INL/MIS-18-51679-Revision-0

Ion Beam Roadmap and the Use of Ion Irradiation as a Surrogate for Neutron Irradiation

October 2018

Changing the World's Energy Future

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Idaho National Laboratory

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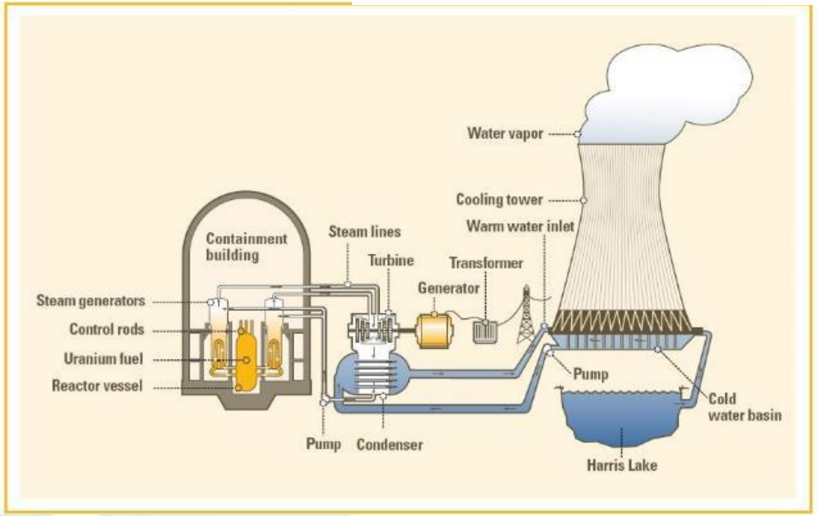
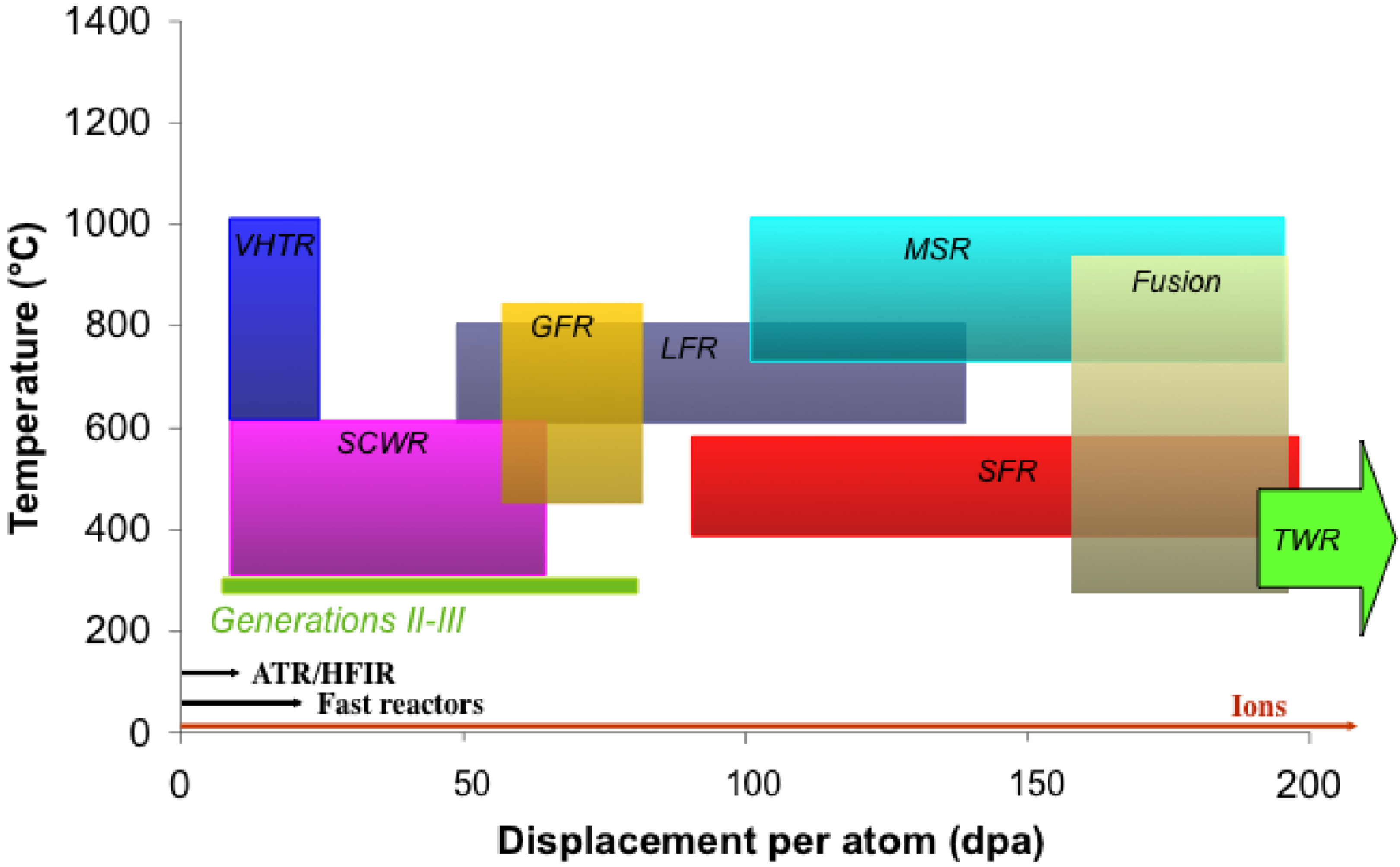
DOE-NE Mission

DOE NE R&D Objectives

1. Support the current fleet of LWRs
2. Deploy advanced reactors
3. Develop a sustainable fuel cycle
4. Reduce or mitigate proliferation risks



