Beam Targetry for LBNF 2.4MW and RPF experiments - needed ACE R&D

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Fermilab ACE Science Workshop
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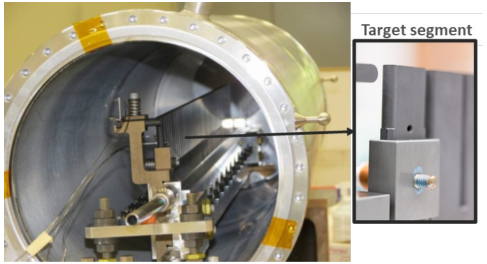
Outline

- Global High Power Targetry Context
  - Challenges
  - Facilitating research: the RadIATE Collaboration
- LBNF 2.4 MW Targetry
  - Concept
  - Challenges
  - Missing R&D
  - R&D Plan
- RPF Experiment Targetry
  - Beam Power evolution
  - R&D approach

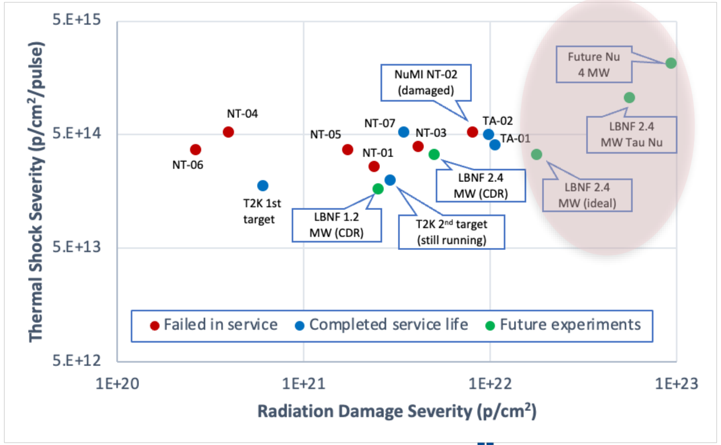
Critical Need for Robust High-Power Targets

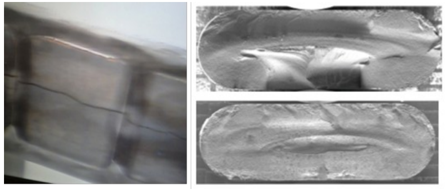
- The ultimate performance of high-power target facilities has been established by maximum capability and reliability of targets, beam windows, and other beam devices
  - Recently, major accelerator facilities have been limited in beam power not by their accelerators, but by target survivability concerns
- Timely HPT R&D research is essential to:
  - Enable and fully reap the physics benefits of next-generation multi-MW accelerator target facilities
  - Optimize the performance, reliability and operation lifetimes of target components as beam power and intensity increase
  - Understanding the radiation damage in material and thermal shock



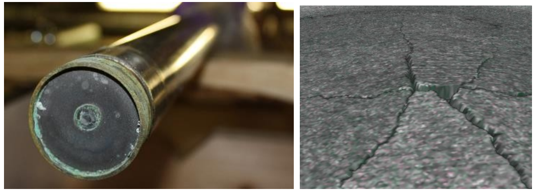
Graphite neutrino target (NOvA MET series)

Neutrino HPT R&D Materials Exploratory Map





MINOS NT-02 target failure: radiation-induced swelling (FNAL)



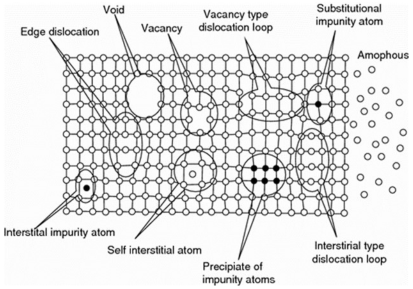
Beryllium window embrittlement (FNAL)

The Leading Material Challenges to Address…

Radiation Damage: Sustained irradiation disrupts the lattice structure of the material

D.L. Porter and F. A. Garner, J. Nuclear Materials, **159**, p. 114 (1988)

Bulk property degradation affects target health/performance



- Hardening and embrittlement
- Creep and swelling
- Fracture toughness reduction
- Thermal/electrical conductivity reduction
- Coefficient of thermal expansion

Relevant FOM is “Displacements per Atom” - DPA

Thermal Shock: Sudden energy deposition from pulsed beam generates dynamic stress waves

- Fast expansion of the material surrounded by cooler material generates localized area of compressive stress
- Stress waves move through the material at sonic velocities
- Plastic deformation, cracking and fatigue failure can occur

Thermal shock effect in an Iridium rod exposed to a high-intensity beam pulse at CERN’s HiRadMat facility

Thermal Fatigue: Cyclic loading progressively damages the material’s microstructure

R a D I A T E Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE collaboration created in 2012, with Fermilab as the leading institution.
Program manager: Dr. Frederique Pellemoine (FNAL) – **radiate.fnal.gov**

The collaboration has grown up to 20 institutions over the years.

