Introducing the MIT PSFC LMNT Facility

Irradiation of Bulk Fusion Materials with 10-30 MeV Protons

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ARPA-E CHADWICK
Kickoff Meeting

Las Vegas, NV
27 Mar 25

Overview

Objectives:		**Agenda:**
Demonstrate why we need a bold new approach to fusion materials	→	Analysis of fusion energy and existing materials irradiation approaches
Propose 10-30 MeV proton irradiation as part of the solution	→	Convey the technical and strategic advantages of the technique
Test and collaborate to enable fusion materials solutions	→	A new facility for 10-30 MeV proton irradiation under construction at MIT

Overview

Plasma Science
& Fusion Center

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Demonstrate why we need a bold new approach to fusion materials

Propose 10-30 MeV proton irradiation as part of the solution

Test and collaborate to enable fusion materials solutions

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Convey the technical and strategic advantages of the technique

A new facility for 10-30 MeV proton irradiation under construction at MIT

Why an aggressive new approach to fusion materials?

1. Nascent $7B private fusion industry:
FPPs in 2030s -> <u>materials decisions in 2020s</u>

2. Re-alignment and increasing pressure
on federal programs to deliver fusion energy

Department of Energy

DOE Announces $46 Million for Commercial Fusion Energy Development

WHITE HOUSE SUMMIT:
Developing a Bold Decadal Vision for Commercial Fusion Energy
THURSDAY, MARCH 17, 2022

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

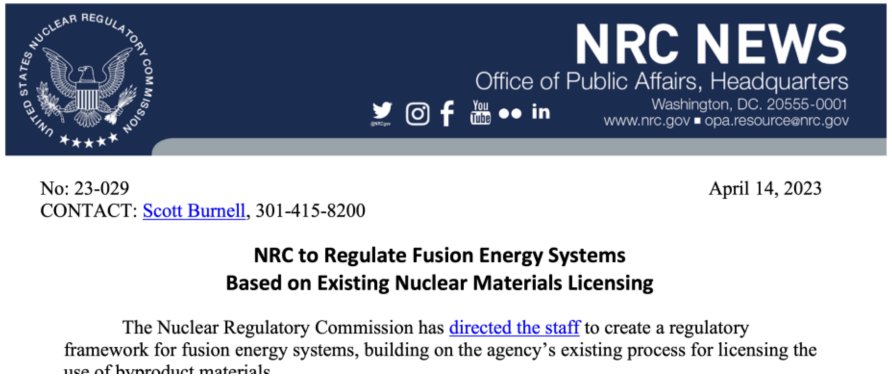
November 16, 2023

Professor Anne White
Associate Provost and Associate Vice President for Research Administration
School of Engineering Distinguished Professor of Engineering
Department of Nuclear Science and Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue, 24-107
Cambridge, Massachusetts 02139

Dear Professor White:

The 2020 report of the Fusion Energy Sciences Advisory Committee (FESAC) Long-Range Plan (LRP) "Powering the Future: Fusion & Plasmas" states in its Executive Summary that "*Now is the time to move aggressively toward the deployment of fusion energy which could substantially power modern society while mitigating climate*

3. Enabling a new approach to fusion regulation
that will accelerate commercial deployment



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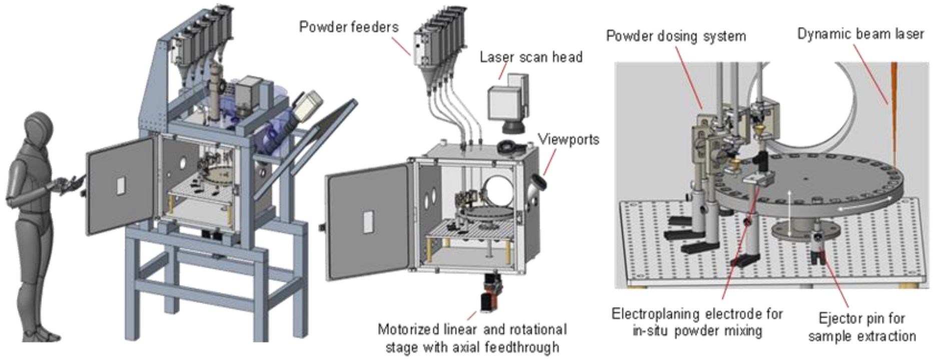
No: 23-029
CONTACT: Scott Burnell, 301-415-8200

April 14, 2023

NRC to Regulate Fusion Energy Systems
Based on Existing Nuclear Materials Licensing

The Nuclear Regulatory Commission has directed the staff to create a regulatory framework for fusion energy systems, building on the agency's existing process for licensing the use of byproduct materials

4. Advances in materials design and fabrication
that <u>exponentially</u> expand the candidate pool



ML-informed alloy 3D printing (courtesy: A. Couet, UWisconsin)

We have to think differently and boldly to tackle fusion materials on relevant timescales.

The approach must accommodate two distinct needs

Track 1: De-risk + Demonstration

- Objective: Minimize uncertainty
- Target: First-of-a-find (FOAK) plants
- Decision timescale: ≤ 5 years
- Likely material candidates:
  - F-M steels, Ni-based steels (?)
  - Graphite
  - Existing copper alloys
  - Existing tungsten alloys

Track 2: Discovery + Down-select

- Objective: Maximize economic viability
- Target: Nth-of-a-kind (NOAK) plants
- Decision timescale: ≥ 10 years
- Potential material candidates:
  - Vanadium-based alloys
  - High entropy alloys
  - Novel tungsten and copper alloys
  - Engineered composites (e.g. SiC-SiC, W-W)

Must accommodate different models of materials development. Examples:

- "FMCC model": Public sector handles TRL 1-> 6 then hands off to industry [1]
- "Terrapower HT9 model": Private development of alloys with public testing + qualification

[1] Fusion Materials Community Roadmap, September 2024, EPRI. https://www.epri.com/research/programs/065093

Neutron irradiation is insufficient to address the need

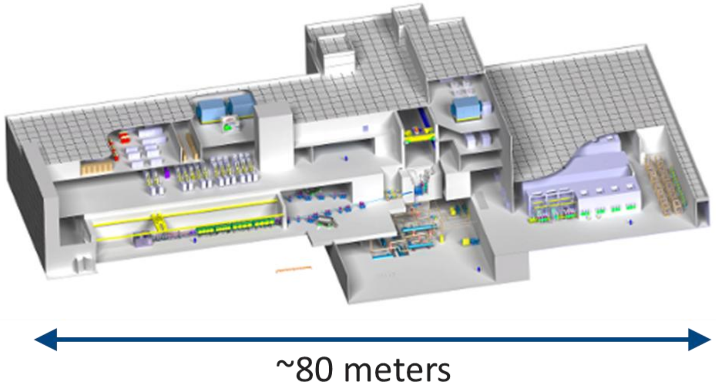
Today: Fission neutron irradiation

The MITR-II core at MIT

Disadvantages:
- Low damage rates (~few dpa/yr)
- Can be far from prototypic for fusion
- High cost; rare + closing facilities

