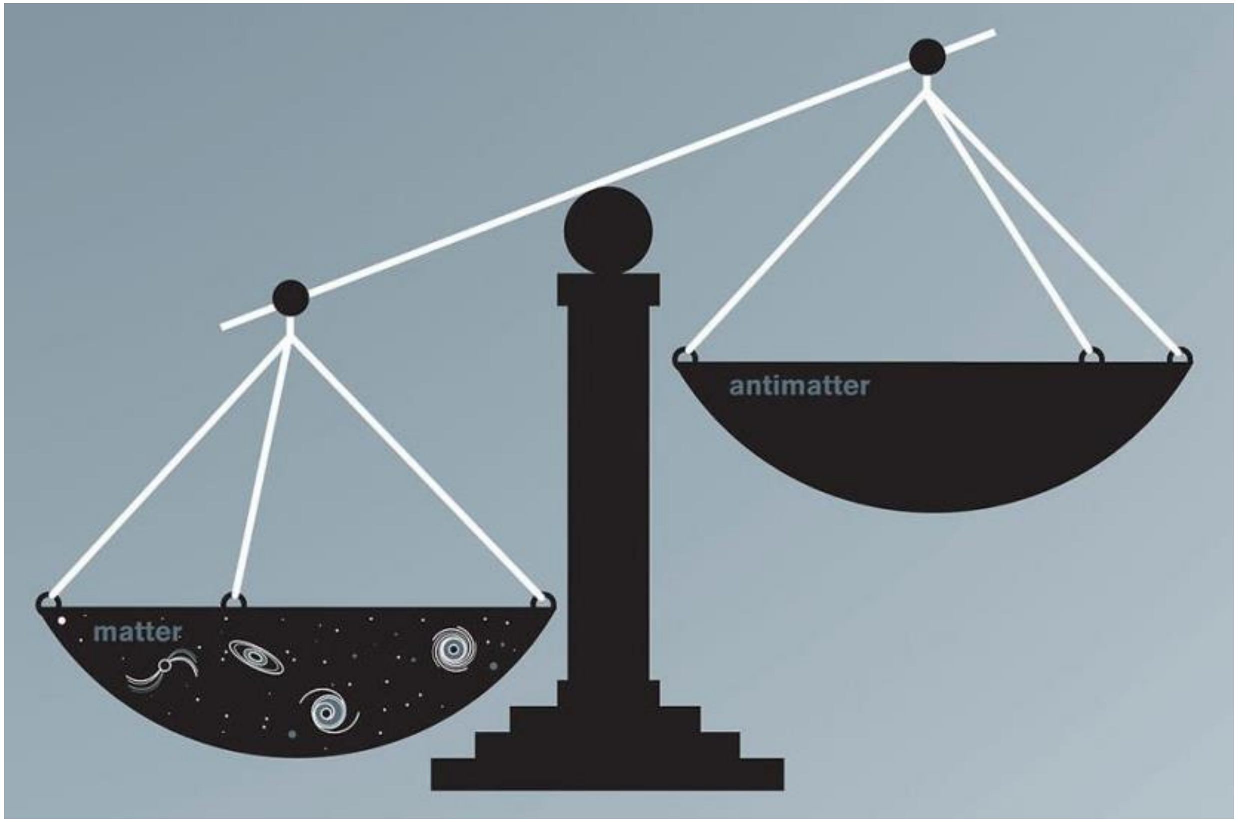


As a neutrino travels through space-time, the mass ratio changes (oscillates) meaning that the probability that it interacts as a certain flavor changes. Which you don’t know until you try to measure it!

Illustration by Fermilab

Are Neutrinos the Reason Matter Exists?

https://neutrinos.fnal.gov/



Are there any right-handed neutrinos?

Charge-parity violation?

One of the biggest mysteries in neutrino research is whether neutrinos and their antimatter twins, antineutrinos, behave the same way. This turns out to be a very important question—if the answer is no, it could explain how our universe full of matter came to exist.

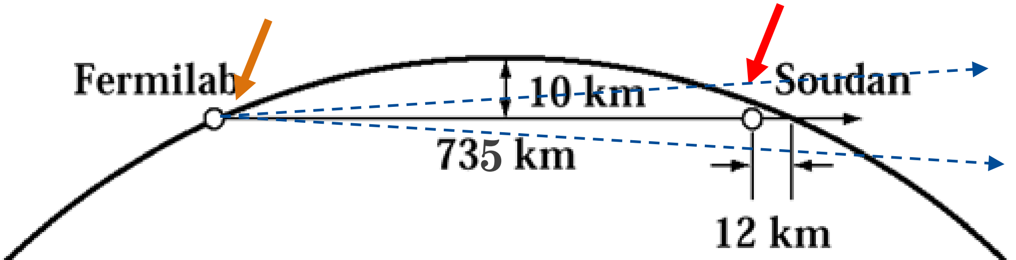
Credit: Symmetry Magazine/Sandbox Studio, Chicago

Fermilab Accelerator Complex

The NuMI Facility

“Neutrinos (v – 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
  - Upgrade to 900+ kW in 2020
- Each pulse produces about 10^{14} v_{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

Defining Characteristics of Long Baseline Beams

- Proton Beams: synchrotron based, nearing 1 MW currently
  - 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
  - Pulsed beam with pulse length of ~4 – 10 µsec
- Pion Focusing: Pulsed horns
  - Horns more efficient than quadrupole magnets
  - High currents: few hundred kA
- Large Decay volume
  - Meters in cross-section and 100s of meters in length
- Beam radiation dispersed over extended area

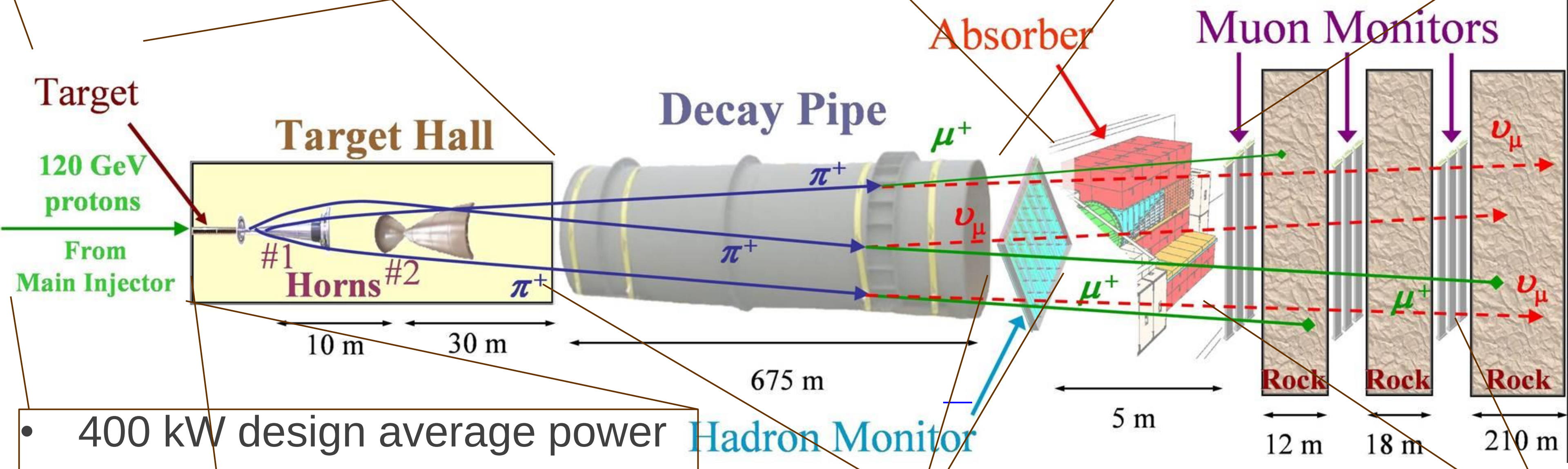
  Tritium, activation, corrosion, cooling

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



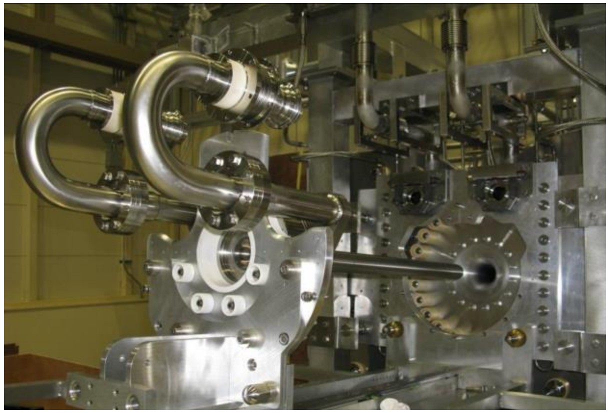
- 400 kW design average power
- 700 kW upgrade for NOvA
- 1 MW capable by 2020
- $\sigma \sim 1$ mm

