Use of Ion Irradiation to Simulate Radiation Damage from Neutrons

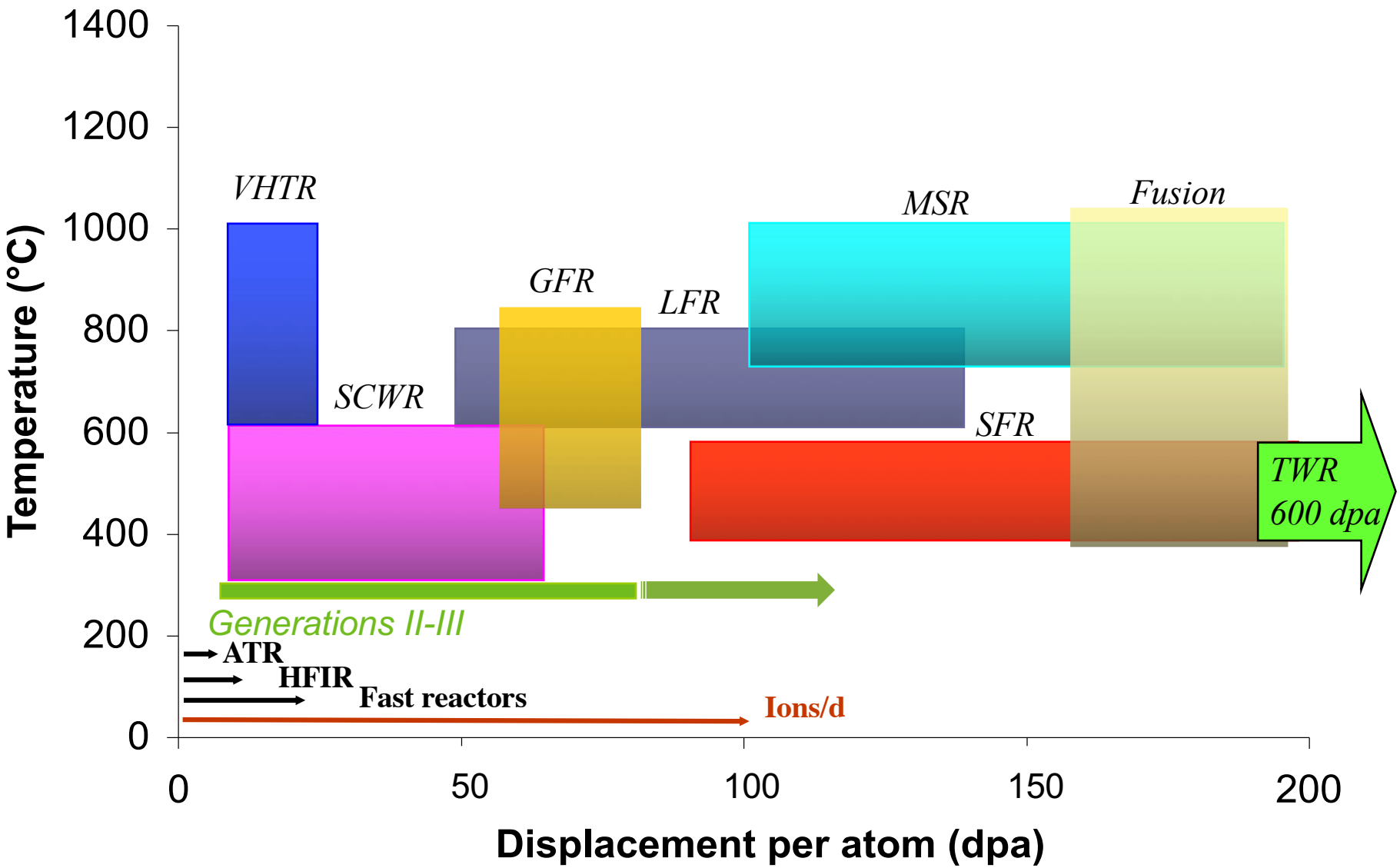
G. S. Was, Elizabeth Getto, Anthony Monterrosa, Stephen Taller,
David Woodley, George Jiao, Kai Sun
University of Michigan

International Nuclear Target Development Society
October 8-12, 2018
Lansing, MI

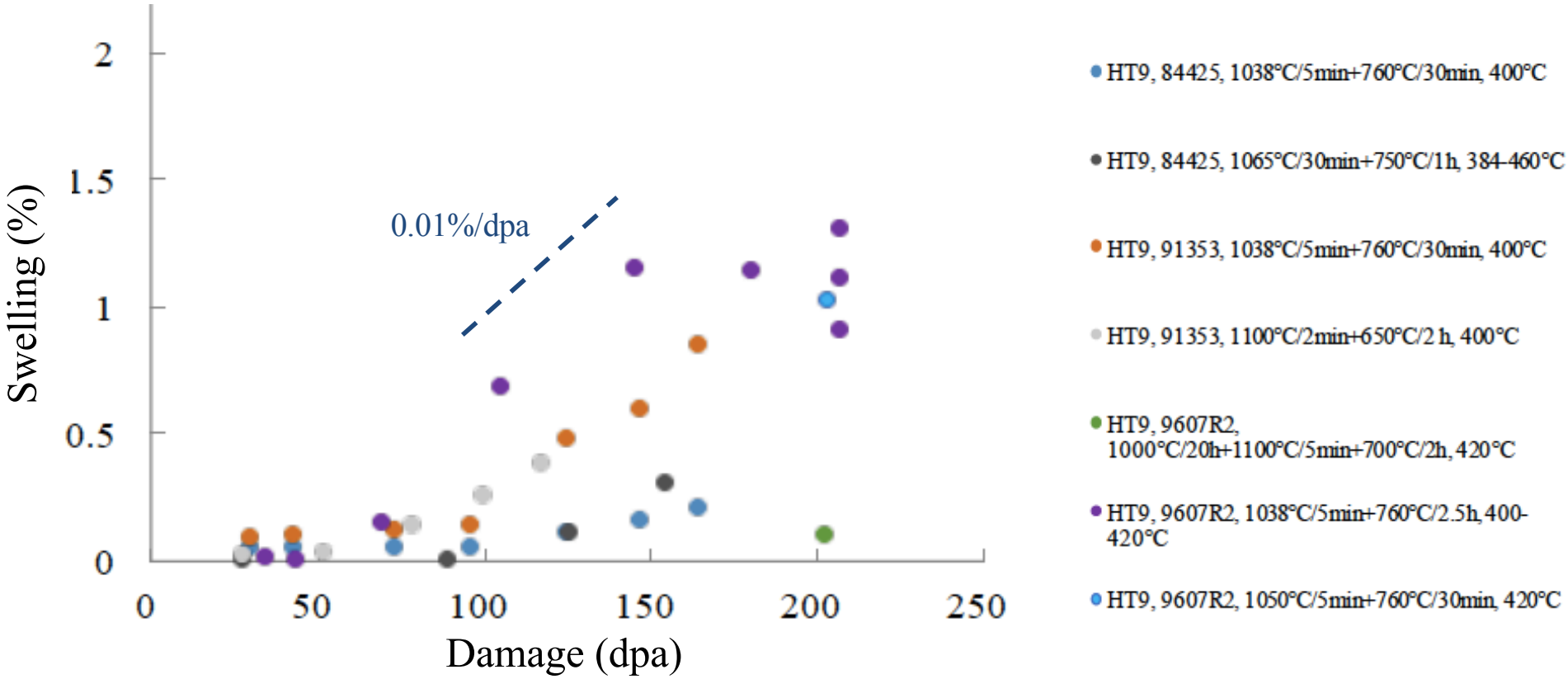
Outline

- Motivation
- Using ion irradiation to simulate radiation damage from neutrons
  - Stainless steels (thermal reactor relevance)
  - Ferritic-martensitic alloys (fast reactor relevance)
    - High dpa
    - He effects
- Capabilities for ion irradiation to contribute to our understanding of microstructure evolution under reactor conditions

Demands on Materials in Advanced Reactor Concepts



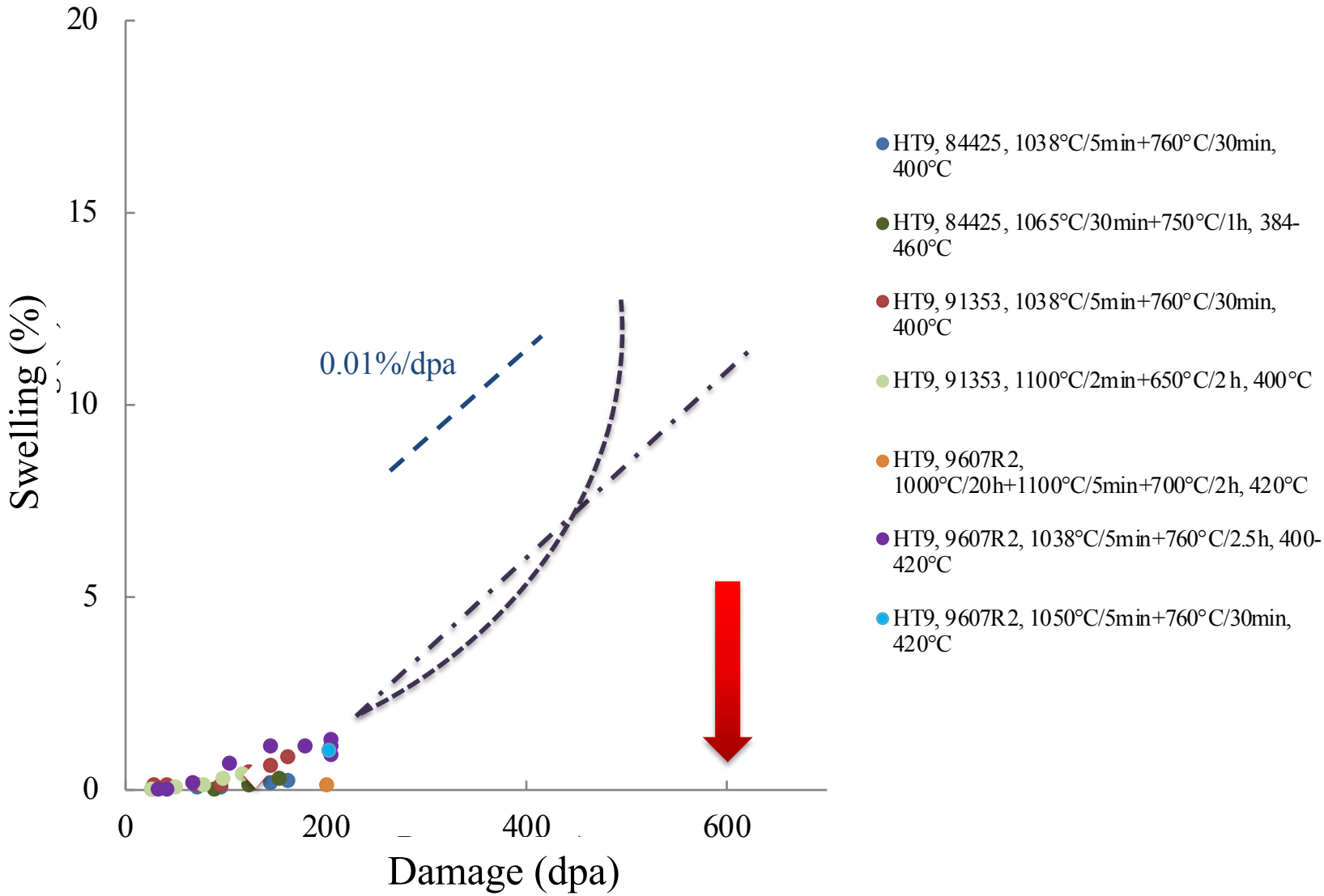
All existing reactor data on swelling in alloy HT9



[1] D. Gelles, J. Nucl. Mater. 237 (1996) 293.
[2] M.B. Toloczko, F.A. Garner, C.R. Eiholzer, J. Nucl. Mater. 215 (1994) 604.
[3] M.B. Toloczko, F.A. Garner, Journal 237 (1996) 289.
[4] M.B. Toloczko, F.A. Garner, Eff. Radiat. Mater. ASTM STP 1325 (1999).
[5] B.H. Sencer, J.R. Kennedy, J.I. Cole, S.A. Maloy, F.A. Garner, J. Nucl. Mater. 393 (2009) 235.
[6] J.J. Kai, R.L. Klueh, J. Nucl. Mater. 230 (1996) 116.
[7] J. Van Den Bosch, O. Anderoglu, R. Dickerson, M. Hartl, P. Dickerson, J.A. Aguiar, P. Hosemann, M.B. Toloczko, S. A. Maloy, J. Nucl. Mater. 440 (2013) 91.

What happens beyond 200 dpa?

- Slow and costly – at 20 dpa/yr, max!



Limitations of test reactors

- Availability

World fast neutron reactor status

Current FNRs

Reactor	Type, coolant	Power thermal/elec	Fuel (future)	Country	Notes
BOR-60	Experimental, loop, sodium	55/10	oxide	Russia	1969-2020
BN-600	Demonstration, pool, sodium	1470/600	oxide	Russia	1980-
BN-800	Experimental, pool, sodium	2100/864	oxide	Russia	2014-
FBTR	Experimental, pool, sodium	40/-	oxide & carbide (metal)	India	1985-2030
PFBR	Demonstration, pool, sodium	1250/500	oxide (metal)	India	(2018?)
CEFR	Experimental, pool, sodium	65/20	oxide	China	2010-
Joyo	Experimental, loop, sodium	140/-	oxide	Japan	1978-2007, maybe restart 2021
Monju	Prototype, loop, sodium	714/280	oxide	Japan	1994-96, 2010, shutdown

WORLD NUCLEAR ASSOCIATION

Limitations of test reactors

- Variability in irradiation conditions

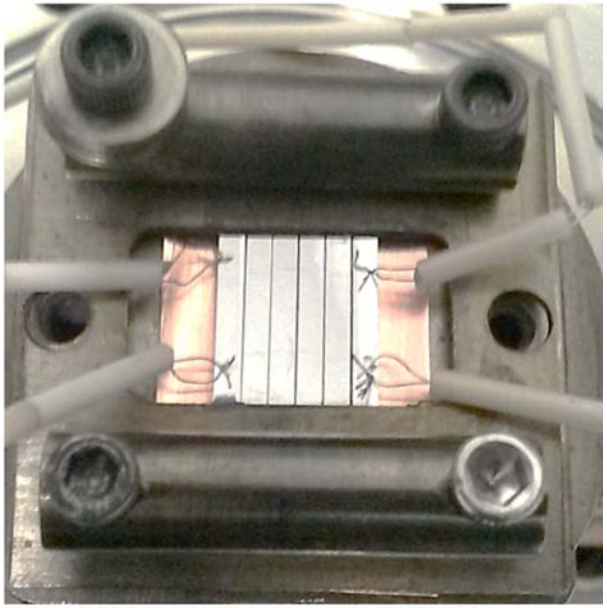
- Reactor irradiations are inherently, poorly controlled “experiments”.
- Temperatures are usually calculated, not measured.
- Fluxes are calculated.
- Shifting of assemblies within a core can result in step changes in fluxes and temperatures at a particular location.

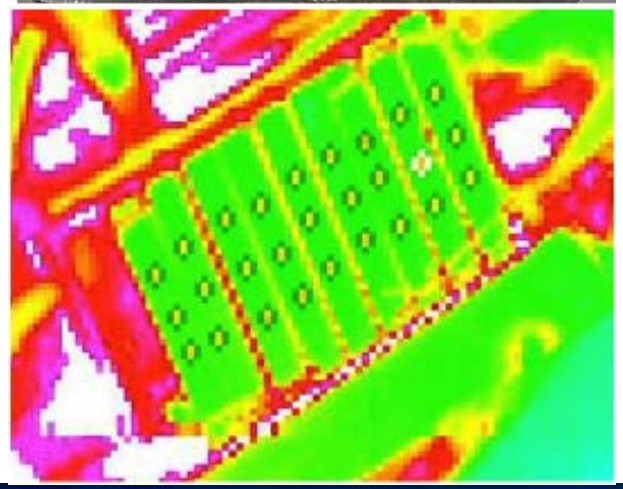
Benefits of ion irradiation

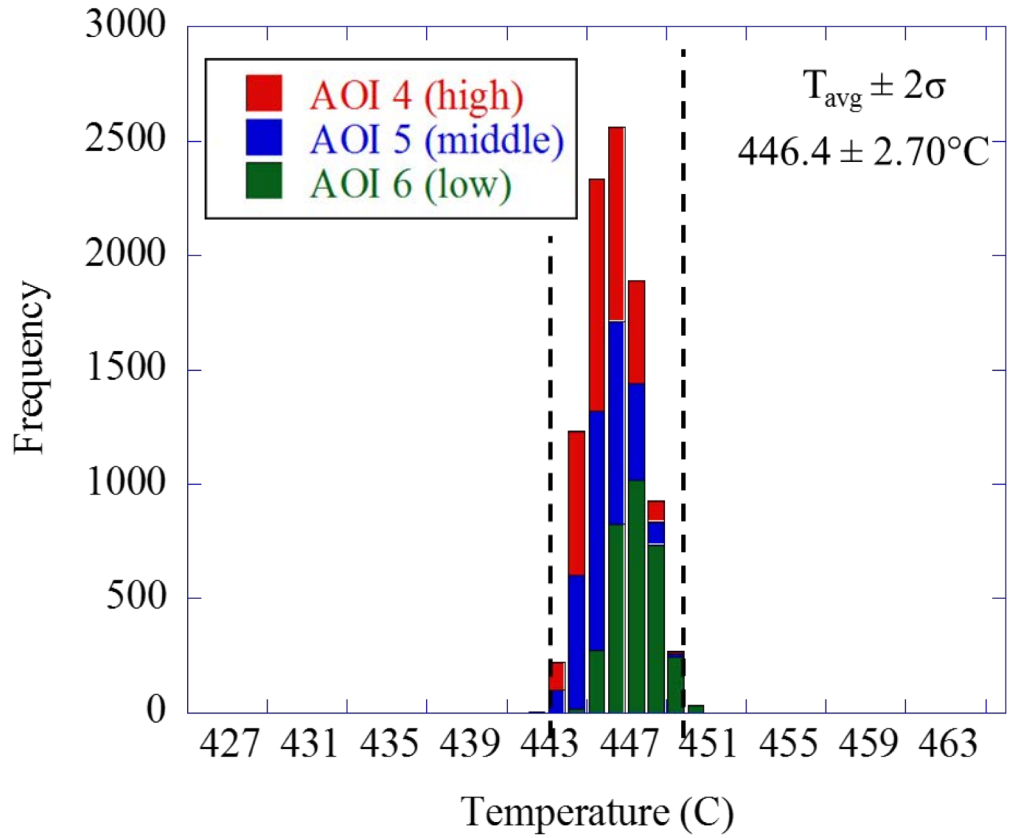
- High doses are easily achievable
  - 1dpa/day for protons
  - 100 dpa/day for heavy ions

- Extremely well-controlled irradiations (temperature, dose, dose rate)

Temperature control during Fe^{++} ion irradiation of alloy 800H to 16.6 dpa with 16.6 appm He (He/dpa = 1) at 446°C







Benefits of ion irradiation

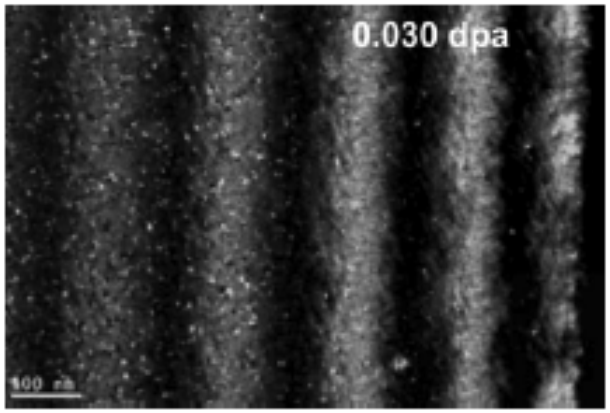
- High doses are easily achievable
  - 1dpa/day for protons
  - 100 dpa/day for heavy ions

- Extremely well-controlled irradiations (temperature, dose, dose rate)

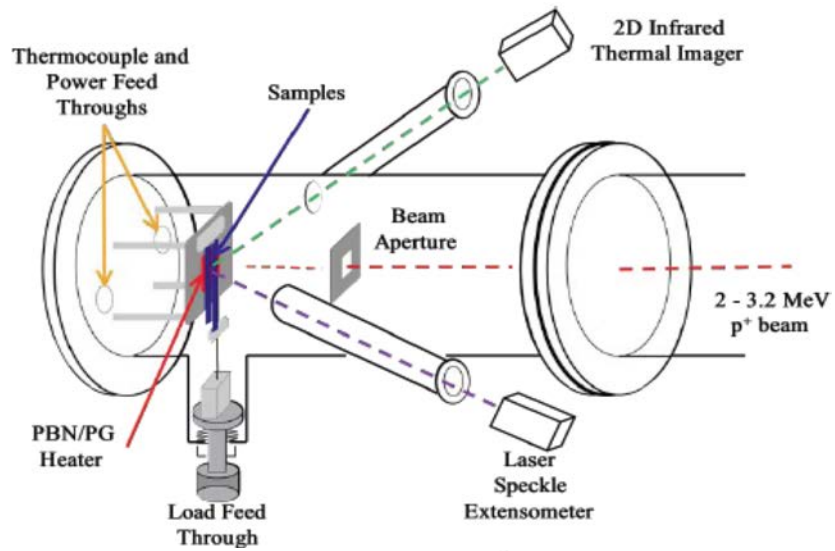
- Can address multiple components of the "extreme environment" and more easily employ in-situ analysis

