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NSUF ION BEAM INVESTMENT OPTIONS WORKSHOP

INL Meeting Center, Energy Innovation Laboratory

March 22-24, 2016

Nuclear Science User Facilities

Idaho National Laboratory

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Nuclear Science User Facilities
Idaho Falls, Idaho 83415

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ACRONYMS

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

EUPS	extreme ultraviolet photoelectron spectroscopy
FCCI	fuel cladding chemical interaction
FCM	fully ceramic microencapsulated
FCRD	Fuel Cycle Research and Development
FEG	field emission gun
FEM	finite element analysis
FFAG	fixed field alternating gradient
FG	fission gas
FHR	fluoride-salt-cooled high-temperature reactor
FIB	focused ion beam
FMI	fuel matrix interaction
GAIN	Gateway for Accelerated Innovation in Nuclear
GB	grain boundary
GISAXS	grazing incidence small-angle x-ray scattering
GIXRD	grazing incidence x-ray diffraction
HAADF	high-angle annular dark field detector
HEDM	high energy diffraction microscopy
HEDP	high-energy density physics
HEU	highly enriched uranium
HFIR	High-Flux Isotope Reactor
HLW	high-level waste
HREM	high-resolution episcopic microscopy
HRTEM	high-resolution transmission electron microscopy
HT	high temperature
HVEM	high-voltage electron microscope
HXN	hard x-ray nanoprobe
I3TEM	in situ ion irradiation transmission electron microscope
IASCC	irradiation-assisted stress corrosion cracking
IBA	ion beam analysis
IBIOW	Ion Beam Investment Options Workshop
IEE	insulator enhanced etch
IMBL	Ion Beam Materials Laboratory
IMPACT	interaction of materials with particles and components testing
IMT	ion microtomography
INL	Idaho National Laboratory
INPP	Institute of Nuclear and Particle Physics
IR	infrared
IRP	Integrated Research Project
ISU	Idaho State University
IVEM	intermediate-voltage electron microscope
IXB	ion x-ray beam
KMC	kinetic Monte Carlo
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBE	lead-bismuth eutectic
LE	low energy
LEAP	local electrode atom probe
LEISS	low-energy ion scattering spectroscopy
LEU	low enriched uranium
LINAC	linear accelerator
LLNL	Lawrence Livermore National Laboratory
LMIG	Laser Material Interaction Group
LN	liquid nitrogen
LP	low pressure
LPP	laser-produced plasma
LT	low temperature
LWR	light-water reactor
LWRS	light-water reactor sustainability

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

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

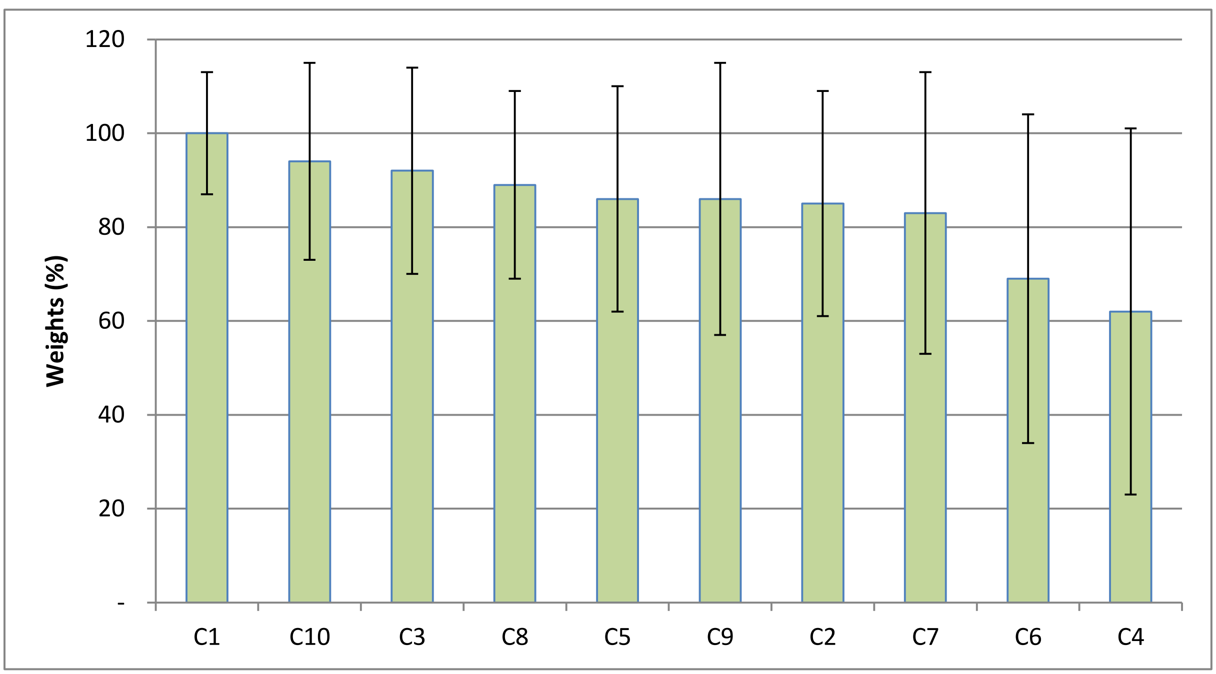

Figure 1. Relative weights of the 10 final criteria and their standard deviations (±1σ).

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.

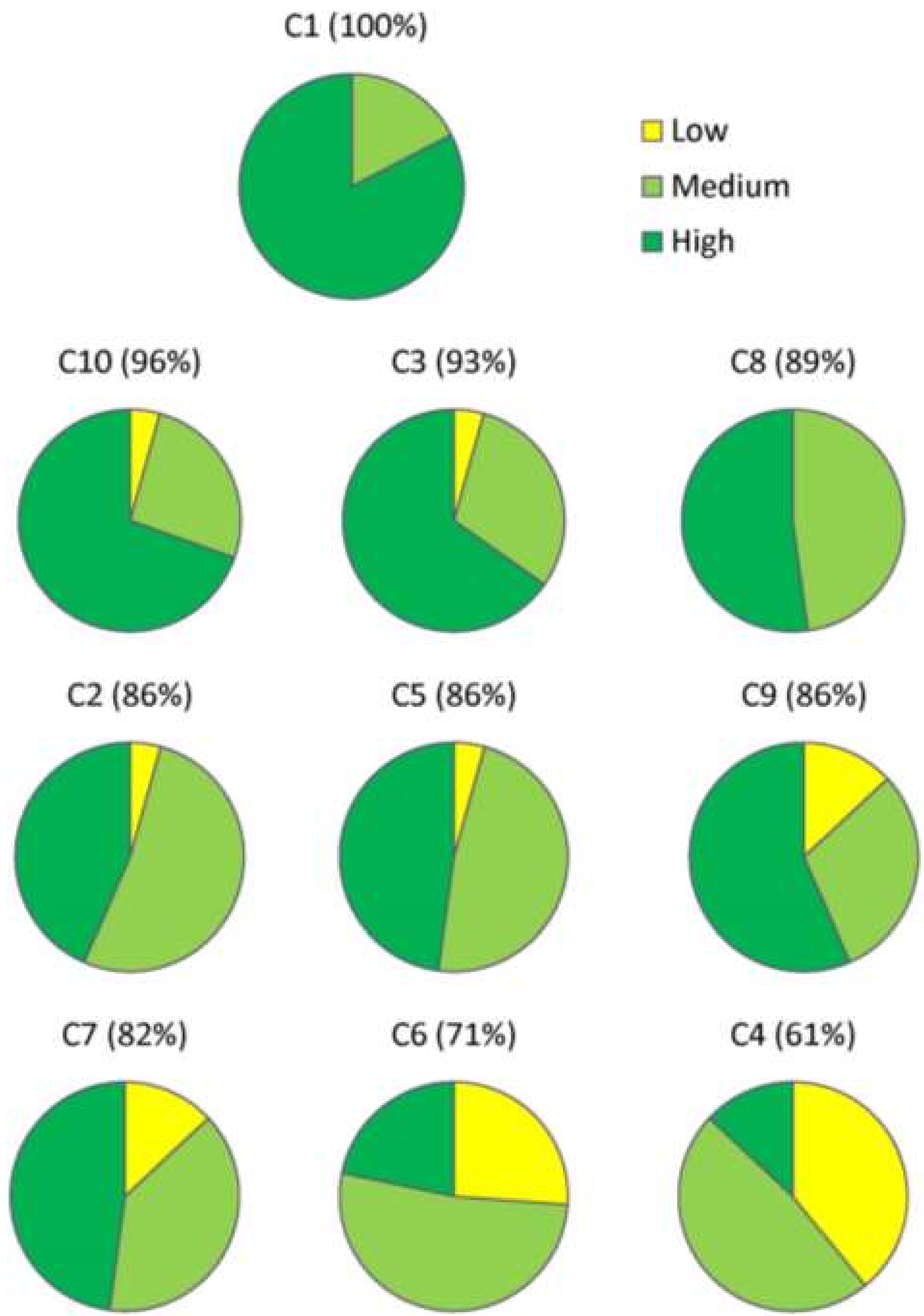

Figure 2. Distribution of votes for criteria weighting exercise.

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.

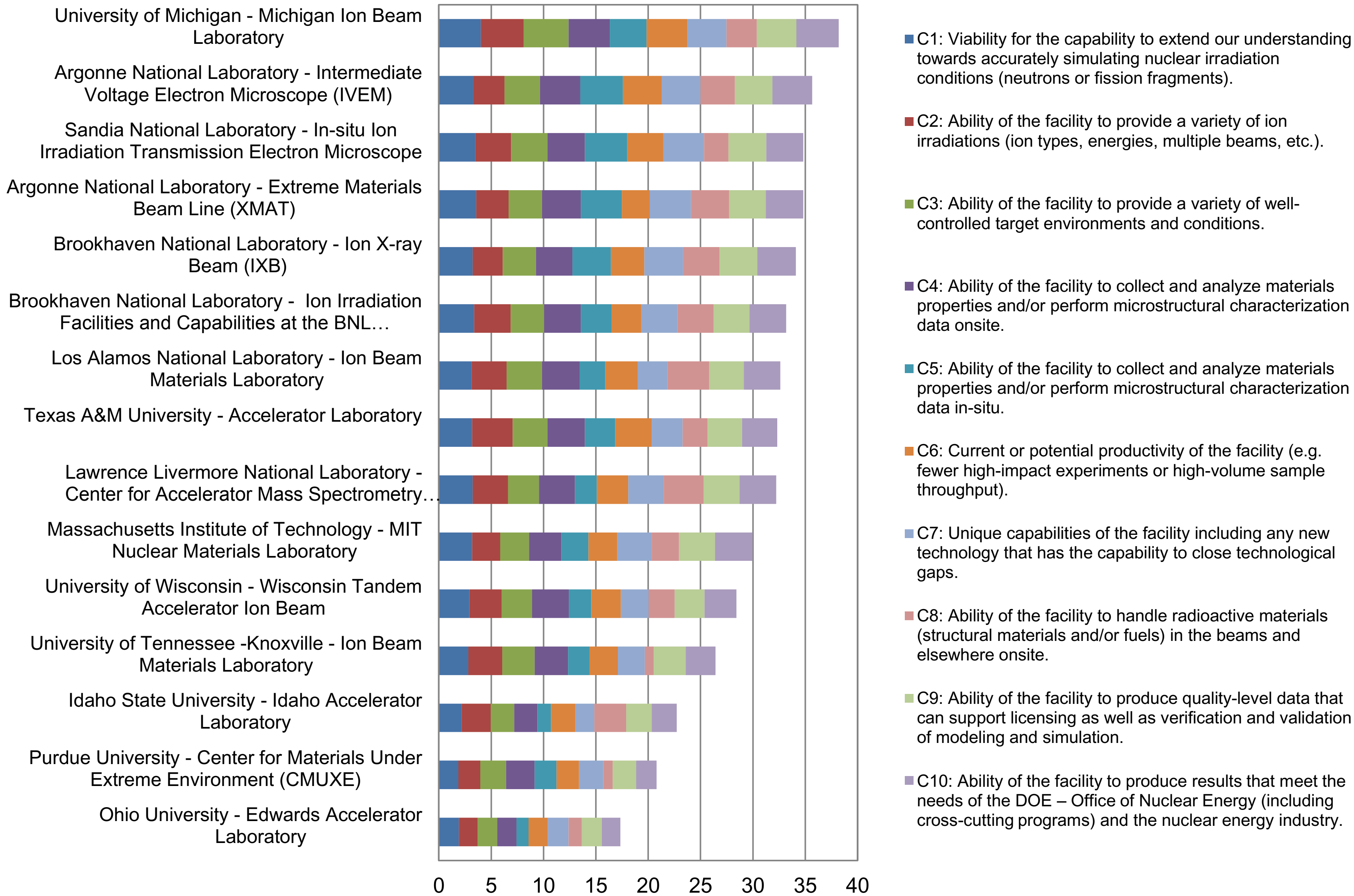

Figure 3. Overall score and ranking of the ion beam facilities.

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 Organization...Peng 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 Teysseyre
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 Line ....Abdellatif 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 University ......Jitendra 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 Needs ....Beata Tyburska-Pueschel
University of Wisconsin Research Faculty

9:30 In-situ Ion Irradiation Transmission Electron Microscope at SNL ....Khalid 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 Testing ....Nick Simos
Brookhaven National Laboratory Scientist

11:30 In-situ X-ray Characterization of Microstructural Evolution due to Ion Beam Irradiation ....Lynne 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

Safety Briefing

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Safety Briefing

NSUF Nuclear Science User Facilities

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

U.S. DEPARTMENT OF ENERGY Nuclear Energy

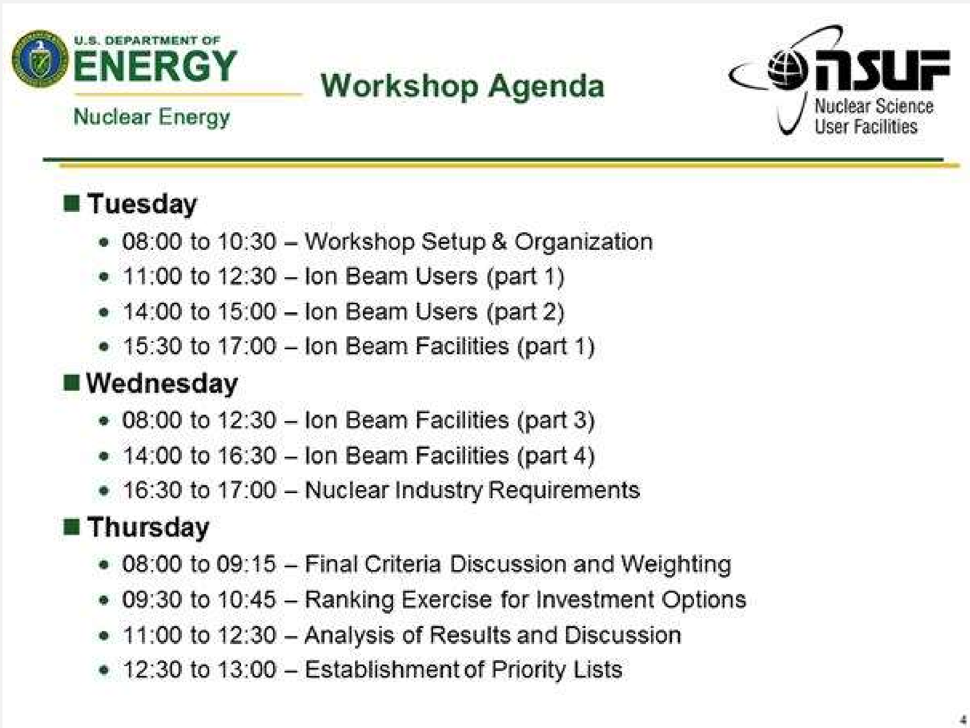
Meeting Conduct

NSUF Nuclear Science User Facilities

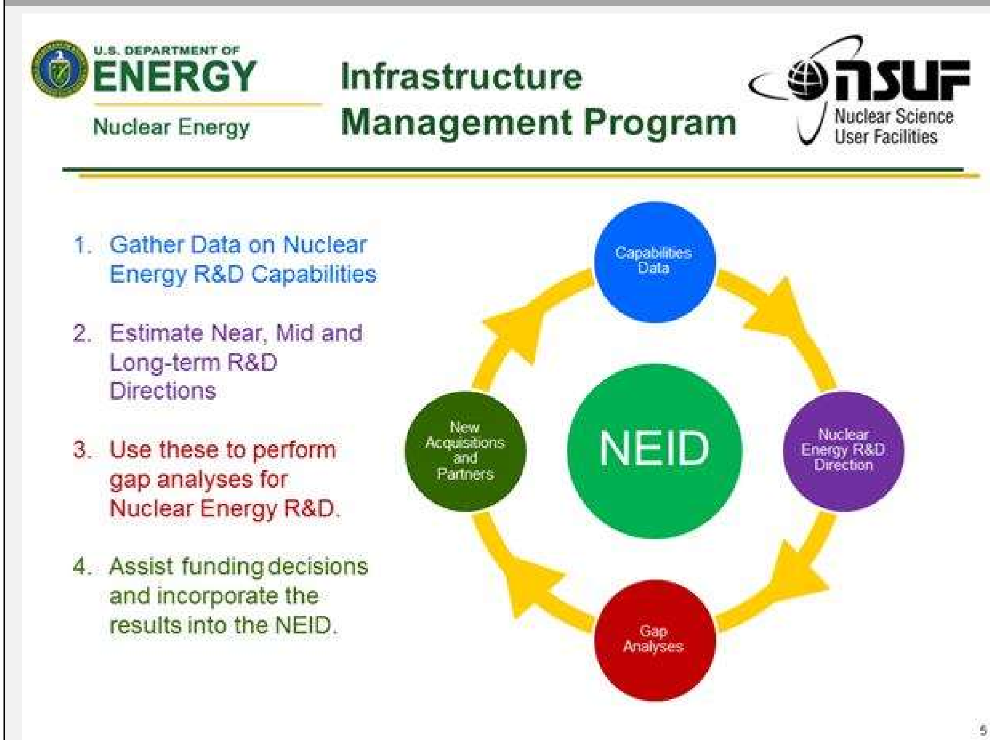
- **The meeting is being run by professional INL facilitators:**
  - Jodi Grgich and Jody Henley.
  - They will be running the ThinkTank software in real-time.
  - Presentation time limits are:
    - 20 minutes for the presentation.
    - 10 minutes for questions and comments.
- **There are a few additional 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

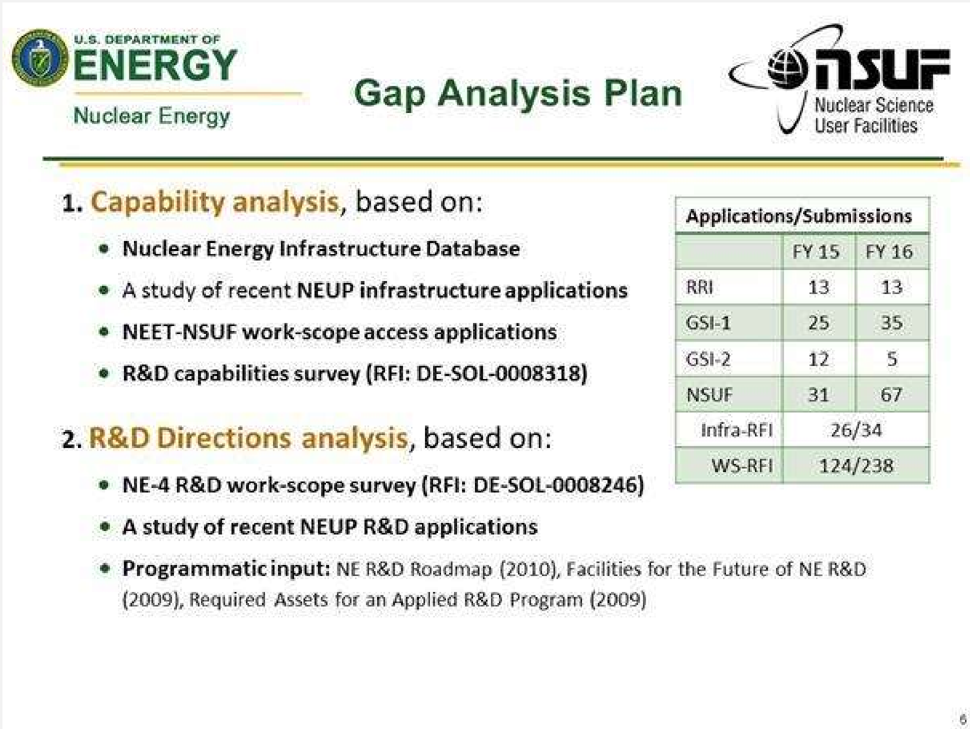
Workshop Agenda



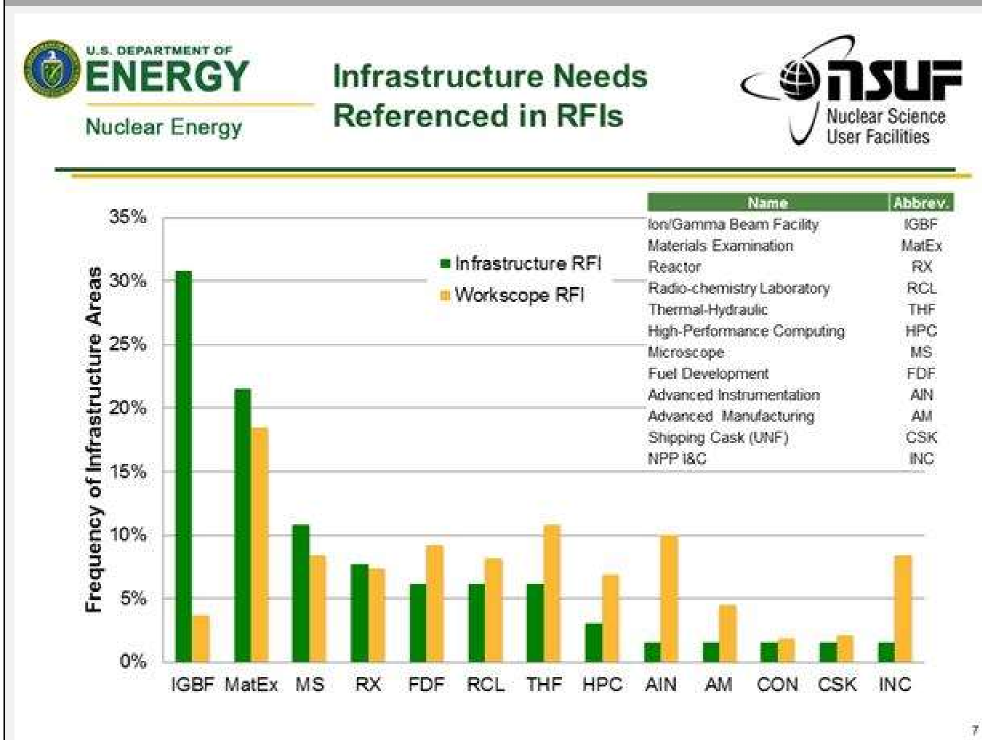
Infrastructure Management Program



Gap Analysis Plan

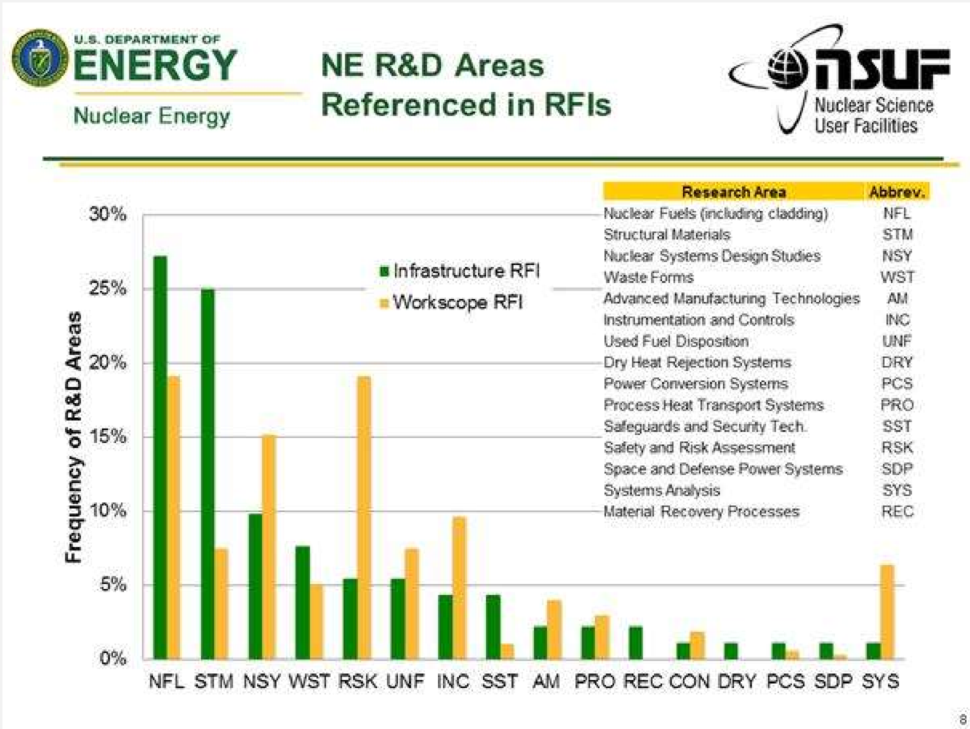


Infrastructure Needs Referenced in RFIs



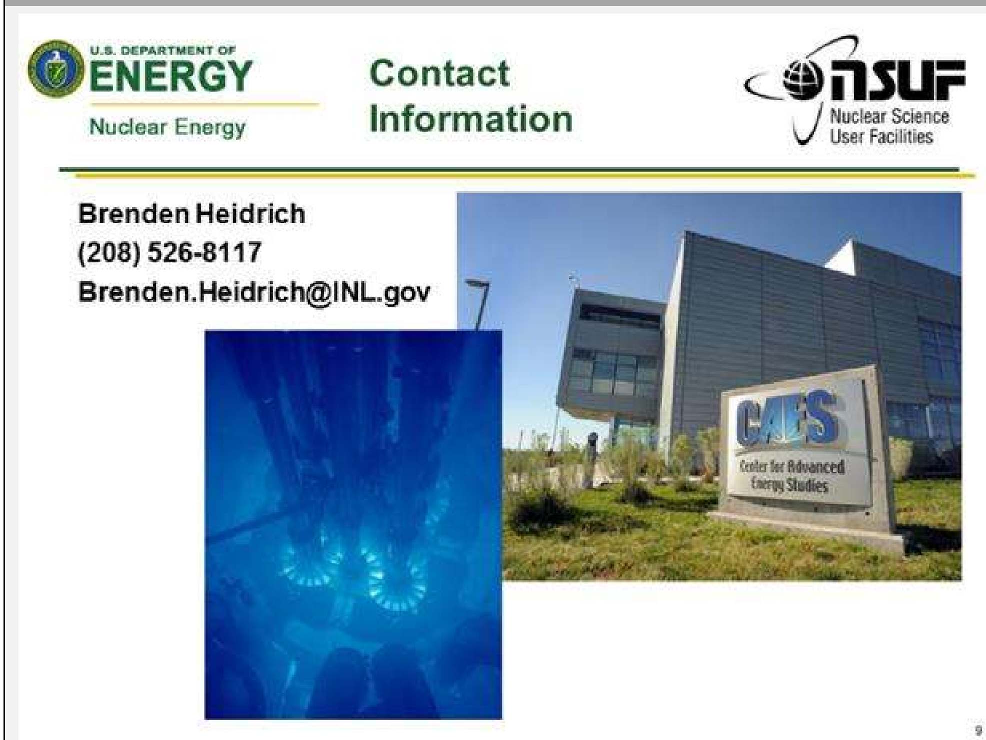
1. IGBF = Ion beams, x-ray light sources and gamma irradiation facilities.

NE R&D Areas Referenced in RFIs



1. Nuclear energy instrument database

Contact Information



Slide 10	
U.S. DEPARTMENT OF ENERGY Nuclear Energy NSUF Nuclear Science User Facilities 10	

DISCLAIMER	
U.S. DEPARTMENT OF ENERGY Nuclear Energy **DISCLAIMER** • This information was prepared as an account of work sponsored by an agency of the U.S. Government. • Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. • References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. • The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof. INL/MIS-16-37818 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

<table>
<tr><th colspan="2">Workshop Criteria</th></tr>
<tr><td>
</td><td>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</td></tr>
</table>

Original Criteria

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Original Criteria

NSUF Nuclear Science User Facilities

#	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

2

Criteria Weights

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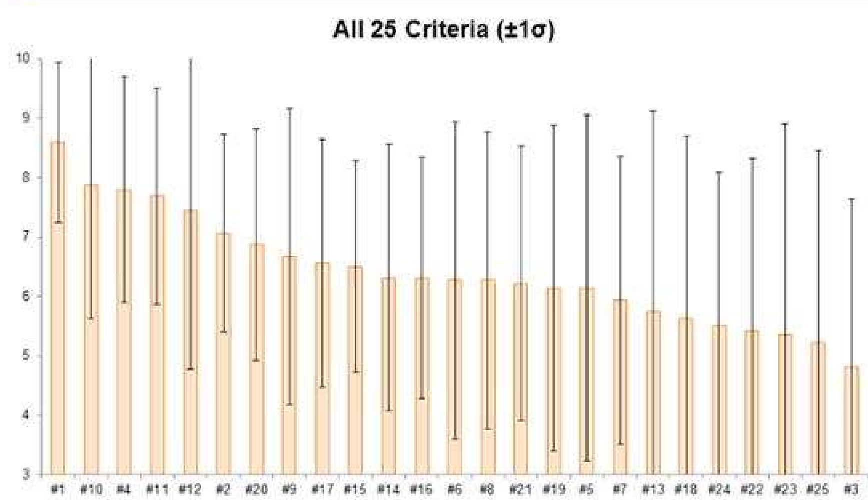
Nuclear Energy

Criteria Weights

NSUF Nuclear Science User Facilities



3

Criteria Summary

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Criteria Summary

Nuclear Science User Facilities (NSUF)

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
#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 NE mission work either through GAIN, 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.	5.8	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				

4

1. Were you able to group those criteria according 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

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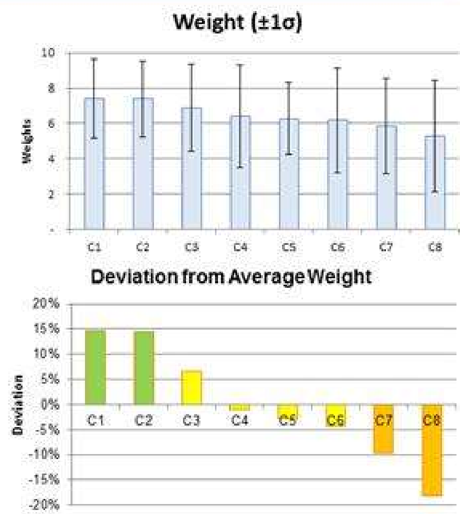
Combined Criteria Weights

Nuclear Science User Facilities (NSUF)

- 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

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C1: Scientific Merit

NSUF Nuclear Science User Facilities

	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

6

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

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C2: Variety of Irradiations

NSUF Nuclear Science User Facilities

	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

7

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

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C3: Irradiation Environments

NSUF Nuclear Science User Facilities

	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

8

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.

C4: Microstructural Characterization

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C4: Microstructural Characterization

NSUF Nuclear Science User Facilities

	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

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.

C5: NE Support and Activities

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C5: NE Support and Activities

NSUF Nuclear Science User Facilities

	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

10

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?

C6: Unique Capabilities

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C6: Unique Capabilities

NSUF Nuclear Science User Facilities

	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	3	2	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

11

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.

C7: Radioactive Material Capabilities

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C7: Radioactive Material Capabilities

NSUF Nuclear Science User Facilities

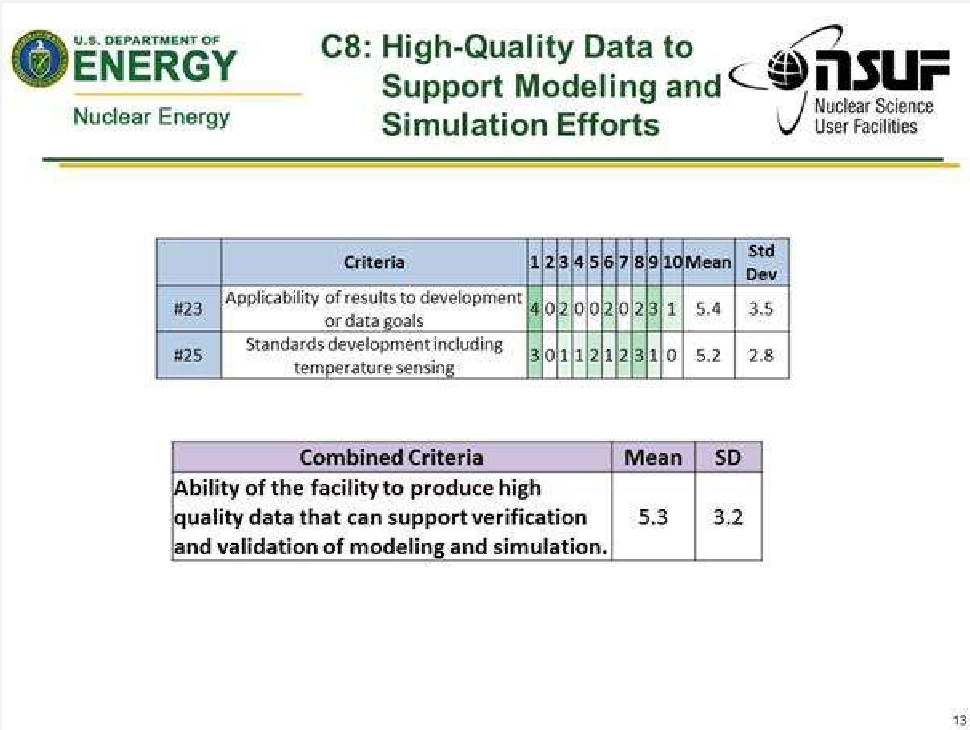
	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	0	0	0	4	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	0	4	0	0	6	1	3	0	1	5.6	2.4
#24	Is there support of small specimen test technology	4	0	0	0	2	1	2	3	1	1	5.5	3.3

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

12

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

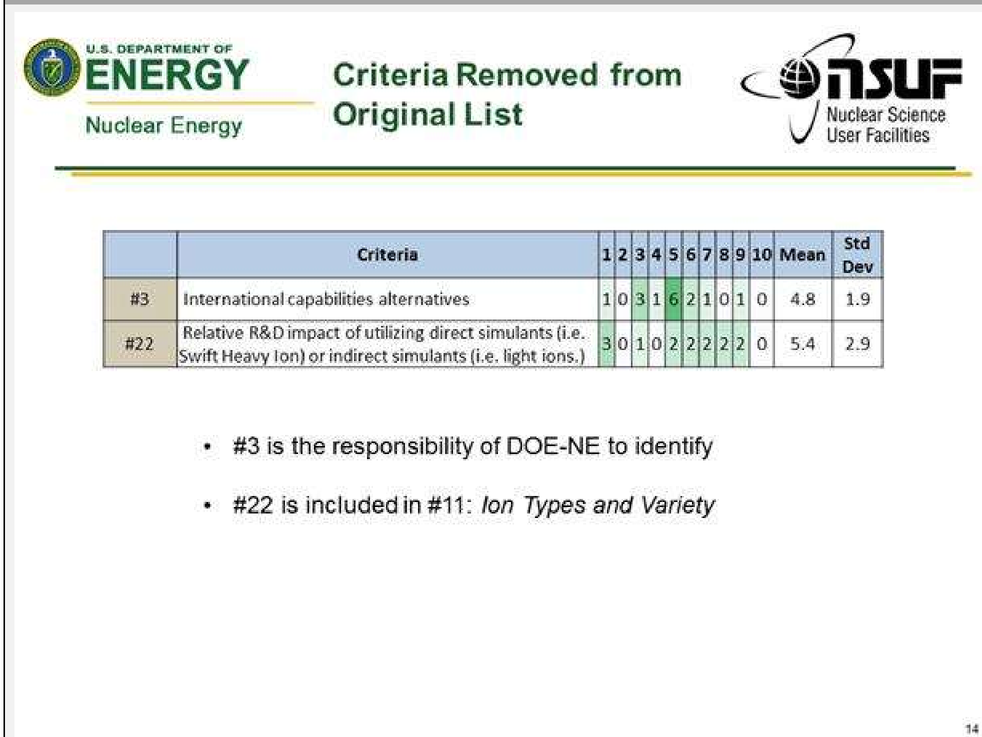


	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8

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.)

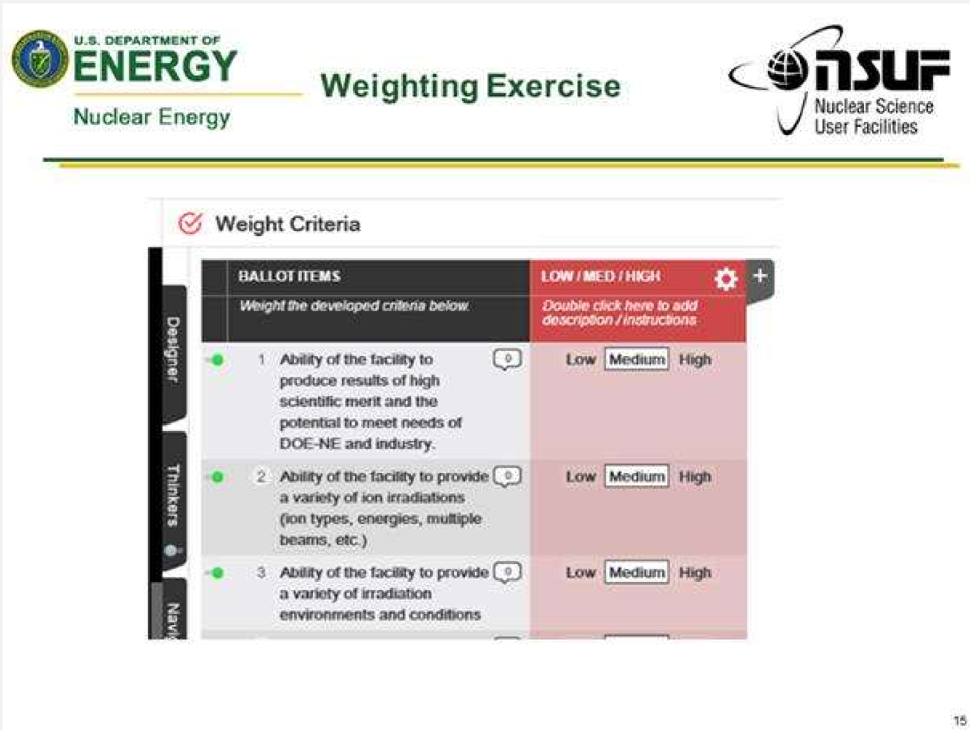
C8: High-Quality Data to Support Modeling and Simulation Efforts	
	10. User community-defined standard methods and measurement techniques need to be developed with data validation with neutron irradiation damage before licensing actions could be considered based on ion beam irradiations alone. The roadmap for ion beams needs to be comprehensive if the licensing path is to be pursued.

Criteria Removed from Original List	
	

	Criteria	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*

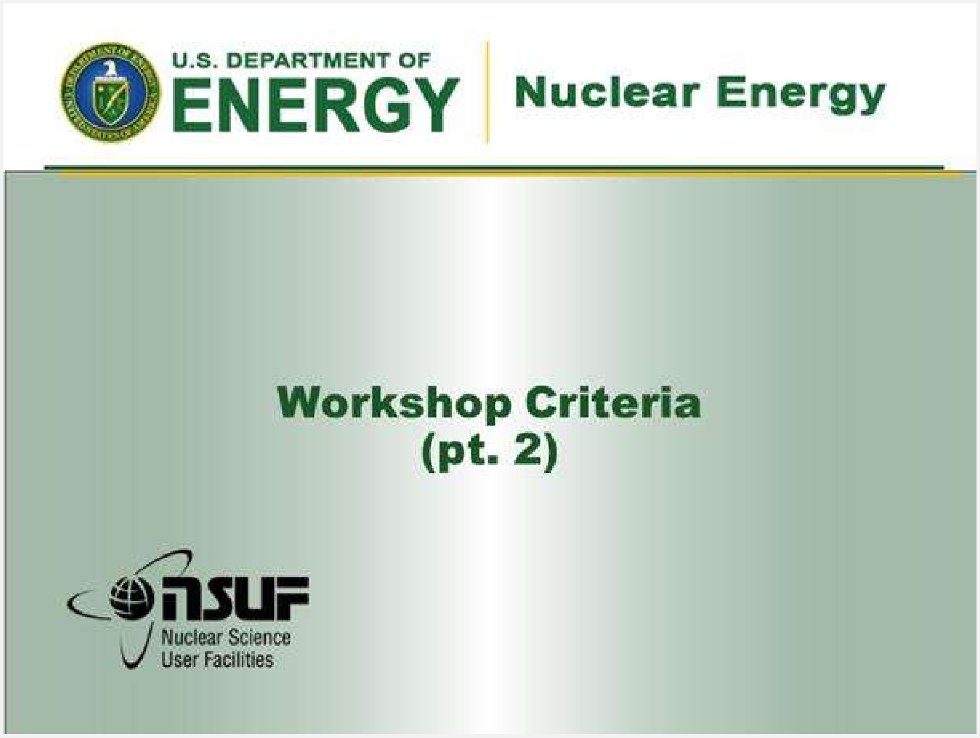
14

Weighting Exercise	
	

Workshop Criteria Presentation 2

Brenden Heidrich

Slide 1



Original Criteria

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Original Criteria

NSUF Nuclear Science User Facilities

#	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

2

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

New Criteria

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

New Criteria

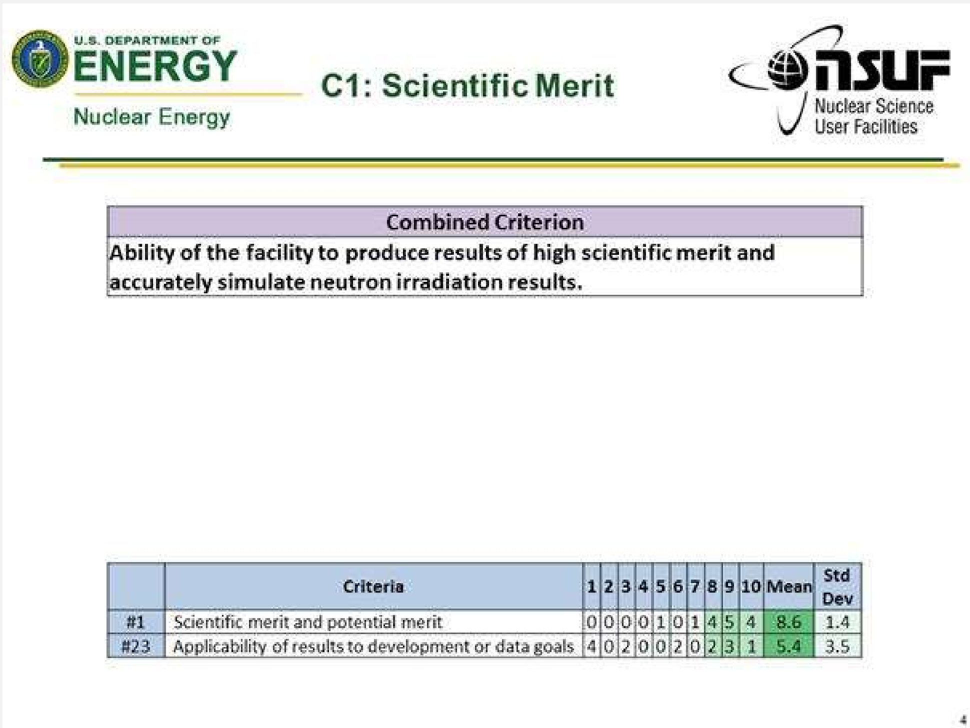
NSUF Nuclear Science User Facilities

#	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

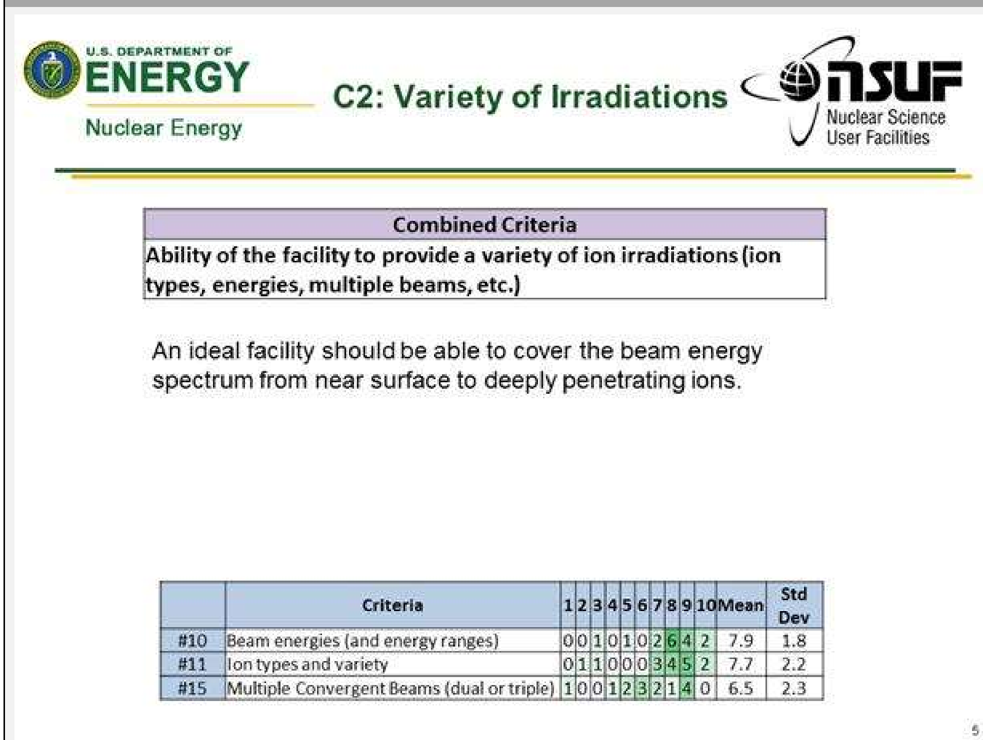
1. Move #17 to C6.
2. Need to add a new criterion: technical support.
3. One strong need for DOE-NE will be to identify important criteria that are not well met by the existing infrastructure. Understanding gaps may lead to investment.
4. There is a strong push from individual groups to "protect their 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

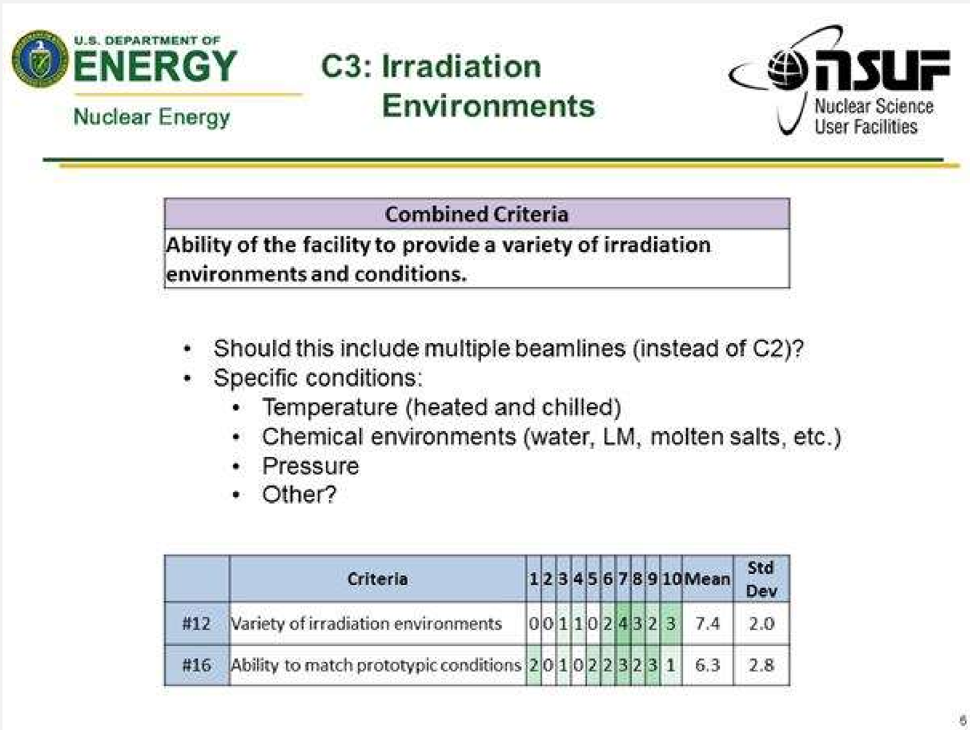


1. Suggestion: add “and simulate fission fragments.”
2. Change to “simulate nuclear irradiation conditions.”
3. Reword: Viability for the capability to extend our understanding toward accurately simulating neutron radiation results.
4. Rank to capability of the facility/team to answer the question: Can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

C2: Variety of Irradiations

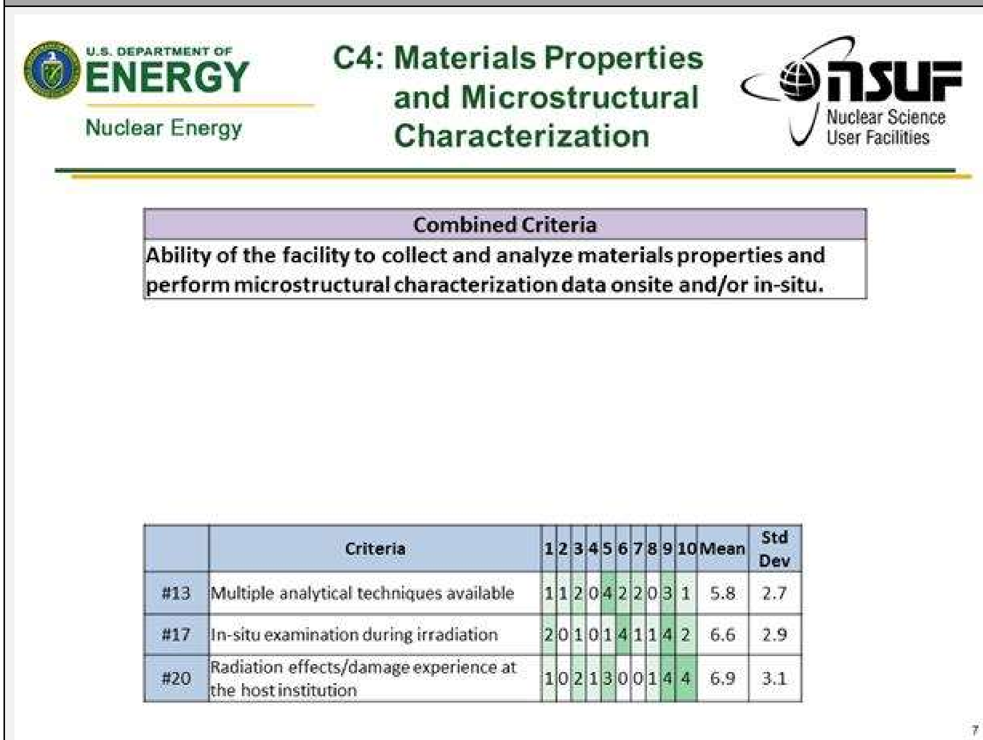


C3: Irradiation Environments



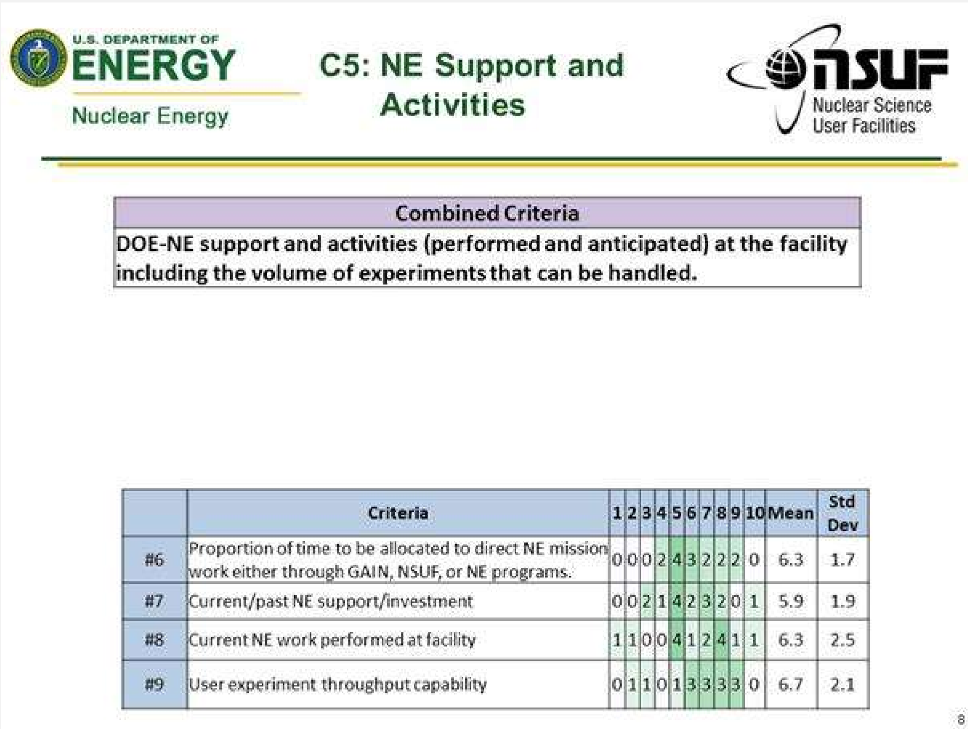
1. Replace irradiation with "target."
2. Well controlled target conditions.

C4: Materials Properties and Microstructural Characterization



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?

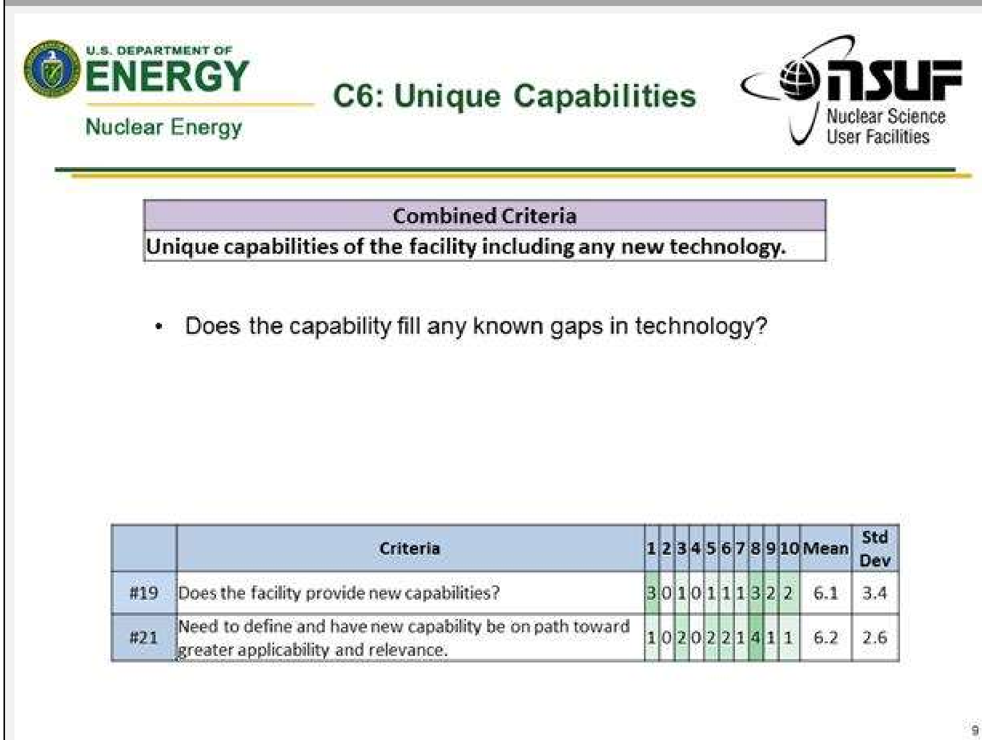
C5: NE Support and Activities



	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?

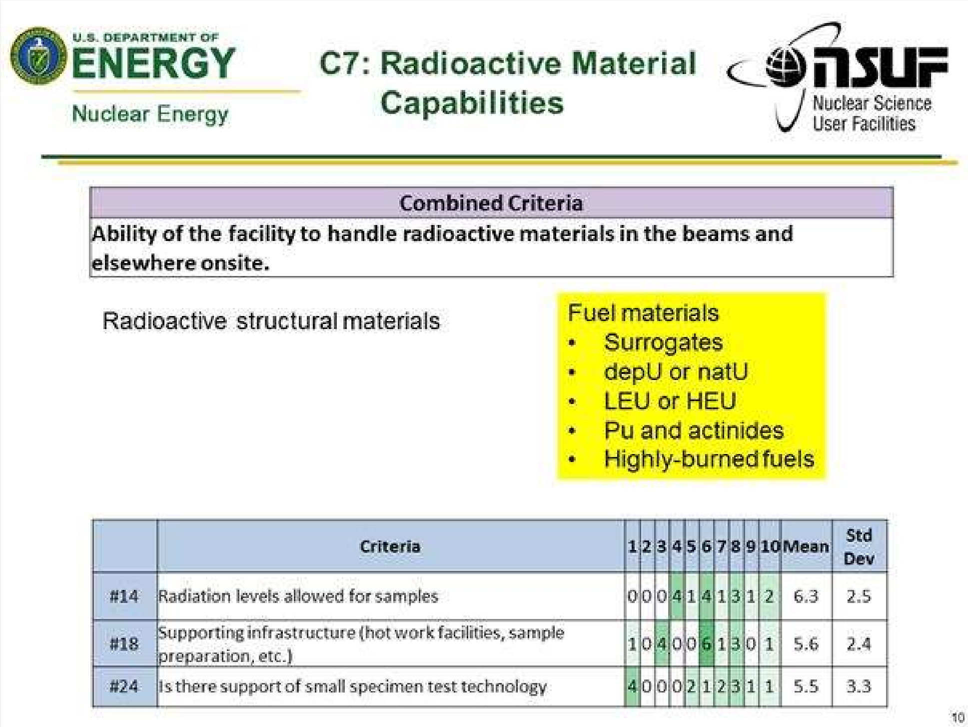
C6: Unique Capabilities



	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	3	2	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

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?

C7: Radioactive Material Capabilities



U.S. DEPARTMENT OF ENERGY
Nuclear Energy

C7: Radioactive Material Capabilities

NSUF Nuclear Science User Facilities

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

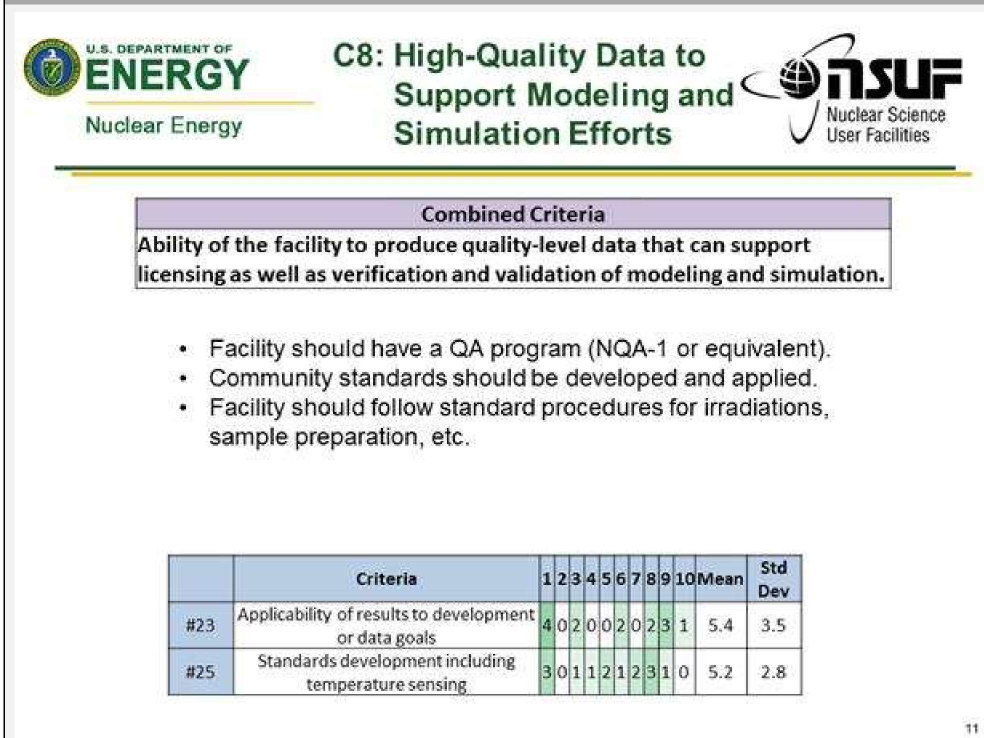
Radioactive structural materials

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



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

NSUF Nuclear Science User Facilities

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

11

C9: Meeting R&D Needs

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C9: Meeting R&D Needs

NSUF Nuclear Science User Facilities

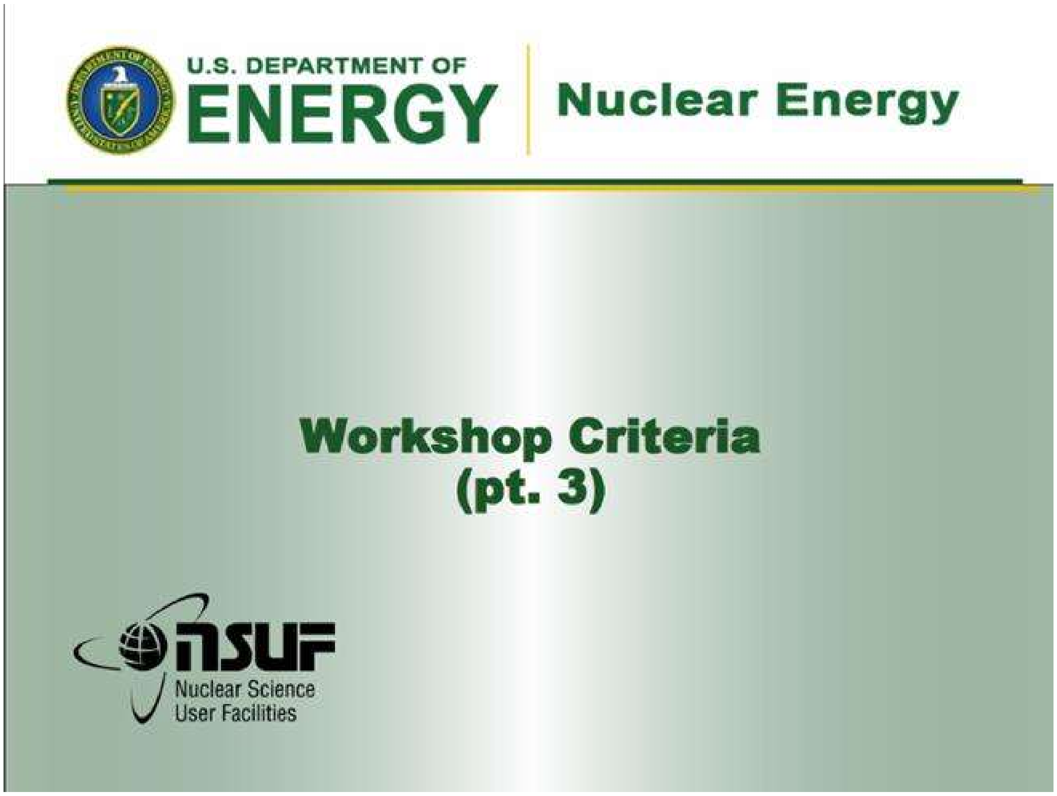
Combined Criterion
Ability of the facility to produce results that meet the needs of the Department of Energy – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

	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

12

Workshop Criteria Presentation 3

Brenden Heidrich



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Final Edit

NSUF Nuclear Science User Facilities

#	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.

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

C1

NSUF Nuclear Science User Facilities

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

6

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C2

NSUF Nuclear Science User Facilities

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

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	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

7

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C3

NSUF Nuclear Science User Facilities

Ability of the facility to provide a variety of well-controlled target environments and conditions.

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

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

8

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C4 & C5

NSUF Nuclear Science User Facilities

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

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C6

NSUF Nuclear Science User Facilities

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

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C7

NSUF Nuclear Science User Facilities

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	3	2	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

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C8

NSUF Nuclear Science User Facilities

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

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C9

NSUF Nuclear Science User Facilities

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

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C10

NSUF Nuclear Science User Facilities

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

14

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

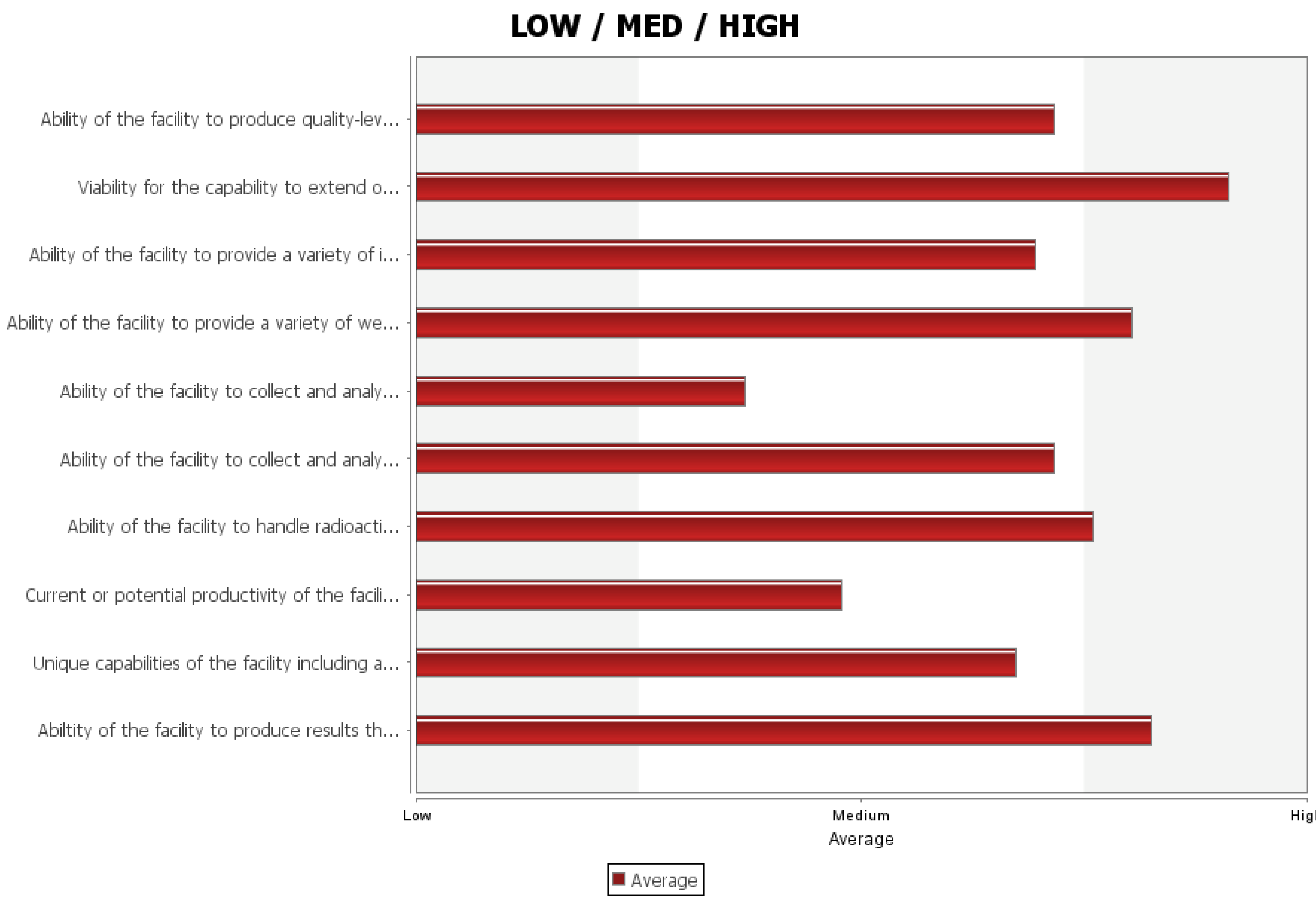
Community Comments on the Criteria (#2)

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



Community Comments on the Criteria (#3)

Combined Criteria	Comments
1. Viability for the capability to extend our understanding toward accurately simulating nuclear irradiation conditions (neutrons or fission fragments)	1. Don't understand what is meant by viability. Suggest removing "viability for." Someone should improve English here. Also, this one is important but difficult to judge/score since it is too abstract. 2. While accurately simulating (or informing) the effects of neutron irradiations is the ultimate goal of ion beams, no single capability or facility can achieve this goal. Rather, a collection of complementary capabilities coupled with a robust user community is required. Thus, scoring individual facilities on these criteria seems difficult. 3. This must be defined by the programs (with input from facilities). We need a collective effort to move forward, and the path forward must be determined before we can decide which facility is best equipped to support such effort. 4. It is critical to determine the limitations, if any, of the use of ion beam irradiation techniques for the simulation of the impacts of neutron irradiation on materials. 5. This criterion cannot be quantified, since we don't have a good

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.)	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.	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	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	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	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	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
	3. Supporting licensing is definitely important, but it is difficult at this stage since we cannot establish ion-neutron correlation yet. 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). 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. 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?
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

History and Missions

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

- 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

Leadership

- Executive Committee
  - Seven members, including one student member, nominated and elected by UO membership plus immediate past char 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

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 Senor, PNNL** (since 2012)
- UO Executive Committee 2016 Spring Election
  - Two regular members and one student member

2013 Executive Committee

CHAIR Dave Senor Pacific Northwest National Laboratory [illegible]	**SECRETARY** Peng Xu Westinghouse Electric Company [illegible]
STUDENT MEMBER Dan LaBrier Idaho State University [illegible]	**MEMBER** Jim Tulenko (2nd Term) University of Florida [illegible] 352-392-1427
MEMBER Yong Yang University of Florida [illegible]	**MEMBER** Mitra Taheri Drexel University [illegible]

2012 Executive Committee

CHAIR Jeff Terry Illinois Institute of Technology [illegible]	**SECRETARY** Dave Senor Pacific Northwest National Laboratory [illegible]
STUDENT MEMBER Peter Wells University of California, Santa Barbara [illegible]	**MEMBER** Denis Beller University of Nevada, Las Vegas [illegible]
MEMBER K.L. Murty North Carolina State University [illegible]	**MEMBER** Jim Tulenko University of Florida [illegible]

Past Members
Sean McDeavitt Texas A&M [illegible]

Executive Committee Led Activities

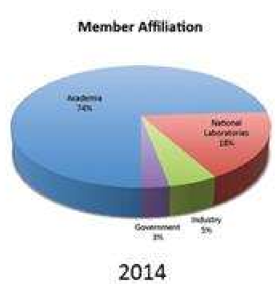
Executive Committee Led Activities

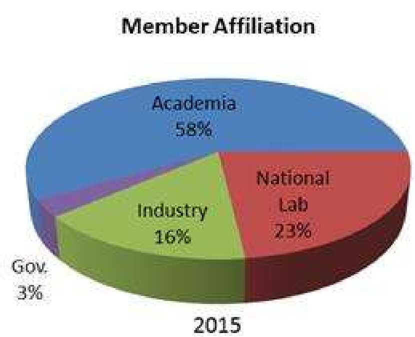
- Provided input/feedback to ATR NSUF management on a variety of topics (mostly driven by comments received from users)
  - Proposal process
  - User engagement
  - Sample library policy
  - Utilization of partner facilities
  - User week meeting
  - Experiment planning, scheduling, and executing
- Created 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

Member Demographics and Status

- NSUO 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





Meetings

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

User Week Committee

- Matthew Swenson and Dave Senor, 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

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 NSUO brochure
  - Developing NSUO website

NSUO Website

NSUO Website

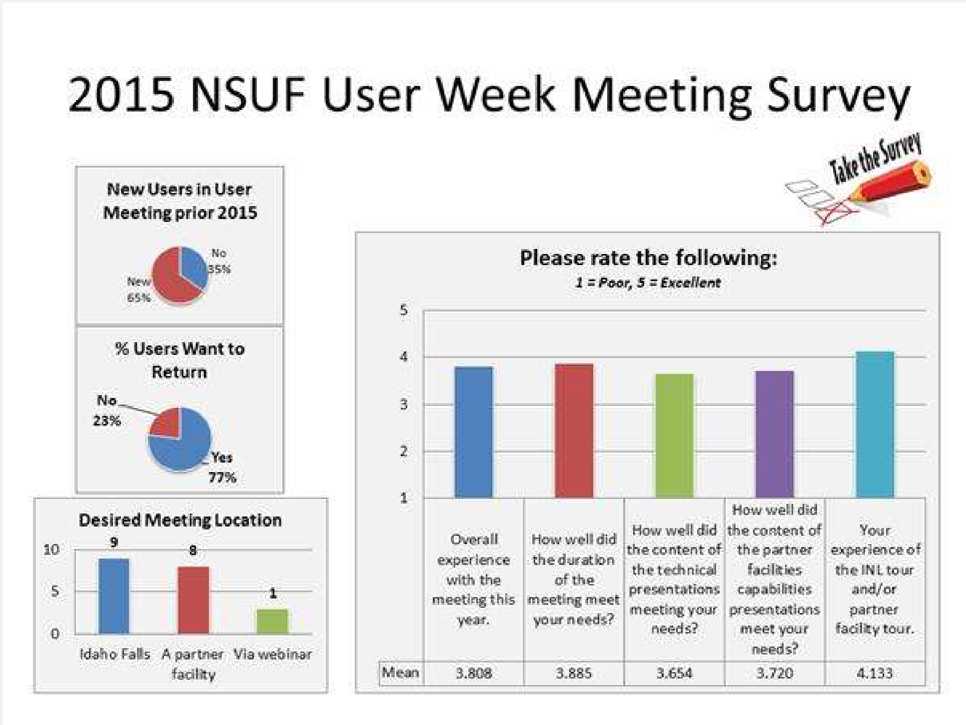
https://atrnsuf.inl.gov/default.aspx?Page=Users Organization&id=230

- NSUO 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

Capabilities and Infrastructure Committee

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

Users Input on Ion Beam Facilities

		Ranking
Technical Considerations	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!

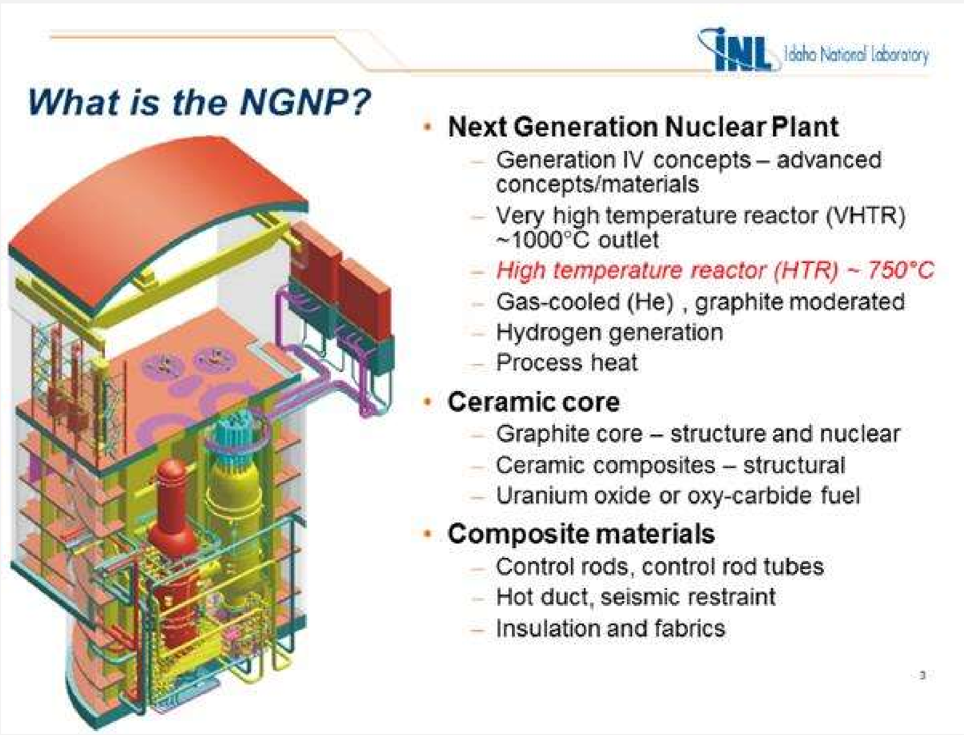
Presentation: Irradiation Material Testing

William Windes

Slide 1

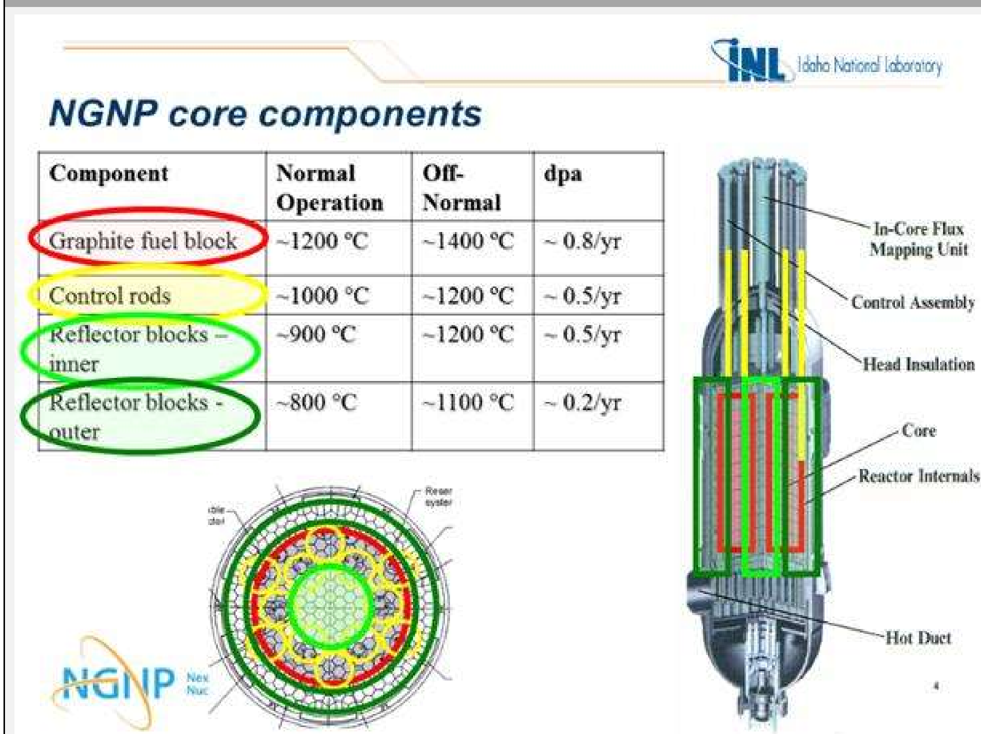
Slide 2

What is the NGNP?