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

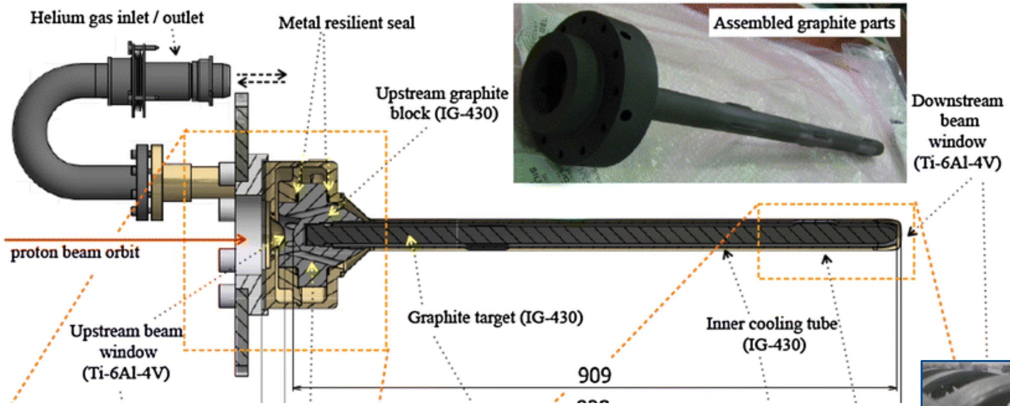
- Measure hadron & muon fluxes
- Arrays measure distributions

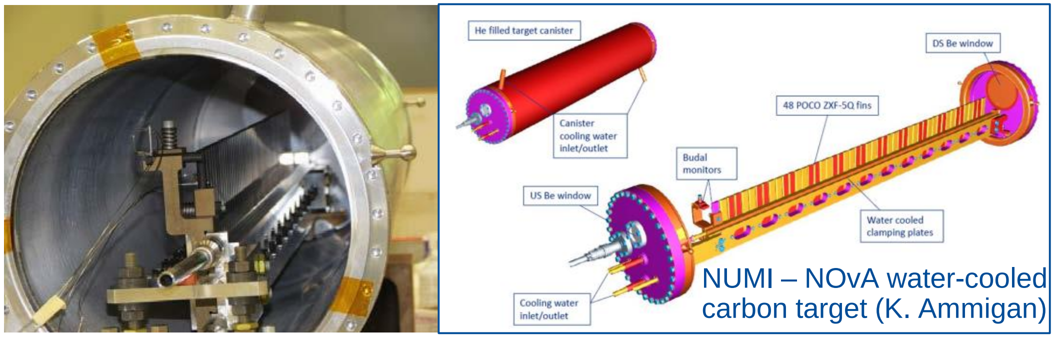
Neutrino Targets Around the World

NuMI - MINOS water-cooled carbon target (J. Hylen)



T2K helium-cooled carbon target (C. Densham)

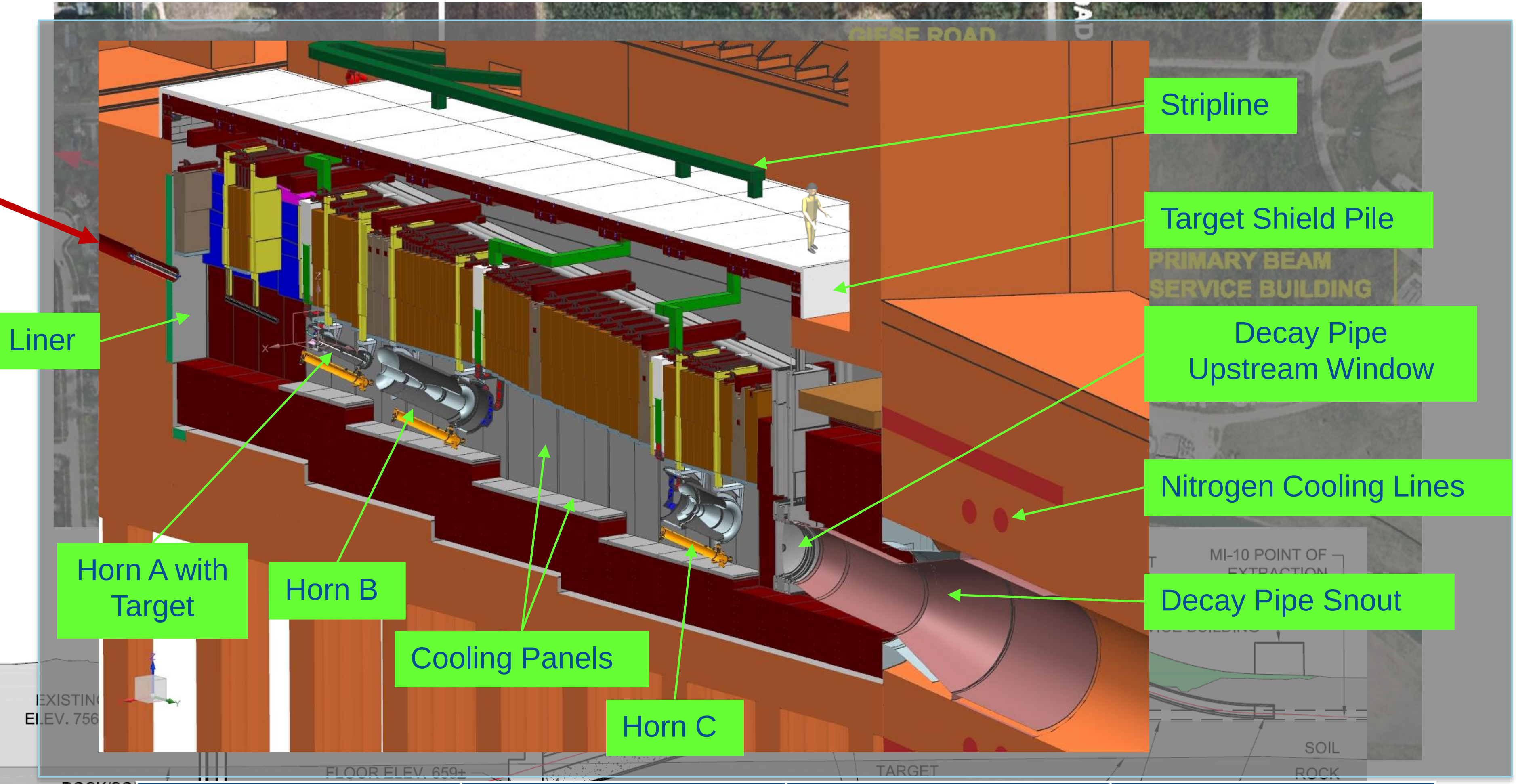




NUMI – NOvA water-cooled carbon target (K. Ammigan)

CNGS radiatively-cooled carbon targets (CERN)

DUNE: Deep Underground Neutrino Experiment
LBNF: Long-Baseline Neutrino Facility (1.2 MW -> 2.4 MW!)



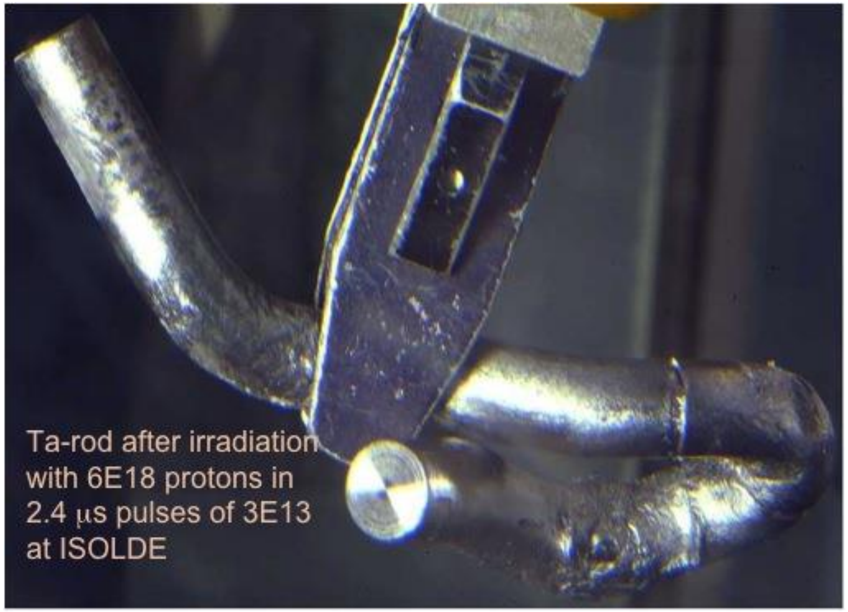
Proton Beam Energy (GeV)	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
120	7.5 x 10^{13}	1.2	1.20
120	1.5 x 10^{14}	1.2	2.40