Multiple components of the "extreme environment"

***In-situ* 1 MeV Kr irradiation (ANL)**

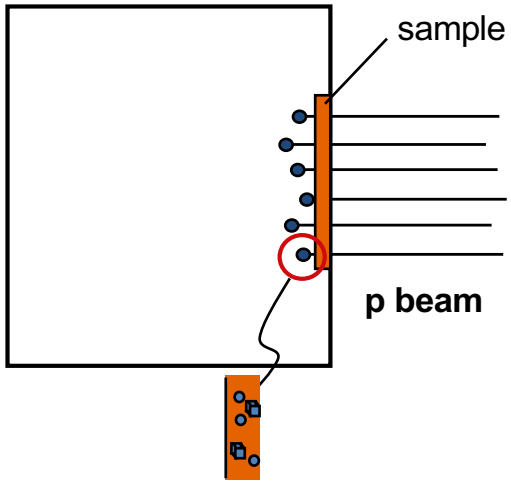


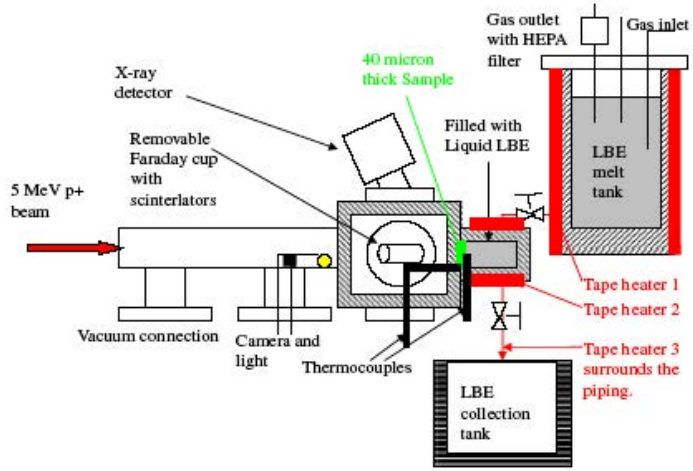
Irradiation creep of F-M alloys, SiC and PyC



In-situ corrosion

Water-UM





LBE-LANL

Benefits of ion irradiation

- High doses are easily achievable
  - 1dpa/day for protons
  - 100 dpa/day for heavy ions

- Extremely well-controlled irradiations (temperature, dose, dose rate)

- Can address multiple components of the "extreme environment" and more easily employ in-situ analysis

- Low sample activation

Ion irradiation can add value to neutron irradiation and give access to the extreme of high dose

Variable	Ion Beams	Test Reactors
Dose	>500 dpa	10-20 dpa max
Dose rate	100 - 1000× reactor rates	Few × reactor rates
Energy	Controlled by ion type (a few keV to ~ 100 MeV)	Neutron spectrum (up to 14 MeV)
Transmutants/fission products	Separable	Controlled by nuclear physics
Temperature	Better than ±10° C	Variable – 10s of ° C
Residual activity	Low to none	high
In-situ observation	TEM, RS, GC, etc.	Some T and displacement, generally PIE only
Unit mechanisms	Demonstrated	Challenging
Cost	Relatively low	Relatively high
Simultaneity (e.g., corrosion and straining)	Corrosion, SCC, creep, diffusion, etc.	Bulk materials, doable but difficult
Sample thickness	A few nm to ~100 μm	bulk

Time - Residual Activity => Cost

from Wayne King

Some results from thermal and fast reactor applications

Direct comparison of neutron and proton irradiation effects on the same alloy *and* heat

Heat B: Commercial purity 304 SS

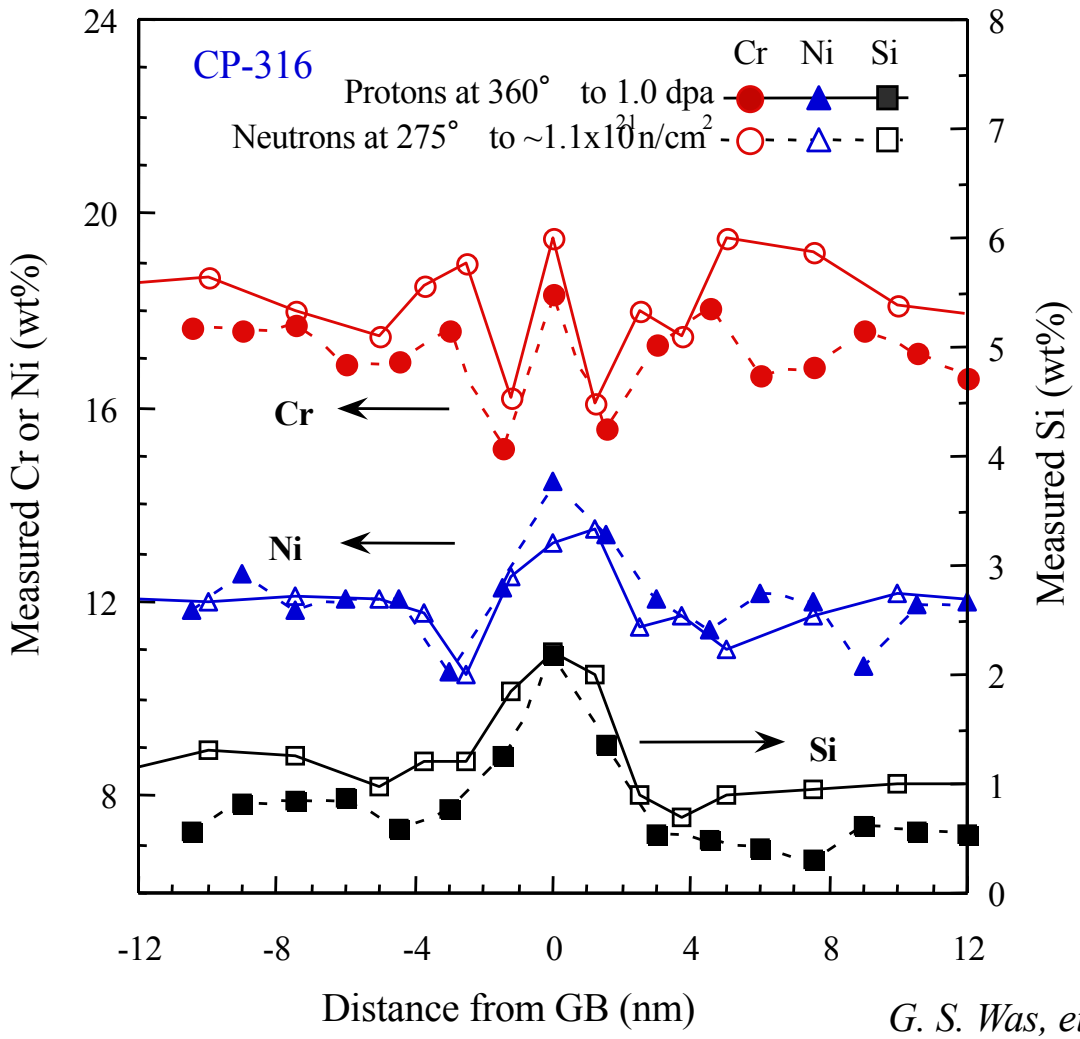
Heat P: Commercial purity 316 SS

Irradiated in Barsebak BWR reactor, Sweden

Neutron-irradiated microstructure analysis: S. Bruemmer, PNNL

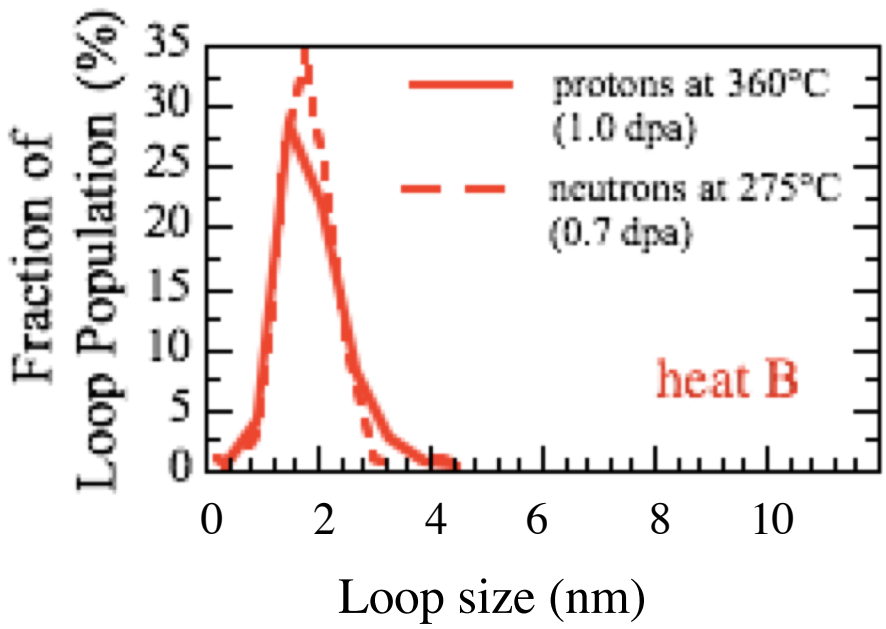
Proton irradiation and microstructure analysis: UM

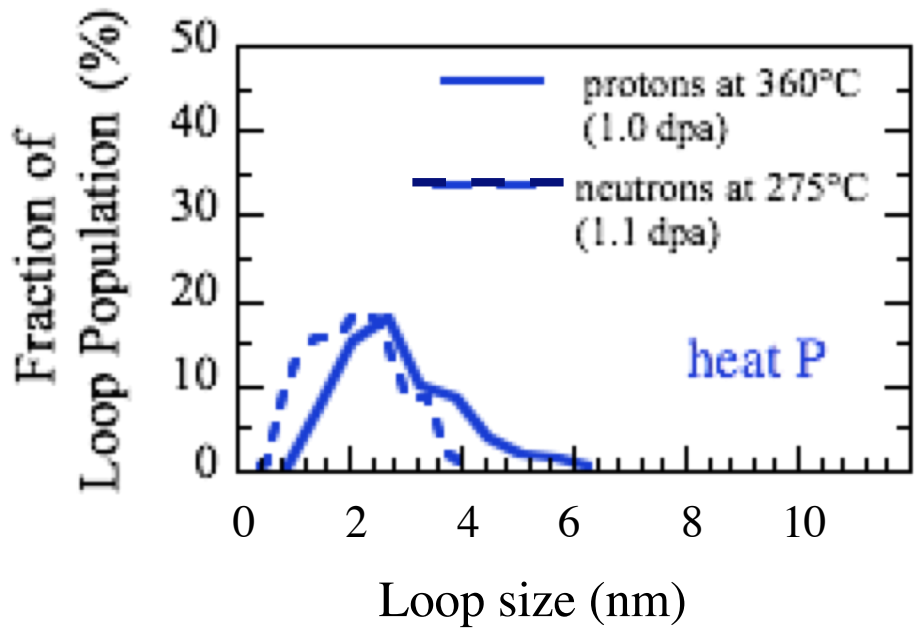
RIS in a single heat of stainless steel irradiated to 1 dpa with protons at 360°C or neutrons at 275°C



G. S. Was, et al., JNM 300 (2002) 198-216

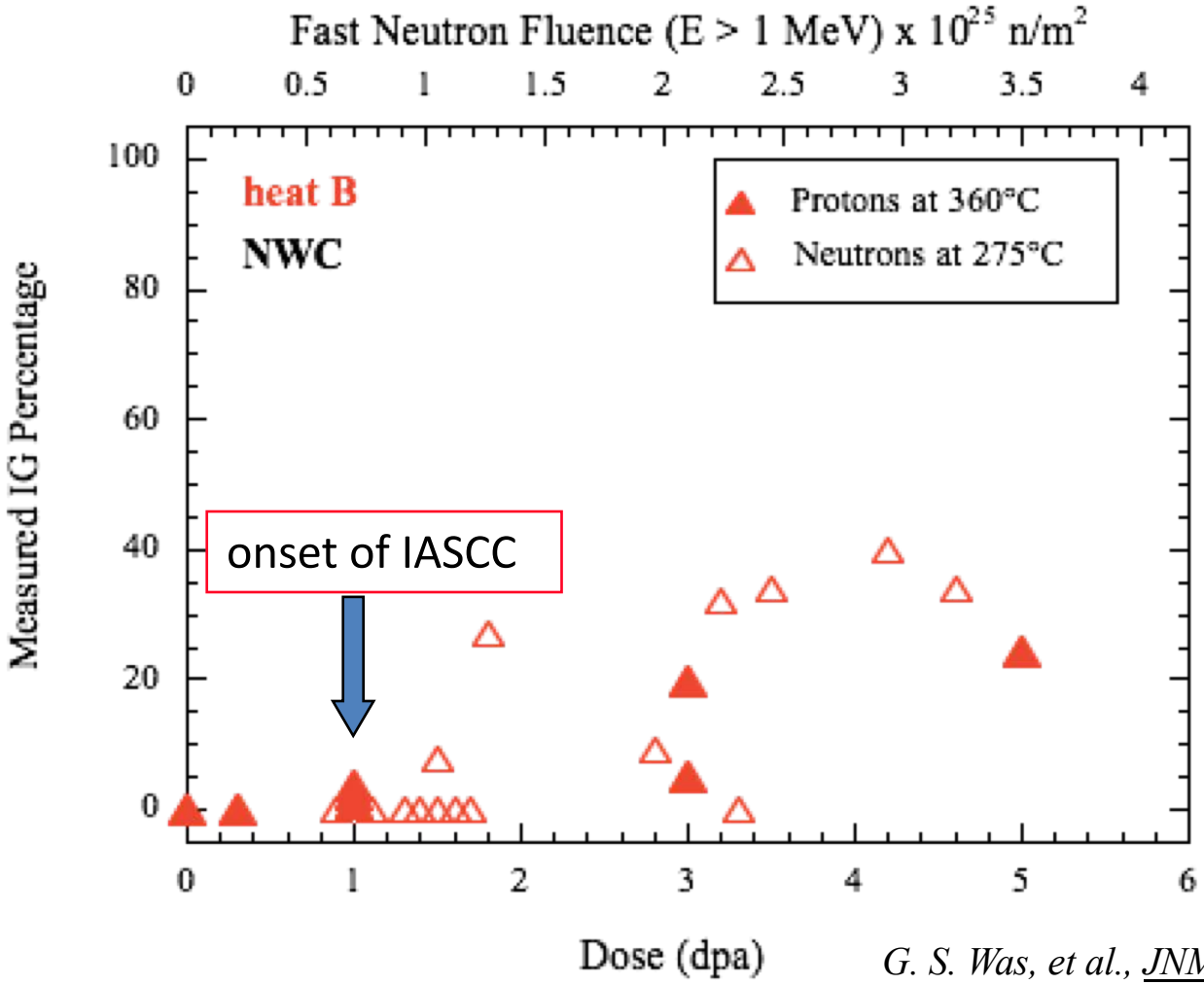
Faulted loop size distributions in stainless steel irradiated with protons at 360°C or with neutrons at 275°C





G. S. Was, et al., JNM 300 (2002) 198-216

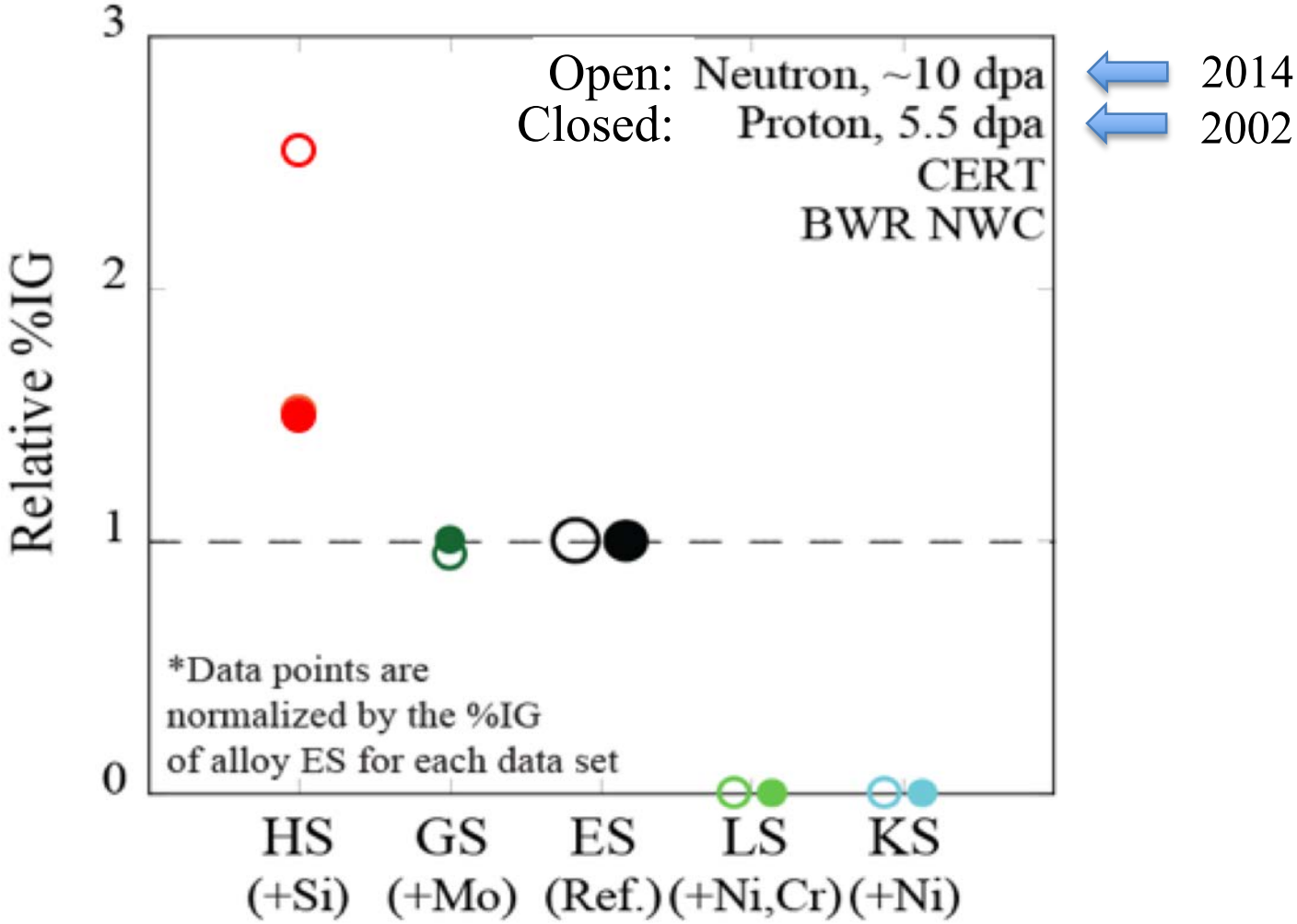
IASCC of neutron- or proton-irradiated 304 SS strained in normal water chemistry



