

NSUF ION BEAM INVESTMENT OPTIONS WORKSHOP

INL Meeting Center, Energy Innovation Laboratory

March 22-24, 2016



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NSUF Ion Beam Investment Options Workshop

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INL Meeting Center, Energy Innovation Laboratory

**Idaho National Laboratory
Nuclear Science User Facilities
Idaho Falls, Idaho 83415**

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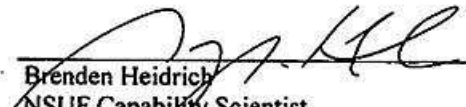
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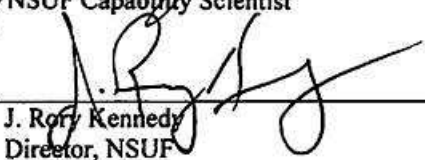
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ACRONYMS

AEC	Atomic Energy Commission	CASS	cast austenitic stainless steel
AFC	Advanced Fuel Campaign	CEA	Commissariat à l’Energie Atomique
AFM	atomic force microscopy	CLIM	Characterization Laboratory for Irradiated Materials
AGR	advanced gas-cooled reactor	CMUXE	Center for Materials under Extreme Environment
ALARA	as low as reasonably achievable	CSTAR	Center for Science and Technology with Accelerators and Radiation
AMS	accelerator mass spectrometry	CT	computed tomography
ANL	Argonne National Laboratory	DBTT	ductile-brittle transition temperature
ANS	American Nuclear Society	depU	depleted uranium
APS	Advanced Photon Source	DFT	density functional theory
ARRM	Advanced Radiation-Resistant Material	DoD	U.S. Department of Defense
ART	Advanced Reactor Technologies	DOE	U.S. Department of Energy
ATLAS	Argonne Tandem-Linac Accelerator System	DOE-BER	U.S. Department of Energy Biological and Environmental Research
ATR	Advanced Test Reactor	DOE-IRP	U.S. Department of Energy Integrated Research Projects
AUGER	auger electron spectroscopy	DOE-NE	U.S. Department of Energy Office of Nuclear Energy
BAM	Federal Institute for Materials Research and Testing (Germany)	DOT	U.S. Department of Transportation
BCC	body-centered cubic	dpa	displacements per atom
BLAIRR	Brookhaven Linear Accelerator Irradiation Test Facility	DR	direct reading
BLIP	Brookhaven Linear Isotope Producer	DTA	differential thermal analysis
BNC	Birck Nanotechnology Center	DuET	Dual-Beam Facility for Energy Science and Technology
BNL	Brookhaven National Laboratory	EAF	environmentally assisted fatigue
BR2	Belgian Reactor 2	EBIC	electron beam induced current
BSD	backscattered electron detector	EBSD	electron backscatter diffraction
BSU	Boise State University	EDS	energy dispersive spectroscopy
BU	burn-up	EMC	Electron Microscopy Center
BWR	boiling water reactor	EPRI	Electric Power Research Institute
CAES	Center for Advance Energy Studies	ERD	elastic recoil detection
CAMS	Center for Accelerator Mass Spectrometry	ERDA	Energy Research and Development Administration
CASL	Consortium for Advanced Simulation of Light Water Reactors		

EUPS	extreme ultraviolet photoelectron spectroscopy	IBA	ion beam analysis
FCCI	fuel cladding chemical interaction	IBIOW	Ion Beam Investment Options Workshop
FCM	fully ceramic microencapsulated	IEE	insulator enhanced etch
FCRD	Fuel Cycle Research and Development	IMBL	Ion Beam Materials Laboratory
FEG	field emission gun	IMPACT	interaction of materials with particles and components testing
FEM	finite element analysis	IMT	ion microtomography
FFAG	fixed field alternating gradient	INL	Idaho National Laboratory
FG	fission gas	INPP	Institute of Nuclear and Particle Physics
FHR	fluoride-salt-cooled high-temperature reactor	IR	infrared
FIB	focused ion beam	IRP	Integrated Research Project
FMI	fuel matrix interaction	ISU	Idaho State University
GAIN	Gateway for Accelerated Innovation in Nuclear	IVEM	intermediate-voltage electron microscope
GB	grain boundary	IXB	ion x-ray beam
GISAXS	grazing incidence small-angle x-ray scattering	KMC	kinetic Monte Carlo
GIXRD	grazing incidence x-ray diffraction	LANL	Los Alamos National Laboratory
HAADF	high-angle annular dark field detector	LANSCÉ	Los Alamos Neutron Science Center
HEDM	high energy diffraction microscopy	LBE	lead-bismuth eutectic
HEDP	high-energy density physics	LE	low energy
HEU	highly enriched uranium	LEAP	local electrode atom probe
HFIR	High-Flux Isotope Reactor	LEISS	low-energy ion scattering spectroscopy
HLW	high-level waste	LEU	low enriched uranium
HREM	high-resolution episcopic microscopy	LINAC	linear accelerator
HRTEM	high-resolution transmission electron microscopy	LLNL	Lawrence Livermore National Laboratory
HT	high temperature	LMIG	Laser Material Interaction Group
HVEM	high-voltage electron microscope	LN	liquid nitrogen
HXN	hard x-ray nanoprobe	LP	low pressure
I ³ TEM	in situ ion irradiation transmission electron microscope	LPP	laser-produced plasma
IASCC	irradiation-assisted stress corrosion cracking	LT	low temperature
		LWR	light-water reactor
		LWRS	light-water reactor sustainability

MAaD	Materials Aging and Degradation	ODS	oxide dispersion strengthened
MBC	Multi-Beam Chamber	ORNL	Oak Ridge National Laboratory
MC	Monte Carlo	PHENIX	Pioneering High Energy Nuclear Interaction Experiment
MD	molecular dynamics	PID	photoionization detector
MIBL	Michigan Ion Beam Laboratory	PIE	post-irradiation examination
MIT	Massachusetts Institute of Technology	PIXE	proton induced x-ray emission
MITR	Massachusetts Institute of Technology Reactor	PKA	primary knock-on atom
MSE	materials science and engineering	PNNL	Pacific Northwest National Laboratory
MTR	materials test reactor	PRIME	particle radiation interaction with matter experiments
NASA	National Aeronautics and Space Administration	PWR	pressurized water reactor
natU	natural uranium	PWSCC	primary water stress corrosion cracking
NC	nanocolumnar	QA	quality assurance
NDE	nondestructive examination	QCM	quartz crystal microbalance
NDMAS	Nuclear Data Management and Analysis System	R&D	research and development
NEAMS	Nuclear Energy Advanced Modeling and Simulation	RBS	Rutherford backscattering spectrometry
NEC	National Electrostatics Corporation	RD&D	research, development, and demonstration
NEET	Nuclear Energy Enabling Technology	RERTR	Reduced Enrichment for Research Test Reactors
NEID	Nuclear Energy Infrastructure Database	RF	radio frequency
NEUP	Nuclear Energy University Program	RFI	request for information
NGNP	Next Generation Nuclear Plant	RHIC	Relativistic Heavy Ion Collider
NIH	National Institutes of Health	RIAM	risk-informed asset management
NNSA	National Nuclear Security Administration	RIP	radiation-induced phasing
NP	nanoparticulate	RISE	Research and Innovation in Science and Engineering
NRA	nuclear reaction analysis	RPV	reactor pressure vessel
NRC	U.S. Nuclear Regulatory Commission	RT	room temperature
NSF	National Science Foundation	RTE	rapid turnaround experiment
NSLS	National Synchrotron Light Source	SANS	small-angle neutron scattering
NSUF	Nuclear Science User Facilities	SAXS	small angle x-ray scattering
		SCC	stress corrosion cracking

SEM	scanning electron microscope	UCB	University of California at Berkeley
SLIA	Spiral Line Induction Accelerator	UCSB	University of California at Santa Barbara
SNF	spent nuclear fuel		
SNICS	source of negative ions by cesium sputtering	UFD	used fuel disposition
SS	stainless steel	UHFI	ultra-high-flux irradiation
SSD	silicon drift detector	UHV	ultra-high vacuum
STAR	Solenoidal Tracker at RHIC	UM	University of Michigan
STEM	scanning transmission electron microscope	UNF	used nuclear fuel
STM	scanning tunneling microscopy	UNT	University of North Texas
STP	standard temperature and pressure	UPS	ultraviolet photoelectron spectroscopy
SUNY	State University of New York	UT	University of Tennessee
SUSNAG	Surface Science and Nanostructures Group	UW	University of Wisconsin
TAMU	Texas A&M University	V&V	verification and validation
TC	temperature calibration	VCU	Virginia Commonwealth University
TDS	thermal desorption spectroscopy	VHTR	very high temperature reactor
TEM	transmission electron microscopy	WAXS	wide-angle x-ray scattering
TGA	Thermogravimetric analysis	WEC	Westinghouse Electric Company
TORVIS	toroidal volume ion source	WNR	weapons neutron research
TREAT	Transient Reactor Test Facility	XFEL	x-ray free electron laser
TRU	transuranic	XMAT	extreme materials beam line
TUF	tandem user facility	XPD	x-ray powder diffraction
UC	University of Colorado	XPS	x-ray photoelectron spectroscopy
		XRD	x-ray diffraction

NSUF Ion Beam Investment Options Workshop

1. INTRODUCTION

The Nuclear Science User Facilities (NSUF) Ion Beam Investment Options Workshop (IBIOW) was held to develop a set of recommendations (i.e., a priority list) for funding domestic ion beam irradiation capabilities available to researchers. These capabilities are focused on the support of nuclear-energy research, development, and deployment. The recommendations are intended for use by the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) when faced with decisions about investments in ion beam support, instruments, and facilities. Recommendations developed during the IBIOW are provided in the *Supplement to the NSUF Ion Beam Investment Options Report: Initial Results and Recommendations* (Heidrich 2016).

As part of their initial discussions of potential future funding, IBIOW participants considered input submitted through DOE-NE Request for Information DE-SOL-0008318, “University, National Laboratory, Industry and International Input on Potential Office of Nuclear Energy Infrastructure Investments (April 13, 2015).” Discussions and presentations of other input, whether specific or general in scope, were also welcomed. Also included was user input, including input regarding DOE-NE program interests and ion irradiation research, development, and deployment needs.

The workshop was held March 22–24, 2016, at the Idaho National Laboratory (INL) Meeting Center in the Energy Innovation Laboratory in Idaho Falls, Idaho. The workshop agenda is included in Appendix A.

2. WORKSHOP PARTICIPANTS

Workshop participants were selected from various sources, i.e., request-for-information respondents, Nuclear Energy University Program/Nuclear Energy Enabling Technology infrastructure applicants, universities with known expertise in nuclear engineering and materials science, and other developed sources.

Thirty-three members of the ion beam community attended the workshop, including 15 representatives of ion beam facilities, six representatives of DOE-NE research and development (R&D) programs, an industry representative from the Electric Power Research Institute, and the chairs of the NSUF User’s Organization and the NSUF Scientific Review Board. Four ion beam users attended as advisors to the process but did not participate in the options assessment. Three members of the sponsoring agency, the Office of Science and Technology Innovation (NE-4), also attended the workshop.

Table 1 lists the workshop participants.

Table 1. Workshop participants.

Name	Organization/Position
Workshop Organizers and Sponsors	
Rory Kennedy	Director, NSUF
Brenden Heidrich	NSUF Capability Scientist
Jodi Grgich	INL Facilitator
Jody Henley	INL Facilitator
Michael Worley	DOE-NE
Thomas Miller	DOE-NE
Alison Hahn	DOE-NE

Table 1. (continued).

Name	Organization/Position
User Community Representatives	
Sean McDevitt	Texas A&M University – NSUF Scientific Review Board
Peng Xu	NSUF User’s Organization Chair – Westinghouse
William Windes	Advanced Reactor Technologies (ART)
Sebastien Teyseyre	Light-Water Reactor Sustainability (LWRS)
Daniel Schwen	Nuclear Energy Advanced Modeling and Simulation (NEAMS)
Shannon Bragg-Sitton	Fuel Cycle Research and Development (FCRD)
Remi Dingreville	Used Fuel Disposition Program
Dean Peterman	Waste Forms Research and Development Program
Tiangan Lian	Electric Power Research Institute – Program Manager
Robert Odette	University of California – Santa Barbara
James Stubbins	University of Illinois – Urbana-Champaign
Ion Beam Facility Representatives	
Abdellatif Yacout	Argonne National Laboratory (ANL) – Extreme Materials Beam Line (XMAT)
Meimei Li	ANL – Intermediate Voltage Electron Microscope (IVEM)
Nick Simos	Brookhaven National Laboratory (BNL) – Brookhaven Linear Isotope Producer (BLIP) – Brookhaven Linear Accelerator Irradiation Test Facility (BLAIRR)
Lynne E. Ecker	BNL – Ion X-Ray Beam (IXB)
Jon L. Stoner	Idaho State University – Idaho Accelerator Facility
Yong Q. Wang	Los Alamos National Laboratory (LANL) – Ion Beam Materials Laboratory
Scott J. Tumey	LLNL – Center for Accelerator Mass Spectrometry
Lance Snead	Massachusetts Institute of Technology (MIT) – Nuclear Materials Laboratory
Steve Grimes	Ohio University – Edwards Accelerator Laboratory
Jitendra Kumar Tripathi	Purdue University – Center for Materials under Extreme Environment (CMUXE) Facility
Khalid Hattar	Sandia National Laboratories – In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
Lin Shao	Texas A&M University – Ion Beam Laboratory
Gary S. Was	University of Michigan – Ion Beam Laboratory
William J. Weber	University of Tennessee – Ion Beam Materials Laboratory
Beata Tyburska-Pueschel	University of Wisconsin – Ion Beam Laboratory

3. WORKSHOP STRUCTURE AND PROCESS FLOW

The NSUF IBIOW process began in December 2015 by soliciting interest in participating in the workshop from the various U.S. ion beam facility owners (universities and national laboratories). This was followed in January and February 2016 by official invitations to the workshop. The participants were asked to become involved in an ongoing process to define and weight criteria that could be used to judge the options available to DOE-NE to support and expand domestic ion beam irradiation capabilities. The assessment process started informally but later transitioned to the ThinkTank collaboration software.

Because the goal of the workshop was to provide recommendations to DOE-NE, a data-driven process was designed with the assistance of the INL's systems engineering division. ThinkTank collaborations software was selected as the tool to gather the data and link the workshop participants together. ThinkTank has been used successfully in a wide variety of government projects, notably the Nuclear Innovation Workshops held in March 2015.

The process outline was:

1. Select workshop participants
2. Determine and weight criteria (online, pre-workshop)
3. Hold the workshop (March 22–24, 2016)
 - a. Review the criteria list
 - i. Combine criteria (25 into 10)
 - ii. Reweight new combined criteria
 - b. View presentations by researchers (DOE-NE programs and ion beam users)
 - c. View presentations by ion beam facilities
 - d. Conduct an assessment and ranking exercise
 - e. Discuss future work
4. Analyze the workshop data, and generate a report

4. CRITERIA SELECTION AND WEIGHTING

The workshop participants generated and weighted a list of criteria against which to compare the various ion beam facilities and estimate the need for future investment. (Appendix B contains the information from the criteria exercises.) The original 15 criteria were generated by NSUF as a starting point for the discussion. Workshop participants then added criteria via email during the lead-up to the workshop. Table 2 shows the resulting 25 criteria and the weights assigned by the workshop participants using the ThinkTank software (before the workshop). The total list of 25 criteria proposed at the start of the workshop was too large to handle in the 3 days allotted for the workshop, so NSUF suggested eight combined criteria to replace the 25 original criteria (see Table 3). Appendix C provides criteria weighting data and comments.

Table 2. Original 25 criteria and weights.

No.	Criteria	Mean	Std. Dev.
1	Scientific merit and potential merit	8.60	1.35
2	Broad applicability (cross-cutting – i.e., multi-program)	7.07	2.25
3	International capabilities alternatives	4.80	1.90
4	DOE-NE programmatic mission need	7.80	1.82
5	Nuclear energy industry needs	6.13	2.67
6	Proportion of time to be allocated to direct DOE-NE mission work through Gateway for Accelerated Innovation in Nuclear [GAIN], NSUF, or DOE-NE programs	6.27	1.67
7	Current/past DOE-NE support/investment	5.93	1.94
8	Current DOE-NE work performed at facility	6.27	2.49
9	User experiment throughput capability	6.67	2.09
10	Beam energies (and energy ranges)	7.88	1.78
11	Ion types and variety	7.69	2.24
12	Variety of irradiation environments	7.44	2.03
13	Multiple analytical techniques available	5.75	2.67
14	Radiation levels allowed for samples	6.31	2.50
15	Multiple convergent beams (dual or triple)	6.50	2.31
16	Ability to match prototypic conditions	6.31	2.75
17	In situ examination during irradiation	6.56	2.92
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	5.63	2.42
19	Does the facility provide new capabilities?	6.14	3.37
20	Radiation effects/damage experience at the host institution	6.88	3.07
21	Need to define and have new capability be on path toward greater applicability and relevance	6.21	2.58
22	Relative R&D impact of utilizing direct simulants (i.e., swift heavy ion) or indirect simulants (i.e., light ions)	5.43	2.90
23	Applicability of results to development or data goals	5.36	3.54
24	Is there support of small specimen test technology?	5.50	3.25
25	Standards development, including temperature sensing	5.21	2.83

Table 3. Original 25 criteria combined into eight.

Original No.	Criteria	Mean	Std. Dev.	Combined	Combined Criteria	Mean	Std. Dev.
1	Scientific merit and potential merit	8.6	1.4	C1	Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry	7.4	2.2
2	Broad applicability (cross-cutting – i.e., multiprogram)	7.1	2.3				
4	DOE-NE programmatic mission need	7.8	1.8				
5	Nuclear energy industry needs	6.1	2.7				
10	Beam energies (and energy ranges)	7.9	1.8	C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	7.4	2.2
11	Ion types and variety	7.7	2.2				
15	Multiple convergent beams (dual or triple)	6.5	2.3				
12	Variety of irradiation environments	7.4	2.0	C3	Ability of the facility to provide a variety of irradiation environments and conditions	6.9	2.4
16	Ability to match prototypic conditions	6.5	2.8				
13	Multiple analytical techniques available	5.8	2.7	C4	Ability of the facility to collect and analyze microstructural characterization data onsite and in situ	6.4	2.9
17	In situ examination during irradiation	6.6	2.9				
20	Radiation effects/damage experience at the host institution	6.9	3.1				
6	Proportion of time to be allocated to direct DOE-NE mission work through GAIN, NSUF, or DOE-NE programs	6.3	1.7	C5	DOE-NE support and activities (performed and anticipated) at the facility, including the volume of experiments that can be handled	6.3	2.0
7	Current/past DOE-NE support/ investment	5.9	1.9				
8	Current DOE-NE work performed at facility	6.3	2.5				
9	User experiment throughput capability	6.7	2.1				
19	Does the facility provide new capabilities?	6.1	3.4	C6	Unique capabilities of the facility, including new technology	6.2	2.9
21	Need to define and have new capability be on path toward greater applicability and relevance	6.2	2.6				

Table 3. (continued).

Original No.	Criteria	Mean	Std. Dev.	Combined	Combined Criteria	Mean	Std. Dev.
14	Radiation levels allowed for samples	6.3	2.5	C7	Ability of the facility to handle radioactive materials in the beams and elsewhere onsite	5.8	2.7
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	5.6	2.4				
24	Is there support of small specimen test technology?	5.5	3.3				
23	Applicability of results to development or data goals	5.4	3.5	C8	Ability of the facility to produce high-quality data that can support verification and validation of modeling and simulation	5.3	3.2
25	Standards development, including temperature sensing	5.2	2.8				

The weights and standard deviations shown in Table 3 for the eight combined criteria are a combination of the standard deviations from the original 25 criteria. During the first day of the workshop, the eight criteria were expanded to the following nine combined criteria based on input from the participants:

1. Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results
2. Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)
3. Ability of the facility to provide a variety of irradiation environments and conditions
4. Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in situ
5. DOE-NE support and activities (performed and anticipated) at the facility, including the volume of experiments that can be handled
6. Unique capabilities of the facility, including any new technology
7. Ability of the facility to handle radioactive materials in the beams and elsewhere onsite
8. Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation
9. Ability of the facility to produce results that meet the needs of DOE-NE (including cross-cutting programs) and the nuclear energy industry.

4.1 Final Criteria

After much discussion, a set of 10 criteria were agreed upon by the workshop participants. These criteria were discussed and weighted during the workshop. Table 4 shows the weights normalized so that the highest weight is equal to 100% and the remaining are relative to that one. The ThinkTank software also calculates the standard deviation of the weights based on the scores and the number of voters. Unfortunately, the spread in scores given by the participants was too large to use the weights in a statistically valid quantitative assessment. The relative weights $\pm 1\sigma$ are shown in Figure 1. The plot shows that there is significant overlap in the weights. Even with this issue, the relative importance of the criteria can be observed through the raw scores. The highest scoring criteria are generally also the ones with the least variation in opinion, as shown by the lower coefficient of variation (CoV) (standard deviation divided by the weight or percent standard deviation).

Table 4. Final 10 criteria used in the NSUF workshop to assess ion beam facilities.

#	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%

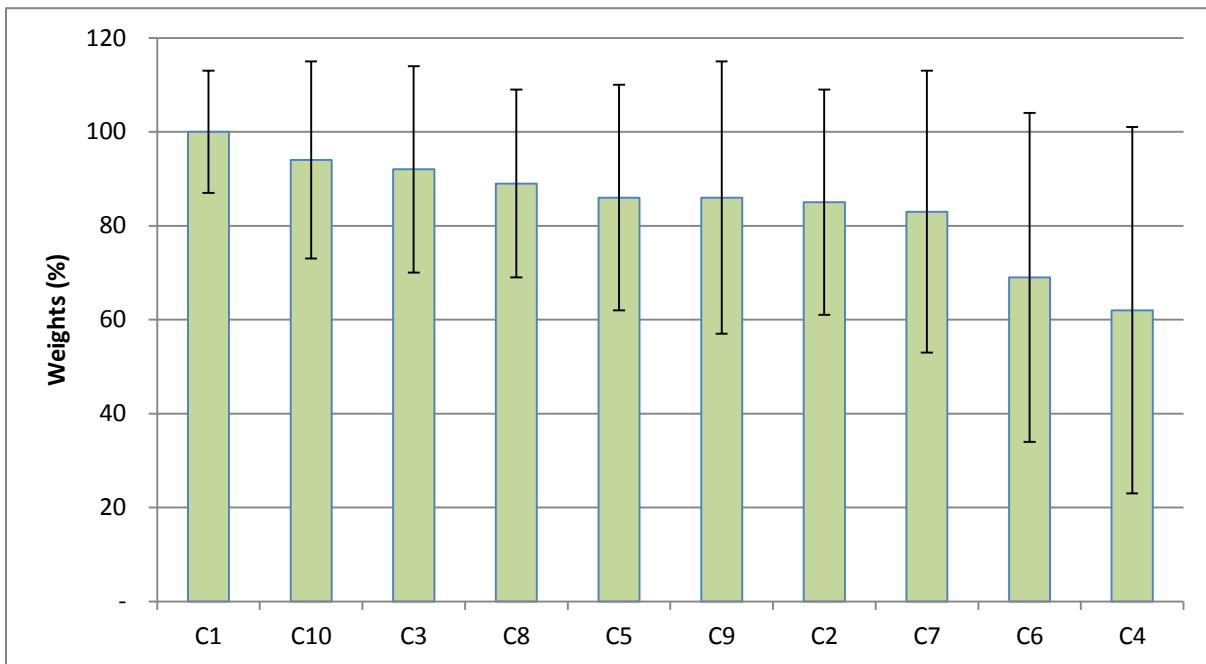


Figure 1. Relative weights of the 10 final criteria and their standard deviations ($\pm 1\sigma$).

Figure 2 shows the final 10 criteria and the proportion of votes to weight each one as high (dark green), medium (light green), or low (yellow). The value in parentheses is the relative weight of the criterion. Note that the final order of the facility rankings was not affected by the use or non-use of the weighting criteria.

The following pages show the data from the ThinkTank software, including the results from the weighting and the comments made by the workshop participants.

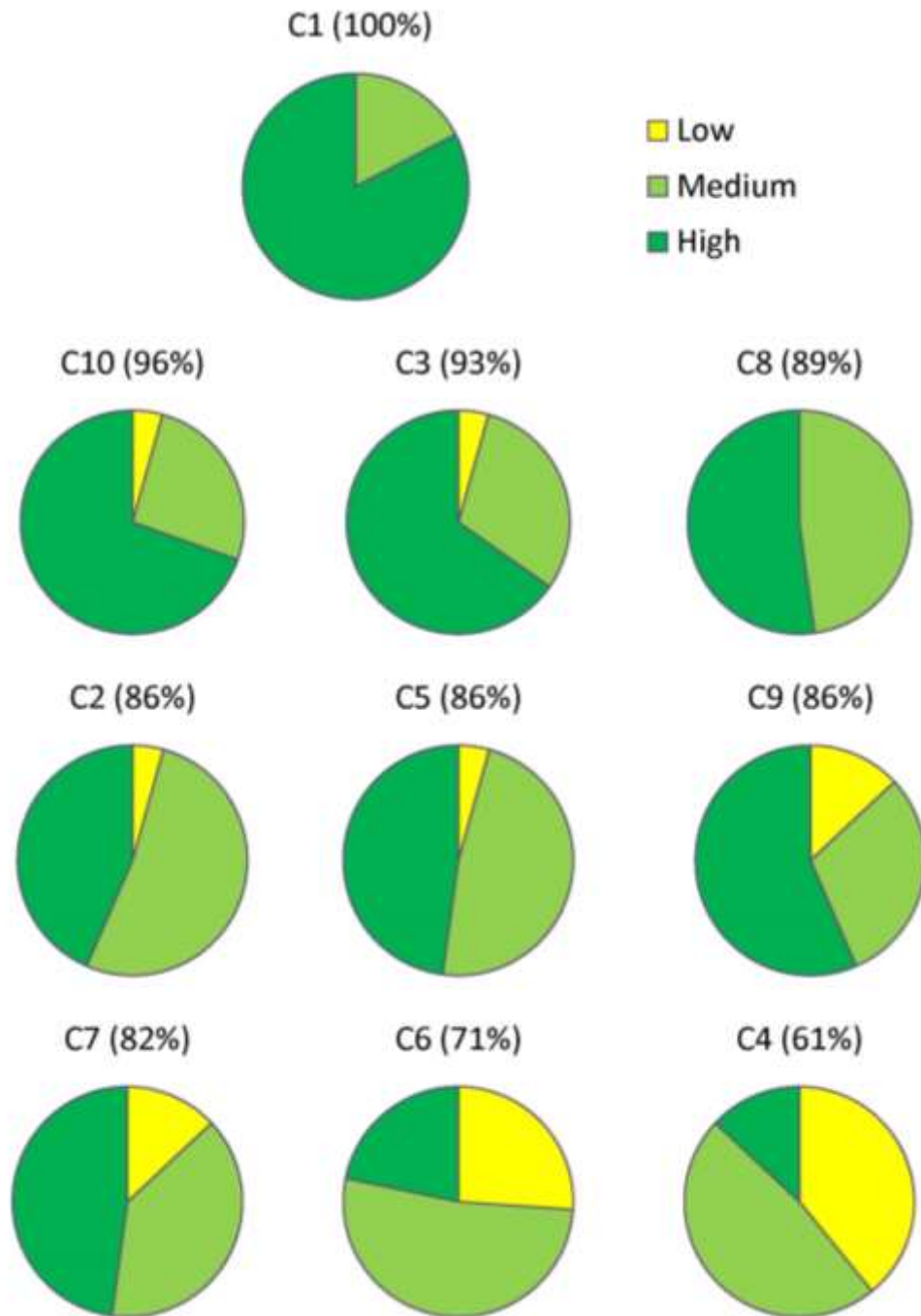


Figure 2. Distribution of votes for criteria weighting exercise.

5. ION BEAM FACILITY ASSESSMENT

In addition to developing and weighting criteria, workshop participants viewed presentations from ion beam users and DOE-NE R&D programs and then the ion-beam facility representatives. These presentations are provided in Appendixes D and E along with any community comments in the sidebar of the slides.

Following the presentations, the workshop participants assessed each ion beam facility against each of the final 10 criteria. This exercise was performed individually, although discussions and questions were allowed. ThinkTank software was used to collect the data from the assessments. The data and comments from the facility ranking exercise are in Appendix F. Figure 3 shows the results of the assessment of the facilities against the criteria. The absolute scores are slightly different if the criteria weights are applied, but the overall ranking does not change.

It should be noted that the facilities are not all focused on the same objectives and therefore may have significantly different designs. Of the 15 facilities that were reviewed, only 11 were operational at the time. Four facilities were proposed to be constructed in the future:

1. Argonne National Laboratory – Extreme Materials Beam Line (XMAT)
2. Brookhaven National Laboratory (BNL) – Ion X-Ray Beam (IXB)
3. BNL – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR
4. Massachusetts Institute of Technology (MIT) – MIT Nuclear Materials Laboratory.

Additionally, the facility at Purdue University focuses on surface science of materials and utilizes much lower energy ions than the others. The Edwards Accelerator Laboratory at The Ohio University is primarily engaged in nuclear data measurement and not in the irradiation effects on materials. The Idaho Accelerator Laboratory at Idaho State University is a multipurpose facility that supports a wide variety of research endeavors. These three facilities should not be judged in the same manner as the others.

Beyond this, the remaining eight currently operating facilities all provide vital support to nuclear materials researchers. The individual capabilities of these eight facilities differ based on their particular missions. Three facilities have (or will have soon) in situ characterization capabilities that combine ion irradiation with a transmission electron microscope. The proposed facilities seek to provide in situ characterization with an x-ray source.

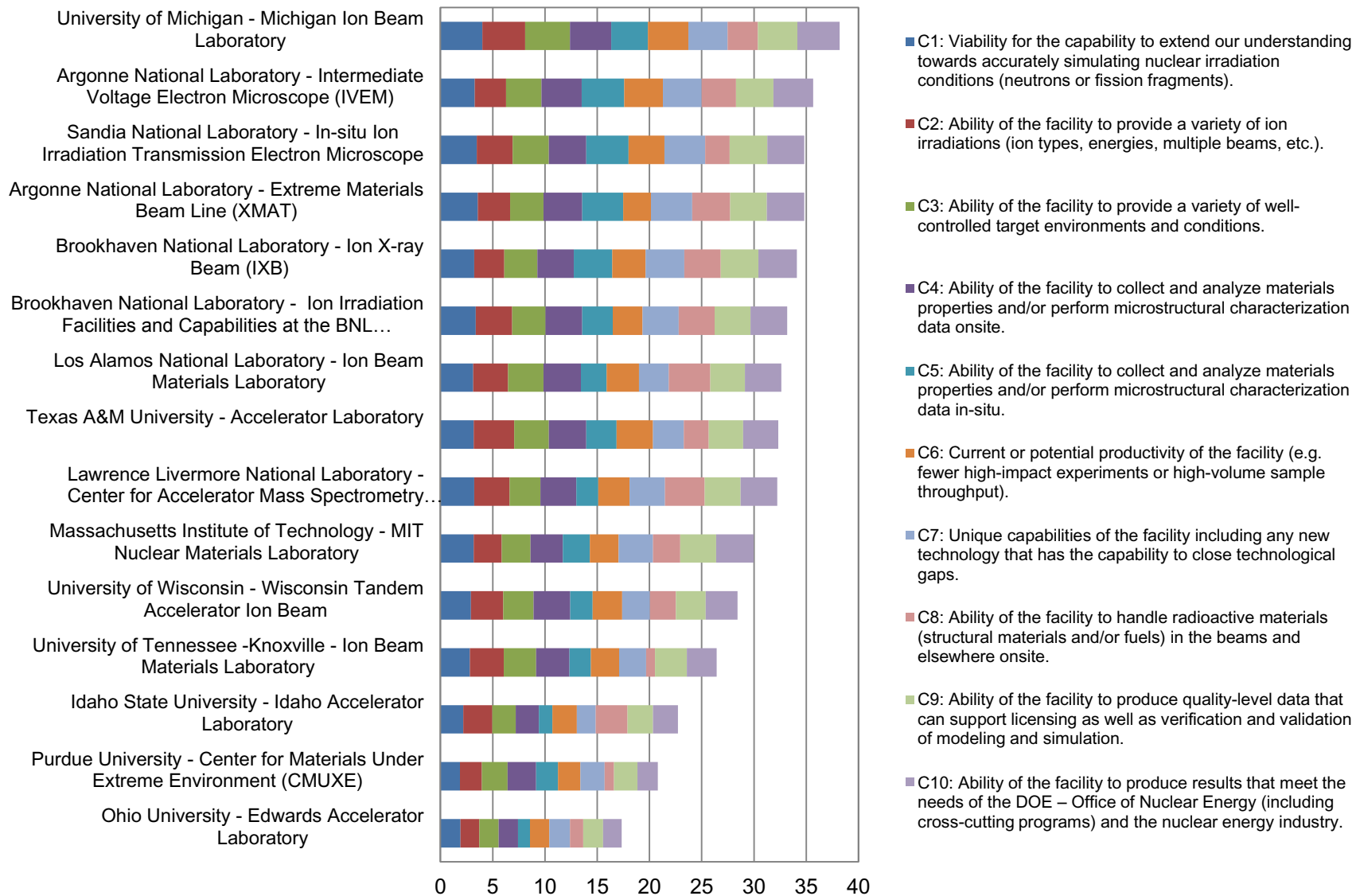


Figure 3. Overall score and ranking of the ion beam facilities.

6. FUTURE WORK

During the closeout discussion from the NSUF IBIOW, three criteria were viewed by the participants as being quantitative in nature and therefore better judged by direct comparison instead of peer assessment. These were Criteria C2, C3, and C8. NSUF gathered quantitative data for these three areas for use in future assessments. These data can be found in Appendix G.

The NSUF IBIOW is the first step in assessing and building a plan for the development and expansion of ion beam irradiation capabilities in the United States. The ThinkTank software can be used in the future to allow additional people, such as a wider community of ion beam users, to review the presentations and quantitative data and to participate in the assessment of the existing and proposed ion beam irradiation facilities. In addition, a road-mapping exercise is planned for Fiscal Year 2017 to layout the direction of R&D efforts.

7. REFERENCES

Heidrich, Brenden J., *Supplement to the NSUF Ion Beam Investment Options Report: Initial Results and Recommendations*, INL/LTD-16-38580, Rev. 0, April 2016.

Appendix A

Workshop Agenda

Appendix A

Workshop Agenda

Tuesday, March 22

- 8:00 ThinkTank and INL Guest Network setup.....Jodi Grgich
Idaho National Laboratory Facilitator
- 8:30 Introductions of Workshop Participants (light breakfast)..... Jody Henley
Idaho National Laboratory Facilitator
- 9:00 Welcome, Introductions and Workshop Overview..... Rory Kennedy
Director, NSUF
- 9:10 Agenda and Conduct of Workshop..... Brenden Heidrich
NSUF Capability Scientist
- 9:20 Introduction to ThinkTank..... Jody Henley
Idaho National Laboratory Facilitator
- 9:30 Discussion of the Workshop Analysis Criteria and Weights..... Brenden Heidrich
NSUF Capability Scientist
- 10:30 *Morning Break (30 min)*
- 11:00 NSUF User's OrganizationPeng Xu
NSUF UO Chair, Westinghouse
- 11:30 Irradiation Material Testing for VHTR Core Materials..... William Windes
Idaho National Laboratory Scientist
- 12:00 Light Water Reactor Sustainability (LWRS) Program Data Needs..... Sebastien Teyssyre
Idaho National Laboratory Scientist
- 12:30 *Lunch (90 min)*
- 2:00 Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program Data
Needs..... Daniel Schwen
Idaho National Laboratory Scientist
- 2:30 Fuel Cycle Research & Development Program Data Needs Shannon Bragg-Sitton
Idaho National Laboratory Scientist
- 3:00 Used Fuel Disposition Program Data Needs.Remi Dingreville
Sandia National Laboratory Scientist

- 3:00 *Afternoon Break (30 min)*
- 3:30 The IVEM-Tandem User Facility: TEM with In-situ Ion Irradiation.....Meimei Li
Argonne National Laboratory Research Scientist
- 4:00 Extreme Materials Beam LineAbdellatif Yacout
Argonne National Laboratory Research Scientist
- 4:30 Capabilities at the Idaho Accelerator and RISE Research Centers at
Idaho State University..... Jon L. Stoner
Idaho State University Research Faculty
- 5:00 Closing Discussion – Day 1 Brenden Heidrich
NSUF Capability Scientist

Wednesday, March 23

- 8:00 Advanced Materials Characterization at CMUXE, Purdue UniversityJitendra Kumar Tripathi
Purdue University, Senior Research Associate
- 8:30 A High-Energy Ion Irradiation Capability for Radiation Damage Experiments at the LLNL
Center for Accelerator Mass Spectrometry..... Scott J. Tumey
Lawrence Livermore National Laboratory Scientist
- 9:00 Wisconsin Ion Beam Laboratory: Capabilities and NeedsBeata Tyburska-Pueschel
University of Wisconsin Research Faculty
- 9:30 In-situ Ion Irradiation Transmission Electron Microscope at SNLKhalid Hattar
Sandia National Laboratory Scientist
- 10:00 *Morning Break (30 min)*
- 10:30 Ion Irradiation Capabilities at the Michigan Ion Beam Laboratory..... Gary S. Was
University of Michigan Research Faculty
- 11:00 Accelerator Based Facility for Materials Irradiation TestingNick Simos
Brookhaven National Laboratory Scientist
- 11:30 In-situ X-ray Characterization of Microstructural Evolution due to
Ion Beam IrradiationLynne E. Ecker
Brookhaven National Laboratory Scientist
- 12:00 University of Tennessee Ion Beam Materials Laboratory William J. Weber
University of Tennessee Research Faculty

12:30 Lunch (90 min)

2:00 Edwards Accelerator Laboratory at the University of Ohio Steve Grimes
University of Ohio Research Faculty

2:30 Ion Beam Laboratory at Texas A&M University Lin Shao
Texas A&M University Research Faculty

3:00 Ion Beam Materials Laboratory Yong Q. Wang
Los Alamos National Laboratory Scientist

3:30 Afternoon Break (30 min)

4:00 U.S. Nuclear Industry User Community Requirements..... Tiangan Lian
EPRI-Program Manager

4:30 Potential for Lab Compact Cyclotrons: Ions at Energies Relevant to
Engineering Properties..... Lance Snead
MIT Research Faculty

5:00 Closing Discussion - Day 2..... Brenden Heidrich
NSUF Capability Scientist

Thursday, March 24

8:00 Discussion of Final Criteria and Weighting Exercise..... Brenden Heidrich/Jody Henley
INL Facilitator

9:30 Ranking Exercise for Investment Options Jody Henley
INL Facilitator

10:00 Analysis of Results and Discussion Jody Henley
INL Facilitator

11:00 Workshop Closeout..... Brenden Heidrich
NSUF Capability Scientist

Appendix B

NSUF Presentations
(Workshop and Criteria Weighting)

Appendix B

NSUF Presentations (Workshop and Criteria Weighting)

This appendix provides NSUF presentations made at the workshop with comments from workshop participants (in the sidebar).

Welcome Presentation

Brenden Heidrich

Nuclear Science user Facilities — Ion Beam Investment Options Workshop – Brenden Heidrich R&D Capability Scientist – NSUF Ion Beam Investment Workshop Idaho National Laboratory Idaho Falls, ID March 22, 2016

The slide is a presentation cover for the NSUF Ion Beam Investment Options Workshop. At the top left is the U.S. Department of Energy logo, featuring a shield with a sun and a gear, and the text "U.S. DEPARTMENT OF ENERGY". To the right of the logo is the text "Nuclear Energy" in a green, sans-serif font. Below this, the title "Nuclear Science User Facilities" is written in a smaller, italicized font. The main title "Ion Beam Investment Options Workshop" is in a large, bold, green font. Below the title, the presenter's name "Brenden Heidrich" is listed, followed by his title "R&D Capability Scientist". The event details "NSUF Ion Beam Investment Workshop", "Idaho National Laboratory", "Idaho Falls, ID", and "March 22, 2016" are listed in a smaller font. In the bottom left corner is the NSUF logo, which consists of a stylized globe with the letters "NSUF" and the text "Nuclear Science User Facilities" below it. In the bottom right corner, the document number "INL/MIS-16-37818" is printed.

U.S. DEPARTMENT OF
ENERGY | Nuclear Energy

Nuclear Science User Facilities

**Ion Beam Investment Options
Workshop**

Brenden Heidrich
R&D Capability Scientist

NSUF Ion Beam Investment Workshop
Idaho National Laboratory
Idaho Falls, ID
March 22, 2016

NSUF
Nuclear Science
User Facilities

INL/MIS-16-37818

Safety Briefing



Safety Briefing



In case of emergency, exit through the south or west doors.

- The assembly area is in the west parking lot towards CAES.
- Please don't try to drive away, it interferes with emergency vehicles.
- No eating or drinking during an emergency situation.
- Restrooms are in the lobby.
- Do not try to enter EIL Bldg. B.
- Smoking areas are outside to the west, 25 ft from the entrances.



2

Nuclear Science User Facilities — Ion Beam Investment Options Workshop – Brenden Heidrich R&D Capability Scientist – NSUF Ion Beam Investment Workshop Idaho National Laboratory Idaho Falls, ID March 22, 2016



Meeting Conduct



- **The meeting is being run by professional INL facilitators:**
 - Jodi Grgich and Jody Henley.
 - They will be running the ThinkTank software in real-time.
 - Presentation time limits are:
 - 20 minutes for the presentation.
 - 10 minutes for questions and comments.
- **There are a few additional people participating over the Bluejeans conferencing system.**
 - Audio only + ThinkTank
 - Audio is fed through the mics in the meeting rooms.
- **Please limit the amount of non-meeting work on laptops and phones during the actual meeting.**

3

Workshop Agenda



Workshop Agenda



■ Tuesday

- 08:00 to 10:30 – Workshop Setup & Organization
- 11:00 to 12:30 – Ion Beam Users (part 1)
- 14:00 to 15:00 – Ion Beam Users (part 2)
- 15:30 to 17:00 – Ion Beam Facilities (part 1)

■ Wednesday

- 08:00 to 12:30 – Ion Beam Facilities (part 3)
- 14:00 to 16:30 – Ion Beam Facilities (part 4)
- 16:30 to 17:00 – Nuclear Industry Requirements

■ Thursday

- 08:00 to 09:15 – Final Criteria Discussion and Weighting
- 09:30 to 10:45 – Ranking Exercise for Investment Options
- 11:00 to 12:30 – Analysis of Results and Discussion
- 12:30 to 13:00 – Establishment of Priority Lists

4

Infrastructure Management Program



Infrastructure Management Program



1. Gather Data on Nuclear Energy R&D Capabilities
2. Estimate Near, Mid and Long-term R&D Directions
3. Use these to perform gap analyses for Nuclear Energy R&D.
4. Assist funding decisions and incorporate the results into the NEID.



5

Gap Analysis Plan



Gap Analysis Plan



1. Capability analysis, based on:

- Nuclear Energy Infrastructure Database
- A study of recent NEUP infrastructure applications
- NEET-NSUF work-scope access applications
- R&D capabilities survey (RFI: DE-SOL-0008318)

Applications/Submissions		
	FY 15	FY 16
RRI	13	13
GSI-1	25	35
GSI-2	12	5
NSUF	31	67
Infra-RFI	26/34	
WS-RFI	124/238	

2. R&D Directions analysis, based on:

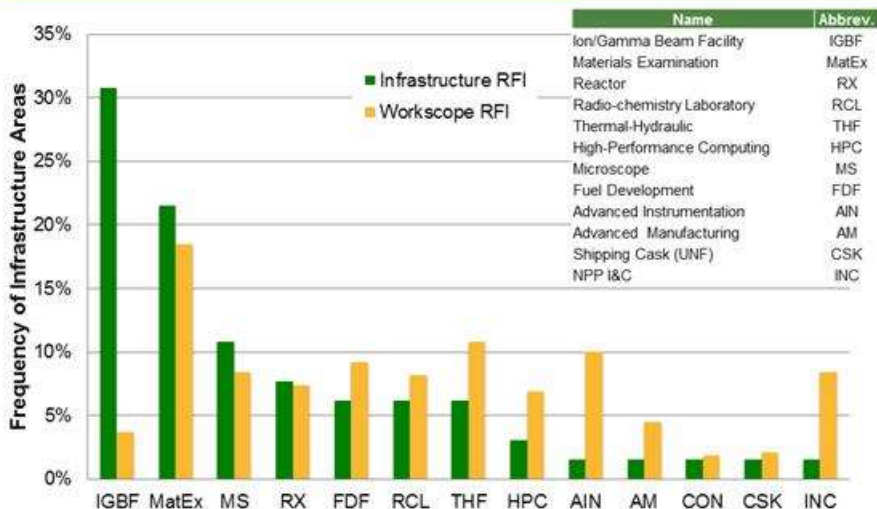
- NE-4 R&D work-scope survey (RFI: DE-SOL-0008246)
- A study of recent NEUP R&D applications
- Programmatic input: NE R&D Roadmap (2010), Facilities for the Future of NE R&D (2009), Required Assets for an Applied R&D Program (2009)

6

Infrastructure Needs Referenced in RFIs



Infrastructure Needs Referenced in RFIs



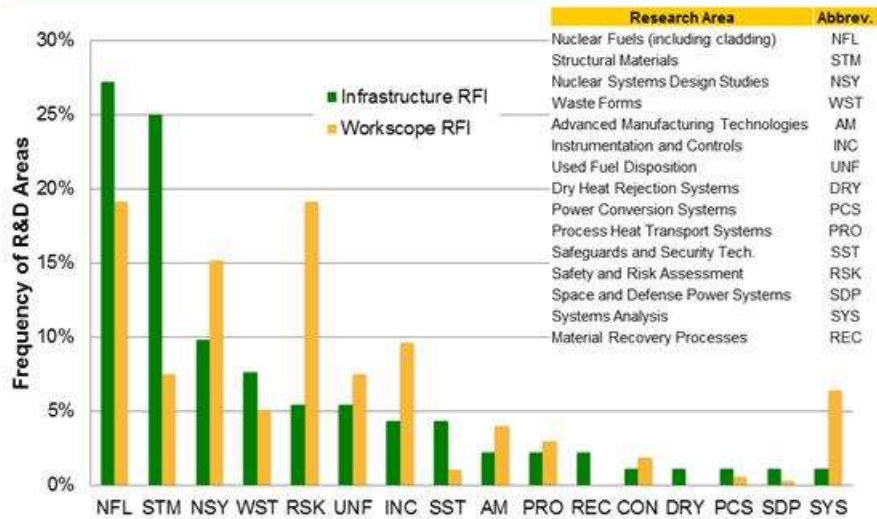
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1. IGBF = Ion beams, x-ray light sources and gamma irradiation facilities.

NE R&D Areas Referenced in RFIs



NE R&D Areas Referenced in RFIs



1. Nuclear energy
instrument database

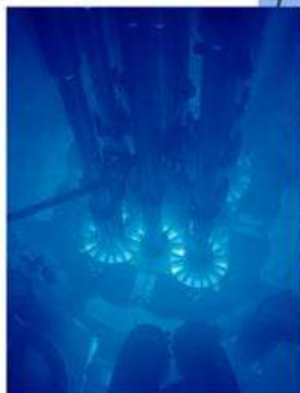
Contact Information



Contact Information



Brenden Heidrich
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Nuclear Energy



10

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11

1. It would be informative to map the allocation of infrastructure resources onto the infrastructure needs by category. That is, are resources being allocated according to needs or is some other criterion being used?

Comments from the Introduction to ThinkTank Exercise

1. To produce heavy damage in a short time.
 - 1.1 Is this equivalent to neutron damage?
 - 1.2 This is connected to neutron damage in some cases and not in others.
2. Fast, low, or no activation, relatively inexpensive.
3. Quantifiable well-defined damage.
4. To emulate neutron irradiation under various conditions.
5. Economical, quick method to implement radiation damage on materials.
 - 5.1 Large accelerators are not very economical
6. Dedicated compact accelerators are affordable.
7. Very important for fundamental research.
8. Ion beams can create damage that is similar to neutrons in certain situations at a much higher damage rate.
9. One important and realistic way to speed up materials screening.
10. Simulation of radiation damage in materials.
11. Offer surrogate irradiation to neutron damage.
12. To perform complex material property measurements unavailable to materials test reactor studies.
13. For creating far-from-equilibrium microstructures.
14. They are the only way to access the high damage rates in both light-water reactor and advanced reactor systems in reasonable times and at reasonable costs.
15. Ion beams allow for separation and control of a wide range of experimental conditions that facilitate the isolation and study of fundamental unit mechanisms that occur by radiation damage.
16. Simulate primary knock-on atoms from neutrons, fission fragments, and energetic particles from alpha and beta decay. Produce damage under controlled conditions on laboratory time scales.
17. To provide an initial look into the microstructure damage before spending the time and money on neutron irradiation.
18. Ion beams serve as surrogate for neutron, provide similar microstructure and effects as neutrons in much shorter time without introducing radioactivity.
19. Train students.
 - 19.1 This is important and often overlooked.
20. Provide data that are easier to use to develop models.
21. Separate effects studies.
 - 21.1 This is key to developing validated computational models.

Workshop Criteria Presentation 1

Brenden Heidrich

Workshop Criteria



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Nuclear Energy

Workshop Criteria



1. It seems that this workshop is focused on opening a complete and open discussion. There seems to be strong concern that it may have the unintended consequence of boxing out future participation (i.e., worries that benefits may flow preferentially to existing capabilities and keeping new capabilities from being built). It seems to me that the purpose of the workshop is to protect existing and consider new opportunities for the entire community. -sm

Original Criteria



Original Criteria



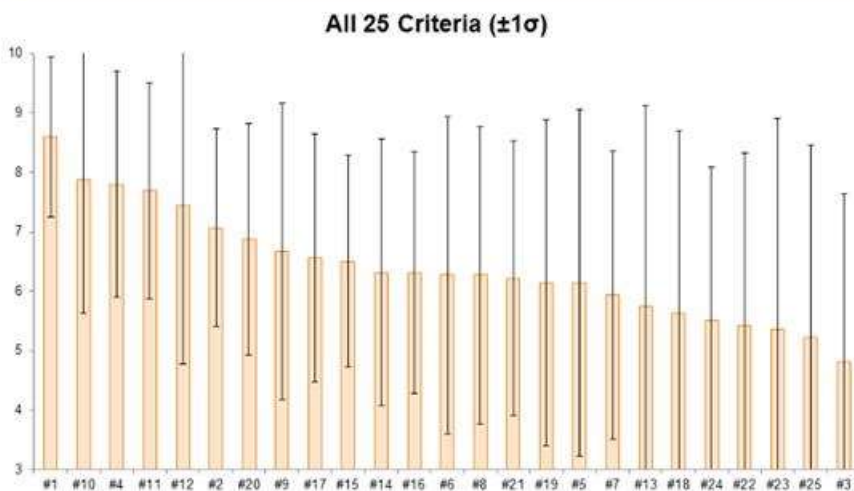
#	Criteria	#	Criteria
1	Scientific merit and potential merit	14	Radiation levels allowed for samples
2	Broad applicability (cross-cutting – i.e. multi-program)	15	Multiple Convergent Beams (dual or triple)
3	International capabilities alternatives	16	Ability to match prototypic conditions
4	DOE-NE programmatic mission need	17	In-situ examination during irradiation
5	Nuclear Energy Industry needs	18	Supporting infrastructure (hot work facilities, sample preparation, etc.)
6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.	19	Does the facility provide New Capabilities?
7	Current/past NE support/investment	20	Radiation effects/damage experience at the host institution
8	Current NE work performed at facility	21	Need to define and have new capability be on path toward greater applicability and relevance.
9	User experiment throughput capability	22	Relative R&D impact of utilizing direct simulants (i.e. Swift Heavy Ion) or indirect simulants (i.e. light ions.)
10	Beam energies (and energy ranges)	23	Applicability of results to development or data goals
11	Ion types and variety	24	Is there support of small specimen test technology
12	Variety of irradiation environments	25	Standards development including temperature sensing
13	Multiple analytical techniques available		

2

Criteria Weights



Criteria Weights



3

Criteria Summary



Criteria Summary



Original	Criteria	Mean	SD	Combined	Combined Criteria	Mean	SD
#1	Scientific merit and potential merit	8.6	1.4	C1	Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.	7.4	2.2
#2	Broad applicability (cross-cutting - i.e. multi-program)	7.1	2.3				
#4	DOE-NE programmatic mission need	7.8	1.8				
#5	Nuclear Energy industry needs	6.1	2.7				
#10	Beam energies (and energy ranges)	7.9	1.8	C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	7.4	2.2
#21	Ion types and variety	7.7	2.2				
#15	Multiple Convergent Beams (dual or triple)	6.5	2.3				
#12	Variety of irradiation environments	7.4	2.0	C3	Ability of the facility to provide a variety of irradiation environments and conditions.	6.9	2.4
#16	Ability to match prototypic conditions	6.5	2.8				
#13	Multiple analytical techniques available	5.8	2.7	C4	Ability of the facility to collect and analyze microstructural characterization data online and in-situ.	6.4	2.6
#17	In-situ examination during irradiation	6.6	2.9				
#20	Radiation effects/damage experience at the host institution	6.9	3.1				
#6	Proportion of time to be allocated to direct NE mission work either through GIN, NSUF or NE programs	6.3	1.7	C5	NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.	6.3	2.0
#7	Current/past NE support/investment	5.9	1.9				
#8	Current NE work performed at facility	6.3	2.5				
#9	User experiment throughput capability	6.7	2.1				
#19	Does the facility provide new Capabilities?	6.1	3.4	C6	Unique capabilities of the facility including new technology.	6.2	2.9
#21	Need to define and have new capability be on path toward greater applicability and relevance.	6.2	2.6				
#14	Radiation levels allowed for samples	6.3	2.5	C7	Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.	5.9	2.7
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	5.6	2.4				
#24	Is there support of small specimen test technology	5.5	3.3				
#23	Applicability of results to development or data goals	5.4	3.5	C8	Ability of the facility to produce high quality data that can support verification and validation of modeling and simulation.	5.3	3.2
#25	Standards development including temperature sensing	5.2	2.8				

4

1. Were you able to group those criteria according to the university, facility, industry needs?
2. How can “the ability to produce high-quality data” end up at the bottom? None of what we’re doing has any value unless the data are of high quality. This is a big issue with this technique.

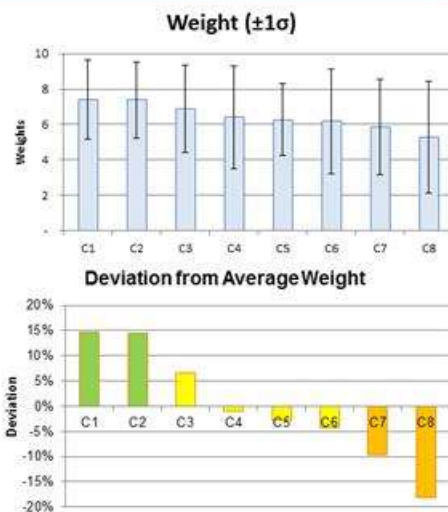
Combined Criteria Weights



Combined Criteria Weights



- The combined criteria have a better distribution of weights, but still not statistically significant.
- Only about 50% of the workshop participants were active in the weighting exercise.
- We will reweight on Thursday morning, prior to ranking the facilities.
- New criteria can be proposed on ThinkTank until 5pm on Wednesday.



5

1. Suggestion: weighting of criteria should be grouped by user type.
2. This may not be the right group to rank each other's facilities.

C1: Scientific Merit



C1: Scientific Merit



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#1	Scientific merit and potential merit	0	0	0	0	1	0	1	4	5	4	8.6	1.4
#2	Broad applicability (cross-cutting—i.e. multi-program)	0	0	2	0	1	3	2	2	3	2	7.1	2.3
#4	DOE-NE programmatic mission need	0	0	0	1	1	1	3	3	3	3	7.8	1.8
#5	Nuclear Energy Industry needs	1	1	0	2	2	2	1	4	0	2	6.1	2.7

Combined Criterion	Mean	Std Dev
Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.	7.4	2.2

1. Group #2, #4, and #5 together into a single criterion. Move #1 elsewhere and maybe revise.
2. #1 should be on its own or eliminated.
3. Interpreted this slide as the ability of the facility to analyze the beam data to simulate accurately neutron data from MTR studies. The combined criterion may need rewriting to address the issue of interpreting ion beam to neutron results.

C2: Variety of Irradiations



C2: Variety of Irradiations



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#10	Beam energies (and energy ranges)	0	0	1	0	1	0	2	6	4	2	7.9	1.8
#11	Ion types and variety	0	1	1	0	0	0	3	4	5	2	7.7	2.2
#15	Multiple Convergent Beams (dual or triple)	1	0	0	1	2	3	2	1	4	0	6.5	2.3

Combined Criteria	Mean	Std Dev
Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	7.4	2.2

1. Do convergent, multiple beams really fit with this criterion?
2. When it comes time to “vote” on how each facility capabilities are able to address individual criteria, I wonder if we should implement the “Russian Judge” model from Olympic sports and throw out the highest and lowest scores recorded (that may be unnecessary, but I thought I’d throw it out for consideration).
3. Beam energy is obviously important. I think the question is more “Cover beam energy spectrum from near surface to deeply penetrating ions.”

C3: Irradiation Environments



C3: Irradiation Environments



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#12	Variety of irradiation environments	0	0	1	1	0	2	4	3	2	3	7.4	2.0
#16	Ability to match prototypic conditions	2	0	1	0	2	2	3	2	3	1	6.3	2.8

Combined Criteria	Mean	Std Dev
Ability of the facility to provide a variety of irradiation environments and conditions.	6.9	2.4

1. C2 and C3 might be combined
2. What is meant as irradiation environments and prototypic conditions (beta)? Could you be more specific?
3. Could move the multiple beams criterion here, as this describes the radiation environment.

8

C4: Microstructural Characterization



C4: Microstructural Characterization



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#13	Multiple analytical techniques available	1	1	2	0	4	2	2	0	3	1	5.8	2.7
#17	In-situ examination during irradiation	2	0	1	0	1	4	1	1	4	2	6.6	2.9
#20	Radiation effects/damage experience at the host institution	1	0	2	1	3	0	0	1	4	4	6.9	3.1

Combined Criteria	Mean	Std Dev
Ability of the facility to collect and analyze microstructural characterization data onsite and in-situ.	6.4	2.9

1. Do you mean in situ analytical techniques or available onsite for a subsequent analysis (beta)?
2. What is meant by damage experience? Do you want to know whether a facility has implantation and/or irradiation capability (beta)?
3. Consider adding material and bulk properties.
4. I would only consider that important only if I expect the facility to do characterization for me. Often characterization is done elsewhere and the facility only provides irradiation service.

9

C5: NE Support and Activities



C5: NE Support and Activities



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.	0	0	0	2	4	3	2	2	2	0	6.3	1.7
#7	Current/past NE support/investment	0	0	2	1	4	2	3	2	0	1	5.9	1.9
#8	Current NE work performed at facility	1	1	0	0	4	1	2	4	1	1	6.3	2.5
#9	User experiment throughput capability	0	1	1	0	1	3	3	3	3	0	6.7	2.1

Combined Criteria	Mean	Std Dev
NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.	6.3	2.0

1. Did DOE-NE weigh in on this one?
2. Isn't this the same as "Support DOE-NE missions" in C1? How is this different?

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C6: Unique Capabilities



C6: Unique Capabilities



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#19	Does the facility provide new capabilities?	3	0	1	0	1	1	1	1	3	2	6.1	3.4
#21	Need to define and have new capability be on path toward greater applicability and relevance.	1	0	2	0	2	2	1	4	1	1	6.2	2.6

Combined Criteria	Mean	Std Dev
Unique capabilities of the facility including new technology.	6.2	2.9

1. What are the gaps within the current existing facilities?
2. Where do we ask the community about the interest/value of being able to test nuclear fuel?
3. New capabilities are only useful if they serve a purpose. So we need to make sure that this new capability will fill a gap.
4. Clarification: "new technology" covers everything.
5. New technology includes irradiation, characterization methods, etc.

11

C7: Radioactive Material Capabilities

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	0	0	0	4	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	0	4	0	0	6	1	3	0	1	5.6	2.4
#24	Is there support of small specimen test technology	4	0	0	0	2	1	2	3	1	1	5.5	3.3

Combined Criteria	Mean	Std Dev
Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.	5.8	2.7

1. C4 and C7 appear very similar. Not sure how they differ from each other?

C8: High-Quality Data to Support Modeling and Simulation Efforts



C8: High-Quality Data to Support Modeling and Simulation Efforts



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8

Combined Criteria	Mean	SD
Ability of the facility to produce high quality data that can support verification and validation of modeling and simulation.	5.3	3.2

1. Combine #1 and #23 to form a new category.
2. I think we need to better define what is meant by high quality and what types of data are most important to the program.
3. I would remove “high-quality data” from definition that can be confused with high-merit data and replace it with “Quality Data” to emphasize the QA aspect of the data rather than the merit.
4. Repeatability and reliability are important.
5. QA plan for data validation.
6. NQA-1?
7. Whether ion irradiation follows standard procedures is very important. The criteria should include repeatability and reliability.
8. I do not think ion irradiation data will ever be used for licensing.
9. For the past many years, the push for ion irradiation and computational materials science has been very active in leading into at least pre-licensing activities. It is not clear that this data will NEVER be used in that way. (But I agree that it’s not likely, and at best it will not comprise the majority of the data generated.)

C8: High-Quality Data to Support Modeling and Simulation Efforts

10. User community-defined standard methods and measurement techniques need to be developed with data validation with neutron irradiation damage before licensing actions could be considered based on ion beam irradiations alone. The roadmap for ion beams needs to be comprehensive if the licensing path is to be pursued.

Criteria Removed from Original List



Criteria Removed from Original List



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#3	International capabilities alternatives	1	0	3	1	6	2	1	0	1	0	4.8	1.9
#22	Relative R&D impact of utilizing direct simulants (i.e. Swift Heavy Ion) or indirect simulants (i.e. light ions.)	3	0	1	0	2	2	2	2	2	0	5.4	2.9

- #3 is the responsibility of DOE-NE to identify
- #22 is included in #11: *Ion Types and Variety*

Weighting Exercise



Weighting Exercise



Weight Criteria

	BALLOT ITEMS	LOW / MED / HIGH
	Weight the developed criteria below.	Double click here to add description / instructions
Designer	1 Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.	Low Medium High
Thinkers	2 Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	Low Medium High
Nav	3 Ability of the facility to provide a variety of irradiation environments and conditions	Low Medium High

Workshop Criteria Presentation 2

Brenden Heidrich

Slide 1



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Workshop Criteria (pt. 2)



Original Criteria



Original Criteria



#	Criteria
1	Scientific merit and potential merit
2	Broad applicability (cross-cutting – i.e. multi-program)
3	International capabilities alternatives
4	DOE-NE programmatic mission need
5	Nuclear Energy Industry needs
6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.
7	Current/past NE support/investment
8	Current NE work performed at facility
9	User experiment throughput capability
10	Beam energies (and energy ranges)
11	Ion types and variety
12	Variety of irradiation environments
13	Multiple analytical techniques available

#	Criteria
14	Radiation levels allowed for samples
15	Multiple Convergent Beams (dual or triple)
16	Ability to match prototypic conditions
17	In-situ examination during irradiation
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)
19	Does the facility provide New Capabilities?
20	Radiation effects/damage experience at the host institution
21	Need to define and have new capability be on path toward greater applicability and relevance
22	Relative R&D impact of utilizing direct simulants (i.e. Swift Heavy Ion) or indirect simulants (i.e. light ions.)
23	Applicability of results to development or data goals
24	Is there support of small specimen test technology
25	Standards development including temperature sensing

1. Scientific knowledge and technical expertise to help with experimental design and execution.

New Criteria



New Criteria



#	Combined Criterion
C1	Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results.
C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)
C3	Ability of the facility to provide a variety of irradiation environments and conditions.
C4	Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in-situ.
C5	DOE-NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.
C6	Unique capabilities of the facility including any new technology.
C7	Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.
C8	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation
C9	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.

3

1. Move #17 to C6.
2. Need to add a new criterion: technical support.
3. One strong need for DOE-NE will be to identify important criteria that are not well met by the existing infrastructure. Understanding gaps may lead to investment.
4. There is a strong push from individual groups to “protect their Wheaties.” There is an appearance that these criteria are becoming a measure of quality on existing facilities with winners and losers emerging from this meeting. How can the discussion be transformed into a discriminating evaluation of facilities to discern what is available at each facility (and globally across the country) without creating the impression of “good/bad” grades?

C1: Scientific Merit



C1: Scientific Merit



Combined Criterion

Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#1	Scientific merit and potential merit	0	0	0	0	1	0	1	4	5	4	8.6	1.4
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5

1. Suggestion: add “and simulate fission fragments.”
2. Change to “simulate nuclear irradiation conditions.”
3. Reword: Viability for the capability to extend our understanding toward accurately simulating neutron radiation results.
4. Rank to capability of the facility/team to answer the question: Can an ion beam simulate a neutron irradiation faster than a reactor can?

4

C2: Variety of Irradiations



C2: Variety of Irradiations



Combined Criteria

Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)

An ideal facility should be able to cover the beam energy spectrum from near surface to deeply penetrating ions.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#10	Beam energies (and energy ranges)	0	0	1	0	1	0	2	6	4	2	7.9	1.8
#11	Ion types and variety	0	1	1	0	0	3	4	5	2		7.7	2.2
#15	Multiple Convergent Beams (dual or triple)	1	0	0	1	2	3	2	1	4	0	6.5	2.3

5

C3: Irradiation Environments



C3: Irradiation Environments



Combined Criteria

Ability of the facility to provide a variety of irradiation environments and conditions.

- Should this include multiple beamlines (instead of C2)?
- Specific conditions:
 - Temperature (heated and chilled)
 - Chemical environments (water, LM, molten salts, etc.)
 - Pressure
 - Other?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#12	Variety of irradiation environments	0	0	1	1	0	2	4	3	2	3	7.4	2.0
#16	Ability to match prototypic conditions	2	0	1	0	2	2	3	2	3	1	6.3	2.8

6

1. Replace irradiation with "target."
2. Well controlled target conditions.

C4: Materials Properties and Microstructural Characterization



C4: Materials Properties and Microstructural Characterization



Combined Criteria

Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in-situ.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#13	Multiple analytical techniques available	1	1	2	0	4	2	2	0	3	1	5.8	2.7
#17	In-situ examination during irradiation	2	0	1	0	1	4	1	1	4	2	6.6	2.9
#20	Radiation effects/damage experience at the host institution	1	0	2	1	3	0	0	1	4	4	6.9	3.1

7

1. Split into two criteria: onsite/in situ separate criteria.
2. There is a tradeoff between what can be done in situ vs. what can be done without that instrument on the target. Doesn't this capability have to be an add-on? All else being equal, does it also have in situ capability and/or micro structural characterization?

C5: NE Support and Activities



C5: NE Support and Activities



Combined Criteria

DOE-NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.	0	0	0	2	4	3	2	2	2	0	6.3	1.7
#7	Current/past NE support/investment	0	0	2	1	4	2	3	2	0	1	5.9	1.9
#8	Current NE work performed at facility	1	1	0	0	4	1	2	4	1	1	6.3	2.5
#9	User experiment throughput capability	0	1	1	0	1	3	3	3	3	0	6.7	2.1

1. Replace volume with productivity (wordsmith).
2. Is this a question of how much work has been done at that site? If it is a projection of how much work will be done, doesn't it have to be based on capability, available time, and cost of the site?

8

C6: Unique Capabilities



C6: Unique Capabilities



Combined Criteria

Unique capabilities of the facility including any new technology.

- Does the capability fill any known gaps in technology?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#19	Does the facility provide new capabilities?	3	0	1	0	1	1	1	1	3	2	6.1	3.4
#21	Need to define and have new capability be on path toward greater applicability and relevance.	1	0	2	0	2	2	2	1	4	1	6.2	2.6

1. Hard to do this unless you take a group of experts (users/modelers) and all the capabilities presented (or the experts from each place) and create a big matrix of available vs. what would be needed. If you don't, you get the problem of ranking wildly different technologies.
2. How far should we look into the past performance—5, 10 years?

9

C7: Radioactive Material Capabilities



C7: Radioactive Material Capabilities



Combined Criteria

Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.

Radioactive structural materials

Fuel materials

- Surrogates
- depU or natU
- LEU or HEU
- Pu and actinides
- Highly-burned fuels

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	0	0	0	4	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	0	4	0	0	6	1	3	0	1	5.6	2.4
#24	Is there support of small specimen test technology	4	0	0	0	2	1	2	3	1	1	5.5	3.3

10

C8: High-Quality Data to Support Modeling and Simulation Efforts



C8: High-Quality Data to Support Modeling and Simulation Efforts



Combined Criteria

Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.

- Facility should have a QA program (NQA-1 or equivalent).
- Community standards should be developed and applied.
- Facility should follow standard procedures for irradiations, sample preparation, etc.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8

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C9: Meeting R&D Needs



C9: Meeting R&D Needs



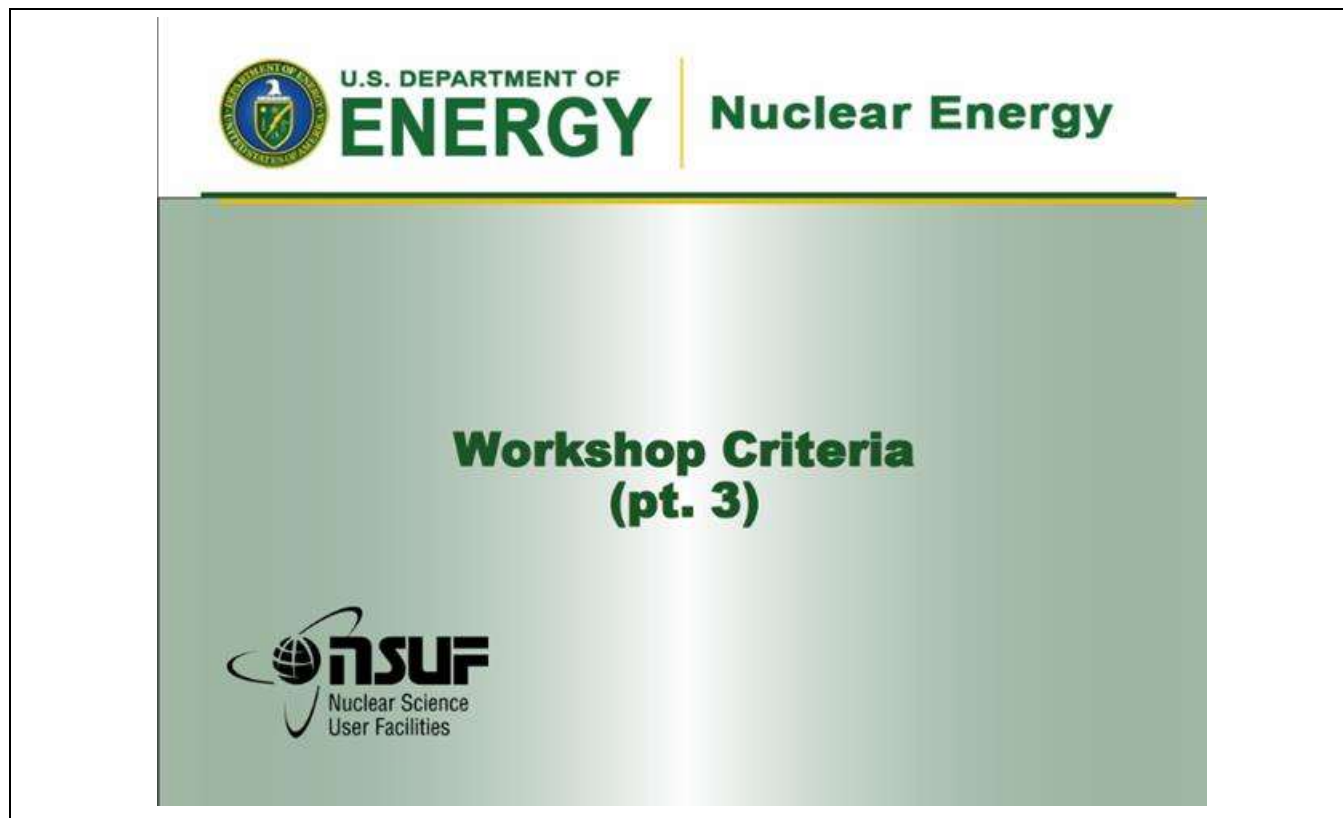
Combined Criterion

Ability of the facility to produce results that meet the needs of the Department of Energy – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#2	Broad applicability (cross-cutting – i.e. multi-program)	0	0	2	0	1	3	2	2	3	2	7.1	2.3
#4	DOE-NE programmatic mission need	0	0	0	1	1	1	3	3	3	3	7.8	1.8
#5	Nuclear Energy Industry needs	1	1	0	2	2	2	1	4	0	2	6.1	2.7

Workshop Criteria Presentation 3

Brenden Heidrich



#	Combined Criteria
C1	Viability for the capability to extend our understanding towards accurately simulating nuclear irradiation conditions (neutrons or fission fragments).
C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)
C3	Ability of the facility to provide a variety of well-controlled target environments and conditions.
C4	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite.
C5	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in-situ.
C6	Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume sample throughput).
C7	Unique capabilities of the facility including any new technology that has the capability to close technological gaps.
C8	Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite.
C9	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.
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.

Viability for the capability to extend our understanding towards accurately simulating nuclear irradiation conditions (neutrons or fission fragments).

Combined Criterion
Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#1	Scientific merit and potential merit	0	0	0	0	1	0	1	4	5	4	8.6	1.4
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5

Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data **onsite**.

Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data **in-situ**.

Combined Criteria												
Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in-situ.												
	Criteria	1	2	3	4	5	6	7	8	9	10	Mean Std Dev
#13	Multiple analytical techniques available	1	1	2	0	4	2	2	0	3	1	5.8 2.7
#17	In-situ examination during irradiation	2	0	1	0	1	4	1	1	4	2	6.6 2.9
#20	Radiation effects/damage experience at the host institution	1	0	2	1	3	0	0	1	4	4	6.9 3.1

9

Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume sample throughput).

Combined Criteria												
DOE-NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.												
	Criteria	1	2	3	4	5	6	7	8	9	10	Mean Std Dev
#6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.	0	0	0	2	4	3	2	2	2	0	6.3 1.7
#7	Current/past NE support/investment	0	0	2	1	4	2	3	2	0	1	5.9 1.9
#8	Current NE work performed at facility	1	1	0	0	4	1	2	4	1	1	6.3 2.5
#9	User experiment throughput capability	0	1	1	0	1	3	3	3	3	0	6.7 2.1

10

**Unique capabilities of the facility including any new technology
that has the capability to close technological gaps.**

Combined Criteria
Unique capabilities of the facility including any new technology.

- Does the capability fill any known gaps in technology?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#19	Does the facility provide new capabilities?	3	0	1	0	1	1	1	1	3	2	6.1	3.4
#21	Need to define and have new capability be on path toward greater applicability and relevance.	1	0	2	0	2	2	1	4	1	1	6.2	2.6

11

**Ability of the facility to handle radioactive materials (structural
materials and/or fuels) in the beams and elsewhere onsite.**

Combined Criteria
Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.

- Radioactive structural materials
- Fuel materials
- Surrogates
 - depU or natU
 - LEU or HEU
 - Pu and actinides
 - Highly-burned fuels

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	0	0	0	4	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	0	4	0	0	6	1	3	0	1	5.6	2.4
#24	Is there support of small specimen test technology	4	0	0	0	2	1	2	3	1	1	5.5	3.3

12

Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.

Combined Criteria

Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.

- Facility should have a QA program (NQA-1 or equivalent).
- Community standards should be developed and applied.
- Facility should follow standard procedures for irradiations, sample preparation, etc.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8

13

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.