High Power/Intensity Targetry Challenges

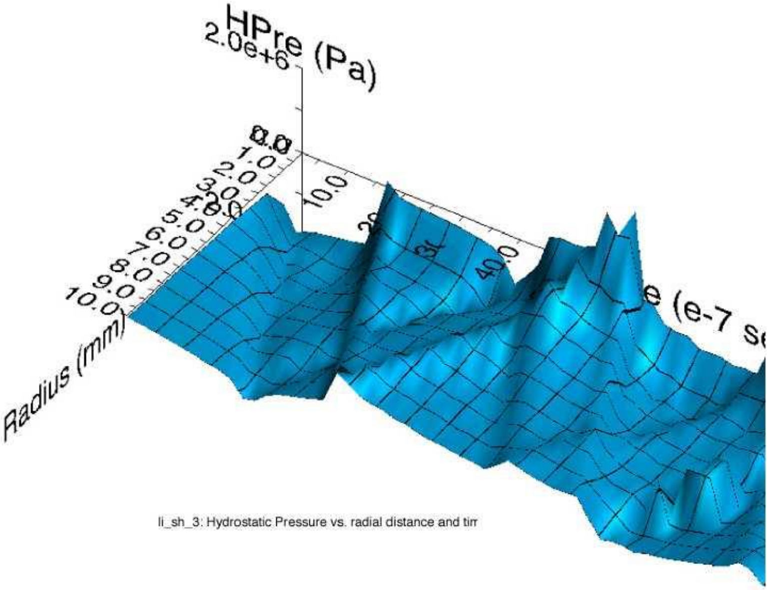
- Material Behavior
  - **Thermal "shock" response**
  - **Radiation damage**
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection
  - Remote handling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

HiRadMat relevant

Thermal Shock (stress waves)



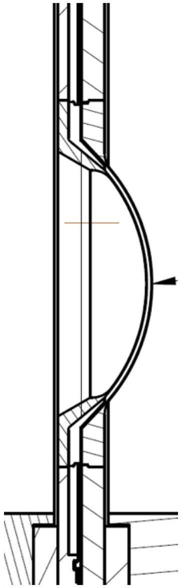
Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)