G. S. Was, et al., JNM 300 (2002) 198-216

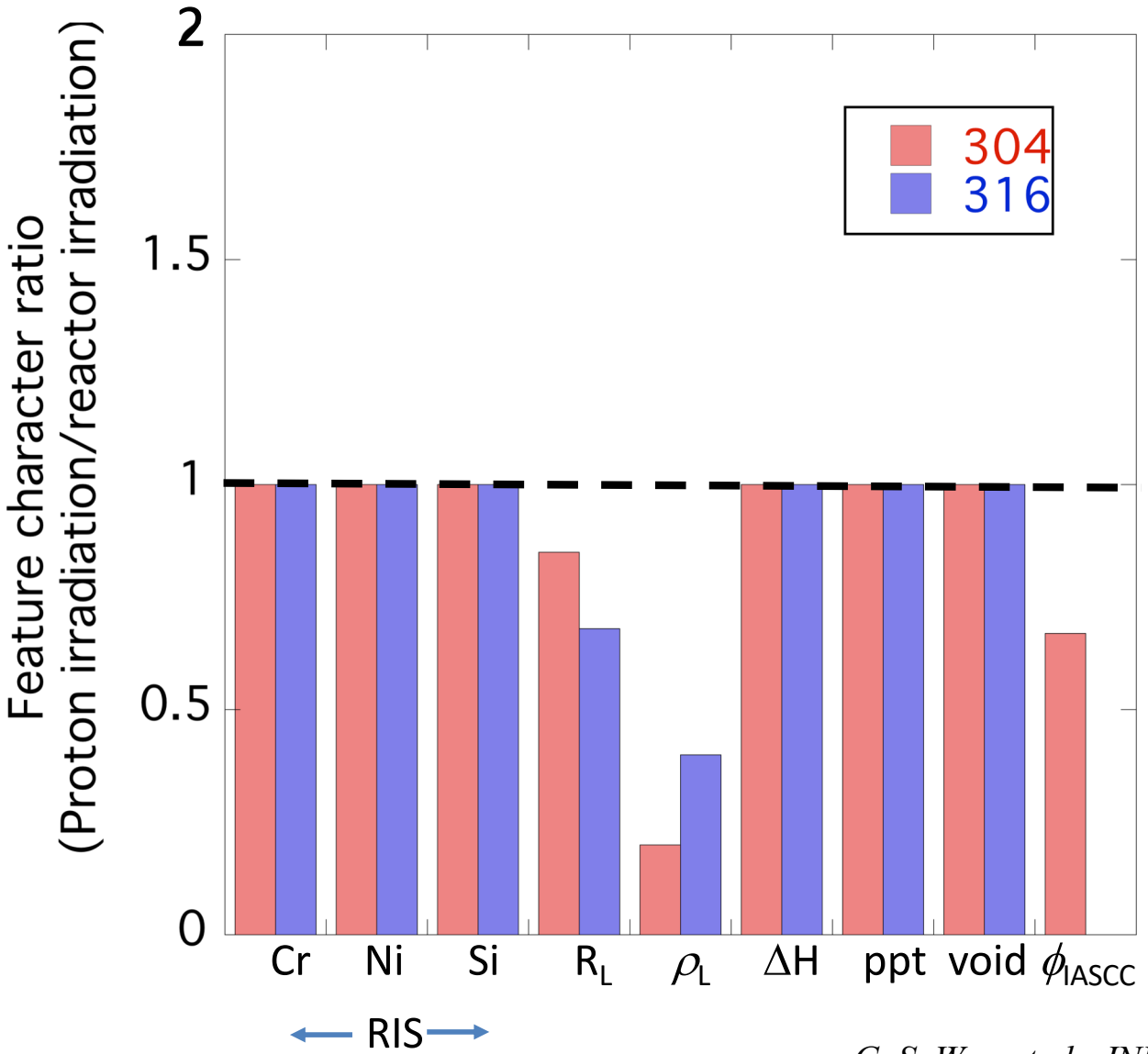
Solute addition stainless steel alloys

IASCC



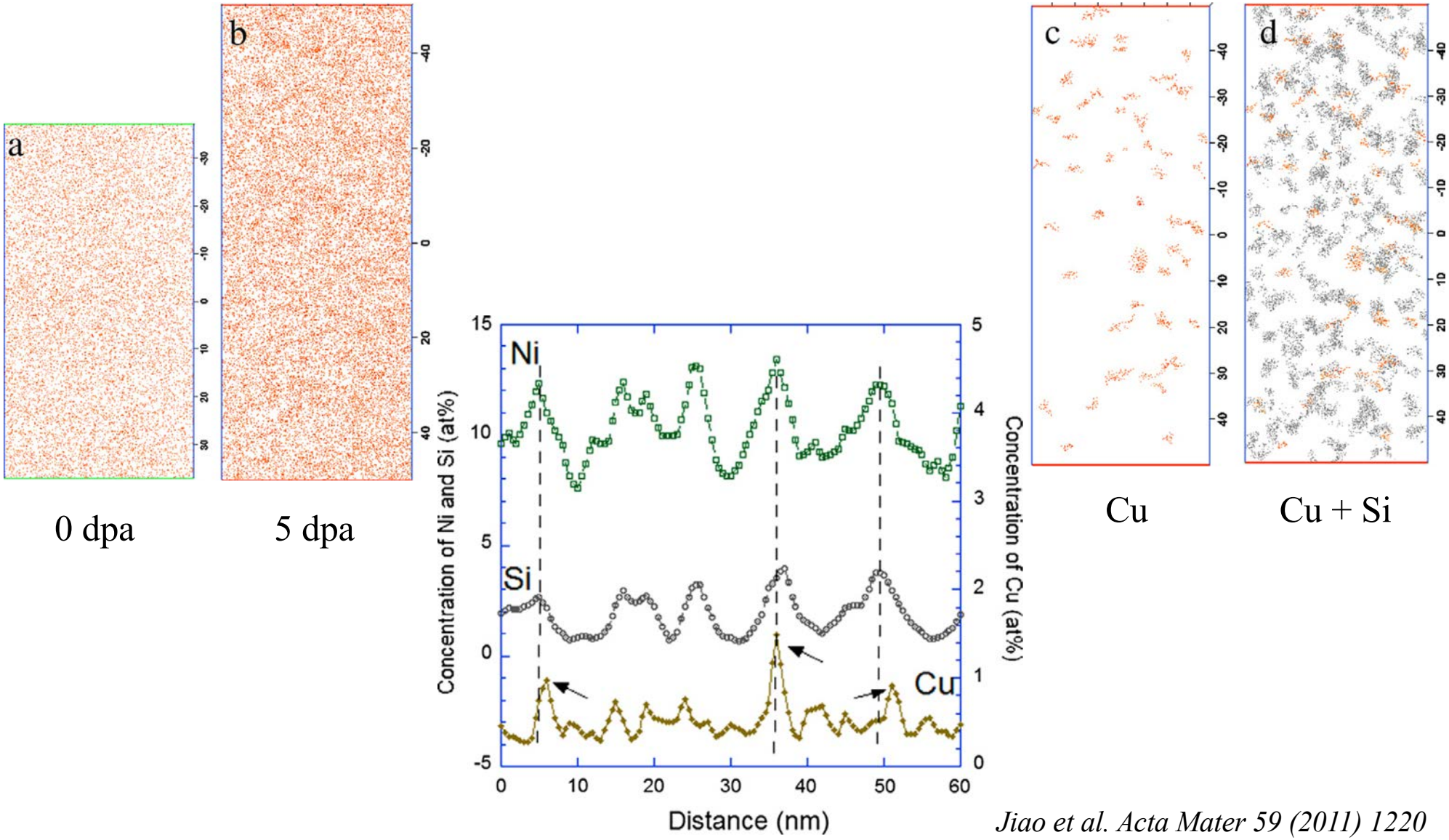
K. Stephenson et al.. JNM 456 (2015) 85.

Overall comparison



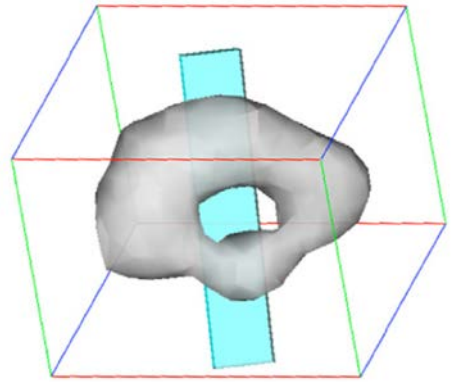
G. S. Was, et al., JNM 300 (2002) 198-216

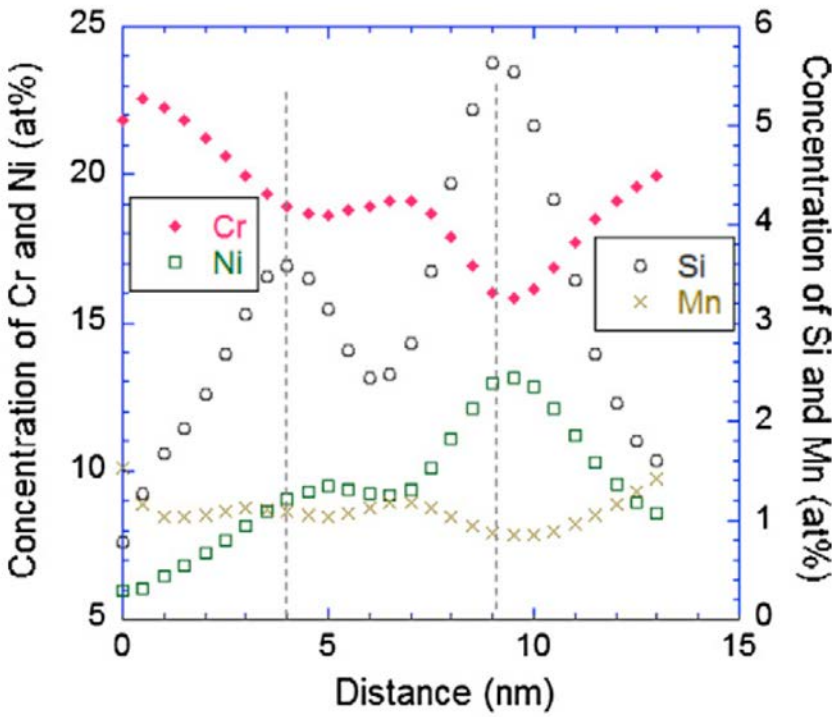
Copper clustering in CP304 SS following proton irradiation to 5 dpa at 360°C

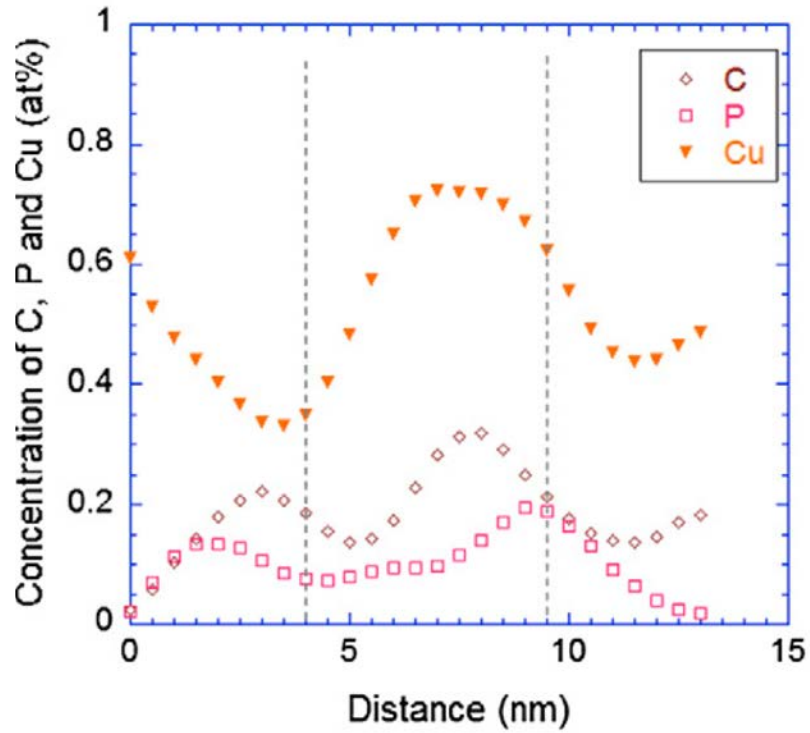


Jiao et al. Acta Mater 59 (2011) 1220

RIS at dislocation loops in irradiated CP 304 SS

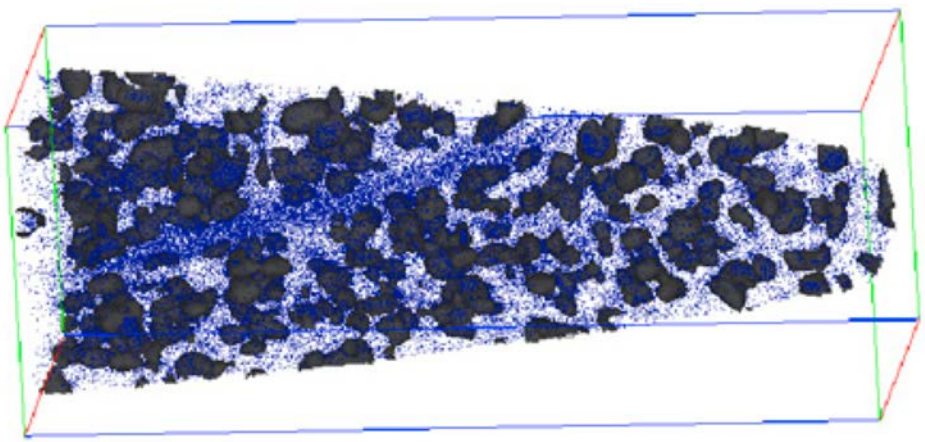


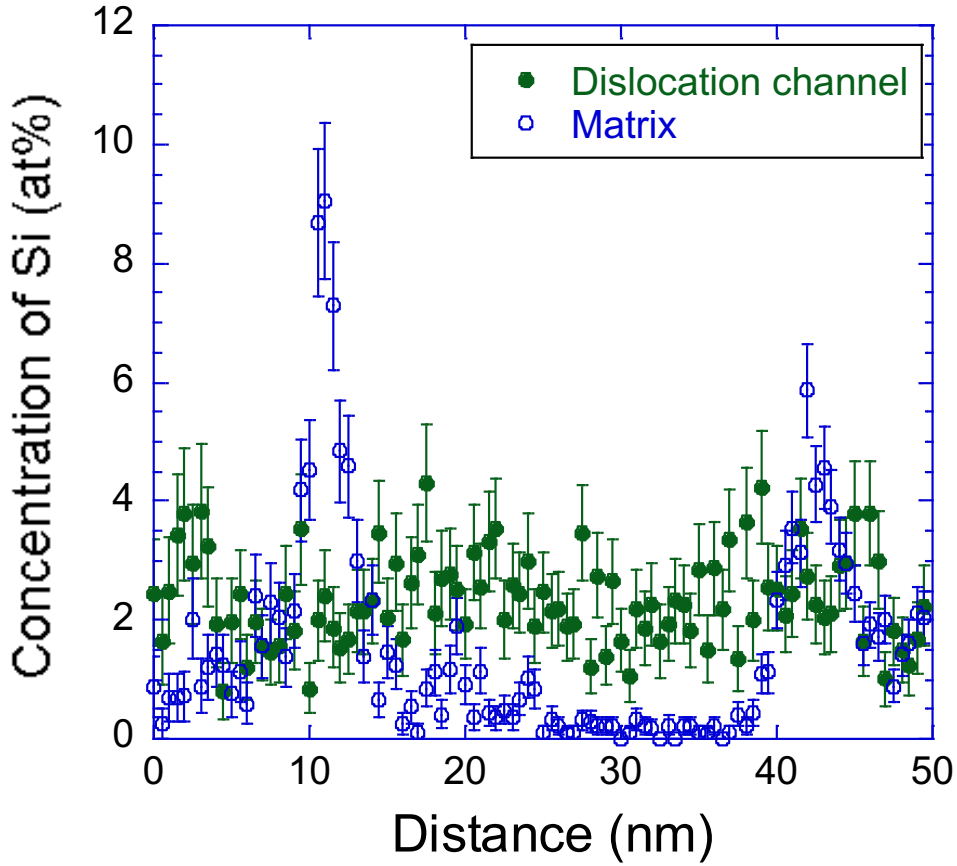




Jiao et al. Acta Mater 59 (2011) 1220

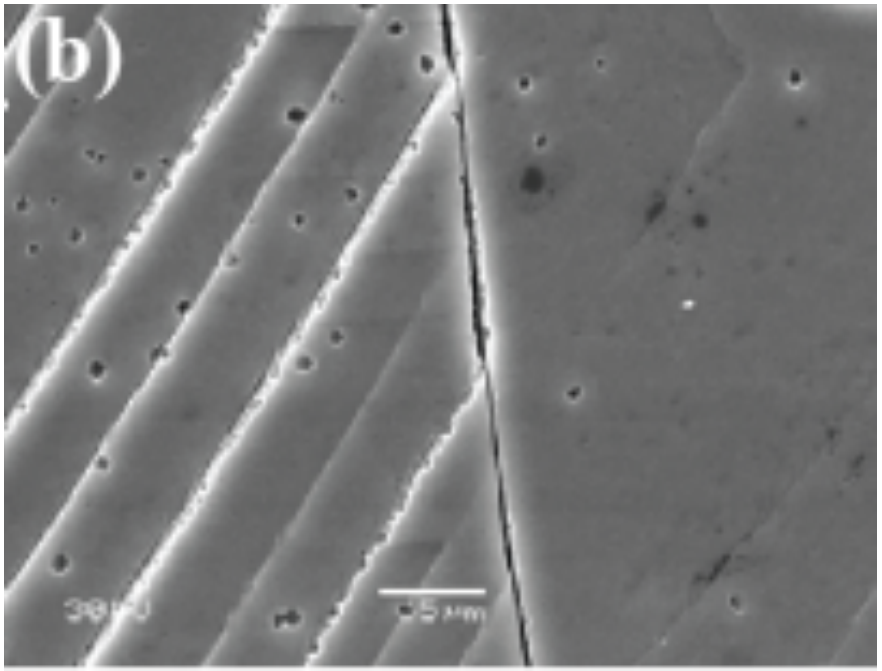
Ni/Si precipitate dissolution in a dislocation channel in HP304+Si

