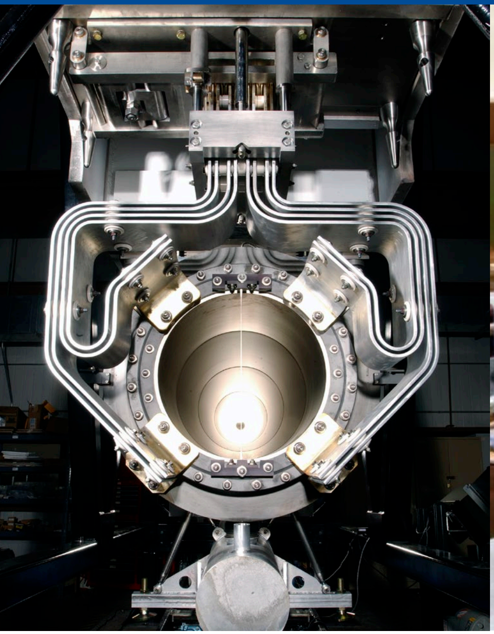
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science



Target Technology

Robert Zwaska, Fermilab

Muon Collider Accelerator School

6 August 2025

Fermilab Makes Neutrinos and Muons

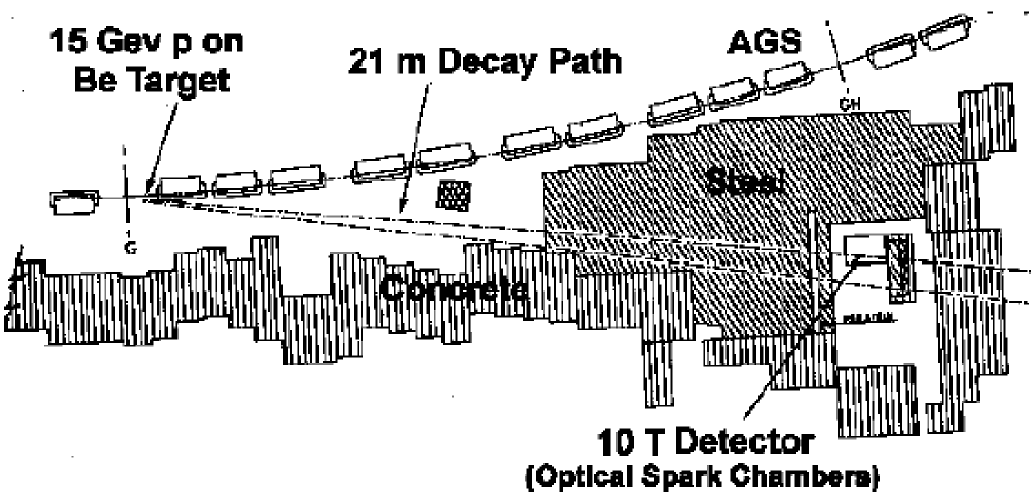
- Particle accelerators provide the raw material in terms of the kinetic energy stored in the high-power beams
- Target Stations convert the kinetic energy into new fundamental particles that are the subject of experiments
  - We do this by building devices (targets) that provide reaction material for the matter-creating collisions, focusing devices to maximize the intensities of our beams, and the numerous additional devices and system to manage these beams
- This talk: example of making a neutrino beam:
  - Interest in neutrinos
  - The accelerators provide the raw energy
  - The target converts the energy to new matter
  - The beamline defines the beam towards detectors
  - Neutrinos go forward (inexorably)
- A little of the challenges of neutrino beams
- Neutrino beams around the world
- An introduction to high-power targetry

The First Neutrino “Beam”

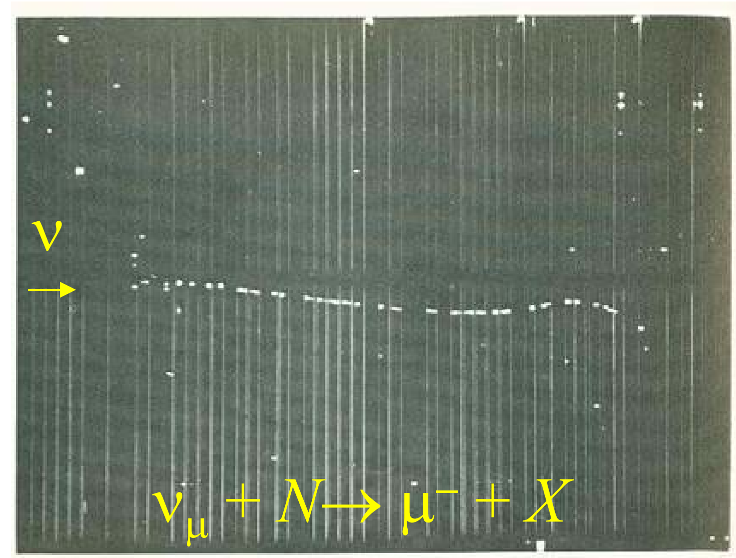
- In 1957, Brookhaven AGS and CERN PS first accelerators intense enough to make ν beam

  $p + Be \rightarrow \pi^+ + X, \qquad \pi^+ \rightarrow \mu^+ \nu$
- 1962: Lederman, Steinberger, Swartz propose experiment to see

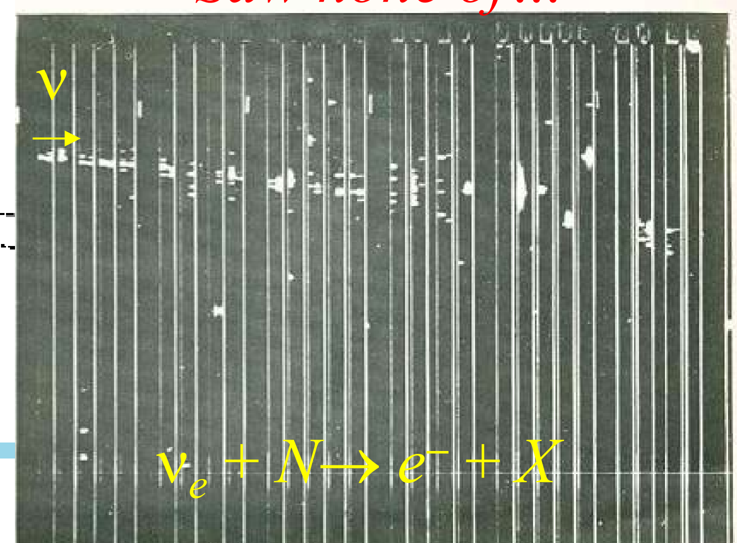
  $\nu_\mu + N \rightarrow \mu^- + X$ (*Phys.Rev.Lett.* **9**, *36 (1962)*)



Saw lots of…



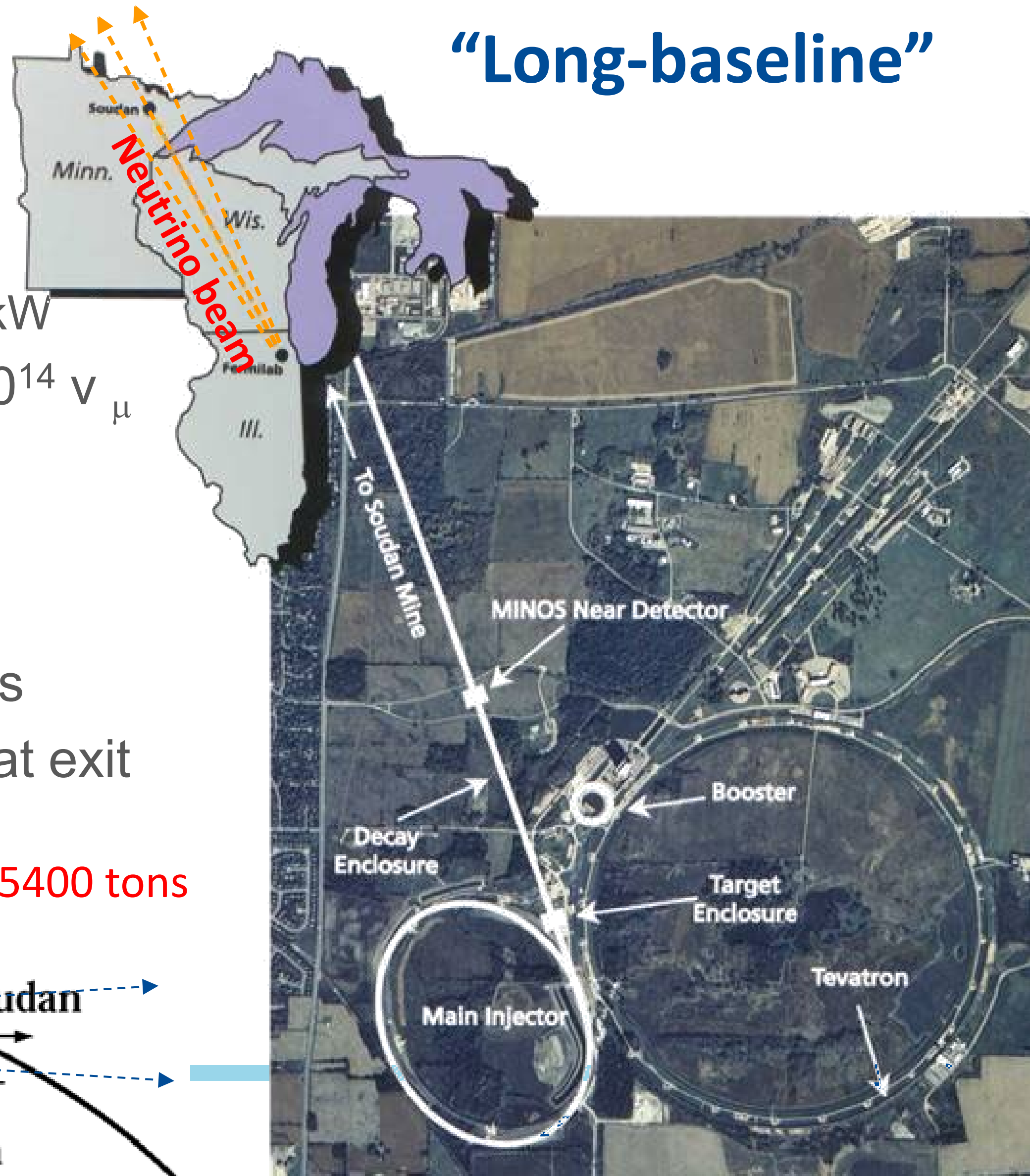
Saw none of…

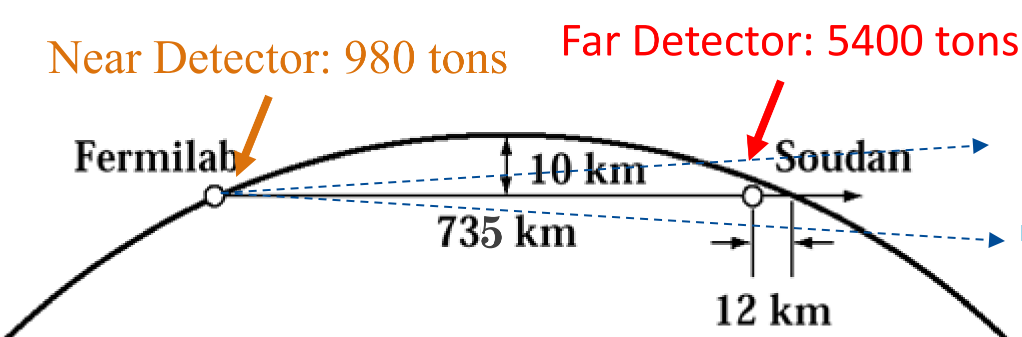


The NuMI Facility

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

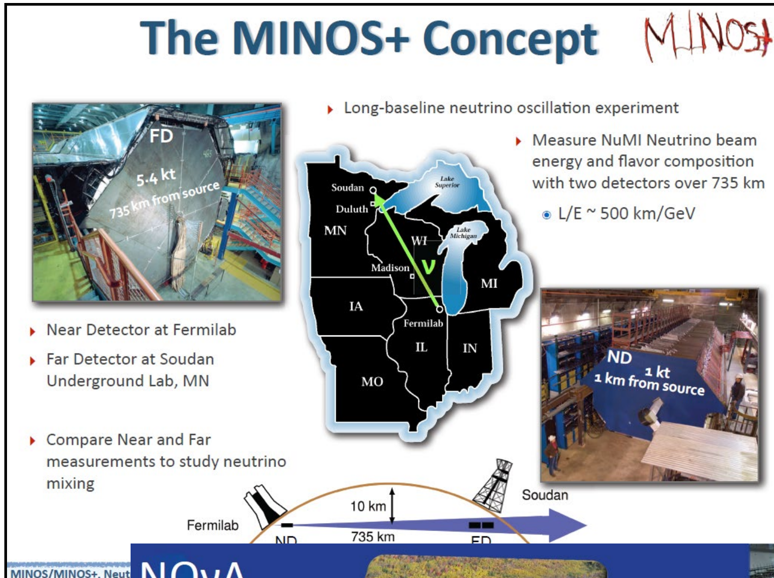
- Intense muon-neutrino beam directed towards Minnesota
- Main Injector supplies 25 – 50 trillion 120GeV protons every 1.4 seconds
  - Operating regularly above 900 kW
- Each pulse produces about $2x10^{14}$ ν_{μ}
  - ~ 20,000,000 Pulses per year
- Direct beam 3^{o} down
- On-site and off-site experiments
- Different types of neutrino beams
- Beam is 10s of kilometers wide at exit