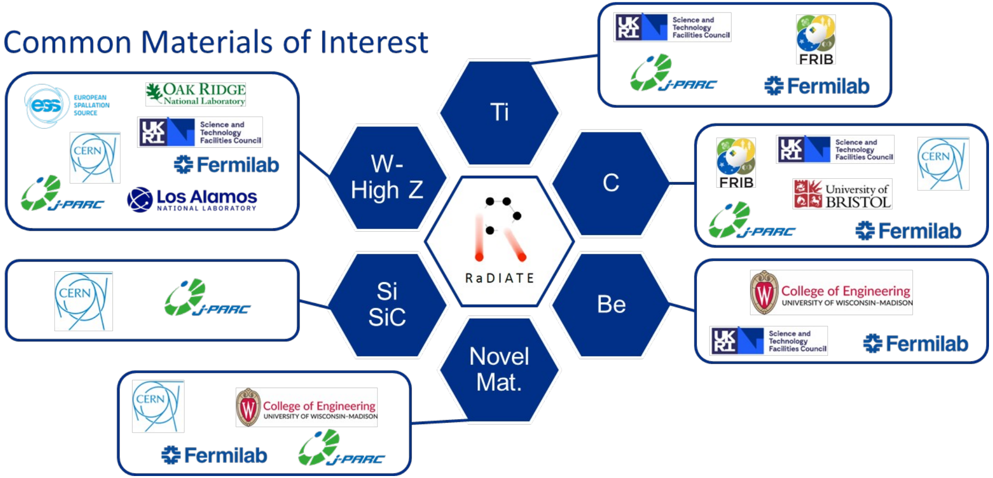
Objective:

- Harness existing expertise in nuclear materials and accelerator targets
- Generate new and useful materials data for application within the accelerator and fission/fusion communities

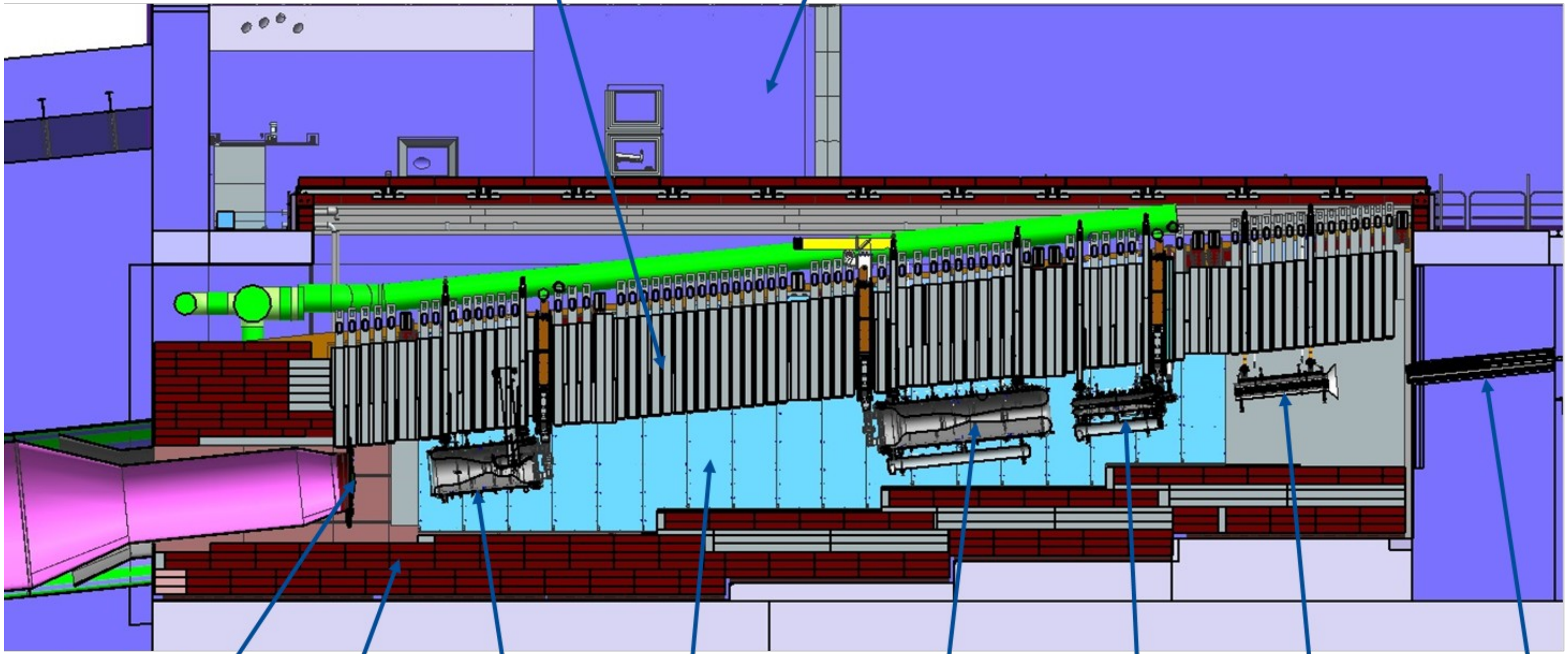
Activities include:

- Analysis of materials taken from existing beamline as well as new irradiations of candidate target materials at low and high energy beam facilities
- In-beam thermal shock experiments

Common Materials of Interest



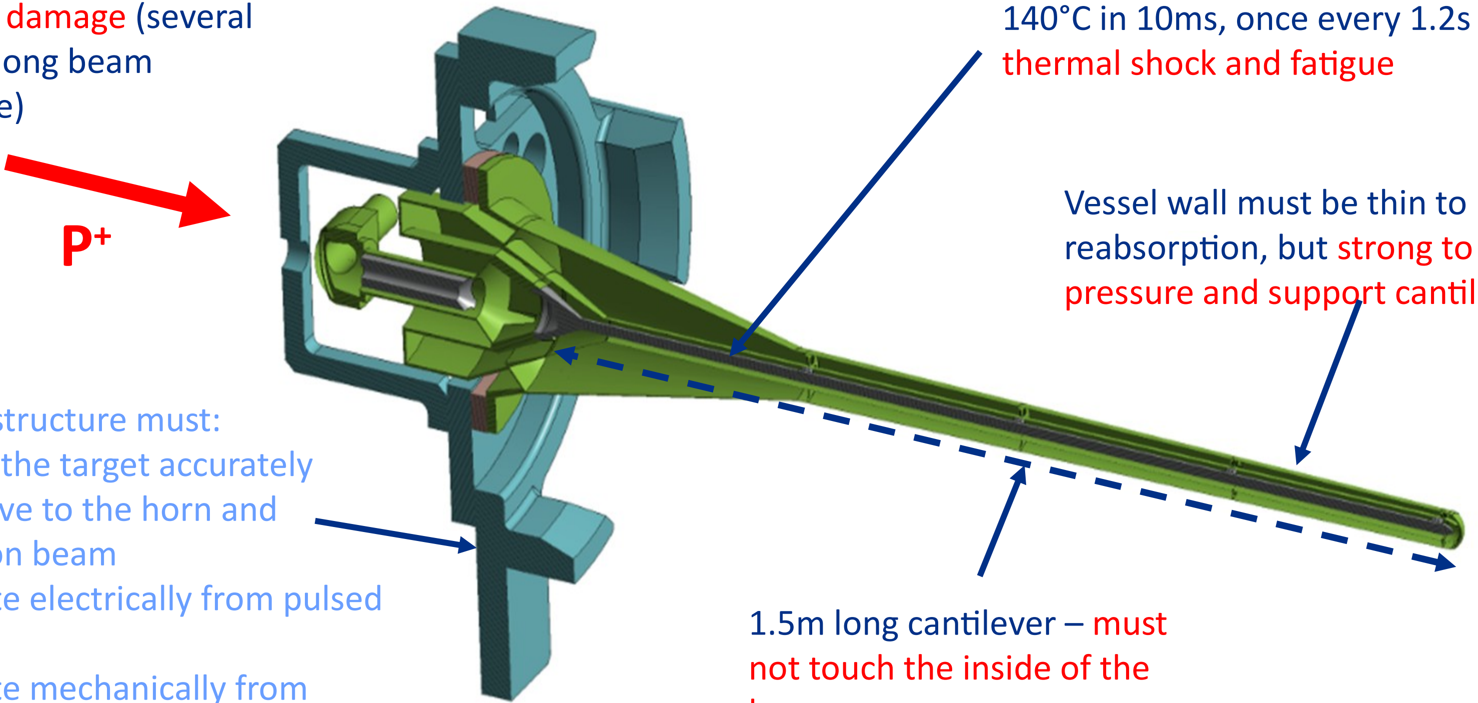
LBNF target systems - Beam-Intercepting Device Inventory



Target Engineering Challenges

Science and Technology Facilities Council

Proton beam causes very high heat deposition and radiation damage (several DPA/yr along beam centreline)



Target core temperature jumps by 140°C in 10ms, once every 1.2s – thermal shock and fatigue

Vessel wall must be thin to prevent pion reabsorption, but strong to contain pressure and support cantilever

Support structure must:

- align the target accurately relative to the horn and proton beam
- Isolate electrically from pulsed horn
- Isolate mechanically from pulsed horn

1.5m long cantilever – must not touch the inside of the horn

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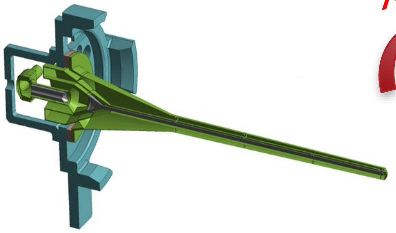
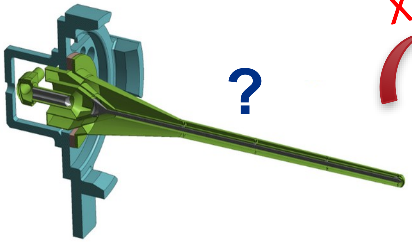
Production target concept – Neutrino Program



PIP-II LBNF 1.2 MW Graphite
1.5-1.8 m x 16 mm
25 kW in target at 120 GeV

X 2



?

ACE (MI) - LBNF 2+ MW
? m
50 kW in target at 120 GeV
same power density/pulse

X 2

?

ACE(BR) - LBNF 2.4 MW
? m
50 kW in target at 120 GeV
higher power density/pulse

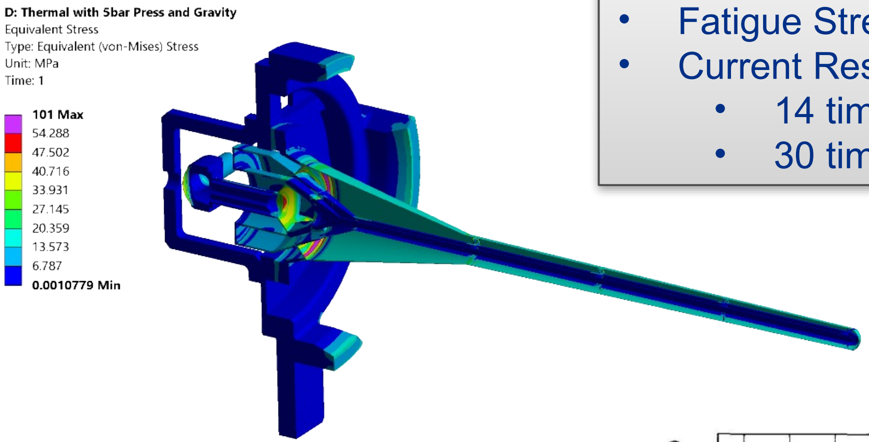
X 2

?

? 4 MW+ ??

More power density = More challenges

2.4 MW Operation: Target Thermal Fatigue in Graphite



- Fatigue Stress Cycle Amplitude will be similar to 1.2 MW
- Current Research Indicates 1.2 MW Design is:
  - 14 times less than graphite endurance limit
  - 30 times less than Ti alloy endurance limit

- No of Cycles x2 at 2.4 MW
- Not much change in endurance limit
- If beam spot same as 1.2 MW then DPA x2

	IG-43 Graphite
UTS at room temp (MPa)	37
Estimated endurance limit (MPa)	18.5
Beam pulse stress amp. (MPa)	1.3
Pulse cycles per year ()	1.50E+07
Beam trip stress amp. (MPa)	0.3
Trip cycles per year ()	4.99E+03

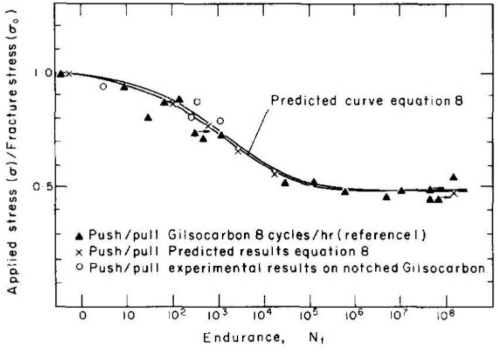


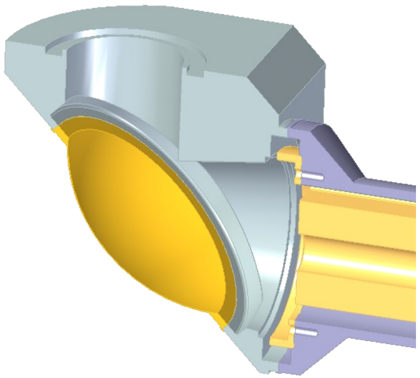
Figure 90. Fatigue strength of unirradiated Gilsocarbon graphite[159].

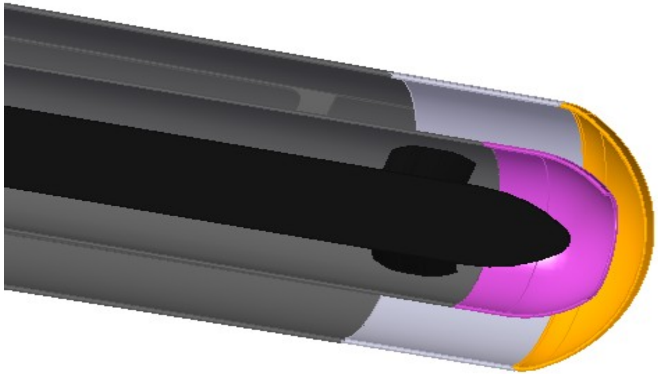
Fatigue lifetime based on un-irradiated material properties and different grade of graphite

Beam Window Ti alloy Selection

- Windows have higher temperature, radiation damage and fatigue than the container
- Peak dose: **0.14 dpa/yr in container**, **2.5 dpa/yr in upstream window**

Upstream Window
t_{min} = 0.3mm
Dose = 2.5dpa/yr
T_{max} = 115°C steady state, 150°C peak
ΔT = 70°C/pulse

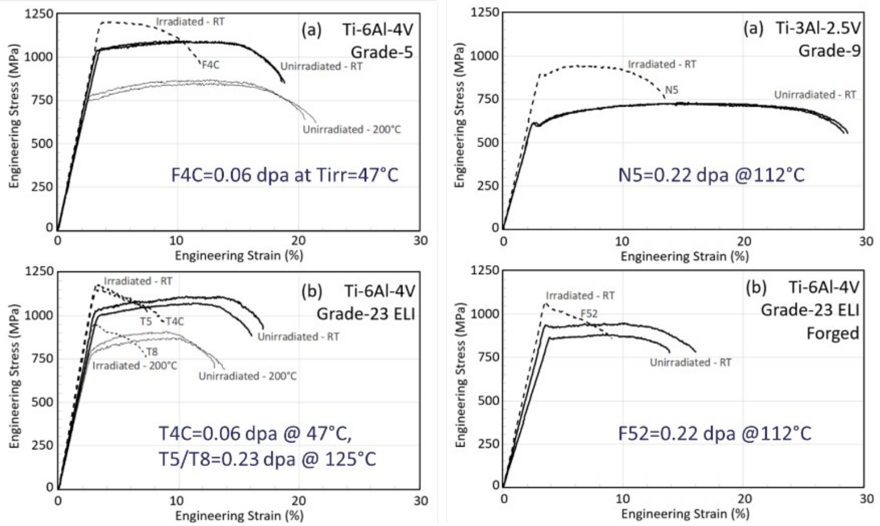




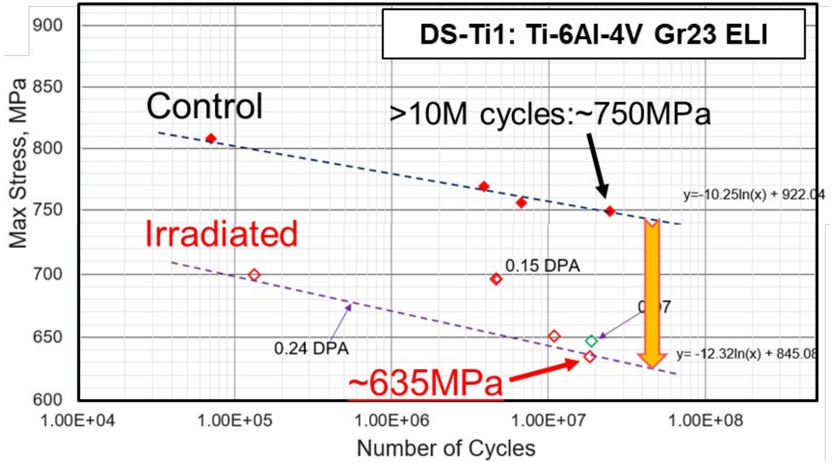
Downstream Window
t_{min} = 0.4mm
Dose = 0.7dpa/yr
T_{max} = 150°C steady state, 175°C peak
ΔT = 55°C/pulse

Irradiated Ti-alloys Data

- Available radiation damage data: up to **0.24 dpa**, mostly for grades 5 and 23



T. Ishida et al., J. Nuclear Materials 541 (2020) 152413



"Fatigue Performance of Proton Irradiated Ti6Al4V Alloy", Sujit Bidhar, 6th RaDIATE Collaboration Meeting, Dec 10, 2019

The few data of irradiated material are within a different range of temperature and dose

LBNF 2.4 MW Target Materials R&D Plan

- We will benefit from material studies for the 1.2 MW target led by UKRI/STFC (RAL)
- Identify candidate materials, grades, and operation conditions
  - Candidate materials: graphite, Ti-alloys, beryllium, aluminum,
    - novel material (nanofiber, High Entropy Alloys), organic material
  - Develop the operation conditions for testing (radiation damage, static stresses, shock, temperature, fatigue cycles)
- Collect experimental data (thermo-mechanical properties, structural change) of irradiated material within operation conditions
  - High-energy irradiation (BLIP or other) of representative material specimens
    - Reach representative levels of radiation damage in characteristic conditions, ideally design-equivalent levels
  - Pulsed-beam Experiments (HiRadMat or other) of irradiated specimens
    - Duplicate loading conditions of beam interactions
  - Non-beam PIE (Post-Irradiation Examination) of irradiated specimens
    - Test change in material properties (strength, CTE, density, hardness, ductility, thermal conductivity, …)
    - Material Science investigations of microscopic changes
    - High-cycle fatigue testing

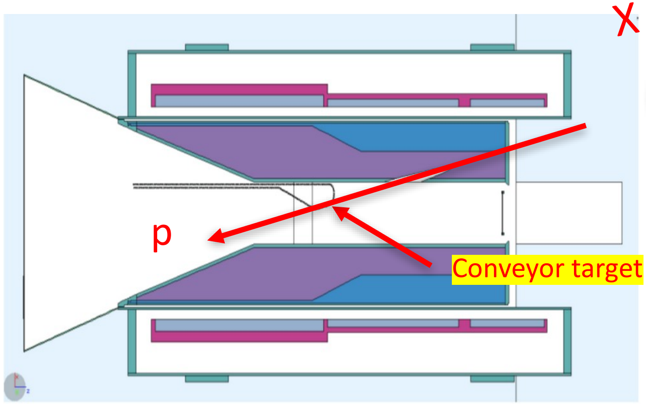
Similar to previous campaigns, but with new materials and specific operational conditions. We will continue the strong synergy within the RaDIATE Collaboration and have anticipating pre-project R&D

RPF Experiment Targetry - Production target concept – Muon Program

X 140

X 2.5

X ?



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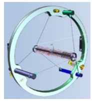

Mu2e Target core Tungsten
6.3 mm x 220 m
700 W in target at 8 GeV

Mu2e-II Target core C, W, WC, SiC,…?
~ 10 mm x 200 mm
100 kW in target at 800 MeV

AMF Target core ?
??
250 kW in target at 800 MeV

Muon Collider 1 to 4 MW
??
300 kW in C target at 8 GeV

More power density = More challenges

RPF Experiment Targetry – R&D Approach for Muon Collider

DESIGN

- FEA simulations

Science and Technology Facilities Council · Fermilab · CERN · J-PARC · Oak Ridge National Laboratory

PHYSICS

- Evaluate physics performance

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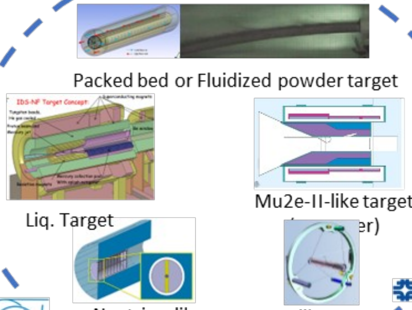

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MATERIAL

- Material Sciences
- Radiation Damage

RaDIATE

R&D Phase up to 2030

Demonstration Phase up to 2040

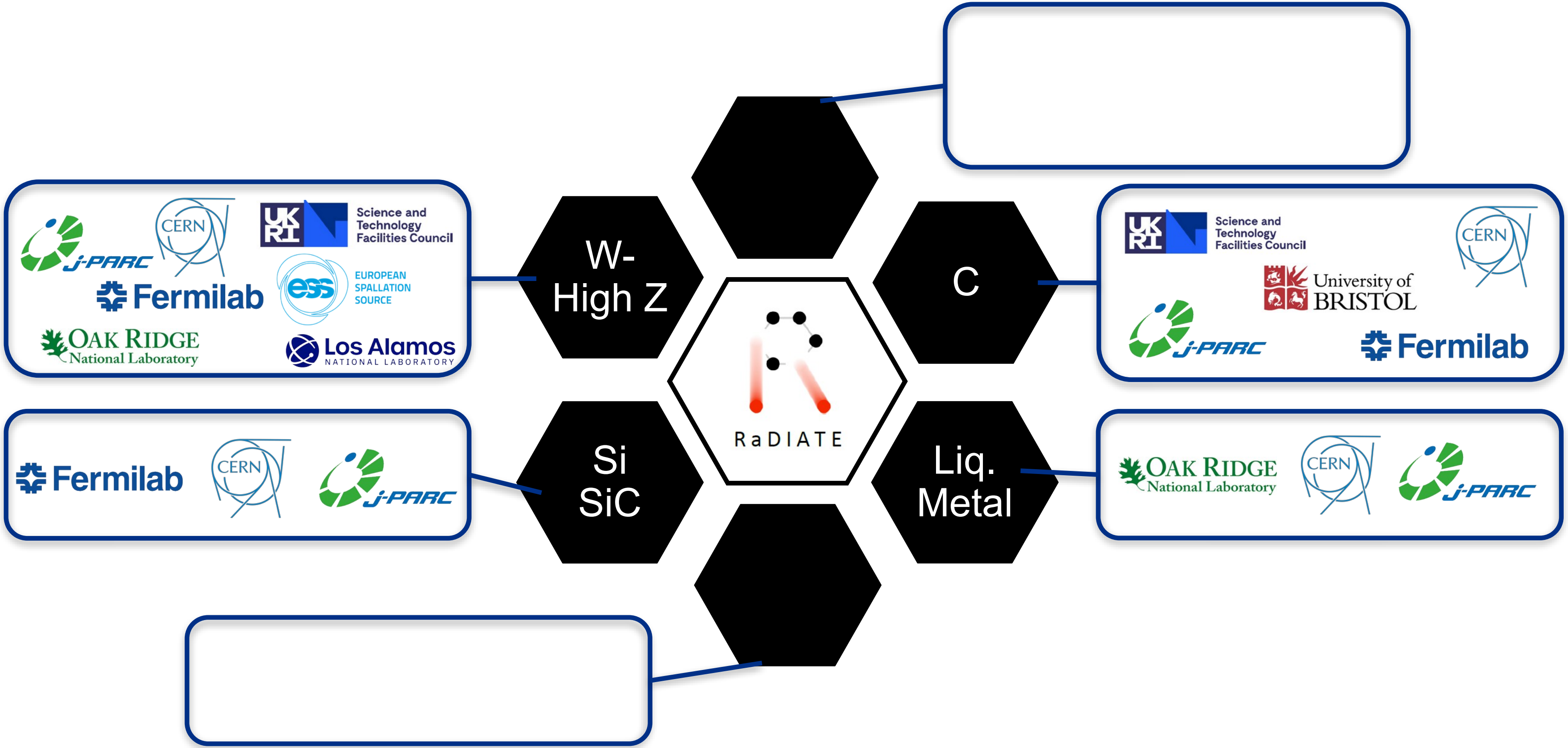
Selected Target Design → Prototype

How can Muon Targetry Fit into Fermilab HPT R&D?

- Funding streams:
  - General Accelerator Research and Development (GARD) - Pre-conceptual design / and Material R&D
  - Operations/Projects fund design and construction
  - Partners: RadiATE support and IKC
- Focus has been on neutrino beams and accelerator components
  - ➢ Can certainly be extended to other HEP applications

  Fermilab HPT R&D so far focused on fixed target made of graphite, beryllium, Ti-alloys, High entropy alloys and ceramic nanofiber
    - High-Z material with very short muon bunches
      - ⇨ Not part yet of HPT R&D program
      - ⇨ R&D already ongoing through RaDIATE collaboration
    - High efficiency cooling and/or novel concept need to be developed
      - ⇨ Not part yet of HPT R&D program
      - ⇨ More R&D needed through our RaDIATE collaboration
  - ➢ Design development:
    - Unproven concept exist for 100 kW (Mu2e-II) but will require significant R&D effort
    - For AMF, no idea how to build a MW scale target
      - ⇨ Synergies with Muon Collider R&D paths

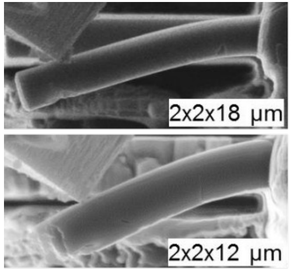
Potential Materials for Muon Production Targets and related R&D



Tools Needed to Support R&D Program

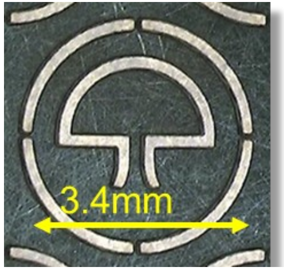
- High energy beam irradiation
  - Highly activated material

➡ **Need to develop PIE: hot cells and specific characterization equipment**

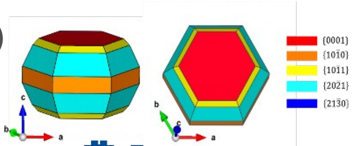


  - High energy ⇨ Low dpa rate ⇨ long irradiation time (order of months) ⇨ Expensive
- Alternative radiation damage method
  - Low-energy ion irradiation
    - Lower cost, high dose rate without activating the specimen
  - Few heavy ion irradiation facilities around the world

➡ **Need more development of such facilities with higher intensity**



- Ab initio and molecular dynamics (MD) modeling
  - still not yet mature enough to model atomistic changes to micro-structural evolution to macro-properties of real-world materials. Prediction of fundamental response of various material classes to irradiation helps steer material choices and experiment design for future irradiation studies
    - Modeling of He gas bubbles in Beryllium and of novel material radiation behavior (HEAs)



➡ **Need to develop this expertise at FNAL**

High Power Targetry R&D Needs Summary

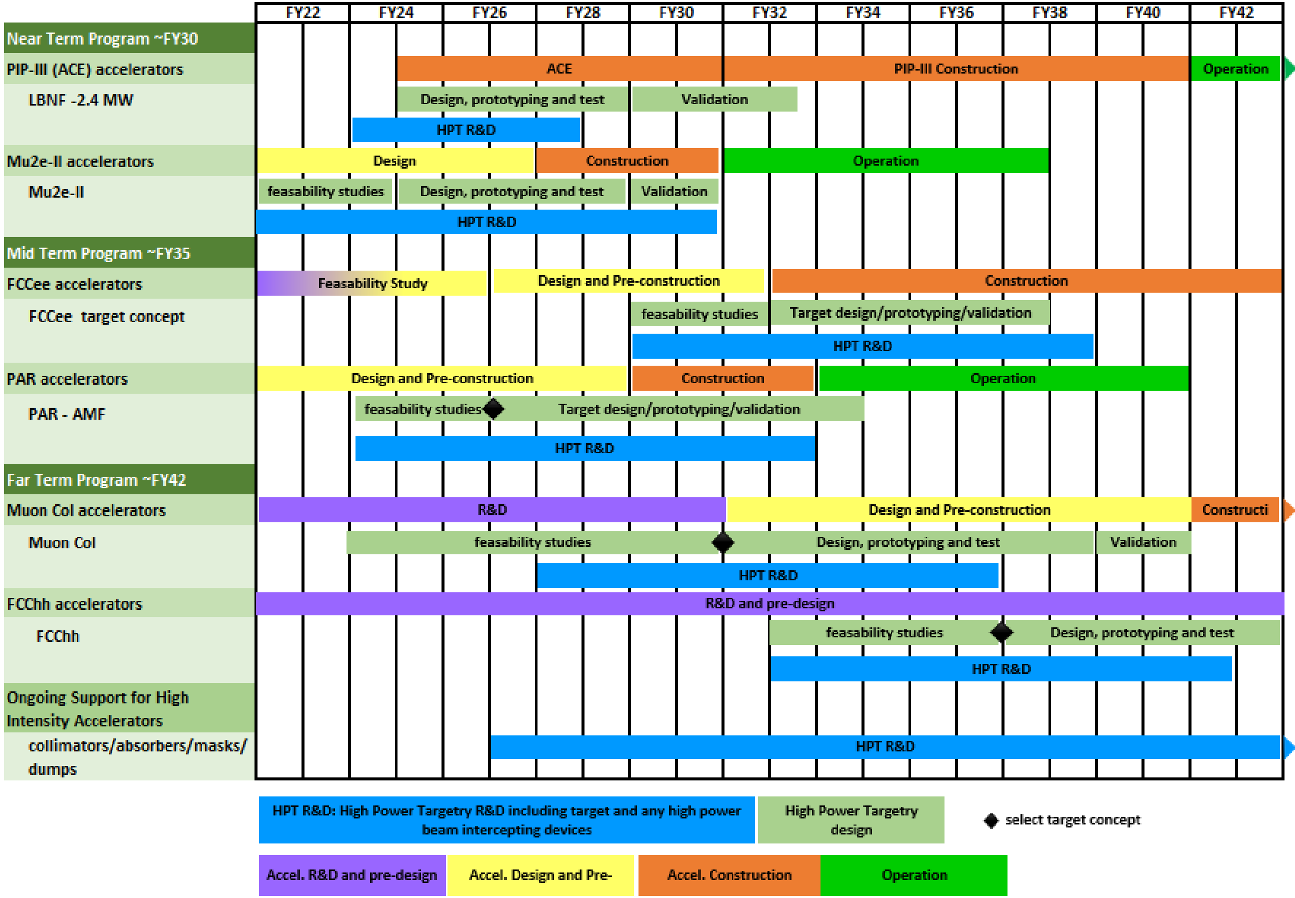
- Future high-power beams present critical target facility challenges
  - Understanding material behavior under intense multi-MW beams is high priority
- Materials R&D essential to help design robust targetry components and maximize primary beam power on target and secondary particle production
  - Globally coordinated R&D activities using in-beam tests to produce useful results
  - Develop alternative irradiation facilities, material testing and characterization methods essential to support R&D program
  - Explore Novel material with enhanced radiation damage and thermal shock resistance to support future high-power Targetry components
  - Develop modeling to support all activities above
- With more resources we can reduce R&D cycle time and cover all the activities needed to support HPT for next generation accelerators

ACE (BR) Questions

- How will your system address the ACE (BR) goals?
  - HPT R&D required for a successful LBNF 2.4MW target and beam windows
  - HPT R&D required for other high power “spigots” (Mu2e-II, AMF, BD, etc)
- What are the biggest risks for targetry?
  - Not getting started early enough! Irradiating materials followed by PIE is time and resource intensive: significant planning, coordination, cooldown, etc
  - Failures/conservative operations limit beam power and physics reach
- What are the most sensible steps to enable progress? What can be done before the next ACE event?
  - We have already articulated a plan to P5 for ACE target R&D, and outlined a roadmap for GARD. Execution requires a funding profile.

HPT R&D Roadmap

- HPT R&D is aligned with timeline of HEP Accelerators



HEP HPT R&D Workshop – April 11-12 2023