Combined Criterion

Ability of the facility to produce results that meet the needs of the Department of Energy – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#2	Broad applicability (cross-cutting – i.e. multi-program)	0	0	2	0	1	3	2	2	3	2	7.1	2.3
#4	DOE-NE programmatic mission need	0	0	0	1	1	1	3	3	3	3	7.8	1.8
#5	Nuclear Energy Industry needs	1	1	0	2	2	2	1	4	0	2	6.1	2.7

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Appendix C

Criteria Weighting Data and Comments

Appendix C

Criteria Weighting Data and Comments

Criteria Weighting – Exercise 1 (pre-workshop exercise)

Votes Cast: 14

No.	Criteria	Avg. Score	+/-	Std Dev	1	2	3	4	5	6	7	8	9	10
1	Scientific merit and potential merit	8.79	26.4%	1.32	0	0	0	0	1	0	0	4	4	5
2	Broad applicability (cross-cutting – i.e., multi program)	7.29	31.7%	2.22	0	0	2	0	1	1	2	3	3	2
3	International capabilities alternatives	4.50	24.9%	1.99	2	0	2	1	6	2	0	0	1	0
4	DOE-NE programmatic mission need	7.93	31.2%	1.87	0	0	0	1	1	1	2	3	2	4
5	Nuclear energy industry needs	6.64	30.2%	2.72	1	1	0	1	2	0	1	5	1	2
6	Proportion of time to be allocated to direct DOE-NE mission work through GAIN, NSUF, or DOE-NE programs	6.36	28.6%	1.72	0	0	0	2	3	3	3	1	1	1
7	Current/past DOE-NE support/investment	5.93	33.5%	2.34	0	0	3	1	4	0	2	2	0	2
8	Current DOE-NE work performed at facility	6.29	29.5%	2.66	1	1	0	0	5	0	1	3	1	2
9	User experiment throughput capability	7.00	27.0%	1.89	0	1	0	0	1	3	3	2	4	0
10	Beam energies (and energy ranges)	7.79	26.0%	1.82	0	0	1	0	1	0	2	5	3	2
11	Ion types and variety	7.79	25.5%	2.04	0	1	0	0	1	0	2	4	4	2
12	Variety of irradiation environments	7.71	28.5%	1.71	0	0	0	1	1	0	4	4	1	3
13	Multiple analytical techniques available	6.21	28.8%	2.60	1	1	0	0	5	0	2	1	3	1
14	Radiation levels allowed for samples	7.14	38.8%	2.33	0	0	0	4	0	2	0	3	2	3
15	Multiple convergent beams (dual or triple)	6.36	27.4%	2.19	1	0	0	1	3	2	2	2	3	0
16	Ability to match prototypic conditions	6.43	29.0%	2.61	2	0	0	0	2	1	4	2	2	1

No.	Criteria	Avg. Score	+/-	Std Dev	1	2	3	4	5	6	7	8	9	10
17	In situ examination during irradiation	7.43	33.5%	3.02	2	0	0	0	1	1	1	1	4	4
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	6.07	29.2%	2.63	1	0	3	0	0	4	1	3	0	2
19	Does the facility provide new capabilities?	6.93	37.4%	3.37	3	0	0	0	1	0	1	3	2	4
20	Radiation effects/damage experience at the host institution	6.86	33.8%	3.04	1	0	1	1	4	0	0	0	2	5
21	Need to define and have new capability be on path toward greater applicability and relevance	6.93	27.4%	2.46	1	0	1	0	1	2	1	5	1	2
22	Relative R&D impact of utilizing direct simulants (i.e. swift heavy ion) or indirect simulants (i.e., light ions)	5.86	35.6%	2.85	3	0	0	0	2	2	2	2	3	0
23	Applicability of results to development or data goals	5.43	40.9%	3.68	5	0	1	0	0	1	0	2	4	1
24	Is there support of small specimen test technology?	5.21	38.1%	3.43	5	0	0	0	2	1	0	3	2	1
25	Standards development including temperature sensing	5.29	37.3%	2.99	4	0	0	1	1	1	2	4	1	0

Community Comments on the Criteria (#2)

Criteria	Comments
8. Current DOE-NE work performed at facility	Although it would be preferable that the person in charge of the facility would be very knowledgeable in the issues we need to tackle upfront, a facility with the capability we need and an advisory board composed of knowledgeable persons would allow any facility to satisfy the requirements of the nuclear-energy research community.
12. Variety of irradiation environments	This question is not clear to me. What variety are we talking about? Ion used? Energy? Something else?
16. Ability to match prototypic conditions	This is a tricky question as, for very high dose, such ability has not been demonstrated yet.

Criteria Weighting – Exercise 3

Votes Cast: 23

No.	Low / Med / High	Avg. Score	+/-	Std. Dev	Low	Medium	High
1	Viability for the capability to extend our understanding toward accurately simulating nuclear irradiation conditions (neutrons or fission fragments)	2.83	37.9%	0.38	0	4	19
2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	2.39	28.5%	0.57	1	12	10
3	Ability of the facility to provide a variety of well-controlled target environments and conditions	2.61	28.5%	0.57	1	7	15
4	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite	1.74	33.7%	0.67	9	11	3
5	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in situ	2.43	28.8%	0.58	1	11	11
6	Current or potential productivity of the facility (e.g., fewer high-impact experiments or high-volume sample throughput)	1.96	34.5%	0.69	6	12	5
7	Unique capabilities of the facility, including any new technology that has the capability to close technological gaps	2.35	34.9%	0.70	3	9	11
8	Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	2.52	50.0%	0.50	0	11	12
9	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation	2.43	35.6%	0.71	3	7	13
10	Ability of the facility to produce results that meet the needs of DOE-NE (including cross-cutting programs) and the nuclear energy industry	2.65	28.0%	0.56	1	6	16

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Combined Criteria	Comments
	idea of what is truly needed to accurately simulate neutron damage in materials from ion beam irradiation. One facility may actually have outstanding potential to produce better results, but AT THIS TIME there is no standard upon which to measure such a claim. Therefore, I graded all facilities the same.
2. Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	<ol style="list-style-type: none"> 1. The variety of ion beam conditions is one of the most important attributes that will enable a facility to meet the needs of the user community and provide DOE-NE with the data it needs to meet its programmatic mission. 2. This speaks to the versatility of the facility, which is an important attribute for an ion beam laboratory, as different conditions may be needed to meet the needs of the experimenter.
3. Ability of the facility to provide a variety of well-controlled target environments and conditions.	<ol style="list-style-type: none"> 1. Because of the large number of damage effects and conditions that nuclear materials experience in a reactor, clearly it is important that ion beam facilities be able to provide a method for emulating these conditions. 2. This is of importance as the effects of radiation on the behavior of materials in nuclear systems are generally not in isolation. Rather, behavior is due to the combination with high temperature, an aggressive environment, stress, etc.
4. Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite	<ol style="list-style-type: none"> 1. How do we rank a facility according to this criterion? 2. Users select the analysis capabilities that are most valuable to their experiments and other than a marginal level of convenience, there is not that much value in the ion beam facility also providing onsite characterization capabilities.
5. Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in situ	<ol style="list-style-type: none"> 1. The ability to generate dynamic data—i.e., watch or record things as they happen—is not represented with sufficient significance in the general weighting criteria.
6. Current or potential productivity of the facility (e.g., fewer high-impact experiments or high-volume sample throughput)	
7. Unique capabilities of the facility, including any new technology that has the capability to close technological gaps	
8. Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	<ol style="list-style-type: none"> 1. NSUF should provide to the facilities a required format for this information. In order to compare facility to facility, the same description must be used, i.e., total activity, dose rate, and ability to handle special nuclear material.
9. Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation	<ol style="list-style-type: none"> 1. This criterion can be simply restated by determining if the facility has a suitable quality assurance program in place. 2. Ion irradiation data will unlikely be accepted for licensing without the support of mechanism models to correlate ion-neutron damage.

Combined Criteria	Comments
	<p>3. Supporting licensing is definitely important, but it is difficult at this stage since we cannot establish ion-neutron correlation yet.</p> <p>4. It is doubtful that ion irradiation alone will lead to licensing. However, only high-quality data will support the efforts toward licensing (which will ultimately be based on neutron data).</p> <p>5. It is nearly impossible to quantitatively differentiate the ability of facilities to meet DOE-NE needs. By definition, all invited participants to the workshop were able (on paper) to meet DOE-NE needs. And after reviewing the Excel summary sheet, no one admitted that they were unable or unwilling to perform DOE-NE work. Consequently, I ranked all facilities the same.</p> <p>6. Understanding this criterion centers on the word “quality.” Researchers view quality as a measure of the precision, accuracy, and impact of their data. Licensing and QA professionals regard “quality” as pertaining to the certification, documentation, and accessibility of the entire data-generation process (i.e., making the data lawyer-friendly). I think the definition of quality for this criterion is the latter. Is that correct?</p>
10. Ability of the facility to produce results that meet the needs of DOE-NE (including cross-cutting programs) and the nuclear energy industry	

Appendix D

Ion Beam Users Presentations

Appendix D

Ion Beam Users Presentations

The first day of the workshop was planned for the ion beam user community (researchers and DOE-NE programs) to present their needs to the community. Their presentations are provided here along with any comments made by workshop participants (in the sidebar).

Presentation: NSUF User's Organization

Peng Xu

Slide 1



NSUF Users Organization

NSUF Executive Committee

Peng Xu, Yong Yang, David Senior, Jessika Rojas, Matthew Swenson, Peter Hosemann, and Ron Ballinger



History and Missions

- Started in 2010
- Defined in UO Charter – updated Oct 2013
 - Provide a formal and clear channel for the exchange of information, advice and best practices between the investigators and the NSUF management
 - Serve as an advocacy group for the experimental activities at the NSUF
 - Facilitate communications among NSUF users, partner facilities, and ATR
 - Charter will be updated this year to enhance user engagement

Membership

- Membership **open to anyone** interested in the ATR NSUF
 - Users
 - Potential users
 - Past users
 - Scientists and engineers engaged in operation and development of ATR NSUF facilities (including partner facilities)
- Why you should become a member
 - Receive funding opportunities announcement and research collaboration opportunities in time
 - Run for executive committee
 - Expand your professional network and strength your career
 - Express your concerns and get problems solved



Leadership

- Executive Committee
 - Seven members, including one student member, nominated and elected by UO membership plus immediate past chair as member ex-officio
 - Four-year terms (one-year term for student member)
 - Chair and Secretary/Chair-Elect selected by Executive Committee members
 - Proposed changes in the new charter: adding two more regular members and one more student member
 - Proposed Extension of student membership from one-year to two-year

Executive Committee

- Current Members
 - Chair – **Peng Xu, Westinghouse** (since 2013)
 - Secretary/Chair-Elect – **Yong Yang, University of Florida** (since 2013)
 - **Ron Ballinger, MIT** (since 2014)
 - **Jessika Rojas, VCU** (since 2015)
 - **Peter Hosemann, UCB** (since 2015)
 - Student Member - **Matthew Swenson, BSU** (since 2015)
 - Immediate Past Chair – **David Senior, PNNL** (since 2012)
- UO Executive Committee 2016 Spring Election
 - Two regular members and one student member

2013 Executive Committee	
CHAIR Peng Xu Pacific Northwest National Laboratory pengxu@pnnl.gov	SECRETARY Yong Yang Westinghouse Electric Company yangyong@westinghouse.com (803) 647-5119
STUDENT MEMBER Dan Laffner Idaho State University dlaffner@isu.edu	MEMBER Jim Tullock (2nd Term) University of Florida jimtullock@ufl.edu (352) 392-1427
MEMBER Yong Yang University of Florida yongyang@ufl.edu	MEMBER Mitra Tazari Carnegie University mihand@uconn-stress.org
2012 Executive Committee	
CHAIR Jill Terry Genes Institute of Technology jterry@giat.edu (531) 252-6708	SECRETARY David Senior Pacific Northwest National Laboratory dsenior@pnnl.gov
STUDENT MEMBER Walter Shells University of California, Santa Barbara wshells@ucsb.edu	MEMBER Dennis Baller University of Nevada, Las Vegas dennis@unlv.edu (702) 656-1452
MEMBER K. L. Harty North Carolina State University kathyharty@ncsu.edu (919) 515-3607	MEMBER Jim Tullock University of Florida jimtullock@ufl.edu (352) 392-1427
Past Members	
David Senior PNNL dsenior@pnnl.gov (509) 962-1745	

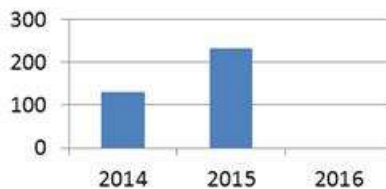
Executive Committee Led Activities

- Provided input/feedback to ATR NSUF management on a variety of topics (mostly driven by comments received from users)
 - Proposal process
 - User engagement
 - Sample library policy
 - Utilization of partner facilities
 - User week meeting
 - Experiment planning, scheduling, and executing
- Created three committees to address specific topics
 - User Week
 - Education and Outreach
 - Capabilities and Infrastructure
 - Membership in committees is open to any UO member and broad participation is encouraged
- Participated in ATR NSUF booth at various national meetings, i.e. ANS Meeting in 2013, TMS meeting in 2014 and 2015

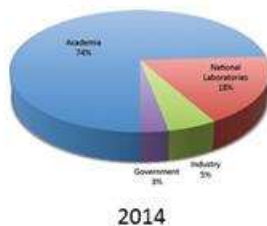
Member Demographics and Status

- NSUF is still young and in his early stage
- Significant growth in 2015
- More members from national labs and industry participated in 2015
- Another strong growth is projected in 2016

Member Growth

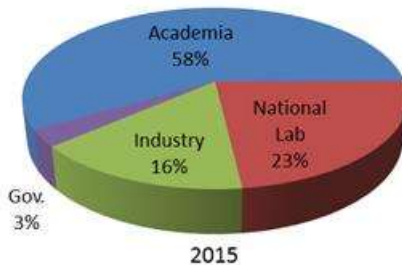


Member Affiliation



2014

Member Affiliation



2015

Meetings

- Annual User Week in June at INL
 - The most important event and communication avenue for UO
- Sponsored technical meetings at national conferences
 - 2016 TMS led by Peter and Jim
 - 2016 ANS led by Yong and Keith
- Executive Committee meetings
 - User Week
 - Teleconference as needed, but at least once per quarter
 - National meetings such as TMS and winter ANS
 - Partner facility site meeting is suggested



User Week Committee

- Matthew Swenson and Dave Senior, Chair
- Provides input on timing, format, content, location and other aspects of User Week
 - Matthew has been leading the effort and put together a draft of User Week Meeting Agenda for 2016 with comments from the rest of committee members
- User Week is the annual meeting of the UO – strong participation and input from members during planning is critical
 - A survey was sent out to all the users to solicit user feedbacks on the user week meeting experience and suggestions on improvement
- Vision for User Week
 - User Week should be “go-to” meeting for users to share experiences and ideas on ATR NSUF projects
 - Helps build a vibrant and interactive user base
 - Fosters communication between users and ATR NSUF staff
 - Transitioning from mostly educational format to mostly technical exchange (will retain some educational component to benefit new users)
 - User week meeting has always been hosted at INL
 - Live conferencing is a great approach to reach out to partner facilities

Education and Outreach Committee

- Jessica Rojas, Chair
- Focuses on growing the UO membership and improving communication with stakeholders
 - Important component to the vision of growing NSUF beyond irradiation testing to embrace the wider nuclear materials and fuels community
 - Tough goal to achieve since NSUF needs to support NE missions
 - Strong university representation in UO, reflecting early focus of ATR NSUF on university-led research
 - Opportunities now exist to grow industry and national laboratory participation in the ATR NSUF and UO
 - **Good accomplishment in 2015**
- Current activities
 - Developing NSUF brochure
 - Developing NSUF website



NSUF Website

<https://atrnsl.inl.gov/default.aspx?Page=Users Organization&id=230>

- NSUF website is available from NSUF homepage
- Currently working on information update to be ready for the NSUF website upgrade



Suggestions on Membership and Engagement Improvement

Suggestions on Membership and Engagement Improvement

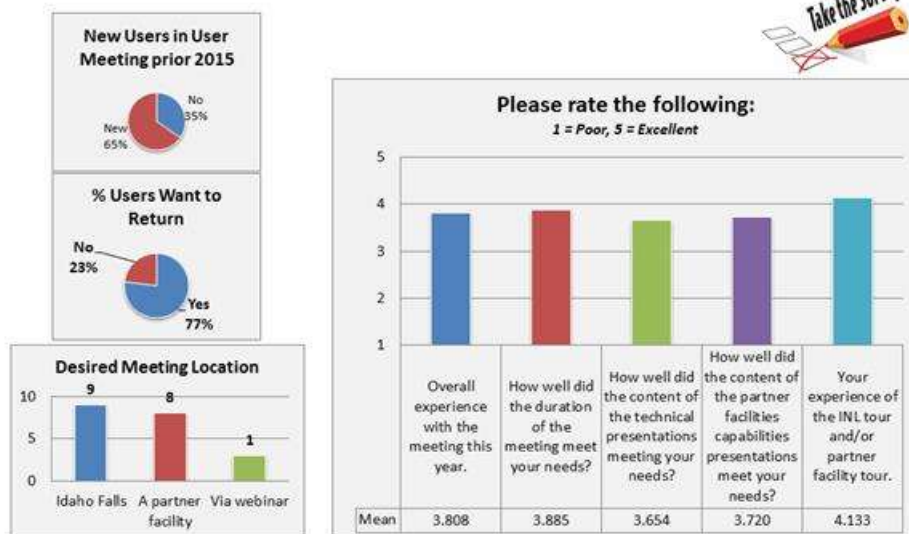
- Need member growth
 - Pls of funded experiments automatically become UO members
 - Attendees at User Week or other ATR NSUF workshops automatically become UO members?
 - Ask people to sign up during professional meetings
 - Ask current users to provide referrals
 - Diversification
- Improve member engagement
 - Suggest to increase rapid turnaround awards
 - Suggest to boost partner facility usage
 - Suggest to sponsor or host technical sessions at professional meetings
 - 2016 TMS Meeting: Accelerated Materials Evaluation for Nuclear Application Utilizing Test Reactors, Ion Beam Facilities and Integrated Modeling — Ion Beam Irradiation and In-situ TEM, organized by James Cole and Peter Hosemann
 - 2016 ANS Meeting: Nuclear Fuels and Structural Materials (NFSM-2016) organized by Yong Yang, and etc.

Capabilities and Infrastructure Committee

Capabilities and Infrastructure Committee

- Yong Yang, Chair
- Work closely with Brenden Heidrich to support the NEID development
 - Participated in database survey and trial runs
 - Collected and Provided comments to the NEID
 - Participated in NEID Database Review Panel
- Will continue to support future efforts in NEID
 - Ion Beam Workshop

2015 NSUF User Week Meeting Survey



User Feedbacks on Ion Beam Facilities at NSUF

User Feedbacks on Ion Beam Facilities at NSUF

- Academia and national lab users
 - Important **education and training function** for students
 - Productive and versatile tools for fundamental studies
- Industry users
 - Tools can be used to expedite product development if used properly
 - Need to show that what we learned from ion irradiation can be used to solve real problems
- Scientific merit

1. Interesting point: DOE has a specific role in Nuclear Engineering education that was part of the congressional act that separated the DOE and NRC from the AEC/ERDA history.
2. While it is commendable that DOE-NE focuses on program relevant applied research, the university faculty and facilities have education and training as primary tasks.
3. But these are not necessarily exclusive objectives. DOE-NE programs can provide good opportunities for training and teaching AND still produce high merit data.

Users Input on Ion Beam Facilities

	Ranking
Beam energies (and energy ranges)	High
Ion (particle) types and variety	High
Variety of irradiation environments (vacuum, water, gas mixture, etc.)	Low to Medium
Multiple analytical techniques available	Low
Radiation levels allowed for samples	Medium to High
Types of sample materials allowed (e.g. alpha emitters/ fresh fuels/ irradiated fuels/TRU)	High
Ability to match prototypic conditions (LWR, advanced reactors, etc.) – High (temperature)	High
In-situ examination during irradiation (TEM, photon source or other) - Medium	Medium
Supporting infrastructure (hot work facilities, sample preparation, etc.) - Medium	Medium
Multiple beam capability	Medium to High
Damage profile modeling capability - High	Medium to High

Summary

Summary

- NSUO is on the right path to become a very vibrant and interactive user group
- NSUO is a fast growing user group
 - NSUO gained tremendous support from NSUF management
 - Significant improvement on funding
 - Focus of the executive committee
 - There is still significant room to grow the user base and engagement
- If you are not a member of NSUO, I will sign you up!

William Windes

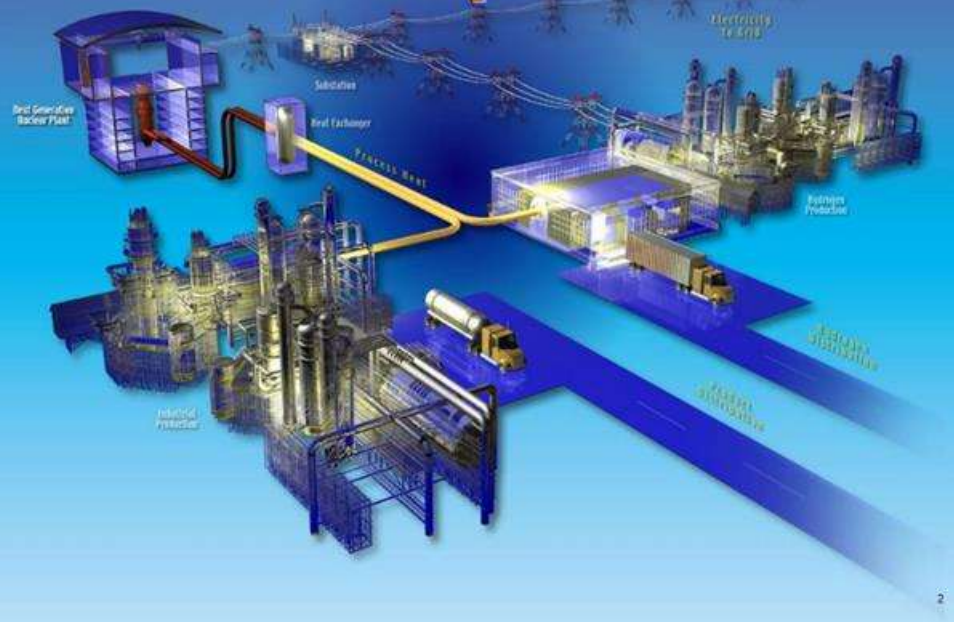


VHTR Technology Development Office

www.int.gov



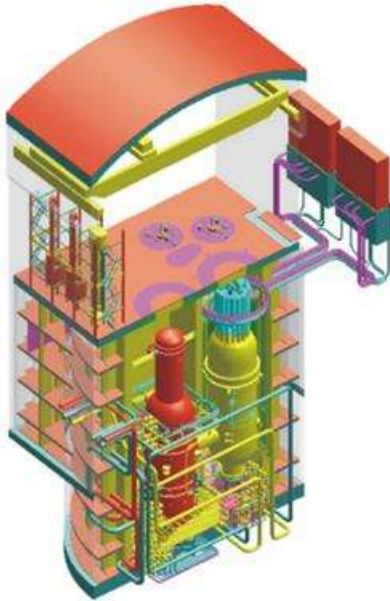
NGNP Concept



What is the NGNP?



What is the NGNP?



- **Next Generation Nuclear Plant**
 - Generation IV concepts – advanced concepts/materials
 - Very high temperature reactor (VHTR) ~1000°C outlet
 - *High temperature reactor (HTR) ~ 750°C*
 - Gas-cooled (He) , graphite moderated
 - Hydrogen generation
 - Process heat
- **Ceramic core**
 - Graphite core – structure and nuclear
 - Ceramic composites – structural
 - Uranium oxide or oxy-carbide fuel
- **Composite materials**
 - Control rods, control rod tubes
 - Hot duct, seismic restraint
 - Insulation and fabrics

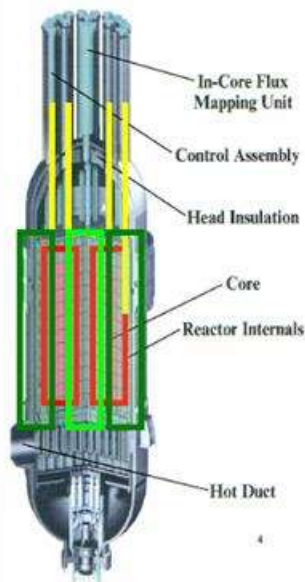
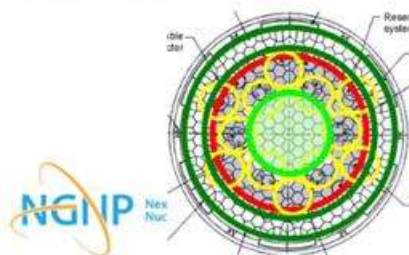
1. Next Generation Nuclear Plant

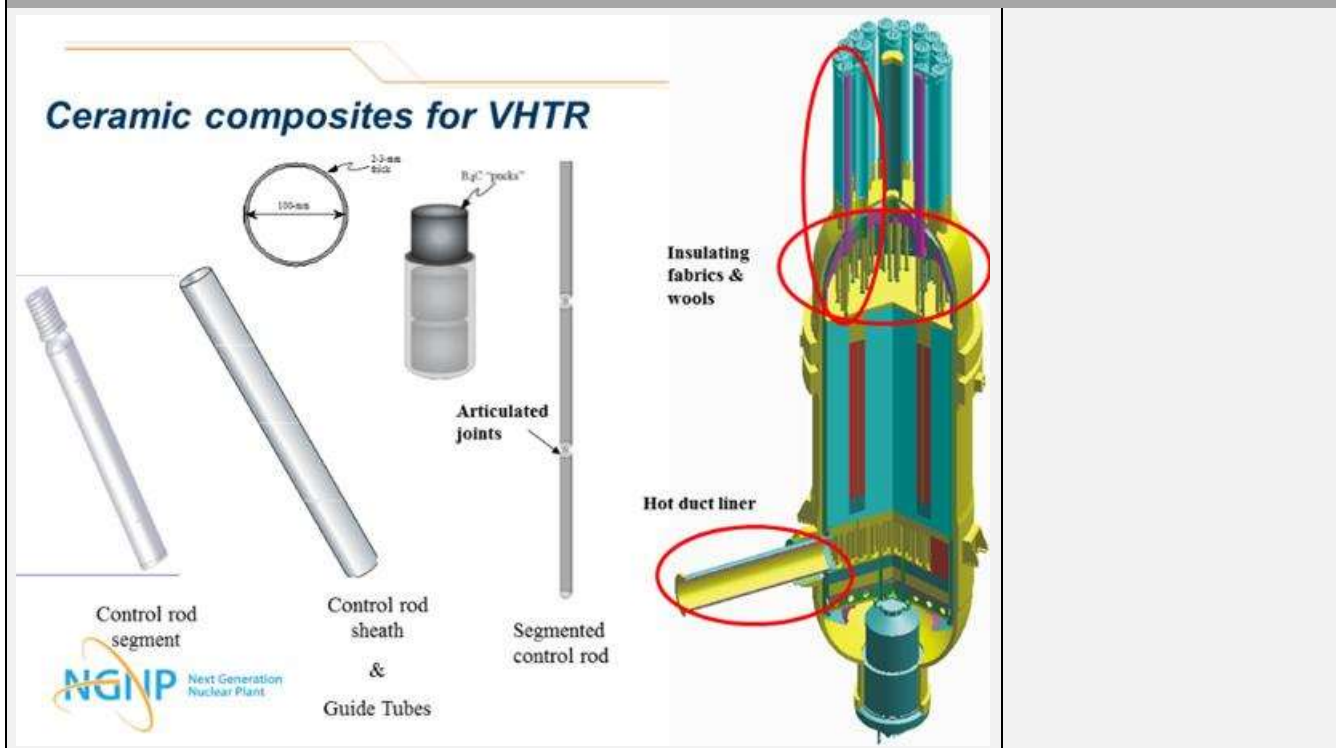
NGNP Core Components



NGNP core components

Component	Normal Operation	Off-Normal	dpa
Graphite fuel block	~1200 °C	~1400 °C	~ 0.8/yr
Control rods	~1000 °C	~1200 °C	~ 0.5/yr
Reflector blocks – inner	~900 °C	~1200 °C	~ 0.5/yr
Reflector blocks – outer	~800 °C	~1100 °C	~ 0.2/yr





Research objectives

- **Reactor parameters**
 - High temperature applications (>1100°C)
 - Graphite = Moderate irradiation levels (8-10 dpa)
 - Composites = High irradiation levels (30 dpa)
 - Low stresses, non-pressurized, low fatigue
- **Defining the safe working envelope**
 - All activities work toward defining the safe limits of using graphite and composites in normal and off-normal events
- **Envelope/information will be codified**
 - All data from program to be used in ASME code case development for graphite and composites in nuclear applications
- **Research objectives**
 - Irradiation material properties & predicting material behavior
 - Primary degradation mechanisms: irradiation dimensional change, creep, strength/stability, & thermal properties

INL Idaho National Laboratory

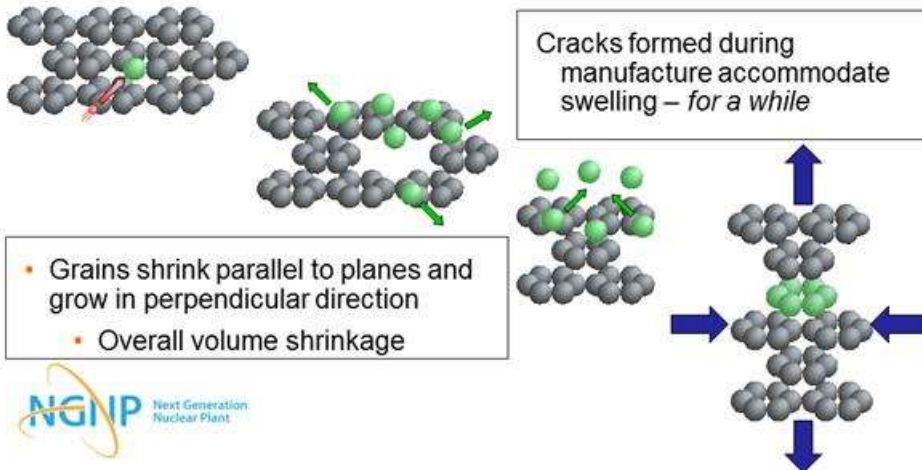
NGNP Next Generation Nuclear Plant

6

Irradiation in Graphite

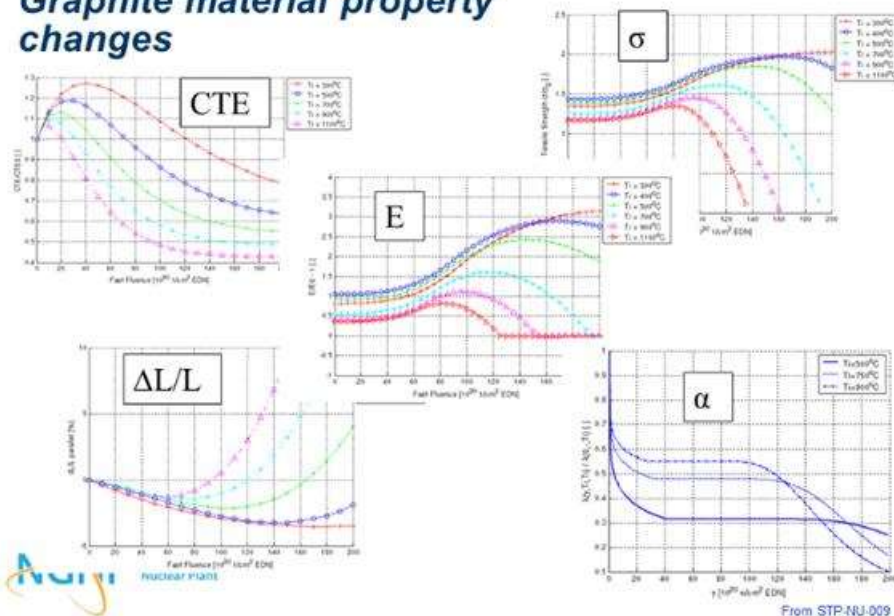
Irradiation in Graphite

- Irradiation performance is dependent on material and conditions
 - Precursor materials, forming process, and irradiation temperature
- Graphite behavior is determined by the crystal structure



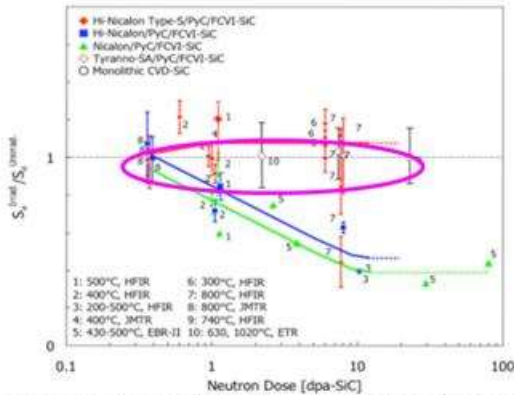
Graphite Material Property Changes

Graphite material property changes



Irradiation performance of C_f/C & SiC_f/SiC

- C_f/C composites react similar to graphite – anisotropic behavior
 - Strength only good to ~1-2 dpa before significant loss of strength
 - Microstructure is compromised by irradiation dimensional change



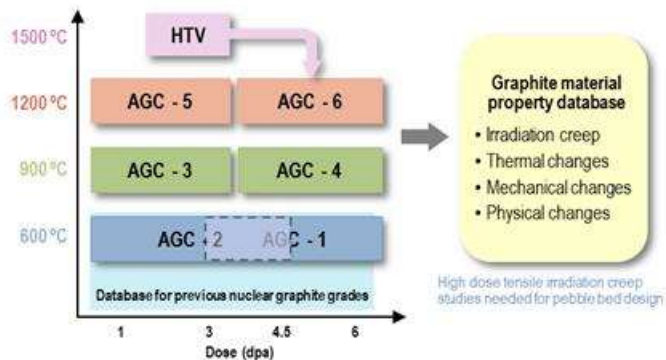
- By contrast silicon carbide (SiC) does not have anisotropic crystal structure
 - Growth is more isotropic and appears to plateau after ~ 1 dpa
 - Resulting in a stable microstructure (at least to 8 dpa levels)

1,2: L.L. Sneed, et al., J. Nucl. Mater., 283-287 (2000) 551-555. 8: T. Nozawa, et al., J. Nucl. Mater., (2002) to be published.
 3,4: T. Hinoki, et al., Mater. Trans., 39, 43 (4) (2002) to be published. 9: R.J. Price, et al., J. Nucl. Mater., 108-109 (1982) 732-738.
 5: R.H. Jones, et al., 1st IEA-SiC/SiC (1996). 10: R.J. Price, J. Nucl. Mater., 33 (1969) 17-22.
 6,7: T. Hinoki, et al., J. Nucl. Mater., (2002) to be published.

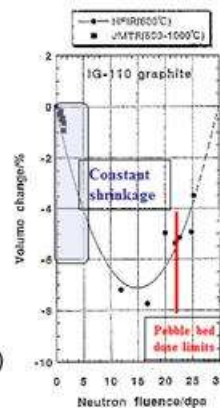
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Advanced Graphite Creep Experiment

Advanced Graphite Creep Experiment



- Compression experiment (below 7 dpa dose limit)
 - Creep rate as a function of temperature (600, 900, 1200°C)
 - Must not achieve turnaround – otherwise not constant
- Investigating effects of forming on performance
 - Grain size, coke sources, forming method
 - Four types of graphite – each from a major graphite supplier



10

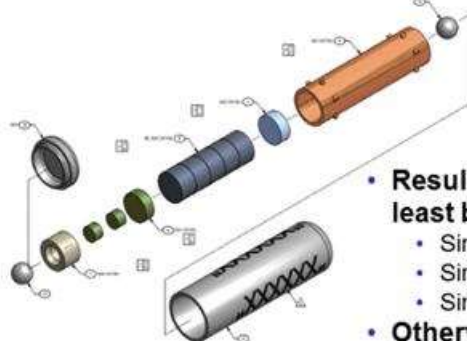
Primary interests in Ion Beam Material Testing

- **Provide data/results comparable to neutron irradiation (C1 & C8)**
 - Must be comparable to neutron irradiation program (AGC)
 - Must be compatible with previous irradiation programs
 - **Ability of facility to provide a variety of testing conditions (C3 & C6)**
 - Testing over temperature range
 - Testing with mechanical load
 - **In-situ testing (C4)**
 - Underlying irradiation damage mechanisms for material property changes
 - Microstructure characterization and evolution
 - **NE support (C1 & C5)**
 - Require high quality scientific merit data & high volume
- but ...*
- Quality Assurance (QA) program measures
 - If data is to be codified → Need QA data

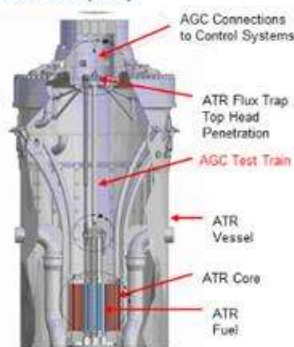
11

Ion beam data versus neutron data (C1)

- **Several ongoing neutron studies**
 - Advanced Graphite Creep (AGC)
 - SAM (1, -2, & -3)
- **International experiments**
 - Japanese grades at HFIR
 - Gilsocarbon creep studies (U.K.)



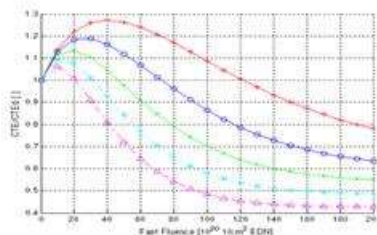
SAM-1 Assembly



- **Results from ion beam studies must at least be comparable**
 - Similar material property changes to dose
 - Similar changes at high irr. temp
 - Similar specimen size (or equivalent)
- **Otherwise can't use the data**
 - Want it for enhanced test results

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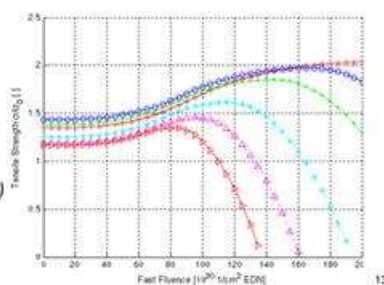
Performing material testing at temperature and/or with mechanical loads (C3 & C6)



- MTRs have a tough time doing more than irradiating and heating samples

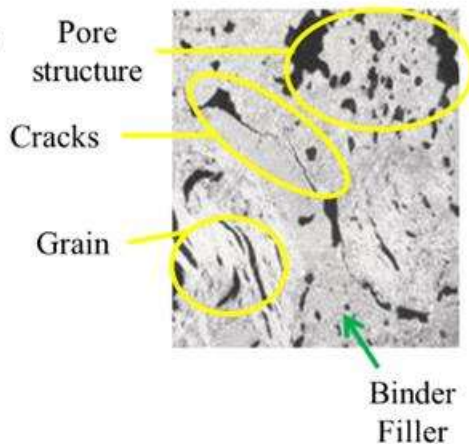
- Material property testing performed **after** irradiation
 - ... after cooling for some time
 - ... at room temperature
 - ... without mechanical loading (*P, L, etc*)

- Ion Beams need to fill in for this deficit of MTRs
- Material property testing during irradiation
 - Material testing at temperature & load
 - Microstructural characterization (*CT, XRD, etc.*)
 - Other interrogation techniques
- Attempt more realistic conditions



Underlying irradiation damage mechanisms (C4)

- Graphite microstructure is complex
 - Controlling feature is **pore structure** (cracks & pores)
 - Pore length scale range (nm to mm)
 - Changes in pore structure lead to material response
 - nm Pore closure = dimensional change
 - Turnaround
 - Nearly all properties reverse after turnaround
- Different material response
 - *Anisotropic* material response at crystallite length scale
 - *Isotropic* material response at macroscopic length scale

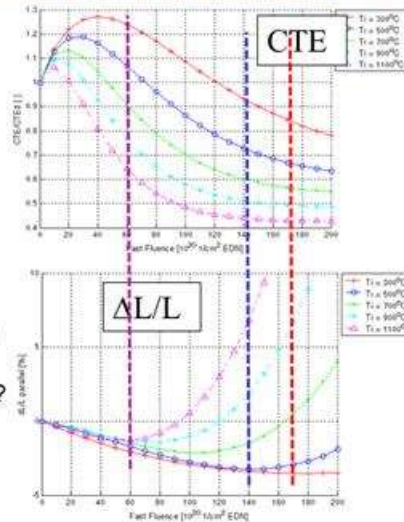


Underlying Irradiation Damage Mechanisms – 2



Underlying irradiation damage mechanisms - 2

- Irradiation increases CTE
 - nm size pores and cracks are closed due to c-direction swelling
 - Higher density = higher CTE
- CTE is reduced after turnaround due to new pore and crack formation
 - Less dense material = lower CTE



Problem is, this doesn't happen!

- CTE changes well before turnaround
- Why? No one really knows
 - Pore re-orientation? Crack formation?
- Need in-situ techniques
 - Microstructure changes.
 - Crystallite changes
- Difficult to do in MTR
 - Need multiple samples, not one sample
 - Needs lots of handling

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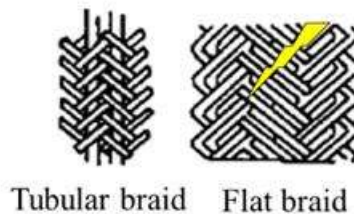
Underlying Irradiation Damage Mechanisms – 3



Underlying irradiation damage mechanisms - 3



- C_f/C composites – low or no irradiation
 - Similar anisotropic irradiation behavior
 - Only high temp and tensile applications
- SiC_f/SiC Composite testing
 - While SiC irradiation response is fairly well understood the composite (fibers + matrix) strength response is not.
- Fracture under irradiation and temperature is desirable

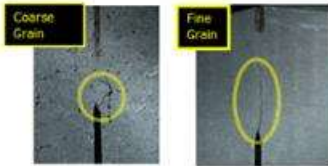
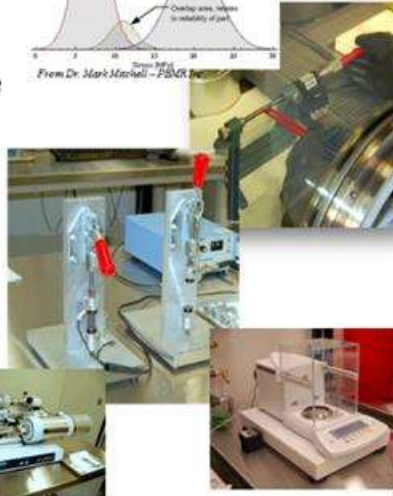
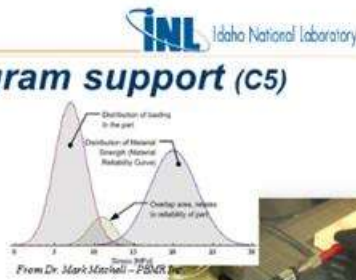


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High Quality Data for NE Program Support (C5)

High quality data for NE program support (c5)

- All measurements performed to ASTM Standards
 - Modification of current Standards.
 - Development of new Standards
 - New irr. testing guidelines
- Development of ASME Code for Graphite Core Components
 - Use of a probabilistic design approach
 - Accounts for environmental effects
 - Requires qualified irradiation data
- NE programs require QA
 - ASME Code requires qualified data (irradiated & unirradiated)
 - Non-qualified data are **scoping studies**



1. Even without the QA level data (to possibly replace the neutron irradiations), can the ion beam data supplement and possibly reduce the amount of MTR in core testing?
2. Show how results were obtained and how they are comparable.

NE Quality Irradiation Data (C5)

NE quality irradiation data (c5)

- Establish changes between pre and post irradiation material properties.
 - Determining thermal, mechanical, and physical material property changes in low activated nuclear materials.
 - Developed in support of design, construction and licensing data for high temperature gas reactor components.

Glovebox & benchtop testing



Experience

- Lab initiated 8+ years ago (2000+ sq.ft.)
- ~ 2700 specimens characterized to NQA-1 standards
- Customized irradiated sample shipping drum
- Materials regularly handled:
 - Nuclear graphite
 - Ceramic & carbon composites
 - Ceramics
- New capabilities
 - Capsule disassembly
 - Specimen prep. (cut saw, TEM disk cutter, etc.)

Programs supported

- ART (VHTR Program)
 - AGC, composites, High temp. Metal, AGR fuel matrix, etc.
 - Thermal, physical, mech, chemical (oxid)
- SAM (INL/NSUF Rabbit)
 - SAM-1, -2, & -3
 - Material prep, thermal and physical
- RERTR
 - Welding & material prep.
- TREAT
 - Thermal, oxidation, physical

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AGC Specimen Characterization INL's Carbon Characterization Lab (CCL)

- 2000+ sqft. with 21 analytical measurement stations.
- Complete material characterization
 - Bulk Density
 - Electrical Resistivity
 - Elastic Modulus
 - Strength
 - Coef. of Thermal Exp.
 - Thermal Diffusivity
 - Specific heat
 - DTA/TGA.
- Automated data acquisition and specimen tracking (no clip boards)
- Materials
 - Low level radioactive (<100 mR)
 - Graphite
 - Carbon composites
 - Ceramics
 - Pre-irr. or low dose metals
- All measurements performed to ASTM standards.
 - STP-Graphite testing for nuclear applications: Significance of specimen geometry and population.
- ASME NQA-1 compliant
 - Documented training
 - Periodic system validation
 - National and International traceable calibration
 - Identification and Control of Materials.



19

Remaining Criteria



Remaining Criteria

- Variety of ion irradiations
 - While this is important to impose similar irr. damage, more important to achieve similar results from neutron dose
- Ability to handle radioactive materials
 - Most VHTR core materials are low activation and not much trouble
 - However, this is an important consideration for general testing
 - How are samples shipped?
 - Shipping container? DOT approved?
 - Specimen handling and ALARA considerations
 - In-situ testing and ALARA considerations
- Modeling and simulation verification/validation
 - VHTR (NGNP) behavior model V&V will come from neutron irradiation
 - However, ion beam studies can dramatically assist in data interpretation and model development
 - Complex experiments that compliment MTR studies would be important
 - Incremental data that "fills in the gaps" between difficult to achieve MTR irradiations will be helpful in developing behavior models.

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In Summary

- **Data must be comparable to neutron studies – Key criteria**
 - If we can't compare ion beam studies to neutron results, data is of little use
- **Complex irradiation and novel testing capabilities – Highly desirable**
 - Complex experiments that compliment the MTR data
 - In-situ measurements at temperature and/or load
 - In-situ chemical attack (corrosion)
 - Internal interrogation (X-ray CT, XRD, others)
 - Other unique conditions or interrogation techniques
- **Support NE Material programs (QA program) – Highly desirable**
 - Need high quality data with scientific merit
 - Can support existing data and assist in understanding material behavior (models)
 - QA program is necessary (Not just good data, but also a high quality program)
 - Codified data : Critical criteria
 - Scoping studies : Highly desirable

21

1. This summary really gets to the heart of what nuclear technology needs. If the ion beam community cannot get to this point, then we will not be able to use this technology in nuclear material irradiation and data use.
2. This seems to reflect an interest in having MTR-like conditions that accelerate results to a couple of days. That reflects an immaturity of the models that represent the two modalities. The QA issue is a function of not having a standard controlled setup for each experiment—which is really not an experiment but a parameterization—getting the parameters for the model at each point in n space.



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Presentation: LWRs Program Data Needs

Sebastien Teyssyre

Slide 1

Light water Reactor Sustainability Program Data Needs



S. Teyssyre

Light Water Reactor Sustainability R&D Program

NSUF Ion Beam Investment Option
Workshop
Idaho Falls
March 22-24 2016



DOE-NE Light Water Reactor Sustainability Program

DOE-NE Light Water Reactor Sustainability Program

Vision

- *Enable existing nuclear power plants to safely provide clean and affordable electricity beyond current license periods (beyond 60 years)*

The program is supporting subsequent license extension decisions

Program Goals

- Develop fundamental scientific basis to understand, predict, and measure changes in materials as they age in reactor environments
- Apply this knowledge to develop methods and technologies that support safe and economical long-term operation of existing plants
- Research new technologies that enhance plant performance, economics, and safety

Scope

- Materials Aging and Degradation (Metals, concrete, cables, mitigation technology)
- Advanced Instrumentation and Controls
- Risk-Informed Safety Margin Characterization
- Reactor Safety Technology



Material Aging And Degradation Pathway Includes Diverse Materials Research Effort Teams

Material Aging and Degradation pathway includes diverse materials research effort teams



1. There are a lot more research facilities than these working on materials aging and degradation in LWR.
2. This map needs an update.

DOE-LWRS Material Aging Areas of Research

DOE-LWRS Material Aging Areas of Research

- High fluence effects on RPV steels
- Aging of cast austenitic stainless steel
- Environmentally assisted fatigue
- SCC initiation in Ni-base alloys
- Mechanisms of IASCC
- High fluence effects on IASCC of stainless steels
- Modeling Tasks:
 - High fluence irradiation-induced phase transformations
 - Radiation induced segregation
 - High fluence swelling
- Post-service examination of materials
 - Zion RPV
 - R.E. Ginna baffle former bolts
- Advanced replacement alloys
- Weld repair techniques

Measurement
Mechanisms
Modeling
Monitoring
Mitigation

LWRS program overview

Risk-Informed Safety Margin Characterization. Research and development to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision-making for nuclear power plants. The R&D products will be used to produce state-of-the-art nuclear power plant safety analysis information that yields new insights on actual plant safety margins and permits cost effective management of these margins during periods of extended operation.

Advanced Instrumentation, Information, and Control Systems Technologies.

The R&D products will be used to design and deploy new instrumentation, information, and control technologies and systems in existing nuclear power plants that provide an enhanced understanding of plant operating conditions, available margins, improved response strategies, and capabilities for operational events.

Reactor Safety Technologies. Research and development to improve understanding of beyond design basis events and reduce uncertainty in severe accident progression, phenomenology, and outcomes using existing analytical codes and information gleaned from severe accidents, in particular the Fukushima Daiichi events. This information will be used to aid in developing mitigating strategies and improving severe accident management guidelines for the current light water reactor fleet.



5

Material Aging Pathway

- **High fluence effects of IASCC of stainless steels**

How will high doses affect the resistance of a component to IASCC?

- Main issue: lack of materials.
- How can we generate the materials needed for the study?
 - Is it relevant to "re-irradiate" a material?
 - Can we use an alternative to neutron irradiation?
 - Do we have the tools to focus an irradiation campaign?

- **Advanced Replacement Materials**

(collaboration with EPRI's Advanced Radiation Resistant Materials program)

- Development of materials with improved radiation resistance
- Increase knowledge on less used alloys in nuclear environment



6

1. If the damage caused by ions and neutrons is different, will re-irradiated materials tell us anything?

Irradiation Needs

Irradiation Needs

- **Generation of highly irradiated materials (>50 dpa)**
 - If ion beam is to be used, validation of ions for high fluence is needed
 - Flux rate effect is a major concern that must be addressed
 - Understanding the developing microstructure which will lead to developing modeling/simulation codes that will allow researchers to utilize less costly alternatives to neutron irradiation experiment campaigns and/or better plan irradiation campaigns.
- **Down selection of radiation damage tolerance** for the Advanced Replacement Materials.

Needs:

- Variety of beam (protons, Fe, Ni)
- Ability to offer multiple beams
- Ability to control irradiation condition (temperature control, energy)
- Ability to handle radioactive material would be a plus



Ion Beam for Characterization

Ion beam for characterization

- **Characterization of cracking** (3D tomography, local strain, local changes in material composition ...) could support the LWRS mission to understand IASCC initiation and propagation.
- **Limited usage of in situ characterization** (IVEM) under LWRS. However, fundamental work on irradiation damage, potentially using such equipment, would benefit LWRS



1. This is a whole different application of ion beams than we have been discussing—may fall better into a PIE category of the eight criteria.
2. On the characterization of cracking: what would an ion beam facility bring to the table here?

Questions ?

Questions ?

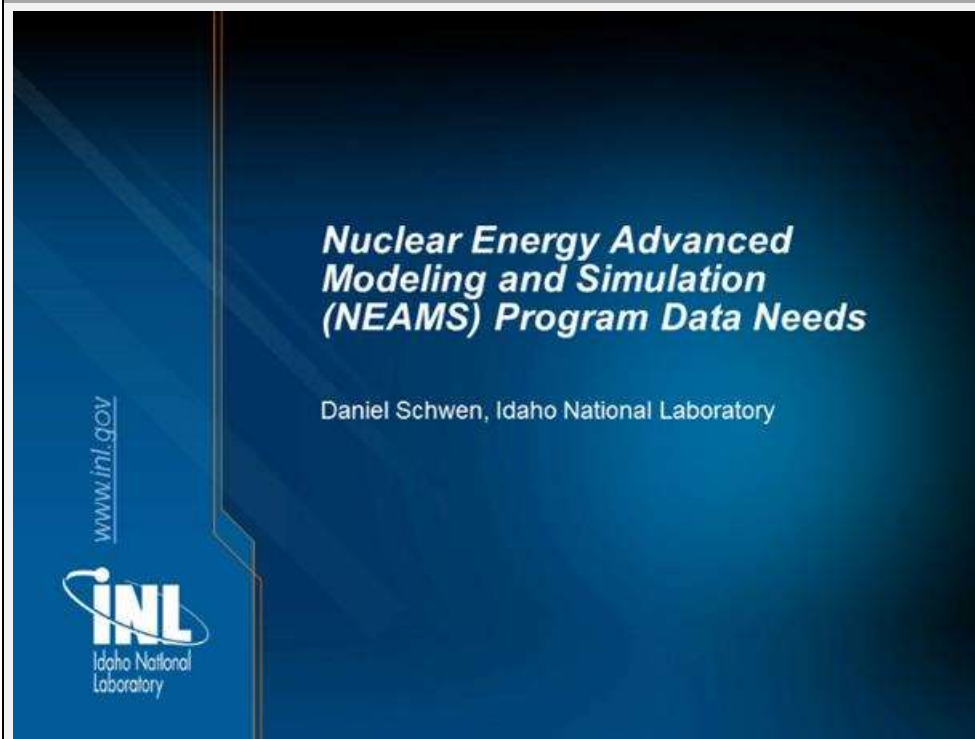


1. Re-irradiation already starts with nucleated material and is much more representative than starting with fresh material.
2. Ion beams can satisfy generic NRC requirements that don't specifically require neutron irradiations.

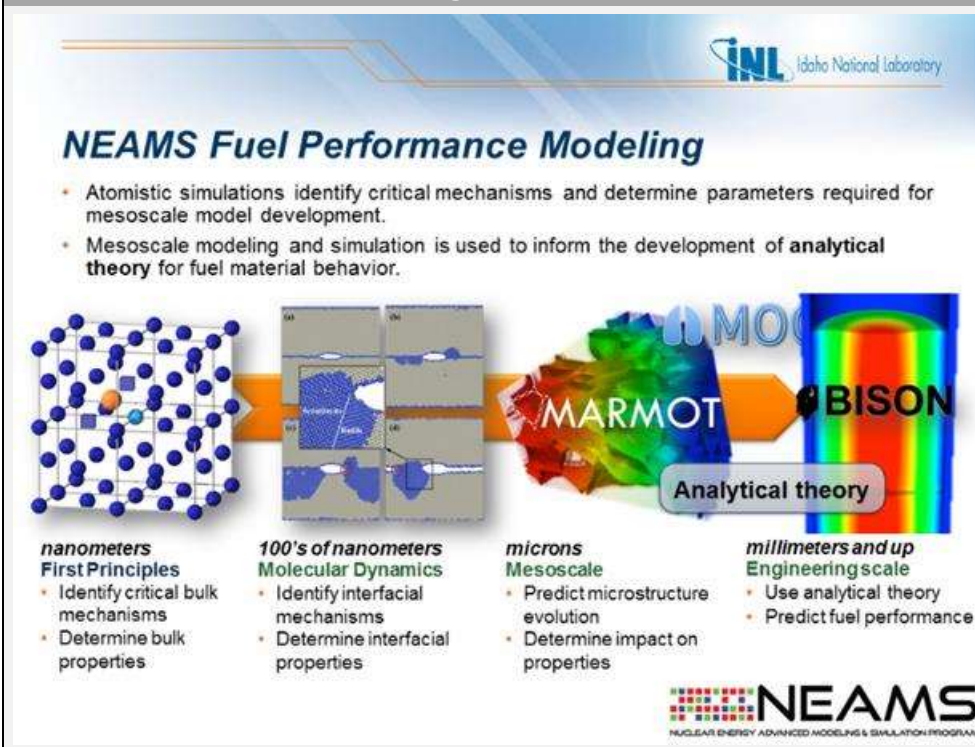
Presentation: Nuclear Energy Advanced Modeling

Daniel Schwen

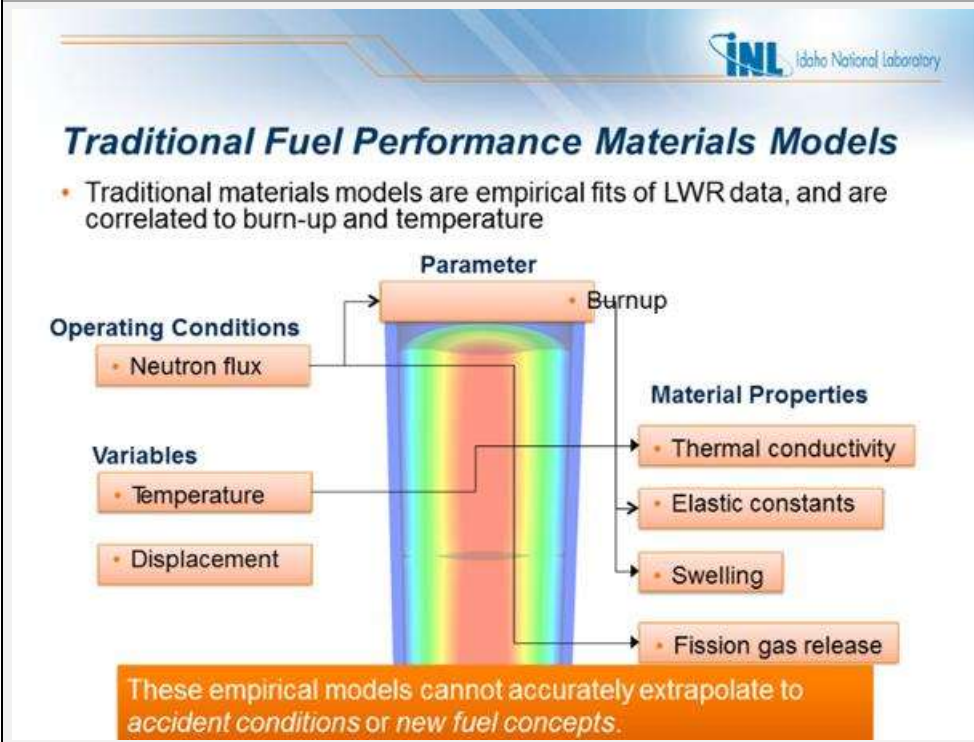
Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program Data Needs



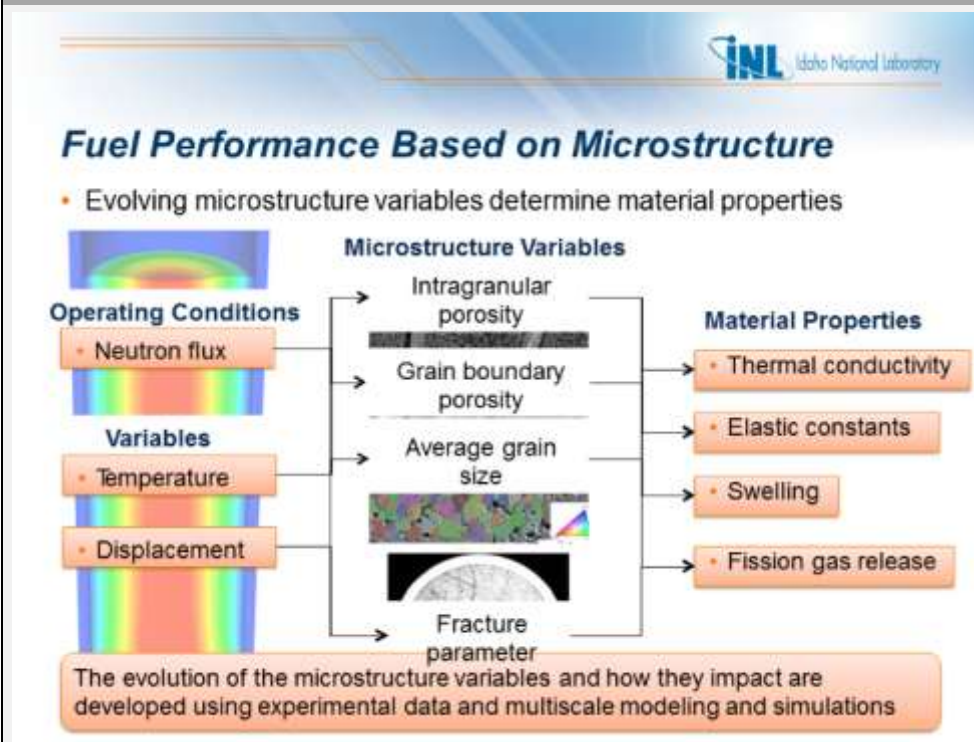
NEAMS Fuel Performance Modeling



Traditional Fuel Performance Materials Models

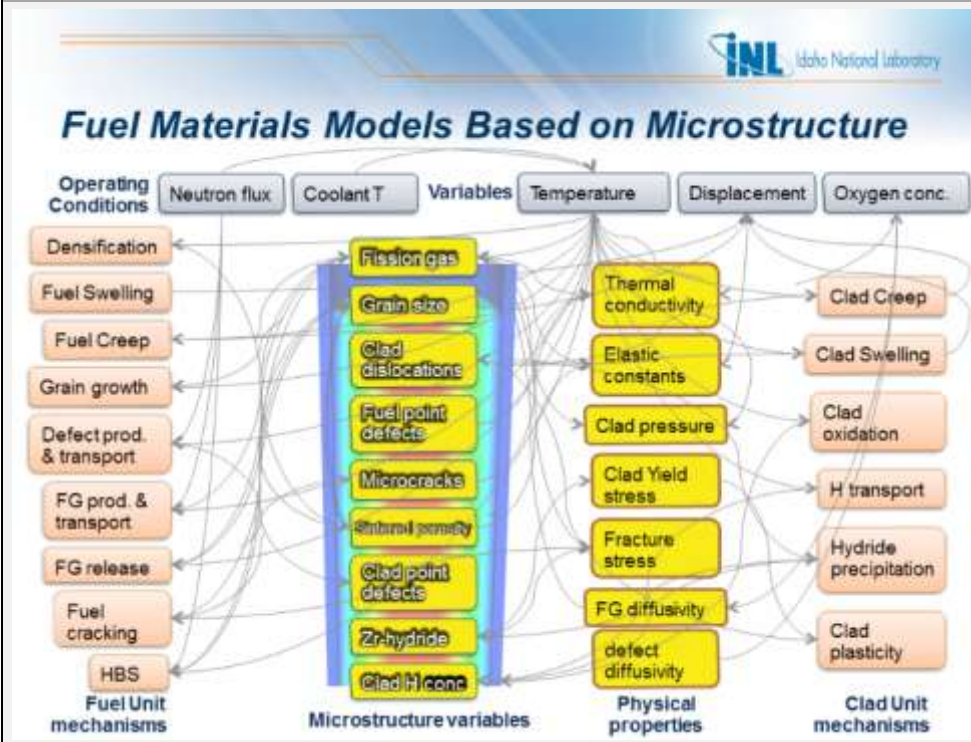


Fuel Performance Based on Microstructure



1. Ion irradiations need to produce the same mesoscale parameters as neutron damage.

Fuel Materials Models Based on Microstructure



1. Can ion beam irradiations be used to investigate single-effect tests for these models?

Mesoscale Multiphysics Simulation Tool

MARMOT
Mesoscale Multiphysics Simulation Tool

- MARMOT predicts coevolution of microstructure and physical properties of nuclear fuel due to applied load, temperature, and radiation damage

Technique: Phase field coupled with large deformation solid mechanics and heat conduction solved with implicit finite elements using INL's MOOSE framework

All models implemented in MARMOT are:

- 1D, 2D or 3D
- Massively parallel, from 1 to 1000's of processors
- Able to employ mesh and time step adaptivity
- Easily coupled to additional physics from the MOOSE modules

MARMOT is being used at various labs and Universities:

Argonne, Los Alamos, Washington State University, Pacific Northwest, Wisconsin, BYU Idaho, Idaho State, MIT, Massachusetts Institute of Technology, and others.

Physical models include:

- GB migration/grain growth
- Species redistribution, phase separation
- Void/Bubble growth and coalescence
- Precipitation and phase change

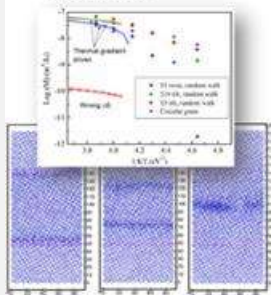
UO₂ Grain Size Model Development

UO₂ Grain Size Model Development

- Grain growth in the fuel is a function of the temperature, manufactured porosity, fission gas bubbles and more.
- Grain size impacts thermal conductivity, creep, swelling, and fission gas release.

GB Mobility

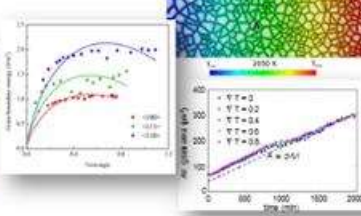
- Intrinsic mobility was calculated using multiple MD methods



$$\bar{D} \uparrow 2M (P_{DF} - P_r)$$

GB Driving Forces

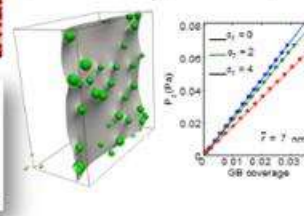
- GB energy calculated for various GB types and misorientations.
- Temperature gradient driving force was found to be insignificant.



GB Resistive Pressure

- Developed analytical model for the resistive pressure from GB bubbles
- Added the impact of the bubble size distribution to the resistive pressure

$$p_{max} = \sqrt{1 + \frac{2 \cdot 10^{-1}}{r^2}} W \frac{1_{GB} f_c}{r}$$



- Should there be specific work scopes written to address these needs?
Access through the RFI.

MARMOT Grain Growth Model Validation

MARMOT Grain Growth Model Validation

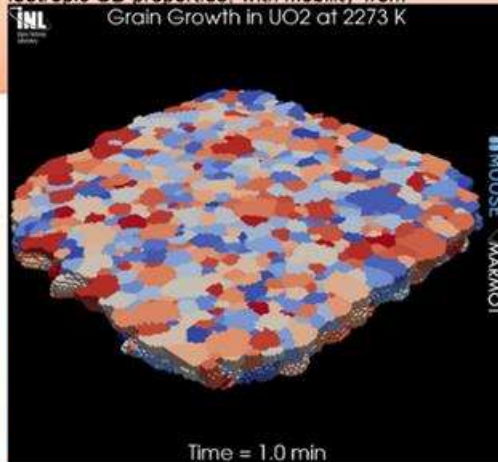


Experimental Setup

- Fully dense UO₂ polycrystal sample was annealed at 2000°C for 200 minutes
- High energy X-ray diffraction microscopy was used to collect 3D microstructure data before and after annealing.
- Grain location and size were monitored in situ (data is being processed).
- Data will provide info anisotropic GB properties and validate our model.

Simulation Using the Phase Field Method

- Initial microstructure reconstructed from data
- Isotropic GB properties, with mobility from Grain Growth in UO₂ at 2273 K



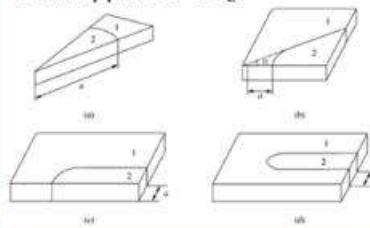
Time = 1.0 min

Data Needs – Grain Boundaries

- Grain boundary mobility under irradiation (in situ)
 - Well characterized nanoscale samples (FIB)

Bicrystal Data

- Experimental techniques have been developed to measure specific mobilities.
- These approaches have never been applied to UO_2 .



UO_2 Fracture Model Development

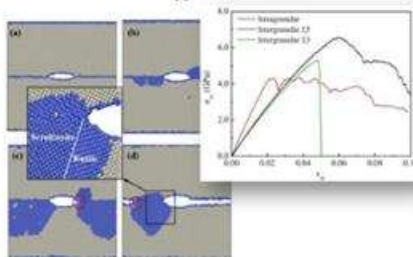
UO_2 Fracture Model Development

- Fuel fracture is impacted by temperature, stress, grain size, and grain boundary fission gas bubbles
- Fracture impacts volumetric expansion, fission gas release, etc.

$$a_f(d, p)$$

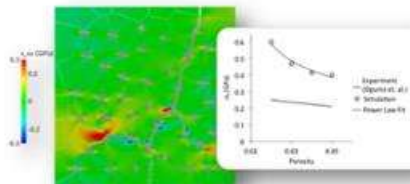
Atomistic Fracture Modeling

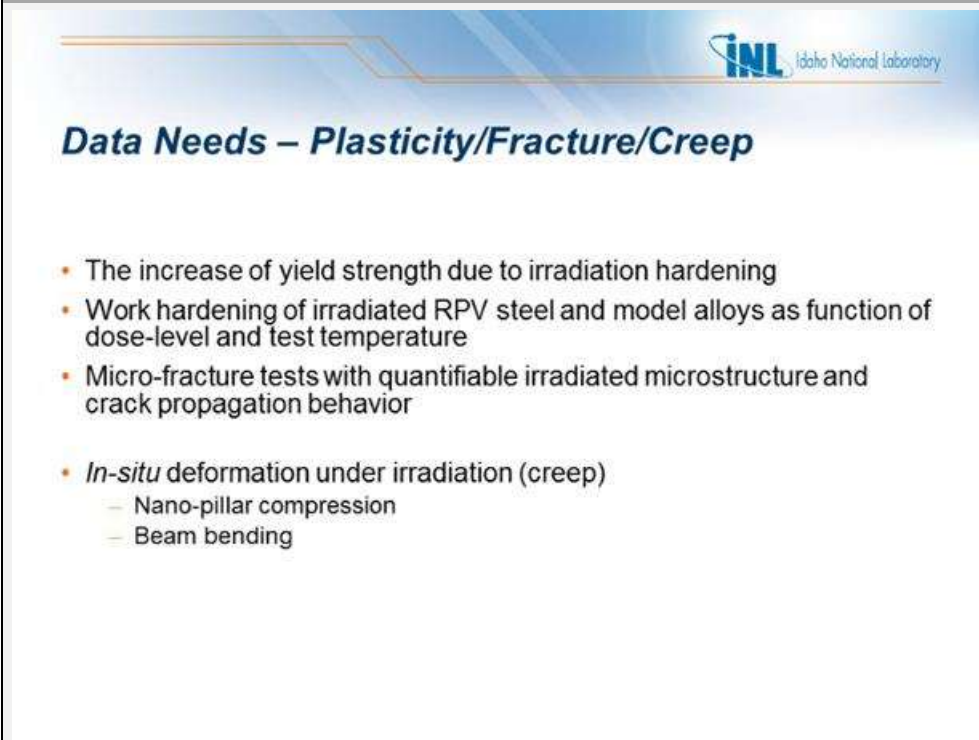
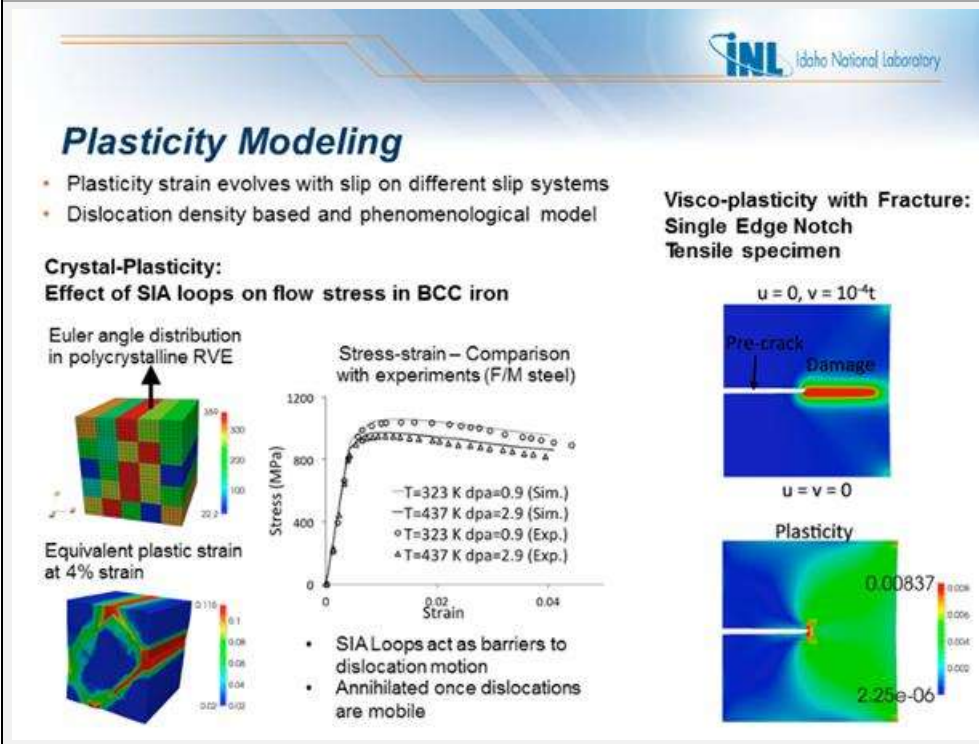
- MD simulations were employed to determine the fracture toughness in UO_2 across a grain and on various GB types.



Mesoscale Fracture Modeling

- A phase field fracture model was developed in MARMOT and parameterized using the MD simulation results.
- The model was used to identify the impact of GB bubbles on the fracture stress in UO_2 fuel.



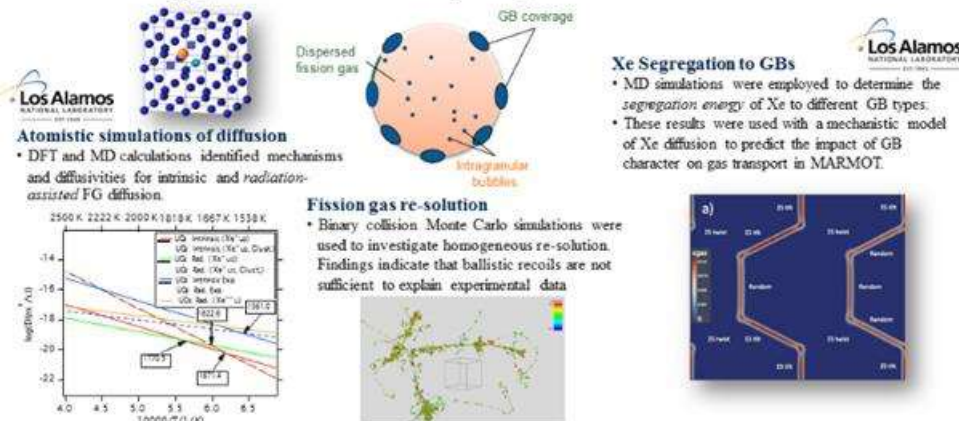


- These are measurements that would be extremely difficult to conduct in core—ion irradiations are the only practical way to get at some of this separate effects data that is needed for model development.

UO₂ Fission Gas Release Model Development

UO₂ Fission Gas Release Model Development

- Fission gas transport and release is a function of temperature, grain size, cracking, and more.
- Fission gas impacts the UO₂ thermal conductivity, bubble pressure, and the gap thermal conductivity and pressure.



1. Wondering why cyclotrons are not considered part of this meeting.

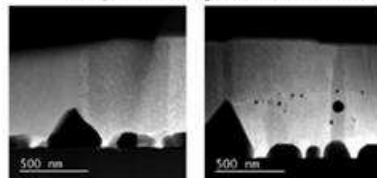
Data Needs – Fission Gas

Data Needs – Fission Gas

- Gas loaded fuel samples
 - Mobility under irradiation
 - Bubble formation and coarsening under annealing/irradiation
 - Gas loading of grain boundaries

Separate Effects Tests

- Samples will be created with fission gas (Xe) already present in the material (implantation or thin film growth)
- Samples will be used for:
 - Diffusivity measurement
 - Bicrystal segregation
 - Bubble nucleation and growth
 - Temperature gradient effects

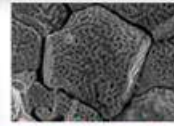
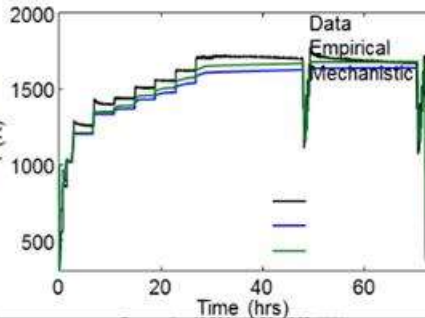
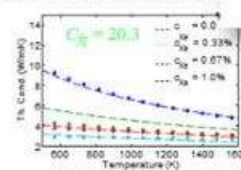


UO₂ Thermal Conductivity Model Development

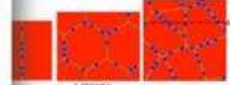
- The fuel thermal conductivity governs the amount of heat that is transported from the fuel and controls the temperature
- It is impacted by the grain size, temperature, fission gas, cracking, defect

MD calculations were conducted at LANL

Dispersed fission gas
MD simulations (correctly account for spin scattering) used to quantify impact of Xe on thermal conductivity



Annular (GB) bubbles



MD and mesoscale heat conduction are used to parameterize constitutive model.

$$\frac{1}{R_k} = \frac{1}{A_{GB} - A_{inh}} \left(\frac{A_{GB}}{R_k} - \frac{A_{inh}}{R_{inh}} \right)$$

1. What quality level is needed for this data?

Data Needs – Thermal Conductivity

Data Needs – Thermal Conductivity

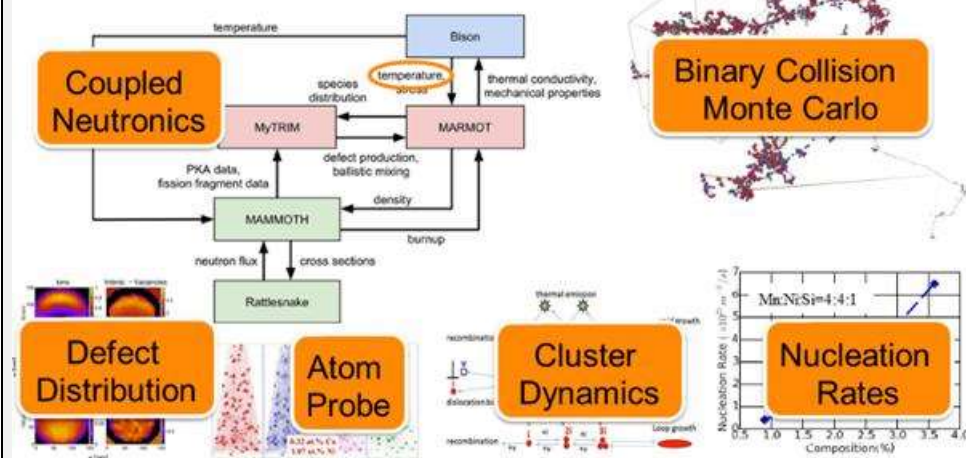
- Well defined samples loaded with dispersed gas
- Thermal/electrical conductivity under irradiation
 - Point defect contributions

Development Plan - Coupled Damage

Development Plan - Coupled Damage

The goal of this task to add a more realistic representation of irradiation damage to MARMOT (defect production, thermal spikes).