NE Requirements and Capabilities



Ion Beam Irradiation as a Surrogate for Neutron Irradiation

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Nuclear Science User Facilities

Radiation Effects in Materials

- Ionization and excitation (electronic stopping)
  - Generally can be neglected for metals
  - Important for polymers, ceramics, semiconductors
  - Dose unit--Gray, *Gy*, the dose for absorption of 1 J/Kg

Ions, electrons, photons

- Displacement of atoms (nuclear stopping)
  - Dominant damage process for metals
  - Significant for ceramics, semiconductors, polymers
  - Dose unit--displacement per atom, *dpa*
  - One dpa is the dose at which on average every atom in the material has been energetically displaced once

Neutrons, ions

- Transmutation reactions
  - Transmutation products

Neutrons, protons

Interaction of Charged Particles with Matter

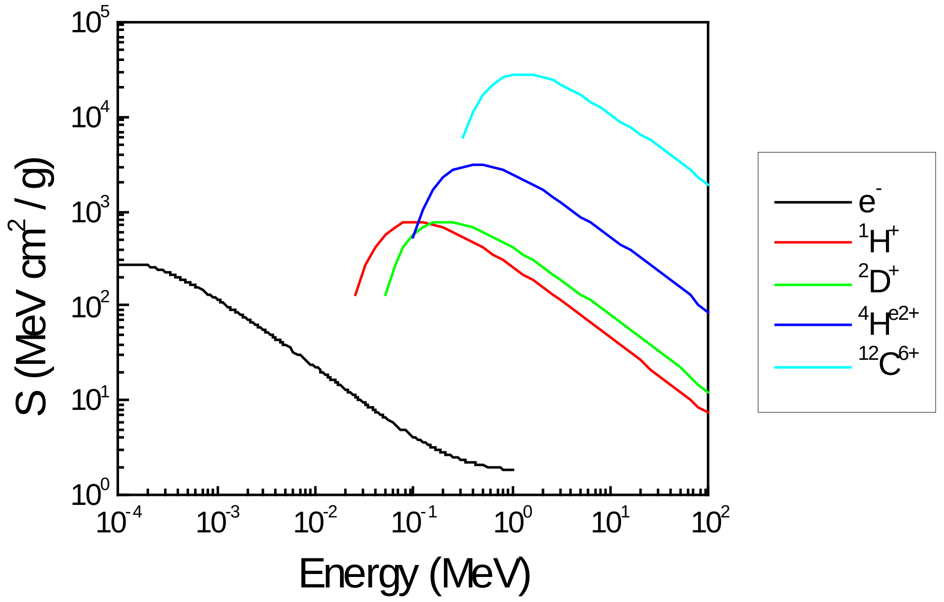
- Heavy charged particles – ^{1}H, ^{2}H, ^{4}He, ^{12}C, ^{16}O, ^{56}Fe ions
- Basic mechanism for slowing down of a charged particle is the Coulombic interaction of the particle with the electrons of the medium.
- Fast charged particles lose energy through ionization and excitation.
  - Ion only loses a small fraction of its energy in a single energy transfer event
    => a track of energy loss events
    => deflection of the particle is negligible
    => heavy charge particles travel in straight lines
- Slow ions also cause displacement damage
  - Energy transfer and collision cascade governed by kinematics
    => a cascade of displacement events
    => deflection of the particle may be significant
    => ion trajectory is not a straight lines

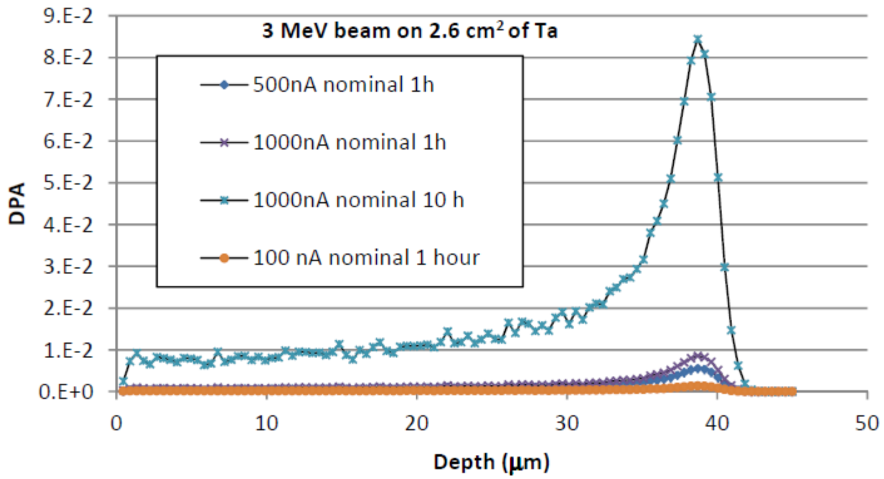
Ion Interaction with Materials

- Energy loss (slowing down) of energetic ions in a solid is characterized by the linear energy transfer rate or stopping power,

$$S(E) = \frac{dE}{dx} = \left.\frac{dE}{dx}\right|_{elec} + \left.\frac{dE}{dx}\right|_{nuclear}$$

- Divided into energy lost in electronic interactions and through atomic collisions (nuclear interactions)





Ions vs Neutrons: Challenges

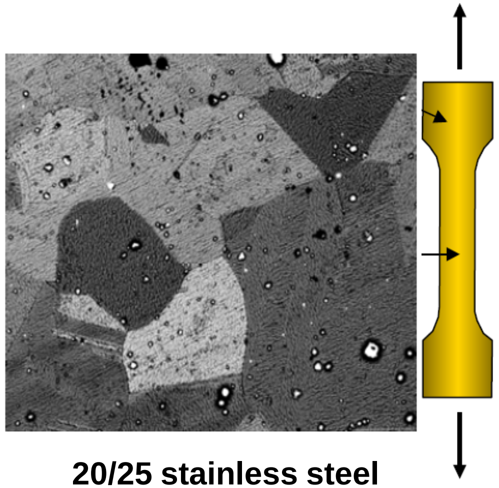
- Electronic interactions of ions:
  Question: Is ionization and radiation chemistry important?
- Penetration:
  Question: Is it possible to simulate neutron damage with ions of limited penetration?
- Nuclear collisions:
  Question: How similar are the ends of ion tracks to neutron induced damage?

