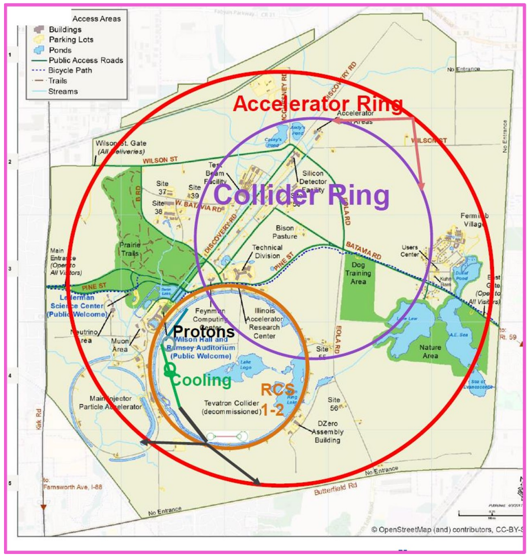
Advancing Targetry R&D for The US Muon Collider

Katsuya Yonehara

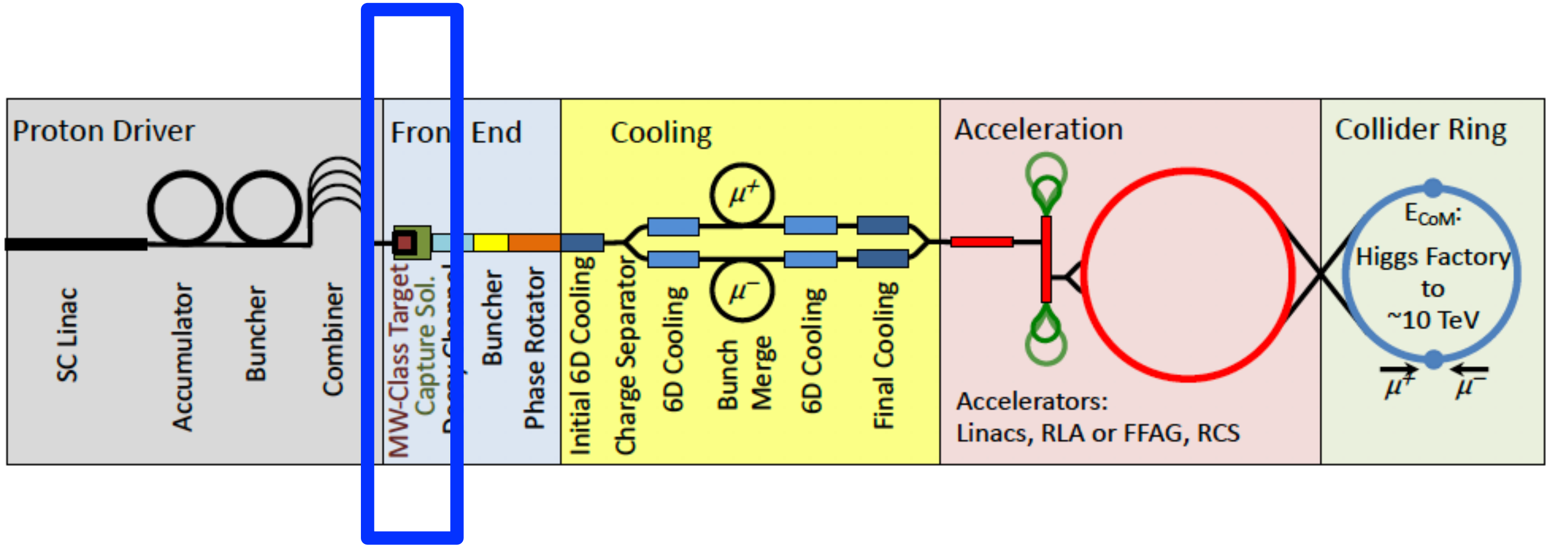
Princeton Workshop

2/23/2024



Layout of muon accelerator complex for colliders

Targetry (cover in this talk)



MAP baseline design (based on simulation study)

- **Proton driver**: 10^{14}-10^{15} protons within 1-3 ns bunch length
- **Front end**: π/μ capture section (μ/p efficiency 10-15 % for each sign)

MW-Class Target: Interface between proton driver and Front end channel

Characteristics of Proton beam parameter at intense beam facility

	Neutron spallation source (ESS, SNS, CSNS)	**Accelerator Neutrino beam (T2K, CNGS, NuMI, SBN, LBNF)**	**Muon collider (MAP, IMCC design)**
Proton beam energy	Low (1-3 GeV)	Wide range (8-400 GeV)	Medium (5-20 GeV)
Proton beam bunch length	Short (105-700 ns)	Long (4.2-10.5 μs)	**Extremely short (1-3 ns)**
Proton beam intensity per bunch	Medium (1e13-1.5e14)	Medium (4.8e13-3.2e14)	**High (1e14-1e15)**
Repetition rate	High (14-60 Hz)	Low (0.4-2 Hz)	Medium (5-15 Hz)
Target material	Liq. Hg, W, Liq. Li etc	graphite	?