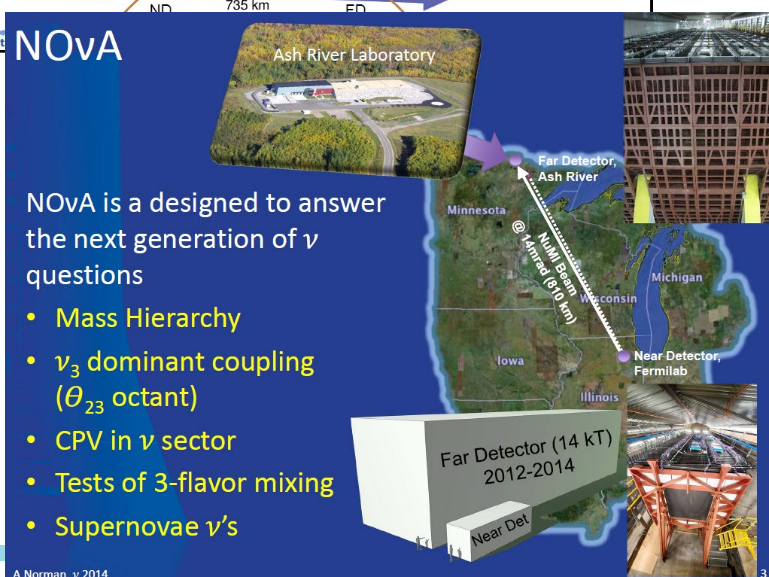




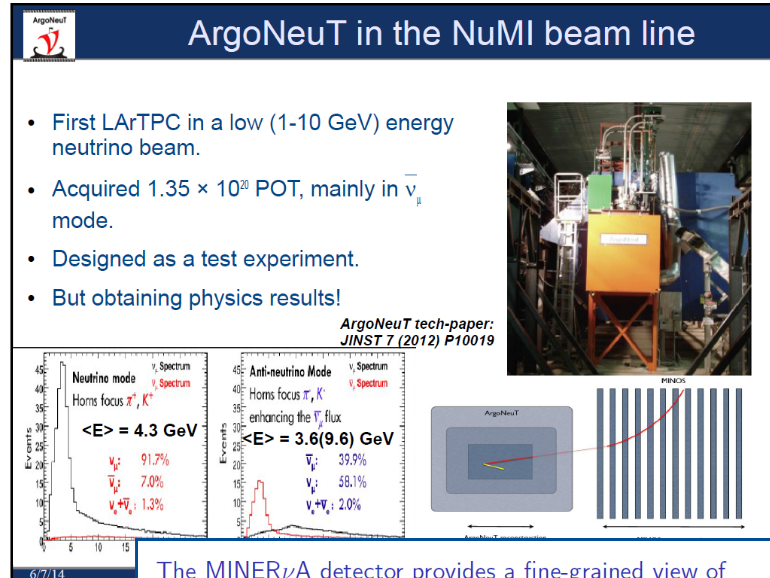
Multiple Experiments in the NuMI Beam

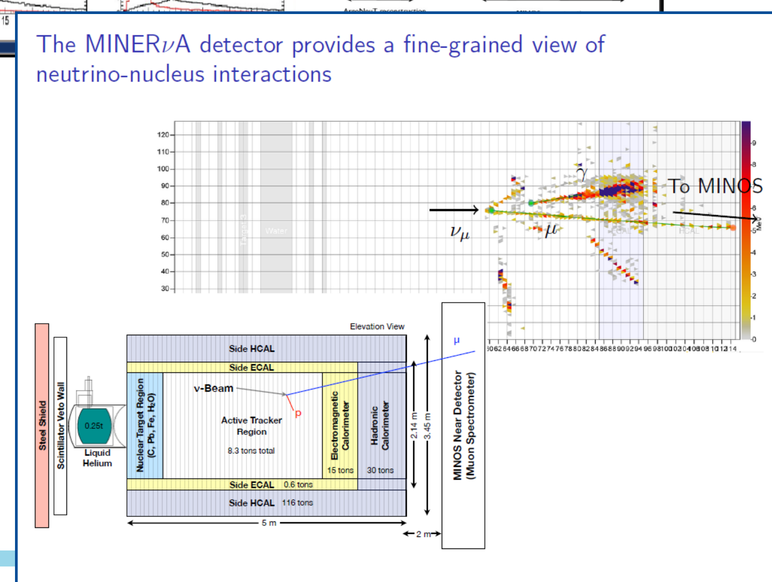
Long-baseline oscillation experiments





Neutrino scattering experiments



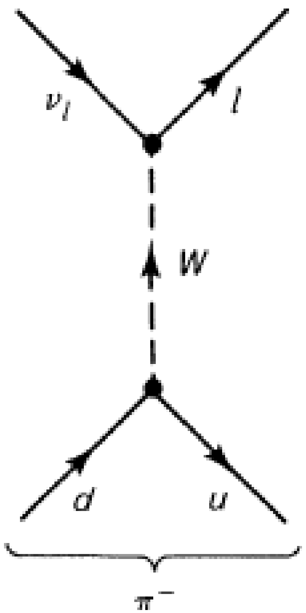


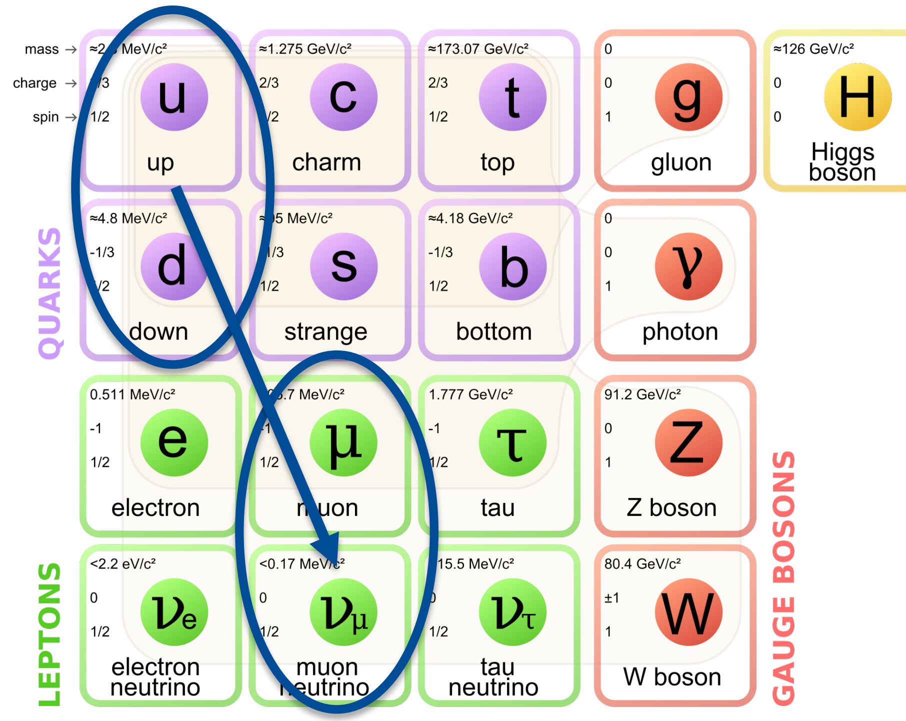
Pion Decay!

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

- Most all of our neutrinos come from pion decays

- Two quarks, bound together by gluons, convert into a neutrino and muon





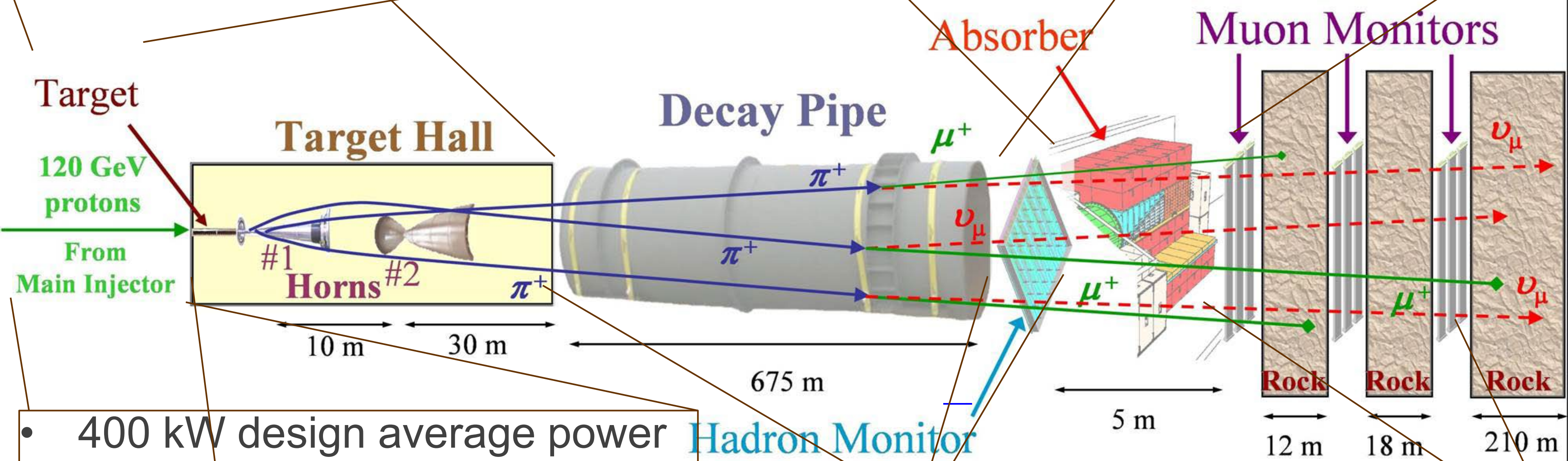
- A "simple" decay (at first)
  - Pion mass ~ 140 MeV/c^2, Muon mass ~ 105 MeV/c^2

The NuMI Beam “Neutrinos at the Main Injector”

- 1 meter long, 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

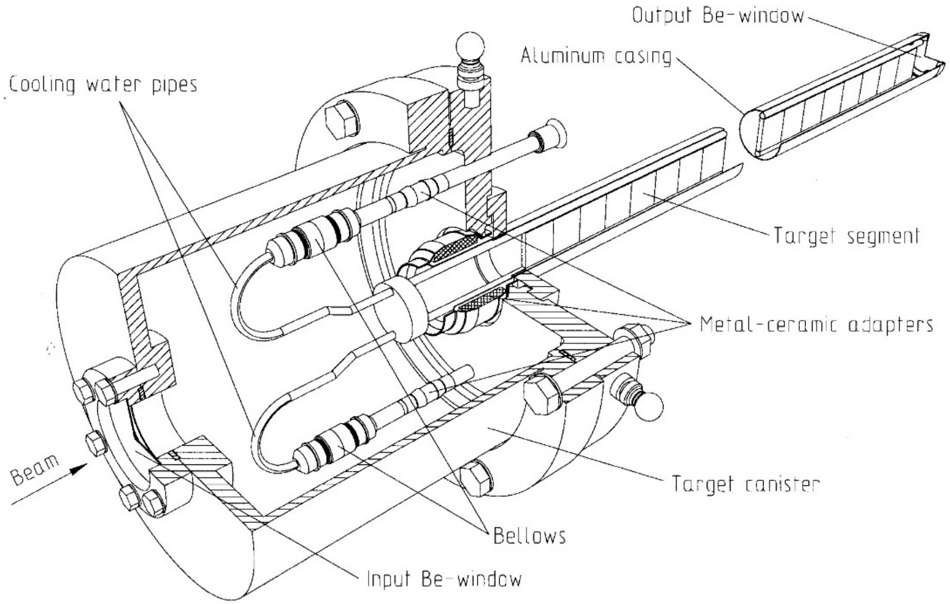


- 400 kW design average power
- 700 kW upgrade for NOvA
- 1 Megawatt Upgrade 2021
- σ ~ 1 mm