Experiments with Ion Beams

Approach

Ion irradiation

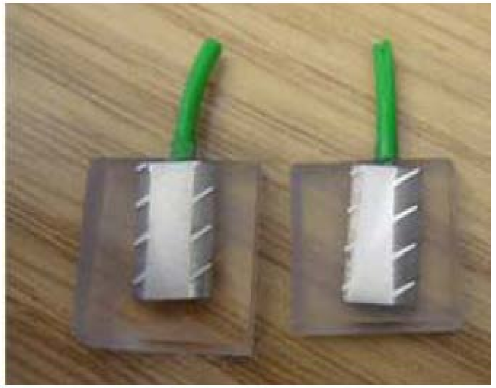
Michigan Ion Beam Laboratory



20/25 stainless steel

Electron microscopy

Electrochemistry



Ion Penetration - 5 MV Pelletron

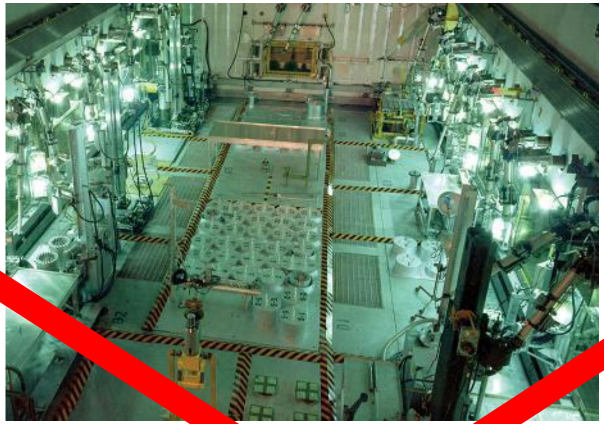
- 10 MeV $^{1}H^{+}$ ions have a penetration of **0.375 mm in Zircalloy** and **0.25 mm in stainless steel**
  - radiation damage of cladding and reactor pressure vessel materials.

- Maximum $^{1}H^{+}$ irradiation current (at 10 MeV) is up to **100 μamps**
  - rapid studies at realistic radiation doses.

- 15 MeV $^{4}He^{2+}$ ions have a penetration of **50 microns in steel**
  - implantation studies – e.g. He bubble formation.

- Maximum $^{4}He^{2+}$ irradiation current (at 15 MeV) is up to **15 μamps**.

Hot Cell Capabilities



Hot Fuel Examination Facility (INL)