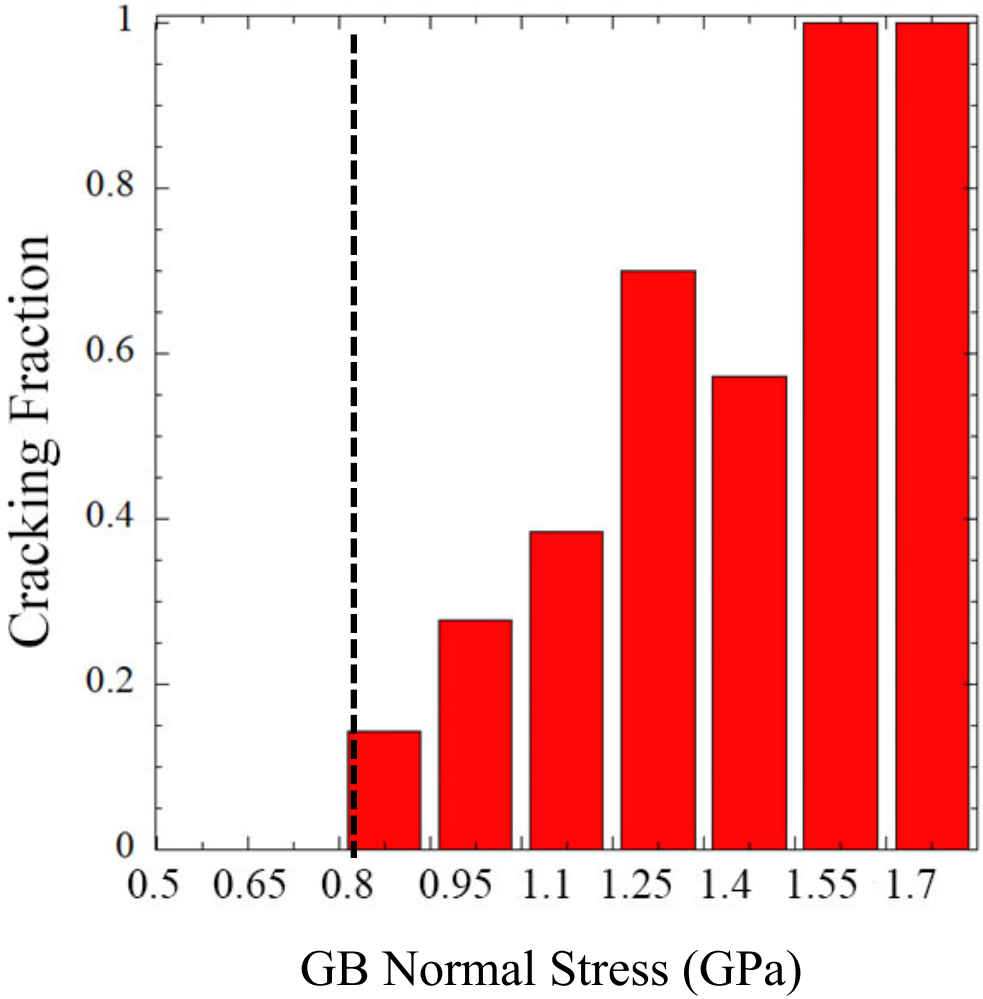




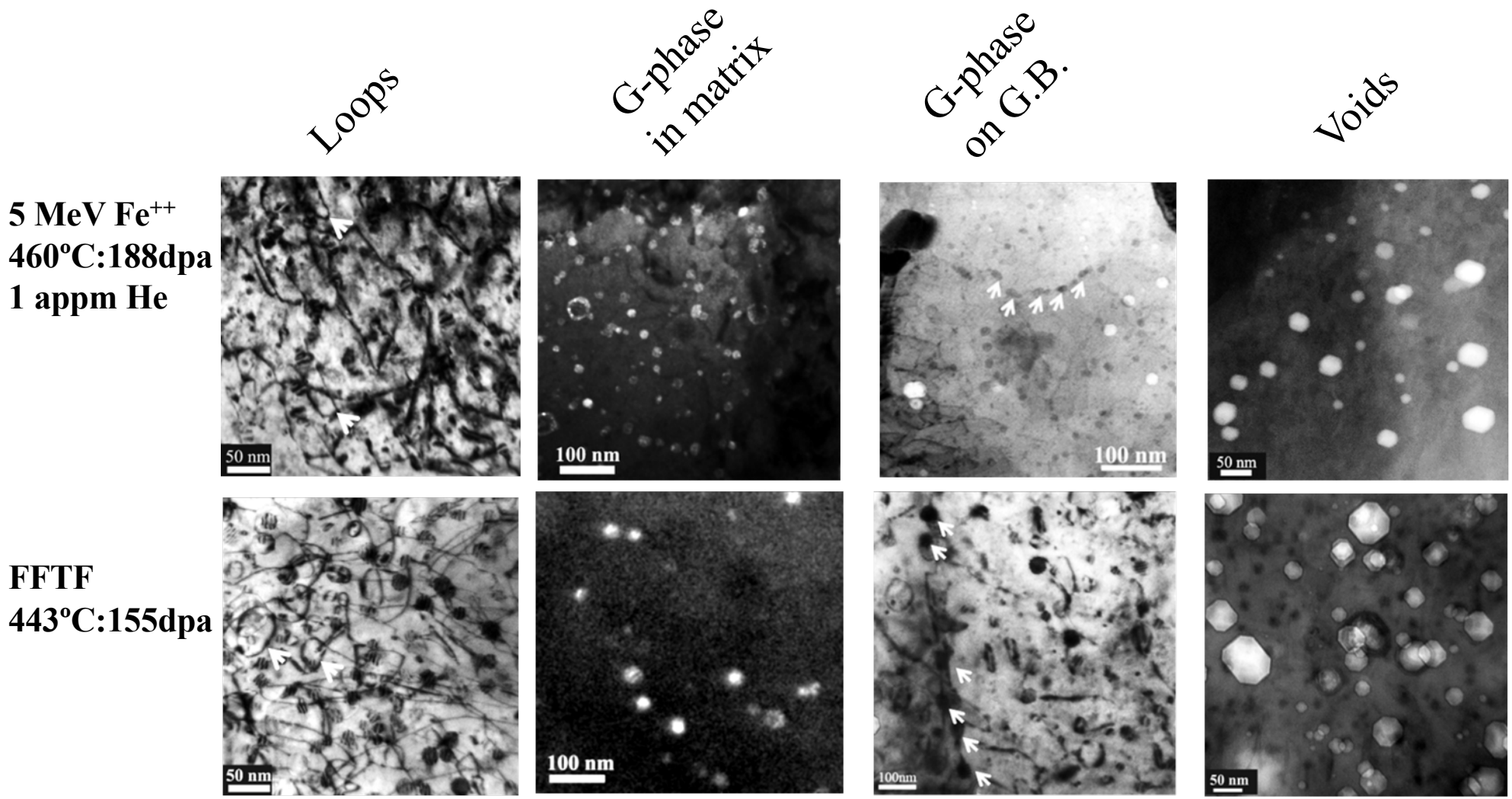
Jiao et al. Scr. Mater 65 (2011) 159

Relationship between GB normal stress and IASCC in 304SS in BWR NWC





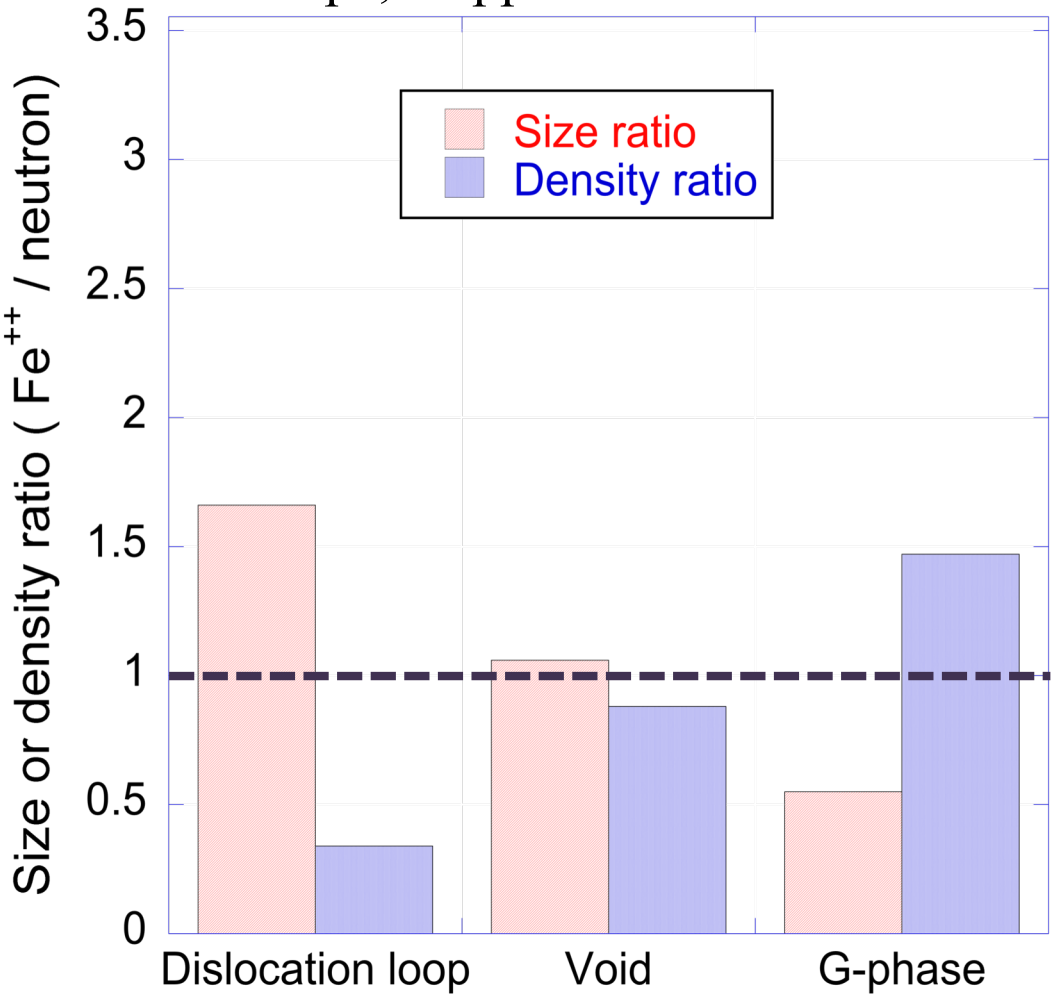
Comparison of multiple features of neutron- and self ion- irradiated microstructures in HT9 ACO3 duct



GS Was et al. Scr Mater 88(2014)33

Comparison of multiple features of neutron- and self ion- irradiated microstructures in HT9 ACO3 duct

Fe^{++} 460ºC:188 dpa, 1 appm He / FFTF 440ºC:155 dpa



GS Was et al. Scr Mater 88(2014)33

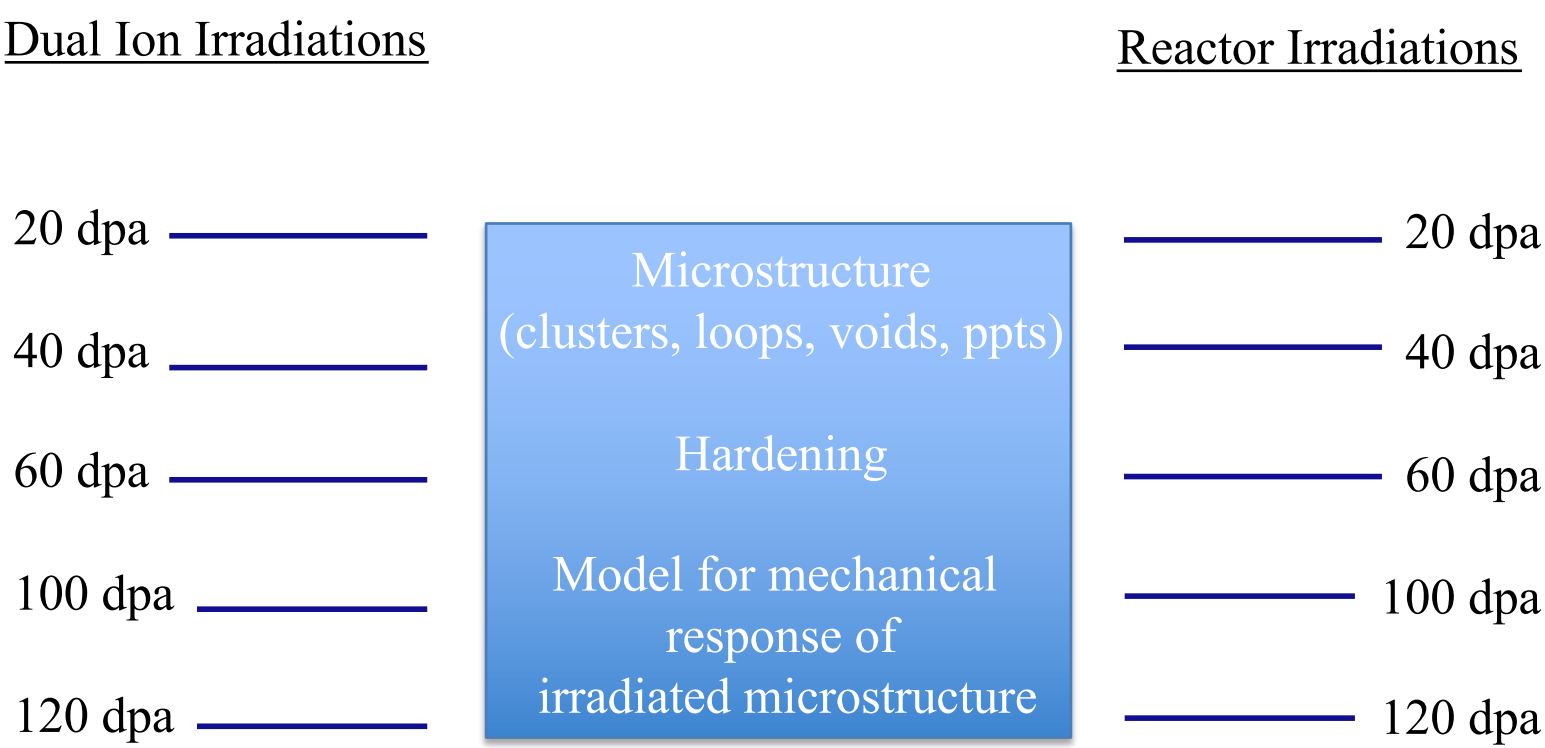
High Fidelity Ion Beam Simulation of High Dose Neutron Irradiation

PI/PD: Gary S. Was, University of Michigan

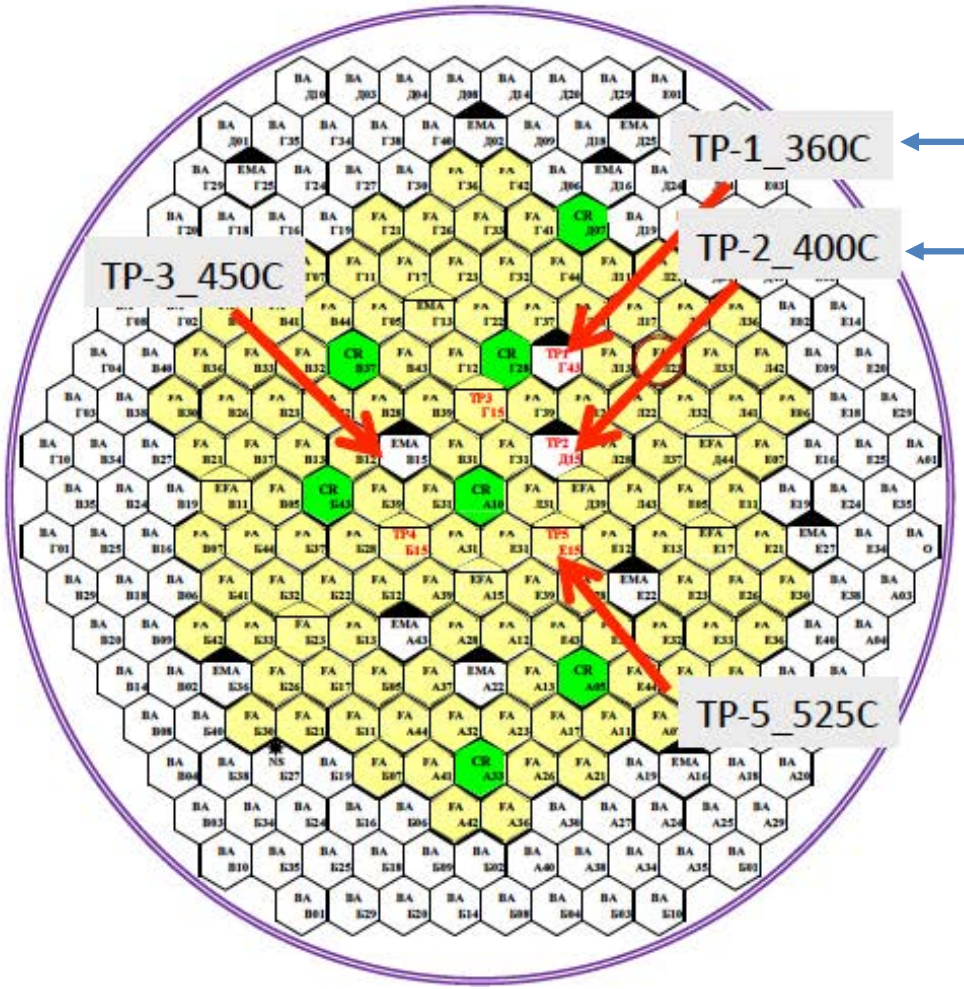
Program: Nuclear Reactor Technologies - IRP

Collaborators: E. Marquis, U. Michigan; Z. Jiao, U. Michigan; J. Marian, U. Michigan; B. Wirth, U. Tennessee; A. Motta, Penn State U.; D. Morgan, U. Wisconsin; D. Kaoumi, U. South Carolina; P. Hosemann, U. C. Berkeley; G. R. Odette, U. C. Santa Barbara; T. S. Byun, ORNL; S. Maloy, LANL; S. Tumey, LLNL; M. Kirk, ANL; J. Cole, INL: M. Hackett, TerraPower LLC; R. Pathania, EPRI; M.G. Burke/M. Preuss, U. Manchester; S. Roberts, U. Oxford; L. Fournier, Areva; M. Daymond, U. Queens; M. Le Flem, CEA

Coordination of ion and reactor irradiations



BOR-60 neutron irradiation



P028 irradiated to ~35.1 dpa:378°C

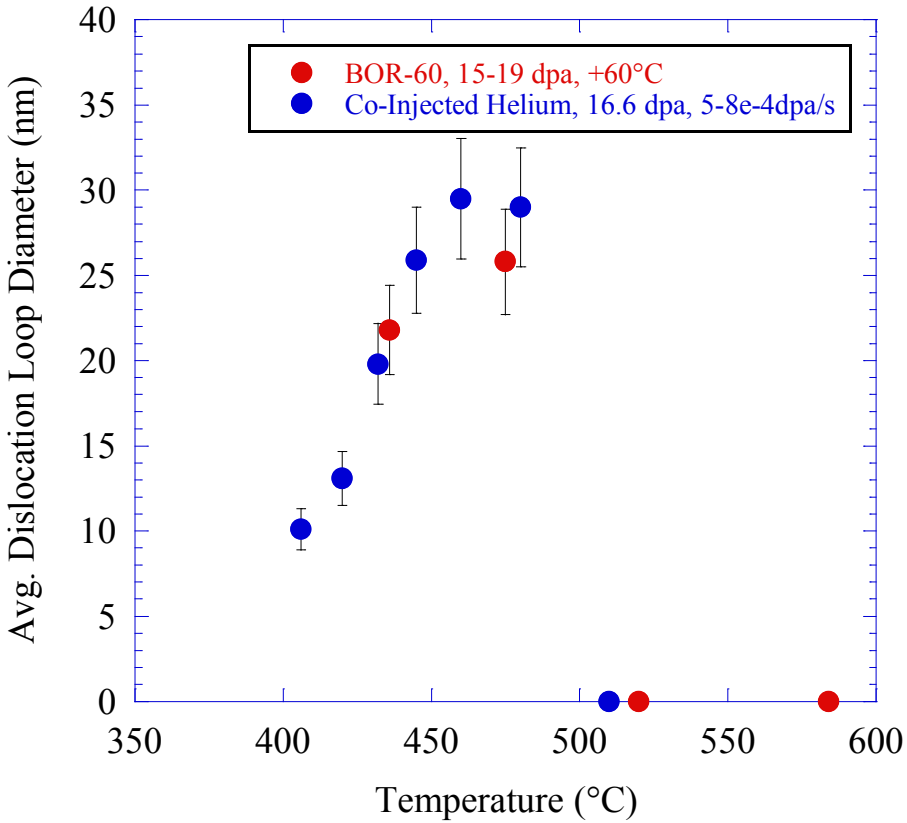
P027 irradiated to ~17.1 dpa:386°C

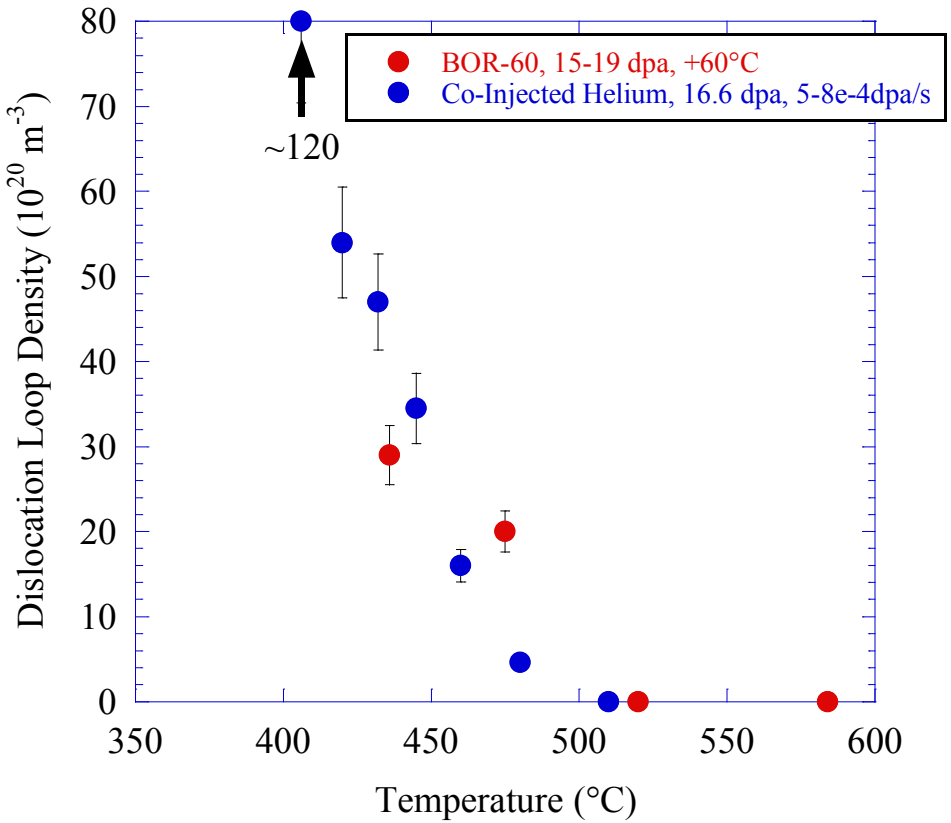
P033 irradiated to ~18.6 dpa:412°C

P037 irradiated to ~14.6 dpa:460°C

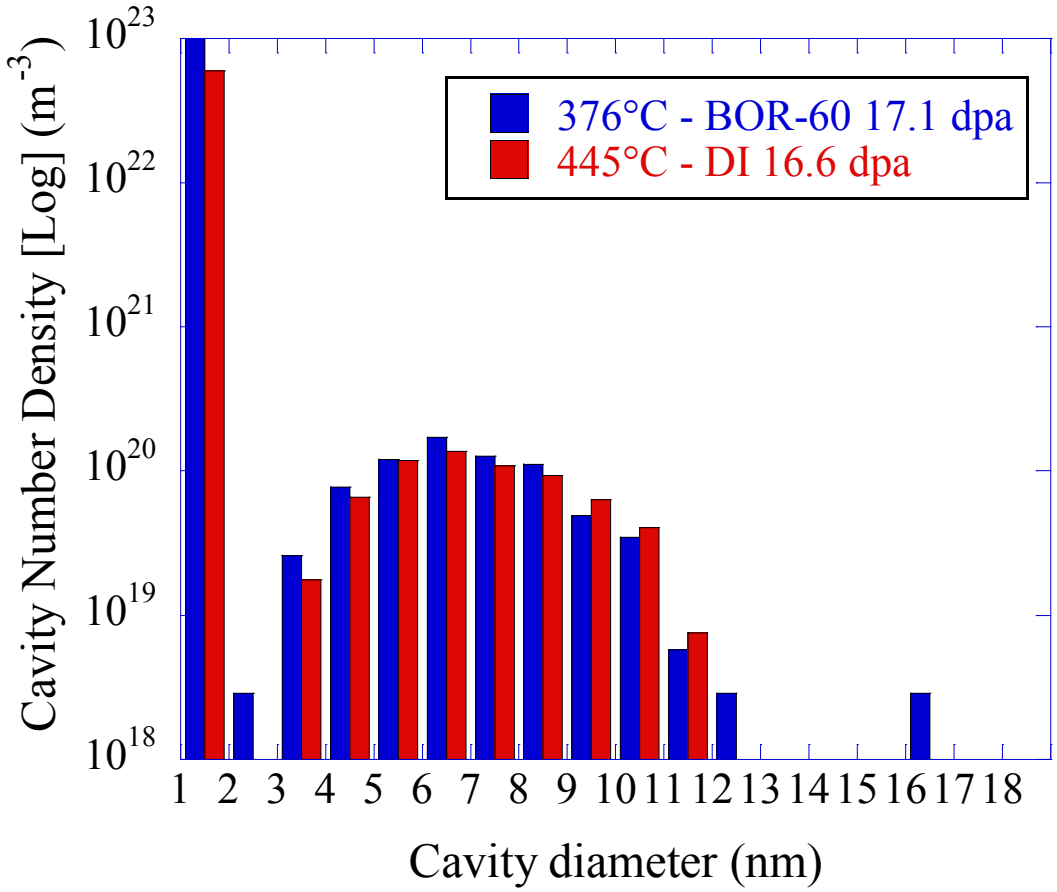
P042 irradiated to ~15.2 dpa:524°C

Dislocation loops, neutron (15-19 dpa +60°C) and dual ion (16.6 dpa) in alloy T91