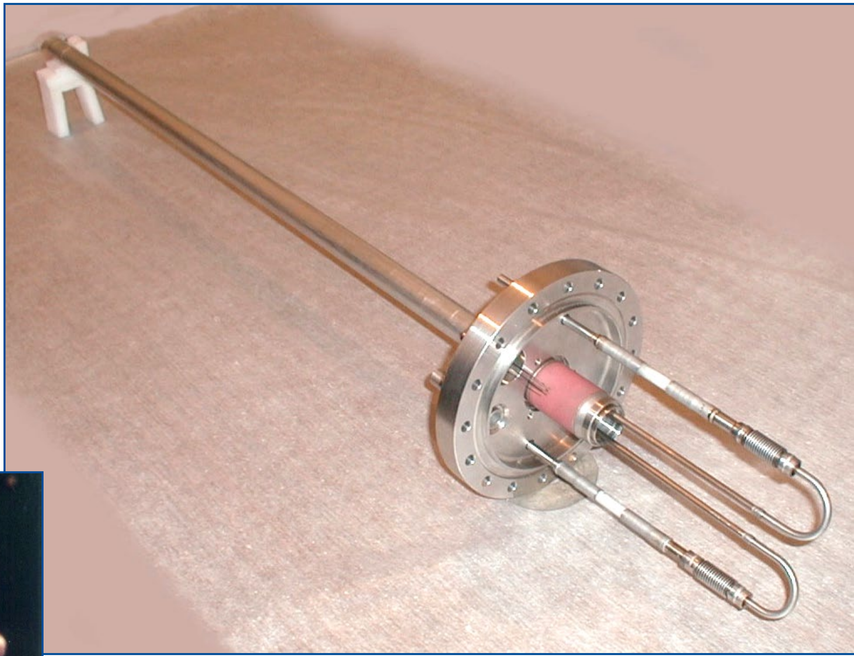
- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focus meson momentum band

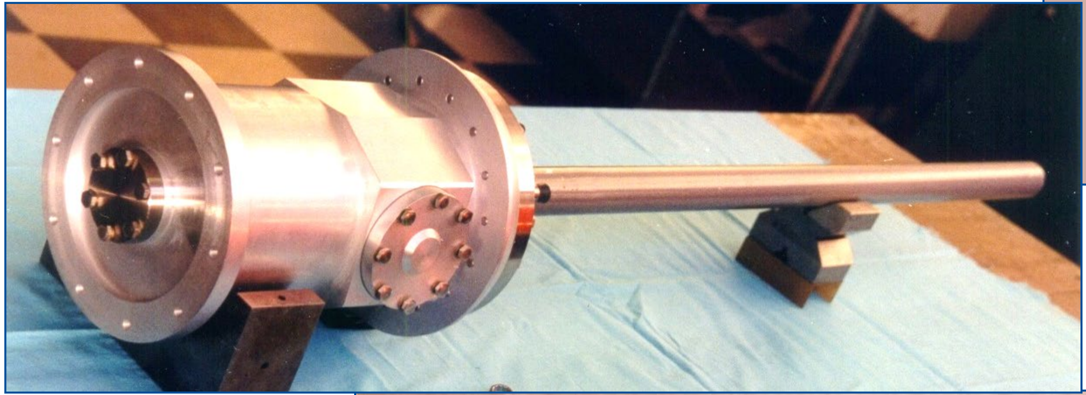
- Measure hadron & muon fluxes
- Arrays measure distributions

The MINOS Target



~ 4 kW beam power deposited in target



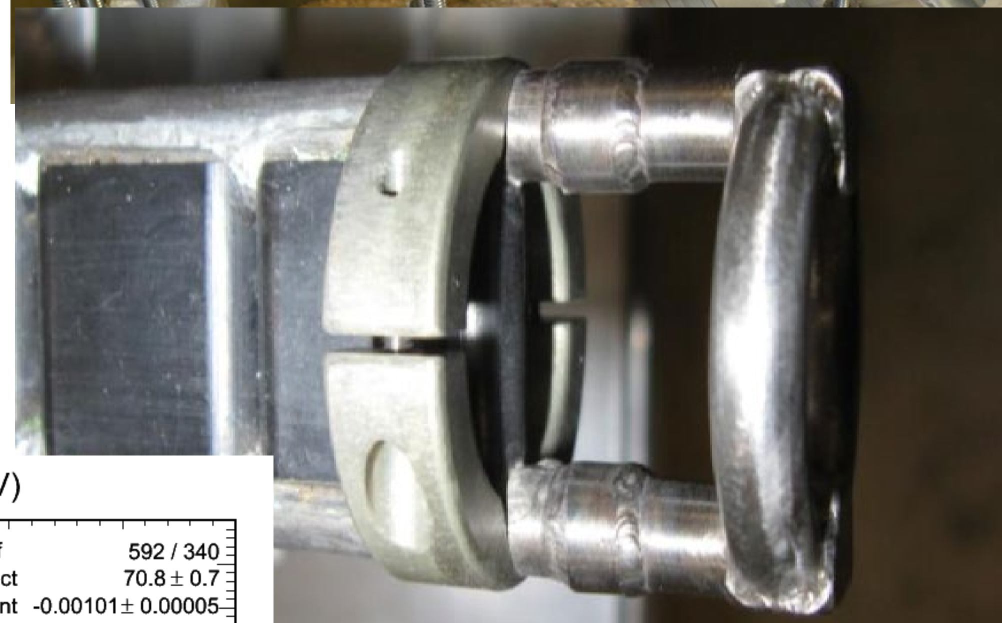


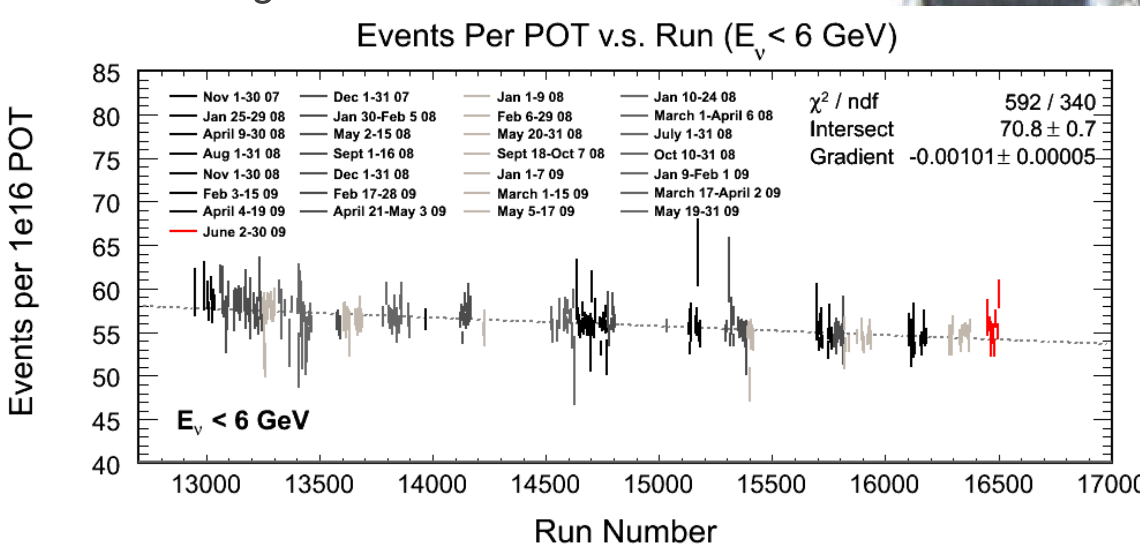
Encased in vacuum / helium can with beryllium windows

Water cooled graphite core

Target Issues

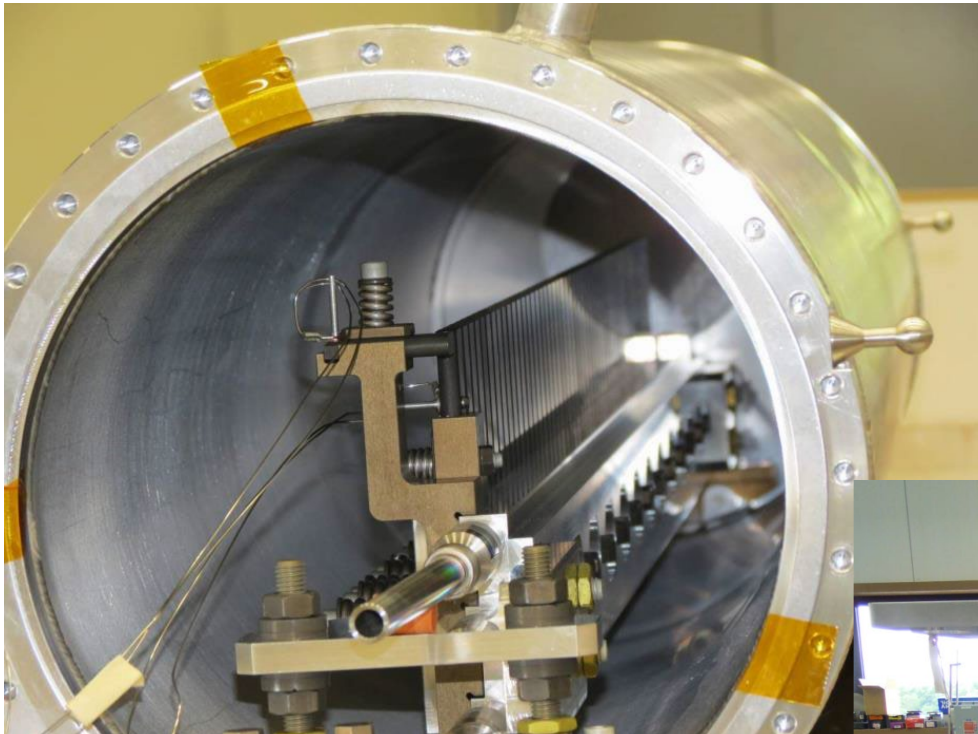
- Common failure mode was water cooling
  - Also, an issue for horns
  - Many lessons were learned in design and in quality control
- NOvA target is more robust in its design
  - Made possible by being outside of the horn.
  - LBNF Design returns to inside the horn
- Graphite degradation was observed on one target
  - May ultimately limit the performance of the target





NOvA Target

- Graphite fins: 50 x 24 mm; 7.4 – 9.0 mm wide
- Helium atmosphere
- Beryllium windows
- Water cooled aluminum pressing plates
- Water cooled outer vessel
- Initially designed for 700 kW, now upgraded to 1 MW

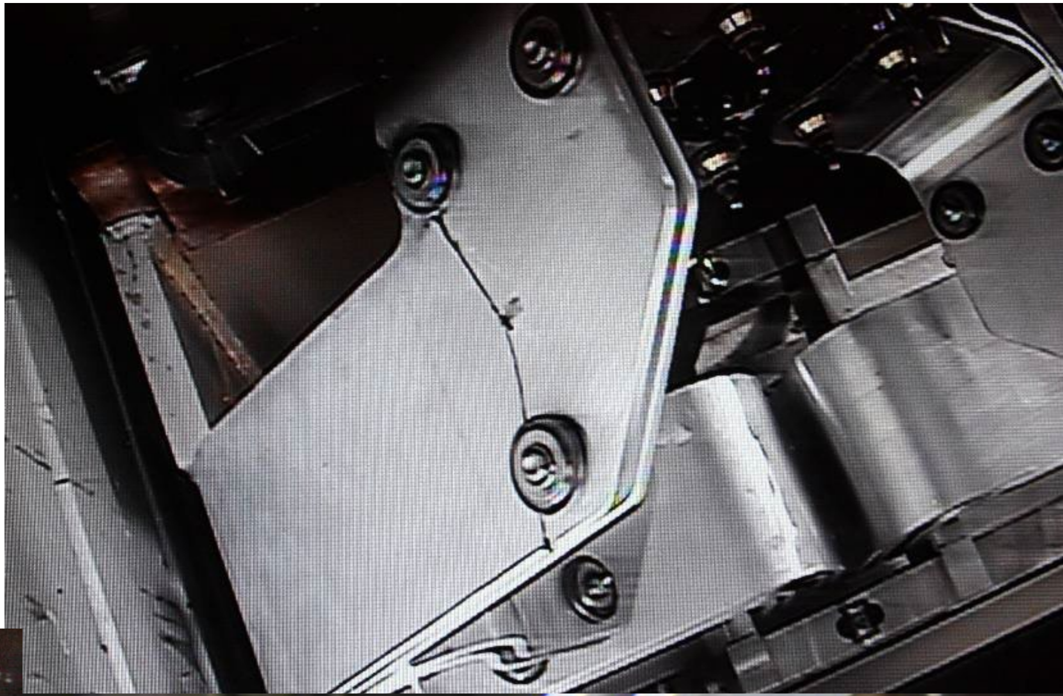


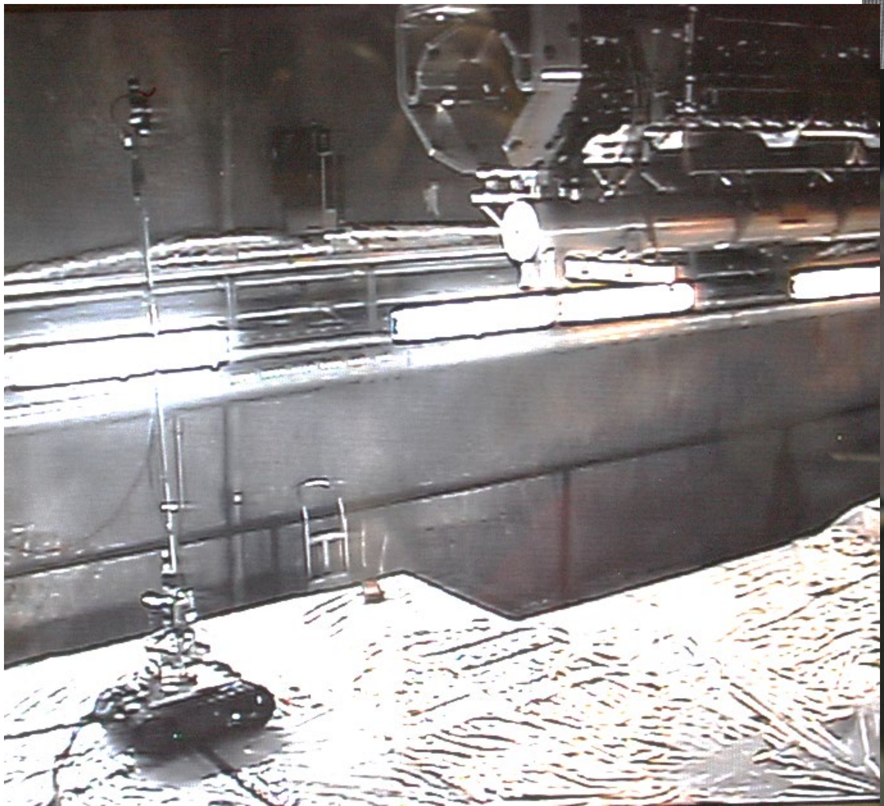
IHEP Protvino (Russia) initial design

STFC-RAL / FNAL final design and construction

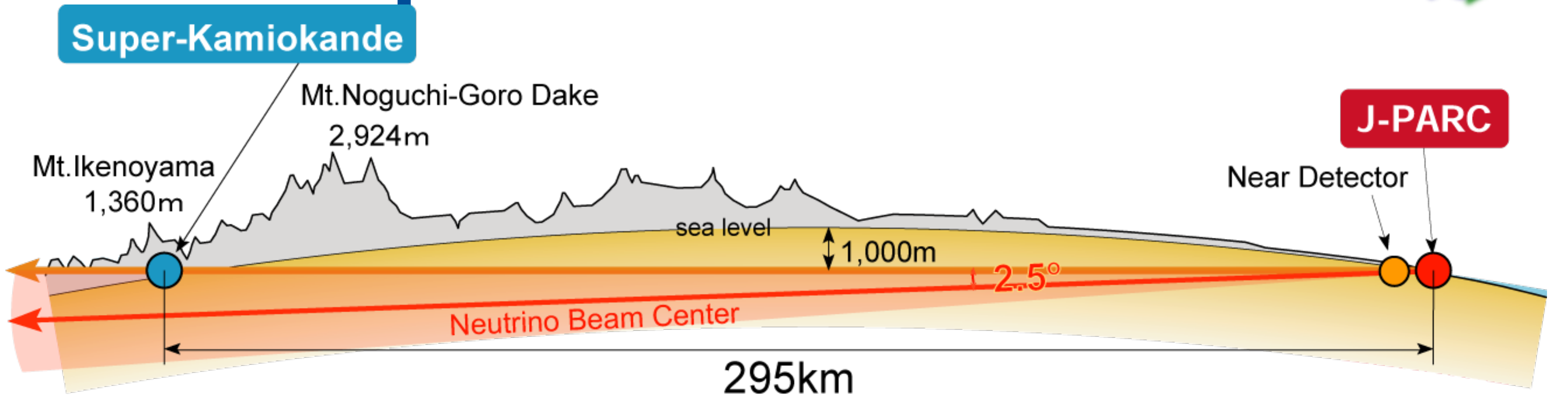
Challenging Environments

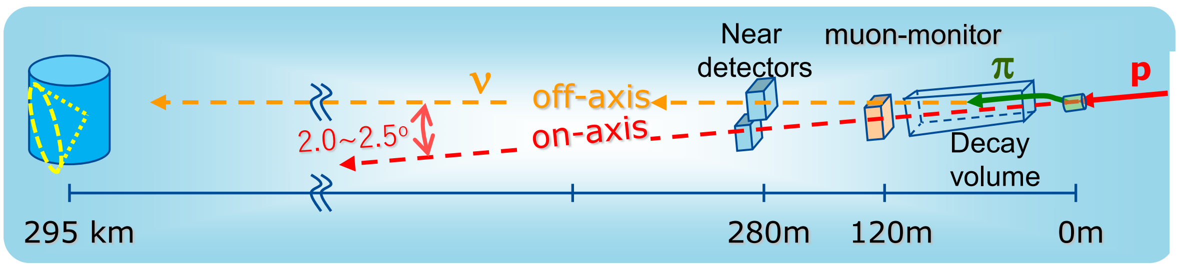
- Replaced NuMI Horn summer 2015 due to failed stripline
  - First 700 kW capable horn, in service since Sept. 2013, accumulated ~ 27 million pulses
- Failure was due to fatigue, likely enhance by vibrations



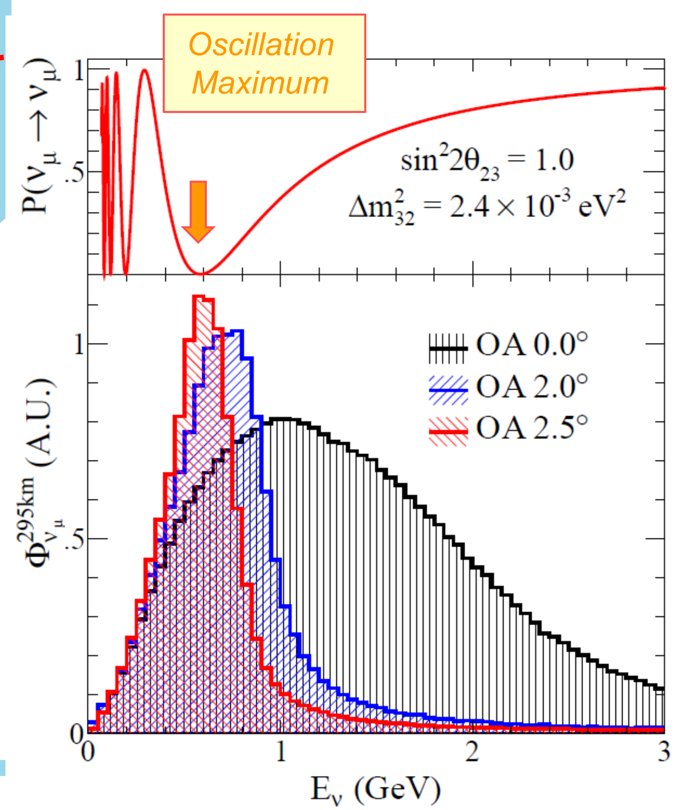


The T2K experiment



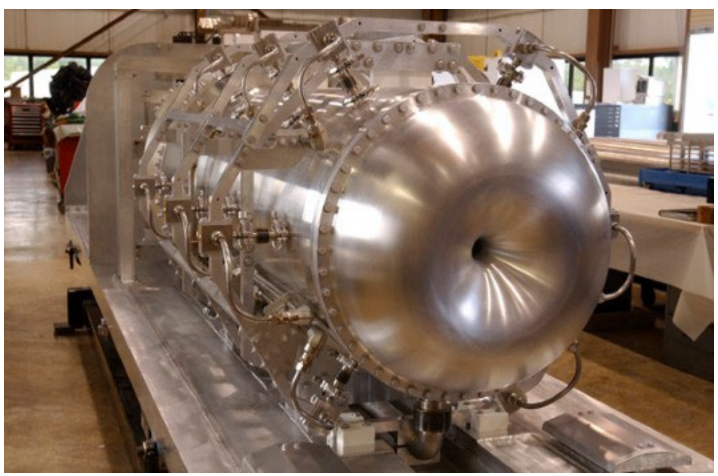


- Conventional "horn-magnet-focused" ν beam
  - 30GeV Protons on a graphite target
  - daughter $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$)
  - Anti-neutrino production by inverse polarity
- First application of Off-Axis(OA) beam: 2.0~2.5° wrt. the far detector direction
  - Low-energy narrow-band beam
  - peak tuned to oscillation maximum
  - Small high-energy tail: reduce inelastic bkgs

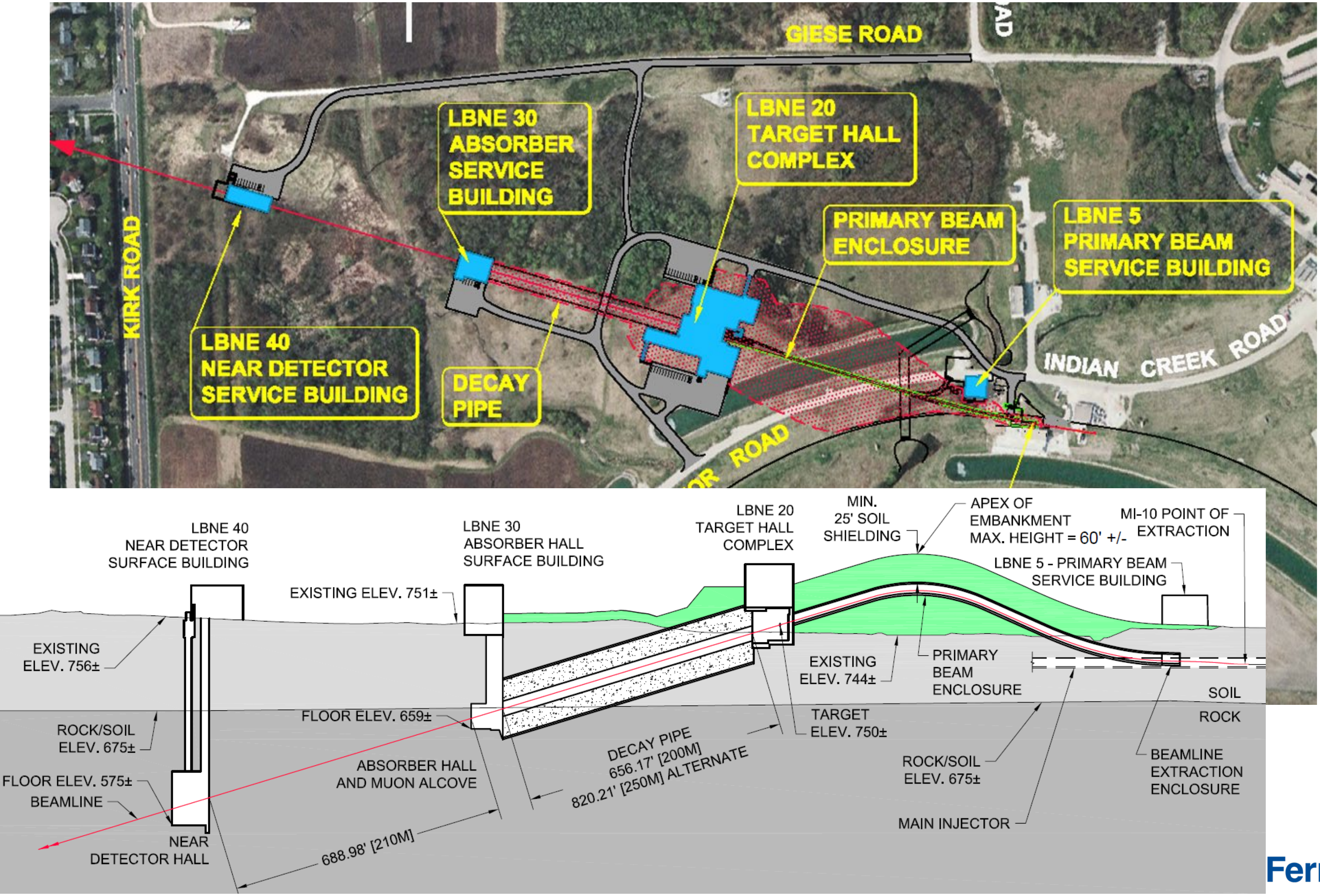


Booster Neutrino Beam (BNB)

- Uses 8 GeV beam from the Fermilab Booster, operating since 2002
  - Up to ~ 30 kW of beam (5e12 ppp)
- Beryllium target integrated with single focusing horn
- Services a suite of experiments at Fermilab: the Short Baseline Neutrino (SBN) program



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



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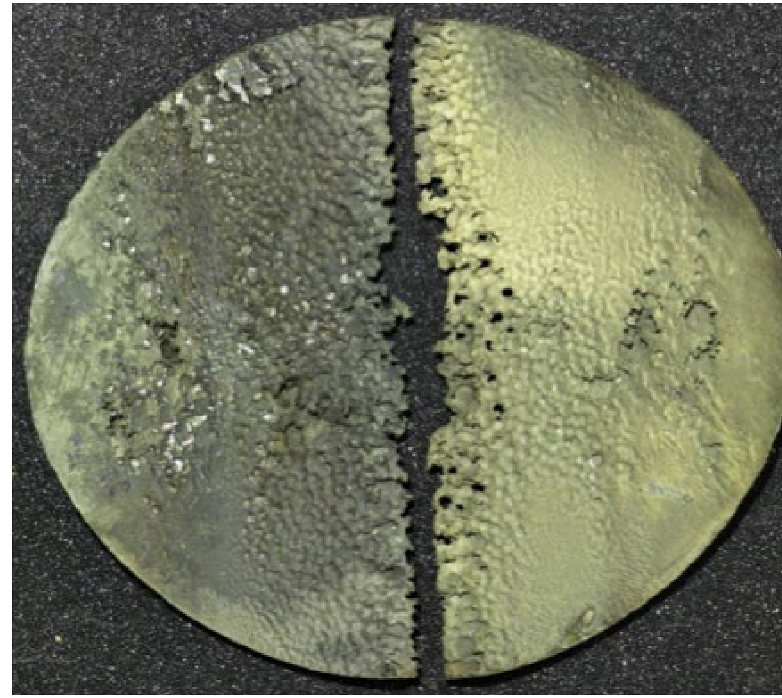
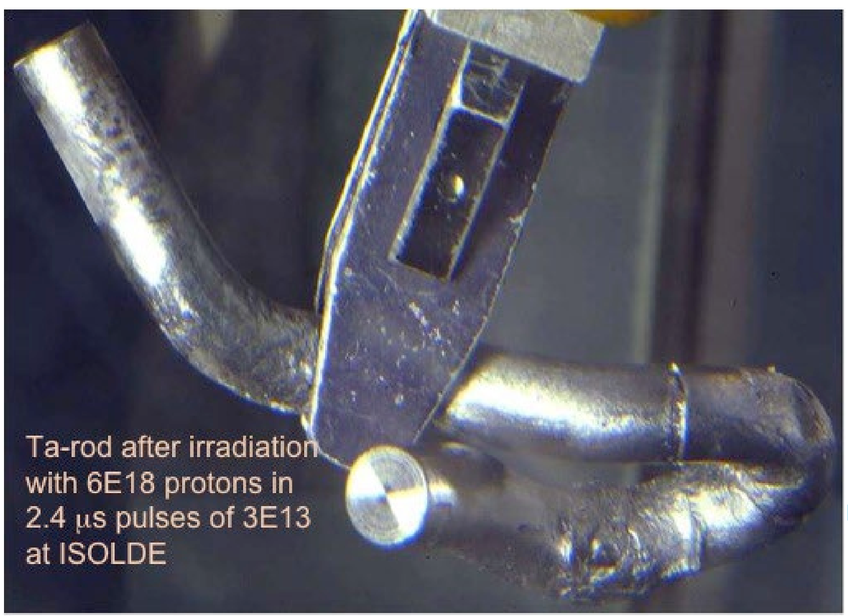
Timeline of High-Power Target Stations at Fermilab

Station	Design Power	Period	Comments
BNB	30 kW	2002 – 2027 (?)	
NuMI	700 kW – 1 MW	2004 – 2027	Megawatt Upgrade in progress.
AP-0 / Muon g-2	20 kW	2017 – 2023 (?)	Using legacy targets & lenses from Antiproton Source.
Mu2e	8 kW	2027 (?) -	Very challenging high-Z, radiatively cooled target, even with low power.
LBNF/DUNE	1.2 MW	2031 (?) -	Challenging, but achievable devices. Rate of production may be greatest challenge.

- Three operating stations, two in various stages of design & construction

What we don't want





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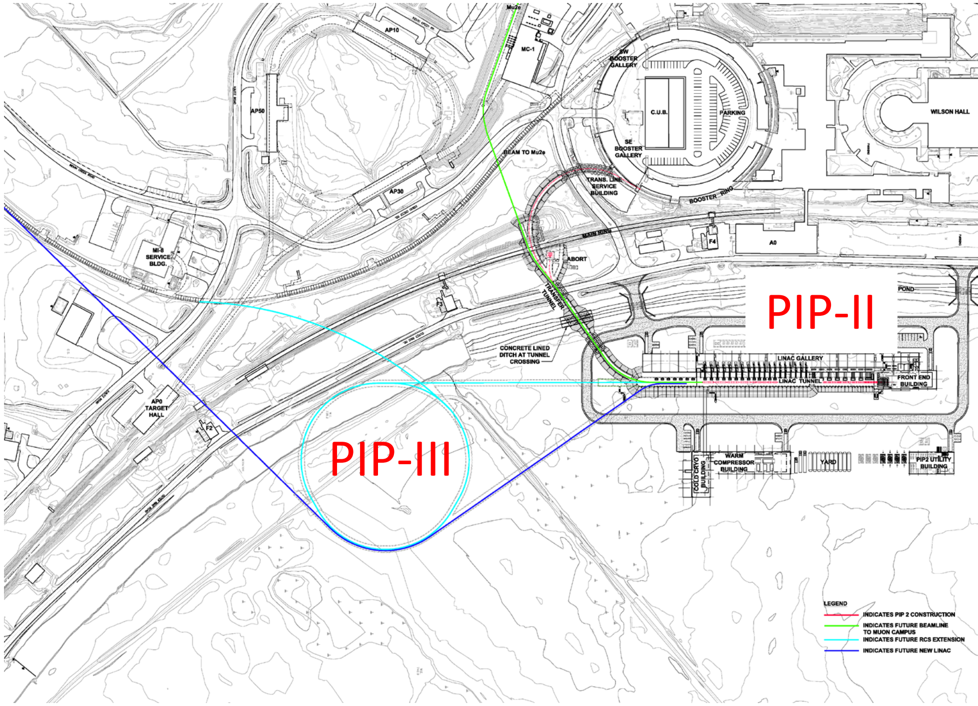
Mu2e-II	**100 kW**	**2030s (?) -**	**"Impossible" Target**
LBNF/DUNE	1.2 MW	2031 (?) -	Challenging, but achievable devices. Rate of production may be greatest challenge.
LBNF w/ ACE-MIRT	**2+ MW**	**2034 (?) -**	**Challenging**

PIP-II + Possibilities

Numbers are examples, not official

- PIP-II itself is a *blowtorch* of an accelerator
  - Capable of 2 mA CW @ 800 MeV -> 1.6 MW
  - One could reasonably expect experiments with that beam…
- Future accelerators adds even more
  - Linac option of 8 GeV?
    - 16 Megawatt beam
  - Linac + RCS
    - 4 MW @ 2 GeV
    - 700 kW @ 8 GeV



	Present	PIP-II	New RCS
MI			
Beam Energy[GeV]	120	120	120
Cycle Time[s]	1.33	1.2	1.45
Protons per pulse[1e12]	49	75	190
Power[MW]	0.7	1.2	2.5
Proton Source			
Injection Energy[GeV]	0.4	0.8	0.8-2.0
Extraction Energy[GeV]	8	8	8
Protons per Pulse[1e12]	4.3	6.4	**32**
Beam Power to MI [kW]	38	82	168

Timeline of High-Power Target Stations

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LBNF/DUNE	1.2 MW	2031 (?) -	Challenging, but achievable devices. Rate of production may be greatest challenge.
LBNF w/ ACE-MIRT	2.5 MW	2034 (?) -	Challenging
800 MeV Exp't(s)	**1.6 MW**	**2030s (?) -**	
2 GeV Exp't(s)	**4 MW**	**2030s (?) -**	
8 GeV Exp't(s)	**0.8 – 16 MW**	**2030s (?) -**	

Bonus

The Multi-Megawatt Frontier

High Power/Intensity Targetry Challenges

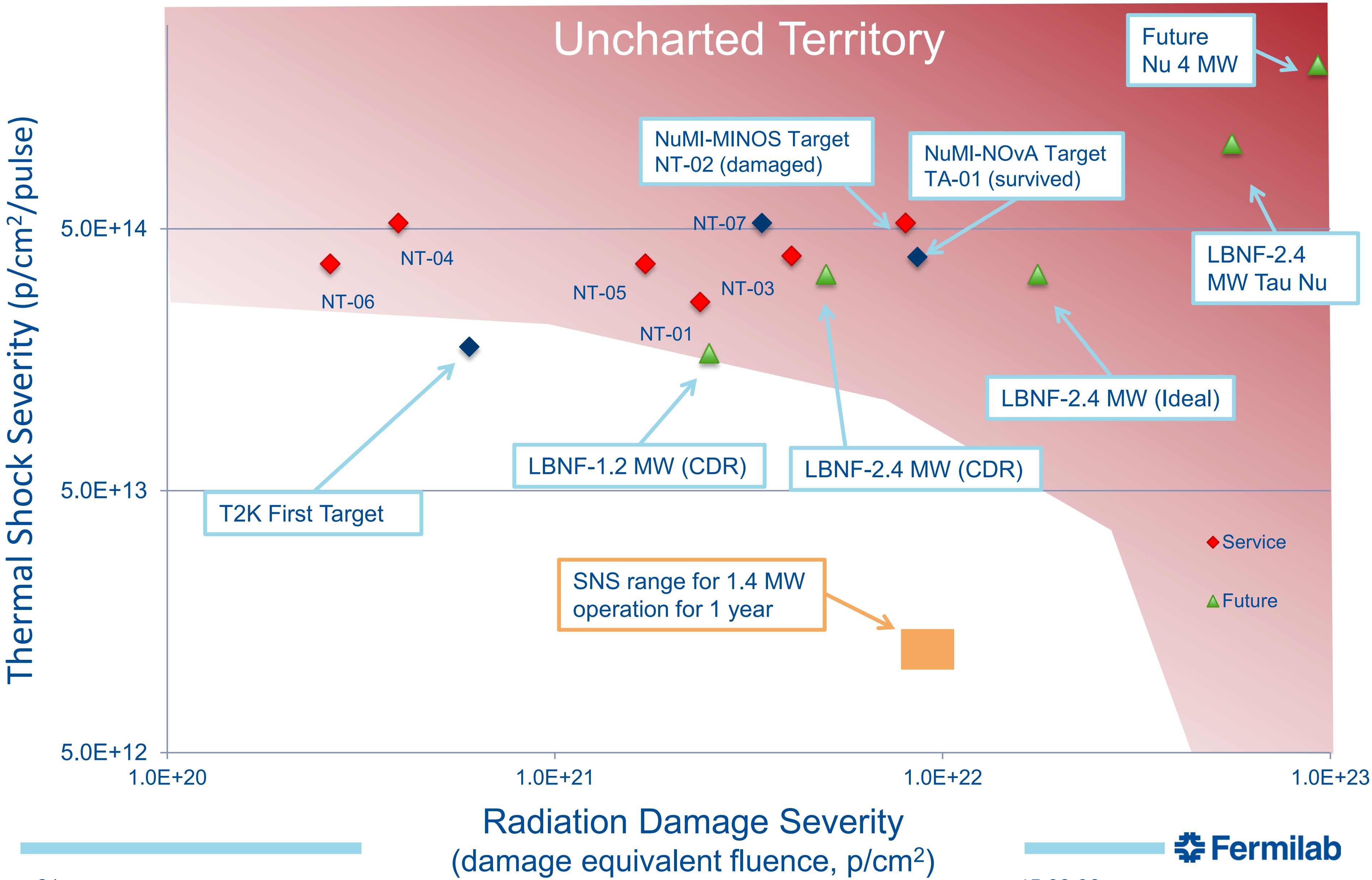
- Target Material Behavior
  - **Radiation damage**
  - **Thermal "shock" response**
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Remote handling
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection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



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High Power Targetry: Materials R&D

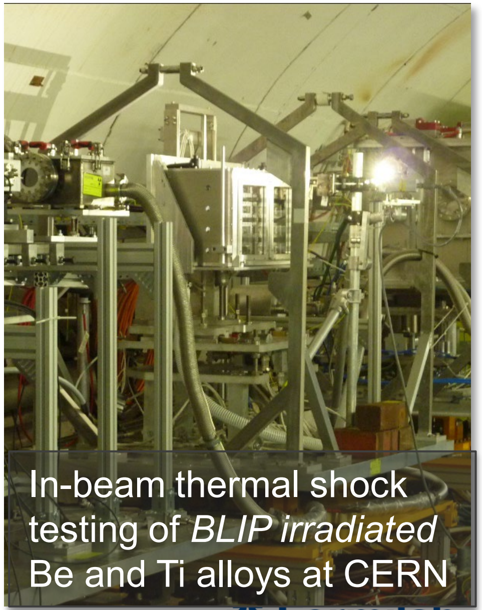
Multi-MW Neutrino Targets & Beam Windows Materials:

- 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

RaDIATE Collaboration

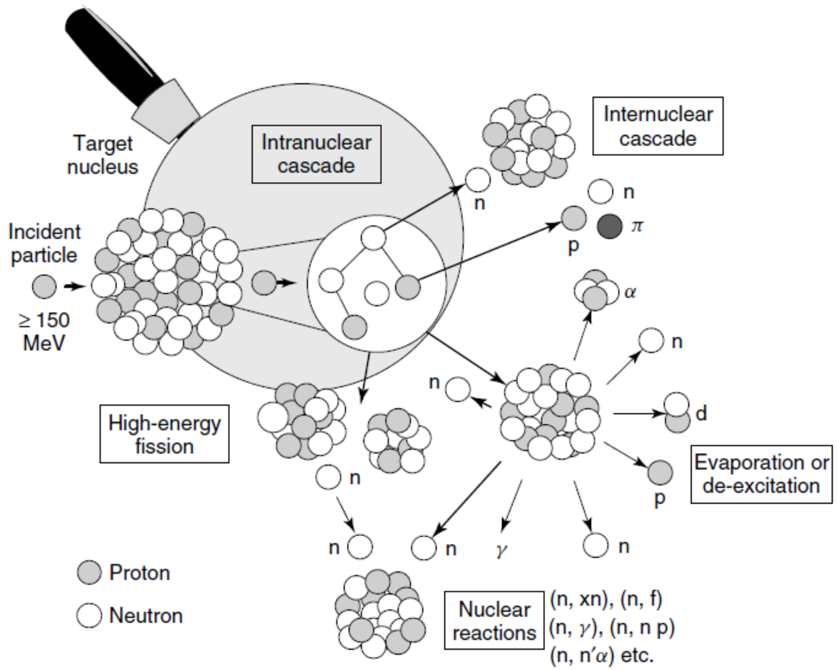
Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

www-radiate.fnal.gov

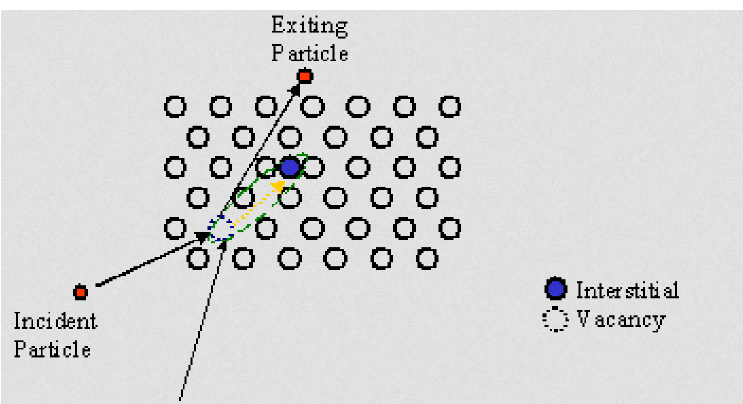
- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

Radiation Damage Disorders Microstructure

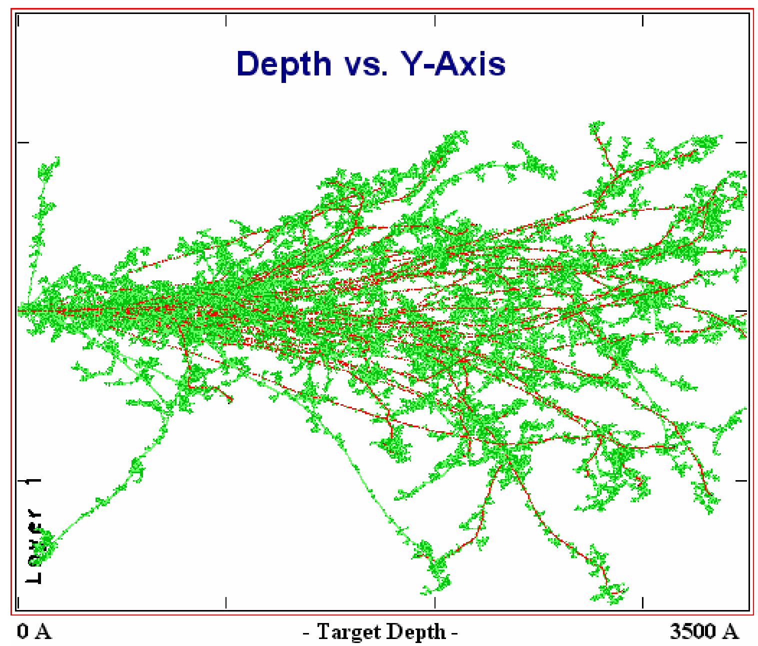


Microstructural response:

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



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



Slide prepared by V. Kuksenko (Oxford)

RaDIATE BLIP irradiation summary

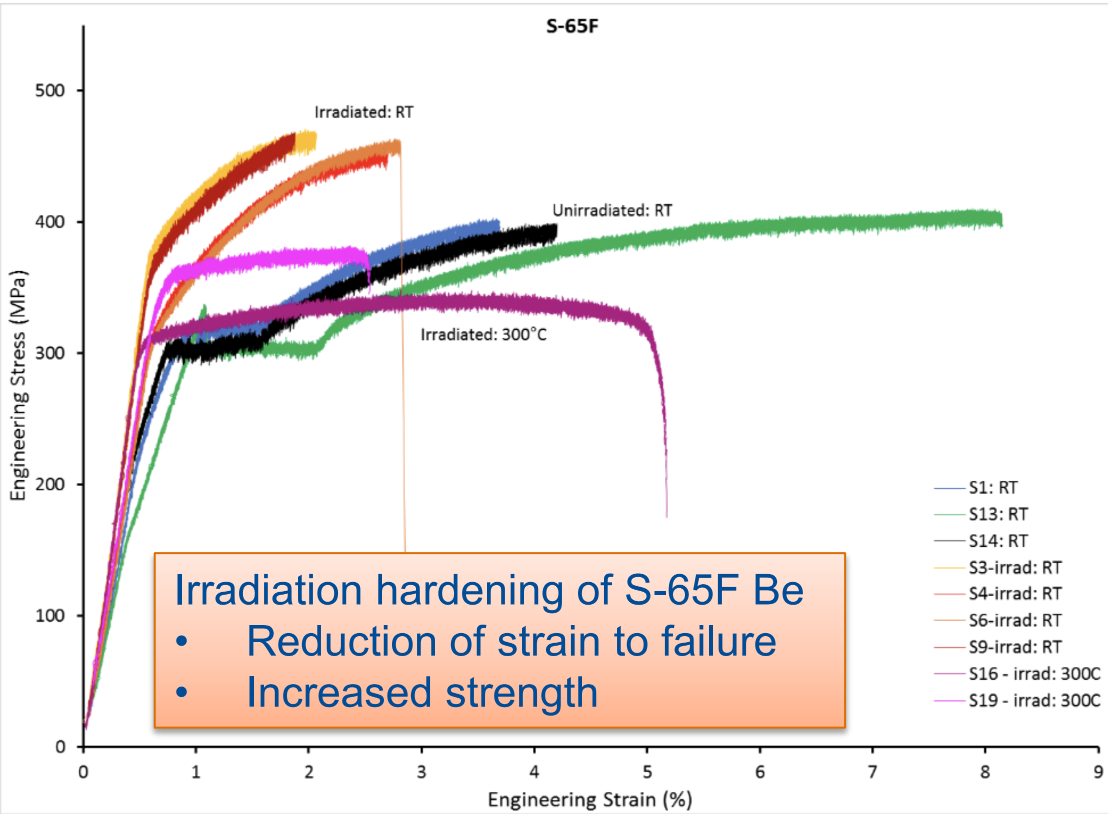
Consisted of **9 capsules** from 6 RaDIATE institutions with **over 200 material specimens** relevant to beam intercepting devices in various current/future accelerator facilities

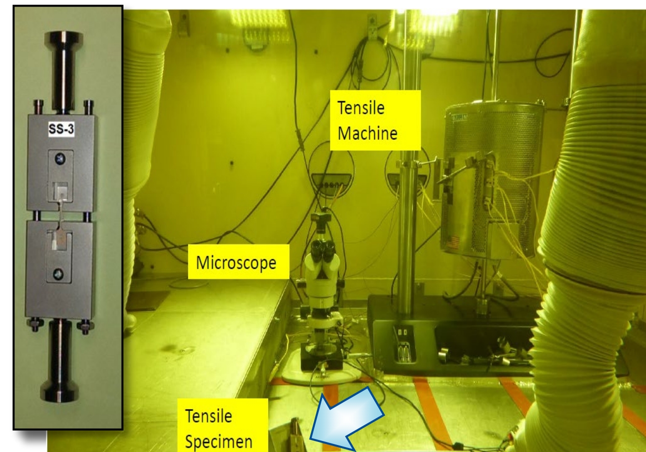
- **181 MeV** incoming protons used for RaDIATE irradiation
- Irradiation campaign executed in **3 phases** with different target box configurations
  - 6 capsules in target box during each irradiation phase
- Total protons on target: **4.57E21** (154 µA avg)

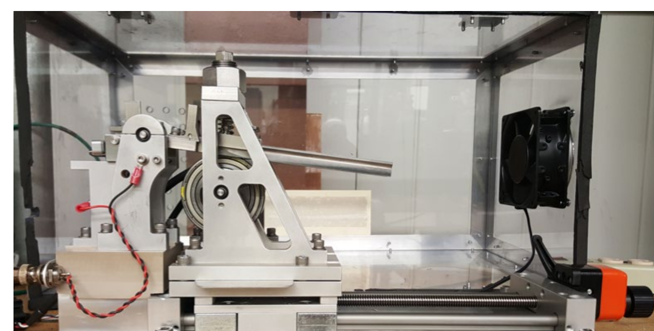
	2017		2018	Total
	Phase 1	Phase 2	Phase 3	
Total µA-hr	32464.49	45614.58	124979.89	203058.96
Total hr	226.27	302.94	789.09	1318.30
Total days	9.43	12.62	32.88	54.93
Total weeks	1.35	1.80	4.70	7.85
Avg. current (µA)	143.48	150.57	158.38	154.03
POT	7.30E+20	1.03E+21	2.81E+21	**4.57E+21**

BLIP Irradiation Examinations

- 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





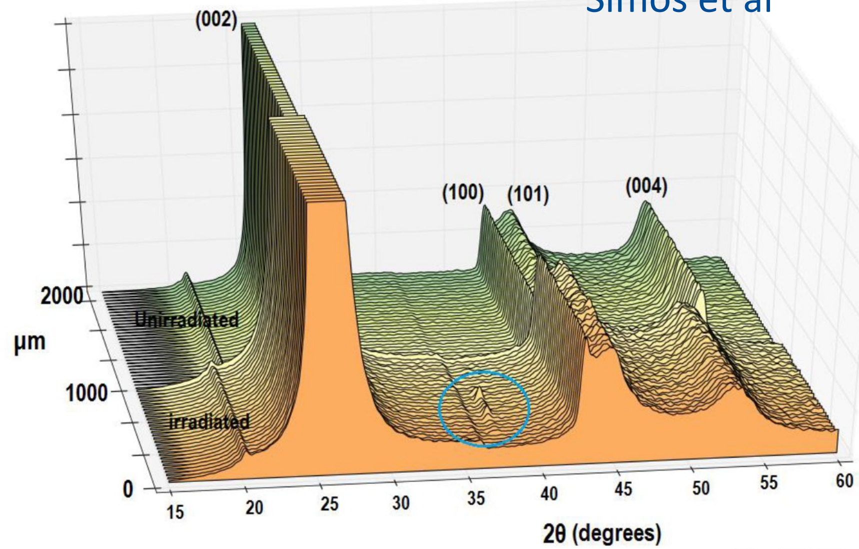


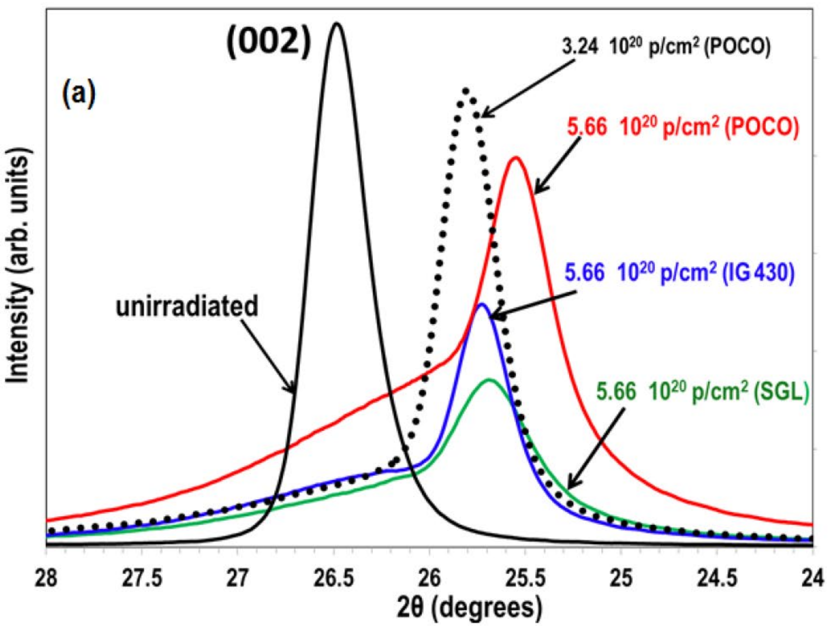
Custom Fatigue Testing Machine for Irradiated Materials (FNAL)

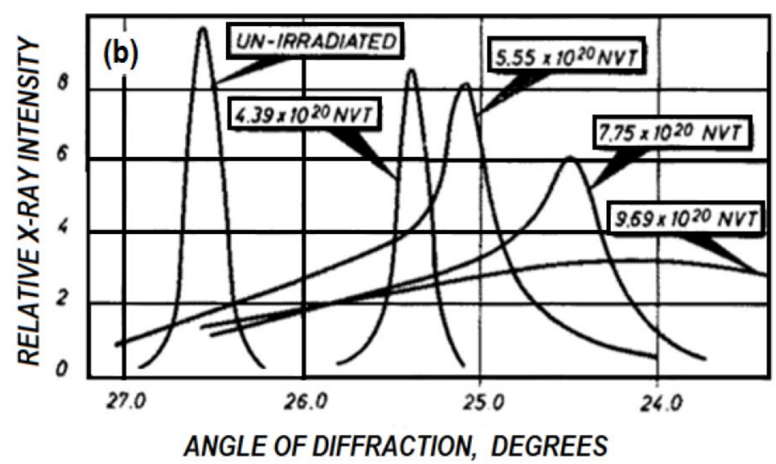
X-ray diffraction – Swelling in BLIP irradiated graphite

Simos et al

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



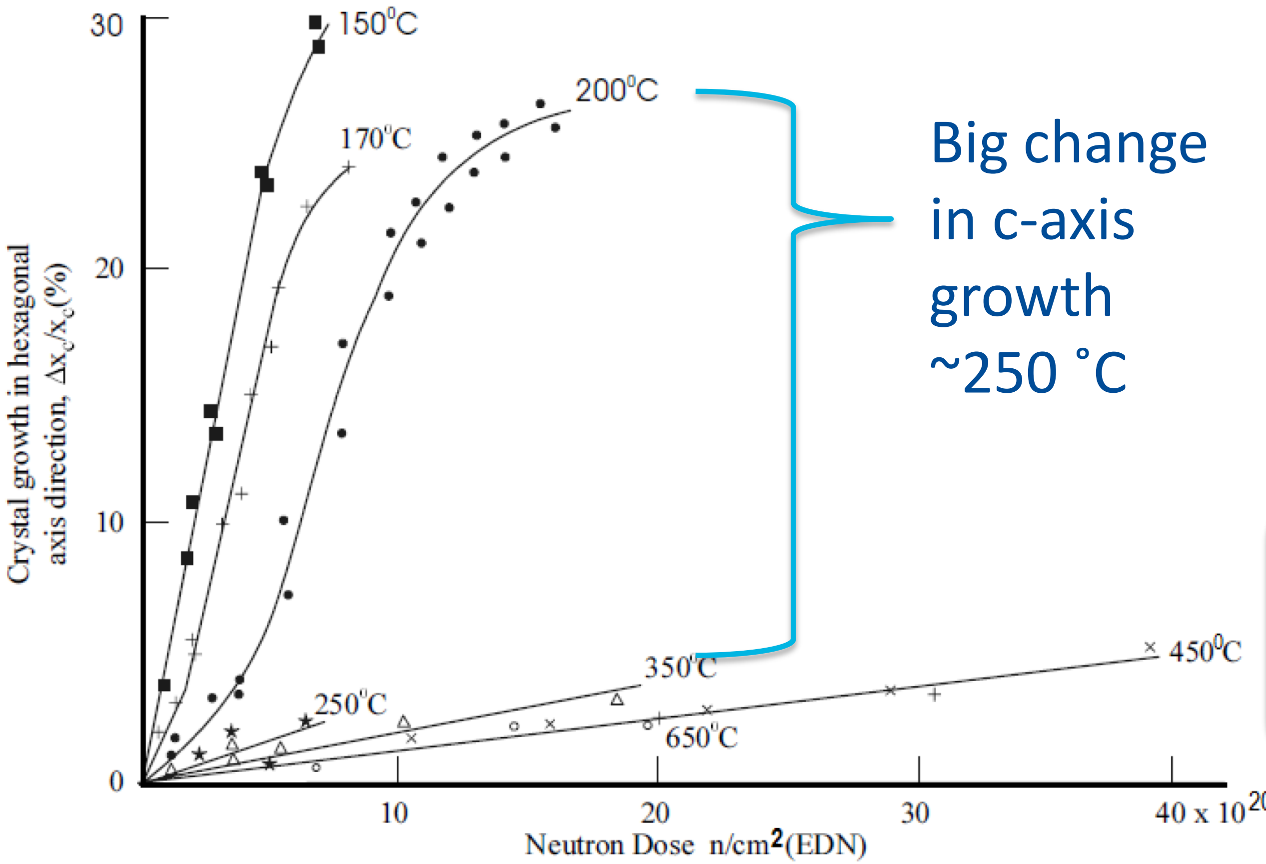




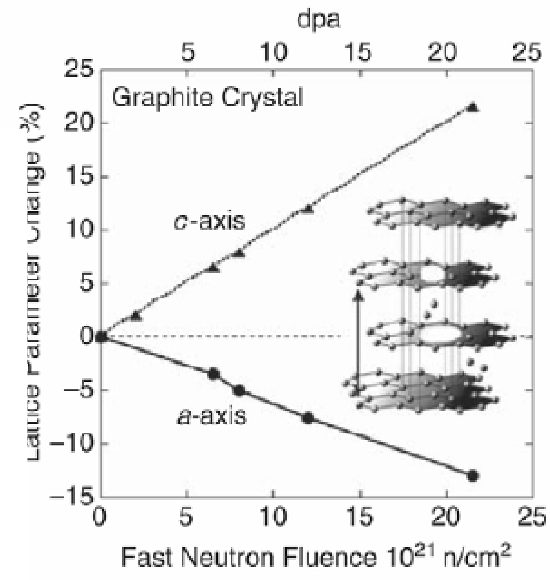
W. Bollmann. "Electron-microscopic observations on radiation damage in graphite" Phil. Mag., 5(54):621-624, June 1960.

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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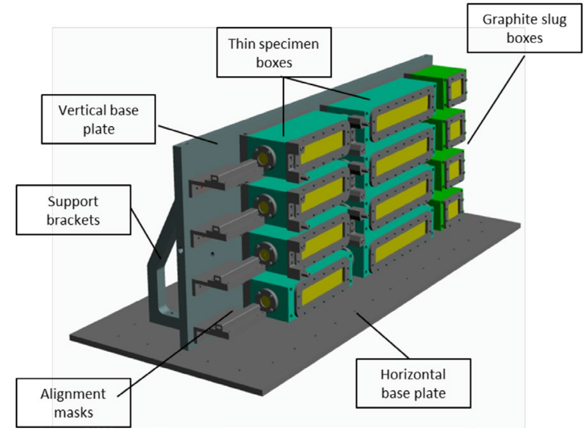
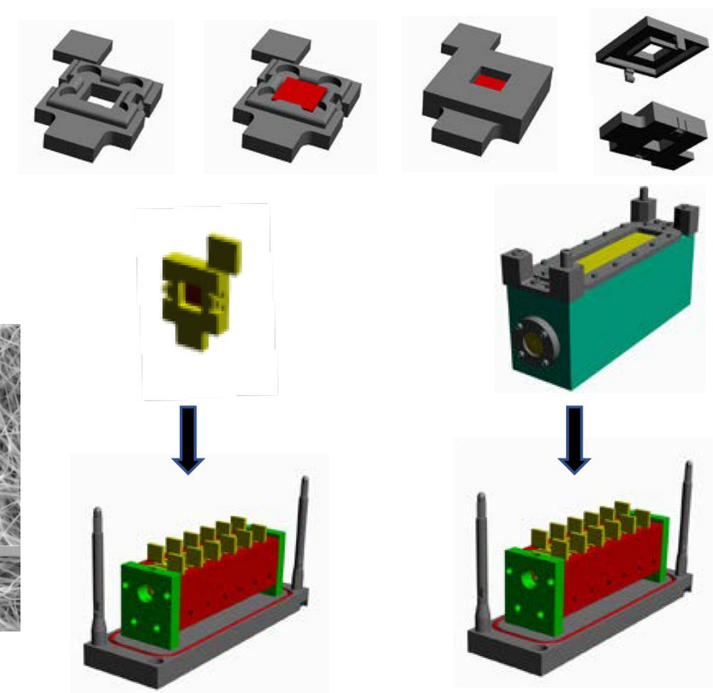
In-Beam Thermal Shock Test: BeGrid2 (HRMT43)

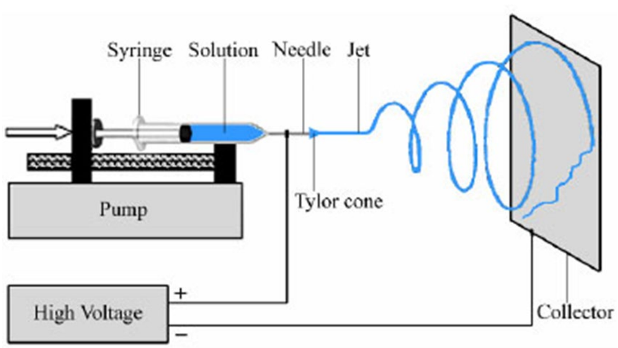


Primary Objectives:

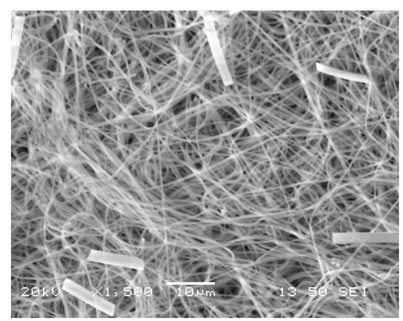
- Compare thermal shock response between <u>non-irradiated and previously irradiated</u> material specimens from BNL BLIP (Be, C, Ti, Si)
  - First/unique test with activated materials at HiRadMat



- 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

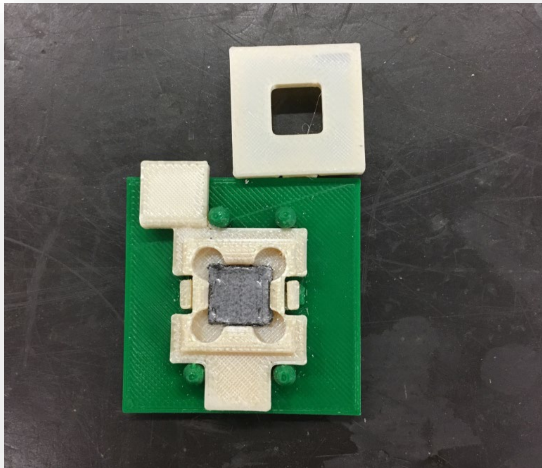


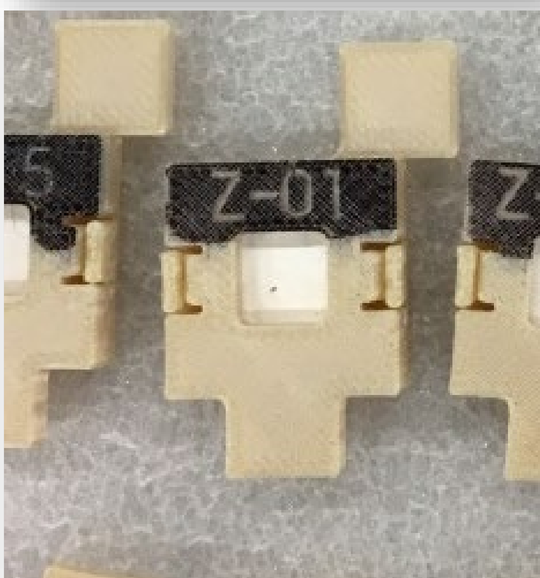
Electrospinning concept

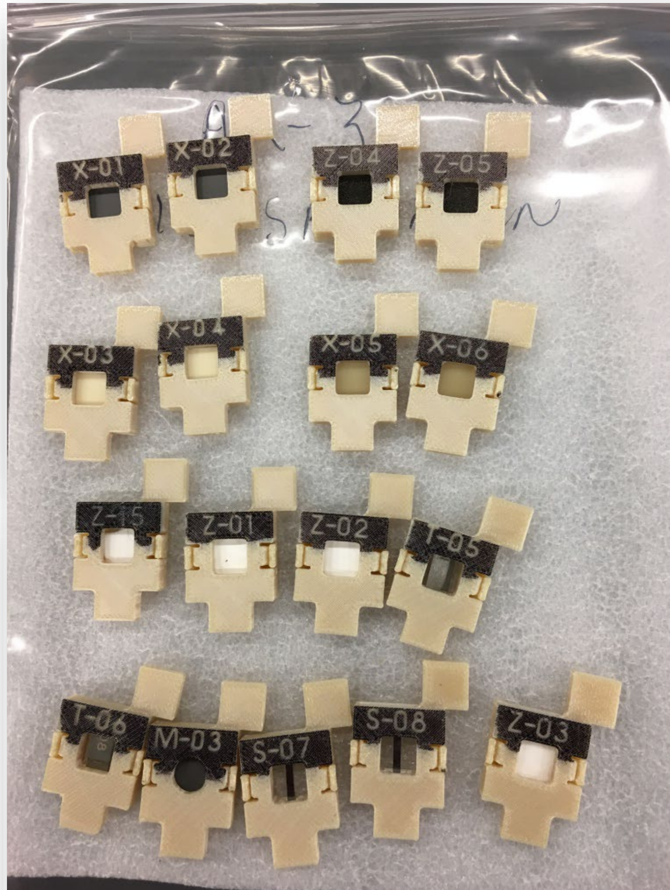


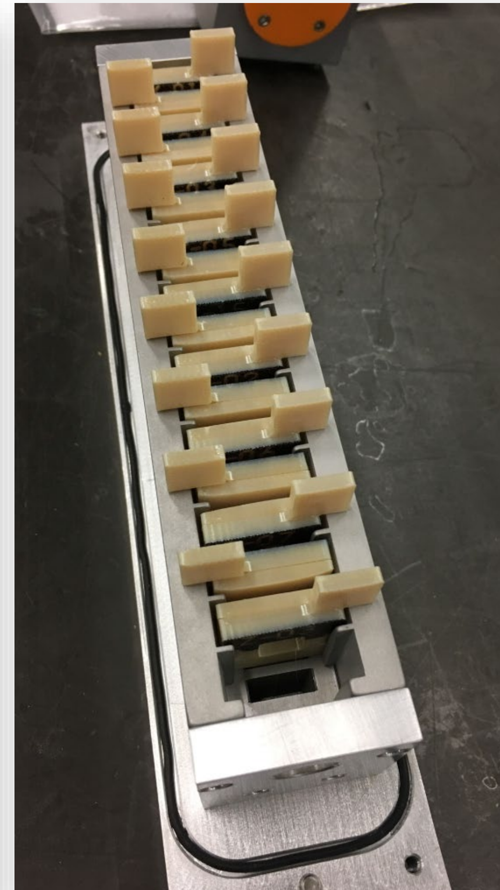
SEM: as-spun Al_2O_3

BeGrid2 (HRMT43) – 3-D printed specimen holders







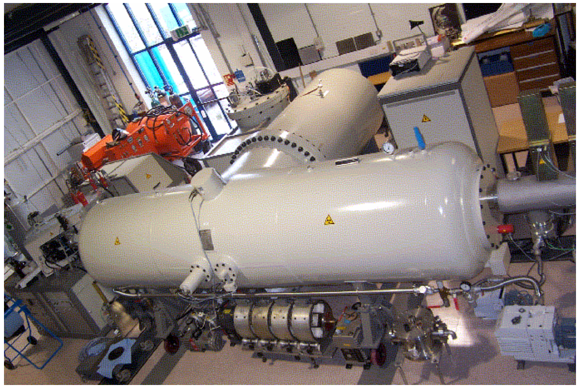


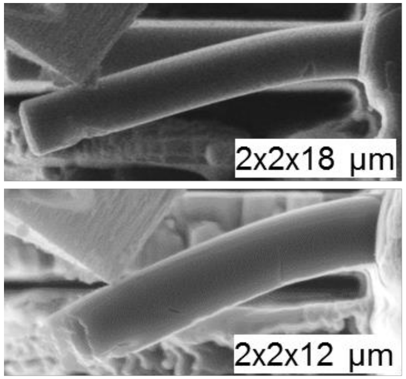
MIMiC - Methods of Irradiated Material Characterization

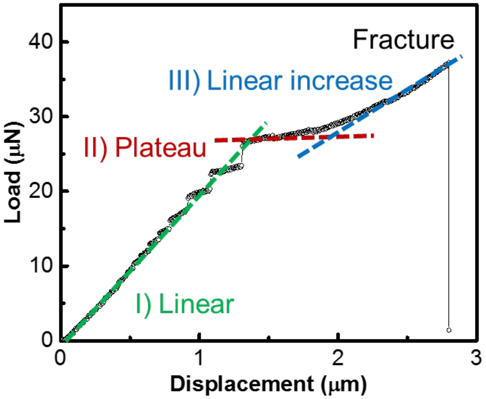
*Replicating proton beam interaction damage **with minimal residual activity***

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

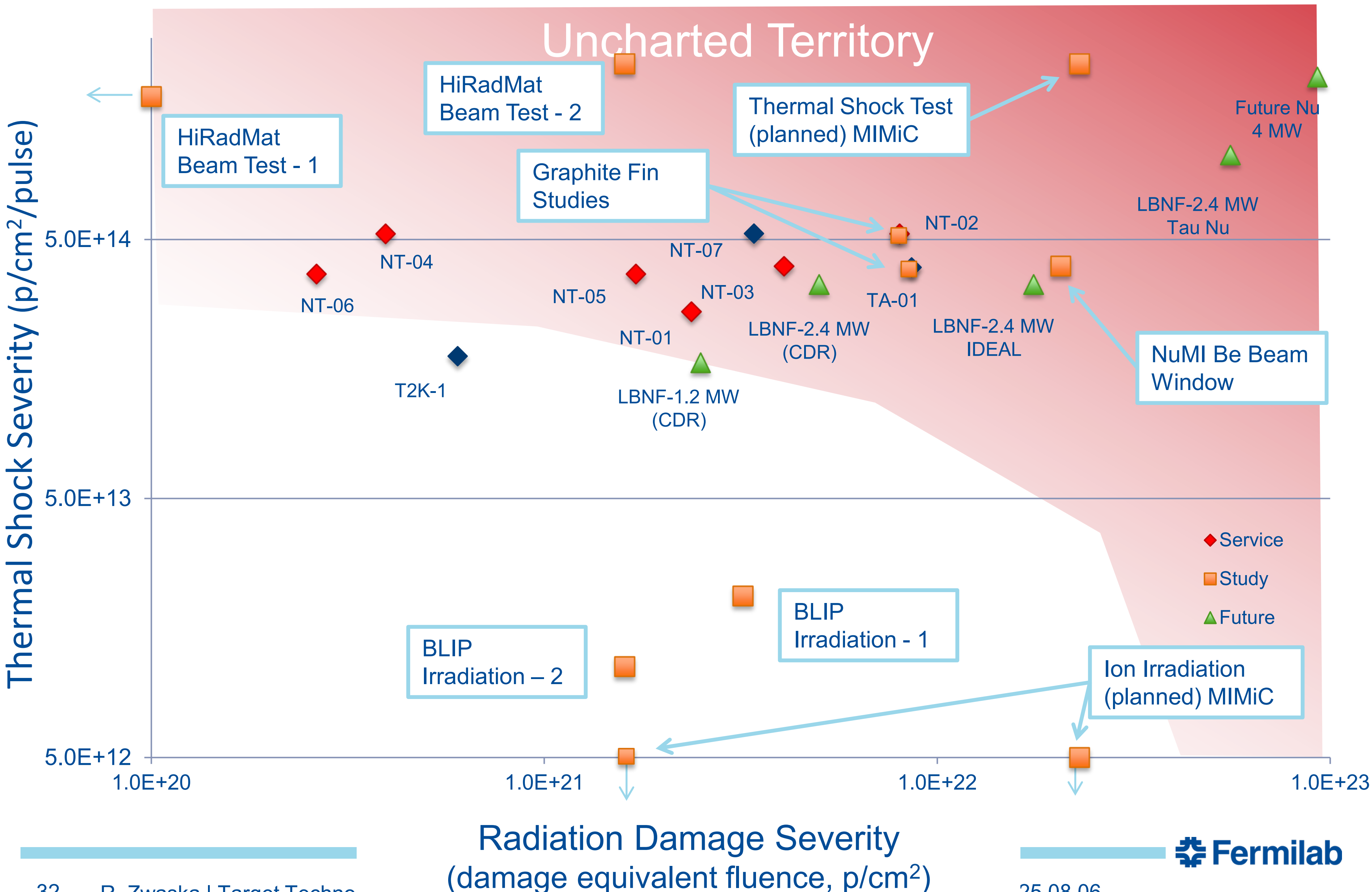
- **Low-energy ion irradiations** are attractive because they allow study of the evolution of the micro-structure during irradiation without activating the specimens, are relatively low cost, and can achieve high dose in very short durations.
- **Micro-mechanics** and meso-scale testing are potential 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

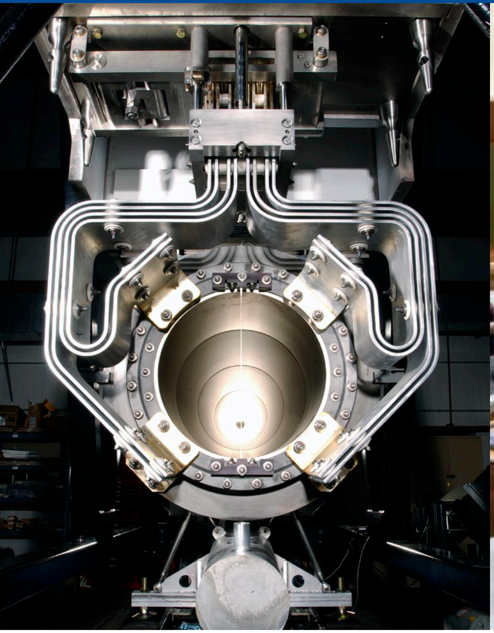


A few notes for Muon Collider Targets

- Most comparable configuration is Mu2e – challenging at 8 kW @ 8 GeV.
  - Extrapolation to Mu2e-II (100 kW @ 1 GeV) has no present solution
  - Cannot Extrapolate to historical Muon Collider (4 MW @ few GeV)
- Higher proton beam energy is better for the target (less power deposited in target for the same beam power)
- Separating target from optics is very beneficial
  - Has the capacity to allow rotation and more robust support systems
  - Can more forward production from higher-energy protons be used?
- Muon collider requirements on precision may be less strict
- Machine Protection is vitally important at high power. Targets and facilities must have this built in from the beginning.
- Attempt to avoid liquid targets. Enormous investment and R&D, many risks. SNS, ESS, J-PARC have all decided against liquid targets for new target stations

Summary

- There is broad experience in targets at Fermilab and elsewhere.
- Targets are challenging and can be the performance-limiting factor of a facility
- There is active development of new targets, and an active R&D program
- Muon Collider targets are beyond state-of-the-art; the facility could benefit from choices that allow more buildable targets



Target Technology

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6 August 2025