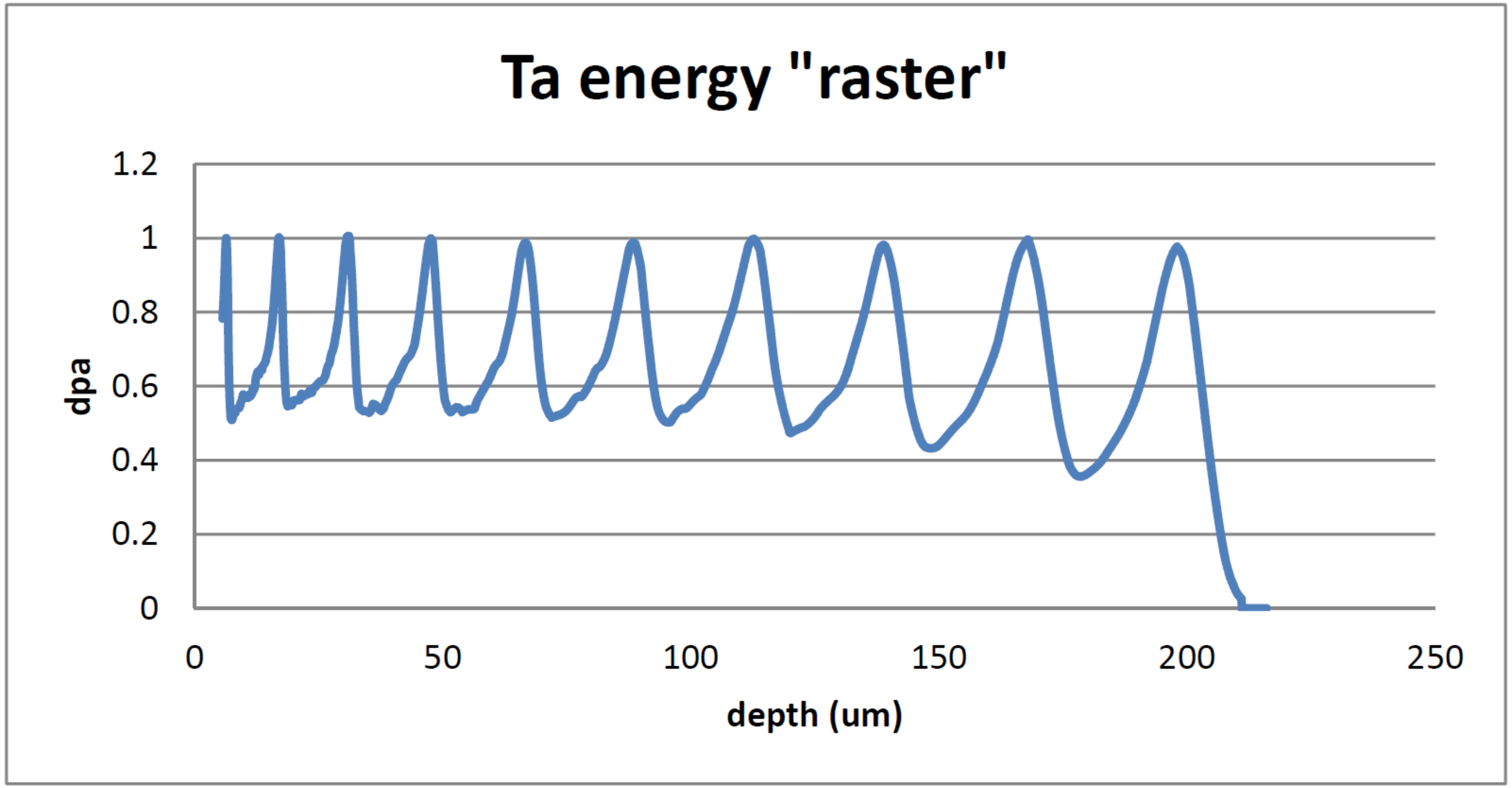
MIT Reactor Hot Cells

Materials Center of Excellence Laboratories (Westinghouse)

Radiochemical Engineering Development Center (ORNL)

Radiochemistry Processing Laboratory (PNNL)

Dose Profile



Windmill degrader?

