Radiation Concerns and Mitigation Schemes for Accelerator Facility Components

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Outline

- Context of High Power Targetry
- Challenges in target and beam-intercepting devices
- Solutions to mitigate radiation damage
  - Annealing with high temperature environment
  - Development of radiation resistance materials
  - Development of novel target concept
- Tools to support R&D program
  - Irradiation stations
  - Alternative methods
  - Simulations

High Power Targetry Context

- Targets to produce secondary beams must survive extreme environment
- Recently, major accelerator facilities have been limited in beam power not by their accelerators, but by target survivability concerns
- With increase intensity for next generation accelerators, attention needs to be brought more carefully to target development
- Few target examples
  - Neutrino production at Fermilab National Accelerator Laboratory
    - ➢ ~ 1 MW of 120 GeV pulsed proton beam
    - ➢ Future up to 2.4 MW
  - Rare Isotope production at Facility for Rare Isotope beam (MSU-FRIB)
    - ➢ 400 kW of heavy ion beams (from O to U) at a minimum of 200 MeV/u
  - Neutron production at Oak Ridge National Laboratory (Spallation Neutron Source)
    - ➢ 1.4 to 2 MW of 1.3 GeV pulsed proton beam

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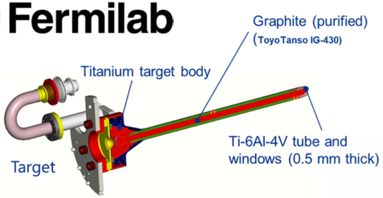
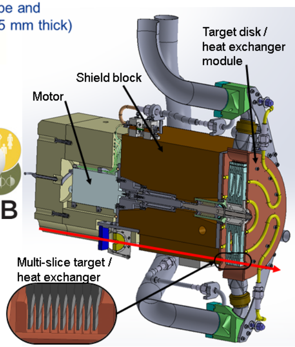
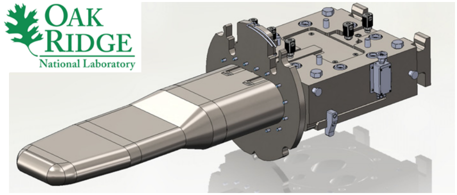


FRIB



OAK RIDGE
National Laboratory



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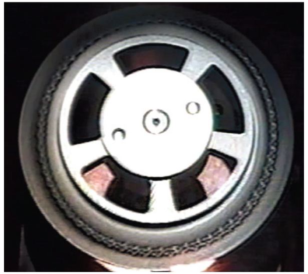
Common Challenges in Targets [1]

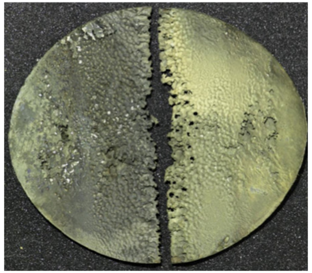
- High Power Density in Matter
  - High temperature
    - ➢ Evaporation, sublimation of solid materials
    - ➢ Boiling of liquid material
    - ➢ Thermal stress
  - Thermo-mechanical constraints
    - ➢ Thermal shock for pulsed beams
    - ➢ Cycling loading environment leading to fatigue if pulsed beam or rotating target
  - Liquid target
    - ➢ Cavitation



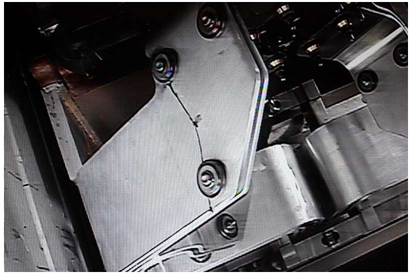
Graphite sublimation in FRIB prototypic target

Thermal stress in FRIB prototypic target

Iridium targets tested at CERN's HiRadMat facility



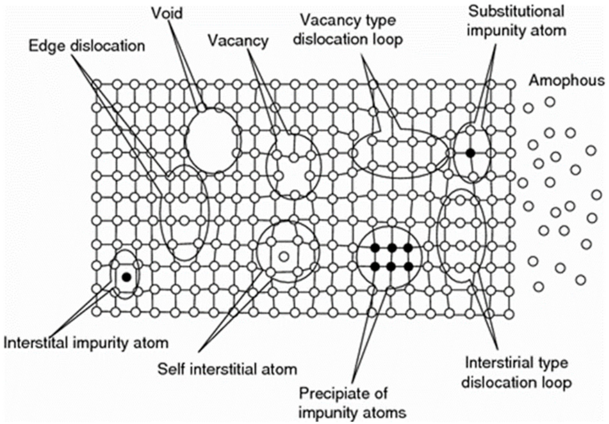
Target containment vessel cavitation (ORNL - SNS)



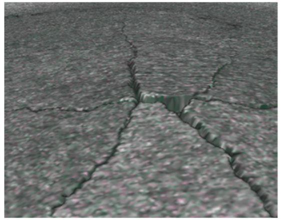
Horn stripline fatigue failure (FNAL)

Common Challenges in Targets [2]

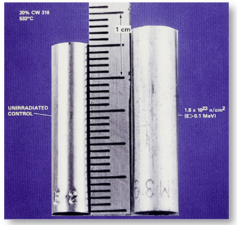
- Radiation Damage in Material - Displacements in crystal lattice expressed as Displacements Per Atom (DPA)
  - Hardening and embrittlement
  - Creep and swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Coefficient of thermal expansion
  - Modulus of elasticity
- Transmutation products (H, He gas production can cause void formation and embrittlement)



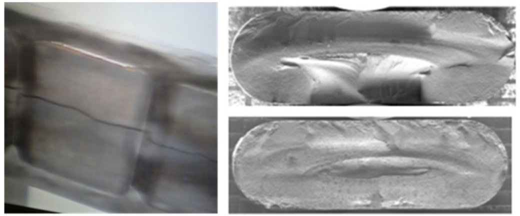
F. Marti et al., LINAC2010, Tsukuba, Japan, TUP105, 2010.



Be window embrittlement (FNAL)



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



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

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Better Understanding of Radiation Damage is Critical

- Radiation damage in material can reduce drastically the lifetime of targets or any beam intercepting devices (Beam dump, collimator, etc)
- More challenges to come!
  - Very limited engineering data (physical properties) exists for high energy proton or heavy ion irradiated target materials
    - ➢ More experimental data from nuclear material research but their use is limited, cannot be directly utilized but give us some insight of radiation damage trends

Irradiation Source	DPA rate (DPA/s)	He gas production (appm/DPA)	Irradiation Temp (˚C)
Mixed spectrum fission reactor	3×10^{-7}	1×10^{-1}	200-600
Fusion reactor	1×10^{-6}	1×10^{1}	400-1000
High energy proton beam	6×10^{-3}	1×10^{3}	100-800

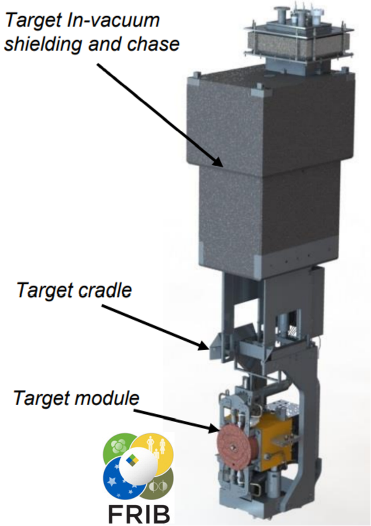
$$n_{1\text{-}14\ MeV} \square\, p_{100+MeV} \square\, HI_{10+\ MeV/A}$$

    - ➢ Necessary to collect relevant data to support target design and material choice
  - Difficulties of Post-Irradiation Examination
    - ➢ Activated samples require remote handling techniques and dedicated microscopy and testing equipment modified for use in ‘hot cells’
    - ➢ Few PIE facilities around the world
    - ➢ Long R&D cycle and high cost

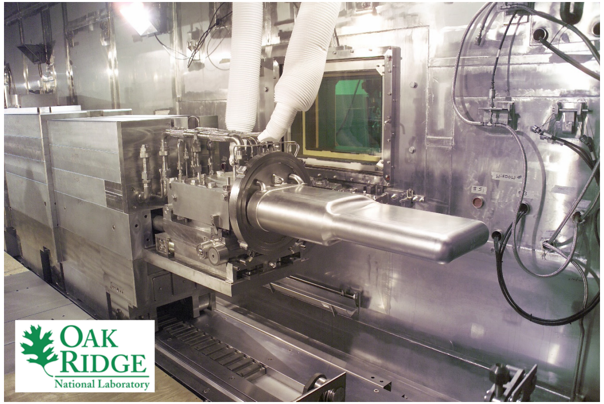
More Challenges for Safe Operations

- Facility requirements for safe operation
  - Remote Handling
  - Shielding & Radiation Transport
  - Air Handling
  - Cooling System
  - Storage and disposal

Storage and disposal at FNAL



Remote handling target module at FRIB



Target module at SNS

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE collaboration created in 2012, with Fermilab as the leading institution

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

Program manager: Dr. Frederique Pellemoine (FNAL)

Future Collaborators

CIMAP
CNRS
University of Birmingham
University of Bristol
TRIUMF
UK Atomic Energy Authority
Department of Engineering Physics, University of Wisconsin–Madison

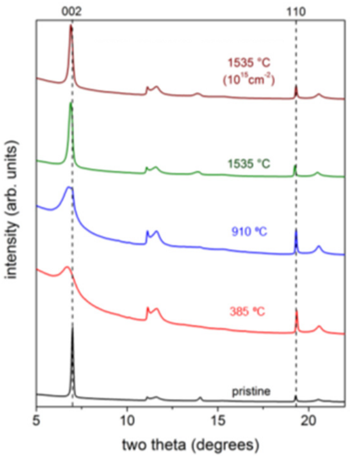
Fermilab
Pacific Northwest National Laboratory
Argonne National Laboratory
Oak Ridge National Laboratory
European Spallation Source
University of Oxford
CERN
FRIB
Los Alamos National Laboratory
Brookhaven National Laboratory
Ciemat – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
UKRI Science and Technology Facilities Council
J-PARC

Few Solutions Exist to Mitigate Radiation Damage in Material

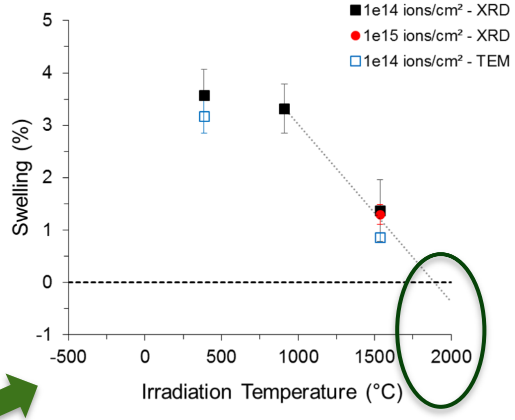
- Radiation damage effects are very dependent upon material and irradiation conditions
  - Temperature, dose rate, particle energy/type
- All the following solutions depend on the constrains for each target
  - Mechanical design and space constrain
  - Target environment
    - Vacuum, atmosphere,
  - Physic performances
- Some solutions
  - Annealing with high temperature environment
  - Development of radiation resistance materials
    - Novel materials
  - Development of novel target concept
    - Granular/Conveyor target
    - Rotating target
    - Flowing target
- Some tools
  - Alternative methods
  - Simulations

Annealing of Damage at High Temperature (> 1300ºC)

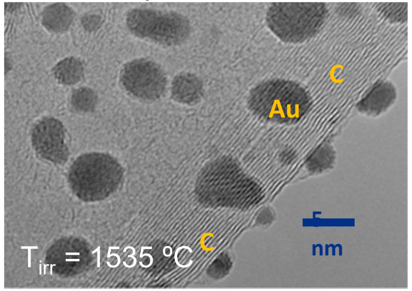
X-Ray Diffraction analyses



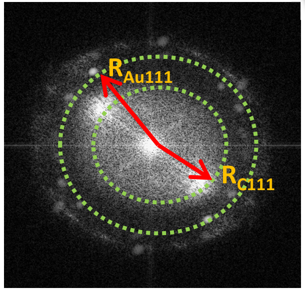
F. Pellemoine et al., NIMB 365 (2015) 522-524



TEM analyses



FFT



Swelling is completely recovered at 1900C

FRIB MICHIGAN GSI

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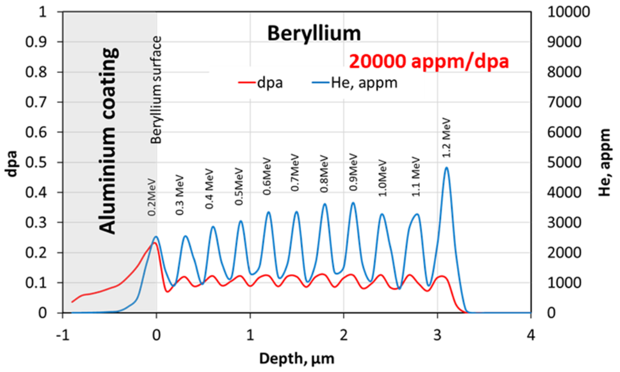
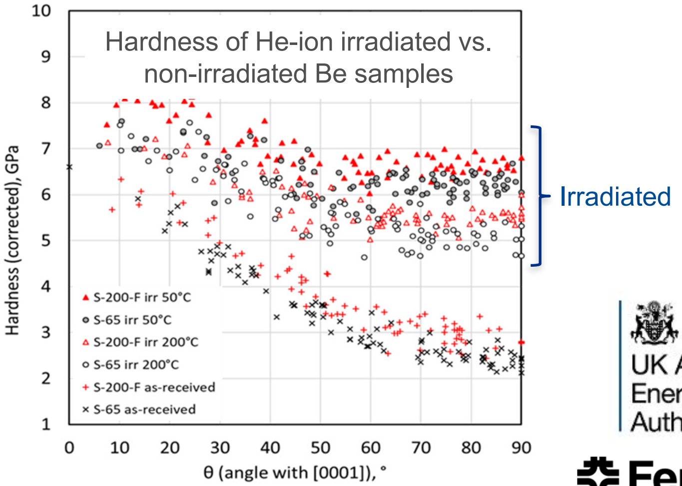
Helium Bubbles in Beryllium and Temperature Effect



3 µm damage layer
T_{irrad}: 50 and 200 ˚C
0.1 DPA, 2000 appm He

S. Kuksenko et al., J. Nuclear Materials, vol. 555, 15130, 2021



UK Atomic Energy Authority

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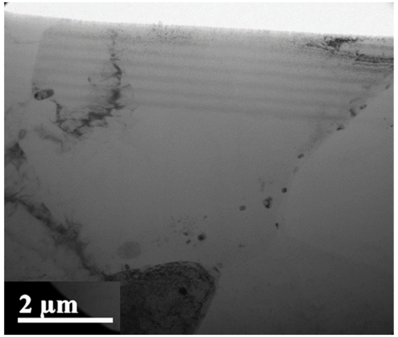
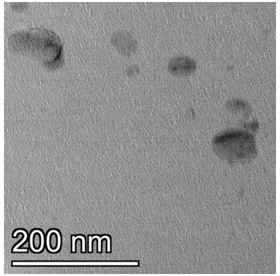


He implantation peaks

S. Kuksenko, RaDIATE Collaboration Meeting, 2019

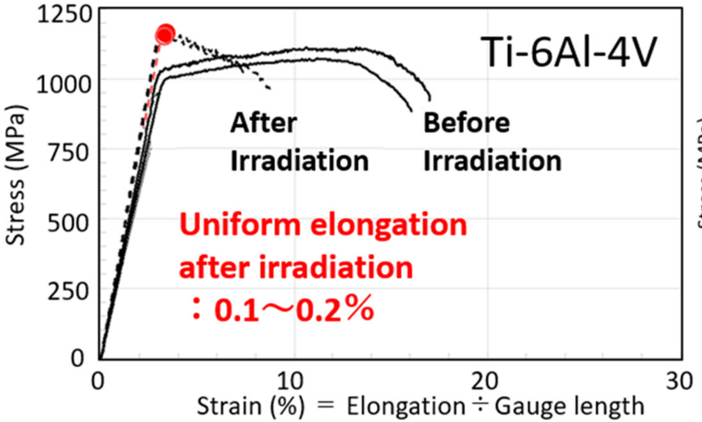
- Helium produced at high rates in Be with high energy proton beams (~3000 appm/DPA)
- At low temperatures, He atoms do not diffuse while at high temperatures, He atoms become mobile and can fill vacancy clusters to form damaging He bubbles
- He bubbles observed in NuMI Be window after **annealing** at 360 °C
- However, higher temperatures are generally desired to anneal displacement damage (see hardness plot above)

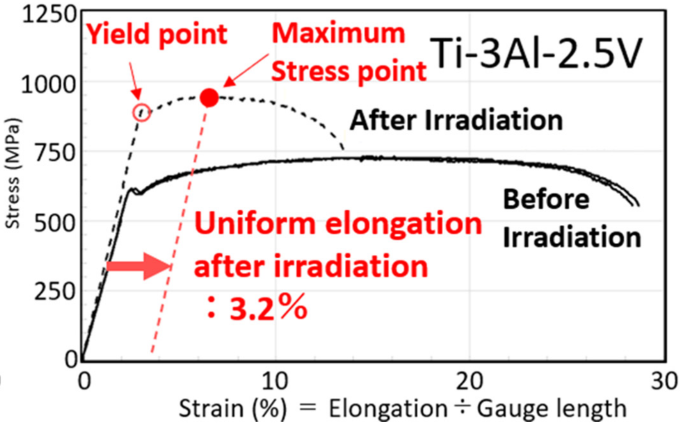


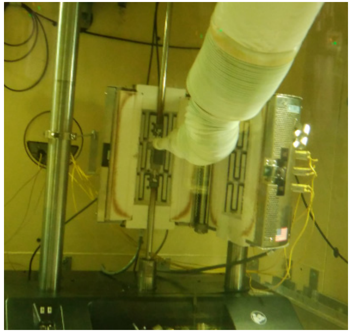
Development of Radiation Resistance Materials [1]

- Metallurgy and post process can significantly affect radiation defect creation

Dose = 0.22 dpa, T_{irr} =112□C







Testing done in hot cell at PNNL

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

- Ti-6Al-4V (□+□ phase) loses almost all of its uniform elongation (UE) after irradiation
- Evidence that Ti-3Al-2.5V alloy (near □-phase) is more radiation-tolerant
- Recent work confirms that □-phase Ti-alloys are better resistant to radiation damage

Pacific Northwest NATIONAL LABORATORY

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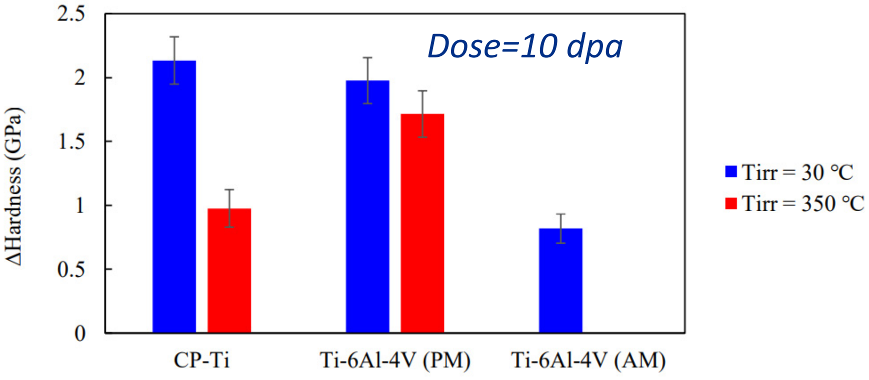
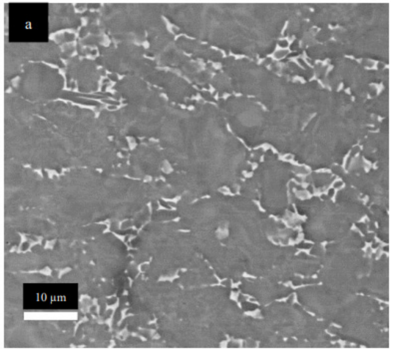
Development of Radiation Resistance Materials [2]

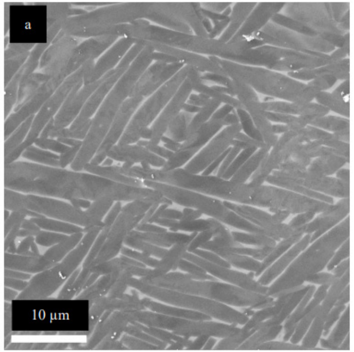
- Metallurgy and post process could significantly affect radiation defect creation



A. Amroussia, Analysis of heavy ion radiation damage in Titanium and Titanium alloy, MSU Thesis 2020



Ti-6Al-4V-Powder Metallurgy Rolled - Equiaxed



Ti-6Al-4V- Additive Manufacturing – lamellar

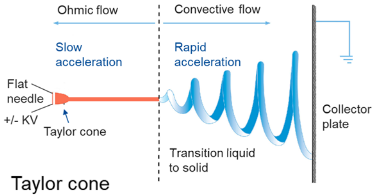
- At low irradiation temperature, CP Ti and Ti-6Al-4V PM exhibited the highest hardening after irradiation up to 10 dpa.
- The Ti-6Al-4V AM exhibited the lowest hardening after RT irradiation.
- At a higher temperature, the average hardness was lower than at RT.

Development of Radiation Resistance Materials [3]

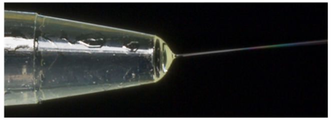
With conventional materials already limiting the scope of experiment it is crucial to investigate novel materials

Nanofiber electro-spinning at Fermilab

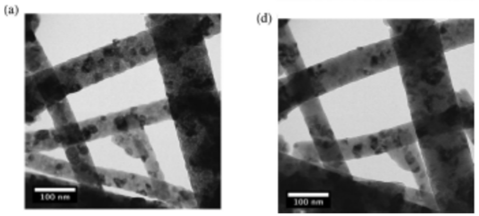
- Nanofiber continuum is discretized at the microscale to allow fibers to absorb and dampen thermal shock, and discontinuity prevents stress wave propagation
- Evidence of radiation damage resistance due to nanopolycrystalline structure of the material



Taylor cone



Electrostatically driven electrospinning process

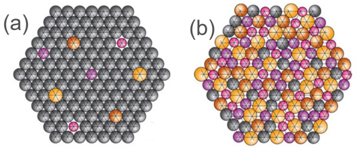


TEM image of Zirconia nanofibers Before (left) and after irradiation at 5 dpa (right)

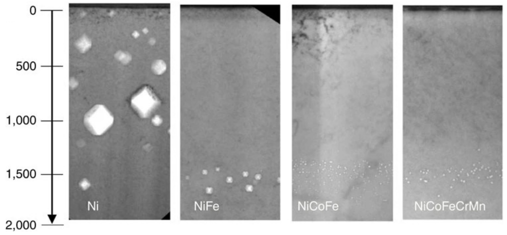
S. Bidhar et al., PRAB 24, 123001, 2021

High-Entropy Alloy (HEA) development at UW-M

- Alloys consisting of 3 or more principal elements
- Excellent inherent properties including enhanced radiation damage resistance



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

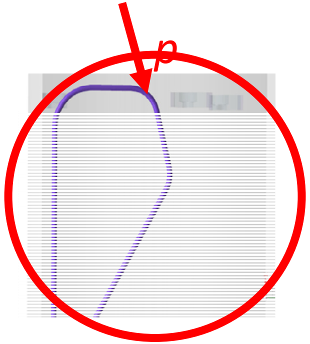


Reduction in irradiation-induced void distribution in nickel and multi-component HEAs after 3-MeV Ni+ ion irradiation at 773 K

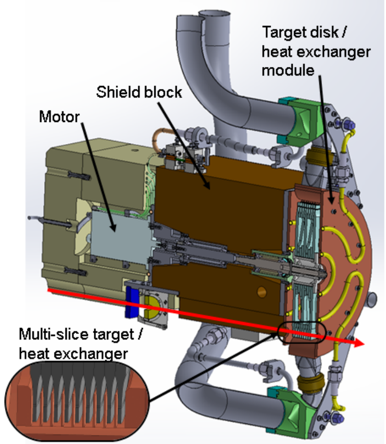
C. Lu, L. Et al., Nat. Commun., 7 (2016), p. 13564

Development of Novel Target Concept [1]

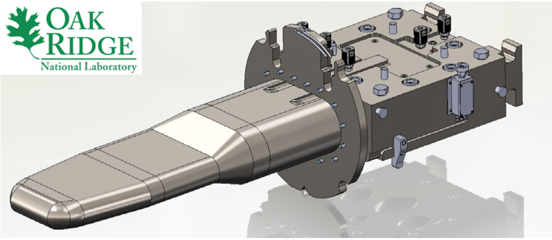
- Conveyor target for Mu2e at Fermilab
  - Spherical tungsten or carbon elements will be supplied to a pipe
  - Radiation damage distributed among a large number of replaceable elements
  - Small space required
  - He gas could be used for both cooling and moving elements inside conveyor
  - Technical complexity (prototyping and R&D needed)



- Rotating multi-slice graphite target at FRIB
  - Increased radiating area and reduced total power per slice by using multi-slice target
  - Use graphite at high temperature for radiation damage annealing
  - Radiation damage distributed at the periphery of the target

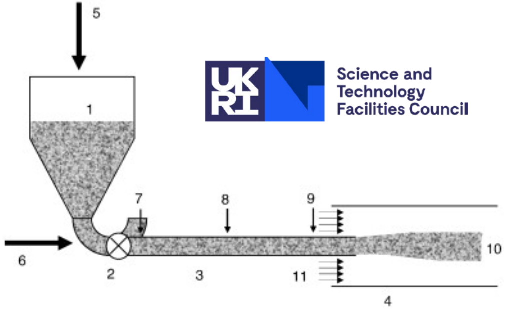


Development of Novel Target Concept [2]



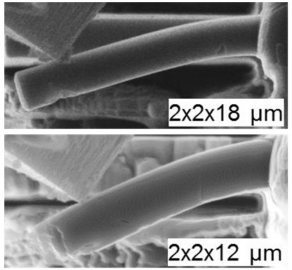
- Flowing target - Fluid Mercury target at SNS
  - can handle much higher power density than solid target without the cracking or radiation damage limitations of solid targets
    - the large power loads can be convected away from the beam-target interaction region with a flowing liquid target
    - much less radiation damage that would occur in a solid target material
  - Issue with cavitation can be mitigated with bubble injection

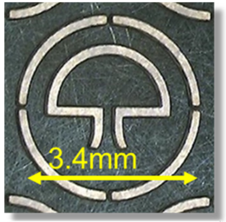
- Granular target – target for muon collider at Rutherford Appleton Laboratory (RAL)
  - fluidized tungsten powder target technology which combines some of the advantages of a liquid metal with those of a solid.
    - granular material flowing within a pipe should withstand extremely intense pulsed beam powers without the cracking or radiation damage limitations of solid targets, and without the cavitation issues associated with liquid target
  - Radiation damage distributed
  - He gas could be used to cool down the powder
  - Requires a lot of R&D



Tools to Support R&D Program

- High energy beam irradiation
  - Highly activated material ⇨ need 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
    - Narrow penetration depth
      - Micro-mechanics and meso-scale testing
    - Doesn't reproduce the gas (H and He) production
      - Additional He implantation
  - 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
  - However: 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





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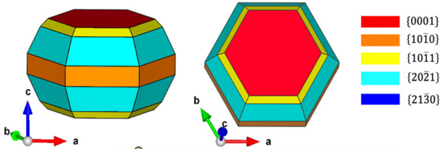

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Summary

- Radiation damage in materials is one of the most limited factor to target and beam intercepting device reliability
  - Need to better understood radiation damage that impacts physical properties of target materials
  - Need to fill the lack of engineering data useful to support target design

- Materials R&D is essential to help the design of robust targetry components and maximize primary beam power on target and secondary particle production
  - R&D activities needs to be coordinated through national and international collaborations
  - Alternative irradiation facilities, material testing and characterization methods are essential and need to be developed to better support R&D program
  - Explore novel material and novel target concept to support future high-power Targetry components
  - R&D needs to start at an early stage of a project to be able to provide enough engineering date during the target design phase

- No universal solutions to mitigate radiation damage

Thank you for your attention

- Acknowledgements

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Fermilab
Brookhaven National Laboratory
Argonne National Laboratory
Pacific Northwest National Laboratory
FRIB
Oak Ridge National Laboratory
Los Alamos National Laboratory EST. 1943
ess European Spallation Source
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
University of Oxford
UKRI Science and Technology Facilities Council
CERN
J-PARC
CIMAP
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University of Bristol
UK Atomic Energy Authority
Department of Engineering Physics University of Wisconsin-Madison
TRIUMF
University of Birmingham