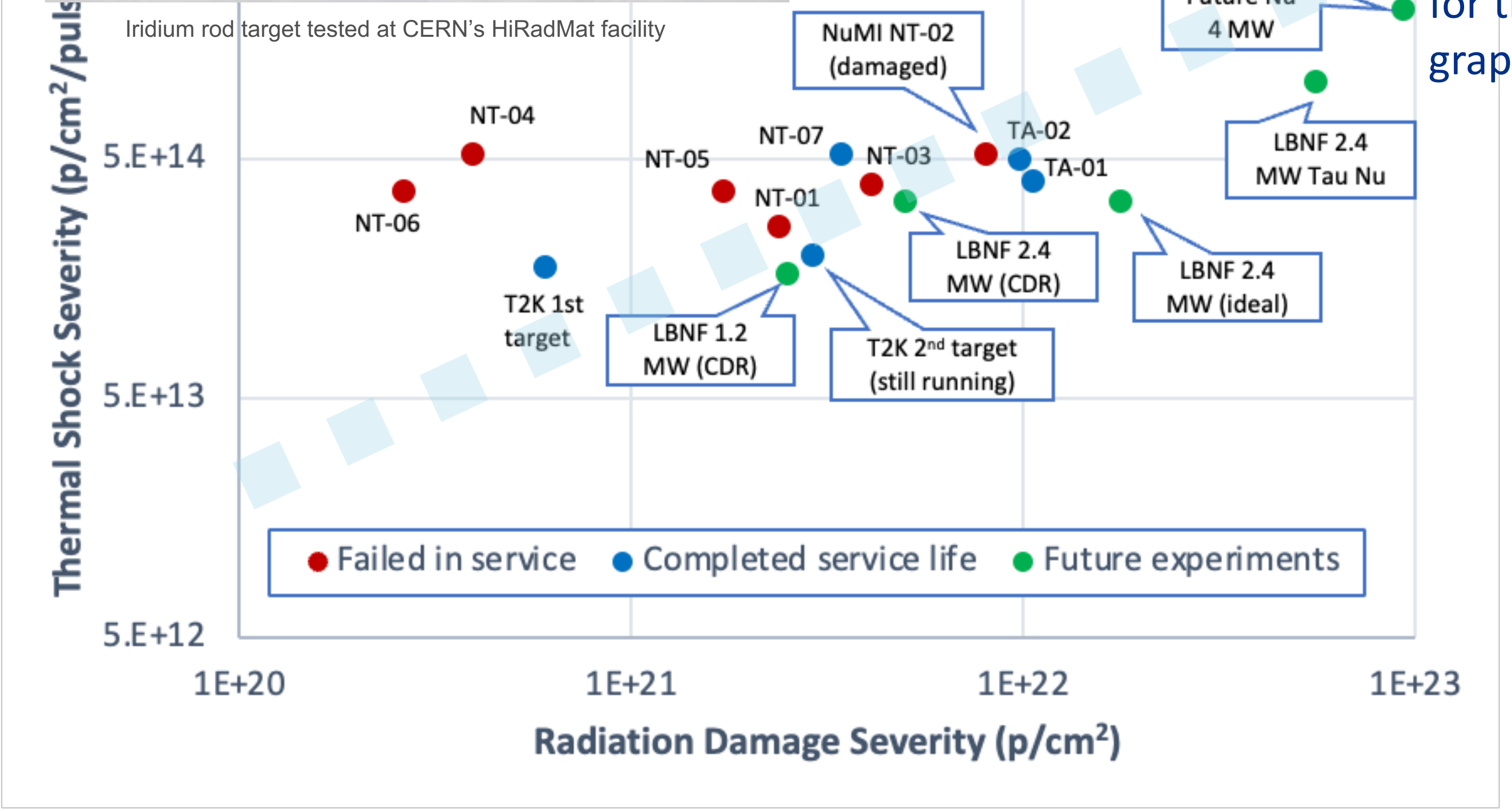
Is there any target capable of withstanding such an exceptionally high thermal shock?

Thermal shock is a key parameter for survivability of High-Power Target

Metal rod exploded by beam impact

Iridium rod target tested at CERN's HiRadMat facility

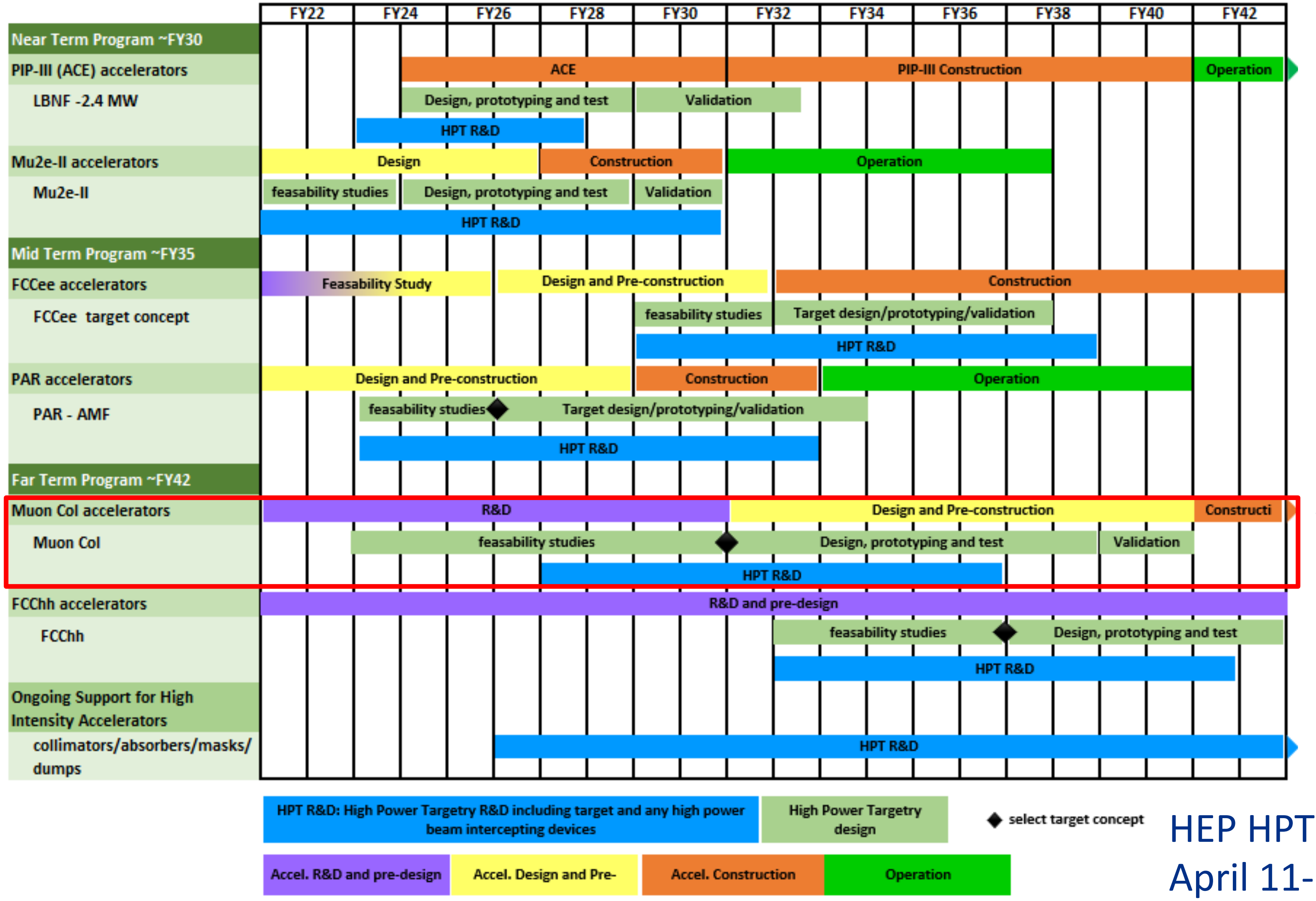
aterials Exploratory Map (Graphite)