Simulate **used fuel** rather than fresh fuel!



Cascade Simulations

Cascade simulations

MAGPIE

- BCME damage production
- Diffusion ($D_i = 10 D_v$)
- 20 keV Xe in 20nm² Cu
- Annihilation reaction

$$\frac{\partial c_i}{\partial t} = D \nabla^2 c_i + \psi_i(r) - \lambda c_i c_v$$

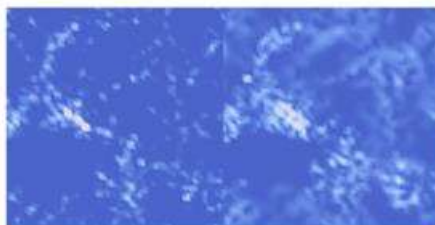
$$\frac{\partial c_v}{\partial t} = D \nabla^2 c_v + \psi_v(r) - \lambda c_v c_i$$

- $r=1\text{nm}$ Xe bubble (3.5g/cm^3) in UO_2 (10.9g/cm^3), $5\text{nm} \times 5\text{nm}$ cell
- ~5000 200 keV Xe cascades
- BCME works on unstructured meshes (AMR here)
- Ballistic gas re-resolution



Ψ_v vacancies

Ψ_i interstitials



c_v vacancies

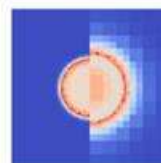
c_i interstitials



Uranium (vac/int)



Oxygen (vac/int)



Xenon (vac/int)

Data Needs – Damage Production

- Cluster dynamics input
 - Mobilities under irradiation (defect clusters, impurities)
 - Cluster size evolution / growth rates
- TRIM/SRIM validation
- Thermal/electrical conductivity under irradiation

Summary

Summary

Atomistics, Mesoscale



Data wishlist

- Grain boundary mobility under irradiation (in situ)
- Yield strength, work hardening, micro-fracture, in-situ deformation
- Gas loaded fuel samples
 - Mobility under irradiation
 - Bubble formation and coarsening under annealing/irradiation
 - Gas loading of grain boundaries
 - Thermal conductivity
- Point defect formation, impact on conductivities
- Defect cluster formation, mobilities under irradiation

Questions?

Presentation: Fuel Cycle R&D

Shannon Bragg-Sitton

Nuclear Science User Facilities



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Fuel Cycle Research and Development

Advanced Fuels Campaign

Shannon Bragg-Sitton

Deputy National Technical Director

March 22, 2016

NSUF Ion Beam Workshop
Idaho Falls, Idaho

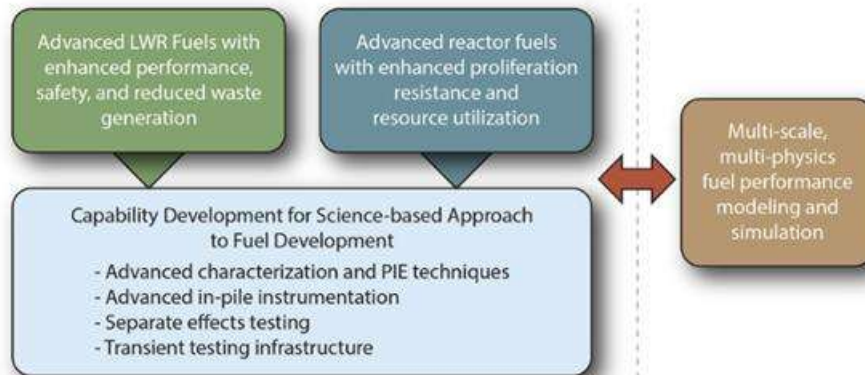


Reduced from INL/MIS-14-33610

The FCRD Advanced Fuel Campaign is tasked with development of near term accident tolerant LWR fuel technology and performing research and development of long term advanced reactor fuel options.



*The FCRD Advanced Fuel Campaign is tasked with development of near term **accident tolerant LWR** fuel technology and performing research and development of **long term advanced reactor fuel** options.*



1. Fuels will experience thousands of dpa as they reach high burnup. I wonder if ion beam irradiation is especially useful for some features. Fission spike damage would be dominant. It's not the case where ions are comparable to neutrons.
2. Some basic property behavior can be explored, though.

Slide 3



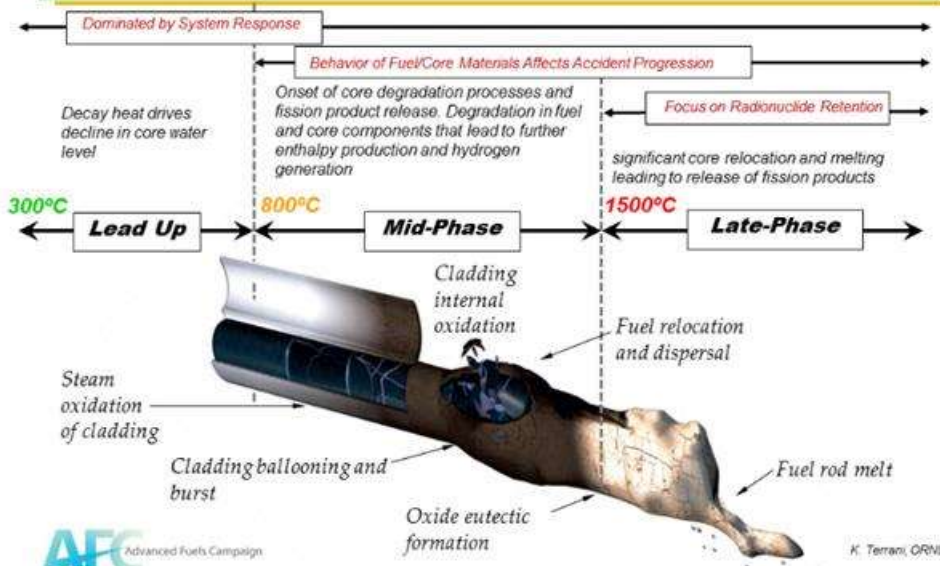
AFC High Level Technical Objectives (5-year)

- Identify and select advanced LWR fuel and cladding concepts for development towards lead test rod testing by 2022.
- Complete the conceptual design for the baseline advanced reactor fuel technologies with emphasis on the fundamental understanding of the fuel fabrication and performance characteristics for recycle fuels.
- Achieve state-of-the art infrastructure that can be used to perform fuel research and development from a "science-based" approach accelerating further development of selected concepts.
- Integrate with the development of the predictive, multi-scale, multi-physics fuel performance code.

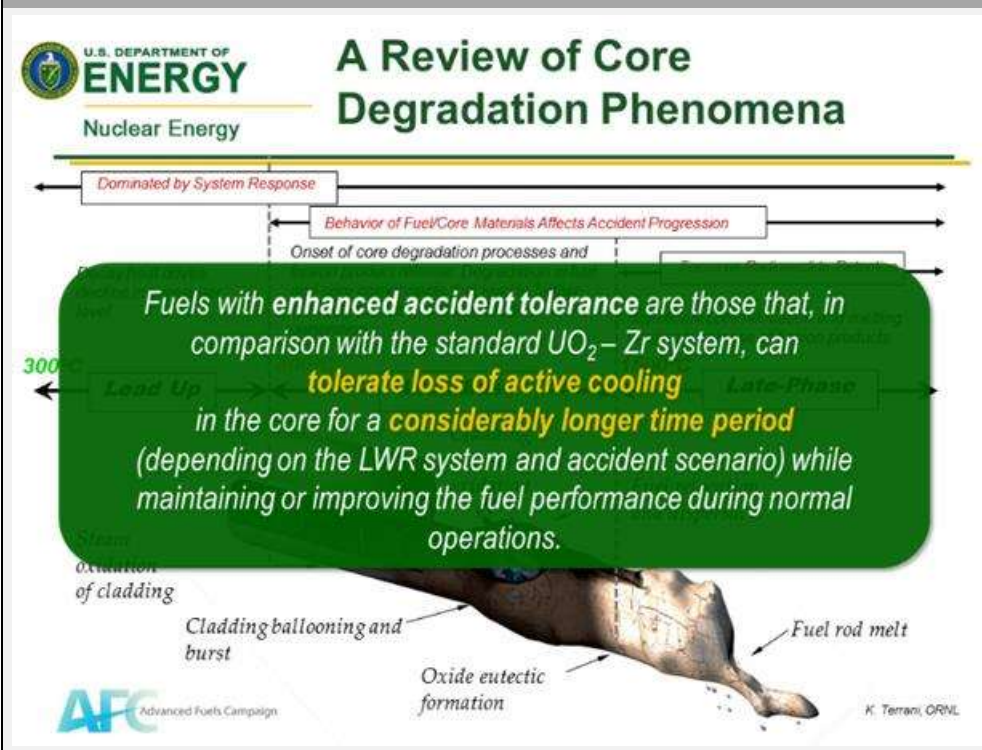
ADVANCED LWR FUEL

A Review of Core Degradation Phenomena

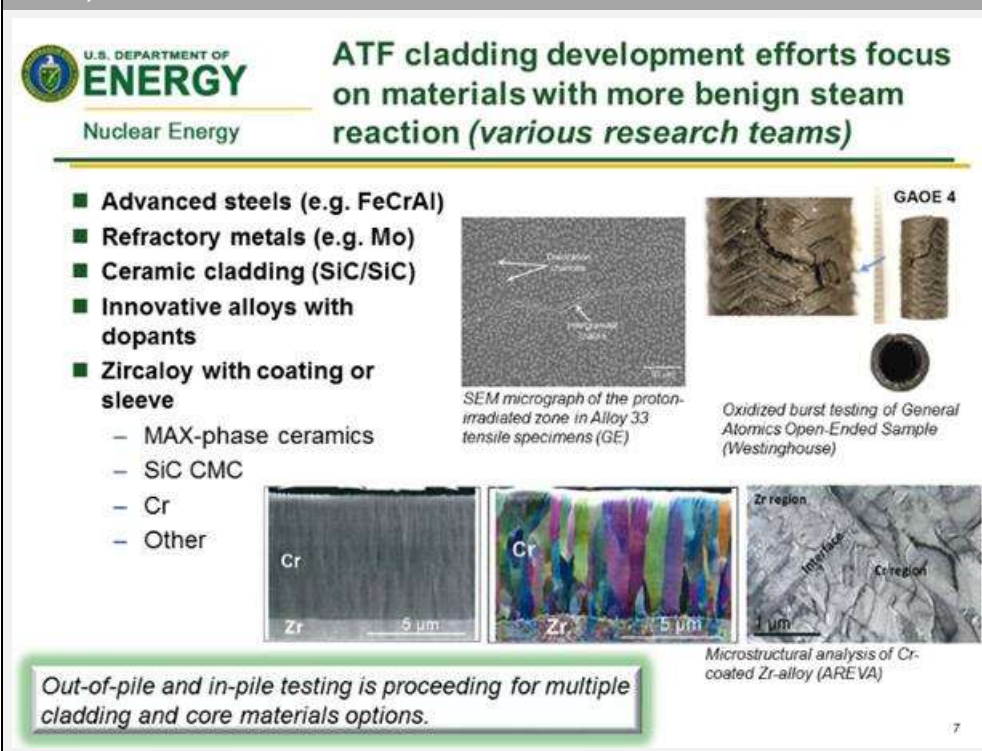
A Review of Core Degradation Phenomena



A Review of Core Degradation Phenomena



ATF cladding development efforts focus on materials with more benign steam reaction (various research teams)



Several advanced fuel concepts are under investigation for accident tolerance (various research teams)



Several advanced fuel concepts are under investigation for accident tolerance (various research teams)

Higher density fuels (metal, nitride, silicide)

- Higher thermal conductivity
- Higher fissile density to compensate for neutronic inefficiency of some cladding concepts without increasing enrichment limits



Sintered full sized UN/U_3Si_2 test pellets for ATR irradiations and two thermophysical samples for thermophysical property measurements (WEC/LANL)

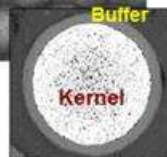
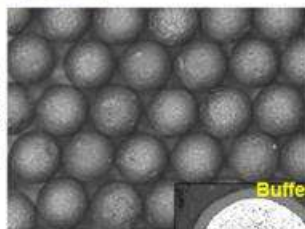
Oxide fuels with additives

- Higher thermal conductivity
- Fission product gettering

Microencapsulated fuels

- Particle fuel dispersed in a ceramic or metallic matrix

UN kernel production for microencapsulated fuel, image shows typical 840 μm diameter $UC_{0.94}Nd_{0.06}$ kernels (ORNL)

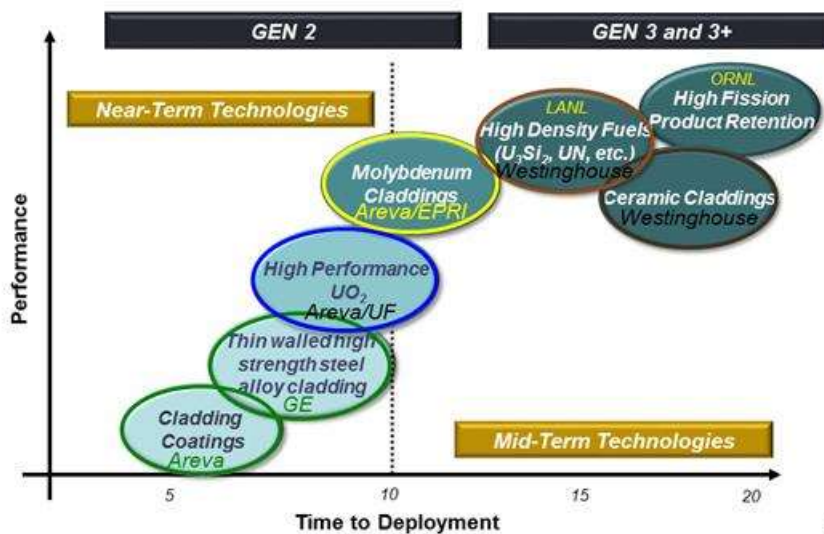


A systematic analytical and experimental evaluation is being performed for multiple fuel options.

A variety of technologies are under study as possible ATF



A variety of technologies are under study as possible ATF



ATF Irradiation Testing Highlights

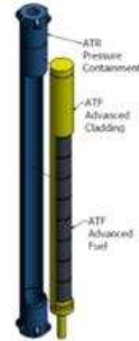


Nuclear Energy

ATF Irradiation Testing Highlights

■ ATF-1 Capsule Irradiation

- Irradiated 19 ATF-1 capsules in ATR
- Continued design and fabrication of additional concepts: Mo cladding, ORNL-FCCI, WEC-1B, LANL-1, ORNL-FCM, AREVA-1B
- Completed NDMAS database development
- Fabricated, inspected, and qualified of 16 rodlets and 19 capsules
- Installed fabrication and inspection enhancements

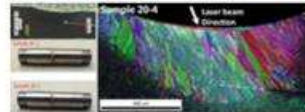


■ ATF-2 Loop Irradiation Testing

- Agreed to test train configuration and dimensions at FOA bi-annual meeting
- Started ATF-2 conceptual design and analysis
- Initiated collaboration with Halden to support in-situ instrumentation

■ HFIR SiC Microcracking Experiment

- Halden 3D Experiment Collaboration (H. Chichester)
 - Began discussions for a bi-lateral loop experiment in Halden



EBSD of PRW

10

Example: Ion beam use in alloy development



Nuclear Energy

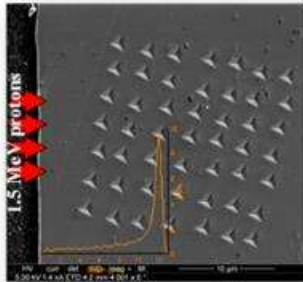
EXAMPLE: ION BEAM USE IN ALLOY DEVELOPMENT

11

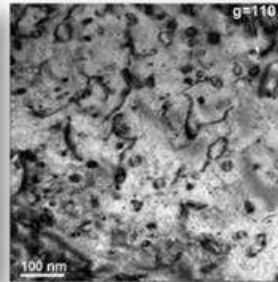
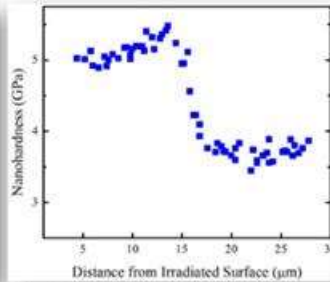
FeCrAl alloys being developed for ATF cladding applications have been tested for irradiation hardening using light and heavy ions



FeCrAl alloys being developed for ATF cladding applications have been tested for **irradiation hardening** using light and heavy ions

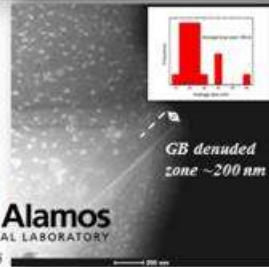


Cross-sectional nano-indentation on 1.5 MeV proton irradiated Gen II FeCrAl at 300°C up to 0.5 dpa together with SRIM profile.



- Irradiation hardening can be measured on ion irradiated alloys
- Microstructural investigation shows dislocation loops that are responsible from the hardening
- Effects of sinks such as GBs can be captured using ion irradiations

O. Anderoglu et al. FCRD report 2014; O. Anderoglu et al. FCRD report 2015

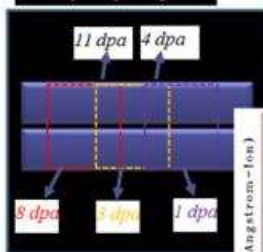


In addition to irradiation hardening, saturation of hardening was also measured using 5 MeV Fe^{2+} irradiations at 300°C up to 11 dpa

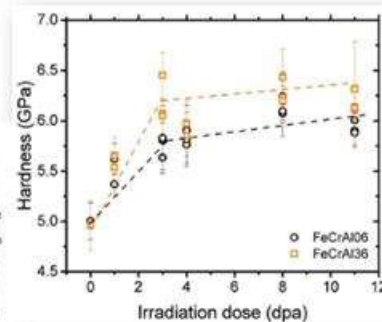
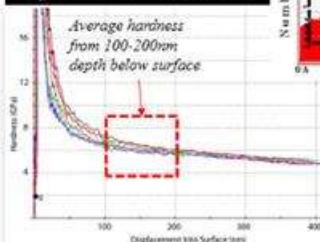


In addition to irradiation hardening, **saturation of hardening** was also measured using 5 MeV Fe^{2+} irradiations at 300°C up to 11 dpa

Multiple dpa regions



Surface hardness in CSM mode



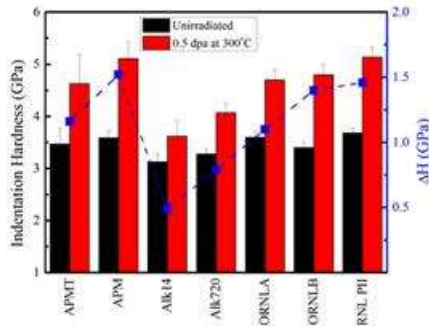
- Hardening mostly saturates by 3 dpa (at 300°C) in agreement with the neutron irradiated ferritic alloys
- Irradiation hardening of ~1 GPa was measured, no significant dependence on Cr content



Ion irradiations very effective in surveying a large number of candidate alloys



Ion irradiations very effective in surveying a large number of candidate alloys



Alloy	C	Si	Mn	Cr	Al	Mo	Fe	Y ₂ O ₃	Ti	Y
APMT	.08	.7	.4	20-24	5	3	Bal	-	-	-
APM	.08	.7	.4	20-24	5.8	-	Bal	-	-	-
Alkrothal 14	.08	.7	.5	14-16	4.3	-	Bal	-	-	-
Alkrothal 720	.08	.7	.7	12-14	4	-	Bal	-	-	-
MA956	.04	-	-	20	4.5	-	Bal	.5	.4	-
PM2000	.01	-	-	20	5.5	-	Bal	.5	.5	-
ORNL A	.004	-	-	14.98	5.02	-	79.87	-	-	.033
ORNL B	.005	-	-	17.51	2.93	-	79.54	-	-	.017

- A large number of candidate alloys were tested at the same time
- No dependence on the Cr was detected
- Rate sensitive defects (e.g. α') were not found



1. No particular QA was needed for the ion irradiations—ions were used as a first cut to focus the research on the highest performing samples.

Benefits of Ion Beam Irradiation in Cladding Development



Benefits of Ion Beam Irradiation in Cladding Development

- **Rapid development of datasets for multiple materials and dose levels**
 - Rapid irradiation to desired dpa
 - Can design test to achieve multiple dpa levels in a single sample
 - No surface activation
 - Rapidly move from irradiation to microstructural characterization
 - Provide data for code development – prediction of microstructural changes as a function of ion irradiation
- **Available measurements that match well to neutron damage**
 - Mechanical Properties: Hardness, evolution of hardness with increasing dpa
 - More challenging, but possible: yield stress, work hardening rate
 - Post-irradiation microstructural testing
 - Some testing of simultaneous irradiation and corrosion (LANL, UM)



15

Challenges / Needs for Ion Beam Irradiation in Cladding Development



Challenges / Needs for Ion Beam Irradiation in Cladding Development

■ Challenges / Needs

- High irradiation rate results in more defects in a small area:
Ability to replicate neutron damage with protons decreases for properties that depend on the time required for damage to precipitate out
- Knowledge of the impact of the defect flux on processes is important
- Ion irradiation physical sample size limits the ability to conduct post-irradiation mechanical testing
- Measurement of processes *in situ* would be very beneficial:
 - Creep
 - Fatigue
 - Other mechanical properties

■ Possible option:

Dedicated proton facility allowing automated sample irradiation over weeks to months vs. hours to a day in duration

- Allows for larger sample size for subsequent characterization tests
- Addressed defect precipitation issue



16

1. Is this dedicated proton option available in any current facilities?

Slide 17



Thank You




17

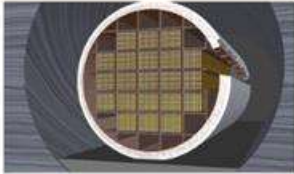


Presentation: Used Fuel Disposition

Remi Dingreville

Slide 1

Exceptional service in the national interest







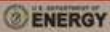
NSUF Ion Beam Investment Options Workshop: Used Fuel Disposition Program Data Needs

INL Meeting Center
Idaho Falls, ID
March 22nd-March 24th

Rémi Dingreville
Sandia National Laboratories
✉ rdingre@sandia.gov

SAND2016-2552 PE

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL55000



Outline

Outline

Used Fuel Disposition (UFD) campaign overview:

- Mission and objectives: Storage / Transportation / Disposal
- UFD R&D in the context of ion beam irradiation capabilities

Storage and transportation:

- Cladding: High-burnup cladding performance
- Cladding: Pellet/clad delamination
- Cladding: Radiation annealing
- Bolted cask: Embrittlement of elastomer seals

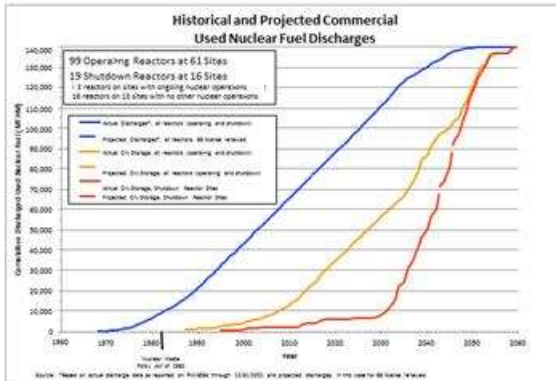
Review of criteria

2

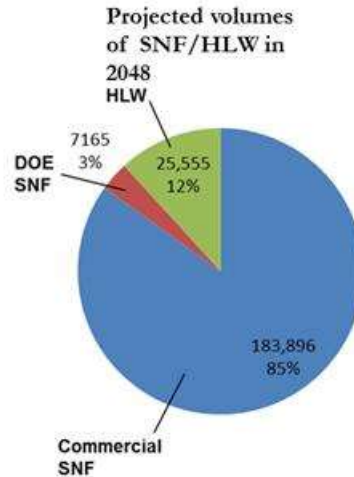
Historical and projected spent nuclear fuel (SNF)

Historical and projected spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in the U.S.

Historical and projected commercial SNF discharges



Currently over 1500 casks loaded in the U.S. located at 50+ interim storage sites



Volumes in m³ (assuming constant rate of nuclear power generation and packaging of future commercial SNF).

1. Zircaloy 4 is the cladding used on most of the currently stored fuel.
2. CEA and AREVA have done significant ion irradiation of zirc alloys.

3

Used Fuel Disposition Campaign mission

Used Fuel Disposition Campaign mission

Identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles



4

Used Fuel Disposition Campaign mission

Identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles

Storage and transportation R&D focus:

- Extended storage of UNF
- Fuel retrievability and transportation after extended storage
- Transportation of high-burnup UNF (>45 GWd/MTU)

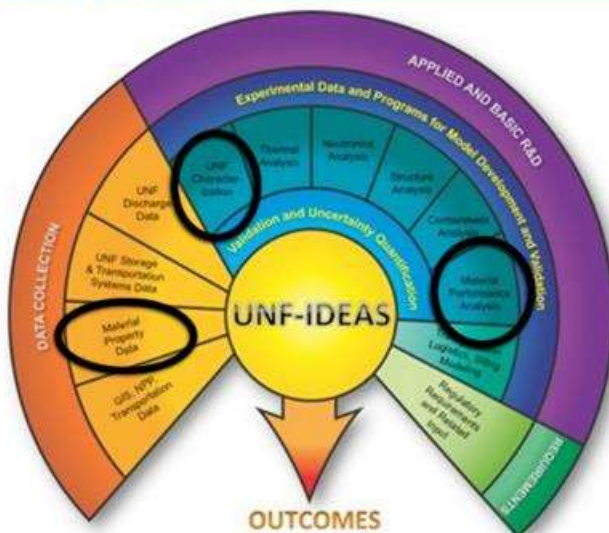
Disposal R&D focus:

- Sound technical basis for multiple viable disposal option in the U.S.
- Increase confidence in robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation

4

Slide 6

UFD R&D data needs in the context of ion beam irradiation capabilities



[Courtesy of J Scaglione, ORNL]

5

UFD data need drivers

What data already exists and relevance to UFD mission

- Data collected within UFD campaign.
- Proprietary data (e.g. ZIRLO™, M5®).
- How do we interpolate gaps between existing data points?

Relevance of data w.r.t. regulatory performance criteria for storage and transportation?

- Metrics extracted from 10CFR71, 10CFR72.
 - "...spent fuel cladding must be protected during storage against degradation that leads to gross ruptures..."
 - "...degradation of the fuel during storage will not pose operational safety problems w.r.t. its removal from storage."
- Recommendations from SFST-ISG-11.3 and NUREG-1567.

Where are the data gaps and why?

- Access to high burn-up data difficult to obtain? What about newer alloys?
- Compliance: DOE Order 435.1 "Radioactive Waste Management".
- Separate effects testing.
- NRC and industry data needs?
- When do we stop collecting data relevant to UFD needs?

1. When are the data good enough to deploy?
2. Since NRC doesn't provide guidance for research needs, how do you know what is necessary for storage? Is this DOE's thought? What does NRC think?
3. DOT data needs are probably different from NRC and DOE.

6

Gaps for storage and transportation

Degradation mechanisms	Storage importance
Annealing of radiation damage	H
H ₂ effects: embrittlement and reorientation	H
H ₂ effects: delayed hydride cracking	H
Oxidation	M
Creep	M
Corrosion and SCC	M
Thermal aging effects	M
Corrosion: blistering	M
Corrosion atmospheric	H
Corrosion: aqueous (pitting, crevice)	H
Thermo-mechanical fatigue of seals and bolts	M
Freeze-thaw	M
Corrosion of embedded steel	M

[Gap Analysis to Support Extended Storage of UNEFCRD, 2011]

7

Ion beam irradiation capabilities that could help closing data gaps

- Do we have sufficient data on cladding and fuel assembly materials once they are stored (e.g. high-burnup)?
- Probability of degradation mechanism occurring?
- Regulatory considerations?
- Impact on safety functions (Retrievability, Radiological Protection, Thermal Performance, Confinement, Subcriticality)?

Storage and transportation R&D:

- Extended storage of UNF
 - Cladding: Annealing of radiation damage.
 - Bolted cask: Embrittlement of elastomer seals.
- Fuel retrievability and transportation after extended storage
 - Cladding: High-burnup cladding performance.
 - Cladding: Hydride reorientation and embrittlement.
- Transportation of high-burnup UNF
 - Cladding: Pellet/clad delamination.
 - Fuel: Pellet/pellet bonding

8

1. Would the facility need to accept highly burned fuel?

Ion beam irradiation capabilities that could help closing data gaps

- ➡ Emulate Initial storage materials conditions (materials damage).
- ➡ Emulate alpha irradiation during storage.
- ➡ Handle irradiated materials.
- ➡ Have the ability to perform accelerated aging.
- ➡ Collect microstructural characterization in coupled environments.

Storage and transportation R&D:

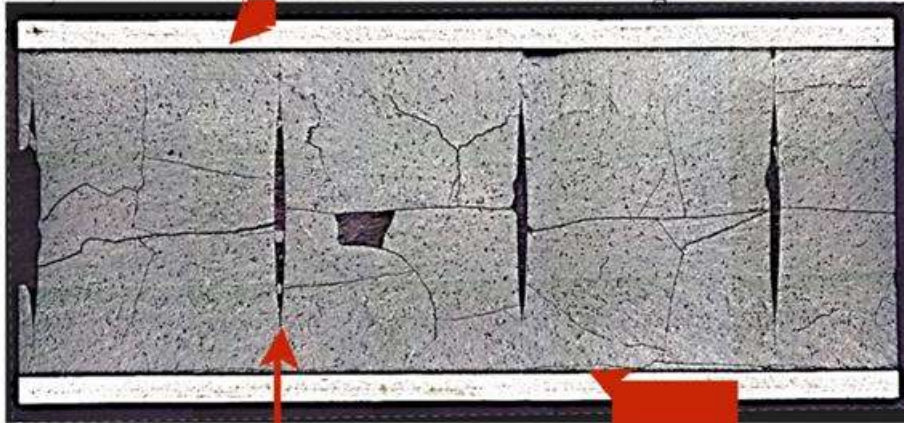
- Extended storage of UNF
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 - Cladding: Hydride reorientation and embrittlement.
- Transportation of high-burnup UNF
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8

Most of the data needs are related to the performance of high burn-up fuel pins

Most of the data needs are related to the performance of high burn-up fuel pins

Hydride formation/re-orientation in the cladding.



[ONRL image]

Pellet/pellet bonding

Pellet/clad debonding

- Integrity of spent-fuel (retrievability and transportation) is highly dependent on cladding and fuel pin performance.
- Lack of data for actual high burn-up fuel due to operational

9

Hydride reorientation and embrittlement (M/H)

Hydride reorientation and embrittlement (M/H)

• Influencing parameters

- § Temperature, H concentration, crystallography, defect density, stress level, solubility limit.

• Data already available

- § Terminal Solid Solubility (TSS), optical microscopy quantification of precipitation morphology (Arborelius, Motta, Billone, Chung), in-situ XRD

• Data needs:

- § Radial-hydride formation below licensing limits (400°C) on irradiated cladding materials.
- § Effect of peak cladding temperature and pressure on hydride formation mechanisms in irradiated materials: Ductile-to-Brittle Transition Temperature (DBTT).
- § Collect microstructural information on interaction between hydride and deformation mechanisms of (irradiated) cladding matrix.
- § Data on fracture toughness for various burn-up level is scarce at best.
 - § No data on radial hydrides cladding.
- § Data on ZIRLO™, M5®.

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Pellet/clad delamination (M/H)

- **Influencing parameters**

- § Temperature, loading mode, burn-up, composition, interface roughness, interface chemistry (intermixing).

- **Data already available**

- § Data associated with in-reactor behavior (fission product swelling, reactivity induced accident).

- **Data needs:**

- § Characterization of interfacial features (roughness, void structure, etc.) and environmental factors (thermal/irradiation) on delamination process.
- § Interfacial fracture toughness data for pellet/clad interfaces (not to mention high burn-up) does not exist to date.
- § Interfacial fracture toughness data for pellet/pellet interface. Emulation of irradiated fuel?

11

Radiation annealing (M)

- **Influencing parameters**

- § Temperature, loading mode, burn-up, composition.

- **Data already available**

- § Hardness tests vs. annealing temperature (Ito, 2004).

- **Data needs:**

- § Low-temperature annealing studies applicable to extended storage (over long period of time).
- § Hardness recovery of irradiated cladding materials (especially for newer alloys ZIRLO™, M5® [high burn-up]) as a function of time during long term annealing.

12

Embrittlement of elastomer seals/polymeric neutron shields (L)

- **Influencing parameters**

- § Temperature, composition, alpha irradiation.

- **Data already available**

- § Rubber-glass transition temperature for unirradiated samples (BAM, Germany).

- **Data needs:**

- § Study of coupled alpha irradiation and temperature on cross-linking of polymer?

- § Failure of elastomer seals.

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Review of criteria

Criterion	Priority
Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.	HIGH*
Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.).	MEDIUM
Ability of the facility to provide a variety of irradiation environments and conditions.	MEDIUM
Ability of the facility to collect microstructural characterization data onsite and in-situ.	HIGH
NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.	LOW
Unique capabilities of the facility including new technology.	LOW
Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.	HIGH
Ability of the facility to produce high quality data that can support verification and validation for modeling and simulation.	HIGH

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Presentation: EPRI

TG Lian

Slide 1



NSUF Ion Beam Irradiation Capabilities Support Industry in Materials R&D

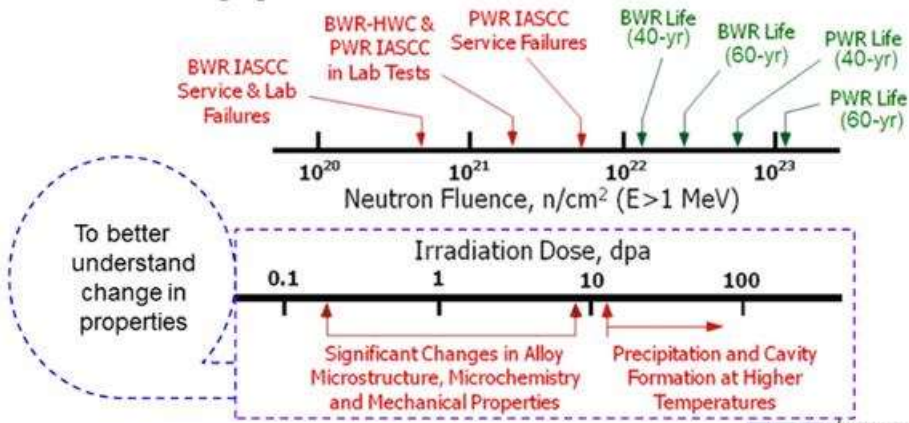
TG Lian
EPRI

NSUF Ion Beam Investment Options Workshop
Idaho Falls, ID; March 22-24, 2016

Life Extension for Existing LWR Plants

Life Extension for Existing LWR Plants

- Sustainability of US nuclear power is essentially important for the nation to achieve a decarbonized, integrated energy system
- Extended operation life requires more effective management of materials aging issues



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2

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Integrated Materials Aging Management for Primary System Components

Physically-based understanding to make engineering tools more effective

Inspection

- how to inspect
- what equipment and techniques are available
- What are the associated uncertainty

Assessment

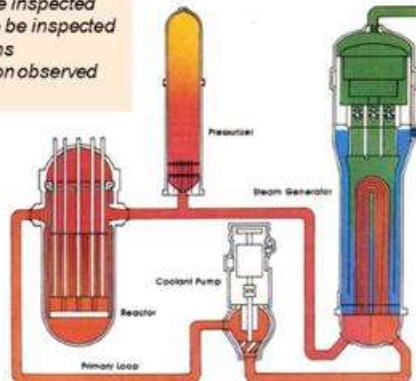
- What needs to be inspected
- When it needs to be inspected
- Inspection options
- How to disposition observed degradation

Mitigation

- How can degradation be prevented or reduced

Repair/Replacement

- What techniques are available
- What are associated requirements that must be met



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3

Slide 4

Challenges in Assuring the Reliability of Reactor Core Components

- BWR and PWR reactor internals are affected by several irradiation-induced degradation mechanisms
 - Irradiation-assisted stress corrosion cracking (IASCC)
 - Radiation embrittlement
 - Creep and stress relaxation
 - Void swelling
- Knowledge gaps exist (identified in MDM and IMTs)
 - Mechanistic understanding and prediction models
 - Impact of high fluence on reliability of internal components
 - Neutron embrittlement of RPV steels
 - Inspection techniques
 - Repair/replacement strategies of Irradiated Materials
- Experimental information is also lacking that could lead to the development of more robust, fundamentally based models and radiation resistant materials



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4

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Challenges in Industry Irradiated Materials Studies

- ❑ Nearly all materials are susceptible
- ❑ Extremely difficult to repair
- ❑ Limited mechanistic understanding
- ❑ Limited data applicable to LWR
- ❑ Limited facilities & capabilities for irradiated materials R&D
- ❑ Prohibitively high cost associated to irradiated materials studies

Ion Irradiation Plays Complementary & Important Role

Ion Irradiation Plays Complementary & Important Role

- ❑ Neutron irradiation provides conditions prototypical to reactor core internal environments
 - Preferred capability to validate engineering solutions
 - Retrieved in-service component expands opportunities
 - The capabilities is extremely limited, only a handful of facilities around the world with the right capabilities for LWR needs
 - Expensive, long time, radiation protection, etc
- ❑ Ion irradiation is a complementary irradiation tool
 - More suitable for mechanistic studies
 - Faster and more cost effective
 - Greater flexibilities
 - Has its own limitations: fidelity of simulation (know-how), limited size, and much more,,,

Use of Ion Irradiation in EPRI Materials R&D

- Ion irradiation has been an important technique to support EPRI primary system corrosion research projects
 - Cooperative IASCC Research (CIR)
 - EPRI-DOE LWRs collaborative research on IASCC mechanisms
 - Use of proton irradiation to study IASCC Proton irradiation and post irradiation annealing to identify the key process in IASCC
 - Use of heavy ion to study irradiation effect on thermally aged CASS → study synergetic aging in CASS
 - Advanced radiation resistant materials (ARRM) project to develop new materials for reactor core internal components
- ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓
- **Rapid simulation of effects of high fluence in reactor core materials to support the need to extend the life of LWR plants**

Rapid Simulation of Irradiation Damage in LWR Internals at High Fluence

Rapid Simulation of Irradiation Damage in LWR Internals at High Fluence

- **Objective:** Develop and validate an approach based on heavy ion irradiation (Fe^{2+} or Ni^{2+}) with He/H implantation for cost effective and rapid simulation of irradiation damage, with a focus on void swelling behavior, in PWR internals at high fluence

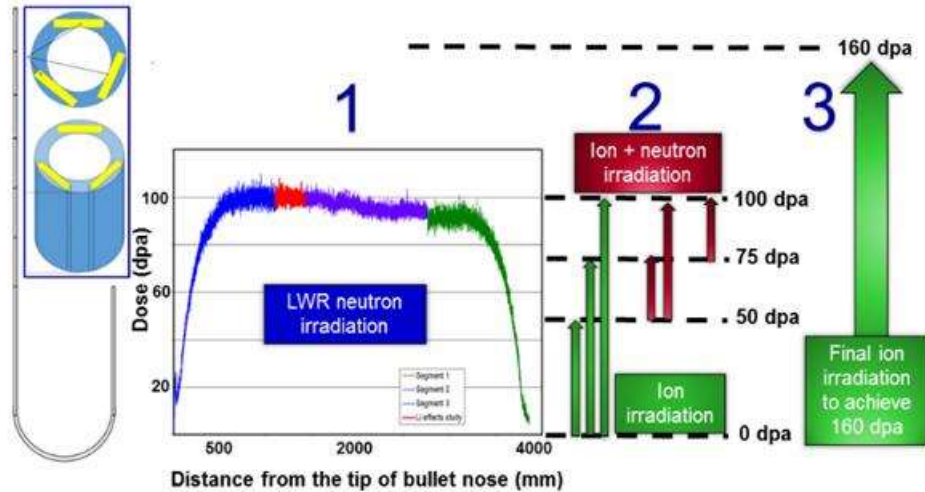
Motivation PWR Internals are expected to experience high fluence well exceeding 100 dpa at certain locations during first and second license renewal (60-80 years). There is a need for data and validated models to predict the degree of irradiation damage expected in austenitic stainless steel internals at high fluence.

- **Approach:** Use the materials retrieved from an operating PWR reactor to perform ion irradiation experiment (see the next 3 slides)

1. Amounts to the re-irradiation approach previously discussed.

Rapid Simulation of High Fluence through Ion Radiation of LWR Flux Thimble Tube (FTT)

Rapid Simulation of High Fluence through Ion Radiation of LWR Flux Thimble Tube (FTT)



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Quantitative Microstructural Characterization

Quantitative Microstructural Characterization

Transmission electron microscopy

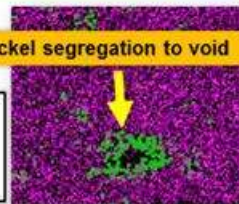
Irradiation induced voids



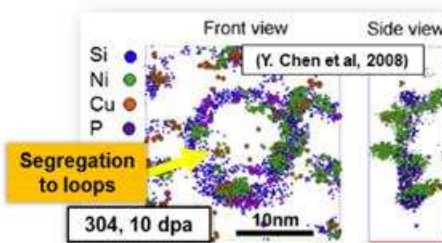
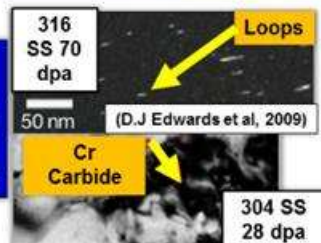
Atom probe tomography

Nickel segregation to void

BWR-irradiated 316L SS, 6.7 dpa



Solute clusters, precipitates and dislocations



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Rapid Simulation of High Fluence through Ion Radiation of LWR Flux Thimble Tube (FTT)

- 1 Obtain LWR plant materials** → Select locations with LWR fluences at 0, 50, 75, 100 dpa
 - Mechanical Property Measurements (Tensile and micro-nano hardness)
 - Microstructural Characterization (TEM, APT)
 - 2 Benchmark ion irradiation** → LWR (neutron) Vs. Simulated (ion+neutron)
 - Mechanical Property Measurements (Tensile and micro-nano hardness)
 - Microstructural Characterization (TEM, APT)
 - 3 Rapid Simulation** → Ion irradiation to achieve high fluence (160 dpa, ion+neutron)
 - Mechanical Property Measurements (Tensile and micro-nano hardness)
 - Microstructural Characterization (TEM, APT)
 - 4 Contribute to models for high fluence (160 dpa) stainless steel**
 - Irradiated microstructure and microchemistry
 - Mechanical properties
 - Void swelling behavior
- ✓ Neutron irradiation
✓ Ion irradiation
✓ PIE
✓ Modeling

We Look for:

We Look for:

- Expertise: to plan right ion irradiation experiments
- Facilities: to perform the experiments
- Integrated capabilities: to coordinate and integrate experiments, characterization and modeling
- Common interests: to maximize and leverage the R&D investments
 - Utilization of NSUF capabilities and resources

Together...Shaping the Future of Electricity

Appendix E

Ion Beam Facility Presentations

Appendix E

Ion Beam Facility Presentations

Presentation: IVEM-Tandem User Facility

Meimei Li

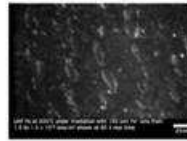
Slide 1



Intermediate Voltage Electron Microscope (IVEM) -Tandem User Facility:

TEM with *in situ* Ion Irradiation

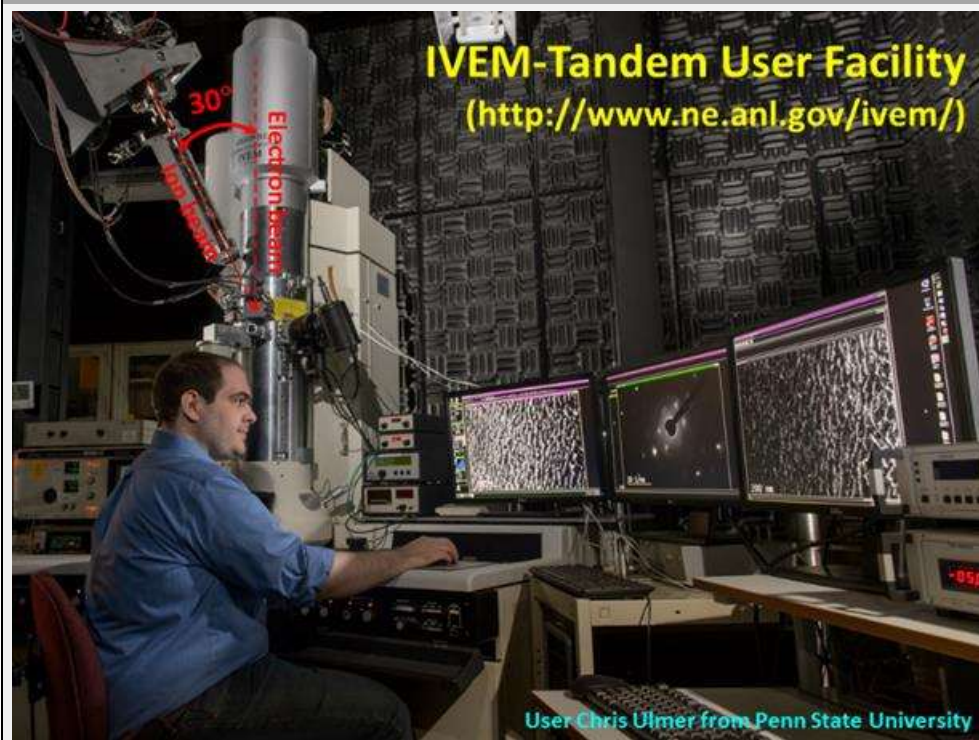
Meimei Li, Mark Kirk, Pete Baldo, Ed Ryan
Argonne National Laboratory



Nuclear Science User Facilities Ion Beam Investment Options Workshop
Idaho National Laboratory
March 22-24, 2016



Slide 2



Slide 3

Ion Irradiation Capability

In situ Ion Irradiation

Beam Energy	50 keV – 1 MeV
Ion Types	H, He, Ne, Ar, Kr, Xe, and many elements from Al to Au
Ion Flux	$10^{10} - 10^{12}$ ions/cm ² /s ($10^{-6} - 10^{-4}$ dpa/s)
High dose	~100 dpa/day
Beam size	Uniform beam, 1.5 mm Ø
Dosimetry	Real-time dosimetry with Faraday cup in the microscope column
Dual-beam	Add a low-energy ion gun to study combined effects of He and displacement damage (under construction).



Pete Baldo tunes the electrostatic deflector to direct the ion beam down into the electron microscope on the 1st floor.

- *Ex situ* ion irradiation
 - Dual-beam, triple-beam ion irradiation capability exists, but is inactive (chamber with three beamlines, a 2 MeV Tandem accelerator, an ion implanter, and a low-energy ion gun)
- Combine *in situ* and *ex situ* ion irradiations
 - Capability for *ex-situ* high-dose combined with *in-situ* ion irradiation is being designed, allowing a unique ability to follow material microstructural development to exceptionally high doses.
- High-energy, heavy-ion irradiation can be performed at Argonne Tandem-Linac Accelerator System (ATLAS) User Facility



Slide 4

Irradiation Environments and Conditions

In situ heating/cooling (20 K to 1300°C)

- Double-tilt LT stage (20 K - 295 K);
- Double-tilt HT stage (20°C - 900°C);
- Single-tilt HT stage (20°C - 1300°C);

In situ straining

- Single-tilt HT straining stage (20°C - 600°C);
- Single-tilt LT straining stage (-196°C - 100°C);

Well-controlled experimental conditions

- **Controlled metallurgical variables**
 - Constant specimen area
 - Crystal orientation
 - Single microstructural feature
- **Controlled irradiation variables**
 - Ion type, energy
 - dose rate, dose
- **Controlled irradiation temperature**

Coupling *in situ* ion irradiation with *in situ* stages for heating, cooling or straining enables studies of combined effects of irradiation, temperature and stress in real reactor environments that cannot be revealed through traditional post-irradiation examination.

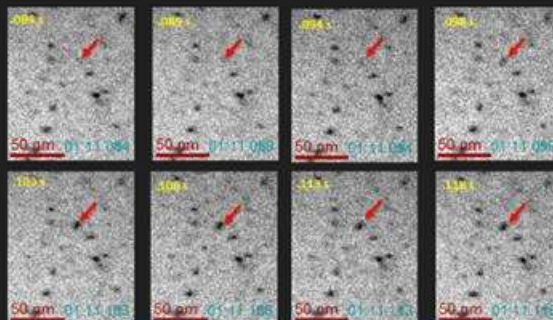
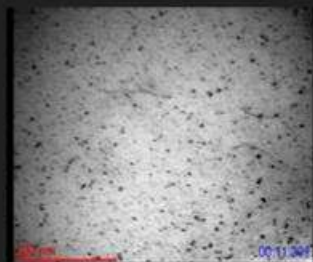


TEM Specimen Holder Vacuum Storage Station

Slide 5

In situ Real-Time TEM

- Hitachi-9000 microscope with accelerating voltage up to 300 kV (examination of thicker samples)
- High-resolution real-space imaging: point resolution of 0.25 nm at 300 kV
- Digital image recording and video recording
- **Recent Upgrade** - installed a high-resolution, high-speed Gatan OneView camera
 - Time resolution 5ms (frame rate increased from 15 frames/sec to 200 frames/sec)
 - Image resolution increased to 4kx4k

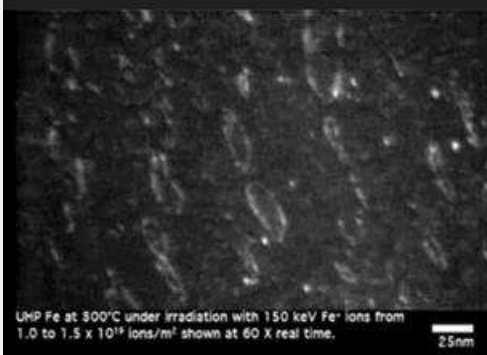


Cascade defect (dislocation loop) formed by single ion impact event between 0.089 and 0.094 sec.

Slide 6

What Distinguishes IVEM-Tandem from Other Ion Irradiation Facilities: *In situ*, real time imaging to track individual nm-sized defects during Irradiation

In situ movie shows irradiation defect formation, motion, and coalescence to form extended dislocation structure.



M. Hernandez-Mayoral, Z. Yao, M. Jenkins, M. Kirk, "Heavy-ion irradiations of Fe and Fe-Cr model alloys Part 2: Damage evolution in thin-films at higher doses," *Phil Mag* 88(21), 2881 (2008).

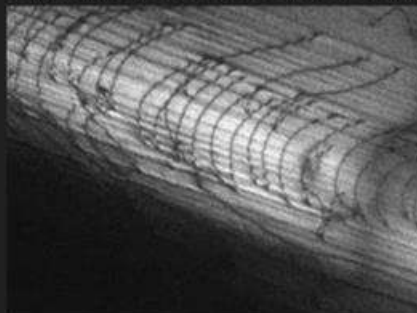
11 video files included in the publication revealed:

- One-dimensional hopping of small dislocation loops
- Dislocation loops with BV = <111> highly mobile in direction of BV.
- Dislocation loops with BV <100> sessile.
- Loop hopping was much less common in Fe-Cr alloys
- Some formed over 0.2 sec consistent with cascade overlap mechanism.
- Dislocation loop coalescence in string alignment.
- Temperature dependence, only <100> loops at ≥500°C.

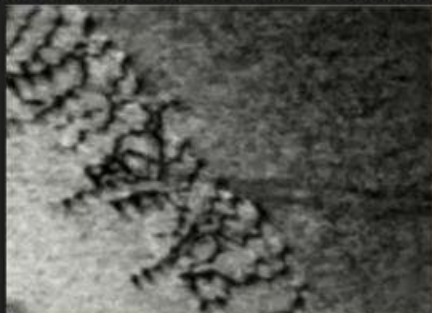
Slide 7

Unique Experiment – Defect and Dislocation Interactions under Irradiation+Temperature+Load

304 SS irradiated *in situ* at 400°C with 1 MeV Kr ions to dose of 3x10¹³ ions/cm².



Without ion irradiation



With ion irradiation

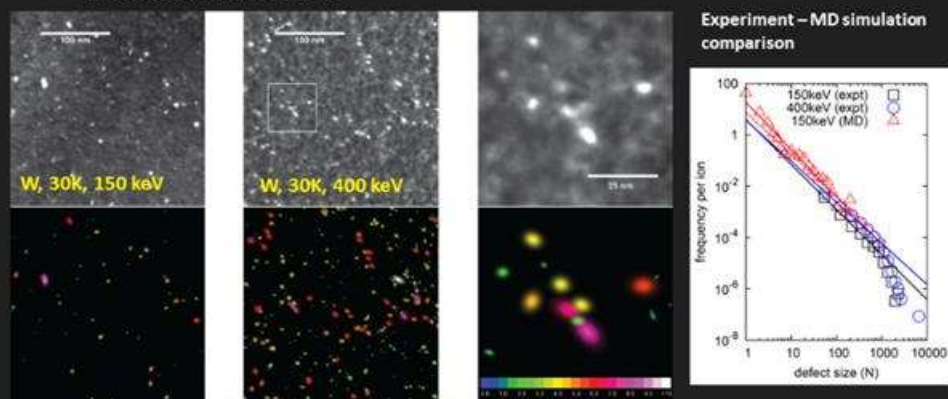
- Direct insight to the mechanisms by which dislocations interact with and annihilate radiation defects to create channels, dispelling some of the common held beliefs about the processes and mechanisms.
- New insight as to how strain is transferred across grain boundaries in irradiated metals, the results of this effort have identified the deterministic step in irradiation stress corrosion cracking.

J. Kacher, I. M. Robertson, *Acta Mater.* 60 (2012) 6657. M. Briceño et al., *J. Nucl. Mater.* 409 (2011) 18.

Unique Experiment – *in situ* Observation of Cascade Damage Events at liquid He Temperature

Unique Experiment – *in situ* Observation of Cascade Damage Events at liquid He Temperature

- The cryogenic temperature irradiation makes it possible to observe the primary cascade events by suppressing defect diffusion.
- The *in situ* TEM observations can be directly compared with MD simulations of cascade damage events.

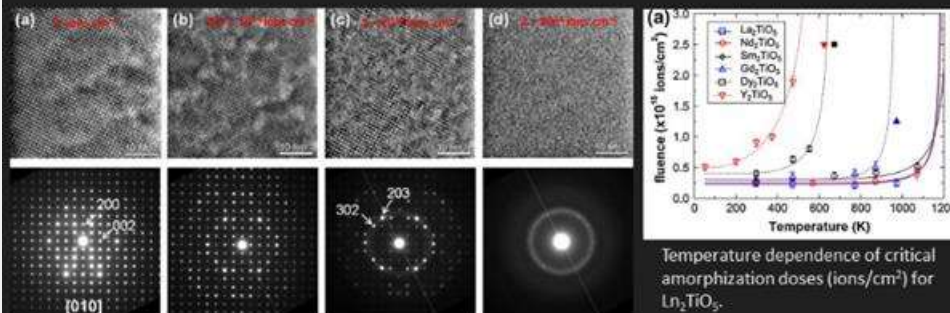


(X. Yi, et al, *Europhysics Letters* 110 (2015) 110.)

Unique Experiment – Mapping Temperature-Dependent Critical Doses for Amorphization of Wasteforms

Unique Experiment - Mapping Temperature-Dependent Critical Doses for Amorphization of Wasteforms

- The temperature dependence of the critical amorphization dose was determined *in situ* for a wide temperature range of 50 – 1073 K under well-controlled experimental conditions at the IVEM-Tandem
- This information can only be obtained *in situ* at the temperature because of spontaneous crystallization during warm-up of the specimen.



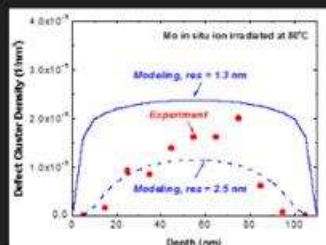
J. Zhang, F. Zhang, M. Lang, F. Lu, J. Liao, R. Ewing, *Acta Mater.* 61 (2013) 4191.

Diffraction Contrast Electron Tomography

3D Characterization of Defect Distribution near Surfaces/Interfaces



3D imaging of spatial distribution of 2 nm dislocation loops in Mo thin foil irradiated with 1 MeV Kr ions at 80°C.

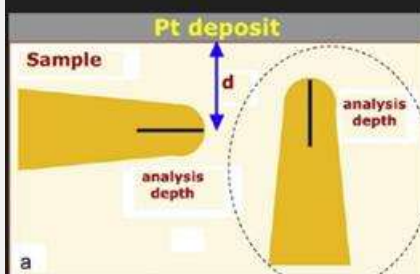


Comparison between tomography data and the model calculations with two different resolution ("res") limits, 1.3 nm and 2.5 nm, respectively.

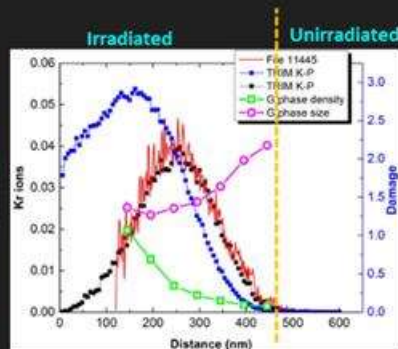
Meimei Li, M.A. Kirk, P.M. Baldo, Donghua Xu, and B. D. Wirth, *Phil Mag.* 92 (2012) 2048.

Coupling with *ex situ* APT

Coupling with *ex situ* APT

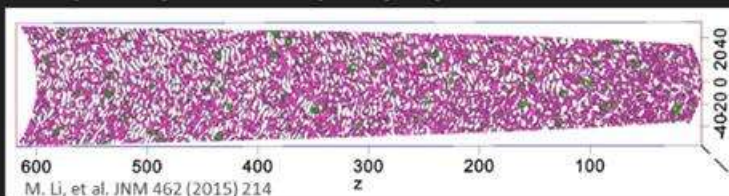


APT specimens can be extracted perpendicular or parallel to the ion irradiation surface.



CF-8
 $T_{ir} = 400^\circ\text{C}$
 Fluence =
 1.88×10^{15}
 ions/cm²

$\alpha - \alpha'$ phase separation and G-phase precipitates in ferrite of CASS CF8



M. Li, et al. *JNM* 462 (2015) 214

Radioactive Materials Handling

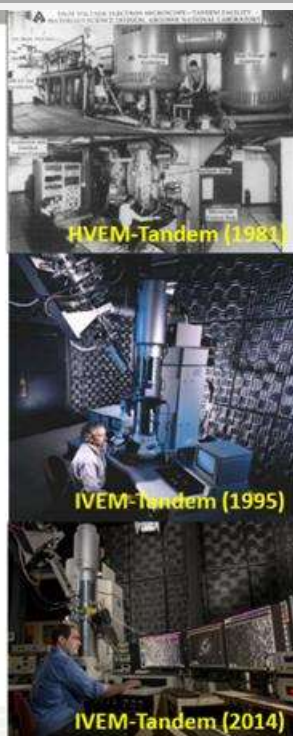
- Radioactive samples have been irradiated at the IVEM-Tandem
 - Low-dose neutron-irradiated steels
 - Nuclear fuels: U, U-Mo, UO_2 , etc.
- Irradiated Materials Laboratory (IML)
 - A radiological Facility in the same building
 - Electro-polishing (Tenupol-5) of radioactive TEM specimens in IML
 - Argonne Nuclear Engineering Division operates both IVEM-Tandem and IML
- Radioactive material characterization using synchrotron X-rays is routinely carried out at the Advanced Photon Source



Facility History and Current Status

Facility History and Current Status

- The 1st generation, **HVEM-Tandem** user facility was commissioned in 1981 in Materials Science Division, ANL, supported by DOE BES.
 - A high-voltage electron microscope (HVEM) interfaced with two accelerators (2 MV tandem and 650 kV ion implanter).
- The 2nd generation, **IVEM-Tandem** was commissioned in 1995, and was part of Argonne's Electron Microscopy Center supported by DOE BES until 2014.
 - Increased imaging spatial resolution by nearly one order of magnitude
- DOE NE and ANL signed Memorandum of Agreement in May 2014 for full time operation of IVEM-Tandem to support nuclear energy research.
- The Facility was transitioned to Nuclear Engineering Division, ANL in June 2014.
- In FY 2016, the IVEM-Tandem received 50% DOE NE support through NSUF.



User Projects in FY15 – FY16

User Projects in FY15 - FY16

- Areva
- Argonne National Lab
- Australian Nuclear Science and Technology Organization (ANSTO)
- CEA
- China University of Petroleum-BEIJING
- Drexel University
- Idaho National Lab
- Los Alamos National Lab
- Louisiana State University
- Massachusetts Institute of Technology
- Michigan State University
- North Carolina State University
- Northwestern University
- Oak Ridge National Lab
- Peking University, China
- Penn State University
- Purdue University
- Queen's University
- Rensselaer Polytechnic Institute
- Stanford University
- TerraPower
- Texas A&M University
- University of California - Berkeley
- University of Florida
- University of Illinois - Urbana
- University of Nebraska-Lincoln
- University of Oxford
- University of Pittsburgh
- University of South Carolina
- University of Tennessee
- University of Wisconsin - Madison

- 40 IVEM user proposals
- FY16 NSUF RTEs:
 - 1 awarded, 3 under review
- 31 institutions (universities, national labs, nuclear industry, international)
- ~80 users
- Fully-booked with >50% over-subscription



1. Can IVEM operate longer hours if funding was expanded?
2. With sufficient staff support, it can operate longer hours.

User Research

User Research

- All user projects are nuclear related. A majority of user projects are funded by NEUP, supporting FCRD, ART, NEAMS, NEET programs. User projects have also been funded/performed by nuclear industry (e.g. EPRI, TerraPower, Areva).
- User Research Areas
 - Fundamental understanding of defect dynamics under irradiation, temperature and stress
 - Validation and verification of computer modeling and simulations of radiation damage
 - Developing advanced radiation-resistant nuclear fuels, cladding and structural alloys, and waste storage materials
 - Developing advanced accident tolerant materials and fuels
 - Developing new material design concepts, e.g. nanostructured materials, high-entropy materials, for enhanced radiation resistance
- High Productivity
 - > 100 publications in the past four years; many of them are published in premier scientific journals with high impact, e.g. Nature, Science
 - Numerous invited and contributed talks at national and international meetings
- Education and Training
 - ~30 PhD student theses in 4 years based on research conducted at the IVEM-Tandem

FY 2015 (229 operation days)

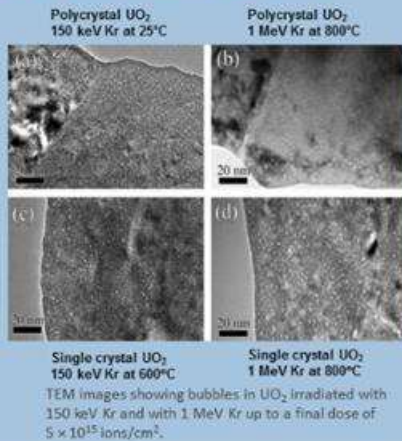


15

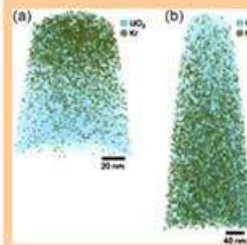
Microstructural Evolution in UO_2 under Irradiation (INL)

- Understand the nucleation and evolution of inert gas bubbles in UO_2

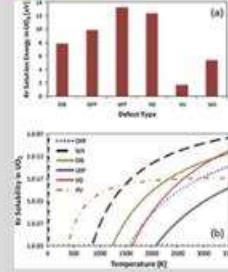
In situ Ion Irradiation with TEM



Atom Probe Tomography



Density Function Theory Calculations



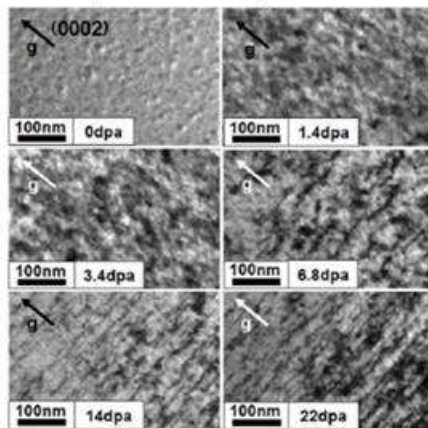
(a) Kr solution energy at 0 K under oxygen-rich condition from DFT calculations in UO_2 and (b) Kr solubility in UO_2 as a function of temperature, contacting with 1 atm air or oxygen with 0.21 atm partial pressure.

L.F. He, B. Valderama, A.-R. Hassan, J. Yu, M. Gupta, J. Pokarinen, H.B. Henderson, J. Gan, M.A. Kirk, A.T. Nelson, M.V. Manuel, A. El-Azab, T.R. Allen, *J. Nucl. Mater.* 456 (2015) 125.

16

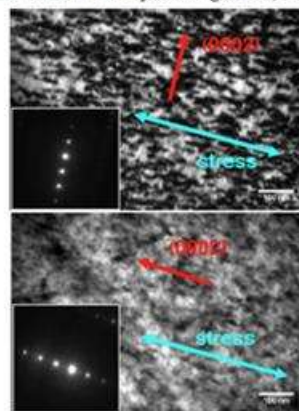
Areva Project: Effect of Stress on Loop Formation in Pressurized Water Reactor Guide Tube

Dose-dependent <c>-loop formation in M5



(*J. Nucl. Mat.* 423, 170-182 (2012))

Influence of tensile stress on <c>-loop formation in adjacent grains, Zry-4



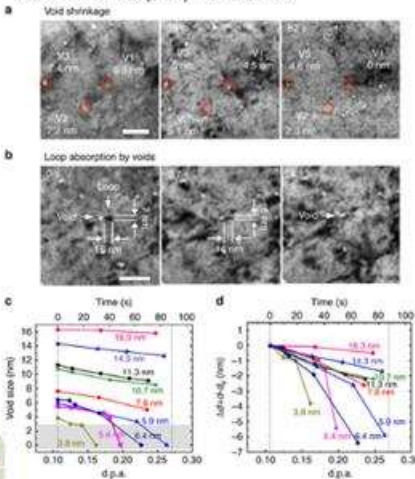
(to be published)

R.M. Hengstler-Eger and W. Petry (Technische Universität München, Germany)
P. Baldo and M.A. Kirk (Argonne National Laboratory, EMC)
P.B. Hoffmann (AREVA NP GmbH, Germany)

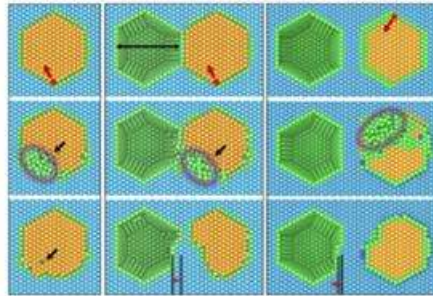
17

Exploring New Alloy Design Concept: Radiation-tolerant Nanotwinned Metals with Nanovoids (Texas A&M, PI: X. Zhang)

In situ Kr ion irradiation studies of nv-nt Cu unravelling continuous shrinkage of nanovoids and absorption of mobile dislocation loops by nanovoids.



MD simulation reveals dynamic process through which a void absorbs a neighboring dislocation loop.



Y. Chen, et al., Nature Communications 6 (2015), 7036.

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Support Verification and Validation of Modeling and Simulation

Support Verification and Validation of Modeling and Simulation

- Many experiments at the IVEM-Tandem are performed to benchmark computer models designed to simulate both ion and neutron irradiation damage;
- Experiments are carried out under **highly-controlled conditions** that allow producing high-quality data for single-mechanism studies or studies of collective behavior
- In situ* TEM observation of heavy ion irradiation damage reveals **cascade damage phenomena**, e.g. single cascade events, cascade – cascade or cascade – subcascade interactions, cascade defect production and annihilation rates, and the experimental data can be directly compared with molecular dynamics simulations of cascade damage.
- In situ* ion irradiation can access **the full history of the kinetic development of the defect structure under irradiation**, providing critical input into the computer models of microstructural evolution during irradiation that determines the lifetime of materials in nuclear systems.
- The high-quality experimental data obtained at the IVEM-Tandem Facility provided useful data for validating the nuclear materials and fuels models being developed under the DOE **Consortium for Advanced Simulation of Light Water Reactor (CASL) and the Nuclear Energy Advanced Modeling and Simulation (NEAMS) programs.**

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Predicting Neutron Irradiation Damage from *in situ* Ion Irradiation through Computer Modeling

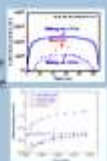
In situ Ion Irradiation Experiments

Well-controlled TEM with *in situ* ion irradiation experiments of thin foils were designed to improve and validate computer models. Experimental data provide a complete set of high-quality, quantitative information, and described the defect behavior at a level of detail unavailable before.



Experiment-Simulation Comparison

Quantitative, absolute comparisons between experiments and modeling at the same spatial and time scales have led to the establishment of accurate, reliable computer models.



Computer Simulations

Multiscale modeling to simulate defect evolution from atomic-scale, pico-second events to nanometer-scale, hour evolution of defect structures.



Prediction of Neutron Damage in Reactors

The experimentally-validated model for ion irradiated thin foils is used to predict neutron damage in Mo irradiated in a reactor, and validated by neutron irradiation data.



Meinel G, M.A. Kirk, P.H. Balds, Donghua Xu, and B. D. Wirth, *Phil Mag. B37* (2012) 3048.
D. Xu, B. D. Wirth, M. Li, and M. Kirk, *Acta Mater.* 60 (2012) 4286.

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Summary

Summary

- TEM with *in situ* ion beam irradiation coupled with computer modeling and simulation provides a new way to understand radiation effects, critical to the development of new high-performance materials and predictive models to reliably forecast material component lifetimes in a nuclear reactor environment.
- The IVEM-Tandem Facility is a world-class facility for *in situ* study of defect dynamics in nuclear reactor materials, fuels, and waste storage materials. User projects support DOE NE's FCRD, ART, NEAMS programs and nuclear industry needs.
- Given the great scientific impact of the IVEM-Tandem research to advance the DOE-NE missions, the high productivity of its users, its importance to education and training of next-generation scientists and engineers, and the potential for future growth, support for the IVEM-Tandem as a user facility should be a priority investment for the DOE Office of Nuclear Energy.

21

Support Letters from the Community

- Stuart A. Maloy, Los Alamos National Laboratory
- T.-L. (Sam) Sham, Argonne National Laboratory
- Tiangan Lian, Electric Power Research Institute
- Rosmarie HENGSTLER-EGER, AREVA
- Arthur T. Motta, Penn State University
- Brian Wirth, University of Tennessee
- James F. Stubbins, University of Illinois at Urbana-Champaign
- Ian M. Robertson, University of Wisconsin – Madison
- Jian Gan, Idaho National Laboratory
- Michael Nastasi, University of Nebraska – Lincoln
- William J. Weber, University of Tennessee
- Mitra L. Taheri, Drexel University
- Djamel Kaoumi, University of South Carolina
- Xinghang zhang, Texas A&M



Presentation: Extreme Materials Beam Line

Abdellatif Yacout

Slide 1



Extreme Materials Beam Line (XMAT)

Abdellatif M. Yacout,
Nuclear Engineering Division
Argonne National Laboratory

NSUF Ion Beam Investment Options Workshop
March 22-24, 2016



Outline

Outline

- Overview
- Unique Capability of XMAT
- Impact to DOE-NE Programs
- Technical Demonstration
- Budget

Proposal - eXtreme MATerials beamline (XMAT)



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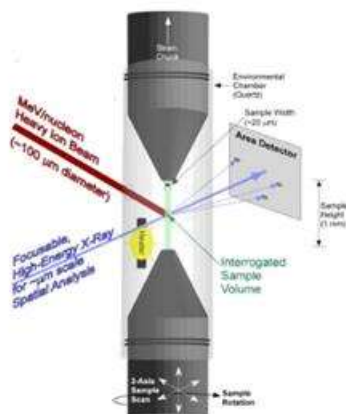
Proposal - eXtreme MATerials beamline (XMAT)

A new beamline at the Advanced Photon Source (APS) for in situ studies of materials under irradiation, temperature, stress, environmental, etc.

XMAT will provide x-ray probes for *in-situ* study of materials in simulated extreme radiation environments, enabling rapid evaluation of materials performance under extreme service conditions including structural materials and in particular for nuclear fuels.

XMAT is made possible by combining the technology of Argonne's unique capabilities:

1. **Energetic, Heavy Ion Beams** (ATLAS- Argonne Tandem-Linac Accelerator System)
2. **Focusable, High Energy X-Rays** (APS)
3. **Multi-modal Imaging** (APS)

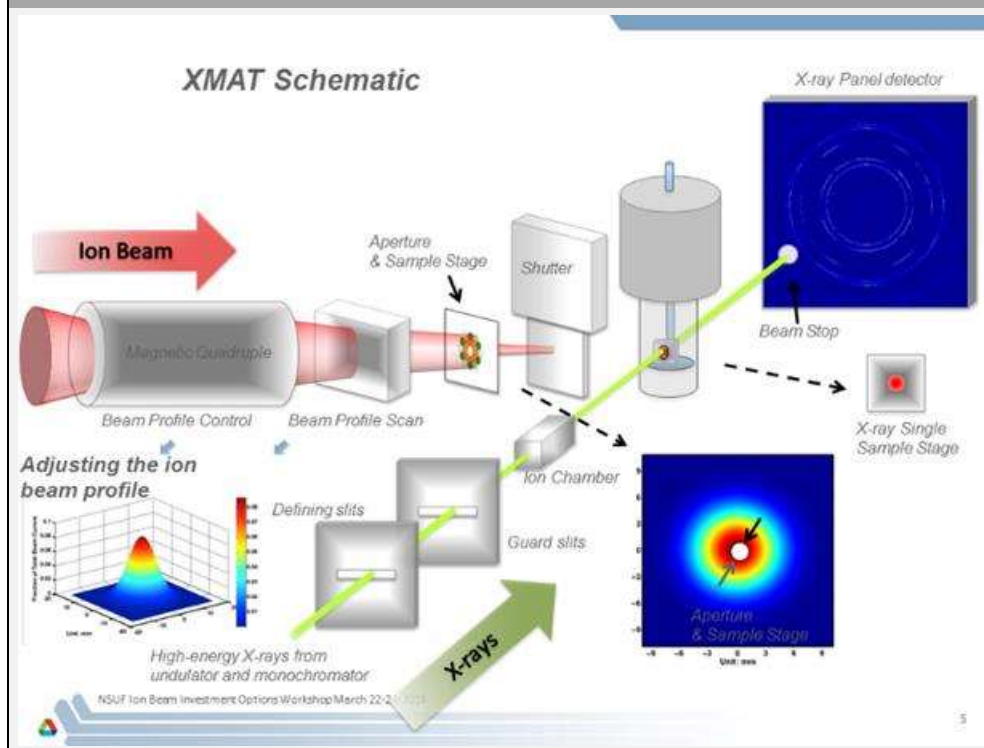


Opportunity Window -> APS/ATLAS Upgrades

Timeline of XMAT

Timeline of XMAT





What's Unique? – High-Energy Ion Irradiation ($H \rightarrow U$)

What's Unique? - High-Energy Ion Irradiation ($H \rightarrow U$)

In Situ, High Energy Ion Irradiation (HEI) C2

- > Damage Rates to 25 DPA/hour (controllable)
- > Damage Doses to >2000 DPAs
- > ~1 MeV/nucleon heavy ion irradiation (e.g. 150 MeV Xe)

X-Ray Line (30 < E < 100 keV) C4

- > Diffraction: Shape, size, orientation of single grains
- > Scattering: defect distributions, aggregate response
- > SAXS: nanoscale voids, bubbles, particles
- > Tomography: three dimensional imaging, scattering
- > APS upgrade

Sample Container

- > Isolated containment
- > In situ strain & thermal gradients
- > Volumes as small as 500 μ^2 minimizing radioactive materials inventories

- In-situ Radiation Damage and Characterization
 - Dynamics
 - Structural evolution
 - "Bulk" measurement
- High energy beam : 1 MeV/nucleon or higher; examples: 4 MeV He ion; 56 MeV Fe ion; 238 MeV U ion. **C2**
- All types of ions: $H \rightarrow Fe \rightarrow U$; almost any element in periodic table and multiple beams (same charge/mass ratio); multiple sample irradiations. **C2**
- High & easily variable damage rate: characterization of dose rate dependence of materials changes – crucial to accelerated materials testing. **C2**



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1. What ion flux is available?
2. High current beams will result in significant sample heating. This will likely require active cooling.