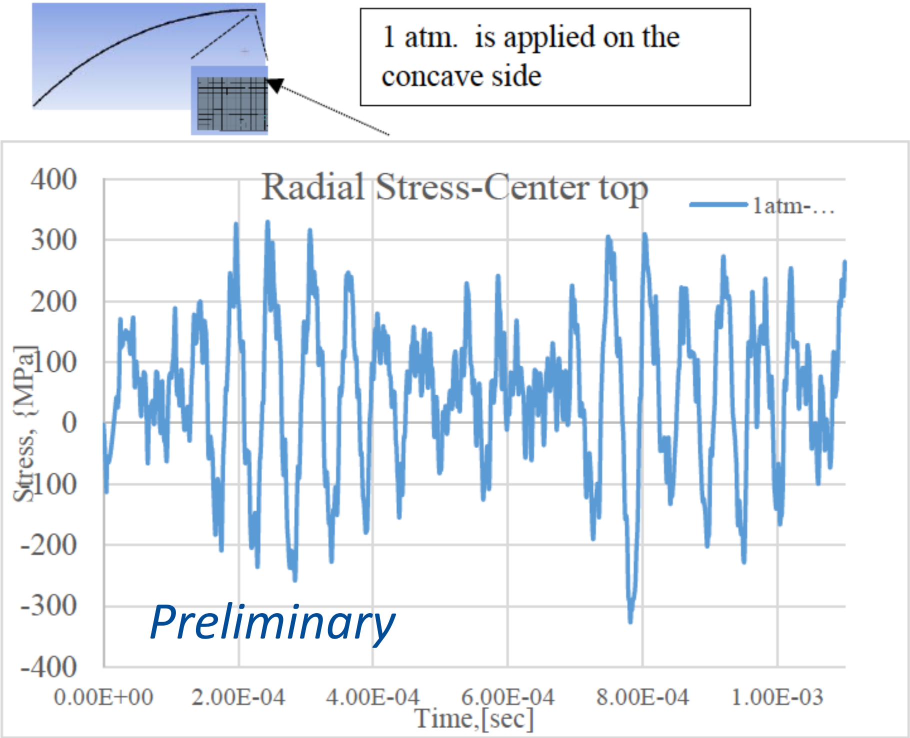


Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

- 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





1 atm. is applied on the concave side

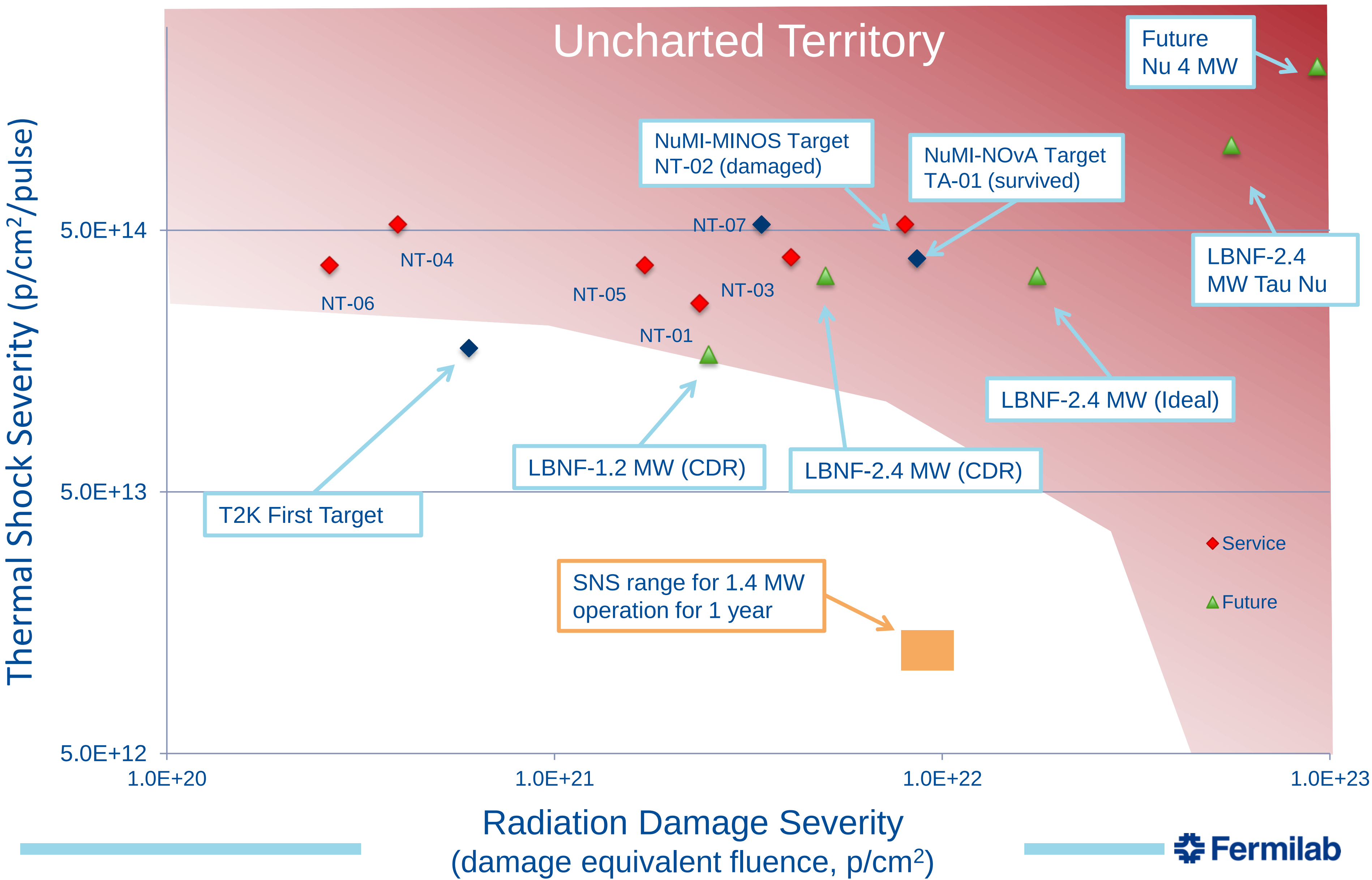
Preliminary

S. Bidhar, FNAL

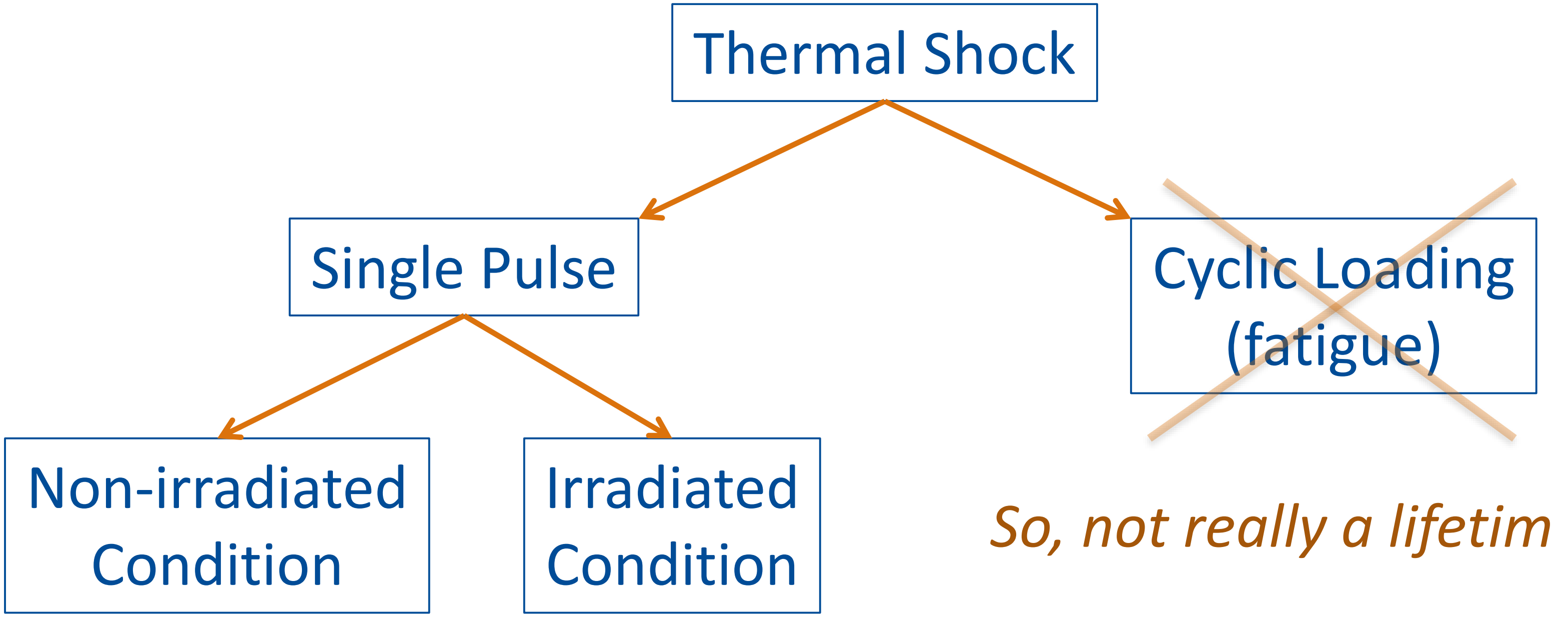
- Material response dependent upon:
  - Specific heat (temperature jump)
  - Coefficient of thermal expansion (induced strain)
  - Modulus of elasticity (associated stress)
  - Flow stress behavior (plastic deformation)
  - Strength limits (yield, fatigue, fracture toughness)

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

Nu HPT R&D Materials Exploratory Map



Role of HiRadMat to Explore Thermal Shock in Nu Targets



Thermal Shock

Single Pulse

~~Cyclic Loading (fatigue)~~

Non-irradiated Condition

Irradiated Condition

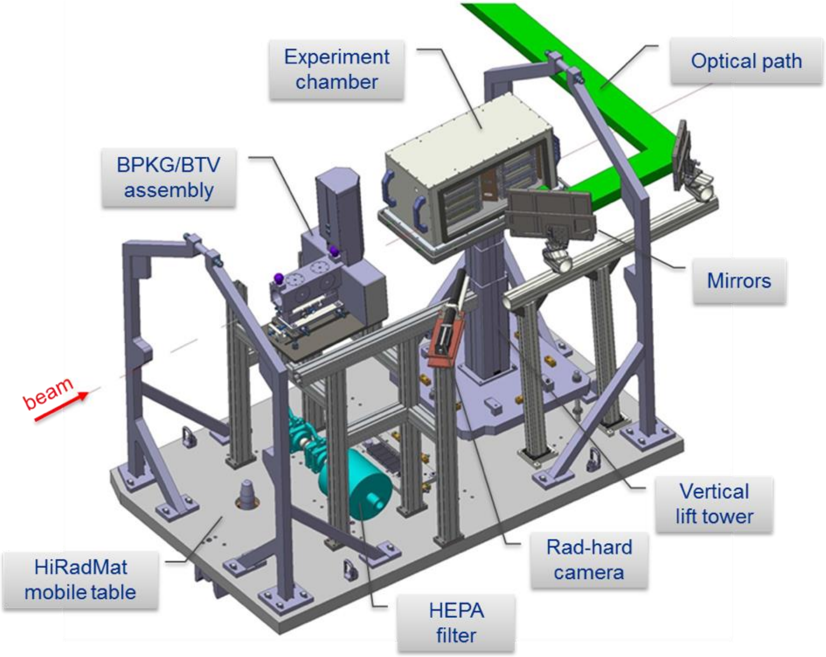
So, not really a lifetime test

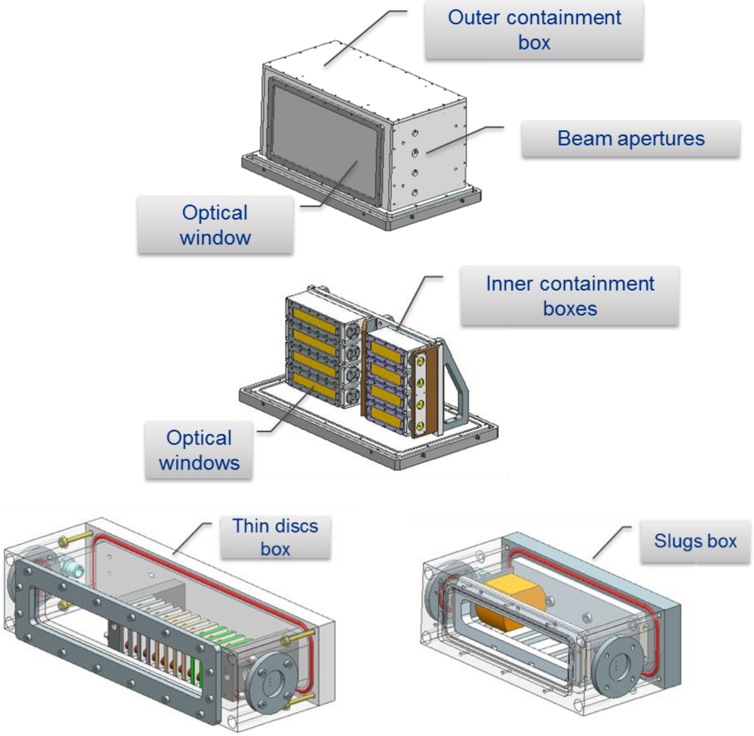
Objectives –

- Material limits in different conditions
- Validate Material Models & Analyses
- Explore Thermal Shock Resistance of Novel Materials (e.g. nano-fibers, expanded graphite)
- Evaluate fracture/deformation mechanisms to develop more thermal shock tolerant materials
- Explore Novel Target Concepts (e.g. powder targets)
- Test prototypes for accident conditions

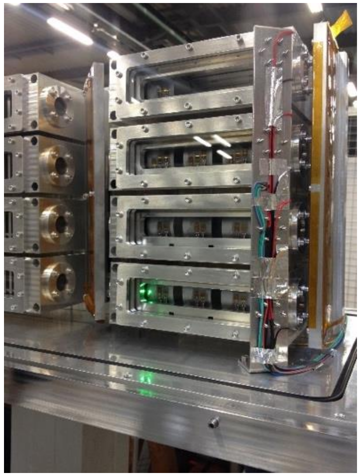
BeGrid1 (HRMT24) – experimental set-up

- Experiment successfully completed in September 2015
- Consisted of four specimen arrays of thin Beryllium discs and slugs
  - Various commercial grades (S200F, S200FH, PF60, S65F) and thicknesses
  - Real time measurements of temperature, strain and displacement
  - PIE of thin disc specimen at the University of Oxford (2016-2017)