Boundary represents operational threshold for thermal shock on graphite targets

DOE suggests to make a roadmap for HPT R&D

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



NOTE:

Each project set a specific target parameter, thus each target has a specific challenge and specific R&D. Current HPT R&D plan works on a generic item. We should identify a specific issue on MC.

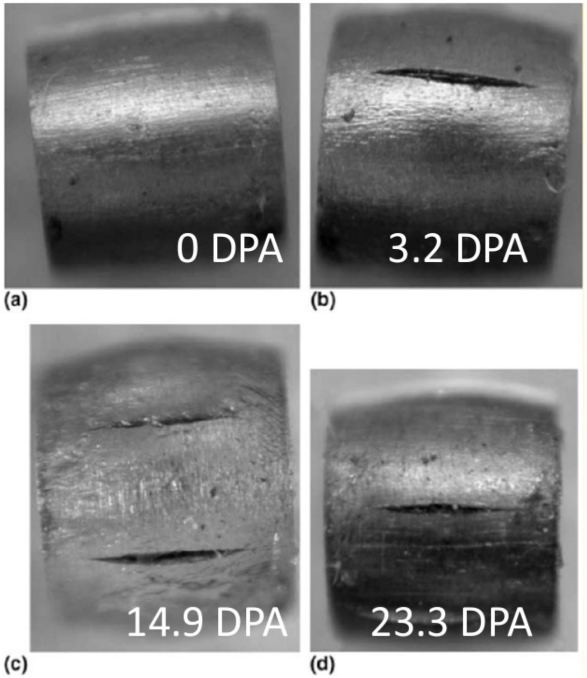
HEP HPT R&D Workshop
April 11-12 2023

Explorer Radiation Material Science for Advancing High Power Target R&D

Challenges associated with Beam Intercepting Device

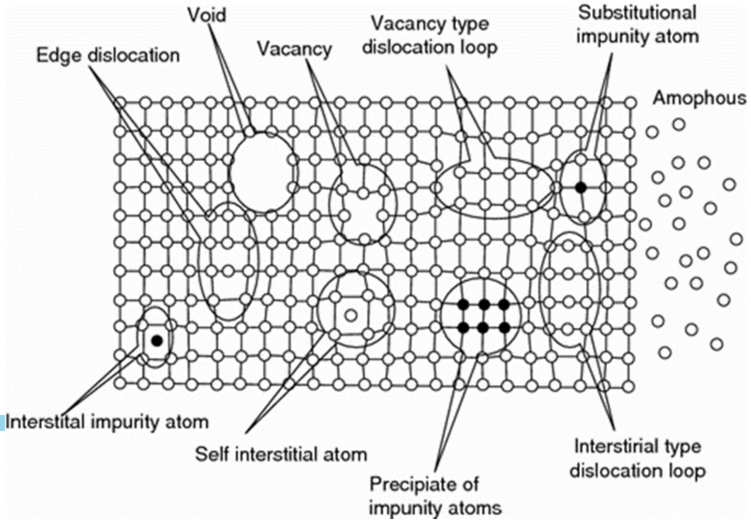
Radiation Damage: Displacements in crystal lattice expressed as Displacements Per Atom (DPA)

- Hardening and embrittlement
- Creep and swelling
- Fracture toughness reduction
- Thermal/electrical conductivity reduction
- Coefficient of thermal expansion
- Modulus of elasticity
- Transmutation products (H, He gas production can cause void formation and embrittlement)



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

Movement of lattice elements mimics like "Billiard ball" influenced by incident particles

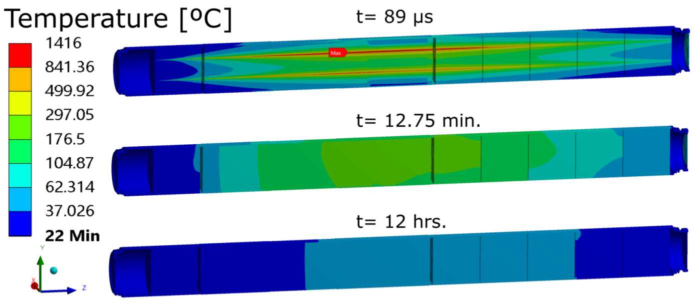


Challenges associated with Beam Intercepting Device

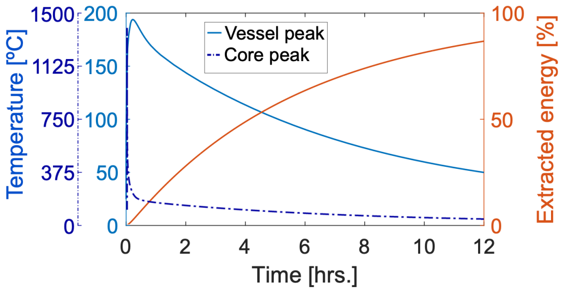
Thermal Shock: Sudden energy deposition from pulsed beam

- 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. Stress waves stay long time.