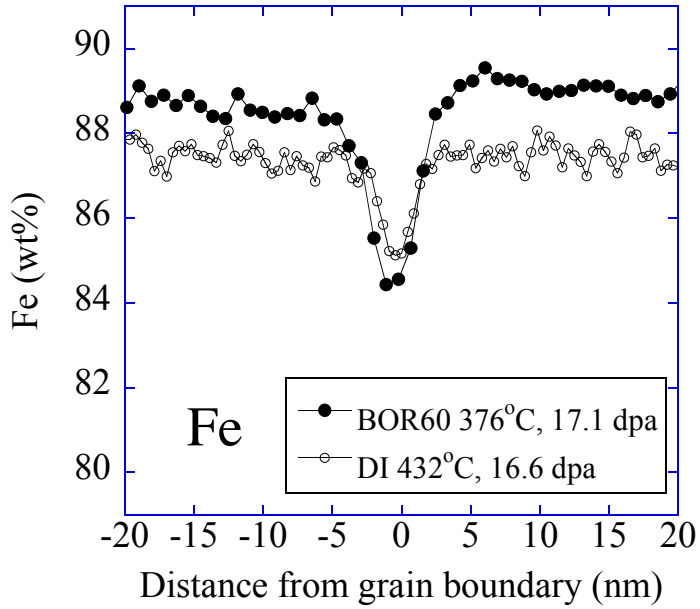


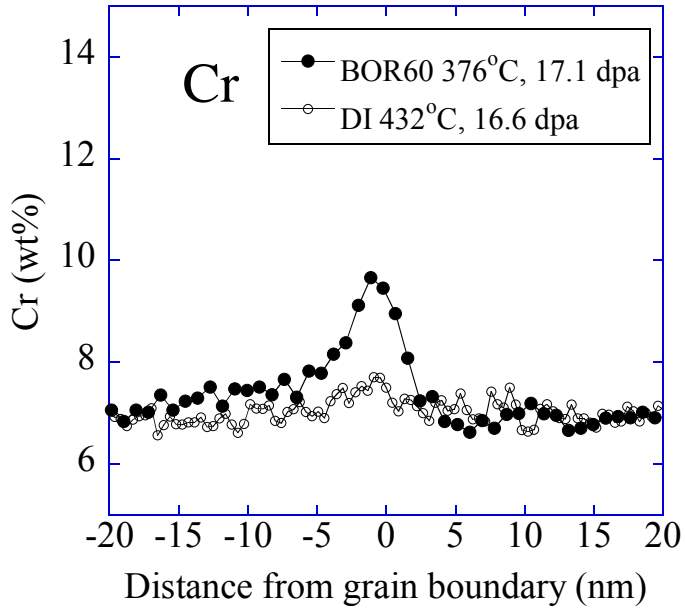
Comparison of distribution of cavities in BOR-60 irradiation at 17.1 dpa and DI irradiation to 16.6 dpa with +60°C shift

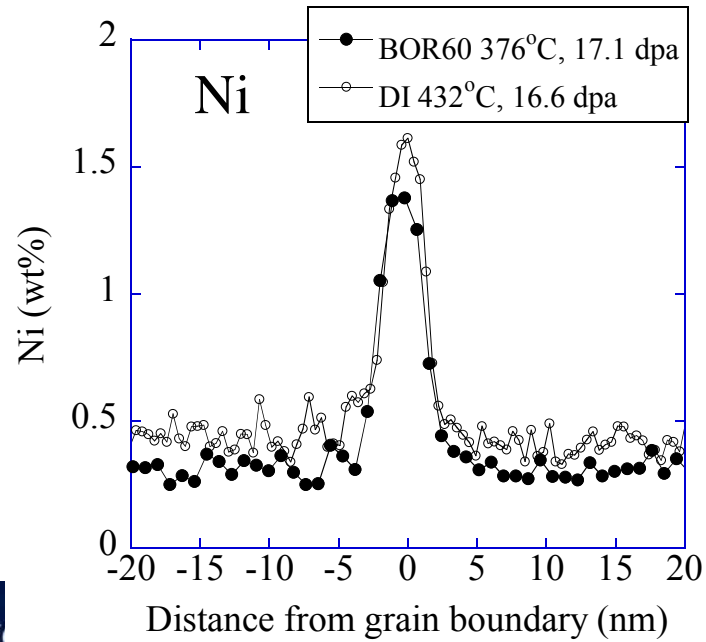


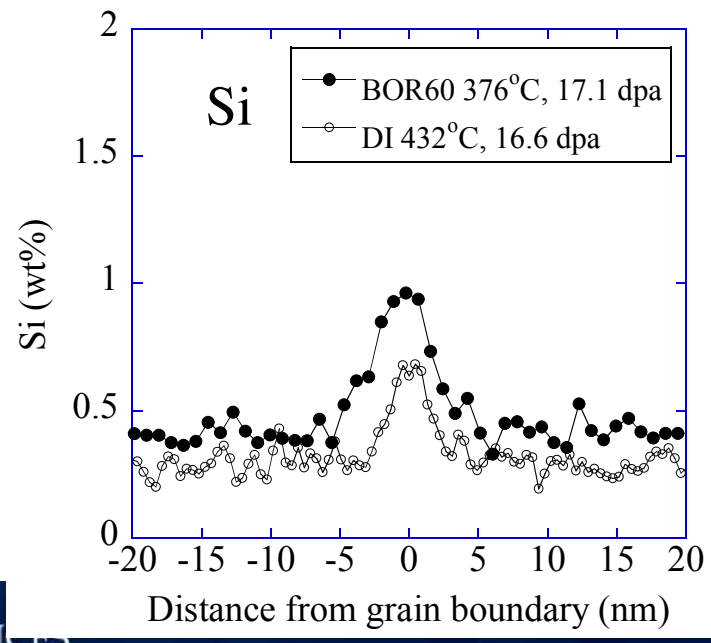
Small cavities dominate the observed number density in both cases

Comparison of RIS between DI and BOR60

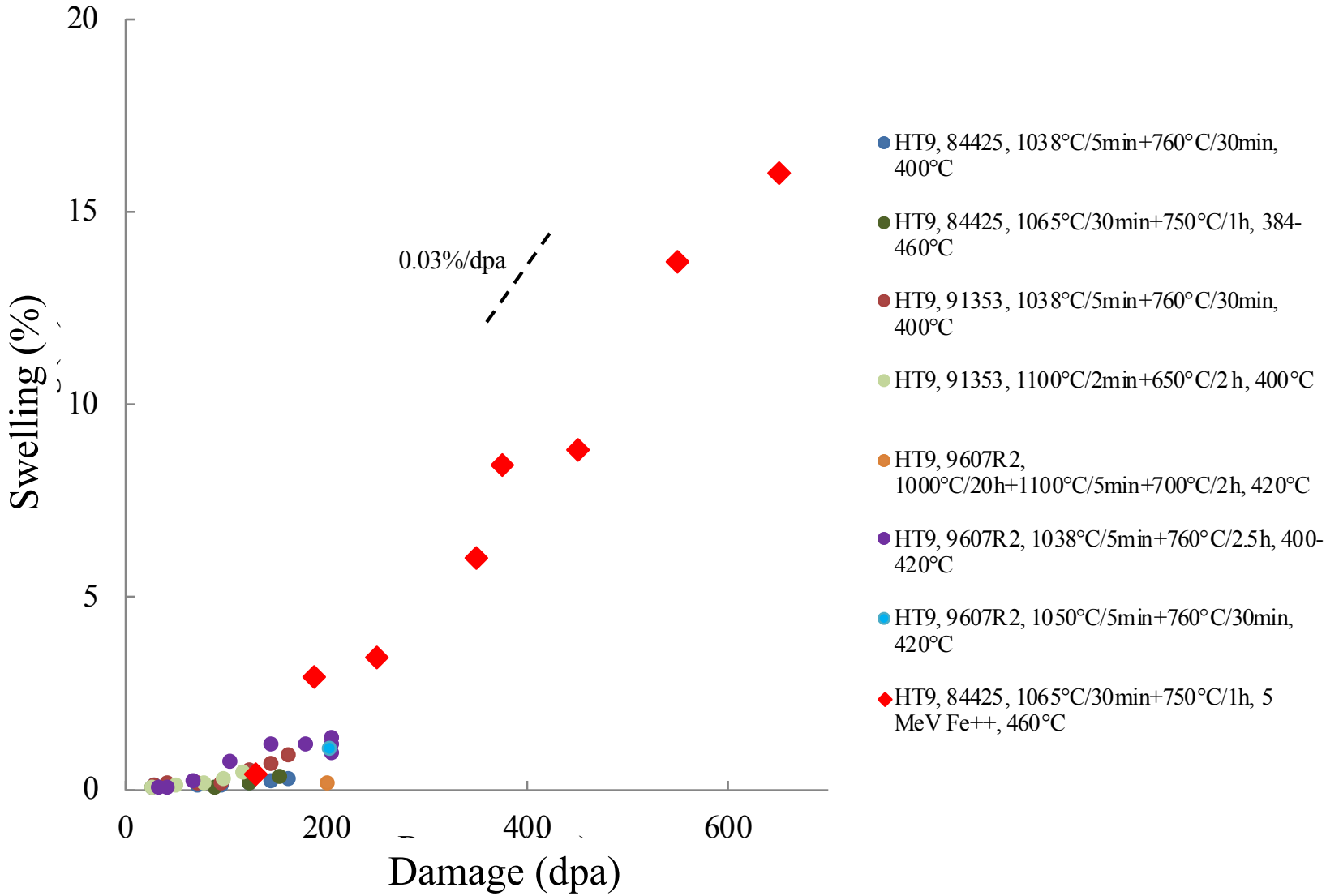






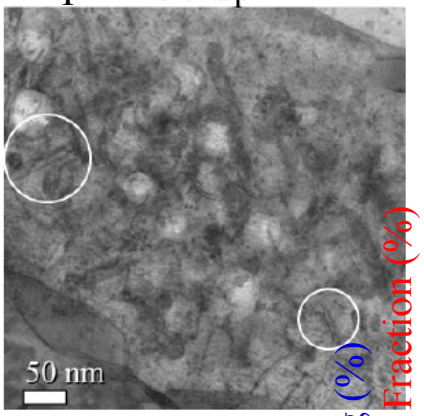


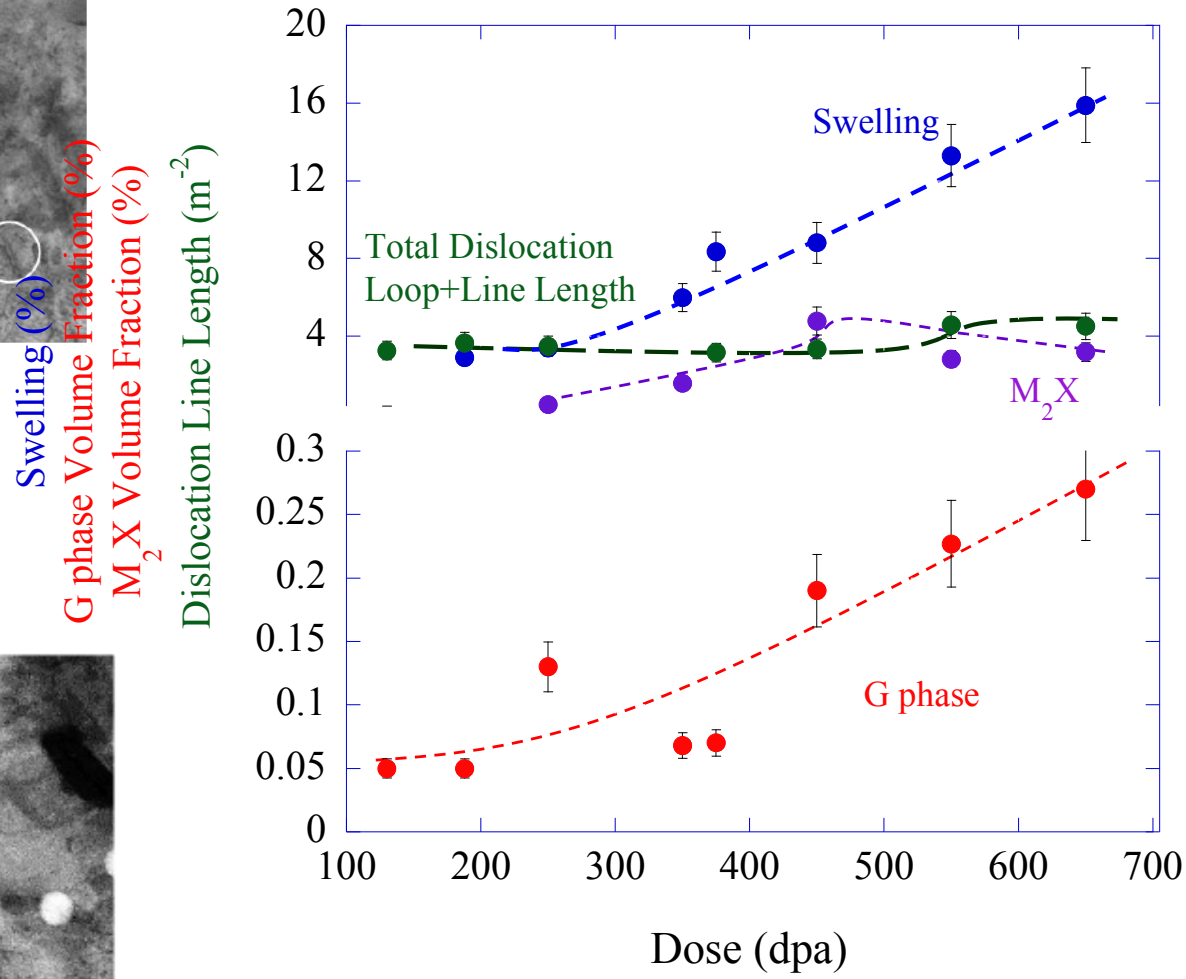
Swelling to 650 dpa using self-ion irradiation following He pre-implantation to 10 appm



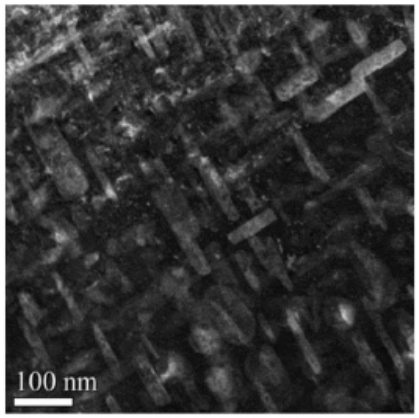
Microstructure evolution in self-ion irradiated HT9