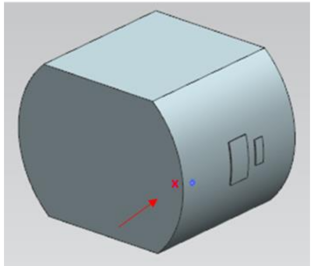
BeGrid1 (HRMT24) – online results



Real-time thermomechanical measurements

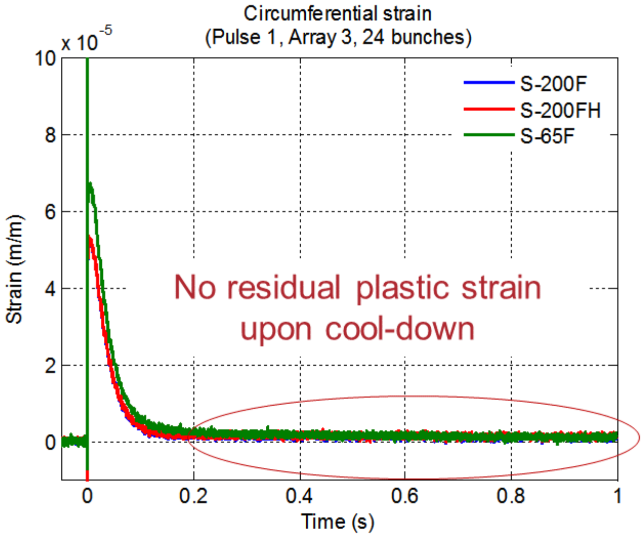
- Instrumented Be slugs in downstream containment boxes
- LDV for radial displacement measurements
- Strain and temperature gages

Ø 40 mm , L: 30 mm

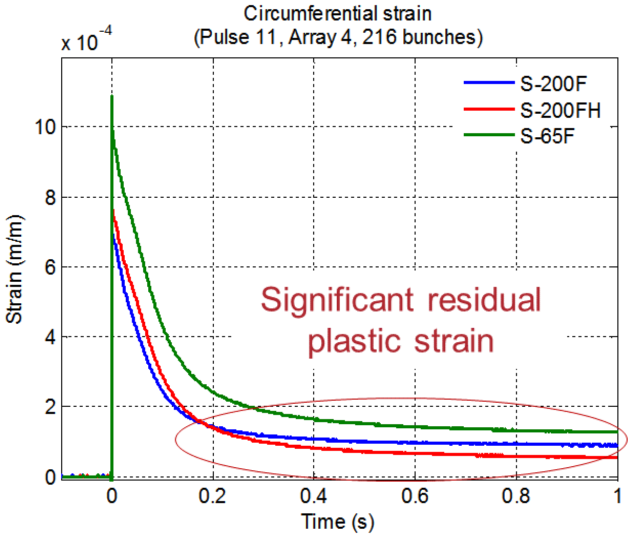


- ➢ Distinctive strain response for the three different Be grades
- ➢ Residual plastic strain observed upon cool-down

Array 3 – 24 bunches, 3.2e12 POT



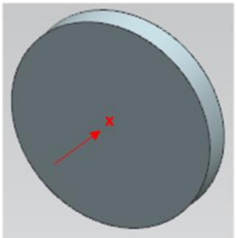
Array 4 – 216 bunches, 2.8e13 POT



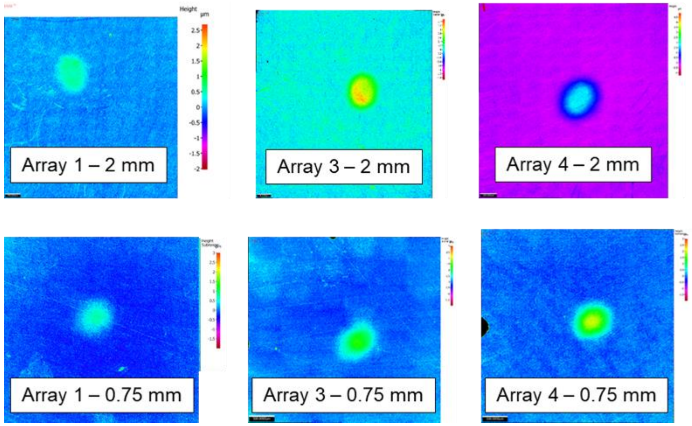
BeGrid1 (HRMT24) – Post Irradiation Examination Results

- Thin disc specimen PIE performed at University of Oxford
- Optical microscopy and profilometry to measure out-of-plane plastic deformations

Ø 15 mm, t: 0.25, 0.75, 2 mm

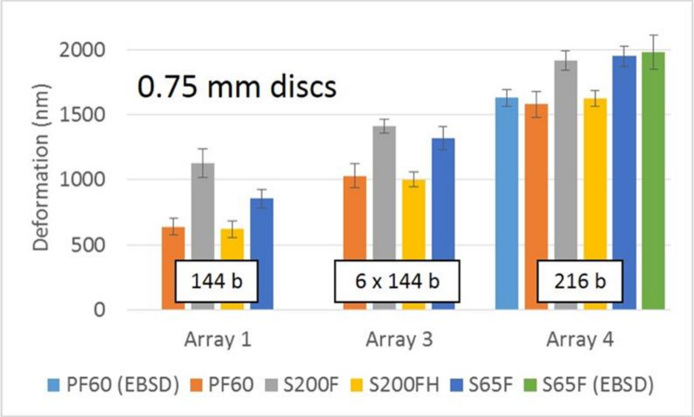


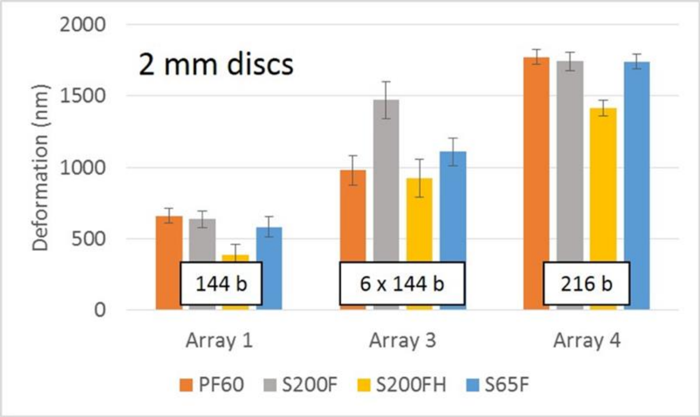
S-65F grade specimens



V. Kuksenko (University of Oxford)

- ➢ All Be grades showed less plastic deformation than predicted by available literature strength models
- ➢ S200FH showed least plastic deformation, in agreement with empirical strength model
- ➢ Observed plastic strain ratcheting in Array 3
- ➢ Glassy carbon windows survived without signs of degradation





BeGrid1 (HRMT24) – data analysis

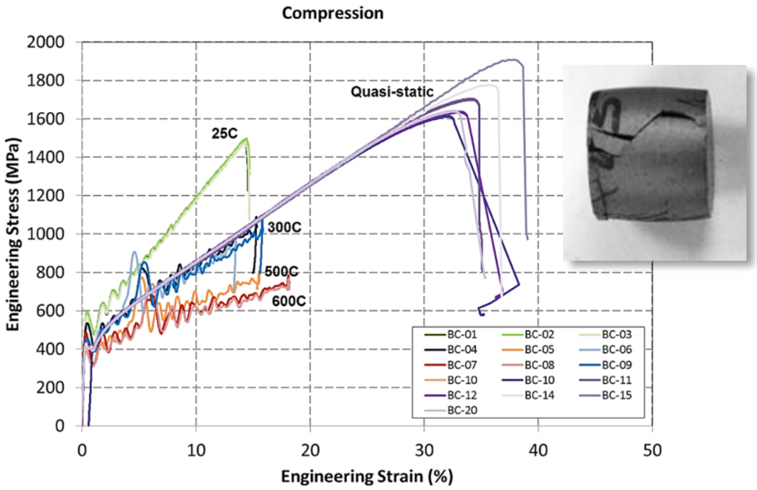
“Thermal shock experiment of beryllium … pulses”, K. Ammigan, et al., Phys. Rev. Accel. Beams 22, 044501, 4 April 2019