Experimental Setup

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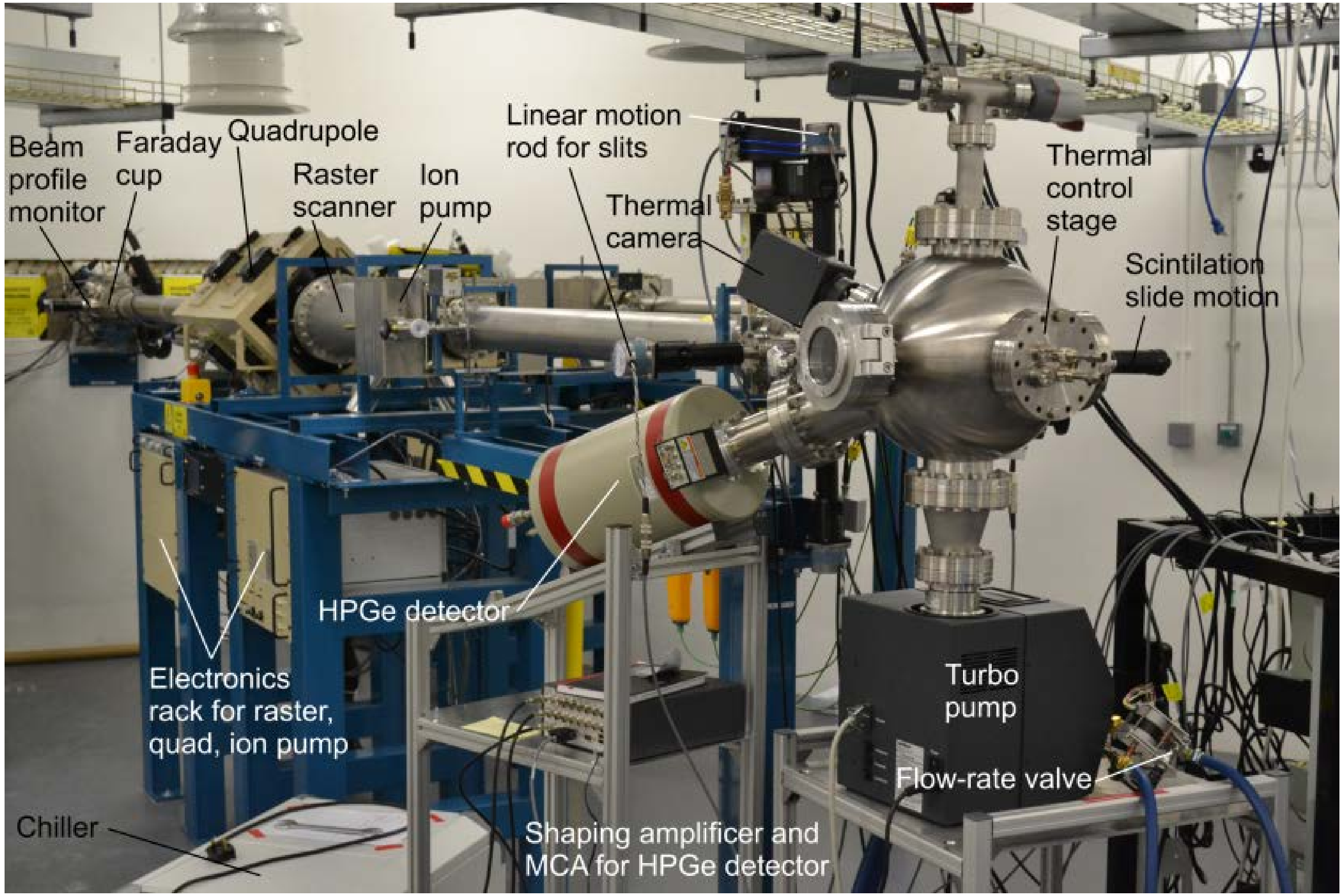
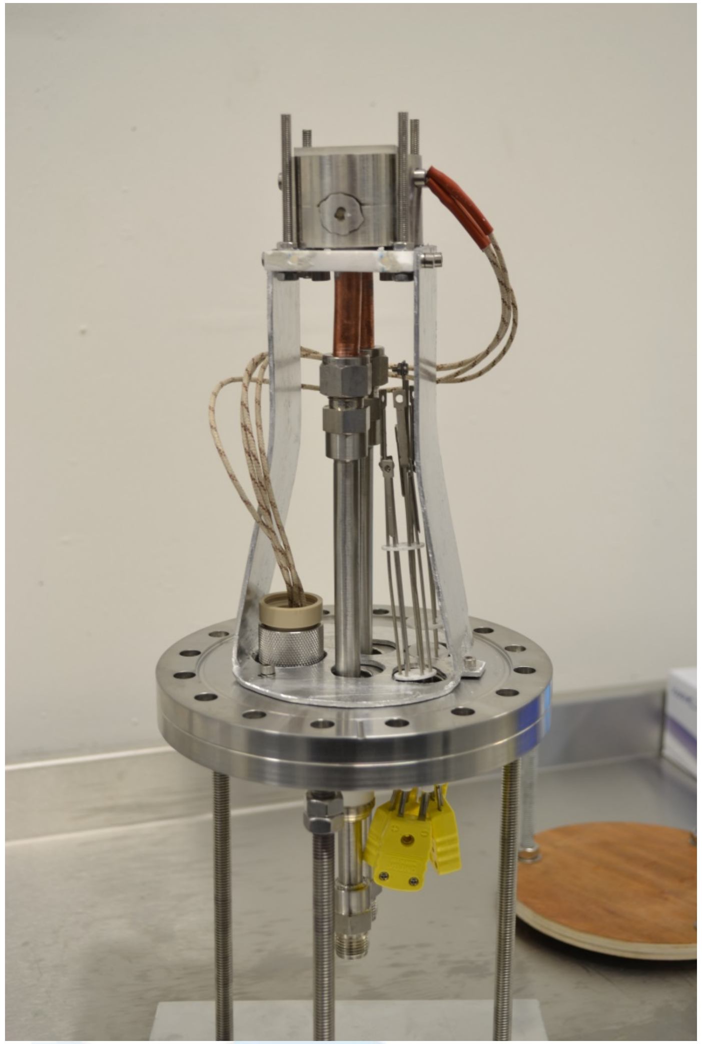
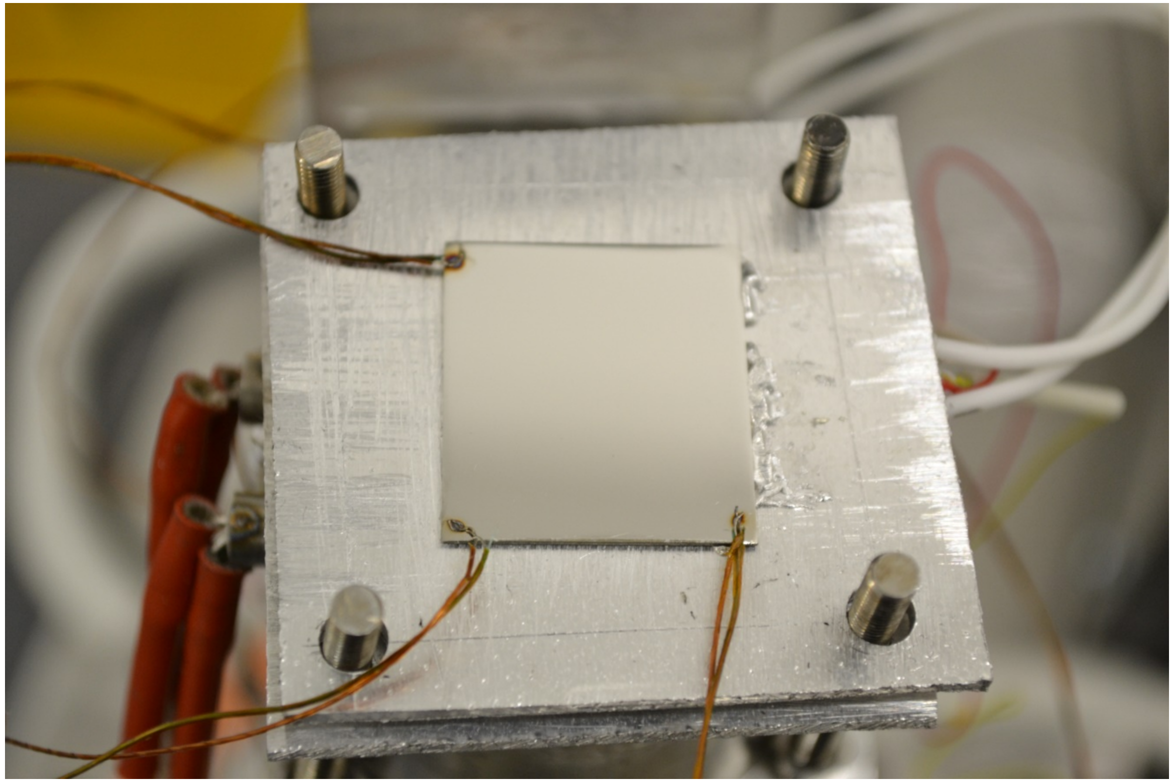
Nuclear Science
User Facilities



Differential pumping employed to achieve a vacuum pressure of < 5 x 10^{-8} torr.

Target





Low temperature melting or soft metal used to improve thermal contact.