What's Unique? – Fission Fragment Damage!

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In Situ, High Energy Ion Irradiation (HEI) C2

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X-Ray Line (30<E<100 keV) C4, C6

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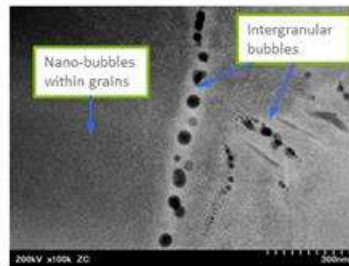
Sample Container

- > Isolated containment
- > *In situ* strain & thermal gradients
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Nuclear Fuel R&D C5

- Directly replicate the high-energy (~100 MeV) fission fragments to study microstructural development in fuels
- Induce high damage level (dpa) in fuels
- Applicable to already neutron-irradiated fuel to achieve higher burnup level
- Gaseous, miscible and immiscible fission products

From SRIM computation, the maximum damage level by applying 1 MeV Kr to UO_2 is a few hundreds dpa due to ion sputtering; we are looking at 1000 to 10000 dpa level for fuel materials



80 MeV Xe implanted U-Mo fuel @ ATLAS C1

1. What is the planned imaging resolution?

What's Unique? – Peak Damage & spatial separation

What's Unique? - Peak Damage & spatial separation

In Situ, High Energy Ion Irradiation (HEI) C2

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Sample Container C3, C4

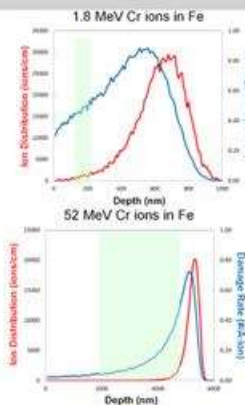
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Structural Materials Study C5

- Deeper damage profile: minimize interference from both surface and added interstitials
- Achieve high radiation dose levels



What's Unique? – Peak Damage & spatial separation

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Sample Container C3, C4

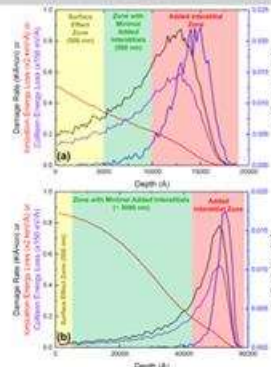
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Damage Profiles Induced by 5 MeV & 54 MeV Fe ions in Steel (SRIM Simulation)

What's Unique? – In Situ Studies in Extreme Environments

What's Unique? - In Situ Studies in Extreme Environments

In Situ, High Energy Ion Irradiation (HEI) C2

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X-Ray Line (30<E<100 keV) C4, C6

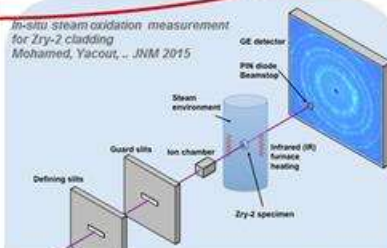
- > Diffraction: Shape, size, orientation of single grains
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Sample Container C3, C4

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- > Volumes as small as 500 μ^2 minimizing radioactive materials inventories

HEI/X-Ray in situ study provides:

- A direct probe of rate effects under radiation damage including the ability to assess the competition between evolving radiation sinks such as interfaces in e.g. ODS steels
- Direct measure of the rate competition among combined effect of dpa and other in-situ parameters (temp., stress, Corrosion [steam, oxidation, etc], ..)
- Insight into structural effects that lead to non-linear rate effects at high doses
- Direct measure of the parameters necessary to understand the effects of accelerated testing



=> In situ provides the ability to mimic the nuclear environment at critical moments providing a direct connection to material performance in a reactor

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Impact on NE Research Programs C5

- Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program:**

- Support fuel and cladding model development and validation for NEAMS codes (e.g., MARMOT code) – single effects:
 - Microstructural evolution, e.g., grain growth, fuel gas & bubble mobility, bubble resolution, recrystallization (HBS rim), ...
 - In-situ characterizations provide key kinetic data on nucleation, diffusion & growth, and 3D structural evolution (temp, stress, dpa,...)
- Modeling new fuel & cladding material behavior; e.g., USi for ATF (ATF-HIP), advanced structural alloys to high dpa.

- Advanced Fuel Campaign (AFC):**

- Accelerate development of high burnup metallic fuel & advanced LWR fuel (USi, UMo, ...) through emulation of fission fragments damage to high burnups (1000's dpa) and associated gas accumulation and release
- Transmutation fuel (4MeV He to emulate a decay & transmutation+100MeV Xe, I, ...); inert matrix fuel with fission fragments damage in both fuel and inert matrix materials

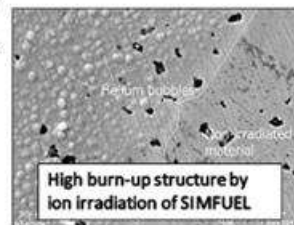
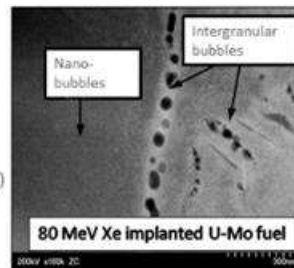
- ARC and LWRs Programs:**

- Advanced structural materials R&D (ARC); high dpa, in-situ bulk characterization (stress, temperature, dpa)
- Pressure vessel materials, high burnup UO₂ (LWRs)

- Waste Management:**

- Effects of radiation damage on waste form-4MeV He

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Baranov, JNM, 452, 2014

1. How do you control beam heating when producing high burnup structure?

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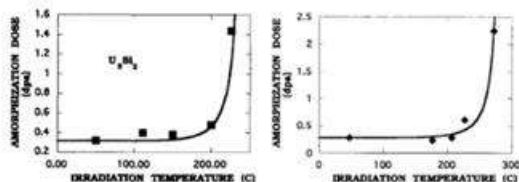
Applications to Oxide and Silicide Fuels C5

- Defect Evolution in Uranium Dioxide:**

- Emulate ~1 MeV/amu fission fragment energy
- Use low energy noble gas (Xe, Kr) ions to implant gas atoms; use high-energy (~1 MeV/amu) solid fission products (Zr, I) ions
- Replication of defect structures observed in in-pile irradiated fuels

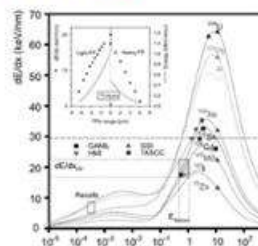
- Amorphization Threshold of Silicide Fuels**

- In situ investigation of the amorphization threshold at low temperatures using IVEM-Tandem
- This dynamic process takes place at low dose and can hardly be captured in in-pile irradiated fuels

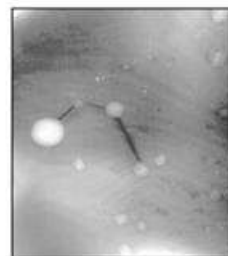


Amorphization threshold of U₃Si₂ and U₃Si by in situ ion irradiation (Bircher, 1996&1997)

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Energy domain of fission fragments and corresponding energy loss rate in UO₂ (Matzke, 2000)

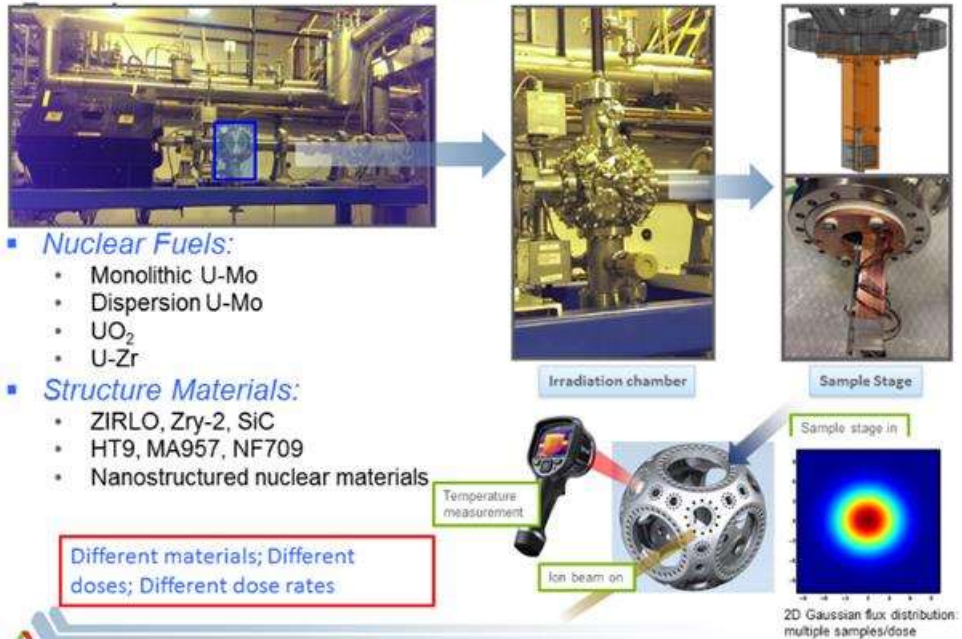


Gas bubble formation induced by 40 keV Kr implantation and 72 MeV I irradiation in UO₂ (Matzke, 2000)

12

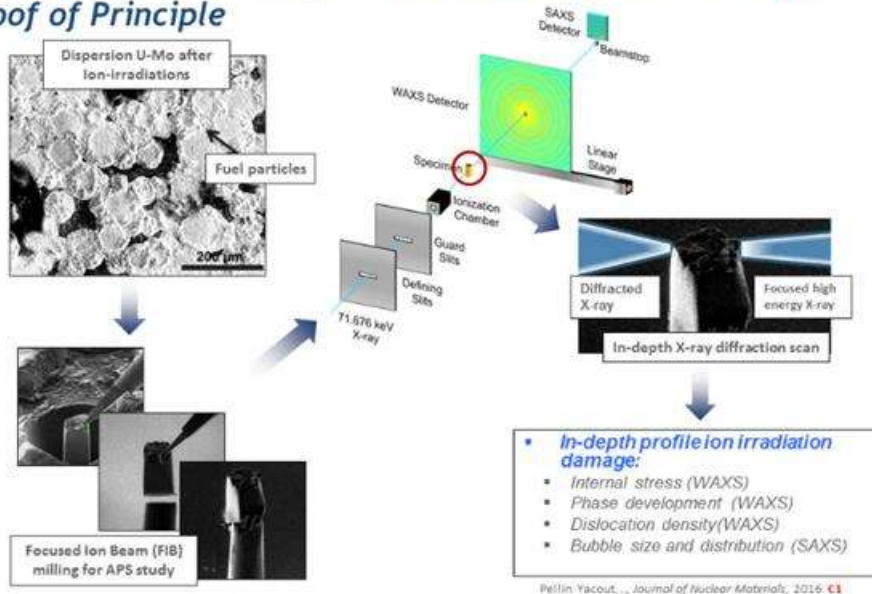
Proof of Principle ATLAS Irradiation Experiments

Proof of Principle ATLAS Irradiation



APS Characterization of Ion-irradiated Nuclear Fuels C1 Proof of Principle

APS Characterization of Ion-irradiated Nuclear Fuels C1 Proof of Principle



Technique Demonstration: Ion-irradiated Nuclear Fuels C1, C8

Technique Demonstration: Ion-irradiated Nuclear Fuels C1, C8

Phase development of U-Mo:

- Only ion-radiation damaged region preserves γ -UMo phase; phase transformation of γ -UMo to (α -UMo + U_2Mo) in the unirradiated region.

Replicated the γ -UMo phase stabilization by neutron irradiation

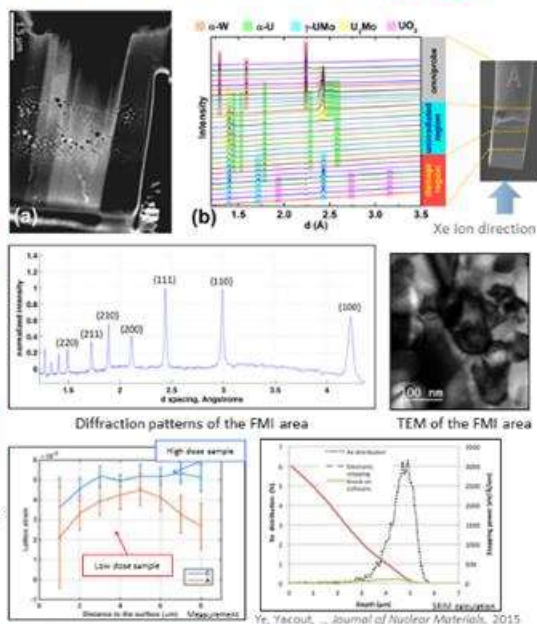
Phase development of FMI:

- FMI was found to be nano-crystalline (U, Mo) Al_3 structure by using both XRD and TEM

Replicated the neutron irradiation driven FMI formation

Lattice strain analysis

- Lattice strain gradients development as a function of dose/Xe concentration
- The strained regions observed in the experiment reasonably agree with the results from SRIM computation

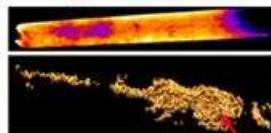


Technique Demonstration: other synchrotron techniques used in studying ion-irradiated materials C1, C8

Technique Demonstration: other synchrotron techniques used in studying ion-irradiated materials C1, C8

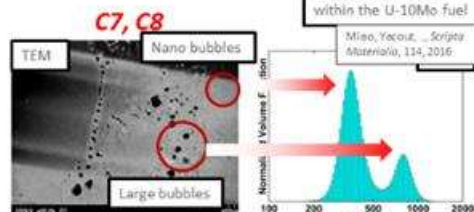
X-ray Tomography Microscopy (XTM, Nano-tomography):

- Characterization of bubble morphology and distribution in Xe irradiated U-10Mo monolithic fuel



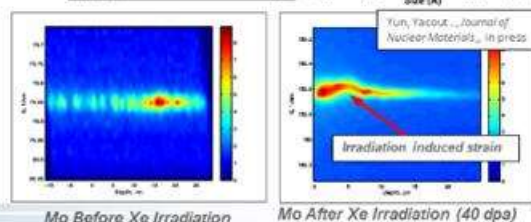
Small Angle X-ray Scattering:

- Characterization of bubble superlattice, and other bubble structures in fuel
- Characterization of nano- and micro-structural development in structural materials



X-ray micro-diffraction:

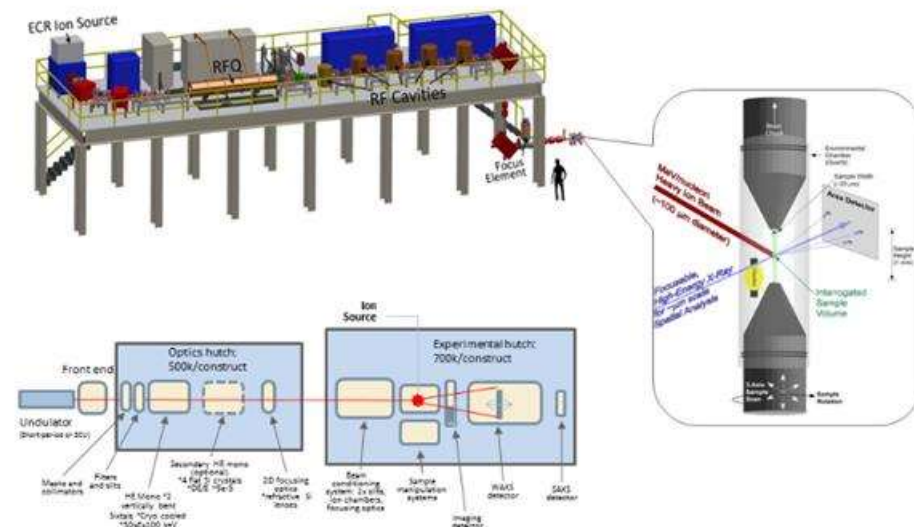
- Characterization of irradiation induced strain development



- Sample size for unirradiated fuel = 1 mm. Irradiated fuel at 10% BU = FIB sample.

XMAT Layout

XMAT Layout

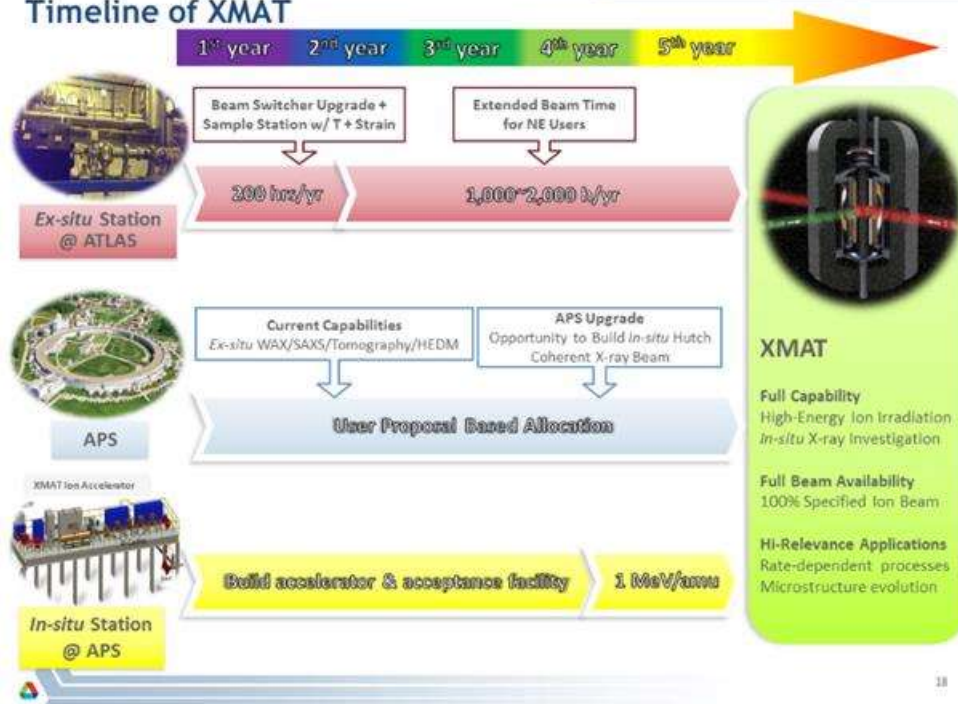


NSUF Ion Beam Investment Options Workshop March 22-24, 2016

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Timeline of XMAT

Timeline of XMAT



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XMAT Schedule and Cost

XMAT Schedule and Cost

A phased approach allows achieving **an operating system within the first year**. Initial operation would allow irradiation at ATLAS (200 hrs first year, 30% of operational days within the two years). In situ operation at APS would come online as the APS upgrade is completed (5 years).

		Description	Achieves	Costs
Year 1	Phase 1	Design & Build multiuser beam switcher at ATLAS and irradiation station	Full beam capability for 30% of yearly operating hours for NE programs - (Until complete 200 hrs of beam time will be allocated)	\$2M (ANL contributes \$0.5 M for design)
	Phase 2	Begin XMAT full accelerator design for APS		\$2 M
Year 2	Phase 1	Complete & Test	Full beam capability for 30% of yearly operating hours for NE programs (ex situ)	\$1 M
	Phase 2	Begin acquisition and testing of accelerator components		\$3 M
Year 3-5	Phase 1	Ex Situ Irradiation Facility operates for 30% of yearly operating hours (~2400 hrs of beam time for NE programs)		\$1M / yr
	Phase 2	Complete operation as part of APS-U beam line	Full in-situ analysis under APS user program + 100% irradiation time	\$3 M / yr
Total Cost Build Cost				\$20 M
Out year operational Costs		ATLAS facility ceases operation	Ion source 1 man year, 3 man year user support & x-ray	\$1.5 M/yr



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Key XMAT Advances

Key XMAT Advances

In comparison to most existing ion irradiation capabilities, the XMAT ion energies and currents are ~100 times higher. The increased ion irradiation energy (e.g., 133 MeV for xenon) enables several critical advances:

- It provides a unique opportunity to **simulate the effects of fission fragments** in nuclear fuels, where ions of all elements can be accelerated to fission fragment energies, while being characterized *in situ*.
- For cladding and structural materials, the **increased penetration depth** of energetic ions allows the "bulk behavior" to be examined, eliminating surface-sink effects, and allows understanding of individual physics of ion damage including electronic, collisional, & added interstitial
- The **in situ penetrating ability** of the APS focusable hard x-rays, applied during ion irradiation, is another key advancement of XMAT that allows the interrogation of individual grains within solid material samples during irradiation.
- With this information and related **computational modeling**, the differences between ion and neutron irradiation as well as the impact of fission products damage become much more understandable.

XMAT can close the design loop for the nuclear materials community in two ways:

- 1) It provides accelerated testing for hundreds of samples (24; 7)
- 2) It reveals the key "single" physics dependences required for accurate computational modeling



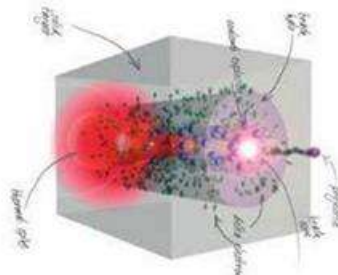
20

BACKUP



Nuclear Waste Forms

- Radioactive decay in waste form materials heats typical structures to ~ 100 C.
- This temperature is reached in a complex way as alpha particles electronically excite waste form materials resulting in high temperatures along 10 nm diameter cylinders with heights extending to 15 microns.
- These cylinders after the passage of the alpha have 20% lower density and many dangling atomic bonds.
- The effect of this radiation on important waste form properties (diffusion, leaching and corrosion) has not been detected, in part, because percolation – the overlap of these tracks – will not occur for many decades.
- XMAT allows an understanding of the effects (diffusion, leaching and corrosion) on individual tracks.
- Theory can then be used to accurately extrapolate to decades and centuries.



Presentation: Capabilities at the Idaho Accelerator

Jon Stoner

Slide 1

Idaho State
UNIVERSITY



Slide 2



The Idaho Accelerator Center:

Jon Stoner – Operations Director

Wendland Beezhold – Director / Faculty Chair

Rick Spielman – Assistant Director



Idaho Accelerator Center
Idaho State University



Idaho State University RISE Complex



Dr. Eric Burgett
Director, RISE Complex
Idaho State University



Idaho Accelerator Center Operating for 20 Years

- Founded in 1994
 - Center at Idaho State University
 - Chartered by State Board of Education
 - Dr. Frank Harmon founding Director
- Mission
 - Applied physics and engineering research
 - Graduate and undergraduate education
 - New accelerator applications
 - Support economic development
- ISU Physics and Nuclear Engineering
 - Faculty : Nuclear Science orientation
 - Graduate MS/PhD programs



ISU RISE Complex

- Unique intersection of nuclear science and nano-technology.
- "Hot" nano-scale fabrication laboratory
- All tools are rated for radioactive material use.
- Radioactive materials license allowing flexibility with most radionuclides including $Z > 83$



BRINGING THE NANO-SCALE INTO EVERYDAY LIFE

World-class capability to research and develop functionalized nano-materials and devices



IAC/RISE Beam line capabilities

IAC/RISE Beam line capabilities

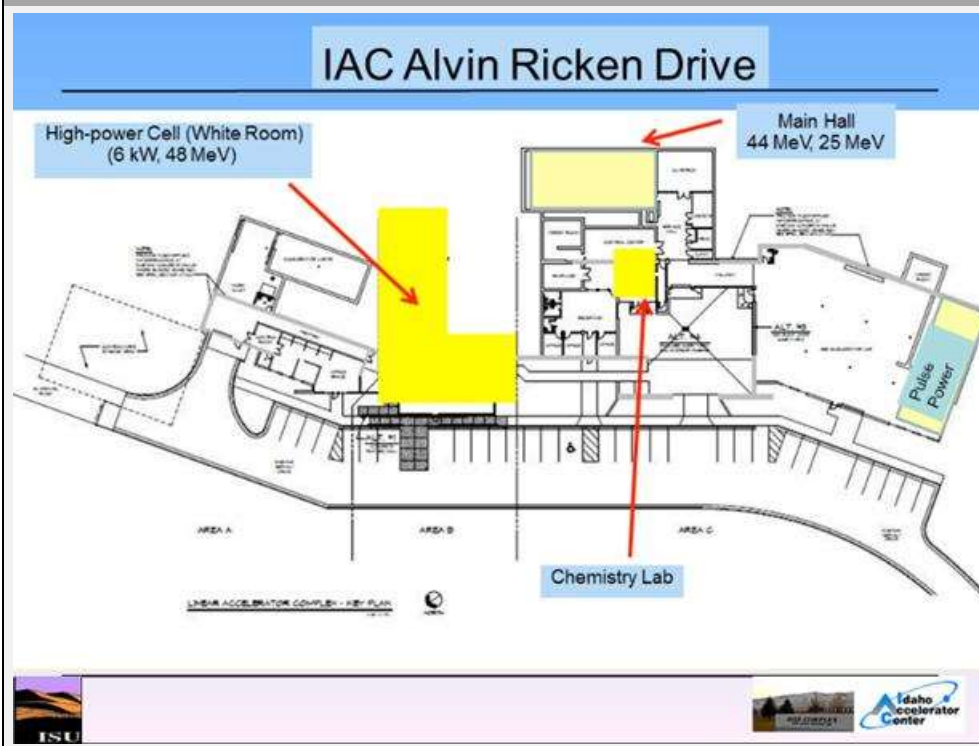
HARDWARE

- **eLINACs**
 - 44 MeV – L-Band, short pulse to 70 ps
 - Zero and 90° ports
 - Experimental Cell
 - 45 MeV – S-band, power to 8 kW
 - Water cooled target chamber
 - Separate Cell
 - (2) 25 MeV – S-band, power to 2 kW
 - Zero, 45°, 90° ports
 - Experimental Cell
 - Radiography equipment
- **Pulse Power electronics**
 - 3 MeV, 20 kA
 - 8 MeV, 10 kA
- **Protons**
 - 4 MV (8MV) Pelletron 200 uA
 - 17 MeV, 50 uA JSR for installation
- **Instrumentation**
 - TEM, SEM, FIB
 - RadioChemistry Lab with ICP-MS
 - HPGe detectors,
 - Multiple Bins for rack mount instrumentation

Capabilities

- **Isotopes via (γ, n)**
 - Commercial shipments of ^{67}Cu
 - Investigations and yield analysis of:
 - ^{135}Xe , ^{139}I ,
 - ^{133}Xe , ^{131}I ,
 - ^{125}Xe , ^{123}I ,
 - $\text{Kr}(\gamma, n)$
 - $\text{Zr}(\gamma, n)$
 - ^{237}U
 - Isotope separation Development
 - Neutron source development
- **Photon Activation Analysis**
 - Nuclear material forensics
 - Raw material analysis (Ores)
- **Radiography of dense materials**
- **Applied Low Energy Nuclear Physics**
 - Laser Compton Scattering
 - Positron production
 - Material Defect analysis
 - Nuclear reaction cross sections
 - LINAC produced Neutrons





44 MeV LINAC (Main Hall)

44 MeV LINAC (Main Hall)

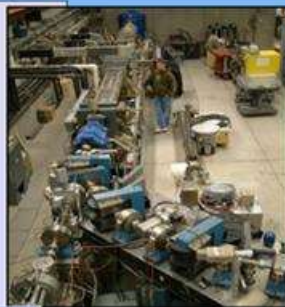
RF Frequency: 1300 MHz (L-Band)

Energy Range: ~2-44 MeV (current varies)

Pulse Width: ~60ps (Bunched only) to 2 micro seconds (certain discrete widths only)

Repetition Rate: single pulse to 180 Hz

Ports: 0 degree and 90 degree (Beam energy resolution ~ 1+/- 15%)



Pulse Width	Maximum Current	Charge/Pulse	Peak e-Dose	Peak Gamma Dose**
50ps	100A	5nC	2×10^{13} rads/s	2.5×10^8 rads/s
2ns	3A	20nC	1×10^{12}	1.2×10^7
20ns	1A	60nC	6×10^{11}	7.5×10^6
100ns	1A	100nC	2×10^{11}	2.5×10^6
2μs	0.5 A	2000nC	1×10^{11}	1.25×10^6

25 MeV LINAC (Main Hall)

25 MeV LINAC (Main Hall)

RF Frequency: 2856 MHz (S-Band)

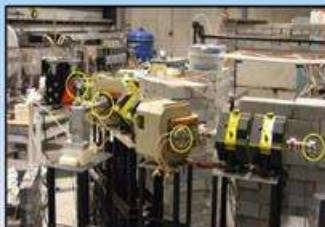
Energy Range: ~4~25 MeV (current varies)

Pulse Width: ~50ns to 4 micro seconds

Repetition Rate: single pulse to 360 Hz

Ports: 0 degree, 45 degree and 90 degree (Beam energy resolution ~ 1 +/- 15%)

Energy (MeV)	0 port (mA)	45 port (mA)	90 port (mA)
23	55	55 @ 3.8 uS	46 @ 3.6 uS
20	100	70 @ 4 uS	65 @ 4 uS
16	100	48 @ 3.6 uS	48 @ 3.6 uS
13	80	30 @ 3.3 uS	15 @ 3.3 uS
10	60	18 @ 3 uS	7.5 @ 3 uS
9	110	30 @ 4 uS	15 @ 4 uS
6	100	80 @ 4 uS	60 @ 4 uS
4	30	20 @ 4 uS	20 @ 4 uS



48 MeV, 8 kW Electron LINAC, (White Room)

48 MeV, 8 kW Electron LINAC, (White Room)

RF Frequency: 2856 MHz (S-Band)

Energy Range: ~25-48 MeV (current varies)

Average Current: 10-150 uAmps

Pulse Width: ~1 to 9 micro seconds

Repetition Rate: single pulse to 300 Hz

Ports: 0 degree, 45 degree

Special features: High power water cooled target



Tri-Mev

Pulse Power Accelerator

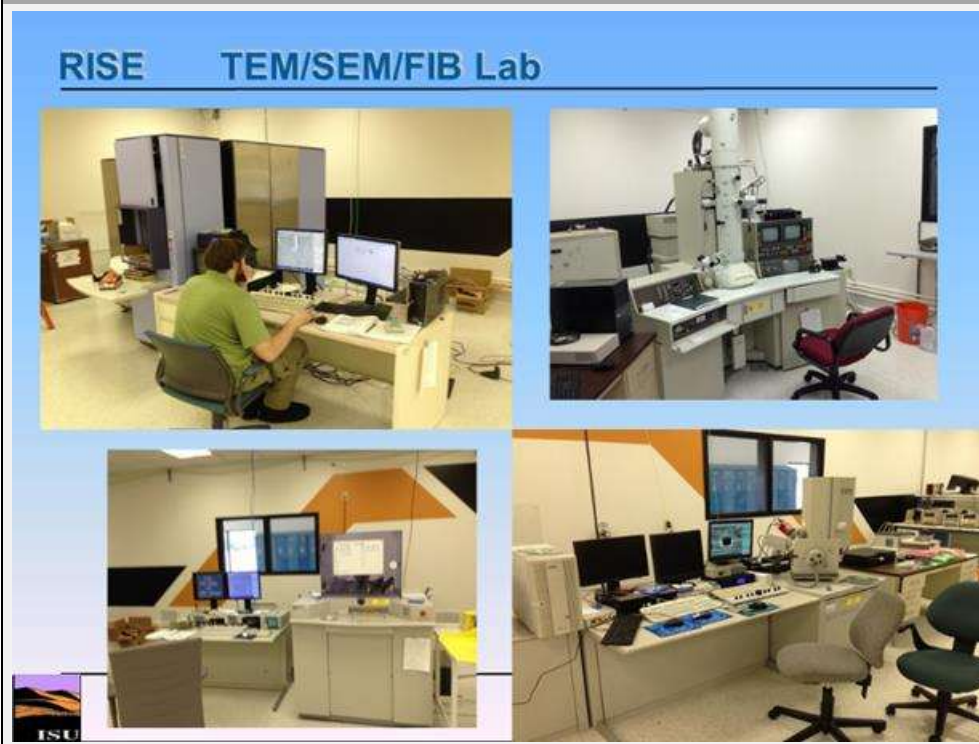
- Energy: 1-3 MV
 - Pulse width: ~20 ns
 - Rep Rate: ~1shot/3-5 minutes
 - Instantaneous current: ~18-30k Amps
- Applications: Radiography, Dose Rate Effects



RISE: 4 MV Tandem Pelletron

Proton/Deuteron Accelerator
8 MV acceleration ~ 200 uA possible
High current source (>1mA)
Chopper/buncher available
Neutron flux $\sim 10^{10}/\text{cm}^2$





RISE Lab: TEM/SEM/FIB Capability

RISE Lab: TEM/SEM/FIB Capability

- 8" FEI FIB with high current column
 - Pt deposit, IEE
 - Nano Secondary Ion Mass Spectrometer (Dynamic nanoSIMS)
- 8" FEI Dualbeam FIB with high current column and cold FEG imaging
 - Omniprobe nanomanipulator
 - Energy Dispersive Analytical X-Ray spectroscopy
 - Pt, W deposit
 - 3D imaging
- FEI ESEM cold FEG XL-30
 - Hot (1200 C) and cold (77K) stages
 - Electron Back Scatter Diffraction (EBSD)
 - Energy Dispersive Analytical X-Ray spectroscopy
 - EBIC spectroscopy
 - Dynamic straining and bending stage
- AMRAY analytical SEM
 - In-situ localized heating (Laser)
 - Heated stage, dynamic straining stage
 - EDAX
- 200 kV digital imaging STEM (0.17 Å resolution) Lorenz lens
 - Heated and cooled stages (1600 C – 77 K)
 - BSD STEM imaging
 - In-situ dynamic laser heating
- 100 kV digital imaging TEM
- X-ray microscope (300 nm resolution)
 - Materials discrimination capability

1. Can you also handle actinides?



Pulse Power Accelerator (SLIA)

Pulse Power Accelerator (SLIA)

Spiral Line Induction Accelerator is a pulsed-power accelerator by Titan Corp. It produces an electron beam of 1-2 cm diameter

Energy Range: ~2.5 to 7 MeV (+/- 10%) (mono-energetic)

Beam Current: 12kA at 2.5 MeV, 7kA at 7 MeV

Pulse Width: ~35 nsecs, rise/fall time 7-15 ns.

Repetition Rate: single shot every 3 minutes

Ports: 0 degree



20 MeV High Rep Rate LINAC (Phys Sciences)

20 MeV High Rep Rate LINAC (Phys Sciences)

RF Frequency: 2856 MHz (S-Band)

Energy Range: ~4-20 MeV (current varies)

Average Current: 1 uAmp

Pulse Width: ~20 - 40 n secs

Repetition Rate: single pulse to 300 Hz

Ports: 0 degree, 90 degree



IAC Airport



IAC Airport offers the ability to house large scale experiments. Located near the Pocatello, ID airport, the facility has open land for field testing, high bay space, offices, and Internet connectivity.

Features:

- 20,000 sq. ft. of high-bay space for large scale systems testing that includes shielded spaces
- 15 acres of open area for field tests
- 25 MeV accelerator
- Field portable digital radiography system
- X-ray generators from 30-450 kV



Specialty Accelerators

The Idaho Accelerator Works, a private contractor, operates this 4MeV portable LINAC out of the IAC. The principle application is for radiography of thick and/or dense materials. It has been used to qualify for NASA the containment of the nuclear thermoelectric batteries for the Mars Rover and the New Horizons spacecraft.



Science Capabilities and Applications

Capabilities in Applied Nuclear Science:

- Gamma and Neutron induced nuclear reactions
- Material analysis
- Detectors, arrays, mathematical analysis
- LINAC configuration, computer control, assembly, and operation
- Radio-Chemical separations
- Neutron production using LINACs
- Positron production

Applications in:

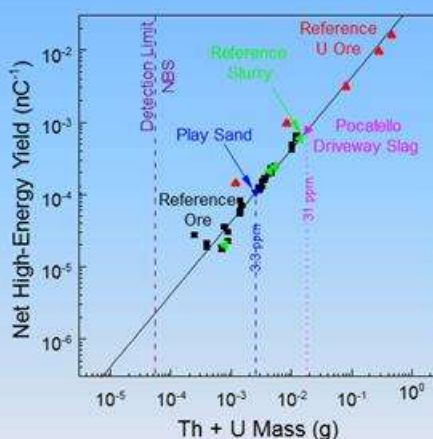
- Damage analysis
- Radiography
- Nuclear non-proliferation and nuclear security R&D
 - Partners with DoE, DoD and private sector.
- Non-destructive Materials Analysis
- Isotope Production for medical and industrial applications
- Accelerator applications



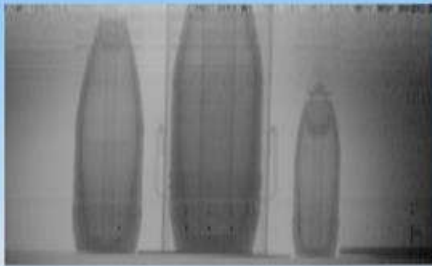
Rapid Activation → Fast Detection Assays

Rapid Activation → Fast Detection Assays

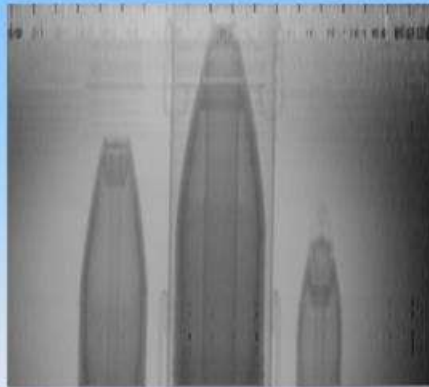
- Rapid activation
 - Increase signal over passive by ~10
 - More signal → faster assay (~ 1 min)
 - Continuous monitoring to segregate
- Signal linearly related to Th+U mass
 - Validates rapid assay
 - Detection limit: ~320 ppb
 - Matrix independent (e.g. dry vs. slurry)
- Optimization possibilities plentiful
 - Higher energy bremsstrahlung
 - Irradiation + detection times
 - More efficient γ -ray detectors
 - Add neutron detectors
 - ...



Integrated Radiography – 22 MeV



25 meter distance



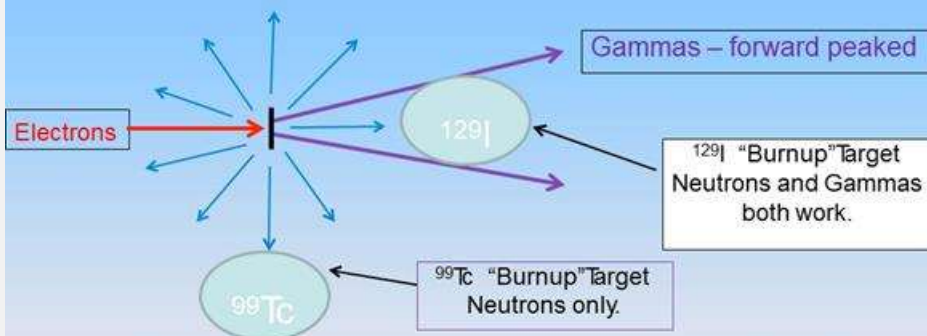
75 meter distance



Example: Energy Production: Nuclear Waste Burn-up

Example: Energy Production: Nuclear Waste Burn-up

Neutrons – emitted in all directions



- Photo-nuclear burnup of ^{129}I and ^{99}Tc with a 100 kW, 50 MeV beam can transmute these species (pure targets) at a rate of approximately 25 kg/yr.



Production of Isotopes

<p>Zn 67 4, 1 α 6.9</p>	<p>Zn 68 18.8 α 0.027, 1.0</p>	<p>Zn 69 13.8 h 56 m β⁻ 0.8 γ 0.09, 1.079, 1.1</p>	<p>Zn 70 0.6 α 0.0087, 0.083</p>
<p>Cu 66 5.1 m β⁻ 2.6... γ 1039; 804... α 135</p>	<p>Cu 67 61.9 h β⁻ 0.4; 0.6... γ 105; 93, 91</p>	<p>Cu 68 3.8 m 30 s β⁻ 5.5... α 111... β⁻ 1.7 γ 107; 101</p>	<p>Cu 69 3.0 m β⁻ 2.5... γ 1007; 804; 501... 0</p>
<p>Ni 65 2.52 h β⁻ 2... γ 1402; 1115; 366... α 24.3</p>	<p>Ni 66 54.6 h β⁻ 0.2 no γ</p>	<p>Ni 67 18 s β⁻ 3.8... γ 1072; 1554; 709; 674</p>	<p>Ni 68</p>

Gama based reactions:


- $^{68}\text{Zn} (\gamma, n) ^{67}\text{Zn}$
- $^{68}\text{Zn} (\gamma, p) ^{67}\text{Cu}$
- $^{68}\text{Zn} (\gamma, pn) ^{66}\text{Cu}$



Presentation: CMUXE, Purdue University

Jitendra Tripathi

Slide 1






An overview and capabilities for advanced materials characterization at CMUXE

Jitendra K. Tripathi
Ahmed Hassanein

Center of Materials Under Extreme Environment (CMUXE)
School of Nuclear Engineering
Purdue University, West Lafayette, IN 47907


Annual NSUF Users Meeting, Idaho Falls, ID

March 22-24, 2016





Slide 2

Outline

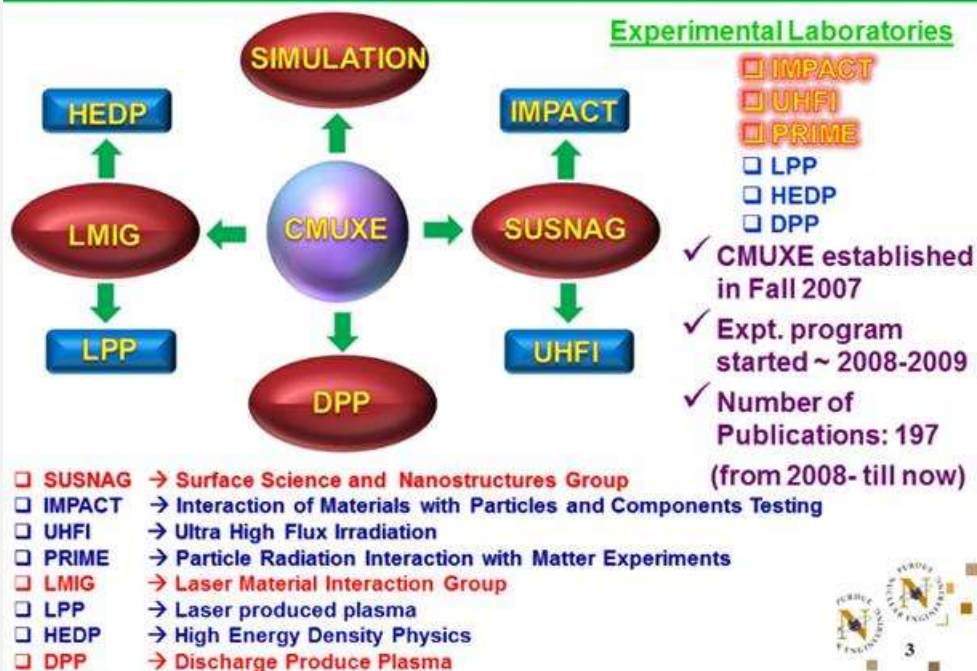


- ☐ Overview of CMUXE
- ☐ Ion irradiation and characterization facilities at CMUXE
- ☐ Recent results using “Ion irradiation and characterization facilities” at CMUXE
- ☐ Conclusion



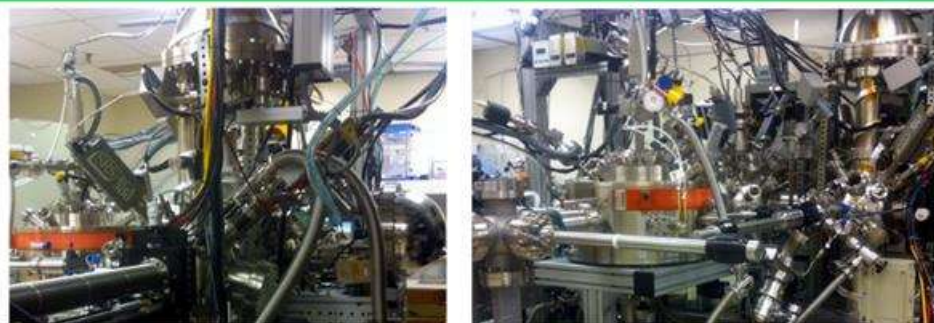
Slide 3

Center of Materials Under Extreme Environment (CMUXE)



Slide 4

IMPACT Laboratory



In-situ advanced materials characterization

- ✓ Thin film & multilayer deposition (using precise four-pocket e-beam evaporator)
- ✓ Ion beam sputter cleaning (NTI 1401 and 1402 ion source gun; 5 eV- 5 keV)
- ✓ Ion irradiation (KDC 10; 300 eV- 1.2 keV; LN₂ to 1100°C substrate temperature)
- ✓ X-ray Photoelectron Spectroscopy (XPS)
- ✓ Auger Electron Spectroscopy (AUGER)
- ✓ Ultraviolet Photoelectron Spectroscopy (UPS)
- ✓ Low-Energy Ion Scattering Spectroscopy (LEISS)

1. IMPACT and UHFI are ion beam facilities.

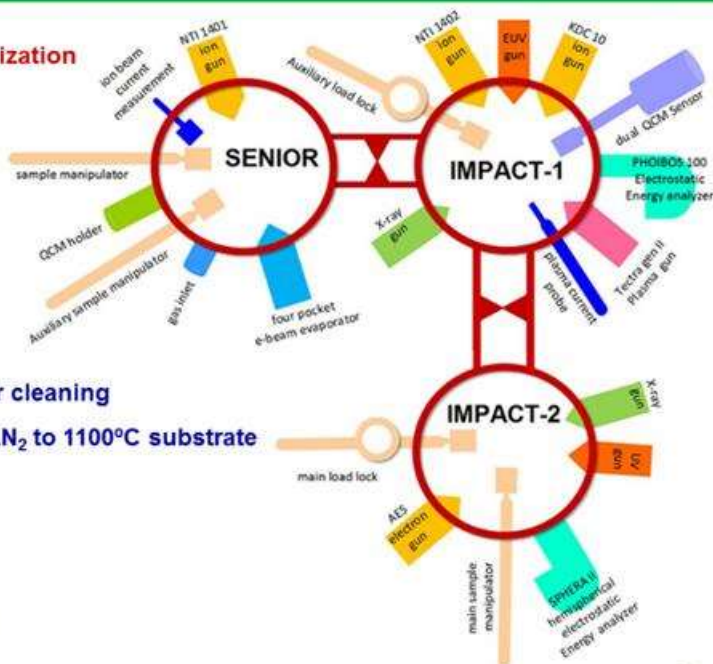
Slide 5

IMPACT Laboratory: schematic diagram

CMU
E

In-situ advanced materials characterization

- ✓ XPS
- ✓ AUGER
- ✓ UPS
- ✓ LEISS
- ✓ EUPS
- ✓ Thin film & ML deposition
- ✓ Ion beam sputter cleaning
- ✓ Ion irradiation (LN₂ to 1100°C substrate temperature)

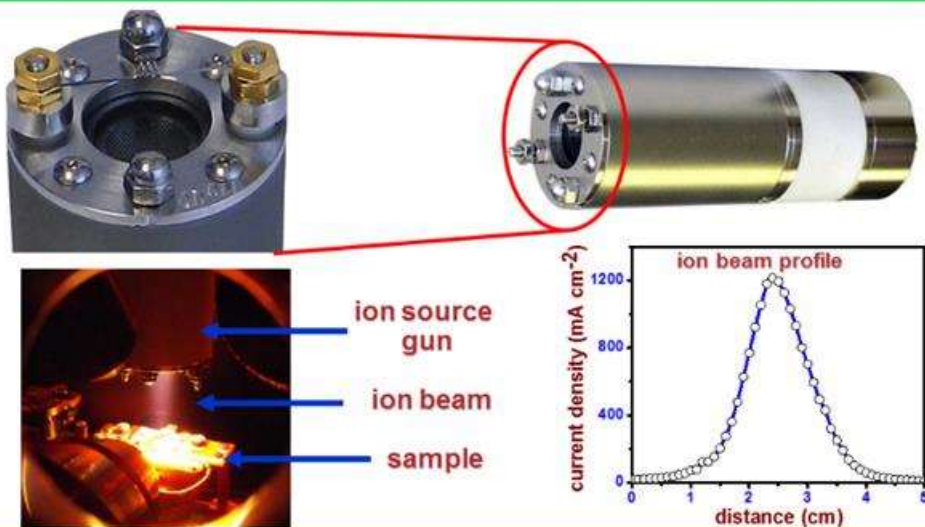


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Slide 6

KDC-10 ion source gun (Graphite two-Grid 1-cm Dia. Ion Optics)

CMU
E



Ion gun	Energy (eV)	Ion Flux (ions m ⁻² s ⁻¹)	beam spot	ion source
KDC-10	300 - 1.2 k	~1 × 10 ²⁰	~1 × 1 cm ²	All inert and some of the reactive gases (H ₂ , CH ₄ etc.)

Slide 7

UHFI Laboratory



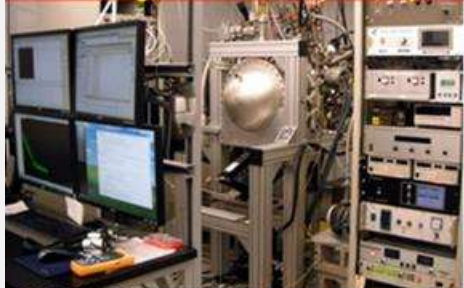
low energy high flux ion irradiation facility



in-situ laser & ion irradiation and pulsed laser deposition facility



multi-diagnostic surface analysis facility



RF sputter deposition Unit

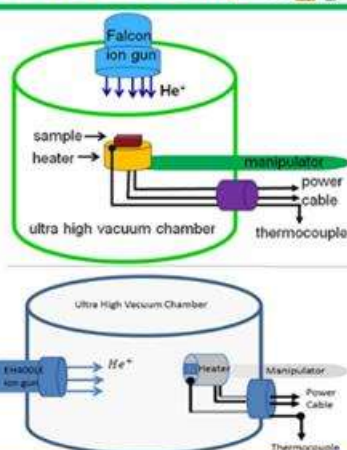
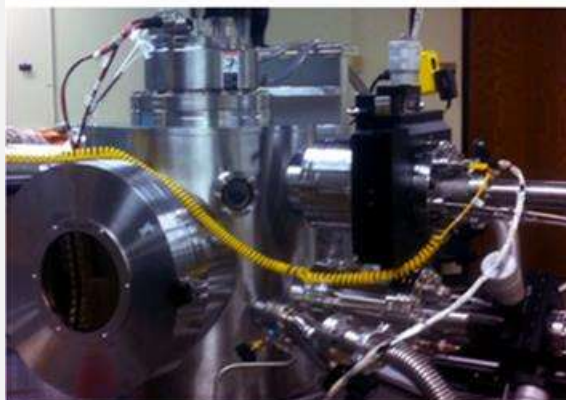


thermal desorption spectroscopy



Slide 8

low energy high flux ion irradiation facility




1. Does the eH-400LE beam spot need to be broad?
2. Yes, in our case need it for homogeneous ion irradiation on the entire sample.

Ion gun	Energy (eV)	Ion Flux (ions m ⁻² s ⁻¹)	beam spot	Ion source
eH-400LE	70- 300	~1 × 10 ²¹	9.4×9.4 cm ² (broad beam)	All inert and some of the reactive gases (H ₂ , N ₂ , O ₂ , CH ₄ etc.)
Falcon	650 – 2 k	~1 × 10 ²¹	broad beam	All inert and some of reactive gases (H ₂ , CH ₄ , N ₂ , O ₂ etc.)

Slide 9


eH-400 LE ion source gun



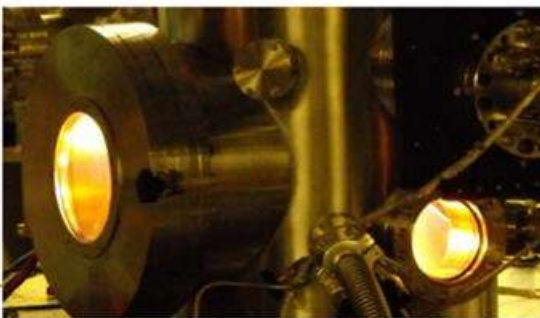
← plug-in filament electron emitter

← modular anode
(anode and gas distribution)

← main module
magnet system &
electrical & gas inlets



- Energy: 70-300 V
- Ion species: Inert gas ions, O⁺, N⁺, H⁺ etc
- Flux → 1.15×10^{21} ions m⁻² s⁻¹



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Slide 10

Falcon ion source gun



← He⁺ ion irradiation



flux (ions m⁻²)

lateral width (mm)



Ion energy distribution function (a.u.)

Ion energy (keV)



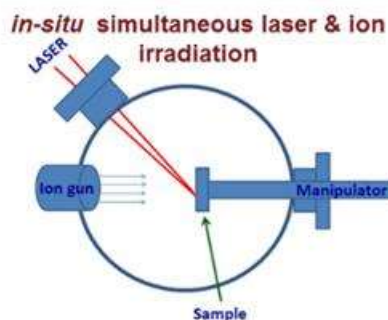
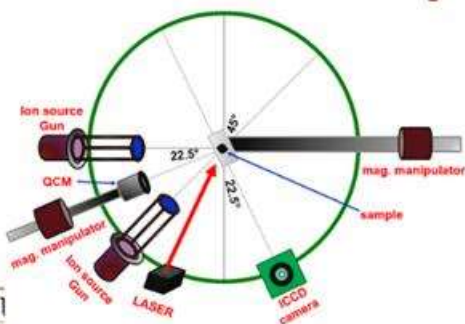
Ion gun	Energy (eV)	Ion Flux (ions m ⁻² s ⁻¹)	beam spot	ion source
Falcon	650 – 2 k	~1 × 10 ²¹	broad beam	All inert and some of reactive gases (H ₂ , CH ₄ , N ₂ , O ₂ etc.)

Slide 11

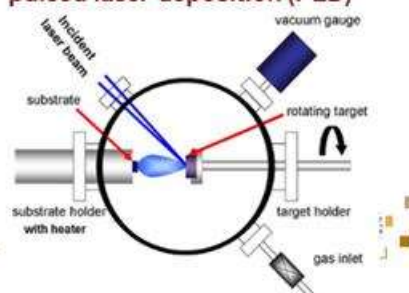
in-situ laser & ion irradiation and pulsed laser deposition facility



In-situ simultaneous dual ion beam irradiation and transient heat loading



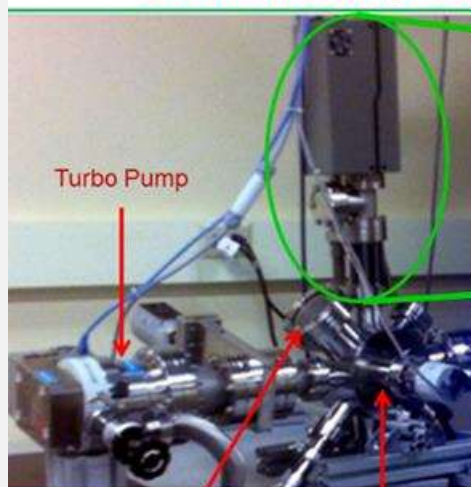
pulsed laser deposition (PLD)



1. Fusion applications, laser heating to 2000°C

Slide 12

thermal desorption spectroscopy (TDS)



Thermal desorption spectrometer: TDS 40A1

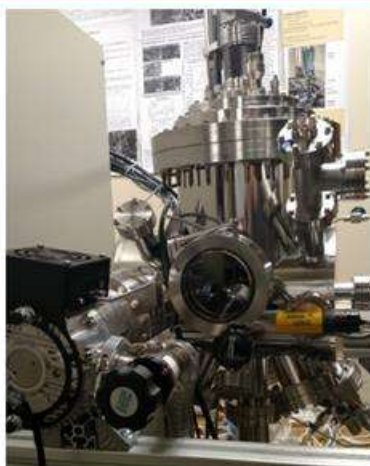


Heating filament

Heating stage (inside the UHV Chamber); this is the place where sample is sitting

- TDS → Ramping of surface temperature and simultaneous measurement of the intensity of the desorbed particles, using residual gas analyzer (RGA).
- Larger desorption temp. → larger binding strength: Larger TDS Peak area → larger coverage.
- A detailed analysis of the obtained curves can yield a number of kinetic parameters, such as: (i) heat of adsorption, (ii) pre-exponential factor, (iii) desorption order, (iv) evidence for different adsorption sites on the surface, and many more.

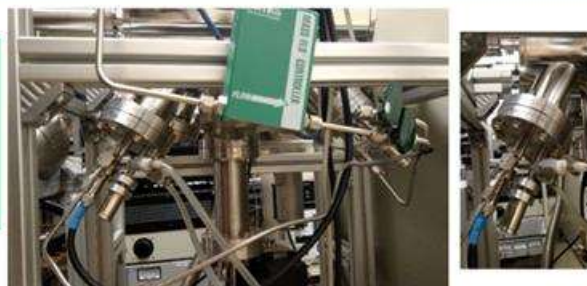
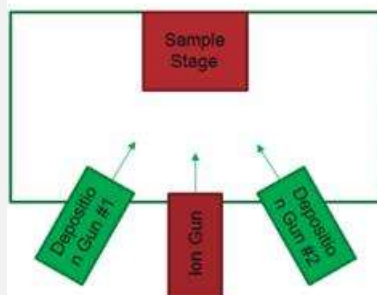
RF sputter deposition facility



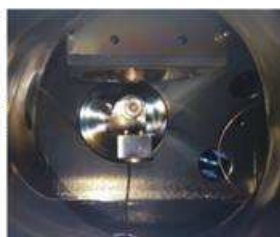
1. 1-2 μm per hour deposition
2. For high-Z materials (W, Mo, Ta, etc.)

- Mantis RF Sputter Deposition Guns: [0-300 watts (RF); Non-ferrous materials; 1 in. sputter target]
- 1 Mantis RF Ion Gun: 0-600 watts (RF)
- Currently capable of running two sources simultaneously
- Film deposition (tested successfully): Ni, W, Co (couple of micro meter thick layers)

RF sputter deposition facility



- All sources converge on a single point enabling co-deposition or **Ion Beam Assisted Deposition (IBAD)**
- Sample stage allows for positioning of the sample in the z (up/down) direction and rotated the sample during deposition for homogeneous coverage
- QCM is mounted in on a y axis (in/out of page)
- Image on the right shows QCM (center) and sample stage (top center)



surface morphology and optical property measurement facility



PURDUE
UNIVERSITY



1. Also has associated user facilities with TEM, S/TEM, etc.

2. Also has access to use the USER facility at BNC (Birck Nanotechnology Center), Purdue University (partial list, closely related to this workshop): With state-of-the-art fabrication and characterization facilities, highly qualified personnel with expertise in design, fabrication, packaging, and characterization, the BNC is the place to work on the development of new systems and technologies. A partial list (related to this workshop) of the research activity at BNC is as follows:

- (i) Nanoscale Metrology: Scanning Probe Microscopy (SPM), STM, AFM, Field Emission (FE)-SEM, TEM, in-situ TEM, XRD, XPS, AES, Electron Energy Loss Spectroscopy (EELS), ISS, Low Energy Electron Diffraction (LEED), Focused Ion Beam Imaging (FIB), Raman Spectroscopy, Photoluminescence (PL), and Near-Field Optical Microscopy (NSOM);
- (ii) Materials Growth and Deposition: Molecular Beam Epitaxy (MBE), Metal-Organic Chemical Vapor Deposition (MOCVD), Plasma-Enhanced

Chemical Vapor Deposition (PECVD), Halide Vapor-Phase Epitaxy (HVPE), Pulsed Laser Deposition (PLD), Atomic Layer Deposition (ALD), Reactive magnetron sputtering, Electron Beam Evaporation, Thermal Evaporation, and Sputter Deposition;

(iii) Nanoelectronics and Microelectronics: Molecular Electronics, Nanowire Electronics, Carbon Nanotube Electronics, Silicon Microelectronics, Compound Semiconductor Devices, Wide Bandgap Semiconductor Devices, Thermoelectric Energy Conversion, and Photovoltaic Energy Conversion;

(iv) Nanofabrication: Optical Photolithography, Electron-Beam Lithography, Circuit Layout Workstation, Optical Mask Generation, Reactive Ion Etching (RIE), Inductively Coupled Plasma (ICP) etching, Focused Ion Beam Machining, Plasma Etching and Cleaning, Wet Chemical Processing, Thermal Oxidation and Diffusion, and Rapid Thermal Processing (RTP);

(v) Electronic Characterization: Current-Voltage

Slide 15

Metrology (μV to 10 kV), Capacitance-Voltage Metrology, Admittance-Voltage Metrology, Admittance-Frequency Metrology, Deep Level Transient Spectroscopy (DLTS), Photoresponse Metrology, Hall Effect Metrology, Microwave Characterization (to over 200 GHz) Variable Temperature Characterization (10 to 650 K), and Ultra-Low-Temperature Electrical Characterization (using liquid helium).

Ion Irradiations and advanced materials characterizations at CMUXE : *Proposals / Projects (examples)*



- ✓ Low energy high-flux ion induced modifications in high-Z refractory metals for nuclear fusion applications.
- ✓ Individual, Sequential, and Simultaneous dual ion beam irradiation induced surface modifications.
- ✓ Laser and ion beam exfoliations in 2D materials.
- ✓ Thermal desorption spectroscopy (TDS) studies.
- ✓ Nano structuring in novel 2D materials using pulsed laser deposition (PLD).
- ✓ In-situ low-energy irradiations (in a temperature range of LN2-1100C).
- ✓ Transient thermal heat loading (1.5 MJ m^{-2}) on high-Z refractory metals for nuclear fusion applications.
- ✓ Nanostructuring in semiconductors *via* ion beam irradiations for their various technological applications.
- ✓ Ion induced surface modifications in thin film and multilayers.
- ✓ Self ordered and self organized nano patterning using ion irradiation.



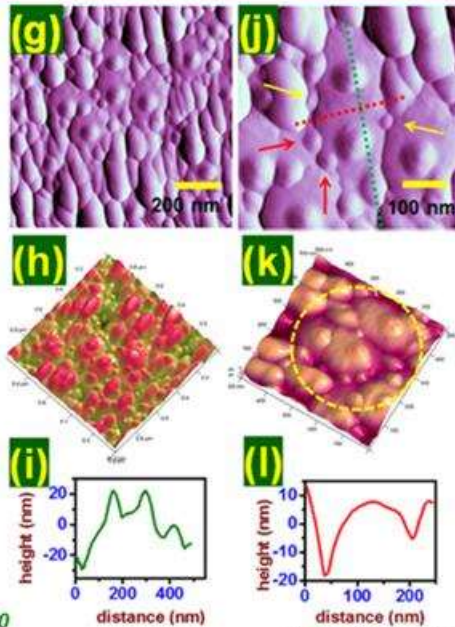
Proposals / studies going on and recently finished in SUSNAG at CMUXE

Slide 20

100 eV He⁺ ions (ion flux → 7.2×10^{20} ions m⁻² s⁻¹) @ 923K

CMU
E

- Line profiles of the typical grain → size of the grain → $\sim 450 \times 162$ nm.
- Evidence of 20 – 45 nm encapsulated bubbles within the grain boundaries of this sub-micron size grain are clearly evidenced (marked arrow on the figure)!
- These preferential bubbles formation at grain boundary shows He accumulation at grain boundary and He diffusion along the grain boundary.
- Evidence of, a few large bubbles on the top of same grain as well.



Tripathi et al. Appl. Surf. Sci. 353 (2015) 1070

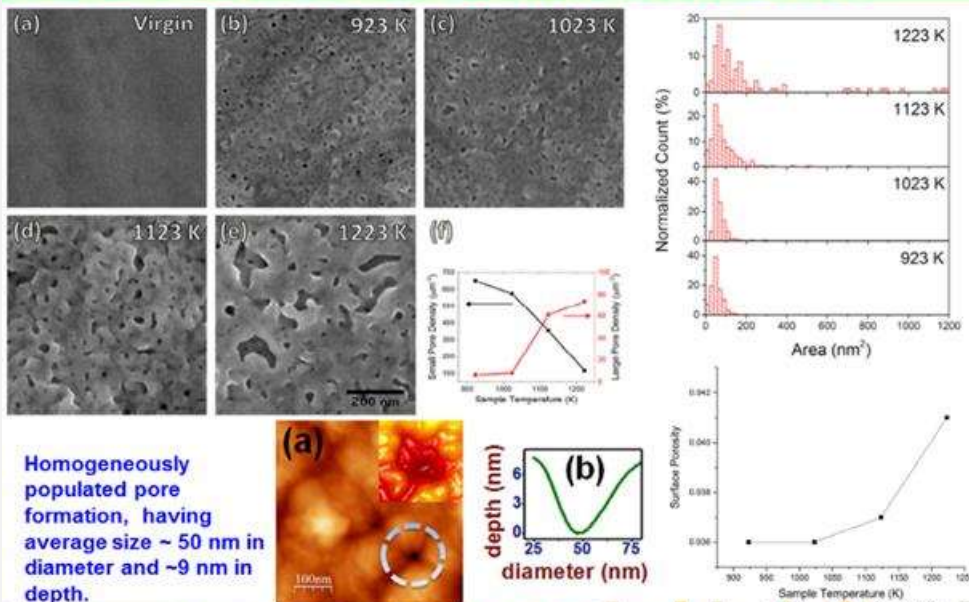
PURDUE UNIVERSITY

CMU
E

Slide 21

Temperature dependent surface modification of Ta due to 100 eV He⁺ ion irradiation @ 4.3×10^{24} ions m⁻² fluence (flux: 1.2×10^{21} ions m⁻² s⁻¹)

CMU
E



Homogeneously populated pore formation, having average size ~ 50 nm in diameter and ~ 9 nm in depth.

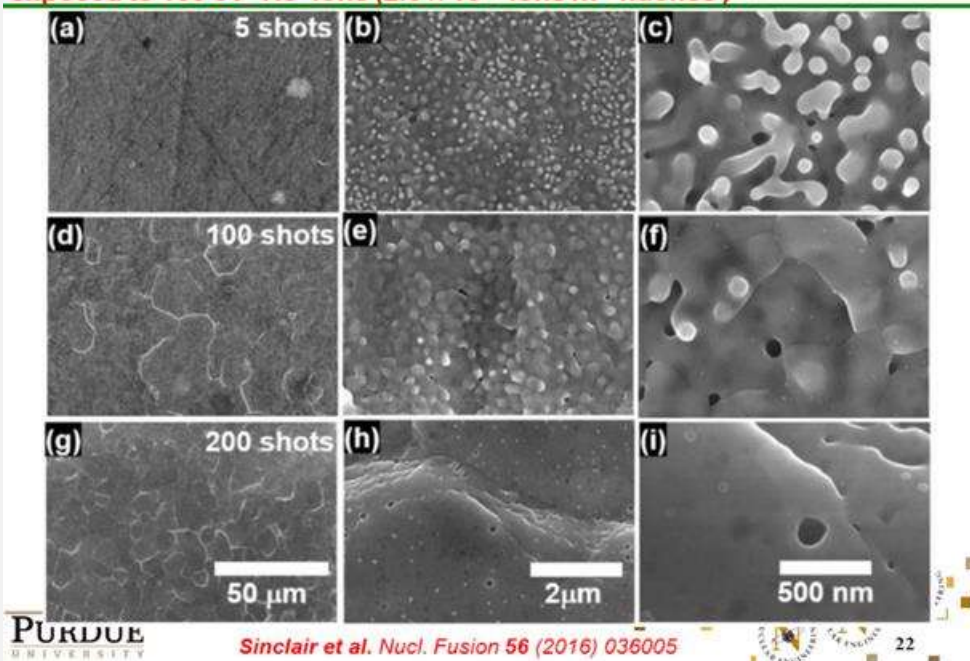
PURDUE
UNIVERSITY

Novakowski et al. J. Nucl. Mater. 467, 244 (2015)

CMU
E

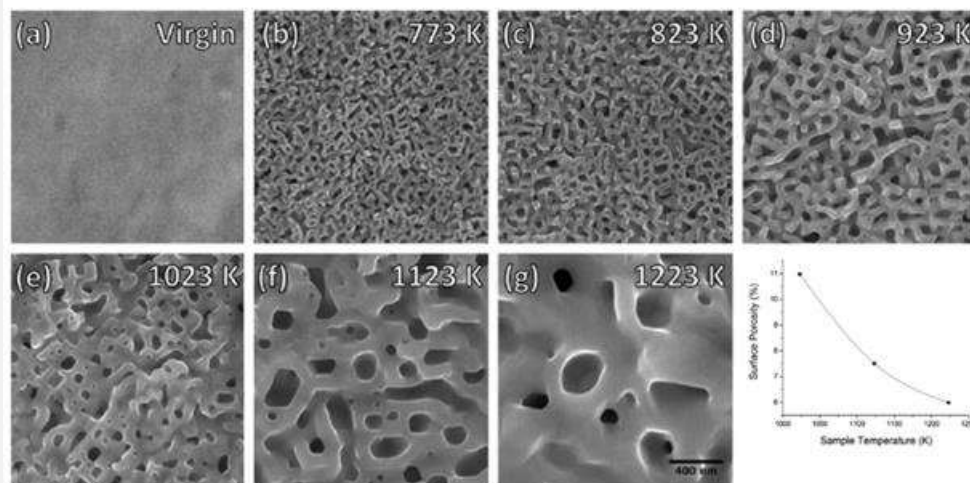
Slide 22

Structural response of transient heat loading (1.5 MJ m^{-2}) on a Mo surface exposed to 100 eV He^+ ions ($2.6 \times 10^{24} \text{ ions m}^{-2}$ fluence)



Slide 23

Temperature-dependent surface porosity of Nb_2O_5 under high-flux, low-energy He^+ ion irradiation



Conclusion



- ❑ Availability of low energy (70 -5 keV) high flux (up to 1.2×10^{21} ions $m^{-2} s^{-1}$) helium, hydrogen, and deuterium ion irradiation facility.
- ❑ Availability of *in-situ* low energy (300- 1200 eV) high flux flux (up to 1.2×10^{21} ions $m^{-2} s^{-1}$) helium, hydrogen, and deuterium ion irradiation facility.
- ❑ Availability of *in-situ* thin film & multilayer deposition, Ion beam sputter cleaning, ion irradiation, XPS, AUGER, UPS, LISS and, EUPS facility.
- ❑ Availability of Individual, Sequential and Simultaneous dual ion beam irradiation facility.
- ❑ E beam, RF sputtering and pulsed laser deposition (PLD) facility
- ❑ Availability of *in-situ* simultaneous “dual ion beam irradiation” and “transient heat loading” (using a ms laser).
- ❑ Possibility of the availability of 10k-100kV electron source gun.
- ❑ Availability of thermal desorption spectroscopy (TDS) facility.
- ❑ More information about the CMUXE are available at :
<https://engineering.purdue.edu/CMUXE/index.html> <https://atrnsof.inl.gov>
- ❑ Contacts:

➤ Prof. Ahmed Hassanein (Director, CMUXE): hassanein@purdue.edu

➤ Dr. Jitendra K. Tripathi (Group leader of SUSNAG at CMUXE): jtripat@purdue.edu

1. What materials can be handled? Actinides?
2. We are NOT handling radioactive materials due to safety issue.

SUSNAG experimental team at CMUXE, Purdue University



A. Hassanein (Director CMUXE)



Jitendra K.
Tripathi



Theodore J.
Novakowski



Sean
Gonderman



Gregory
Sinclair



Joseph Fiala



Nikhil
Bharadwaj



Arvind
Sundaram



Presentation: High-energy Ion Implantation Capability at LLNL

Scott Tumey

Slide 1

The high-energy ion implantation capability at the LLNL Center for Accelerator Mass Spectrometry

NSUF Ion Beam Investment Options Workshop

Scott Tumey

March 23, 2016



LLNL-PRES-XXXXXX

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC02-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore
National Laboratory

Slide 2

CAMS is recognized as a signature scientific user facility at LLNL.

- Routinely measures >20,000 samples each year for a wide range of sponsors.
- Generates dozens of high-impact publications each year.
- Home of the NIH National Resource for biomedical AMS
- Primary capability for national-scale carbon cycle program funded by DOE-BER
- Over 100 PI collaborators in academia mostly funded by NSF



Lawrence Livermore National Laboratory
LLNL-PRES-XXXXXX

NSF

Slide 3

CAMS was established as a center of excellence for the application of accelerators for basic science and national security research.



1.0 MV Compact AMS



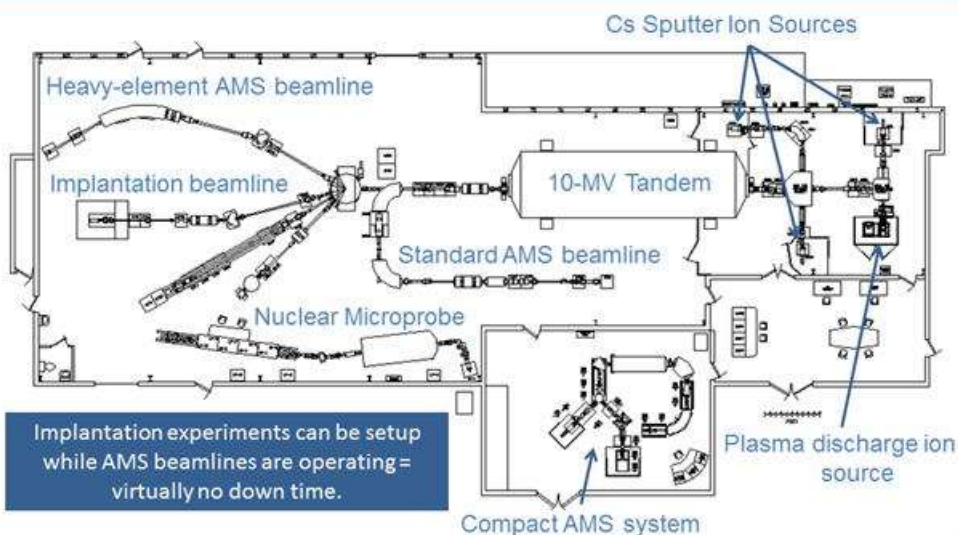
10 MV Multi-purpose tandem



1.7 MV Nuclear microprobe

Slide 4

Versatile design enables a wide range of accelerator-based research activities with high-throughput.



1. Couple minute switch between ion sources.
2. Since there are four computer controlled ion sources, you can do one type right after another for quasi-multi-ion irradiations.
3. Additional flexibility due to multiple beam lines.

Slide 5

Modular design of end-station allows for customization for each experiment.



Retractable shielding box



High-current chamber



Radioactive chamber



High-temp chamber

- Wide temperature range (0-750 °C).
- Can conduct experiments with radioactive materials (e.g., HEU, Pu, etc).
- Shielding enables experiments that produces prompt radiation.

Slide 6

Multiple ion sources can produce ions from nearly every element on the periodic table.

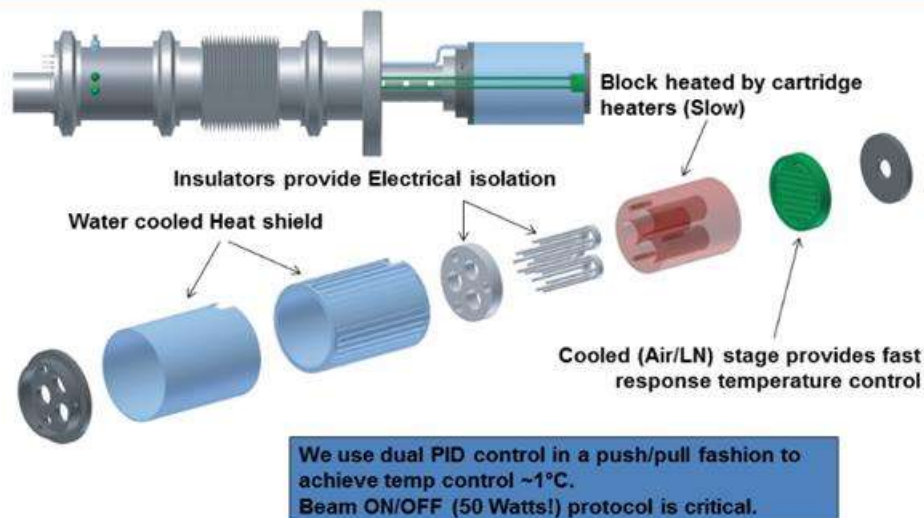
	H/D	He	Heavy ions (C, Fe, U)	Noble Gases
Typical energy	2-18 MeV	4-27 MeV	20-100 MeV	Under development
Maximum current	20-30 uA	5-10 uA	1-10 uA	
Applications	Isotope production, H injection	He injection	dpa	Fission product injection



1. Can generate negative ions of some noble gases (work in progress).

Slide 7

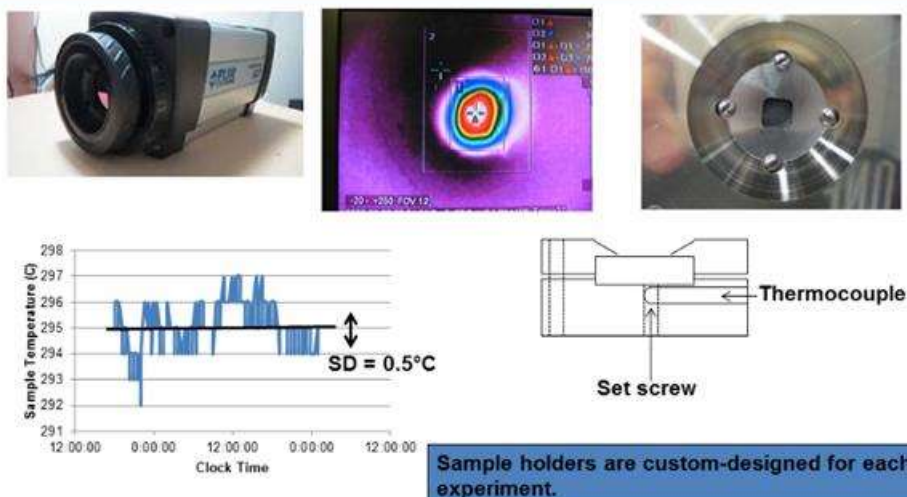
A custom designed heated sample stage provides stable and precise temperature control up to 750°C.



1. Is the sample temperature stage feedback looped into the beam production?
2. Response to Comment 1: We do have the capability to have these controlled with an automatic feedback loop; however, we find that because the factors that can affect beam current have a wide range of magnitudes and time constants, precisely tuning this loop is difficult. So in practice, we maintain feedback between ion current and temperature manually.

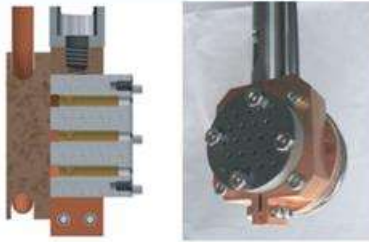
Slide 8

Robust sample mounting and high-resolution IR imaging are critical to temperature control and measurement.

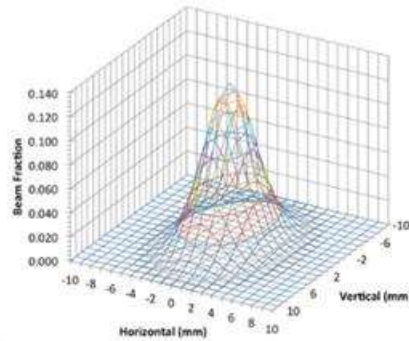
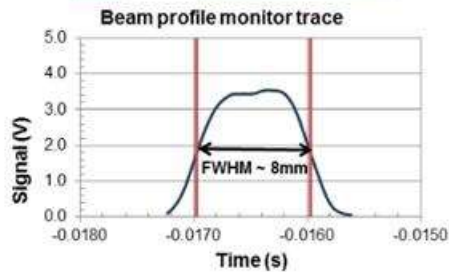


1. Calibrates the IR camera to the TC behind the sample for each run.

Absolute, two-dimensional beam dosimetry is challenging, but necessary when using a defocused beam.



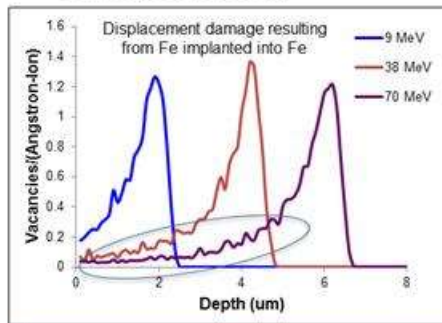
- Custom-designed multi-pin Faraday cup enables reconstruction of spatial beam intensity.
- Rotating wire (BPM) provides diagnostic information in between Faraday cup measurements.



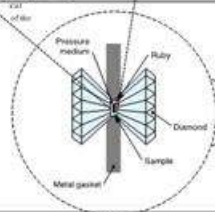
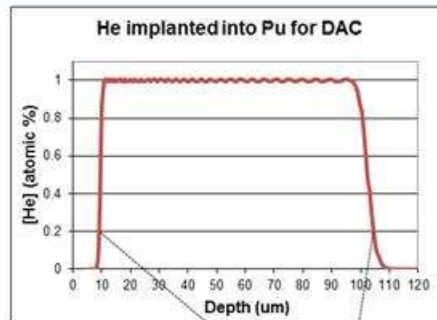
1. Do you keep a running tally of the beam profile, or is it an in-beam/out-of-beam measurement?
2. Regarding your comment about using the tails of the beam profile to achieve different damage levels, can you trust this method when the damage varies so steeply with position? Any beam “drift” will have a big impact on the actual damage to the sample.
3. Response to Comment 1: The Faraday cup measurements are periodic in beam measurements. We augment this with the BPM, which provides relative measurements constantly throughout the experiment.
4. Response to Comment 2: This is a very good point. Our beam stability is quite good, typically ± 0.1 to 0.2 mm, and the drifts are captured by the BPM, which runs continuously throughout the experiment.

Deeper penetration depth afforded by high energy enables “volumetric” implantation.

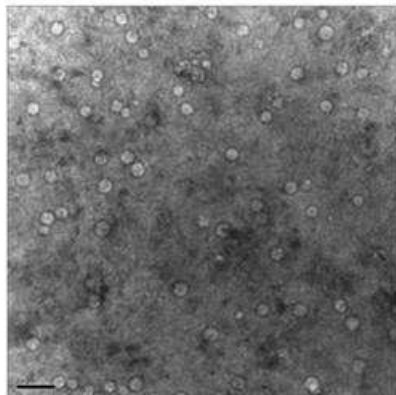
- “Peak” dpa rates: 10^{-6} to 10^{-3} dpa/sec
- Sample area:
 - 25 x 25 mm (rastered)
 - 10 mm defocused beam



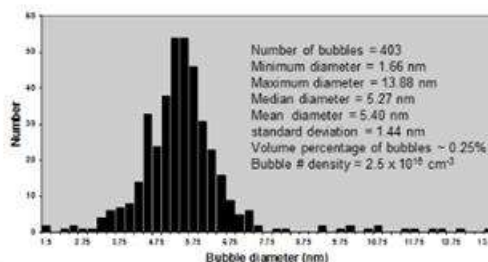
Deep ion penetration creates a gradually-increasing damage profile over a large area. Factor of 5 range in dpa (and dpa rate) can be covered in a single experiment.



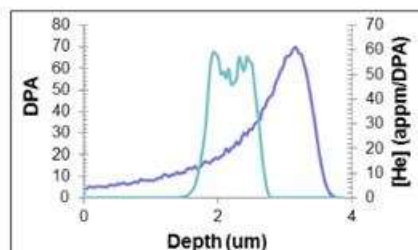
Implantation capability provided key data to the LLNL weapons program.



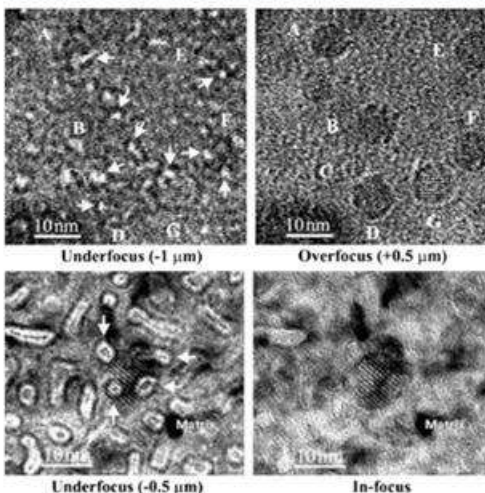
- Implanted He into Pu at 40 discrete energies to produce “uniform” deposition over 70 um.
- Analyzed samples for microstructure (TEM) and equation-of-state (DAC) to assess effects of long-term (~200 years) aging of stockpile.



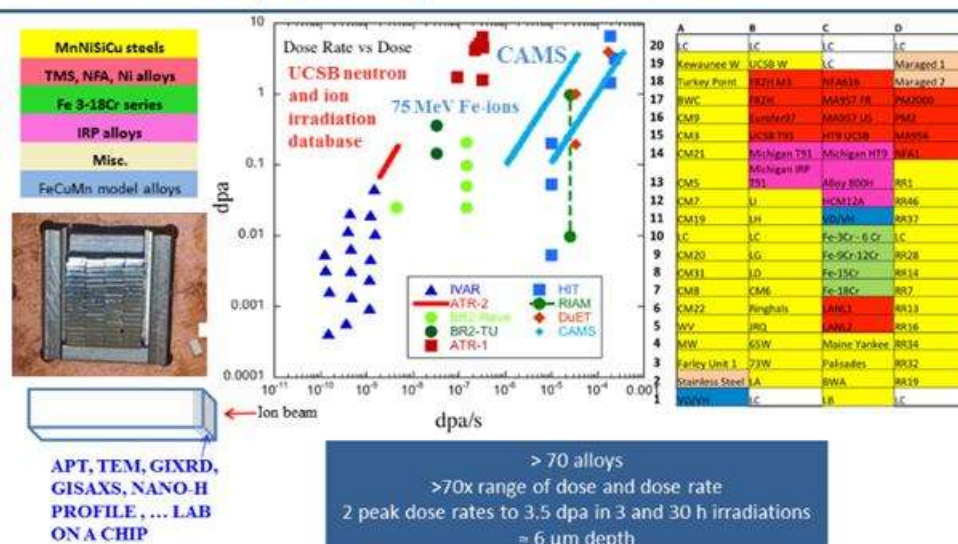
Ion implantation helped elucidate the role of ODS nanoparticles in radiation tolerant steels.



- ODS samples irradiates with Fe (displacement damage) and He ions.
- TEM analysis showed small (~2 nm) bubbles coalesced around ODS particles (Top figures)
- Cavities observed in areas of steel with low concentration of ODS particles (Bottom figures)



Recent collaboration with UCSB produced A "big data" library: peak dpa ≈ 3.5 at 295°C



Slide 14

Accelerator is currently utilized at ~75% of available capacity.

Typical usage	
Maintenance	35 days
Radiocarbon	150 days
Be-10, Cl-36, Al-26	50 days
Actinides, I-129	25 days
Implantation	15 days
Unused	90 days

- Modular design of accelerator system enables setup of ion beam experiments during other operations so nearly all unused days could be used for high-energy ion irradiation.

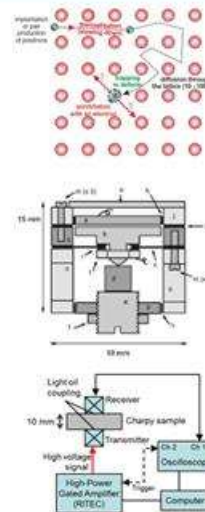
Accelerator is supported by a large number of diverse sponsors, but there is sufficient capacity available to perform research relevant to NE.

- Approximately 90 days available for additional work. Setup can be performed when the system is being used for another irradiation.

Slide 15

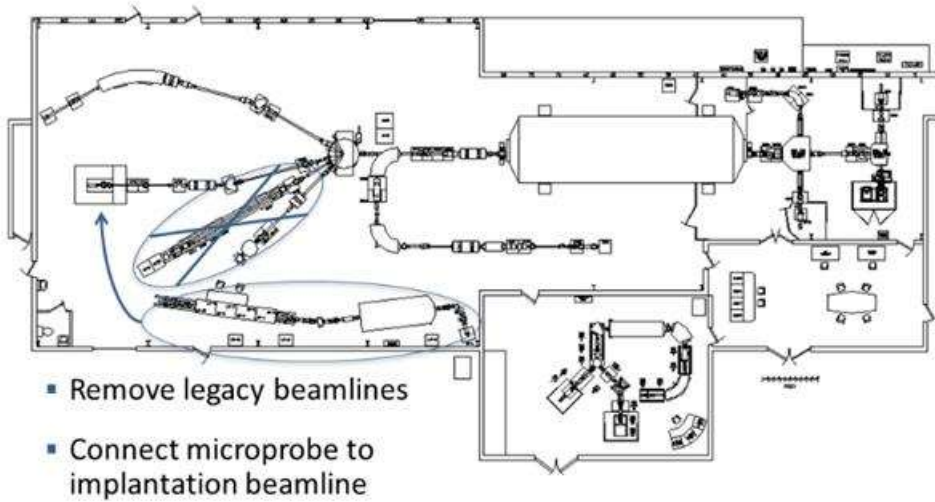
Upgrades to implantation end-station would greatly enhance the experimental capabilities available to NE.

- Low-energy accelerator coupled with TEM (e.g., IVEM at ANL) is a powerful tool for in-situ characterization of microstructure evolution
- A similar approach built around the CAMS high-energy implantation beamline could allow for real-time studies of bulk property changes to materials under irradiation:
 - Non-equilibrium defect concentration via positron annihilation spectroscopy
 - Dimensional instability via capacitive plate dilatometry
 - Embrittlement and stress-corrosion cracking via non-linear acoustic ultrasound



- Proposed experiments bridge the gap between micro and macro structure properties.
- Could measure both microstructure as well as physical properties.

System could be reconfigured to enable dual-beam (Heavy ion + H or He) irradiations.



1. This would create a true dual-beam system.

Presentation: Wisconsin IBL

Beata Tyburska-Pueschel

Wisconsin ion beam laboratory: capabilities and needs

Wisconsin ion beam laboratory: capabilities and needs



DEPARTMENT OF
Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

Beata Tyburska-Püschel

University of Wisconsin-Madison

Idaho Falls, March 23rd, 2016

Introduction

Introduction

CLIM – Characterization Laboratory for Irradiated Materials

- Ion beam lab – ion-irradiation and IBA
- ATR-NSUF facility since 2011
- PIE equipment
- Sample preparation
- Non- and **radioactive** samples: 10 mCi storage, 100 mR/hr unshielded on contact, no transuranic products

2 of 13



1. No pre-irradiated material (transuranics).
2. How much NSUF use to you get?

Ion-irradiation



- 1.7 MV tandem accelerator from NEC, 3 beamlines
- TORVIS and SNICS ion sources
- Almost all types of ions possible, no Noble gases except He, no low-current cathodes
- Max. area: 4 cm², various sample holders
- Temperature controlled by thermocouples and IR camera
- Beam spot observation and recording by a digital camera

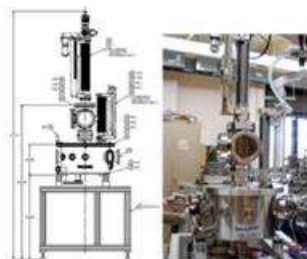
3 of 13



1. Commissioning a new sample chamber in April.

New irradiation chamber

- Remote four jaws Ti slits
- Chamber with a pre-chamber
- Sample goniometer
- In-situ RBS, NRA, PIXE
- Digital and IR camera



Irradiation parameters

External heating: -150° C – 800° C, 900° C flash

Proton flux range: 1×10^{11} – 2×10^{15} p/(cm²)

Ion flux range: 4×10^{10} – 6×10^{14} ion/(cm²)

4 of 13



1. Can change samples without breaking vacuum.

Sample goniometer

Sample goniometer

- Motorized 2-axis MultiCentre manipulator
- 1" diameter puck sample holder
- 6 pin type K thermocouple feedthrough
- Sample biasing/current measurement
- Tantalum wire heater element on a boron nitride mandrel for heating up 900° C (flash heating) and 800° C (radiative heating)
- LN2 sample cooling facility to -150° C



5 of 13



Other equipment

Other equipment

Radiation certified:

- Sample preparation equipment – low speed saw, polisher, ion mill etc.
- Analysis techniques CLIM – SEM with EDS and EBSD, TEM, XRDs
- MSC – non dust producing equipment, e.g. Raman, AFM, etc.



6 of 13



1. What is the activity or dose rate level you can handle?
2. Answer: exposure 100 mRem/hr unshielded, on contact.

Projects

1. NSUF: 40-50% in 2016.

Projects

400 - 800 hours of irradiation per year, 10-20% NSUF

Federal grants

- Defects in off-stoichiometric UO_2
- Densification and thermal conductivity in irradiated UN and U_3Si_2
- SiC: Ag diffusion, dose to amorphization, BSDs
- Neutron damaged simulation in steels
- Hardness change with dpa in new Zr-containing ferritic steels

Current NSUF projects

- Irradiation effects on properties of LWR concrete
- Irradiation study of zirconium diboride

7 of 13



Lab needs

Lab needs

Lab needs:

- Support to pay staff salary
- Upkeep of equipment
- Annual cost \$200k
- Currently supported by NEUP/NSUF - subject to fluctuation

8 of 13



Beamline 1 – *in-situ* irradiation and TEM

Beamline 1 – *in-situ* irradiation and TEM

Shift from subsequent to simultaneous

We have:

- The 1.7 MV tandem accelerator
- JEOL 200CX TEM
- TEM technician for adjustments

We need:

- Space – digitalize control room \$50k
- Adjust TEM \$20k
- Adjust the beamline
- Know-how – ANL



9 of 13

1. Consider applying to the DOE-NE General Scientific Infrastructure Program for FY 2017 for this modification.
2. Would the in situ TEM be placed on one of the two unused beamlines?
3. What is the cost of microscope modifications?
4. Yes, it will be attached to Beamline 1, which at this moment still hosts an old irradiation chamber.
5. We estimate the total cost to be around \$130K.

Beamline 2 – *in-situ* corrosion, triple beam

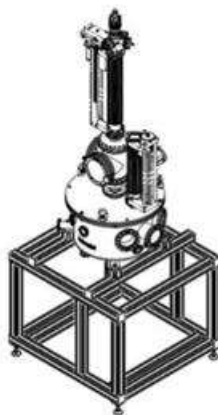
Beamline 2 – *in-situ* corrosion, triple beam

Triple beam (\$250k)

- Low-energy ion guns for simulations irradiation with e.g. He (bubble formation) and Ag (diffusion in SiC)

In-situ corrosion stage (\$50-100k)

- Study synergistic effects of irradiation and environment in FHR
- Development of a dedicated beamline for studying the coupling effect of irradiation and corrosion in HT/LP molten salts.



10 of 13

1. Consider applying to the DOE-NE Infrastructure grant program for these modifications.

Criteria

Criteria

	Criteria	Facility Response or Programmatic/User Needs
C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	1 MeV - 5.2 MeV, max. 8.5 MeV after repairs and upgrades. IONS: H, D, He, sputtered ions; no Nobel gases. Single gun, triple beam is planned
C4	Ability of the facility to collect and analyze microstructural characterization data onsite and in-situ.	In-situ depth profiling and concentration analysis of implanted species through ion beam analysis; surface chemistry monitoring through PIXE
C5	NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.	About 20% of irradiation time goes to NSUF, 70% to federal projects, and 10% to other projects. Recently won a NEUP infrastructure grant (\$200k), total 4 NSUF project, currently 2 ongoing, numerous NEUP, IRP, and NSF projects. Total irradiation hours about 400-800/year, estimate for 2016 is 1200 h
C7	Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.	State license for storage and treatment of radioactive material. No transuranic products. Storage limit 10 mCi. Max. exposure of 100mR/hr unshielded, on contact. Hot cell, sample storage, licenced equipment for sample prep and analysis.



11 of 13

Contact

Contact

Beata Tyburska-Püschel: tyburska@engr.wisc.edu

ibl.ep@wisc.edu



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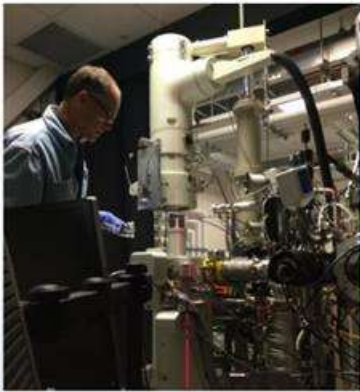
Presentation: *In situ* Ion Irradiation Transmission

Khalid Hattar

In situ Ion Irradiation Transmission Electron Microscope at Sandia National Laboratories

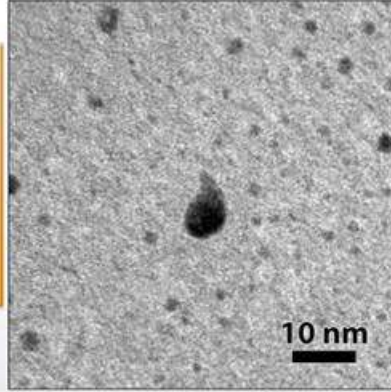
***In situ* Ion Irradiation Transmission Electron Microscope at Sandia National Laboratories**

K. Hattar
Ion Beam Lab at Sandia National Laboratories
March 23, 2016



Outline

- 1) Recent results in Au (NP and NC films)
- 2) Recent results in Ni films
- 3) Future directions
- 4) Far-out future directions



Collaborators:

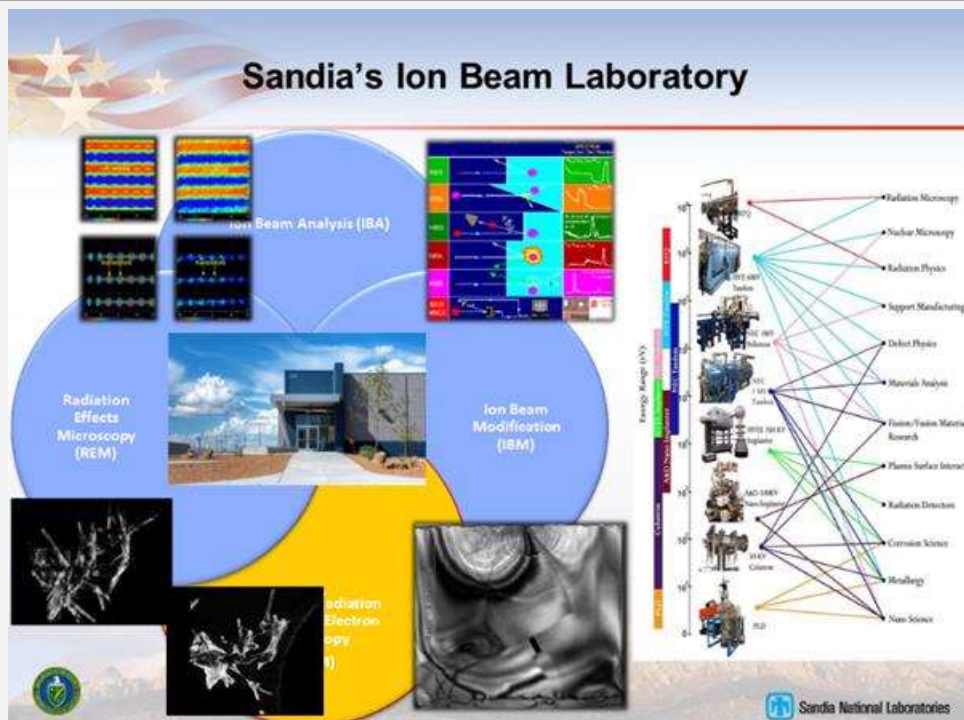
- IBL: D.C. Bufford, D. Buller, C. Chisholm, B.G. Clark, J. Villone, S. H. Pratt, M. Steckbeck, J. Kojar & M.T Marshall
- Sandia: B. Boyce, T.J. Boyle, P.J. Cappillino, J.A. Scott, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, W.M. Mook, F. Abdeljawad, & S.M. Foiles
- External: A. Minor, L.R. Parent, I. Arslan, H. Bei, E.P. George, P. Hosemann, D. Gross, J. Kacher, & I.M. Robertson

This work was supported by the US Department of Energy, Office of Basic Energy Sciences.
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC05-84OR21400.

1. This facility has greater specific capabilities that appear different than other facilities we heard about. In addition, there seems to be quite a bit of room in their schedule to do more experiments from NSUF.
2. This facility was amazing!

Sandia's Ion Beam Laboratory

Sandia's Ion Beam Laboratory



Capabilities:

- Ion Beam Analysis (IBA)
- Radiation Effects Microscopy (REM)
- Ion Beam Modification (IBM)
- Radiation Electron Spectroscopy (RES)

Energy Range (eV): 0 to 10⁶

Research Areas:

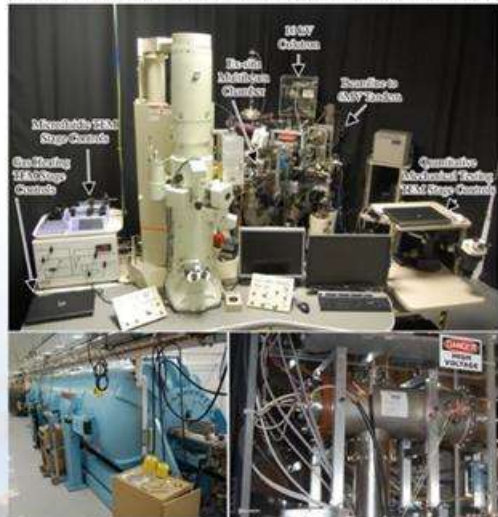
- Radiation Microscopy
- Nuclear Microscopy
- Radiation Physics
- Support Manufacturing
- Debris Physics
- Materials Analysis
- Fusion/Fusion Materials Research
- Plasma Surface Interactions
- Radiation Detection
- Corrosion Science
- Metallurgy
- Nano Science

Sandia National Laboratories

Sandia's Concurrent *In situ* Ion Irradiation TEM Facility

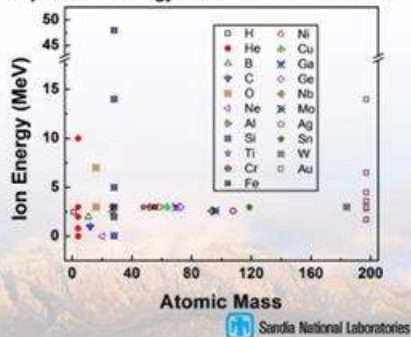
Collaborator: D.L. Buller

10 kV Colutron - 200 kV TEM - 6 MV Tandem



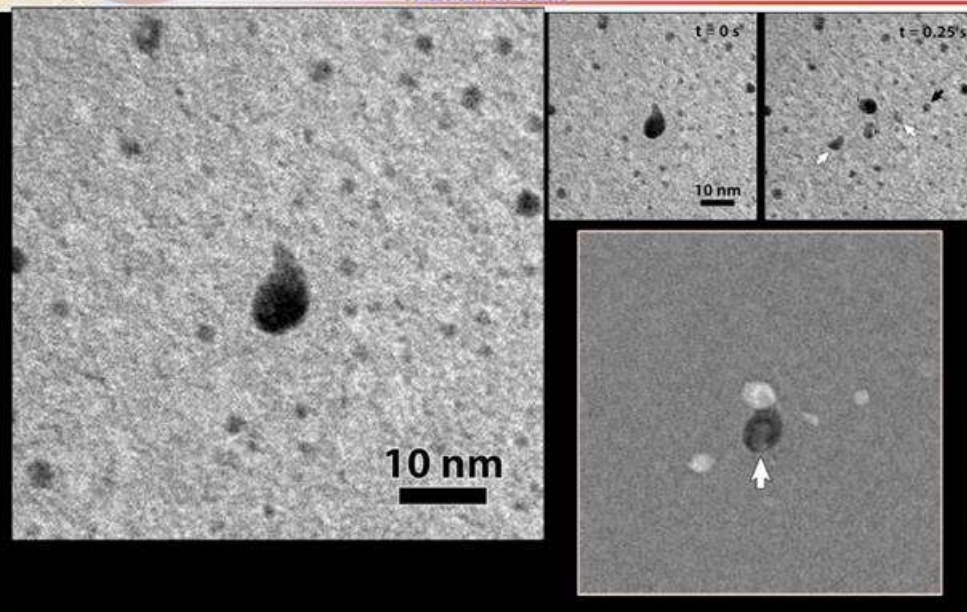
Direct real time observation of ion irradiation, ion implantation, or both with nanometer resolution

Ion species & energy introduced into the TEM

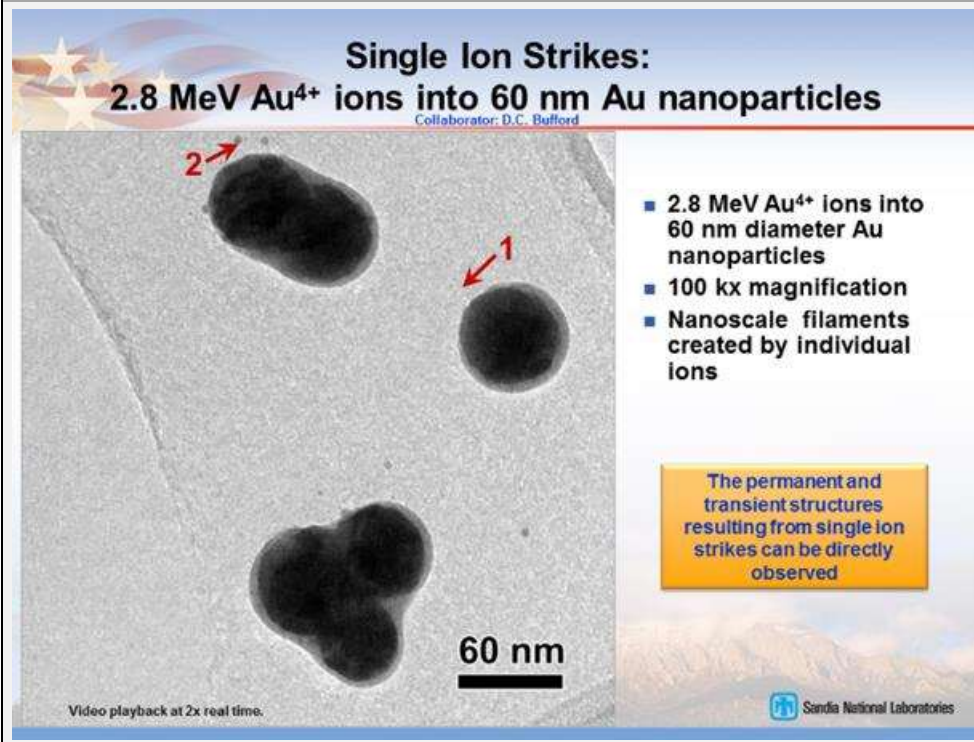


Single Ion Strikes: 46 keV Au¹⁺ ions into 5 nm Au nanoparticles

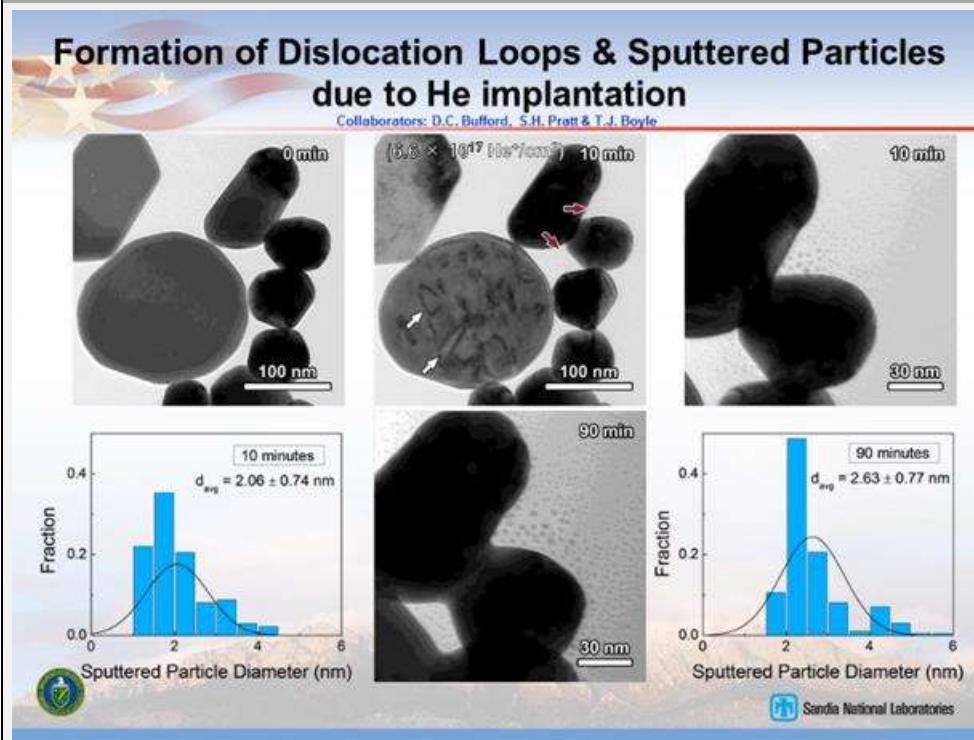
Collaborator: D.C. Bufford



Single Ion Strikes: 2.8 MeV Au⁴⁺ ions into 60 nm Au nanoparticles



Formation of Dislocation Loops & Sputtered Particles due to He implantation



Electron Tomography Provides 3D Insight

Electron Tomography Provides 3D Insight

Collaborators: S.H. Pratt & T.J. Boyle

In situ Ion Irradiation TEM (I³TEM)

Aligned Au NP tilt series - unirradiated

Unirradiated Au NP model

Aligned Au NP tilt series - irradiated

Irradiated Au NP model

Hummingbird tomography stage

The application of advanced microscopy techniques to extreme environments provides exciting new research directions

Dose Rate Effects

Dose Rate Effects

Collaborators: C. Chisholm, P. Hosemann, & A. Minor

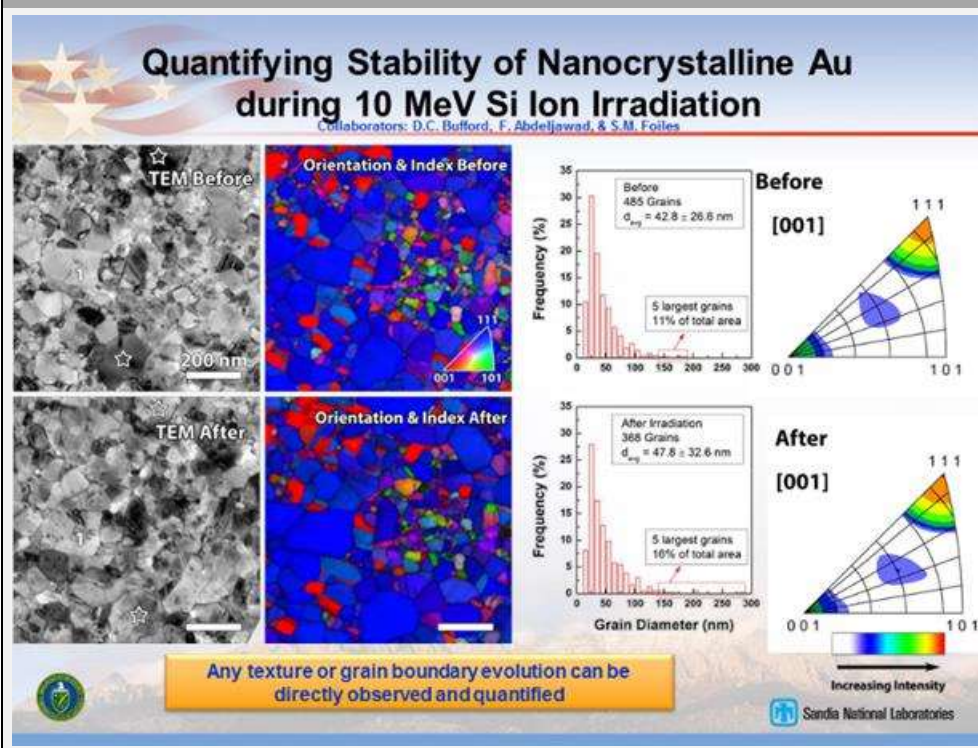
7.9×10^9 ions/cm²/s

6.7×10^7 ions/cm²/s

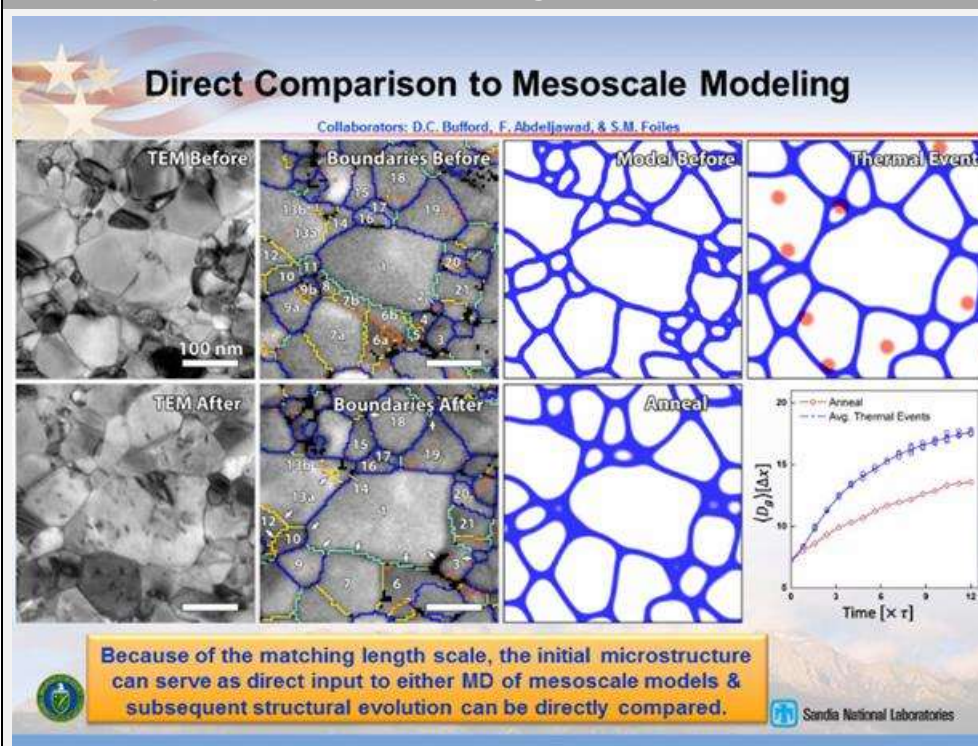
VS

Improved vibrational and ion beam stability permits us to work at 120kx or higher permitting imaging of single cascade events

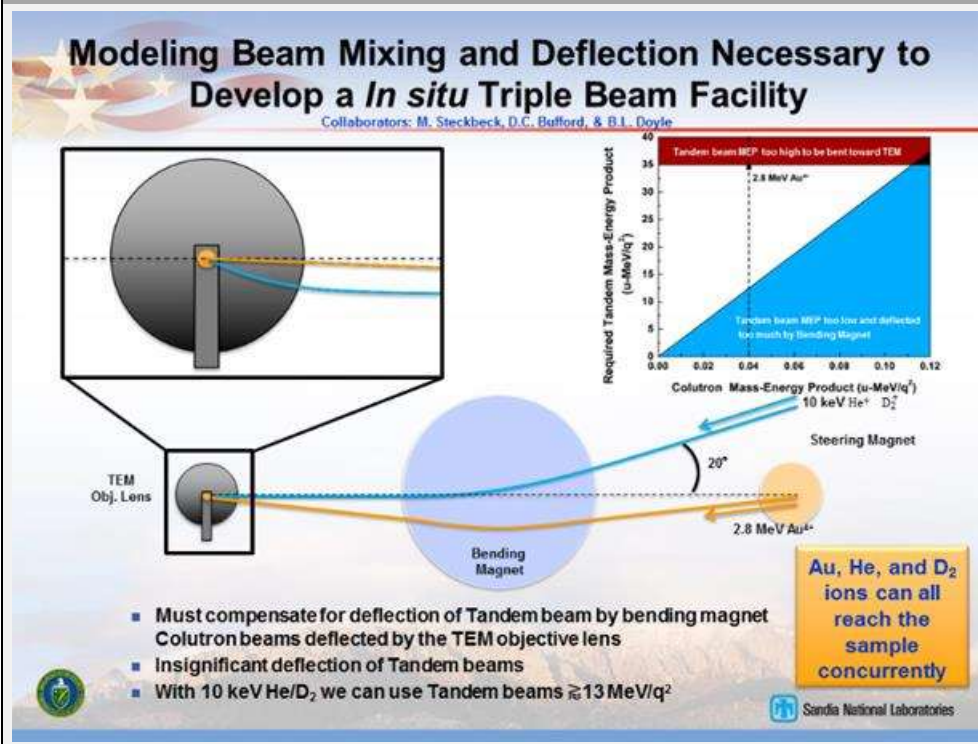
Quantifying Stability of Nanocrystalline Au during 10 MeV Si Ion Irradiation



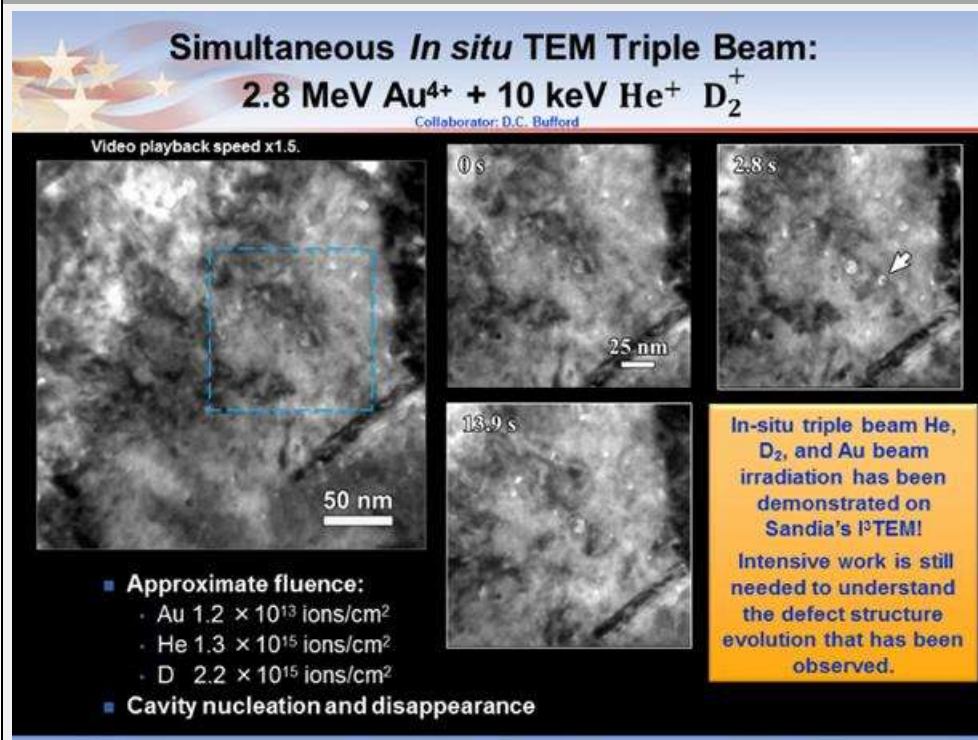
Direct Comparison to Mesoscale Modeling



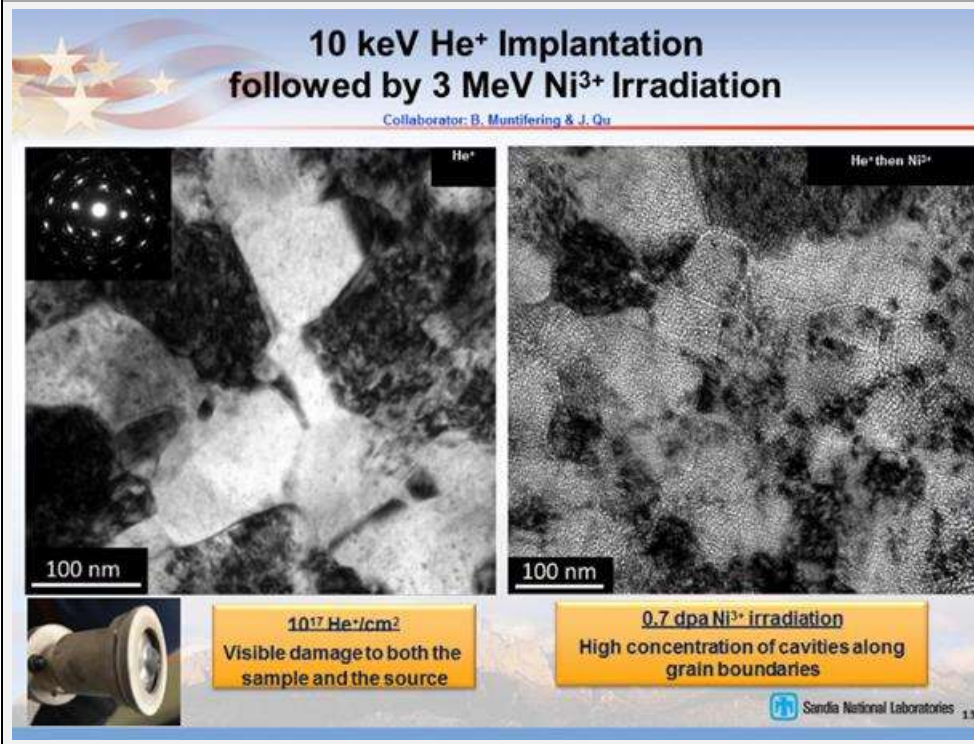
Modeling Beam Mixing and Deflection Necessary to Develop a *In situ* Triple Beam Facility



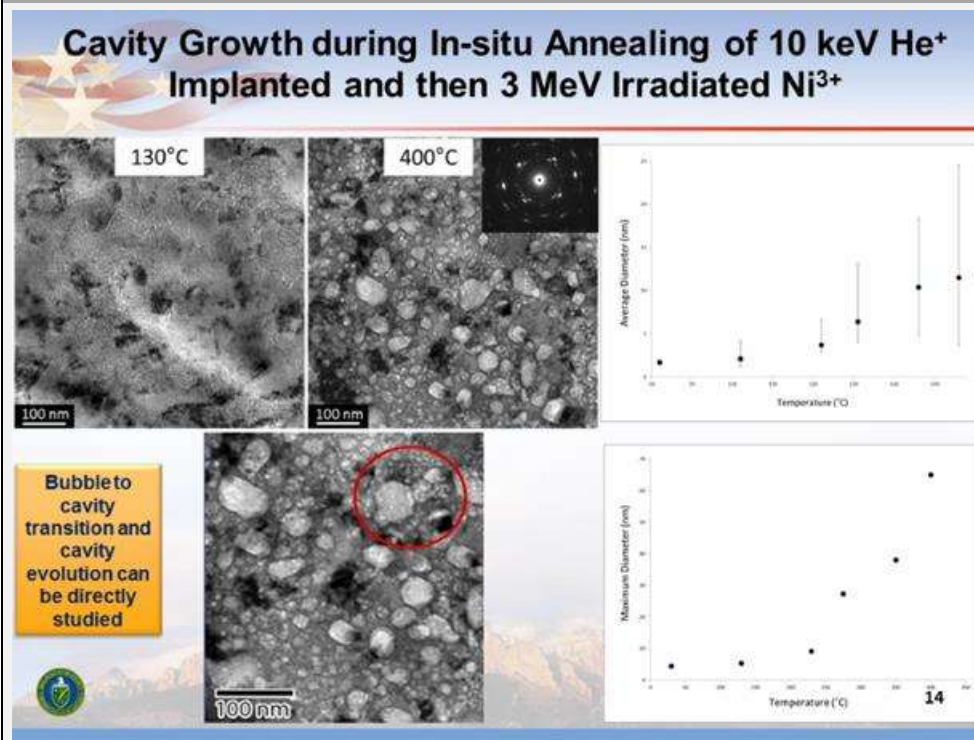
Simultaneous *In situ* TEM Triple Beam: 2.8 MeV Au⁴⁺ + 10 keV He⁺ D₂⁺



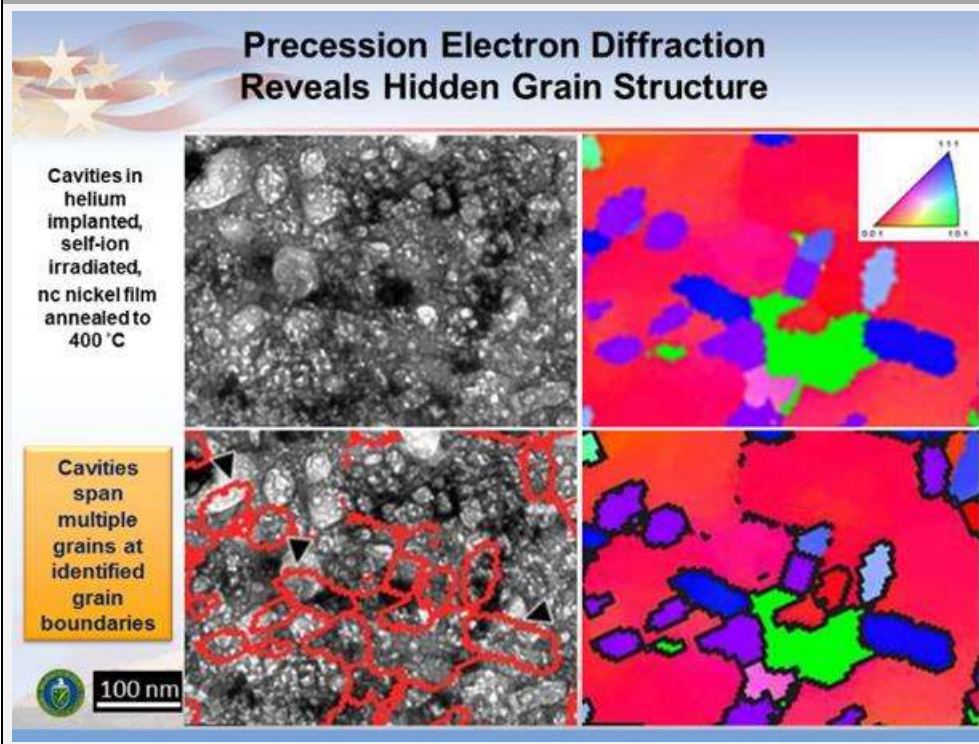
10 keV He⁺ Implantation followed by 3 MeV Ni³⁺ Irradiation



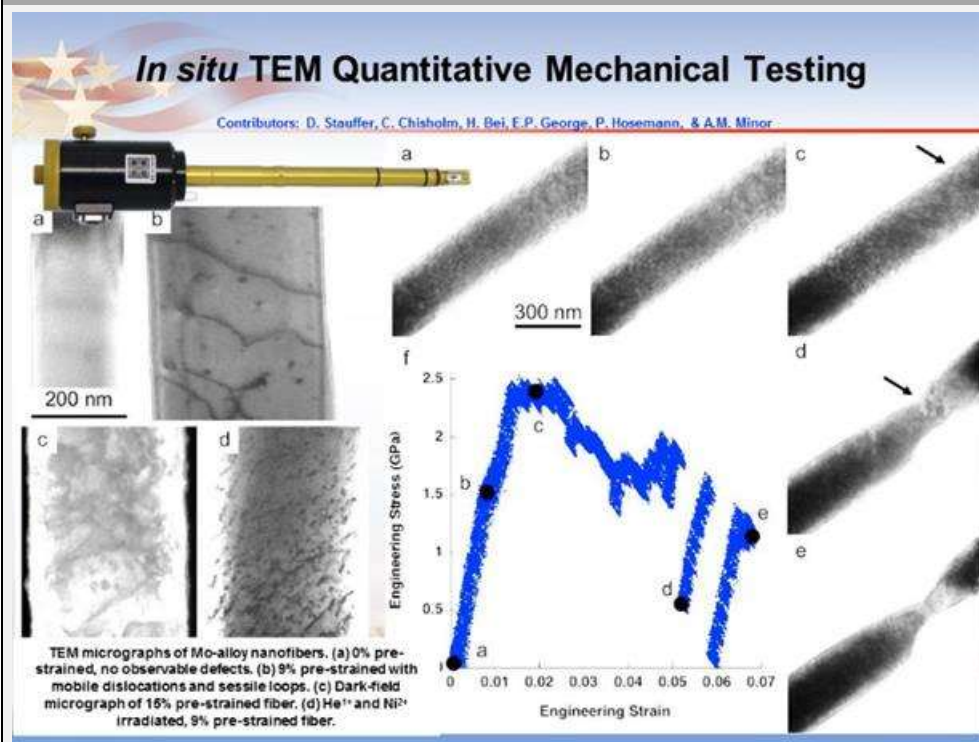
Cavity Growth during *In-situ* Annealing of 10 keV He⁺ Implanted and then 3 MeV Irradiated Ni³⁺



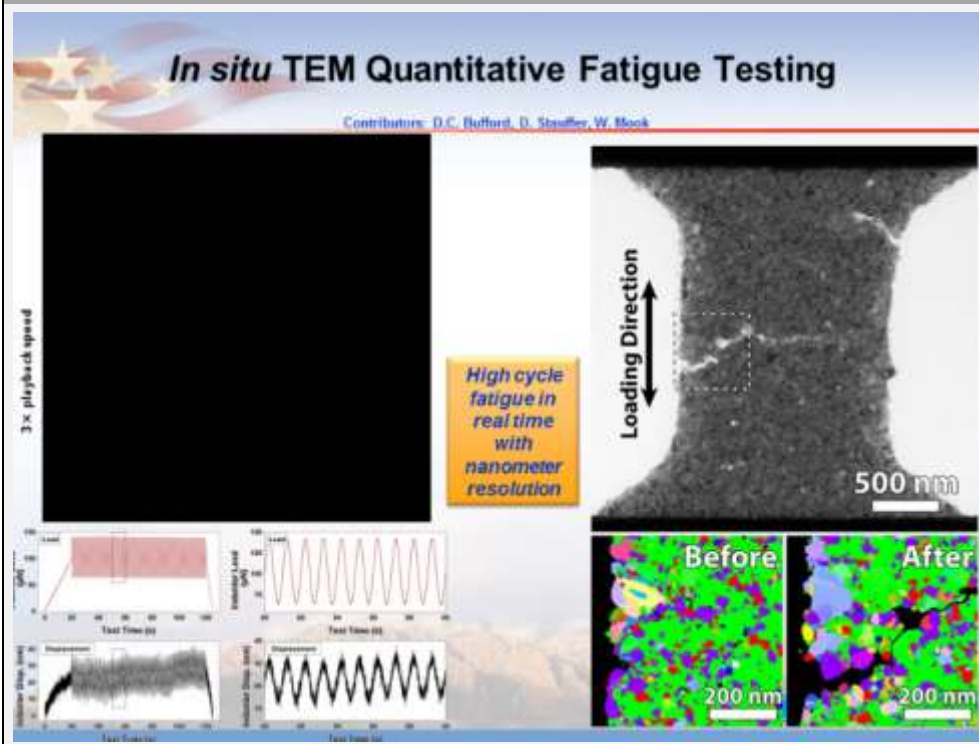
Precession Electron Diffraction Reveals Hidden Grain Structure



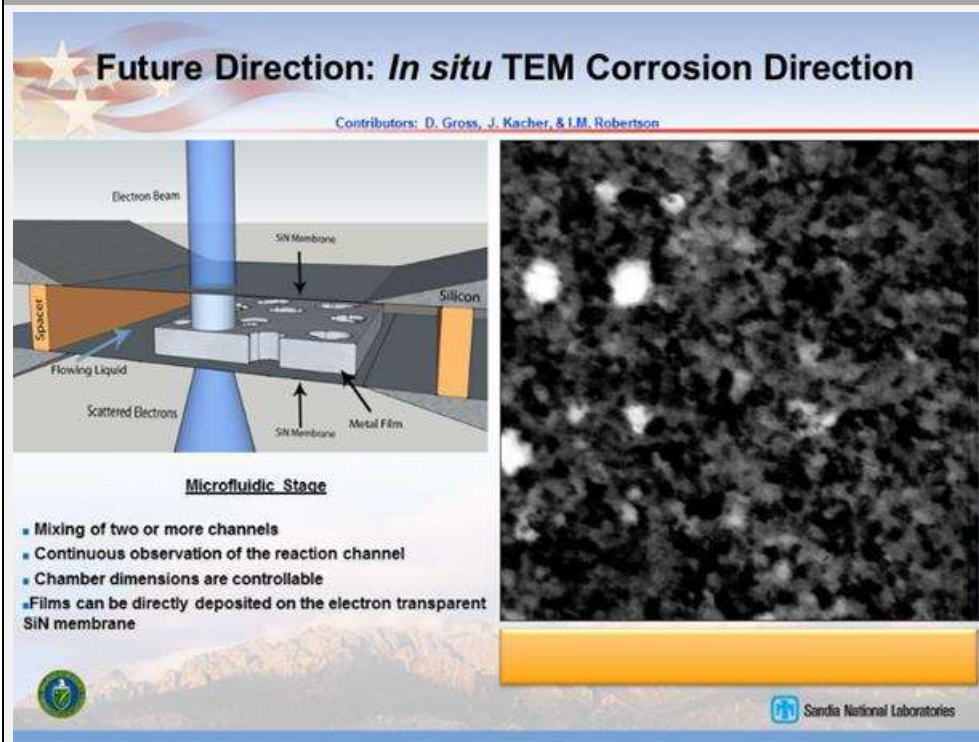
In situ TEM Quantitative Mechanical Testing



In situ TEM Quantitative Fatigue Testing



Future Direction: In situ TEM Corrosion Direction



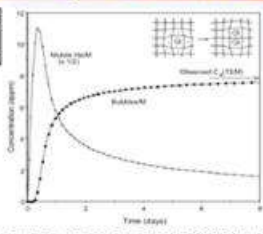
Future Direction: *In situ* TEM Hydrogen Exposure

Future Direction: *In situ* TEM Hydrogen Exposure

Contributors: B.G. Clark, P.J. Cappillino, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, L.R. Parent, I. Arslan, & Protochips, Inc.



R. Dolmello, J. Phys. Chem. Chem. Phys., (2011) p.11412



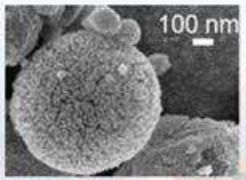
Cowgill, D., Fusion Sci. & Tech., 28 (2005) p. 539
Trinkaus, H. et al., JNM (2003) p. 229
Thiebaut, S. et al. JNM (2000) p. 217

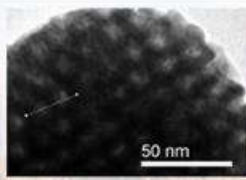
Vapor-Phase Heating TEM Stage

- Compatible with a range of gases
- In situ* resistive heating
- Continuous observation of the reaction channel
- Chamber dimensions are controllable
- Compatible with MS and other analytical tools



Harmful effects may be mitigated in nanoporous Pd







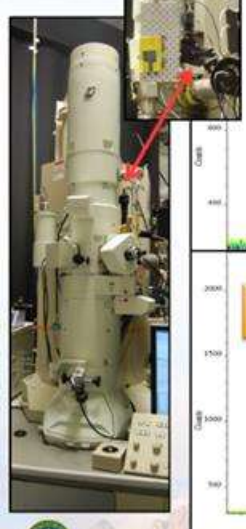
125° C 200° C 300° C

1 atm H₂ after several pulses to specified temp.

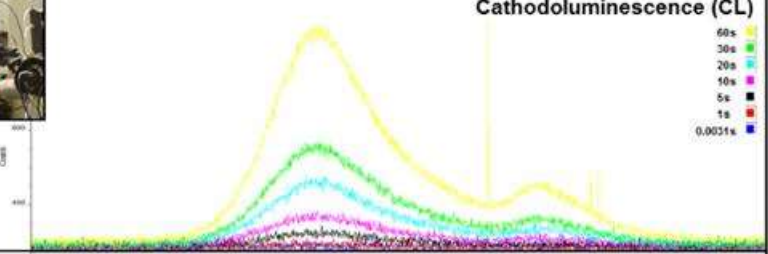
Future Direction: *In situ* TEM Ion beam Induced Luminescence (IBIL)

Future Direction: *In situ* TEM Ion beam Induced Luminescence (IBIL)

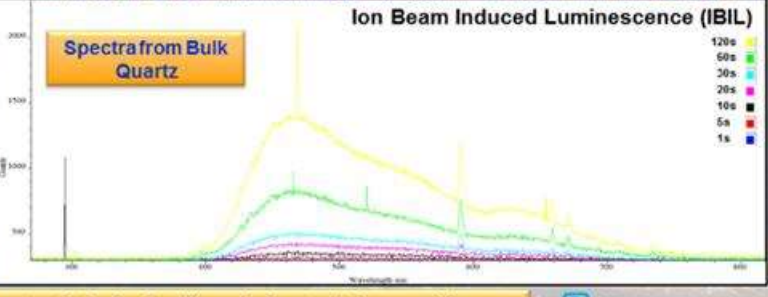
Collaborator: J. Gutierrez-Kolar



Cathodoluminescence (CL)



Ion Beam Induced Luminescence (IBIL)



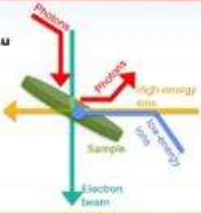

Spectra from Bulk Quartz

Significant optimization is still needed; potential is promising

Sandia National Laboratories

Summary & Still Father-out Future Directions

- Sandia's I³TEM capabilities:**
 - In situ high energy ion irradiation from H to Au
 - In situ gas implantation
 - Heating up to 1,000 °C
 - Quantitative and bulk straining
 - Two-port microfluidic cell
 - Gas flow/heating stage
 - Electron tomography
 - Precession Electron Diffraction





Currently applying the current I³TEM capabilities to various material systems in sequential or combined harsh environmental conditions

- Sandia's I³TEM future capabilities being developed:**
 - In situ ion irradiation TEM in liquid or gas (currently capable)
 - DTEM: Nanosecond resolution (laser optics being developed)
 - Beamline: Add 1 MV NEC Tandem & convert 90° magnet to bend beams 45°

Collaborators:

- IBL: D.C. Bufford, D. Buller, C. Chisholm, B.G. Clark, J. Villone, S. H. Pratt, M. Steckbeck, J. Kolar & M.T. Marshall
- Sandia: B. Boyce, T.J. Boyle, P.J. Cappillino, J.A. Scott, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, W.M. Mook, F. Abdeljawad, & S.M. Foiles
- External: A. Minor, L.R. Parent, I. Arslan, H. Bei, E.P. George, P. Hosemann, D. Gross, J. Kacher, & I.M. Robertson



This work was partially funded by the Division of Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL55000.

Sandia National Laboratories

Presentation: Michigan IBL

Gary Was

Ion Irradiation Capabilities and Needs at the Michigan Ion Beam Laboratory – a NSUF Partner Facility –
Nuclear Engineering and Radiological Sciences University of Michigan

Ion Irradiation Capabilities and Needs at the Michigan Ion Beam Laboratory a NSUF Partner Facility

Nuclear Engineering and Radiological Sciences
University of Michigan

Gary S. Was
March 23, 2016



Slide 2

ANNOUNCING THE
➡ **MICHIGAN ION BEAM LABORATORY**
FOR SURFACE MODIFICATION AND ANALYSIS

OPEN HOUSE

Thursday, October 16, 1986

2 - 6 PM

120 NAME Bldg.
2600 Draper Road, North Campus
(follow signs)

FACULTY - STAFF - STUDENTS WELCOME

The Michigan Ion Beam Laboratory for Surface
Modification and Analysis was established to explore
both the fundamentals of ion-solid interactions as well
as the practical applications to surface modification
and analysis for research and industry.

For more information call:

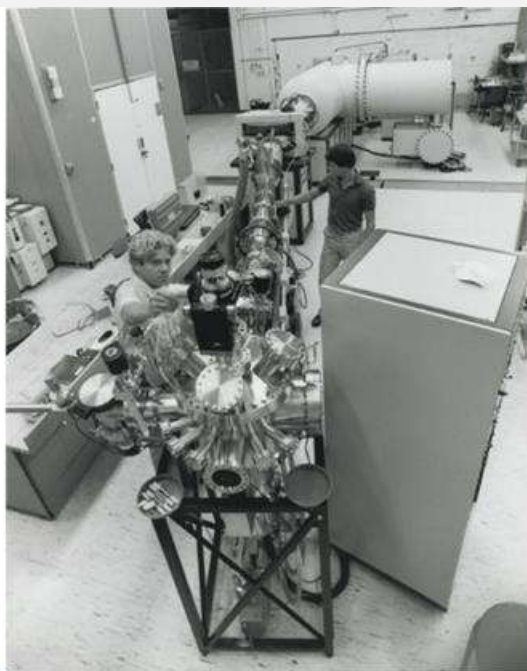
Professor Gary S. Was 763-4675
or Dr. Victor Rotberg 936-0166



2

Slide 3

MIBL
October, 1986



3

Slide 4

ATR-NSUF Partnership

Date: Thu, 5 Feb 2009 09:52:31 -0700

Dear Dr. Was:

Congratulations, your facility has been selected to join the ATR NSUF as a research partner. Attached below is the formal selection letter.

Welcome to the NSUF team. If you have any questions about your selection, please don't hesitate to contact me.

Todd R. Allen
Scientific Director
ATR National Scientific User Facility



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Slide 5



Slide 6

Summary of Instrumentation at MIBL

Accelerators

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

Ion sources

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

Target temperature range: 77K to 1500K

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

Irradiated area: up to 200 mm²

9 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

*in progress

Fly around MIBL

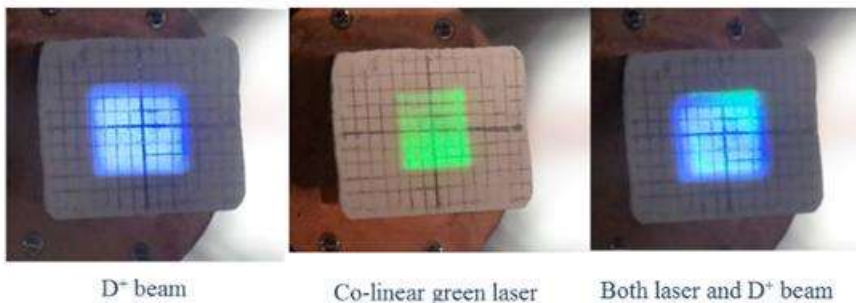


Ion Irradiation Capabilities at MIBL

- 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

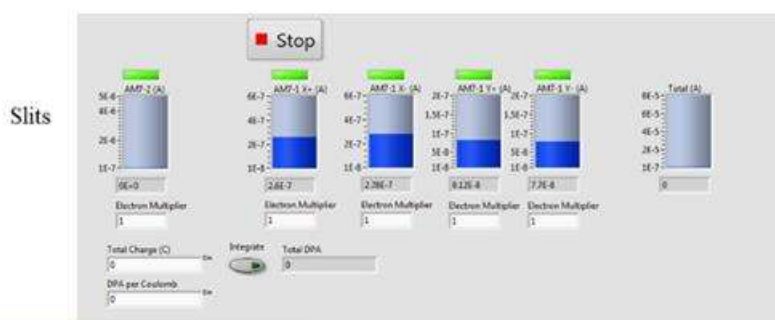
Laser alignment of ion beams for multi-beam irradiations

Laser alignment of ion beams for multi-beam irradiations



Beam shape and current balancing of raster-scanned beams

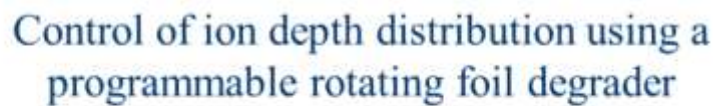
Beam shape and current balancing of raster-scanned beams



Defocused beam - shape and spread

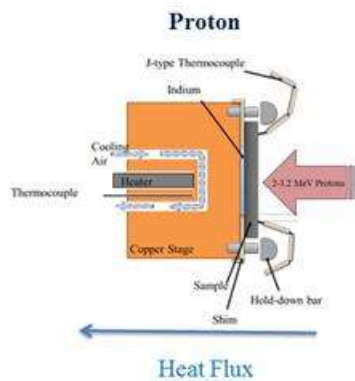


Control of ion depth distribution using a programmable rotating foil degrader

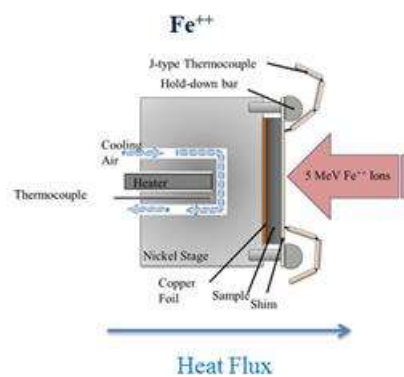


Stage Design for Proton and Fe⁺⁺ Temperature Control

Stage Design for Proton and Fe⁺⁺ Temperature Control



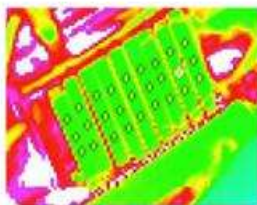
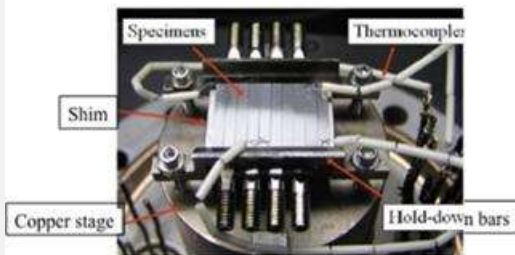
- Indium layer ensures good thermal contact
- Addition of proton beam heating (100°C) provides major heat flux



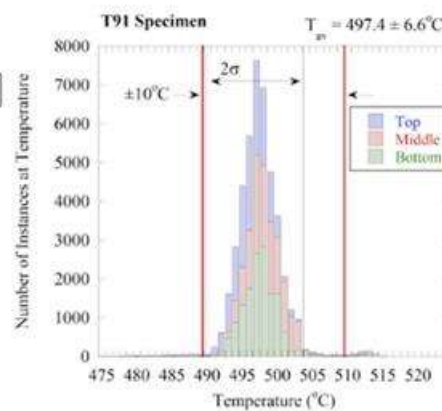
- Copper foil provides sufficient thermal contact
- Low current Fe⁺⁺ beam contributes minimal beam heating (5-10°C)

Irradiations

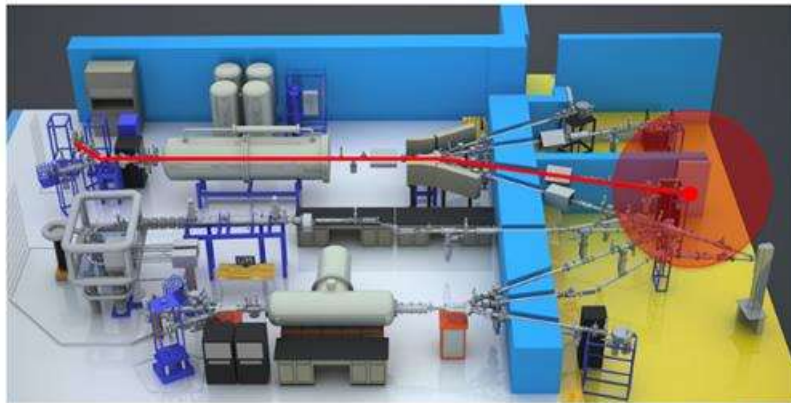
Temperature Monitoring



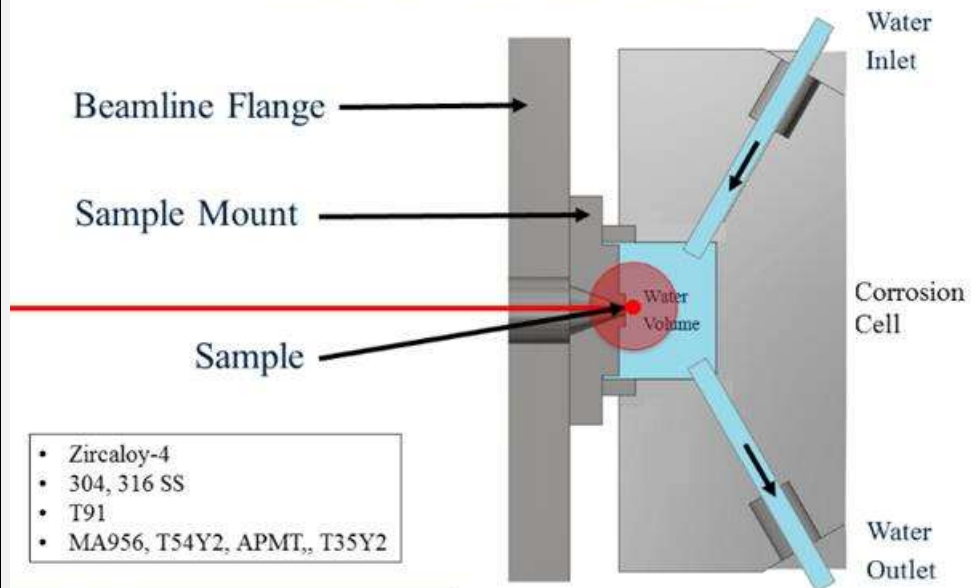
2-D thermal image



Irradiation Accelerated Corrosion (IAC)

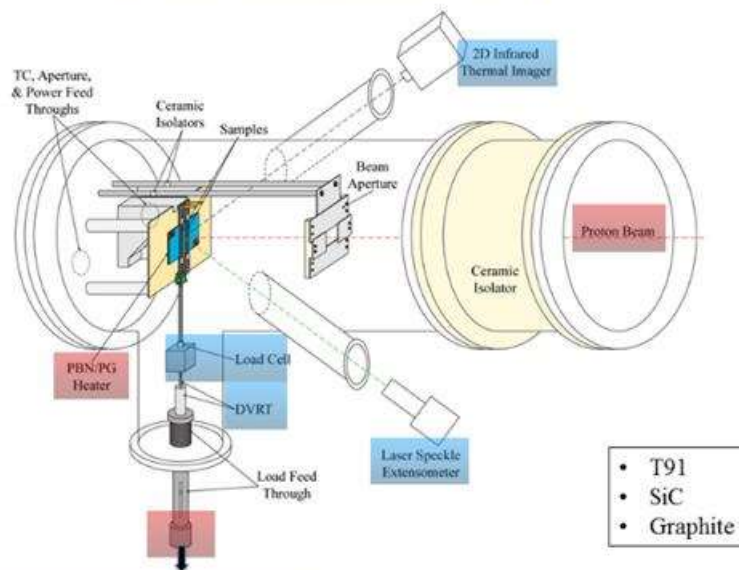


Corrosion cell and sample



- Zircaloy-4
- 304, 316 SS
- T91
- MA956, T54Y2, APMT,, T35Y2

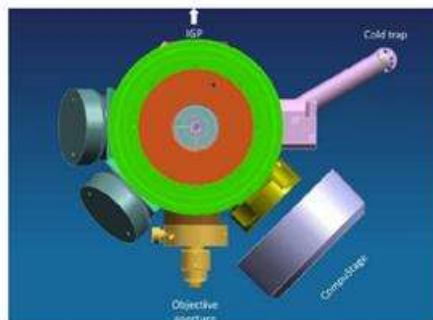
In-situ irradiation creep



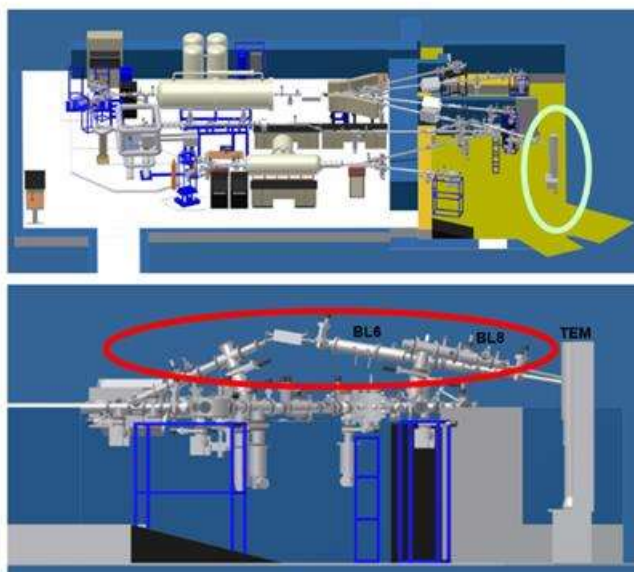
FEI Tecnai G2 F30 TWIN (300kV, LaB₆ filament)



- 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



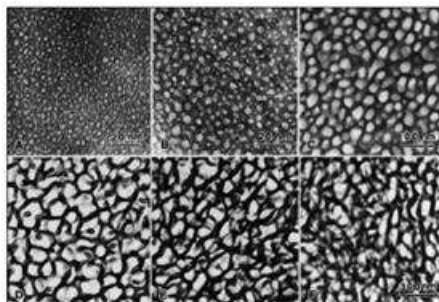
In-situ Dual Beam Facility



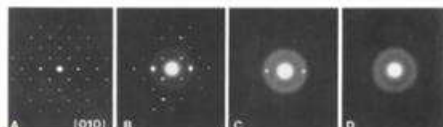
Our experience on *in situ* TEM during ion irradiation with the HVEM- and IVEM-Tandem Facility at ANL since 1989



Over 70 SCI journal papers and 1800 citations on TEM with *in situ* irradiation



Wang and Birtcher, (APL 1989, Phil Mag A 1991)



Wang and Ewing, (MRS Bulletin 1992)

Slide 21



Slide 22


MICHIGAN ENGINEERING
MICHIGAN ION BEAM LABORATORY

Michigan Ion Beam Laboratory

Michigan Ion Beam Laboratory

About MIBL

- Overview
- "Flyaround" the Lab
- Take a Walking Tour
- Zoom In for More Detail
- View a narrated video of MIBL
- View Some Possible Experiments
- Capabilities
- Major Instruments
- Research at MIBL
- Work with MIBL
- People
- Other Links



CONTACT ORVILLE THOMAS
 orville@umich.edu
 734-936-0166

About MIBL



The Michigan Ion Beam Laboratory (MIBL) for Surface Modification and Analysis was established in October of 1988. The Laboratory is part of the Department of Nuclear Engineering and Radiological Sciences in the College of Engineering, and is located on the University of Michigan's North Campus. MIBL is part of the National Nanotechnology Infrastructure Network (NNIN). The laboratory was created for the purpose of advancing our understanding of ion-solid interactions by providing unique and extensive facilities to support both research and development in the field. Researchers have available to them several instruments for conducting ion beam surface modification and on beam surface analysis under a wide range of conditions. Experiments can be conducted at high or low temperature, in ultra-high vacuums, in a reactive gas and in short turnaround times. A knowledgeable scientific staff and a large number of supporting facilities are also available for surface preparation and analysis. Browse the site and see if anything interests you.



ANNUAL RESEARCH REPORT

2016

Gary S. Was, Director
Ovidiu Toader, Manager and Research Specialist
Fahim Naab, Research Specialist
Ethan Uebereder, Research Specialist
Thomas Kabley, Research Engineer

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Telephone: (734) 936-0131

Fax: (734) 763-4540



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Triple beams: Self-ion (Fe^{++}) + He and H injection in the MBC

Triple beams: Self-ion (Fe^{++}) + He and H injection in the MBC



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Addressing a wide range of dpa, He, H production

Damage rate, He/dpa and H/dpa for various reactor types

Reactor type	Fast (F-M)	LWR (stainless)	CANDU (Ni-base)	Fusion (F-M)	SNS (F-M)
Dose rate (dpa/s)	1×10^{-6}	5×10^{-8}	2×10^{-7}	10^{-7} - 10^{-6}	10^{-8} - 10^{-7}
He/dpa (appm/dpa)	0.2	2-5	300	~10	~100
H/dpa (appm/dpa)	-	12	60	70	1700

Achievable damage rate, He/dpa and H/dpa in MIBL

Ion	400 KV implanter	1.7 MV Tandem	3.0 MV Tandem
Fe ²⁺	-	10^{-5} - 10^{-3} dpa/s	10^{-8} - 10^{-3} dpa/s
He ²⁺	$0.1 - 10^5$ appm/dpa	$0.1 - 10^5$ appm/dpa	$0.1 - 10^5$ appm/dpa
H ⁺	$0.1 - 10^5$ appm/dpa	$0.1 - 10^5$ appm/dpa	$0.1 - 10^5$ appm/dpa

Use of Ion Irradiation to Study Nuclear Fuel

- Xe (up to 1 μ A of 1.6 MeV Xe) and Kr (up to 1.5 μ A of 1.2 MeV) ion irradiation to study fission gas effect.
- He ion irradiation to study α particle irradiation effect.
- In-situ Kr/Xe ion irradiation in TEM to study microstructural evolution with or without gas effect depending on ion energy and sample thickness.
- Heavy ion irradiation with Zr or Mo ions (both with high fission yield) to study interface stability under irradiation.
- Ion irradiation to study fuel-matrix-interaction (FMI) or fuel-cladding-chemical-interaction (FCCI) behavior.

Experience and capability

In 2013 >6600 beam hr logged on irradiation effects studies in MIBL (~200 irradiations) for 130 researchers and 52 projects. In last five years:

- **Labs:** INL, LANL, ORNL, PNNL, Bettis, U.S. Army Research Lab
- **Universities:** Boise State, Wisc., Connecticut, Texas A&M, Windsor, Illinois, Va. Tech, Virginia, Cornell, Colorado School of Mines, Southern California, Wayne State, Ohio State, Buffalo, Notre Dame, San Antonio, Tennessee, Alabama A&M, Duke Univ., Brown Univ., UCLA, Rutgers, Delaware, Pennsylvania, McMaster
- **International:**
 - France - Areva, CEA, CNRS, U. de Toulouse, Ecole Nat' l Sup. Paris
 - U.K. - U. Manchester, Oxford
 - China - IMR, SNPRI, SNERDI, Northeastern U., SJTU, U. Electr. Sci. and Technol.
 - Canada - AECL
 - Japan - INSS (Japan)
 - Germany - Helmholtz Center
 - Poland - Institute of Physics
 - Czech Republic - NRI
 - Korea - KAERI
 - Pakistan - Lahore College for Women, NIOP, Pakistan Inst. of Engin & Appl Sci



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Current UM-based Projects at MIBL

- EPRI ARRM program on IASCC
- EPRI 718 program on IASCC of 718 as a function of microstructure
- DOE-BES program on mechanism of IASCC
- DOE/EPRI LWRS program on IASCC mechanism and modeling
- NEUP program on IASCC mitigation
- MAI/EdF program on IAC
- 5 NEUP programs on Accident Tolerant Fuel Development
- NEUP program on accelerated irradiations for high dose microstructures
- NEUP program on radiation induced segregation
- CASL project on oxidation and hydrogen uptake in Zr under irradiation
- DOE-IRP on High Fidelity Ion Irradiation to Emulate Reactor Irradiation
- TerraPower project on core materials development



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Accomplishments



Journal of Nuclear Materials 300 (2002) 198–216



www.elsevier.com/locate/jnmat

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



Available online at www.sciencedirect.com

ScienceDirect

Scripta Materialia 88 (2014) 33–36



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



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Professional Staff at MIBL



Ovidiu Toader, PhD; Lab Manager



Fabian Naab, PhD; Research Specialist



Ethan Uberseder, PhD; Research Specialist

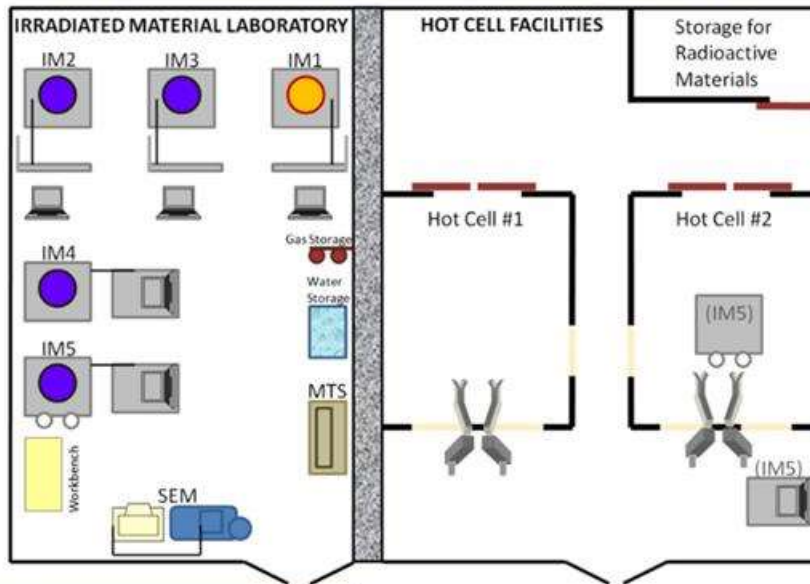


Thomas Kubley, MS; Accelerator Engineer



30

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

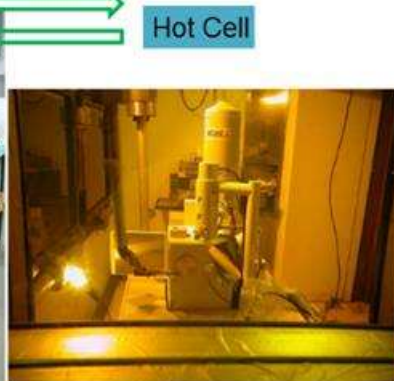
Irradiated Materials Testing Laboratory



Control Panel
& Water Columns



Movable Autoclave
& Loading System



Dedicated Hot SEM

On-site: Michigan Center for Materials Characterization

Available techniques

- Scanning electron microscopy (SEM)
- Focused ion beam (FIB) milling and imaging
- X-ray energy dispersive spectrometry (XEDS)
- Electron backscattered diffraction (EBSD)
- Cryo electron microscopy
- Transmission electron microscopy (TEM)
 - diffraction imaging
 - high resolution (HREM)
 - scanning (STEM)
 - aberration-corrected
- In-situ electron microscopy
 - (straining, heating, indentation)
- Electron energy loss spectrometry (EELS)
- Atom probe microscopy (APM)
- Atomic force microscopy (AFM)
- X-ray photoelectron spectroscopy (XPS)
- tribo/pico-indentation
- Sample preparation

Instruments

- Specimen preparation
- Philips XL30 FEG SEM
- FEI Quanta 3D e-SEM/FIB
- FEI Nova 200 Nanolab SEM/FIB
- FEI Helios 650 Nanolab SEM/FIB
- JEOL 2010F Analytical Electron Microscope
- JEOL 2100F Probe-corrected Electron Microscope
- JEOL 3011 High Resolution Electron Microscope
- JEOL 3100R05 Double Cs Corrected TEM/STEM
- TEM holders
- Cameca LEAP 4000X HR Atom Probe
- Veeco Dimension Icon AFM
- Kratos Axis Ultra XPS
- Hysitron tribo-indenter
- Hysitron pico-indenter

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.



ELECTRIC POWER
RESEARCH INSTITUTE



MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN



COLLEGE OF ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN



Michigan Ion Beam Laboratory

Presentation: Accelerator Based Facility for Materials Irradiation Testing

Nick Simos

Slide 1

Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex

N. Simos



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a passion for discovery



Slide 2

ION Irradiation Workshop Objective

Goal: Identification of ion beam irradiation capabilities for nuclear energy focused RD&D

Availability of Neutron SURROGATE Irradiating species and facilities

Challenges:

- **IDENTIFY** a reasonable correlation between damage caused by fast neutrons and surrogate species (energetic protons, heavy ions, etc.)
- **REPORT** on recent experimental data towards meeting the challenge based on graphite

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Slide 3

BNL Irradiation and Characterization Facilities Synergy

BLIP (Brookhaven Linear Isotope Producer):

Irradiation studies using (a) high energy protons (66 MeV to 200 MeV) and (b) spallation neutrons from 118 MeV protons on target.

Materials for fusion and fission reactors as well as high power accelerators (LHC, LBNF, FRIB, etc.)

NSRL – 2 GeV protons + High Energy Ions

Tandem Van de Graaff:

Irradiation facility with 28 MeV protons or ions from an ion array up to ^{197}Au

Isotope Extraction-Processing Facility:

An experimental area in the facility hot cells for complete macroscopic analysis of irradiated samples

NSLS II - X-ray diffraction

Center for Functional Nanomaterials (CFN) - Characterization

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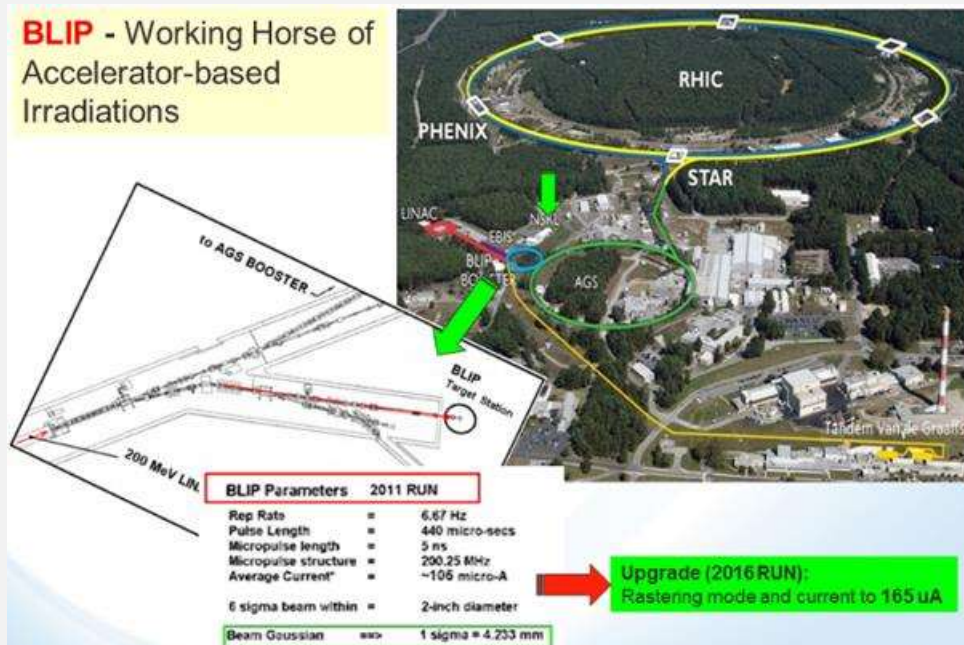
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1. Working on getting CFN to handle radioactive materials.

Slide 4

BLIP - Working Horse of Accelerator-based Irradiations



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Slide 5

High Energy Proton Irradiation

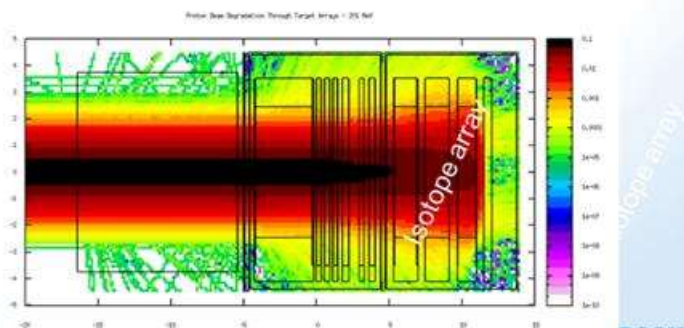
(energies up to 200 MeV)

Material Irradiation Damage Studies for:

- DOE NE
- Large Hadron Collider (CERN)
- Long Baseline Neutrino Facility
- Neutrino Factory

Beam POWER ~32 kW

Simultaneous isotope production & irradiation



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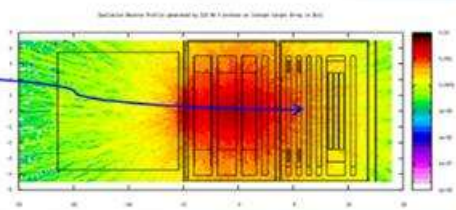
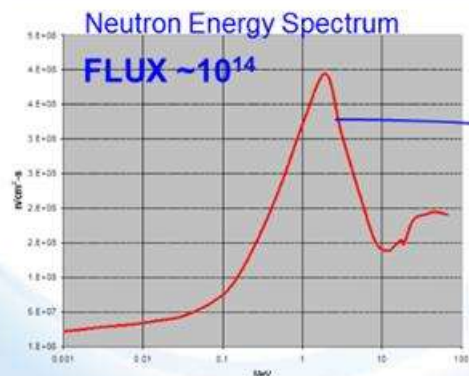
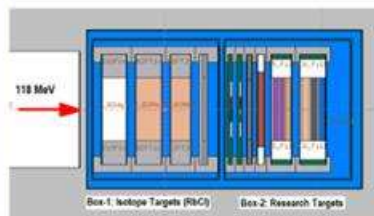
Slide 6

Spallation-induced Fast Neutron Irradiation at BLIP

Irradiation damage studies from mixed spectrum (dominated by fast neutrons)

Studies:

- Fusion Reactor Materials and Composites
- DOE-NE materials (super-alloys, ceramic and amorphous coatings on reactor steels, etc.)



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Irradiation Damage of Graphite

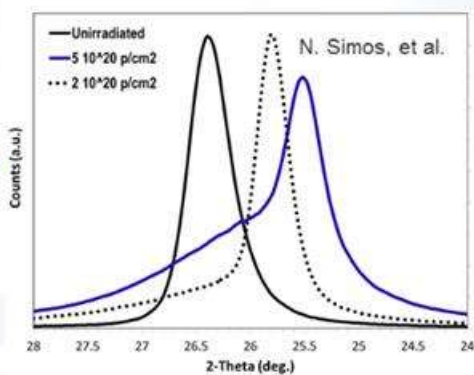
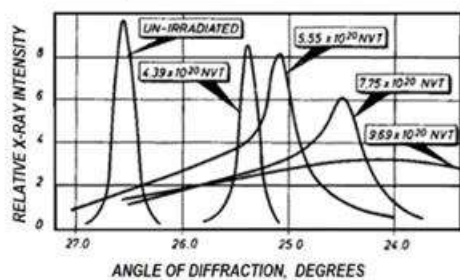
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Neutron Surrogate Irradiation – Recent results on graphite

Neutron Surrogate Irradiation - Recent results on graphite

B.J. Marsden, "Irradiation Damage in Graphite due to fast neutrons in fission and fusion systems," IAEA-TECDOC-1154, 2000

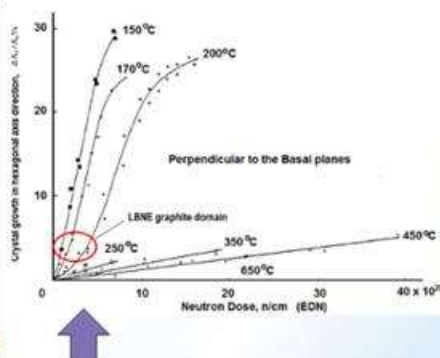
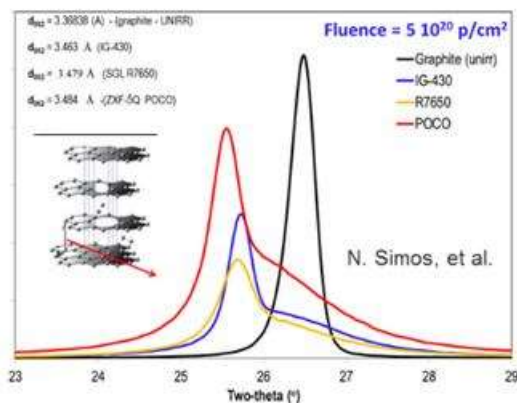


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Neutron Surrogate Irradiation – Recent results on graphite

Neutron Surrogate Irradiation - Recent results on graphite



Proton irradiation to fluence $5 \times 10^{20} \text{ p/cm}^2$

POCO (ZXF-5Q) ($5 \times 10^{20} \text{ cm}^{-2}$) c-axis growth ~3.17%

IG-430 ($\sim 5 \times 10^{20} \text{ p/cm}^2$) c-axis growth ~2.83%

R7650 ($5 \times 10^{20} \text{ p/cm}^2$) c-axis growth ~2.95%

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B.J. Marsden, "Irradiation Damage in Graphite due to fast neutrons in fission and fusion systems," IAEA-TECDOC-1154, 2000

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1. Did Brookhaven measure the macroscopic (i.e., sample) dimensional change after irradiation? This can be directly compared to neutron irradiation dim. Change from multiple programs to illustrate direct macroscopic response. - Will Windes
2. DOE-NE ART Graphite program has neutron irradiated IG-430 graphite, which is currently undergoing d-spacing change analysis. These results can be utilized to directly compare the microscopic response of the same grade. -Will Windes

Slide 10

Tandem Van de Graaff Accelerator Ion irradiation



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Slide 11

28 MeV Proton & Heavy ion irradiation at Tandem – 2 uA current



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Z	Symbol	Mass AMU	Max Energy		Surface LET		Surface Range	
			MeV	MeV AMU	MeV mg/cm ²	microns	MeV mg/cm ²	microns
1	¹ H	1.0079	28.75	28.52	<u>0.0153</u>	4550	<u>0.0118</u>	2610
3	⁷ Li	7.0160	57.2	8.15	<u>0.369</u>	390	<u>0.273</u>	240
5	¹¹ B	11.0093	85.5	7.77	<u>1.08</u>	206.13	<u>0.754</u>	132.55
6	¹² C	12.0000	99.6	8.30	<u>1.46</u>	180.43	<u>1.03</u>	115.82
8	¹⁶ O	15.9994	128	8.00	<u>2.61</u>	137.78	<u>1.83</u>	88.9
9	¹⁹ F	18.9954	142	7.48	<u>3.51</u>	118.88	<u>2.45</u>	77.12
12	²⁴ Mg	23.9927	161	6.71	<u>6.01</u>	84.16	<u>4.17</u>	55.13
14	²⁸ Si	28.0855	187	6.66	<u>7.81</u>	77.16	<u>5.42</u>	50.66
17	³⁵ Cl	34.9688	212	6.06	<u>11.5</u>	64.41	<u>7.93</u>	42.71
20	⁴⁰ Ca	39.9753	221	5.53	<u>15.8</u>	51.89	<u>10.9</u>	34.7
22	⁴⁸ Ti	47.9479	232	4.84	<u>19.6</u>	47.8	<u>13.4</u>	32.36
24	⁵² Cr	51.9405	245	4.72	<u>22.3</u>	45.86	<u>15.3</u>	31.06
26	⁵⁶ Fe	55.9349	259	4.63	<u>25.1</u>	44.24	<u>17.2</u>	30.09
28	⁵⁸ Ni	57.9353	270	4.66	<u>27.9</u>	44.56	<u>19.1</u>	30.47
29	⁶³ Cu	62.9296	277	4.40	<u>30.1</u>	42.06	<u>20.6</u>	28.79
32	⁷² Ge	71.9221	273	3.80	<u>35.9</u>	37.94	<u>24.4</u>	26.25
35	⁸¹ Br	80.9163	287	3.55	<u>41.3</u>	37.50	<u>28.0</u>	26.11
41	⁹³ Nb	92.9060	300	3.23	<u>47.5</u>	36.32	<u>32.1</u>	25.4
47	¹⁰⁷ Ag	106.9051	313	2.93	<u>59.2</u>	32.48	<u>39.9</u>	22.89
53	¹²⁷ I	126.9045	322	2.54	<u>66.9</u>	32.54	<u>45.0</u>	23.17
79	¹⁹⁷ Au	196.9665	337	1.71	<u>84.6</u>	29.21	<u>56.2</u>	21.18

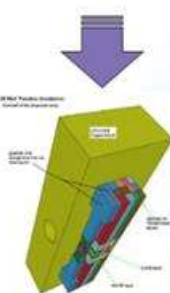
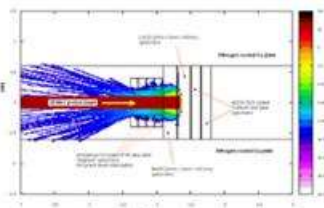
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1. How hot are typical samples after a high-dose irradiation study?

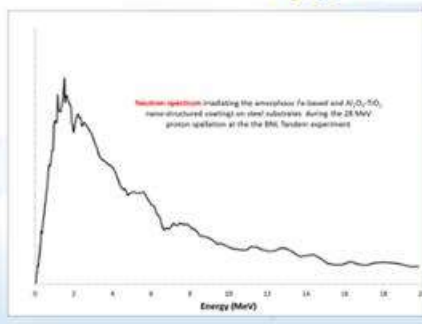
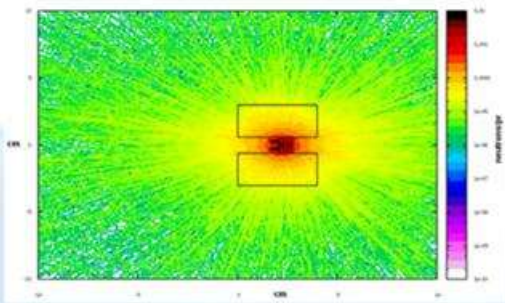
Slide 12



Recent 28 MeV proton + spallation neutron irradiation experiment at sub-zero temperatures at Tandem (Simos, et al)



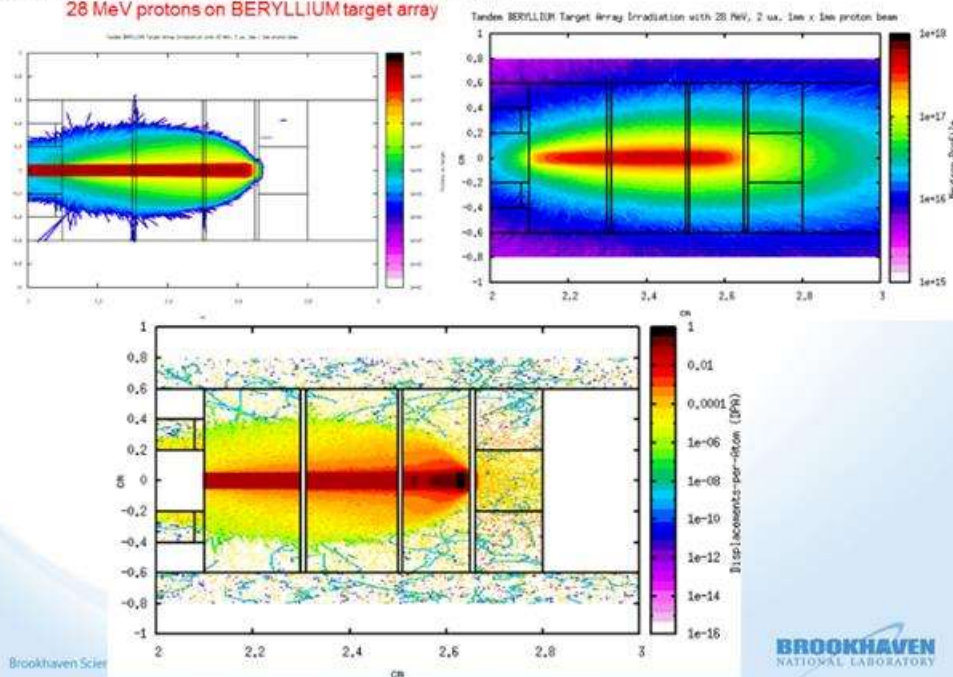
Generated Rontgen Profile inside the ORTEC Vacuum Chamber



Slide 13

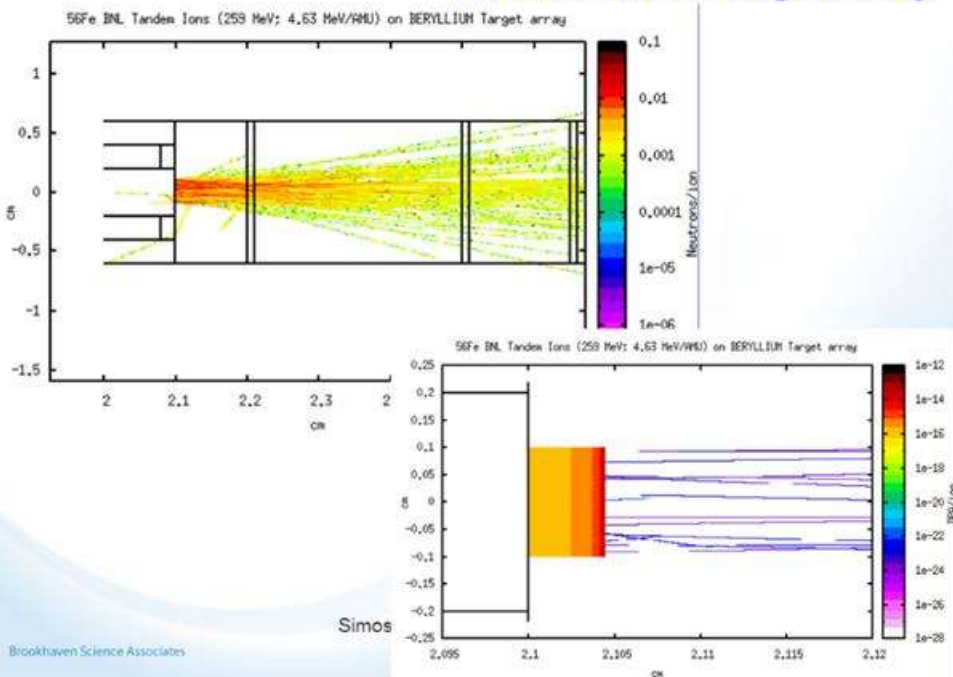
What Damage Can One Achieve at Tandem?

28 MeV protons on BERYLLIUM target array



Slide 14

^{56}Fe ion on Be target Array



Slide 15

BNL Post-Irradiation Facilities Isotope Extraction and Processing Facility at BNL

PIE analyses performed are:

- Stress-strain (tension, 3-point and 4-point bending)
- Thermal Expansion and annealing (extremely sensitive dilatometer)
- Thermal Conductivity (electrical resistivity)
- Magnetic Whole probe
- Ultrasonic measurements
- Photon spectra and isotopic analysis
- Activity measurements
- Weight loss or gain



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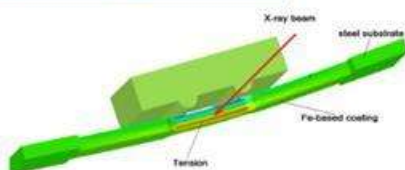
Slide 16

BNL Post-Irradiation Facilities X-ray Diffraction at NSLS II



X-ray diffraction studies of irradiated samples with the aid of a multi-functional experimental stage enabling:

- Tension/twisting/4-point-bending
- Exposure to different environments
 - Laser-induced annealing
 - Diamond anvil cell to be introduced in future update



Stage at NSLS II XPS Beamline

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Looking ahead

BLAIRR

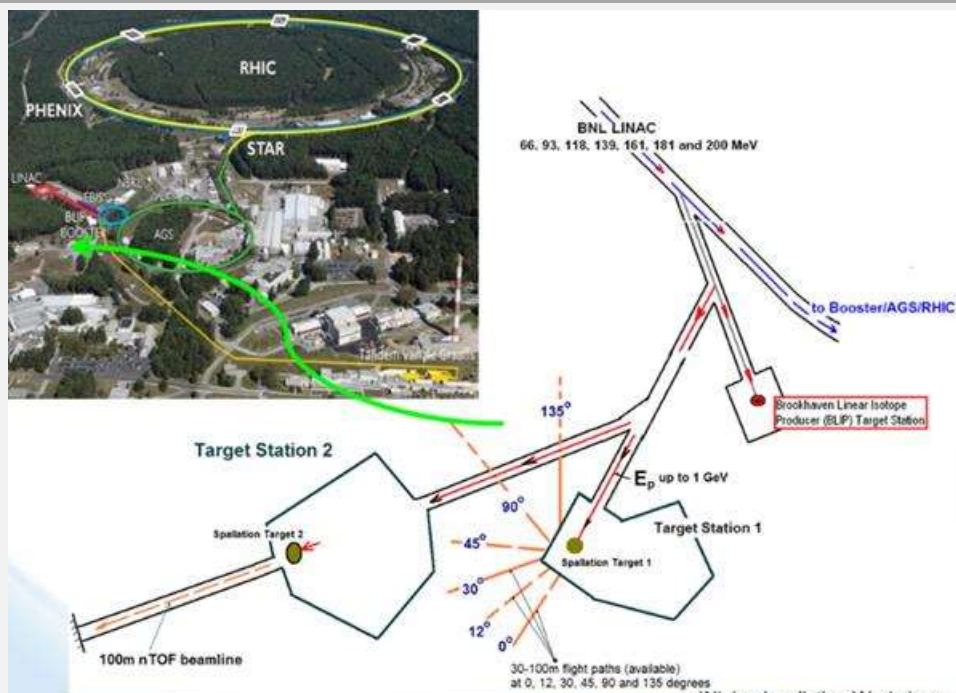
A Dedicated, Accelerator-driven Irradiation Facility offering DOE-NE a complementary approach to the research reactors (ATR, etc.)

BLAIRR aims to capitalize on the existing/dormant infrastructure of the old REF/NBTF complex and update it into an irradiation and test facility that can fill the gap in the DOE complex

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Slide 19

Aim: Capitalize on Complex Unique Features:

- Multitude of energies the Linac can provide
 - Polarized H⁺
 - **Beam current** (165 μA \rightarrow 2 x in planned update)
 - Heavy ions from Tandem down same beamline
 - Availability of infrastructure (currently dormant)
 - Neutron time-of-flight path lengths of 30-100 meters at 0, 12, 30, 45, 90 and 135°
 - Single micro-pulse selection (<1 ns) with period as low as 400ns
- **FAST neutron damage studies of materials for fast neutron and fusion reactors**
 - Proton irradiation damage of materials for accelerator initiatives as a function of energy
 - Validating experiments of neutron flux/reaction rates for accelerator-driven systems
 - Blanket, moderator, reflector concept validation/optimization
 - **Nuclear cross-section data**
 - Neutron detector studies
 - **Expansion of the range of isotope generation augmenting BLIP capabilities**
 - Neutron scattering potential
 - **Neutron time of flight (nTOF) and nuclear physics experiments**

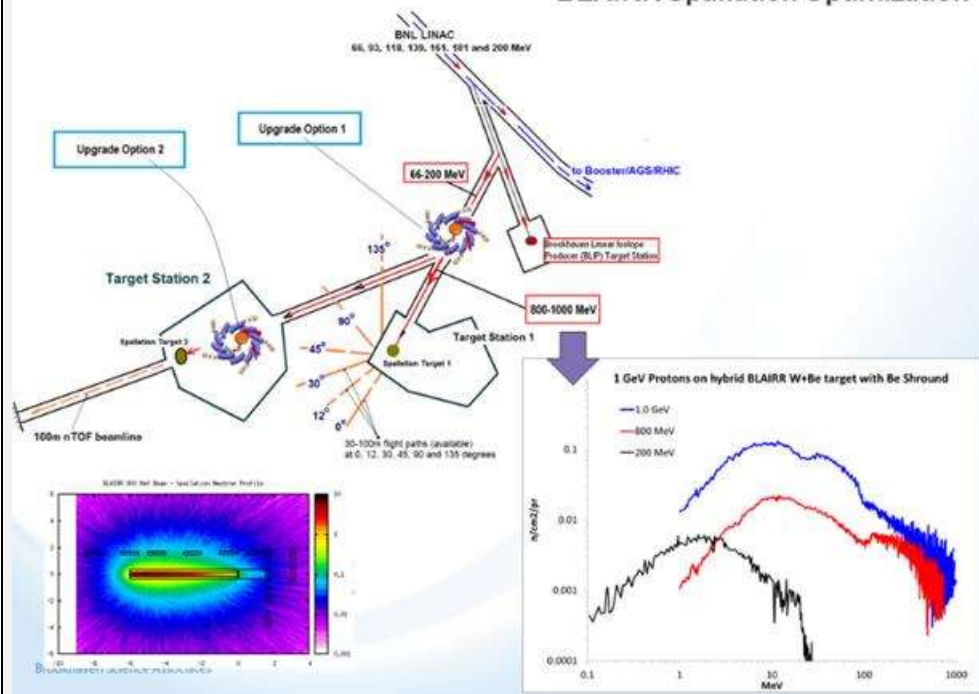
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Slide 20

BLAIRR Spallation Optimization



BLAIRR Proposal to BNL

Option-1:

Use Booster to accelerate up to 2 GeV and feed BLAIRR

LINAC: 200MeV/30kW
(200 MeV, 6.67 Hz, 7.0×10^{14} pps)

Booster: 0.2-1.5 GeV/30kW
(1.5 GeV, 6.67 Hz, 1.0×10^{14} pps)

Assessment:

- Getting DESIRED Energy
- Loosing CURRENT (big time)



Option-2:

Update LINAC and Utilize Transfer Line Straight (~125 m)

LINAC: 200MeV/30kW
(200 MeV, 6.67 Hz, 7.0×10^{14} pps)

- CCA
- Normal Conducting DTL with high accelerating gradients

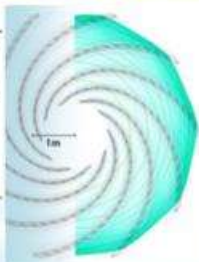
Assessment:

POSSIBLE !!!!

or, look into cyclotrons/FFAG

Table 2: Parameters of the Planar Cyclotron

Energy range	40-1500	MeV
Radius range	0.8684-2.9032	m
Maximum field on orbit	6.690	T
Revolution frequency	15.323 ± 0.017	MHz
Sectors	10	
Sector edge angle θ_s	-63.43	°
Packing factor	10.21	%
Fringe extent θ_f	7.04	°
Mean field ($y=1$) B_0	-1	T
Asymptotic radius R	3.1297	m



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Presentation: *In-Situ* X-ray Characterization of Microstructural Evolution

Lynne Ecker

Slide 1

In situ X-ray Characterization at the National Synchrotron Light Source-II of Microstructural Evolution During Ion Irradiation

Lynne E. Ecker

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a passion for discovery

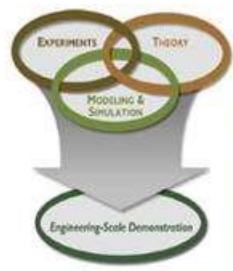
U.S. DEPARTMENT OF
ENERGY | Office of
Science

Slide 2

In situ X-ray characterization of radiation effects is a supporting technology for the DOE-NE mission.

Nuclear Energy Research and Development Roadmap:

- Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.
- Develop sustainable fuel cycles.
- Understand and minimize the risks of nuclear proliferation and terrorism.



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Slide 3

Outline



X-rays for Characterization of Radiation Damage



Synchrotron Beamline for Radioactive Materials



Proposed In Situ Ion Beam Capability

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3

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Slide 4

The National Synchrotron Light Source II (NSLS-II) is a new facility for materials characterization



Beam current $I_{\text{beam}} = 500 \text{ mA}$
Small electron source size: $40 \times 2.5 \text{ } \mu\text{m}$
Beam Energy: 3 GeV
Circumference: 792 m
Project cost: 912 M

First light October 23, 2014



More than 10,000 times brighter than the NSLS

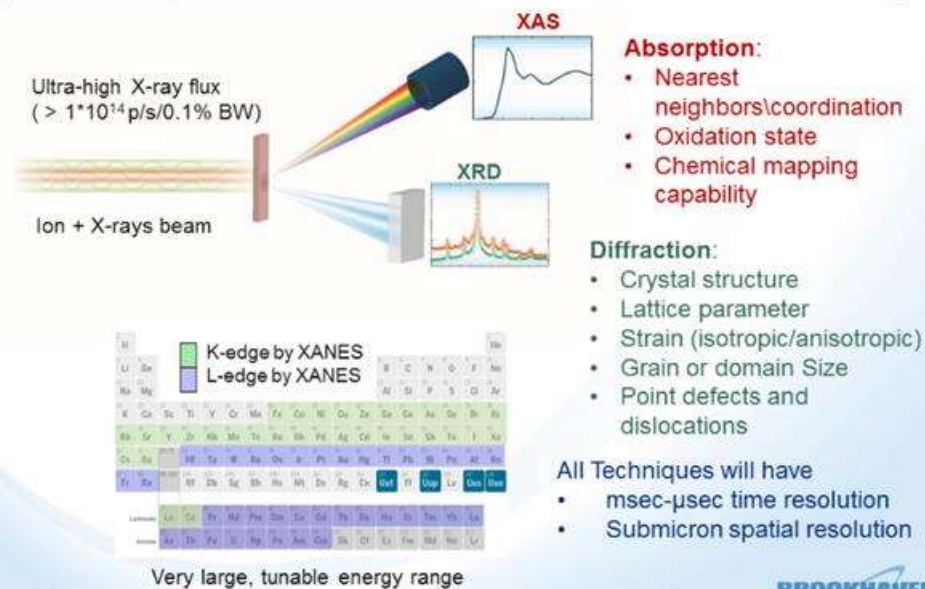
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Slide 5

In situ characterization of the evolving microstructure will provide unprecedented time resolution of structural changes

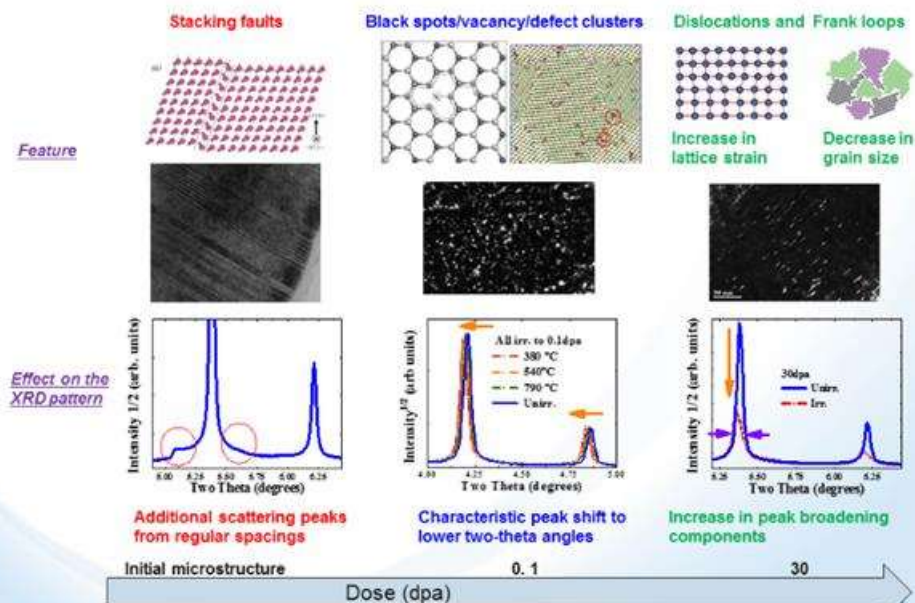


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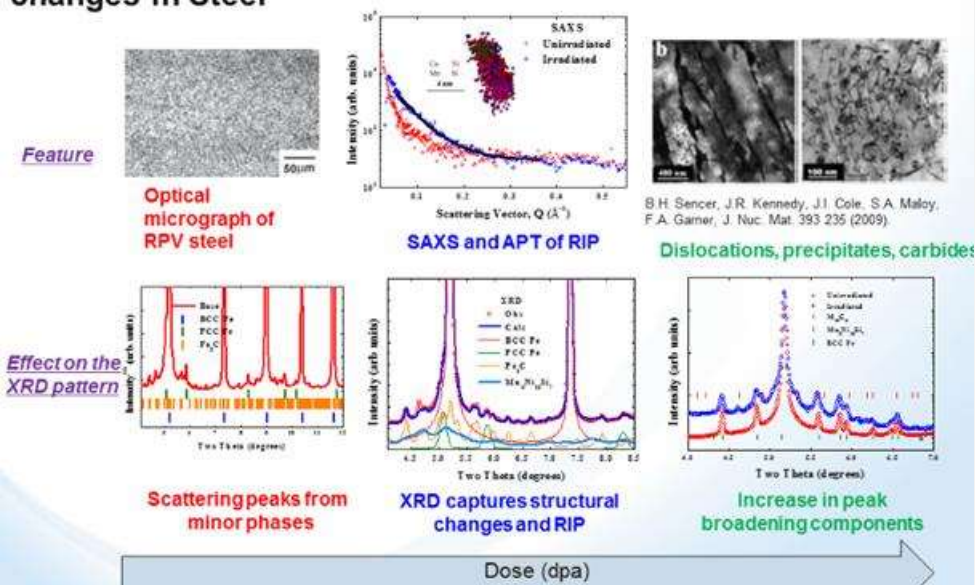
Slide 6

XRD can observe radiation induced structural changes in SiC



Slide 7

XRD and SAXS can observe radiation induced structural changes in Steel



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D.J. Sprouster et al., Scripta Met. 113, 18 (2016)

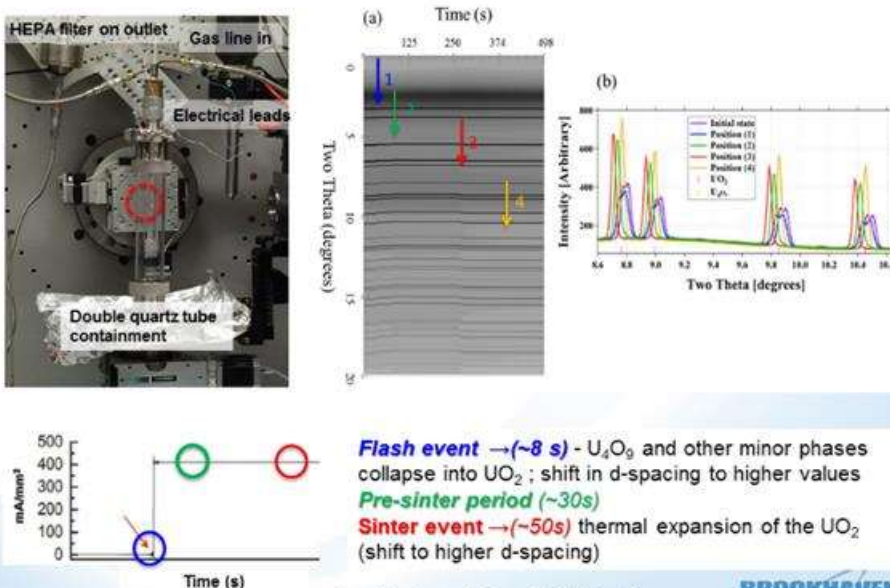
Funding from LWS and NEET

7

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Slide 8

Phase changes were observed using in situ XRD of field assisted sintering of UO_2 (BNL-LANL)



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Funding from AFC and NEET

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Slide 9

DOE-NE has invested the X-ray Powder Diffraction (XPD) Beamline at the NSLS-II



Users with interest in nuclear materials:

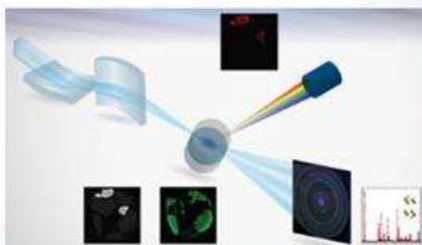
- Metallic Fuels (UMo U₂Zr)
- SiC and SiC-SiC composites
- Reactor Pressure Vessel Steels
- Oxide Dispersion Strengthened Steels
- Advanced Cladding (APMT/HT9)
- Alloy 690



Robot at XPD

Sample holder

216 Samples in 48 hours during "First Light" experiment



Schematic of a Diffraction Tomography Experiment

Synchrotrons will be a crucial part of the nuclear test-bed

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9

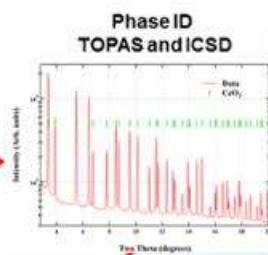
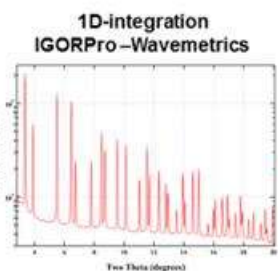
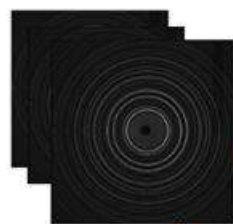
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Slide 10

NSLS-II will support users with data analysis

Over 12000 2D patterns for in situ experiment

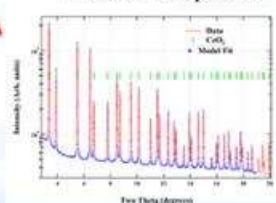
Data flow for 2D-1D and Rietveld Fitting



Batch analysis

Users have real time analysis and leave with data and results

Fit/calculated pattern



Center for Data Driven Discovery at Brookhaven will specialize in large data sets

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Slide 11

In situ materials for corrosion resistance

What:

- ability to study materials in their real-world operating environments

Why:

- provides actionable information to industry

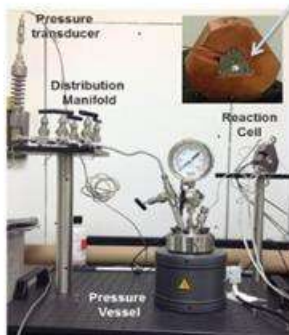
"Our collaborations with the National Synchrotron Light Source have helped understanding how protective passive films develop and operate on engineering alloys candidate for accident tolerant nuclear fuel cladding. These advancements are crucial for designing safer reactors to produce clean energy for the community at large."

Raul Rebak, GE Global Research

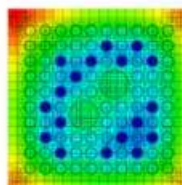
This could ONLY be done in partnership with a National Lab

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Advanced cladding probed while corroding



Reaction cell and fluid delivery system



Thermal flux in assembly with APMT clad



1. Connection to GAIN?

11

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Slide 12

NSLS-II has world leading beamlines for ex situ characterization of low activity samples

Submicron Resolution X-ray Spectroscopy (SRX)



K Emission line can be detected
L Emission line can be detected

Source	In-vacuum undulator
Energy range	4.65 keV ≤ E ≤ 25 keV
Energy resolution	Focusing mode: DE = 1.5-2.5 eV @ 12 keV DE = 0.9 eV @ 7 keV
High-flux setup	Focal spot 0.5 x 0.5 μm ² (H x V) at > 10 ¹³ phot/sec
High-resolution setup	Focal spot 70 x 70 nm ² (H x V) at 10 ¹¹ - 10 ¹² phot/sec @ 7 keV And 30 x 30 nm ² (H x V) at 10 ¹¹ phot/sec @ 12 keV

Hard X-ray Nanoprobe (HXN)

- Explore new frontiers of hard x-ray microscopy with the highest achievable spatial resolution: Long-term goal 1~10 nm
- Complement electron microscopy capabilities with higher elemental sensitivity, and enable in situ imaging in a variety of realistic environmental conditions.

Comparison of SEM vs. HXN

SEM



HXN

- Pt XRF
- 5 nm/pixel
- 50 ms/pixel



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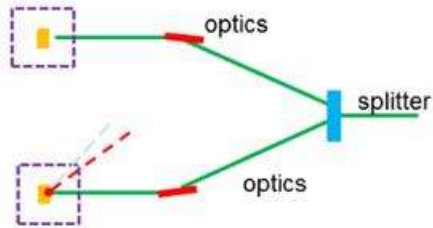
12

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NATIONAL LABORATORY

An Ion X-ray Beam (IXB) capability would enhance the scope of a beamline to study radioactive materials

Located in a separate building and will provide two unique capabilities:

Station 1: Characterization of more highly-radioactive materials than are currently allowed at US synchrotrons



Proposed Site

Station 2: Ion X-ray Beam (IXB) In situ studies of radiation damage with particle beams from multiple accelerators

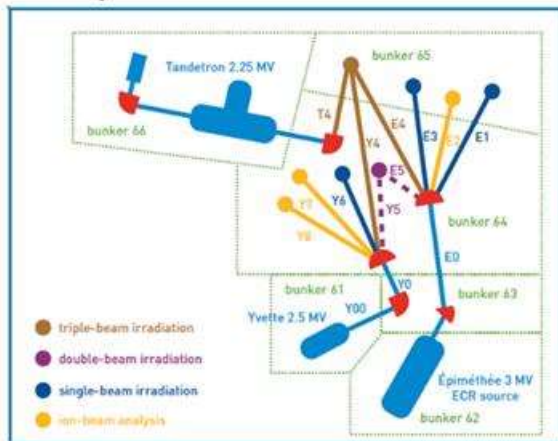
Brookhaven Science Associates

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IXB will provide new capabilities that are unique in the world

JANNUS platform



Schematic of the triple-beam installation at Saclay

"The possibility to combine ion irradiation/implantation with synchrotron radiation would be a very fruitful strategy to better understand these mechanisms in cladding but also nuclear fuel materials."

"Such equipment would be to our knowledge unique in the world."

- F. Touboul Basic Research Project Manager, Nuclear and Alternative Energies Council, CEA-Saclay

Synchrotron techniques are ideally suited to verifying simulations

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Slide 15

An endstation for in situ studies with particle accelerators will be located in a separate facility (IXB) outside of the NSLS II ring

- Space for multiple particle accelerators and supporting infrastructure
- Customizable user experiments
- Higher radioactivity in the samples
- Larger samples (prototypical of bulk)
- Previously irradiated (activated) materials
- Dispersible materials



GE PETtrace cyclotron



NEC 6MV

No restrictions on number or type of accelerators because of space

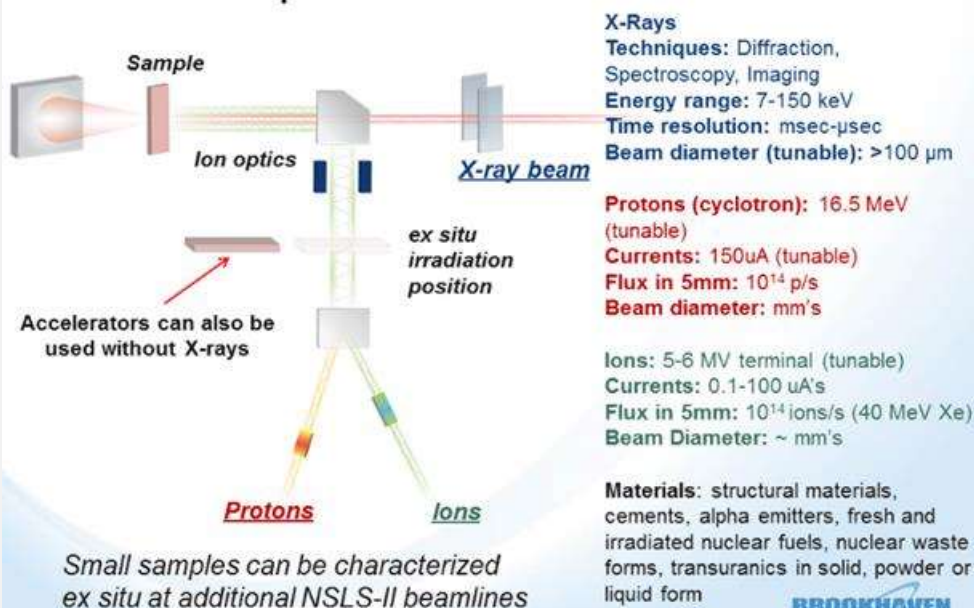
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15

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Slide 16

IXB will characterize mesoscale microstructural evolution under proton and/or ion radiation

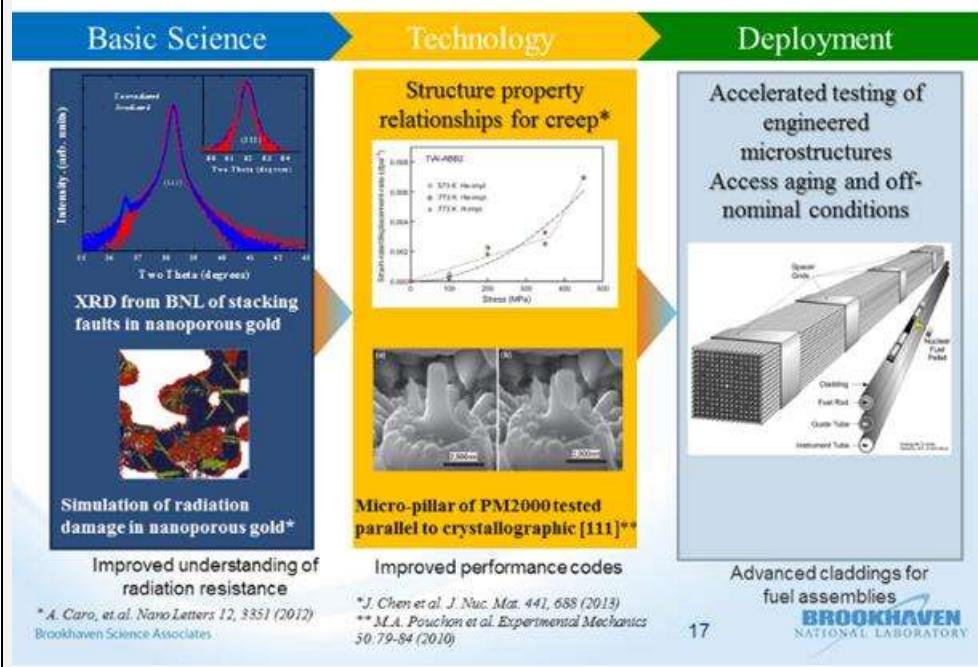


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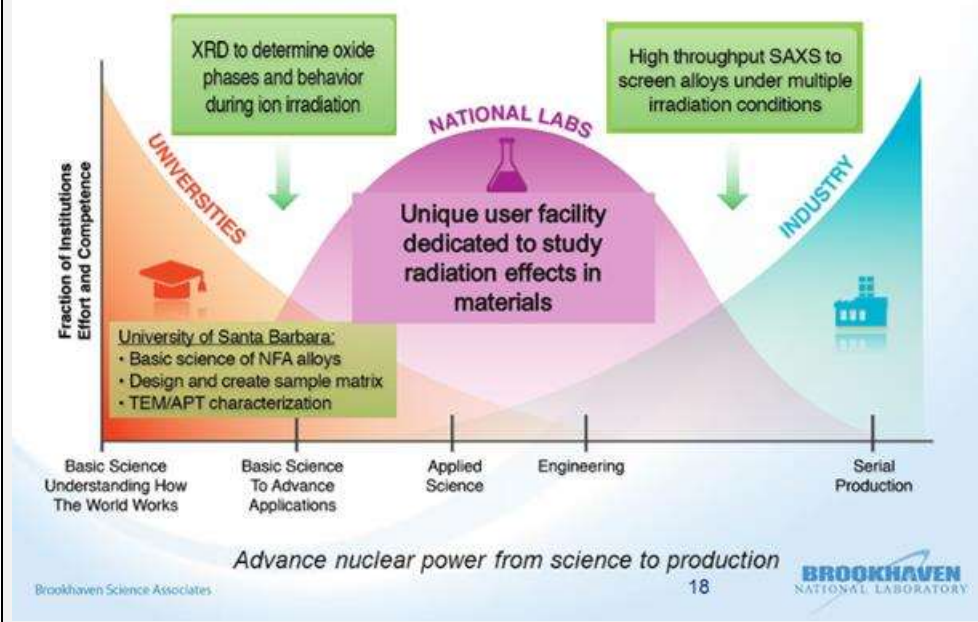
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IXB will be used from discovery to deployment



17

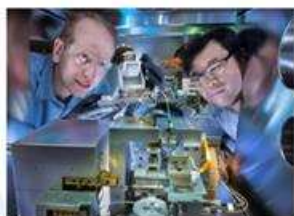
IXB is an ideal facility for a national laboratory and will help span the "Valley of Death"



18

Access IXB is provided through a DOE User Facility: the NSLS-II

- Access to world-leading, complementary beamlines at NSLS-II
- Accommodate industry (rapid access to beamtime, remote access, proprietary)
- NSLS-II 5000 hrs/year
- DOE user facility with support infrastructure, guest center, training, accommodations, established proposal process
- Radiation handling, shipping and receiving, remote hot cells
- Maintenance on x-ray source from NSLS-II
- New directorate for data analysis



HXN



SRX



XPD

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Criteria



Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.



Provide a variety of ion irradiations



Irradiation environments and conditions.



Collect microstructural characterization data onsite and in-situ.



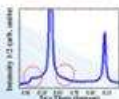
NE activities / volume of experiments that can be handled.



Unique capabilities of the facility including new technology



Handle radioactive materials in the beams and elsewhere onsite.



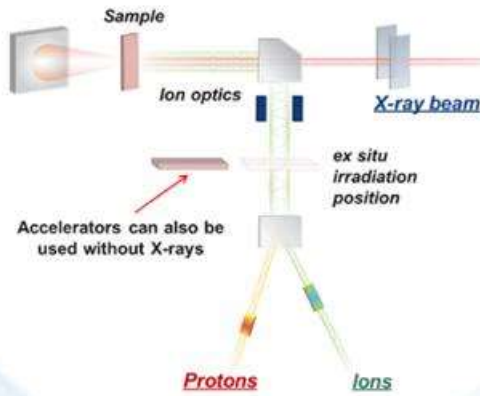
Produce high quality data that can support verification and validation for modeling and simulation.

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Summary



- A unique user facility for studying radiation effects
- Leverage DOE investment in state-of-the-art synchrotron
- Impact basic understanding of radiation damage, performance codes, and new and existing nuclear reactors

Thank you

Presentation: Univ. of Tennessee IBML

William Weber

UT-ORNL Ion Beam Materials Laboratory

UT-ORNL Ion Beam Materials Laboratory

William J. Weber and Yanwen Zhang

<http://ibml.utk.edu/>

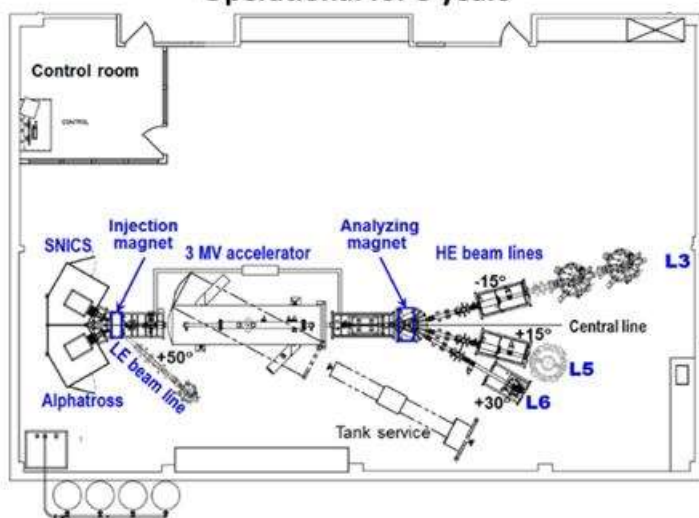


Y. Zhang et al., *Nucl. Instrum. Methods Phys. Res. B* 338 (2014) 19-30.

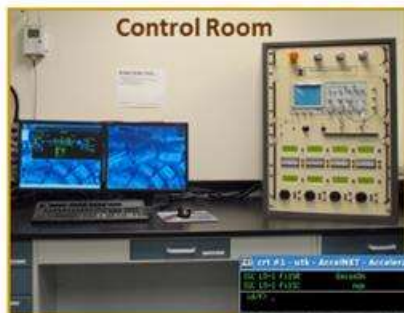
UT-ORNL Ion Beam Materials Laboratory

UT-ORNL Ion Beam Materials Laboratory

Operational for 3 years



UT-ORNL Ion Beam Materials Laboratory



Control Room

Ion Accelerator

- 3.0 MV tandem accelerator (terminal voltage up to 3.2 MV)
- Three beam lines with 4 end stations
- Ions from 600 keV to 27 MeV (charge states from 1^+ to 8^+)



3

UT-ORNL Ion Beam Materials Laboratory

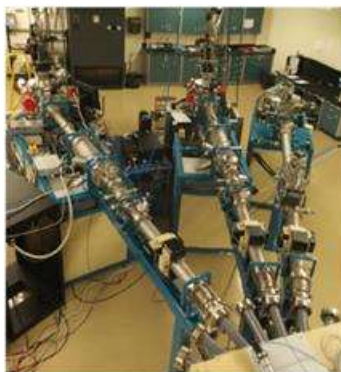
Two Ion Sources

- **Alphatross source:** producing ions from gases, such as He ions
- **SNICS source:** producing ions from solid sources using Cs^+ sputtering, such as H, C, O, ... up to Pt, Au and Bi ions



4

UT-ORNL Ion Beam Materials Laboratory



5

Typical Ion Flux on Target (without raster)

Typical Ion Flux on Target (without raster)

He¹⁺ 3.5 MeV:

85 nA in $1.5 \times 1.5 \text{ mm}^2$ ($2.4 \times 10^{13} \text{ ions cm}^{-2} \text{ s}^{-1}$)

Si¹⁺ 1 MeV:

550 nA in $3 \times 3 \text{ mm}^2$ ($3.8 \times 10^{13} \text{ ions cm}^{-2} \text{ s}^{-1}$)

Si⁴⁺ 13.5 MeV:

1300 nA in $3 \times 3 \text{ mm}^2$ ($2.3 \times 10^{13} \text{ ions cm}^{-2} \text{ s}^{-1}$)

Au¹⁺ 1 MeV:

200 nA in $3 \times 3 \text{ mm}^2$ ($1.4 \times 10^{13} \text{ ions cm}^{-2} \text{ s}^{-1}$)

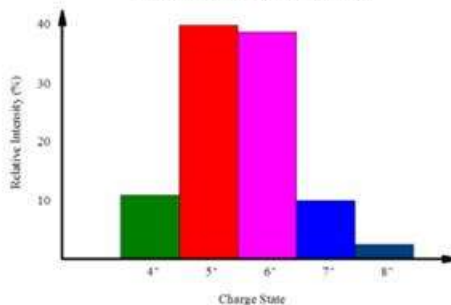
Au⁷⁺ 23 MeV

60 nA in $3 \times 3 \text{ mm}^2$ ($5.95 \times 10^{11} \text{ ions cm}^{-2} \text{ s}^{-1}$)

Au⁸⁺ 25 MeV

15 nA in $3 \times 3 \text{ mm}^2$ ($1.30 \times 10^{11} \text{ ions cm}^{-2} \text{ s}^{-1}$)

Charge state distribution of Ni
accelerated with 2.5 MV



6

High-Energy End Stations

Station L3A: Radiation Effects – 100 to 1500 K

- Manipulator has 1 axis of tilt and 3 axes of translation
- Beam rastering capability
- Time-of-Flight spectrometer (ERDA, electronic stopping, etc.)

Station L3B: Closed-cycle helium system (25 to 300 K) - Under testing

- Manipulator has 3 axes of rotations and 3 axes of translation
- IBA capabilities
- 30 keV electron gun
- *In situ* luminescence

Station L5: Radiation Effects – 150 to 1000 K

- Manipulator has 3 axes of rotations and 3 axes of translation; ideal for channeling measurements
- Beam rastering capability
- IBA capabilities

Station L6: Ion Beam Analysis (300 K)

- Designated for routine, rapid analysis.
- A large number of samples can be mounted on two sample holders
- Equipped with standard IBA capabilities, e.g. RBS, NRA, ERDA, PIXE

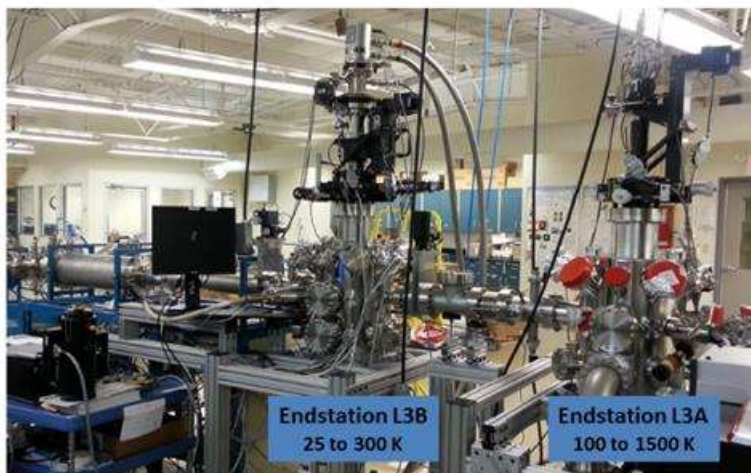
No Radioactive Materials at this Time!



UT-ORNL IBML End Stations



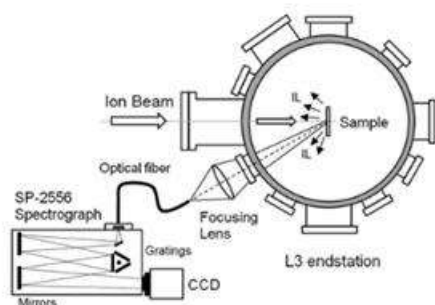
UT-ORNL IBML Endstations



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In Situ Ion-Beam Induced Luminescence

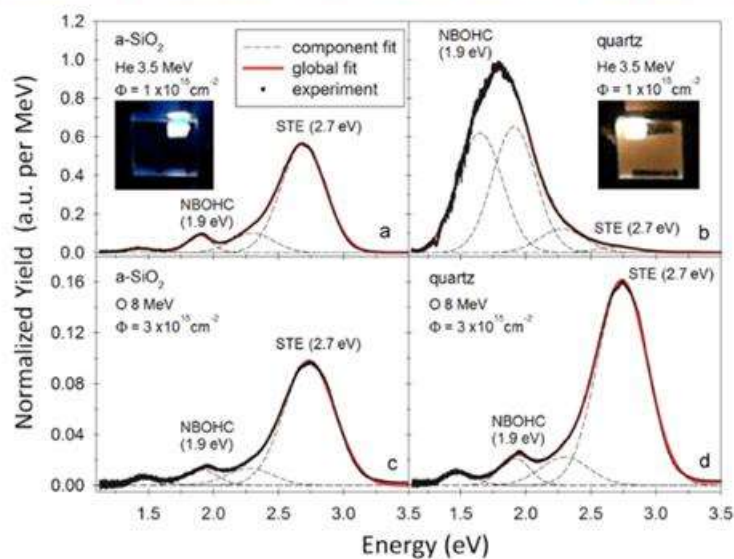
In Situ Ion-Beam Induced Luminescence



- Light emitted from sample transmitted through silica window port (at 150° with respect to ion beam direction)
- Light collected using 25mm diameter, 4 cm focal-length silica lens into silica optical fiber (1 mm diameter)

10

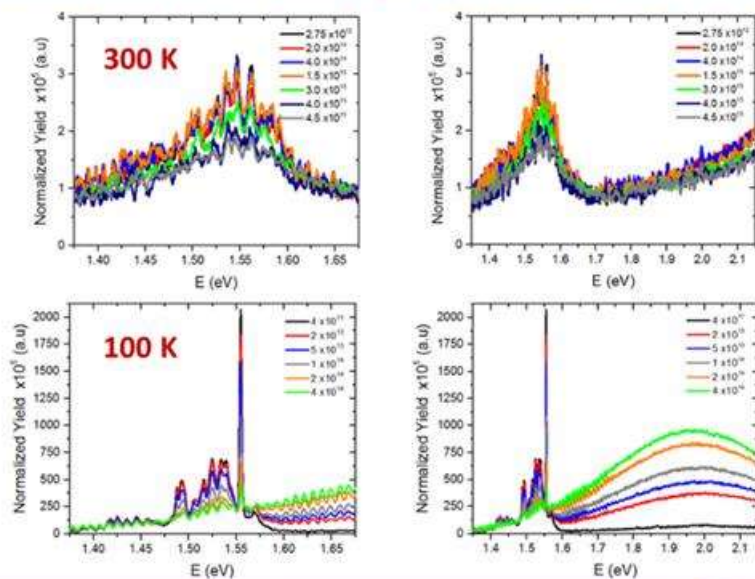
Luminescence from Electronic Defects



11

Luminescence in SrTiO₃ Irradiated with 3 MeV H

Luminescence in SrTiO₃ Irradiated with 3 MeV H

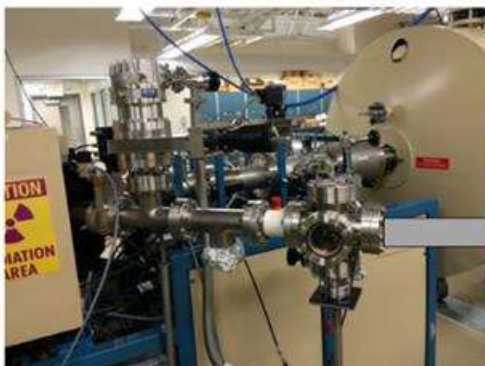


12

Low-Energy Beam Line / End Station

Low-Energy Station: **support is needed**

- Energies up to 100 keV with μA beam currents, mainly for H and He implantation



Need to Add:

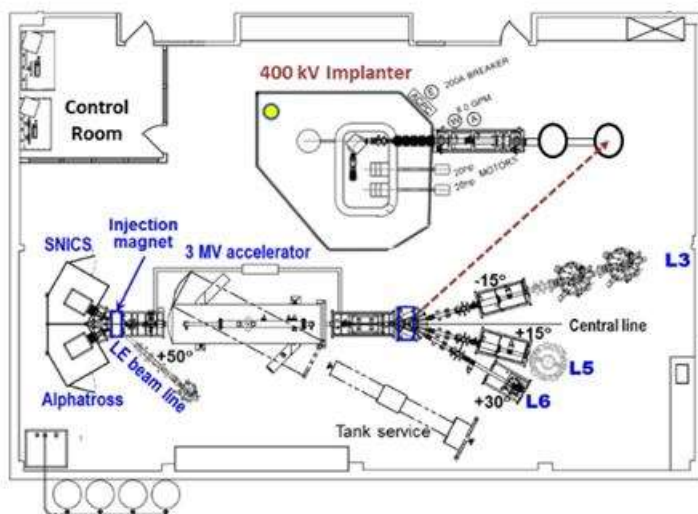
- Beam Line
- Focusing Optics & Slits
- Target Chamber
- Faraday Cup

Target Chamber

LE – Endstation
RT Implantation

13

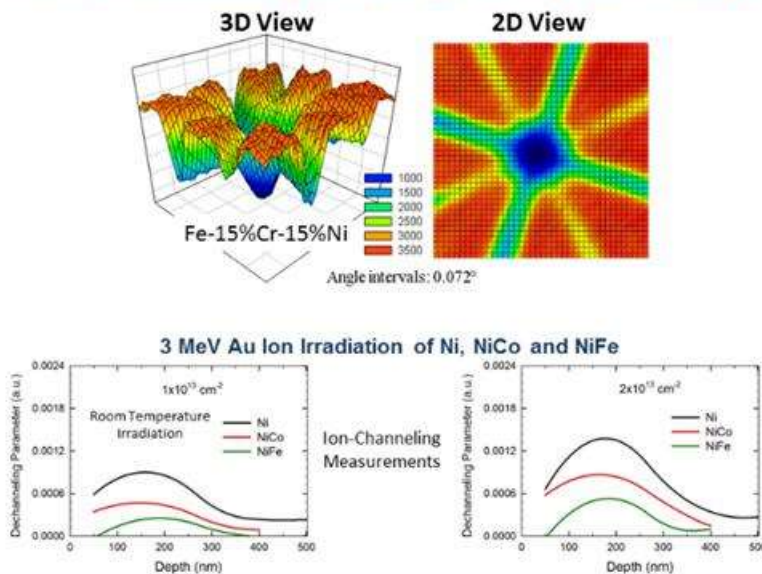
UT-ORNL IBML – Future?



14

Ion Channeling in Single Crystal Alloys

Ion Channeling in Single Crystal Alloys



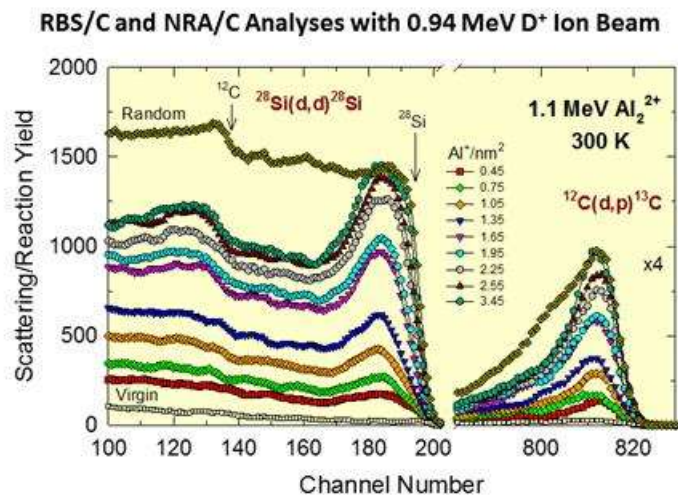
1. Running at roughly 25% utilization.

15



RBS/C & NRA Spectra for Irradiated 4H-SiC

RBS/C & NRA Spectra for Irradiated 4H-SiC



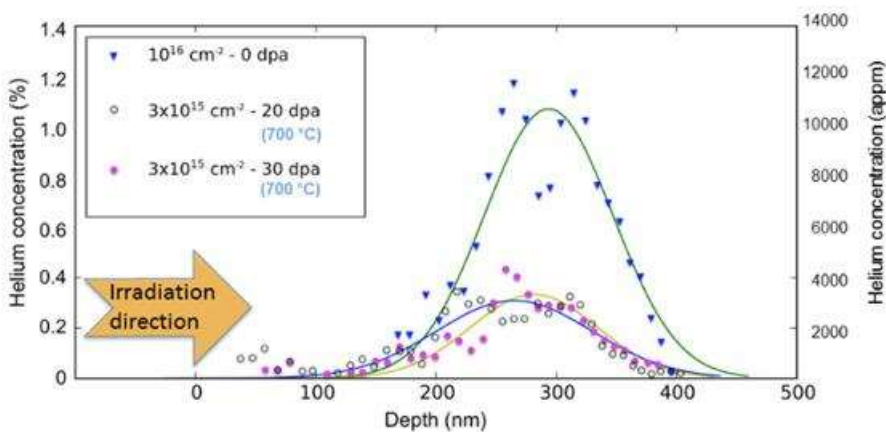
Y. Zhang et al., *J. Appl. Phys.* **91** (2002) 6388-6395

16



Helium Implantation Profiles in 3C-SiC

Time-of-Flight Elastic Recoil Detection Analysis (ToF-ERDA)



C.-H. Chen et al., *J. Nucl. Mater.* **472** (2016) 153-160

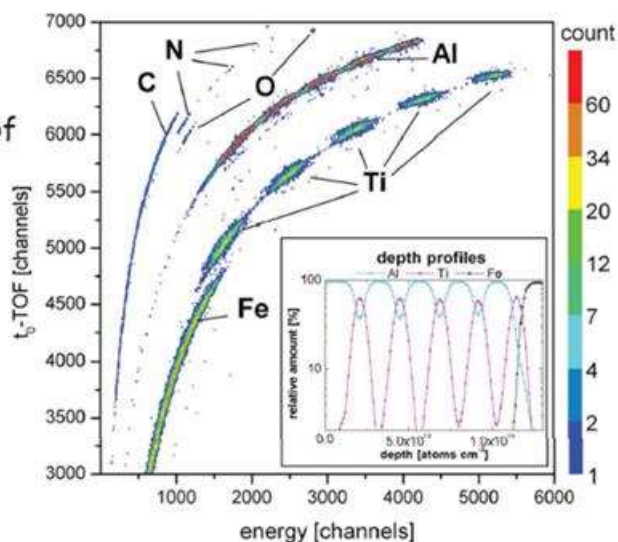
17



ToF-ERDA of Multilayer Coating on Steel

ToF-ERDA of Multilayer Coating on Steel

example:
Ti/Al multilayer
on steel
5 double layers of
150 nm Al and
100 nm Ti

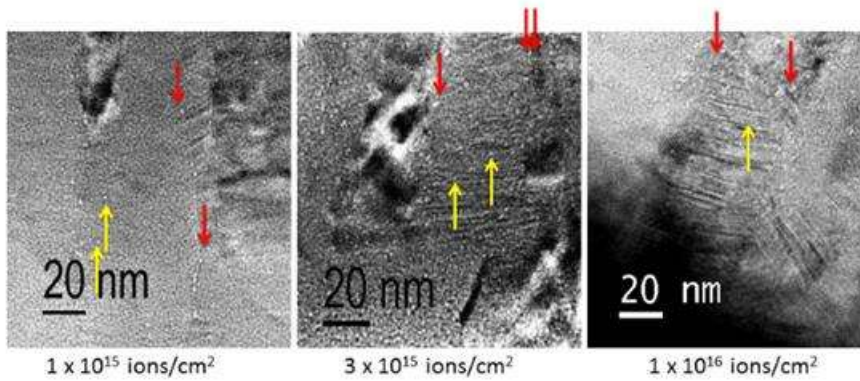


18



Helium Bubble Formation in SiC at 700 °C

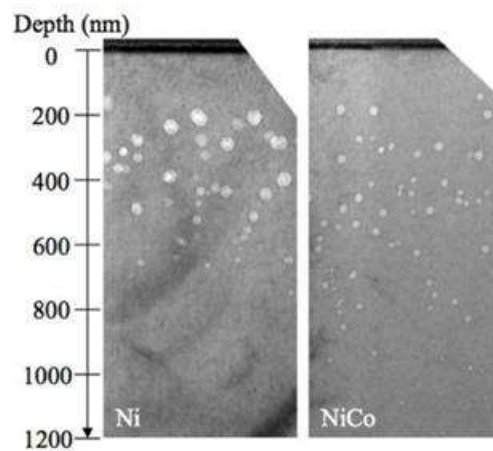
Pre-Implanted Samples Irradiated with 9 MeV Au³⁺ ions 30 dpa



C.-H. Chen *et al.*, J. Nucl. Mater. (2016) submitted

19

Void Formation after Irradiation with 1.5 MeV Ni at 500 °C to 3×10^{15} ions/cm²



C. Lu *et al.*, Nature (2016) submitted

20

Users

- University of Tennessee – MSE, NE, Physics
- Oak Ridge National Laboratory
- North Carolina State University
- University of Michigan
- University of California – Irvine
- Missouri University of Science & Technology
- Kyushu Institute of Technology
- Kyoto University
- University Paris – Sud (Orsay)

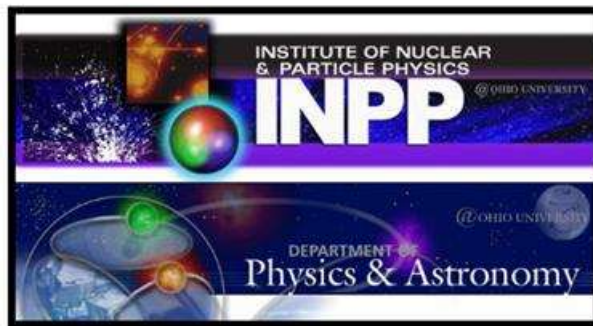
Presentation: Edwards Accelerator Laboratory at the University of Ohio

Steve Grimes

Edwards Accelerator Lab

Edwards Accelerator Lab

Ohio University, Athens Ohio



NSUF Workshop

March 22-24 2016

Accelerator

Accelerator

- Tandem van de Graaff with upgrade to pelletron.
- 4.5 MV Maximum Terminal Voltage
- Design maximum current 200 μ A.
- Pulsing 200 ns to 204.8 μ s in factor of 2 increments.
- Provides beams of: ^1H , ^2H , ^3He , ^4He , ^6Li , ^7Li , ^{10}B , ^{11}B , ^{12}C , ^{13}C , ^{16}O

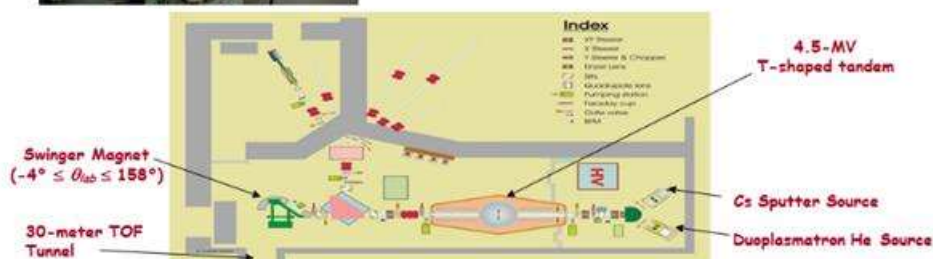
Beam Swinger Neutron Time-of-Flight Facility at Ohio University



Edwards Accelerator Laboratory



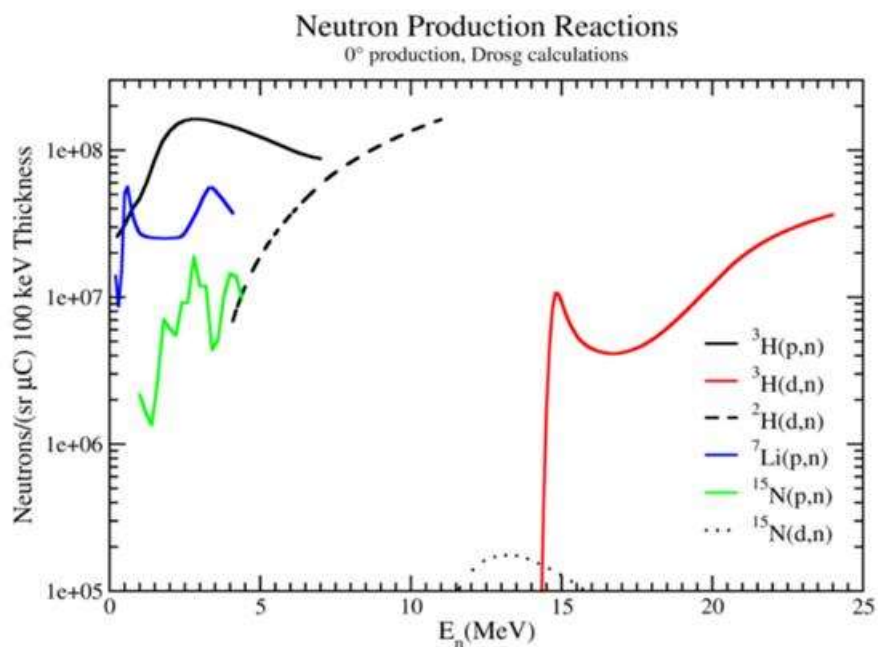
Target chamber



Neutron Source Reactions

Neutron Source Reactions

- Monoenergetic Sources: $^3\text{H}(p,n)$, $^2\text{H}(d,n)$, $^3\text{H}(d,n)$, $^7\text{Li}(p,n)$, $^{15}\text{N}(p,n)$, $^{15}\text{N}(d,n)$
- Both ^3H gas targets and ^3H solid targets are available
- White sources with stopping targets:
 $^9\text{Be}(p,n)$, $^9\text{Be}(d,n)$, $^{10}\text{B}(d,n)$, $^{11}\text{B}(p,n)$, $^{11}\text{B}(d,n)$,
 $^{13}\text{C}(p,n)$, $^9\text{Be}(\alpha,n)$, $^{13}\text{C}(\alpha,n)$, $^{19}\text{F}(p,n)$, $^{27}\text{Al}(d,n)$,
 $\text{V}(d,n)$



Neutron Capability

Neutron Capability

- Beam Swinger allows angular distributions to be measured with one Time-of-Flight Tunnel flight path – 4.5 to 30 meters , $-4^\circ < \theta < 158^\circ$.
- Beam Pulsing ~ 1 ns width for ^1H , ^2H and ~ 2.5 ns for other beams.
- A dual gas cell is available for background subtraction.

Neutron Detectors

- Liquid Scintillators NE213
- Lithium glass
- BF_3
- Fission chambers- ^{235}U , ^{238}U

Advanced Method for Calibration

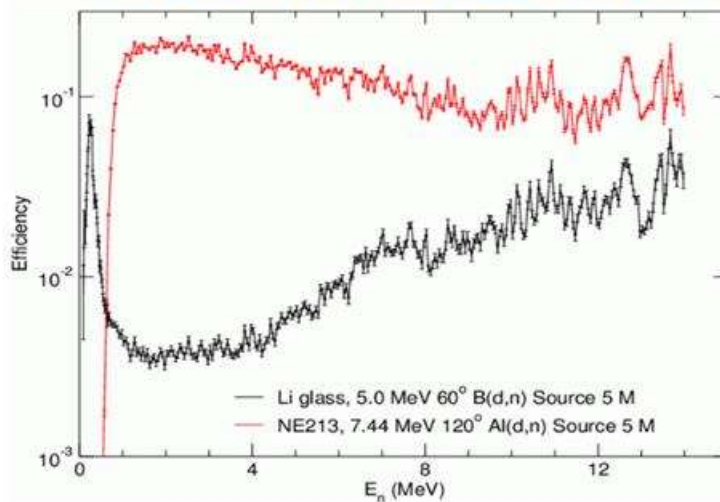
- The neutron spectrum for a stopping target using the $^{27}\text{Al}(\text{d},\text{n})$ reaction at $E_d = 7.44$.
- The spectrum has been measured at 120° using a ^{235}U fission chamber.
- This spectrum can be used to calibrate a detector from 0.2 to 12 MeV in a short time.
- The NE213 efficiencies obtained by this method are close to the calculated efficiencies.

Lithium Glass Detectors

- The measured efficiencies of lithium glass detectors differ from the calculated shape from just the ${}^6\text{Li}(n,\alpha)$ reaction.
- Contributions from ${}^{16}\text{O}(n,n'\gamma)$ and ${}^{28}\text{Si}(n,n'\gamma)$ are important above 1.8 MeV.
- Detectors which have the same specification of ${}^6\text{Li}$ content have efficiencies which varied by a factor of two at the 250 keV resonance.

Neutron Detector Calibration

Neutron Detector Calibration

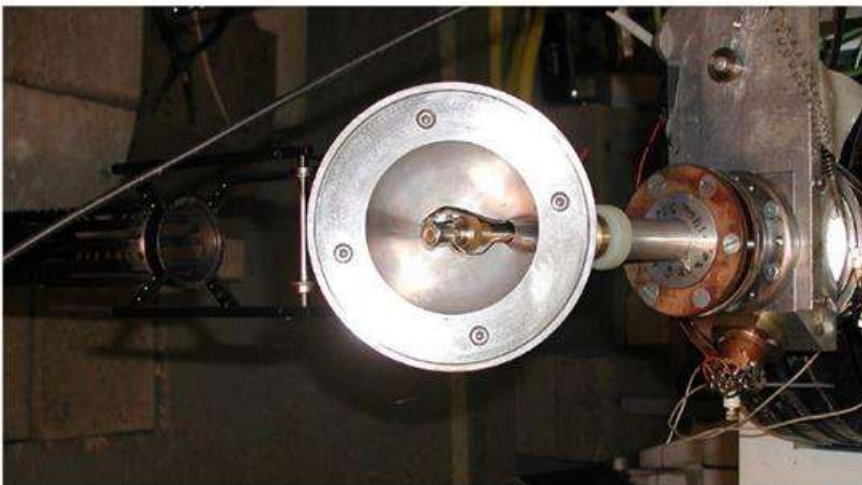


Li glass detector was 8 mm thick and the NE213 was 6.08 cm thick

Pulsed Neutron Spheres

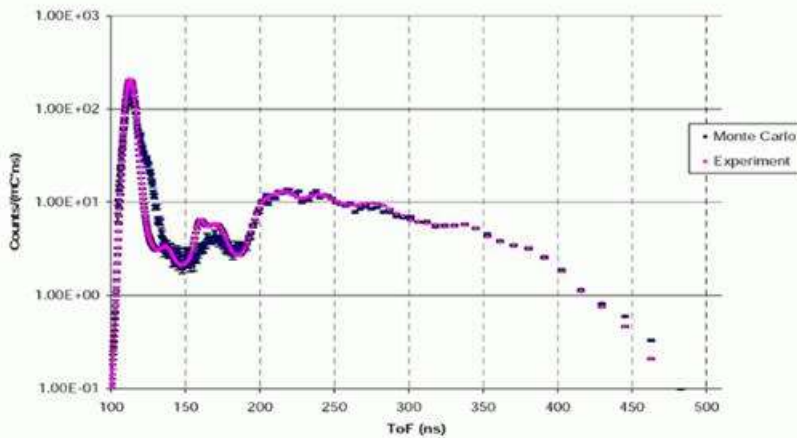
- A gas cell is placed in the center of a spherical shell with high purity material.
- The Time-of-Flight for the emerging neutrons is measured with a neutron detector.
- The spherical shell is typically 0.5 to 2.0 mean free paths thick.
- The energy of the neutrons cannot be directly measured due to multiple scattering.
- The experiment is modeled with Monte Carlo to calculate the arrival time spectrum

The Iron Sphere Setup



Pulsed Iron Sphere Measurements

Pulsed Iron Sphere Measurements



Previous data (M.T. Wenner et al. NSE **170** 207 (2012).) taken with a mean source energy of **7 MeV**, **zero degrees** and a 5-m flight path. The comparison to the simulation suggests the ENDF-B/VI library for $n+^{56}\text{Fe}$ needs improvement.

Published Iron Sphere Results

Published Iron Sphere Results

- At $E_n = 1$ MeV the spectrum is in agreement with ENDFB_VII.
- For $E_n > 5$ MeV, the sphere results disagree with predictions.
- Modifications are required for the ENDFB_VII evaluation.
- Elements that need to be checked are C, Zr, U and Pu.

Time-of-Flight, Energy spectrometer

- It is difficult to optimize for ΔE thickness for a ΔE -E telescope if both alphas and protons are detected.
- Measuring E and ToF allows the separation of the different particles emitted.
- This spectrometer has 10 instrumented angles and has 85 cm or 170 cm flight paths.
- Additional neutron or gamma detectors can be added.

Facility Upgrades-Negative Ion Source

- Torvis (NEC) estimate \$500,000
 - 40 μA He
 - 100 μA H, D
- Aphotross(NEC) \$250,000
 - 4 μA He
 - 10 μA H, D
- The ion optics are being checked for compatibility with our accelerator

Other facilities

- Two spectrometers available for (n,Z) reactions.
- Facilities for surface science measurements
- A code which allows correct calculation of cross sections using the Hauser-Feshbach formalism for deformed nuclei.

Materials Science with the Application of Nuclear Physics

- Nuclear Science
 - Detection of fissile materials
 - Neutron Resonance Radiography
 - Neutron Imaging and Tomography
 - Neutron Detector development and calibration
 - Materials for Nuclear Reactors
 - Neutron Induced Single Event Upsets
 - Measurement of the p, d and t, alpha elastic recoil cross-sections
 - Nuclear Reaction Analysis

Materials Science with the Application of Nuclear Physics (cont.)

- Other materials science techniques
 - Proton Induced X-ray Emission (PIXE)
 - X-ray Photo-electron Spectroscopy (XPS)
 - Low Energy Electron Diffraction (LEED)
 - *In-situ* growth and analysis of materials under ultra-high vacuum (uhv)

Summary

Summary

During the past 25 years-

- Numerous elastic and inelastic neutron scattering measurements completed.
- Measurement of $\text{Fe}(n,p)$, $\text{Fe}(n,\alpha)$, $\text{Cu}(n,p)$, $\text{Cu}(n,\alpha)$, $\text{Ni}(n,p)$, $\text{Ni}(n,\alpha)$, completed.
- Stopping target neutron spectra measurements.
- Measurements and calculation of level densities.

Summary- continued

- Collaboration with LLNL, LANL, ANL, Ohio State University, University of Michigan, Michigan State University, SUNY Geneseo, and Oak Ridge National Lab on neutron calibrations and activation capture measurements.
- Pulsed Sphere (Fe) measurements at 4 bombarding energies
- Condensed Matter studies.

Presentation: Ion Beam Laboratory at Texas A&M University

Lin Shao

Slide 1

INL Ion Beam Workshop, March 23, 2016

Ion Beam Lab at Texas A&M University

Lin Shao
Associate Professor
Director, Ion Beam Laboratory
Department of Nuclear Engineering
Texas A&M University

Slide 2

Texas A&M University: Aggieland (College Station)



Facts

about TAMU-Nuclear Engineering

Undergraduate: ~300

Graduate: ~150

Faculty Members: 22

Rank (among public institutions):

Undergraduate: 3

Graduate: 2



Slide 3

Radiation Materials Science Group (Accelerator Lab)



Lin Shao, Leader



Mark Hollander
Lab Manager



Xuemei Wang
Lab Manager



Wayne Kinnison
Senior Scientist



Frank Garner
Senior Scientist

Ph.D. students



Josey Wallace
Carbon



Jonathan Gigax
F/M alloys



Jing Wang
Modeling



Lloyd Price
Metallic glass



Tianyi Chen
ODS alloys



Eda Aydogan
Low activation alloys



Tianyao Wang
Fuel cladding



Aaron French
Fuel-clad interact.



Robert Balerio
Nitriding



Jianyuan Fang
Fuel cladding



Hyosim Kim
Nano carbon



Elizabeth Castanon
Fuel cladding

Slide 4

Acquisition of 1 MV and 1.7 MV accelerators from the Cornell University

9 years ago



Terminal Voltages: 1 MV and 1.7 MV

Slide 5

Acquisition of 3 MV NEC accelerator from PNNL (Aug. , 2015)



Slide 6

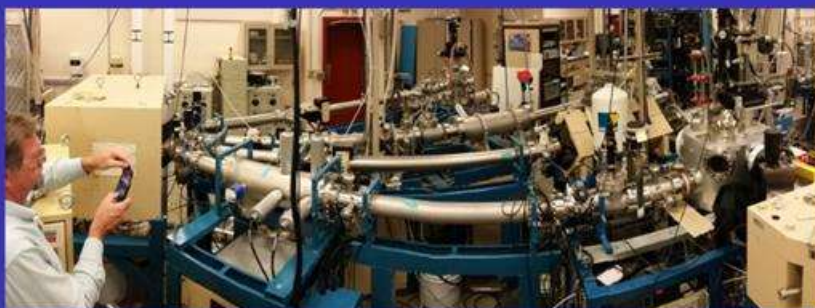


10 kV

140 kV

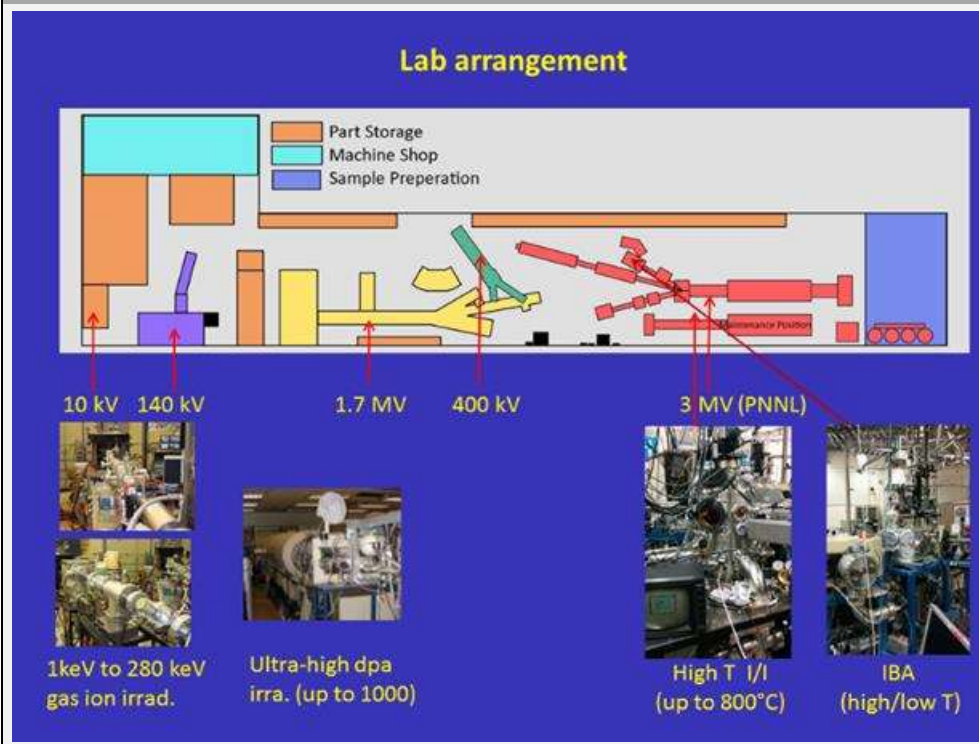
400 kV

1.7 MV

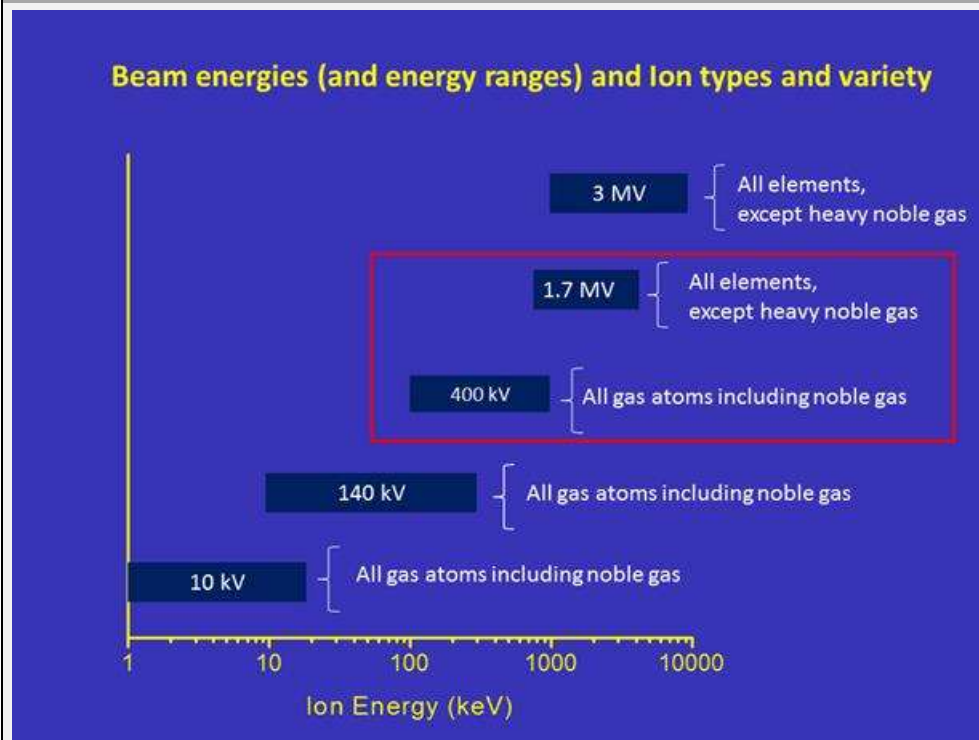


3 MV

Slide 7

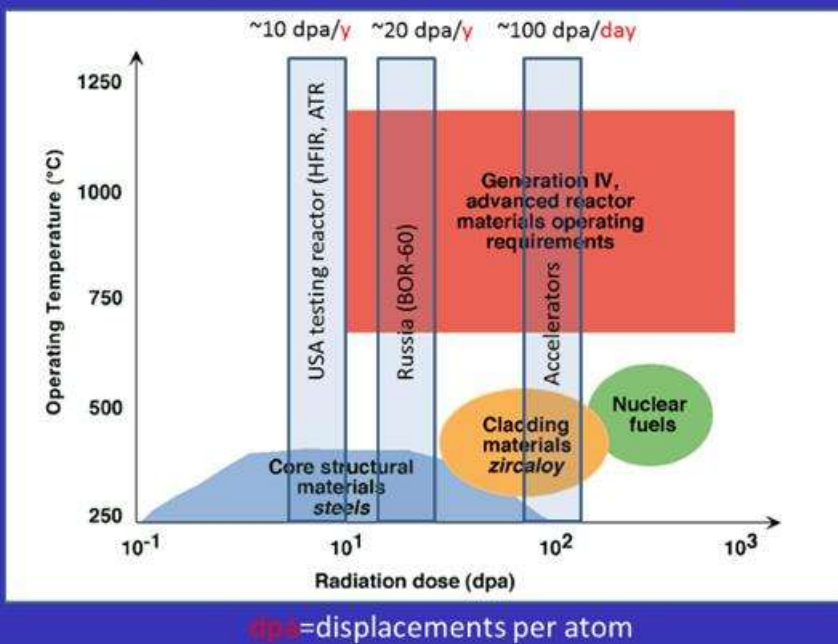


Slide 8



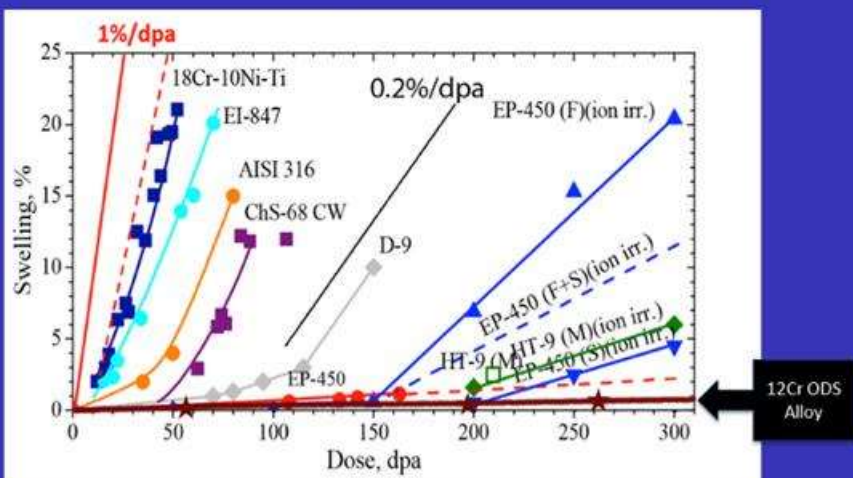
Slide 9

Accelerator: the only choice for fast testing



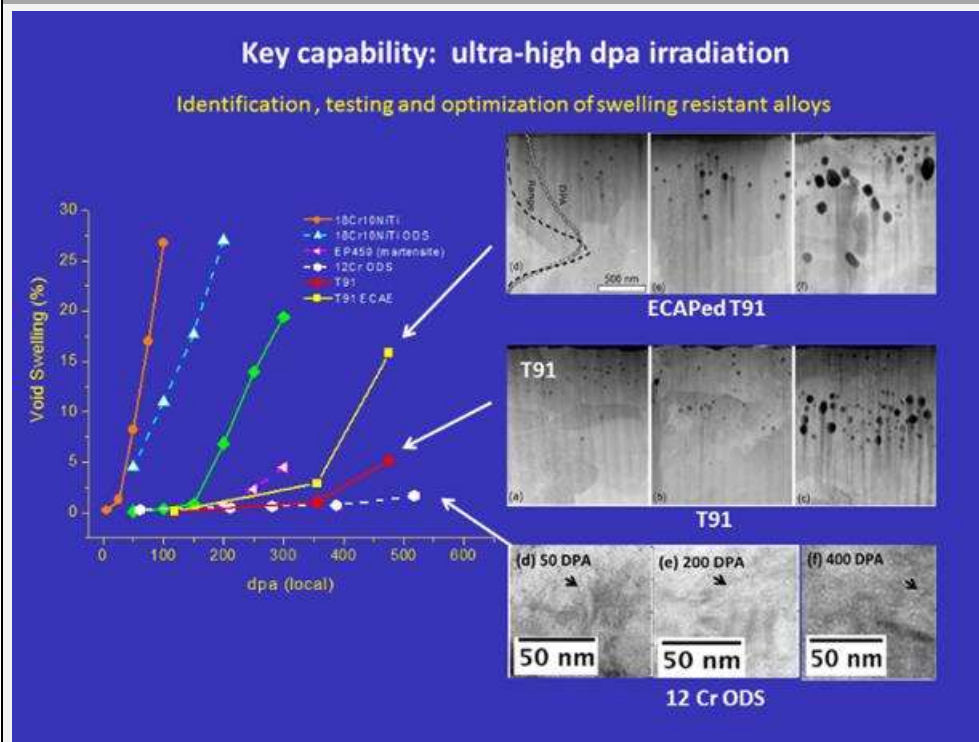
Slide 10

Accelerators have greatly benefited materials screening

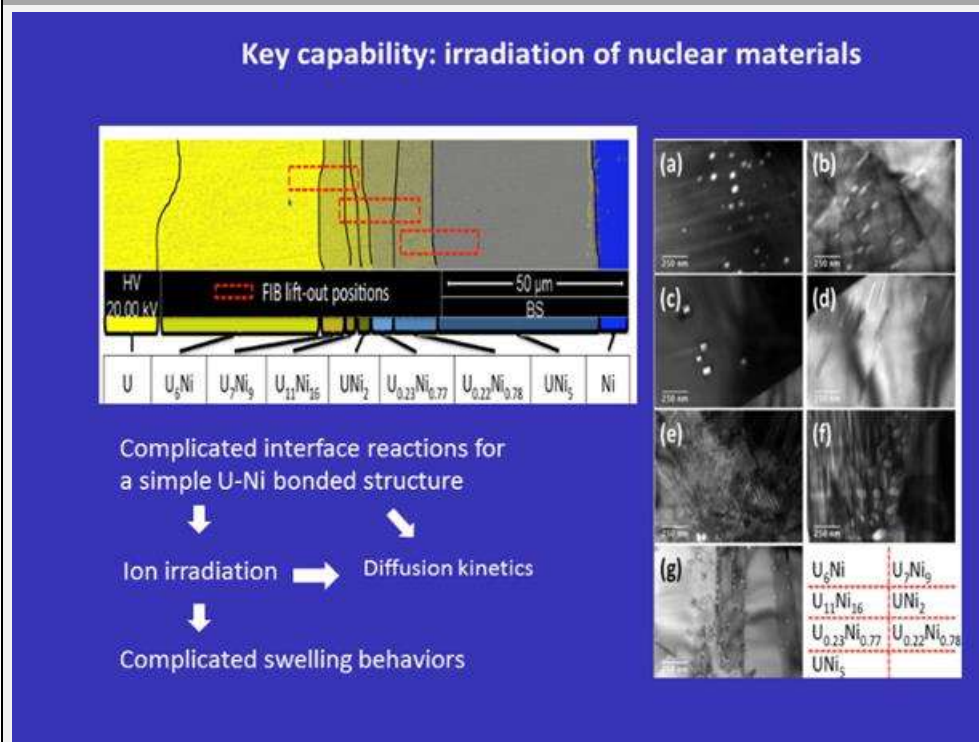


Swelling resistance: Austenite < Ferrite < Ferritic-Martensitic < Martensitic

Slide 11



Slide 12



Ultra high dpa testing of nuclear materials

- 24/7 irradiation up to a few weeks
- Peak dpa in steels up to 1000

Proportion of time to be allocated to direct NE mission work

- ~100% for 3 MV Accelerator
- ~50% for 1.7 MV Accelerator

Radiation level allowed for samples
<0.1 mCi

Types of sample materials allowed

- Depleted uranium
- Reactor treated stainless steels

Supporting infrastructures (for radiative materials)

- Cutting and polishing of radioactive materials
- SEM characterization of radioactive materials

Supporting infrastructures (for nonradioactive materials)
FIB, TEM, SEM, too much to list...

Slide 15

Provide a variety of ion irradiations

Dual beam irr. capability



Slide 16

Provide a variety of irradiation environments



Recently updated target chambers

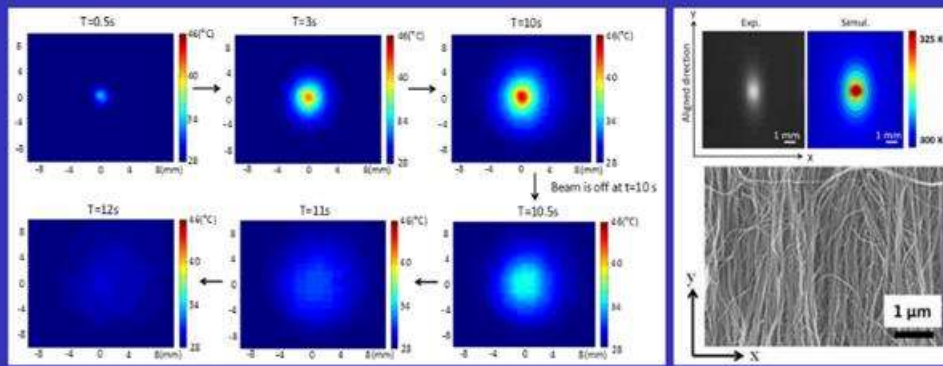
Irradiation temperature up to 800°C

Vacuum during irradiation: $< 1 \times 10^{-6} \text{ torr}$

Slide 17

In-situ examination during irradiation

In situ characterization of thermal conductivities of irradiated solids by using ion beam heating and infrared imaging



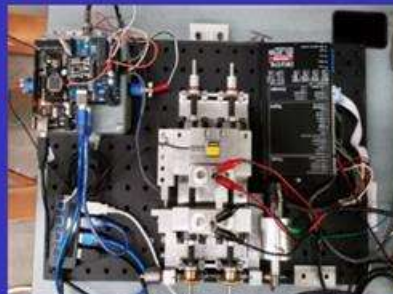
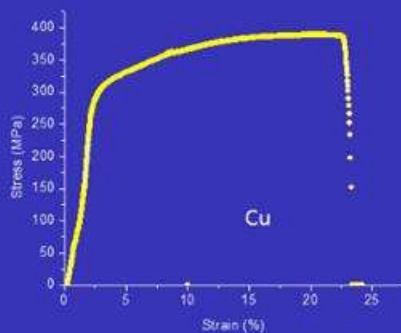
Nucl. Instrum. Methods B 332, 381-384 (2014)

Appl. Phys. Lett 107, 151904(2015)

Slide 18

In-situ examination during irradiation

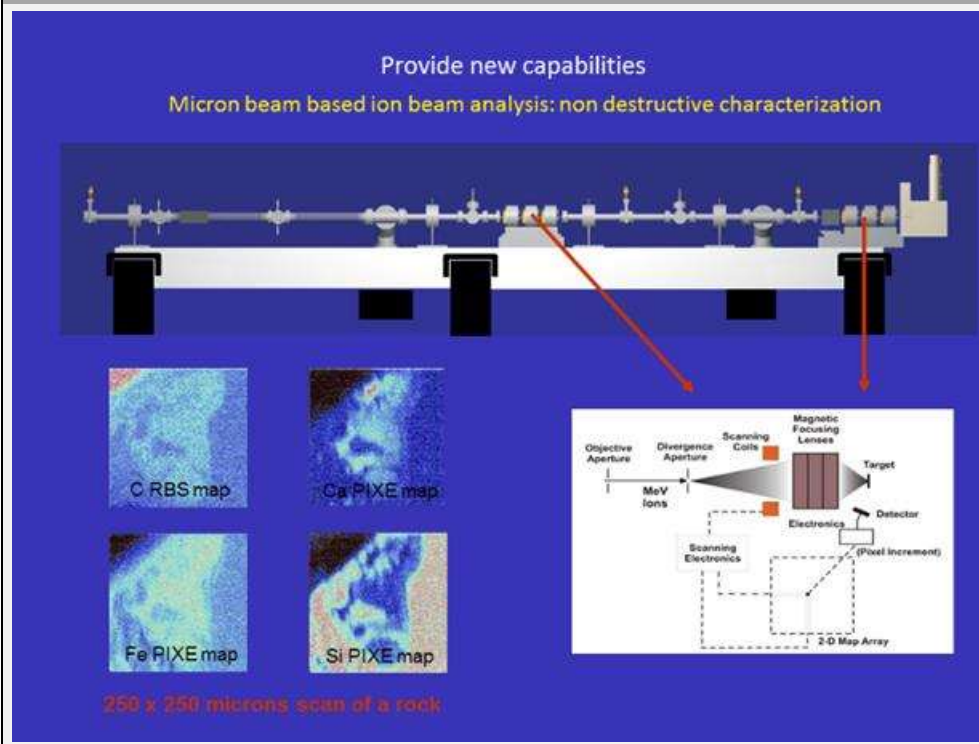
In situ strain-stress testing of irradiated solids



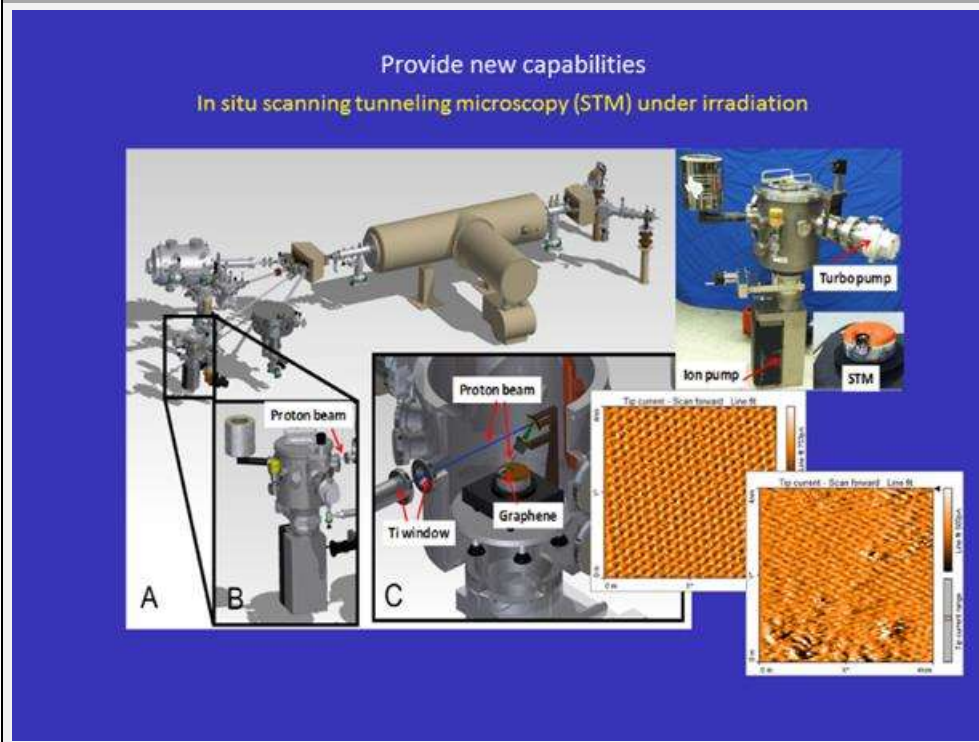
- Applying a stress during the ion irradiation
- Perform strain-stress test after ion irradiation

1. New model will be able to do creep testing.
2. What are the sizes of samples? And what geometry/configurations are they?

Slide 19



Slide 20



Slide 21

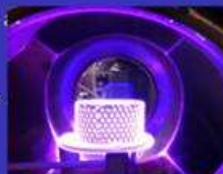
Current NE work performed at facility

Advanced surface plasma nitriding for development of corrosion resistant cladding

Sponsor: DOE-NEUP-NEET

PI: Lin Shao; Co-PI: Don Lucca (Oklahoma State Univ.), Frank Garner (Texas Short (MIT).

Total amount: \$800,000; Period: 10/01/2015-09/30/2018

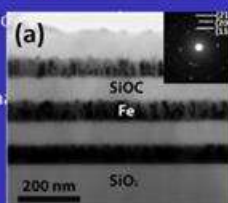


Radiation tolerance and mechanical properties of nanostructured amorphous composites

Sponsor: DOE-NEUP-NEET

PI: Michael Nastasi (Univ of Nebraska-Lincoln); Co-PI: Don Lucca (Oklahoma (Texas A&M Univ.), Michael Demkowicz (MIT).

Total amount: \$994,997 ; Period: 10/01/2015-09/30/2018

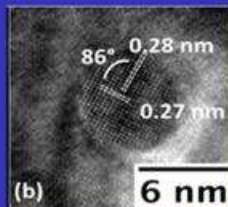


Development of accident tolerant fuel options for near term applications

Sponsor: DOE-NEUP-IRP

PI: Jacopo Buongiorno (MIT); Co-PI: Lin Shao and seven others

Total amount: \$3,000,000 ; Period: 10/01/2015-09/30/2018



Development of High Performance ODS Alloys

Sponsor: DOE-NEUP

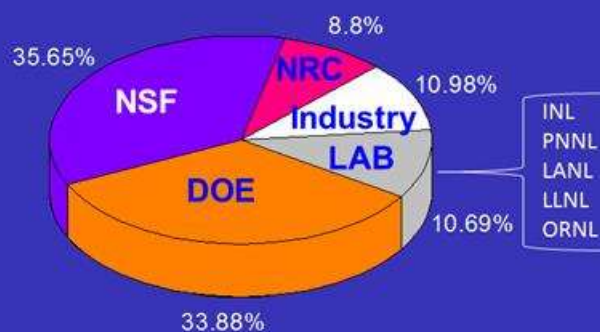
PI: Lin Shao; Co-PI: Frank Garner and Fei Gao

Total Amount: \$800,000; Period: 09/01/2014-08/30/2017

Slide 22

External Funding

Since 2007, 24 funded projects, total amount: \$12.5 millions.



NE supports through standard R&D grants: about 4 millions (since 2007).

NE investment on equipment and lab infrastructure : \$0

Key Capabilities

(a) Various Ion Beam Analysis

- Rutherford backscattering spectrometry (RBS)
- Elastic backscattering spectrometry (EBS)
- Elastic recoil detection (ERD)
- Particle induced X-ray emission (PIXE)
- Nuclear reaction analysis (NRA)

(b) Various Ion Beam Modification of Materials

- Ion implantation
- Ion smoothing
- Ion mixing
- Defect engineering

(c) In situ Sample Characterization

- Ion beam analysis + ion irradiation, simultaneously.

(d) Multiple Ion Beam Irradiation

- Ion irradiation with different ions at different energies, simultaneously.

(e) Prolonged Ion Irradiation vs. Fast Ion Irradiation

- Study radiation response of materials at different stages of structural transformation.

Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry:

Journal paper published: 108 (from 2007 to 2016)

Book chapters: 3 (from 2007 to 2016)

Thanks!

Ishao@tamu.edu

Presentation: IBML at LANL

Yong Wang

Ion Beam Materials Laboratory in Los Alamos

Ion Beam Materials Laboratory in Los Alamos

Yong Q. Wang

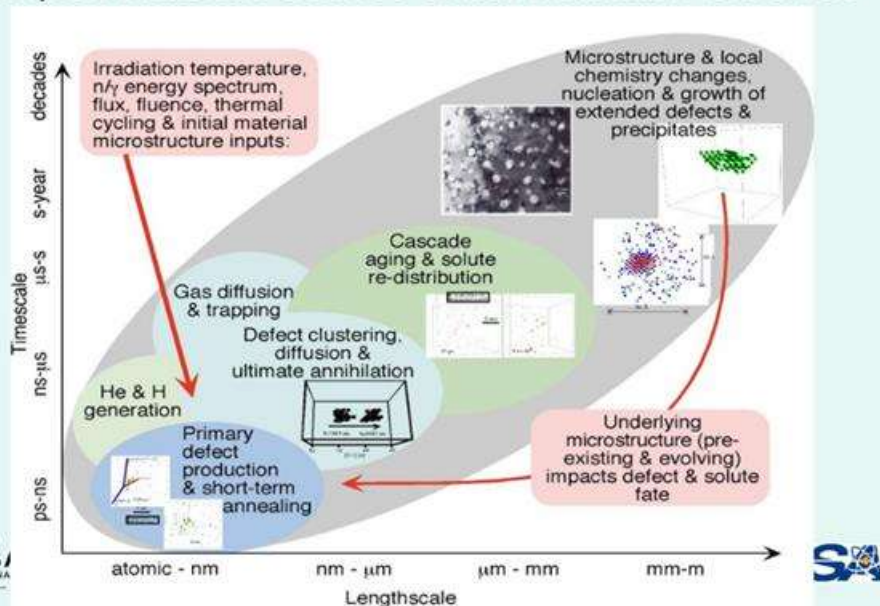
Materials Science in Radiation and Dynamics Extremes Group
Materials Science and Technology Division
Los Alamos National Laboratory



NSUF Ion Beam Workshop, Idaho Falls, ID March 22-24, 2016

Challenges: Complex materials science under irradiation extremes

Challenges: Complex materials science under irradiation extremes



Challenges: Lack of Neutron Sources for Research - Accelerator Ions vs. Reactor Neutrons



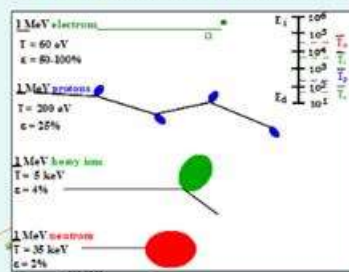
- Irradiation volume
- Irradiation dpa rate

dpa

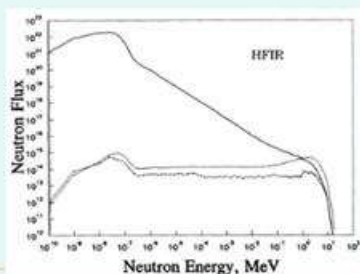
Modeling and simulations



G. Was and T. Allen, *Mater Character.*, 32 (1994) 239.



Beyond dpa:
Atomic mixing in cascade
Recombination of defects in cascade
Other complex defects formation



Frontier of Materials Radiation Damage Science

Frontier of Materials Radiation Damage Science - Radiation Tolerant Materials by Design

Beyond "Cook and Look:" In-situ diagnostics and tailored materials

Multiscale modeling and simulation tools

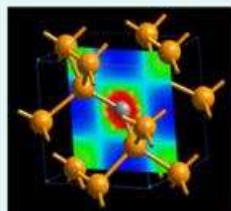
- Use *ab initio* to derive empirical potentials needed by MD/MC
- Feed in the mesoscale codes with correct thermodynamic and kinetic databases
- Modify the continuum model by including voids with pressure (bubbles)

ab initio DFT

molecular dynamics

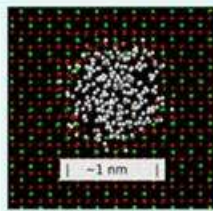
phase field

continuum



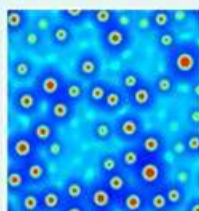
Å – a few nm

Energetics
Thermodynamics



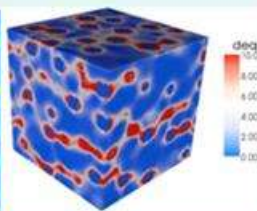
nm – 10s nm

Free functional
Mobility database
Segregation effects
He bubble nucleation
Dislocation pinning



100s nm – μ m

Irradiation dose effect
He bubble distribution
Dislocation pinning
Grain size effect
Alloy effect



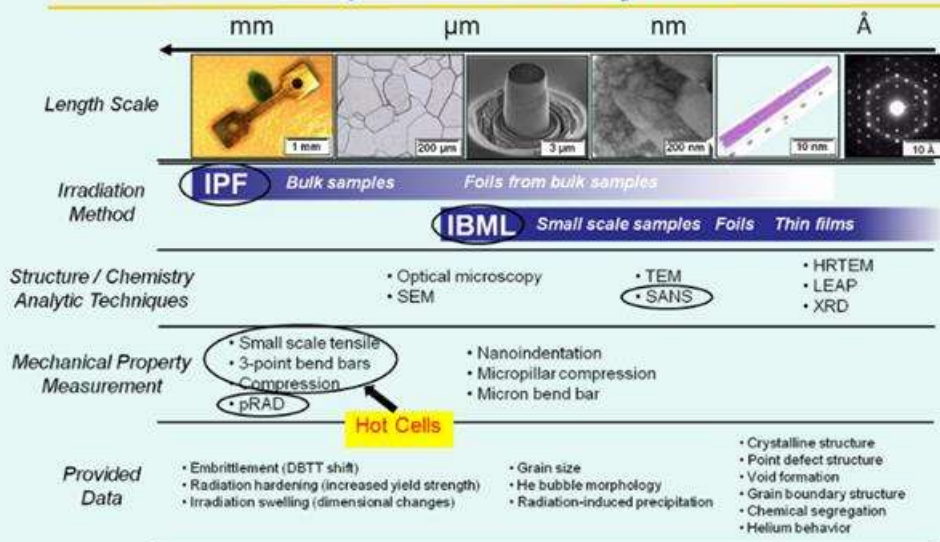
μ m – mm

strain states
dislocation



Multiscale experiments to verify the models

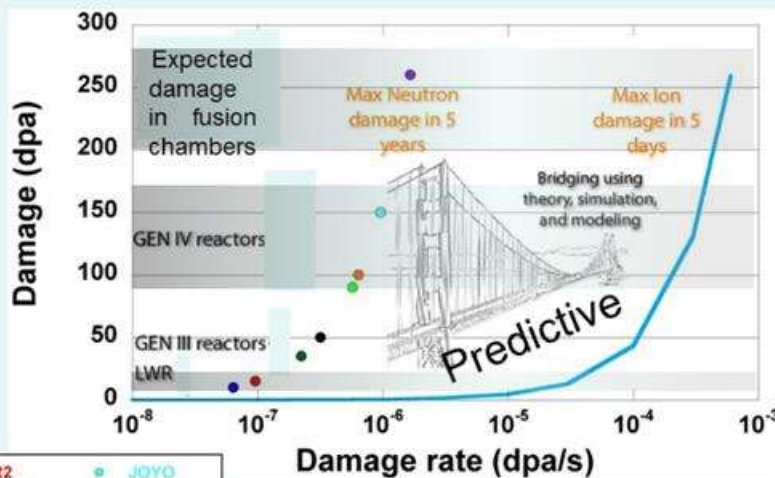
Multiscale experiments to verify the models



Linking evolved structure and chemistry observed on the μm , nm, and Å scales to mechanical property changes on the mm scale is possible through combined IPF and IBML irradiations

Ion beams can provide the experimental means to accelerate the use of advanced modeling and simulation

Ion beams can provide the experimental means to accelerate the use of advanced modeling and simulation



LLNL Triple Beam Workshop (2009)

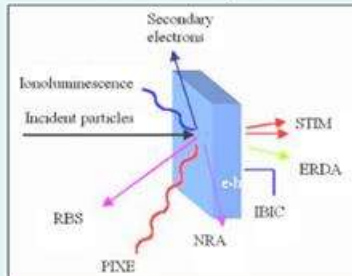


Ion – Solid Interactions

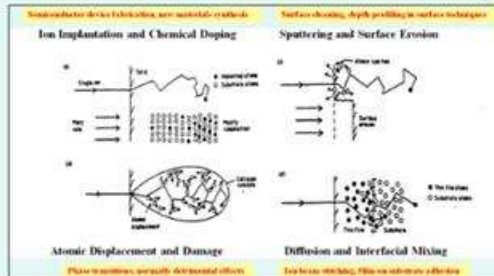
Ion Beams Contribute to Nuclear Materials Research

Ion – Solid Interactions

Materials Analysis



Materials Modification and Radiation Damage



Ion beams can contribute to materials research in three ways:

- ✓ **Radiation damage effects** in materials by ion bombardment
- ✓ Materials characterization with **ion beam analysis (IBA)** techniques
- ✓ Materials modification and synthesis through **ion implantation**



Ion Accelerator Facilities for Materials Research

Ion Accelerator Facilities for Materials Research

Many ion accelerator laboratories in the world conduct materials research: Europe Union, Japan, United States, and the rest of the world.

Established Conference Series by this community:

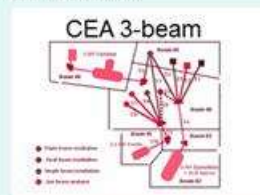
- ✓ Ion Beam Modification of Materials (IBMM)
- ✓ Ion Beam Analysis (IBA)
- ✓ Application of Accelerators in Research and Industry (CAARI)
- ✓ Radiation Effects in Insulators (REI)
- ✓ Symposiums at MRS and TMS annual meetings
- ✓ Nuclear Materials Congress

Ion Implanters:

- ✓ Ion species: virtually any element in PT
- ✓ Energies (a few keV to a few MeV)
- ✓ Beam currents (a few uA to a few mA)
- ✓ Modification through ion implantation
- ✓ Ion irradiation damage research
- ✓ Large sample sizes
- ✓ ...

Ion Implanters + Ion Accelerators:

- ✓ Synergistic activities
- ✓ Damage plus transmutation products
- ✓ Dual-beam or Triple-beam capabilities



Ion Accelerators:

- ✓ Ion species: many ion species
- ✓ Energies (100s keV to 10s MeV)
- ✓ Beam currents (10s nA to 10s uA)
- ✓ Ion beam analysis
- ✓ Modification through ion implantation
- ✓ Ion irradiation damage research
- ✓ Small sample sizes
- ✓ ...

Ion Accelerators + TEM:

- ✓ In-situ characterization of radiation damage
- ✓ Synergistic activities
- ✓ Damage plus Transmutation products
- ✓ 2-beam, 3-beam, 4-beam capabilities



Accelerator Beam Facilities at Los Alamos

Accelerator Beam Facilities at Los Alamos:

Los Alamos Neutron Science Center (LANSCE):

- ✓ Los Alamos Meson Physics Facility (LAMPF)
- ✓ 800 MeV Linear Proton Accelerator
- ✓ Manuel Lujan Neutron Scattering Center (MLNSC)
- ✓ Medical Radioisotope Production Facility (IPF)
- ✓ Proton Radiography (P-Rad) Facility
- ✓ Weapons Neutron Research (WNR) Facility

Dual Axis Radiographic Hydrodynamic Test Facility (DARHT):

- ✓ 18 MeV Pulsed Electron Beam Accelerator Facility (2 kA, 1.6 μ S, 1.25 mm Spot)
- ✓ X-ray doses: 100 rads @ 1m

Los Alamos Ion Beam Facility (IBF):

- ✓ Two Accelerators: Van De Graaff (6 MV Vertical) + FN Tandem (9 MV)
- ✓ Nuclear Physics Research Facility (protons, deuterons, tritons, alphas etc.)
- ✓ Superconducting Solenoid Magnet Nuclear microprobe was constructed (1980)
- ✓ Largely funded by weapons science programs
- ✓ The facility was officially shutdown in 1995

Ion Beam Materials Laboratory (IBML) (since 1986)



LANSCE Experimental Areas

LANSCE Experimental Areas

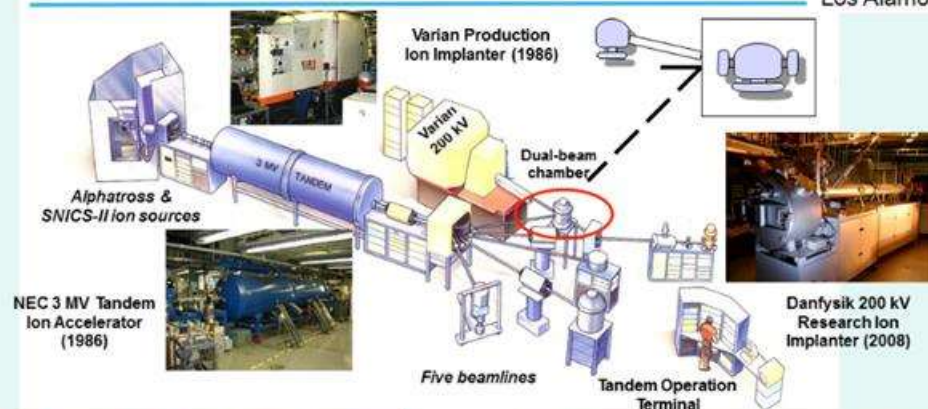
MaRIE 1.0 – 12 GeV e-Accelerator to produce XFEL source



- Lujan Center
 - National security research
 - Materials, bio-science, and nuclear physics
 - NNSA user facility
- WNR
 - National security research
 - Nuclear Physics
 - Neutron Irradiation
- Proton Radiography
 - National security research
 - Dynamic Materials science
 - Hydrodynamics
- Isotope Production Facility
 - Medical radioisotopes



Ion Beam Materials Laboratory



High Energy Ion Beam Capabilities:

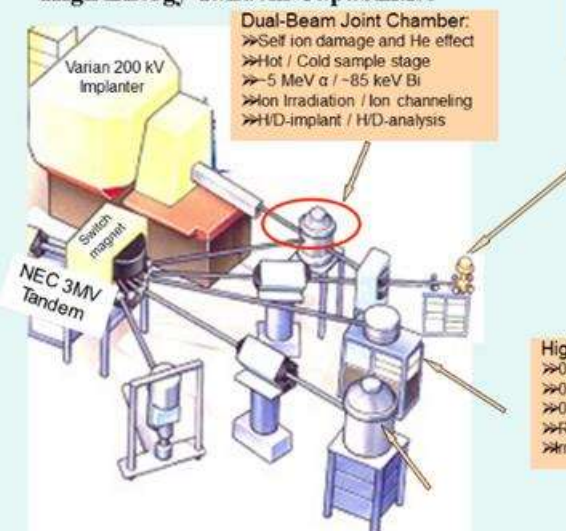
- Gas & sputter ion sources and five beamlines
- Proton beam: 200 keV to 6 MeV
- Alpha beam: 200 keV to 9 MeV
- Heavy ions (C, Si, Cu, Au): 200 keV to 18 MeV
- Beam currents: from a few pA to a few μ A
- Ion Beam Analysis (RBS/NRA/PIXE/channeling)
- High temperature ion irradiation (1000°C)
- Ion irradiation and corrosion (ICE) experiment
- Tunable actinide alpha source: \sim μ Ci to \sim kCi

High Current Ion Beam Capabilities:

- Gas-Oven-Sputter source and up to three beamlines
- Proton beam: 5 keV to 200 keV
- Helium beam: 10 keV to 400 keV
- Heavy ions (N, Ar, Fe, Xe, Au): 30 keV to 800 keV
- Beam currents: a few μ A to a few mA
- Target implantation temperature: LN₂ to 1000°C
- In-situ characterization: HREED
- Materials synthesis and modification
- Radiation damage science through ion irradiation

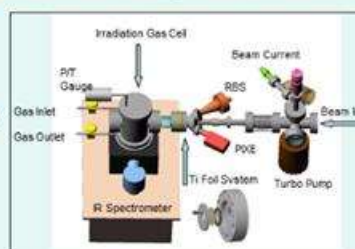
High Energy Tandem Capabilities

High Energy Tandem Capabilities



In-situ FTIR Gas Radiolysis Chamber:

- Beam current: \sim pA to \sim μ A
- Tunable actinide alpha source: \sim mCi to \sim kCi



High-E / High-T Irradiation Chamber:

- 0.2 to 6 MeV protons
- 0.2 to 9 MeV alphas
- 0.2 to 18 MeV heavy ions
- RT to 1200°C
- Radiation and corrosion experiment (ICE)

General Purpose IBA Chamber:

- RBS, ERD, PIXE, NRA, Channeling



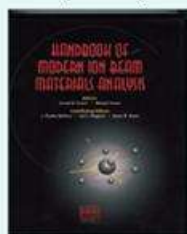
Slide 13



Ion Beam Materials Research at LANL (1986-2016) (Courtesy of Nastasi, Tesmer, Sickafus, Maggiore, Misra, Maloy, Uberuaga, Picraux, Jia, and others)

Ion Beam Materials Research at LANL (1986-2016)

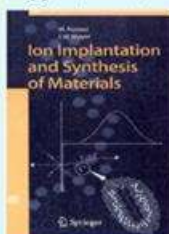
(Courtesy of Nastasi, Tesmer, Sickafus, Maggiore, Misra, Maloy, Uberuaga, Picraux, Jia, and others)



1995



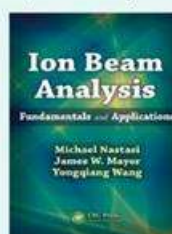
1996



2007



2009



2014

IBML related publications: Well over 1000 refereed papers have been published by LANL researchers using the IBML Facility since its inception, including journals like Science, Nature Materials, PRL, APL, Advanced Materials, JNM, JMR, NIM etc.

IBML user sponsored conferences: MRS symposium (1989), IBMM (1996), IIT (2002), IBA (2003), REI (2005), CAARI (2006-2014), IBA (2013).

IBML supported programs: BES (EFRC, CINT, Single PIs), LDRD, NE (FCR&D, NEUP), Weapons, Space Programs, UCOP, WFO etc.



Ion Irradiation Ion accelerator

Ion Irradiation

Ion accelerator



Characterization

FEI Titan 80-300™



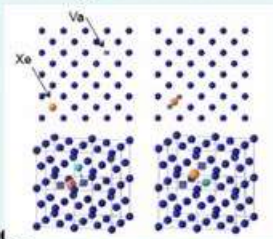
Load Frame in Wing 9
CMR Hot Cell



Modeling & Simulations

NEAMS

CASL



National User Facilities



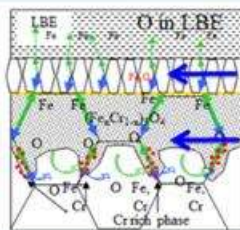
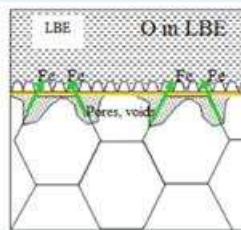
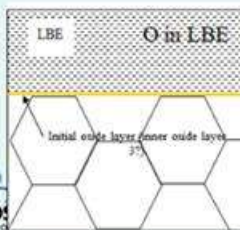
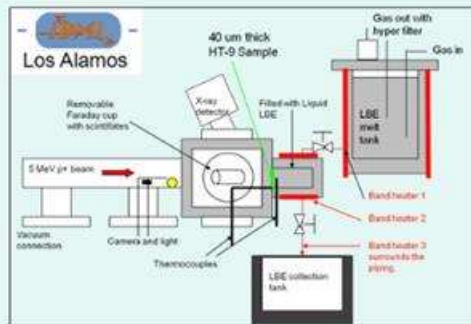
Irradiation and corrosion experiment (ICE) at IBML

Irradiation and corrosion experiment (ICE) at IBML

(P. Hosemann et al., J. of Nucl. Mater. 376 (2008) 392)
(S. Qvist et al. Nucl. Instrum. Meth. A 698 (2013) 98)

HT9 - LBE
Interface:

Synergistic effects
between corrosion
and irradiation on
HT-9 steel clad at
450 C and ~22 dpa
(~60 hours proton
irradiation)



Magnetite

Spinel

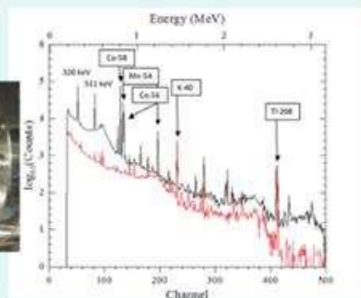
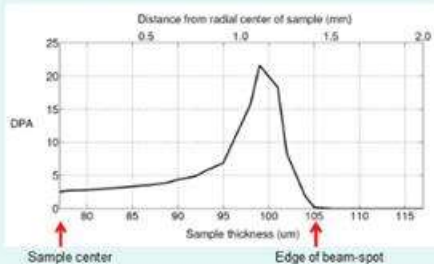


Slide 17

Table 1.1. Campaign-averaged & cumulative experimental parameters

Sample temperature	450 °C
LBE (bulk) temperature	420 °C
Particle energy	5.50 MeV
Particle current	2.0 μ A
Beam spot-size	3x3 mm
LBE oxygen content	300 ppm
Cumulative irradiation time	58 h
Cumulative LBE-melt contact time	80 h
Bulk sample DPA	3.8 dpa
Maximum sample DPA	22.1 dpa

5.5 MeV protons irradiated for ~60 hours on 3 x 3 mm² beam spot size

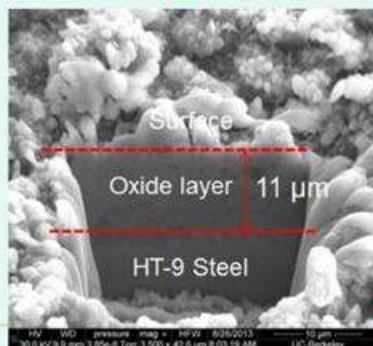


Irradiation under corrosion lasted for ~60 hours

Irradiation under corrosion lasted for ~60 hours

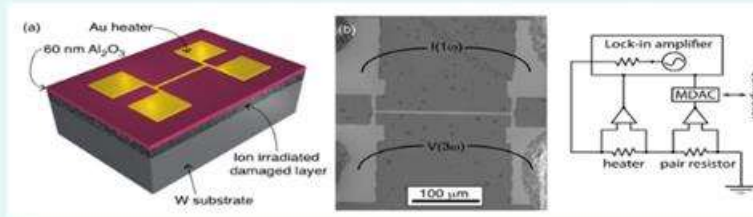


The oxide layer formed within the beam region is significantly thicker than outside the beam region, suggesting a strong synergistic effect due to radiation enhanced diffusion and corrosion.



Thermal conductivity by 3- ω Method

Thermal conductivity by 3- ω Method



$$\delta_p = \sqrt{\frac{2\alpha}{\omega q}} = \sqrt{\frac{2\kappa}{\rho C \omega q}} \quad I = I_0 \sin \omega t \quad P = [I_0 \sin(\omega t)]^2 R = \frac{I_0^2 R}{2} + \frac{I_0^2 R}{2} \cos(2\omega t)$$

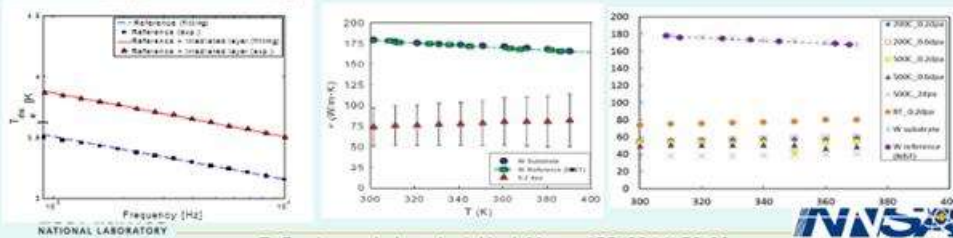
$$T_{rise} = T_{DC} + T_{2\omega} \cos(2\omega t + \phi) \quad V_{3\omega} = \frac{I_0}{2} \frac{dR}{dT} T_{2\omega} \sin(3\omega t + \phi)$$

$\Delta T_{ref+irr, layer} - \Delta T_{ref} = \Delta T_{irr, layer}$

Use $\Delta T_{irr, layer}$ to calculate $K_{irr, layer}$

Thermal conductivity of irradiated W layer

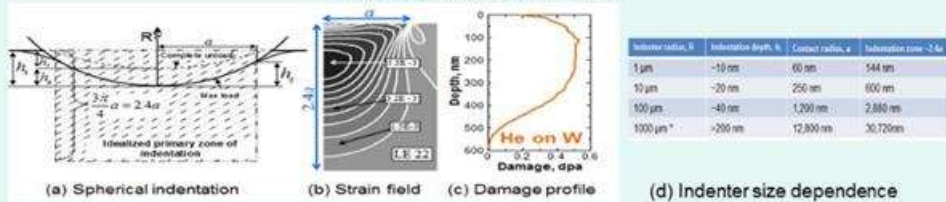
Irradiation temperature and dose dependence



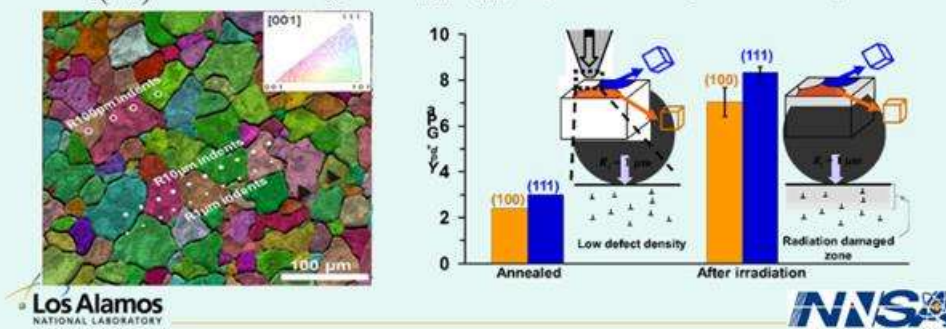
E. Dechaumphai, et al. J. Nucl. Mater. 455 (2014) 56-60.

Nanomechanical properties by spherical nanoindentation

Nanomechanical properties by spherical nanoindentation



$$S = \frac{3P}{2h_c} = \frac{3(P-h_c)}{2(h_c-h)} \quad \sigma_{ind} = E_{eff} \epsilon_{ind}, \quad \sigma_{ind} = \frac{P}{\pi a^2}, \quad \epsilon_{ind} = \frac{4}{3\pi} \frac{h_c}{a} = \frac{h_c}{2.4a} \quad \frac{1}{E_{eff}} = \frac{1-\nu^2}{E_s} + \frac{1-\nu_i^2}{E_i} \quad \frac{1}{E_{eff}} = \frac{1-\nu^2}{E_s} + \frac{1-\nu_i^2}{E_i} \quad \frac{1}{R_{eff}} = \frac{1}{R_i} + \frac{1}{R_s}$$



Los Alamos
NATIONAL LABORATORY
EST. 1943

NNSA

In-situ nano-mechanical testing on ion irradiated materials

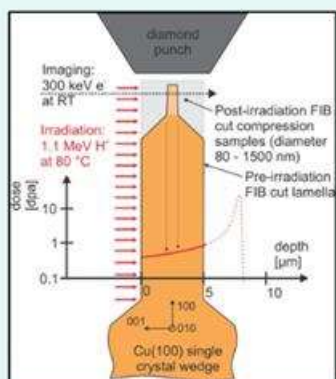
- A case study on single crystal Cu (100)

FCR&D (P. Hosemann and S. Maloy)

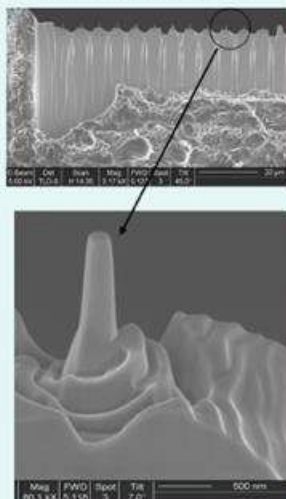
D. Kiener et al. *Nature Materials*, 10 (2011) 608.

Motivation

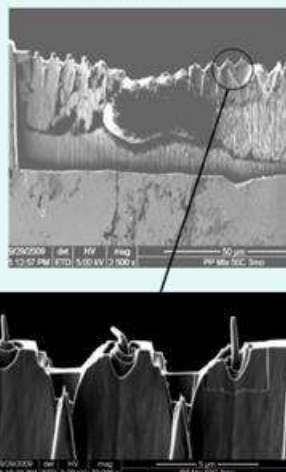
Is nano-mechanical testing on ion irradiated samples a viable way to obtain bulk mechanical properties?



Before irradiation



After irradiation



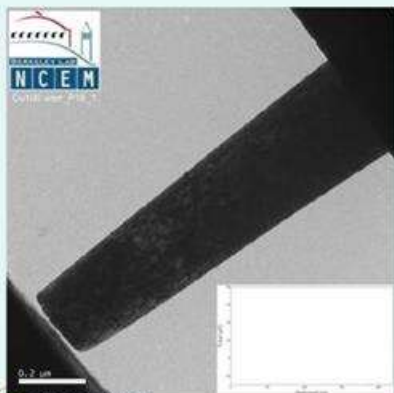
In-situ compression testing on Cu (100) under TEM

Before irradiation

Material: Cu (100)

Tes,ng: Displacement controlled, 1 nm/s

Dimensions: $d_{top} = 136 \text{ nm}$ $d_{avg} = 206 \text{ nm}$ $h = 904 \text{ nm}$

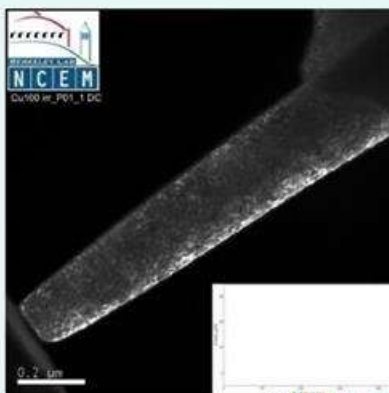


After irradiation

Material: Cu (100) irradiated to 0.8 dpa

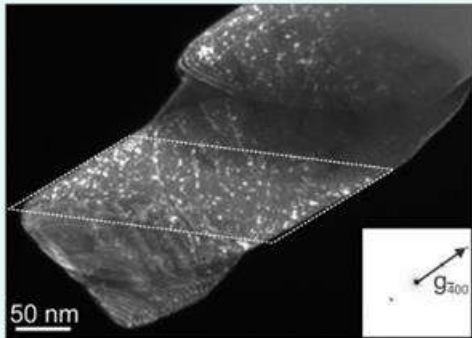
Tes,ng: displacement controlled, 1 nm/s

Dimensions: $d_{top} = 118 \text{ nm}$ $d_{avg} = 198 \text{ nm}$ $h = 1143 \text{ nm}$

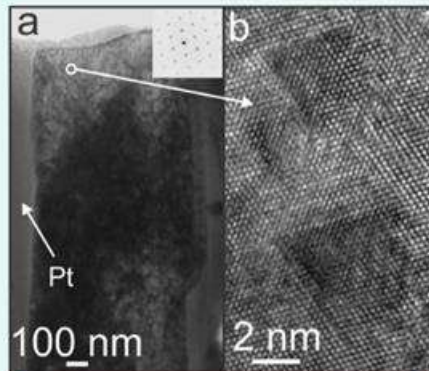


Post-compression TEM examination

Ion irradiated pillar structure



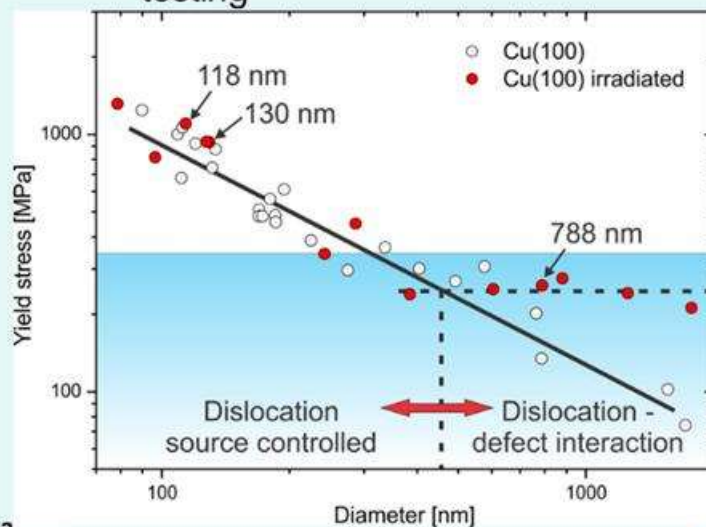
- ✓ Slip localization on a slip plane in the middle of the sample
- ✓ Many defects in the undeformed regions
- ✓ Defect densities: $1.4 \times 10^{23} \text{ m}^{-3}$
- ✓ Defect spacing: $\sim 20 \text{ nm}$



Stacking fault tetrahedrons (SFT) as pinning defect blocks

Slide 24

Size dependent of yield strength from micropillar compression testing



Dual ion beam capability at Los Alamos

Dual ion beam capability at Los Alamos



Nuclear Instruments and Methods in Physics Research B 99 (1995) 556-566

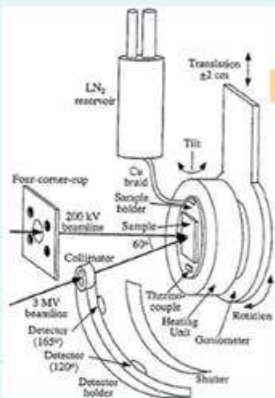
1995



In-situ capability of ion beam modification and characterization of materials at Los Alamos National Laboratory *

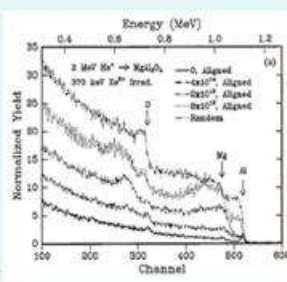
Ning Yu **, Michael Nastasi *, Timothy E. Levine **, Joseph R. Tesmer **, Mark G. Hollander **, Caleb R. Evans **, Carl J. Maggiore *

* Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
** Department of Materials Science and Engineering, Cornell University, Ithaca, NY, 14853, USA

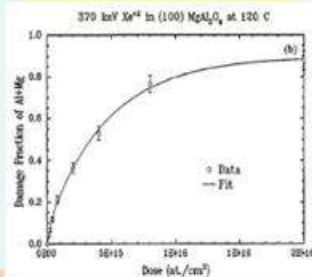


Yu et al., NIM B 99 (1995) 556.