Beryllium S-200FH Johnson-Cook strength model

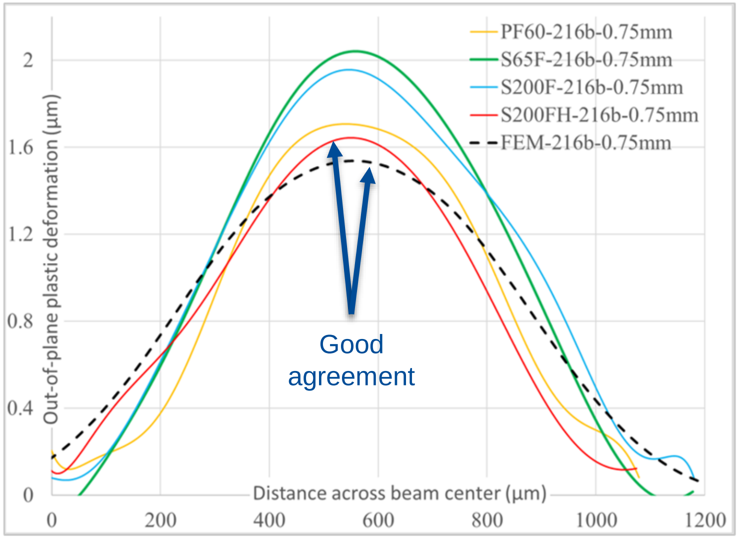
- Strength model parameters empirically determined at Southwest Research Institute (SwRI)
- High strain rate and elevated temperature testing with Split-Hopkinson pressure bar

$$\sigma_Y = \left[A + B(\varepsilon_{eff}^{p})^{n}\right][1 + C\ln\dot{\varepsilon}^{*}][1 - T_H^{m}]$$

- ➢ Yield stress (σ_y) dependent on strain rate and temperature
- ➢ Model parameters A, B, C, m, n empirically determined
- ➢ Be JC damage model postponed due to limited funding



S-200FH 0.75 mm thick specimen



S. Bidhar (FNAL)

- ➢ HRMT24 completed successfully and safely with valuable PIE results and validation of advanced strength model

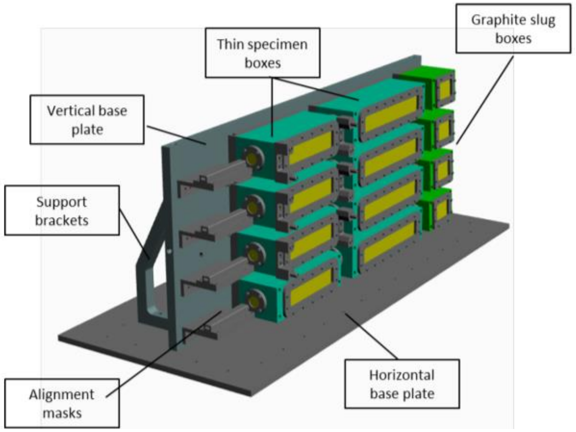
BeGrid2 (HRMT43)

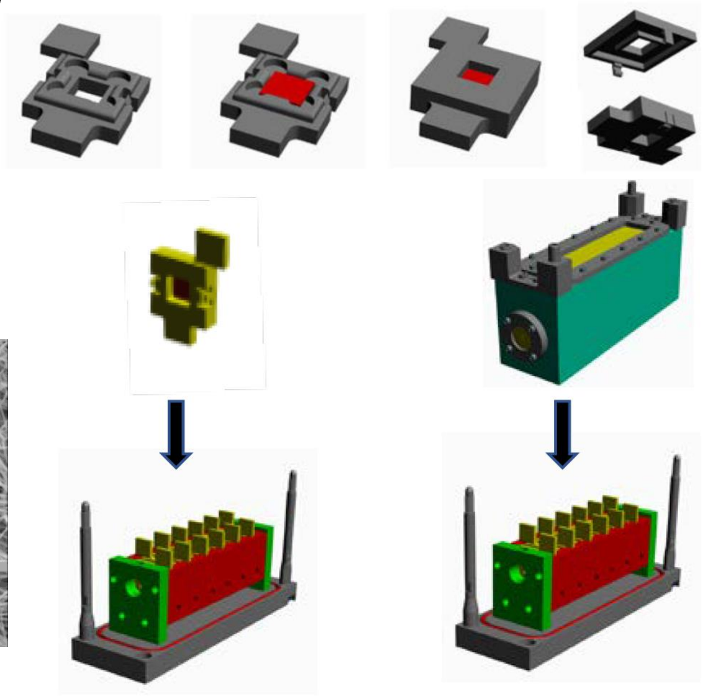
Beam taken on Oct. 1st week (2018)

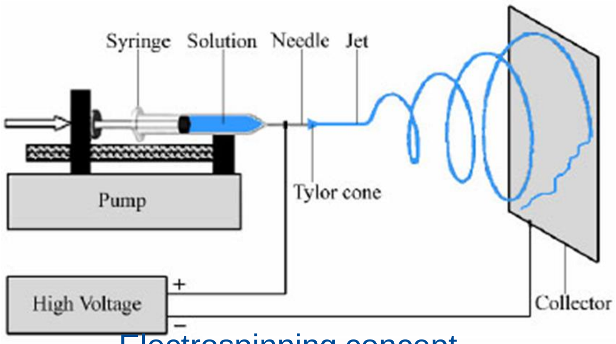
Primary Objectives:

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

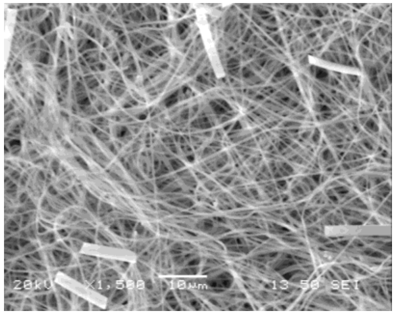
- Explore <u>novel materials</u> such as metal foams (C, SiC) and electrospun fiber mats (Al_2O_3, ZrO_2) to evaluate their resistance to thermal shock and suitability as target materials