Loops 450 dpa

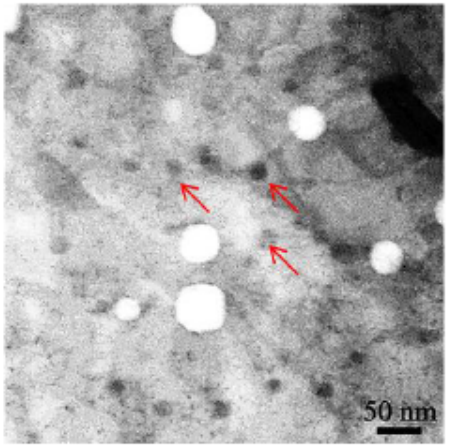




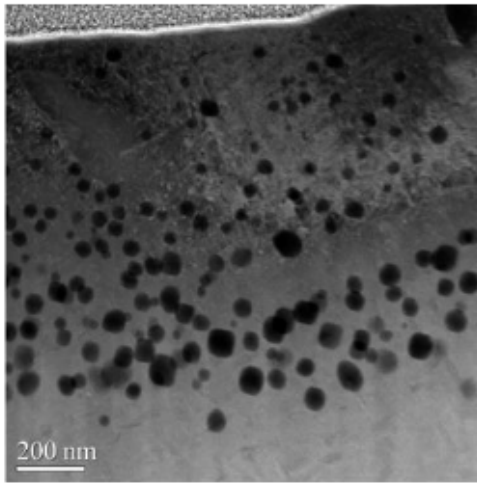
M_2X 450 dpa



G-phase 450 dpa

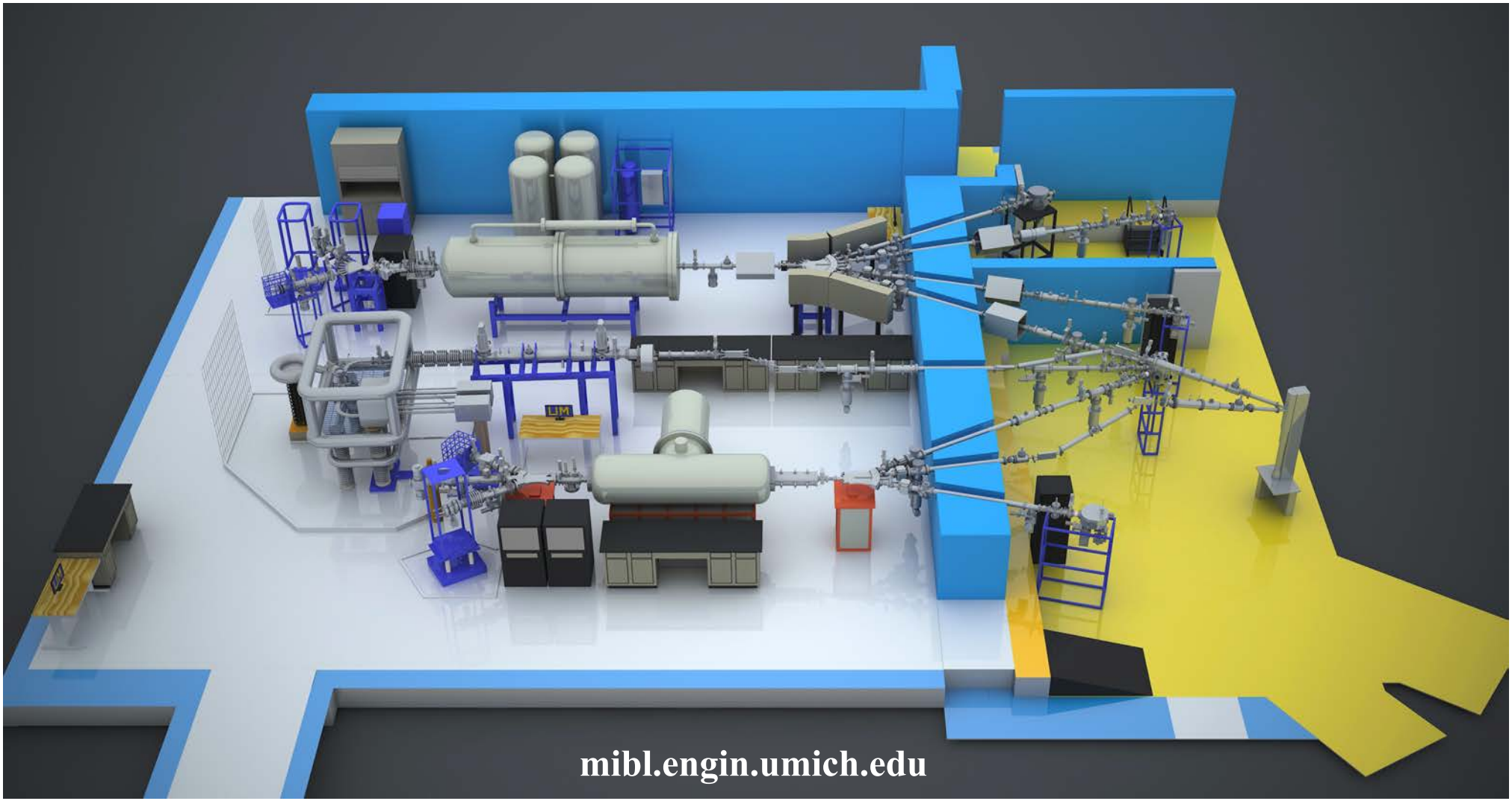


Voids 450 dpa

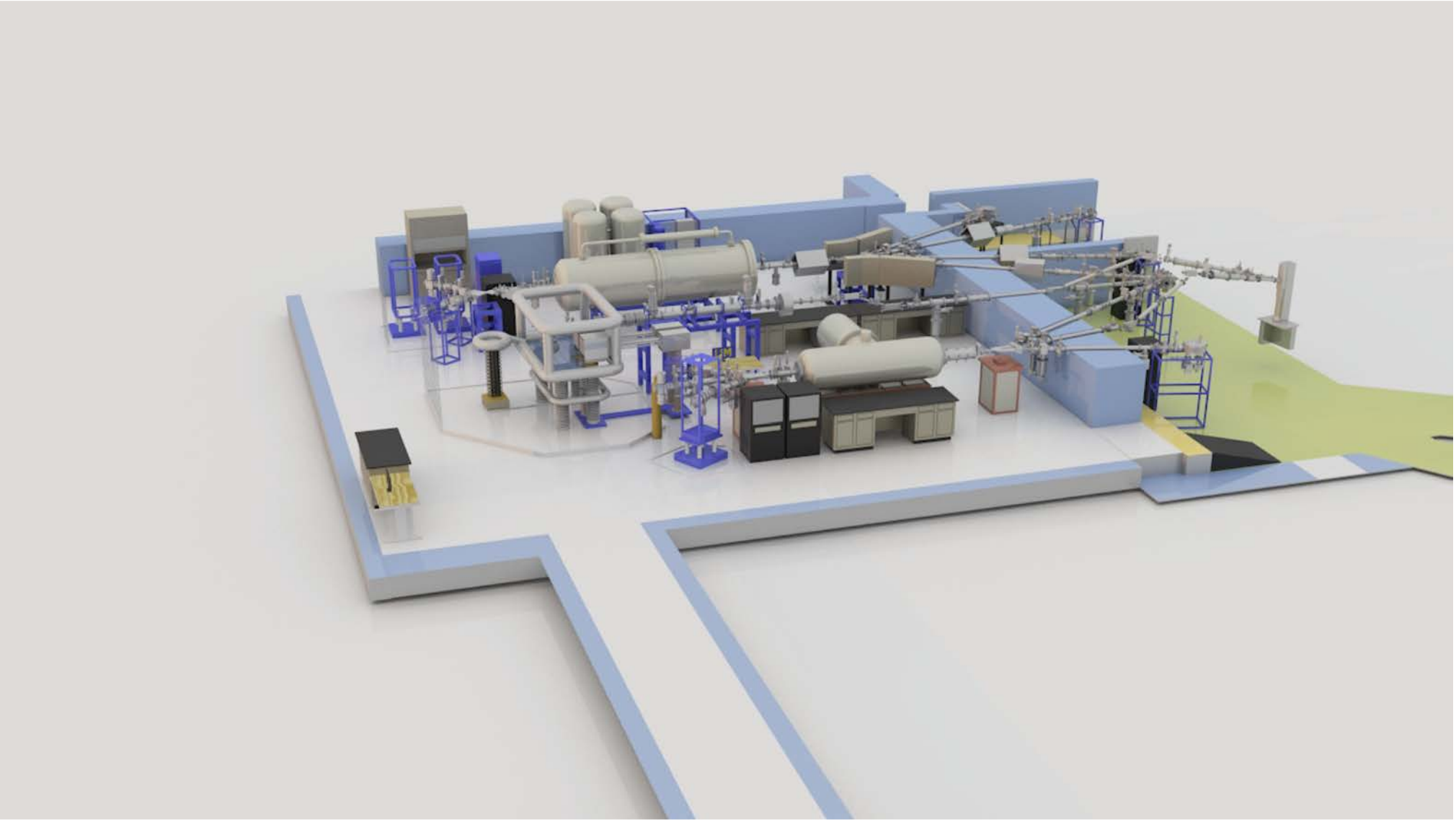


Capabilities for ion irradiation to contribute to our understanding of microstructure evolution under reactor conditions

Michigan Ion Beam Laboratory



Fly around MIBL

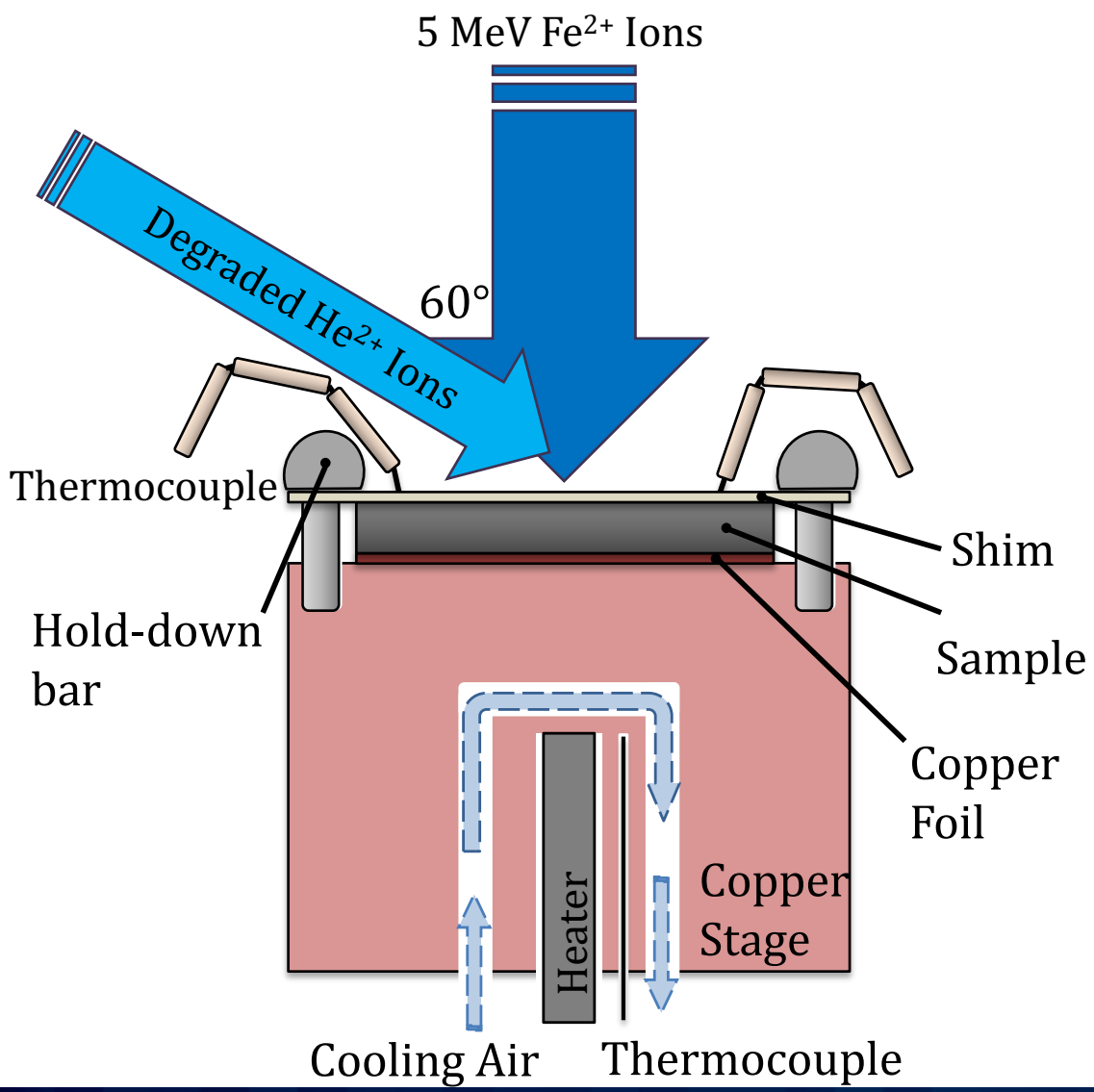


Michigan Ion Beam Laboratory

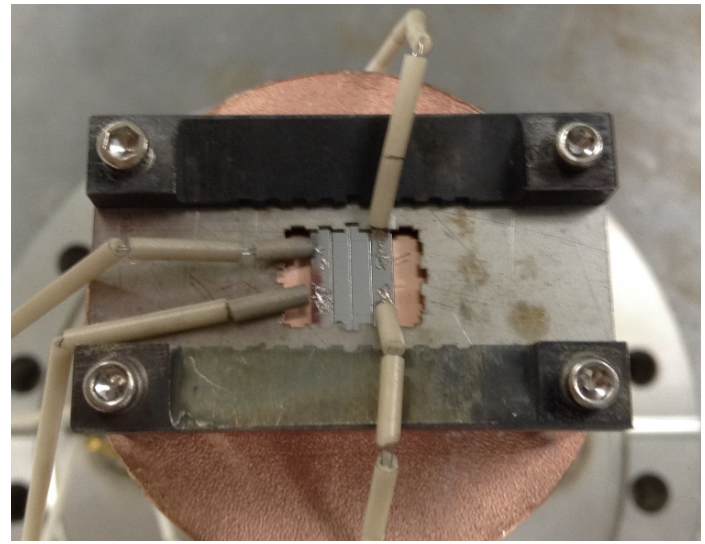
NUCLEAR ENGINEERING AND RADIOLOGICAL SCIENCES

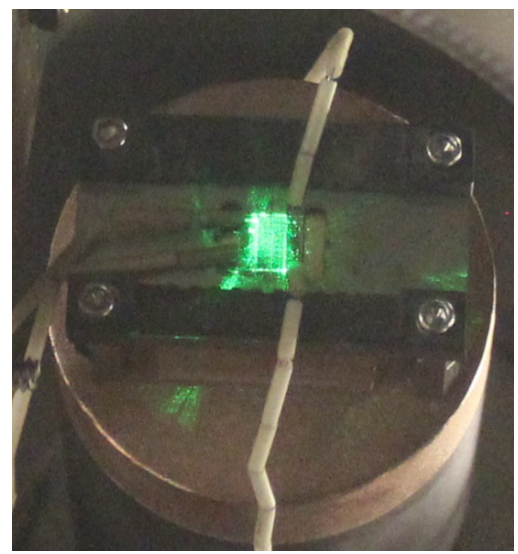
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Multi-Beam Irradiation Stage



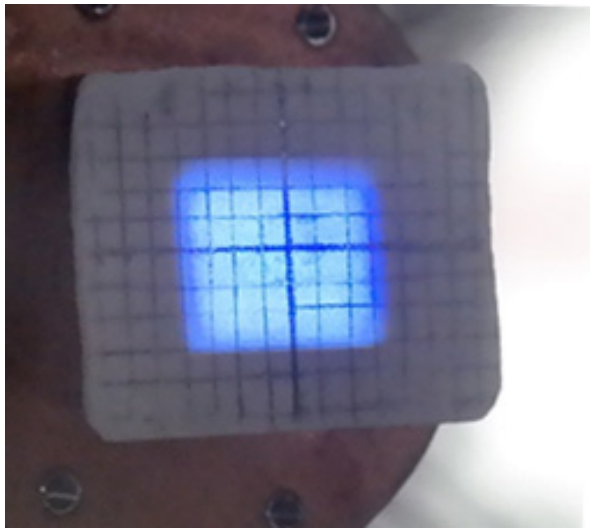
On benchtop



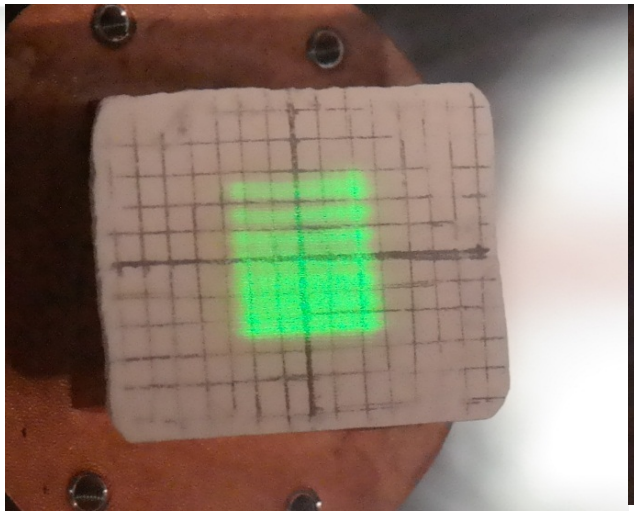


Loaded into MBC

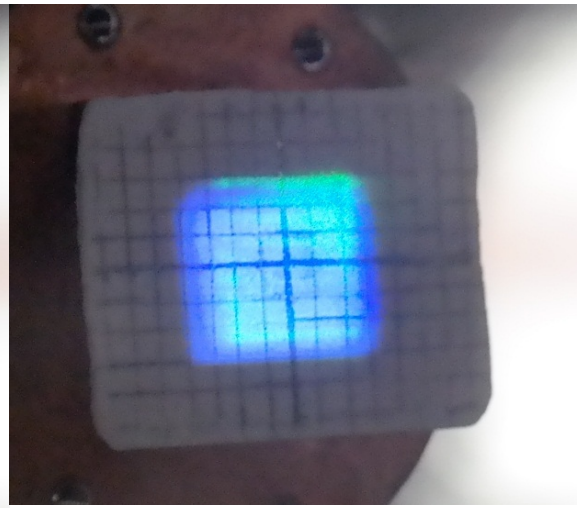
Laser alignment of ion beams for multi-beam irradiations



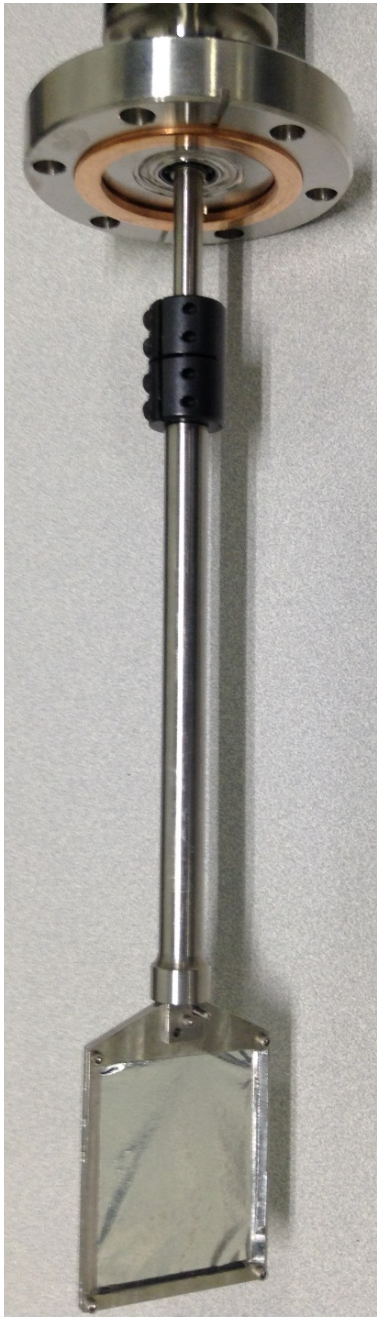
D^+ beam



Co-linear green laser

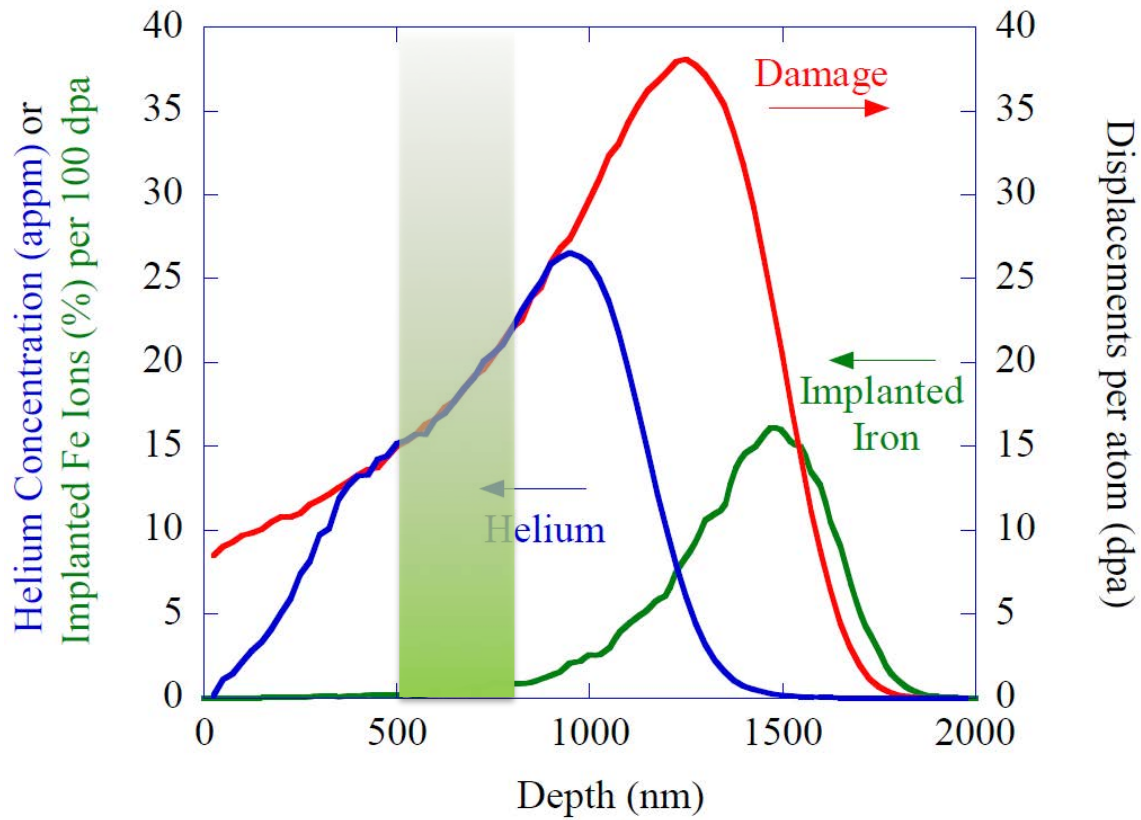


Both laser and D^+ beam

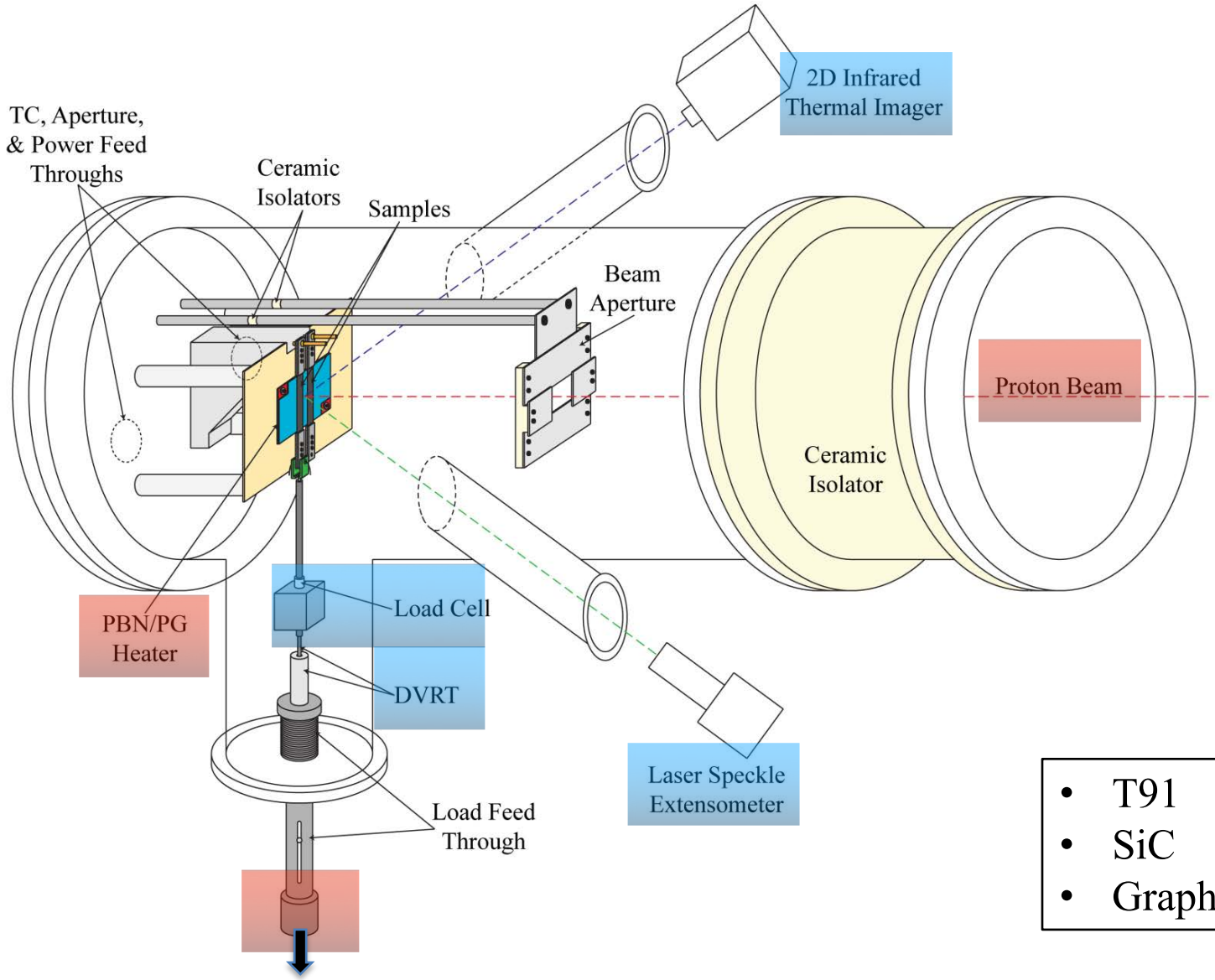


Light ion implant distribution using a foil degrader

- A thin foil is used to lower the energy of the beam through electronic energy loss and scattering.
- By controlling the rotation, we can create a variety of implantation profiles.