Relaxation time of thermal vibration is very long

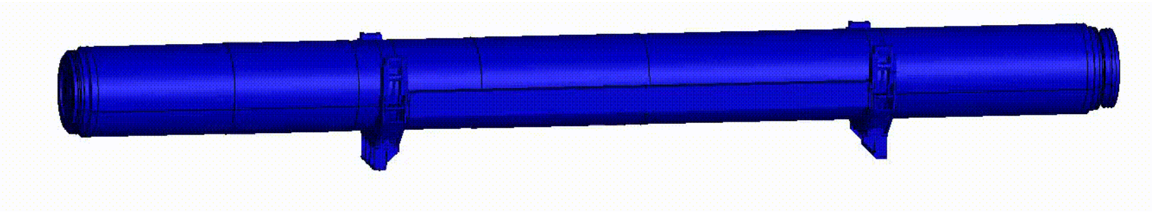


(a)



(b)

Simulated displacement of LHC beam damper

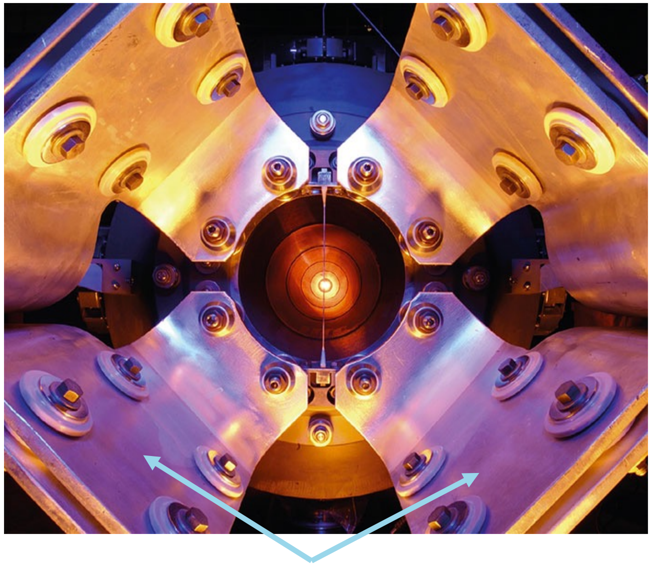


Challenges associated with Beam Intercepting Device

Thermal Fatigue: Cycling loading environment

- Cycling loading progressively damage material's microstructure such that it can ultimately fail at stress levels that are actually lower than its failure strength

Horn stripline fatigue failure after 20M pulses (2023)



NuMI horn striplines

- 200 kA pulsed current flows every second

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE collaboration created in 2012, with Fermilab as the leading institution. The collaboration has grown up to 20 institutions over the years.
First MoU was signed with 5 institutions 10 years ago!

HAPPY 10th BIRTHDAY

Brookhaven National Laboratory

Fermilab

Pacific Northwest NATIONAL LABORATORY

UKRI Science and Technology Facilities Council

UNIVERSITY OF OXFORD

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

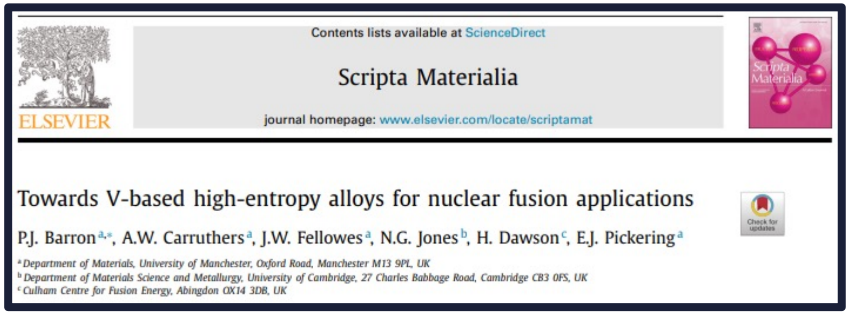
Contact:

- Frederique Pellemoine, fpellemo@fnal.gov
- Web: radiate.fnal.gov

High Entropy Arroy for Accelerator Beam Windows

Elemental selection considerations

- Light-weight elements (low density)
  - Reduced interaction with protons
  - Minimize energy loss and multiple scattering
- Primarily a single-phase alloy
  - Better ductility and manufacturability
- Minimal activation
  - Safer/easier to handle and dispose after use



Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

ELSEVIER

Towards V-based high-entropy alloys for nuclear fusion applications

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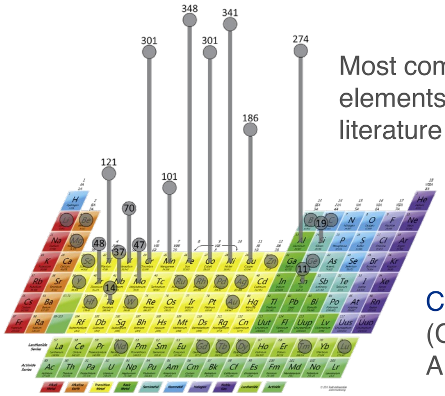