Examples: ATR, HFIR, BOR-60

Future: Fusion-like neutron irradiation



Rendering of the International Fusion Materials Irradiation Facility

Disadvantages:
- Moderate damage rates (~10 dpa/yr)
- Operational in the 2030s? 2040s?
- Impossible to scale to meet demand

Examples: IFMIF (EU+JP)

Existing facilities are oversubscribed, slow, costly, and often highly non-prototypic [1,2]

[1] S. Taller, G. vanCoevering, B. Wirth, G. Was. Scientific Reports **11** (2021) 2949
[2] S. Zinkle and L. Snead. *Scripta Materiala* **143** (2018) 154.

Ion irradiation in existing facilities is insufficient

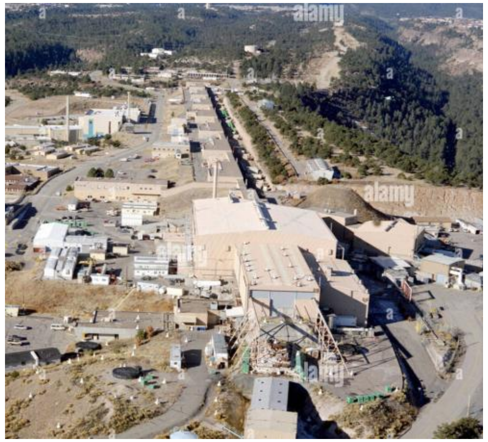
Low energy ion accelerators

CLASS 2 MV tandem at MIT

Disadvantages:

- Damage surface layers not bulk materials
- Difficult to extrapolate to bulk properties
- Confounding effects (e.g. ion implantation)
- Can be far from prototypic for fusion

High energy national lab accelerators



LANSCE 0.8 GeV LinAc at LANL

Disadvantages:

- Low damage rates (~mdpa/day)
- Oversubscribed; high cost
- Impossible to scale to meet demand
- Can be far from prototypic for fusion

While providing valuable insights, these approaches have significant limitations [1]

[1] S. J. Zinkle and A. Moslang, *Fusion Engineering and Design*, **88** (2013) 472-482.

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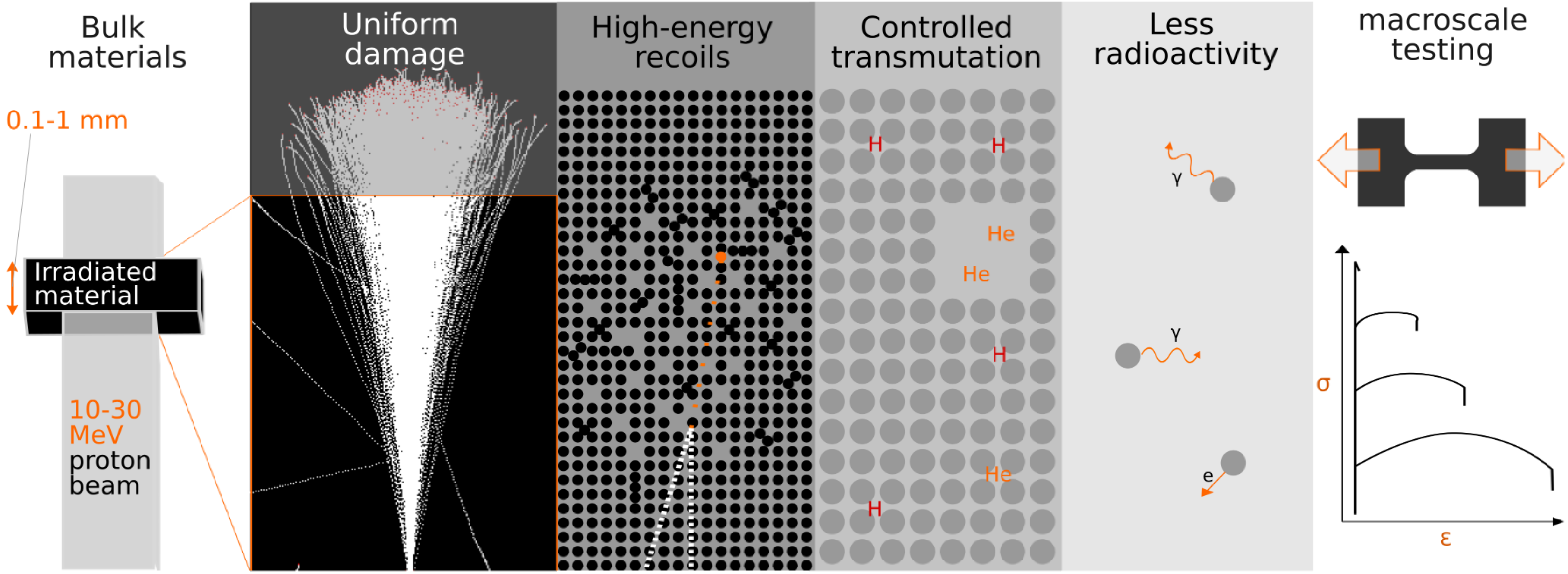
10-30 MeV proton irradiation offers a compelling alternative

Advantages of the intermediate energy proton irradiation technique



A technique that is faster, lower cost, lower activity, near-prototypic, and scalable

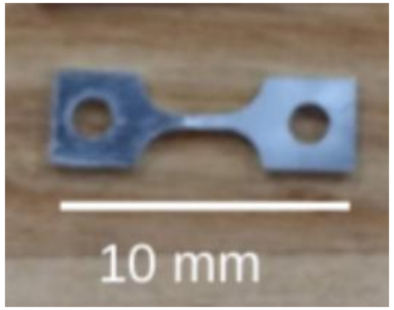
S. J. Jepeal, L. L. Snead, Z.S. Hartwig. *Materials and Design,* **200** (2021) 109445. https://arxiv.org/abs/2009.00048