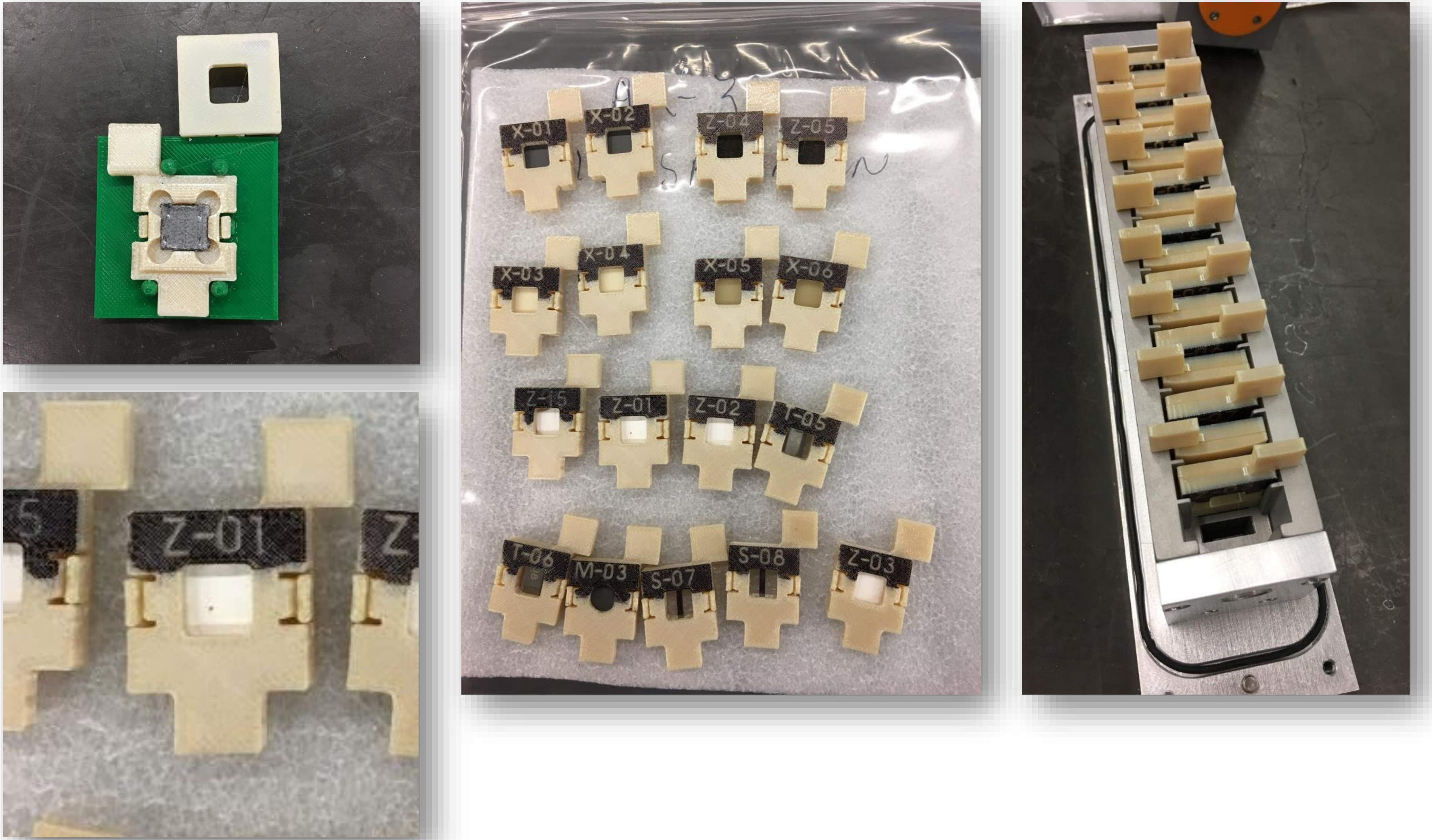


Electrospinning concept



SEM: as-spun Al_2O_3

BeGrid2 (HRMT43) – 3-D printed specimen holders



BeGrid2 – Remote handled installation & beam impact

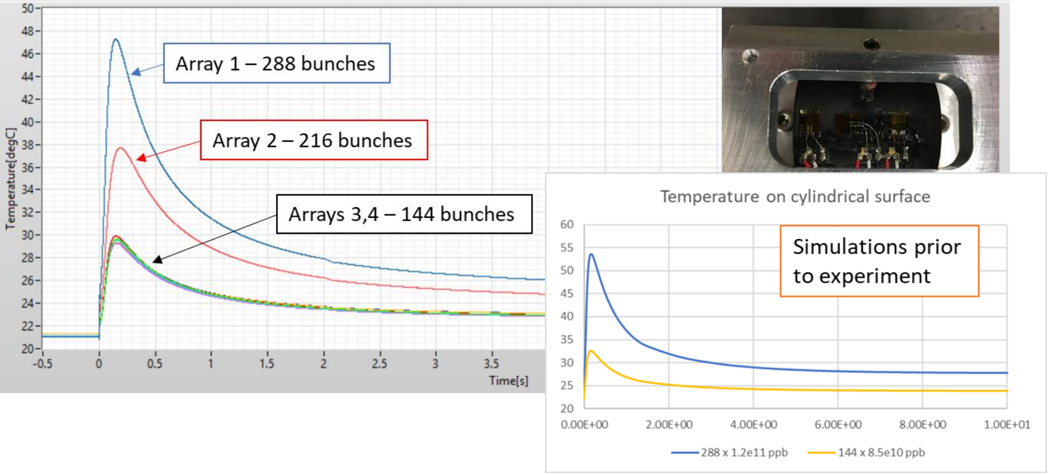
October 1 – 2, 2018 4:00am
BeGrid2 Exposure has been completed !

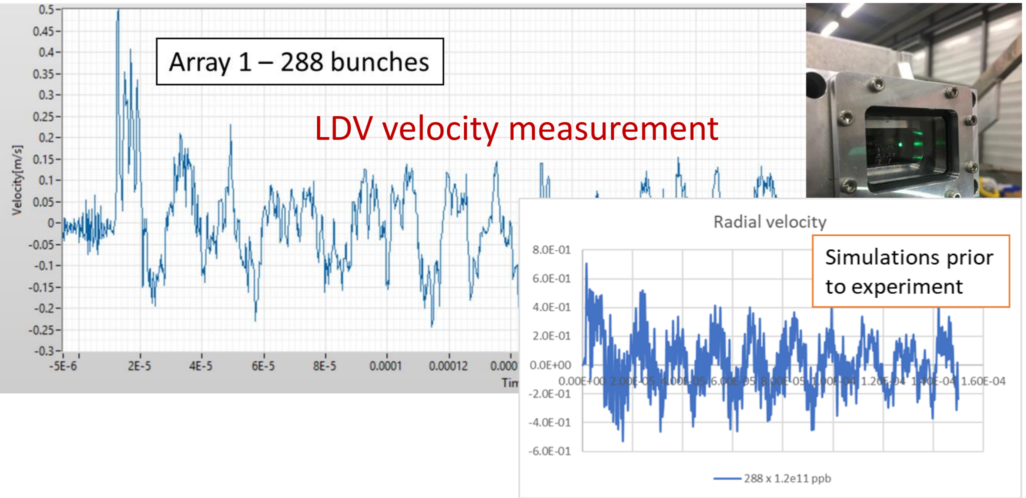
PIE to begin in July 2019

Impact: Benefits facilities that use Be or Ti beam windows or graphite targets (LBNF, T2K, FRIB, and more)

HRMT43 online data and PIE plans

Temperature on cylindrical surface of slugs

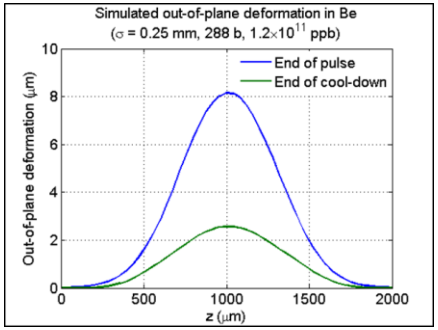


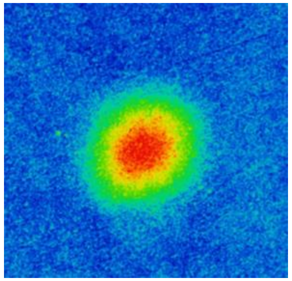


Numerical simulations currently being updated with experimental beam parameters to benchmark results

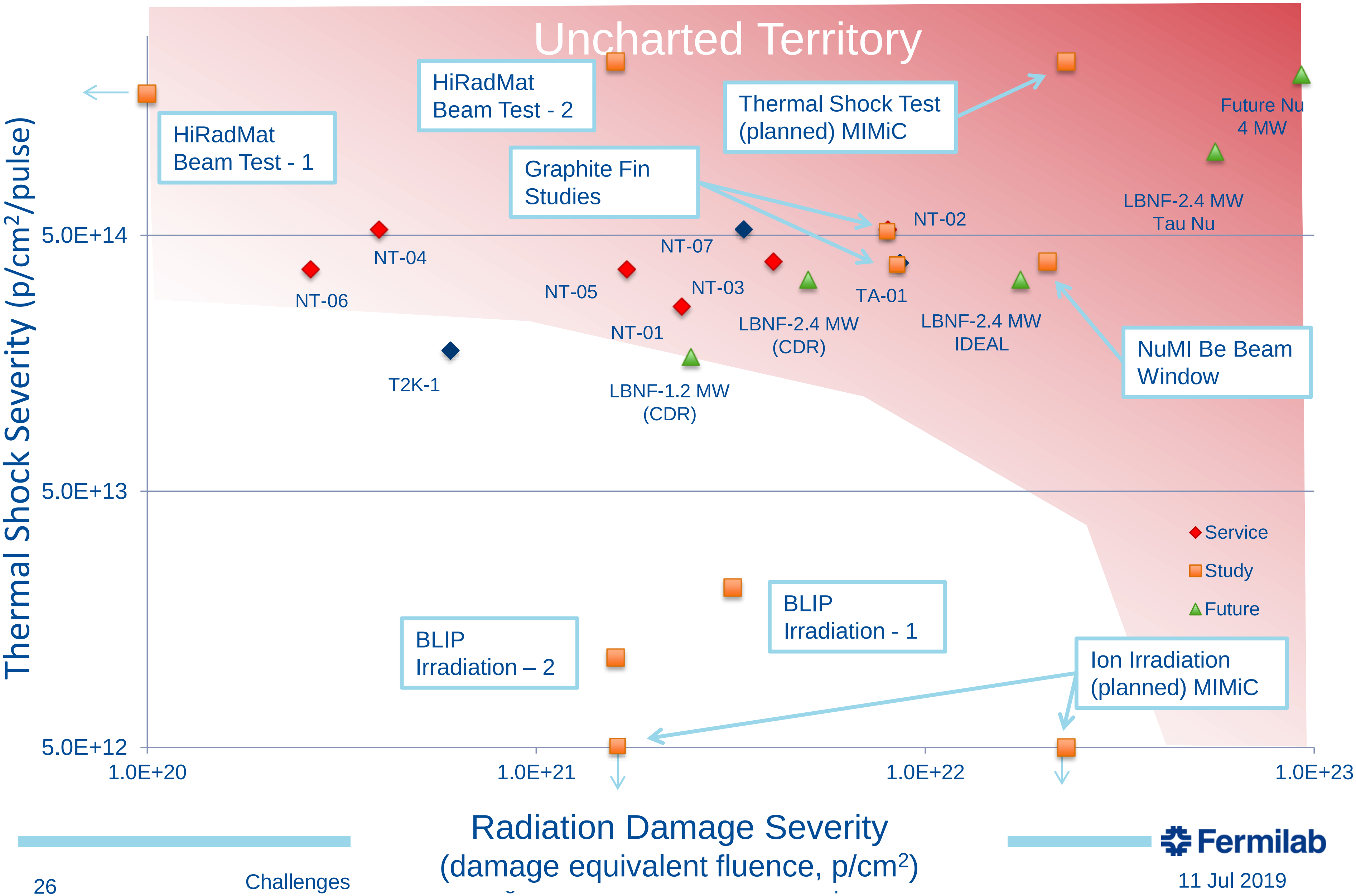
Bulk of results will be generated from PIE work (86 specimens)