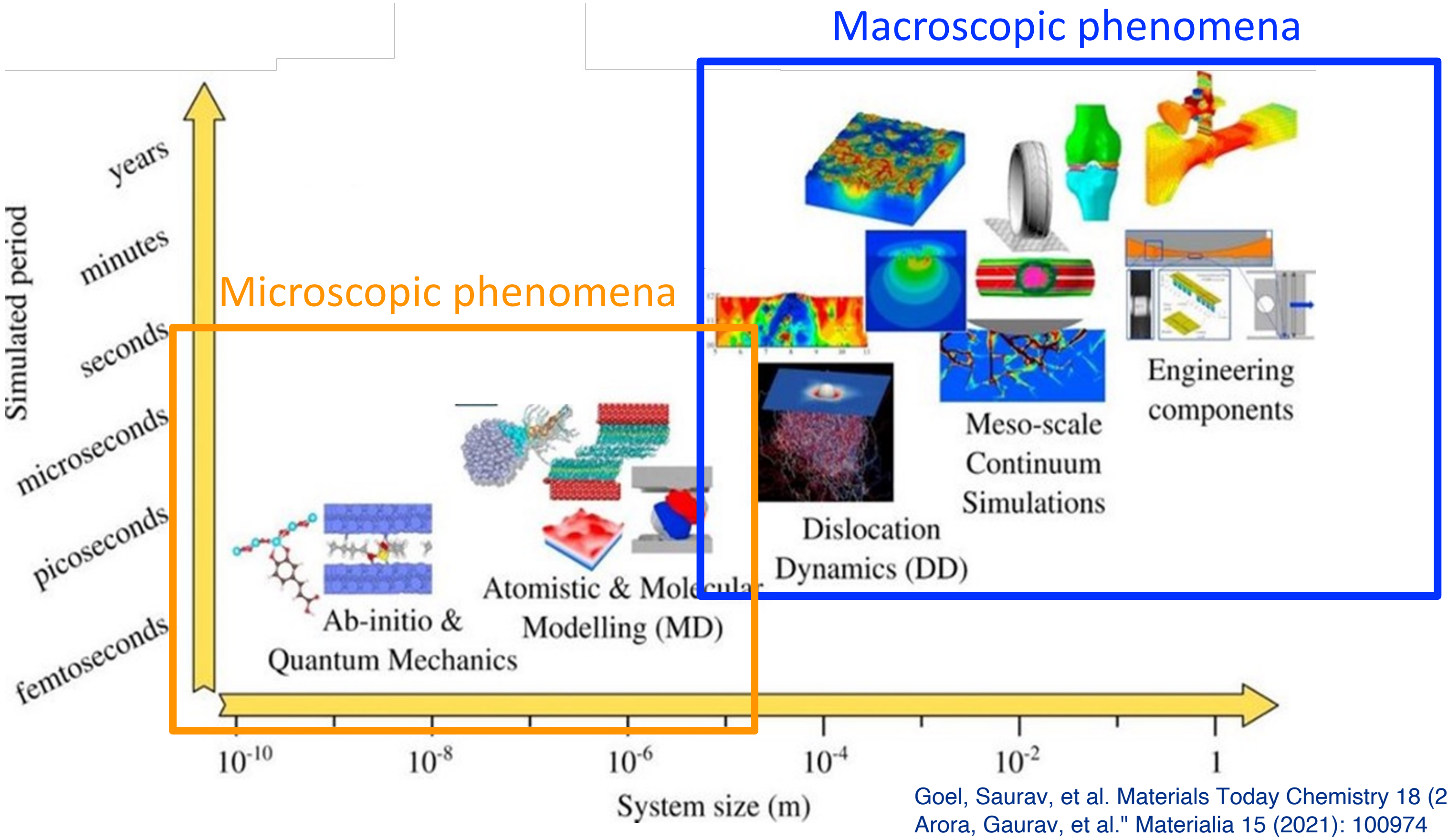
Most commonly used elements in HEAs from literature (Miracle, 2017)

Common alloys: CoCrFeMnNi (Cantor alloy), $Al_xCoCrFeNi$, $Al_xCoCrCuFeNi$

- Equimolar Cr-Mn-V shown to be single-phase BCC
- Ti additions reduce concentration of interstitial impurities by forming Ti-(C,O,N)
- Concerns Ti concentrations above ~8% will promote Laves phase formation
- Fe forms intermetallic compounds near the equimolar ratio with Cr, Ti, V

- HEA technology drastically grows over the past decade
- Optimal blending configurations is designed in advanced simulation

Types of simulations: Time *vs.* system size



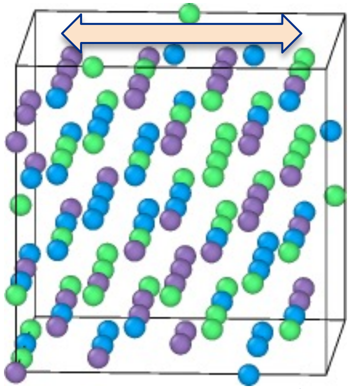
Goel, Saurav, et al. Materials Today Chemistry 18 (2020): 100356
Arora, Gaurav, et al." Materialia 15 (2021): 100974

- Density functional theory (DFT): Defect formation energies, band gap, etc.
  - Apply this technique to design HEA
- Molecular dynamics (MD): Radiation damage such as void formation, evolution of system with respect to temperature, etc.

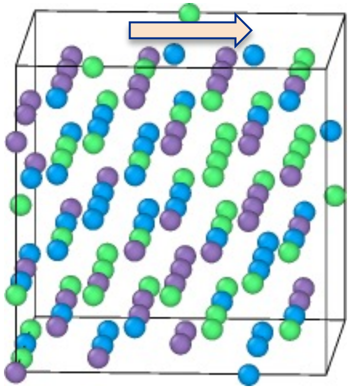
DFT is capable to simulate defect annihilation, clustering and mobility in sub-pico-sec time step

Apply DFT simulation for designing HEA

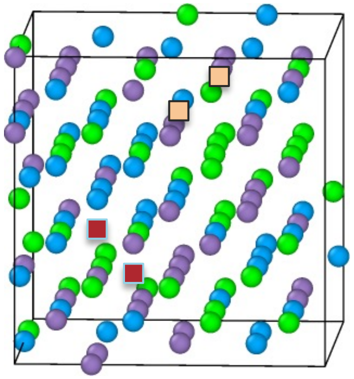
- To study the evolution of system following set of simulations are performed



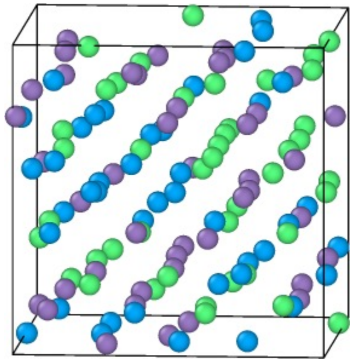
Compressive and tensile strain



Shear strain



Vacancies and interstitial



Different temperature

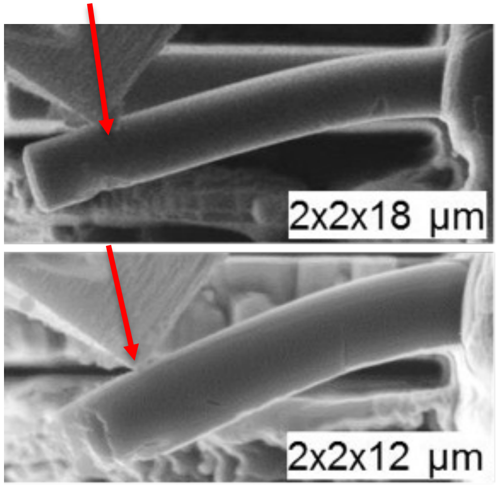
- Approximately 600 simulations are performed for each composition.
- Forces and energies are extracted and fed into making of machine learning potential.

- Including beam interaction models into DFT is currently considered
- FY25 LDRD approved to develop non-contact ultra high-speed radiation damage sensor for observing pico-sec phenomena

New technology for High Power Targetry R&D

Post Irradiation Examination (PIE) technology significant advancements over past decade

Apply force



Specific shape of sample for micro-scale PIE

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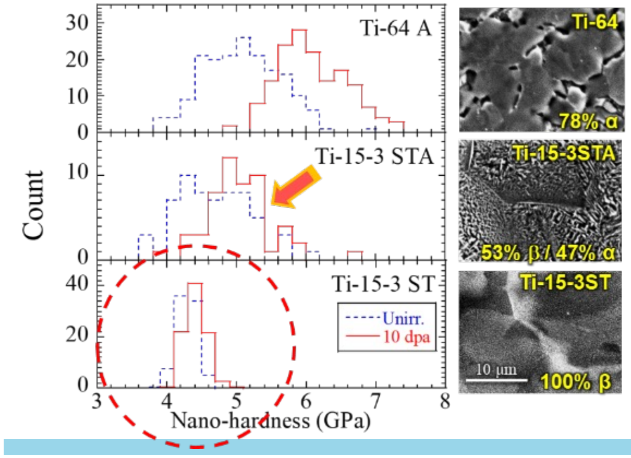
Science and Technology Facilities Council

UK Atomic Energy Authority

Phase transition of Tungsten



J-PARC

PIE in atomic scale by using TEM and SEM

Optimize MC target system (Physics output)

Enhance MC targetry performance

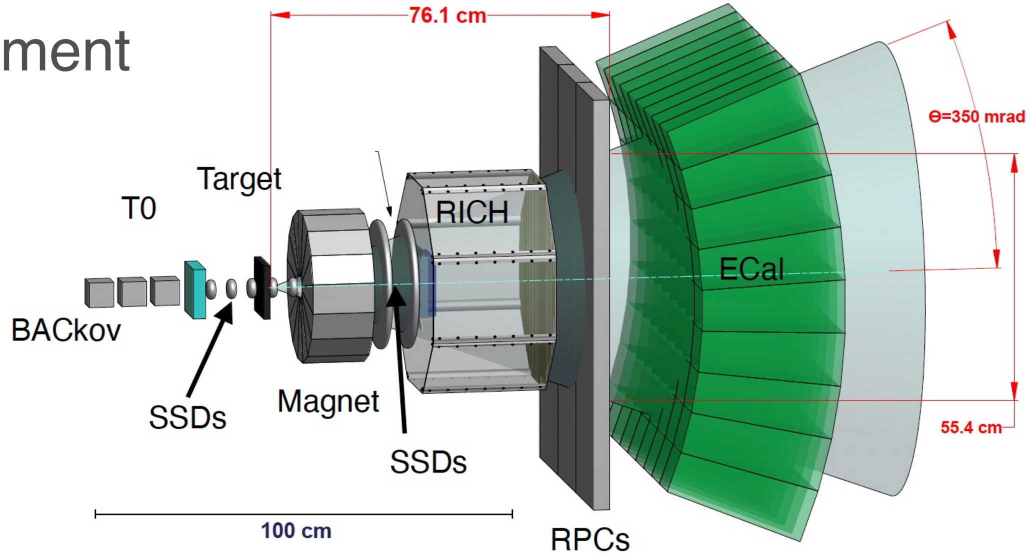
- Manage mechanical stress within specified tolerances
- Maximize pion yield with preferred energy band
  - Find most effective configuration of low Z (to reduce edep and pion recapture) and high Z materials (to increase and localize pion yield)
  - Determine optimal dimensions to satisfy engineering tolerance as well as pion yield
- Capture pions & muons
  - Ideally capture both signs → Solenoid or FODO cell magnet
  - Transport them into the downstream channel
  - Remove primary proton beam from muons
  - Manipulate phase space of pions and muons if needed

Develop AI technology to enhance target performance

Pion yield measurement at Fermilab

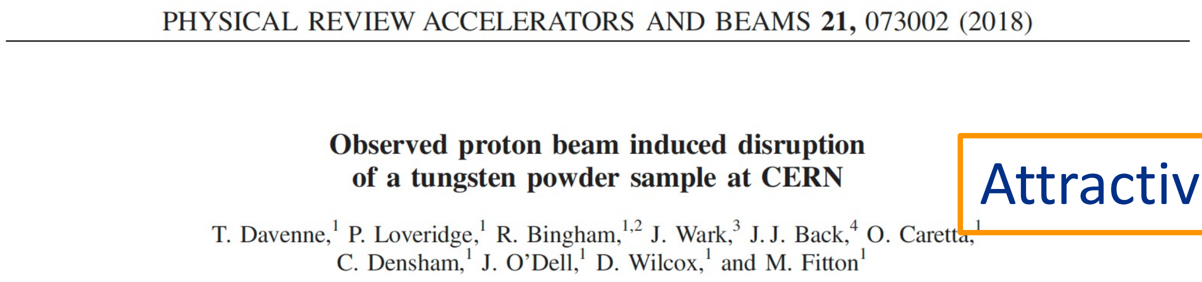
- Study beam interactions in beam intercepting devices
- Because the EMPHATIC spectrometer is compact, it realizes
  - Large angular acceptance
    - Small dead space
  - Fine position detection
    - Precise angular distribution measurement
- Pico sec fast counter
  - Precise energy measurement
- US-Japan collaboration
  - FY25 budget requested

EMPHATIC spectrometer



Granular Tungsten Target R&D

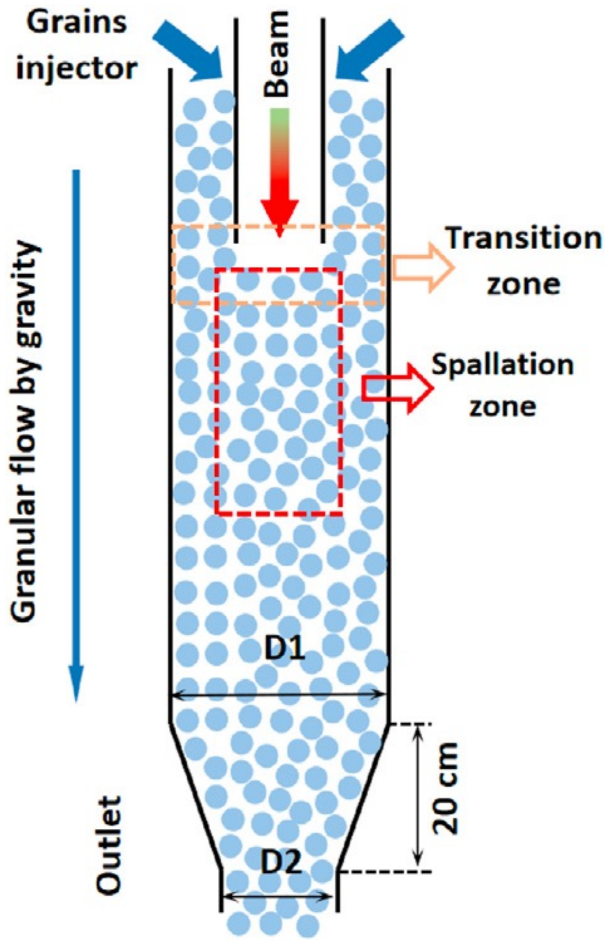
- The RAL group has pioneered the development of granular tungsten targets
  - Tungsten powder is ionized and scattered in the target chamber
- CSNS group has developed the concept and use large sphere particle
  - Gravity force is employed to mitigate the dispersal by charge
  - No beam window needed



PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 073002 (2018)

Observed proton beam induced disruption of a tungsten powder sample at CERN

T. Davenne,[1] P. Loveridge,[1] R. Bingham,[1,2] J. Wark,[3] J. J. Back,[4] O. Caretta,[1]
C. Densham,[1] J. O'Dell,[1] D. Wilcox,[1] and M. Fitton[1]

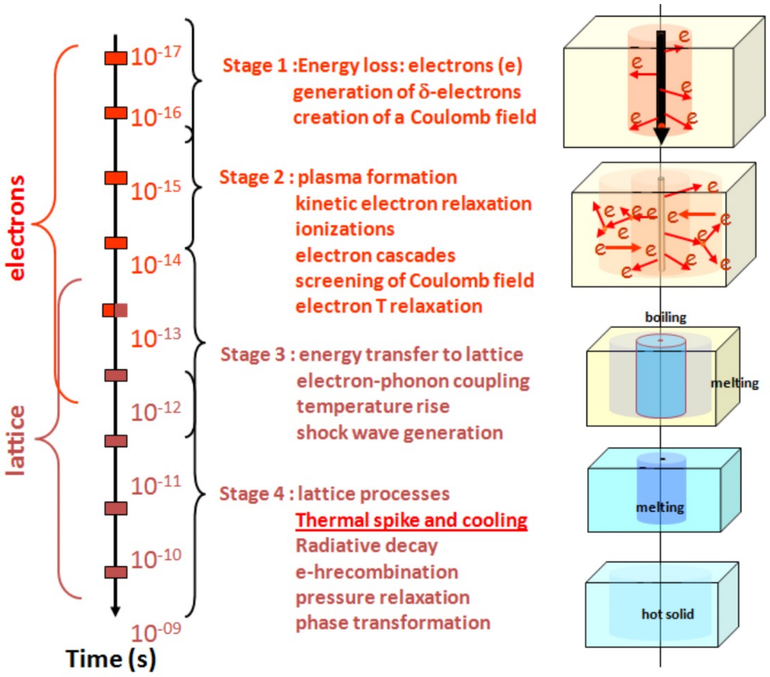


Attractive option for MC target

Propose MC High Power Targetry R&D

Specific subject on the MC Target R&D

- Utilize High Performance Computing Facility
  - Build AI to enhance target performance
    - Look into the MC target system from multiple view-point
  - Develop simulation to study sub-pico second evolution of defect
    - Develop the sub-pico radiation damage sensor to validate the simulation
- Propose pion-yield measurement
- Propose beam irradiation test and PIE



Stage 1 : Energy loss: electrons (e)
generation of δ-electrons
creation of a Coulomb field

Stage 2 : plasma formation
kinetic electron relaxation
ionizations
electron cascades
screening of Coulomb field
electron T relaxation

Stage 3 : energy transfer to lattice
electron-phonon coupling
temperature rise
shock wave generation

Stage 4 : lattice processes
Thermal spike and cooling
Radiative decay
e-hrecombination
pressure relaxation
phase transformation

Image courtesy of Marcel Toulemonde, GANIL

HiRadMat@CERN

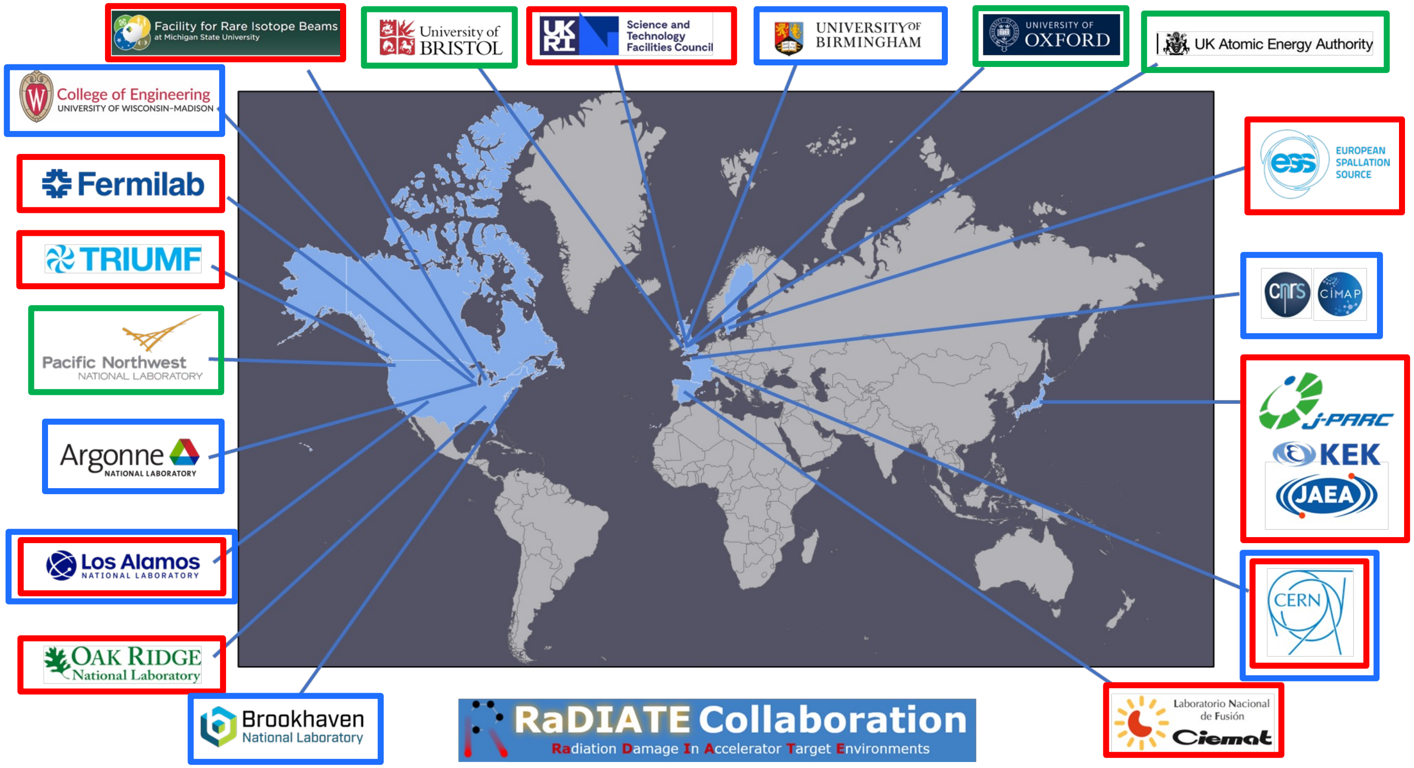
PNNL

Plan

- Forming MC Targetry R&D working group
  - Scientist + Target engineer + AI scientist
  - Join RaDIATE collaboration
    - Utilize their expertise and facility to develop the MC target technology (next slide shows the current world RaDIATE map)
- Gain resources
  - FY25 LDRD approved to make an ultra-high-speed non-contact radiation damage sensor for future HPT system
  - FY25 US-Japan collaboration requested
  - Anticipate more resources from the GARD HPT
    - Budget for utilizing Beam Irradiation Facility & PIE Facility

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments



🟥 Facility/Accelerator

🟦 Irradiation station

🟩 Post Irradiation Examination