Advantage: Obtain irradiated bulk material property changes

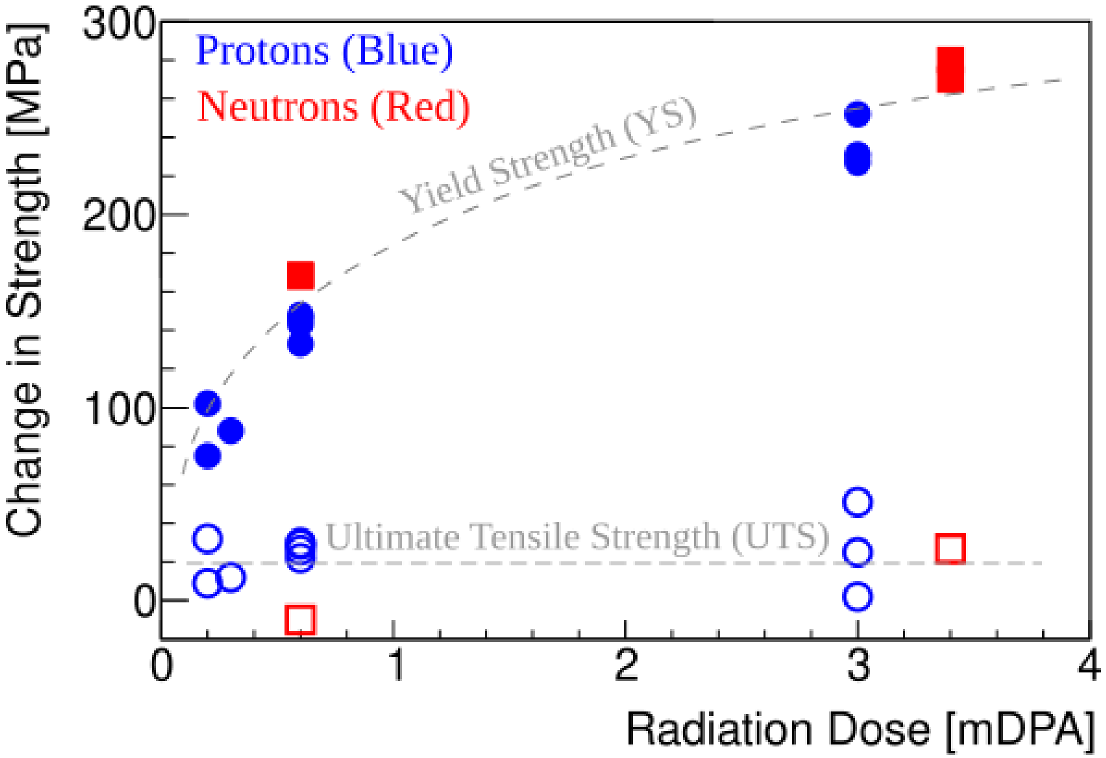
MIT site (~10 mDPA/day) is exploring irradiation of bulk (>100 um) samples with 12 MeV to emulate bulk mechanical property changes from neutrons.

12 MeV, 10 µA Cyclotron

Irradiation tensile target

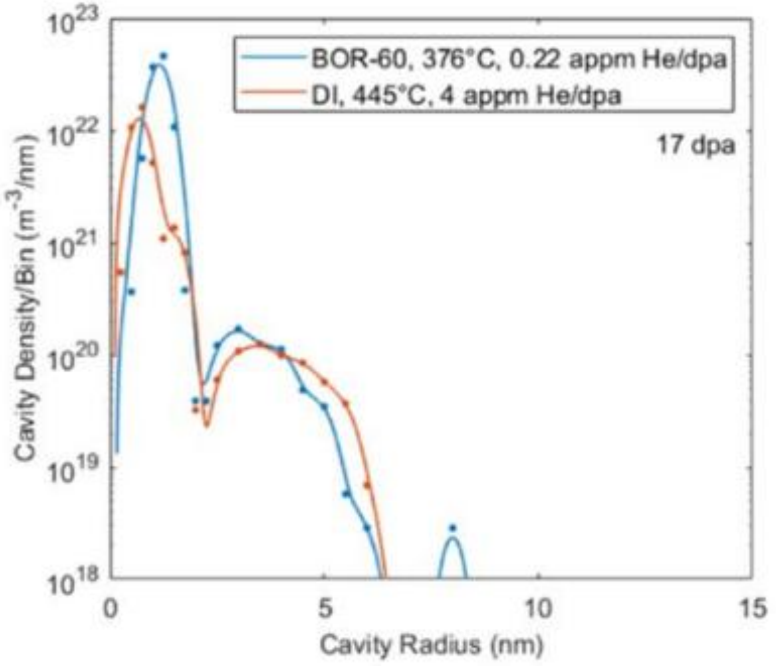


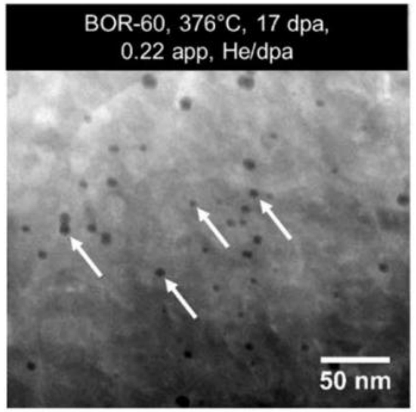
Change in Inconel 718 strength showing agreement between protons and neutrons

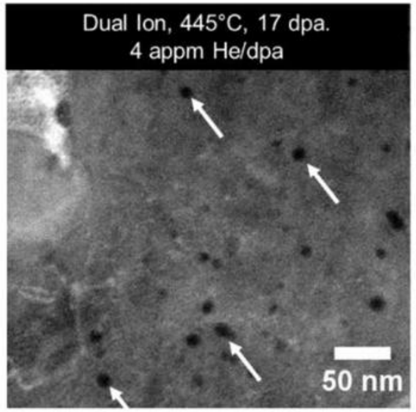


Technique can bridge from microstructure to macrostructure engineering properties

Advantage: Leverage foundation in proton-neutron similarity







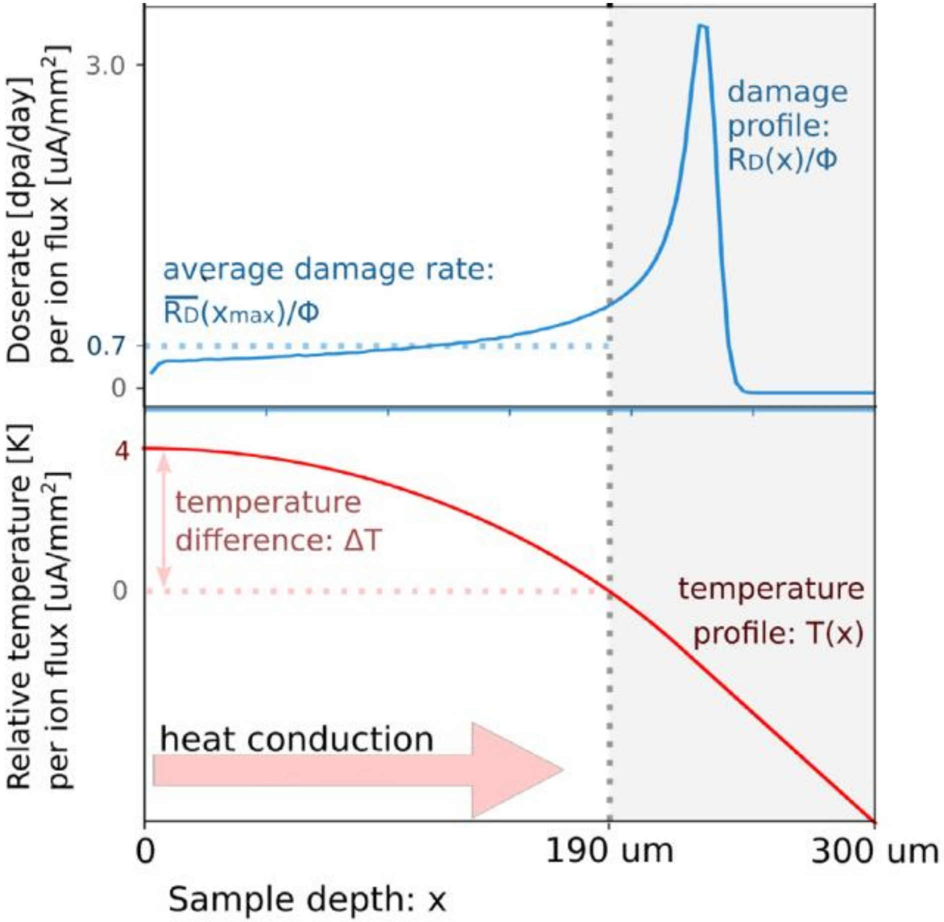
- Protons [1] and heavier ions [2] are being used successfully to replicate microstructural evolution caused by neutron in fission materials.

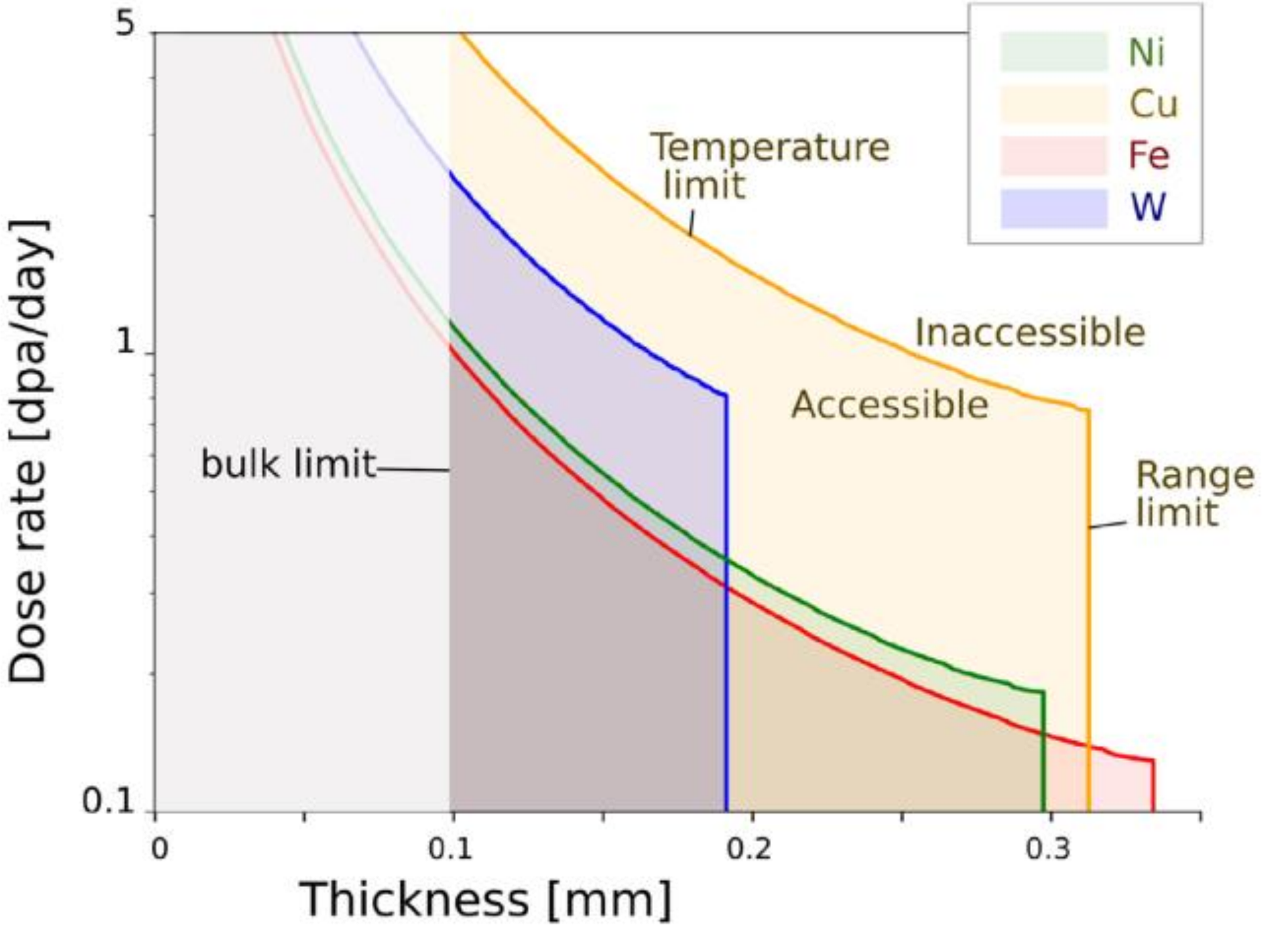
- Similarity achieved w/ irradiation “recipes”: material- and dose-dependent shifts in temperature (diffusion kinematics) and helium implantation (void stabilizer)

- Example: Neutron emulation of void swelling in T91 steel at 1000x damage rate with Fe + He irradiation [3]
  - Modified Mansur $T_{irradiation}$ shift [4] (120 -> 70 ^{o}C)
  - Enhanced He/DPA ratio (4 @ 18x application)

[1] K.J. Stephenson and G.S. Was, J. Nucl. Mat. **456** (2015) 85.
[2] G. S. Was *et al. Scripta Materiala,* **88** (2014) 33.
[3] S. Taller, G. vanCoevering, B. Wirth, G. Was, *Scientific Reports* **11** (2021) 2949
[4] L. K. Mansur, *J. Nucl. Materials* **206** (1993) 306-323.

Advantage: Moderate DPA rate limited only by heat removal





S. J. Jepeal, L. L. Snead, Z.S. Hartwig. *Materials and Design,* **200** (2021) 109445. https://arxiv.org/abs/2009.00048

Advantage: High-fidelity transmutation in parallel with DPA

Nuclear physics gives similar cross sections for transmutation products between fusion n spectra and that accessible with 10-30 MeV p+

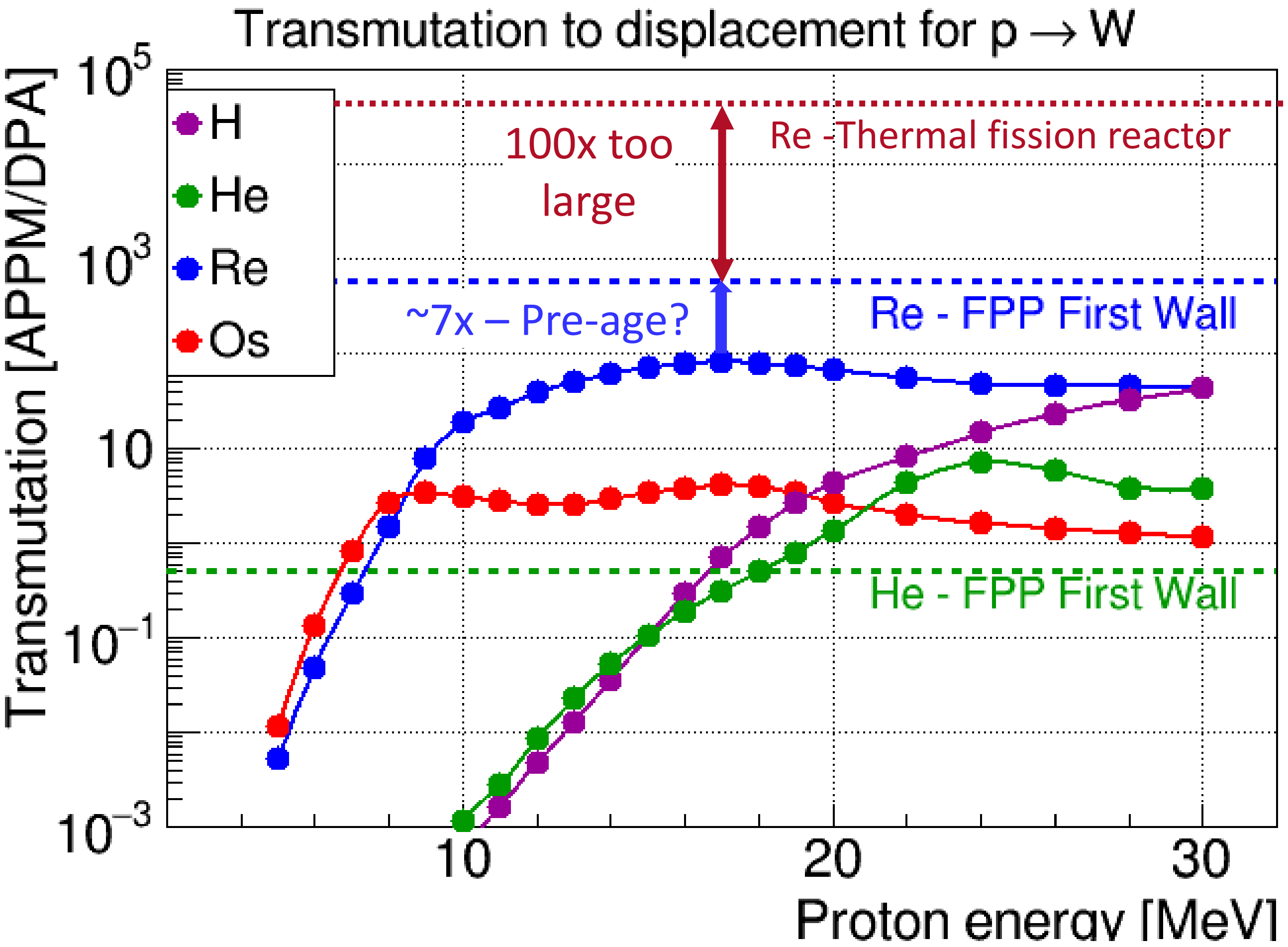
- Gas transmutation: (p,p') for H, (p,α) for He
- Solid transmutation: (p,x) reactions

Proton energy provides independent control over DPA and transmutation rate. For example, in W:

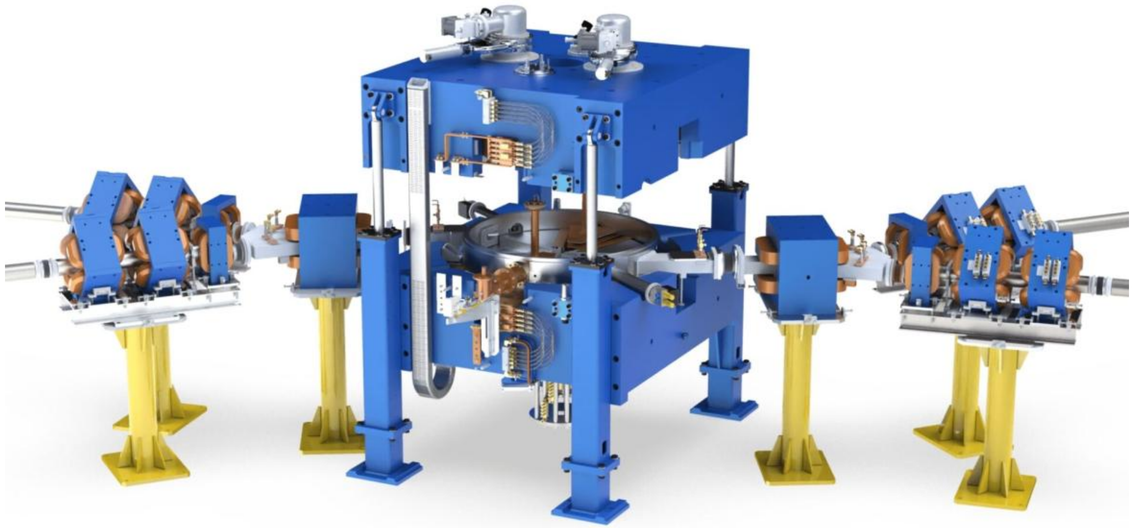
- APPM/DPA range: He =10^{-4} to 10^{1} Re = 1 to 50

High-fidelity to compact FPP first wall transmutation to DPA rates are achievable for worst-case elements:

- Re production 100x too high in thermal fission
- "pre-aging" strategy with fission for rhenium
- Wide range achievable for helium



Advantage: Leverage commercial accelerator technology



Advanced Cyclotron Systems Inc. – TR-FLEX Cyclotron

- Proven commercial technology
- 10-30 MeV proton beams
- 800 uA maximum proton current (24 kW power)
- Dual beam extraction @ variable current
- 99% uptime, minimal maintenance/consumables
- Purchase-to-install in <18 months

Maximizing deployment speed and facility availability requires using commercial off the shelf (COTS) accelerator technology.

High current cyclotrons in the 10-30 MeV range have been used for decades by the medical isotope production industry.

Cyclotrons exist today from a half-dozen companies that provide cost, schedule, and operations effective proton beams

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A new facility for 10-30 MeV proton irradiation under construction at MIT

LMNT - A high power 30 MeV proton irradiation facility

PSFC has begun construction of a philanthropically funded facility to be largely "outward facing" to the community

- Re-use of $45M shielded vault from Alcator C-Mod tokamak
- <u>Cyclotron ordered; demo finishing; construction of laboratory underway</u>
- Cyclotron arrives in Q4 2025; first science results expected by Q2 2026
- DOE FIRE award was announced and is expected mid-2025, but these dates are not dependent on this funding.

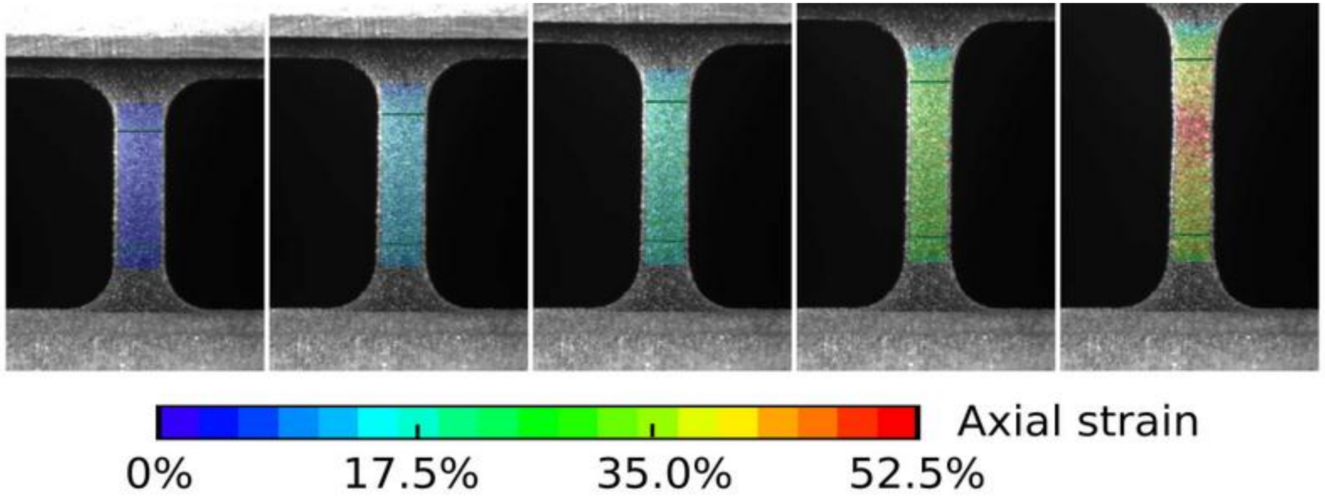
Overall features and capabilities of the facility

What parameters can we vary?

- DPA/Dose/Damage
- H/He/Other Transmutation Rates
- Irradiation Temperature
- *In-situ* Coolant Immersion
- Sample Preparation
- Alloy Composition

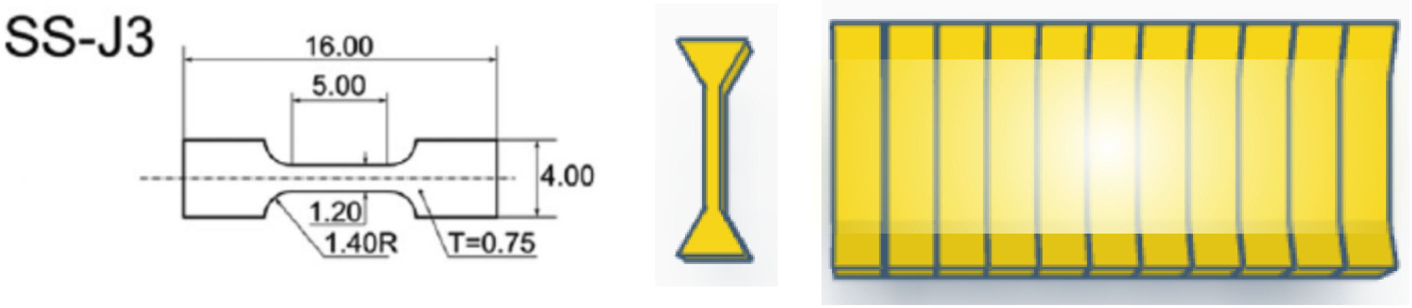
What are we proposing to measure?

- Yield and Ultimate Tensile Strength
- Hardness/Toughness (Charpy)
- Thermal/Electrical Conductivity
- Dimensional Changes
- Corrosion Behavior with Radiation
- Microstructure/Defect Evolution

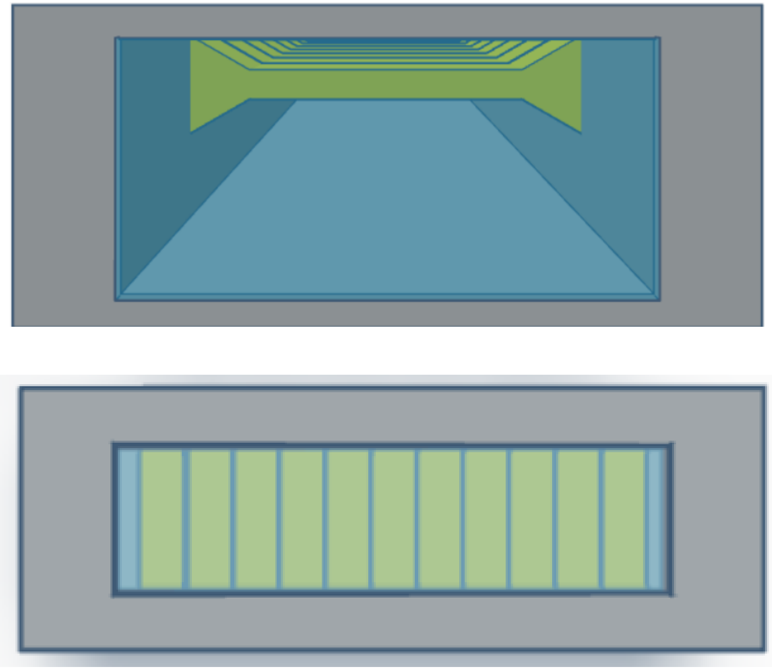


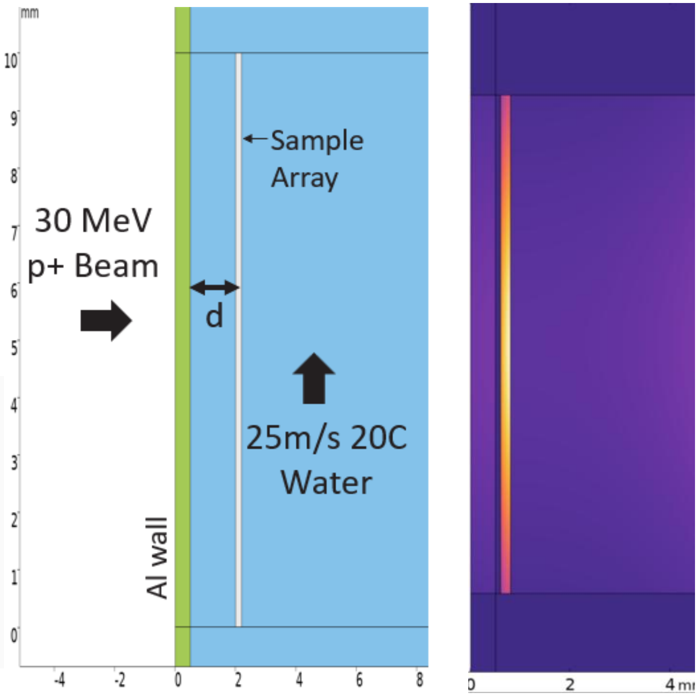
Example: Submerged sample array for high heat removal

1) Small tensile samples allow focused beams maximizing current density (i.e. damage rates)

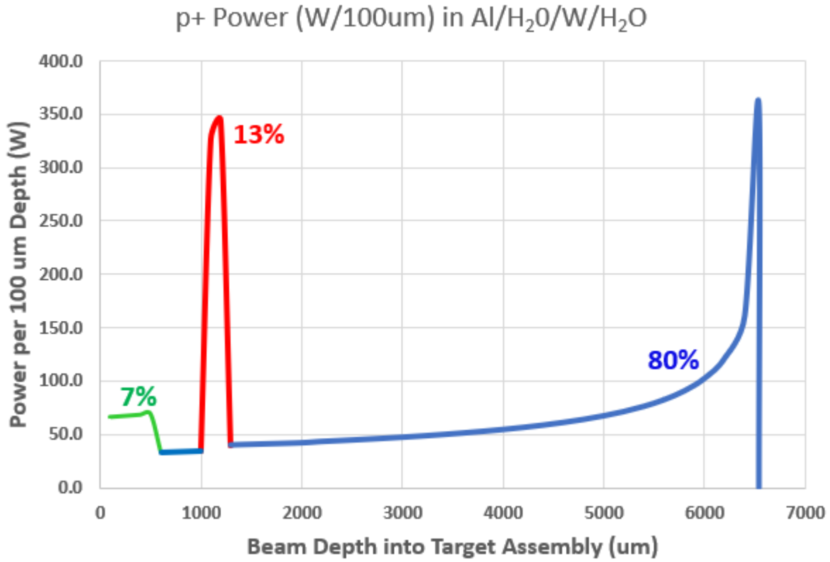


2) Submerge samples in coolant to maximize heat transfer





3) Most power deposits in coolant



4) Arrays can include multiple alloys

Four modular ‘caves’ enable flexible testing capabilities

Initial Configurations

A – Low currents/doses

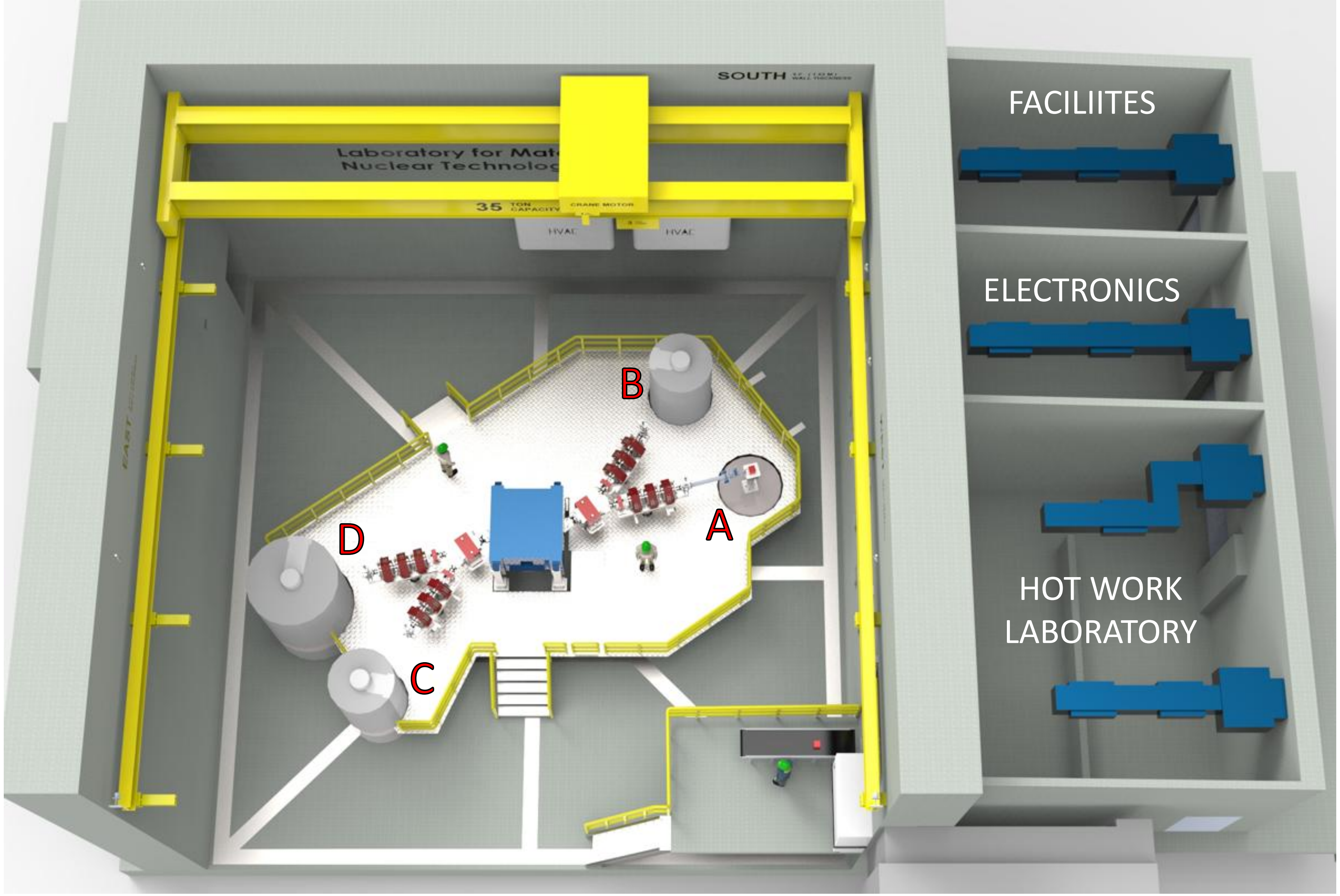
R&D new hardware, in-situ metrology, corrosion tests

B&C – High current/power

Primary testing sites, long duration exposure with damage from ~1-10 DPA, elevated sample temps.

D – Neutron Source

30 MeV p+ into Be generates ~10^{13} n/scm^2 or near-prototypic fusion spectra at ~10^{10} n/s*cm^2*



Vision of an “outward facing” ops model to maximize impact

MIT Plasma Science & Fusion Center

Industrial consortium from private companies

- Who: Fusion + materials companies
- How: Tiered membership model for access as-needed by companies at different levels.
  Why: Fees support facility OpEx in exchange for beam time and irradiation/testing services

Platform for federally funded materials scientists

- Who: Academic and national lab users
- How: DOE FES, DOE NE, ARPA-E, and others using grants for beam time in exchange for OpEx
  Why: Fees support facility OpEx in exchange for beam time and irradiation/testing services

U.S. DEPARTMENT OF ENERGY Office of Science

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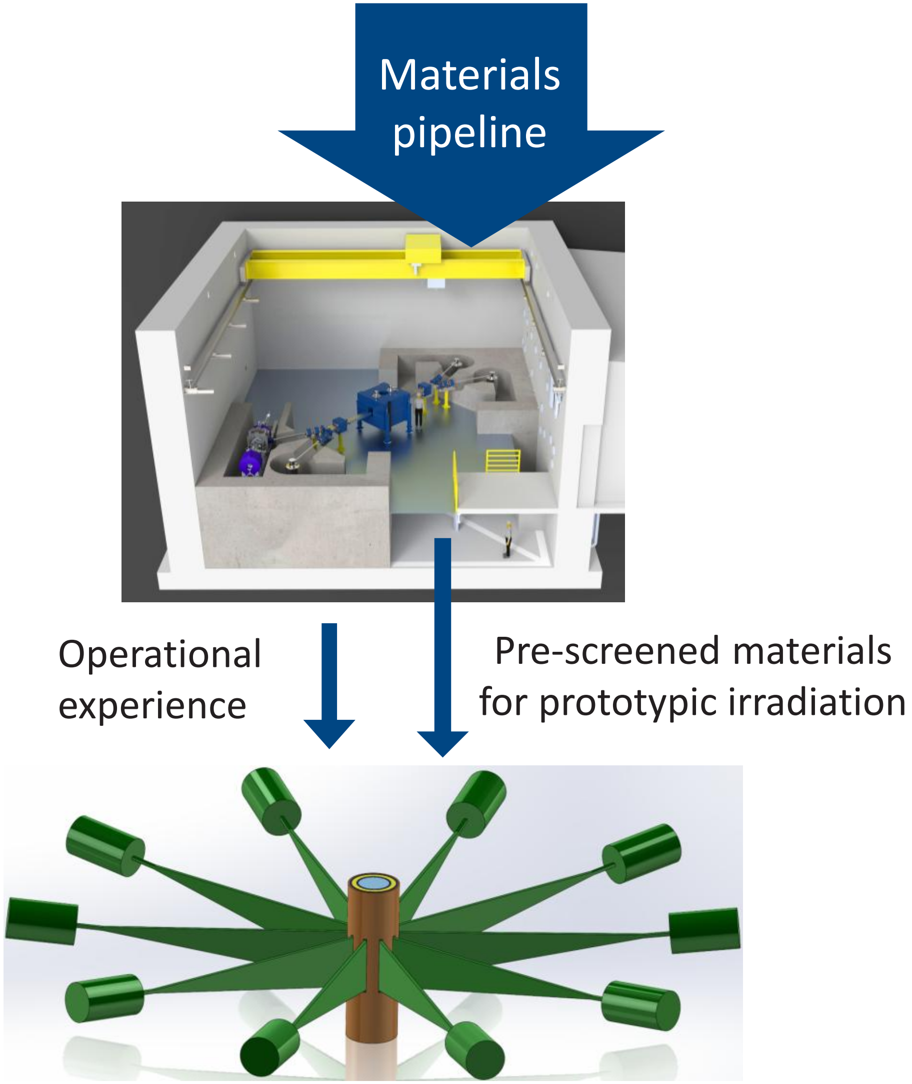
arpa·e

NEUP Nuclear Energy University Program U.S. Department of Energy

EPRI ELECTRIC POWER RESEARCH INSTITUTE

The new facility is highly synergistic with future US FPNS

- Acceleration: Tackle high DPA bulk materials irradiation, testing, and model development & validation ASAP.
- Optimization: Rapid, high throughput screening of alloy families to maximize the utility of FPNS dose rate
- Stepping stone: Experience with high current cyclotrons, liquid target design, initial low-flux component testing.
- Integration: Tackle complex *in situ* environment challenges for which FPNS may not be suitable.



Materials pipeline

Operational experience

Pre-screened materials for prototypic irradiation

Cyclotron-based FPNS

L. L. Snead *et al.* arXiv arXiv:2302.09011 2023.

Summary

Objectives:

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Propose 10-30 MeV proton irradiation as part of the solution

Test and collaborate to enable fusion materials solutions

Key Takeaways

The boundary conditions for fusion materials development have shifted and the stakes are higher

PSFC is constructing a 30 MeV proton irradiation facility that will start science operations in 2026

The facility is intended to serve this community and focus on taking materials from TRL 1 to 4/5.