- Profilometry to measure beam-induced out-of-plane plastic deformation
  - Confocoal Laser Raman Microscopy, with specimens in their 3D-printed holders
- Optical and Scanning Electron Microscopy (SEM) of beam spot area of specimens to image surface cracks (if any)





Nu HPT R&D Materials Exploratory Map



Nu Targetry Future HiRadMat Needs

- Higher DPA irradiated materials thermal shock testing
- Higher protons per pulse
  - Enables 40% larger beam sigma while preserving required high fluence per pulse
- Elevated temperature testing
  - Important to test thermal shock at prototypical operating conditions, especially to evaluate impact of radiation damage
- Pinpoint beam position accuracy
  - Pre-cracked specimens (crack propagation)
  - Match pre-irradiated small beam spot (< 0.5 mm) to replicate radial gradient in radiation modified material properties
- More Novel materials and target concepts
  - Advances in materials and fabrication require constant evaluation
  - Stress-wave diffusion/dampening concepts

Nu and Muon Related LOI’s

- RaDIATE Collaboration – P. Hurh
- J-PARC-KEK Nu beam – T. Nakadaira/T. Ishida
- STFC-RAL Powder Targets – C. Densham
- J-PARC-KEK Muon production – S. Makimura
- INFN LEMMA Muon Collider – G. Cesarini

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

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

http://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

In 2017, MoU revision has counted J-PARC (KEK+JAEA) & CERN as official participants

@J-PARC, Sep.20, 2017

@FNAL, Dec.11, 2017

Back-Up Slides Follow

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
  - CP violation

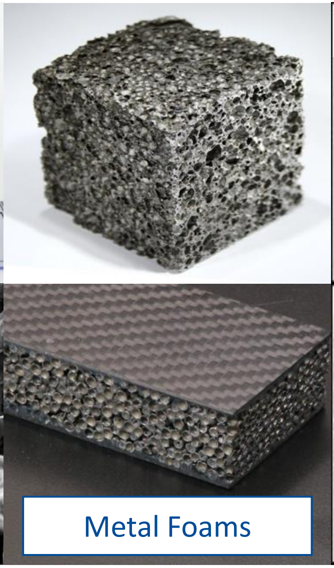
Development of New Targetry Materials

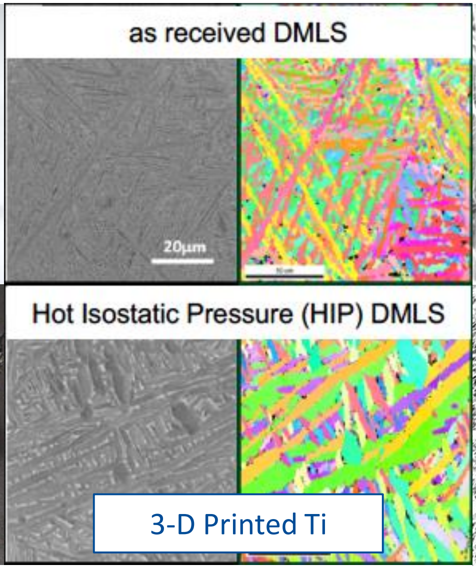
An ultimate objective is to develop new materials specifically addressing the requirements of future target facilities. Some progress is being made in exploring some of the newer materials and forms of material that have been developed.

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

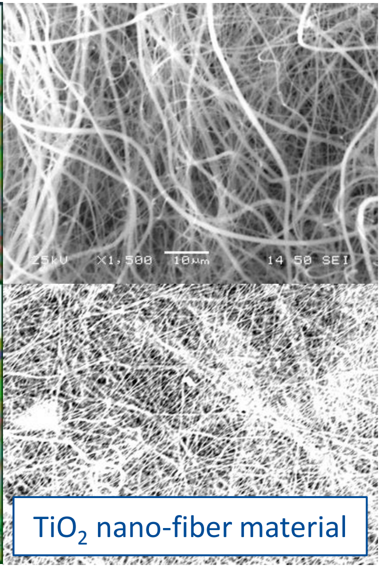

Glassy Carbon


Moly Graphite


Metal Foams



3-D Printed Ti

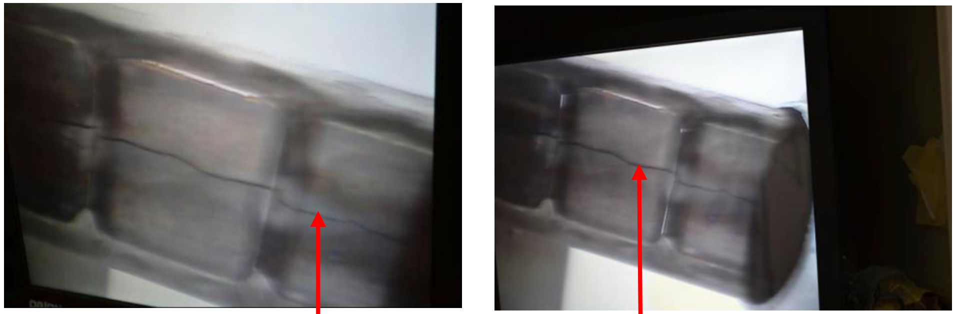


TiO_2 nano-fiber material

NT-02 Target

- 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



Cracks along centerline

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

Autopsy work by V. Sidorov, Fermilab

Slides courtesy of K. Ammigan, Fermilab

BLIP Graphite Irradiation Run (2010)

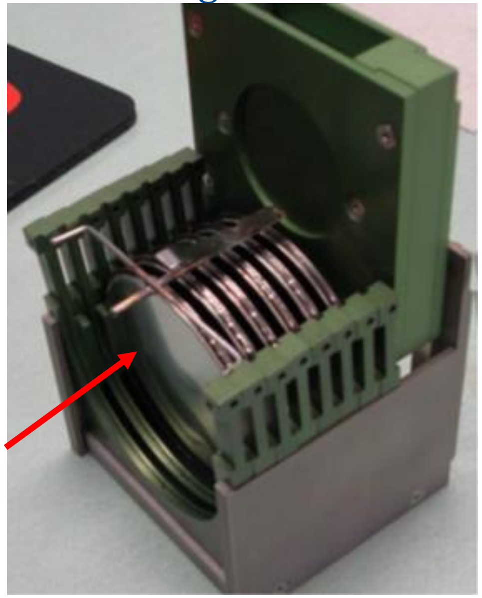
Specimen irradiation

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

Graphite specimens

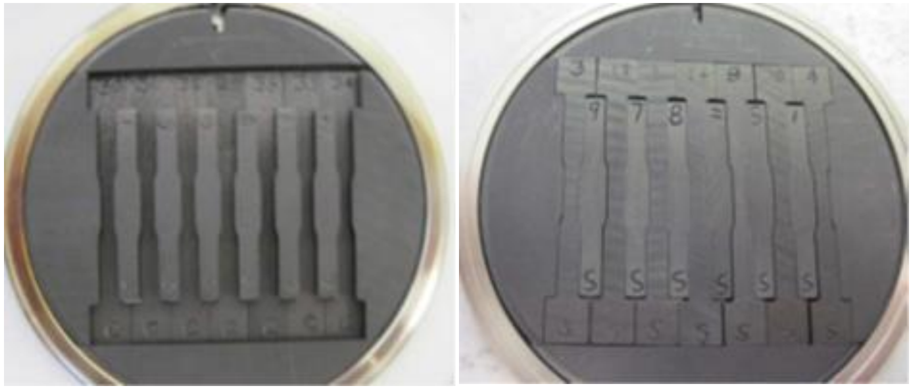
POCO ZXF-5Q	[27]
IG-430	[48]
SGL R7650	[27]
C2020	[27]
3D C/C composite	[18]

Target box



Proton beam

Layered graphite specimens



Slides courtesy of K. Ammigan, Fermilab