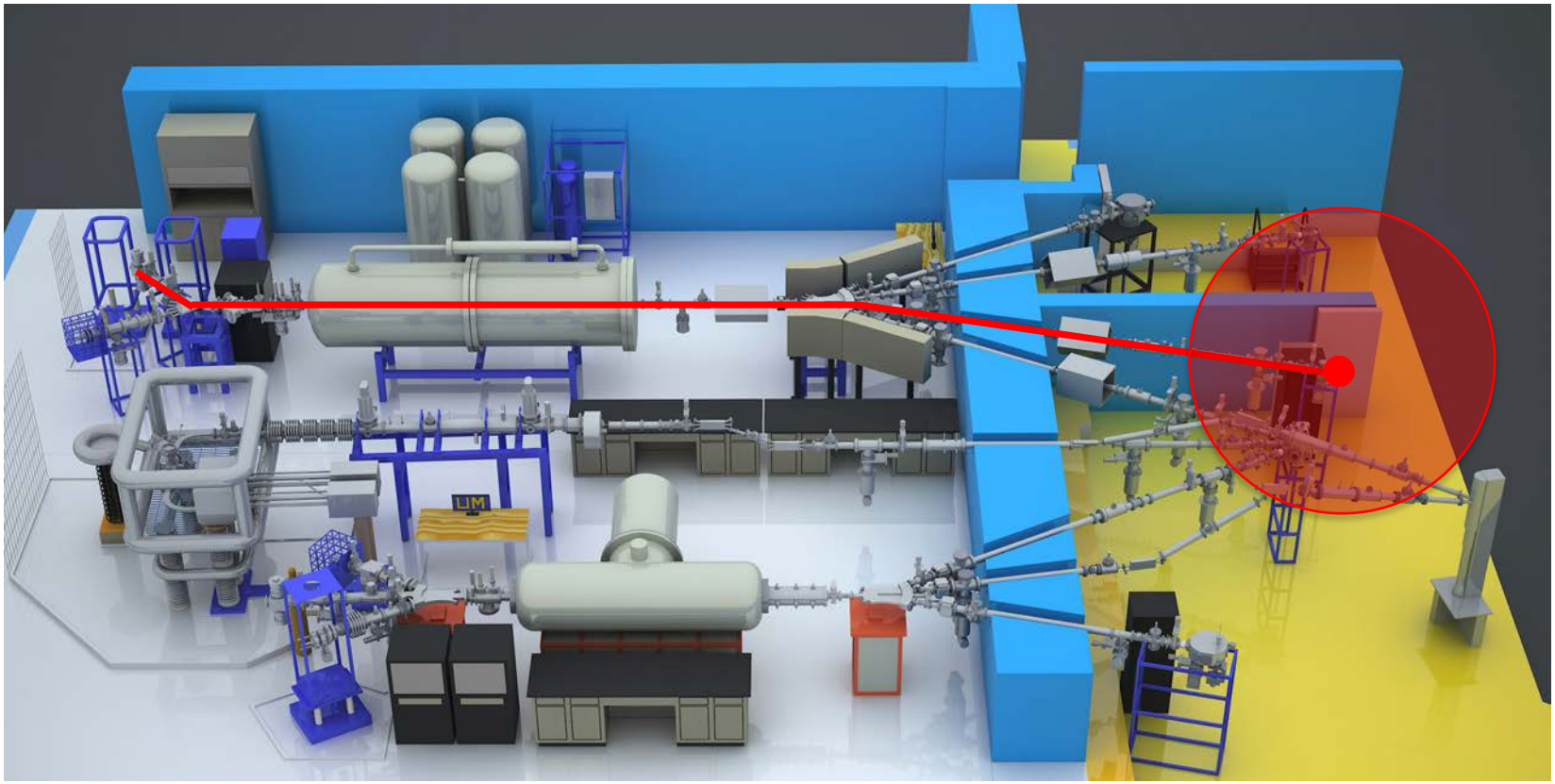


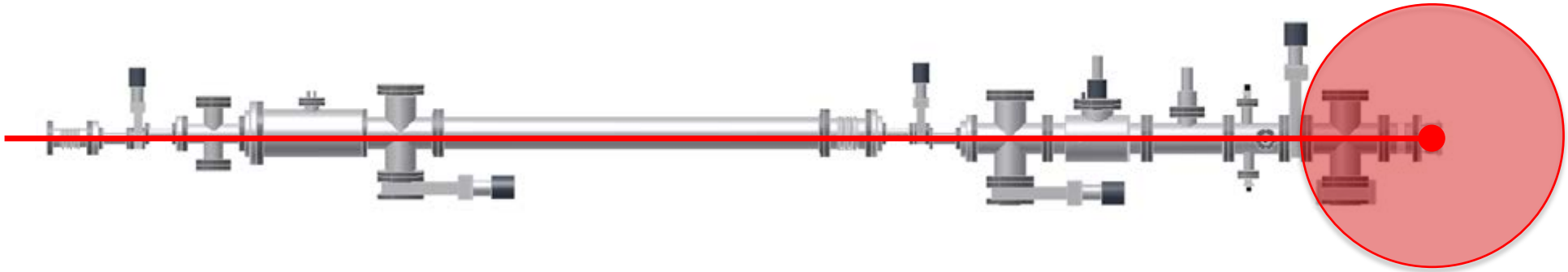
In-situ irradiation creep



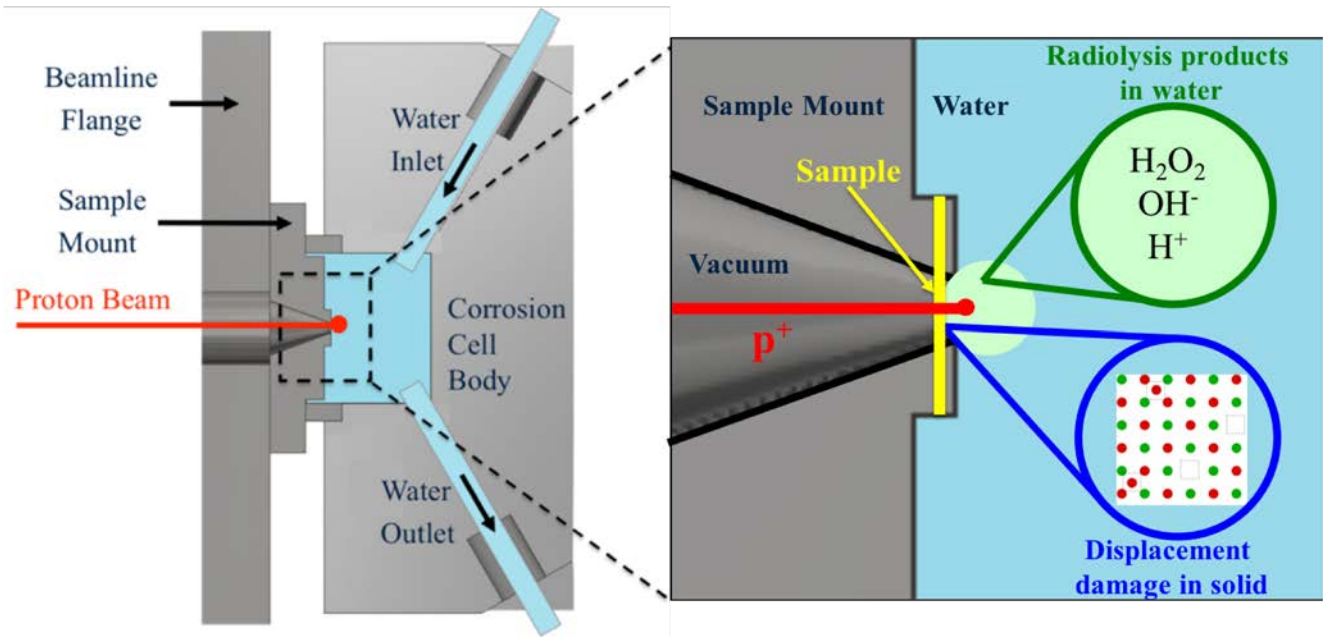
- T91
- SiC
- Graphite

Irradiation accelerated corrosion (IAC) facility

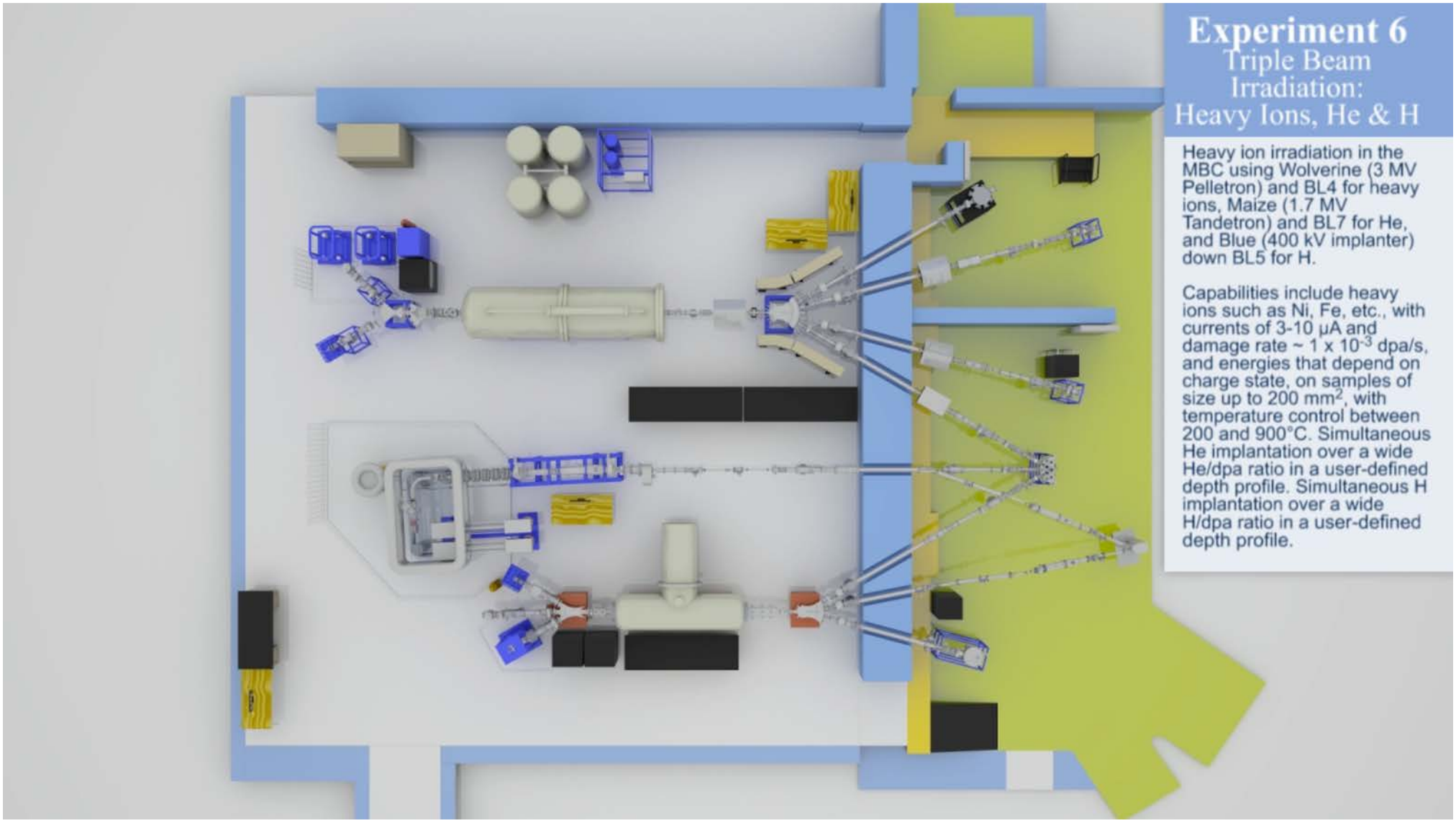




In-situ Proton Irradiation-Corrosion Experiment

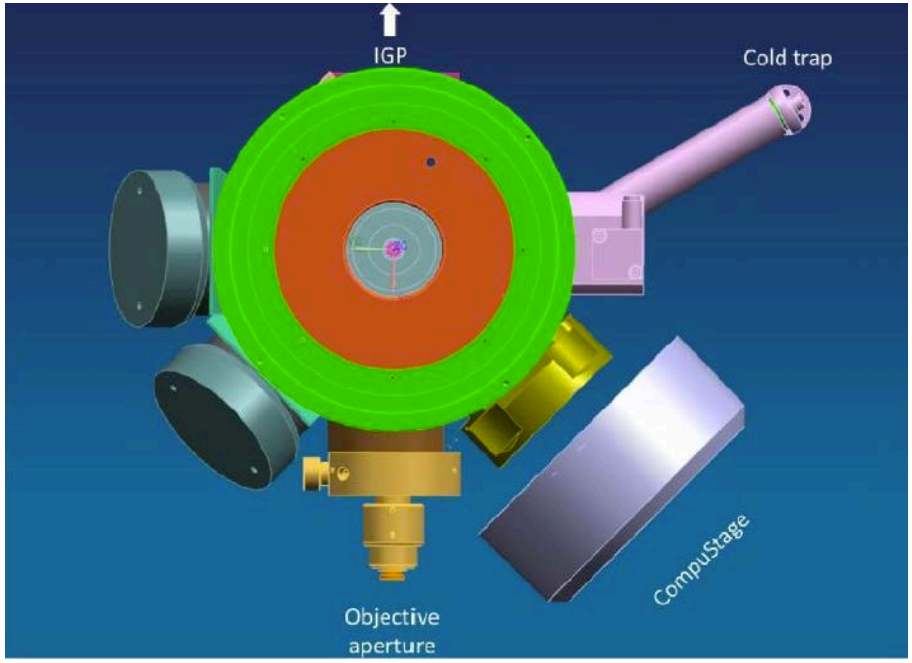


Triple beam irradiation experiment

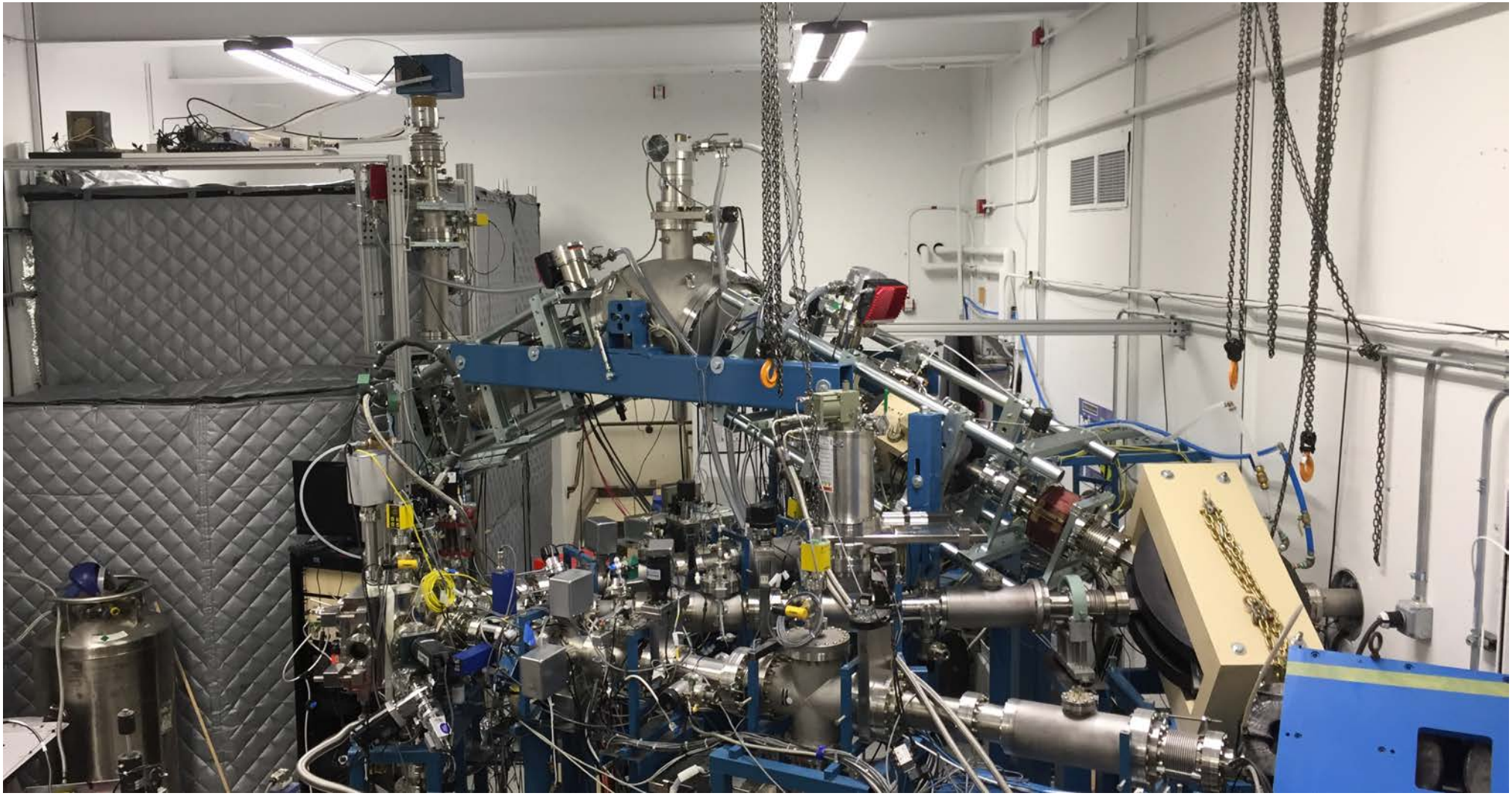


FEI Tecnai G2 F30 TWIN (300kV, LaB_6 filament)

- Gatan US1000XP-P high speed camera
- EDAX SSD EDS
- Low background, double-tilt heating stage
- HAADF detector
- STEM system
- Remote operation from MIBL control room



Beam lines 6 and 8 and the FEI Tecnai G2 F30 TWIN



Summary of Instrumentation at MIBL

Accelerators
- 3 MV Tandem (Pelletron) (Wolverine)
- 1.7 MV Tandem (Tandetron) (Maize)
- 0.4 MV implanter (Blue)

Ion sources
- TORVIS (protons) – Wolverine
- Peabody (sputter) – Wolverine
- Alphatross (He) - Wolverine
- ECR (gases, e.g. He) – Maize
- Multi-cathode SNICS (sputter) – Maize
- Danfysik, multi-mode source – Blue

8 (+1*) Beam lines

5 Target chambers
- ion irradiation
- irradiation accelerated corrosion
- multi-beam chamber
- 2 ion beam analysis chambers

300 kV FEI TEM*
- Dual beam interface for simultaneous damage and gas injection

Target temperature range: 77K to 1500K

Damage rate: < 10^{-5} dpa/s (protons), 10^{-3} dpa/s (heavy ions)

Irradiated area: up to 200 mm^2

*in progress

Ion Irradiation Capabilities at MIBL

- Single Ion Irradiations
  - Proton irradiation to moderate dose
  - Self-ion irradiation to high dose
  - In-situ corrosion
- Dual Beam Irradiations
- Triple Beam Irradiations
- Dual Beam In-situ TEM (*in progress*)
- Ion Beam Analysis
  - Rutherford backscattering spectroscopy (RBS)
  - Nuclear Reaction Analysis (NRA)
  - Particle Induced X-ray Emission (PIXE)
  - Elastic Recoil Detection (ERD)
  - Ion channeling

Use of MIBL

In 2017 ~ 290 irradiations were conducted by 130 researchers working on 50 projects and using 9400 hr of beam time. In the last several years:

- **Labs/Co's**: TerraPower, INL, LANL, ORNL, PNNL, LLNL, Bettis, U.S. Army Research Lab, U. S. Air Force Lab, GE, Dow, Seagate, Svaati Sci.
- **Universities**: Boise State, U. Wisc., Connecticut, Texas A&M, Windsor, UIUC, Va. Tech, Virginia, Cornell, Colorado School of Mines, Southern California, Purdue, Wayne State, Ohio State, Buffalo, Notre Dame, San Antonio, Tennessee, Alabama A&M, Duke Univ., Brown Univ., UCLA, Rutgers, Delaware, Pennsylvania, McMaster, IA State, UT, Texas A&M, U. Illinois, Iowa State, U. North Texas, MIT
- **International**:

  Belgium – SCK-CEN
  France - Areva, CEA, CNRS, U. de Toulouse, Ecole Nat'l Sup. Paris
  U.K. - U. Manchester, U. Oxford
  China – IMR, SNPRI, SNERDI, Northeastern U., SJTU, U. Electr. Sci. and Technol.
  Canada – AECL/CNL
  Japan - INSS (Japan)
  Germany - Helmholtz Center
  Poland – Institute of Physics
  Chech Republic – NRI
  Korea – KAERI, KAIST
  Pakistan – Lahore College for Women, NILOP, Pakistan Inst. of Engin & Appl Sci

Accomplishments

ELSEVIER

Journal of Nuclear Materials 300 (2002) 198–216

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Emulation of neutron irradiation effects with protons: validation of principle

G.S. Was [a,*], J.T. Busby [a], T. Allen [b], E.A. Kenik [c], A. Jenssen [d], S.M. Bruemmer [e], J. Gan [e], A.D. Edwards [e], P.M. Scott [f], P.L. Andresen [g]

ELSEVIER

CrossMark

Available online at www.sciencedirect.com

ScienceDirect

Scripta Materialia 88 (2014) 33–36

Scripta MATERIALIA

www.elsevier.com/locate/scriptamat

Emulation of reactor irradiation damage using ion beams

G.S. Was,[a,*] Z. Jiao,[a] E. Getto,[a] K. Sun,[c] A.M. Monterrosa,[a] S.A. Maloy,[b] O. Anderoglu,[b] B.H. Sencer[c] and M. Hackett[d]

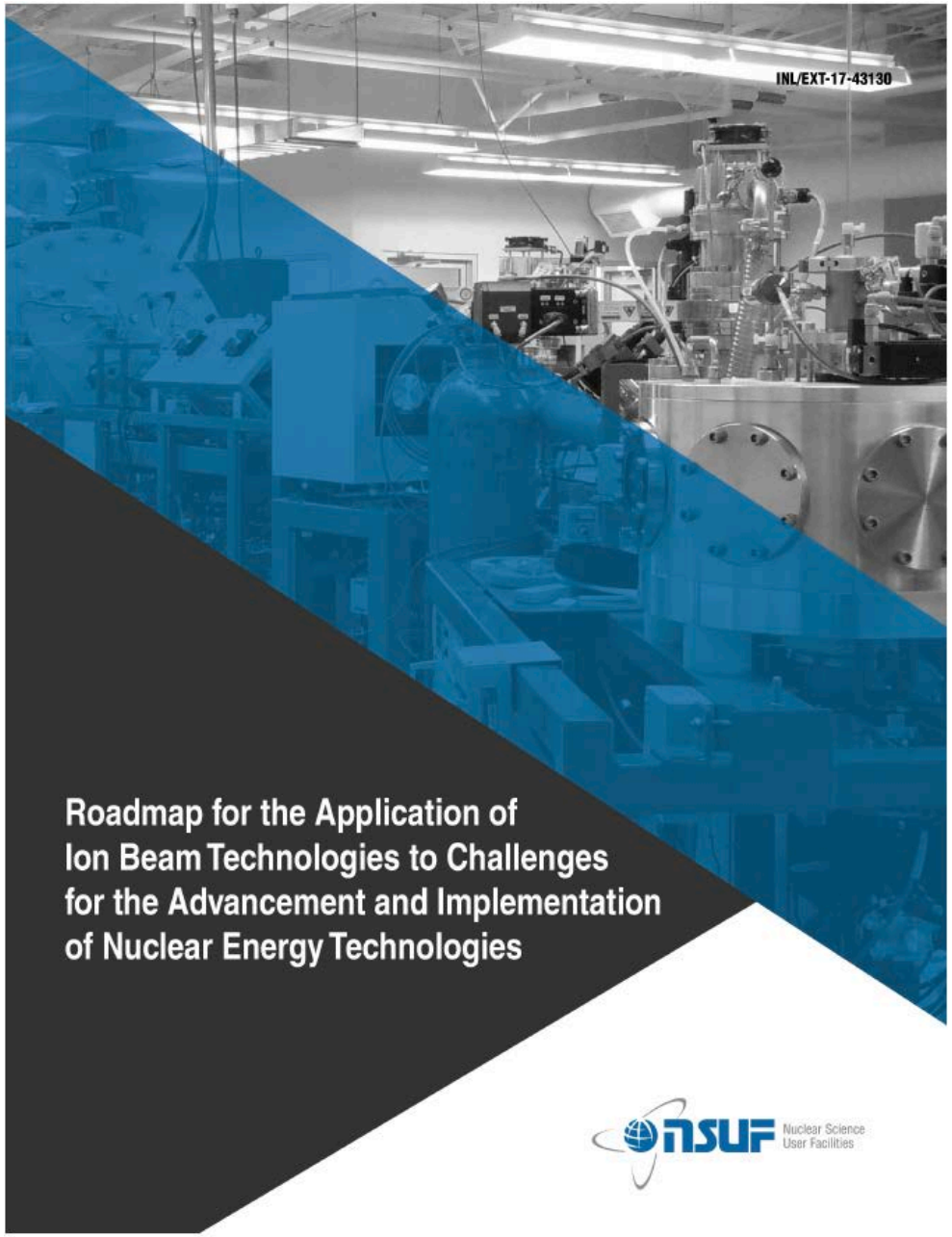
INL/EXT-16-38957

NSUF ION BEAM INVESTMENT OPTIONS WORKSHOP

INL Meeting Center, Energy Innovation Laboratory

March 22-24, 2016

NSUF Nuclear Science User Facilities | INL Idaho National Laboratory



INL/EXT-17-43130

Roadmap for the Application of Ion Beam Technologies to Challenges for the Advancement and Implementation of Nuclear Energy Technologies

NSUF Nuclear Science User Facilities

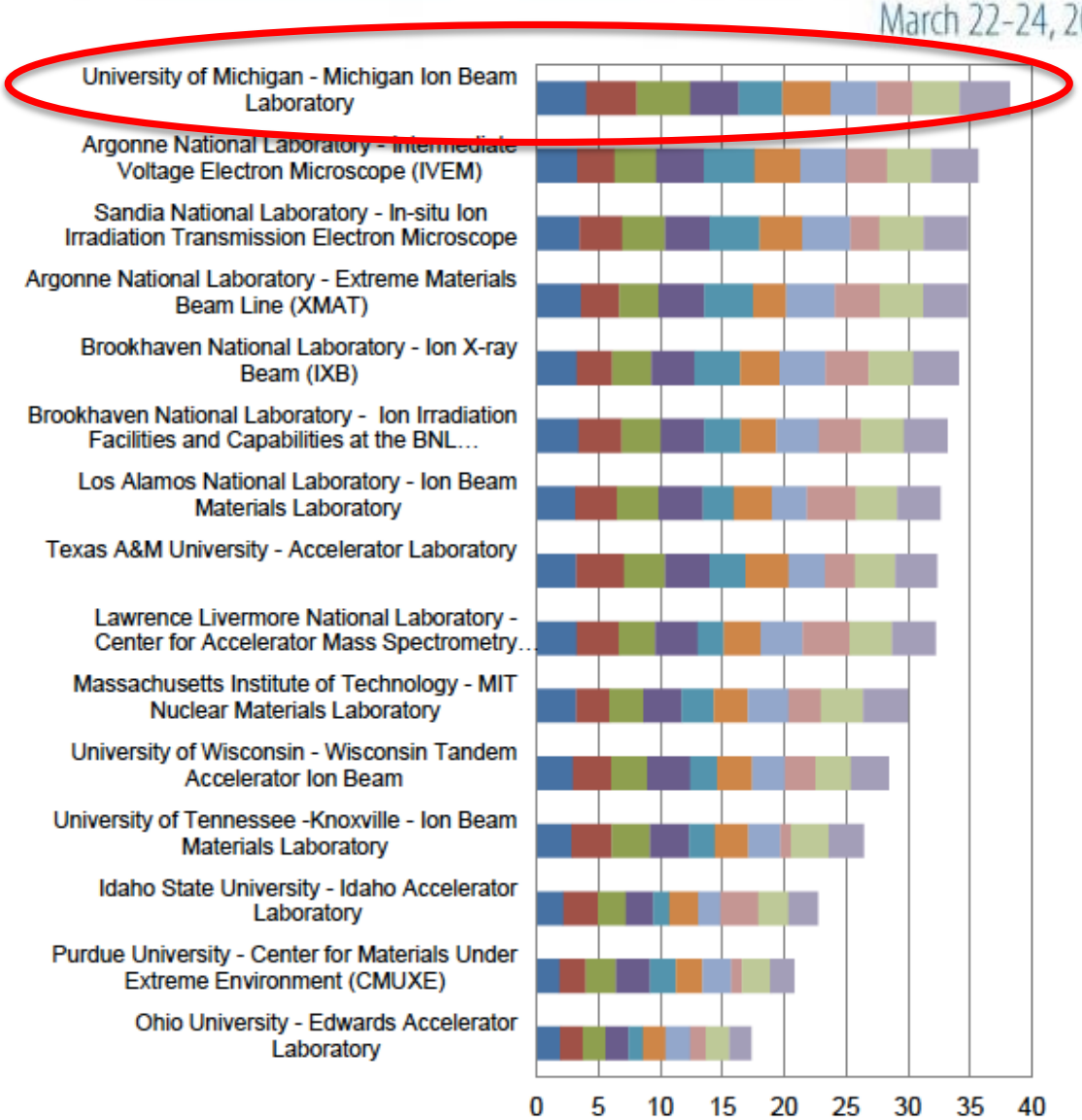
NUCLEAR ENGINEERING AND RADIOLOGICAL SCIENCES

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

NSUF ION BEAM INVESTMENT OPTIONS WORKSHOP

INL Meeting Center, Energy Innovation Laboratory

March 22-24, 2016



Professional Staff at MIBL

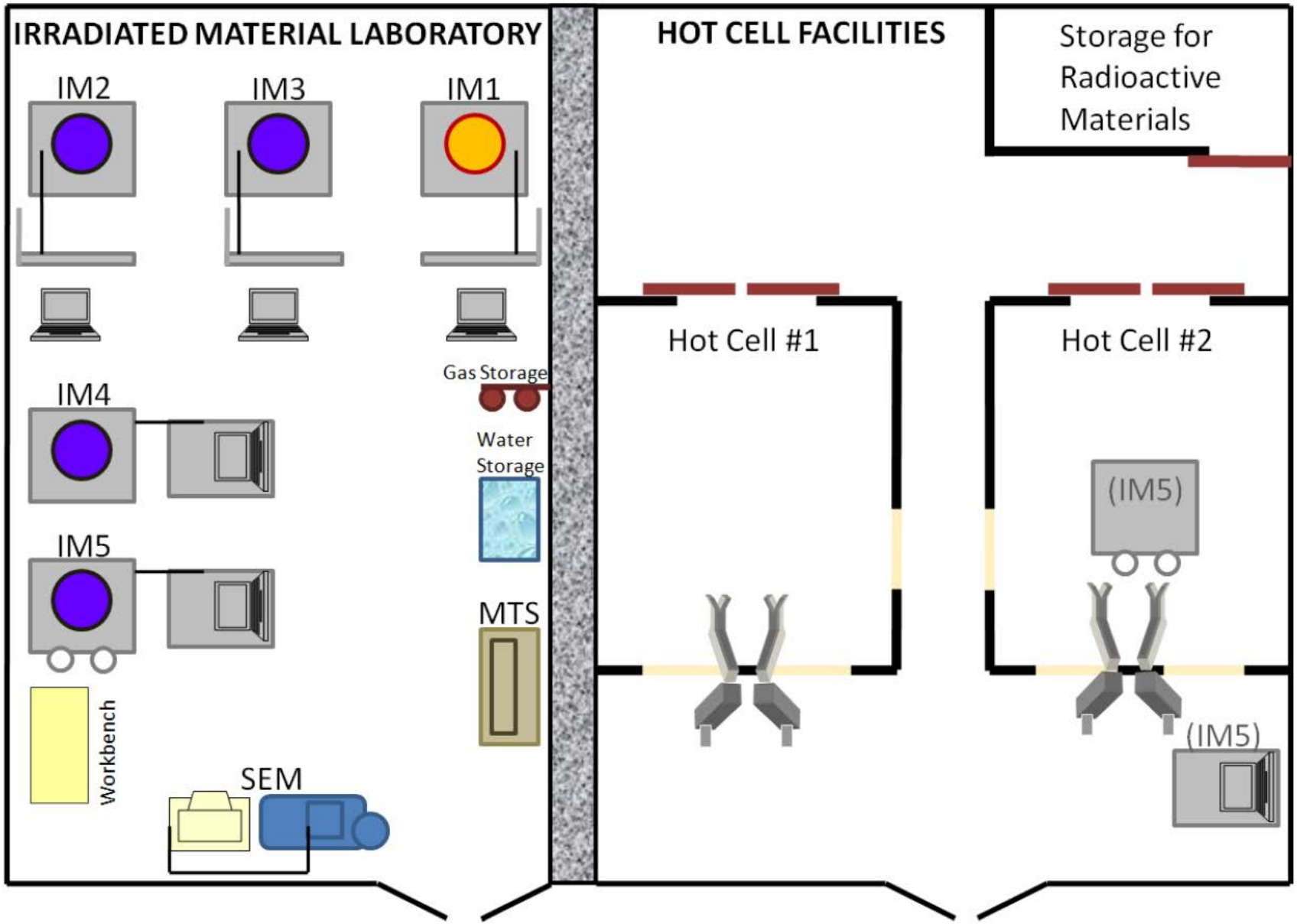
Ovidiu Toader, PhD; Lab Manager

Fabian Naab, PhD; Research Specialist

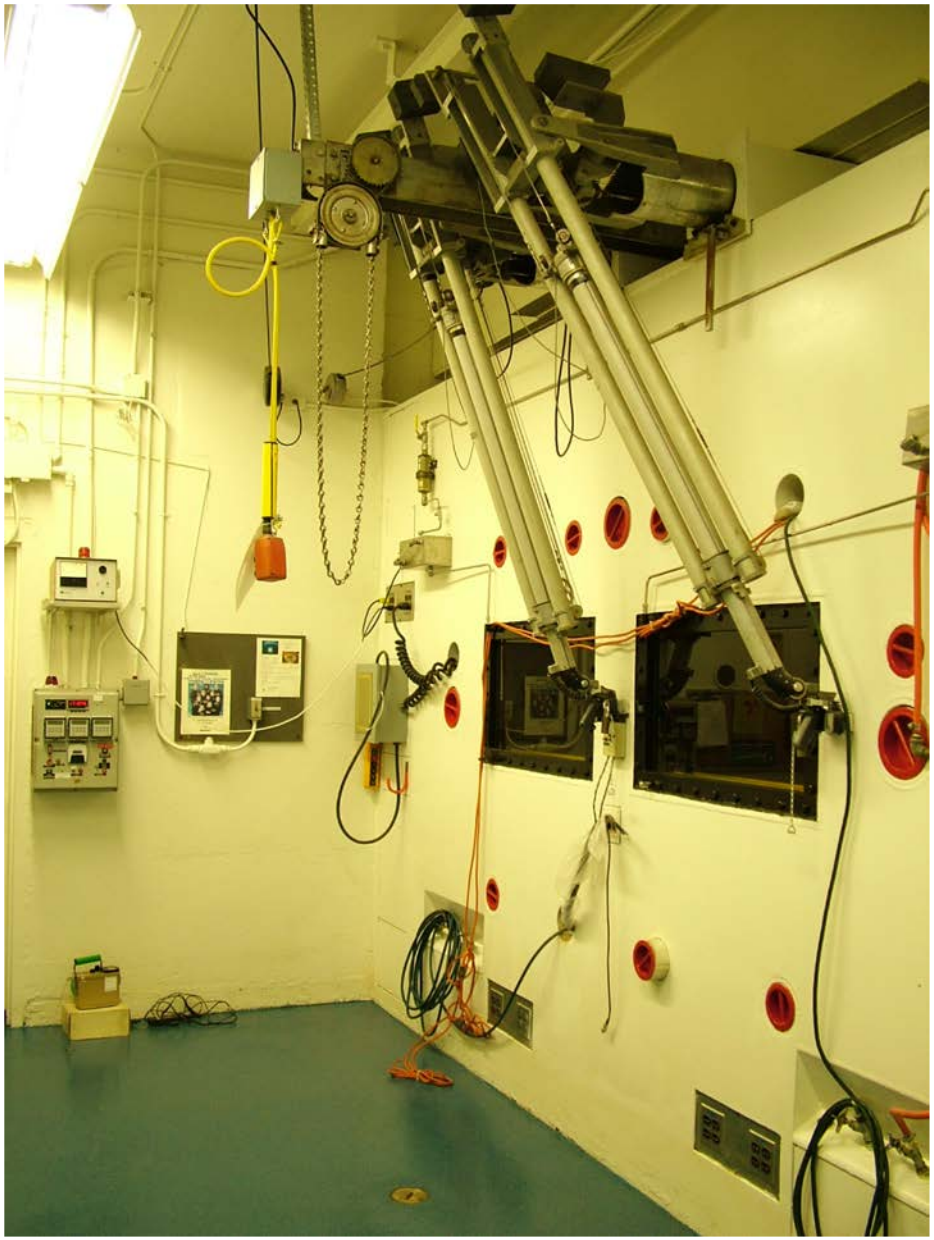
Eliseo Gamboa, PhD; Research Specialist

Thomas Kubley, MS; Accelerator Engineer

On-site: Irradiated Material Testing Complex



Hot cells for sample loading and high activity in-cell testing

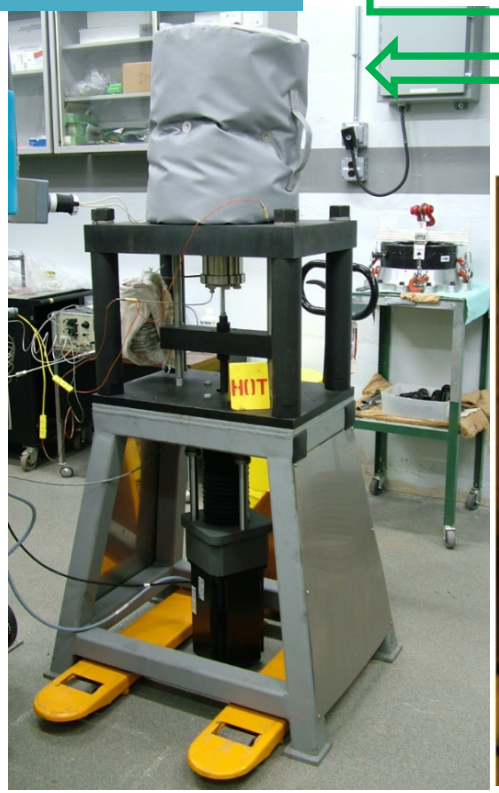


Facilities for Crack Growth Rate and Crack Initiation Testing

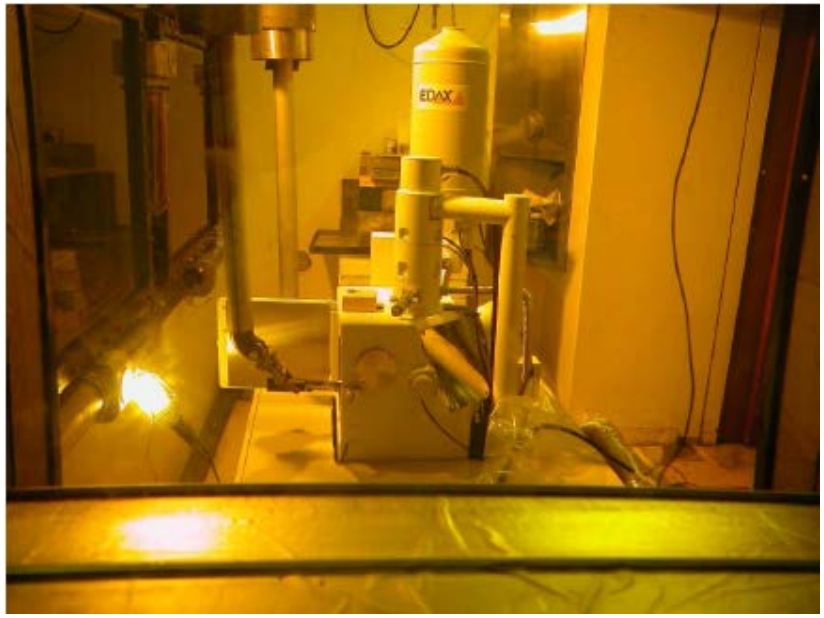
Irradiated Materials Testing Laboratory

Hot Cell

Control Panel
& Water Columns



Movable Autoclave
& Loading System



Dedicated Hot SEM

Questions?

Visit mibl.engin.umich.edu for more information on MIBL and working with us.

The expansion and new capabilities of the **Michigan Ion Beam Laboratory** were made possible with support from the DOE Nuclear Energy University Program, Electric Power Research Institute, TerraPower Inc., Oak Ridge National Laboratory, the University of Michigan's College of Engineering, and the University of Michigan's Nuclear Engineering and Radiological Sciences department.

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

EPRI ELECTRIC POWER RESEARCH INSTITUTE

TerraPower

OAK RIDGE National Laboratory

MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN