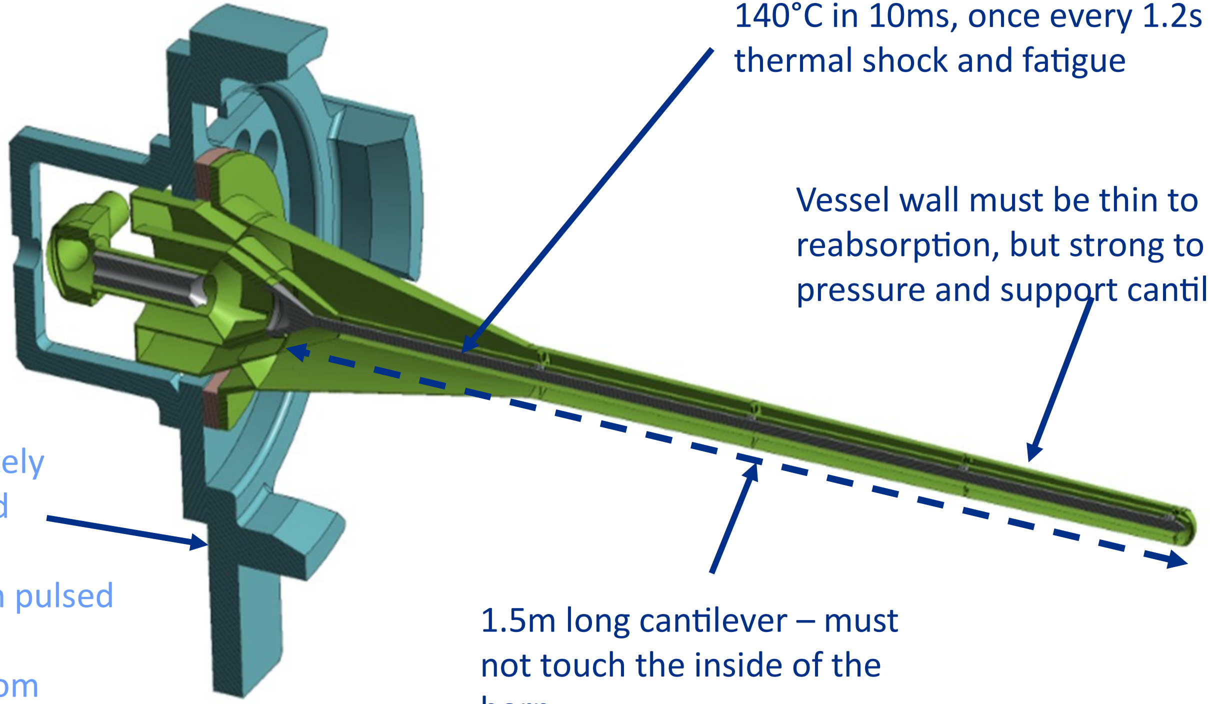
Target Engineering Challenges

Science and Technology Facilities Council

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

P^+



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

Fermilab

LBNF Target and Window Material R&D for 2.0+ MW

- Current LBNF Target is designed for 1.2 MW
- Option zero
  - Stress level similar to 1.2MW target but number of cycle x 2 for 2.4 MW
  - If same beam size as 1.2 MW the damage dose (dpa) X 2
- R&D Status
  - Fatigue lifetime and design based on un-irradiated material properties and different grade of material
  - The few data of irradiated material are within a different range of temperature and damage dose

LBNF 2.4 MW Target Materials R&D Plan

- We will benefit from material studies for the 1.2 MW target led by STFC
- 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

Target Technology for Muon Collider

- Targets are challenging:
  - Remove a lot of deposited heat
    - Convection, conduction, radiation
  - Survive thermal shock, survive radiation damage
  - Minimal/remote maintenance – high activation area
- Need more than just beam power to describe challenge
  - Many small pulses have less thermal shock than few large pulses
  - High energy low current has less thermal shock than low energy high current
    - Multi-MW at 120 GeV (LBNF) is very different than multi-MW at 4-8 GeV (MuC)
- MuC target also has large, high field solenoid that must be protected from radiation
- MuC isn't the only HEP customer for beyond-state-of-the-art targets: LBNF/DUNE Phase II, Mu2e-II, AMF

How can Muon target fit into HPT R&D?

- General Accelerator Research and Development (GARD)
- High-Power Targetry (HPT)
- Potential successors to Mu2e: Mu2e-II and AMF
- Focus has been on neutrino beams and accelerator components
  - Can certainly be extended to other HEP applications
  - 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
      - ⇨ Some investigation through our RaDIATE collaboration
    - High efficiency cooling and/or novel concept need to be developed
      - ⇨ Not part yet of HPT R&D program
      - ⇨ Some studies through our RaDIATE collaboration already ongoing
  - Design development:
    - Unproven concept exist for 100 kW (Mu2e-II) but will require R&D effort
    - For AMF, no idea how to build a MW scale target

Production target concept – how to transfer knowledge to next generation

LBNF Target core Graphite
16 mm x 1.5 m
25kW in target at 120 GeV

X 140

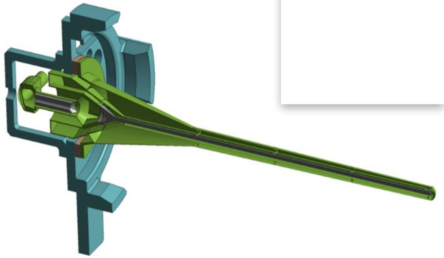
Mu2e Target core Tungsten
6.3 mm x 220 m
700 W in target at 8 GeV

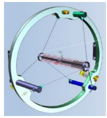
X 2.5

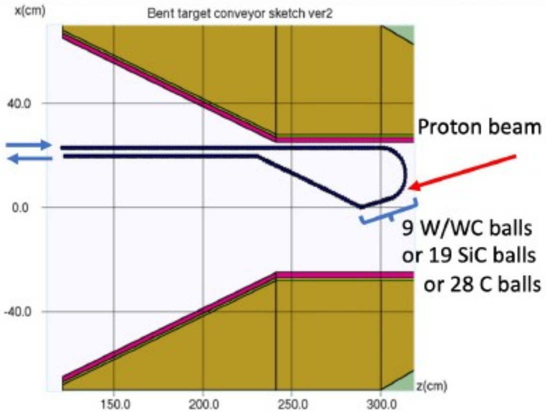
Mu2e-II Target core C, W, WC, SiC,…?
~ 10 mm x 200 mm
100 kW in target at 800 MeV

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

More power density = More challenges







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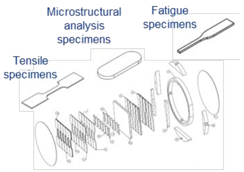
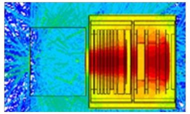
R&D, prototyping are needed!

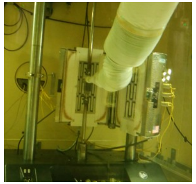
High Power Targetry R&D Approach





<u>In-Beam Studies</u>: *collect needed information to support Target design for future generation.*

- **<u>Irradiated Material Studies</u>** (high energy proton irradiation at BNL-BLIP)
- **<u>thermal shock testing</u>** (CERN-HiRadMat)

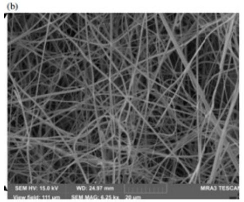


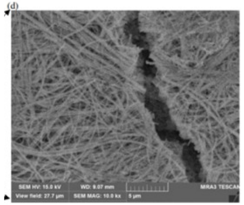
RaDIATE

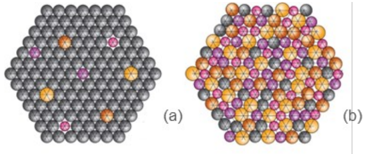
<u>Novel Material Development</u>: *new materials with enhanced physical properties and radiation damage resistance.*

Kavin Ammigan's ECRP awarded in July 2022

- **<u>High Entropy Alloys</u>** (HEAs)
- Ceramic and Metalic **<u>Nanofiber</u>**



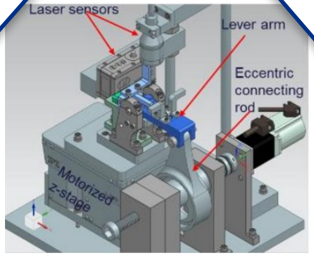




(a) Conventional alloy, (b) High-entropy alloy (Miracle & Senkov, 2016)

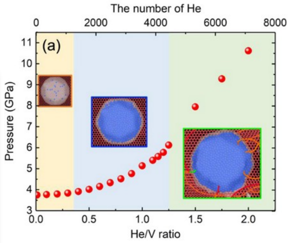
<u>Alternative Methods</u>: *Mimic high energy proton irradiation with alternative beam for cost and time effective irradiation*

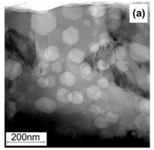
- **<u>Low Energy Heavy Ion</u>** Irradiation for radiation damage
- **<u>Electron beam</u>** for thermal shock test
- **<u>Mechanical testing</u>** for fatigue studies



<u>Modelling</u>: *Prediction of fundamental response of various material classes to irradiation. steer material choices and experiment design for future irradiation studies*

- **<u>He gas bubbles</u>** in Beryllium
- **<u>Radiation damage</u>** in High Entropy Alloys
- **<u>Heat transfer mechanism</u>** in nanofiber media





Tools to Support R&D Program

- High energy beam irradiation
  - Highly activated material

Need to develop PIE: hot cells and specific characterization equipment

  - High energy **p** Low dpa rate **p** long irradiation time (order of months) **p** Expensive
- Alternative radiation damage and thermal shock method
  - Low-energy ion irradiation
    - Lower cost, high dose rate without activating the specimen
    - Few heavy ion irradiation facilities around the world
  - Electron beam for thermal shock

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