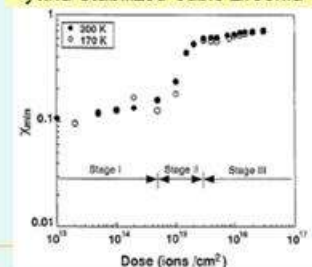
Yasuda et al. NIM B 136-138 (1998) 499



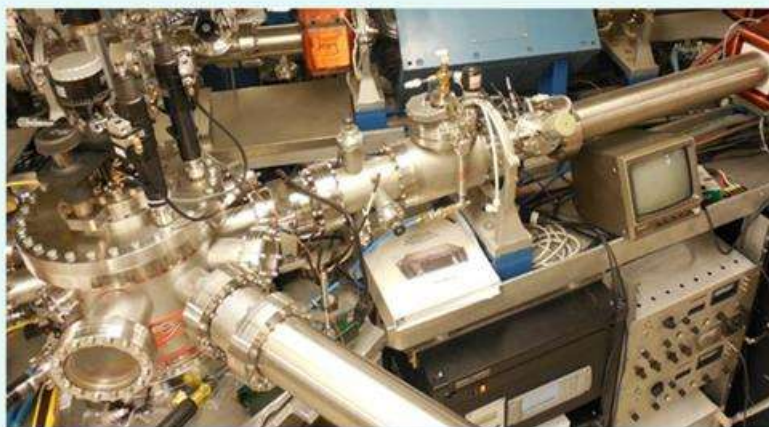
Damage accumulation in MgAl_2O_4 Spinel Crystal



Damage accumulation in yttria-stabilized cubic zirconia



Slide 26



Dual-beam tuning

160 keV He ions

4-cup Dosimetry

W coupons at 950 °C

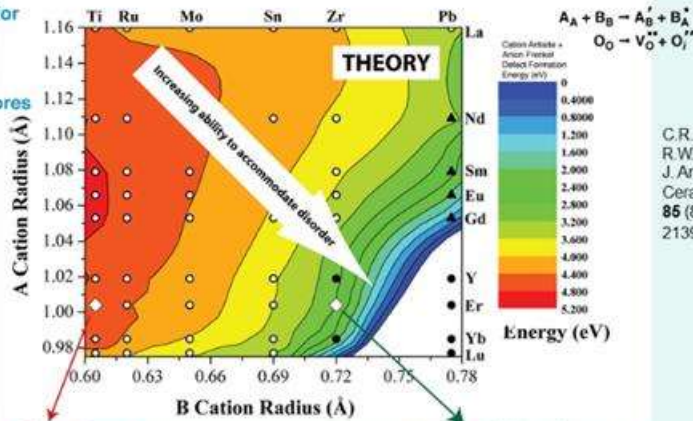


2.5 MeV Cu ions

Relationship Between Disordering Tendencies and Radiation Tolerance

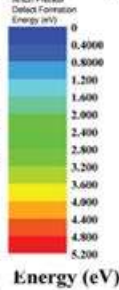
Energy Contours for
Cation Antisite +
Anion Frenkel
Defect Formation
in $A_2B_2O_7$ Pyrochlores

K.E. Sickafus et al., Science **289** (2000) 748-751.



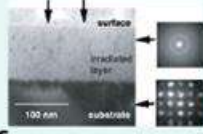
$$A_A + B_B = A_B + B_A$$

$$O_O = V_O + O_i$$



C.R. Stanek,
R.W. Grimes,
J. Amet.
Ceram. Soc.
85 (8) (2002)
2139-2141.

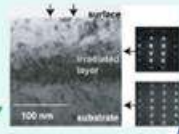
BAD radiation tolerance
350 keV Xe^{++} ions $\Phi=1 \cdot 10^{15} Xe/cm^2$



EXPERIMENT

$Er_2Ti_2O_7$

GOOD radiation tolerance
350 keV Xe^{++} ions $\Phi=1 \cdot 10^{16} Xe/cm^2$



$Er_2Zr_2O_7$

Los Alamos
NATIONAL LABORATORY
EST. 1943

NNSA

Understanding physics of palladium hydride behavior

Understanding physics of palladium hydride behavior

- Channeling NRA to determine 3He or 2D locations in Pd lattice

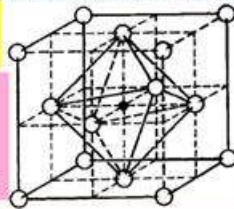
(Courtesy of D. Safarik and R. Schwarz)

- ✓ Relevant to hydrogen economy
- ✓ Important to defense applications

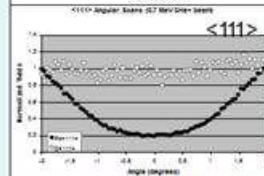
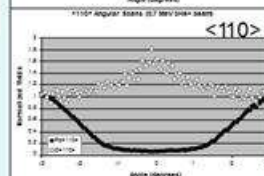
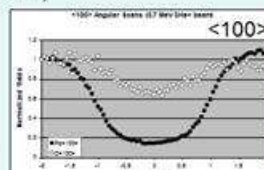
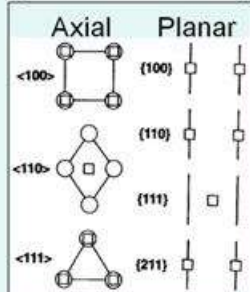
Pd Lattice: fcc structure
 $Pd_{0.8}T$ at octahedral site
 $^3T \rightarrow ^3He + \beta^- + \text{anti-neutrino}$
Does 3He occupy the same 3T site?

Method:

- ✓ Using D to substitute T to form PdD : using channeling NRA
 $^2H(^3He, p)^4He$ to determine D (thus T) lattice site
- ✓ After tritium decay, PdT to become $Pd(^3He)$; then isotope exchange to form $PdH(^3He)$: using channeling NRA $^3He(d, p)^4He$ to determine 3He lattice location in Pd lattice



H at octahedral site



Los Alamos
NATIONAL LABORATORY
EST. 1943

NNSA

A science based Ion beam program will have impact on the technological issues relevant to nuclear fusion

A science based Ion beam program will have impact on the technological issues relevant to nuclear fusion

	He & H generation	Primary defect production & short-term annealing	Defect recombination, clustering & migration	Gas diffusion and trapping	Cascade aging & local redistribution	Long-range defect transport & annihilation	Radiation enhanced diffusion & segregation of solutes	Nano/microstructure evolution, chemistry changes, nucleation & growth of defects & precipitates
Hardening & Embrittlement		A,B,D	A,B,C,D	B,C,D	A,B,C,D	A,B,C,D	A,D	A,B,C,D
Phase Instabilities		A,B,C,D	A,B,C,D		A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D
Irradiation Creep	A,B,C,D		A,B,C,D	B,C,D	A,B,C,D	A,B,C,D	A,B,C	A,B,C,D
Volumetric Swelling	B,C	A,B,C	A,B,C	B,C,D	A,B,C	A,B,C,D	A,B,C	A,B,C
He Embrittlement	A,B,C		B,C,D	B,C,D	B,C,D	B,C,D	B,C,D	

Ion-Beam R&D

- A) Single low Z ion (p, He)
- B) Sequential Irradiations (p, He, HI)
- C) Dual and Triple Beam (p, He, HI)
- D) Ion Beam and electron microscope (single and dual and TEM)

White = Strong Impact
Grey = Some Impact
Black = Little or no impact

GREEN = Accessible
YELLOW = DIFFICULT
RED = NO CHANCE



Livermore Triple Beam Workshop (April 2009)



Presentation: Potential for Laboratory Compact Cyclotrons

Lance Snead

Slide 1



Potential for Laboratory Cyclotrons: Ions at Energies Relevant to Engineering Properties

Lance Snead

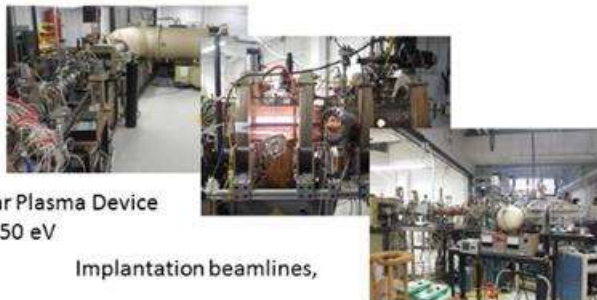
NSUF Ion Beam Investment Options Workshop
Idaho Falls, March 22-24, 2016

Slide 2



CSTAR Facility

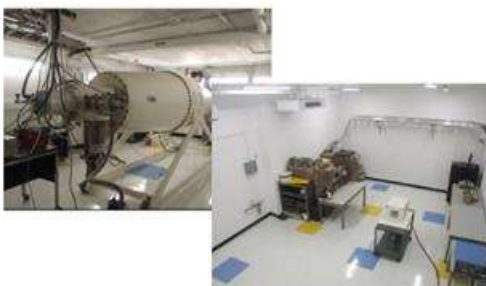
2 MeV Tandem Ion Accelerator,
<100 microAmp



DIONISOS linear Plasma Device
 10^{22} D⁺/m²-s, 350 eV

Implantation beamlines,

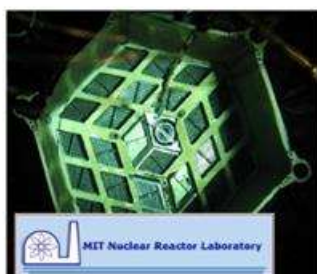
1.5 MeV Tandem Accelerator
D-T neutron Generator
Underground Vault Room



Slide 3



Facility (the capability) will Reside Within the Current MIT Ion Beam Laboratory with Access to Radiological Facilities

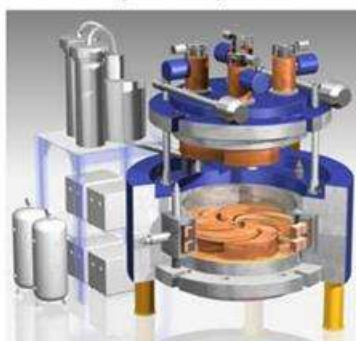


Slide 4



Facility (the capability) will Reside Within the Current MIT Ion Beam Laboratory with Access to Radiological Facilities

Cutaway of SC cyclotron



3 m diameter 250 MeV Superconducting cyclotron for proton therapy

Compact cyclotron evolution is presenting an opportunity for irradiation materials science:

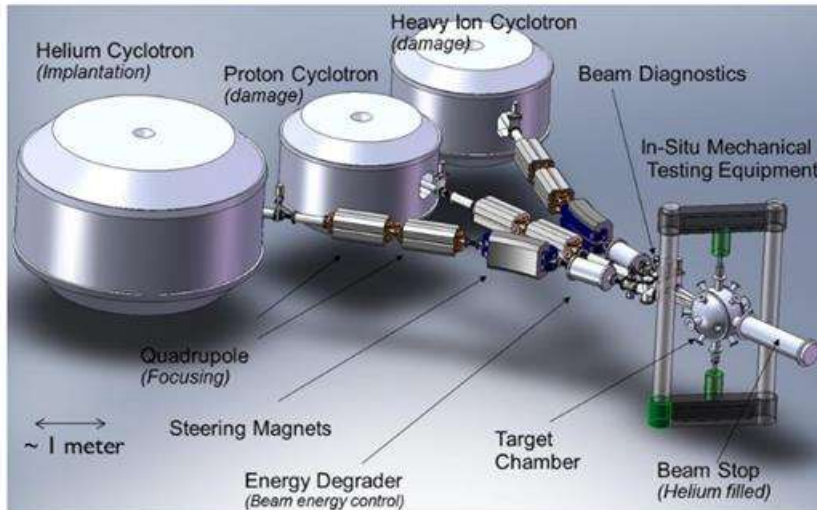
- compact footprint, reasonable capital procurement, low power consumption, continuous beam, high-energy.
- opportunity and goal: chart a path to irradiation of bulk samples while measuring physical of microstructural properties.
- Use data to seamlessly tie out understanding gained from low and intermediate energy ions to our limited data from neutron irradiated materials.

An internal MIT initiative for a combined Compact Cyclotron (10's of MeV), a compact High-brilliance X-ray capability, coupled with the native MITR neutron scattering beam.



Long-Range Goal: Engineering Properties by Leveraging Coupled Modeling and Reduced Cyclotron Costs.

An internal MIT initiative for a combined Compact Cyclotron (10's of MeV), a compact High-brilliance X-ray capability, coupled with the native MITR neutron scattering beam.

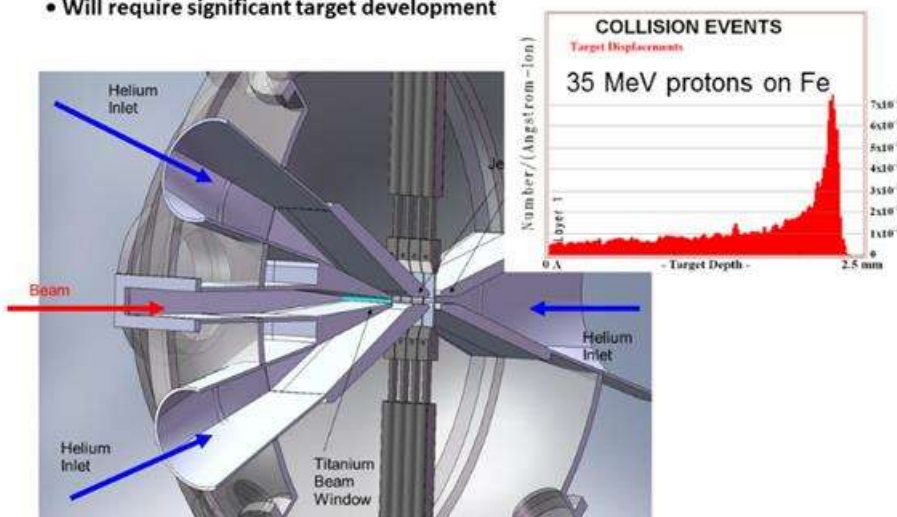


Slide 6



Conceptual Facility Combining High-Energy Ions, Neutron Scattering and Compact High-Brilliance X-rays

- Taking advantage of New Superconducting Cyclotrons
- Taking advantage of Developing Compact High Brilliance X-ray Sources
- Will require significant target development

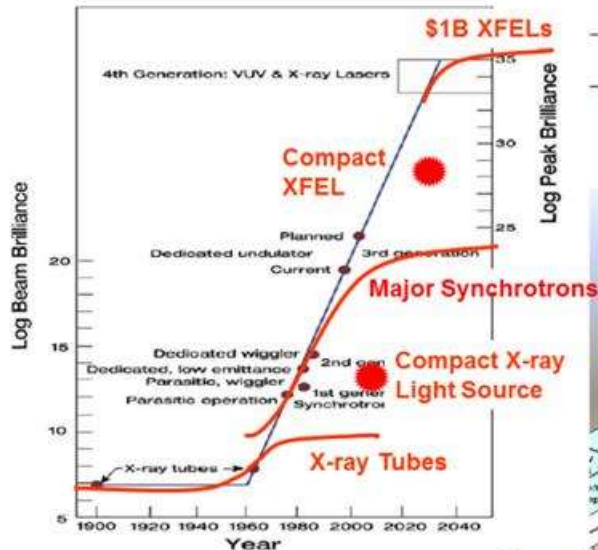


1. These energies open up bulk sample irradiations ~2.5-mm thickness.

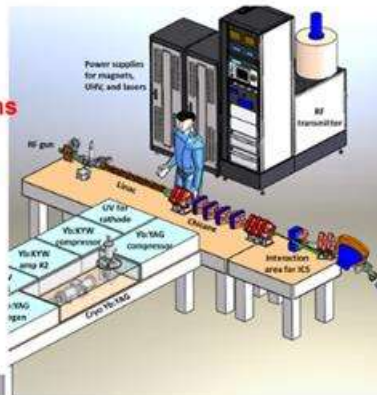
Slide 7



Compact High-Brilliance X-ray Source Provides 4-order Brilliance Increase of X-ray tubes



- Access to actinide edges (uranium K-edge is 98 keV)
- High x-ray energy required for penetration of heavy metals
- Expected techniques include powerful fluorescence-based CT imaging with 20 nm resolution



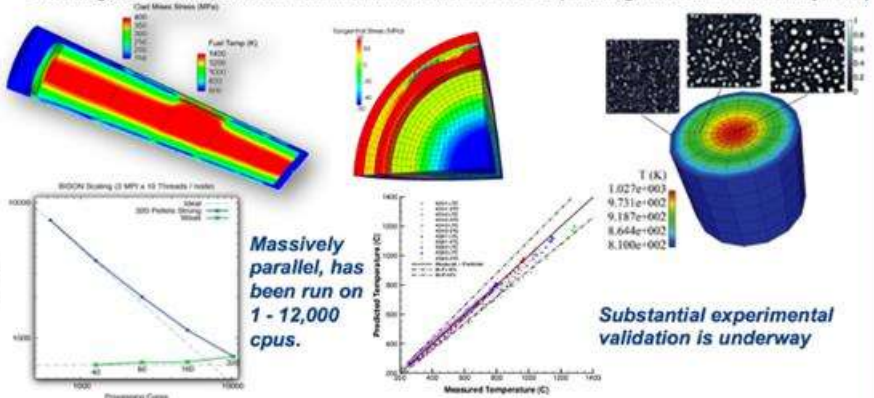
Slide 8



BISON Fuel Performance Code

Solution method: Implicit finite element solution of the coupled thermomechanics and species diffusion equations using the MOOSE framework

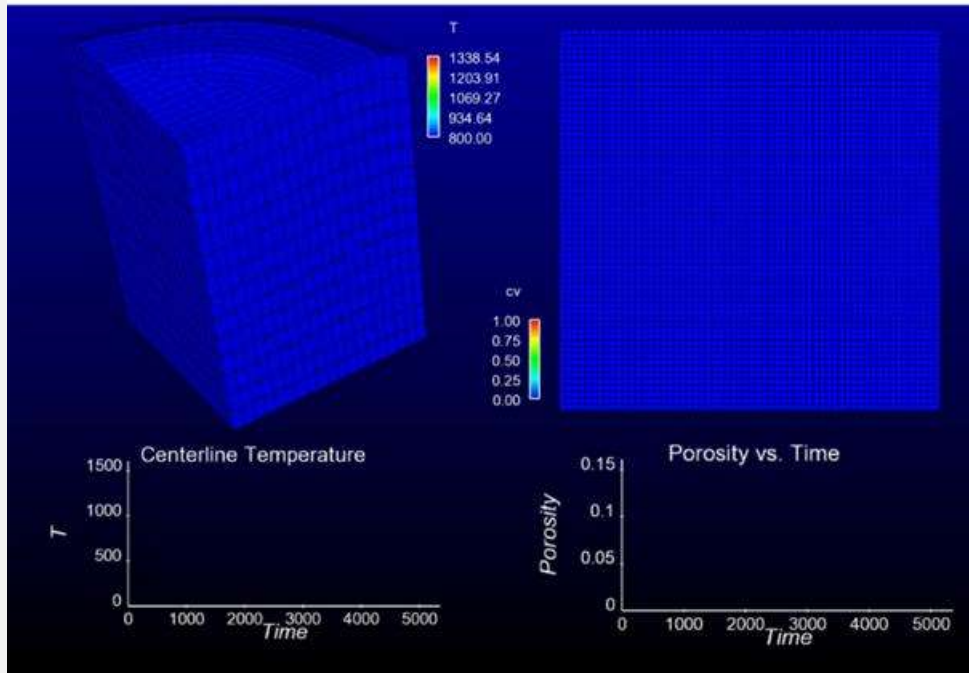
Multiphysics constitutive models: large deformation mechanics (plasticity and creep), cracking, thermal expansion, densification, radiation effects (swelling, thermal conductivity, etc.)



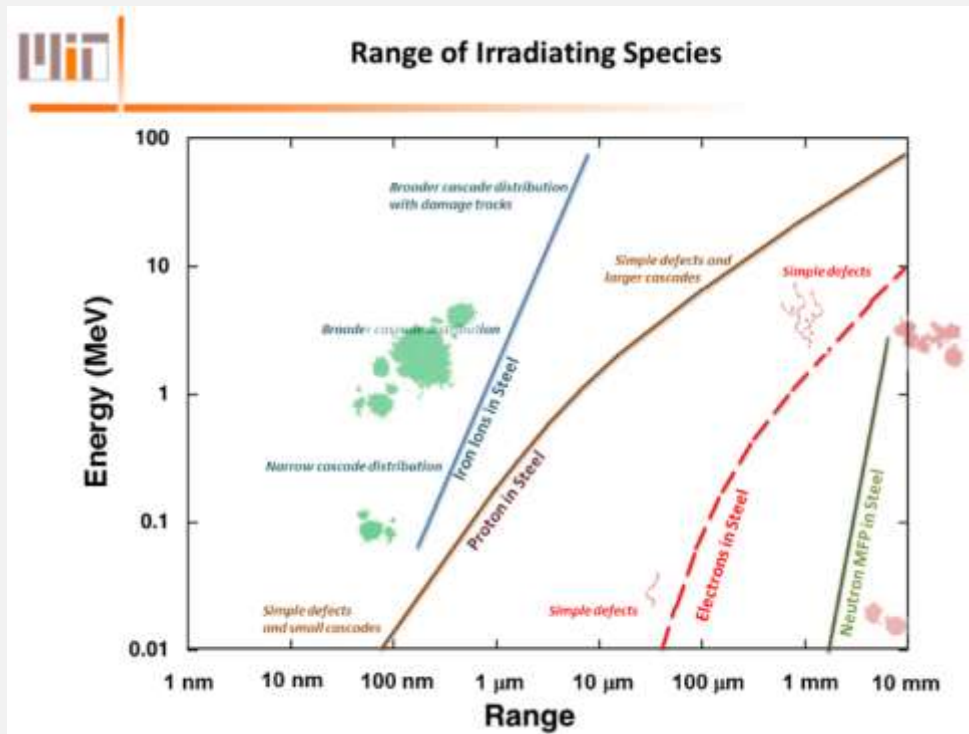
R. L. Williamson, J. D. Hales, S. R. Novascone, M. R. Tonks, D. R. Gaston, C. J. Permann, D. Andrs and R. C. Martineau, "Multidimensional Multiphysics Simulation of Nuclear Fuel Behavior," *Journal of Nuclear Materials*, 423, 149 (2012)

Slide 9

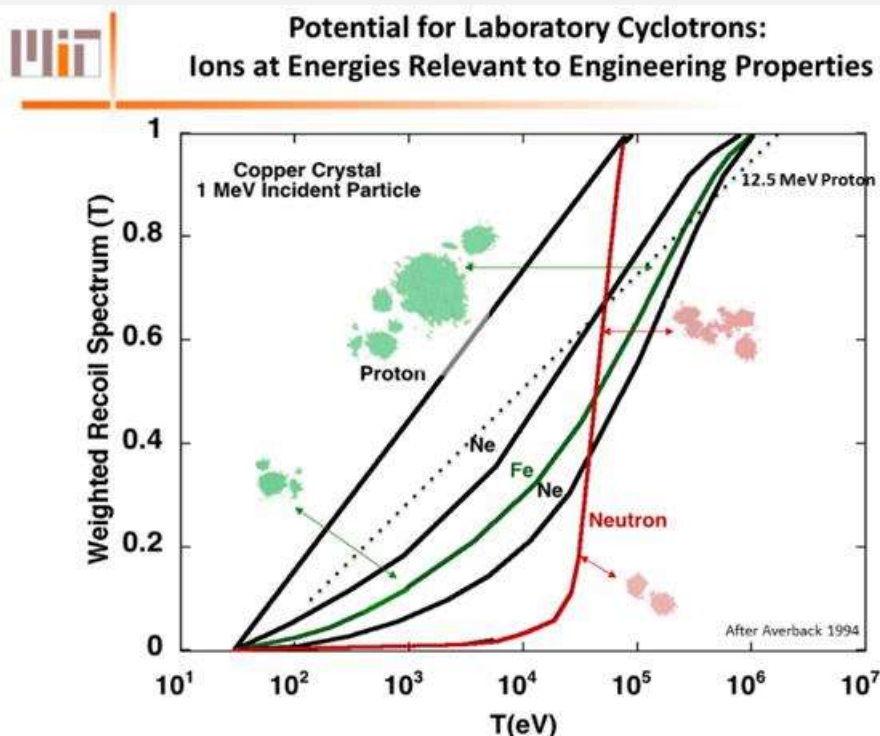
Fundamental Fuel Modeling, Courtesy of Michael Tonks, INL (now PSU)



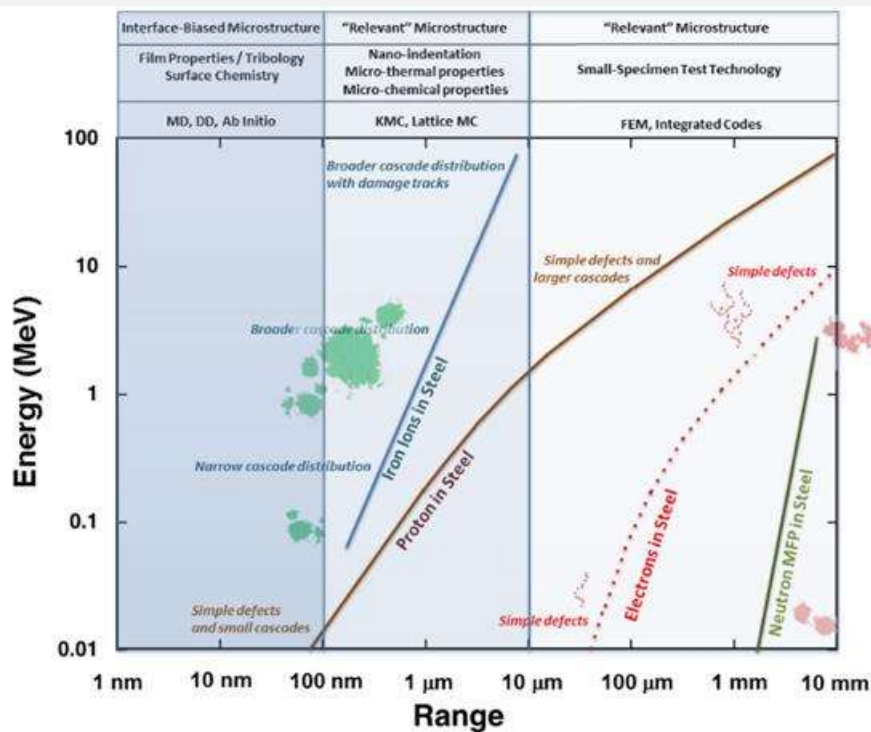
Slide 10



Slide 11

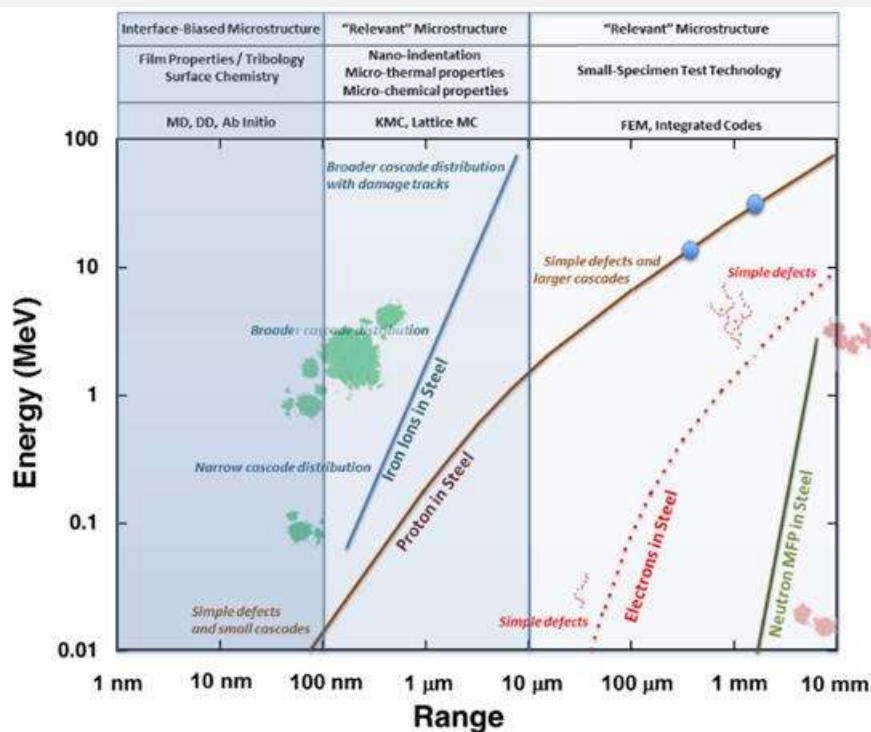


Slide 12



1. Need to get >1-MeV protons to get the depth that will allow mechanical testing on small samples.

Slide 13



Slide 14



Near-term Goal : Demonstrate Compact Cyclotron to Provide Relevant Engineering Data for Model Validation

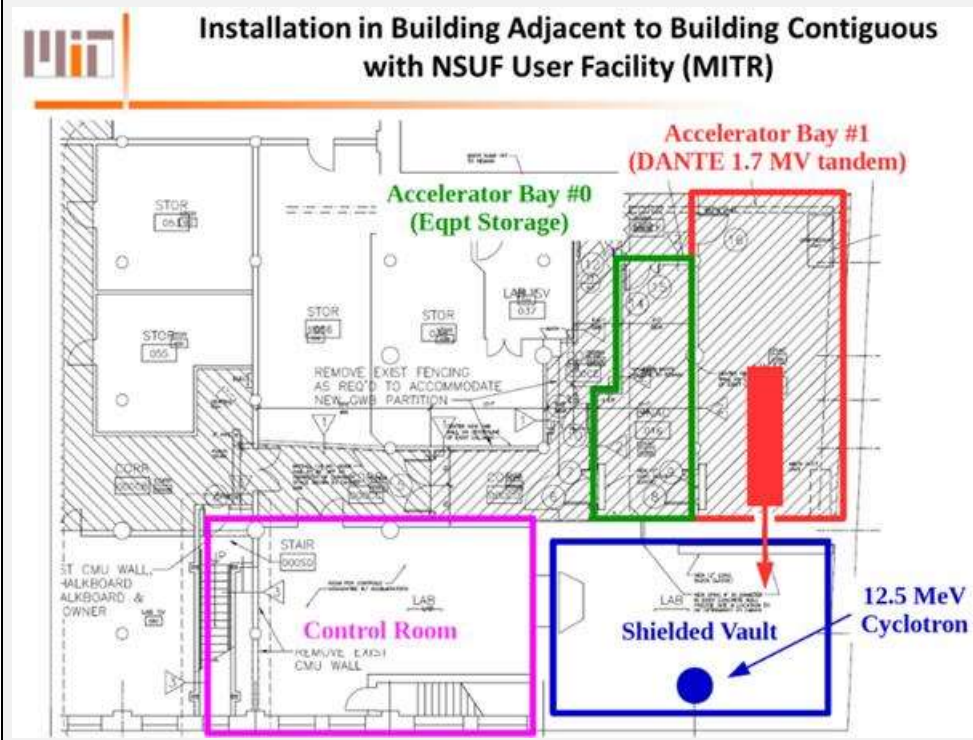
Particle	Proton+ (deuteron+)
Energy	12.5 MeV (6.25 MeV)
Current	<50 μ A
Dimensions	0.96 m ϕ x 1.75 m
Weight	1800 kg (4000 lb)
Power	208V 3-phase, 125A
Peak power	35 kW (consumption)
Magnets	Superconducting (always on)
Magnetic field	4.5 T (internal); 50 gauss (1 m); 5 gauss (4 m)
Cryogenics	Liquid-free; closed loop He
Target	Internal (no external beam)
Target material	Variable



Lab Under Construction
Safety Evaluation Underway
Instrument Installation April/May 2016

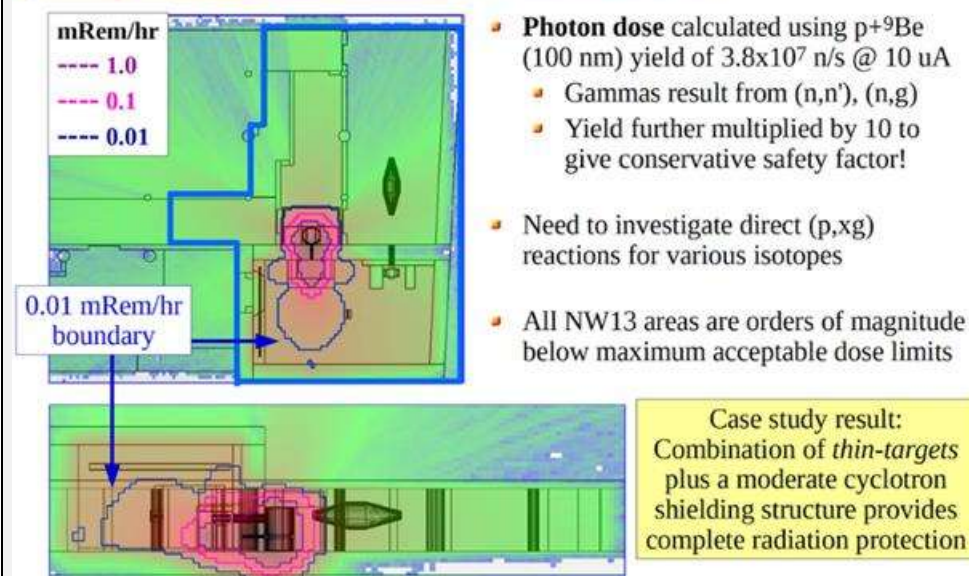
1. What is the timeframe for getting this operational?
How long for the rest of the pieces?
2. [Lance Snead] The instrument will be operational within a month of delivery. Target design is underway. Construction of target thimble this summer. Irradiation late this year.

Slide 15

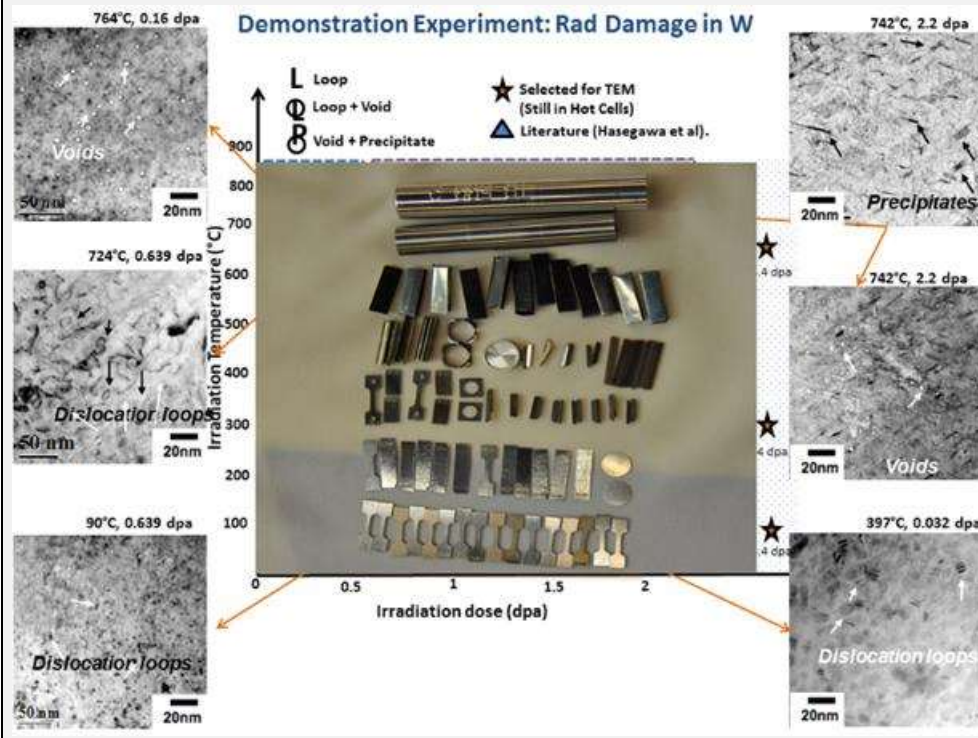


Slide 16

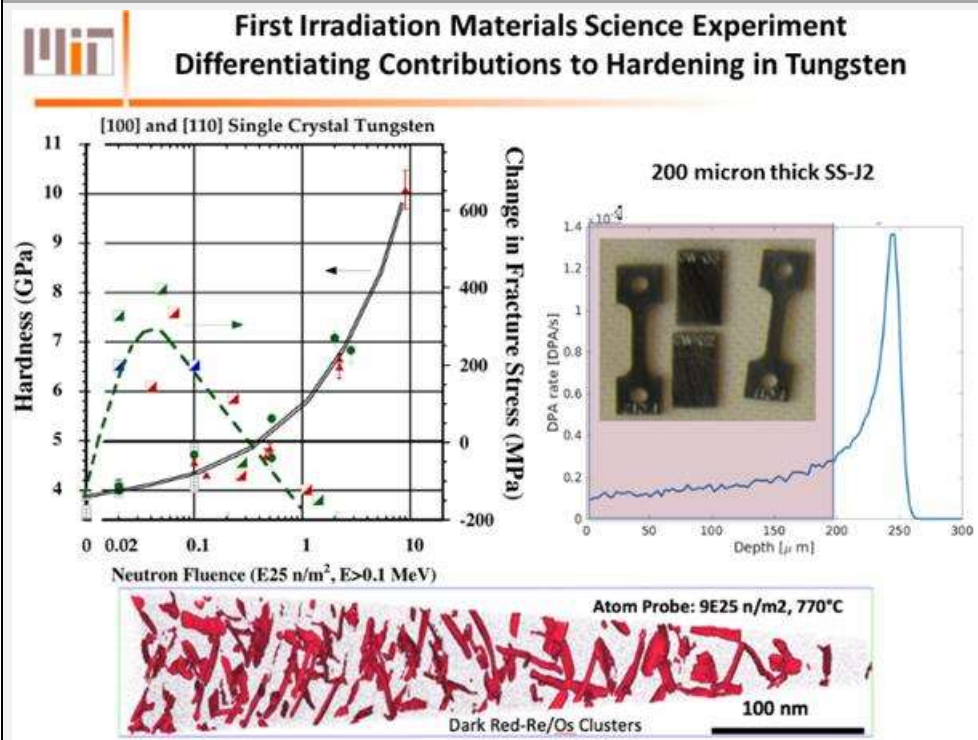
Realistic “worst case” result: complete prompt *gamma* radiation protection for all areas of concern in facility



Demonstration Experiment: Rad Damage in W



Slide 18



1. Provides direct comparison of hardening with and without the transmutation product (difference between n and p irradiations).



Concluding Remarks

- MIT will be exploring bulk ion irradiation and techniques to characterize samples while under irradiation. The ultimate goal is to provide a bridge from the bulk of irradiation materials science from low-to-intermediate energy ions to what is and will continue to be a limited set of neutron irradiation data.
- As a NSUF user facility and with a local reactor (MITR), comparison with neutron irradiated material will be straight forward.
- Given throughput issues, radiological issues and somewhat higher costs that the low-to-intermediate ion beam facilities such a “penetrating sources” will likely be unique facilities and their science largely guided by modeling goals.
- We will embark on the building blocks of such a facility with the development of compact high brilliance x-ray sources and demonstrating the usefulness of compact superconducting cyclotrons.
- It would be very useful to decide if such a facility is on critical path by carrying out a community roadmap exercise.

1. Primary purpose is to dead reckon the models—few facilities like this needed.

Appendix F

Facility Ranking Exercise

Appendix F

Facility Ranking Exercise

Facility Ranking by Criteria

Votes Cast: 21

No.	C1: Viability for the capability to extend our understanding toward accurately simulating nuclear irradiation conditions (neutrons or fission fragments)	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.00	0.93	0	0	2	3	9	7
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.57	0.95	0	0	4	4	10	3
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.48	0.85	0	0	2	10	6	3
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.38	1.13	0	1	4	6	6	4
1	Argonne National Laboratory - Intermediate Voltage Electron Microscope (IVEM)	3.29	0.98	0	1	3	8	7	2
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.24	0.87	0	0	5	7	8	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.24	0.81	0	0	4	9	7	1
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.19	1.30	1	2	1	8	6	3
12	Texas A&M University – Accelerator Laboratory	3.19	1.01	0	2	2	8	8	1
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.14	0.83	0	2	0	12	7	0
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.90	0.92	0	1	5	12	1	2
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.81	0.79	0	2	2	16	0	1
5	Idaho State University – Idaho Accelerator Laboratory	2.19	0.85	0	5	8	7	1	0
9	Ohio University – Edwards Accelerator Laboratory	1.90	1.06	2	6	6	6	1	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	1.86	0.99	1	9	3	8	0	0

No.	C2: Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.10	0.87	0	0	1	4	8	8
12	Texas A&M University – Accelerator Laboratory	3.86	0.89	0	0	1	7	7	6
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.48	1.14	0	1	3	7	5	5
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.43	0.95	0	0	4	7	7	3
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.38	0.84	0	0	3	9	7	2
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.33	1.04	0	1	2	11	3	4
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.24	1.02	0	1	3	10	4	3
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.10	1.23	1	0	6	6	5	3
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	3.10	1.11	0	1	7	4	7	2
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.00	1.31	0	3	5	6	3	4
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	2.86	1.21	1	2	3	10	3	2
5	Idaho State University – Idaho Accelerator Laboratory	2.76	1.19	0	4	4	8	3	2
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.67	1.08	1	2	5	8	5	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.10	1.34	1	8	5	4	1	2
9	Ohio University – Edwards Accelerator Laboratory	1.81	1.10	2	8	4	6	1	0

No.	C3: Ability of the facility to provide a variety of well-controlled target environments and conditions	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.29	0.70	0	0	0	3	9	9
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.48	1.01	0	1	2	7	8	3
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.38	1.05	0	1	3	7	7	3
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.38	0.90	0	1	1	10	7	2
12	Texas A&M University – Accelerator Laboratory	3.33	0.84	0	0	3	10	6	2
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.19	0.85	0	0	5	8	7	1
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.19	0.91	0	1	2	12	4	2
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.19	1.14	0	2	3	8	5	3
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.10	0.75	0	0	4	12	4	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	2.95	1.05	1	0	5	9	5	1
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.90	0.92	0	1	5	12	1	2
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.76	1.06	1	1	5	10	3	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.48	1.01	0	4	7	6	4	0
5	Idaho State University – Idaho Accelerator Laboratory	2.24	1.19	2	3	8	4	4	0
9	Ohio University – Edwards Accelerator Laboratory	1.86	0.99	2	6	6	7	0	0

No.	C4: Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite	Avg. Score	Std Dev	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	3.95	0.79	0	0	0	7	8	6
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.86	1.21	0	2	0	5	6	8
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.71	1.12	0	1	2	5	7	6
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.57	1.00	0	1	1	8	7	4
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.57	1.18	0	1	3	6	5	6
12	Texas A&M University – Accelerator Laboratory	3.57	0.95	0	0	2	10	4	5
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.52	1.05	0	0	5	4	8	4
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	3.52	1.01	0	0	4	6	7	4
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.48	1.22	0	1	5	3	7	5
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.43	1.00	0	0	4	8	5	4
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.19	1.05	0	1	4	9	4	3
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.10	1.02	0	2	3	8	7	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.71	1.20	1	2	5	9	2	2
5	Idaho State University – Idaho Accelerator Laboratory	2.24	0.81	0	4	9	7	1	0
9	Ohio University – Edwards Accelerator Laboratory	1.86	1.04	2	6	7	5	1	0

No.	C5: Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in situ	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	4.05	1.21	0	1	2	3	4	11
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	4.05	1.29	1	0	1	4	4	11
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.90	1.02	0	1	0	6	7	7
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.67	1.36	0	3	0	6	4	8
13	University of Michigan – Michigan Ion Beam Laboratory	3.52	1.22	1	0	2	7	6	5
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	2.90	1.41	1	4	1	8	4	3
12	Texas A&M University – Accelerator Laboratory	2.90	1.27	2	1	2	9	6	1
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.57	1.53	2	5	2	5	5	2
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	2.48	1.43	2	4	4	6	3	2
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.14	1.25	2	5	5	7	1	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	2.10	1.41	4	3	5	6	2	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.10	1.31	2	7	3	5	4	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.05	1.05	2	4	7	7	1	0
5	Idaho State University – Idaho Accelerator Laboratory	1.29	1.03	6	6	6	3	0	0
9	Ohio University – Edwards Accelerator Laboratory	1.14	0.83	5	9	6	1	0	0

No.	C6: Current or potential productivity of the facility (e.g., fewer high-impact experiments or high-volume sample throughput)	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	3.86	1.08	0	1	0	8	4	8
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.71	1.08	0	0	3	7	4	7
12	Texas A&M University – Accelerator Laboratory	3.48	0.85	0	0	2	10	6	3
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.43	0.73	0	0	1	12	6	2
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.19	1.05	0	1	4	9	4	3
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.10	0.81	0	1	2	13	4	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.00	0.93	0	1	5	9	5	1
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	2.86	1.12	0	2	7	6	4	2
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.81	0.79	0	1	6	10	4	0
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.76	0.87	0	2	5	10	4	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.71	0.88	0	2	6	9	4	0
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	2.67	1.04	0	4	3	11	2	1
5	Idaho State University – Idaho Accelerator Laboratory	2.33	1.13	1	5	4	8	3	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.14	1.21	2	5	4	9	0	1
9	Ohio University – Edwards Accelerator Laboratory	1.86	1.04	2	7	4	8	0	0

No.	C7: Unique capabilities of the facility, including any new technology that has the capability to close technological gaps	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.95	0.84	0	0	0	8	6	7
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.90	0.97	0	0	2	5	7	7
13	University of Michigan – Michigan Ion Beam Laboratory	3.76	1.06	0	1	1	6	7	6
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.71	1.03	0	0	3	6	6	6
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.71	0.98	0	0	2	8	5	6
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.48	1.18	0	1	4	5	6	5
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.38	0.90	0	0	4	7	8	2
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.29	1.20	0	2	3	7	5	4
12	Texas A&M University – Accelerator Laboratory	2.95	0.90	0	2	3	10	6	0
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	2.86	0.94	1	0	5	10	5	0
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.67	0.78	0	1	8	9	3	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.57	0.79	0	2	7	10	2	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.33	0.89	0	4	8	7	2	0
9	Ohio University – Edwards Accelerator Laboratory	1.95	1.25	3	5	6	4	3	0
5	Idaho State University – Idaho Accelerator Laboratory	1.81	1.01	2	7	5	7	0	0

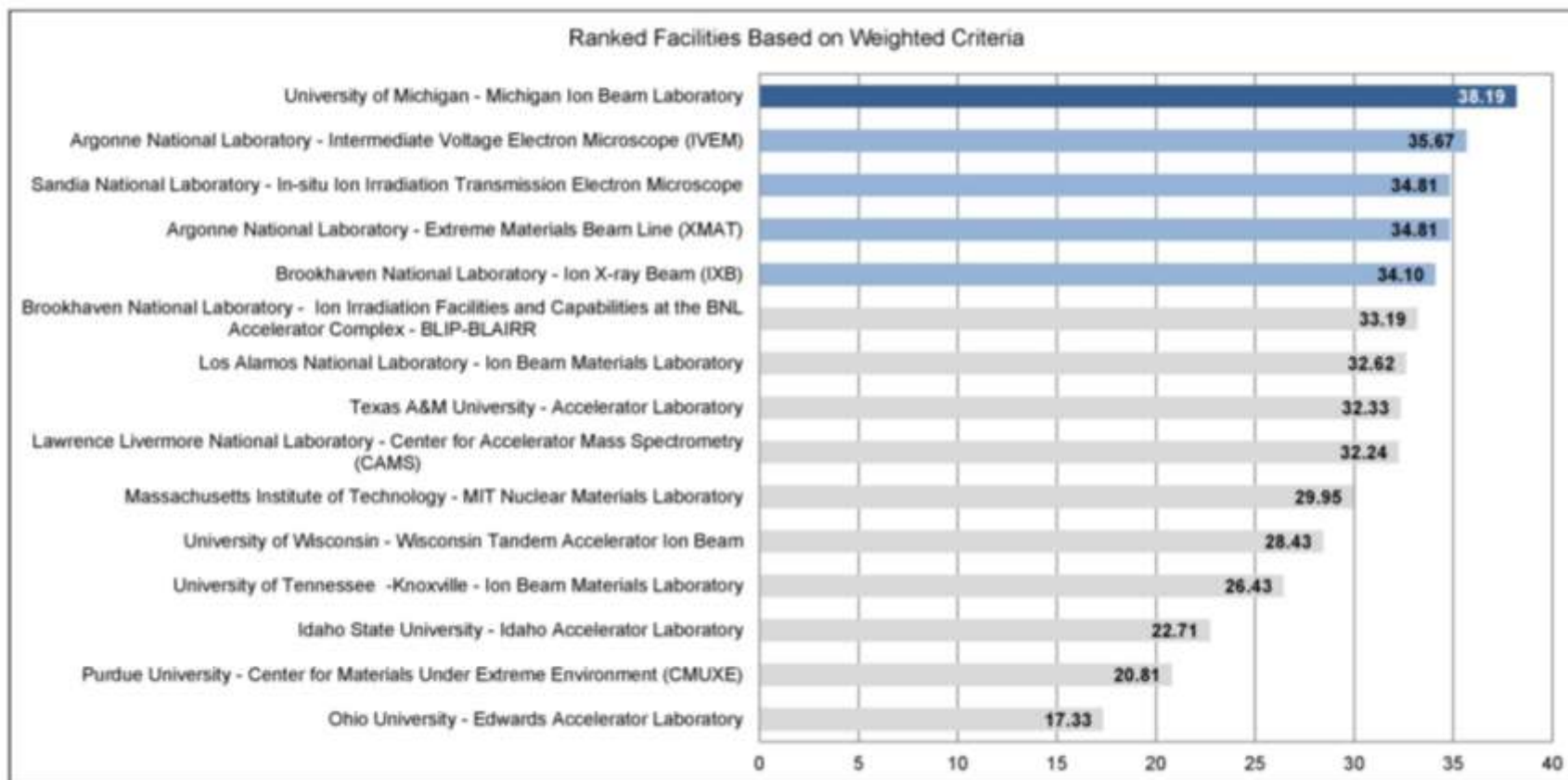
No.	C8: Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.95	1.00	0	1	1	2	11	6
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.81	1.01	0	1	1	4	10	5
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.62	1.09	0	1	2	6	7	5
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.48	1.10	0	1	2	9	4	5
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.43	1.14	0	1	4	5	7	4
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.29	1.16	0	1	5	6	5	4
5	Idaho State University – Idaho Accelerator Laboratory	3.05	1.05	1	1	1	12	5	1
13	University of Michigan – Michigan Ion Beam Laboratory	2.90	1.27	2	0	3	12	1	3
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.62	1.33	1	4	5	4	6	1
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.48	1.14	1	4	3	11	1	1
12	Texas A&M University – Accelerator Laboratory	2.38	0.90	1	2	7	10	1	0
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	2.33	0.94	0	5	6	8	2	0
9	Ohio University – Edwards Accelerator Laboratory	1.29	1.35	8	5	4	3	0	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	0.90	0.92	9	6	5	1	0	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	0.86	1.12	12	3	3	3	0	0

No.	C9: Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	3.76	1.02	0	0	3	5	7	6
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.62	0.84	0	0	1	10	6	4
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.62	0.90	0	0	2	8	7	4
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.57	1.40	1	1	2	5	5	7
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.52	1.01	0	1	1	9	6	4
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.43	1.09	0	1	3	7	6	4
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.43	0.90	0	0	3	9	6	3
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.43	1.14	0	2	1	8	6	4
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.33	1.04	0	1	2	11	3	4
12	Texas A&M University – Accelerator Laboratory	3.29	1.20	0	1	5	7	3	5
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.05	0.95	0	1	5	8	6	1
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.86	1.21	1	1	6	7	4	2
5	Idaho State University – Idaho Accelerator Laboratory	2.43	0.95	0	4	7	7	3	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.24	1.23	1	7	3	6	4	0
9	Ohio University – Edwards Accelerator Laboratory	1.90	1.11	1	9	4	5	2	0

No.	C10: Ability of the facility to produce results that meet the needs of DOE–NE (including cross-cutting programs) and the nuclear energy industry	Avg. Score	Std Dev	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.05	0.90	0	0	2	2	10	7
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.81	1.14	0	1	2	4	7	7
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.67	0.94	0	0	1	11	3	6
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.57	1.09	0	1	2	7	6	5
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.57	1.29	1	0	3	5	6	6
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.52	1.18	0	1	3	7	4	6
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.52	1.30	0	3	0	7	5	6
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.52	0.91	0	0	2	10	5	4
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.48	1.22	0	2	2	6	6	5
12	Texas A&M University – Accelerator Laboratory	3.38	1.00	0	1	2	9	6	3
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	3.05	1.33	0	3	5	5	4	4
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.86	1.08	0	3	4	8	5	1
5	Idaho State University – Idaho Accelerator Laboratory	2.38	1.09	1	3	8	5	4	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	1.95	1.13	1	9	3	6	2	0
9	Ohio University – Edwards Accelerator Laboratory	1.76	1.23	3	8	3	5	2	0

Overall Facility Rankings

No.	Facility	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Total
13	University of Michigan – Michigan Ion Beam Laboratory	4.00	4.10	4.29	3.95	3.52	3.86	3.76	2.90	3.76	4.05	38.19
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.29	3.00	3.38	3.86	4.05	3.71	3.71	3.29	3.57	3.81	35.67
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.57	3.10	3.19	3.71	3.90	2.67	3.95	3.62	3.52	3.57	34.81
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.48	3.43	3.48	3.57	4.05	3.43	3.90	2.33	3.62	3.52	34.81
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.24	2.86	3.19	3.48	3.67	3.19	3.71	3.48	3.62	3.67	34.10
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex - BLIP-BLAIRR	3.38	3.48	3.19	3.52	2.90	2.86	3.48	3.43	3.43	3.52	33.19
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.14	3.33	3.38	3.57	2.48	3.10	2.86	3.95	3.33	3.48	32.62
12	Texas A&M University – Accelerator Laboratory	3.19	3.86	3.33	3.57	2.90	3.48	2.95	2.38	3.29	3.38	32.33
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.24	3.38	2.95	3.43	2.10	3.00	3.38	3.81	3.43	3.52	32.24
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.19	2.67	2.76	3.10	2.57	2.76	3.29	2.62	3.43	3.57	29.95
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.90	3.10	2.90	3.52	2.14	2.81	2.67	2.48	2.86	3.05	28.43
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.81	3.24	3.10	3.19	2.05	2.71	2.57	0.86	3.05	2.86	26.43
5	Idaho State University – Idaho Accelerator Laboratory	2.19	2.76	2.24	2.24	1.29	2.33	1.81	3.05	2.43	2.38	22.71
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	1.86	2.10	2.48	2.71	2.10	2.14	2.33	0.90	2.24	1.95	20.81
9	Ohio University – Edwards Accelerator Laboratory	1.90	1.81	1.86	1.86	1.14	1.86	1.95	1.29	1.90	1.76	17.33



Community Comments on Facility Rankings

Facilities	Any Comments
Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	<ol style="list-style-type: none"> 1. Comment was made that there should be an “n/a” option in the scoring levels. 2. The IVEM is a clearly an important facility for high-impact science. However, I see no direct linkage between the data emanating from this facility and licensing data. I only see indirect linkage through multi-length-scale modeling. 3. Ion irradiation data will unlikely be used for licensing purpose without the strong support of computer models to correlate the ion irradiation to neutron irradiation damage. The IVEM-Tandem Facility provides unique capability to facilitate the development of such computer models.
Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	
Brookhaven National Laboratory – Ion X-ray Beam (IXB)	
Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	
Idaho State University – Idaho Accelerator Laboratory	<ol style="list-style-type: none"> 1. No in situ capabilities. 2. Lack of in situ capabilities specifically mentioned in the Excel file.
Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	<ol style="list-style-type: none"> 1. No mention of specific in situ capabilities either in the presentation or in the Excel file.
Los Alamos National Laboratory – Ion Beam Materials Laboratory	<ol style="list-style-type: none"> 1. These facilities appear duplicative of what is being productively used in the complex. 2. No mention of specific in situ capabilities either in the presentation or in the Excel file.
Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	<ol style="list-style-type: none"> 1. Entries in the spreadsheet are either not there or statements like “yes.” I cannot work with that. 2. No mention of specific in situ capabilities either in the presentation or in the Excel file. Saying “yes” to the presence of capabilities is not enough.
Ohio University – Edwards Accelerator Laboratory	<ol style="list-style-type: none"> 1. No info provided on ability to handle radioactive materials. 2. No info provided in the spreadsheet. 3. Cannot handle radioactive materials. 4. Ohio can handle 100 mR/hr beta/gamma activity at 25 cm separation. 5. No mention of specific in situ capabilities either in the presentation or in the Excel file.
Purdue University – Center for Materials Under	<ol style="list-style-type: none"> 1. Not able to handle active materials.

Facilities	Any Comments
Extreme Environment (CMUXE)	<ol style="list-style-type: none"> No info provided on ability to handle radioactive material. We do not agree with the zero score for Criteria #2, #3, #4, #5, #6, #7, #9, and #10. Someone gave us “zero score” for these criteria, which is certainly NOT true. CMUXE has capability for these criteria, which is self reflected from our presentation slides.
Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	<ol style="list-style-type: none"> That is BS! Assuming that comment refers to the 0 in situ rating. If so, then agreed.
Texas A&M University – Accelerator Laboratory	<ol style="list-style-type: none"> Apparently not an accurate comment.
University of Michigan – Michigan Ion Beam Laboratory	<ol style="list-style-type: none"> MIBL has the capability to handle 100 mR/hr samples and so should be scored a 3 according to the Criteria Scoring Definitions.
University of Tennessee-Knoxville – Ion Beam Materials Laboratory	<ol style="list-style-type: none"> Not able to handle active materials. Stated inability to handle radioactive materials. Cannot handle radioactive material. Cannot handle radioactive materials. Cannot handle radioactive materials. The University of Tennessee has a full suite of materials characterization capabilities onsite, including all the capabilities in the new Joint Institute for Advanced Materials that has opened on campus. We also have all the characterization capabilities available at Oak Ridge National Laboratory.
University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	<ol style="list-style-type: none"> We can handle 100 mR/hr on contact—there should be no standard deviation here. UW-Madison supports DOE-NE through a vast number of NEUP projects. UW-Madison has in situ ion beam analysis (RBS, NRA), in situ chemical analysis through PIXE, and we plan for in situ TEM and molten salt corrosion.

Appendix G

Ion Beam Facilities' Quantitative Data

Appendix G

Ion Beam Facilities' Quantitative Data

National Laboratories

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
In Situ Ion Beam Characteristics	Beam #1 Ions	H, He, Li, C, Si, Fe, Ni, Cu, Ag, W, Au, and more	H, He, Ne, Ar, Kr, Xe, and many elements from Al to Au		H, He, B, C, O, Ne, Al, Si, Ti, Cr, Fe, Ni, Au, Ag, etc.
	Beam #1 Energy (Low) (MeV)	0.4	0.05		0.01 He
	Beam #1 Energy (High) (MeV)	21	1		14 (Si)
	Beam #2 Ions	H, He, N, O, Ne, Si, Ar, Fe, Kr, Xe, etc.			
	Beam #2 Energy (Low) (MeV)	0.01			
	Beam #2 Energy (High) (MeV)	0.38			
	Beam #3 Ions				
	Beam #3 Energy (Low) (MeV)				
	Beam #3 Energy (High) (MeV)				
	Maximum Flux (1E+12 nv)	1E13 ions/cm ² /s	1		
	Maximum Dose Rate (1E-4 dpa/s)	1E-2 dpa/s	1		
	Beam Spot Diameter (mm)	10.0 - 50.0	1.5		

National Laboratories (continued)

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
Ex Situ Ion Beam Characteristics	Beam #1 Ions	H, He, Li, C, Si, Fe, Ni, Cu, Ag, W, Au, and more	He	H, He, and all heavy ions except noble gases	
	Beam #1 Energy (Low) (MeV)	0.4	0.003	1	
	Beam #1 Energy (High) (MeV)	21	0.02	100	
	Beam #2 Ions	H, He, Ne, Ar, Kr, Xe, etc.	Heavy ions (e.g., Fe, Ni, Au, Si, etc.)		
	Beam #2 Energy (Low) (MeV)	0.01	0.1		
	Beam #2 Energy (High) (MeV)	0.38	4		
	Beam #3 Ions	H, He, Ne, Ar, Kr, Xe, C, Si, Fe, Ni, Cu, Ag, W, Au, and more			
	Beam #3 Energy (Low) (MeV)	0.02			
	Beam #3 Energy (High) (MeV)	0.8			
	Maximum Flux (1E+12 nv)	1E13 ions/cm2/s		10000	
	Maximum Dose Rate (1E-4 dpa/s)	1E-2 dpa/s		100	
	Beam Spot Diameter (mm)	10.0 to 50.0		0.5-10	

National Laboratories (continued)

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
Accelerators	Accelerator #1	3 MV NEC Pelletron tandem with radio frequency plasma and sputter ion sources and five beamlines	2 MeV tandem (IVEM)	10 MV FN tandem Pelletron	HVE 6 MV tandem
	Accelerator #2	200 kV Varian DF-3000 ion implanter with gas ion source	500 keV ion implanter (IVEM)	NEC 1.7 MV tandem accelerator	NEC 1 MV tandem
	Accelerator #3	200 kV Danfysik high current ion implanter with gas-oven-sputter ion source with potential for up to three beamlines	Low-energy ion gun (IVEM)		NEC 3 MV Pelletron
	Accelerator #4				350 kV High-Voltage Engineering Europa Implanter
	Accelerator #5				A&D 100 kV nanoImplanter
	Accelerator #6				10 kV Colutron
	Accelerator #7				Radio frequency quadrupole booster
Environment	Temperature (Low) (K)	77	20	273 (routine), LN ₂ (possible)	43
	Temperature (High) (K)	1473	1573	1273 (routine), 1473 (possible)	1473
	Air				x
	Gas		Environment cell holder (700°C)		x
	Water				x
	Vacuum	~5E-8 Torr		<2E-7 Torr	~10-7 Torr (normal operation)
	Other	Corrosion experiment chamber and radiation shielding for performing corrosion of lead-bismuth eutectic or molten salts			Liquid cell, gas cell, electrical bias, 77 K to 1000°C

National Laboratories (continued)

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
Specimen Stages	Stage #1	Ion beam analysis chamber (RBS, ERD, NRA, PIXE, and channeling)	Double-tilt low-temperature stage (20–295 K)	Single-tilt general purpose stage (0–1000°C)	Single-tilt, room-temperature straining stage
	Stage #2	High-energy, high-temperature irradiation chamber	Double-tilt, high-temperature stage (20–900°C)	Single-tilt stage for radiological materials (samples over Class III threshold, 0–200°C)	Hysitron PI-95
	Stage #3	Tandem-Varian dual-beam chamber for damage/He experiments (77 to 1473 K)	Single-tilt, high-temperature stage (20–1300°C)		Double-tilt rotate stage
	Stage #4	High-energy helium implantation chamber	Single-tilt, high-temperature straining stage (20–600°C)		High-tilt (+/- 81) tilt stage
	Stage #5	Irradiation and Corrosion Experiment (ICE) chamber	Single-tilt, low-temperature straining stage (-196–100°C)		2.3-mm heating (800°C) and LN ₂ (77 K) stages
	Stage #6	Low-energy implantation chambers (77–1473 K)			Gas/heating and liquid mixing stages
Characterization	TEM	Three TEMs at Electron Microscopy Laboratory	In situ @ IVEM	Ex situ	In situ @ I3TEM
	Hardness Testing	Two nanoindenters at the Center for Integrated Nanotechnologies user facility		Ex situ	Quantitative mechanical (Hysitron PI-95)
	Strain/Tension Testing	In situ strain/tension stage attached to TEMs	- Single-tilt, high-temperature straining stage (20–600°C) - Single-tilt, low-temperature straining stage (-196–100°C)	Ex situ	Quantitative mechanical (Hysitron PI-95 w/P2P)
	X-Ray Techniques	Several x-ray diffraction instruments, including high-temperature grazing incident x-ray diffraction for shallow-depth regions	Ex situ @ Advanced Photon Source	Ex situ	

National Laboratories (continued)

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
	Fatigue Testing			Ex situ	Quantitative mechanical (Hysitron PI-95 w/P2P) under beta test
Radioactive Material	Not Permitted				
	Trace Amount (TEM Lamellae)	Yes	x and 3-mm disk	Yes	Yes
	Contact Direct Reading (DR) Limit (mR/hr)	3000	500		100
	30 cm DR limit (mR/hr)	100	5	100	
	Uranium Fuel	x	x	Y	x
	N-Irradiated U Fuel	x	x	Y	x
	Actinides	Depends on activity		Y	
	Beta-Gamma Activity Limit (Ci)	Isotope specific, e.g., 290 Ci for Co-60		0.005	
	Alpha Activity Limit (Ci)	Isotope specific, e.g., 14.6 Ci for U-235		0.0005	
	Pu-239 Grams Equivalent	38.6 grams		0.5	
	Can Ship and Receive	Yes	@ ANL-IML	Y	Receive
	Radiological Sample Preparation	At nearby Sigma uranium facility and Chemistry Metallurgy Research facility hot cell	@ ANL-IML	Y	

Universities (Texas A&M University, University of Michigan, and University of Wisconsin)

	Institution	Texas A&M University	University of Michigan	University of Wisconsin
	Facility	Accelerator Laboratory	Ion Beam Laboratory	Tandem Accelerator Ion Beam
In Situ Ion Beam Characteristics	Beam #1 Ions	All elements, except heavy noble gases	H, He, D, O, Ar, Ni, Fe, etc.	H, D, He, O, N
	Beam #1 Energy (Low) (MeV)			0.7 MeV
	Beam #1 Energy (High) (MeV)	3	>1.5	4 MeV (depends on ion)
	Beam #2 Ions	All elements, except heavy noble gases		All sputtered ions if commercial cathode available
	Beam #2 Energy (Low) (MeV)			0.7 MeV
	Beam #2 Energy (High) (MeV)	1.7	1.2	8.5 MeV (depends on ion)
	Beam #3 Ions			
	Beam #3 Energy (Low) (MeV)			
	Beam #3 Energy (High) (MeV)			
	Maximum Flux (1E+12 nv)			2e15 ion/cm2/s
	Maximum Dose Rate (1E-4 dpa/s)		1	1 dpa/s
	Beam Spot Diameter (mm)		2	1–600 mm2
Ex Situ Ion Beam Characteristics	Beam #1 Ions			H, D, He, O, N
	Beam #1 Energy (Low) (MeV)			0.7 MeV
	Beam #1 Energy (High) (MeV)			4 MeV (depends on ion)
	Beam #2 Ions		Zr or Mo	All sputtered ions if commercial cathode available
	Beam #2 Energy (Low) (MeV)			0.7 MeV
	Beam #2 Energy (High) (MeV)			8.5 MeV (depends on ion)
	Beam #3 Ions			
	Beam #3 Energy (Low) (MeV)			
	Beam #3 Energy (High) (MeV)			
	Maximum Flux (1E+12 nv)			2e15 ion/cm2/s
	Maximum Dose Rate (1E-4 dpa/s)			1 dpa/s

Universities (Texas A&M University, University of Michigan, and University of Wisconsin) (continued)

	Institution	Texas A&M University	University of Michigan	University of Wisconsin
	Facility	Accelerator Laboratory	Ion Beam Laboratory	Tandem Accelerator Ion Beam
	Beam Spot Diameter (mm)			1–600 mm ²
Accelerators	Accelerator #1	1.7 MV ion accelerator	3 MV tandem (Pelletron) (Wolverine)	1.7 MV tandem
	Accelerator #2	3 MV ion accelerator	1.7 MV tandem (Tandetron) (Maize)	
	Accelerator #3	400 kV Van de Graaff	0.4 MV implanter (Blue)	
	Accelerator #4	140 kV gas atom accelerator		
	Accelerator #5	10 kV gas ion source		
	Accelerator #6			
	Accelerator #7			
Environment	Temperature (Low) (K)	573 (also LN ₂ temps)	77	77
	Temperature (High) (K)	1073	1500	1500
	Air			
	Gas			
	Water		High-temperature/high-pressure water (PWR PW, BWR NWC, BWR HWC)	
	Vacuum	Greater than 2E-7 Torr	10E-8 Torr	1e-8 Torr
	Other			Planned molten salt corrosion
Specimen Stages	Stage #1		High temperature and under static load	
	Stage #2			
	Stage #3			
	Stage #4			
	Stage #5			
	Stage #6			
Characterization	TEM			FEI Titan aberration-corrected STEM, Phillips CM200 Ultra Twin TEM, Tecnai T-12 Cryo TEM, Tecnai TF-30
	Hardness Testing		Buehler hardness indenter	Hysitron Tribonanoindenter
	Strain/Tension Testing			
	X-Ray Techniques		PIXE	Bruker D8 Discovery, PANalytical X'Pert PRO, Rigaku small angle x-ray scattering, Siemens Stoe, PIXE

Universities (Texas A&M University, University of Michigan, and University of Wisconsin) (continued)

	Institution	Texas A&M University	University of Michigan	University of Wisconsin
	Facility	Accelerator Laboratory	Ion Beam Laboratory	Tandem Accelerator Ion Beam
	Fatigue Testing			
Radioactive Material	Not Permitted			
	Trace Amount (TEM Lamellae)	x	x	Yes
	Contact DR Limit (mR/hr)	10	100	1000
	30cm DR limit (mR/hr)			100
	Uranium Fuel			Yes
	N-Irradiated U Fuel			Not allowed
	Actinides			Not allowed
	Beta-Gamma Activity Limit (Ci)			0.01
	Alpha Activity Limit (Ci)			Not allowed
	Pu-239 Grams Equivalent			Not allowed
	Can Ship and Receive		@ Michigan Irradiated Materials Testing Complex	Yes, at Characterization Laboratory for Irradiated Materials
	Radiological Sample Preparation			Yes

Universities (University of Tennessee, Idaho State University, Purdue University, and Ohio University)

	Institution	University of Tennessee-Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
In Situ Ion Beam Characteristics	Beam #1 Ions	Most elements, except heavy noble gases	Electrons	Inert and some of the reactive gases (H ₂ , CH ₄ , etc.)	
	Beam #1 Energy (Low) (MeV)	0.5	2 MeV	0.0003	
	Beam #1 Energy (High) (MeV)	27	25 MeV	0.0012	
	Beam #2 Ions		Electrons		
	Beam #2 Energy (Low) (MeV)		2 MeV		
	Beam #2 Energy (High) (MeV)		44 MeV		
	Beam #3 Ions		H,D, others with source		
	Beam #3 Energy (Low) (MeV)		0.5 MeV		
	Beam #3 Energy (High) (MeV)		8 MeV		
	Maximum Flux (1E+12 nv)				
	Maximum Dose Rate (1E-4 dpa/s)	100			
	Beam Spot Diameter (mm)	2 to 5 mm	~10	10	

Universities (University of Tennessee, Idaho State University, Purdue University, and Ohio University) (continued)

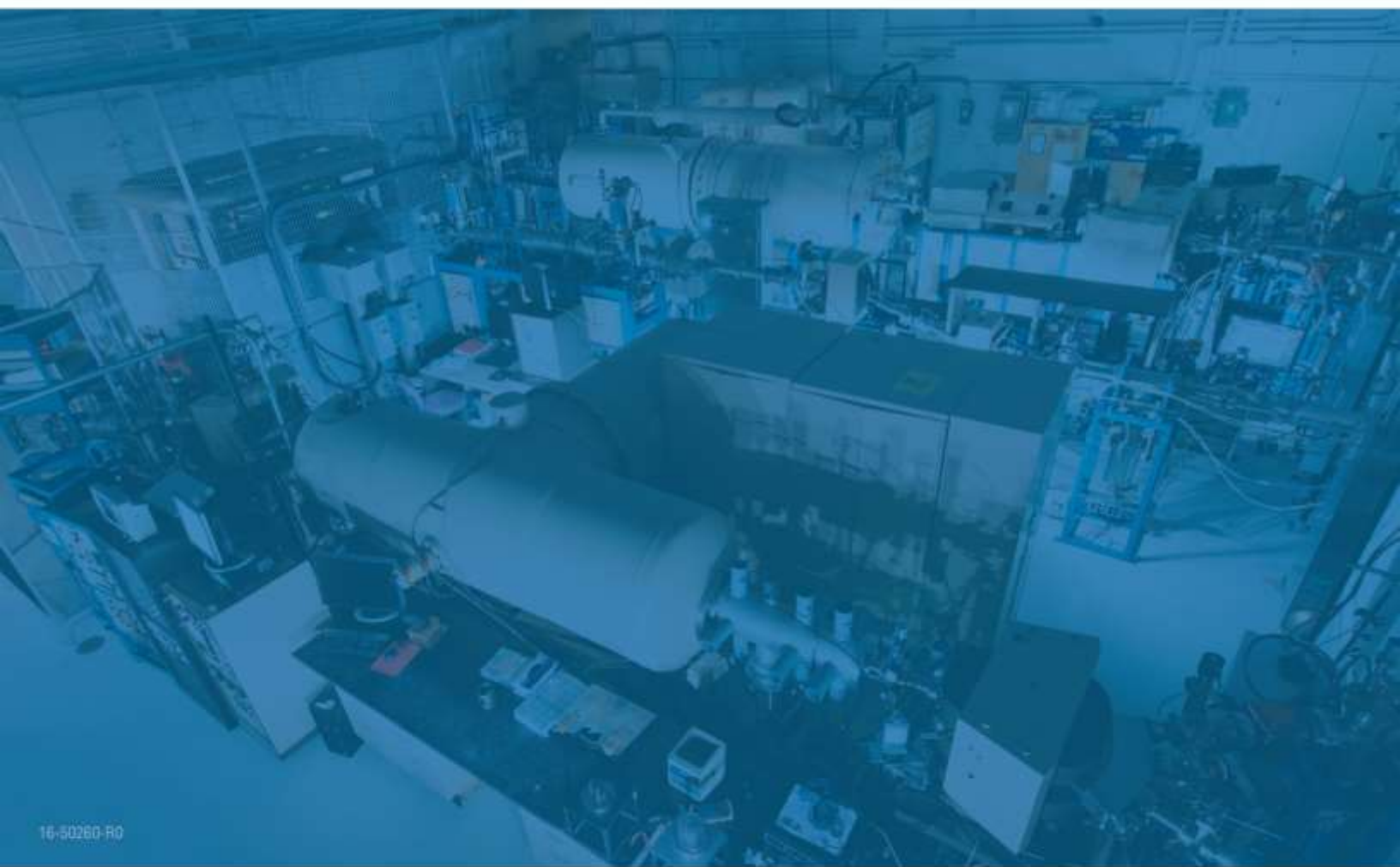
	Institution	University of Tennessee-Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
Ex Situ Ion Beam Characteristics	Beam #1 Ions				
	Beam #1 Energy (Low) (MeV)				
	Beam #1 Energy (High) (MeV)				
	Beam #2 Ions				
	Beam #2 Energy (Low) (MeV)				
	Beam #2 Energy (High) (MeV)				
	Beam #3 Ions				
	Beam #3 Energy (Low) (MeV)				
	Beam #3 Energy (High) (MeV)				
	Maximum Flux (1E+12 nv)				
	Maximum Dose Rate (1E-4 dpa/s)				
	Beam Spot Diameter (mm)				
Accelerators	Accelerator #1	3.0 MV tandem	25 MeV LINAC		4.5 MV Tandem Van de Graaff
	Accelerator #2		44 MeV LINAC		
	Accelerator #3		8 MV Tandem		
	Accelerator #4		45 MV LINAC		
	Accelerator #5		3 MeV pulse power (30kA)		
	Accelerator #6				
	Accelerator #7				

Universities (University of Tennessee, Idaho State University, Purdue University, and Ohio University) (continued)

	Institution	University of Tennessee-Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
Environment	Temperature (Low) (K)	25	298		
	Temperature (High) (K)	1475			
	Air				
	Gas				
	Water				
	Vacuum	High vacuum	High vacuum available		
	Other				
Specimen Stages	Stage #1				
	Stage #2				
	Stage #3				
	Stage #4				
	Stage #5				
	Stage #6				
Characterization	TEM		x		
	Hardness Testing				
	Strain/Tension Testing				
	X-Ray Techniques				
	Fatigue Testing				

Universities (University of Tennessee, Idaho State University, Purdue University, and Ohio University) (continued)

	Institution	University of Tennessee-Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
Radioactive Material	Not Permitted	x			
	Trace Amount (TEM Lamellae)		x		
	Contact DR Limit (mR/hr)		100		
	30-cm DR limit (mR/hr)				
	Uranium Fuel				
	N-Irradiated U Fuel				
	Actinides				
	Beta-Gamma Activity Limit (Ci)				
	Alpha Activity Limit (Ci)				
	Pu-239 Grams Equivalent				
	Can Ship and Receive		Hot lab for radiochemistry and an SEM/TEM/FIB lab that can handle moderate activity material		
	Radiological Sample Preparation				



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