Post Irradiation Examination

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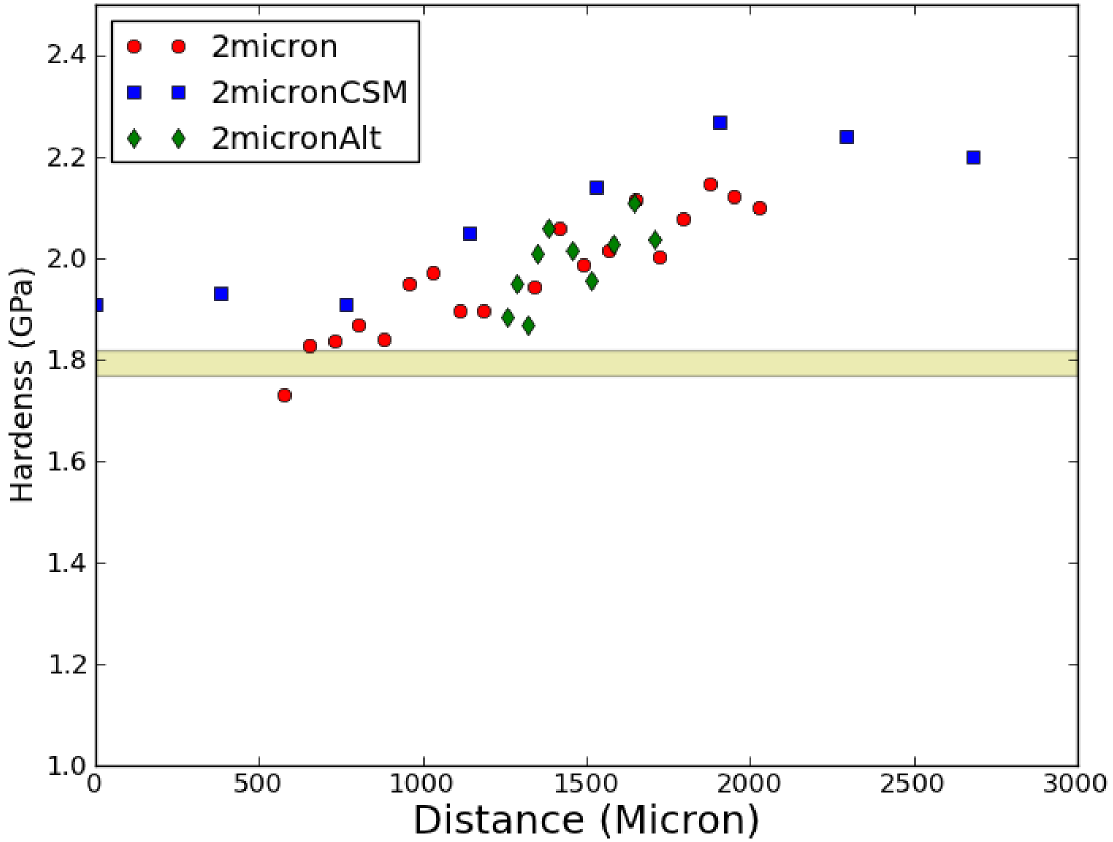
Nuclear Science
User Facilities

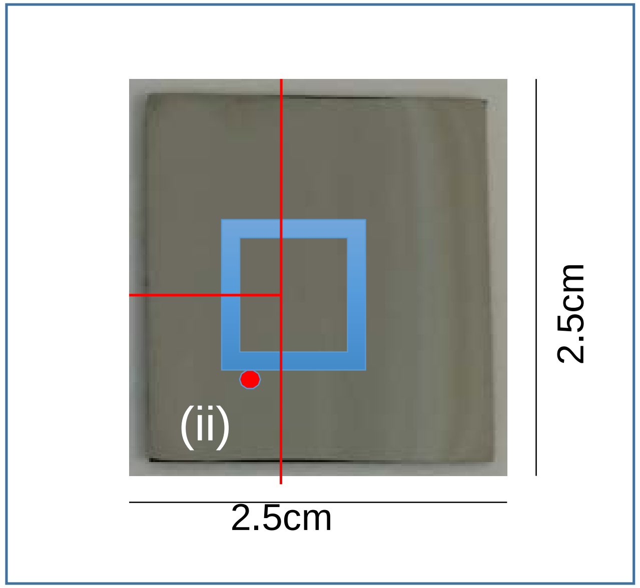
930°C HT + 0.5 dpa (1 MeV)

<u>Nanoindentation (OPS polished surface)</u>

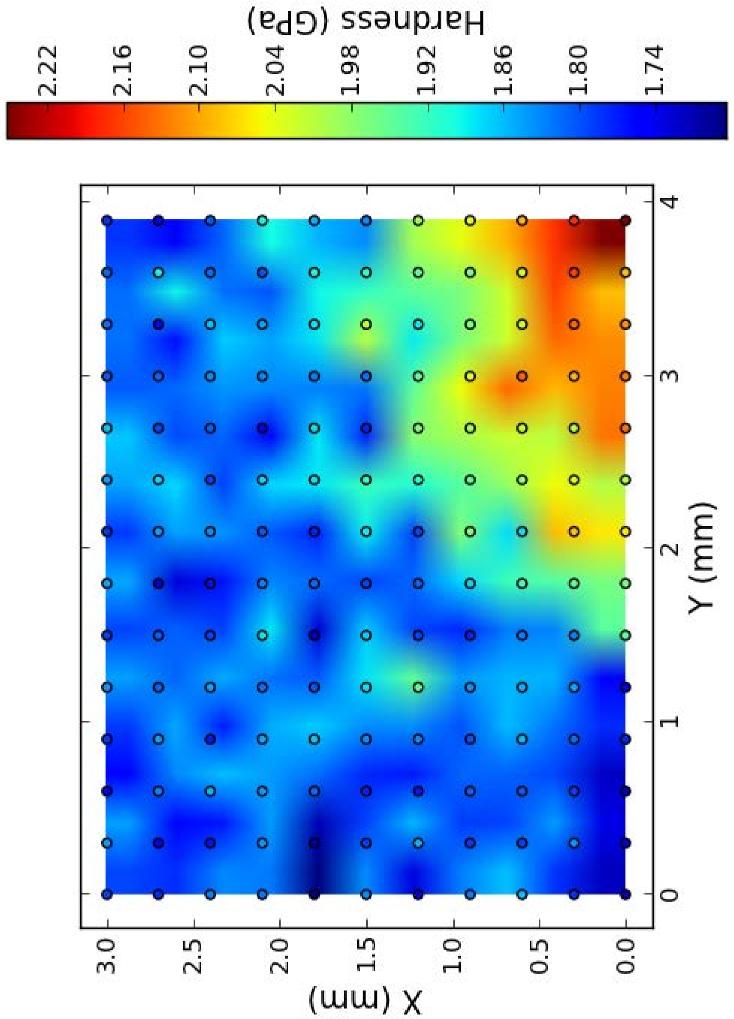
- The yellow bar represents the max. and min. in the non-irradiated region.
- Clear increase in hardness as the indents move into the irradiated area.

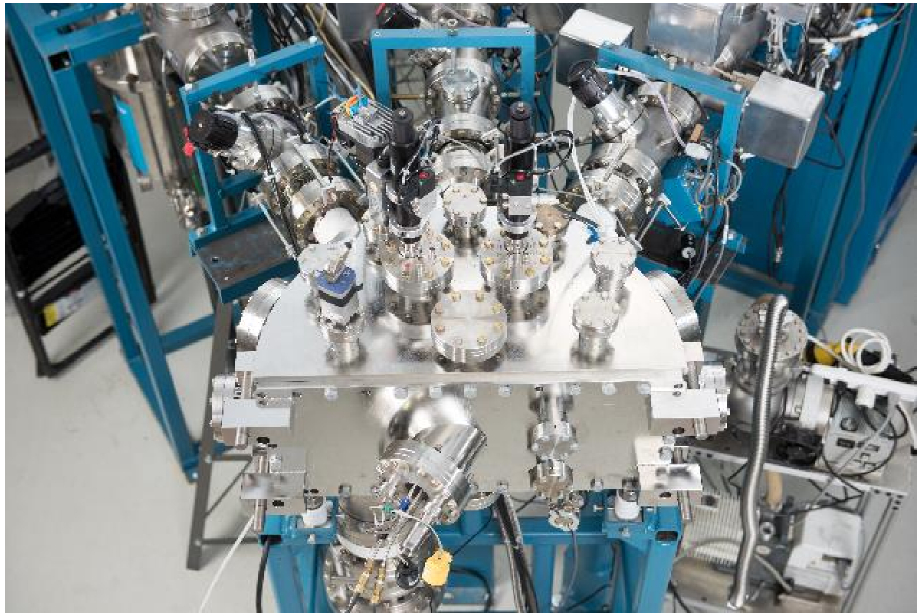


930°C HT + 0.5 dpa (1 MeV)



Proton irradiated
(7 mm x 7 mm)





Nuclear Science User Facilities

2016 ION BEAM INVESTMENT OPTIONS WORKSHOP

Purpose of the workshop

- **There was funding available…**
  - Infrastructure funding for universities and national laboratories via Consolidated Scientific Infrastructure Support FOA (**neup.inl.gov**)
  - Consideration of NSUF partnerships (**nsuf.inl.gov**)
  - Possibility of support for large projects.

- DOE wanted a **ranked list** of the "best" ion beam facilities
  - Who should be funded and why?

R&D Community Represented

Constituency	Home Institution
US Nuclear Industry	Electric Power Research Institute
Advanced Reactor Technologies (ART)	Department of Energy Office of Nuclear Energy
Light-Water Reactor Sustainability (LWRS)	
Nuclear Energy Advanced Modeling and Simulation (NEAMS)	
Fuel Cycle Research and Development (FCRD)	
Used Fuel Disposition Program	
Waste Forms Research and Development Program	
NSUF Scientific Review Board	Texas A&M University
NSUF User's Organization Chair	Westinghouse
NSUF Researcher	University of California - Santa Barbara
NSUF Researcher	University of Illinois - Urbana-Champaign

Facilities Attending - Operational

Institution	Facility
Argonne National Laboratory	Intermediate Voltage Electron Microscope (IVEM)
Idaho State University	Idaho Accelerator Facility
Los Alamos National Laboratory	Ion Beam Materials Laboratory
Lawrence Livermore National Laboratory	Center for Accelerator Mass Spectrometry
Ohio University	Edwards Accelerator Laboratory
Purdue University	Center for Materials under Extreme Environment Facility
Sandia National Laboratories	In Situ Ion Irradiation Transmission Electron Microscope
Texas A&M University	Ion Beam Laboratory
University of Michigan	Ion Beam Laboratory
University of Tennessee	Ion Beam Materials Laboratory
University of Wisconsin	Ion Beam Laboratory

Facilities Attending - Proposed

Institution	Facility
Argonne National Laboratory	Extreme Materials Beam Line
Brookhaven National Laboratory	Brookhaven Linear Isotope Producer / Brookhaven Linear Accelerator IRRadiation Test Facility
	Ion X-Ray Beam
Massachusetts Institute of Technology	Nuclear Materials Laboratory

Evaluation Criteria

#	Combined Criteria	Relative Weight	CoV
C1	Viability for the capability to extend our understanding towards accurately simulating nuclear irradiation conditions (neutrons or fission fragments).	100%	13%
C10	Ability of the facility to produce results that meet the needs of the DOE – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.	94%	21%
C3	Ability of the facility to provide a variety of well-controlled target environments and conditions.	92%	22%
C8	Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite.	89%	20%
C5	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in-situ.	86%	24%
C9	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.	86%	29%
C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	85%	24%
C7	Unique capabilities of the facility including any new technology that has the capability to close technological gaps.	83%	30%
C6	Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume sample throughput).	69%	35%
C4	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite.	62%	39%

Summary

Facilities ranked and recommendations made:

1. DOE-NE-5 provided **infrastructure improvement funds:**
   - **IVEM at Argonne National Laboratory**
   - **MIBL at University of Michigan**

2. NSUF began **partnership** process with:
   - **Accelerator Laboratory at TAMU**
   - **IVEM at Argonne National Laboratory**
   - **CAMS at Lawrence Livermore National Laboratory**
   - **I^{3}TEM at Sandia National Laboratory**

Nuclear Science User Facilities

2017 ION BEAM ROADMAP WORKSHOP

2017 Workshop - Purpose & Scope

Purpose

- The NSUF Ion Beam Irradiation Roadmap Committee is established to provide to the DOE-NE a report describing:

  1. **current and potential future contributions** of ion beam technologies
  2. addressing the **technical & regulatory challenges of nuclear energy**
  3. for the **advancement and implementation of nuclear energy technologies** that are part of the mission of DOE-NE.

Committee Membership

- **Executive Committee:**

Steve Zinkle (University of Tennessee)
Gary Was (University of Michigan)
Simon Pimblott (INL/NSUF formerly University of Manchester)

- **Contributors:**

Todd Allen (Univ. of Wisconsin)	Lin Shao (TAMU)
Michelle Bales (U.S. NRC)	Lance Snead (Stony Brook Univ.)
Lynne Ecker (BNL/NSLS-II)	Ming Tang (LANL)
John Jackson (INL/GAIN)	Cem Tobasi (EPRI)
Meimei Li (ANL/IVEM)	Blas Uberuaga (LANL)
Stu Maloy (LANL)	Yong Yang (University of Florida)
Daniel Schwen (INL)	Yongfeng Zhang (INL)

Introduction

- Role of Ion Beam Systems in Addressing the Materials Challenges in Nuclear Energy
  - *Developing and supporting methods for **accelerated materials qualification** with respect to licensing current and adv. reactor tech.*
  - *Development of a deeper understanding of factors that control the **evolution of microstructure** and properties under irradiation*
  - *Development and validation of fuels and materials **models***
- Development of Ion Beam Systems as a Tool
  - ***Method development** and technology enhancement*
  - *Motivation for standardization of techniques and methods for **quality assurance***

Current State of Affairs

- ***Best Practices*** ***for Conducting Ion Irradiations:***

Study Radiation Damage in Materials	*Emulate Reactor Irradiation Conditions*
Irradiation mode	Irradiation Rate
Temperature Control	Damage Rate
Temperature Monitoring	Ion Selection
Dosimetry	Penetration Depth (ion energy)
Vacuum Control	Injected Interstitials
Determination of dpa	Techniques to flatten damage profile
	Injection of He

Selection of ion type: *"For bulk irradiations (ions remain in sample), ion species should usually be the same as one of the major alloying elements so as to minimize the change in composition in the sample. For both bulk and in situ irradiations in the TEM, the selected ion/energy combination should be made so as to produce a primary knock-on atom energy spectrum that is as close as possible to that produced by neutrons in reactor."*

Chapter 3: Issues and Answers

Topics areas each with a problem statement and a proposed solution pathway.

1. Developing and Supporting Methods for Rapid and Cost Effective Materials Selection and Development
2. Characterizing Fundamental Material Response under Irradiation
3. Developing a Mechanistic Understanding of Microstructure Evolution under Irradiation
4. Development and Validation of Robust Predictive Models for Microstructure Evolution under Irradiation
5. Developing Methods for Scoping, Focusing, and Limiting In-pile Tests Needed for Material Licensing Basis

Examples of Applications

- **Structural Materials**
  - For the sodium-cooled fast reactors (SFRs), alloy NF-709 was on the priority list of austenitic stainless steels. As the core support structural material, A709 alloy is expected to receive a **dose of 20 dpa** or more. However, to date, there is **neutron data for 3-6dpa**.

- **Nuclear Reactor Fuels**
  - The experimental investigation of **High Burn-up Structure in commercial LWR fuel** is challenging due to the very limited restructured fuel occurring at typical operational burn-up levels and the related complexity in working on high burnup fuels. The **dual-beam irradiation offers all three effects** including irradiation-induced dislocation, fission gas and void swelling, and radiation from energetic fission fragments.

- **Radioactive Waste Storage**
  - Radiation stability is one of the requirements for nuclear waste form development. The primary challenge is the **various radiation sources** in nuclear waste. (1) short-lived actinides incorporation, (2) actinides in natural minerals, (3) gamma irradiation utilizing 60Co or 137Cs sources, (4) neutron irradiation, and (5) charged-particle irradiation using electrons, protons, α-particles, and heavy ions.

Path Forward

- Barriers to Implementation
  - Ions are great for separate effects testing, where test reactors are weak.
  - How do we deal with rate effects?
- Regulatory Challenges
  - How do we get the NRC to trust us?
  - Regulations are focused on neutron irradiation.
- Path Forward
  - Download the Roadmap (https://nsuf.inl.gov/Page/about)
  - Send me (or the authors) feedback.

NSUF
Nuclear Science
User Facilities

QUESTIONS?

Development and Deployment Process for Nuclear Materials