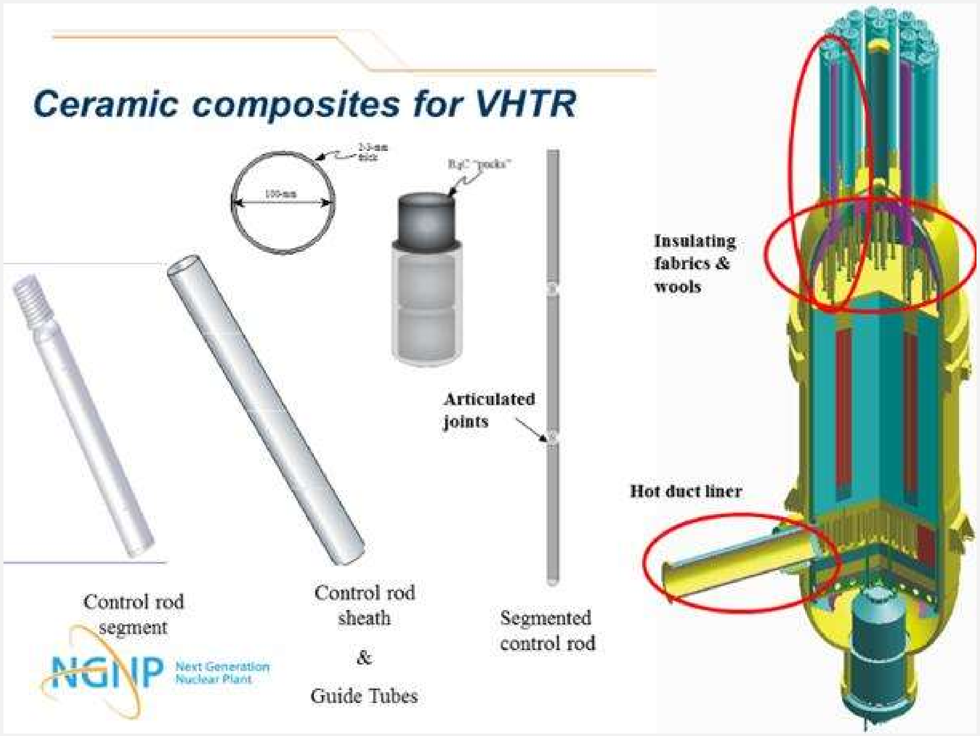
1. Next Generation Nuclear Plant

NGNP Core Components



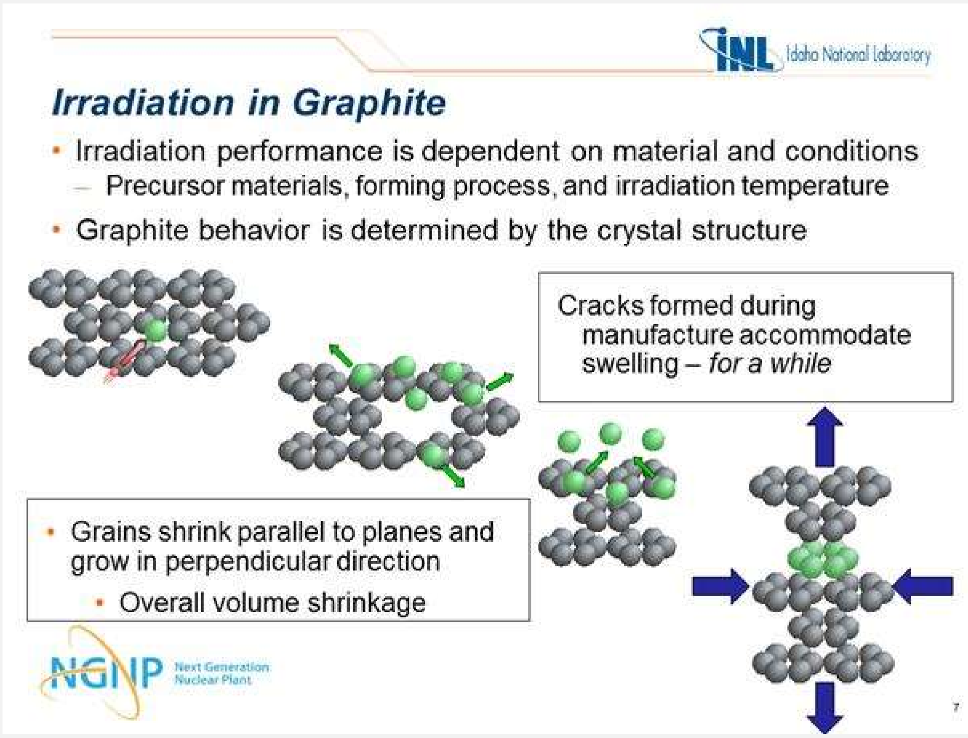
Component	Normal Operation	Off-Normal	dpa
Graphite fuel block	~1200 °C	~1400 °C	~ 0.8/yr
Control rods	~1000 °C	~1200 °C	~ 0.5/yr
Reflector blocks – inner	~900 °C	~1200 °C	~ 0.5/yr
Reflector blocks - outer	~800 °C	~1100 °C	~ 0.2/yr

Ceramic Composites for VHTR

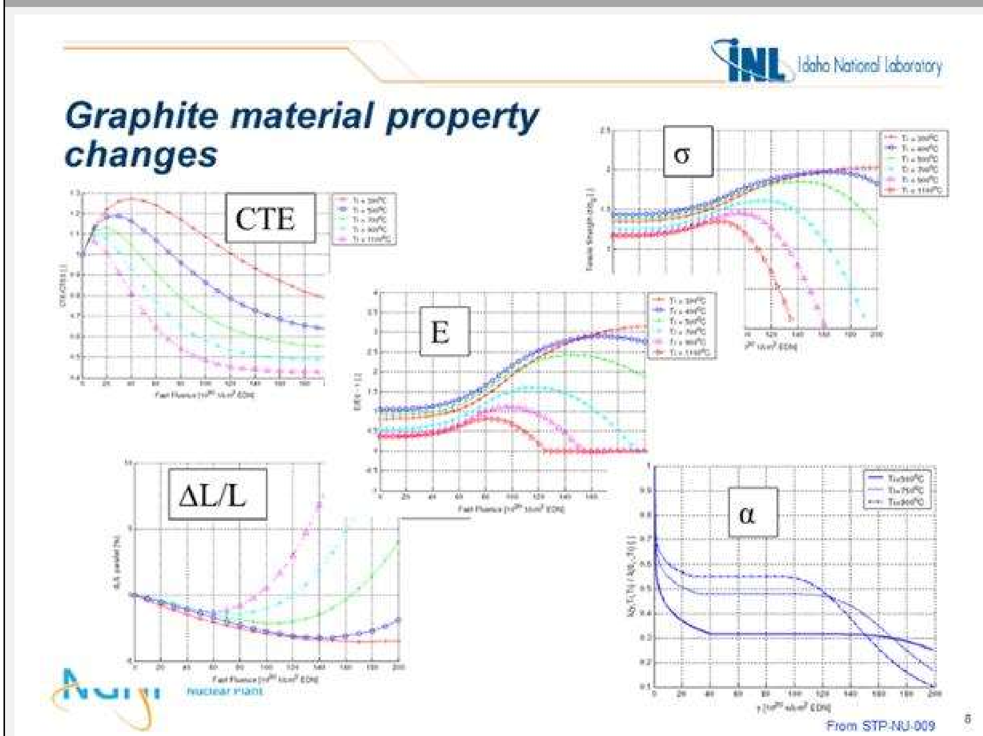


Slide 6

Irradiation in Graphite



Graphite Material Property Changes

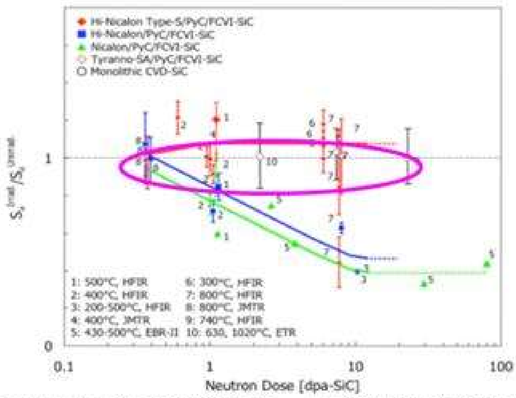


Slide 9

Idaho National Laboratory

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



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

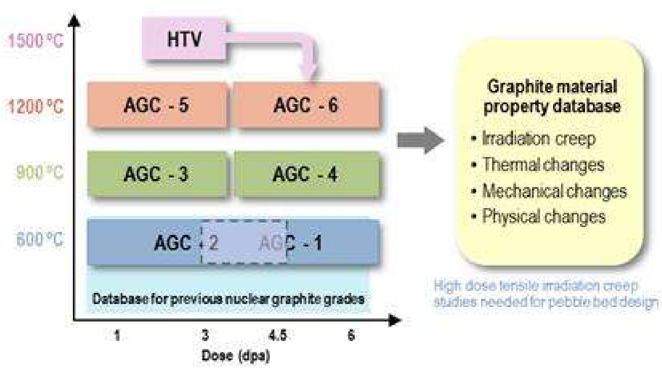
- By contrast silicon carbide (SiC) does not have anisotropic crystal structure
  - Growth is more isotropic and appears to plateau after ~ 1 dpa
  - Resulting in a stable microstructure (at least to 8 dpa levels)

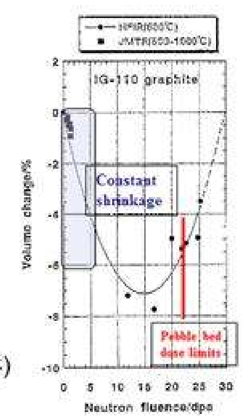
9

Advanced Graphite Creep Experiment

Idaho National Laboratory

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

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 …

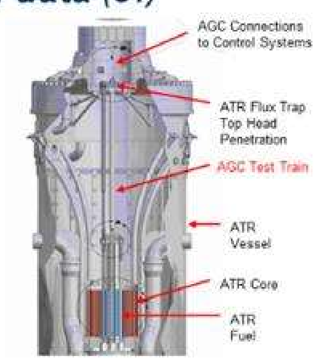
  - Quality Assurance (QA) program measures
    - If data is to be codified → Need QA data

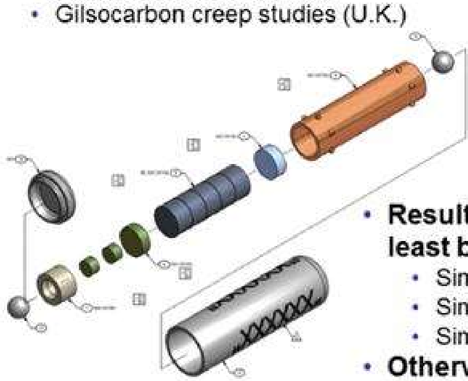
11

Ion Beam Data Versus Neutron Data (C1)

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.)



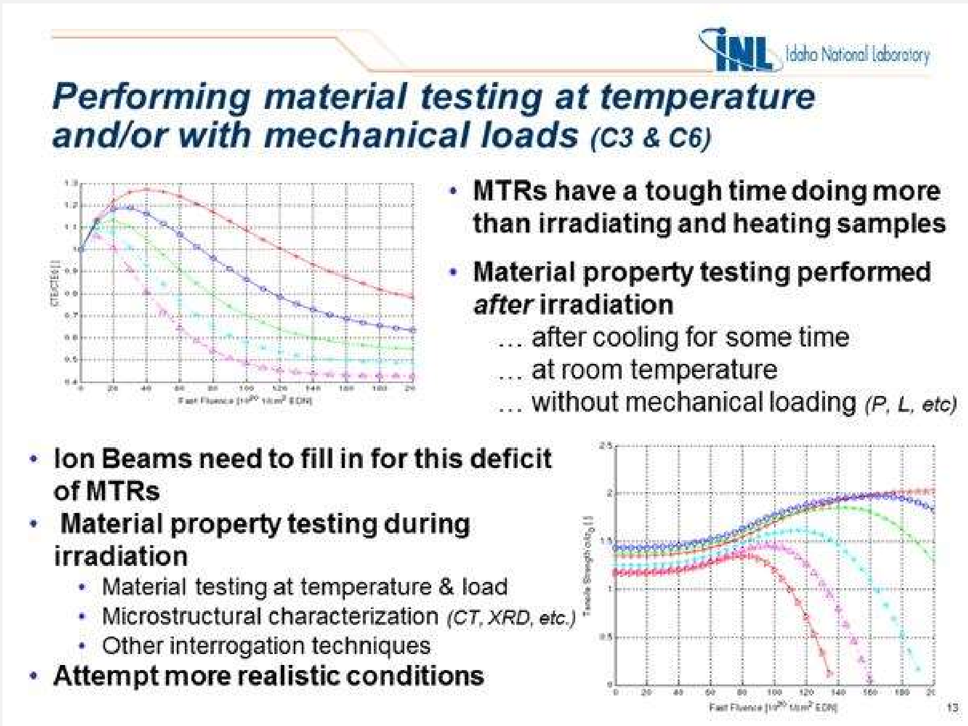


SAM-1 Assembly

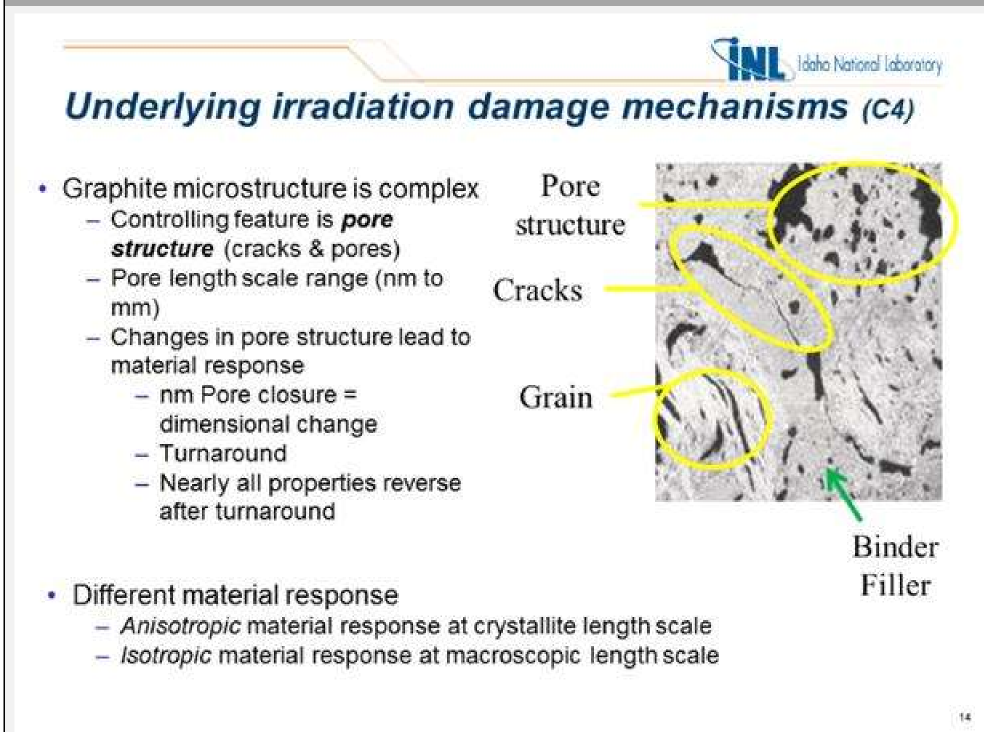
- **Results from ion beam studies must at least be comparable**
  - Similar material property changes to dose
  - Similar changes at high irr. temp
  - Similar specimen size (or equivalent)
- **Otherwise can't use the data**
  - Want it for enhanced test results

12

Performing Material Testing at Temperature and/or with Mechanical Loads (C3 & C6)



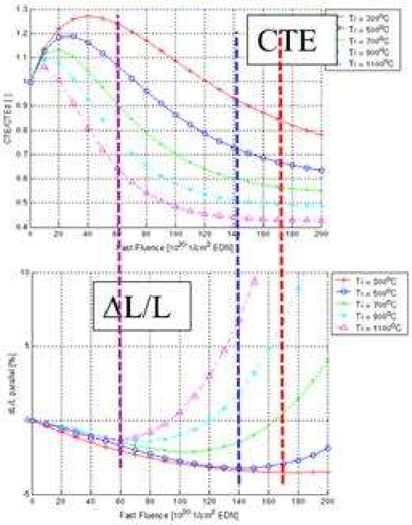
Underlying Irradiation Damage Mechanisms (C4)



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

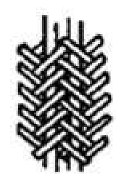
- **Difficult to do in MTR**
  - Need multiple samples, not one sample
  - Needs lots of handling

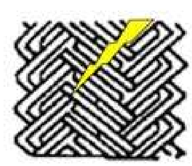
15

Underlying Irradiation Damage Mechanisms – 3

Underlying irradiation damage mechanisms - 3

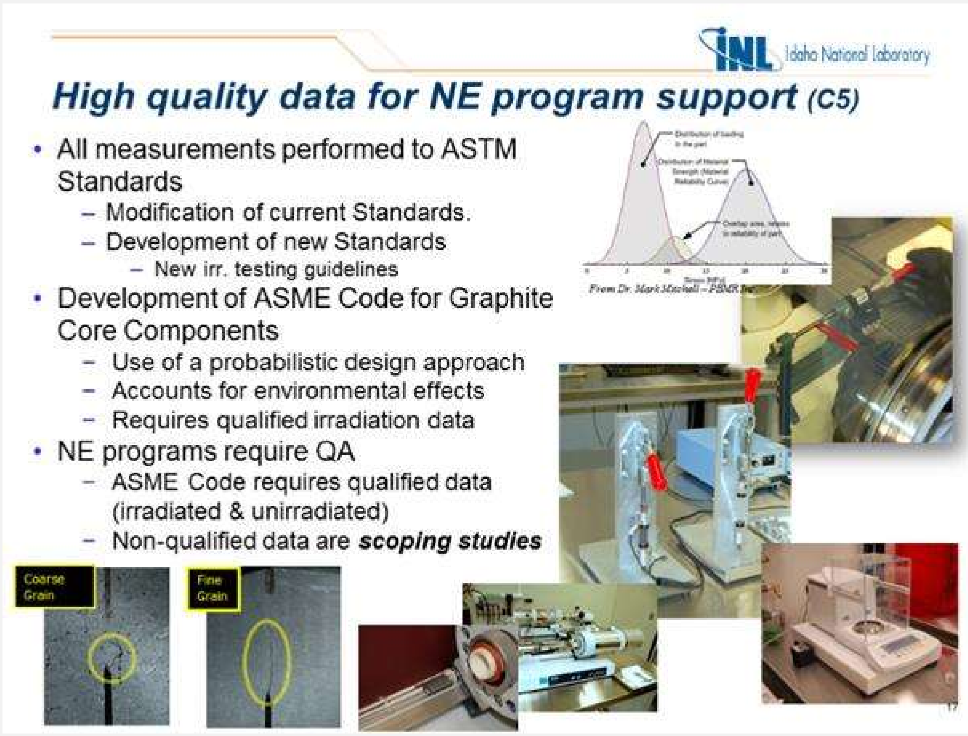
- C_f/C composites – *low or no irradiation*
  - Similar anisotropic irradiation behavior
  - Only high temp and tensile applications
- SiC_f/SiC Composite testing
  - While SiC irradiation response is fairly well understood the composite (fibers + matrix) strength response is not.
- Fracture under irradiation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


Tubular braid


Flat braid

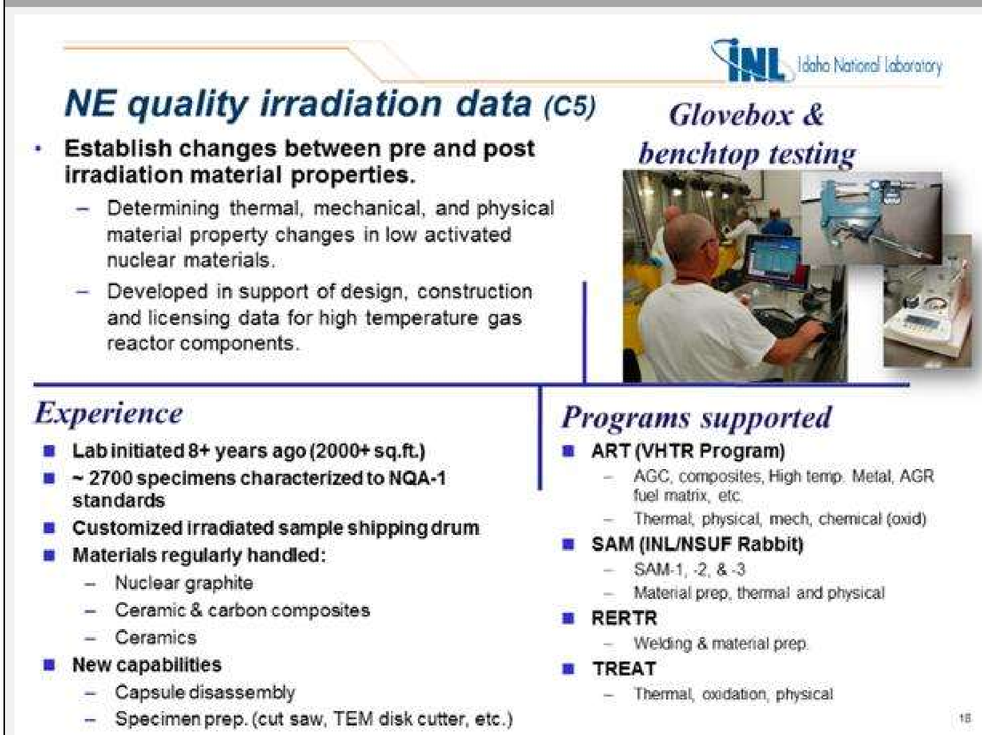
16

High Quality Data for NE Program Support (C5)



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)



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

Idaho National Laboratory

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

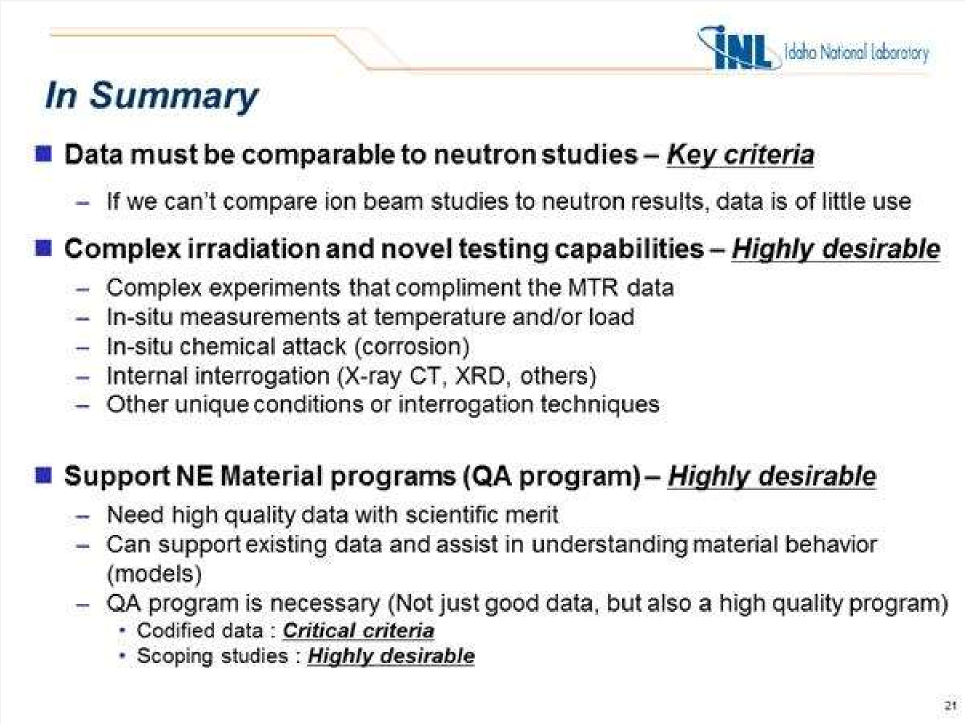
Idaho National Laboratory

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.

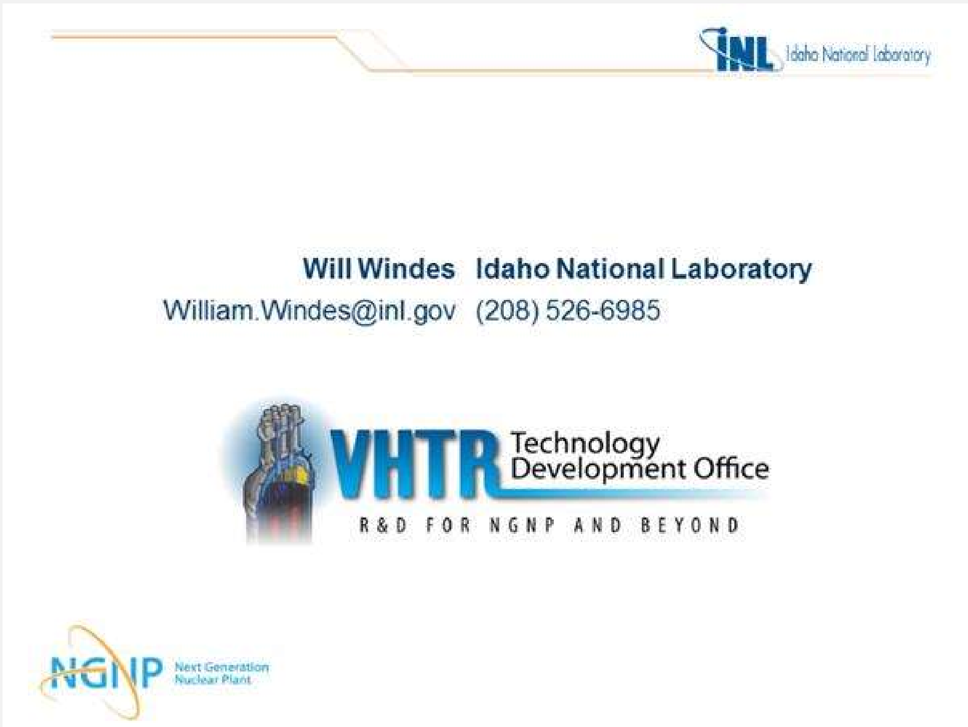
20

In Summary



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.

Slide 22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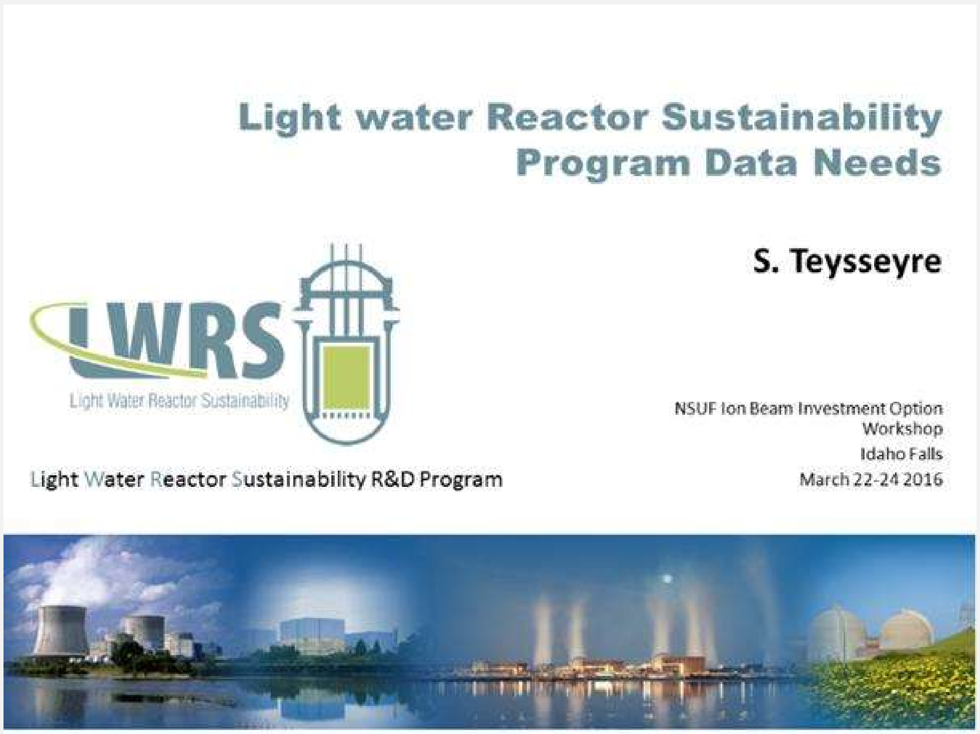
VHTR Technology Development Office
R&D FOR NGNP AND BEYOND
NGNP Next Generation Nuclear Plant

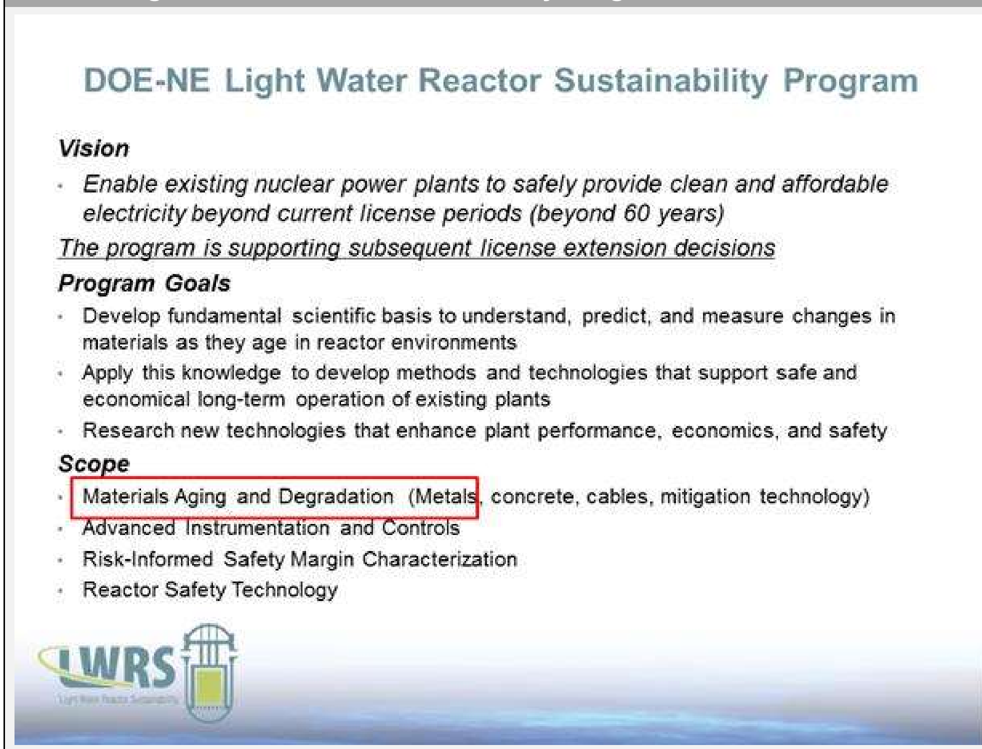
Presentation: LWRS Program Data Needs

Sebastien Teysseyre

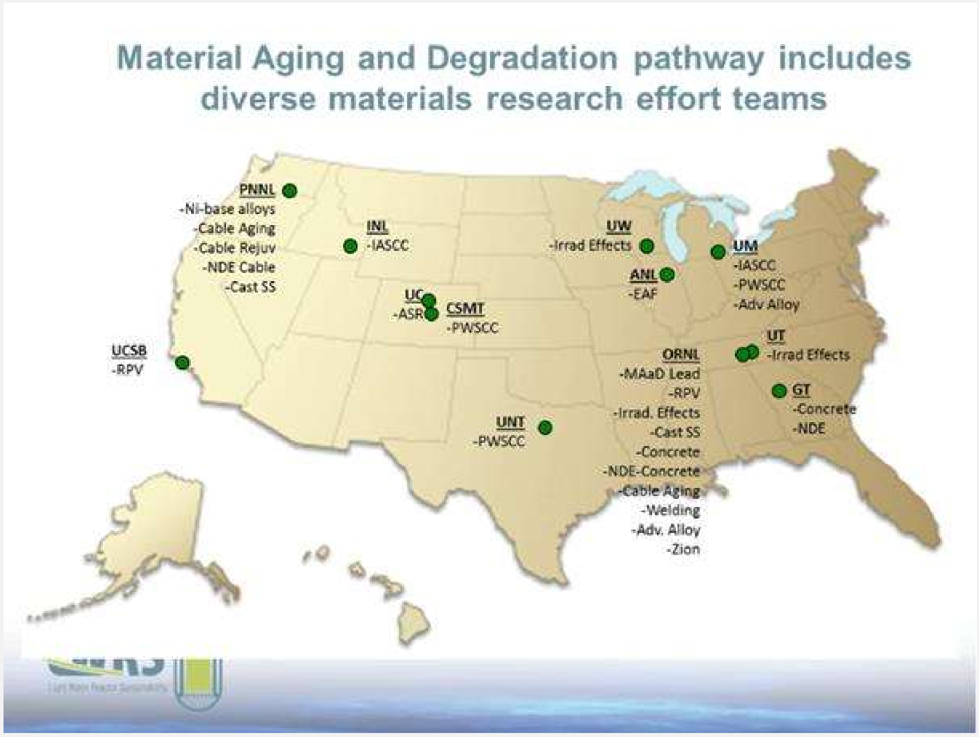
Slide 1



DOE-NE Light Water Reactor Sustainability Program

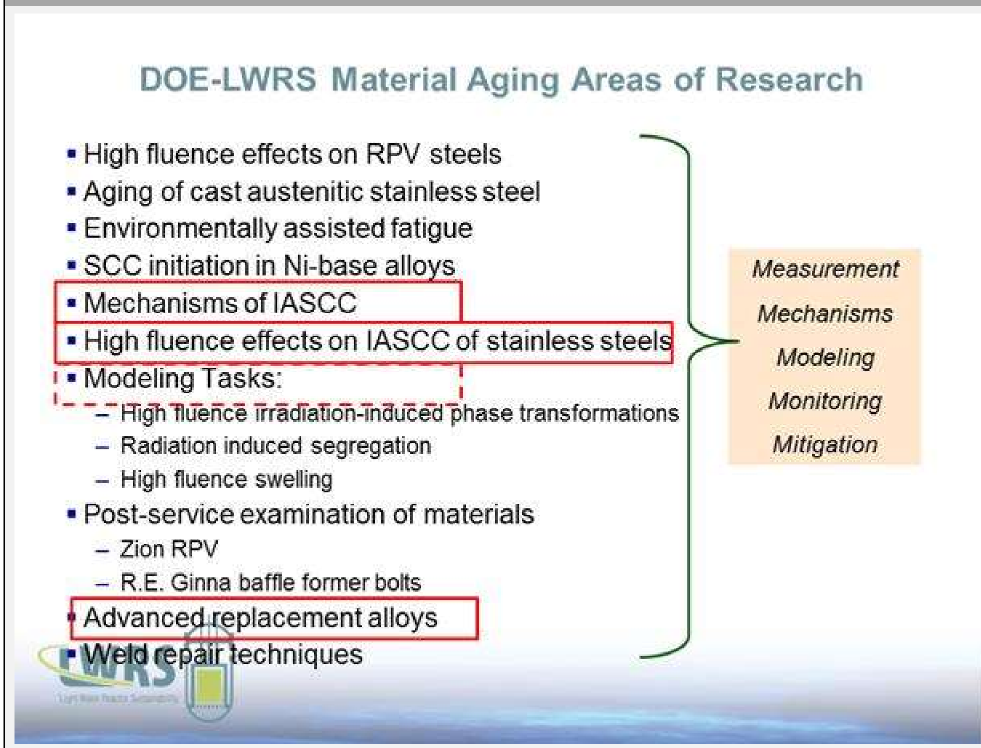


Material Aging And Degradation Pathway Includes Diverse Materials Research Effort Teams



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



LWRS Program Overview

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.

LWRS

Material Aging Pathway

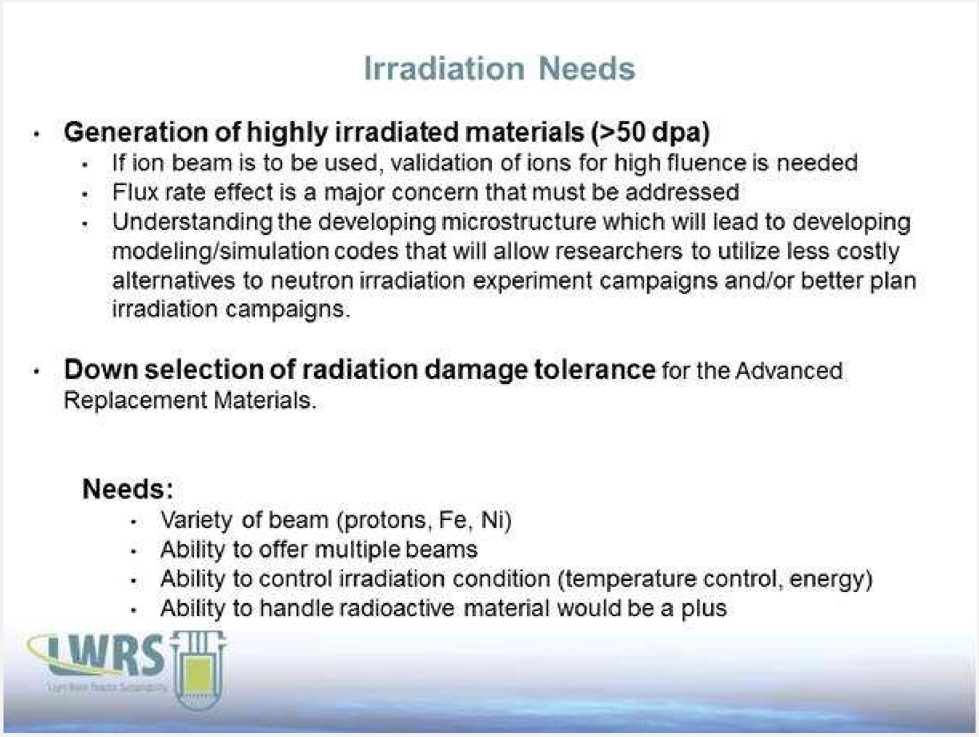
Material Aging Pathway

- **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

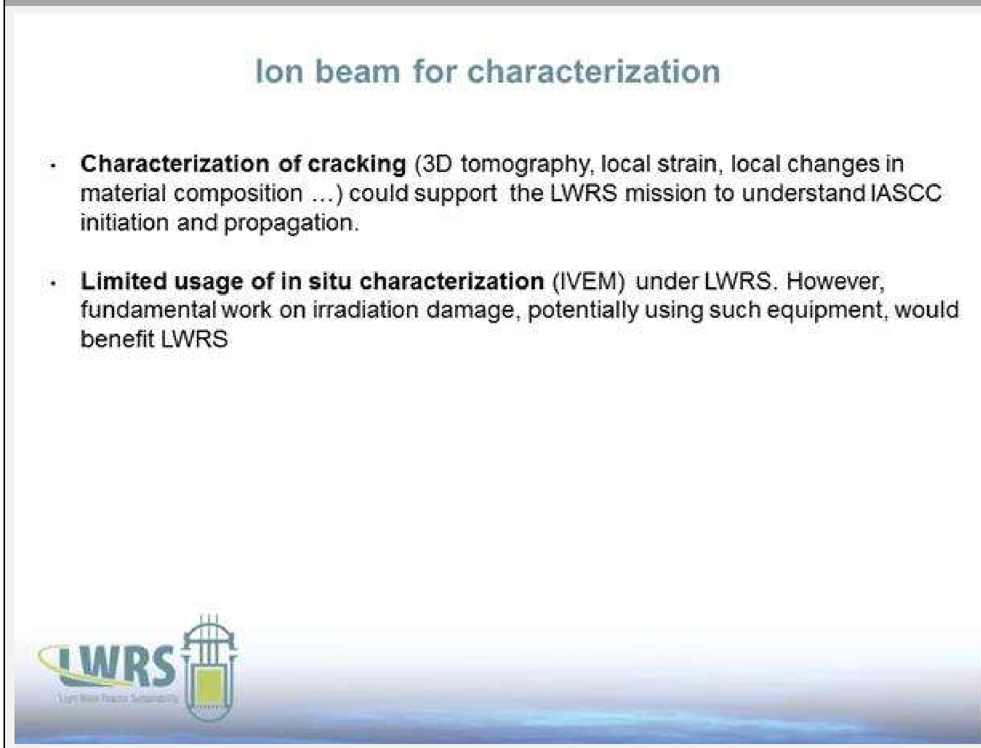
LWRS

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

Irradiation Needs



Ion Beam for Characterization



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 ?

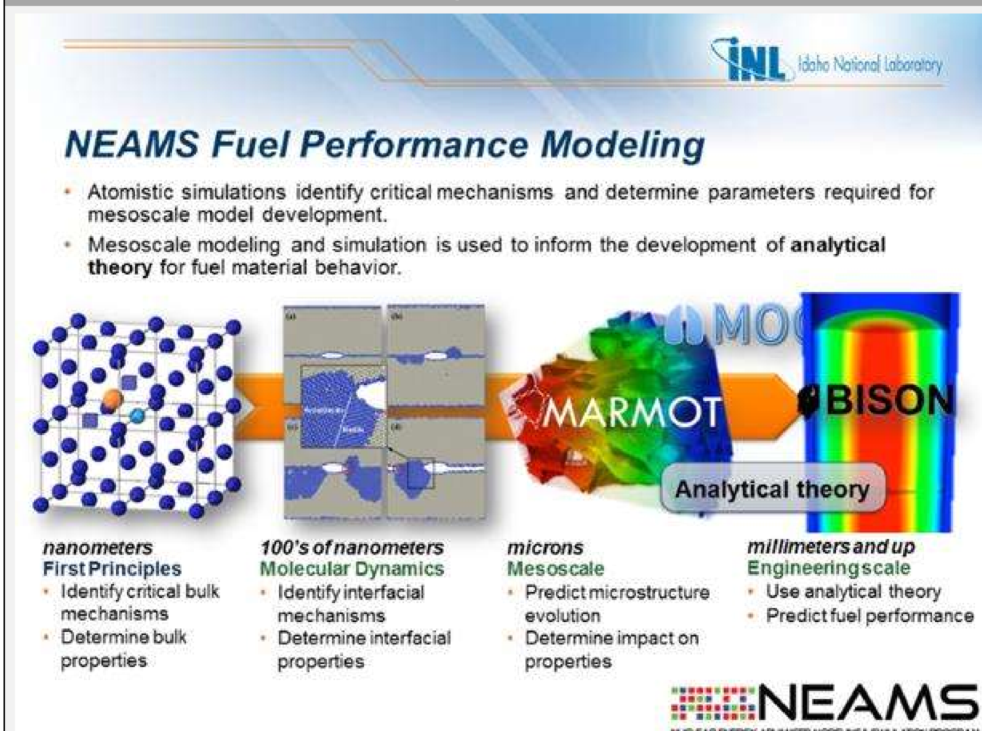
1. Re-irradiation already starts with nucleated material and is much more representative than starting with fresh material.
2. Ion beams can satisfy generic NRC requirements that don't specifically require neutron irradiations.

Presentation: Nuclear Energy Advanced Modeling

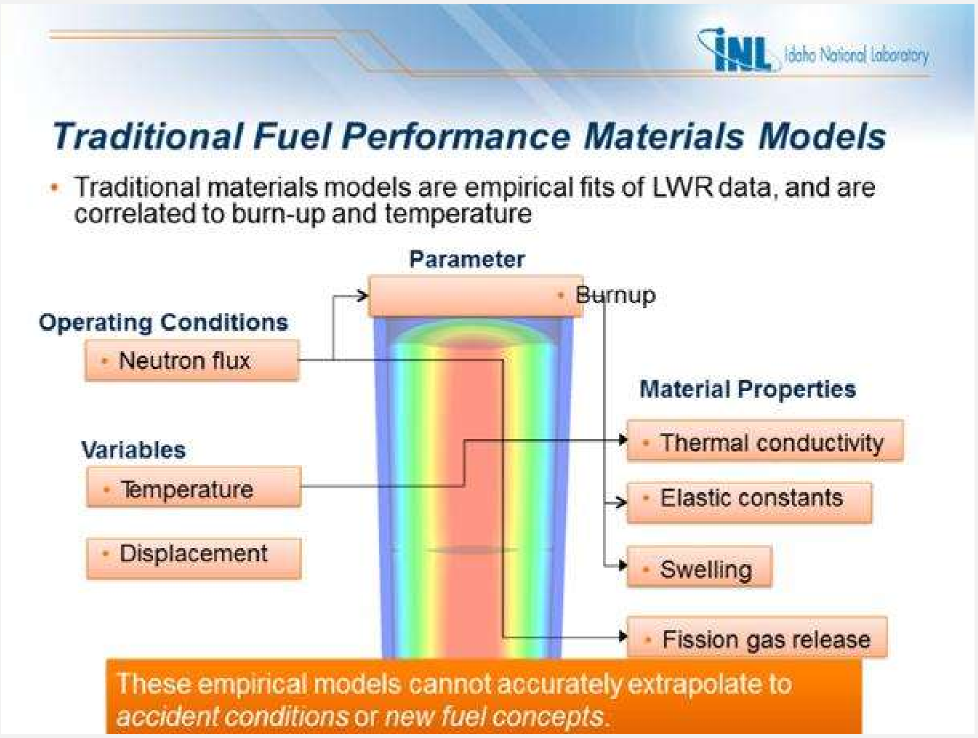
Daniel Schwen

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

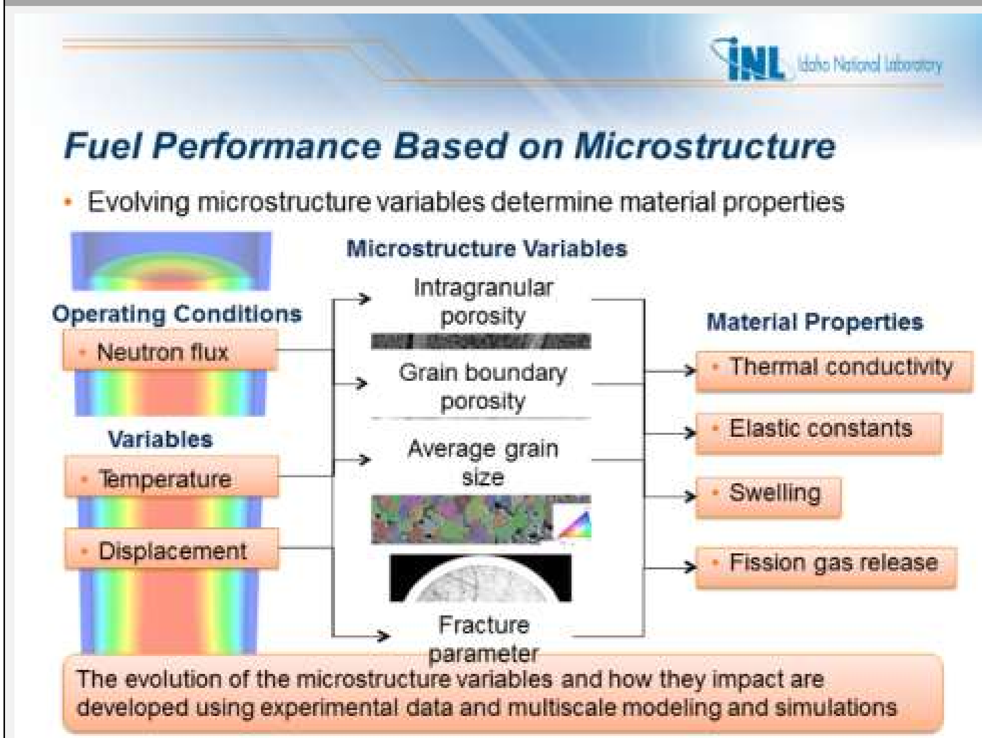
NEAMS Fuel Performance Modeling



Traditional Fuel Performance Materials Models

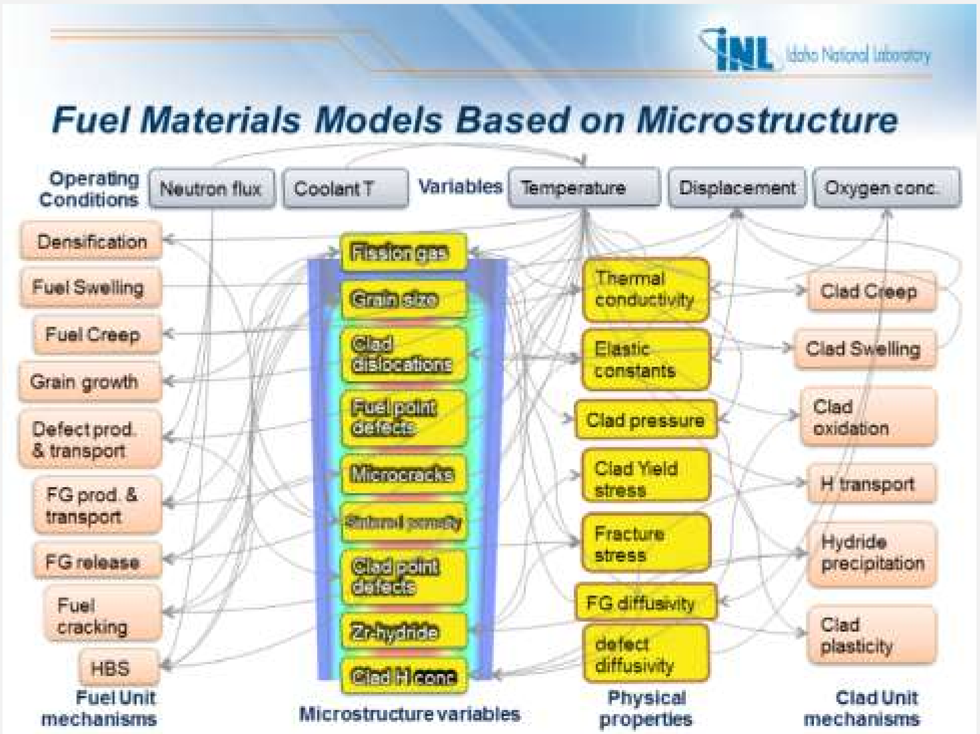


Fuel Performance Based on Microstructure



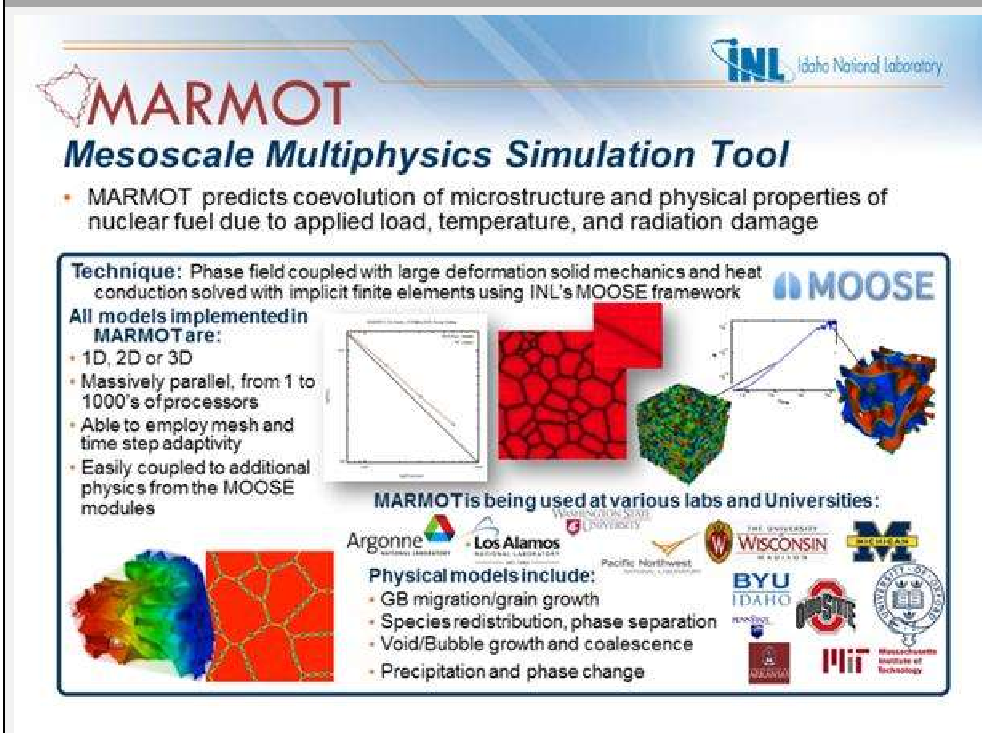
1. Ion irradiations need to produce the same mesoscale parameters as neutron damage.

Fuel Materials Models Based on Microstructure

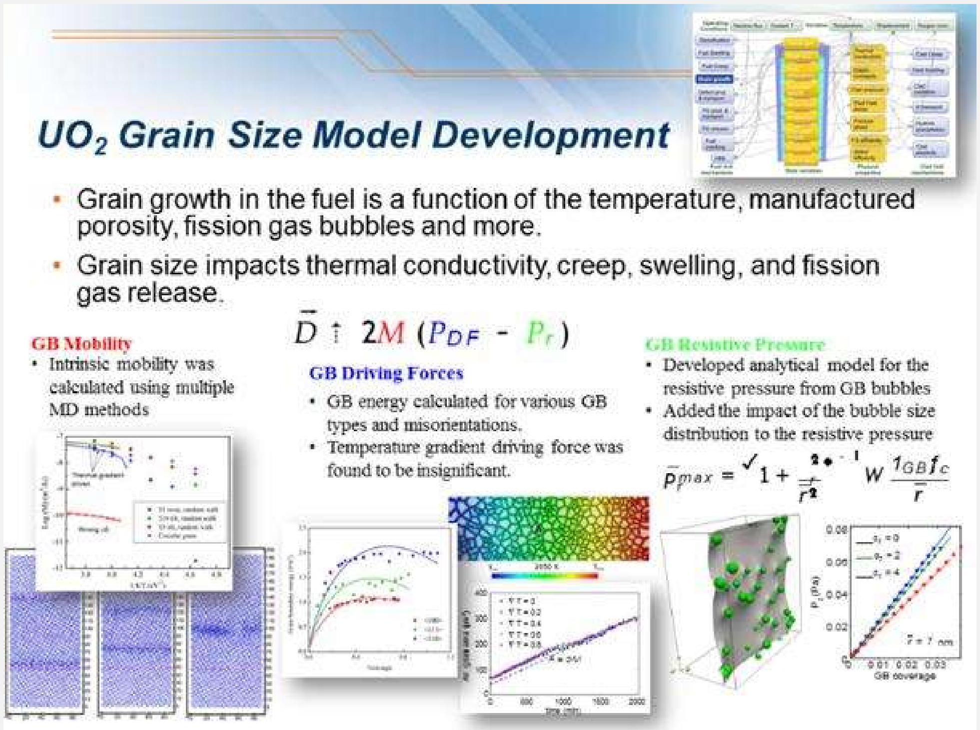


1. Can ion beam irradiations be used to investigate single-effect tests for these models?

Mesoscale Multiphysics Simulation Tool

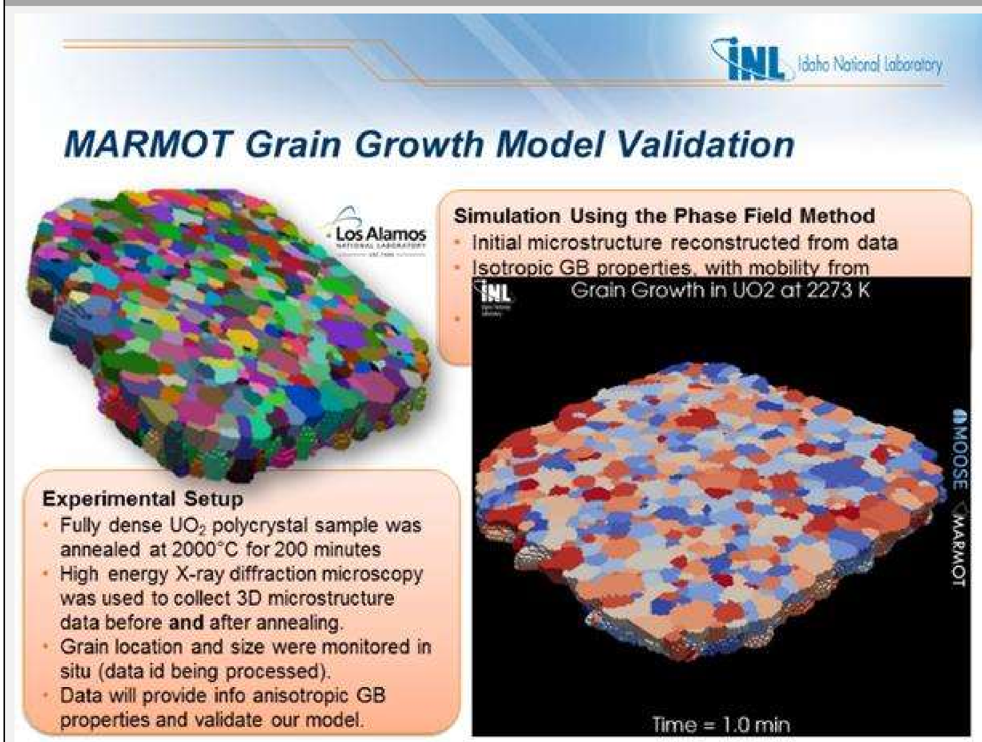


UO_2 Grain Size Model Development



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

MARMOT Grain Growth Model Validation

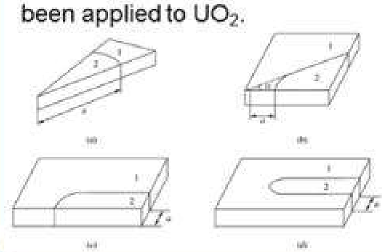


Data Needs – Grain Boundaries

Data Needs – Grain Boundaries

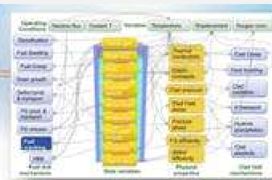
- Grain boundary mobility under irradiation (in situ)
  - Well characterized nanoscale samples (FIB)

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

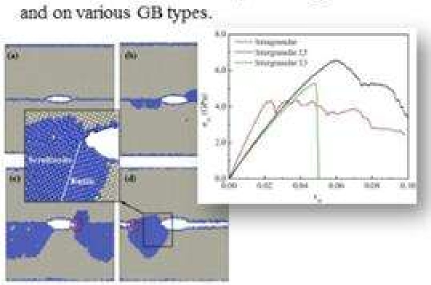


- Fuel fracture is impacted by temperature, stress, grain size, and grain boundary fission gas bubbles
- Fracture impacts volumetric expansion, fission gas release, etc.

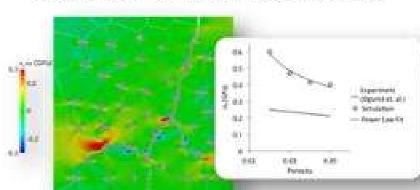
Fracture Stress

$$a_f(d, p)$$

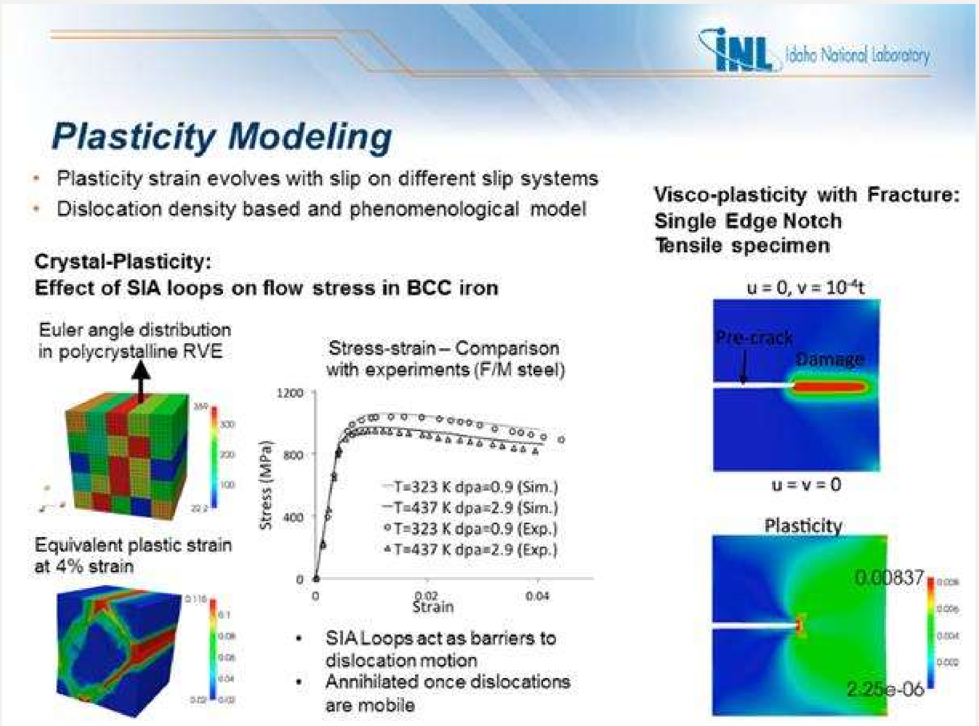
Atomistic Fracture Modeling
- MD simulations were employed to determine the fracture toughness in UO_2 across a grain and on various GB types.



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



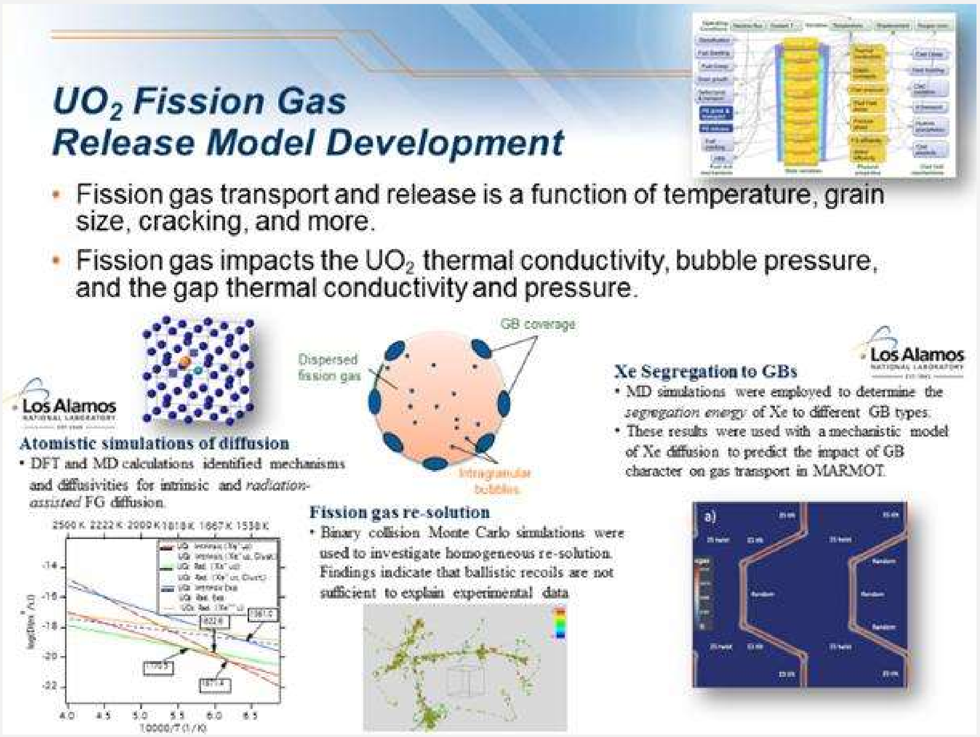
Plasticity Modeling



Data Needs – Plasticity/Fracture/Creep

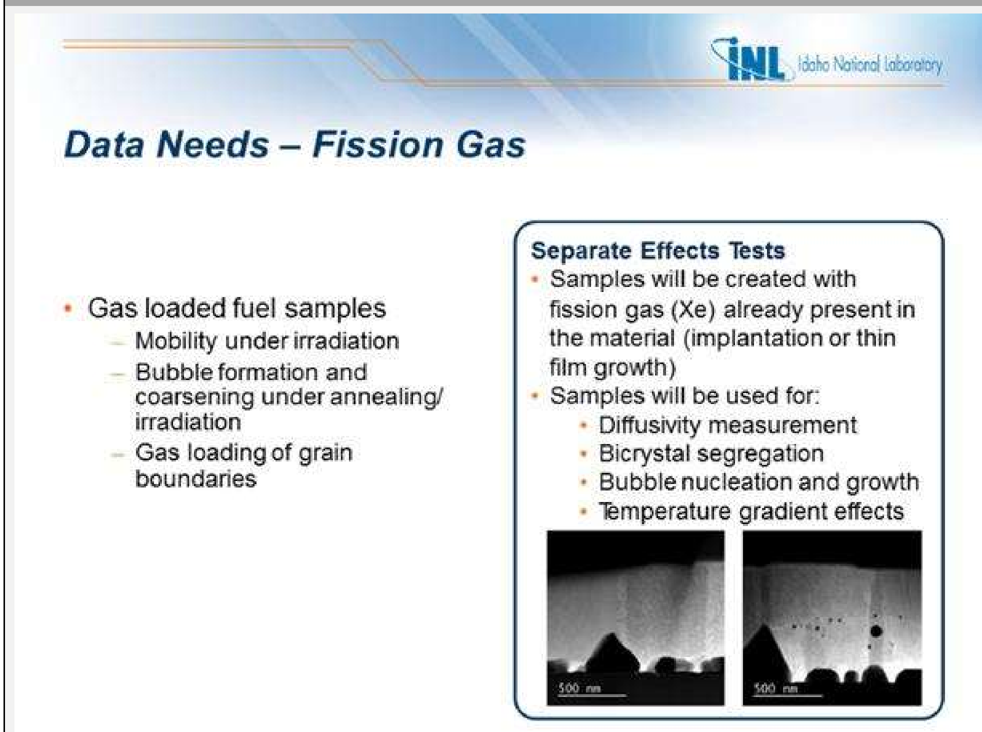
1. These are measurements that would be extremely difficult to conduct in core—ion irradiations are the only practical way to get at some of this separate effects data that is needed for model development.

UO_2 Fission Gas Release Model Development

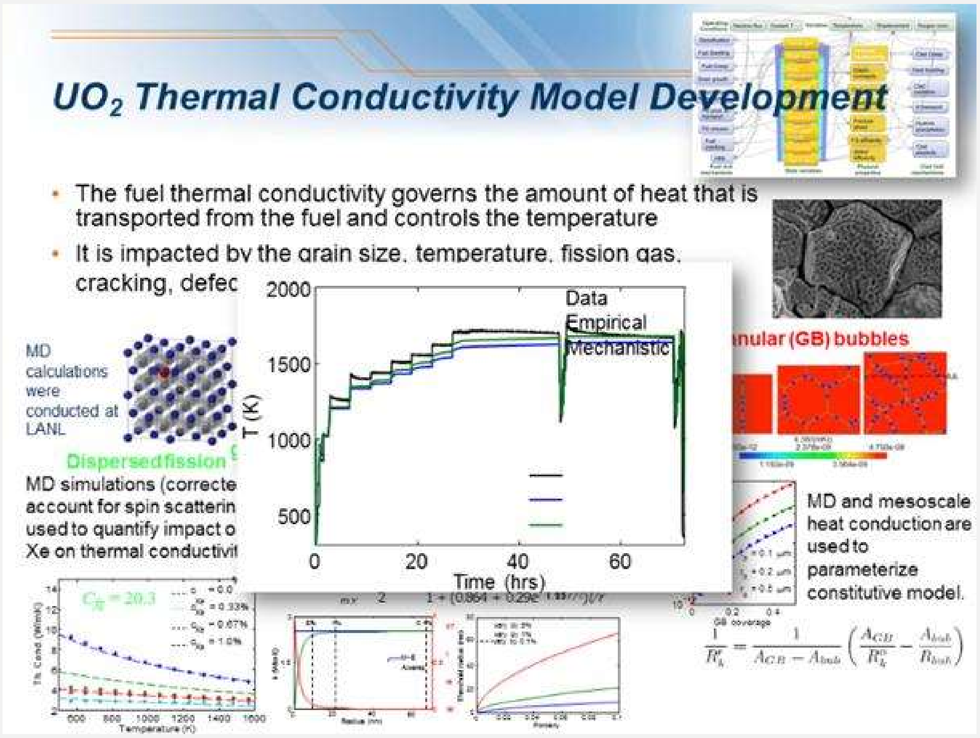


1. Wondering why cyclotrons are not considered part of this meeting.

Data Needs – Fission Gas

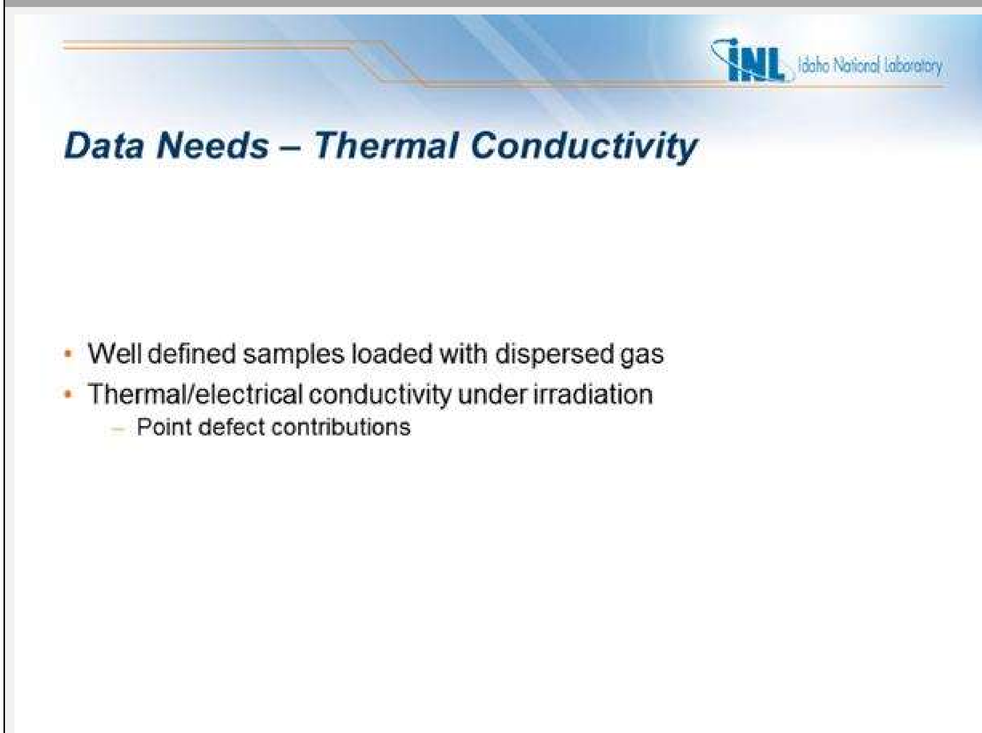


UO_2 Thermal Conductivity Model Development

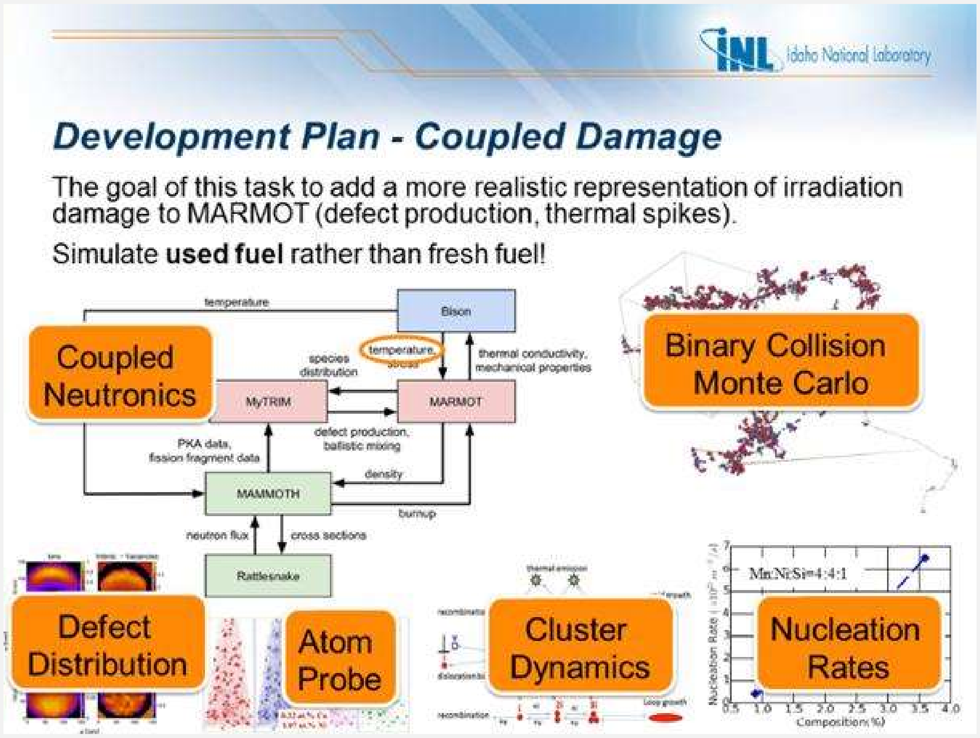


1. What quality level is needed for this data?

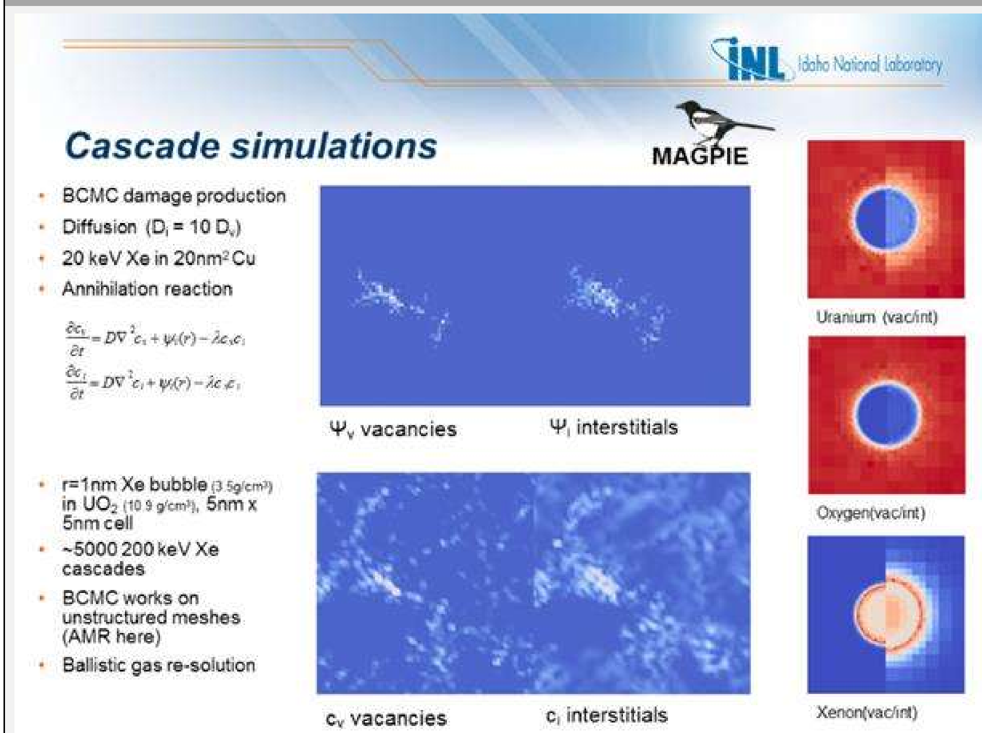
Data Needs – Thermal Conductivity



Development Plan - Coupled Damage



Cascade Simulations



Data Needs – Damage Production

INL Idaho National Laboratory

Data Needs – Damage Production

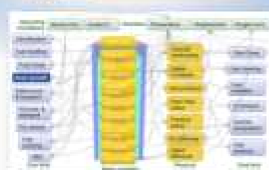
- Cluster dynamics input
  - Mobilities under irradiation (defect clusters, impurities)
  - Cluster size evolution / growth rates
- TRIM/SRIM validation
- Thermal/electrical conductivity under irradiation

Summary

INL Idaho National Laboratory

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

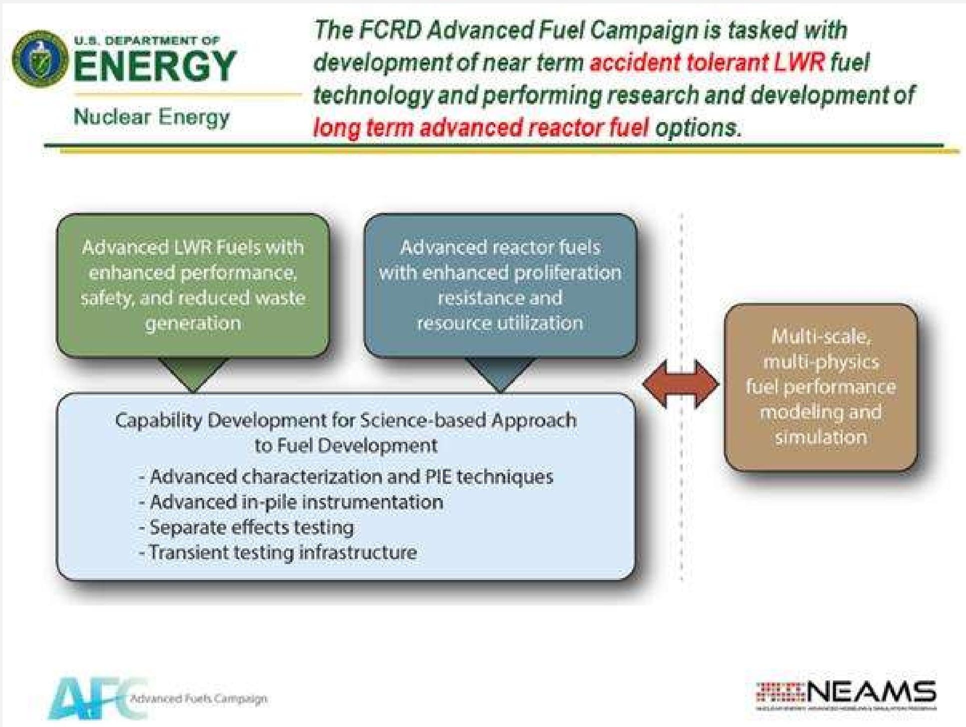
Questions?

Presentation: Fuel Cycle R&D

Shannon Bragg-Sitton

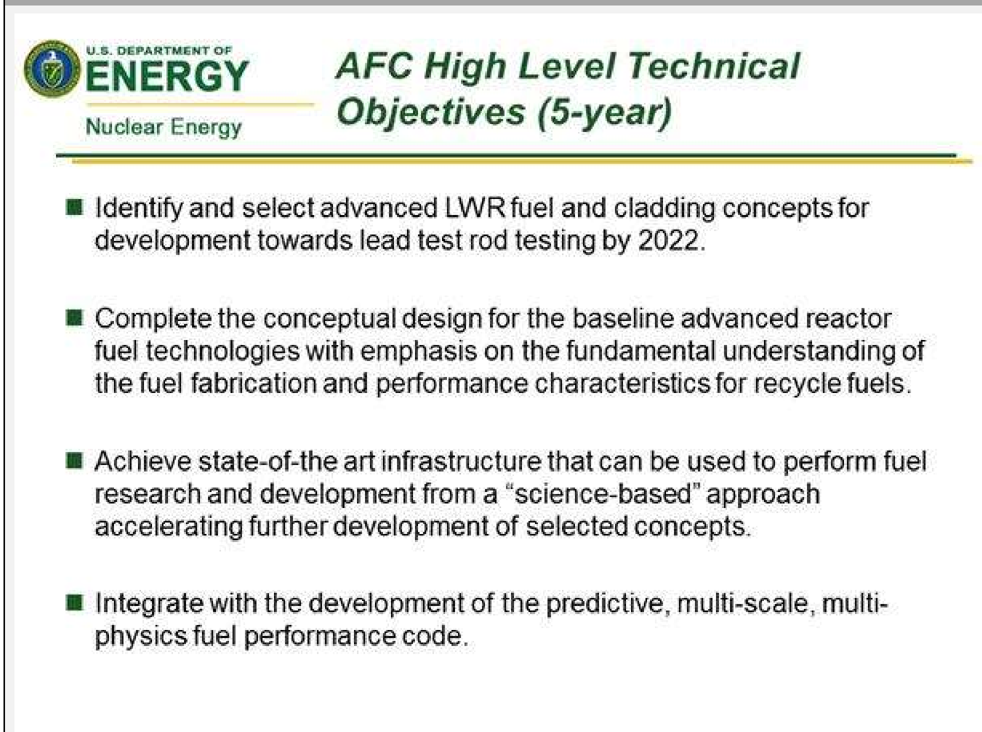
Nuclear Science User Facilities

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



Advanced LWR Fuel

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

ADVANCED LWR FUEL

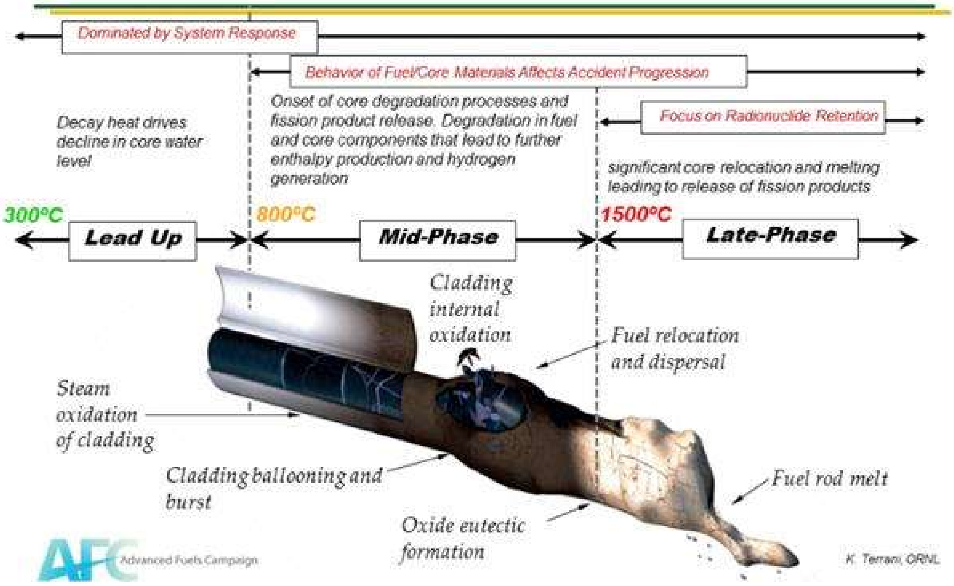
Advanced Fuels Campaign 4

A Review of Core Degradation Phenomena

U.S. DEPARTMENT OF ENERGY

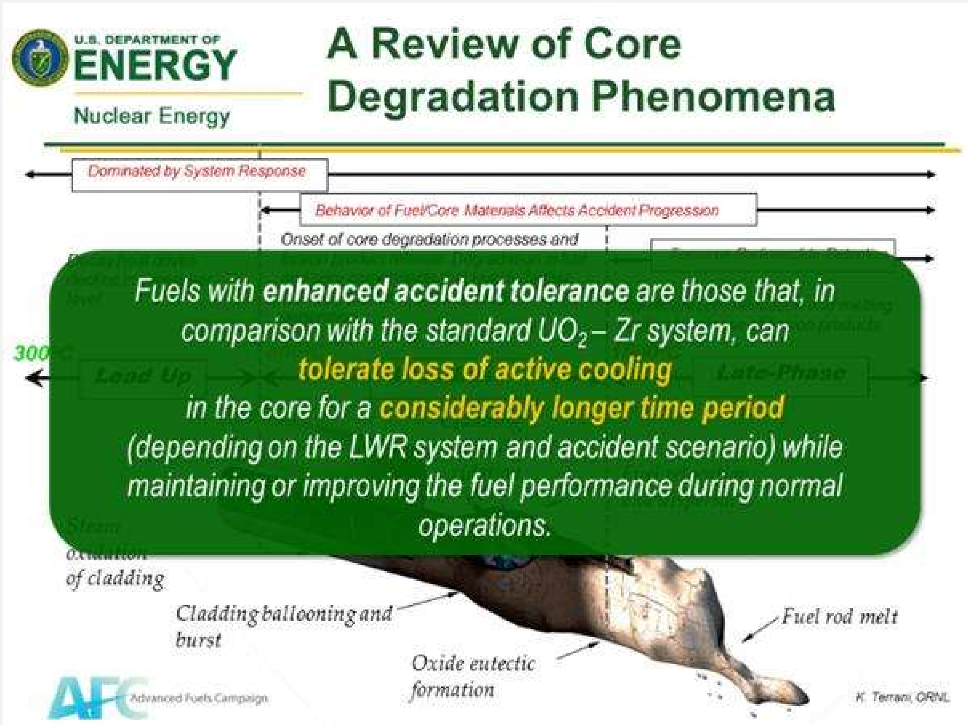
Nuclear Energy

A Review of Core Degradation Phenomena

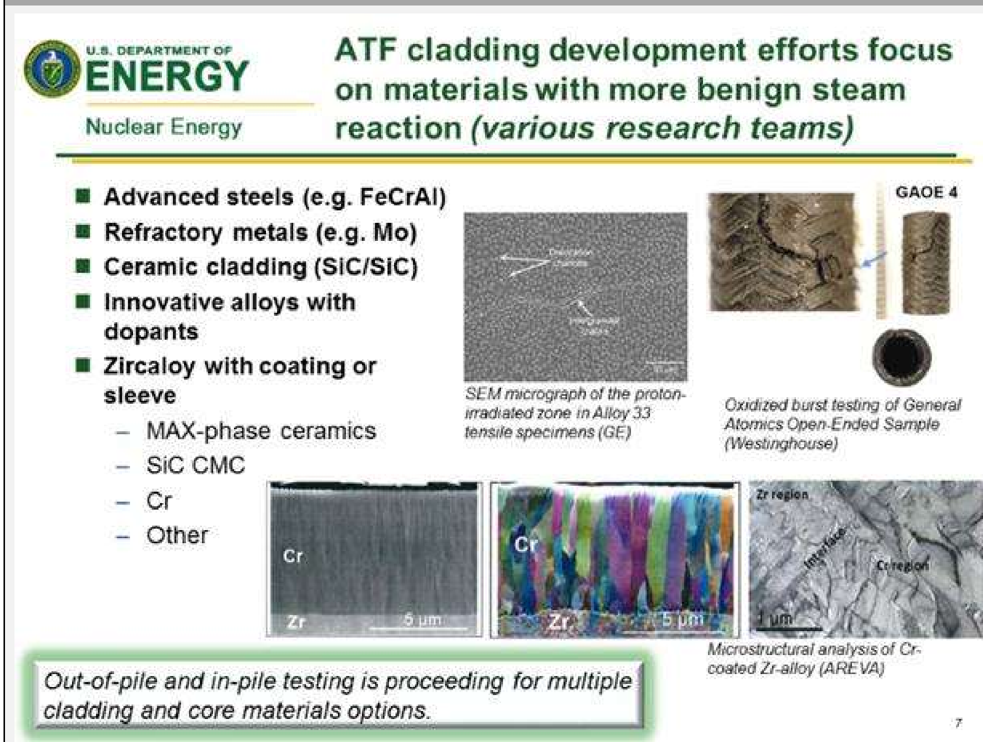


Advanced Fuels Campaign K. Terrani, ORNL

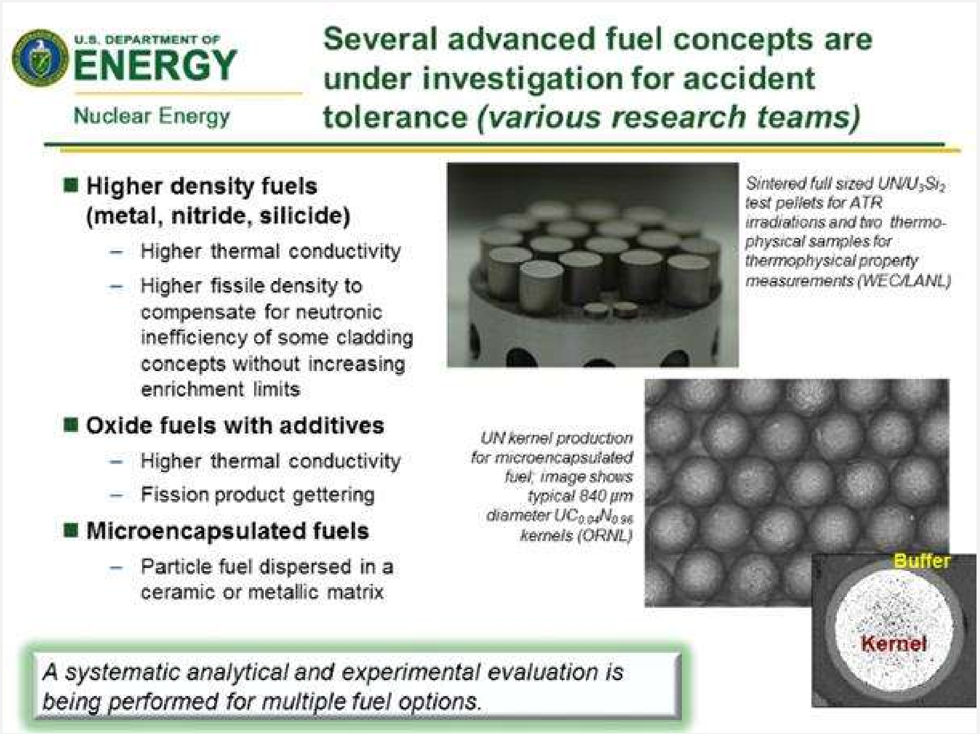
A Review of Core Degradation Phenomena



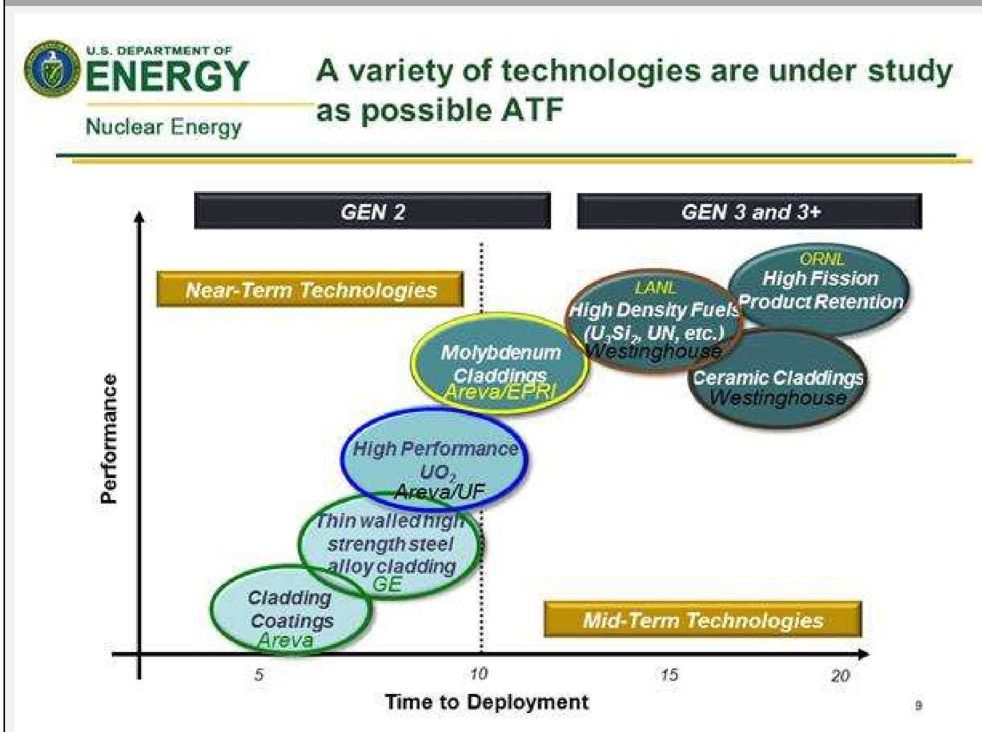
ATF cladding development efforts focus on materials with more benign steam reaction (various research teams)



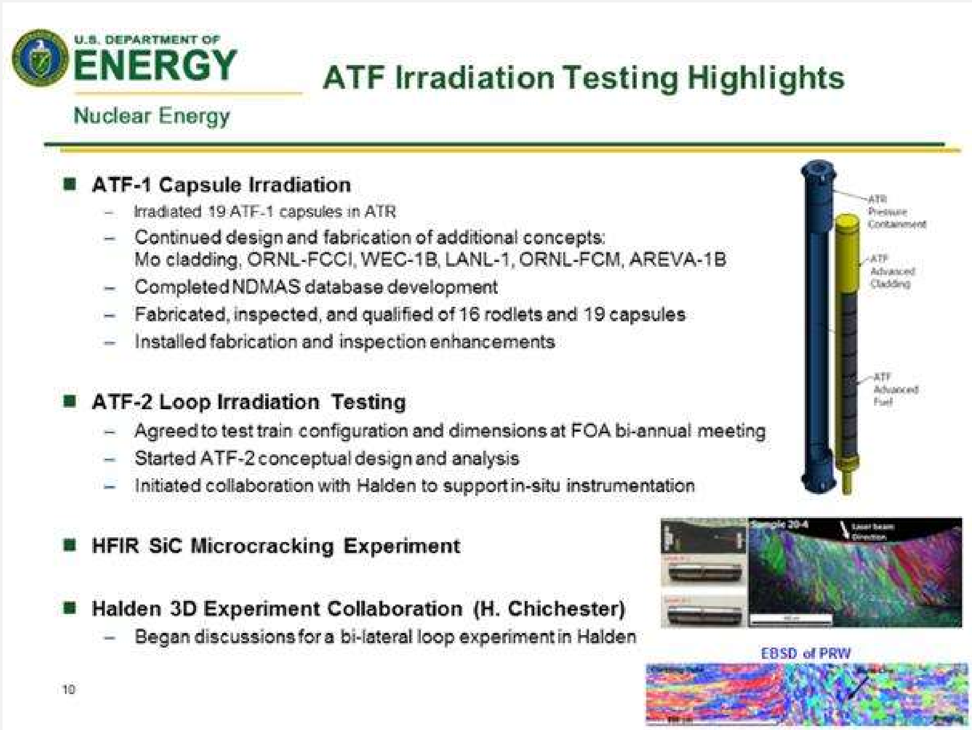
Several advanced fuel concepts are under investigation for accident tolerance (various research teams)



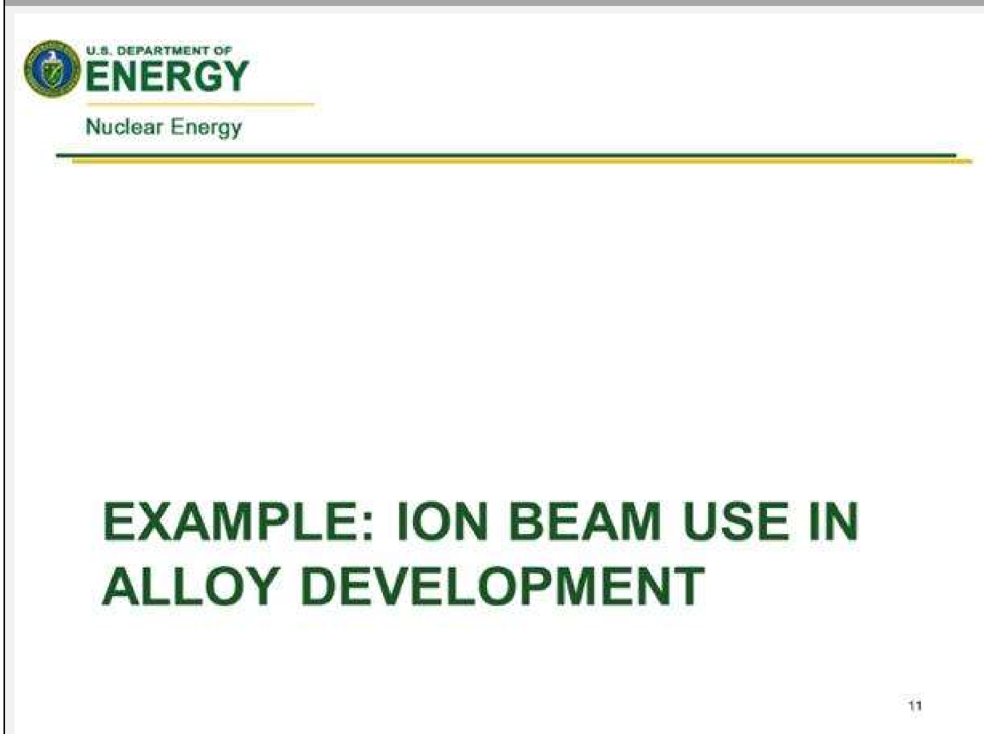
A variety of technologies are under study as possible ATF



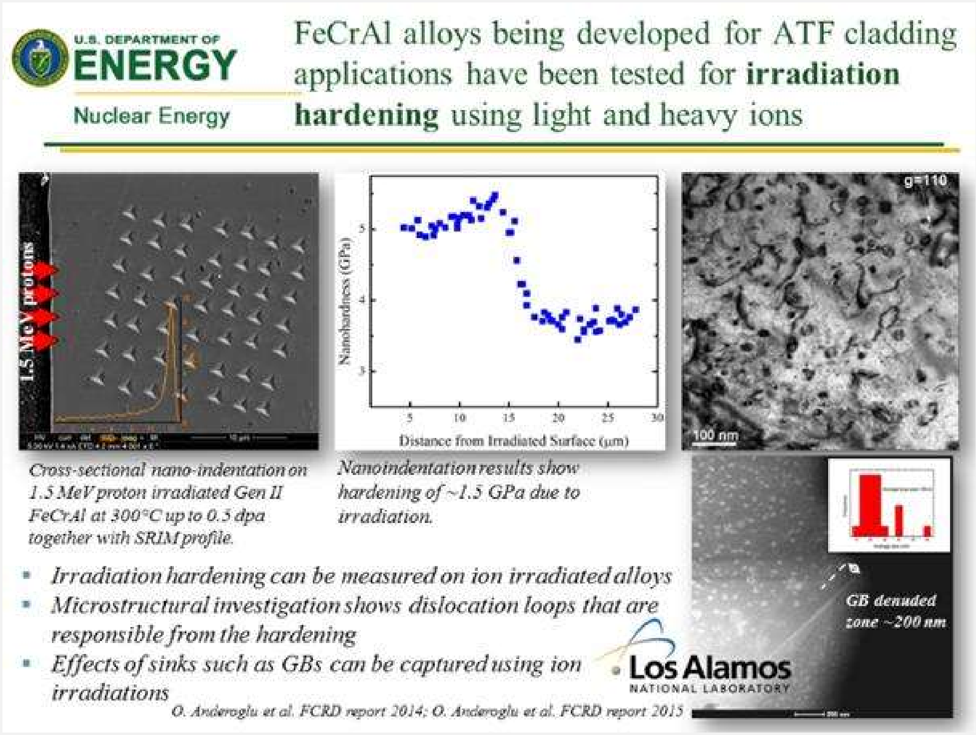
ATF Irradiation Testing Highlights



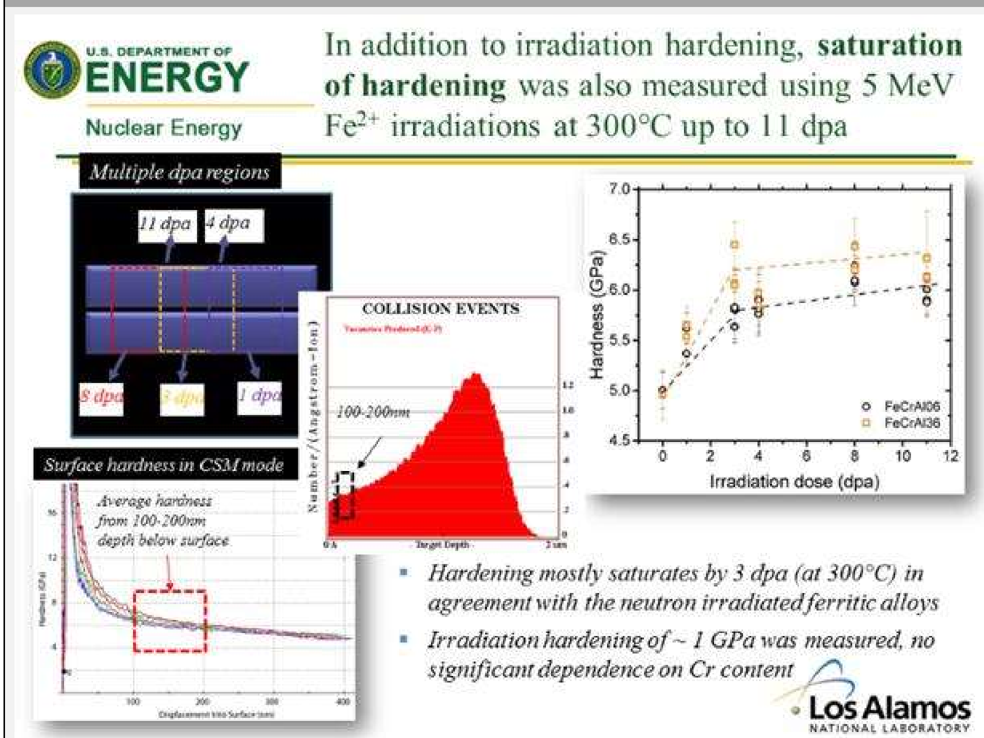
Example: Ion beam use in alloy development



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



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



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

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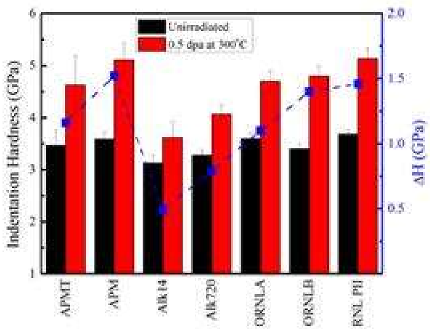
Ion irradiations very effective in surveying a large number of candidate alloys



Alloy	C	Si	Mn	Cr	Al	Mo	Fe	Y_2O_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*

Los Alamos NATIONAL LABORATORY

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

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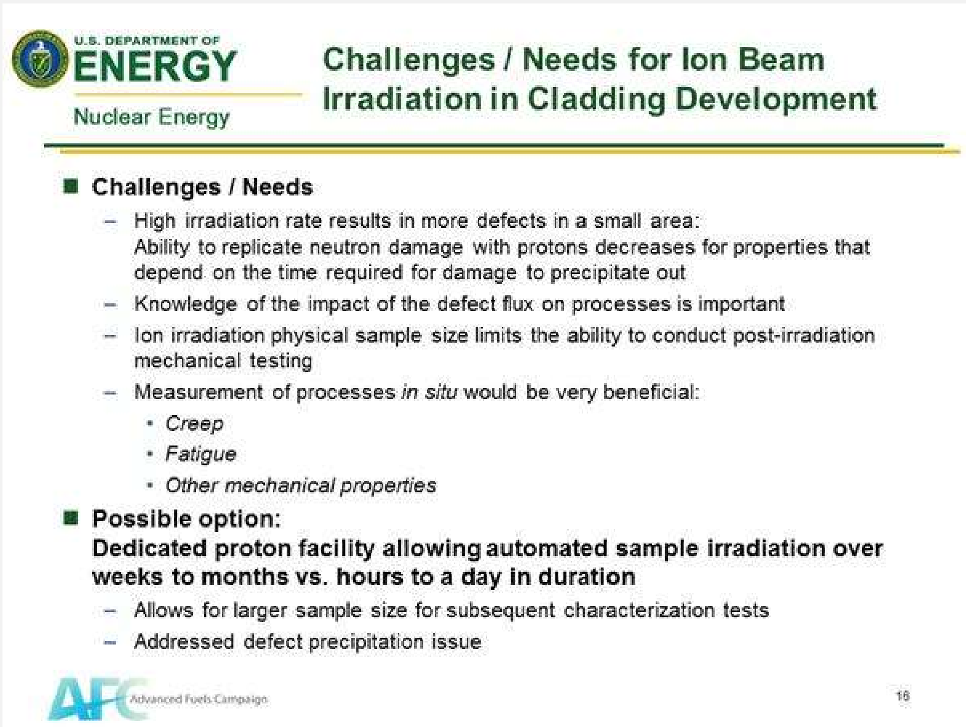
Benefits of Ion Beam Irradiation in Cladding Development

- **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)

AFC Advanced Fuels Campaign

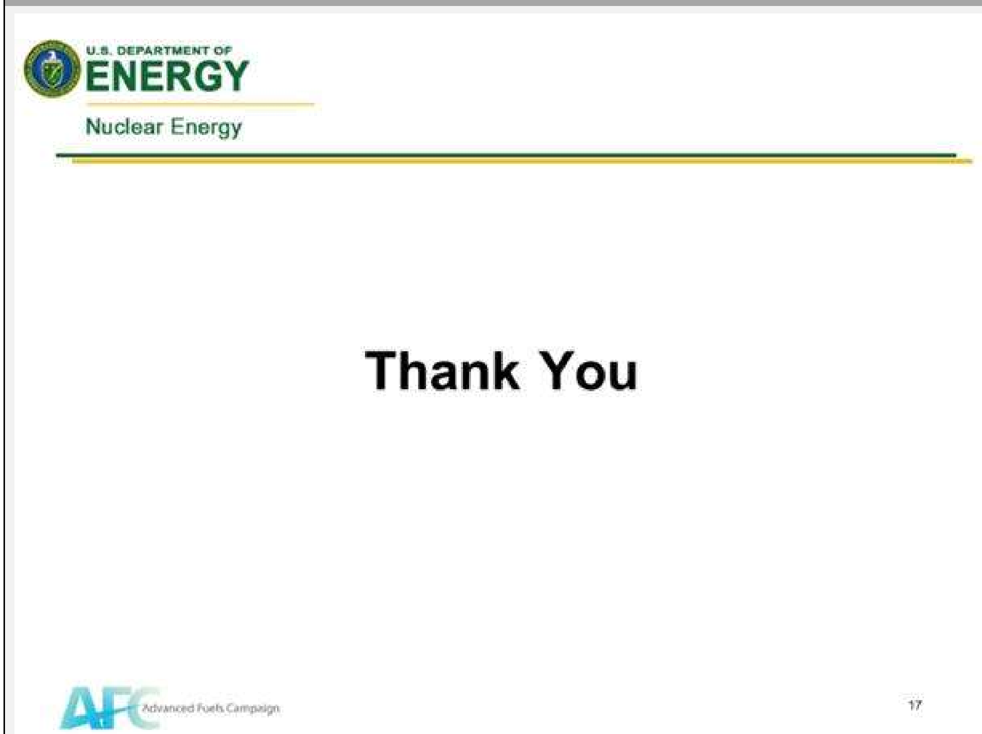
15

Challenges / Needs for Ion Beam Irradiation in Cladding Development



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

Slide 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-AC04-94AL85000

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

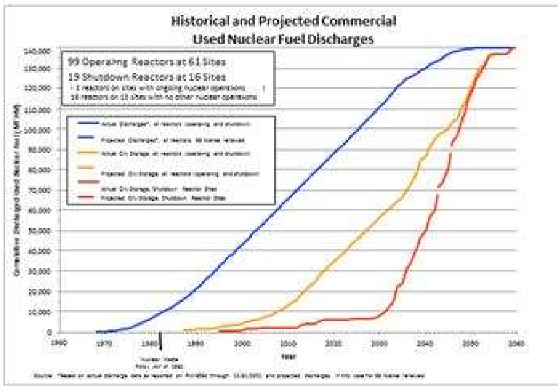
Storage and transportation:
- Cladding: High-burnup cladding performance
- Cladding: Pellet/clad delamination
- Cladding: Radiation annealing
- Bolted cask: Embrittlement of elastomer seals

Review of criteria

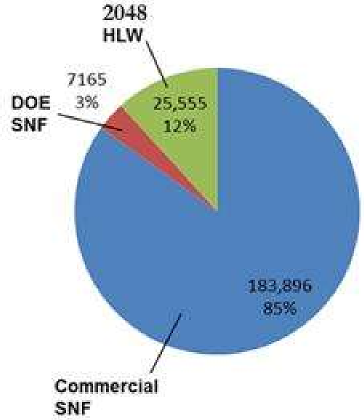
2

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

Historical and projected commercial SNF discharges



Projected volumes of SNF/HLW in 2048



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

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

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

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)

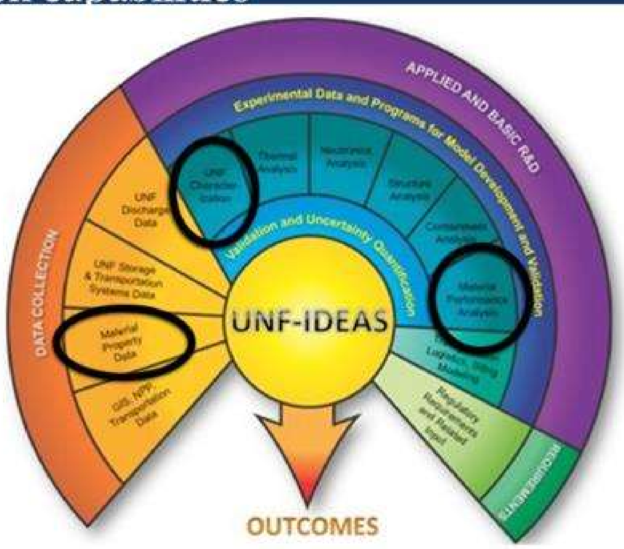
Disposal R&D focus:

- Sound technical basis for multiple viable disposal option in the US.
- 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

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?

6

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.

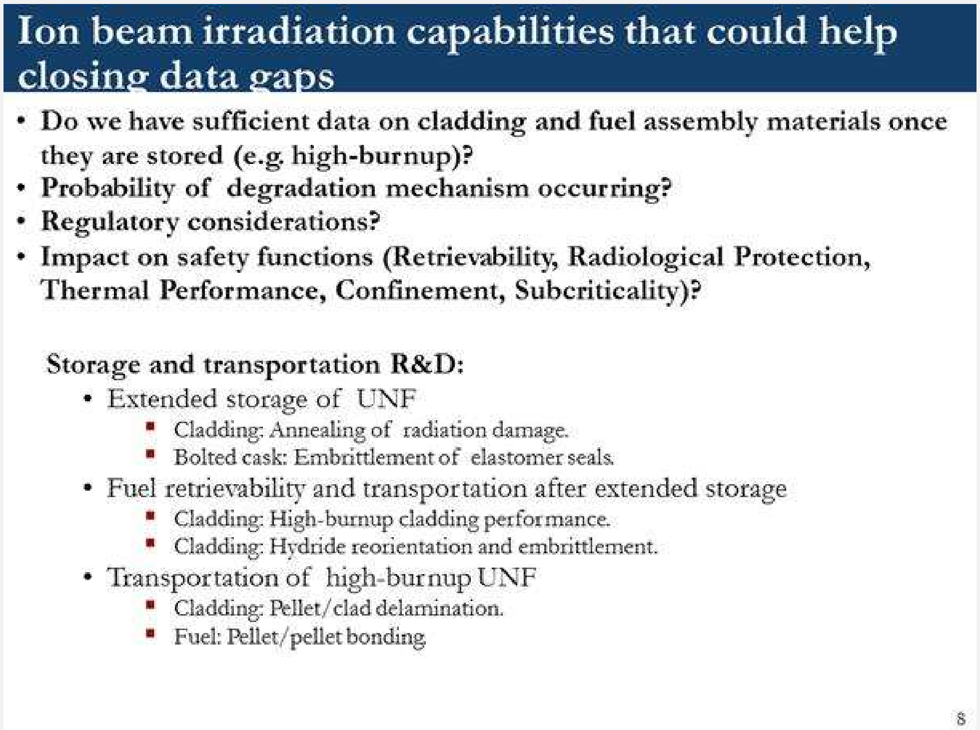
Gaps for storage and transportation

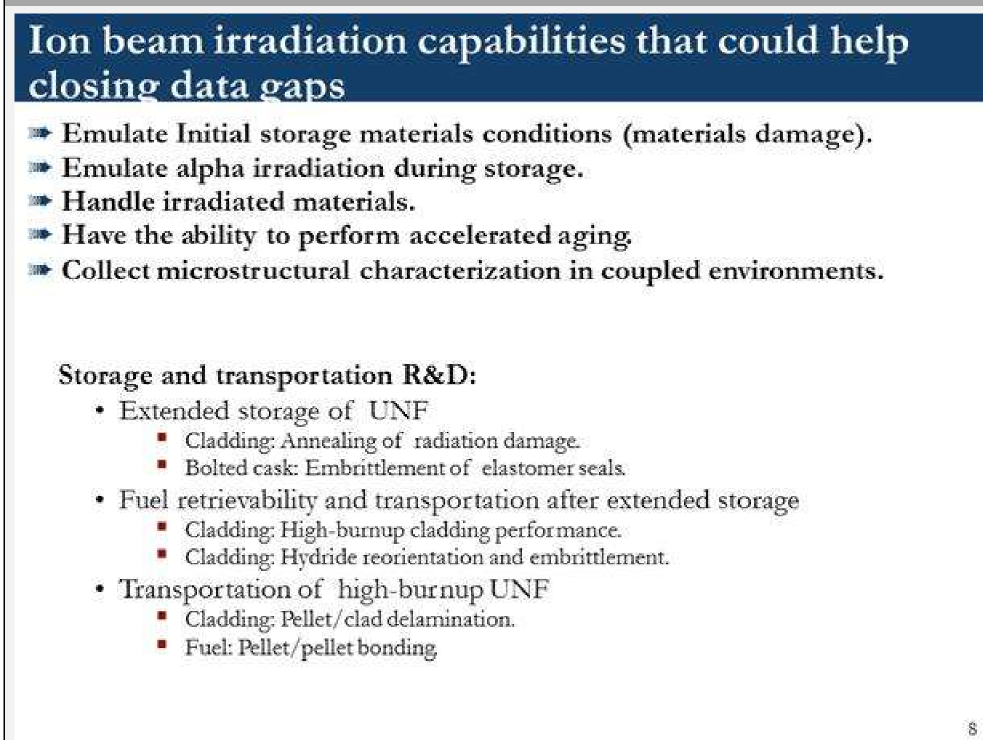
Gaps for storage and transportation

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 UNF, FCRD, 2011]

7

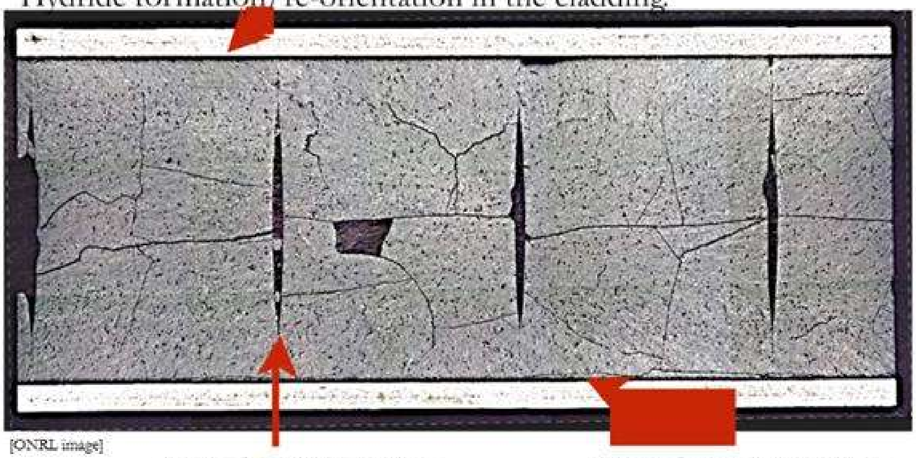
Ion beam irradiation capabilities that could help	
	1. Would the facility need to accept highly burned fuel?

Ion beam irradiation capabilities that could help	
	

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®.

10

Pellet/clad delamination (M/H)

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)

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)

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.

13

Review of criteria

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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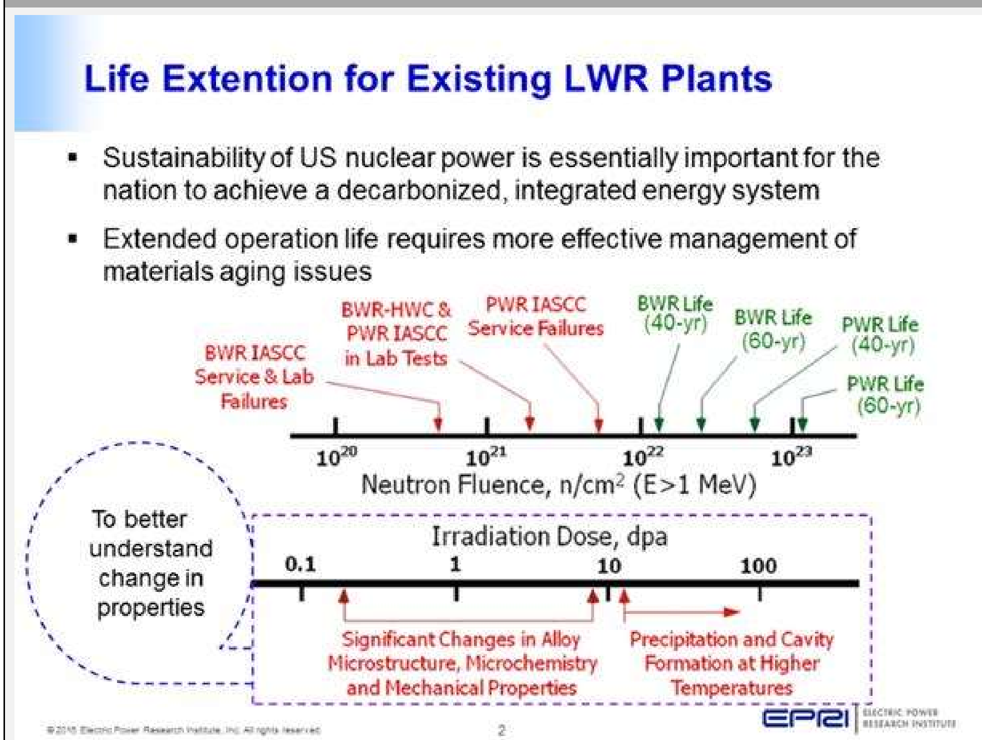
Presentation: EPRI

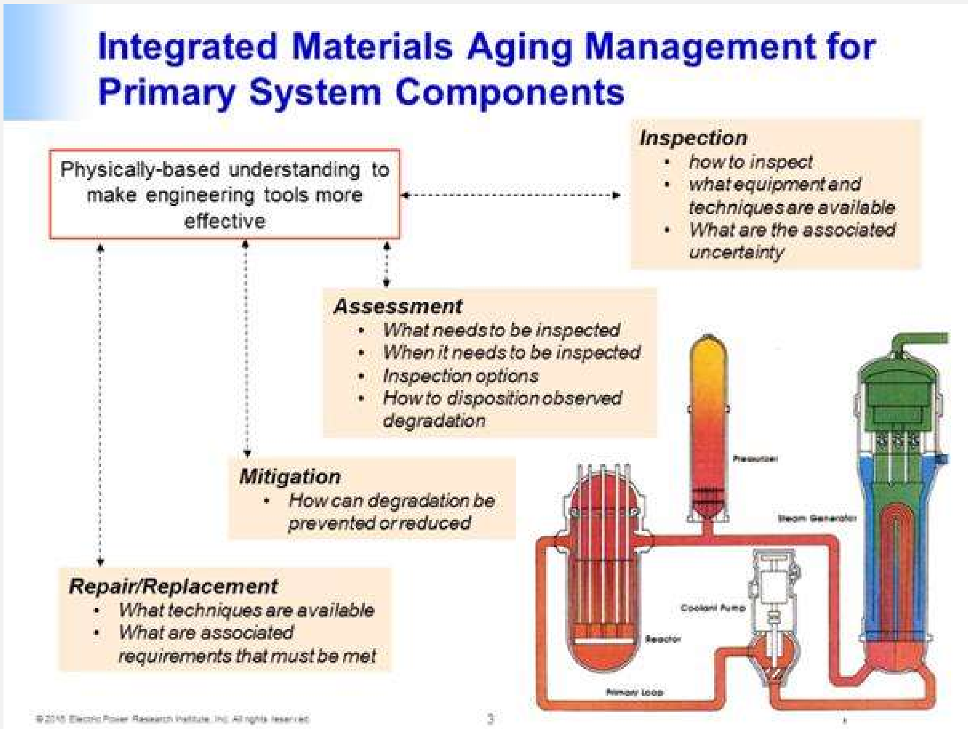
TG Lian

Slide 1

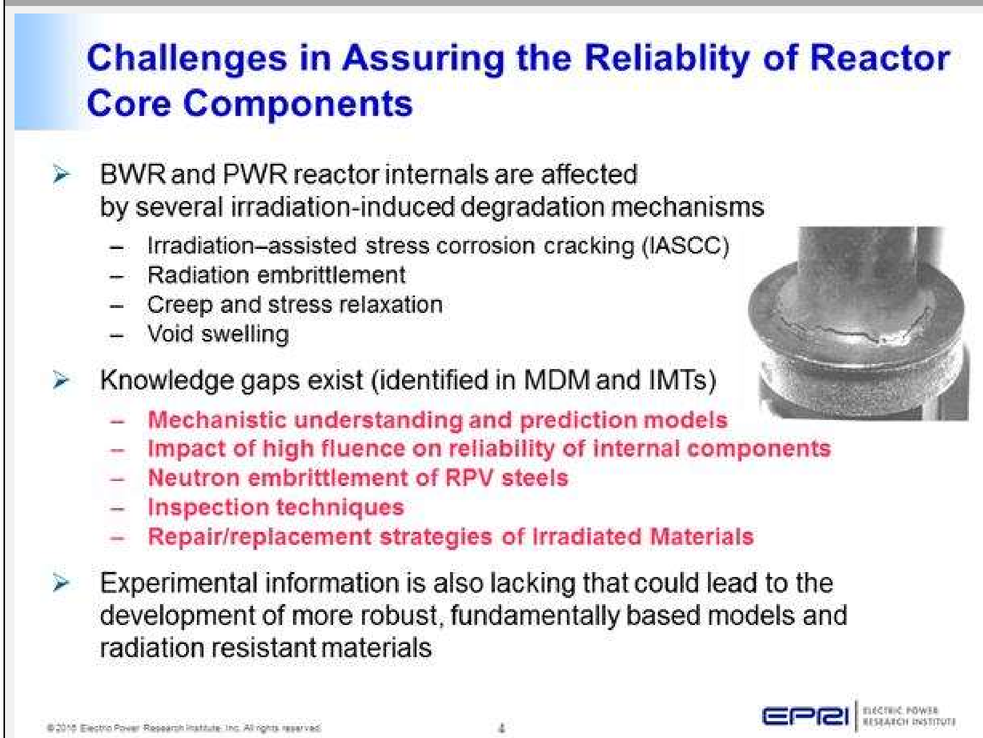
Life Extention for Existing LWR Plants



Integrated Materials Aging Management for Primary System Components



Slide 4



Slide 5

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

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Ion Irradiation Plays Complementary & Important Role

Ion Irradiation Plays Complementary & Important Role

- Neutron irradiation provides conditions protypical to reactor core internal environments
  - Preferred capability to validate enginnering 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,,,

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Use of Ion Irradiation in EPRI Materials R&D

Use of Ion Irradiation in EPRI Materials R&D

- Ion irradiation has been an important technique to support EPRI primalry 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 irradiatio 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**

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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)

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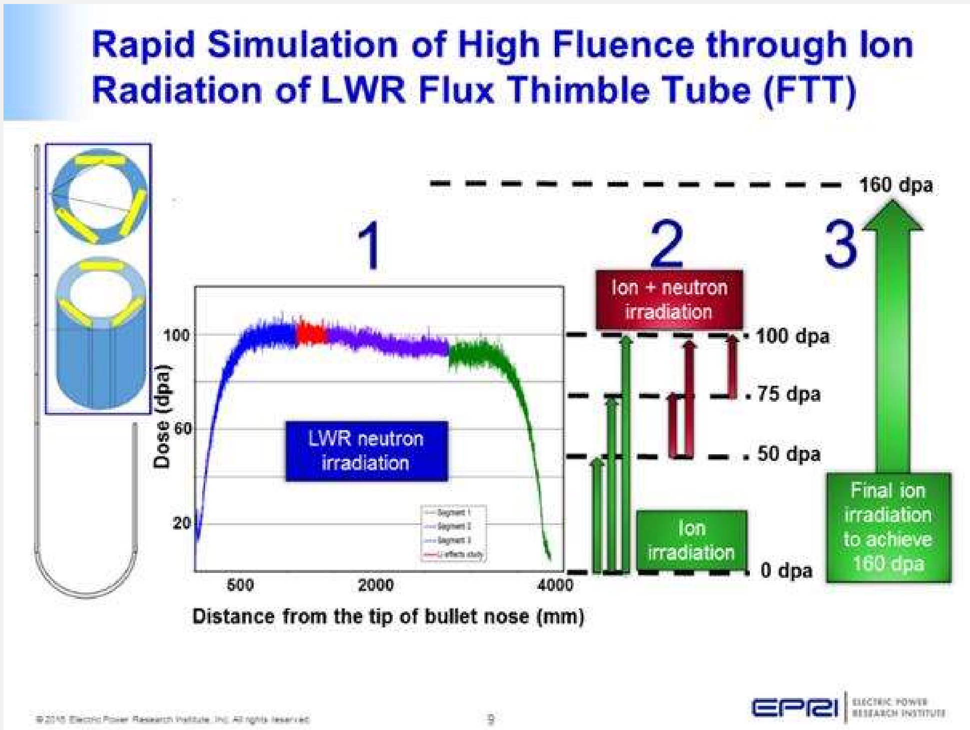
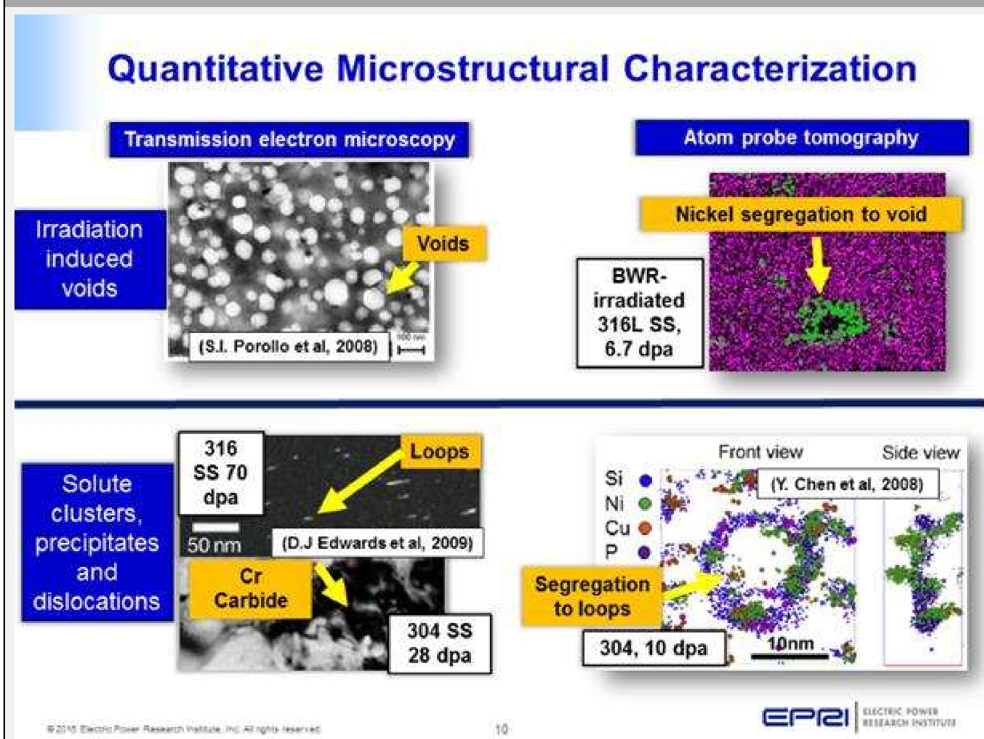
1. Amounts to the re-irradiation approach previously discussed.

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



Quantitative Microstructural Characterization



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)

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

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We Look for:

We Look for:

- Expertise: to plan right ion irradiation experiments
- Facilities: to perform the experients
- 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

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Together…Shaping the Future of Electricity

Appendix E

Ion Beam Facility Presentations

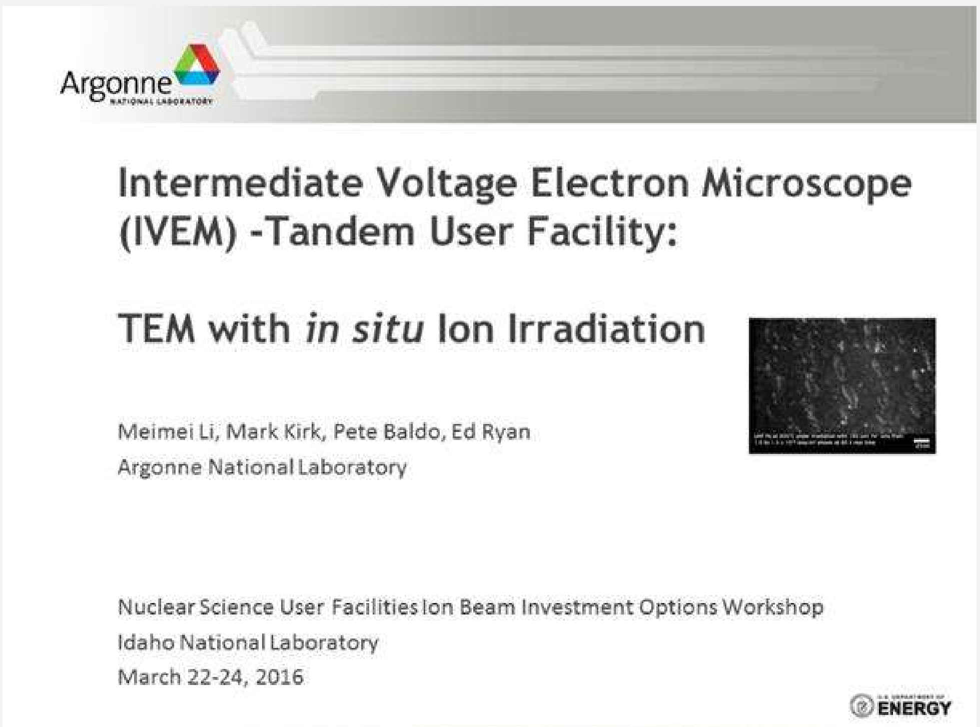
Appendix E

Ion Beam Facility Presentations

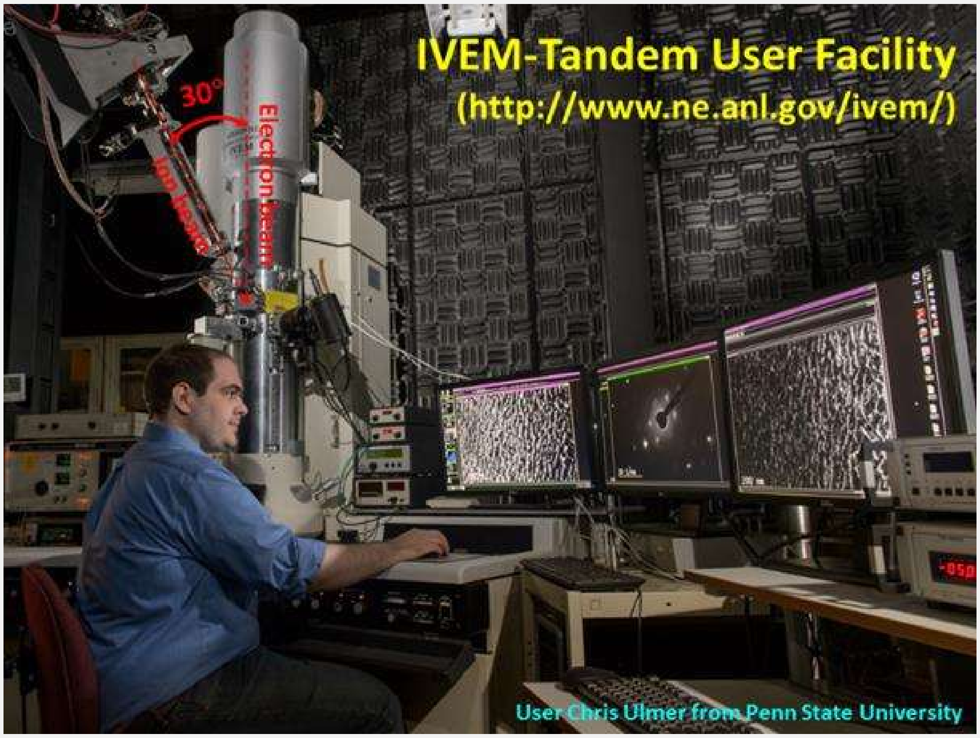
Presentation: IVEM-Tandem User Facility

Meimei Li

Slide 1



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/cm²/s (10^{-6}– 10^{-4} dpa/s)
High dose	~100 dpa/day
Beam size	Uniform beam , 1.5 mm ∅
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**

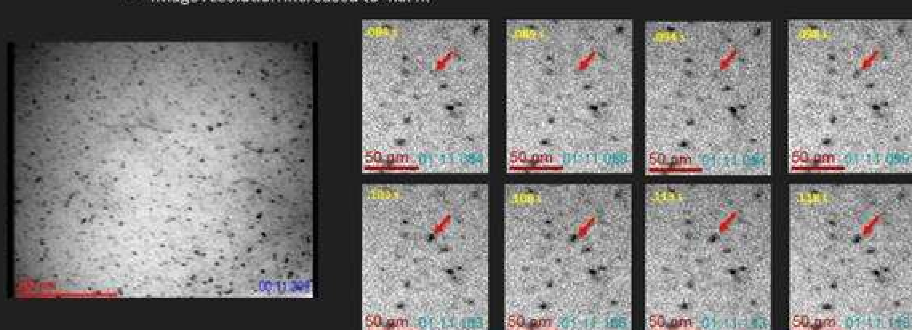
Coupling *in situ* ion irradiation with *in situ* stages for heating, cooling or straining enables studies of combined effects of irradiation, temperature and stress in real reactor environments that cannot be revealed through traditional post-irradiation examination.

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



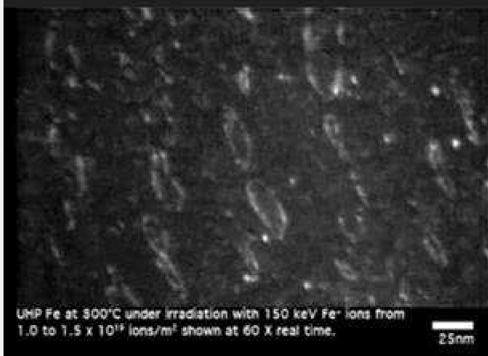
Cascade defect (dislocation loop) formed by single ion impact event between 0.089 and 0.094 sec.

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.



UHP Fe at 300°C under irradiation with 150 keV Fe^{+} ions from 1.0 to 1.5 x 10^{19} ions/m² shown at 60 X real time.

11 video files included in the publication revealed:

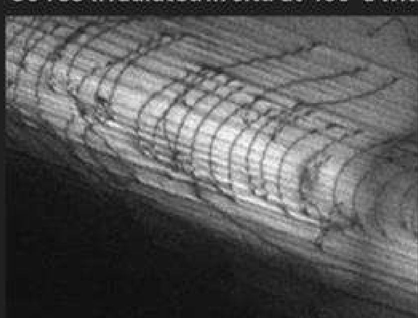
- One-dimensional hopping of small dislocation loops
- Dislocation loops with BV= <111> highly mobile in direction of BV.
- Dislocation loops with BV <100> sessile.
- Loop hopping was much less common in Fe-Cr alloys
- Some formed over 0.2 sec consistent with cascade overlap mechanism.
- Dislocation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

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-foils at higher doses," Phil Mag 88(21), 2881 (2008).

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 $3x10^{13}$ ions/cm².



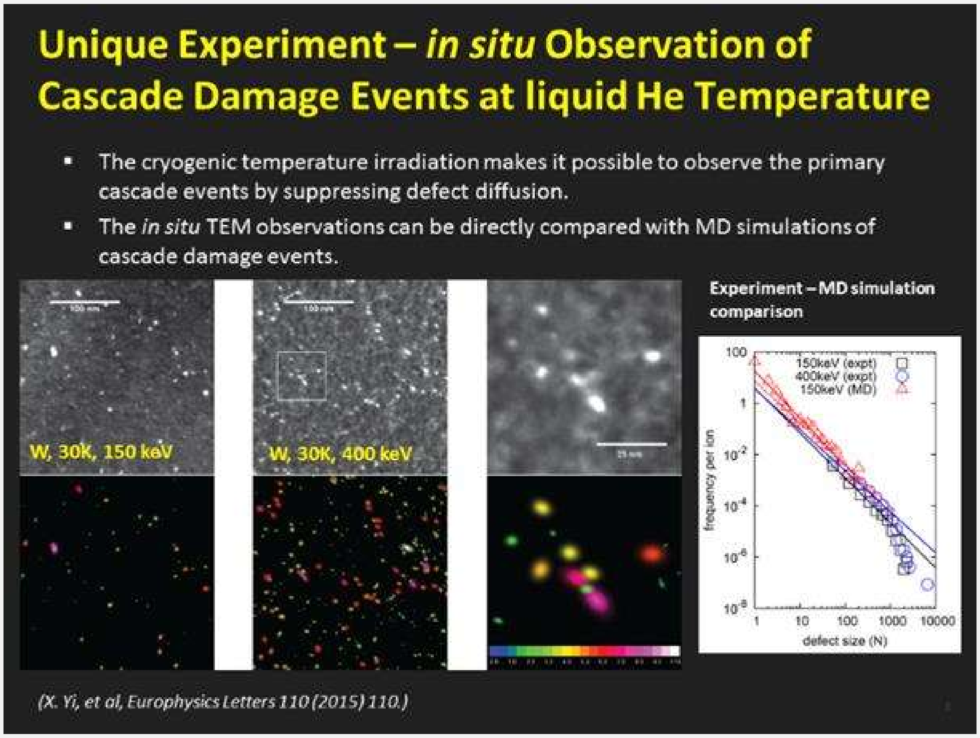
Without ion irradiation

With ion irradiation

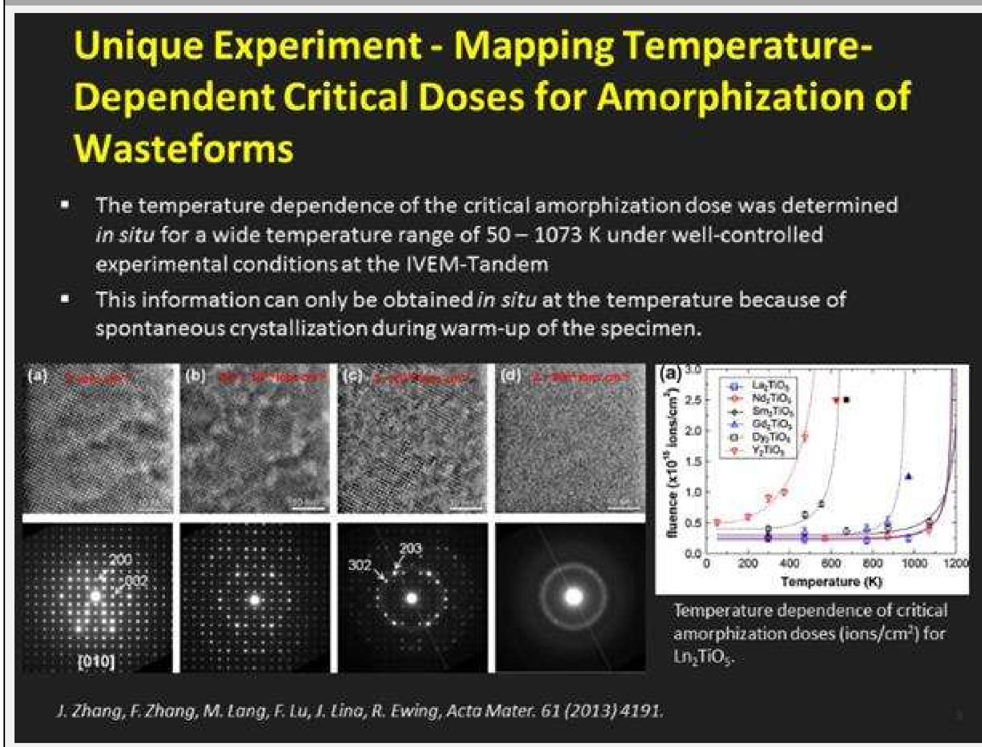
- Direct insight to the mechanisms by which dislocations interact with and annihilate radiation defects to create channels, dispelling some of the common held beliefs about the processes and mechanisms.
- New insight as to how strain is transferred across grain boundaries in irradiated metals, the results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

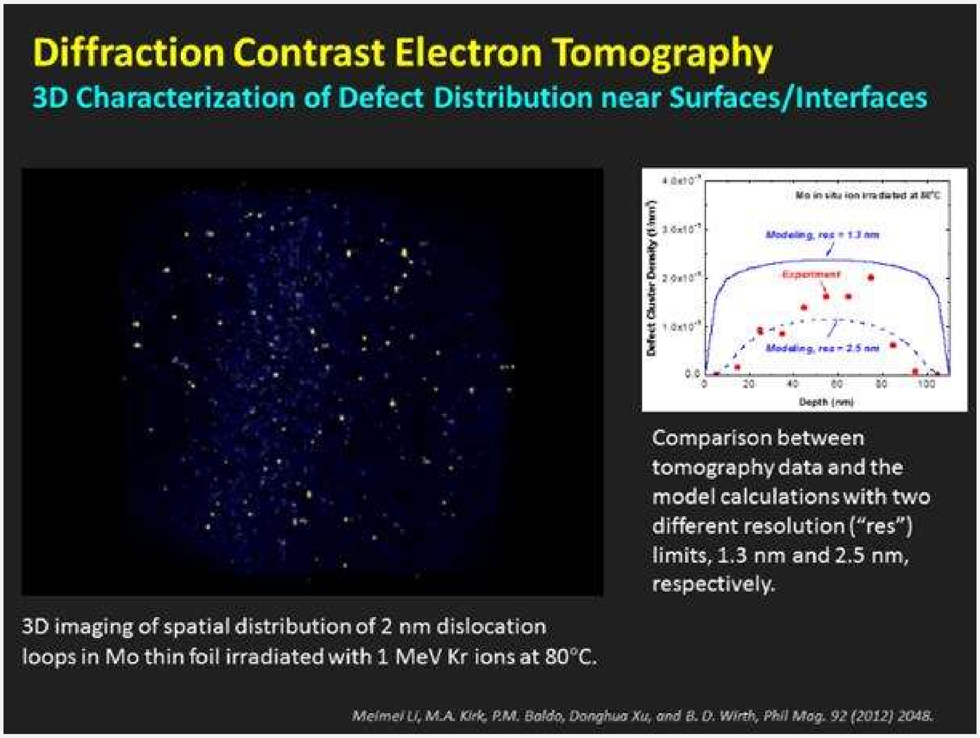
Unique Experiment – *in situ* Observation of Cascade Damage Events at liquid He Temperature



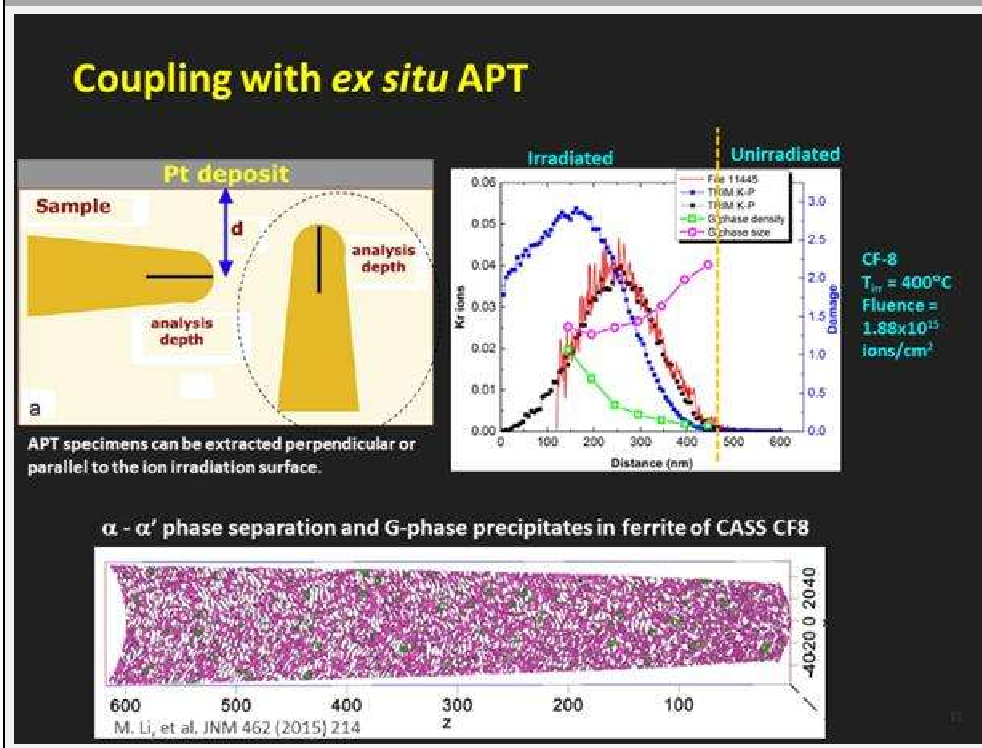
Unique Experiment – Mapping Temperature-Dependent Critical Doses for Amorphization of Wasteforms



Slide 10



Coupling with *ex situ* APT



Slide 12

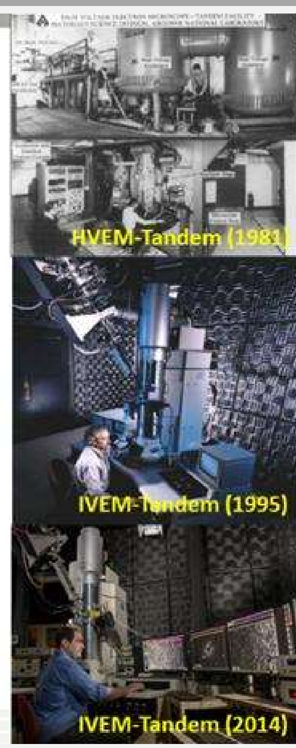
Radioactive Materials Handling

- 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

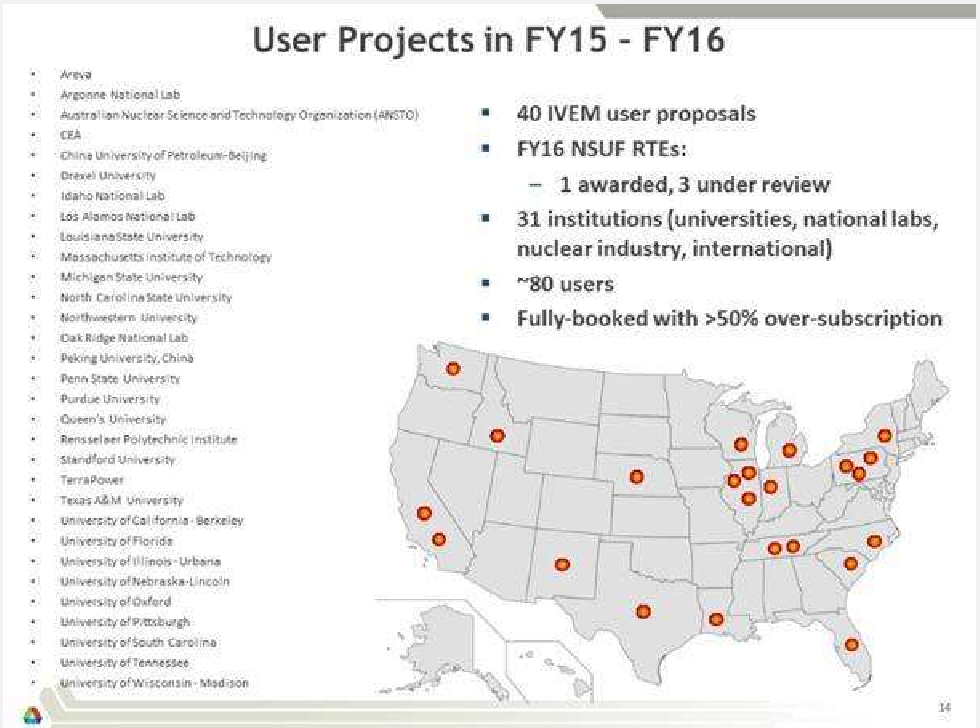
Facility History and Current Status

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.

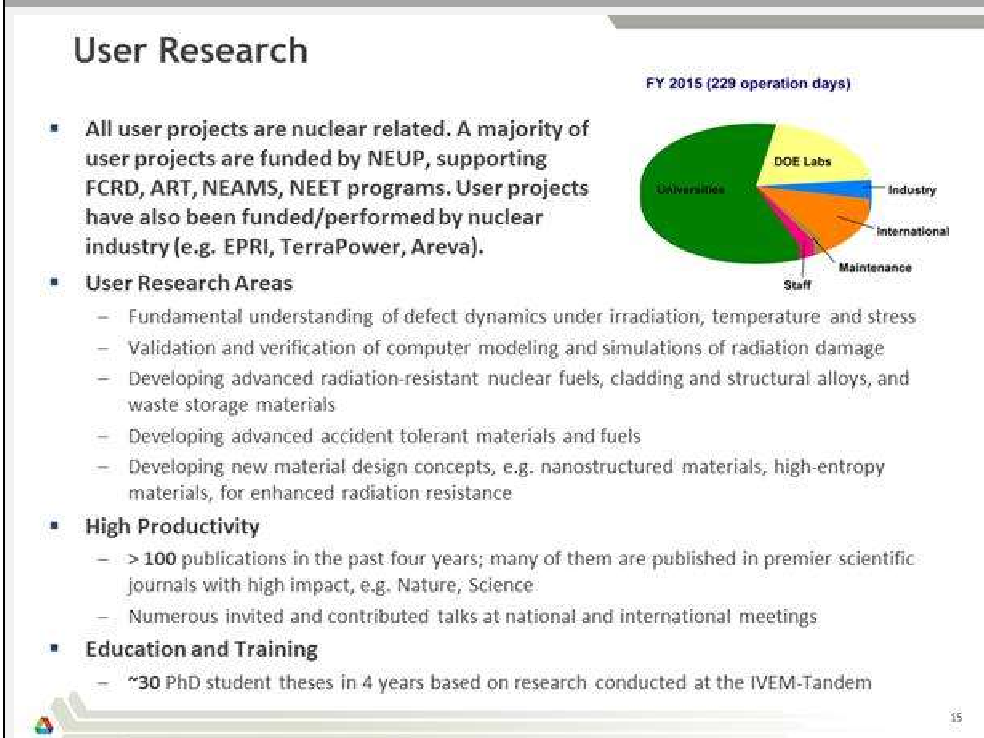


User Projects in FY15 – FY16

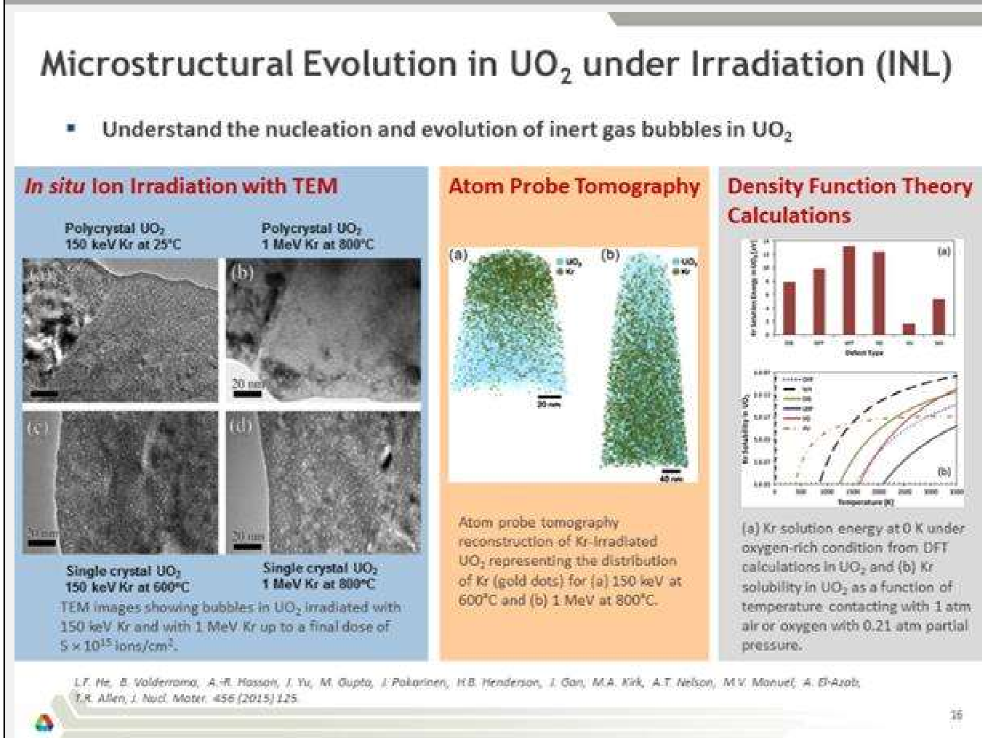


1. Can IVEM operate longer hours if funding was expanded?
2. With sufficient staff support, it can operate longer hours.

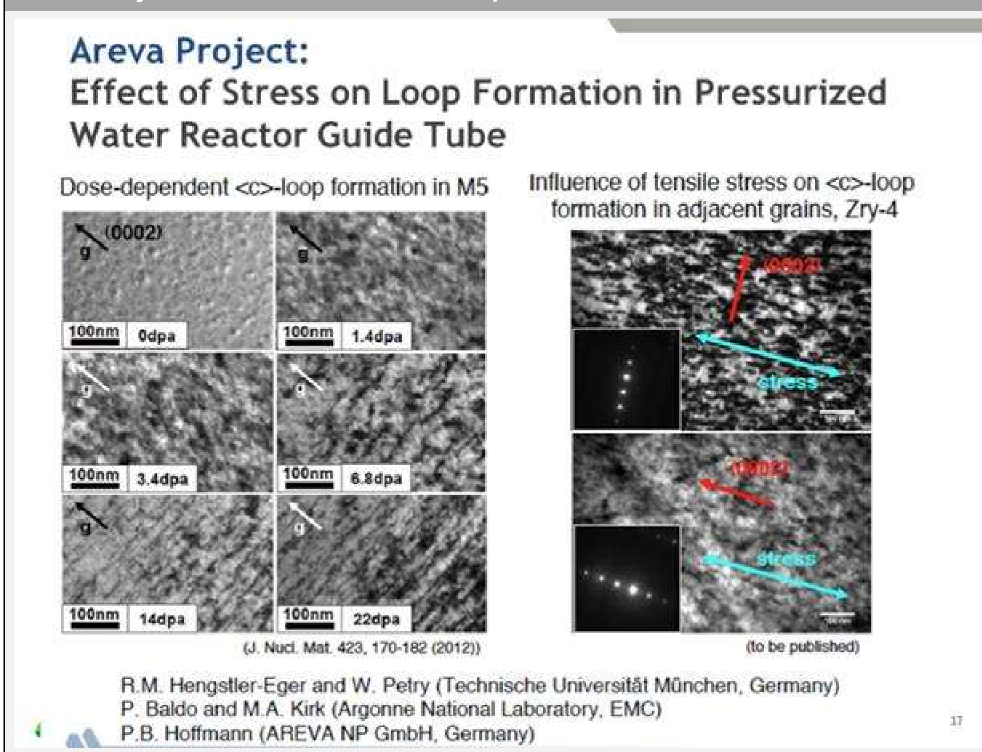
User Research



Microstructural Evolution in UO_2 under Irradiation (INL)



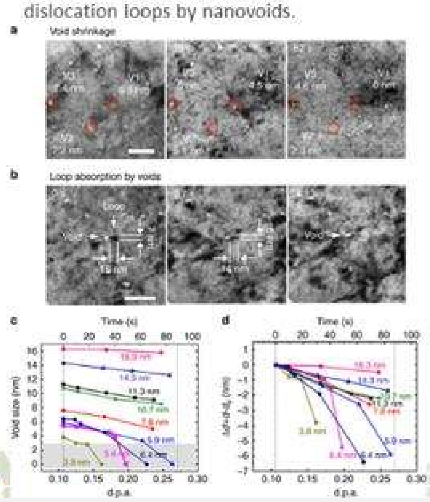
Areva Project: Effect of Stress on Loop Formation in Pressurized Water Reactor Guide Tube



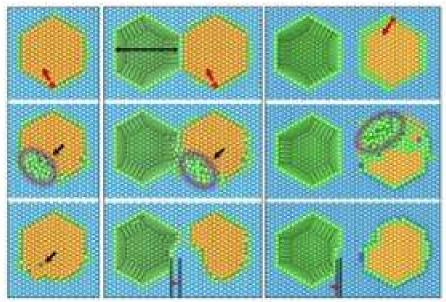
Exploring New Alloy Design Concept: Radiation-tolerant Nanotwinned Metals with Nanovoids (Texas A&M, PI: X. Zhang)

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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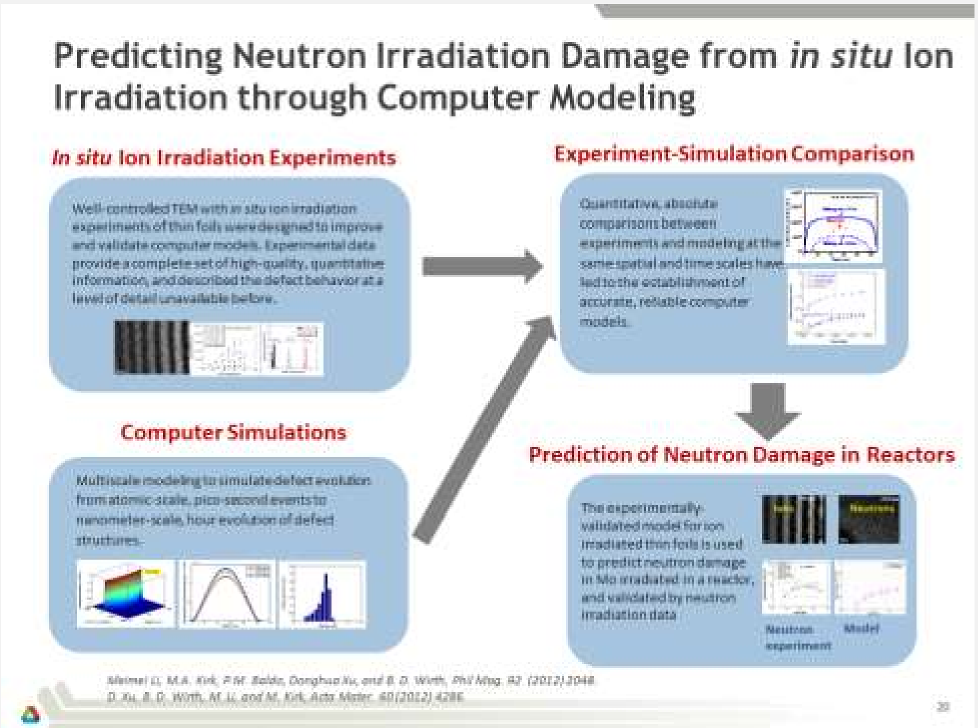
Slide 20



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.

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Support Letters from the Community

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

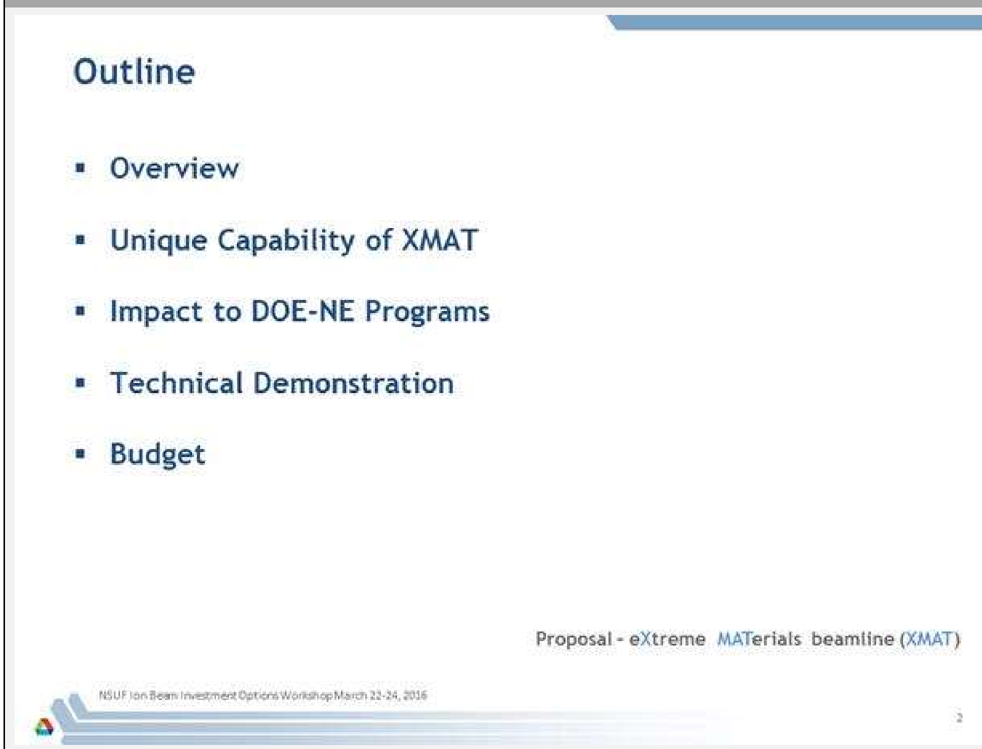
22

Presentation: Extreme Materials Beam Line

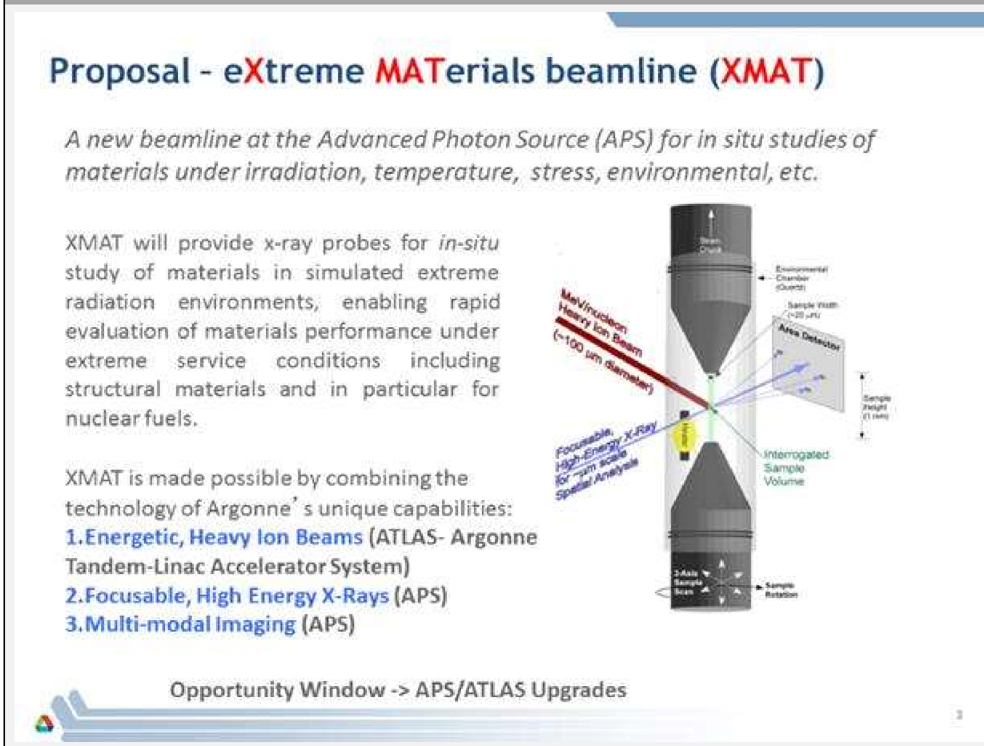
Abdellatif Yacout

Slide 1

Outline

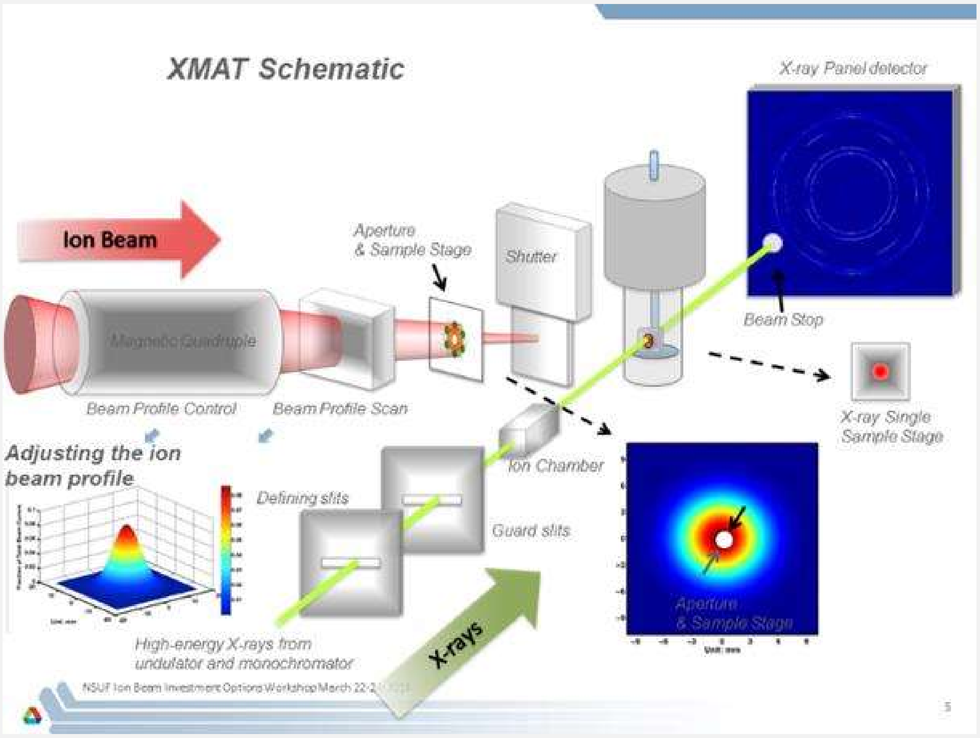


Proposal – eXtreme MATerials beamline (XMAT)

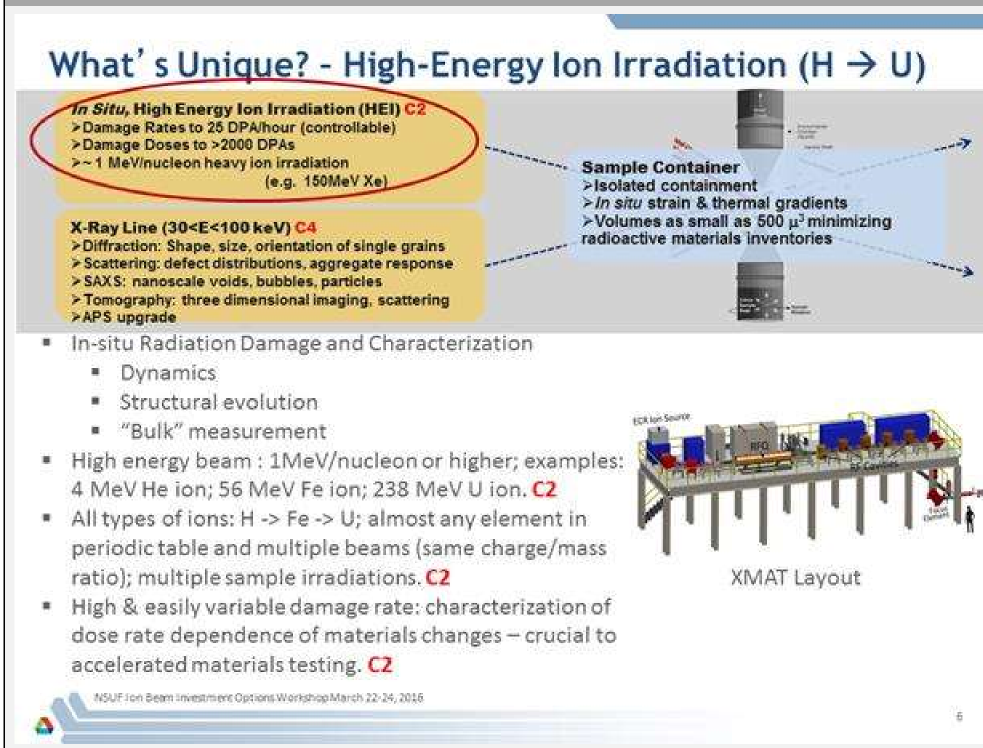


Timeline of XMAT

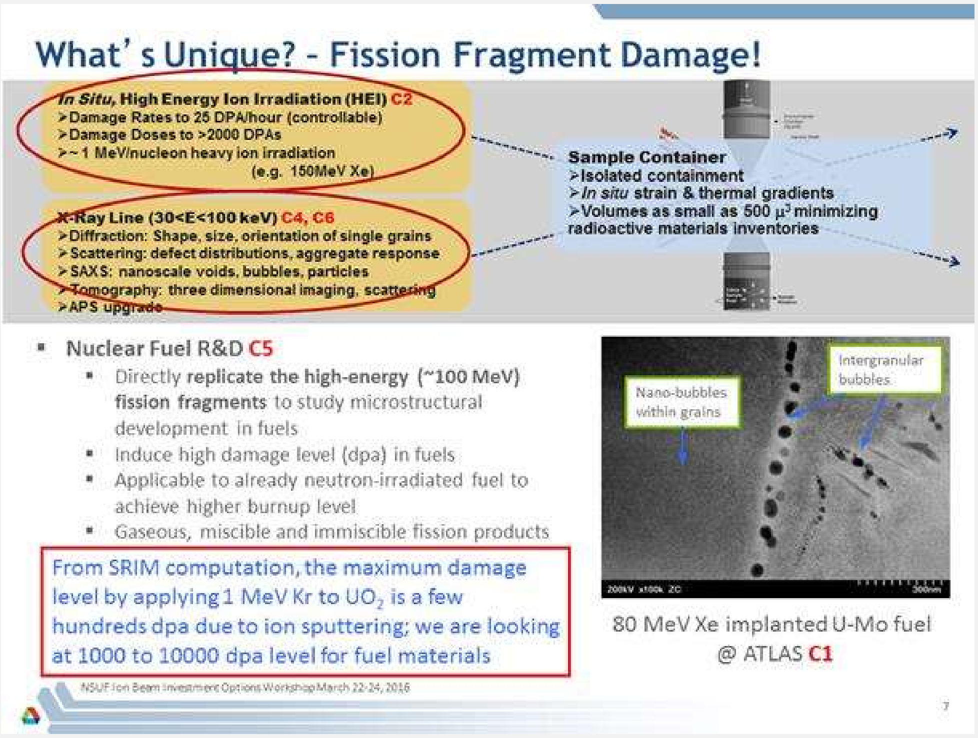
Slide 5

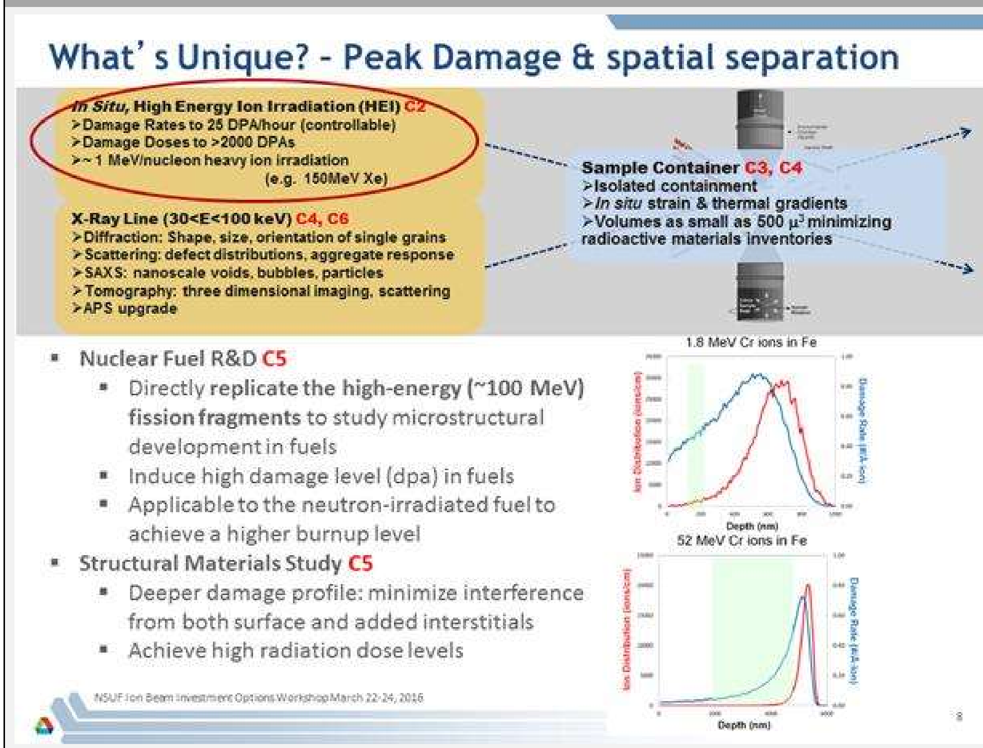


What's Unique? – High-Energy Ion Irradiation (H → U)

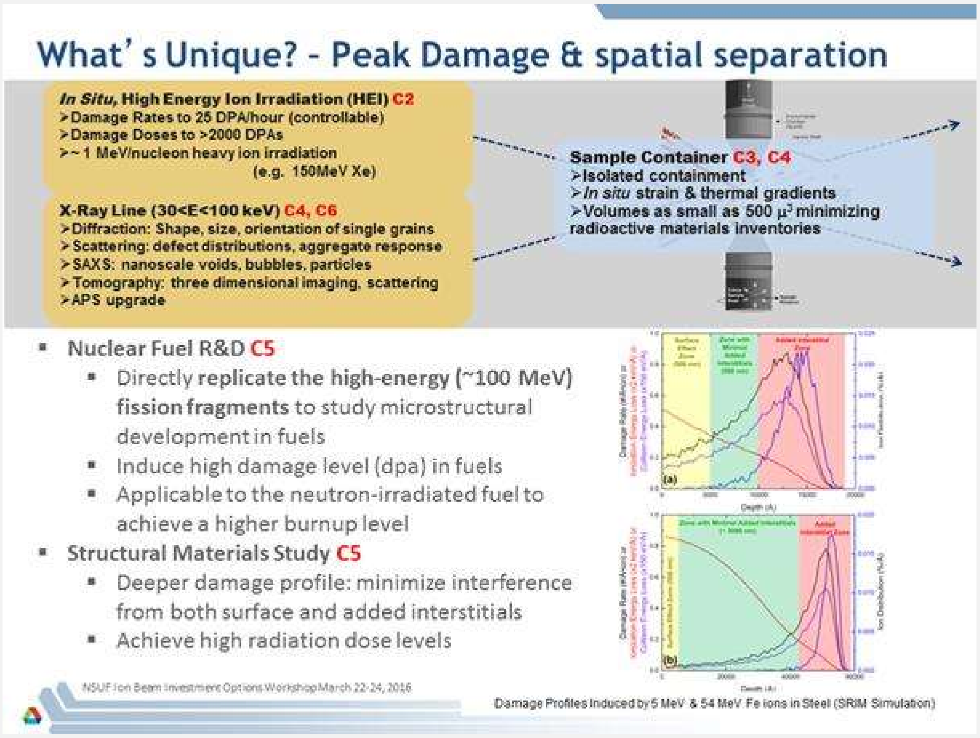


1. What ion flux is available?
2. High current beams will result in significant sample heating. This will likely require active cooling.

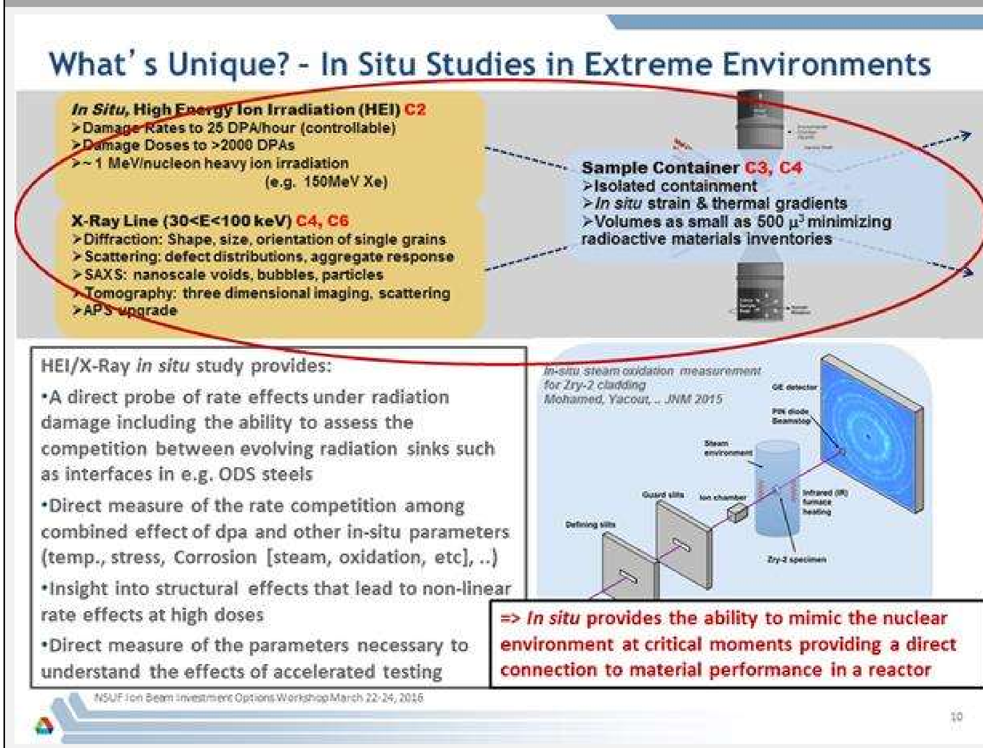
What's Unique? – Fission Fragment Damage!	
	1. What is the planned imaging resolution?

What's Unique? – Peak Damage & spatial separation	
	

What's Unique? – Peak Damage & spatial separation



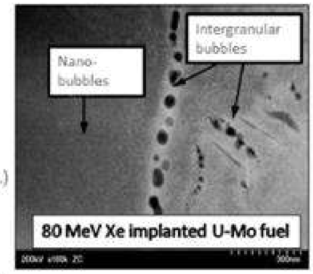
What's Unique? – *In Situ* Studies in Extreme Environments

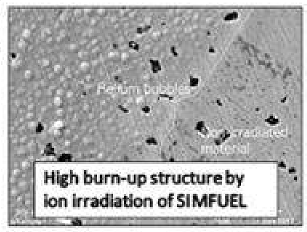


Impact on NE Research Programs C5

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 burnps (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





Baranov, *JNM*, 452, 2014

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

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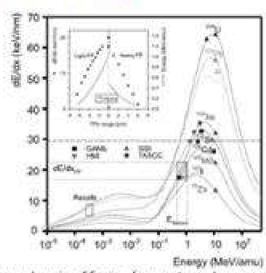
1. How do you control beam heating when producing high burnup structure?

Applications to Oxide and Silicide Fuels C5

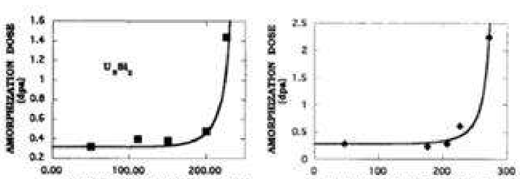
Applications to Oxide and Silicide Fuels C5

- **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



Energy domain of fission fragments and corresponding energy loss rate in UO_2 (Matzke, 2000)

Gas bubble formation induced by 40 keV Kr implantation and 72 MeV I irradiation in UO_2 (Matzke, 2000)



Amorphization threshold of U_3Si_2 and U_3Si by *in situ* ion irradiation (Birtcher, 1996&1997)

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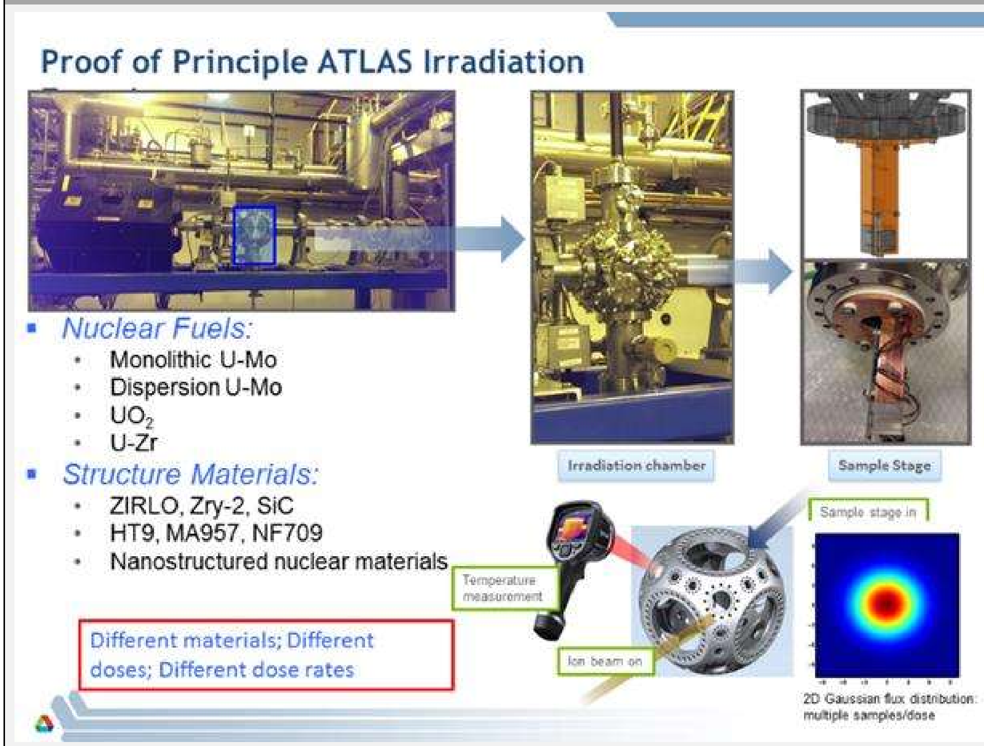
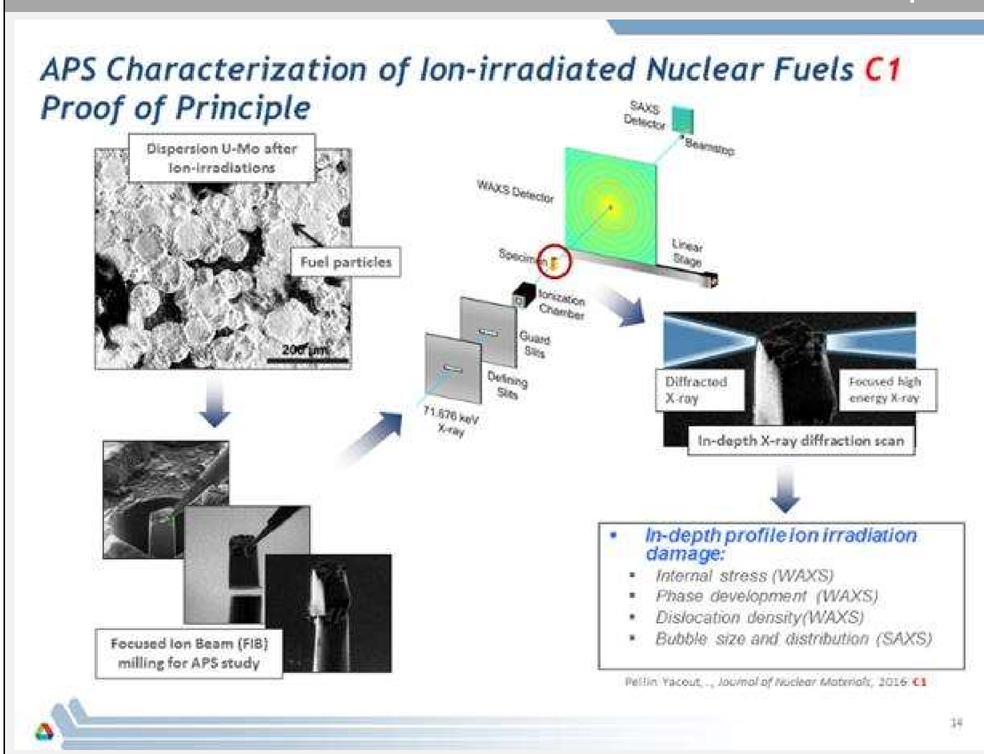
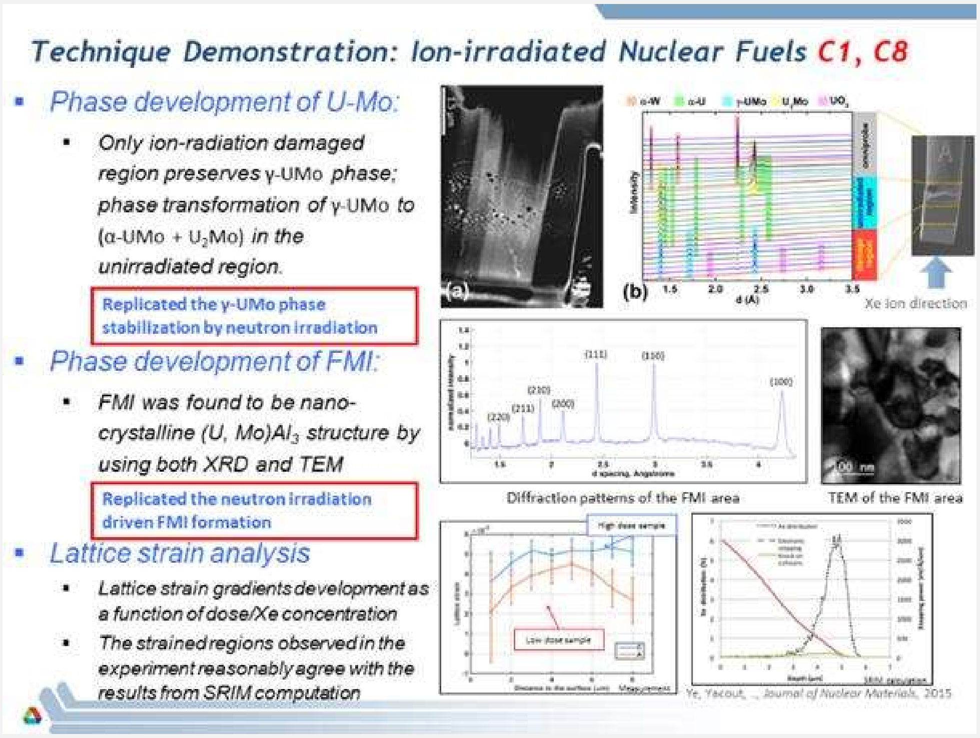
Proof of Principle ATLAS Irradiation Experiments



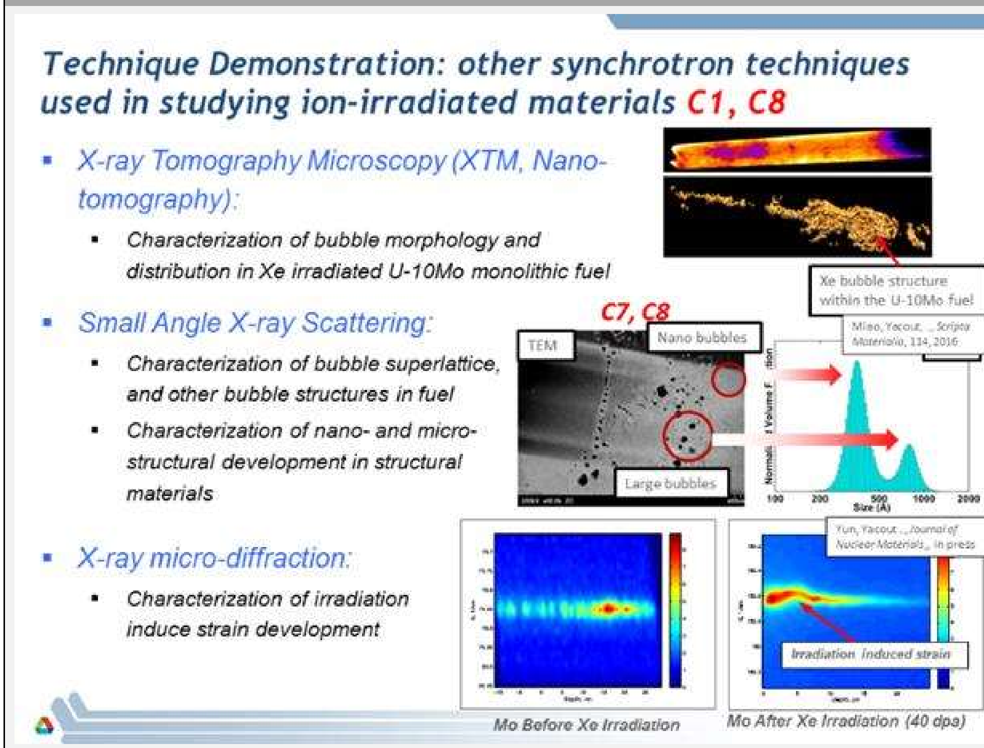
APS Characterization of Ion-irradiated Nuclear Fuels C1 Proof of Principle



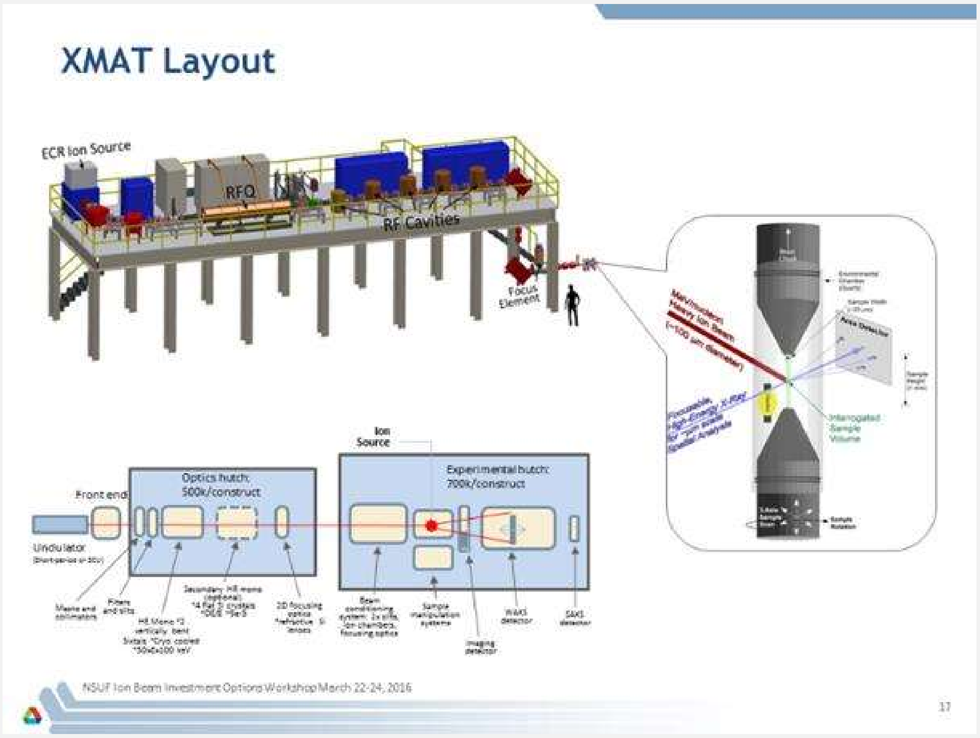
Technique Demonstration: Ion-irradiated Nuclear Fuels C1, C8	



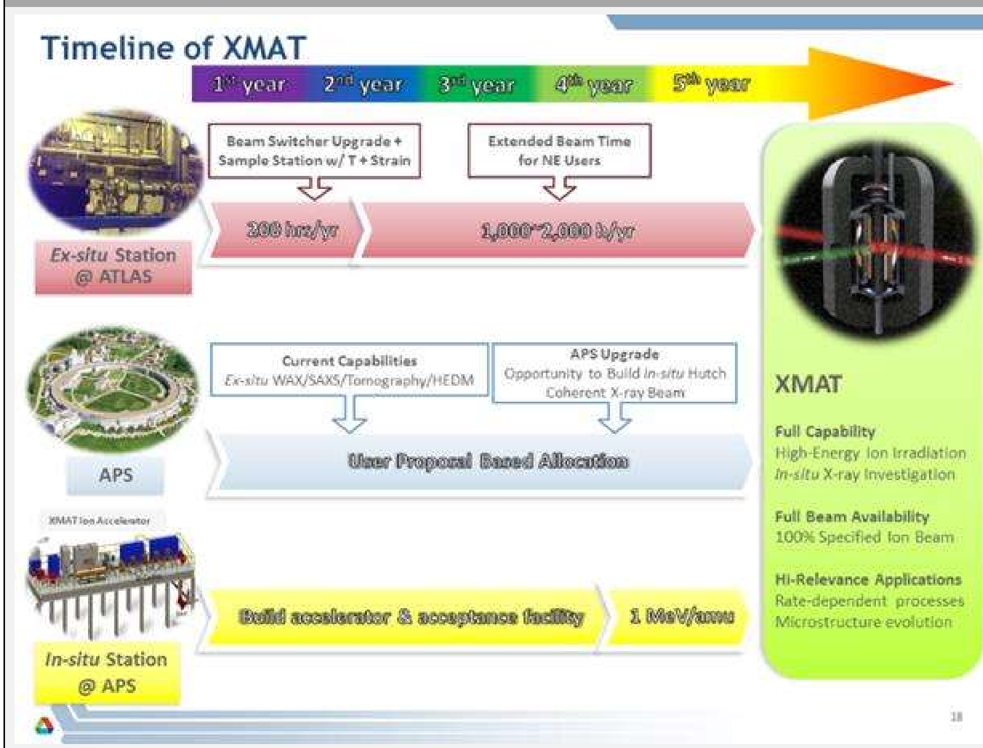
Technique Demonstration: other synchrotron techniques used in studying ion-irradiated materials C1, C8	
	1. Sample size for unirradiated fuel = 1 mm. Irradiated fuel at 10% BU = FIB sample.



XMAT Layout



Timeline of XMAT



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

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BACKUP

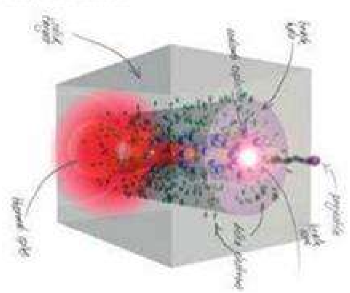
BACKUP

Nuclear Waste Forms

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

Slide 2

Idaho State University RISE Complex

Idaho State University
RISE Complex

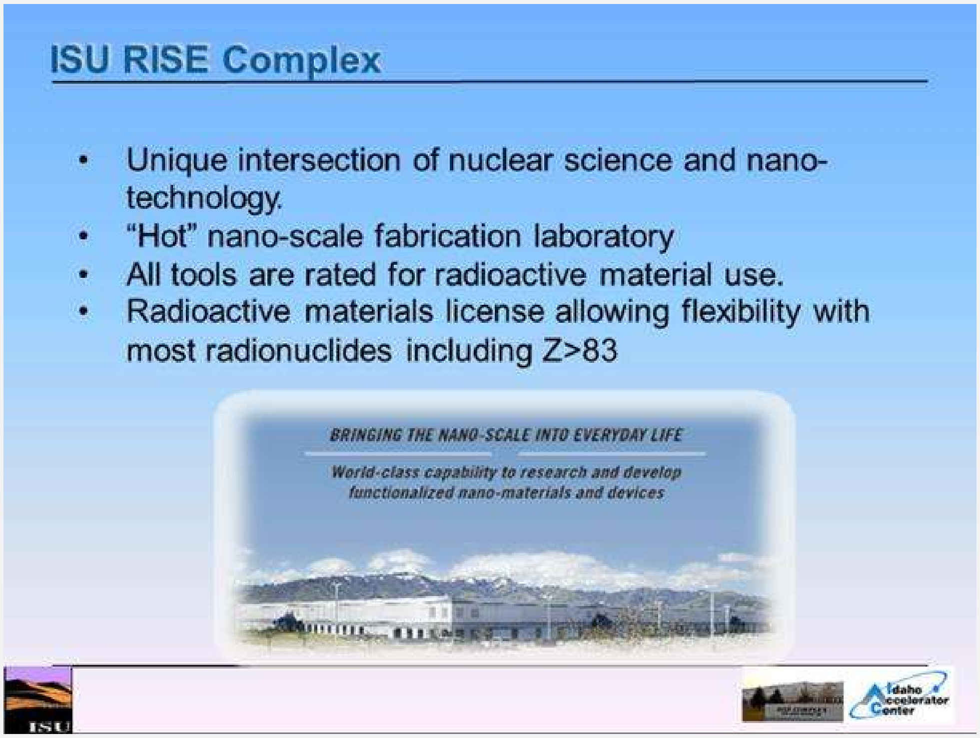
Dr. Eric Burgett
Director, RISE Complex
Idaho State University

Idaho Accelerator Center Operating for 20 Years

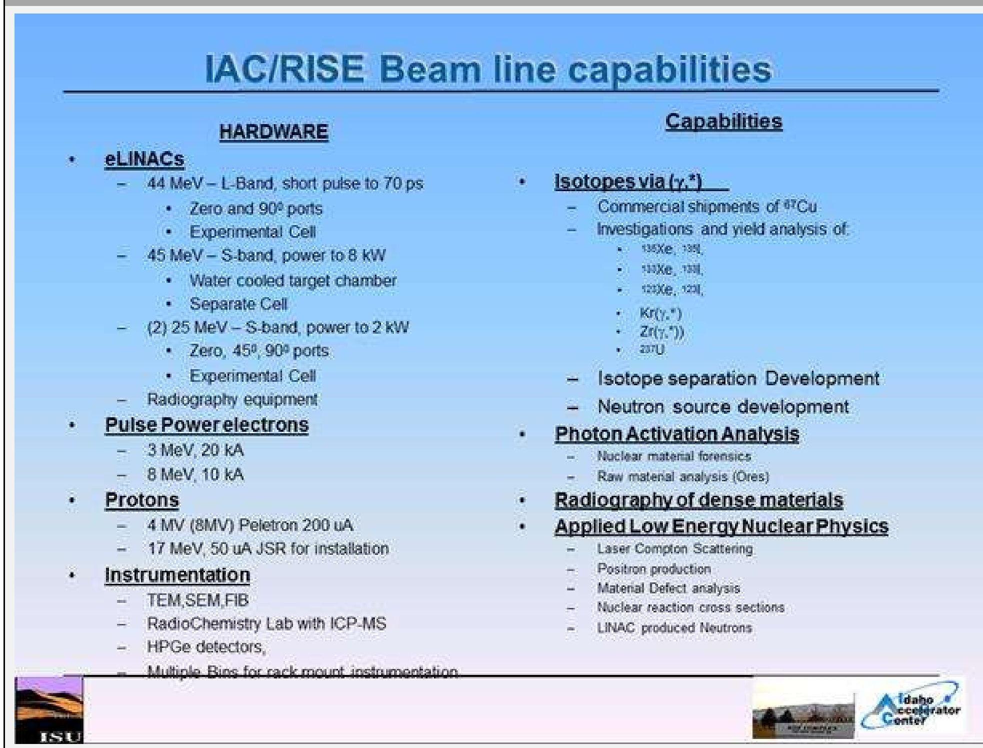
Idaho Accelerator Center Operating for 20 Years

- 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

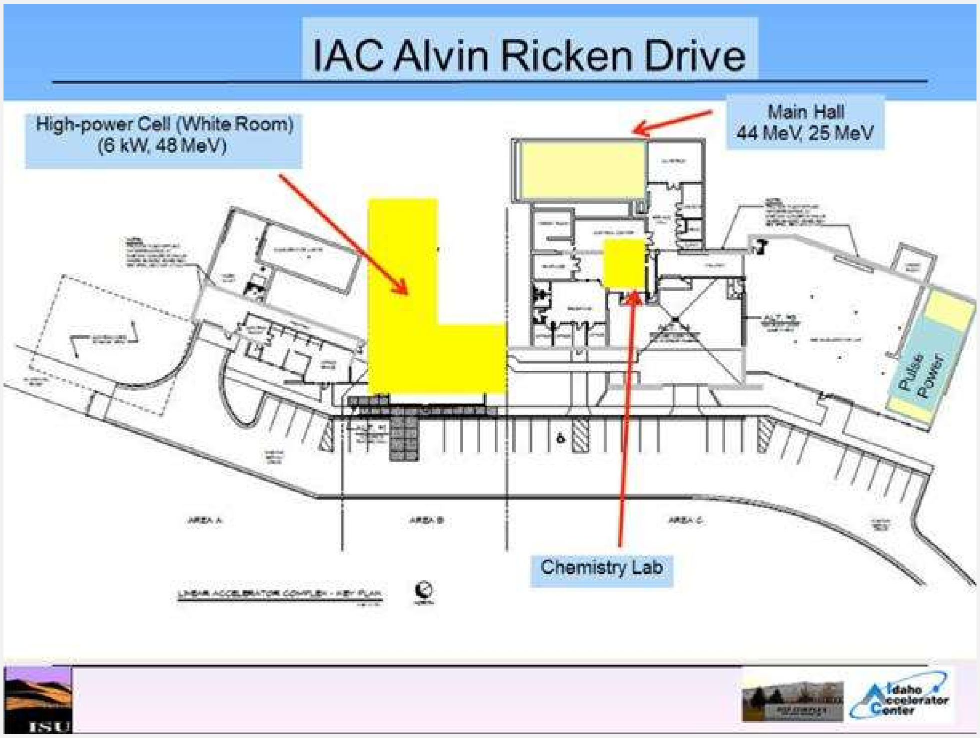
ISU RISE Complex



IAC/RISE Beam line capabilities



IAC Alvin Ricken Drive



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	0.5A	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%)

25B Energy vs Current

Energy (MeV)	0 port (mA)	45 port (mA)	90 port (mA)
23	55	55 @ 3.8uS	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 @ 3.3uS
10	60	18 @ 3 uS	7.5 @ 3 uS
9	110	30 @ 4uS	15 @ 4 uS
6	100	60 @ 4 uS	60 @ 4 uS
4	50	20 @ 4 uS	20 @ 4 uS

ISU

Idaho Accelerator Center

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

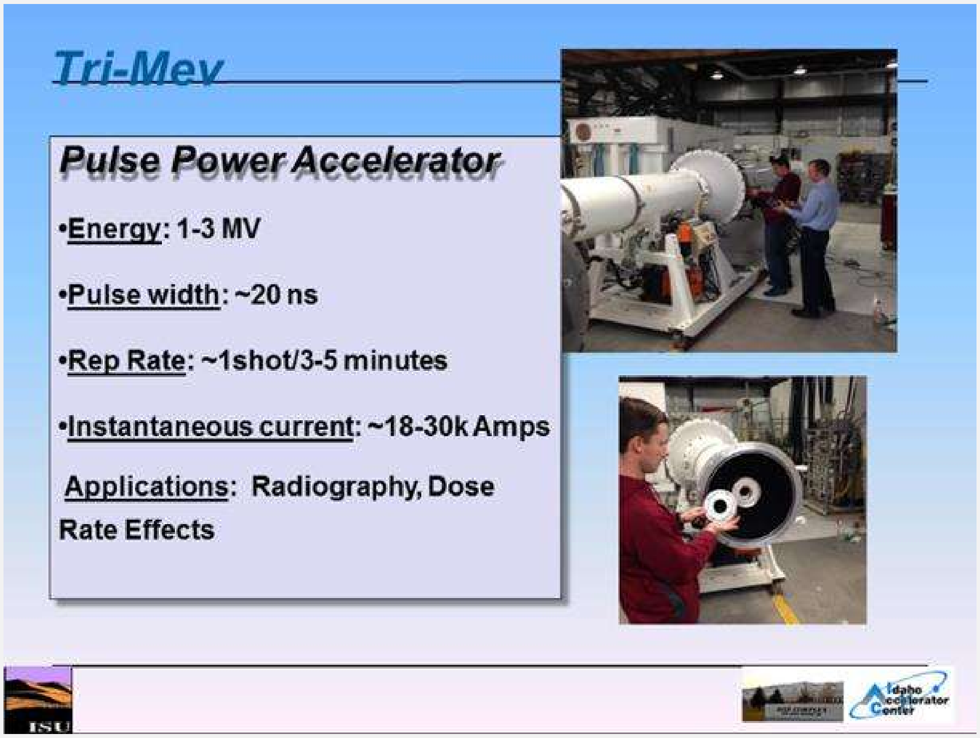
Ports: 0 degree, 45 degree

Special features: High power water cooled target

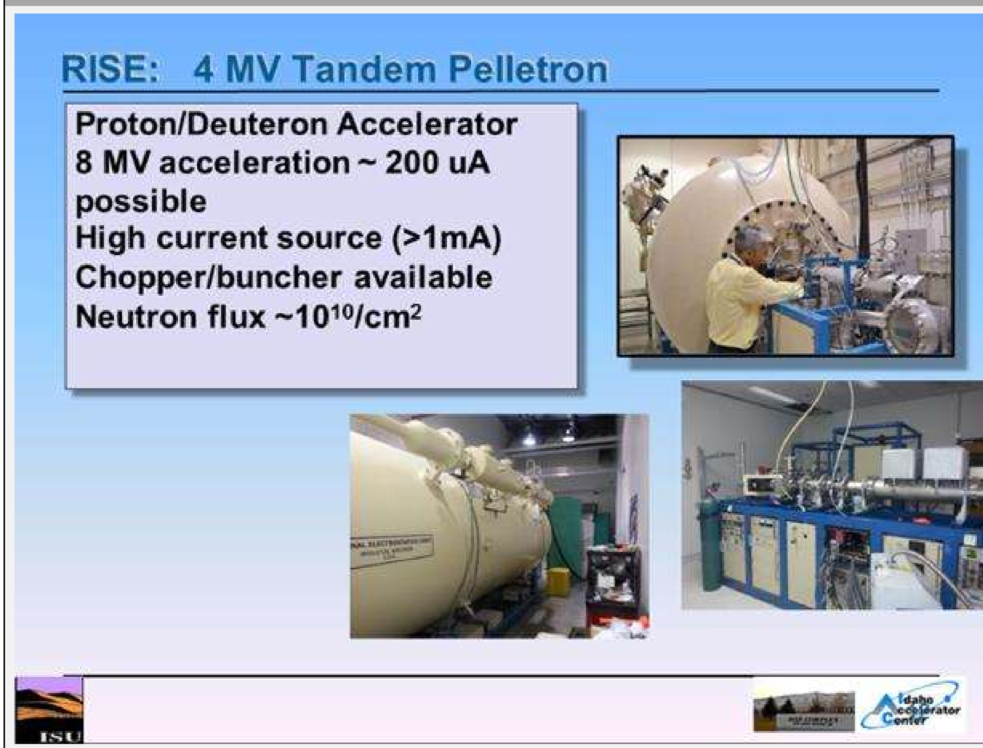
ISU

Idaho Accelerator Center

Tri-Mev



RISE: 4 MV Tandem Pelletron



TEM/SEM/FIB Lab

RISE TEM/SEM/FIB Lab

RISE Lab: TEM/SEM/FIB Capability

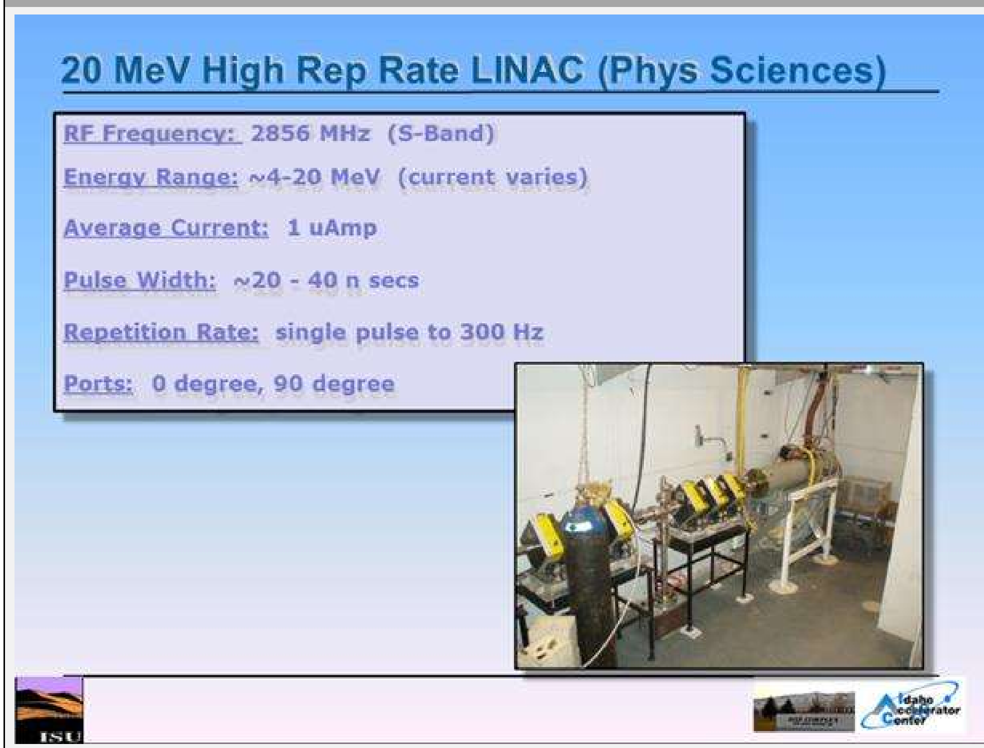
RISE Lab: TEM/SEM/FIB Capability

- 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 A 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)

20 MeV High Rep Rate LINAC (Phys Sciences)



IAC Airport

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

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

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

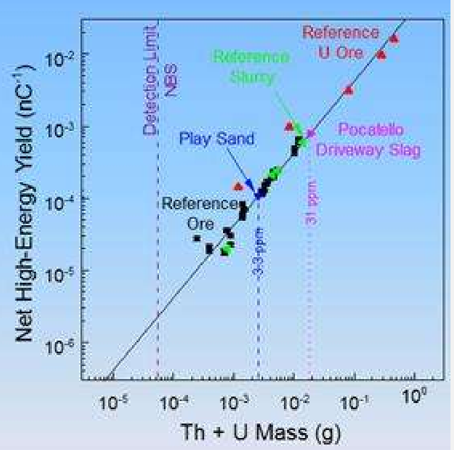
Applications in:

- 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

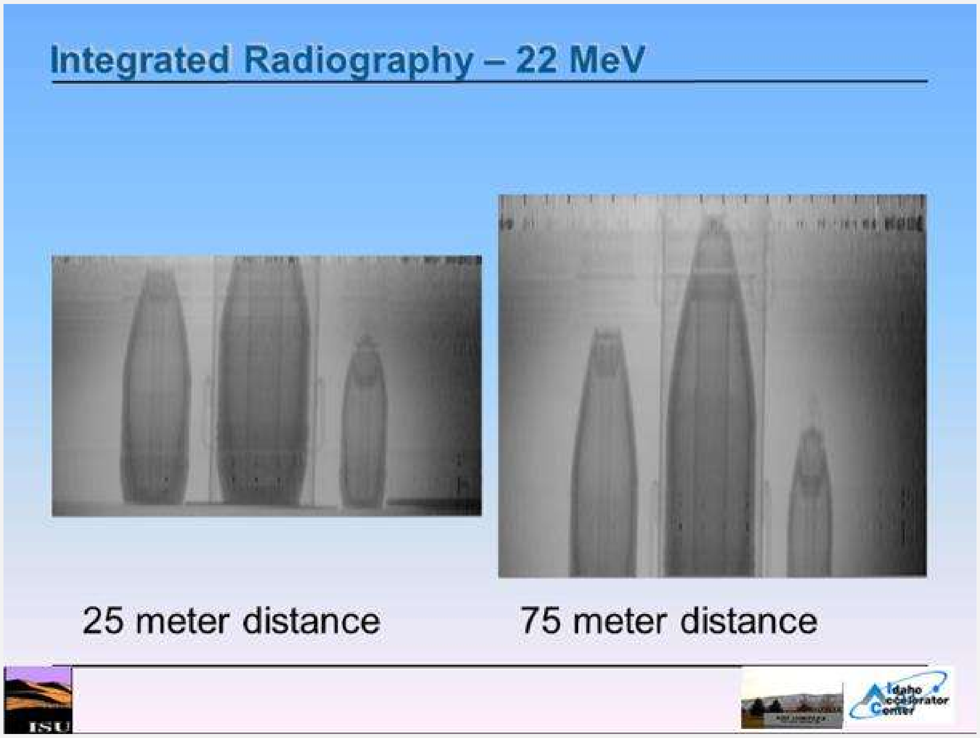
Rapid Activation → Fast Detection Assays

Rapid Activation → Fast Detection Assays

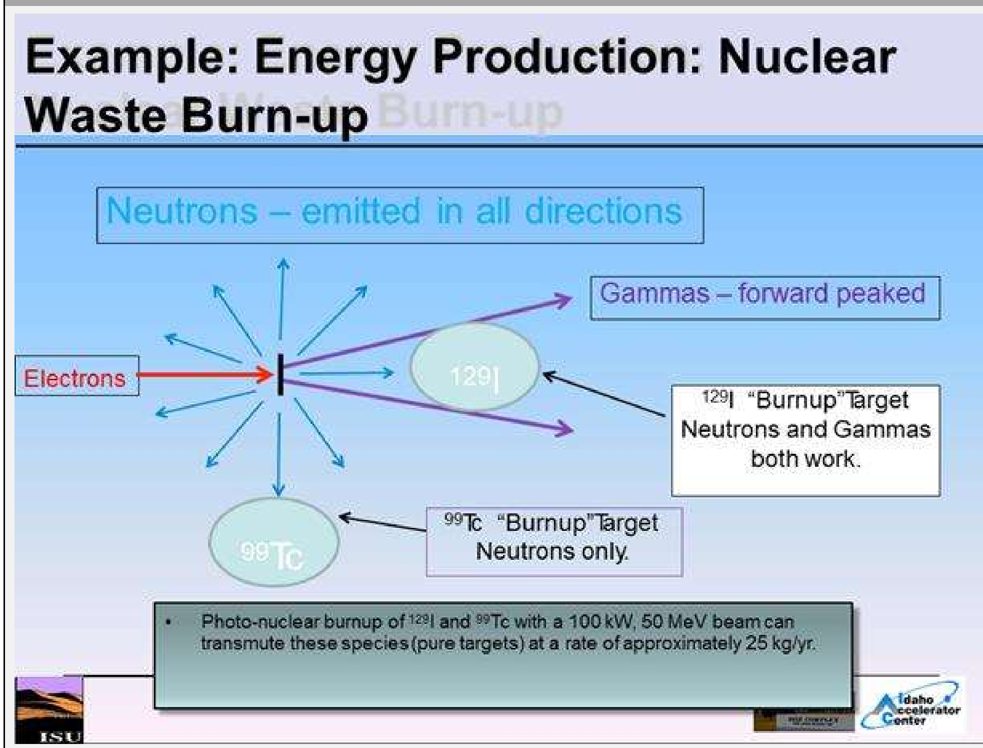
- Rapid activation
  - Increase signal over passive by ~10
  - More signal → faster assay (~ 1 min)
  - Continuous monitoring to segregate
- Signal linearly related to Th+U mass
  - Validates rapid assay
  - Detection limit: ~320 ppb
  - Matrix independent (e.g. dry vs. slurry)
- Optimization possibilities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



Integrated Radiography – 22 MeV

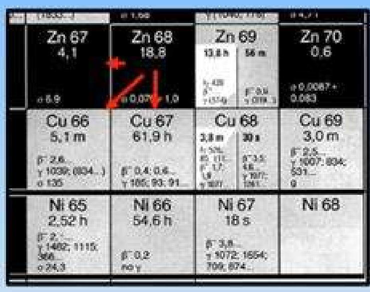


Example: Energy Production: Nuclear Waste Burn-up



Production of Isotopes

Production of Isotopes



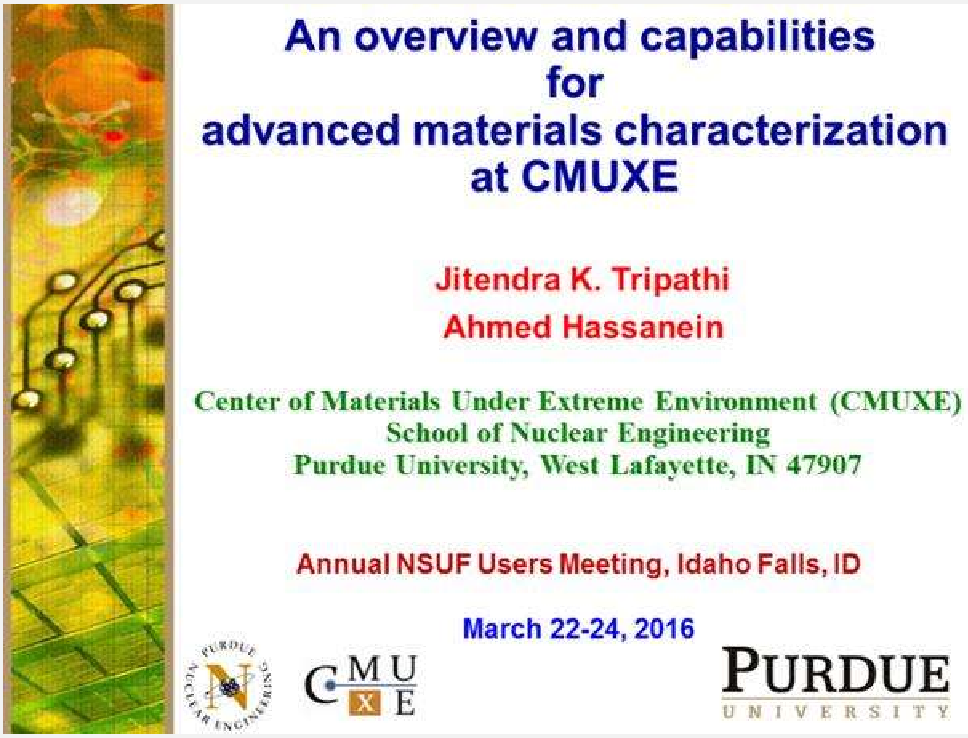
Gama based reactions:

- ^{68}ZN (γ,n) ^{67}Zn
- ^{68}ZN (γ,p) ^{67}Cu
- ^{68}ZN (γ,pn) ^{66}Cu

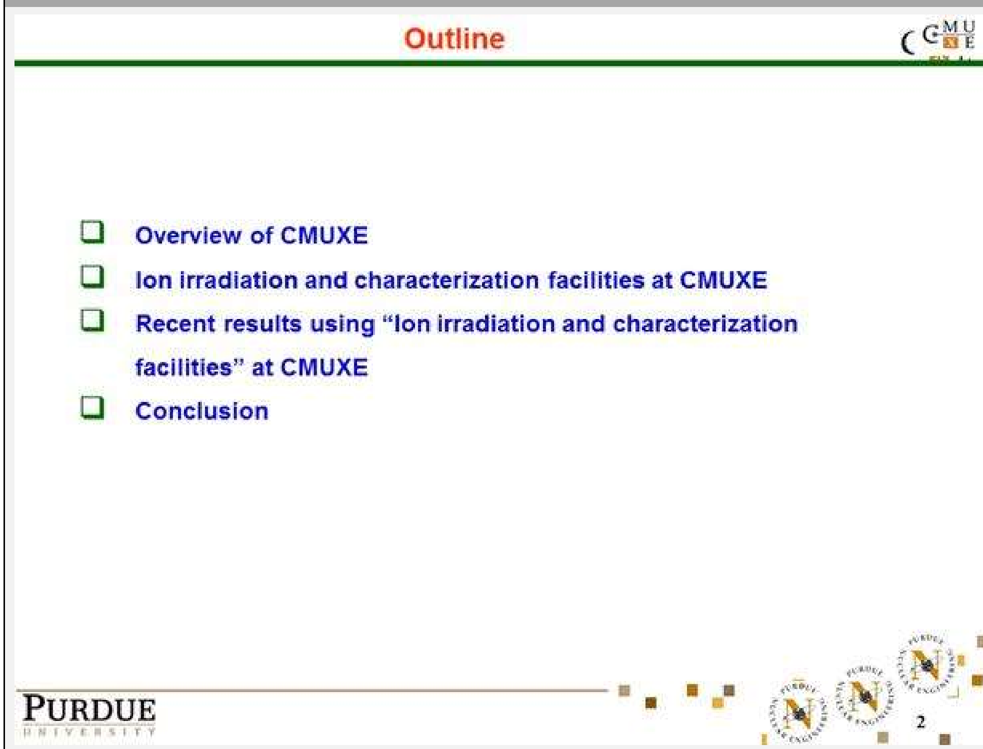
Presentation: CMUXE, Purdue University

Jitendra Tripathi

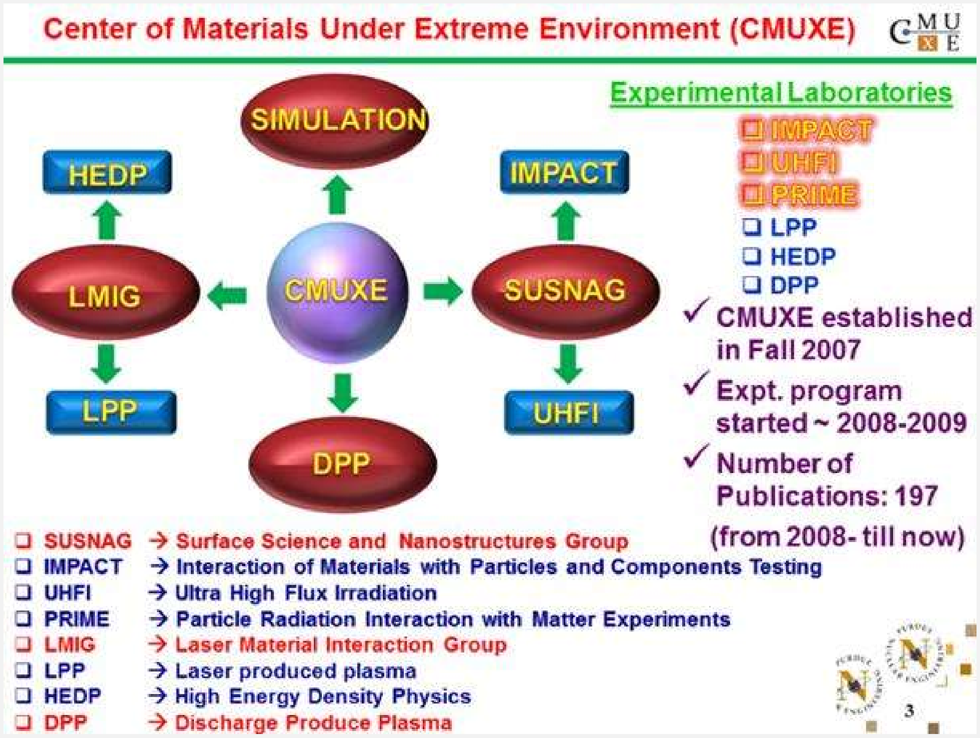
Slide 1



Slide 2



Slide 3



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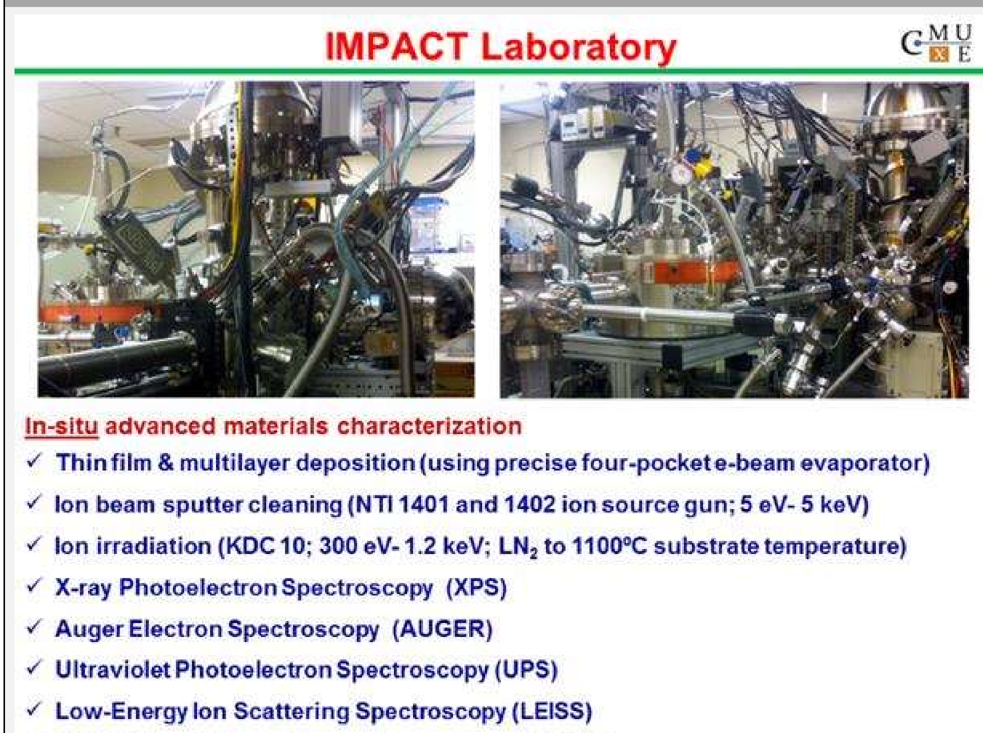
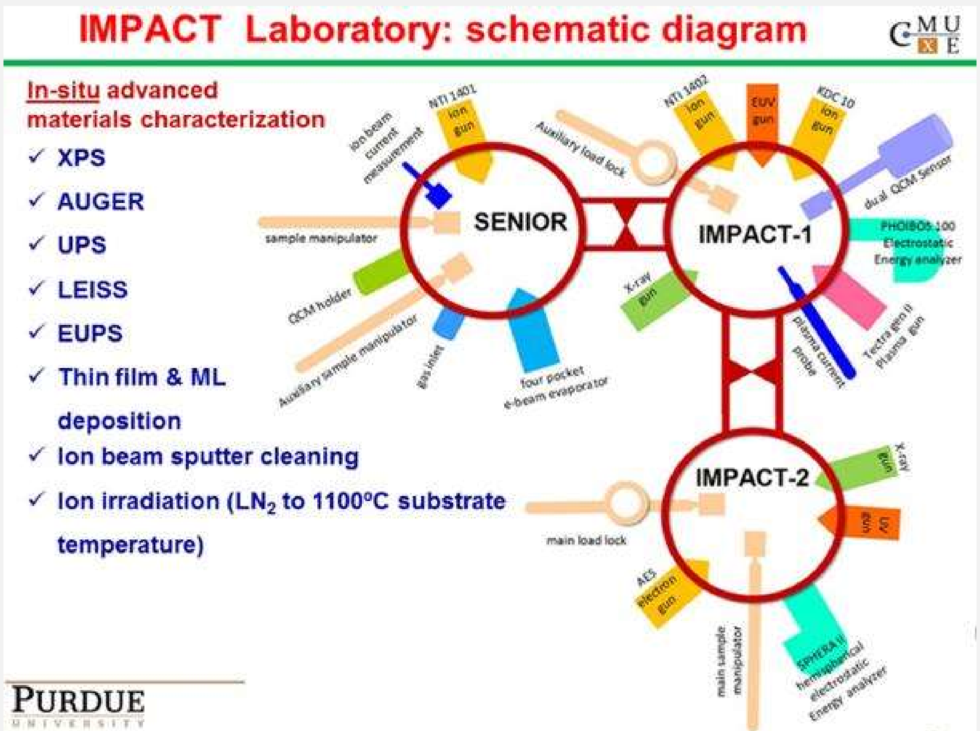
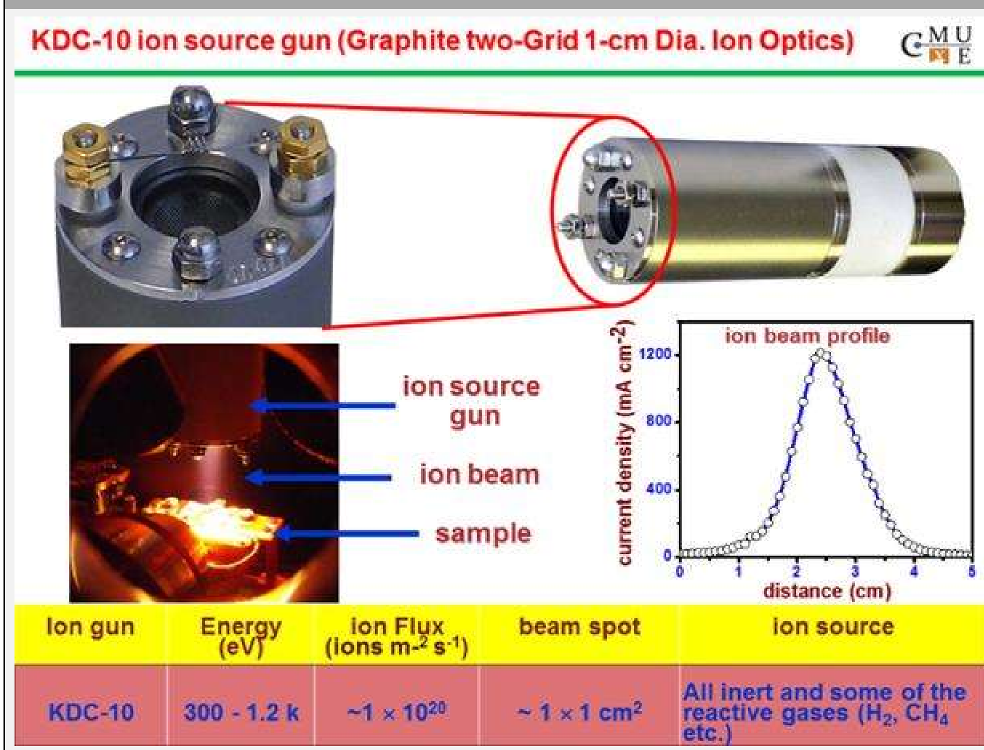


1. IMPACT and UHFI are ion beam facilities.

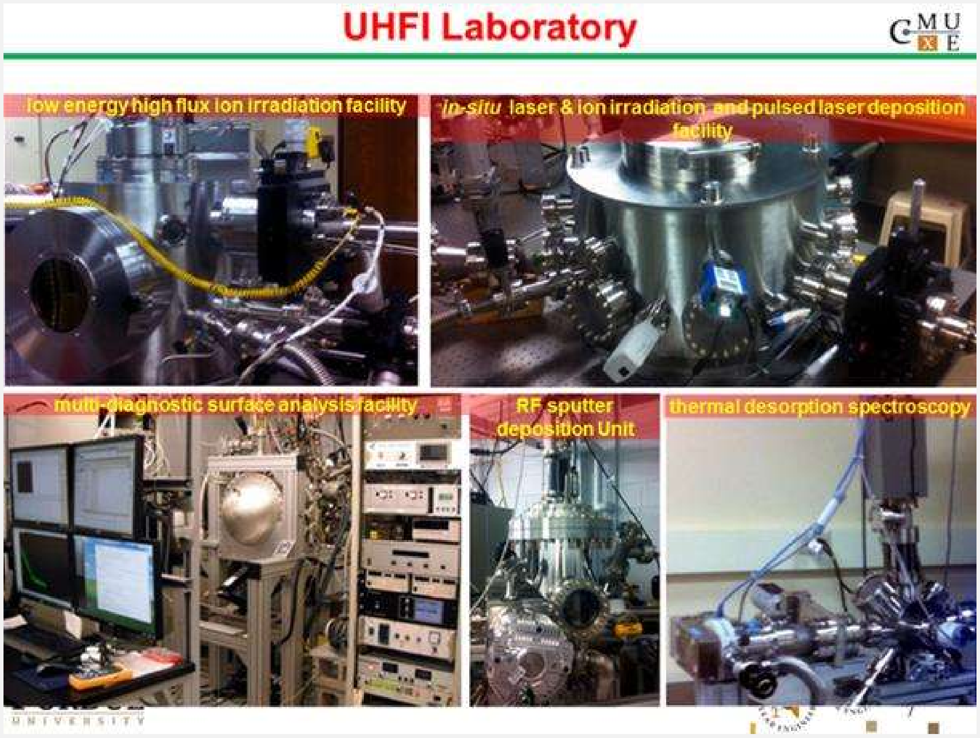
Slide 5



Slide 6

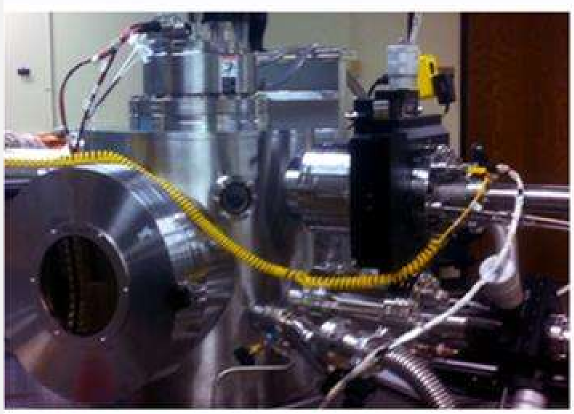


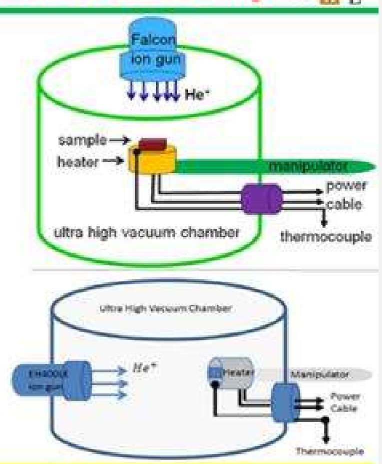
Slide 7



Slide 8

low energy high flux ion irradiation facility

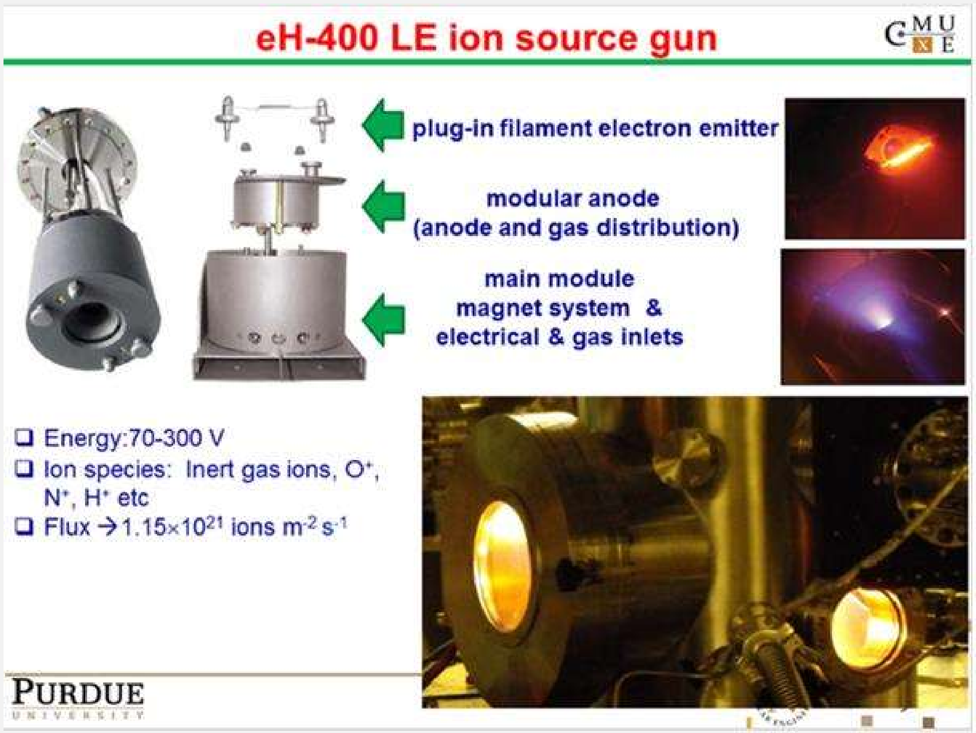




Ion gun	Energy (eV)	Ion Flux (ions $m^{-2}s^{-1}$)	beam spot	ion source
eH-400LE	70- 300	~1×10^{21}	9.4×9.4 cm^2 (broad beam)	All inert and some of the reactive gases (H_2, N_2, O_2, CH_4 etc.)
Falcon	650 – 2 k	~1×10^{21}	broad beam	All inert and some of reactive gases (H_2, CH_4, N_2, O_2 etc.)

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.

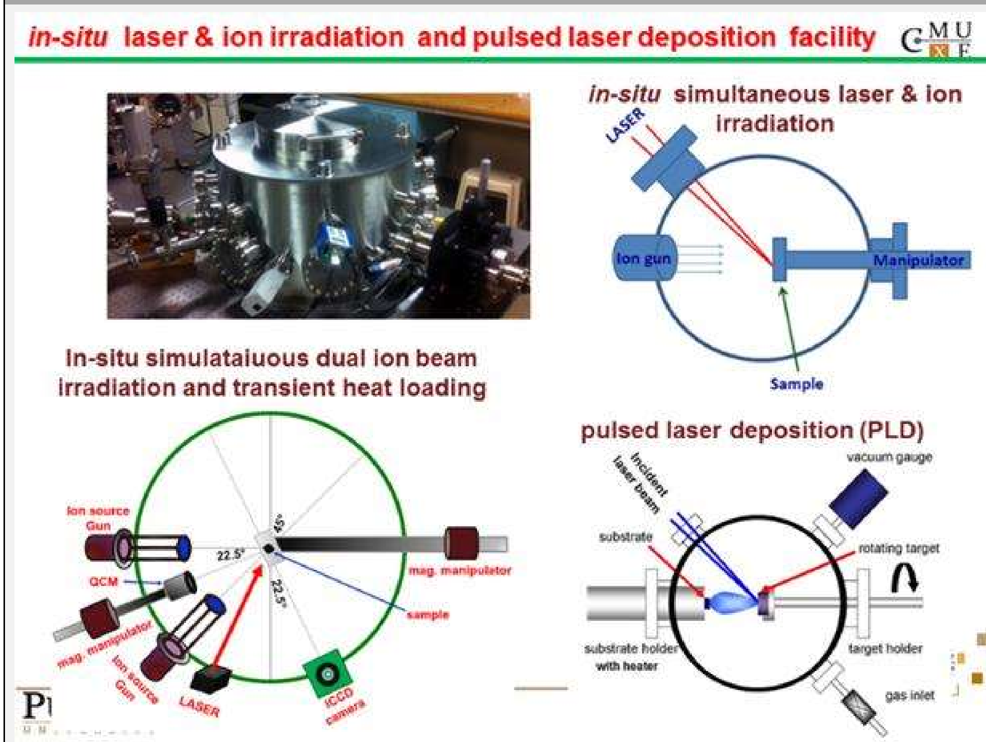
Slide 9



Slide 10

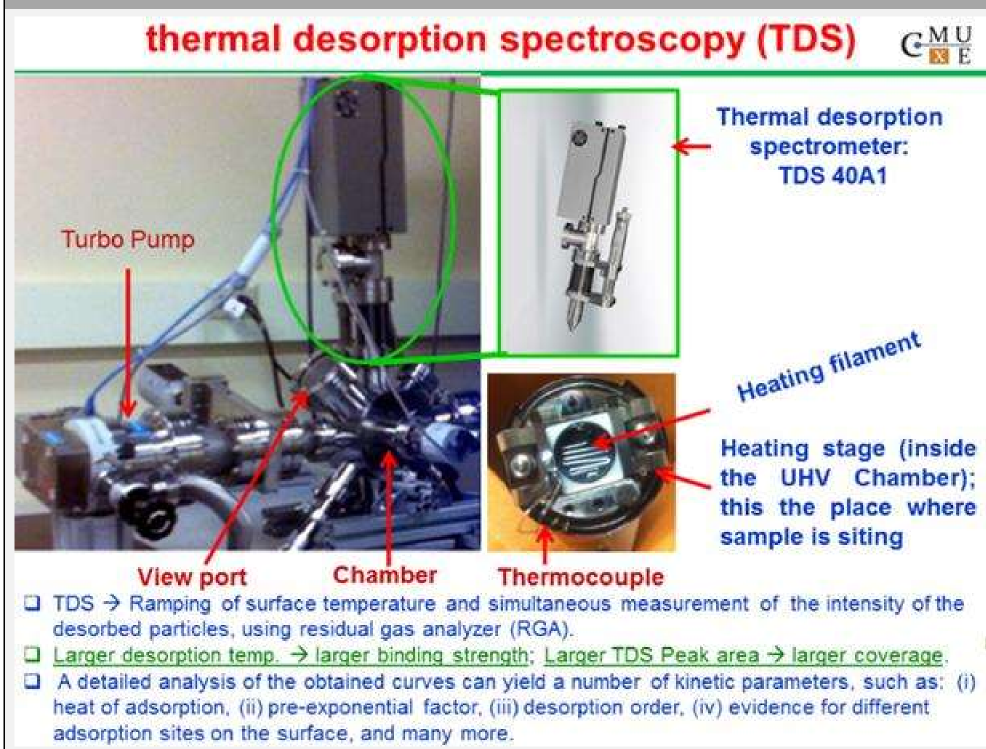
Ion gun	Energy (eV)	ion Flux (ions $m^{-2}s^{-1}$)	beam spot	ion source
Falcon	650 – 2 k	~1 × 10^{21}	broad beam	All inert and some of reactive gases (H_2, CH_4, N_2, O_2 etc.)

Slide 11



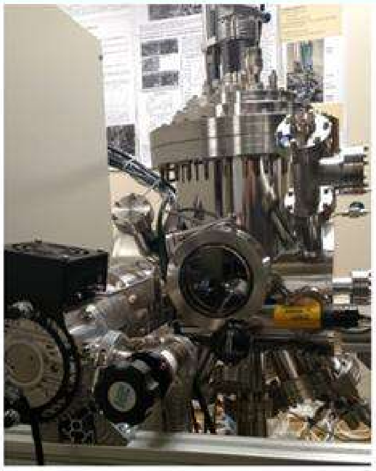
1. Fusion applications, laser heating to 2000°C

Slide 12



Slide 13

RF sputter deposition facility

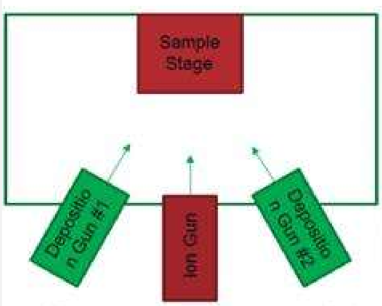


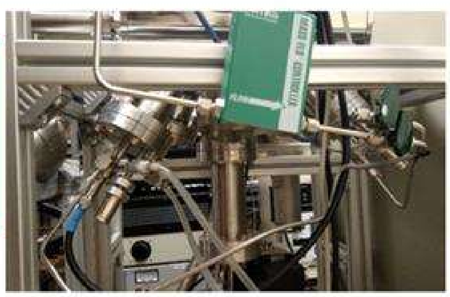
- Mantis RF Sputter Deposition Guns: [0-300 watts (RF); Non-ferrous materials; 1 in. sputter target]
- 1 Mantis RF Ion Gun: 0-600 watts (RF)
- Currently capable of running two sources simultaneously
- Film deposition (tested successfully): Ni, W, Co (couple of micro meter thick layers)

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

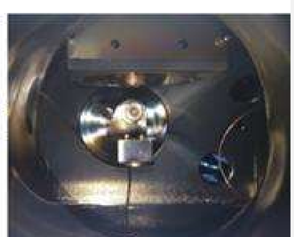
Slide 14

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)



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Slide 15

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

Slide 15	
	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).

Slide 16

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 nuclar 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.

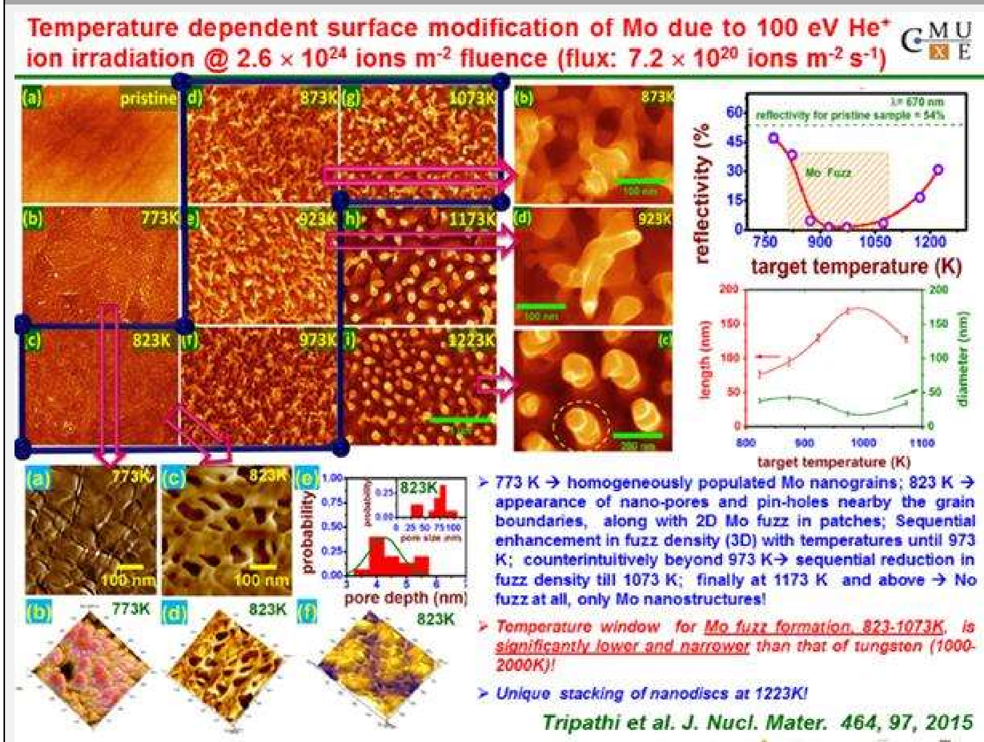
PURDUE UNIVERSITY 16

Slide 17

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

PURDUE UNIVERSITY 17

Slide 18



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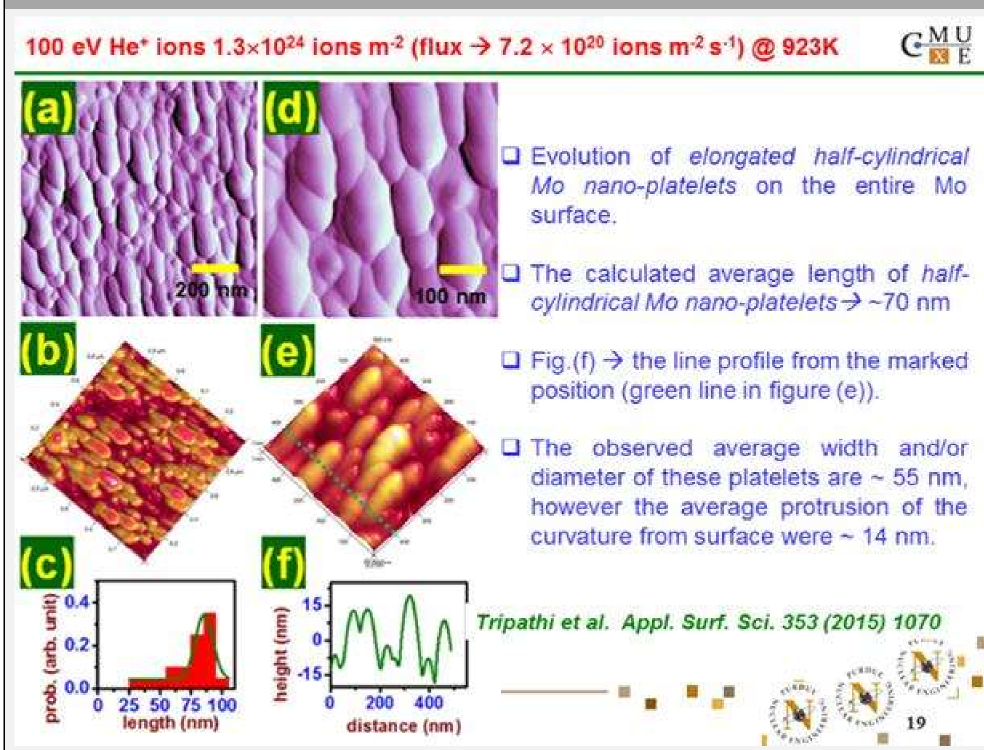

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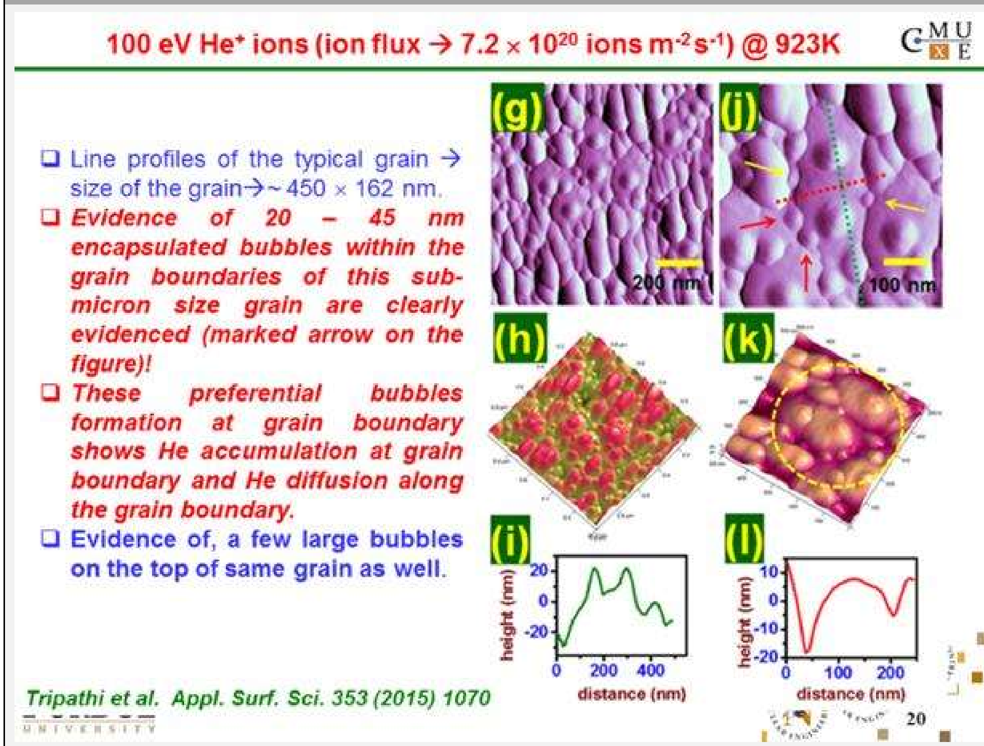
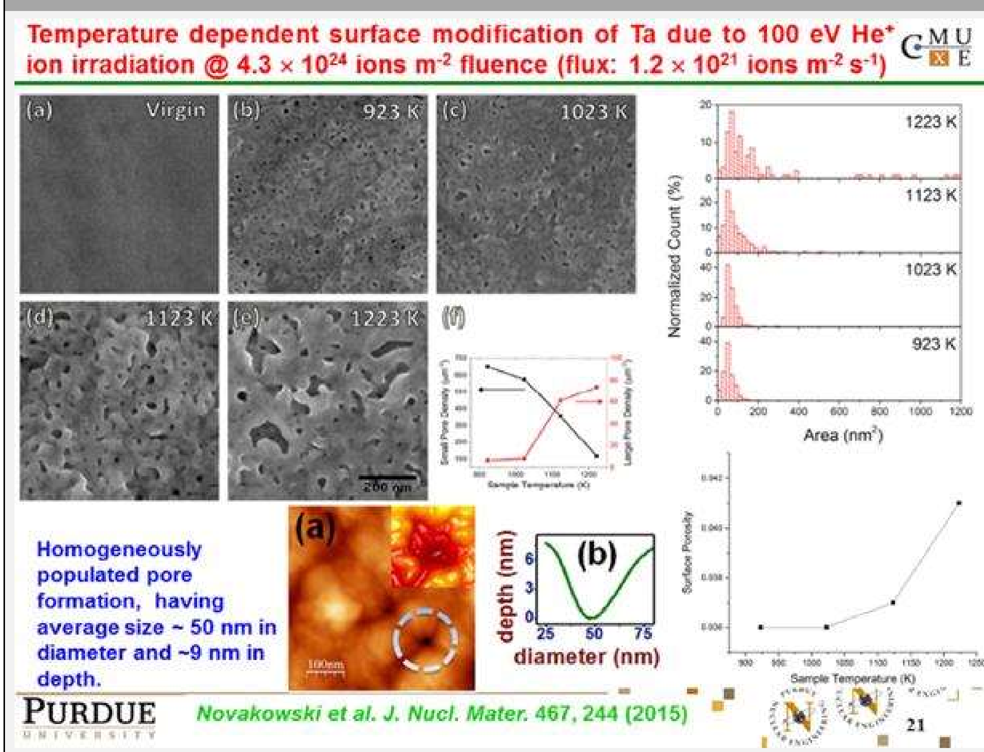
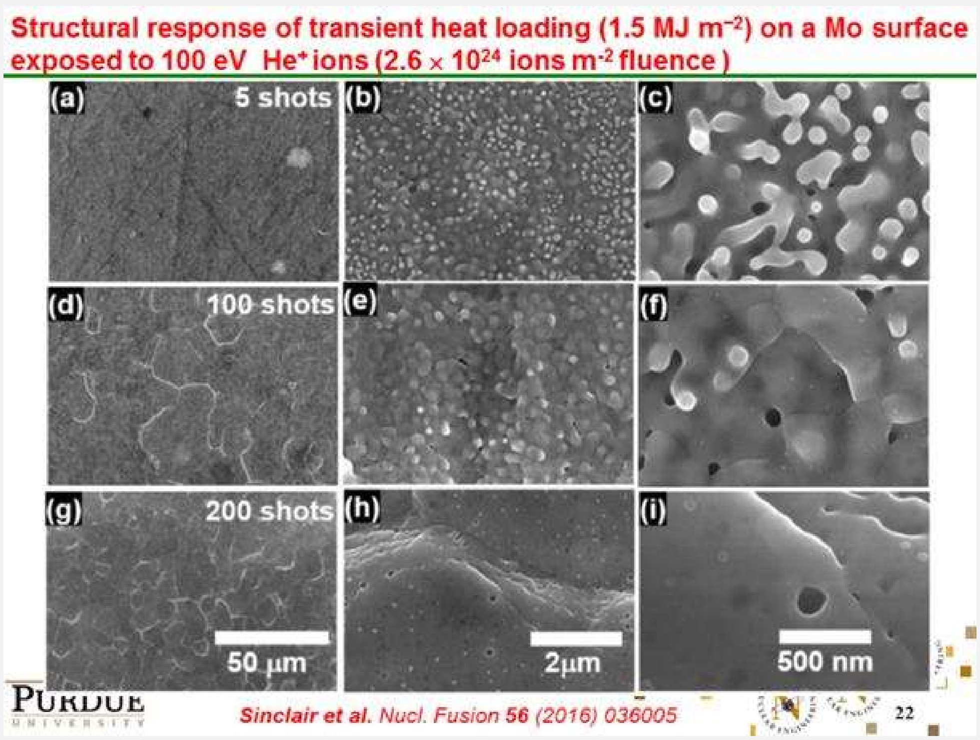


Slide 21



Slide 22



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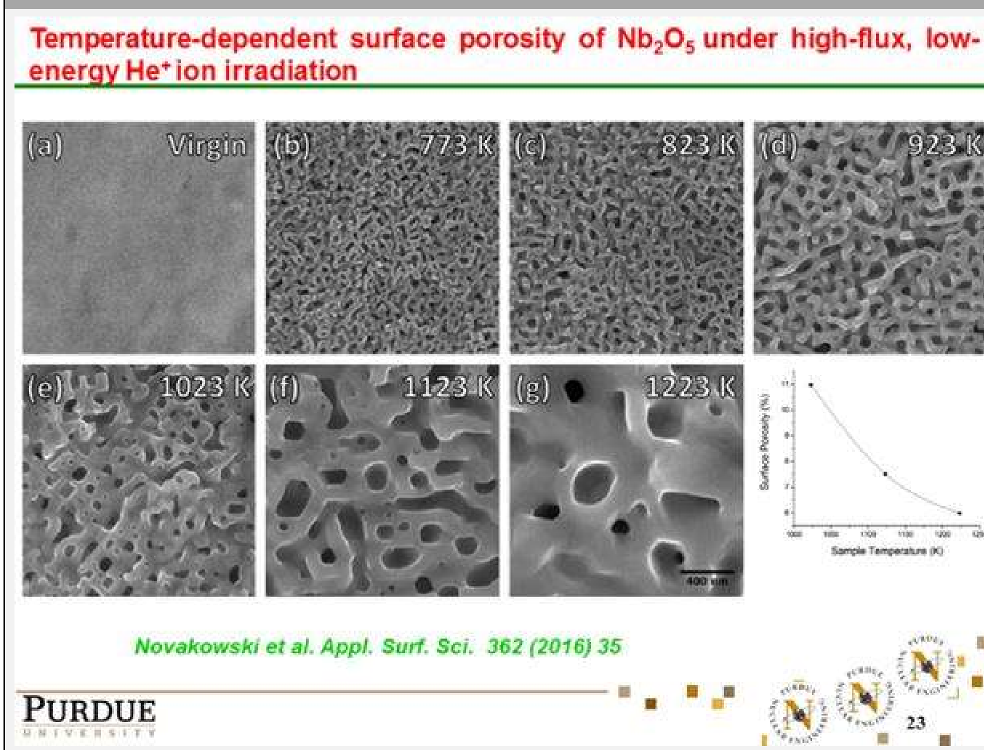

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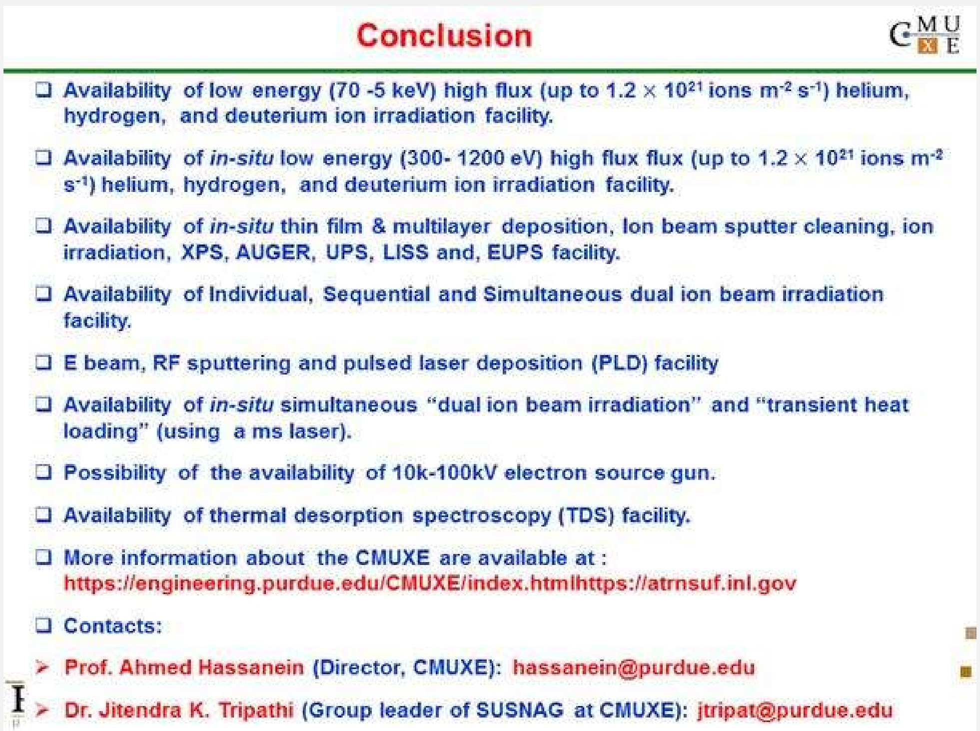
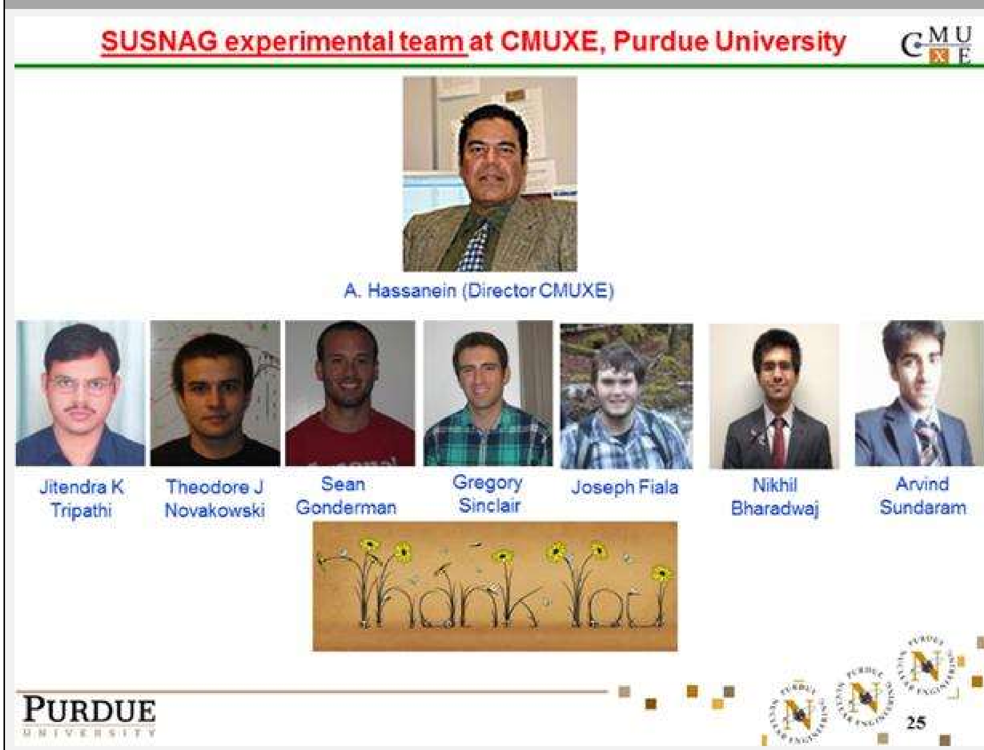


1. What materials can be handled? Actinides?
2. We are NOT handling radioactive materials due to safety issue.

Slide 25

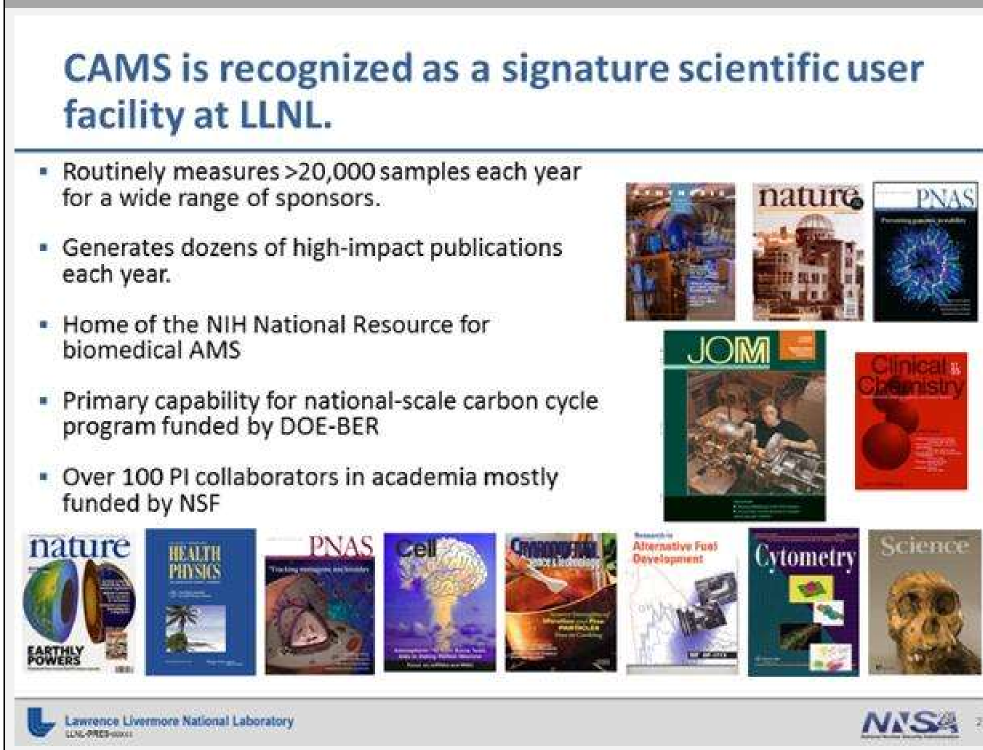


Presentation: High-energy Ion Implantation Capability at LLNL

Scott Tumey

Slide 1

Slide 2



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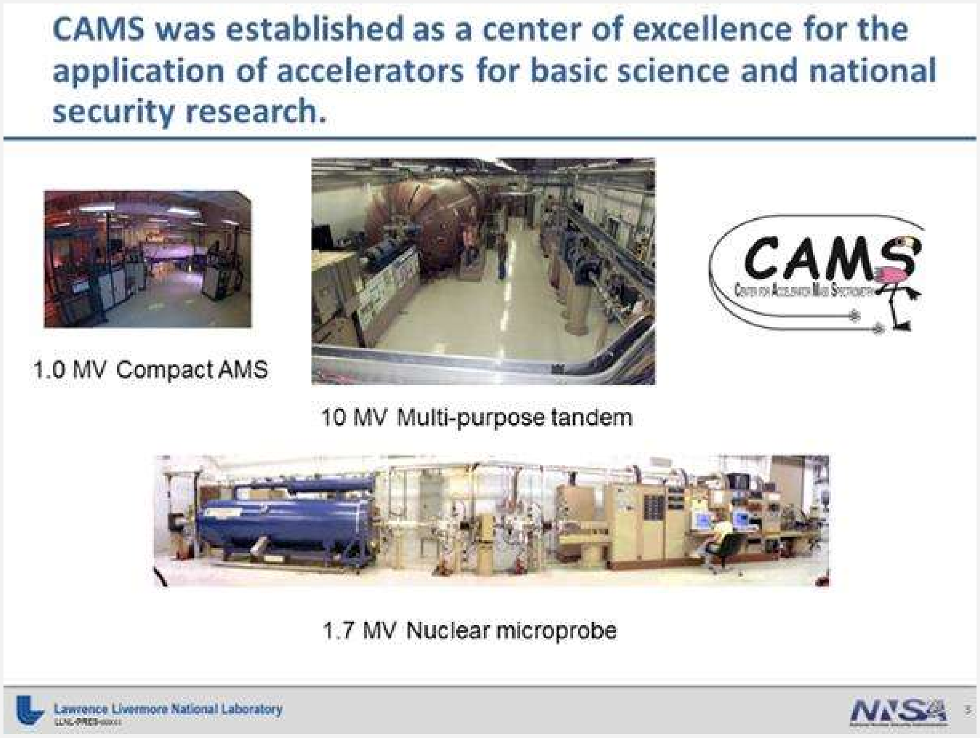

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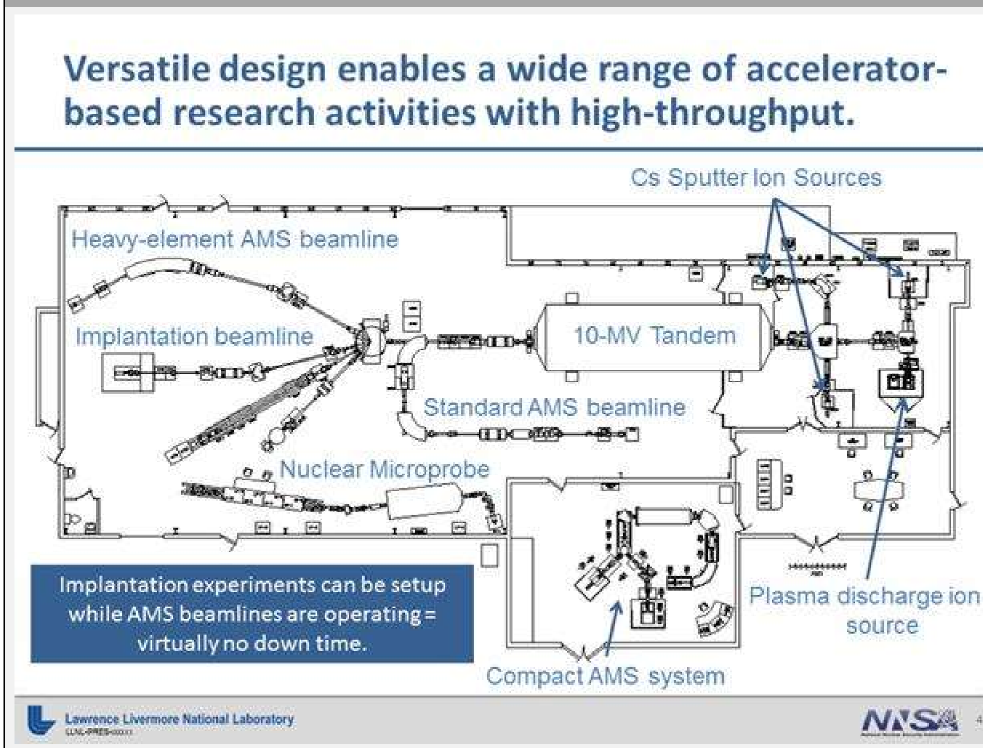


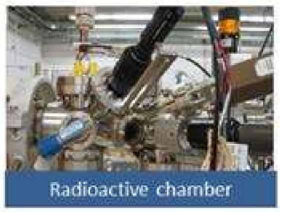
1. Couple minute switch between ion sources.
2. Since there are four computer controlled ion sources, you can do one type right after another for quasi-multi-ion irradiations.
3. Additional flexibility due to multiple beam lines.

Slide 5

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


Retractable shielding box


High-current chamber


Radioactive chamber

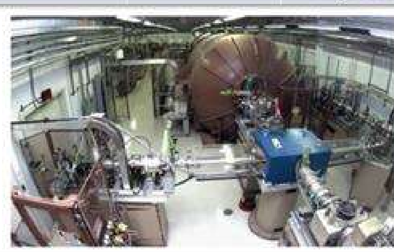

High-temp chamber

- 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

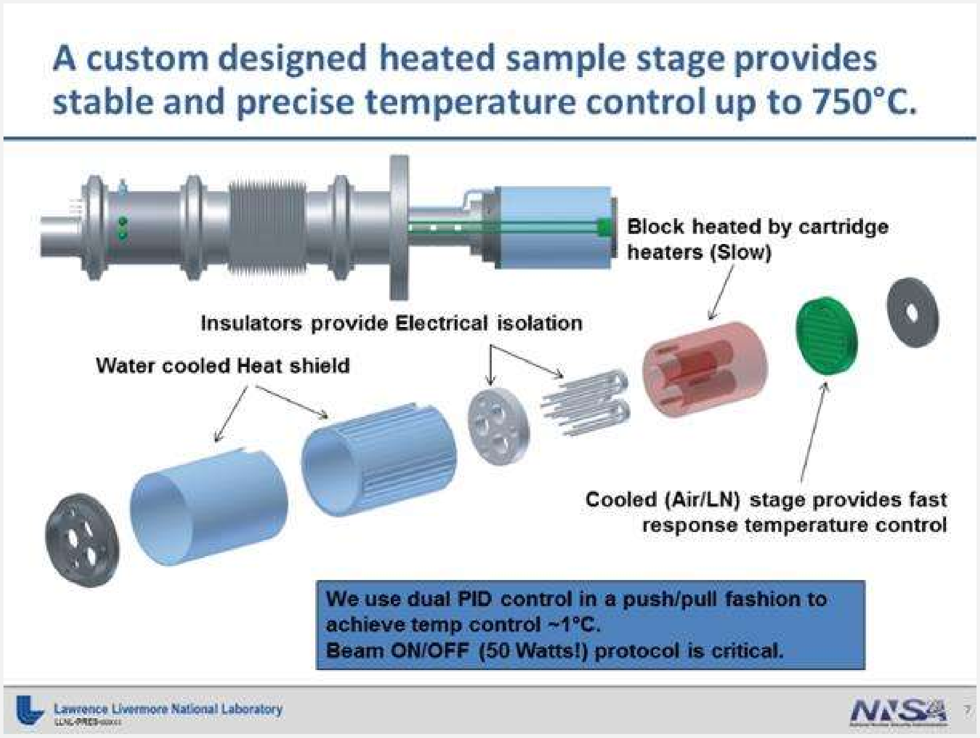
Multiple ion sources can produce ions from nearly every element on the periodic table.

	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



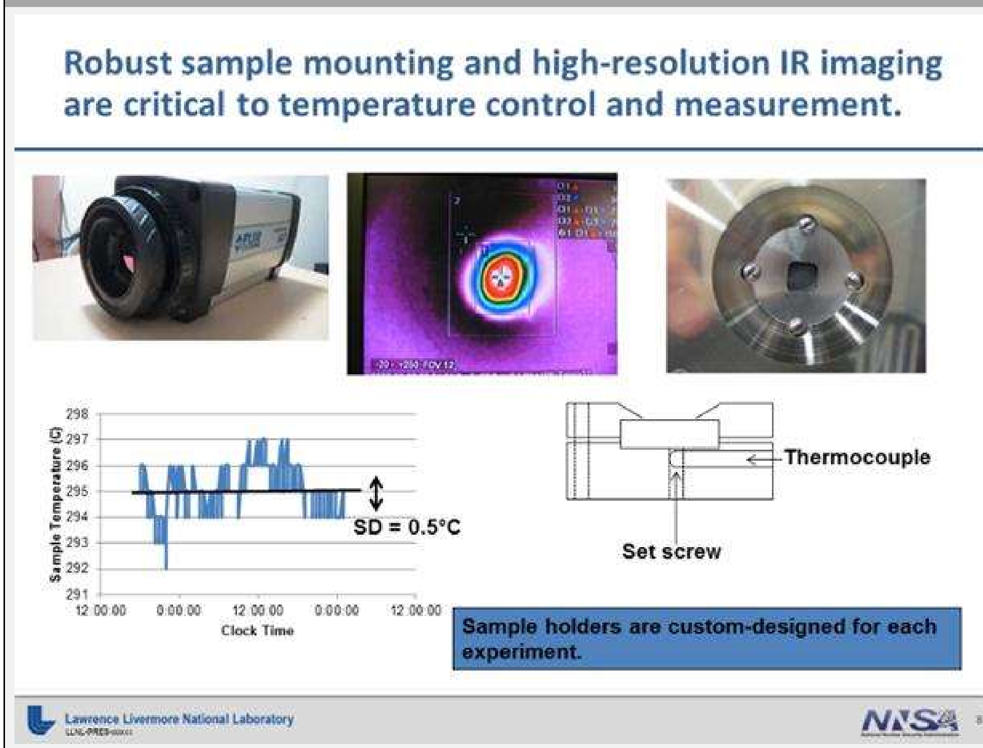
1. Can generate negative ions of some noble gases (work in progress).

Slide 7



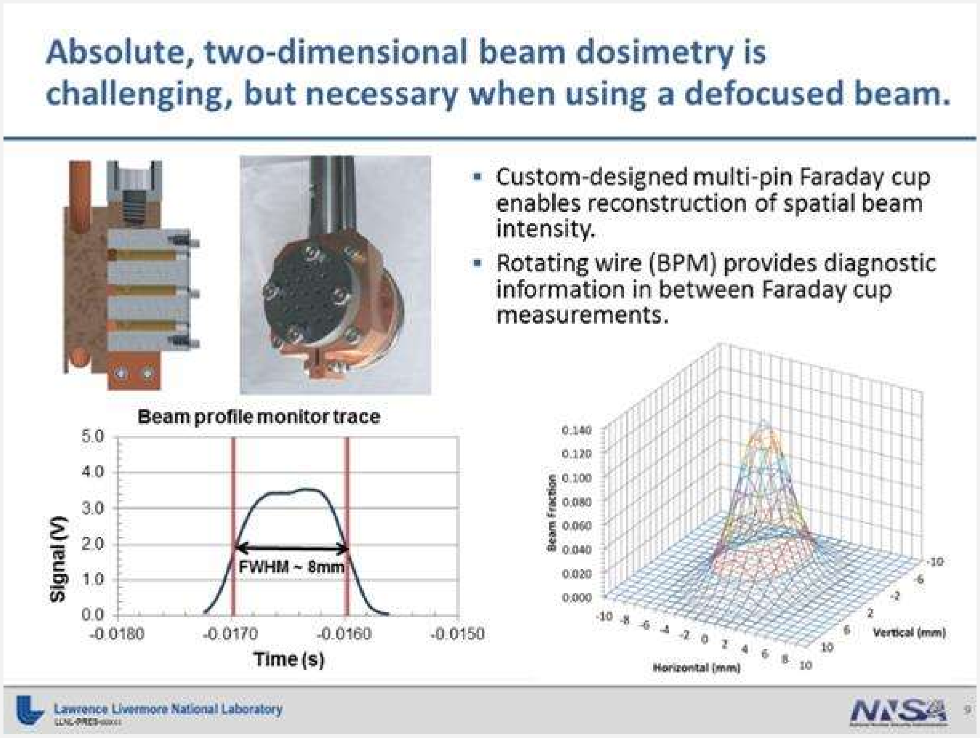
1. Is the sample temperature stage feedback looped into the beam production?
2. Response to Comment 1: We do have the capability to have these controlled with an automatic feedback loop; however, we find that because the factors that can affect beam current have a wide range of magnitudes and time constants,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

Slide 8



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

Slide 9

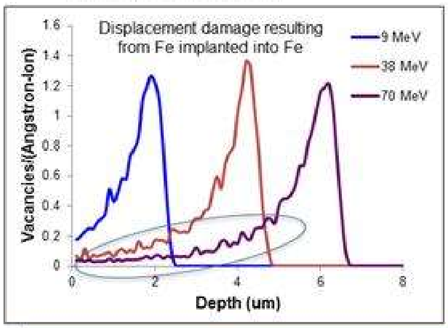


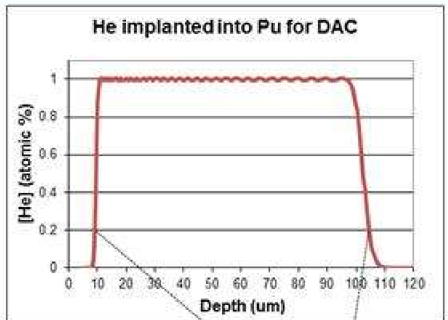
1. Do you keep a running tally of the beam profile, or is it an in-beam/out-of-beam measurement?
2. Regarding your comment about using the tails of the beam profile to achieve different damage levels, can you trust this method when the damage varies so steeply with position? Any beam "drift" will have 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.

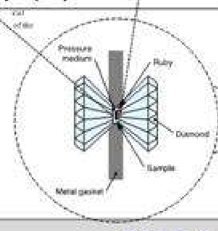
Slide 10

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



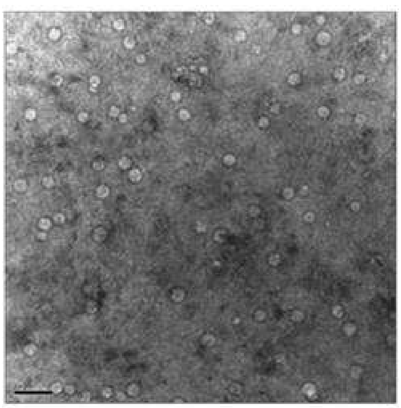




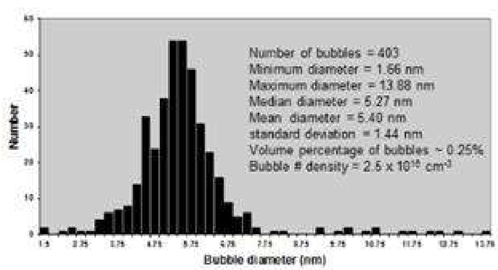
Deep ion penetration creates a gradually-increasing damage profile over a large area. Factor of 5 range in dpa (and dpa rate) can be covered in a single experiment.

Slide 11

Implantation capability provided key data to the LLNL weapons program.

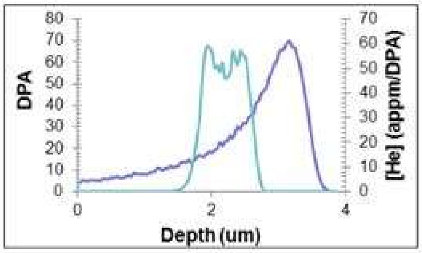


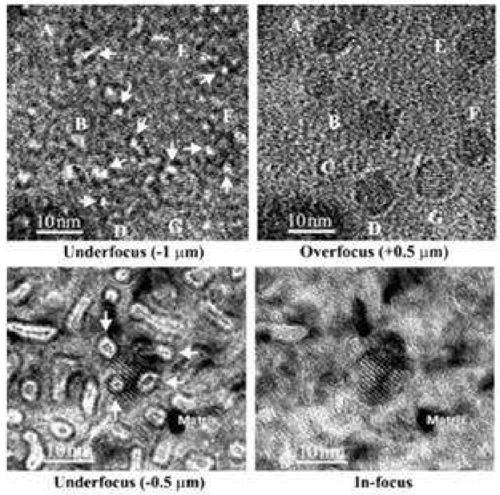
- Implanted He into Pu at 40 discrete energies to produce "uniform" deposition over 70 um.
- Analyzed samples for microstructure (TEM) and equation-of-state (DAC) to assess effects of long-term (~200 years) aging of stockpile.



Slide 12

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

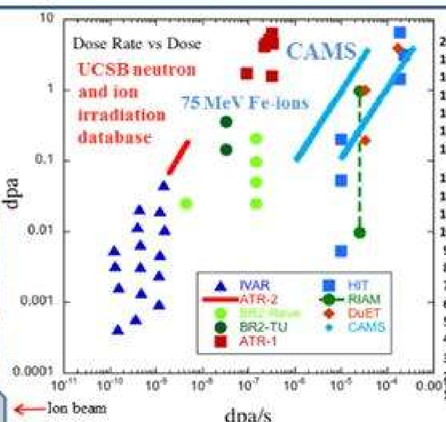




- ODS samples irradiates with Fe (displacement damage) and He ions.
- TEM analysis showed small (~2 nm) bubbles coalesced around ODS particles (Top figures)
- Cavities observed in areas of steel with low concentration of ODS particles (Bottom figures)

Slide 13

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

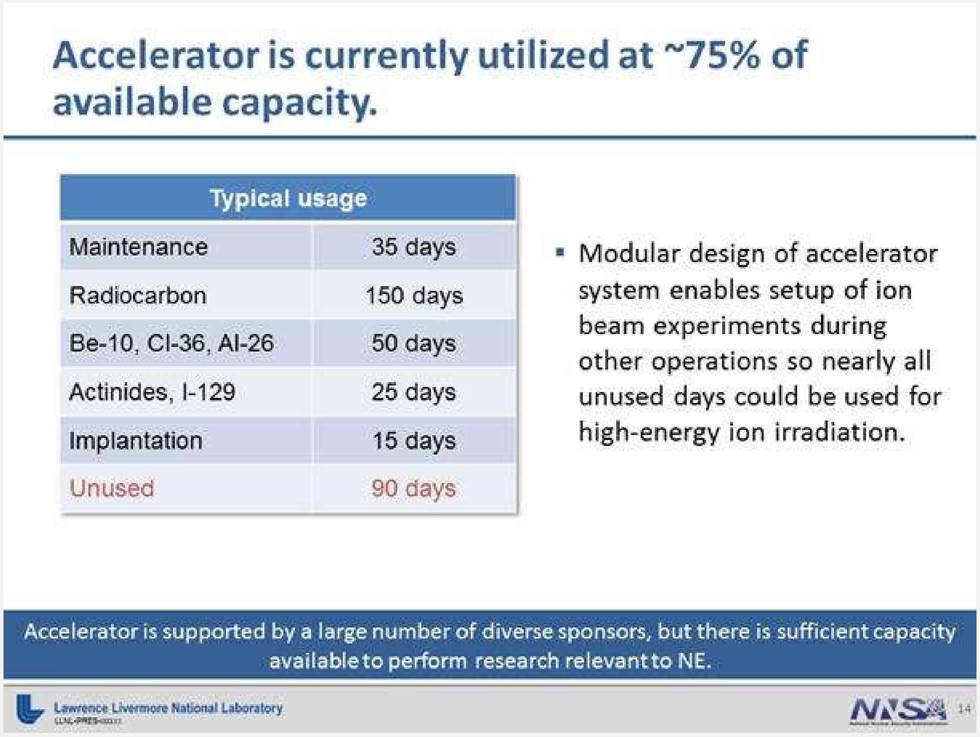


	A	B	C	D
20	LC	LC	LC	LC
19	Kewaunee W	UCSB W	LC	Maraged 1
18	Turkey Point	F82H M3	NFA616	Maraged 2
17	BWC	F82H	MA957 FR	PM2000
16	CM9	Eurofer97	MA957 US	PM2
15	CM3	UCSB T91	HT9 UCSB	MA956
14	CM21	Michigan T91	Michigan HT9	NFA1
13	CM5	Michigan IRP T91	Alloy 800H	RR1
12	CM7	LI	HCM12A	RR46
11	CM19	LH	VD/VH	RR37
10	LC	LC	Fe-3Cr - 6 Cr	LC
9	CM20	LG	Fe-9Cr-12Cr	RR28
8	CM31	LD	Fe-15Cr	RR14
7	CM8	CM6	Fe-18Cr	RR7
6	CM22	Ringhals	LANL1	RR13
5	WV	JRQ	LANL2	RR16
4	MW	65W	Maine Yankee	RR34
3	Farley Unit 1	73W	Palisades	RR32
2	Stainless Steel	LA	BWA	RR19
1	VD/VH	LC	LB	LC

APT, TEM, GIXRD, GISAXS, NANO-H PROFILE, … LAB ON A CHIP

> 70 alloys
>70x range of dose and dose rate
2 peak dose rates to 3.5 dpa in 3 and 30 h irradiations
≈ 6 μm depth

Slide 14



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

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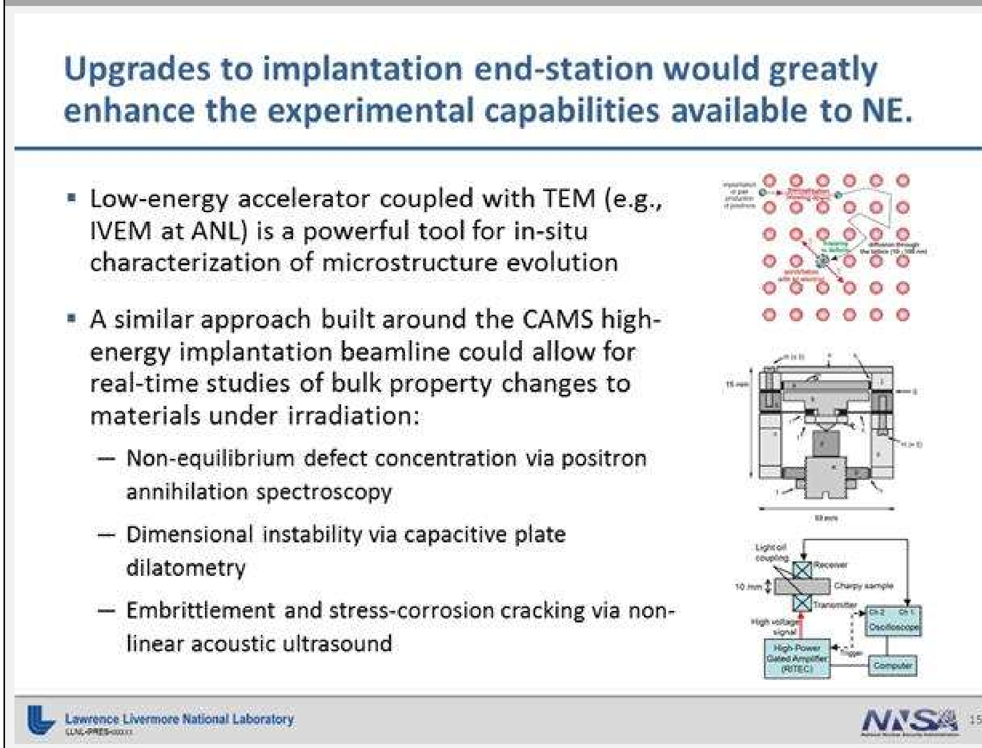

1. Proposed experiments bridge the gap between micro and macro structure properties.
2. Could measure both microstructure as well as physical properties.

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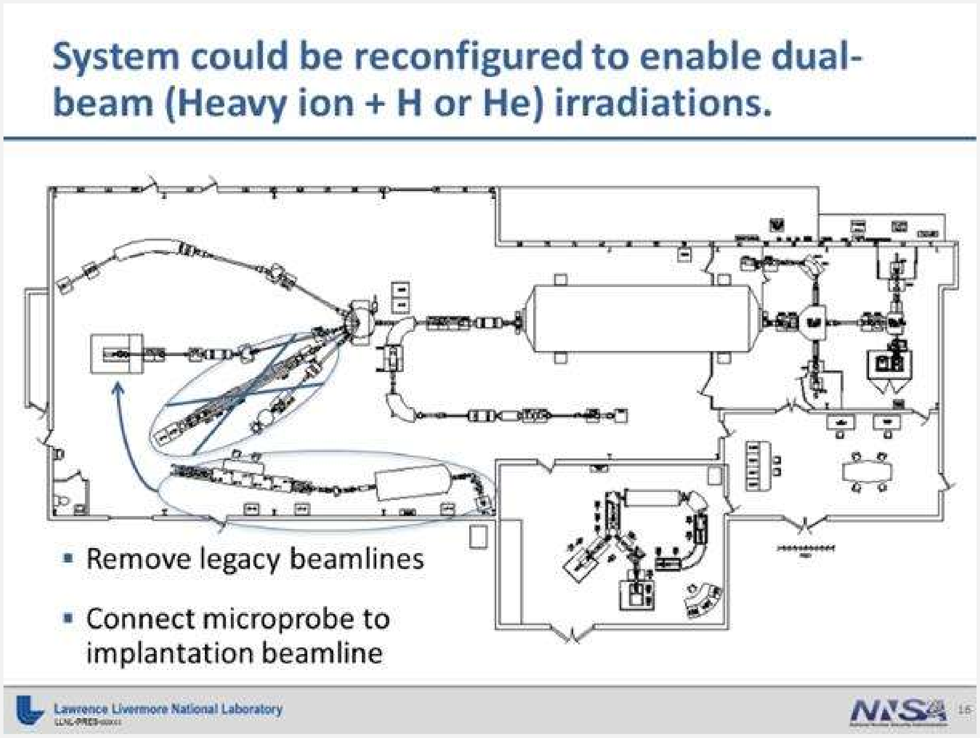
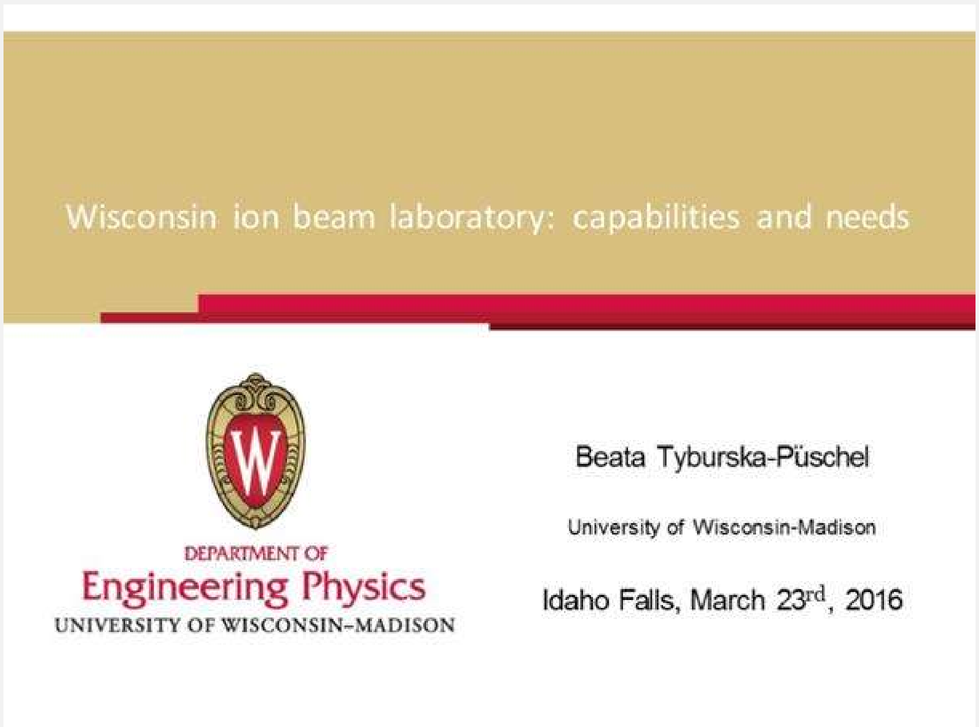


1. This would create a true dual-beam system.

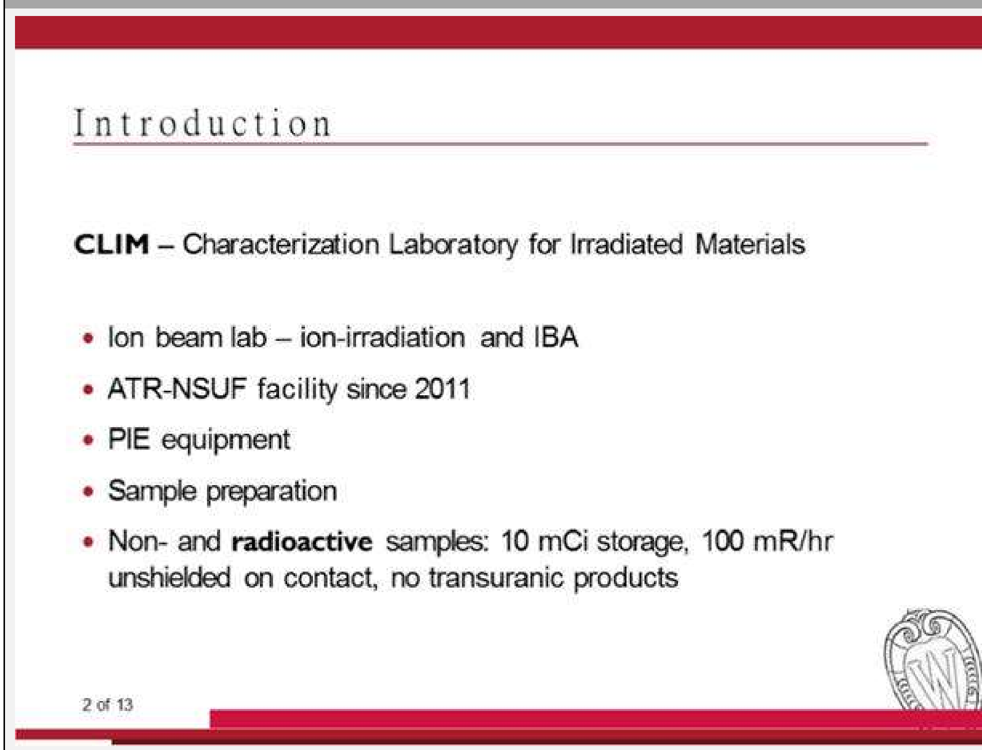
Presentation: Wisconsin IBL

Beata Tyburska-Pueschel

Wisconsin ion beam laboratory: capabilities and needs

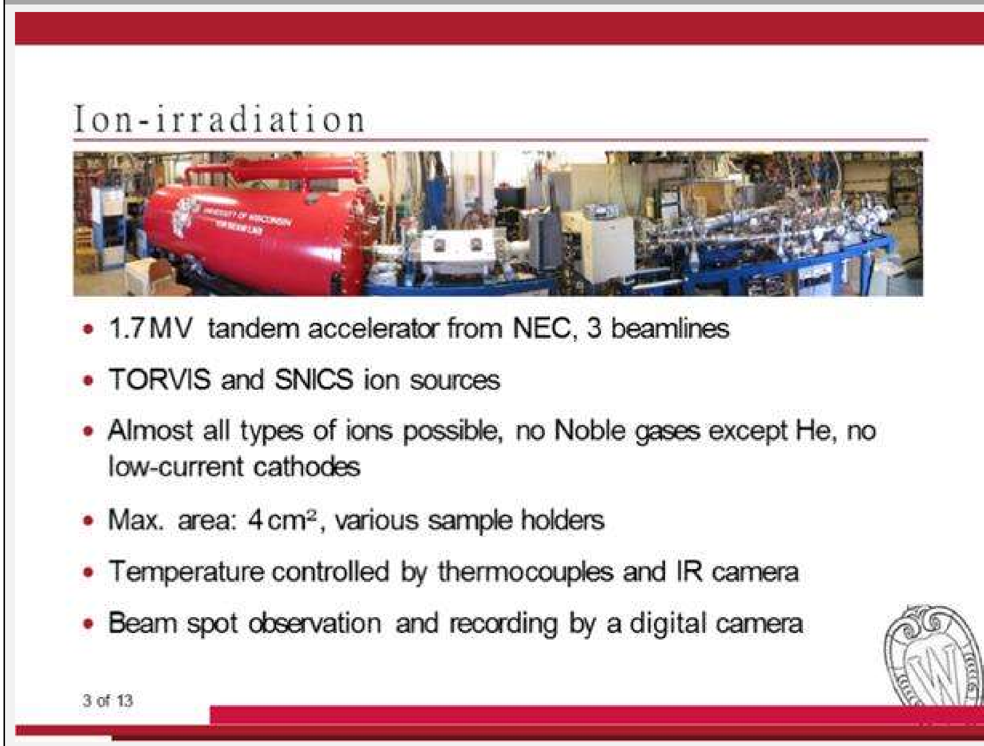


Introduction



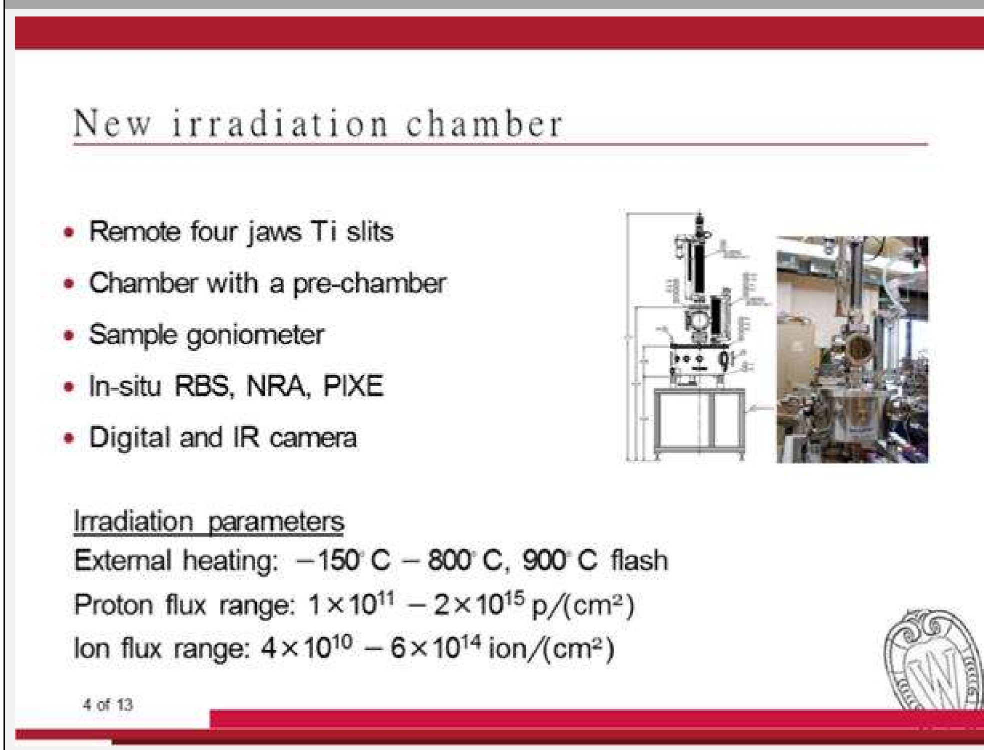
1. No pre-irradiated material (transuranics).
2. How much NSUF use to you get?

Ion-irradiation



1. Commissioning a new sample chamber in April.

New irradiation chamber



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

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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.

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

Projects

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

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1. NSUF: 40-50% in 2016.

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

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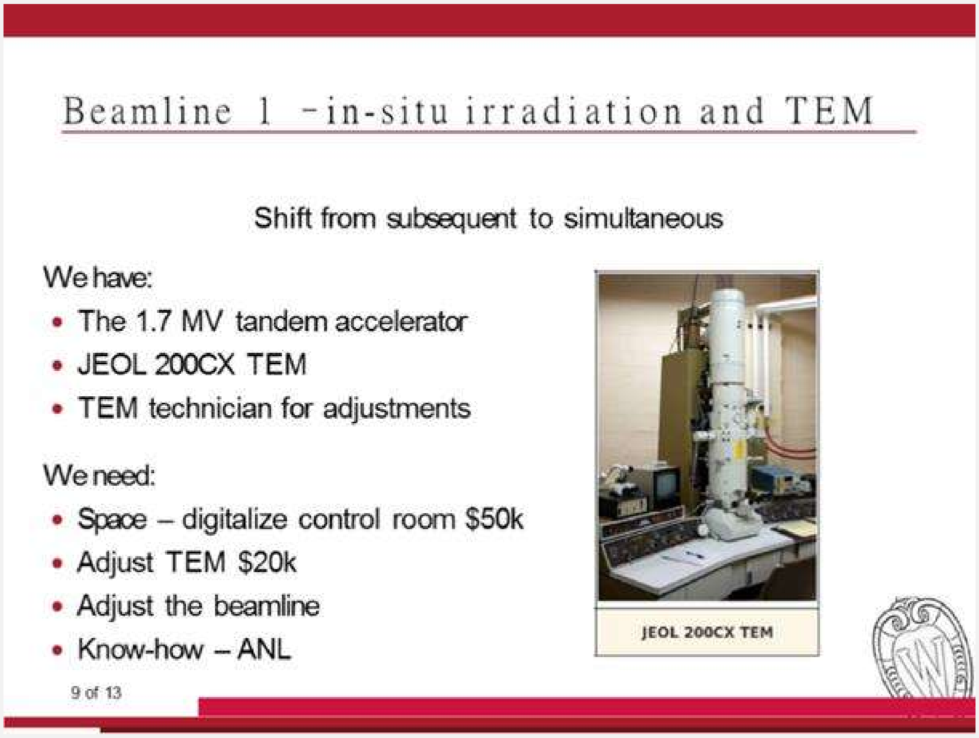
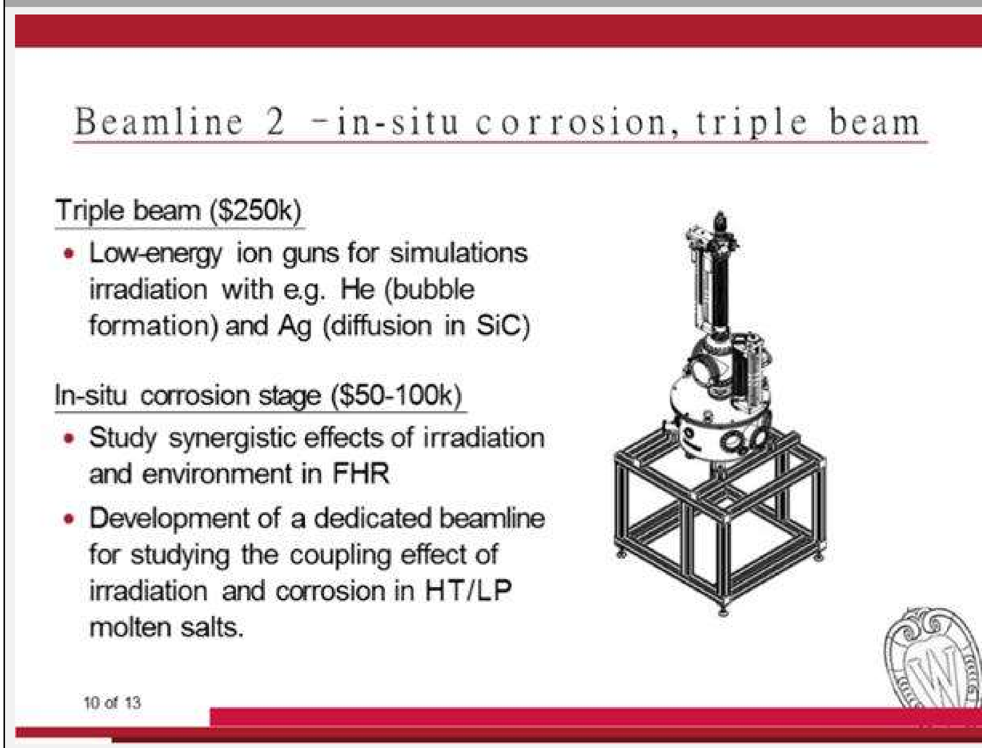
Beamline 1 – *in-situ* irradiation and TEM



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



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 infrasturcture 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.

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Contact

Contact

Beata Tyburska-Püschel: tyburska engr.wisc.edu

ibl.ep.wisc.edu

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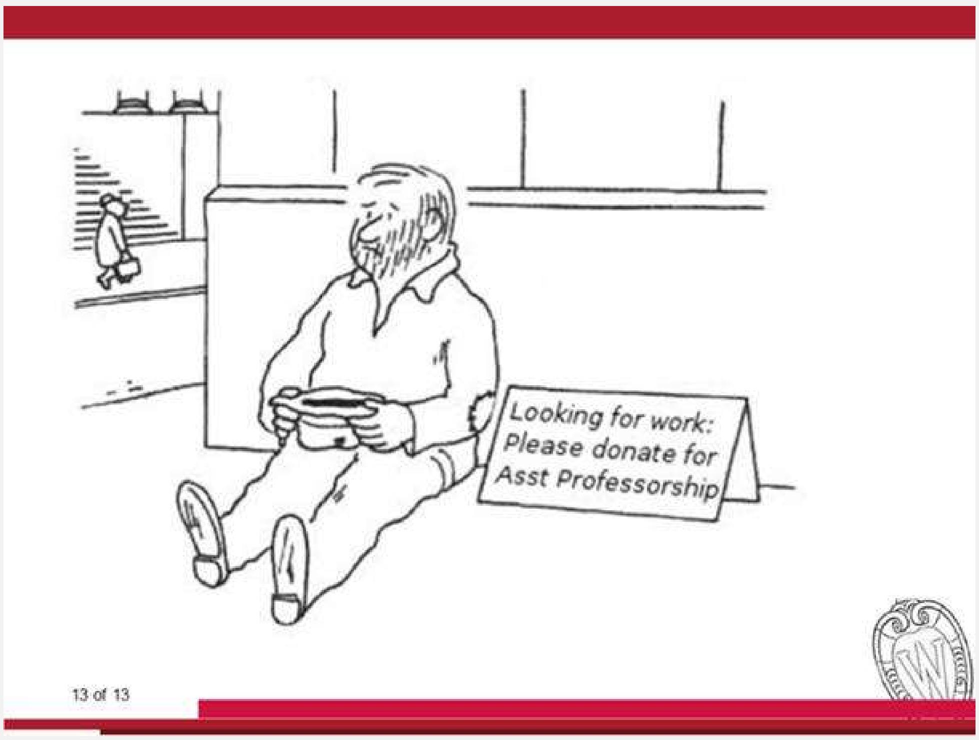
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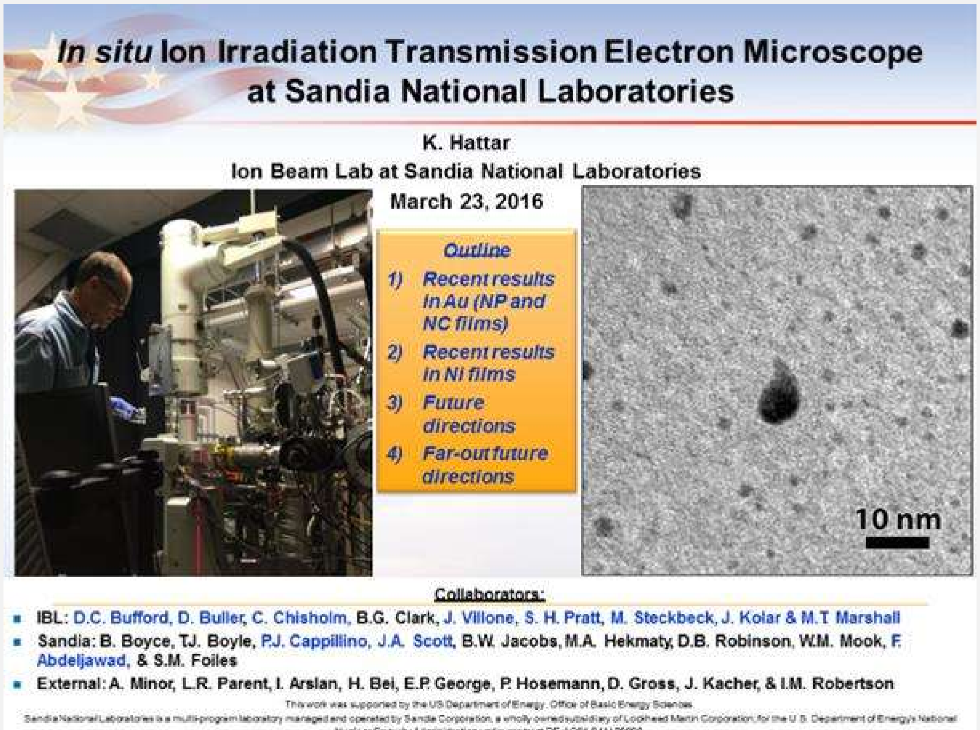
13 of 13

Presentation: *In situ* Ion Irradiation Transmission

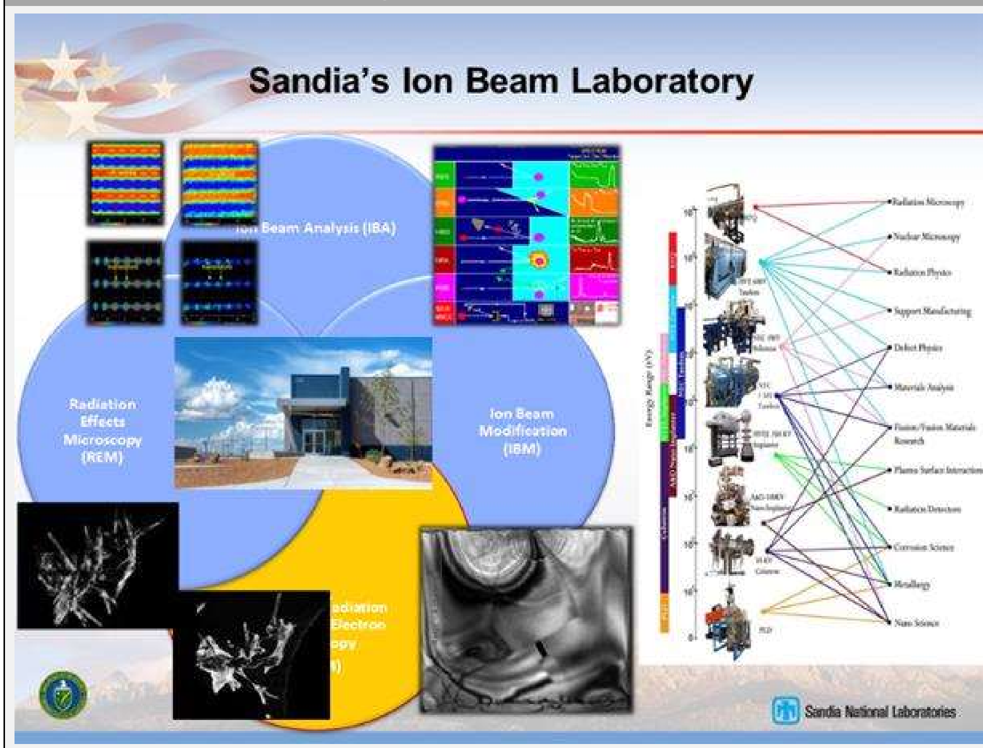
Khalid Hattar

In situ Ion Irradiation Transmission Electron Microscope at Sandia National Laboratories

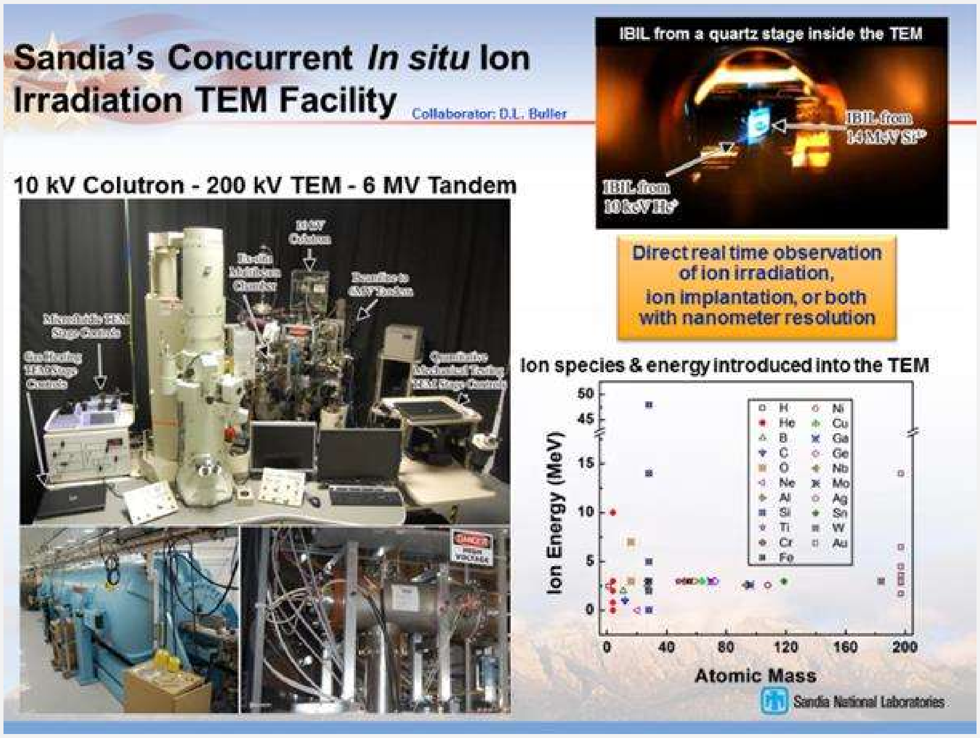


1. This facility has greater specific capabilities that appear different than other facilities we heard about. In addition, there seems to be quite a bit of room in their schedule to do more experiments from NSUF.
2. This facility was amazing!

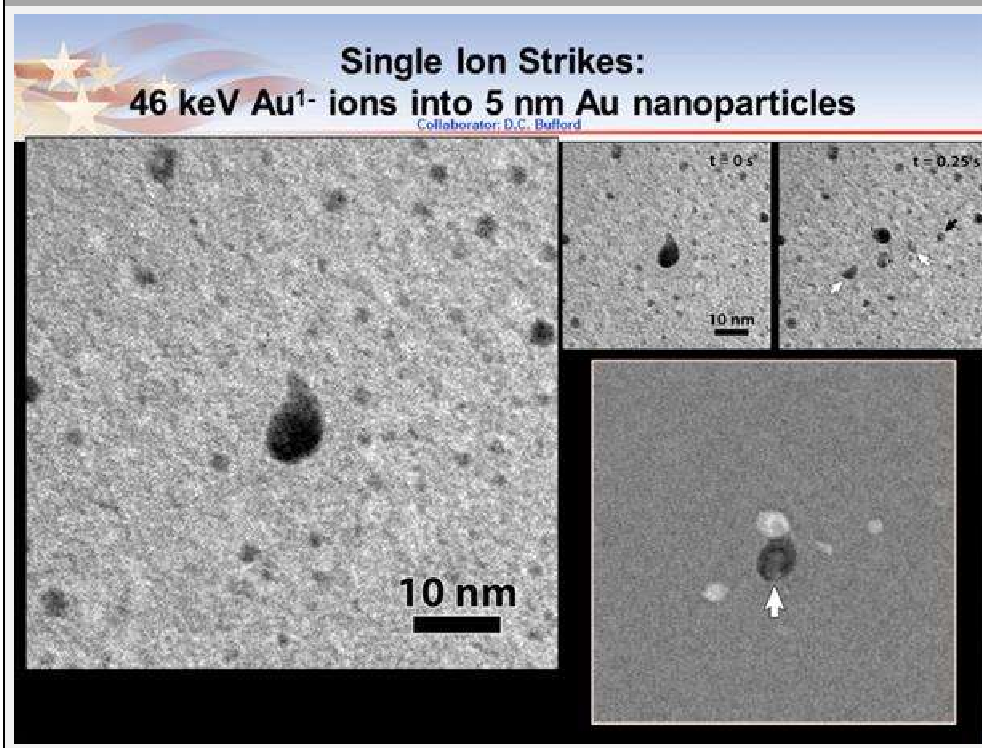
Sandia's Ion Beam Laboratory



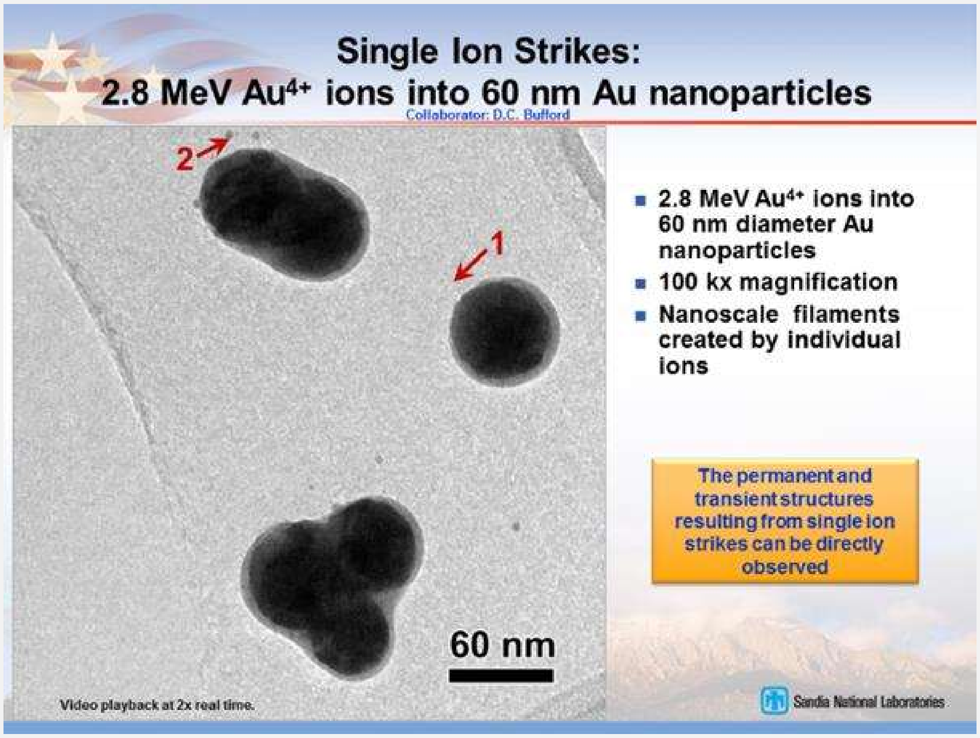
Sandia's Concurrent *In situ* Ion



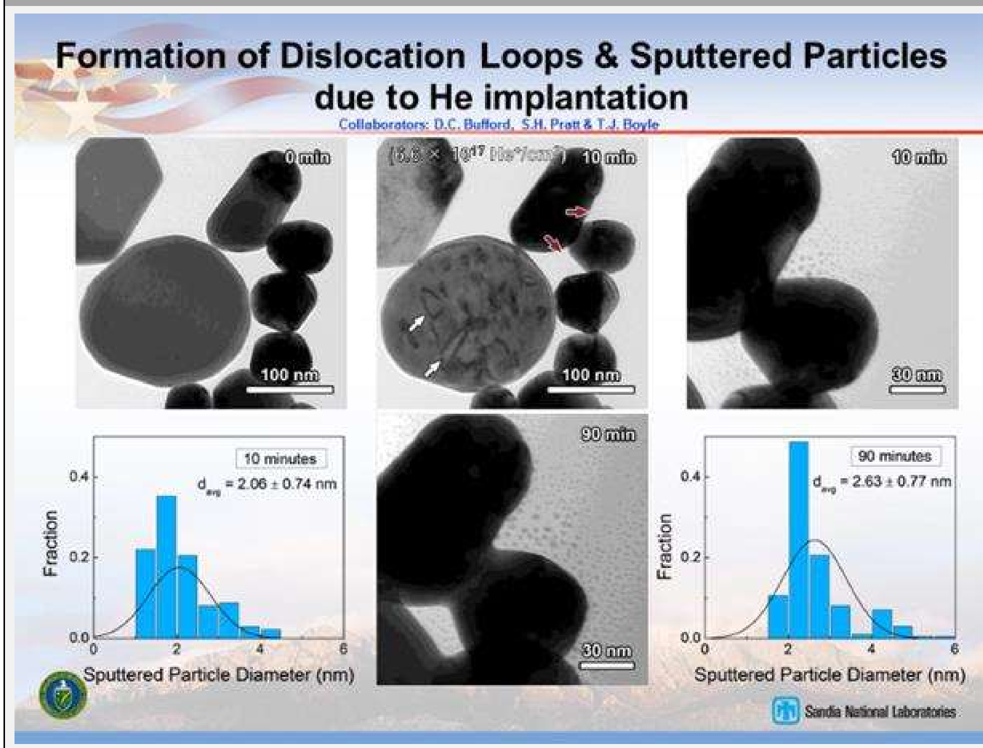
Single Ion Strikes: 46 keV Au[1]- ions into 5 nm Au nanoparticles



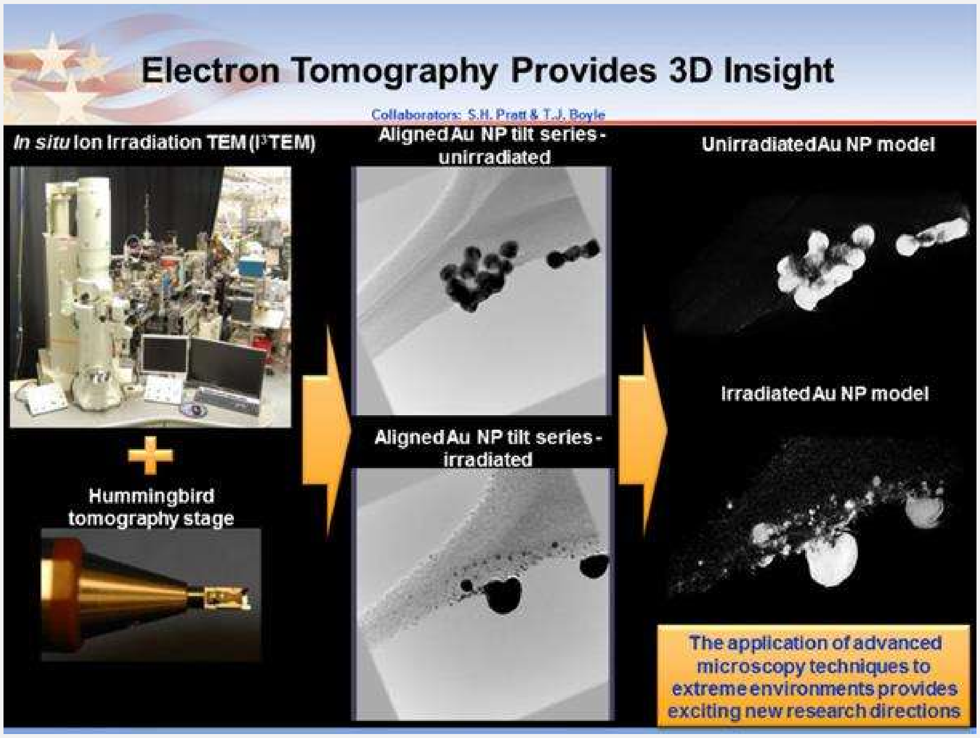
Single Ion Strikes: 2.8 MeV Au^{4+} ions into 60 nm Au nanoparticles



Formation of Dislocation Loops & Sputtered Particles due to He implantation

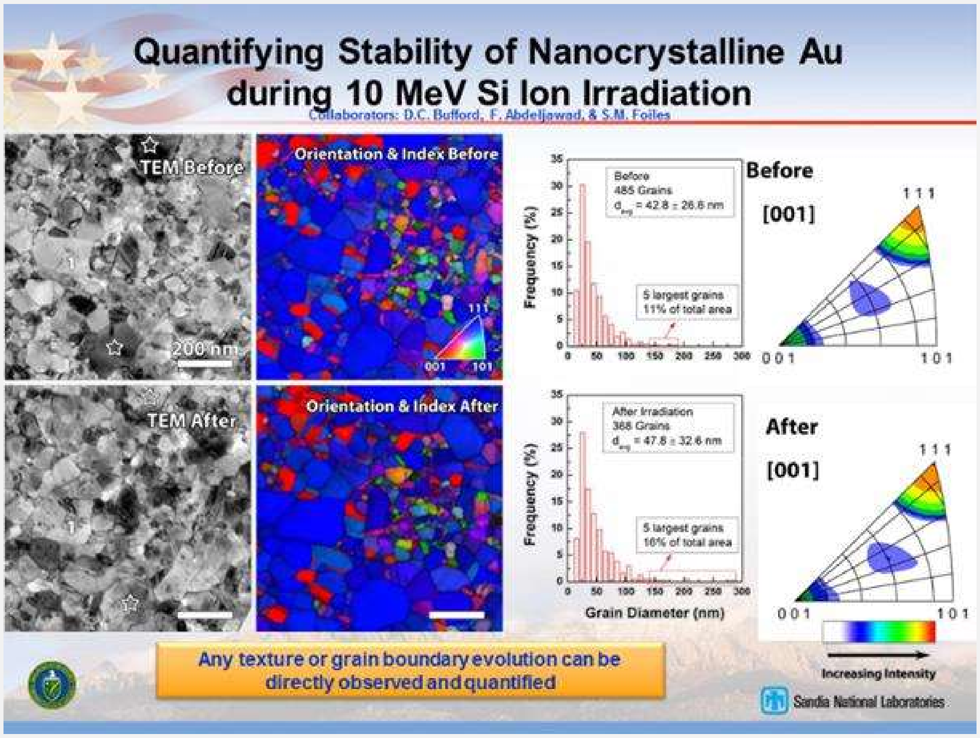


Electron Tomography Provides 3D Insight

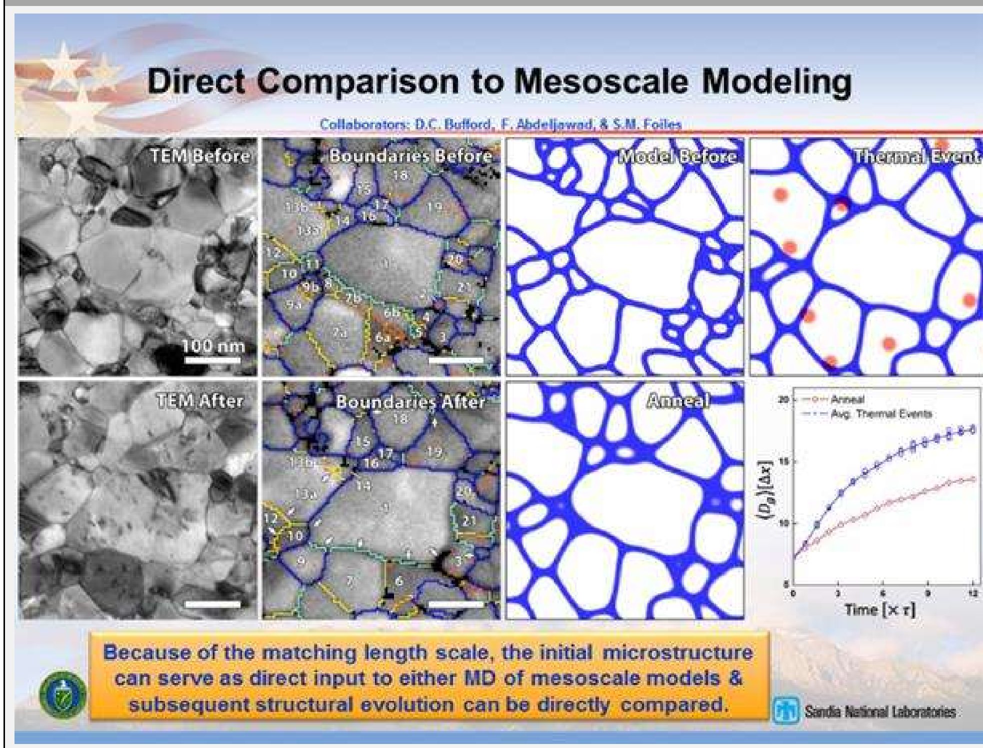


Dose Rate Effects

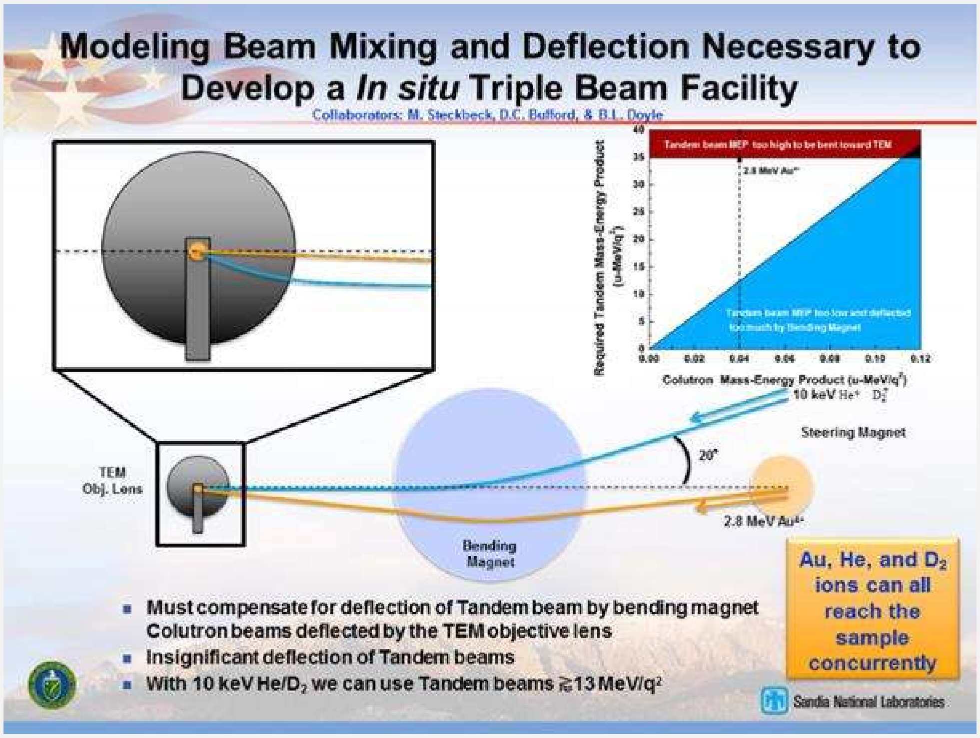
Quantifying Stability of Nanocrystalline Au during 10 MeV Si Ion Irradiation



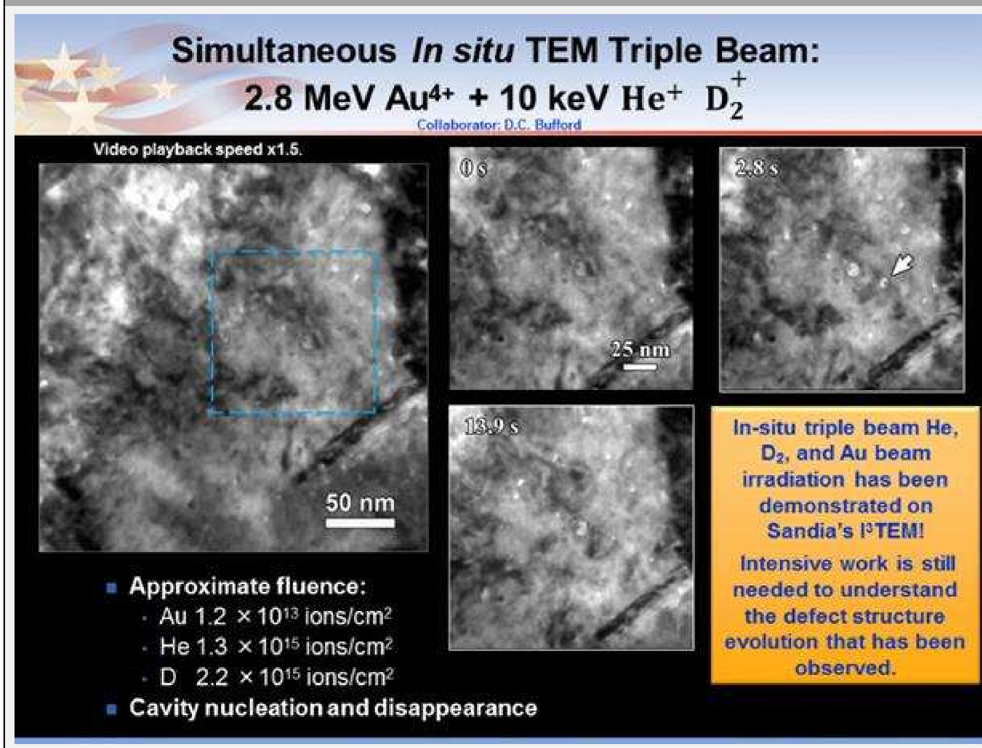
Direct Comparison to Mesoscale Modeling



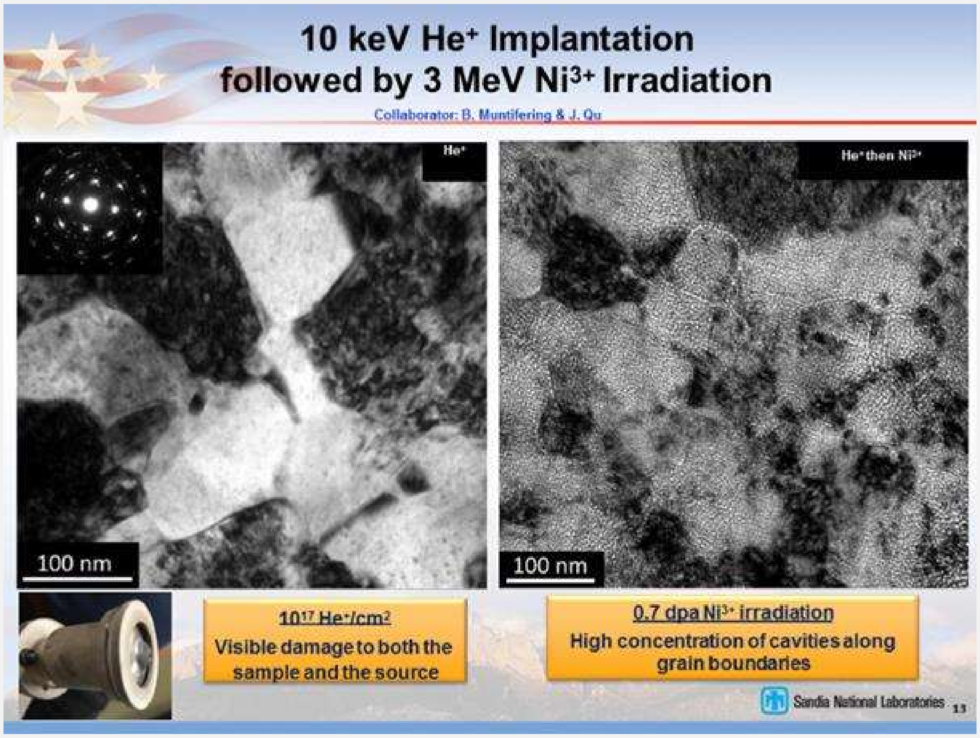
Modeling Beam Mixing and Deflection Necessary to Develop a *In situ* Triple Beam Facility



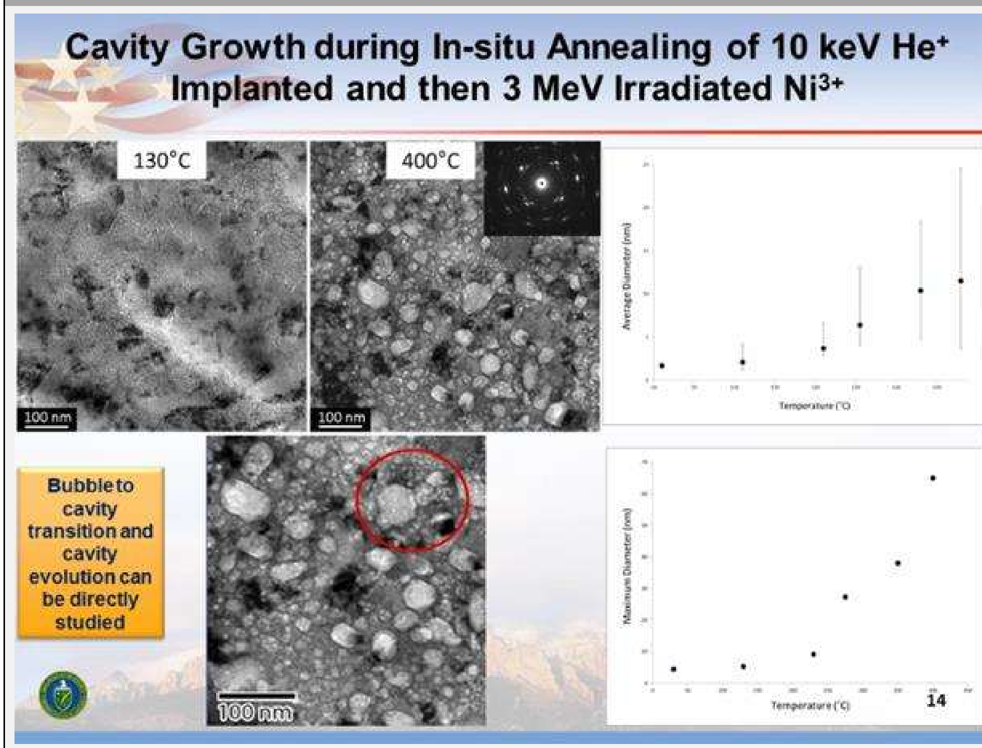
Simultaneous *In situ* TEM Triple Beam: 2.8 MeV Au^{4+} + 10 keV He^+ D_2^+



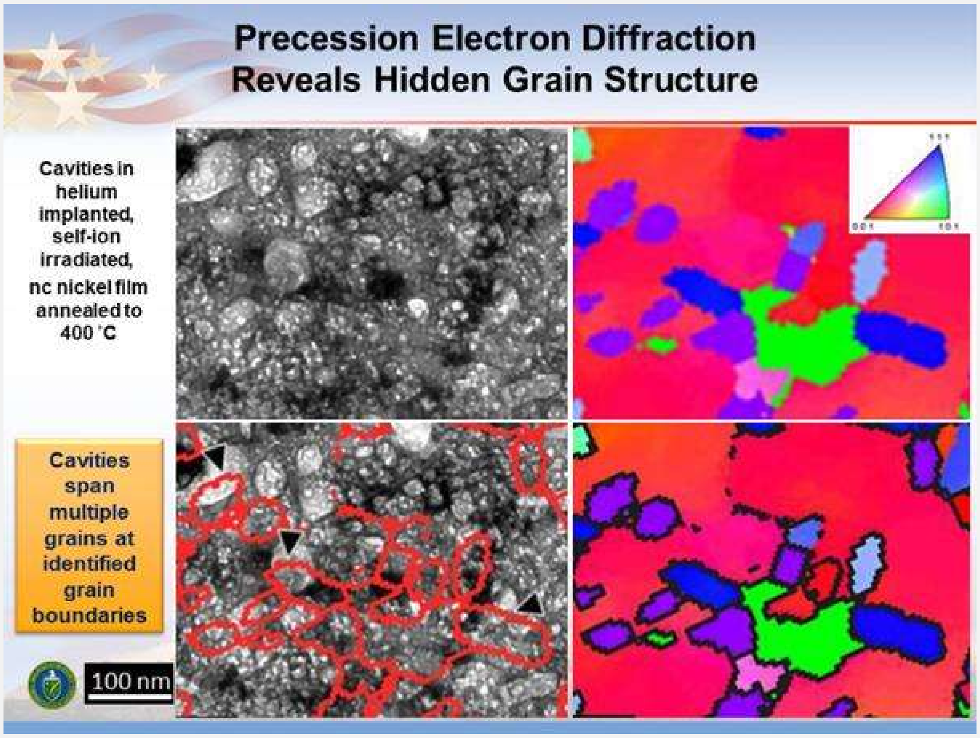
10 keV He^{+} Implantation followed by 3 MeV Ni^{3+} Irradiation



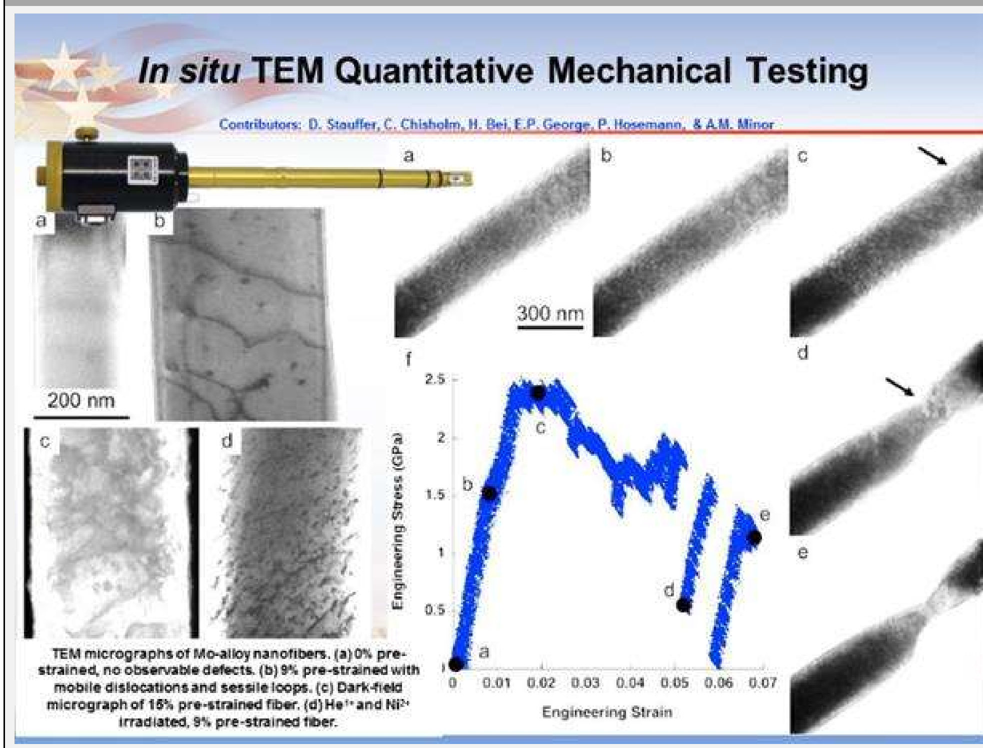
Cavity Growth during *In-situ* Annealing of 10 keV He^{+} Implanted and then 3 MeV Irradiated Ni^{3+}



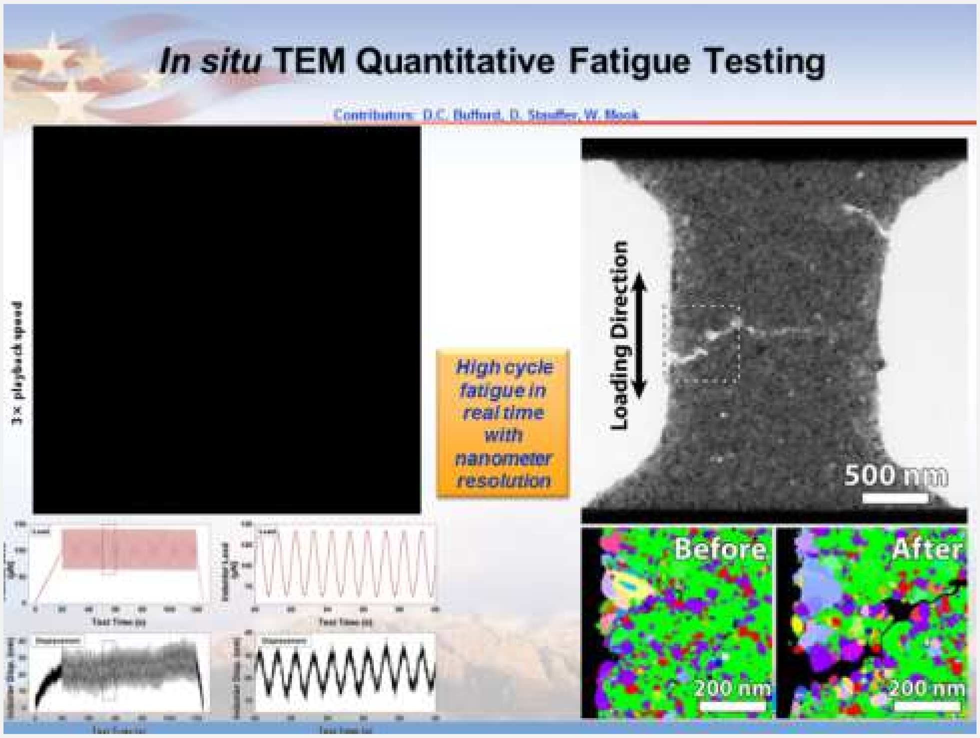
Precession Electron Diffraction Reveals Hidden Grain Structure



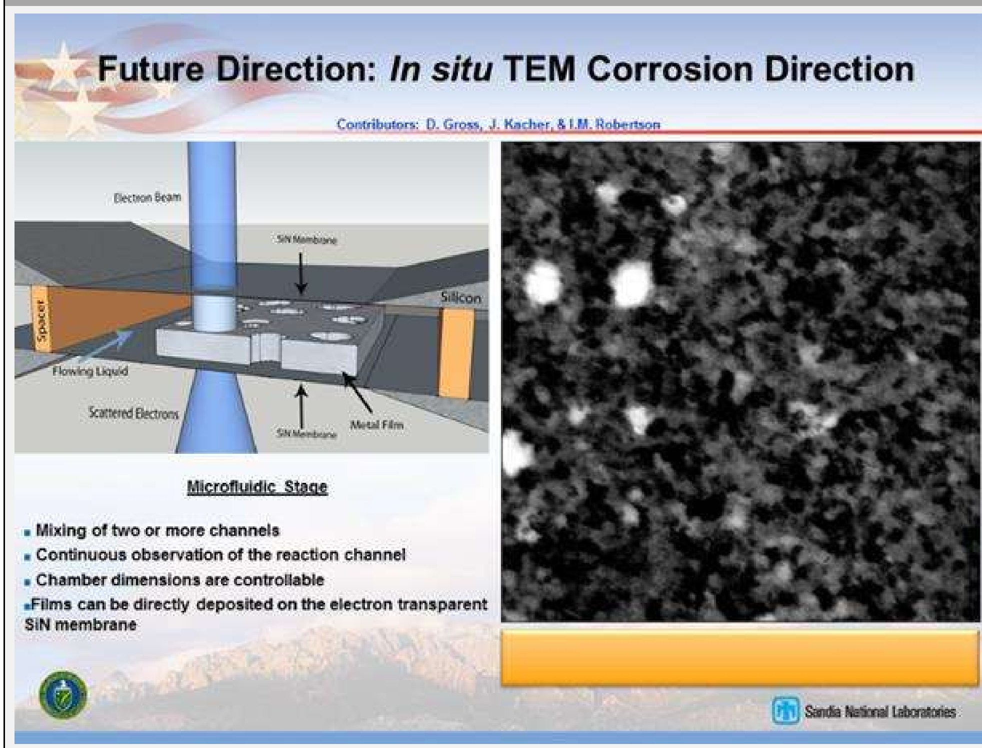
***In situ* TEM Quantitative Mechanical Testing**



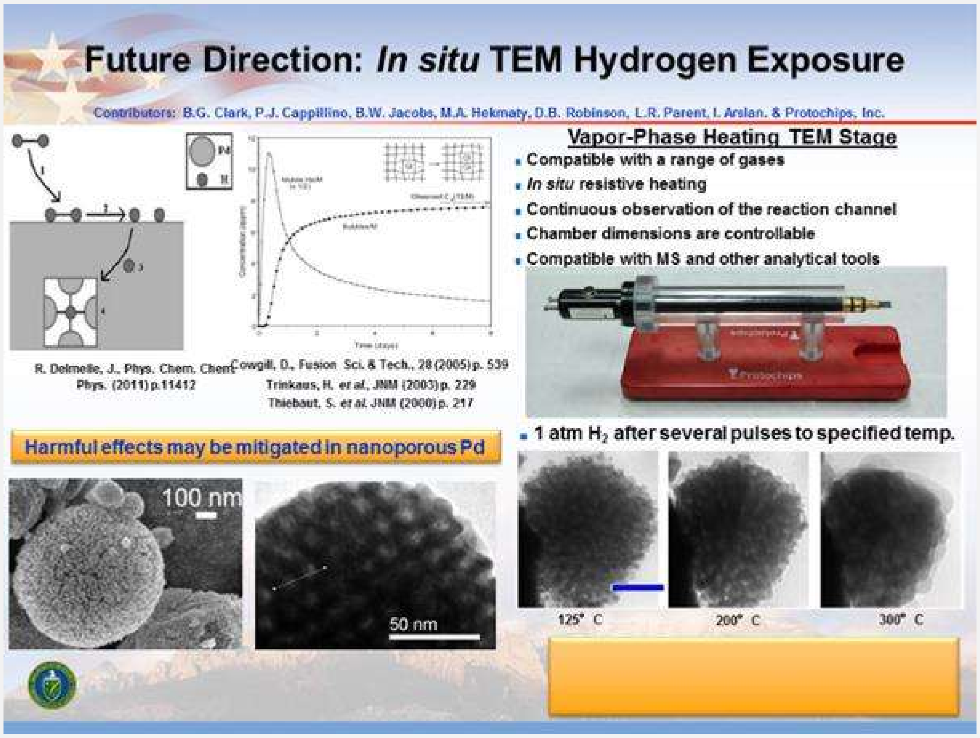
In situ TEM Quantitative Fatigue Testing



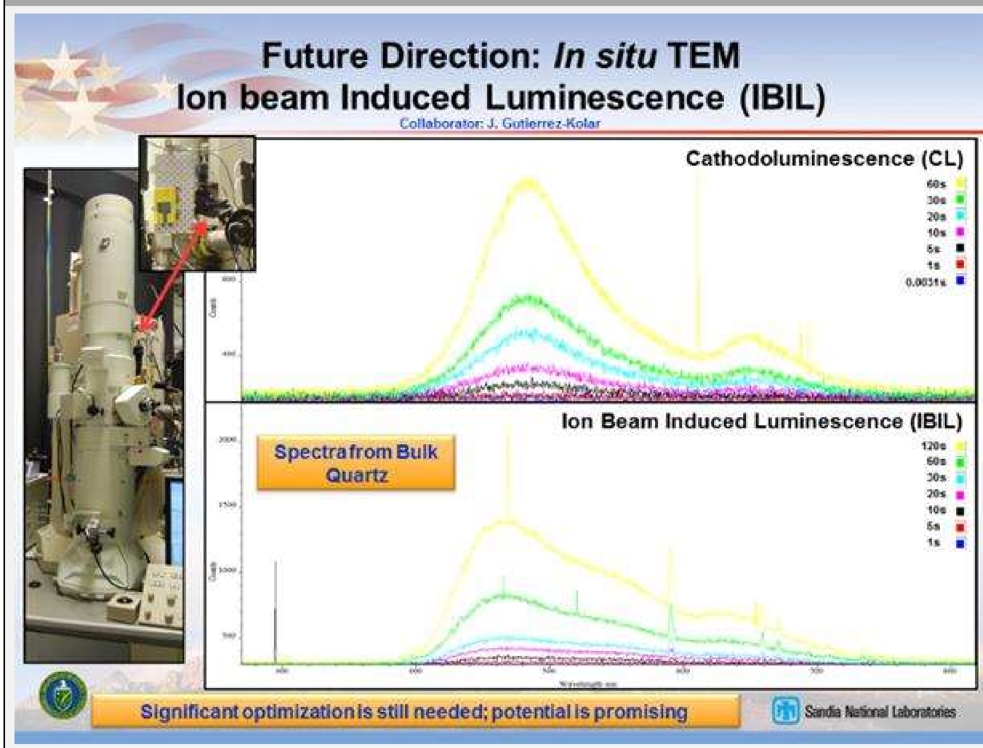
Future Direction: *In situ* TEM Corrosion Direction



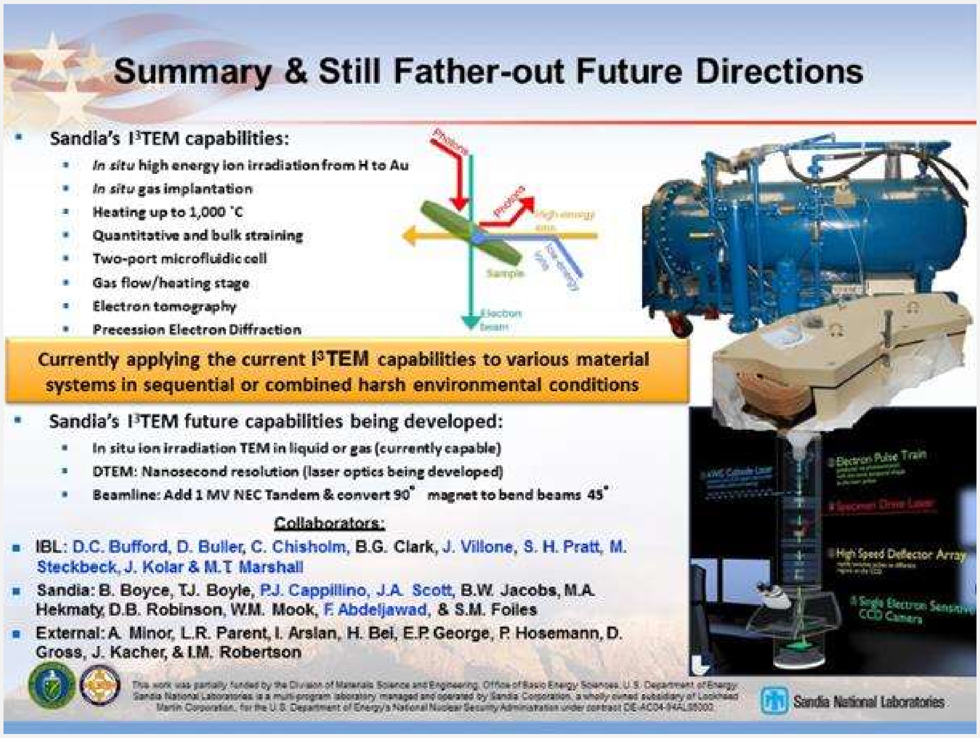
Future Direction: *In situ* TEM Hydrogen Exposure



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



Summary & Still Father-out Future Directions

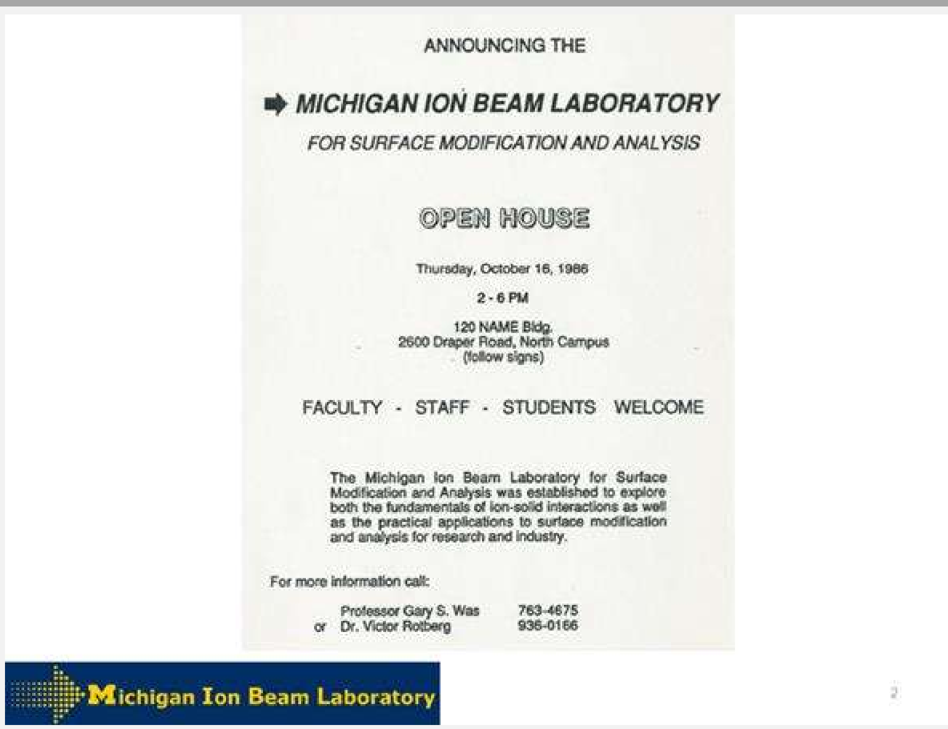


Presentation: Michigan IBL

Gary Was

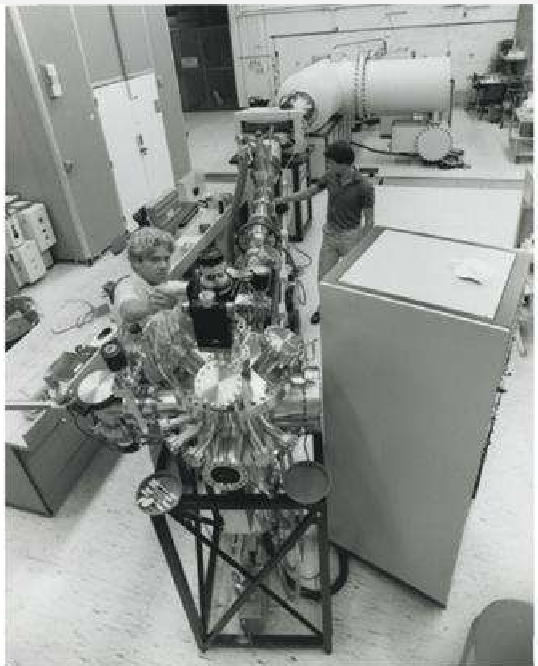
Ion Irradiation Capabilities and Needs at the Michigan Ion Beam Laboratory – a NSUF Partner Facility – Nuclear Engineering and Radiological Sciences University of Michigan

Slide 2



Slide 3

MIBL
October, 1986



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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

Michigan Ion Beam Laboratory

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Slide 6

Summary of Instrumentation at MIBL

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

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

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

Target temperature range: 77K to 1500K
Damage rate: < 10^{-5} dpa/s (protons), 10^{-3} dpa/s (heavy ions)
Irradiated area: up to 200 mm^2

*in progress

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Fly around MIBL

Fly around MIBL

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Ion Irradiation Capabilities at 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

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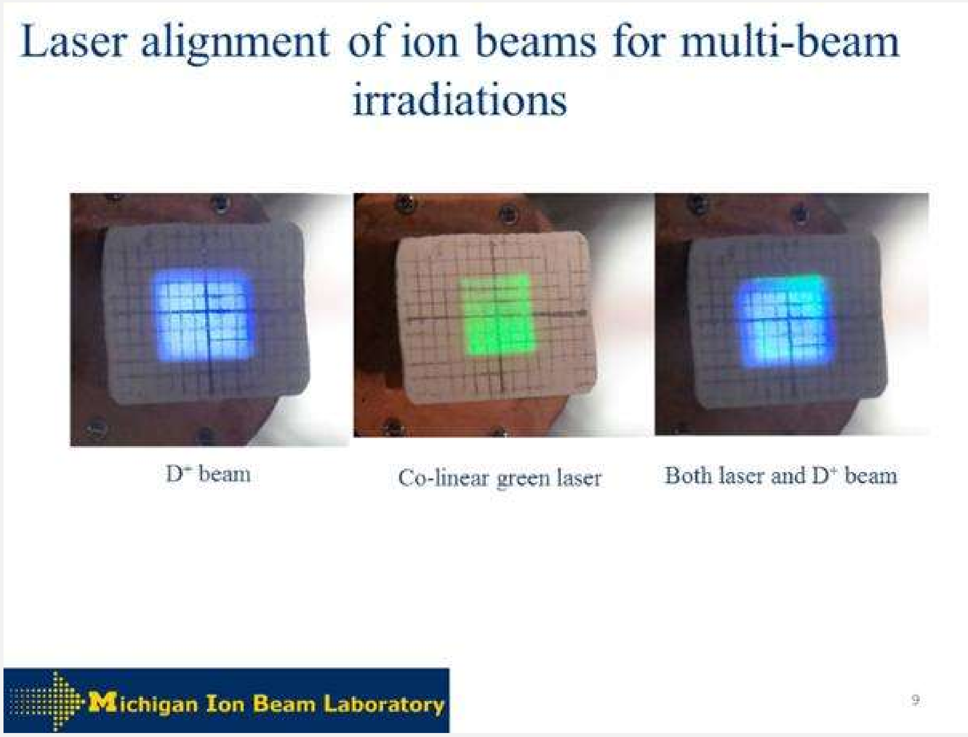
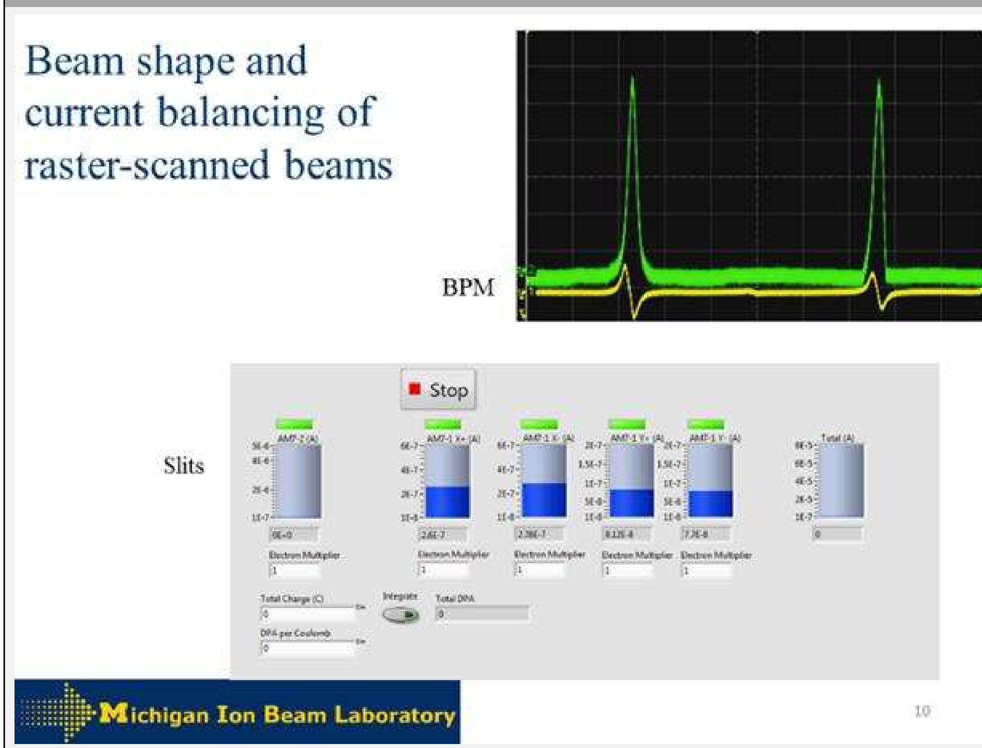
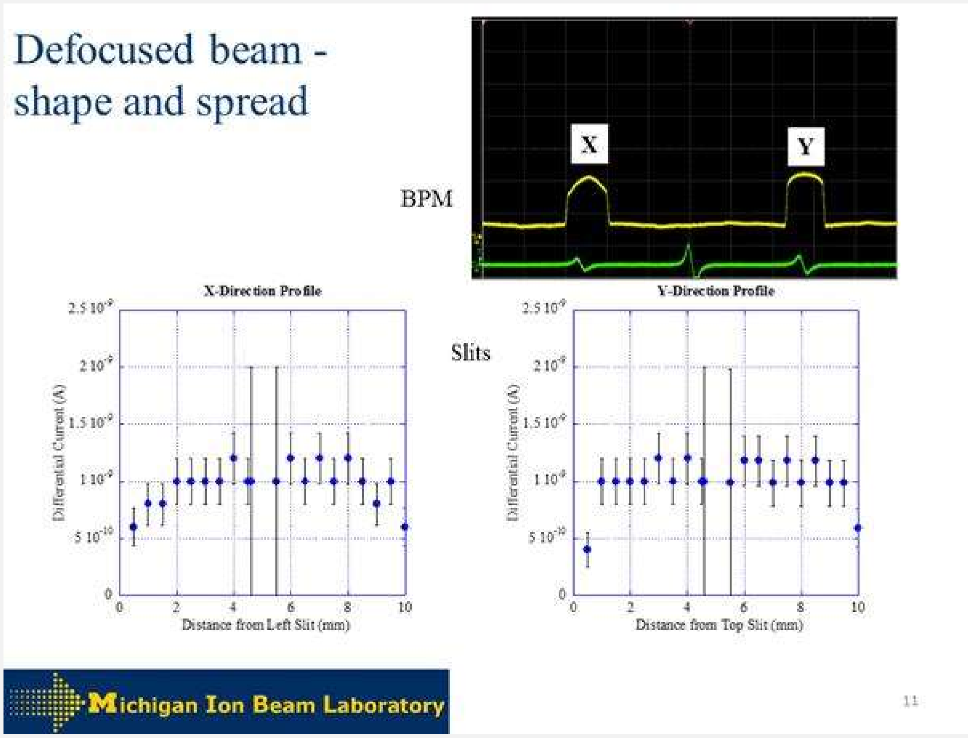
Laser alignment of ion beams for multi-beam irradiations



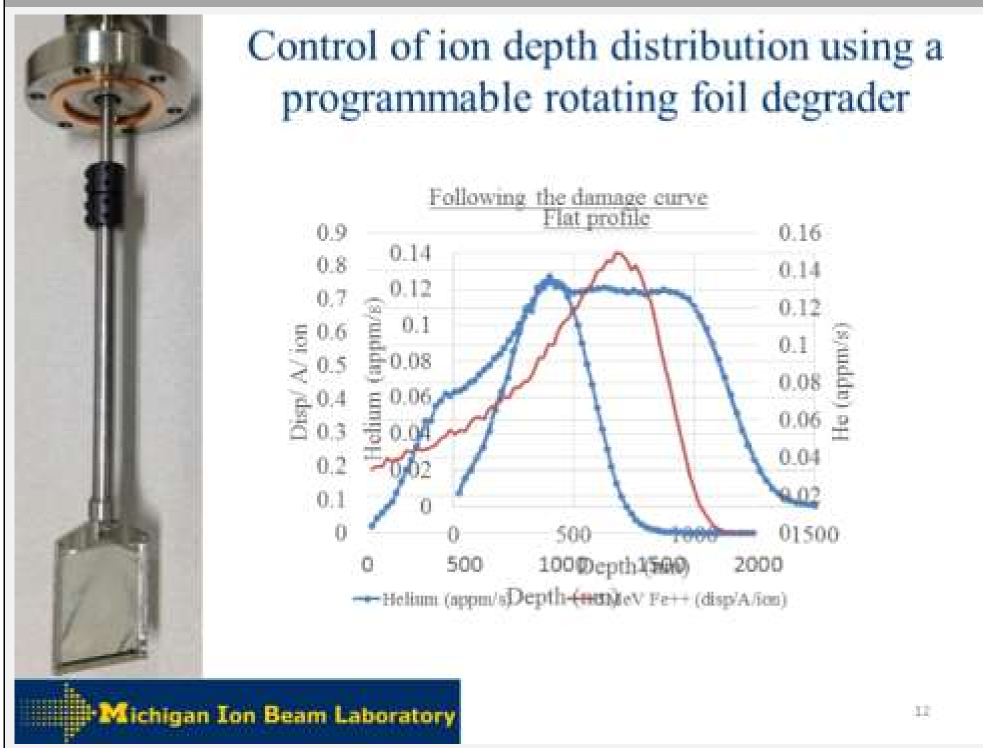
Beam shape and current balancing of raster-scanned beams



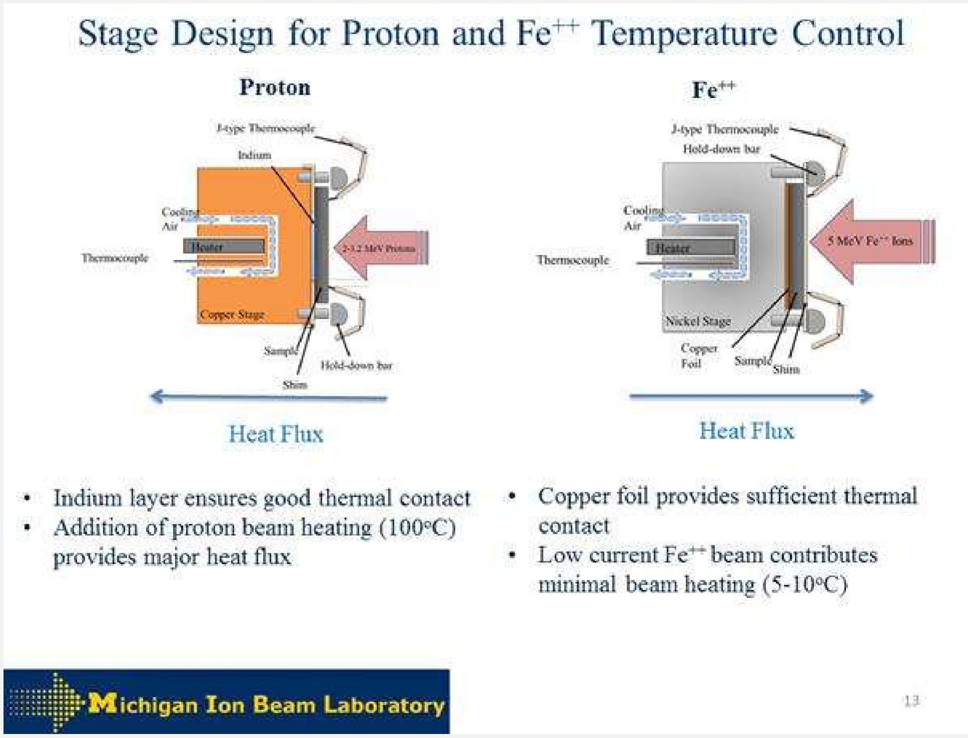
Slide 11



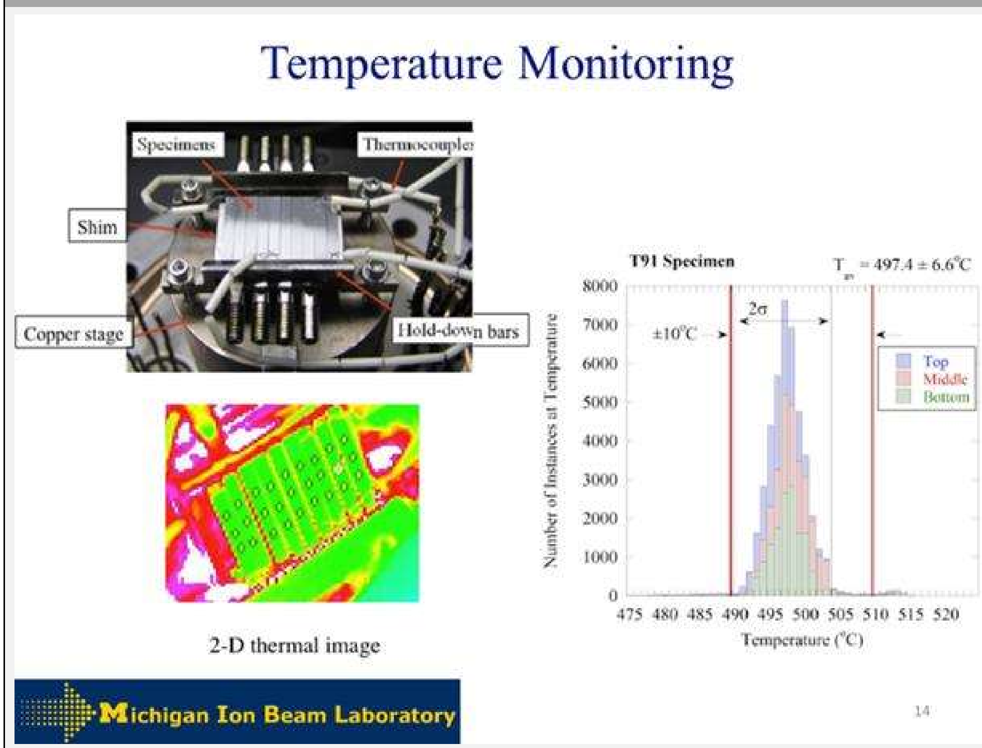
Control of ion depth distribution using a programmable rotating foil degrader



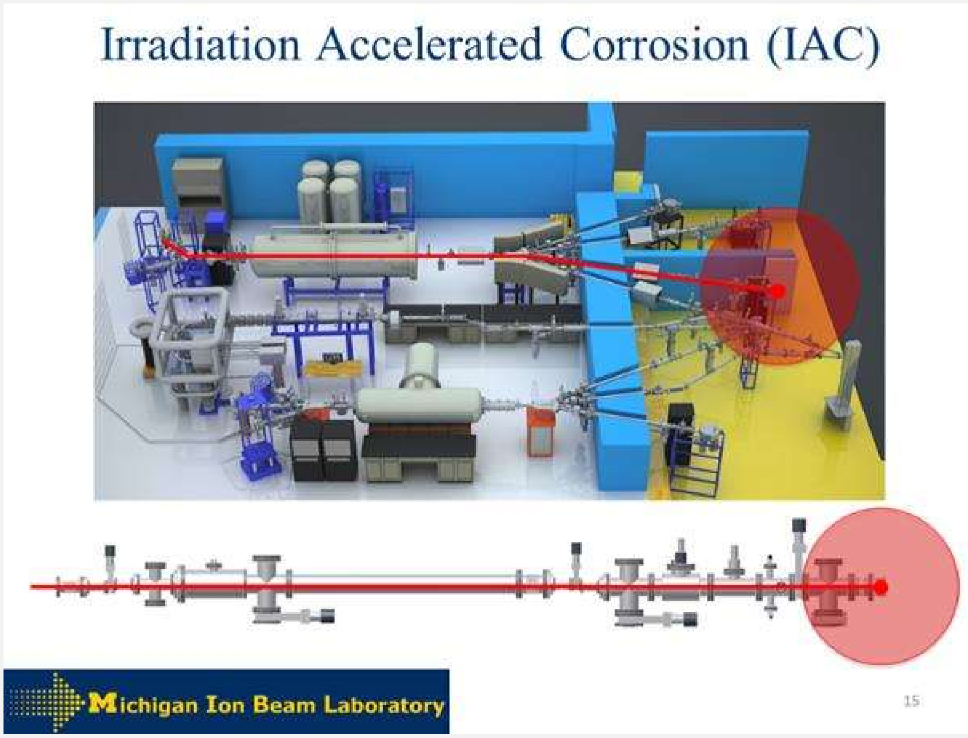
Stage Design for Proton and Fe^{++} Temperature Control



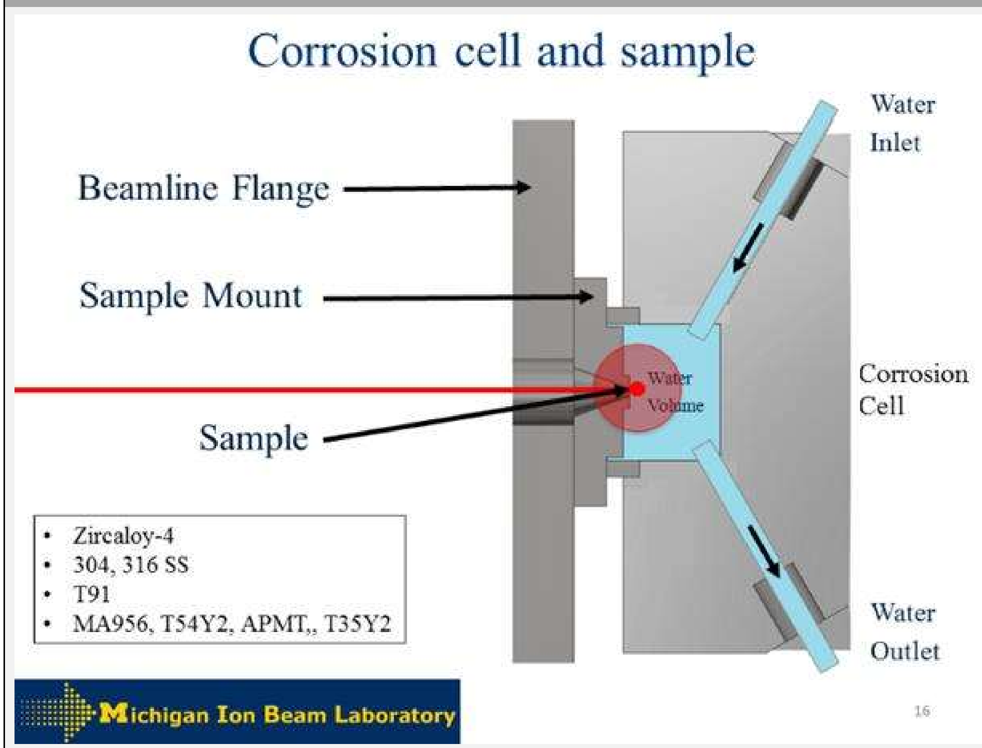
Irradiations



Irradiation Accelerated Corrosion (IAC)

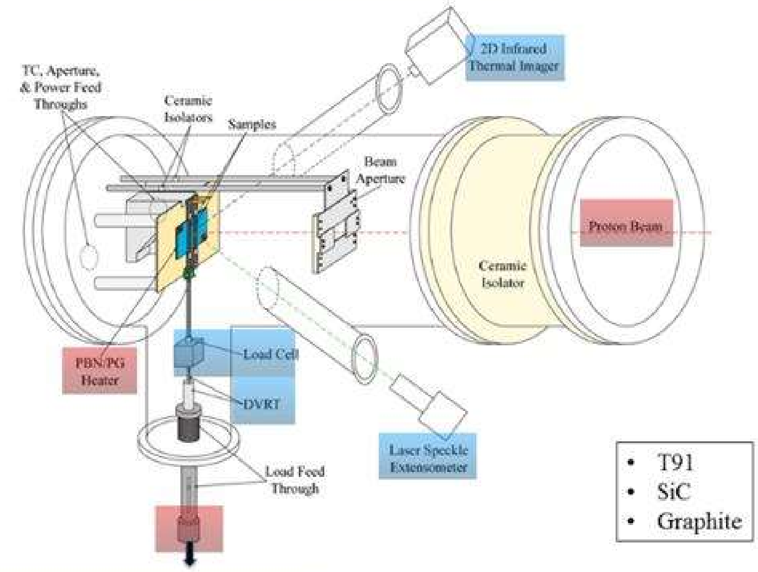


Corrosion cell and sample



In-situ irradiation creep

In-situ irradiation creep



- T91
- SiC
- Graphite

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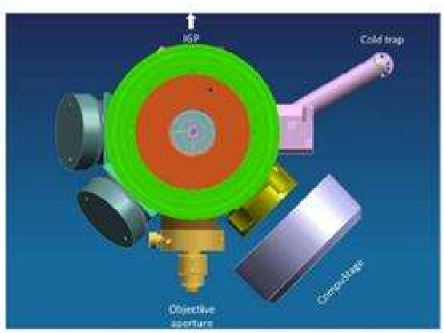
Slide 18

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

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



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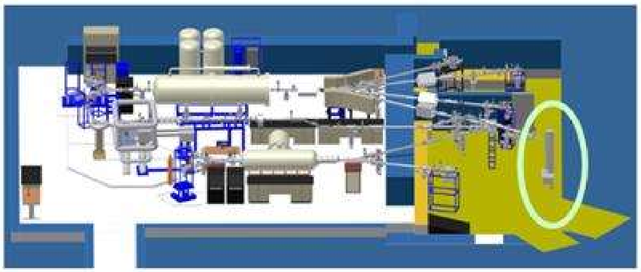
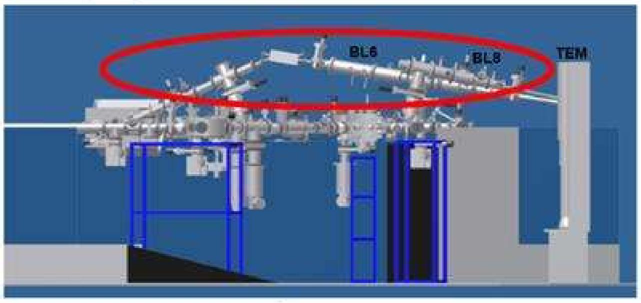
Slide 19

In-situ Dual Beam Facility





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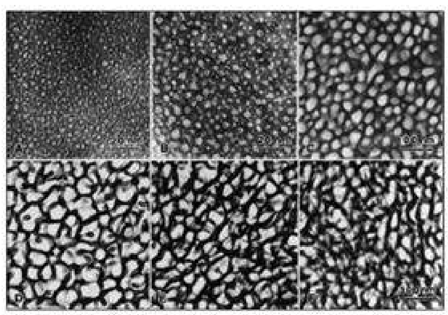
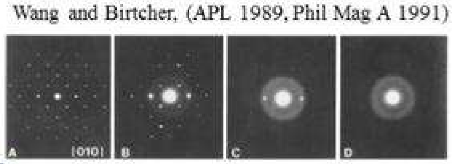
Slide 20

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)

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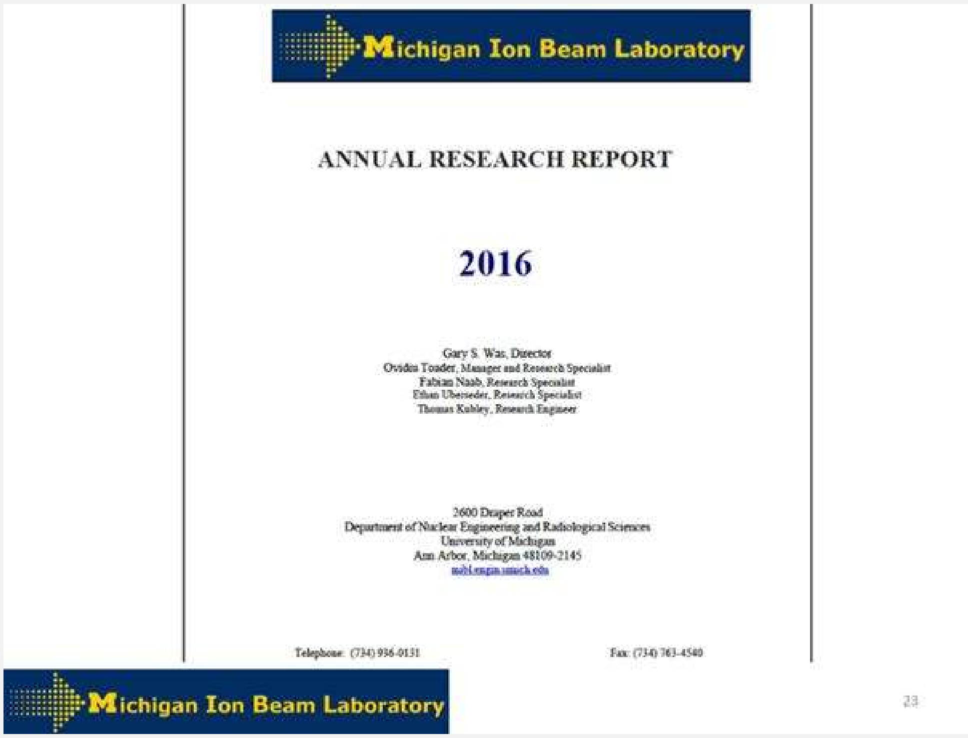
Slide 21

Slide 22

Slide 23



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

Slide 25

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^{-6}-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^{++}	-	10^{-5}-10^{-3} dpa/s	**10^{-5}-10^{-3}** dpa/s
He^{2+}	0.1 - 10^{3} appm/dpa	**0.1 - 10^{3}** appm/dpa	0.1-10^{3} appm/dpa
H^{+}	**0.1-10^{3}** appm/dpa	0.1-10^{3} appm/dpa	0.1-10^{3} appm/dpa

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Slide 26

Use of Ion Irradiation to Study Nuclear Fuel

- Xe (up to 1 µA of 1.6 MeV Xe) and Kr (up to 1.5 µA 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.

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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
  Chech Republic – NRI
  Korea – KAERI
  Pakistan – Lahore College for Women, NILOP, 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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Slide 29

Accomplishments

ELSEVIER

Journal of Nuclear Materials 300 (2002) 198–216

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Emulation of neutron irradiation effects with protons: validation of principle

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

ELSEVIER

CrossMark

Available online at www.sciencedirect.com

ScienceDirect

Scripta Materialia 88 (2014) 33–36

Scripta MATERIALIA

www.elsevier.com/locate/scriptamat

Emulation of reactor irradiation damage using ion beams

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

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Slide 30

Professional Staff at MIBL

Ovidiu Toader, PhD; Lab Manager

Fabian Naab, PhD; Research Specialist

Ethan Uberseder, PhD; Research Specialist

Thomas Kubley, MS; Accelerator Engineer

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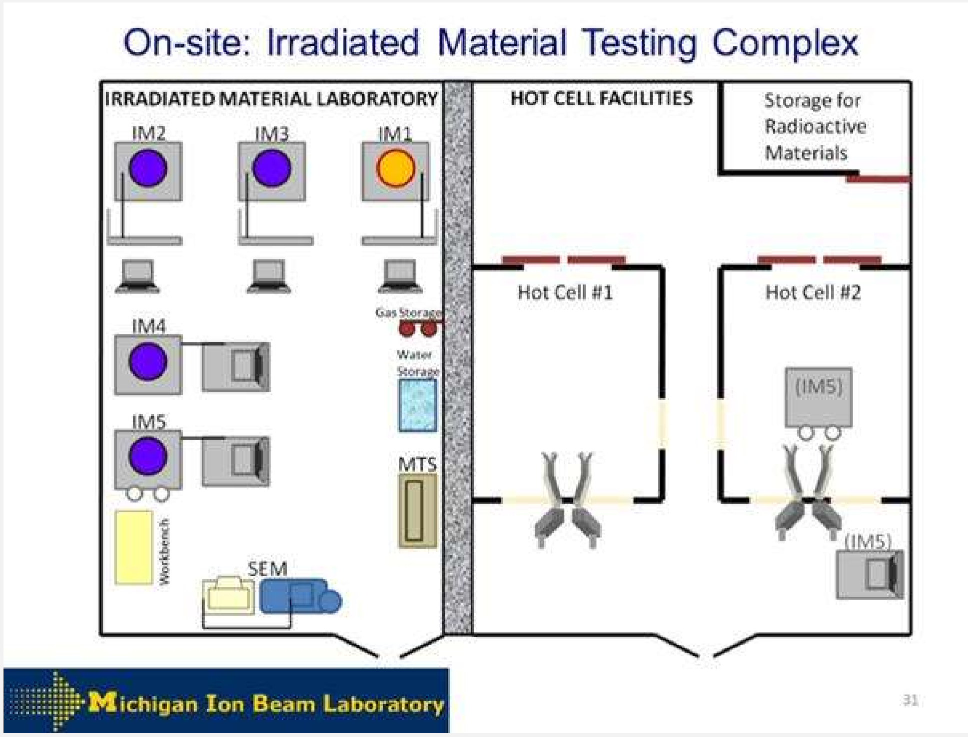
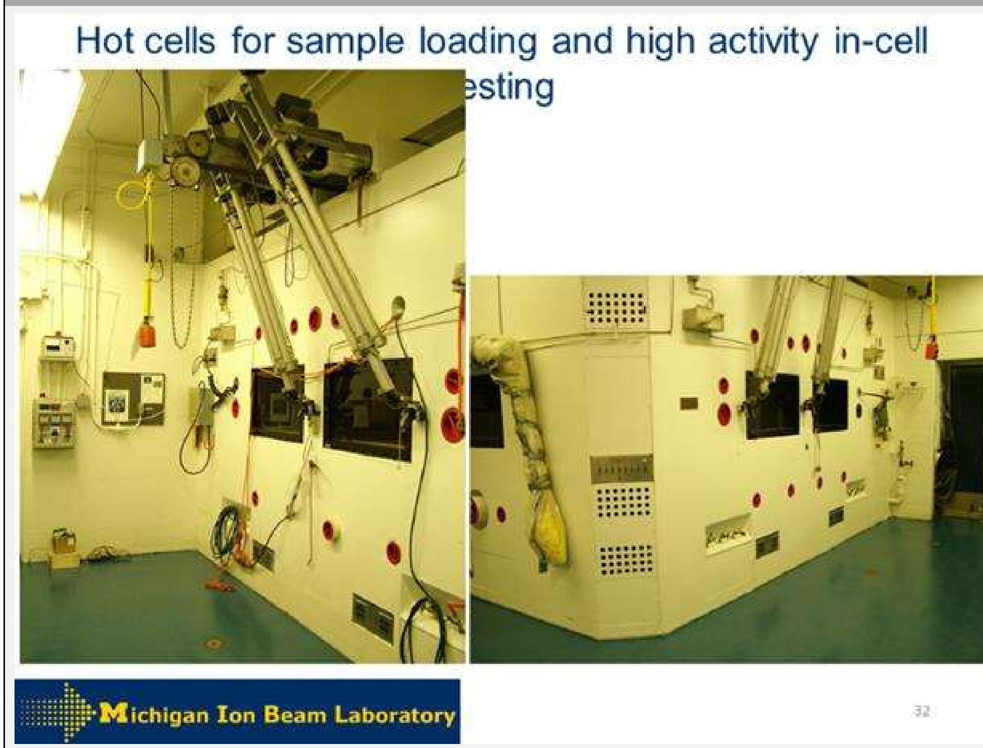
Slide 31



Slide 32



Slide 33

Facilities for Crack Growth Rate and Crack Initiation Testing

Control Panel & Water Columns

Movable Autoclave & Loading System

Dedicated Hot SEM

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Slide 34

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

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Questions?

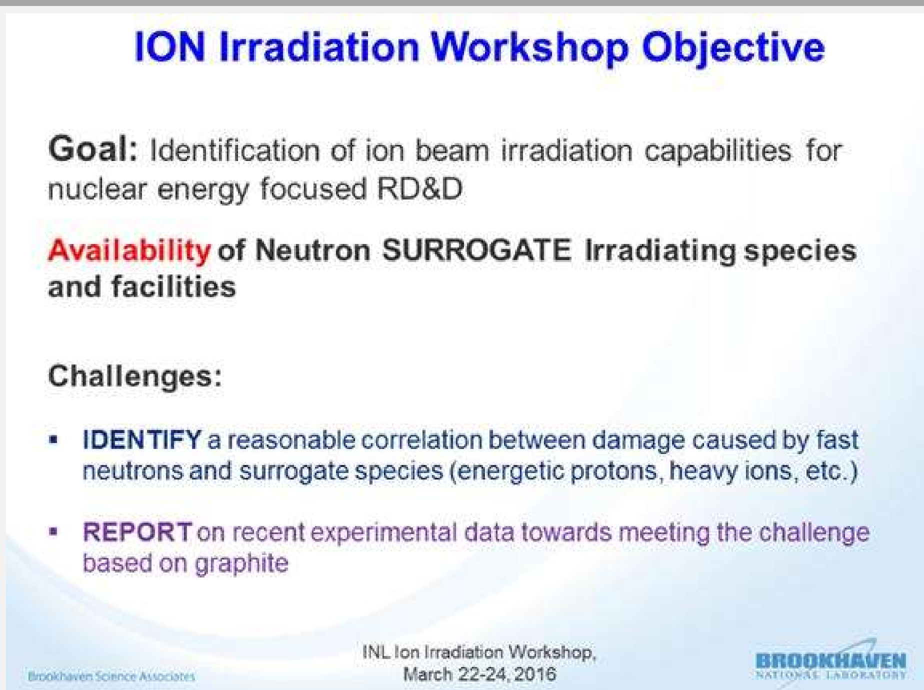

Questions?
Visit mibl.engin.umich.edu for more information on MIBL and working with us.
The expansion and new capabilities of the Michigan Ion Beam Laboratory were made possible with support from the DOE Nuclear Energy University Program, Electric Power Research Institute, TerraPower Inc., Oak Ridge National Laboratory, the University of Michigan's College of Engineering, and the University of Michigan's Nuclear Engineering and Radiological Sciences department.
NEUP
U.S. Department of Energy
EPRI
ELECTRIC POWER RESEARCH INSTITUTE
TerraPower
OAK RIDGE
National Laboratory
MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN
Michigan Ion Beam Laboratory

Presentation: Accelerator Based Facility for Materials Irradiation Testing

Nick Simos

Slide 1

Slide 2



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

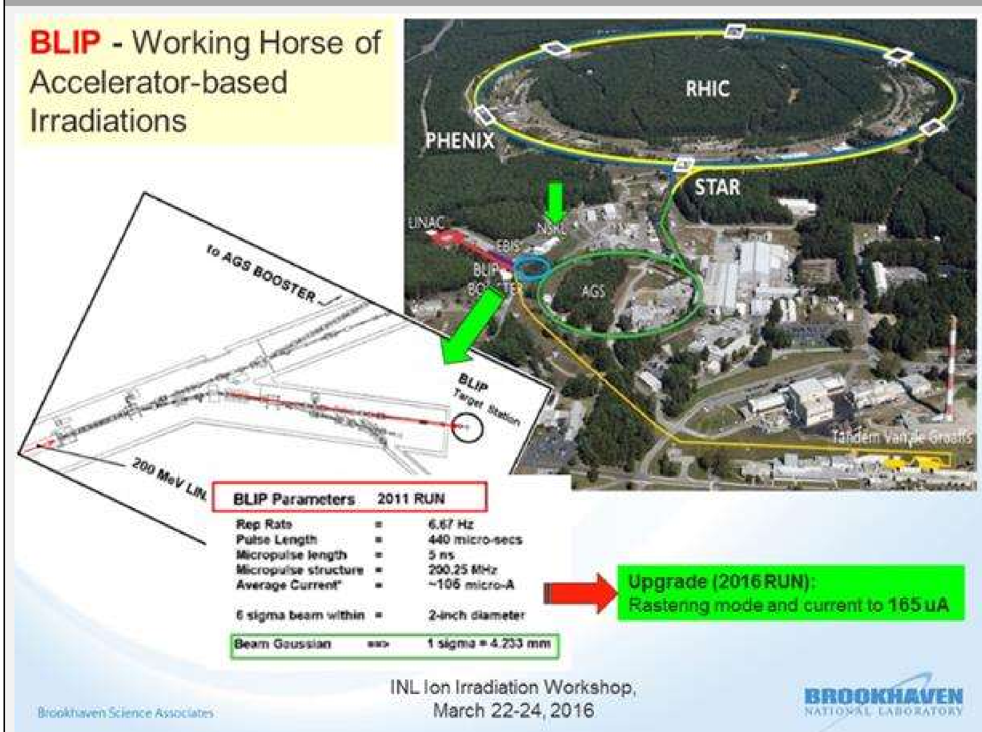
Brookhaven Science Associates

INL Ion Irradiation Workshop, March 22-24, 2016

BROOKHAVEN NATIONAL LABORATORY

1. Working on getting CFN to handle radioactive materials.

Slide 4



Slide 5

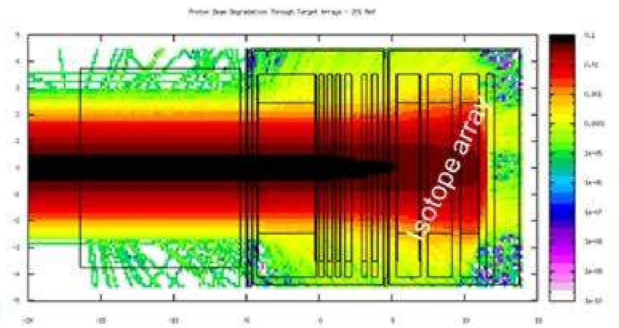
High Energy Proton Irradiation

(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



Brookhaven Science Associates

INL Ion Irradiation Workshop,
March 22-24, 2016

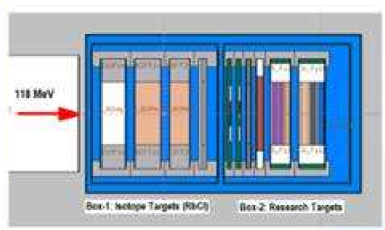
BROOKHAVEN NATIONAL LABORATORY

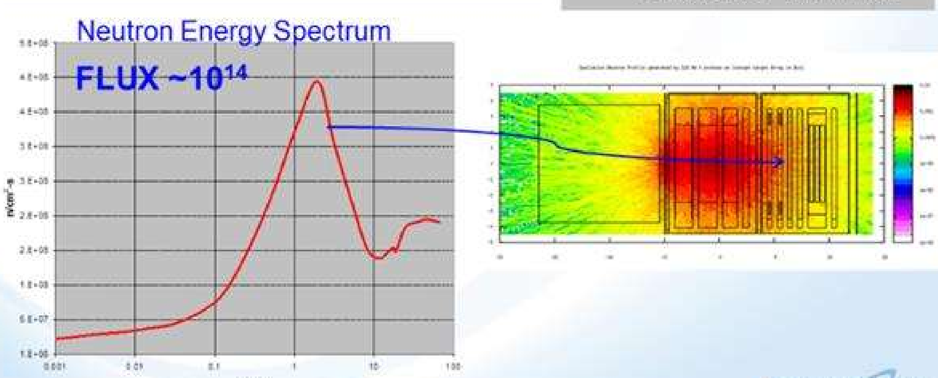
Slide 6

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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Slide 7

Irradiation Damage of Graphite

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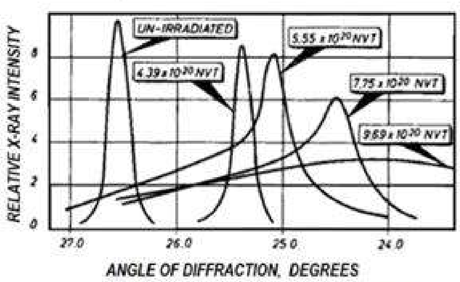
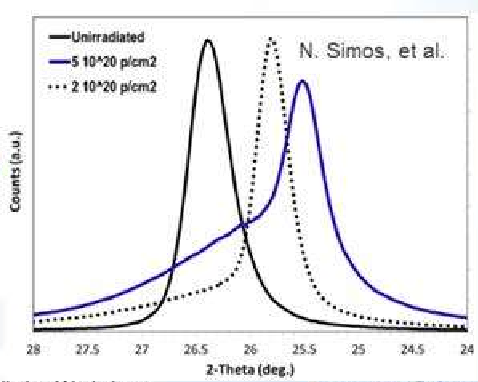
Neutron Surrogate Irradiation – Recent results on graphite

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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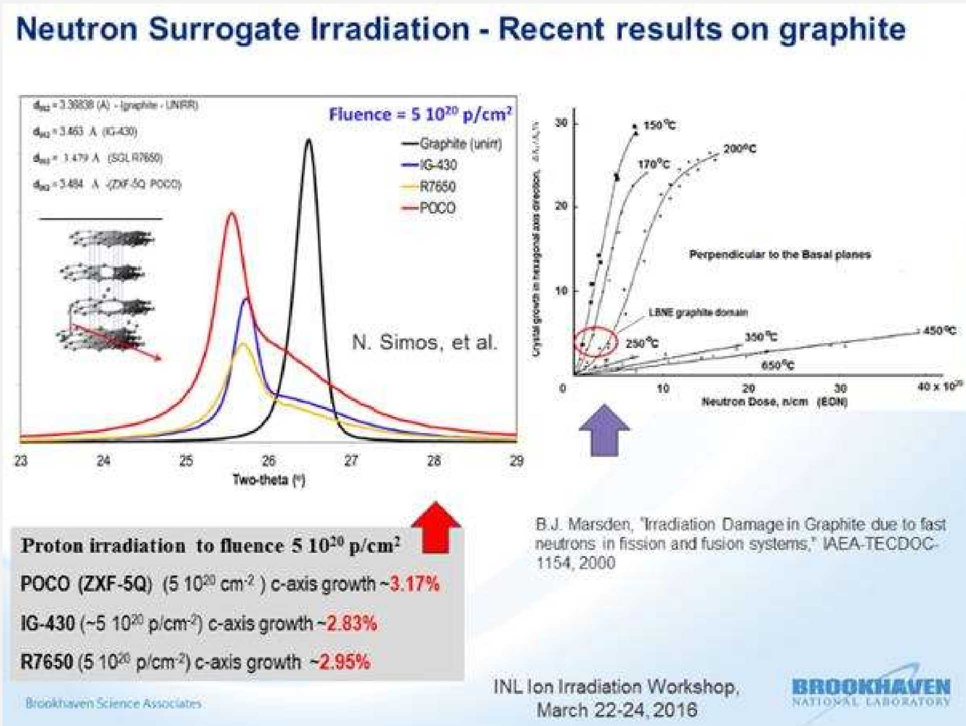
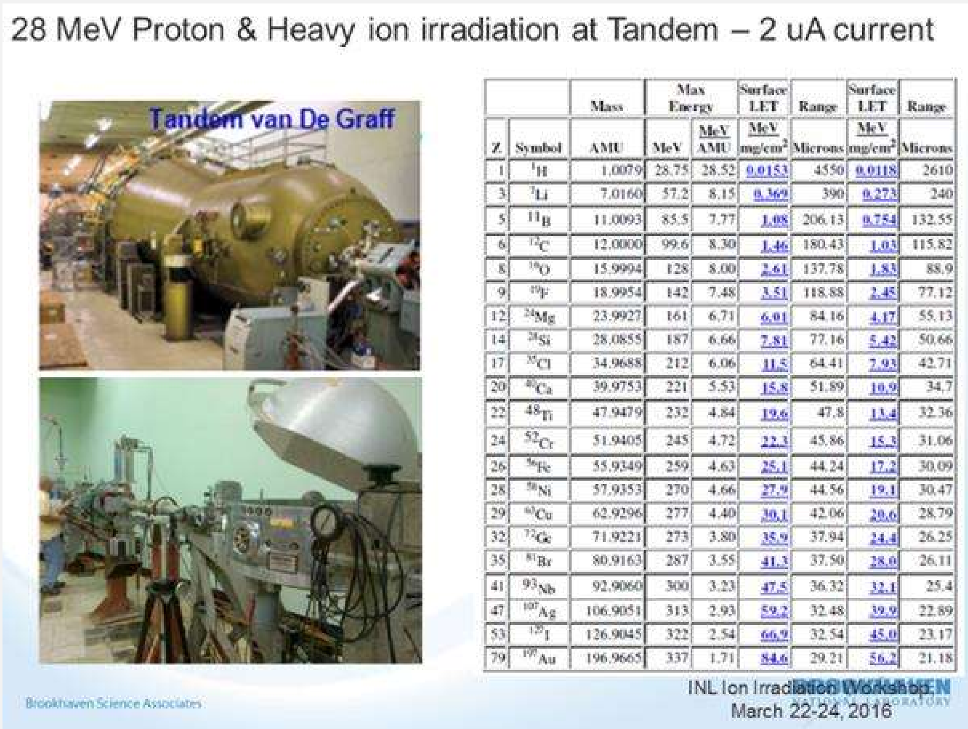
Neutron Surrogate Irradiation – Recent results on graphite



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

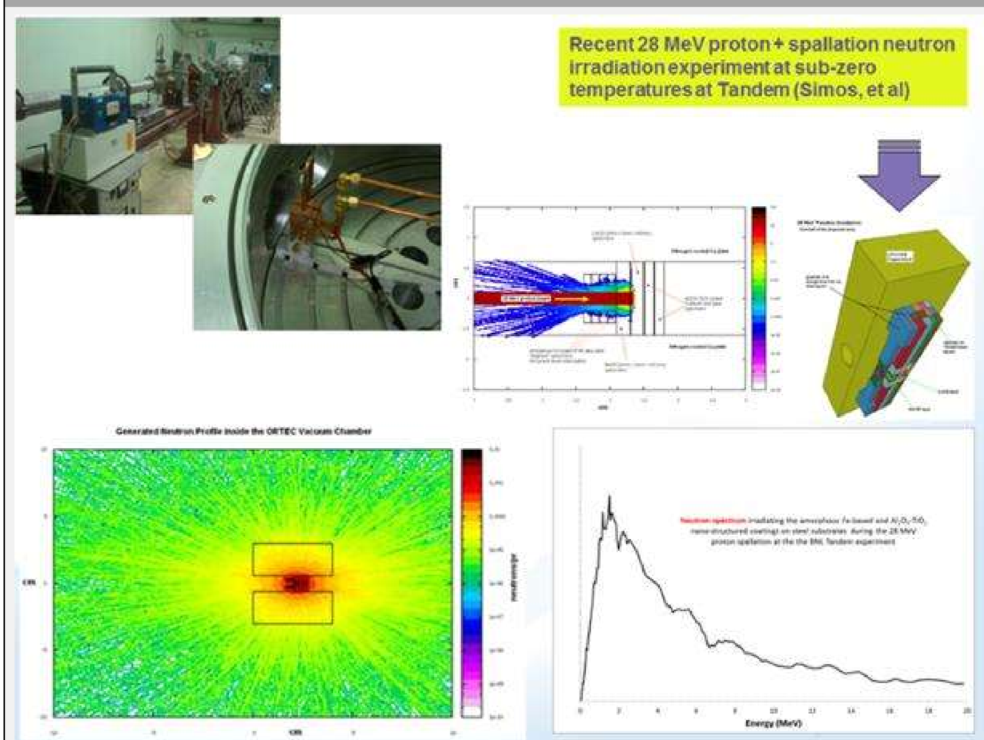
Slide 11



Z	Symbol	Mass AMU	Max Energy MeV	Max Energy MeV/AMU	Surface LET MeV/(mg/cm²)	Range Microns	Surface LET MeV/(mg/cm²)	Range Microns
1	^{1}H	1.0079	28.75	28.52	0.0153	4550	0.0118	2610
3	^{7}Li	7.0160	57.2	8.15	0.369	390	0.273	240
5	^{11}B	11.0093	85.5	7.77	1.08	206.13	0.754	132.55
6	^{12}C	12.0000	99.6	8.30	1.46	180.43	1.03	115.82
8	^{16}O	15.9994	128	8.00	2.61	137.78	1.83	88.9
9	^{19}F	18.9954	142	7.48	3.51	118.88	2.45	77.12
12	^{24}Mg	23.9927	161	6.71	6.01	84.16	4.17	55.13
14	^{28}Si	28.0855	187	6.66	7.81	77.16	5.42	50.66
17	^{35}Cl	34.9688	212	6.06	11.5	64.41	7.93	42.71
20	^{40}Ca	39.9753	221	5.53	15.8	51.89	10.9	34.7
22	^{48}Ti	47.9479	232	4.84	19.6	47.8	13.4	32.36
24	^{52}Cr	51.9405	245	4.72	22.3	45.86	15.3	31.06
26	^{56}Fe	55.9349	259	4.63	25.1	44.24	17.2	30.09
28	^{58}Ni	57.9353	270	4.66	27.9	44.56	19.1	30.47
29	^{63}Cu	62.9296	277	4.40	30.1	42.06	20.6	28.79
32	^{72}Ge	71.9221	273	3.80	35.9	37.94	24.4	26.25
35	^{81}Br	80.9163	287	3.55	41.3	37.50	28.0	26.11
41	^{93}Nb	92.9060	300	3.23	47.5	36.32	32.1	25.4
47	^{107}Ag	106.9051	313	2.93	59.2	32.48	39.9	22.89
53	^{127}I	126.9045	322	2.54	66.9	32.54	45.0	23.17
79	^{197}Au	196.9665	337	1.71	84.6	29.21	56.2	21.18

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

Slide 12



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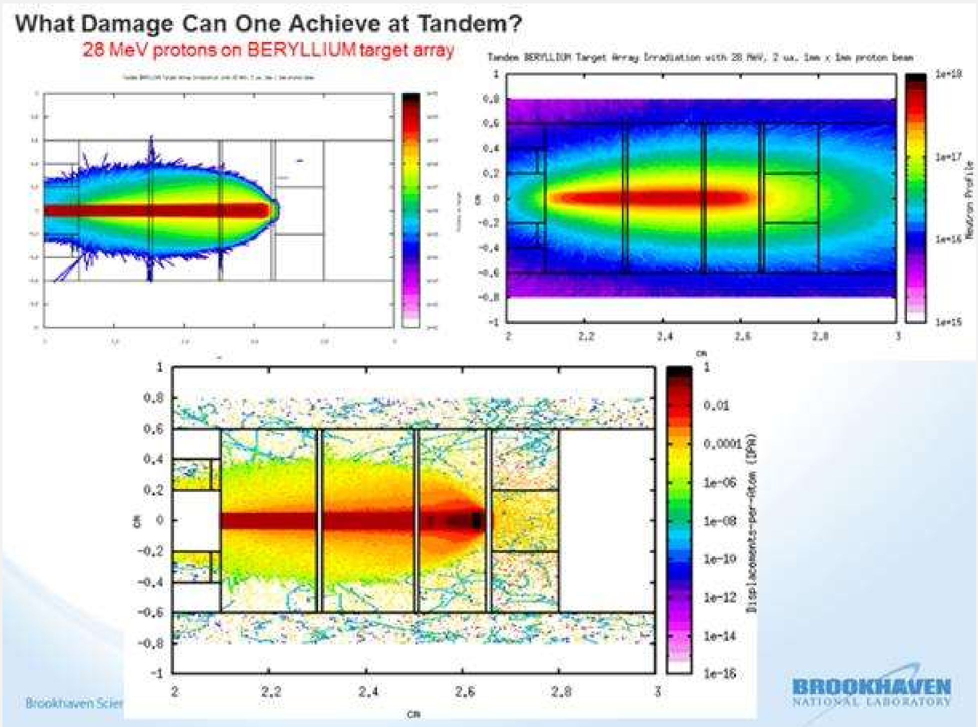
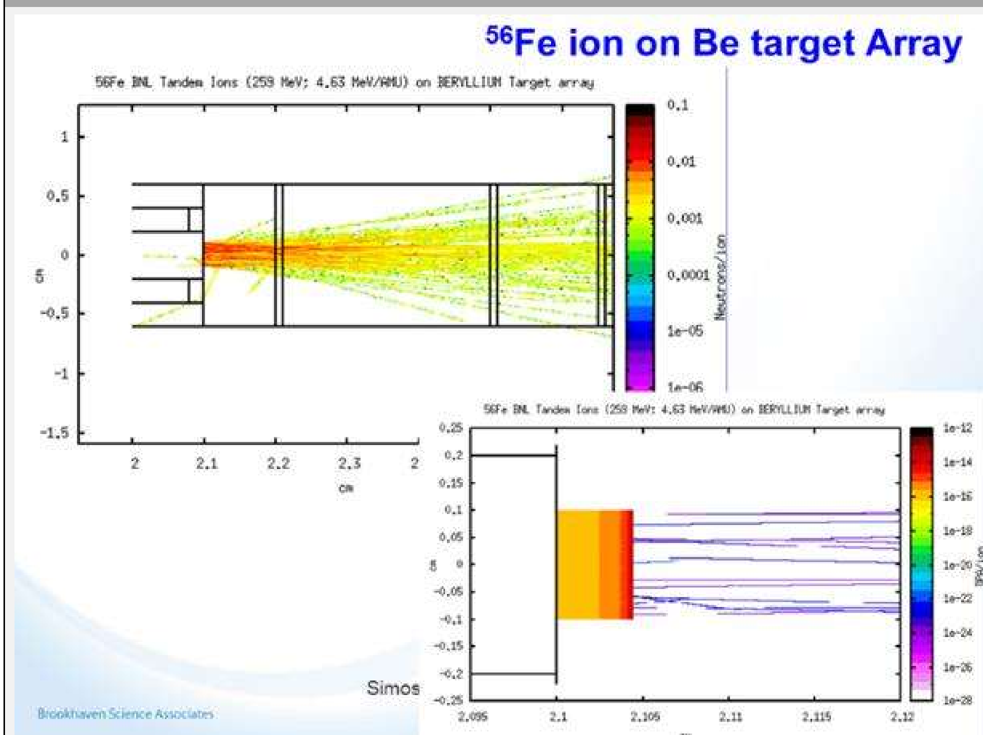
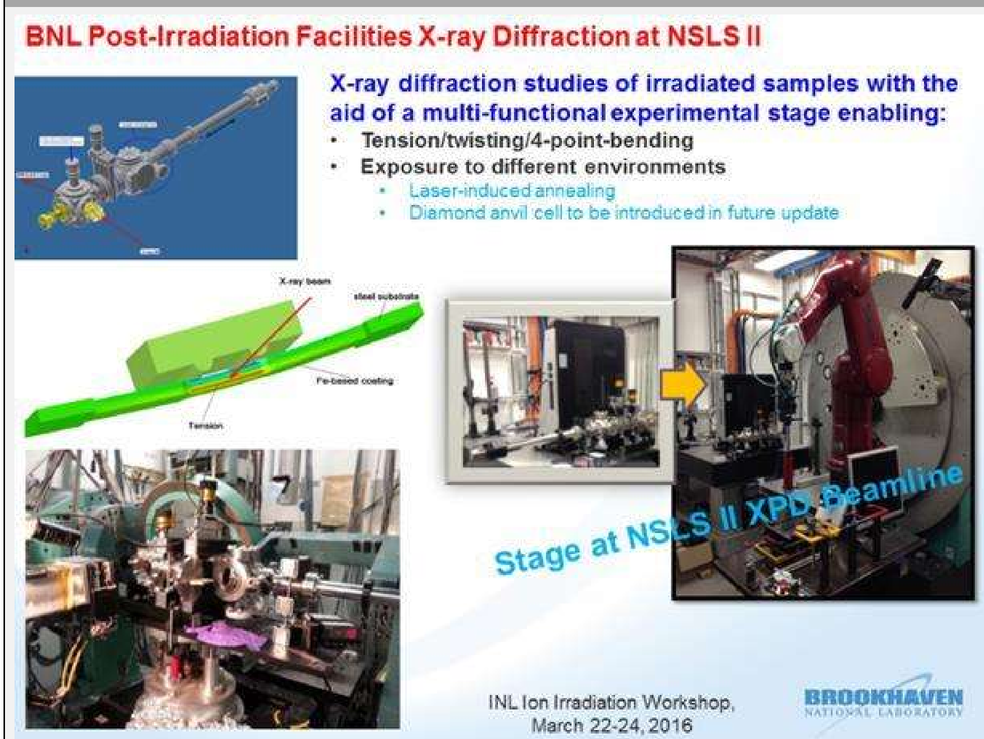


Slide 14



Slide 15

Slide 16



Slide 17

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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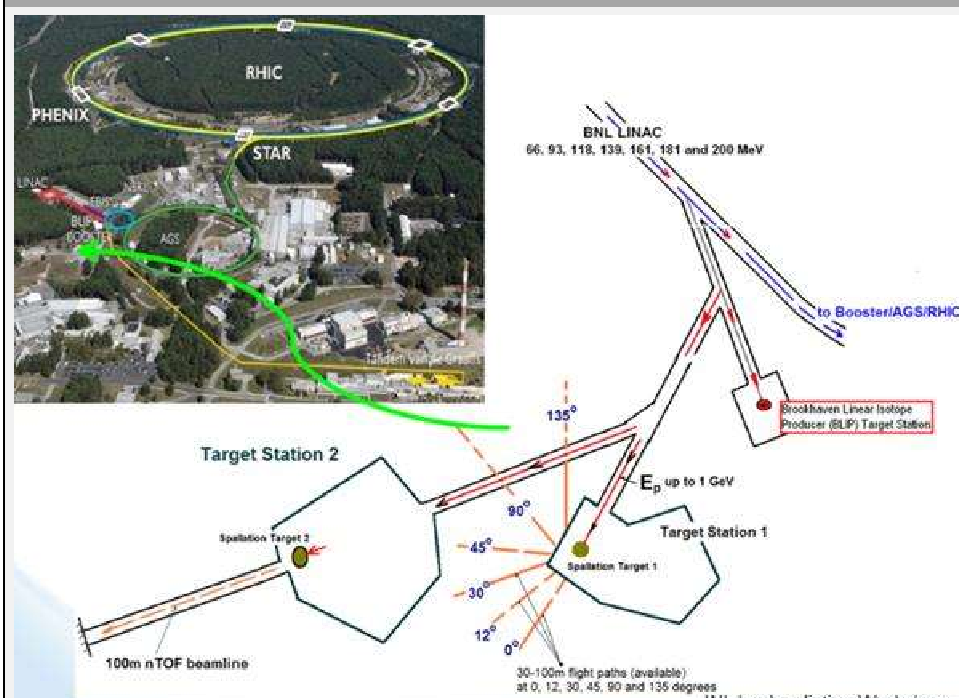

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Slide 19

Aim: Capitalize on Complex Unique Features:

- Multitude of energies the Linac can provide
- Polarized H^-
- **Beam current** (165 μA → 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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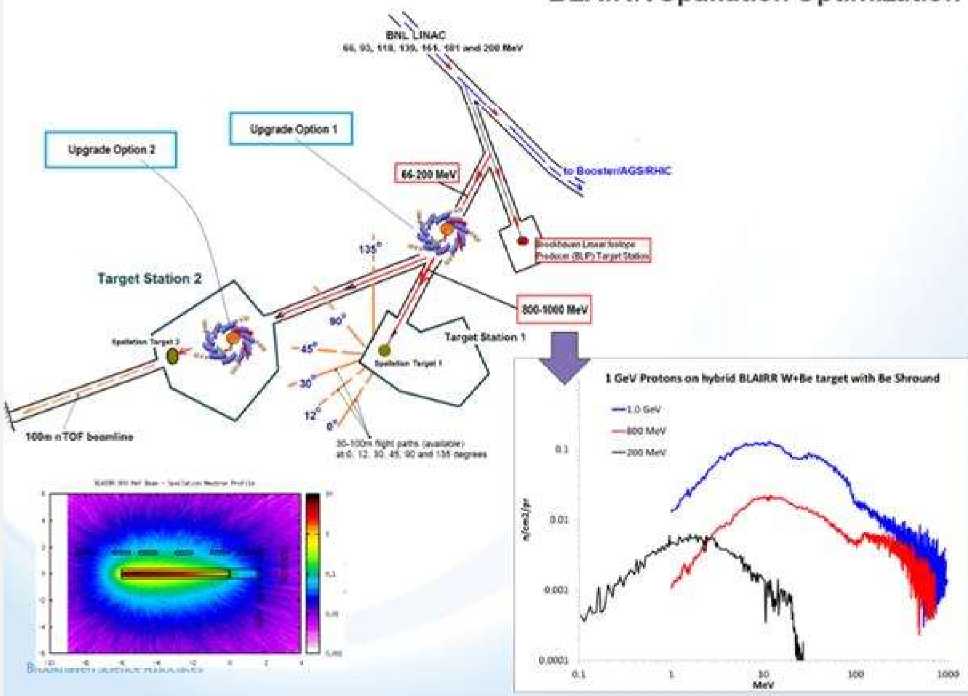
BLAIRR Spallation Optimization



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Slide 21


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, 7.0e+14 pps)
Booster: 0.2-1.5 GeV/30kW
(1.5GeV, 6.67Hz, 1.0e14pps)
Assessment:
Getting DESIRED Energy
Loosing CURRENT (big time)
LINAC
EBIS
NSRL
BLIP
BOOSTER
AGS
Option-2:
Update LINAC and Utilize Transfer Line Straight (~125 m)
LINAC: 200MeV/30kW
(200 MeV, 6.67 Hz, 7.0e+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 −63.43 °
Packing factor 10.21 %
Fringe extent 7.04 °
Mean field (y=1) −1 T
Asymptotic radius R 3.1297 m
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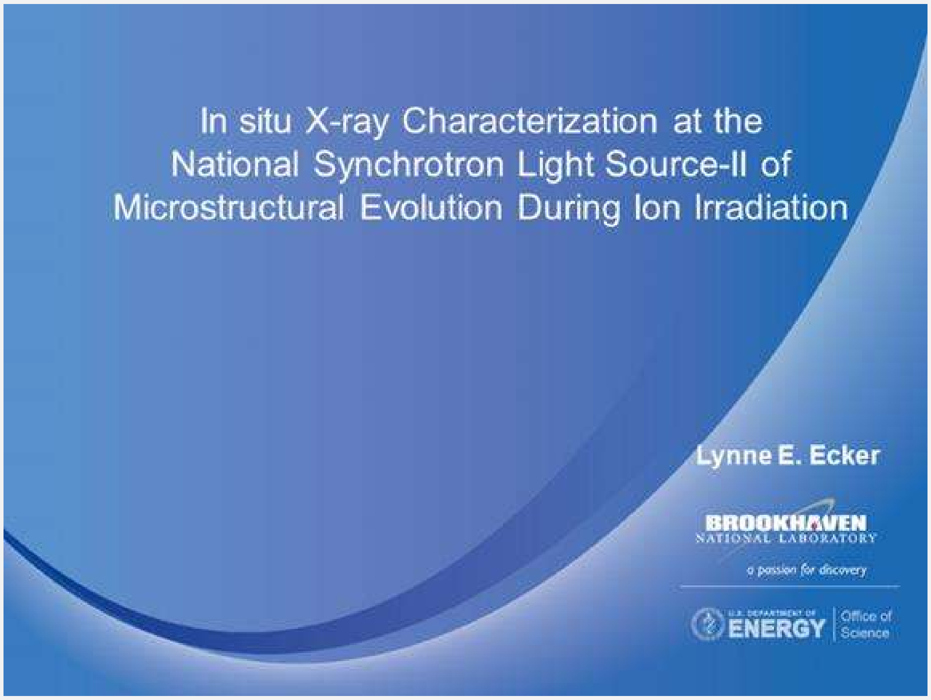
March 22-24, 2016

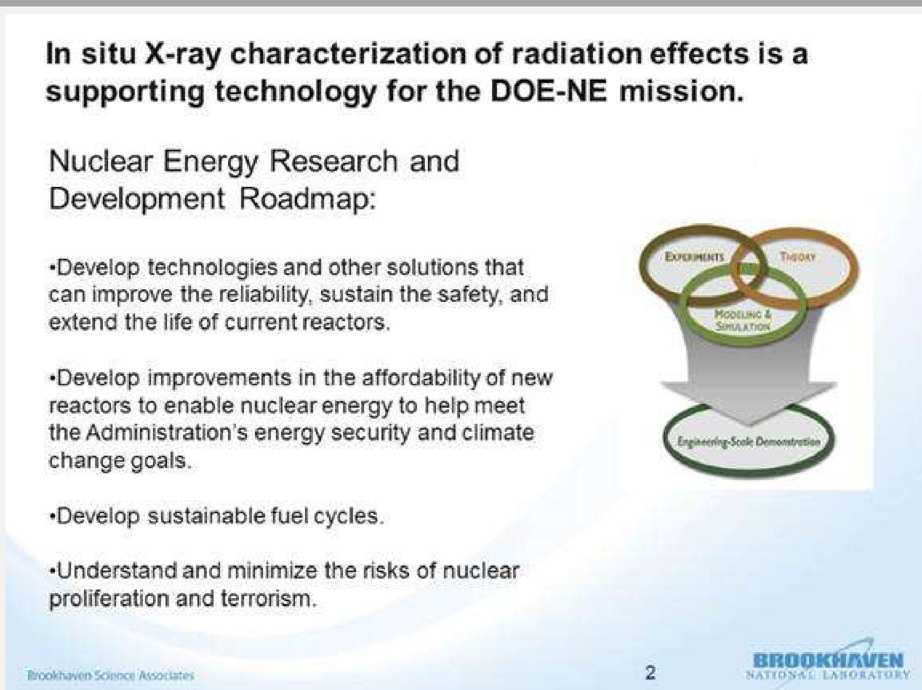
Presentation: *In-Situ* X-ray Characterization of Microstructural Evolution

Lynne Ecker

Slide 1

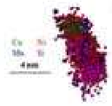


Slide 2



Slide 3

Outline



X-rays for Characterization of Radiation Damage

Synchrotron Beamline for Radioactive Materials

Proposed In Situ Ion Beam Capability

Slide 4

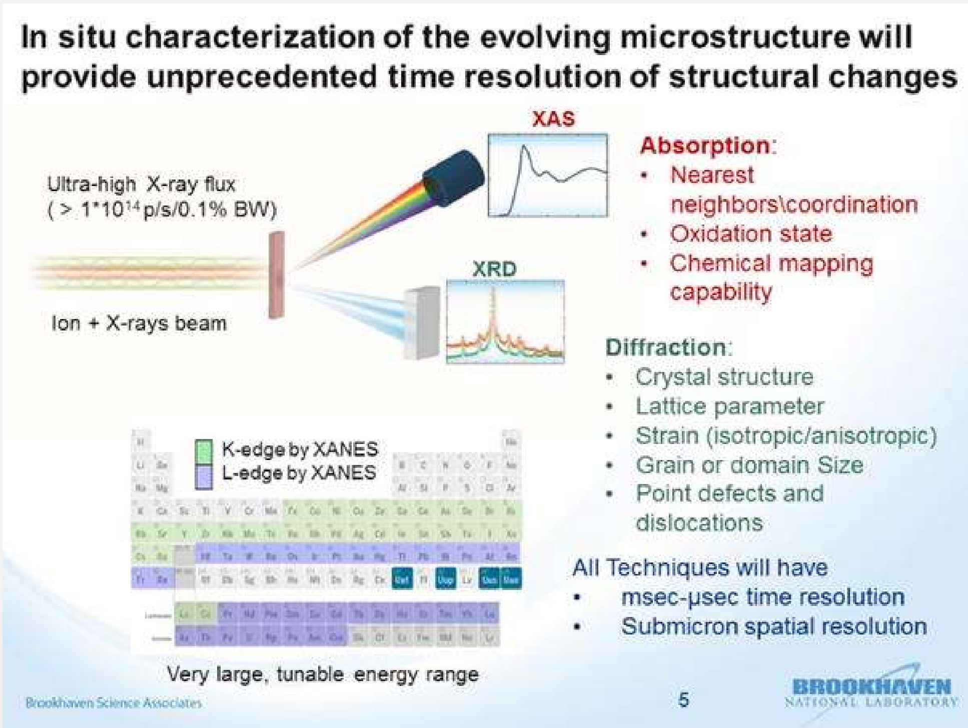
The National Synchrotron Light Source II (NSLS-II) is a new facility for materials characterization

Beam current I_{beam} = 500 mA
Small electron source size: 40 x 2.5 μm
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

Slide 5



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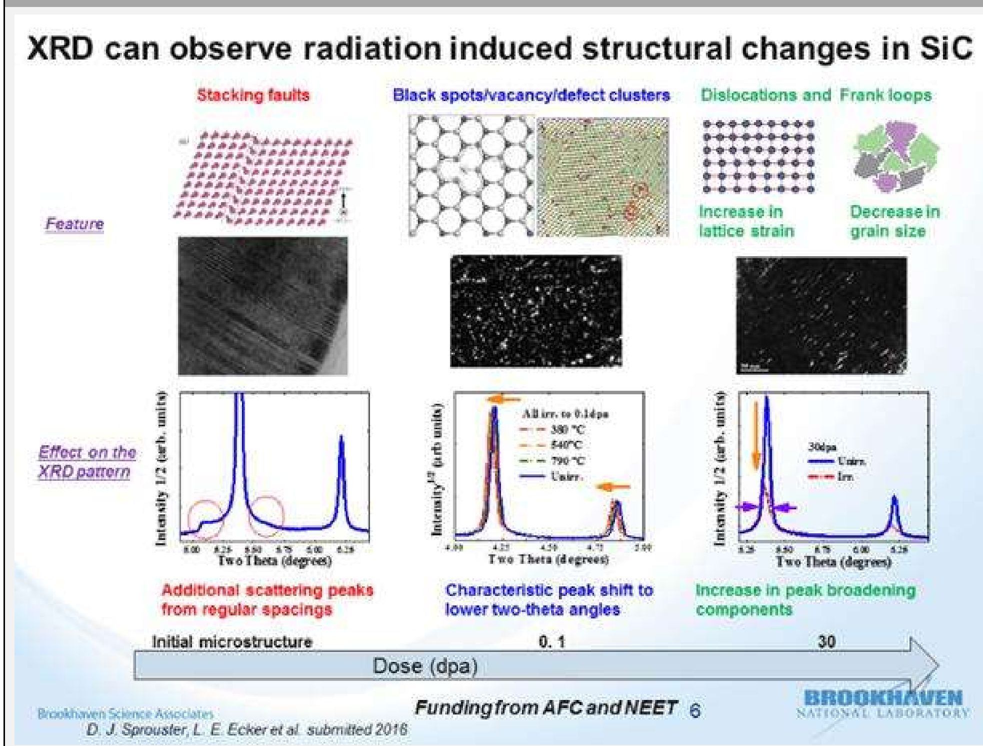

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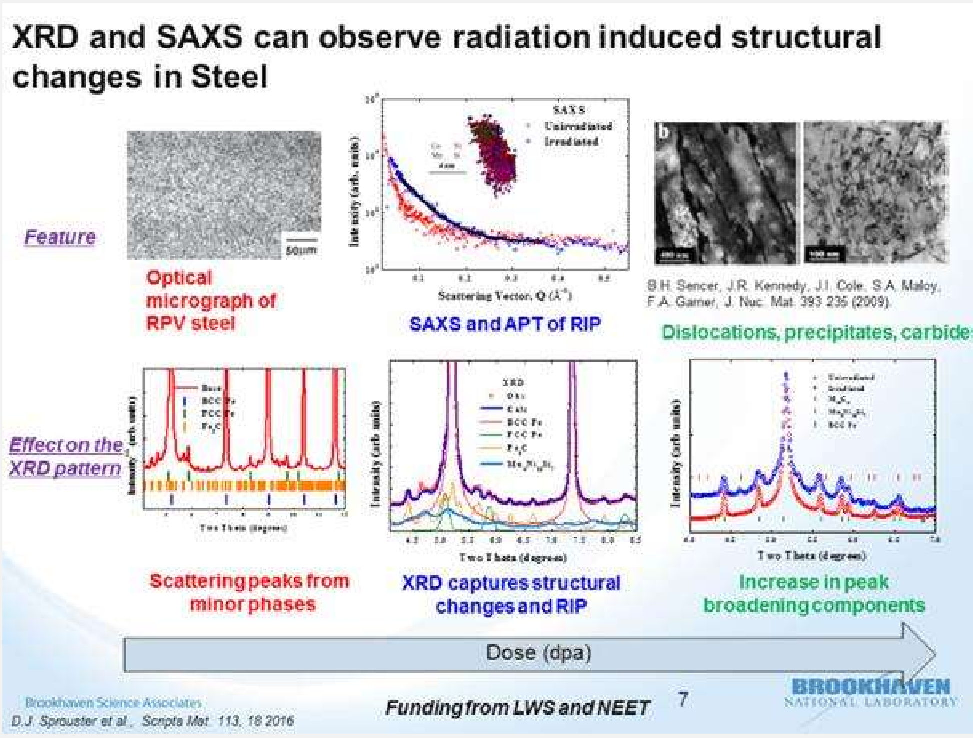

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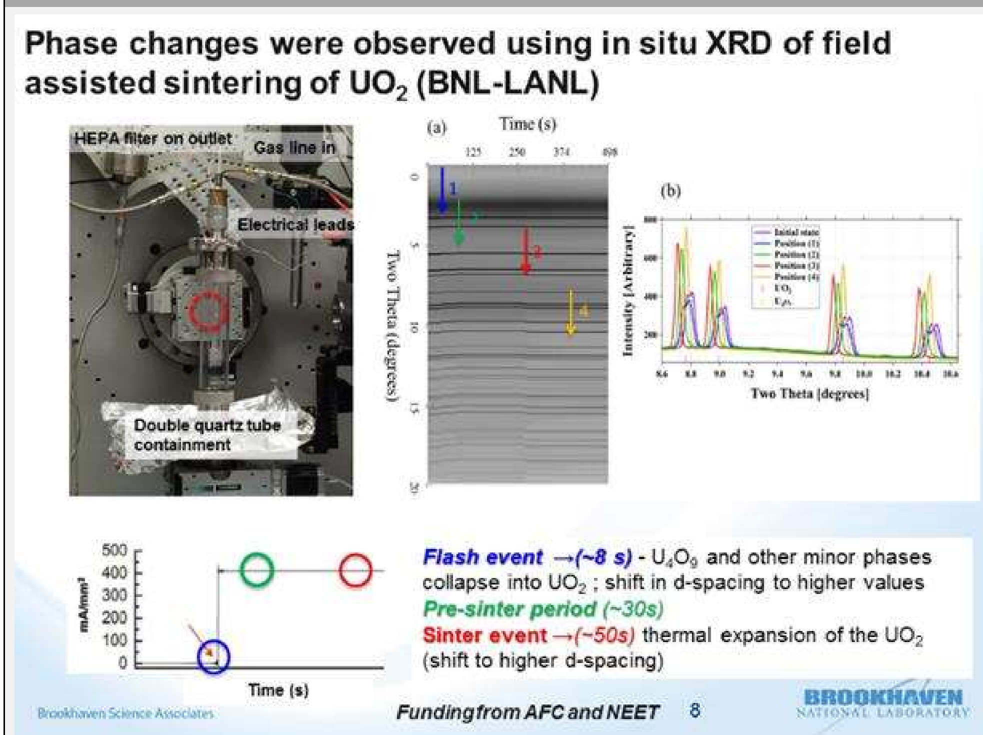
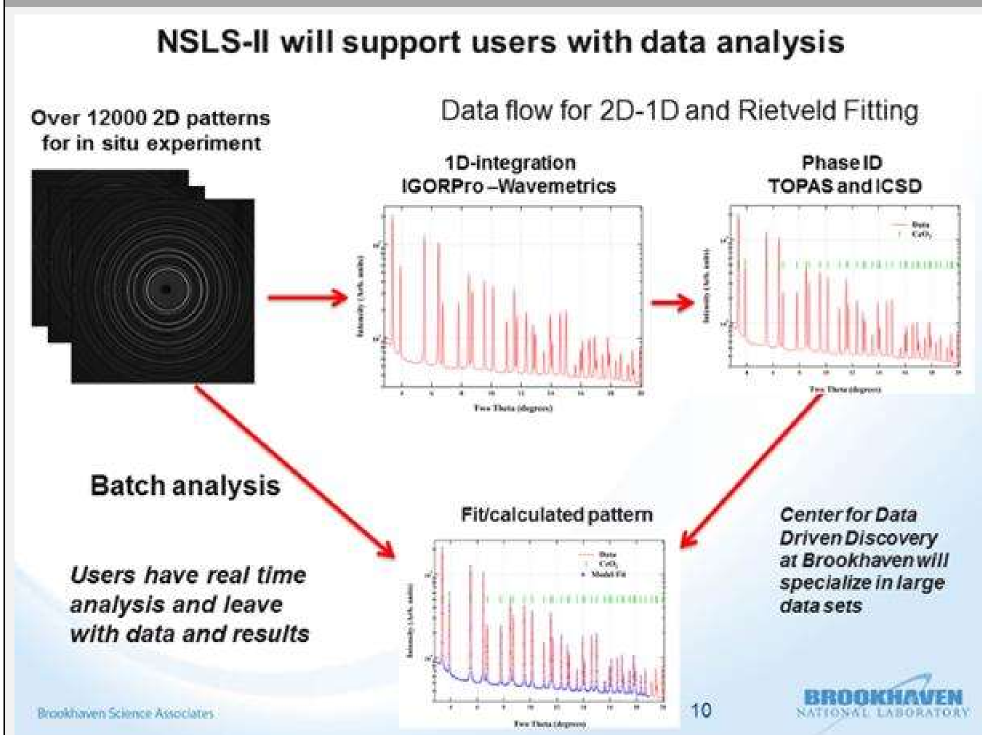
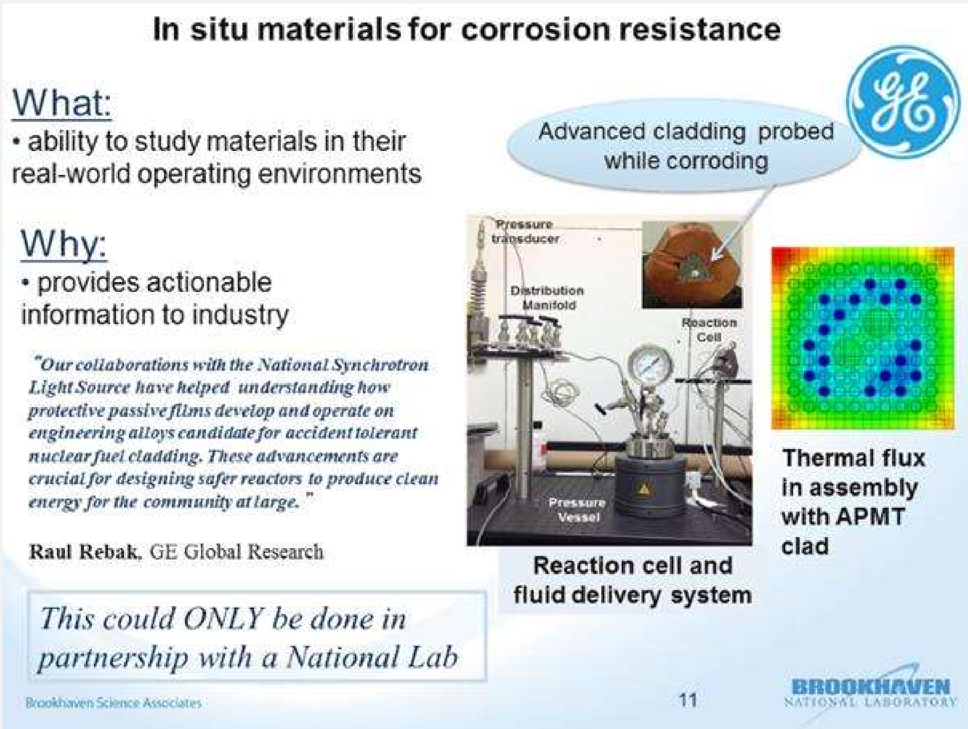


Slide 9

Slide 10

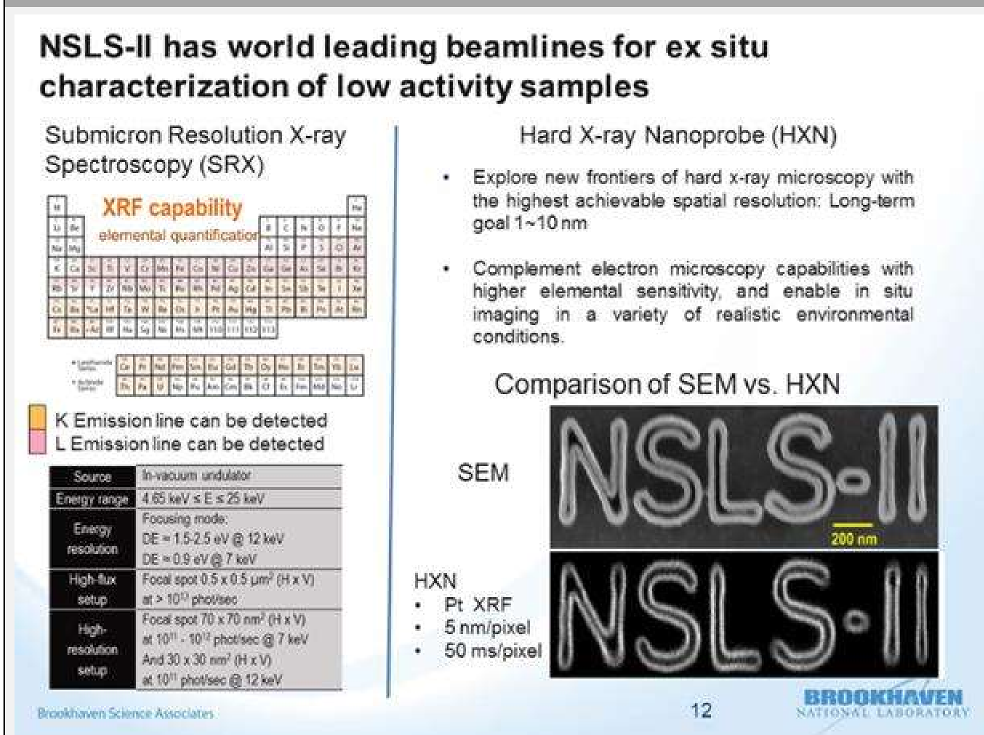


Slide 11



1. Connection to GAIN?

Slide 12

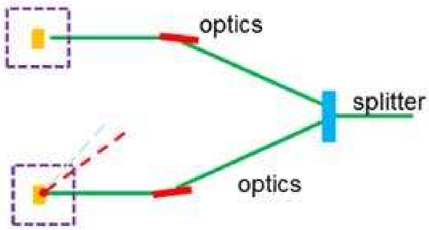


Slide 13

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



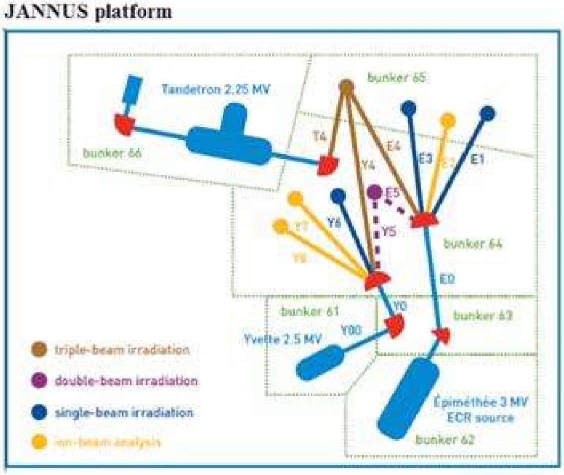
Proposed Site

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

Slide 14

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

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

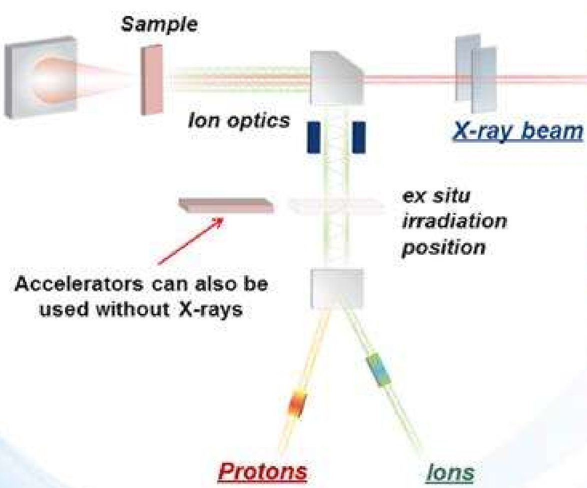
GE PETtrace cyclotron

NEC 6MV

No restrictions on number or type of accelerators because of space

Slide 16

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



Small samples can be characterized ex situ at additional NSLS-II beamlines

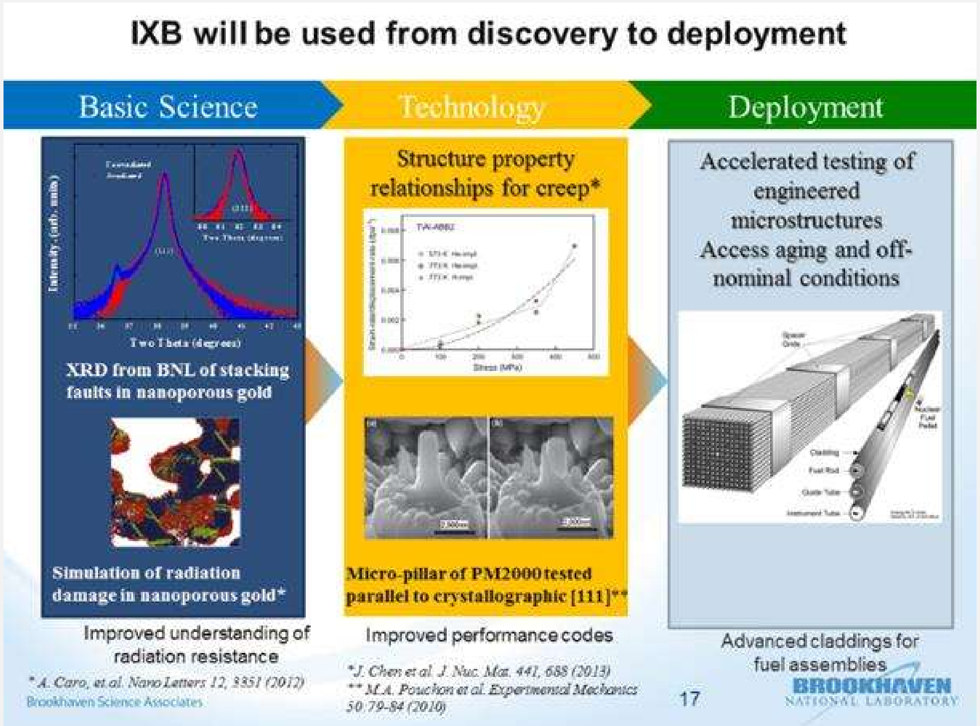
X-Rays
Techniques: Diffraction, Spectroscopy, Imaging
Energy range: 7-150 keV
Time resolution: msec-μsec
Beam diameter (tunable): >100 μm

Protons (cyclotron): 16.5 MeV (tunable)
Currents: 150uA (tunable)
Flux in 5mm: 10^{14} p/s
Beam diameter: mm's

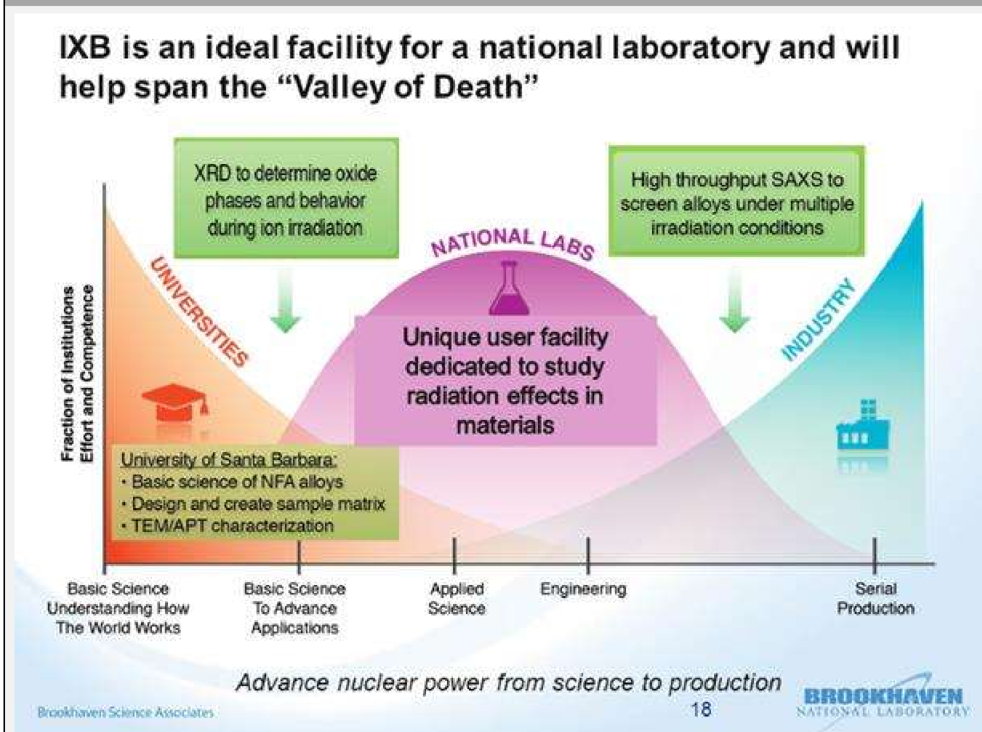
Ions: 5-6 MV terminal (tunable)
Currents: 0.1-100 uA's
Flux in 5mm: 10^{14} ions/s (40 MeV Xe)
Beam Diameter: ~ mm's

Materials: structural materials, cements, alpha emitters, fresh and irradiated nuclear fuels, nuclear waste forms, transuranics in solid, powder or liquid form

Slide 17



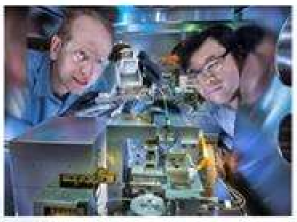
Slide 18

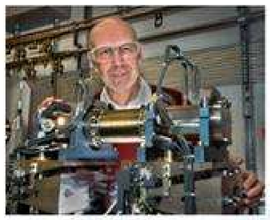


Slide 19

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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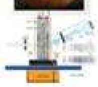
Slide 20

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

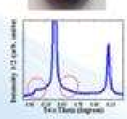

Irradiation environments and conditions.


Collect microstructural characterization data onsite and in-situ.


NE activities / volume of experiments that can be handled.

NSLS-II
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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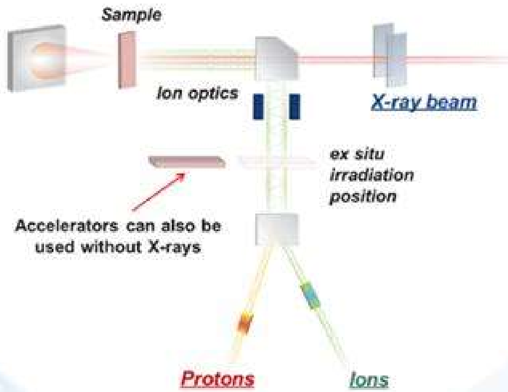
Slide 21

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

Slide 22

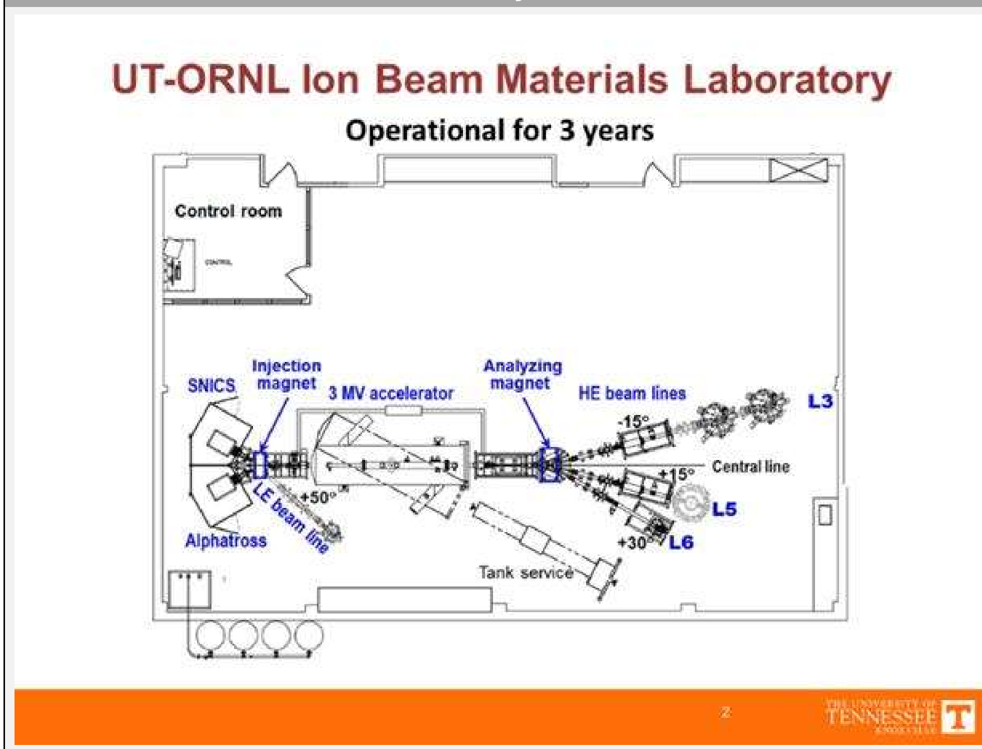
Thank you

Presentation: Univ. of Tennessee IBML

William Weber

UT-ORNL Ion Beam Materials Laboratory

UT-ORNL Ion Beam Materials Laboratory



UT-ORNL Ion Beam Materials Laboratory

UT-ORNL Ion Beam Materials Laboratory

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^+)

UT-ORNL Ion Beam Materials Laboratory

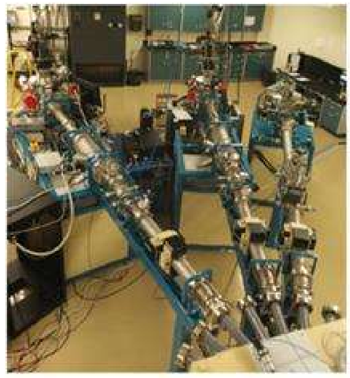
UT-ORNL Ion Beam Materials Laboratory

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

UT-ORNL Ion Beam Materials Laboratory

UT-ORNL Ion Beam Materials Laboratory



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Typical Ion Flux on Target (without raster)

Typical Ion Flux on Target (without raster)

He^{1+} 3.5 MeV:
85 nA in 1.5×1.5 mm^2 (2.4×10^{13} ions cm^{-2} s^{-1})

Si^{1+} 1 MeV:
550 nA in 3×3 mm^2 (3.8×10^{13} ions cm^{-2} s^{-1})

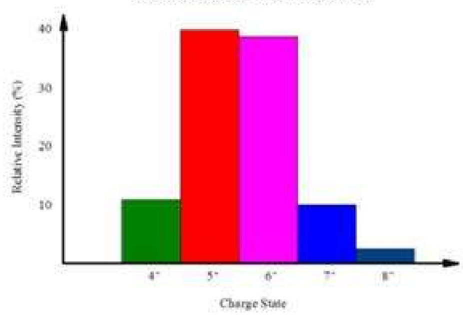
Si^{4+} 13.5 MeV:
1300 nA in 3×3 mm^2 (2.3×10^{13} ions cm^{-2} s^{-1})

Au^{1+} 1 MeV:
200 nA in 3×3 mm^2 (1.4×10^{13} ions cm^{-2} s^{-1})

Au^{7+} 23 MeV
60 nA in 3×3 mm^2 (5.95×10^{11} ions cm^{-2} s^{-1})

Au^{8+} 25 MeV
15 nA in 3×3 mm^2 (1.30×10^{11} ions cm^{-2} s^{-1})

Charge state distribution of Ni accelerated with 2.5 MV



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High-Energy End Stations

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! 7

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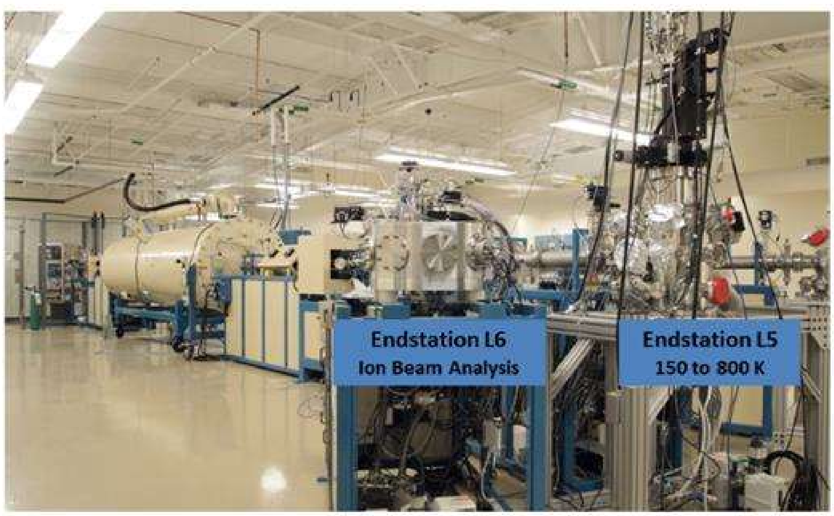
UT-ORNL IBML End Stations

UT-ORNL IBML End Stations



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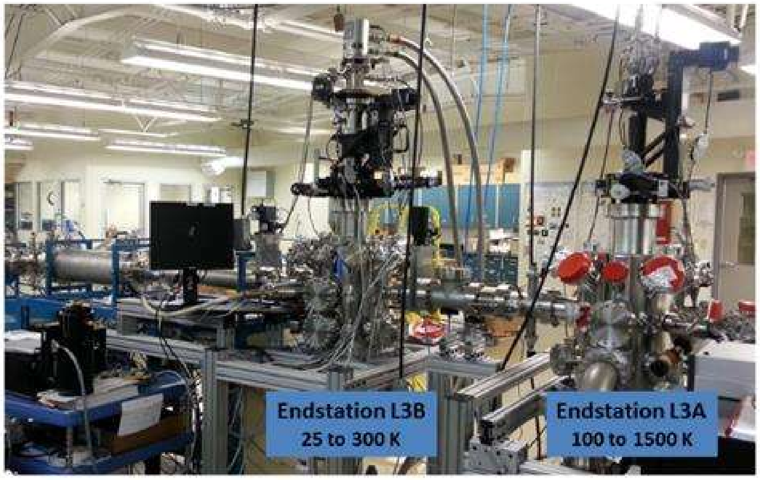
UT-ORNL IBML Endstations

UT-ORNL IBML Endstations



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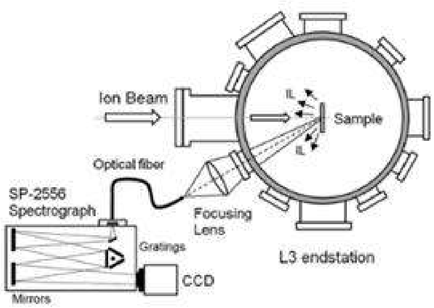
In Situ Ion-Beam Induced Luminescence

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)

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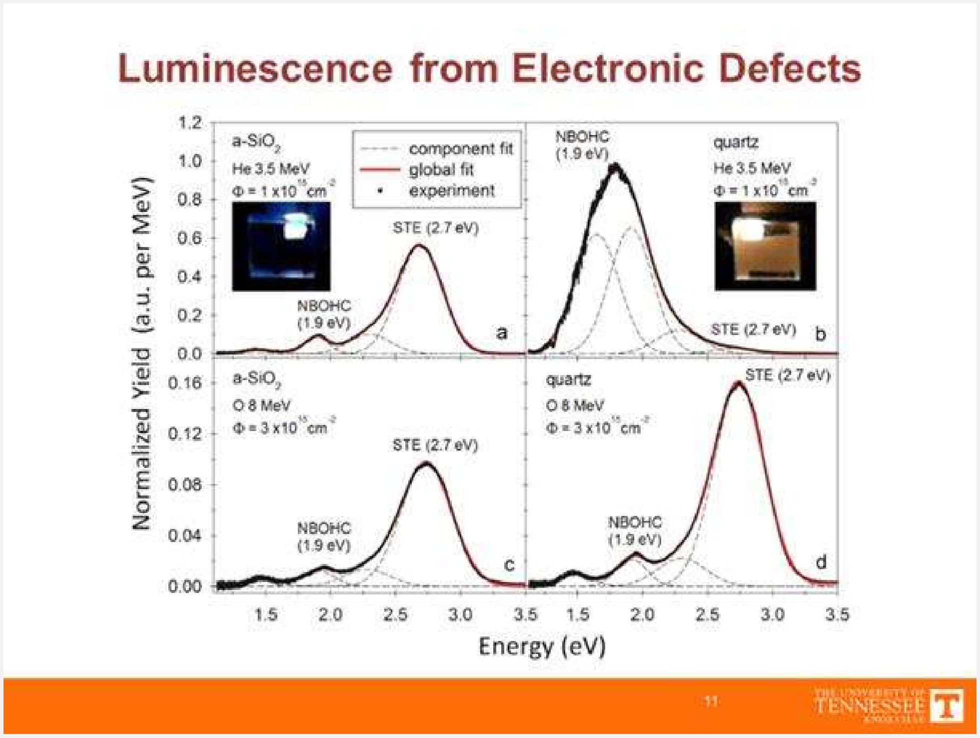
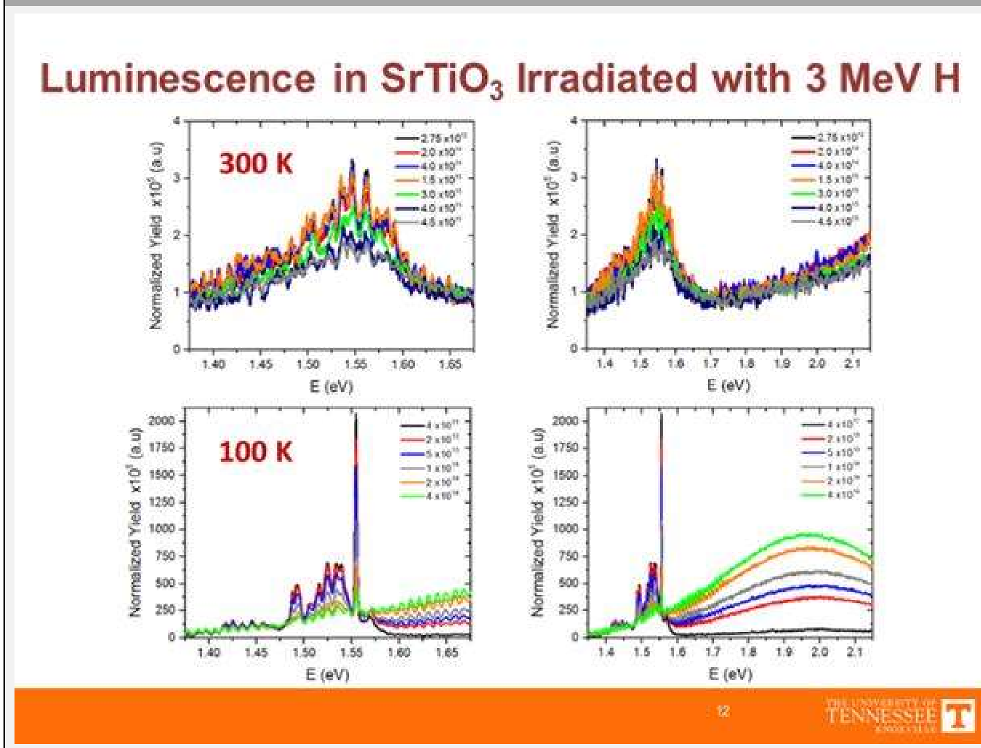
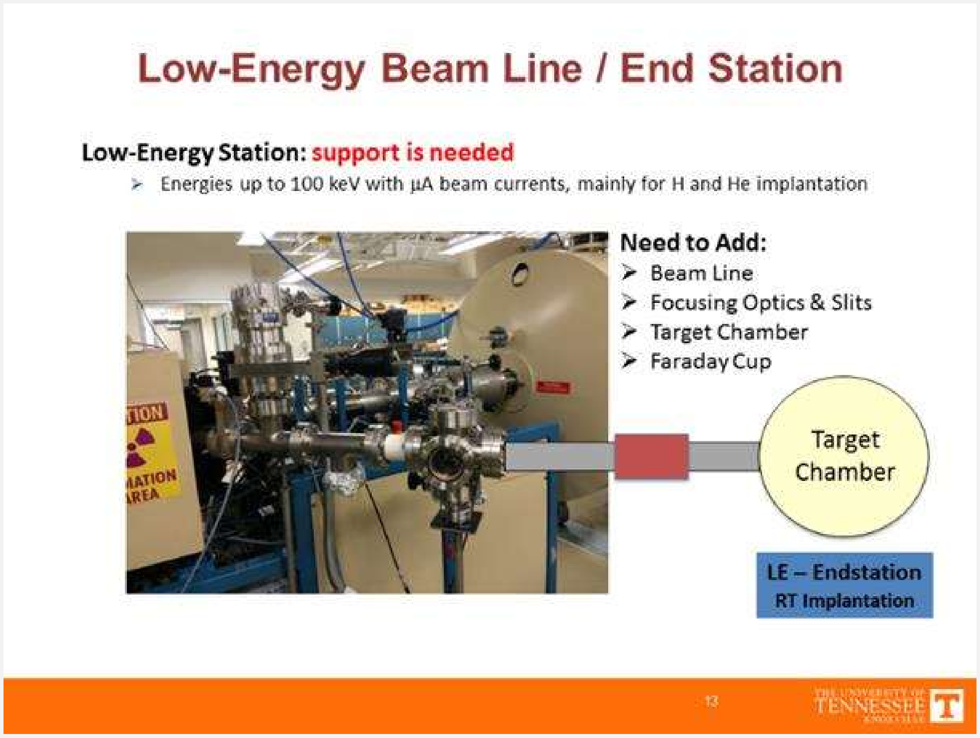
Luminescence from Electronic Defects



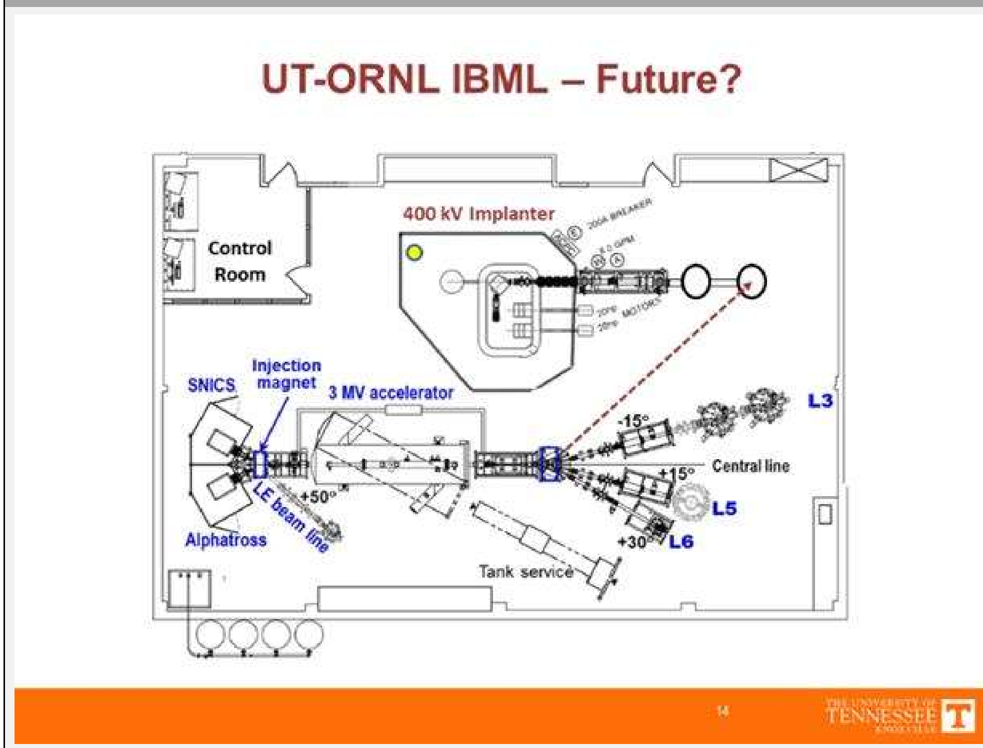
Luminescence in $SrTiO_3$ Irradiated with 3 MeV H



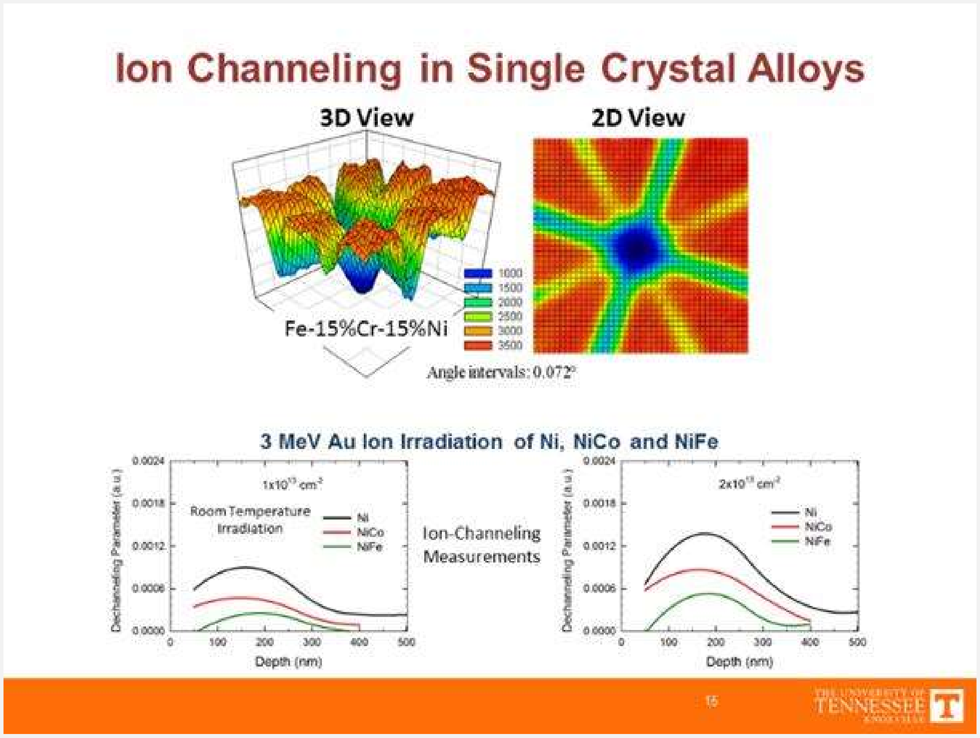
Low-Energy Beam Line / End Station



UT-ORNL IBML – Future?

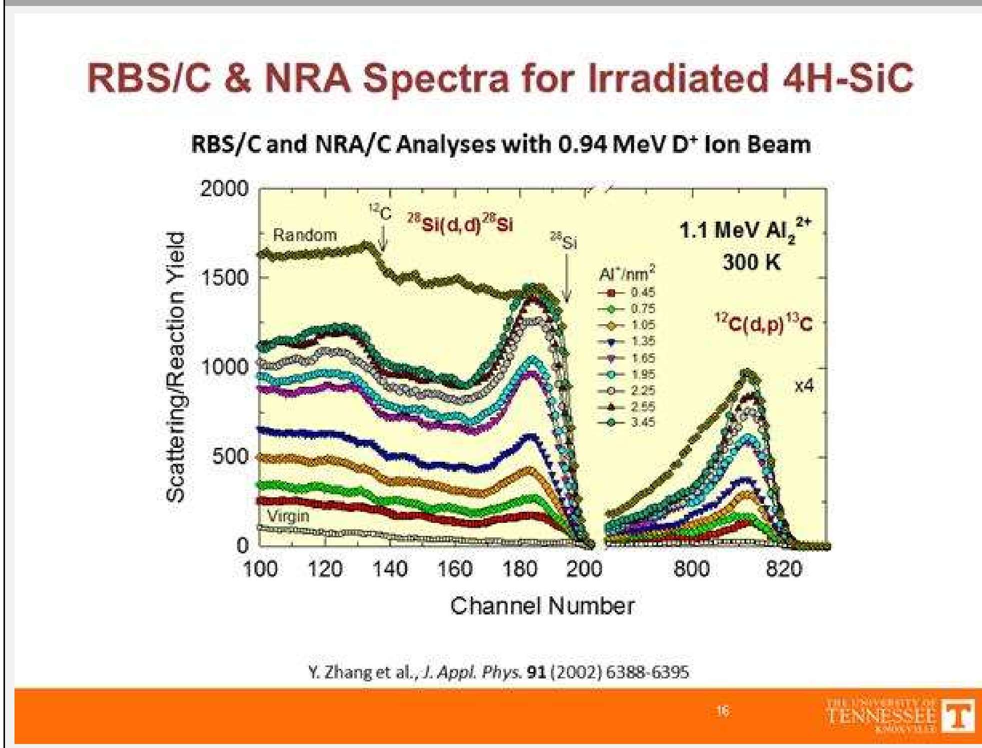


Ion Channeling in Single Crystal Alloys

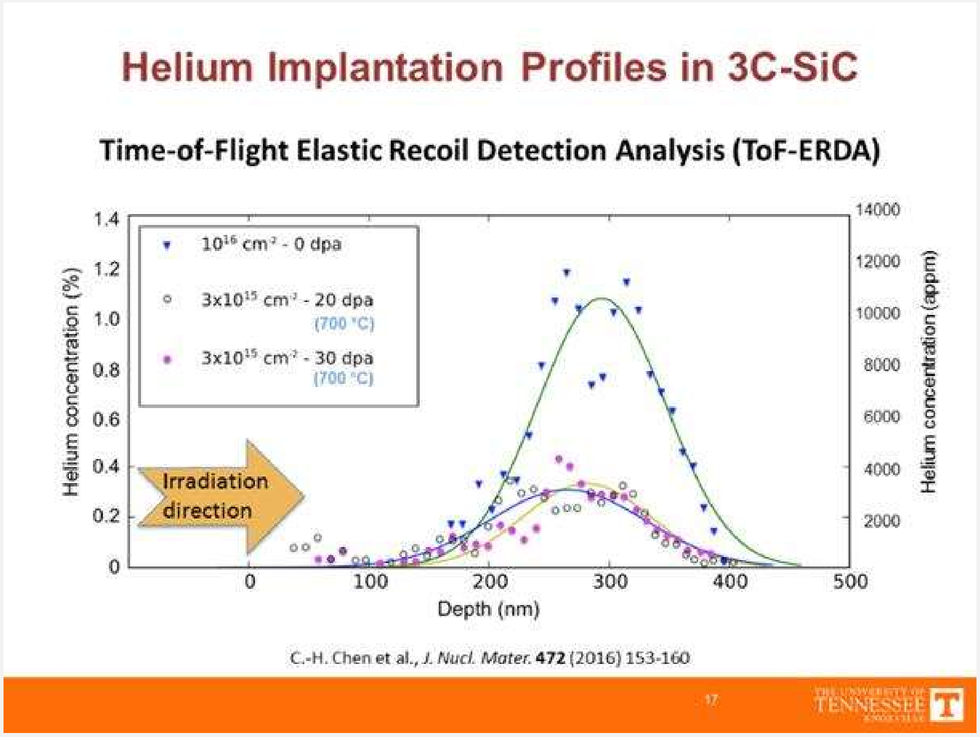


1. Running at roughly 25% utilization.

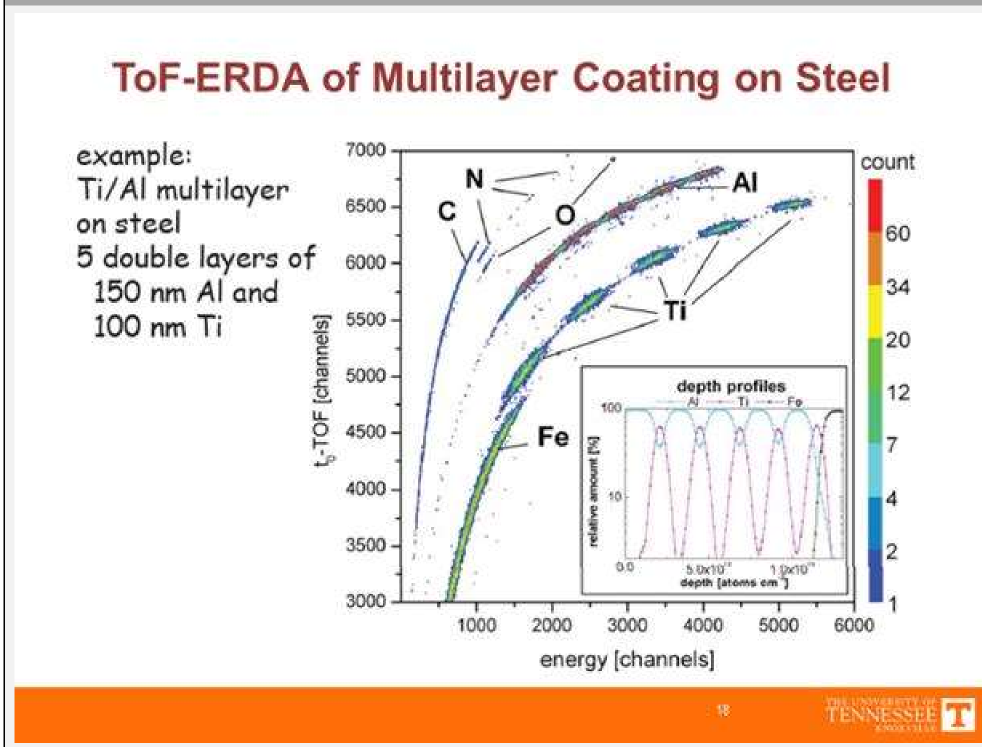
RBS/C & NRA Spectra for Irradiated 4H-SiC



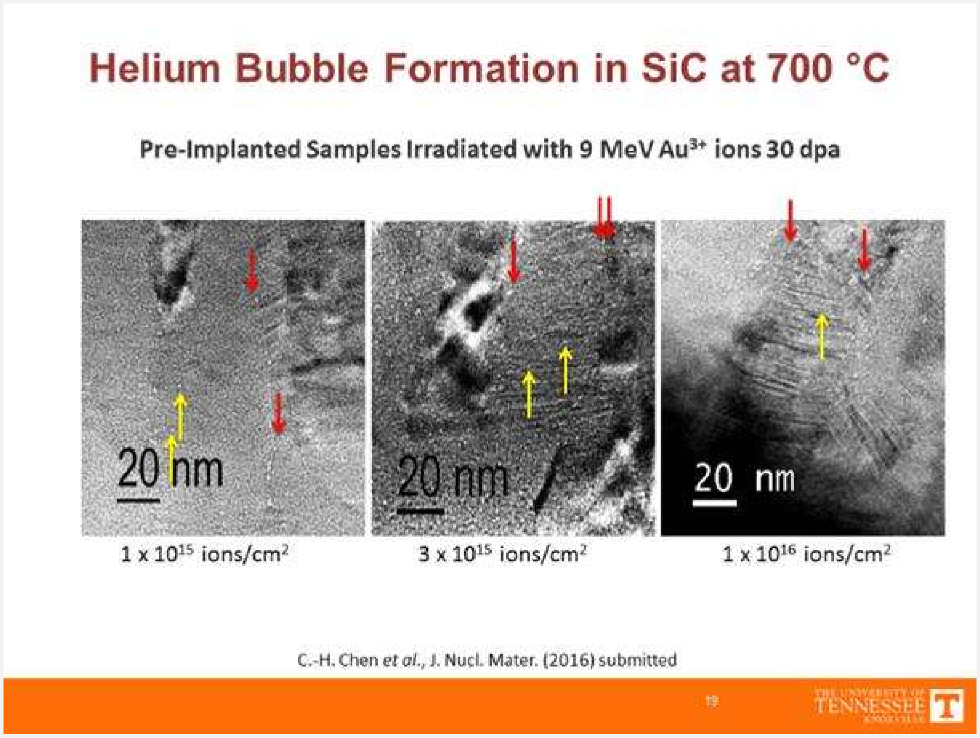
Helium Implantation Profiles in 3C-SiC



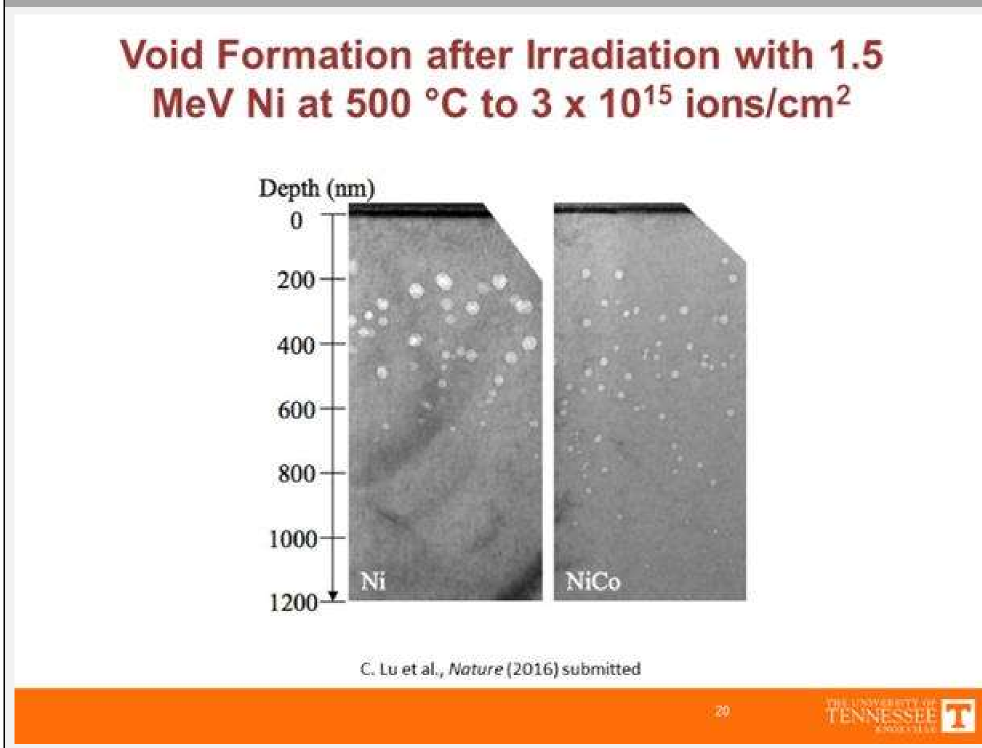
ToF-ERDA of Multilayer Coating on Steel



Helium Bubble Formation in SiC at 700°C



Void Formation after Irradiation with 1.5 MeV Ni at 500°C to 3 × 10^{15} ions/cm^2



Users


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)
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THE UNIVERSITY OF TENNESSEE KNOXVILLE

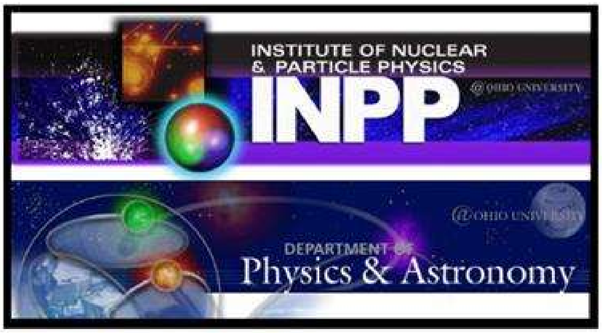
Presentation: Edwards Accelerator Laboratory at the University of Ohio

Steve Grimes

Edwards Accelerator Lab

Edwards Accelerator Lab

Ohio University, Athens Ohio



NSUF Workshop

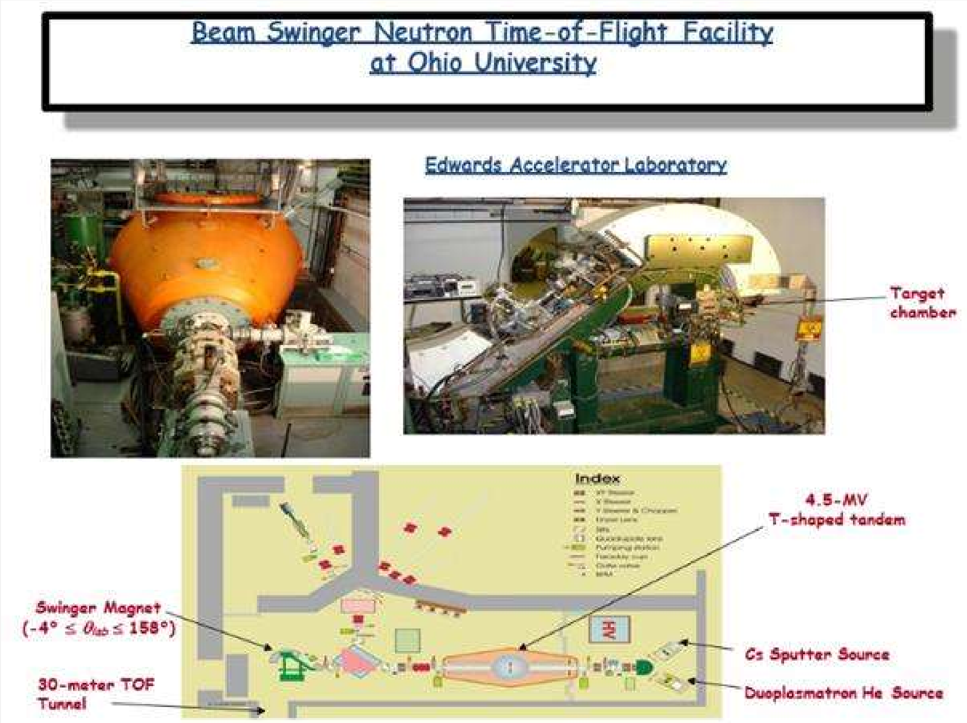
March 22-24 2016

Accelerator

Accelerator

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

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



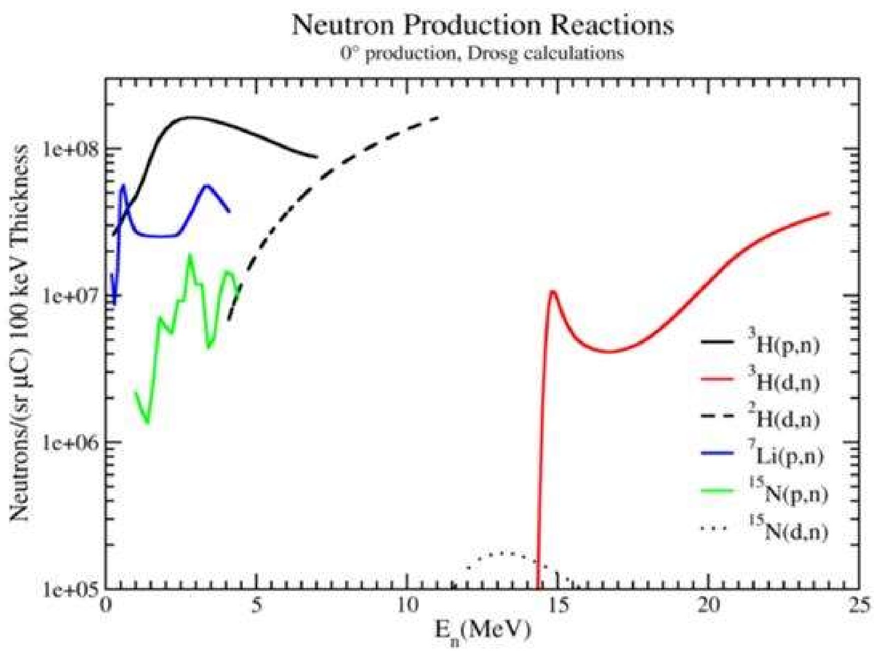
Neutron Source Reactions

Neutron Source Reactions

- Monoenergetic Sources: ^{3}H(p,n),^{2}H(d,n), ^{3}H(d,n), ^{7}Li(p,n),^{15}N(p,n),^{15}N(d,n)
- Both ^{3}H gas targets and ^{3}H solid targets are available
- White sources with stopping targets:

  ^{9}Be(p,n), ^{9}Be(d,n), ^{10}B(d,n), ^{11}B(p,n), ^{11}B(d,n), ^{13}C(p,n), ^{9}Be(α,n), ^{13}C(α,n), ^{19}F(p,n), ^{27}Al(d,n), V(d,n)

Slide 5



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 , $-4^{o} < \theta < 158^{o}$.
- Beam Pulsing ~1 ns width for ^{1}H, ^{2}H and ~2.5 ns for other beams.
- A dual gas cell is available for background subtraction.

Neutron Detectors

Neutron Detectors

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

Advanced Method for Calibration

Advanced Method for Calibration

- The neutron spectrum for a stopping target using the $^{27}Al(d,n)$ 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.

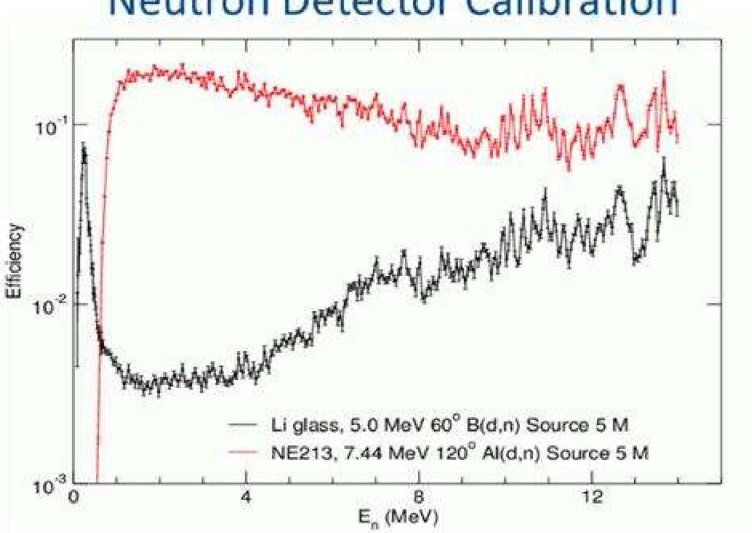
Lithium Glass Detectors

Lithium Glass Detectors

- The measured efficiencies of lithium glass detectors differ from the calculated shape from just the ^{6}Li(n,α) reaction.
- Contributions from ^{16}O(n,n'γ) and ^{28}Si(n,n'γ) are important above 1.8 MeV.
- Detectors which have the same specification of ^{6}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

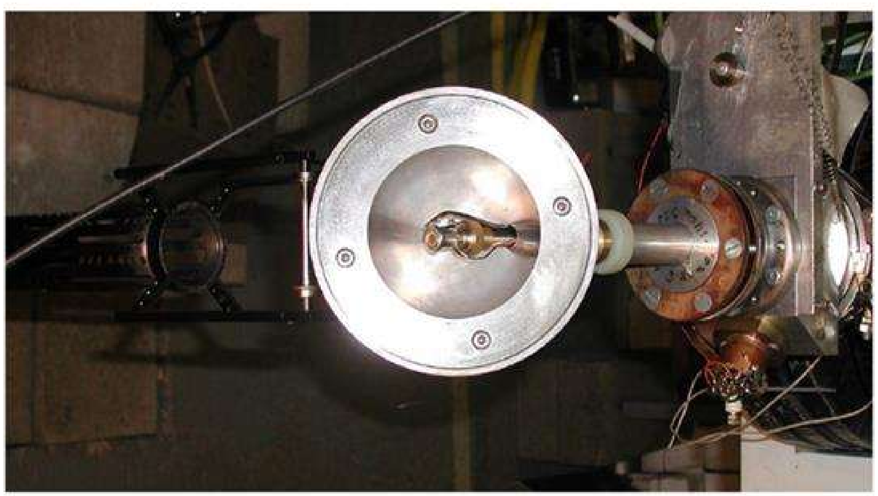
Pulsed Neutron Spheres

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

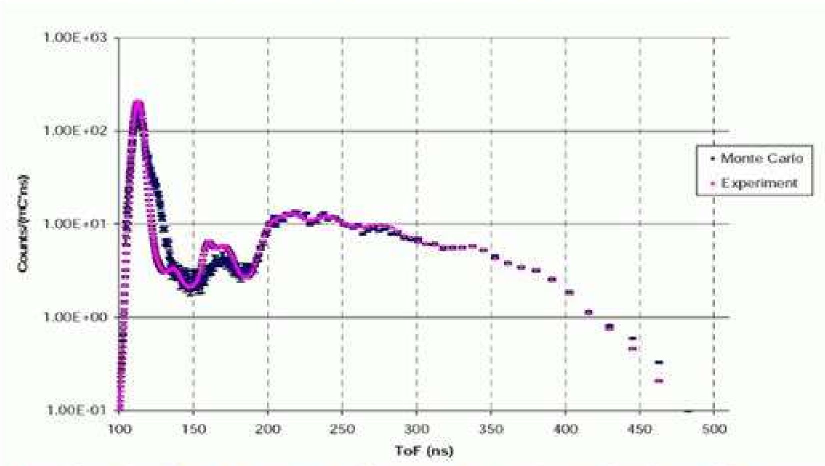
The Iron Sphere Setup

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}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 En > 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

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

Facility Upgrades-Negative Ion Source

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

Other facilities

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

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.)

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 Fe(n,p), Fe(n,α), Cu(n,p), Cu(n,α), Ni(n,p), Ni(n,α), completed.
- Stopping target neutron spectra measurements.
- Measurements and calculation of level densities.

Summary – continued

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

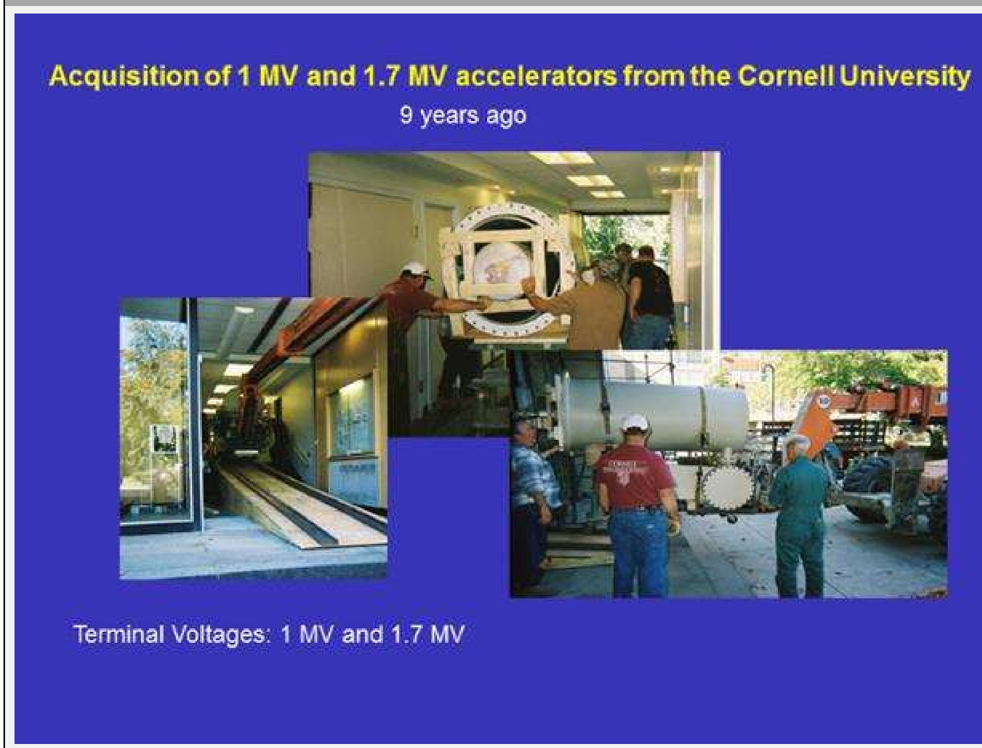
Lin Shao

Slide 1

Slide 2

Slide 3

Slide 4



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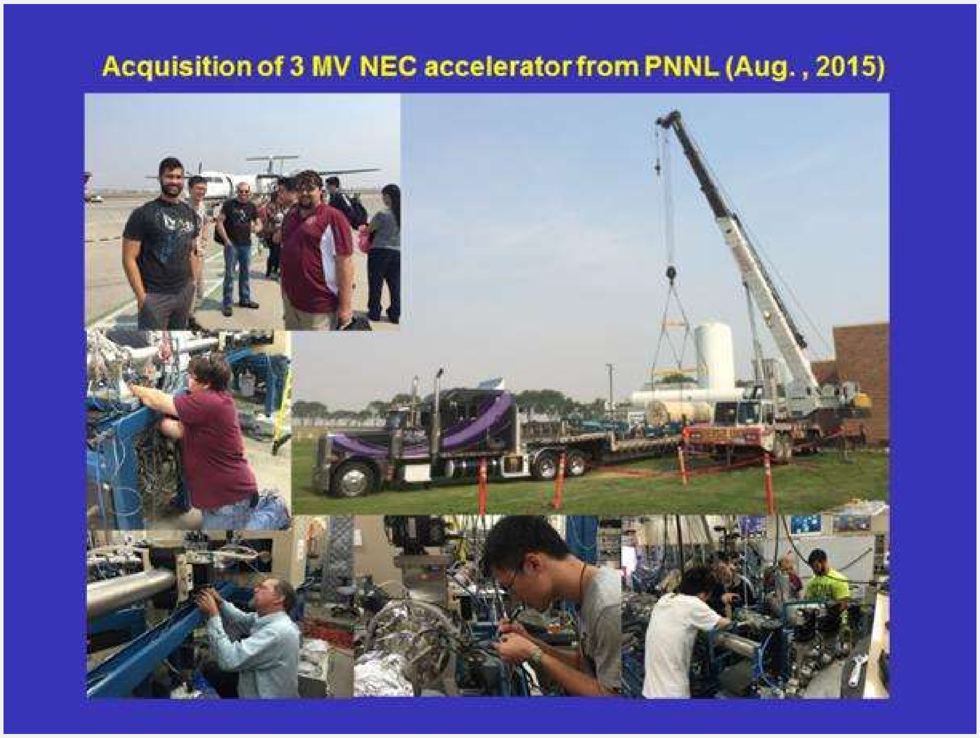

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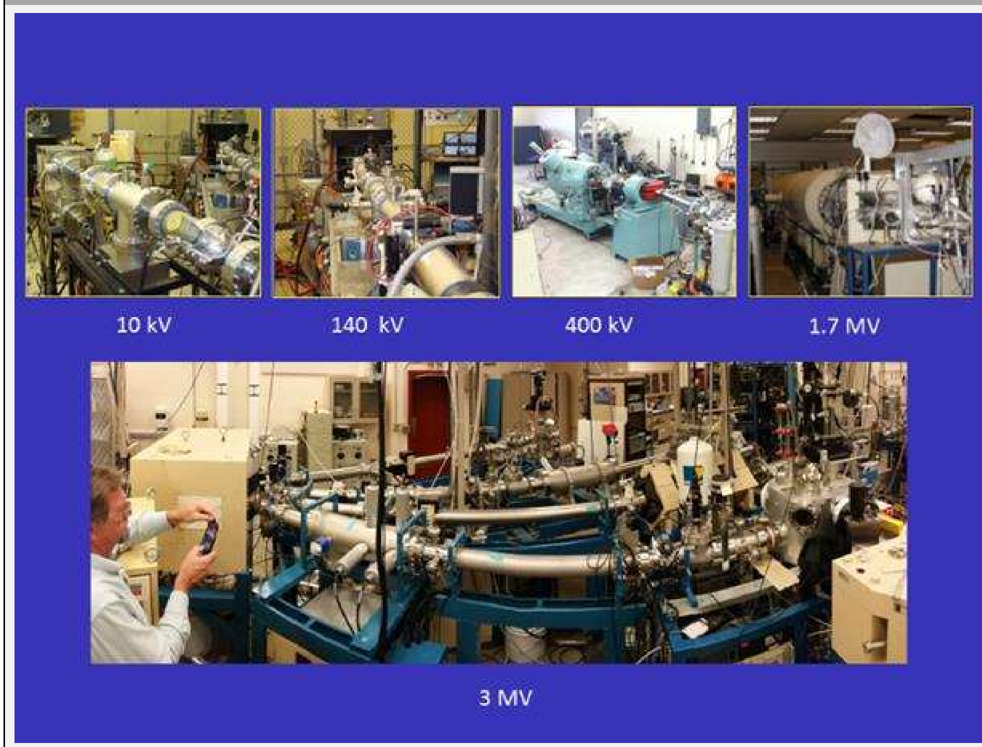

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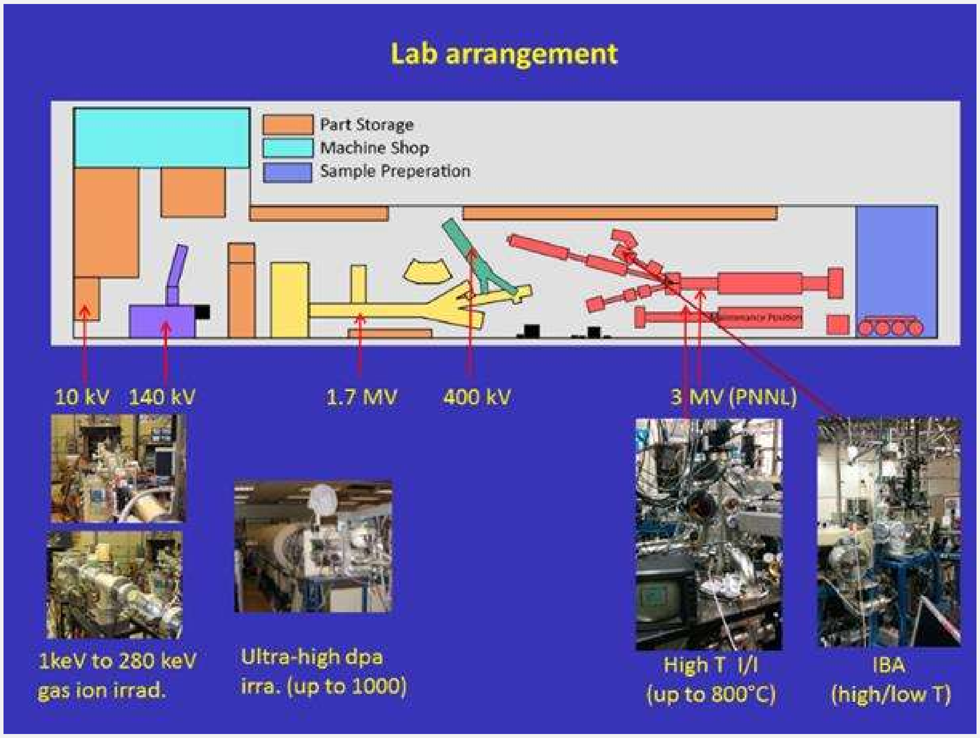

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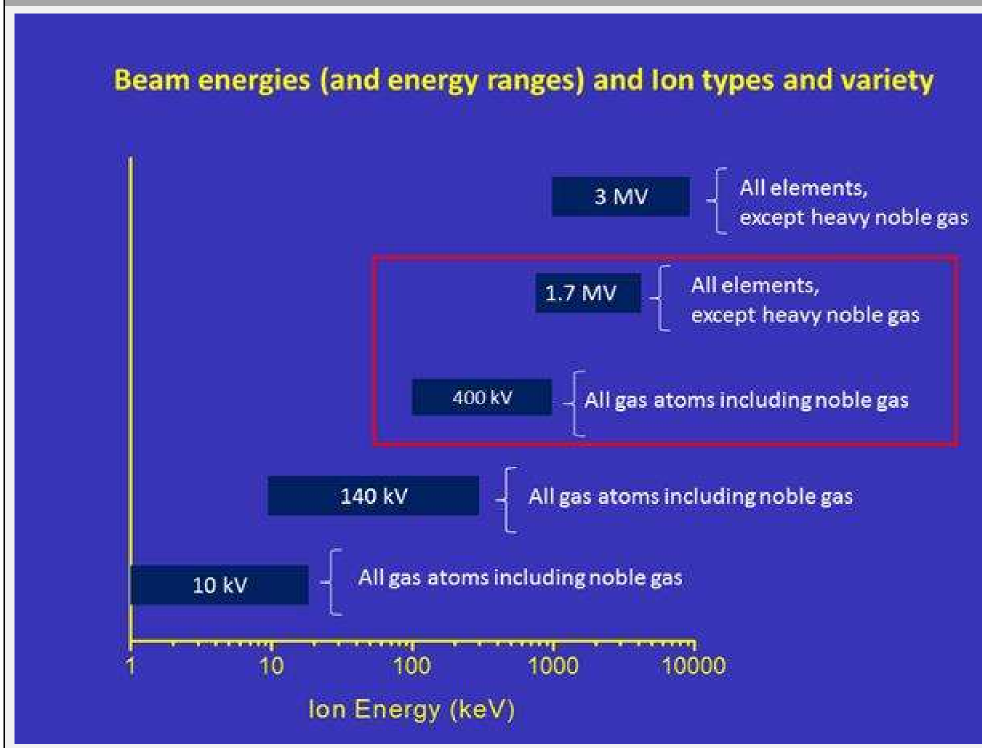

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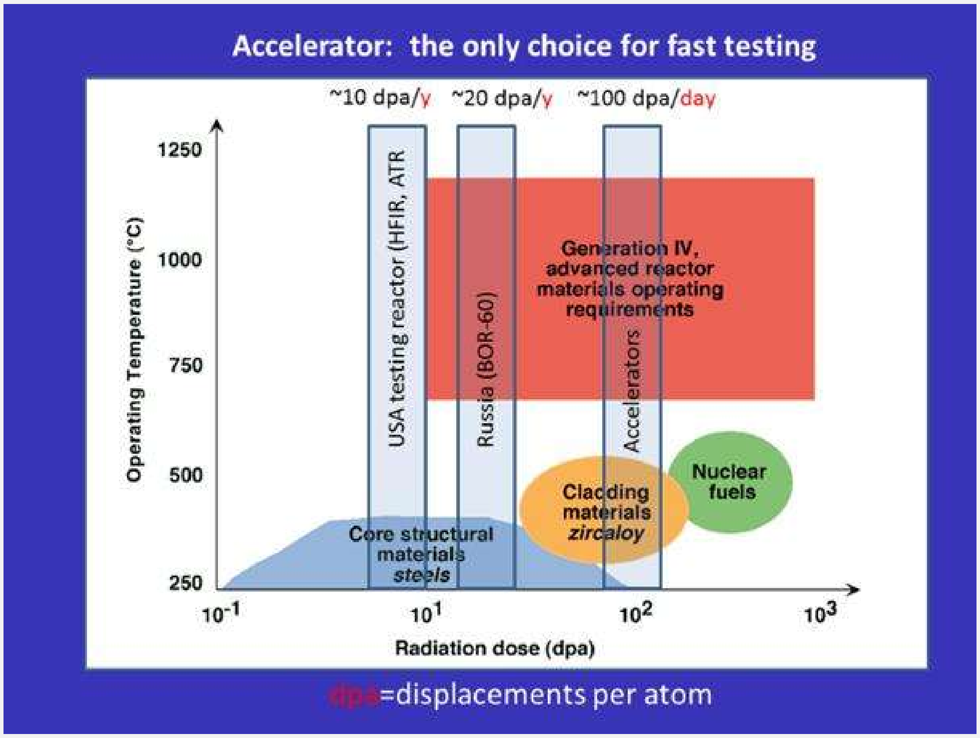

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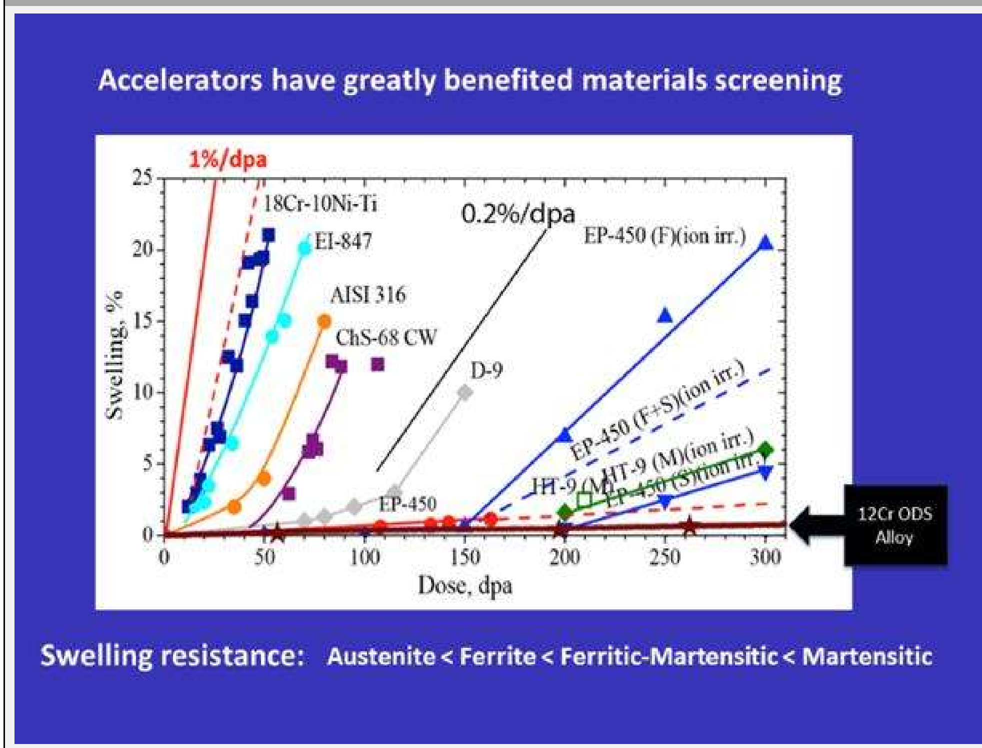

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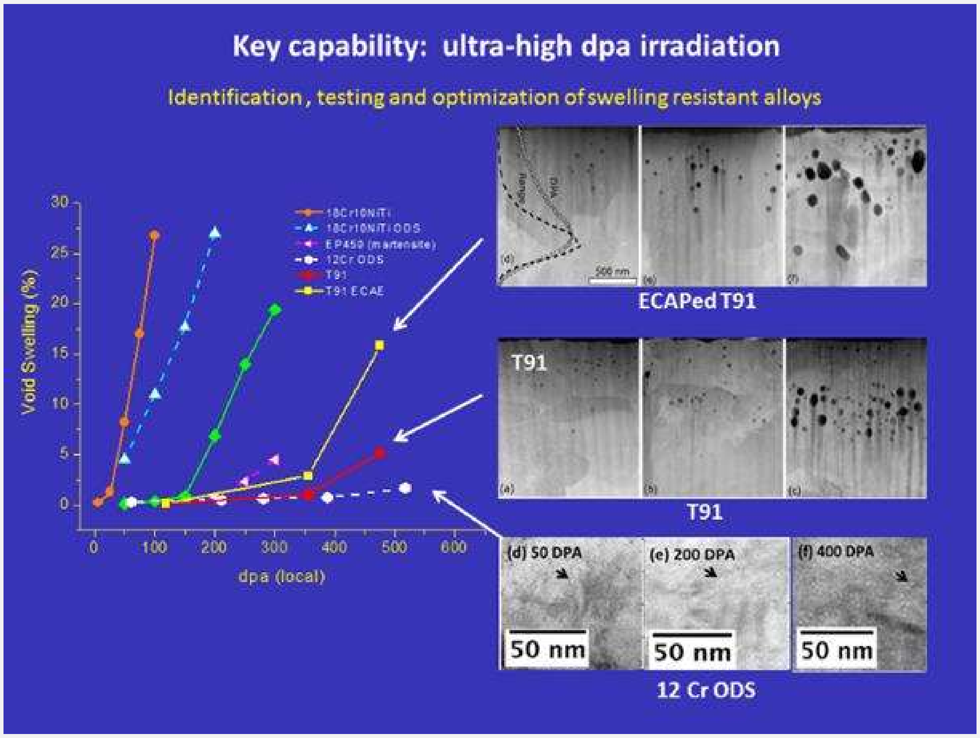
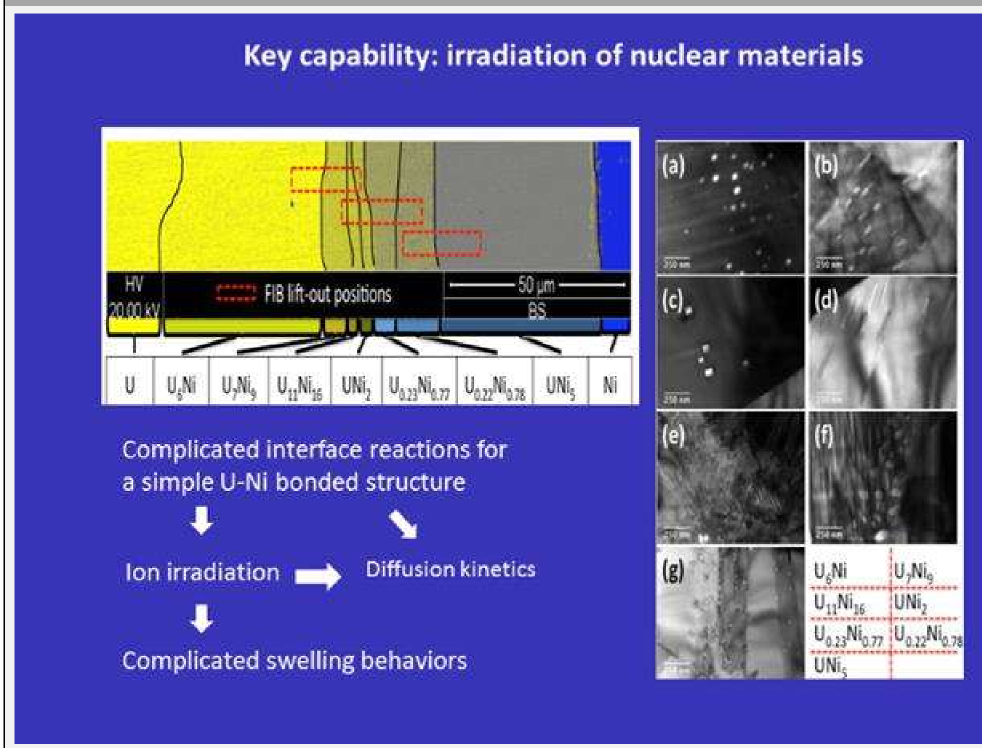


Slide 12



Slide 13

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

Slide 14

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 irrad. capability

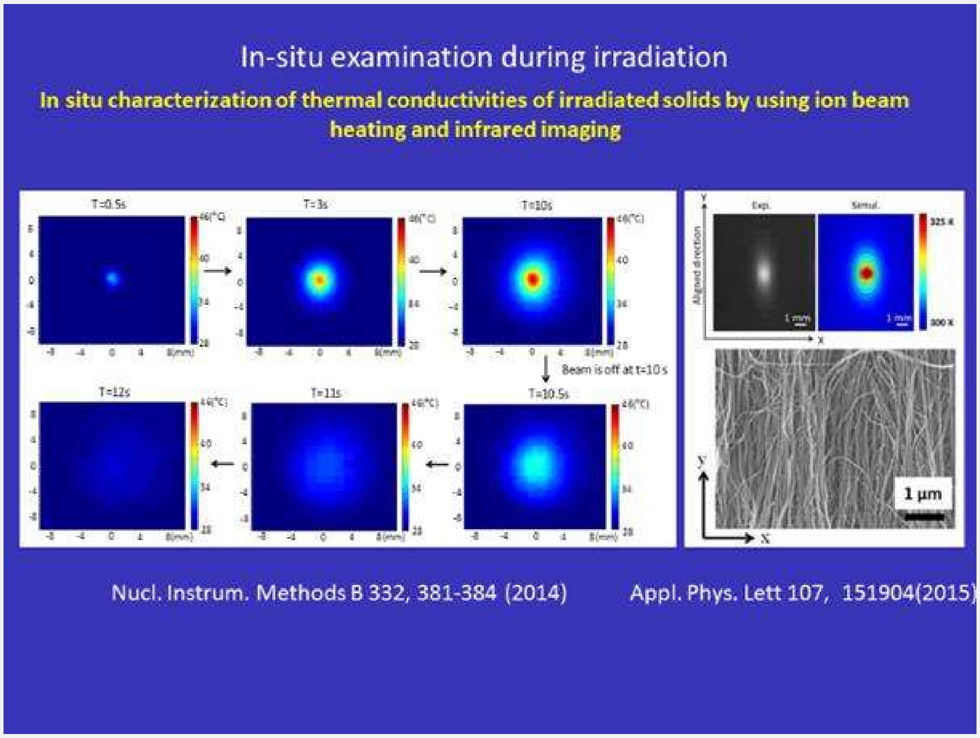
Slide 16

Provide a variety of irradiation environments

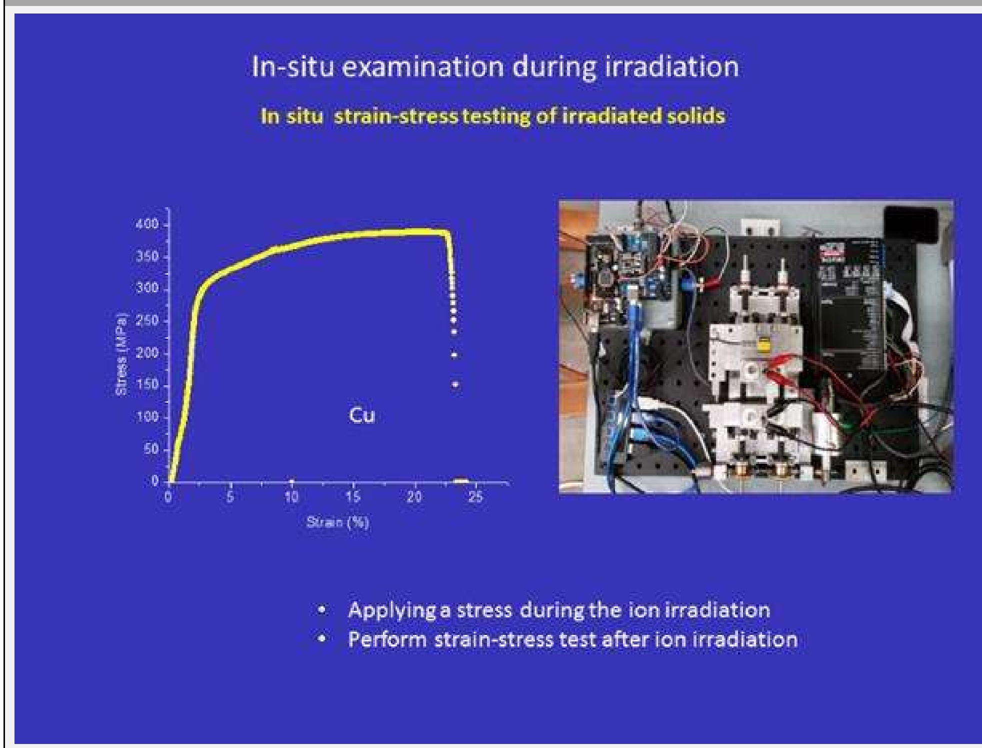
Recently updated target chambers

Irradiation temperature up to 800°C
Vacuum during irradiation: <2×10[illegible] torr

Slide 17

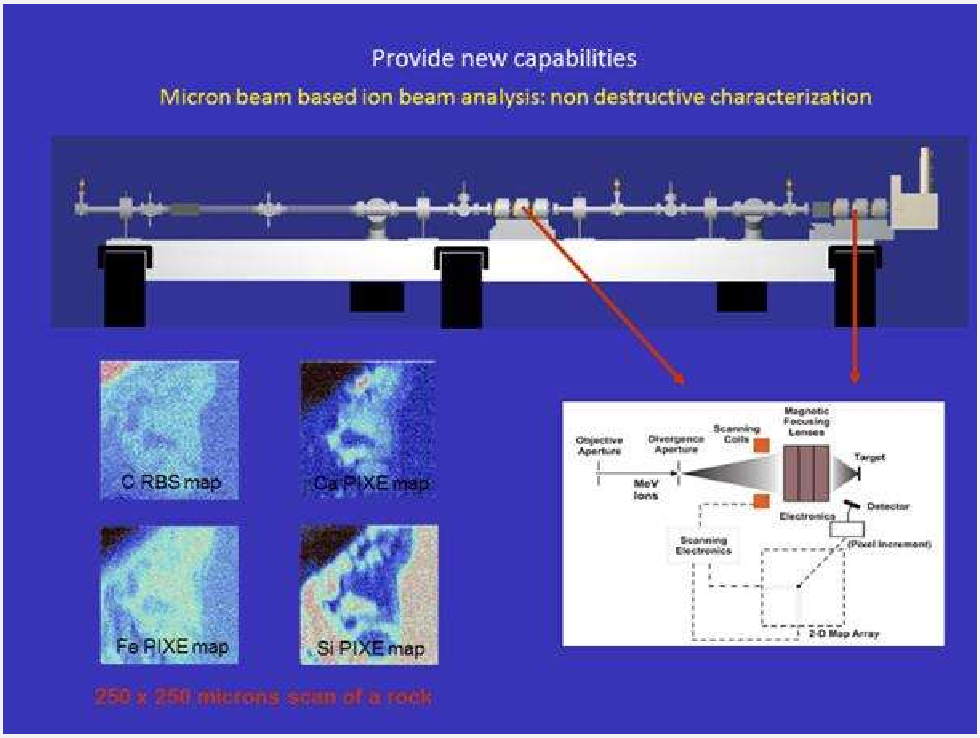


Slide 18

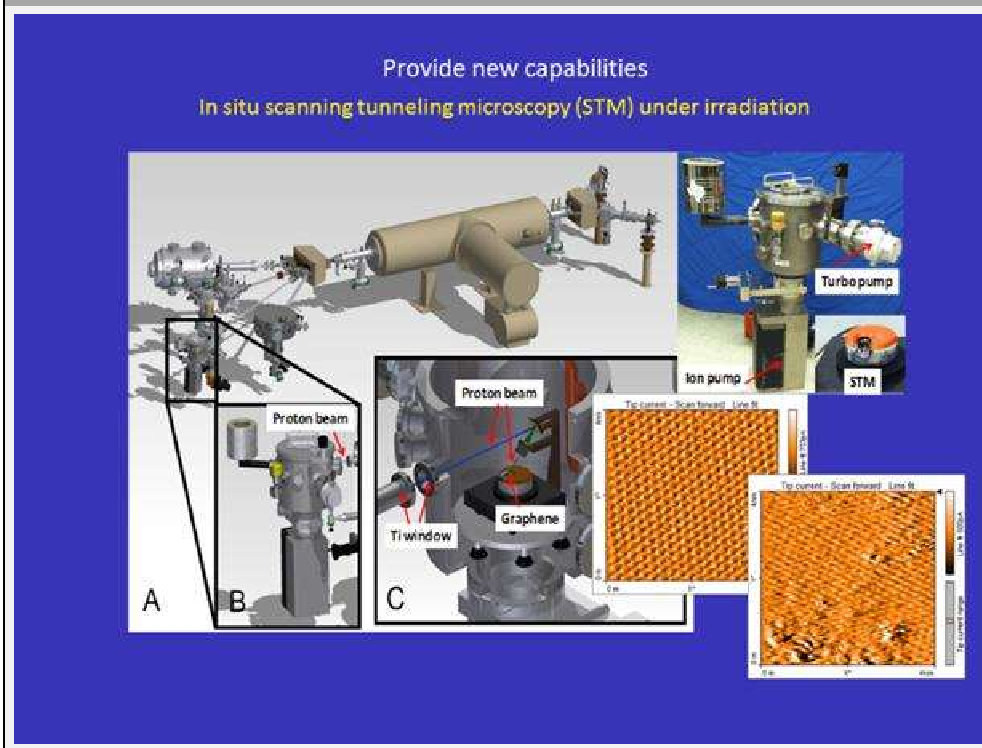


1. New model will be able to do creep testing.
2. What are the sizes of samples? And what geometry/configurations are they?

Slide 19

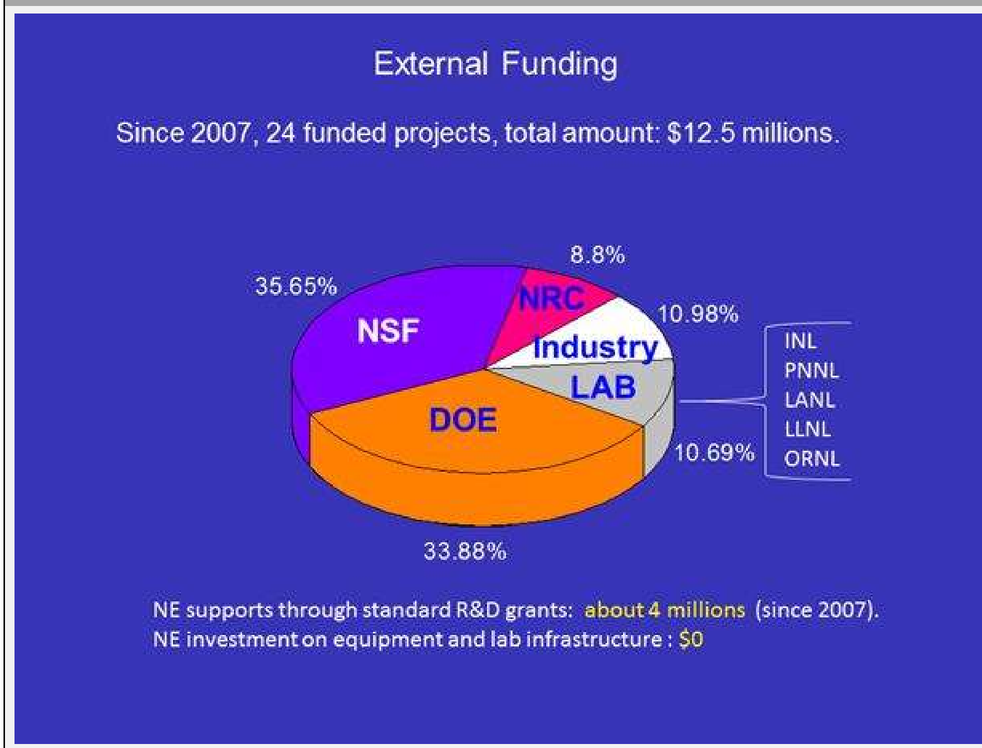


Slide 20



Slide 21

Slide 22



Slide 23

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.

Slide 24

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)

Slide 25

Thanks!

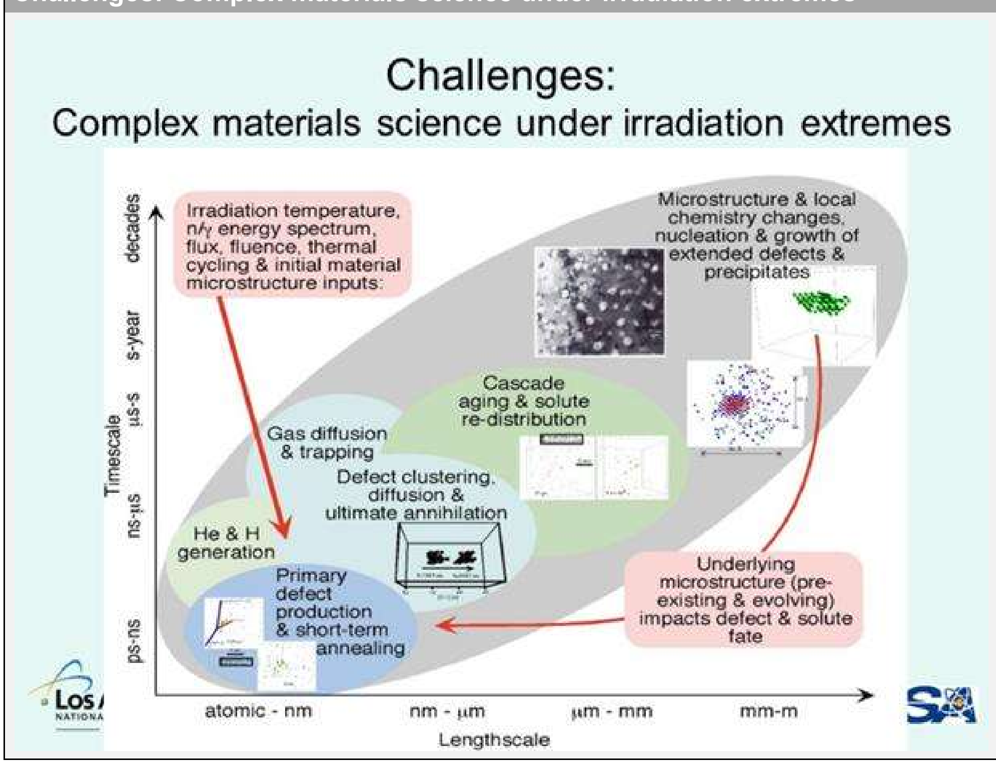
lshao@tamu.edu

Presentation: IBML at LANL

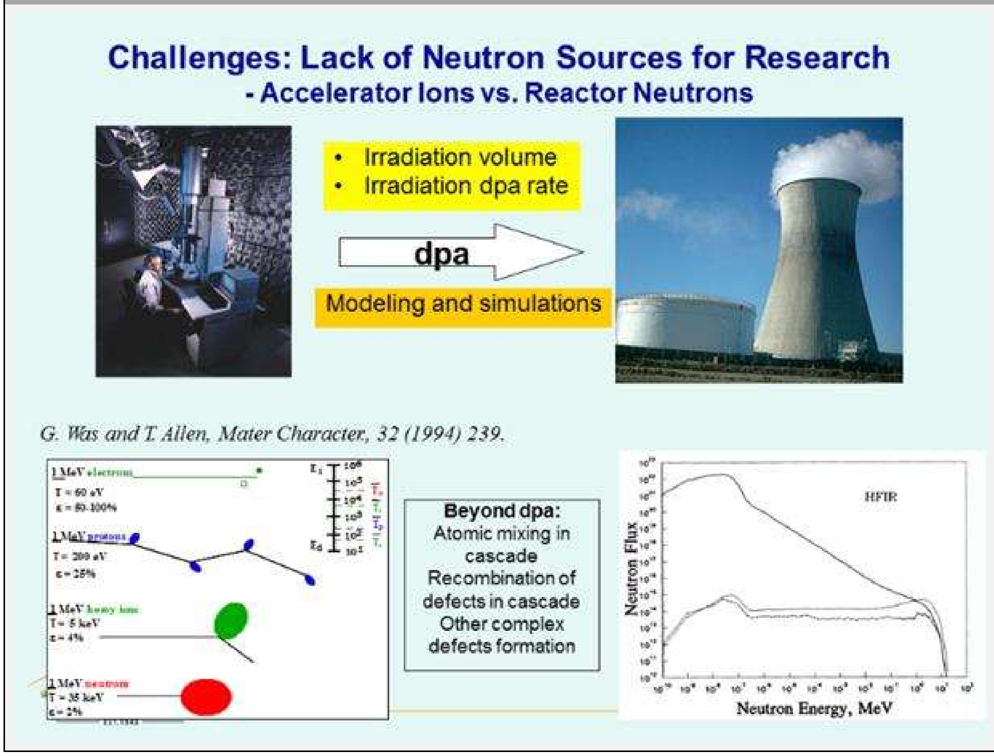
Yong Wang

Ion Beam Materials Laboratory in Los Alamos

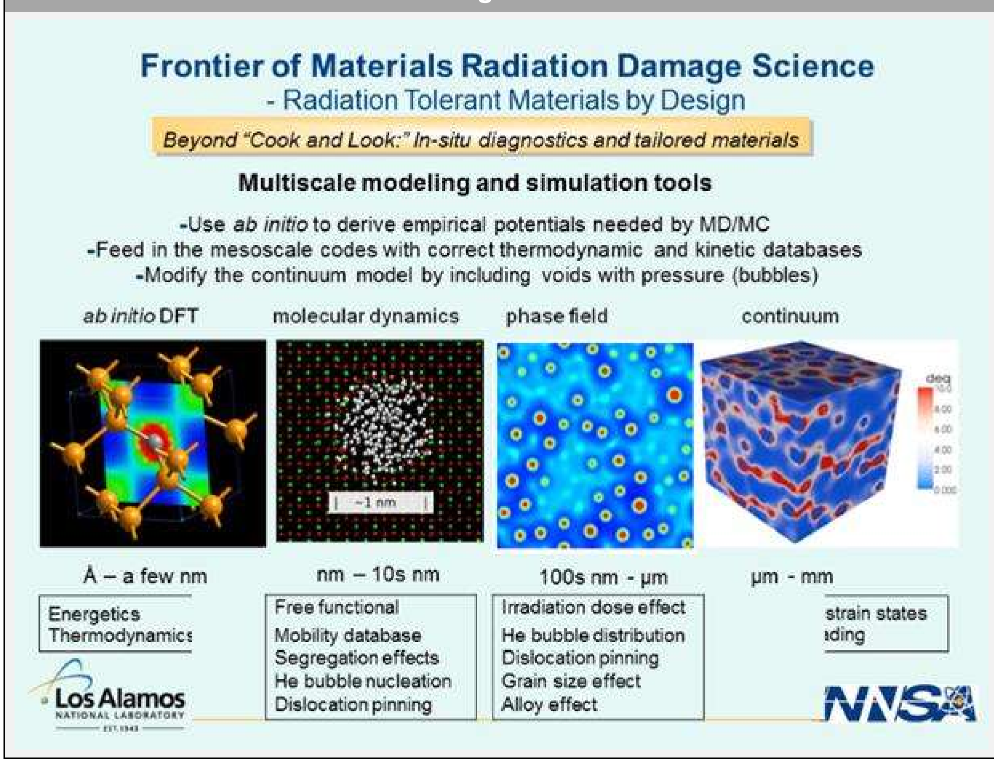
Challenges: Complex materials science under irradiation extremes



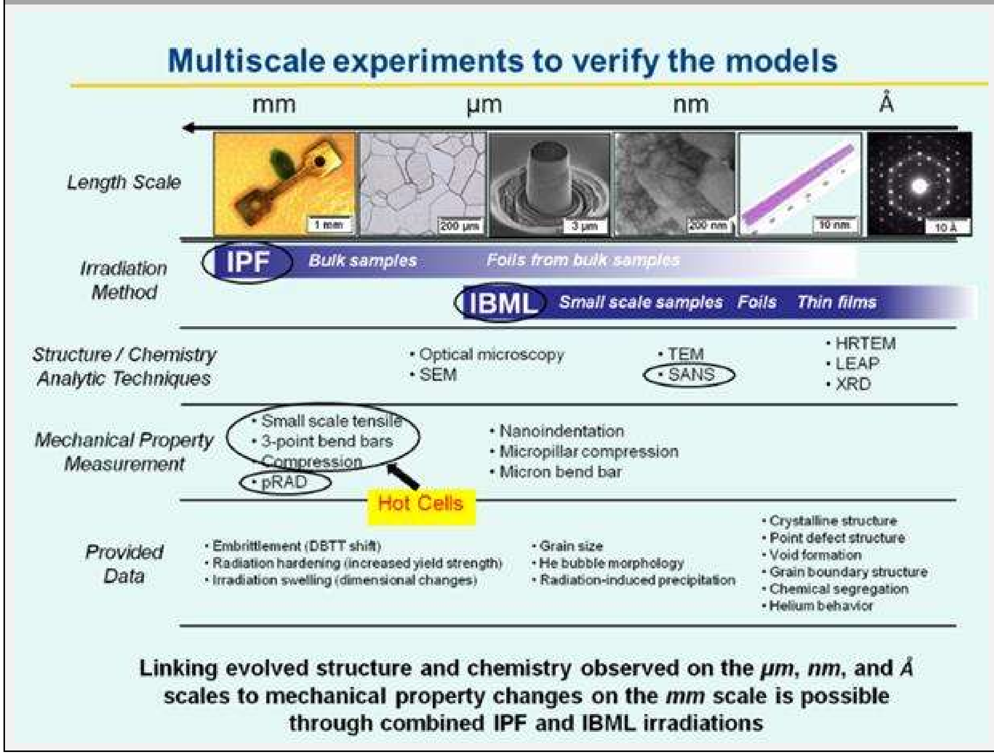
Challenges: Lack of Neutron Sources for Research - Accelerator Ions vs. Reactor Neutrons



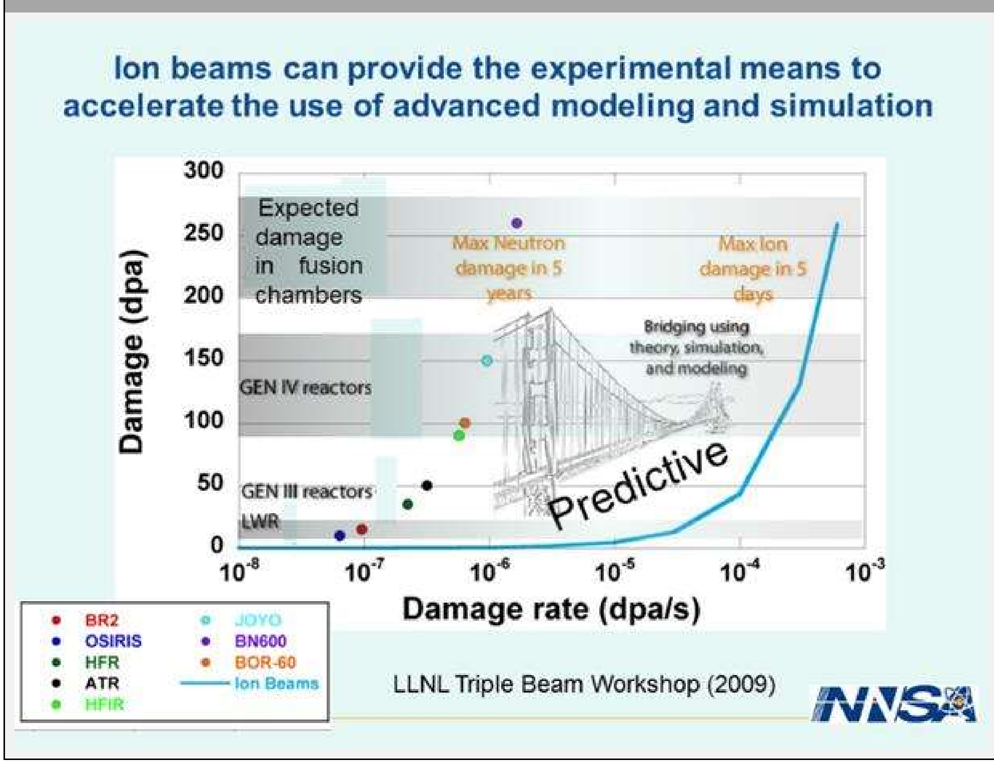
Frontier of Materials Radiation Damage Science



Multiscale experiments to verify the models



Ion beams can provide the experimental means to accelerate the use of advanced modeling and simulation

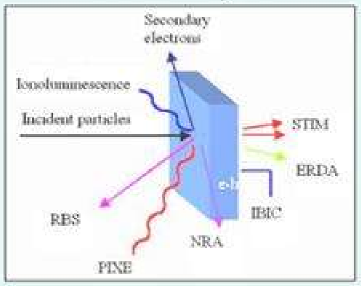


Ion – Solid Interactions

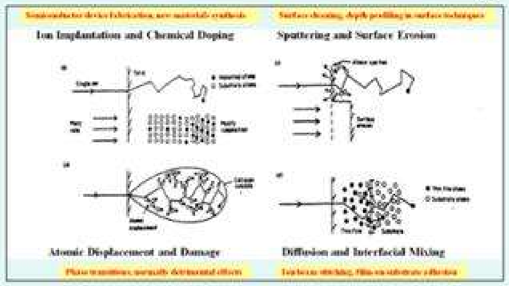
Ion Beams Contribute to Nuclear Materials Research

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**

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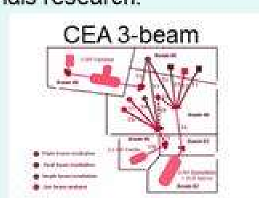
Ion Accelerator Facilities for Materials Research

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 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 Implanters + Ion Accelerators:

- ✓Synergistic activities
- ✓Damage plus transmutation products
- ✓Dual-beam or Triple-beam capabilities

Ion Accelerators + TEM:

- ✓In-situ characterization of radiation damage
- ✓Synergistic activities
- ✓Damage plus Transmutation products
- ✓2-beam, 3-beam, 4-beam capabilities

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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 μS, 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)

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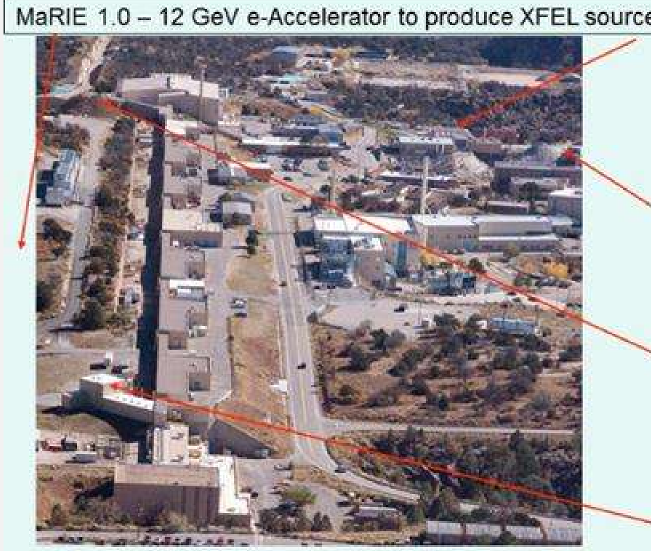
LANSCE Experimental Areas

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*

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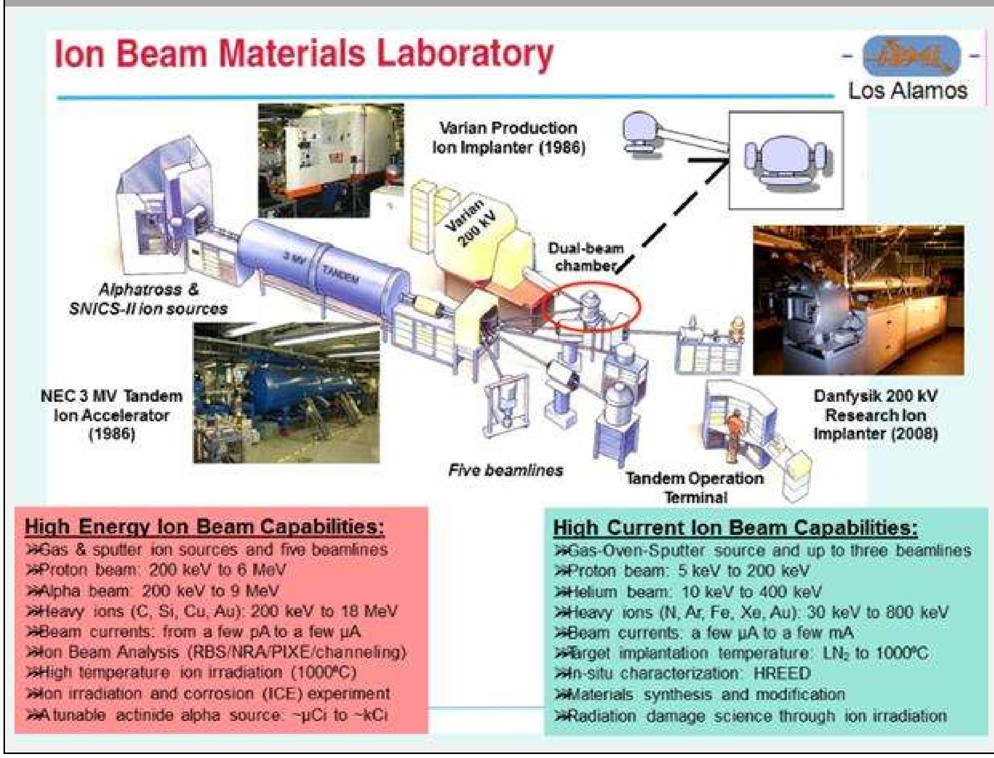
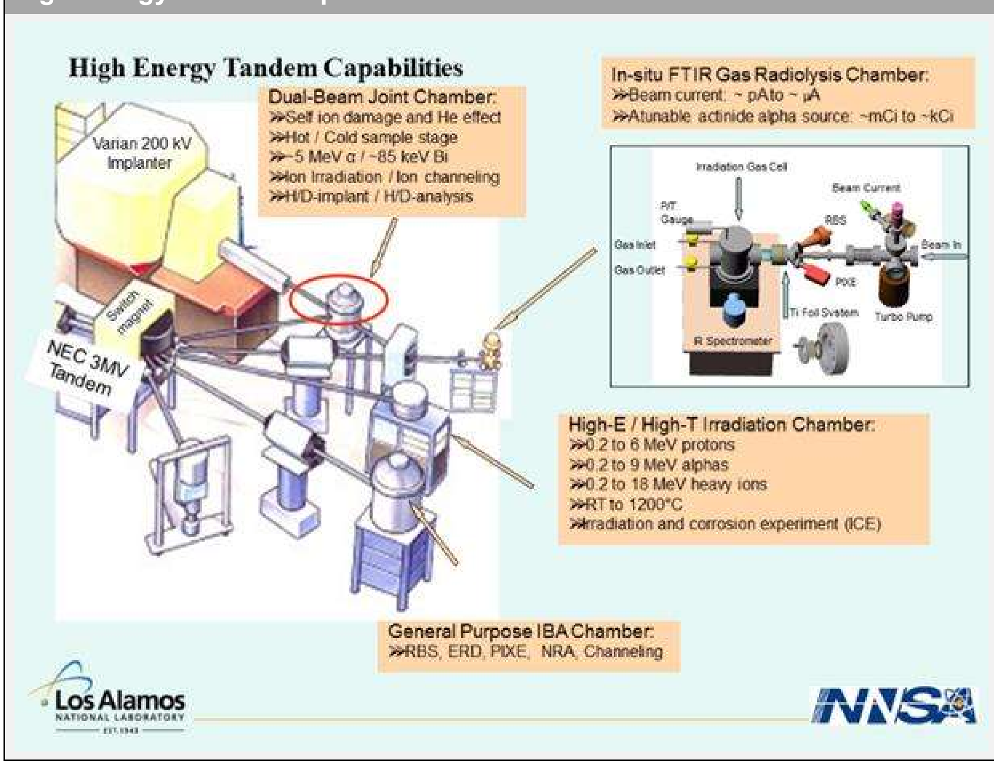
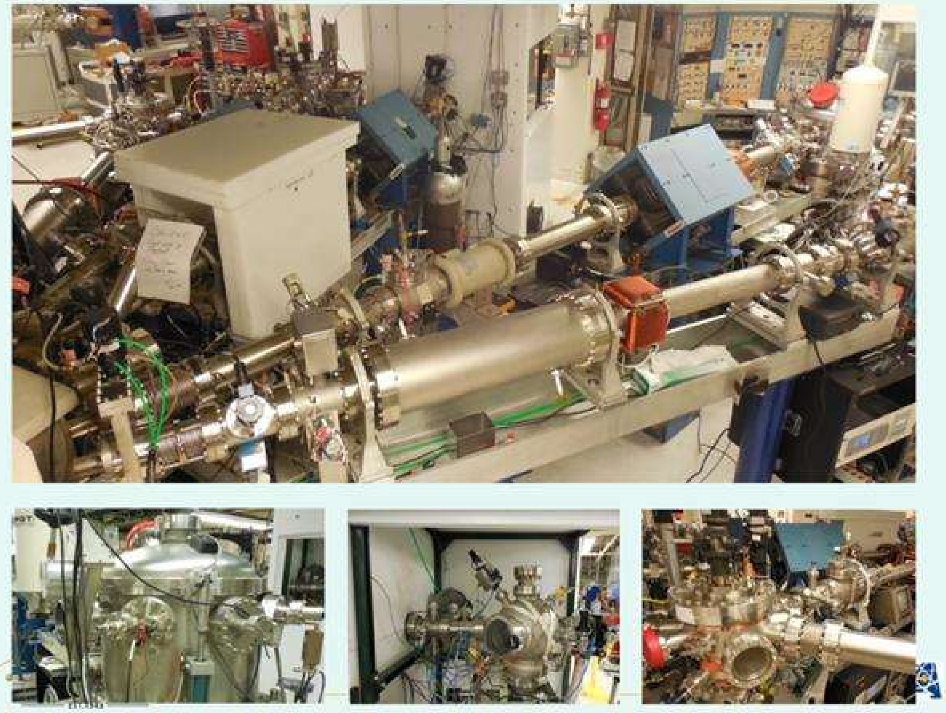
Slide 11



High Energy Tandem Capabilities

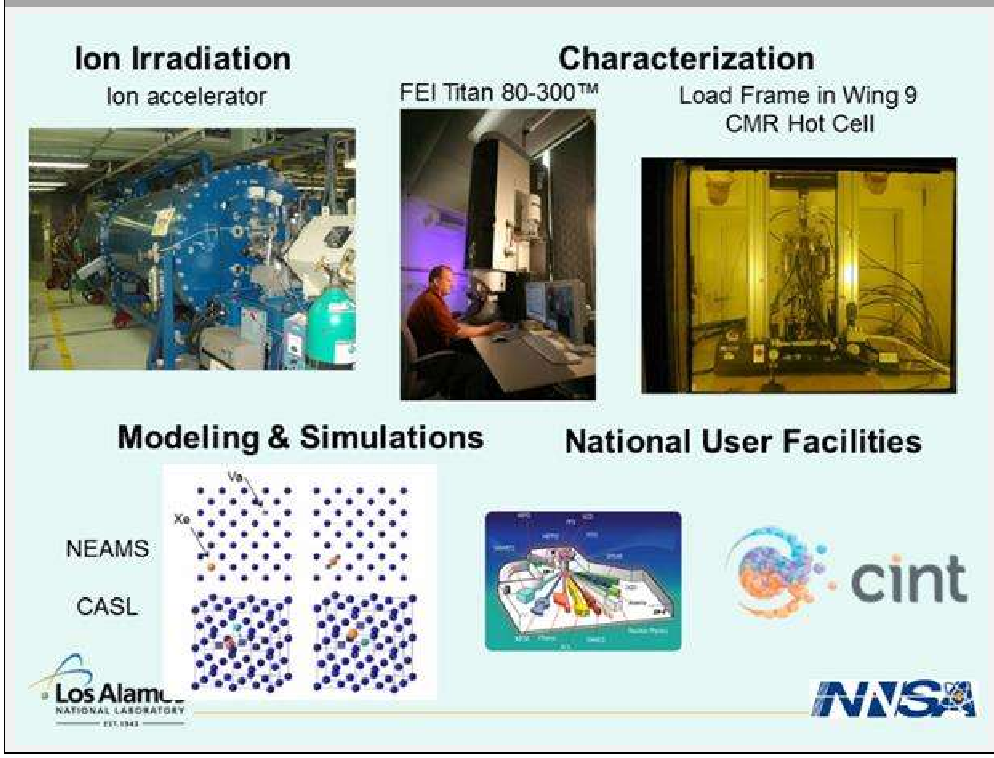


Slide 13

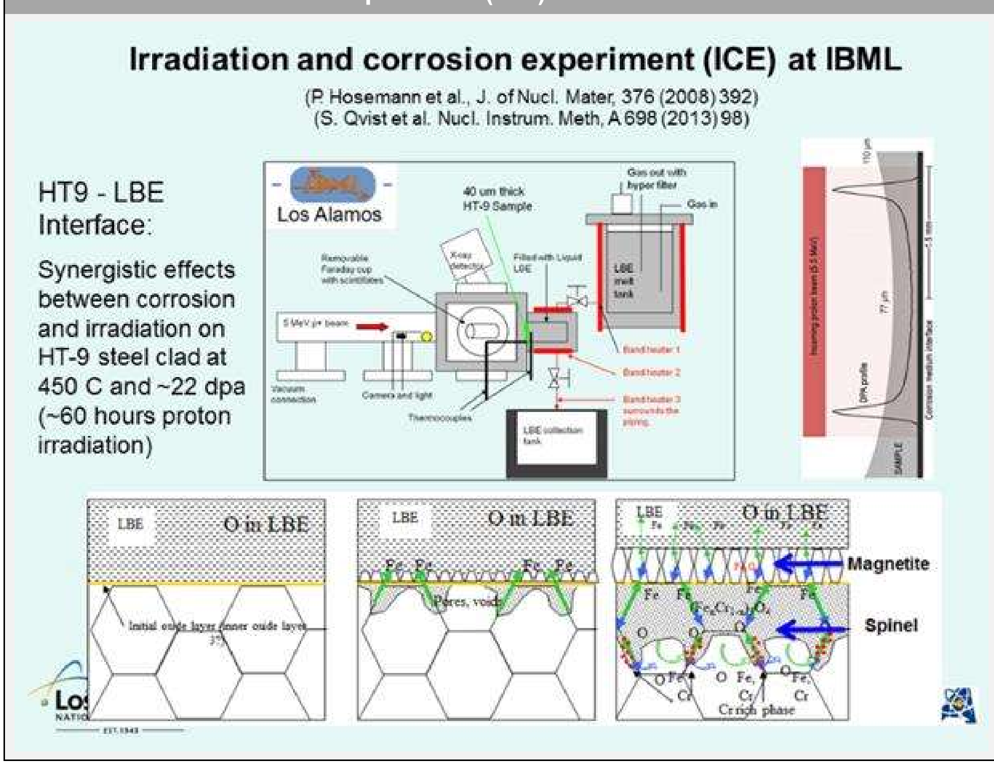


Ion Beam Materials Research at LANL (1986-2016) (Courtesy of Nastasi, Tesmer, Sickafus, Maggiore, Misra, Maloy, Uberuaga, Picraux, Jia, and others)

Ion Irradiation Ion accelerator



Irradiation and corrosion experiment (ICE) at IBML



Slide 17

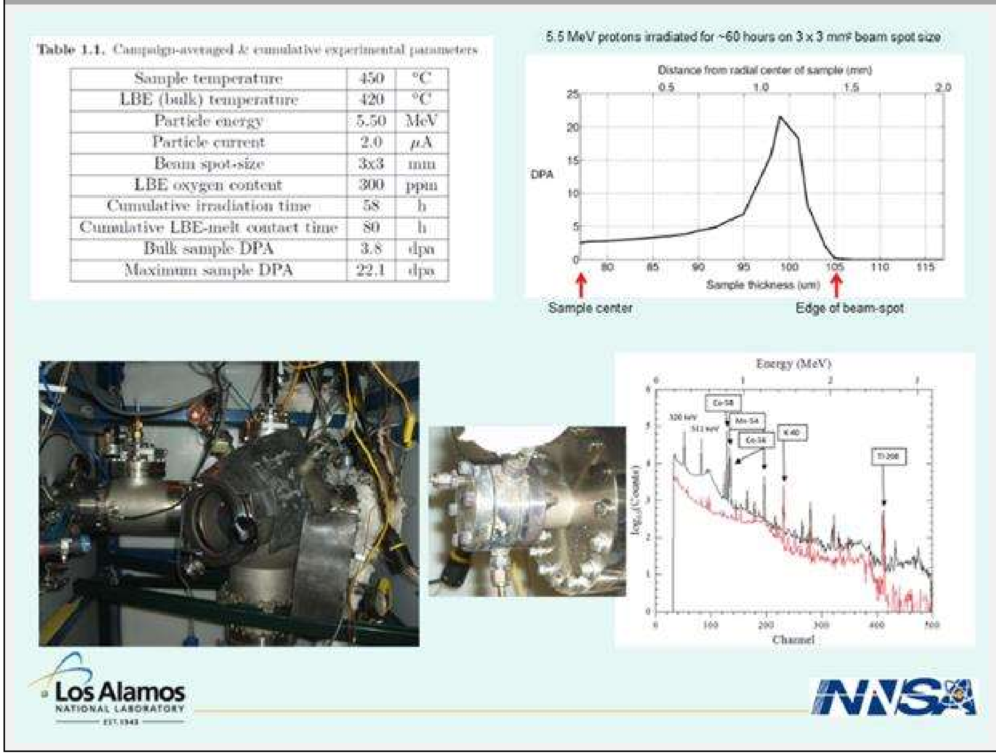
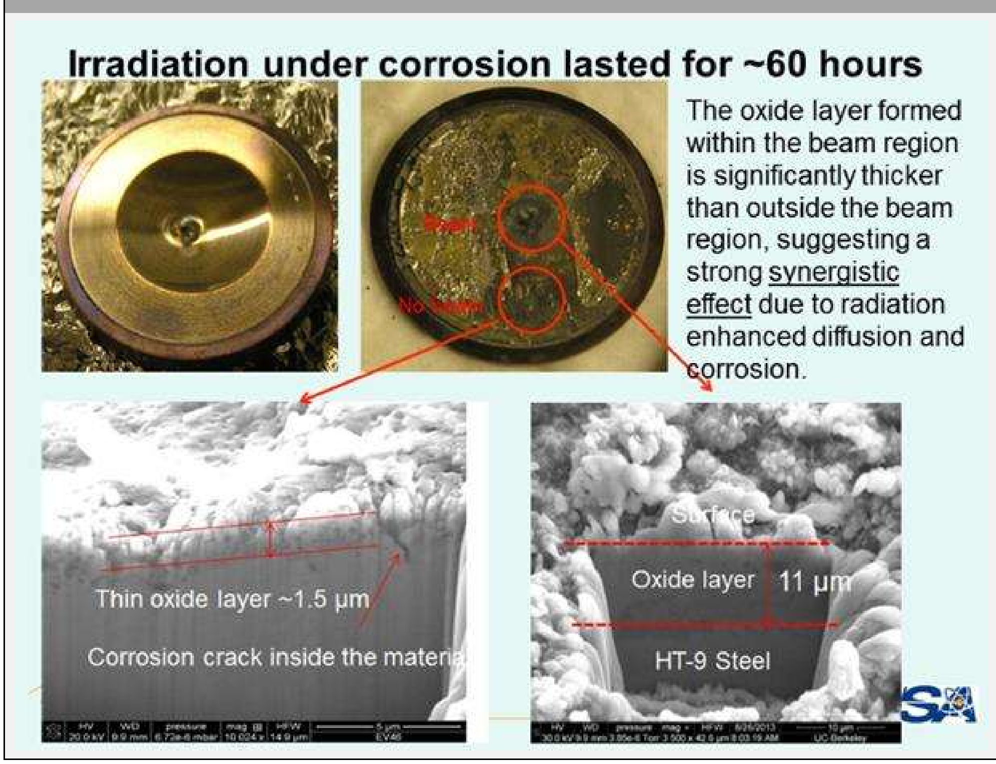


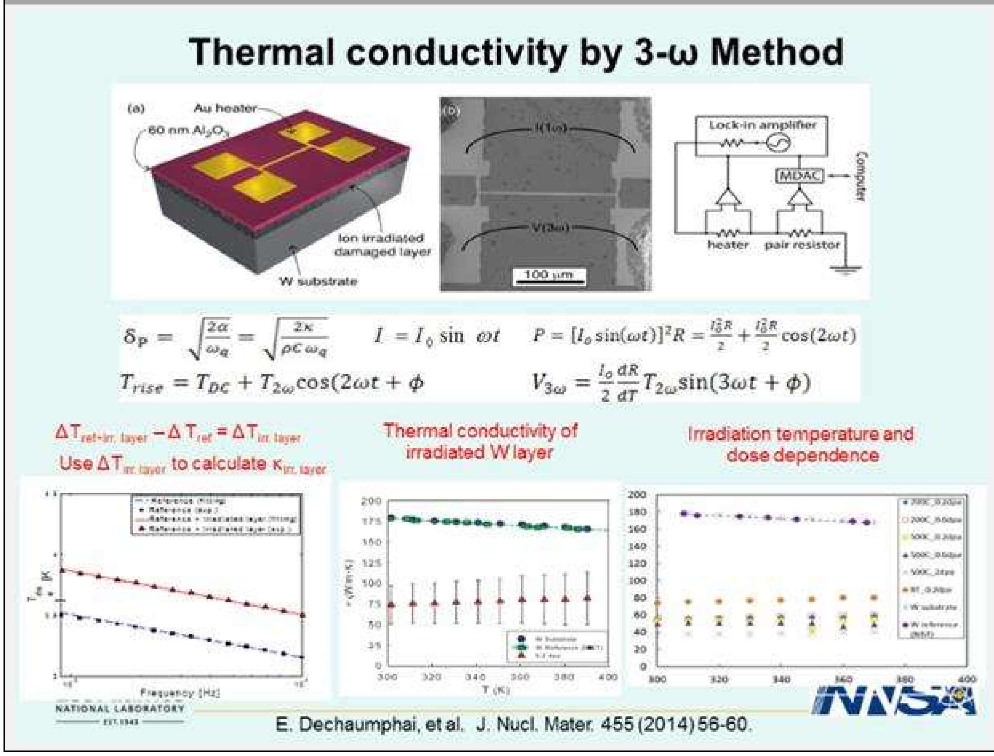
Table 1.1. Campaign-averaged & cumulative experimental parameters

Sample temperature	450	°C
LBE (bulk) temperature	420	°C
Particle energy	5.50	MeV
Particle current	2.0	μA
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

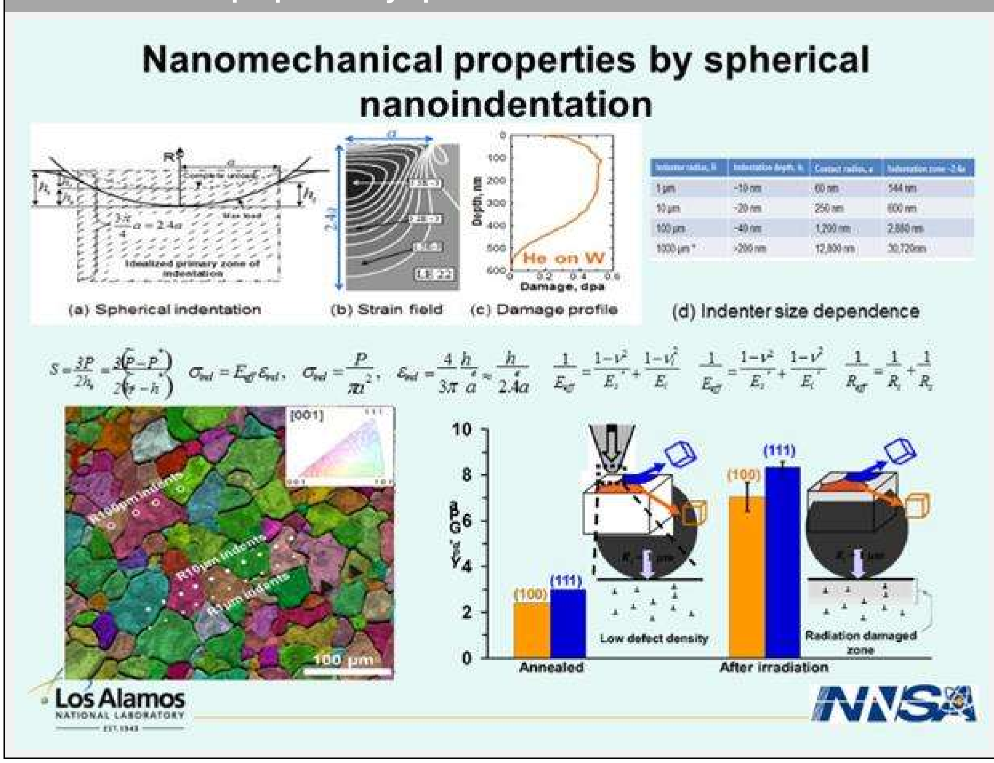
Irradiation under corrosion lasted for ~60 hours



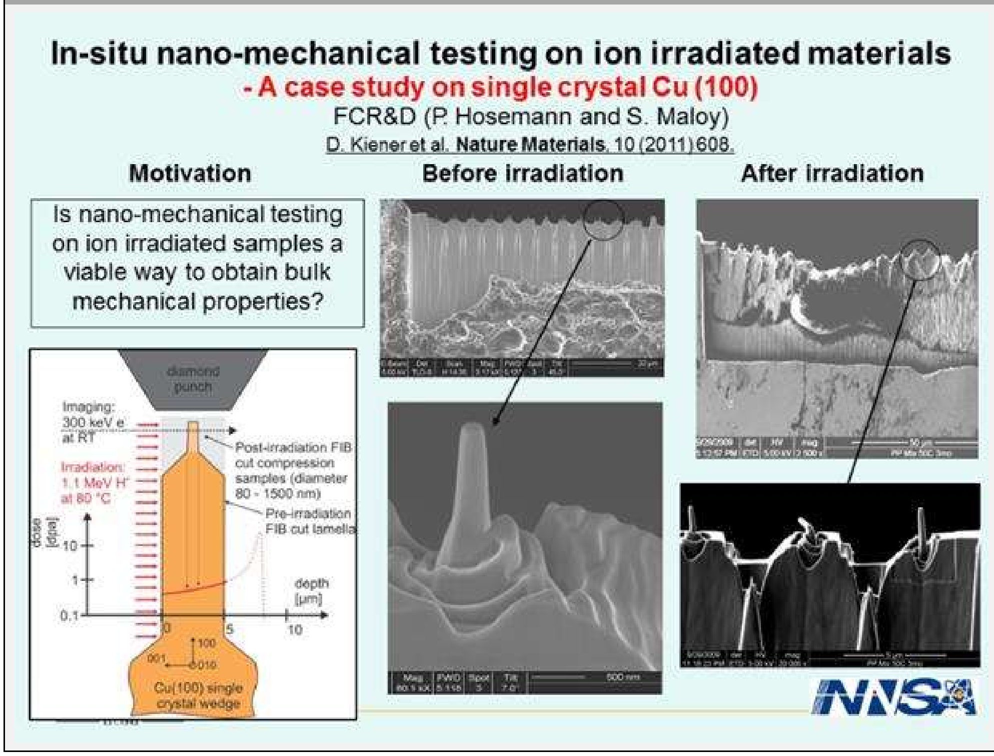
Thermal conductivity by 3-ω Method



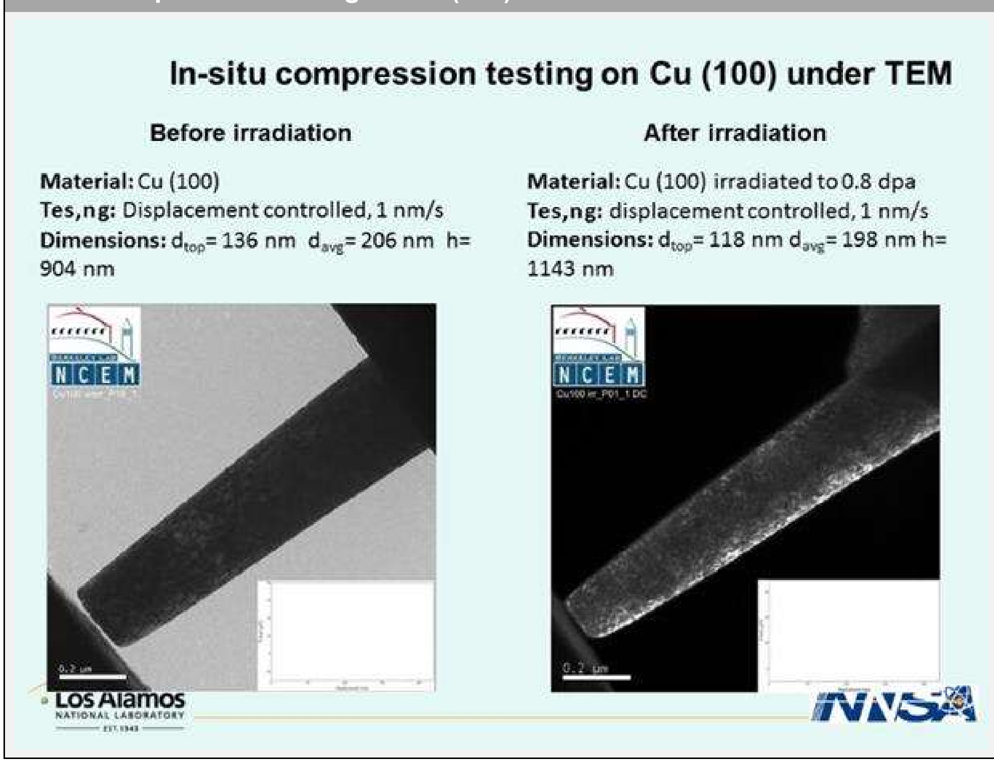
Nanomechanical properties by spherical nanoindentation



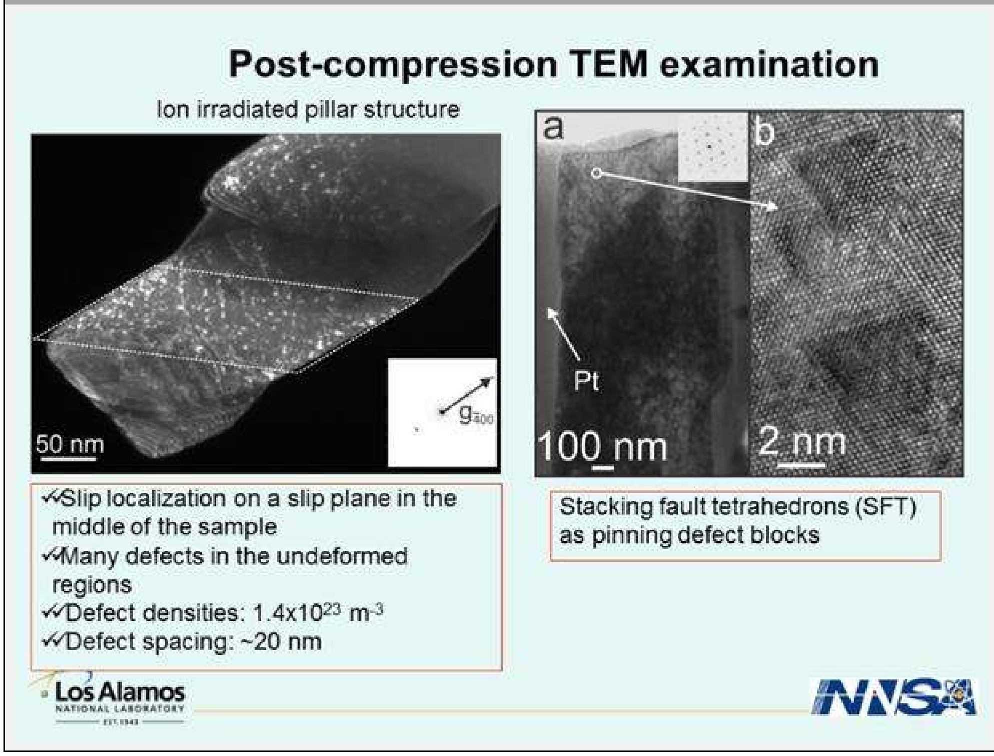
In-situ nano-mechanical testing on ion irradiated materials



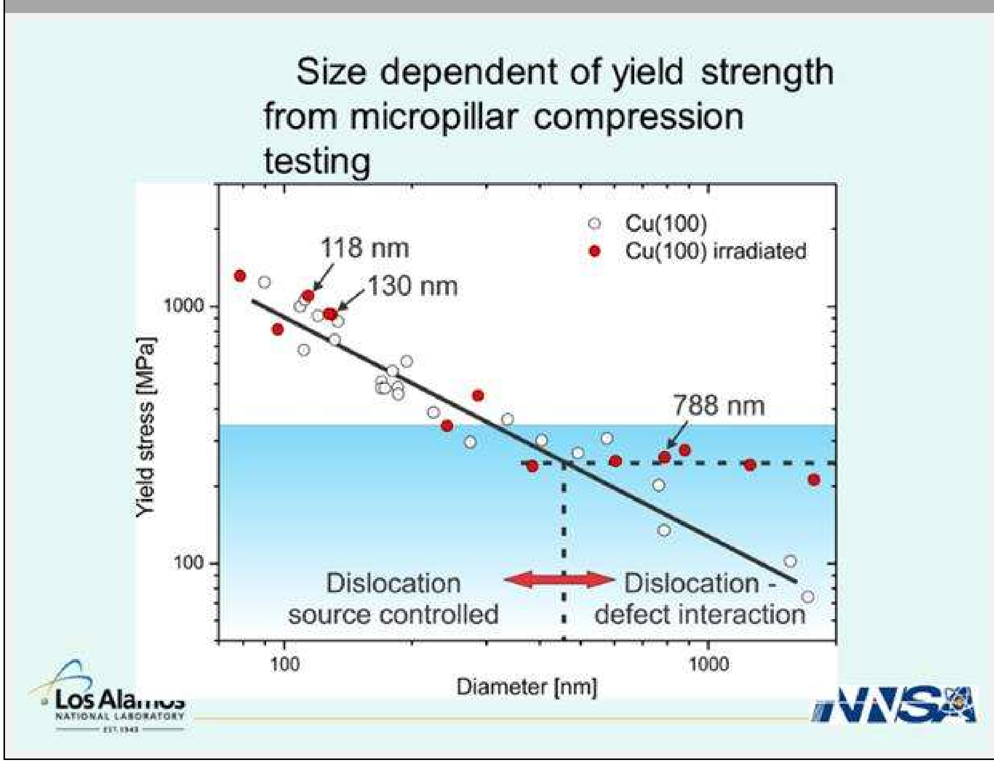
In-situ compression testing on Cu (100) under TEM



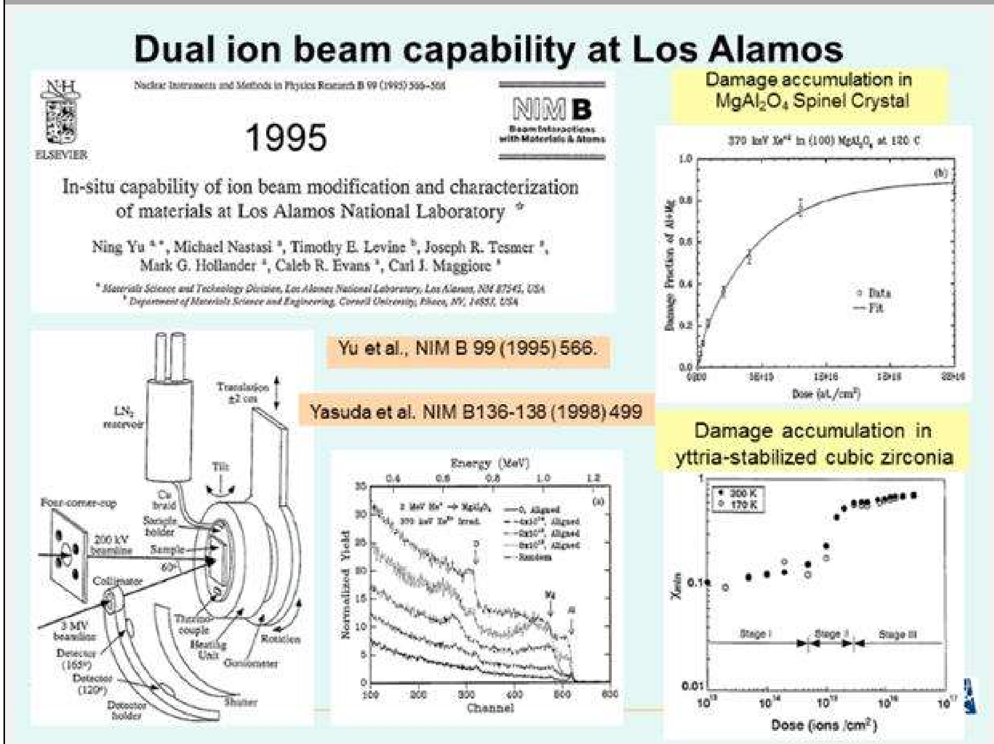
Post-compression TEM examination



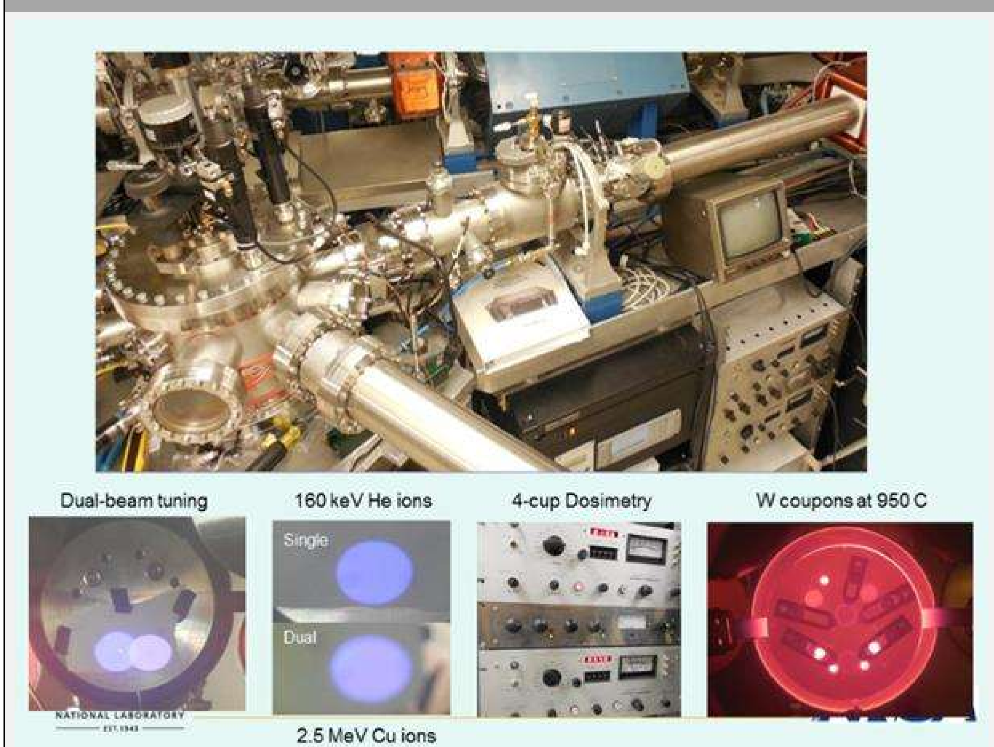
Slide 24



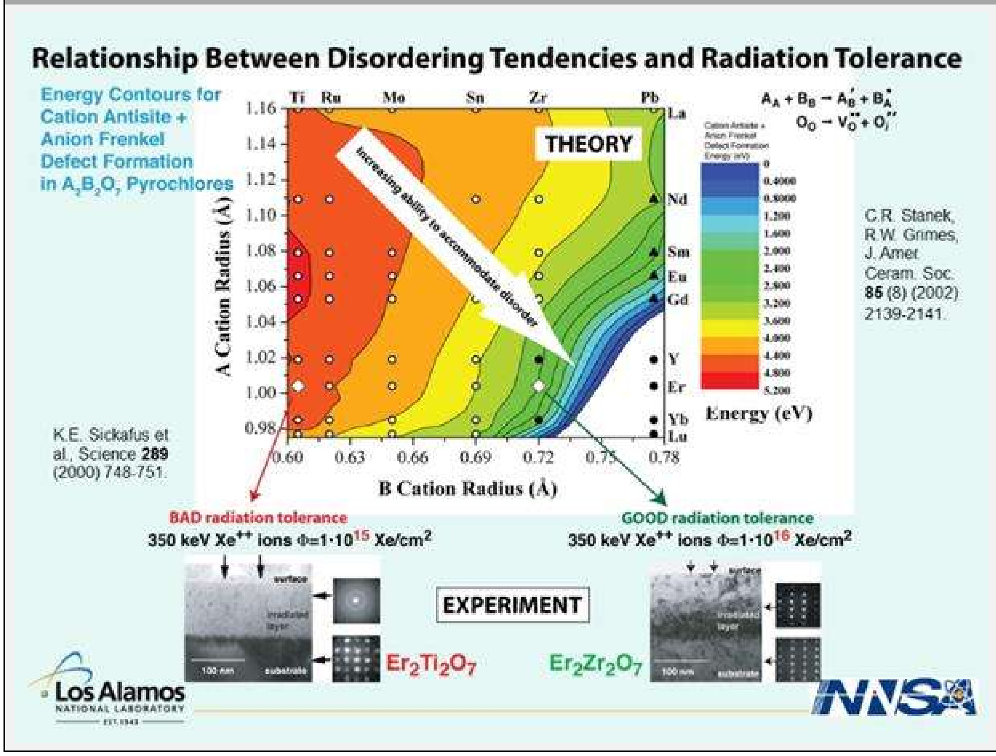
Dual ion beam capability at Los Alamos



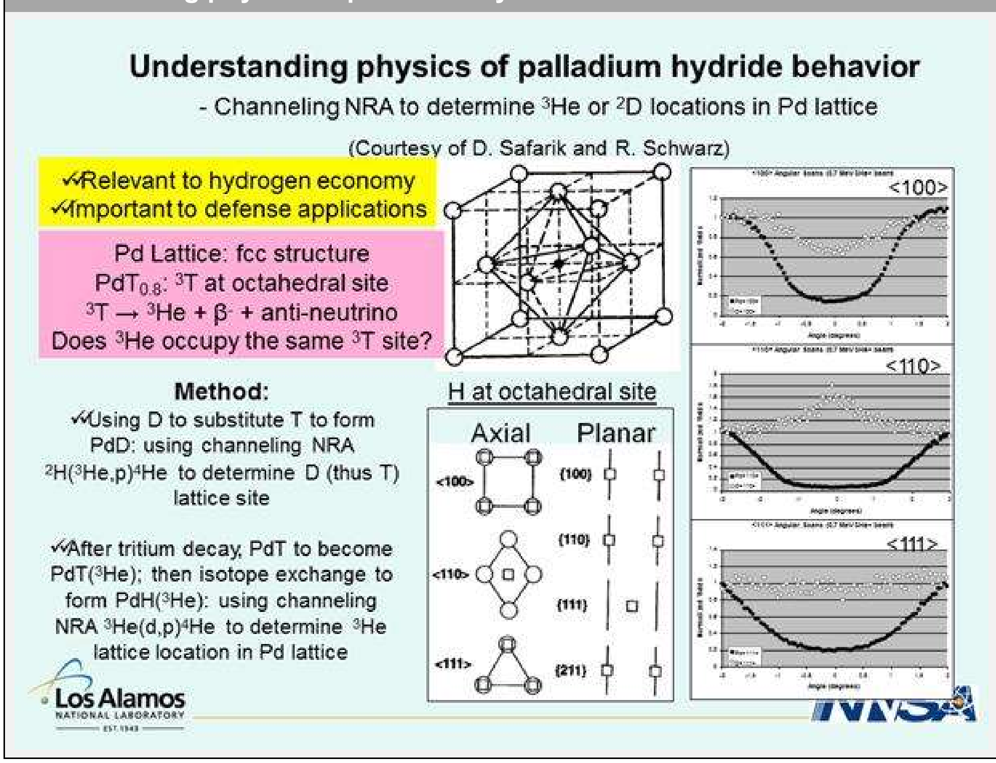
Slide 26



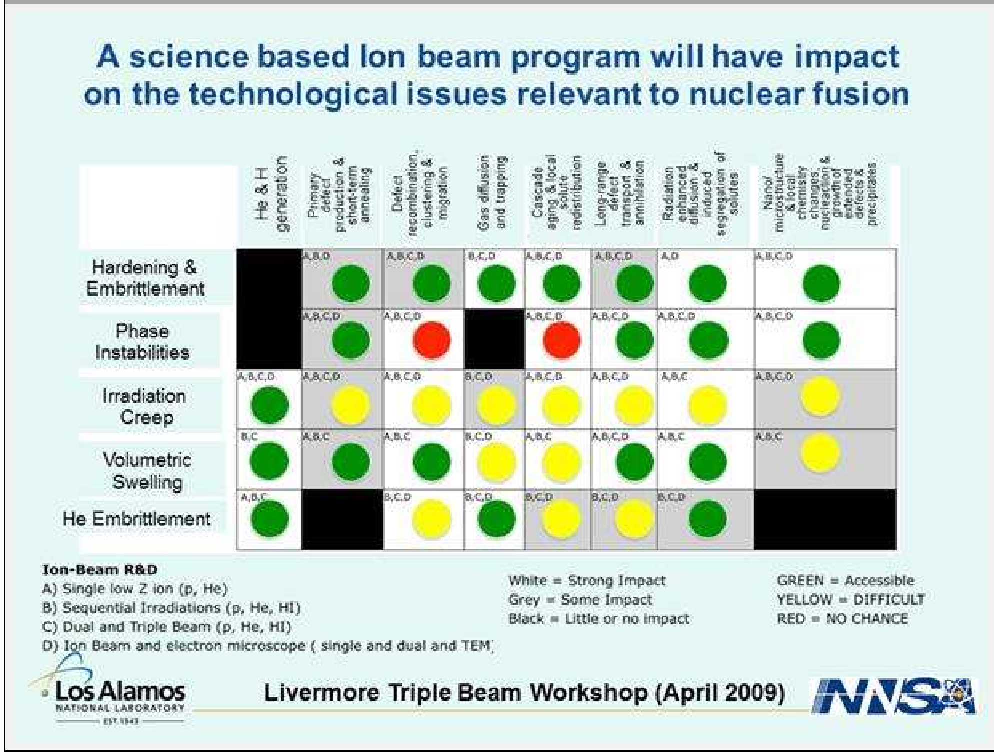
Slide 27



Understanding physics of palladium hydride behavior



A science based Ion beam program will have impact on the technological issues relevant to nuclear fusion



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

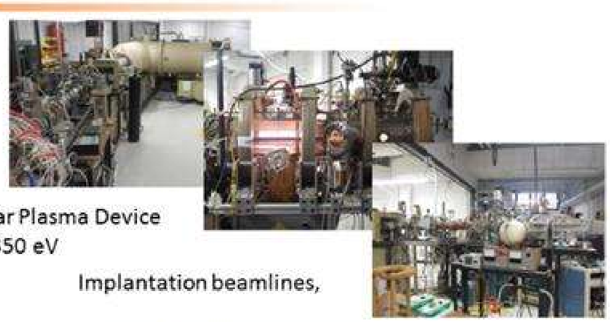
Slide 2

CSTAR Facility

2 MeV Tandem Ion Accelerator,
<100 microAmp

DIONISOS linear Plasma Device
10^{22} D^{+}/m^{2}-s, 350 eV

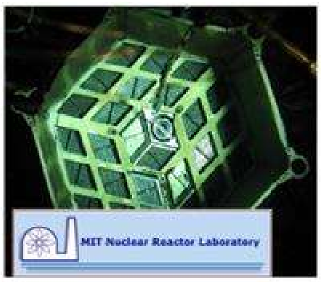
Implantation beamlines,



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

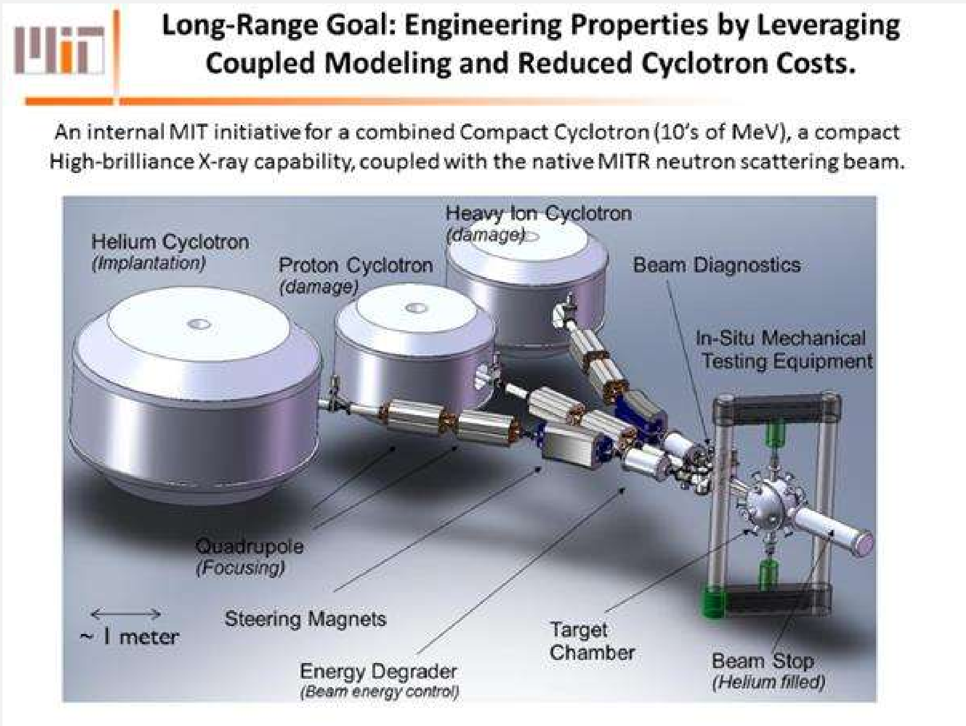
Cutaway of SC cyclotron

3 m diameter 250 MeV Superconducting cyclotron for proton therapy

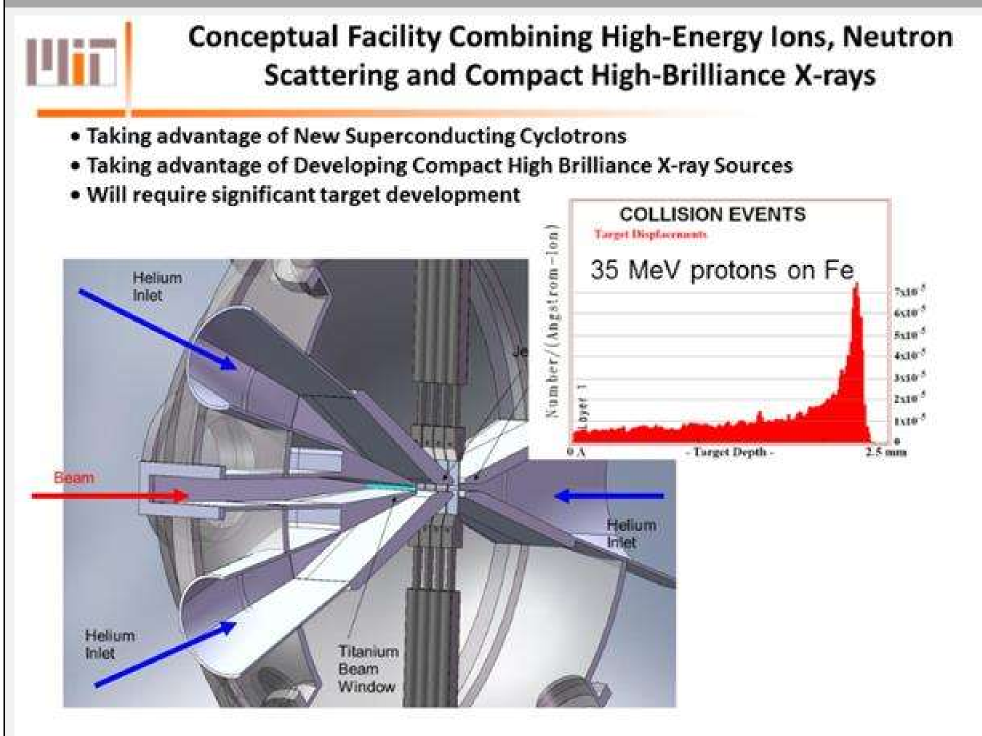
Compact cyclotron evolution is presenting an opportunity for irradiation materials science:

- 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.

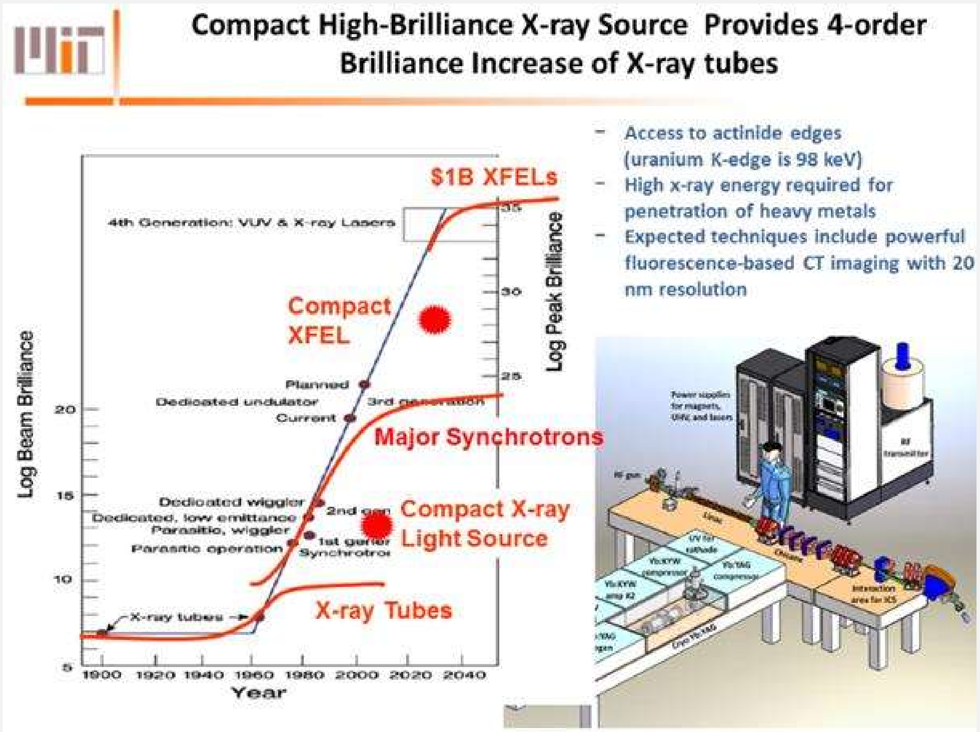


Slide 6

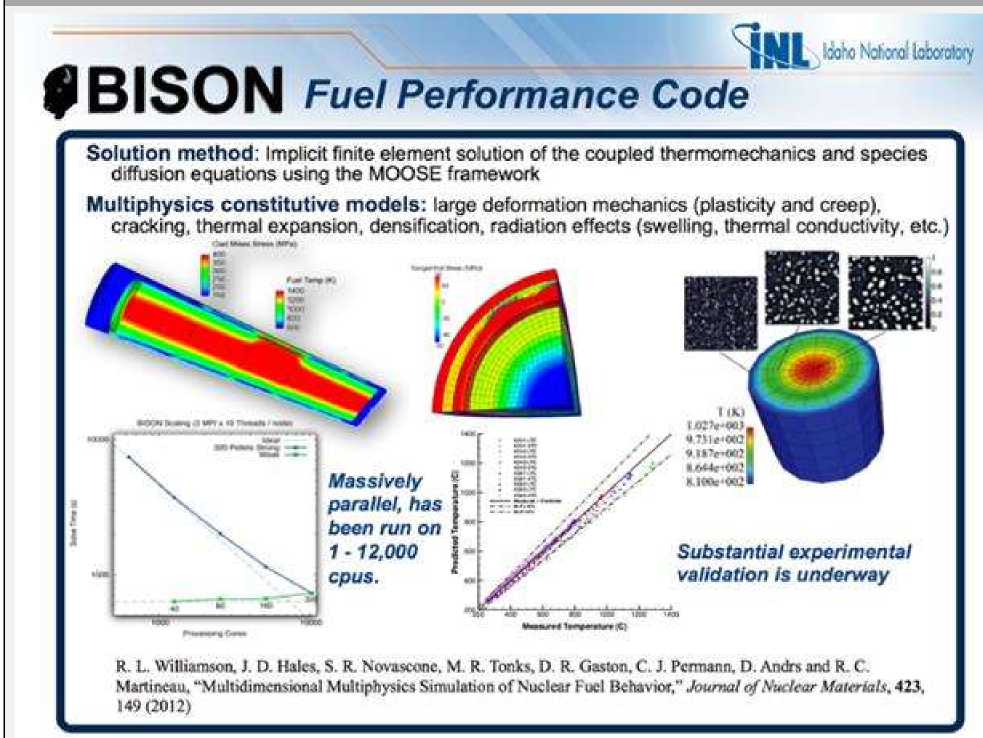


1. These energies open up bulk sample irradiations ~2.5-mm thickness.

Slide 7



Slide 8



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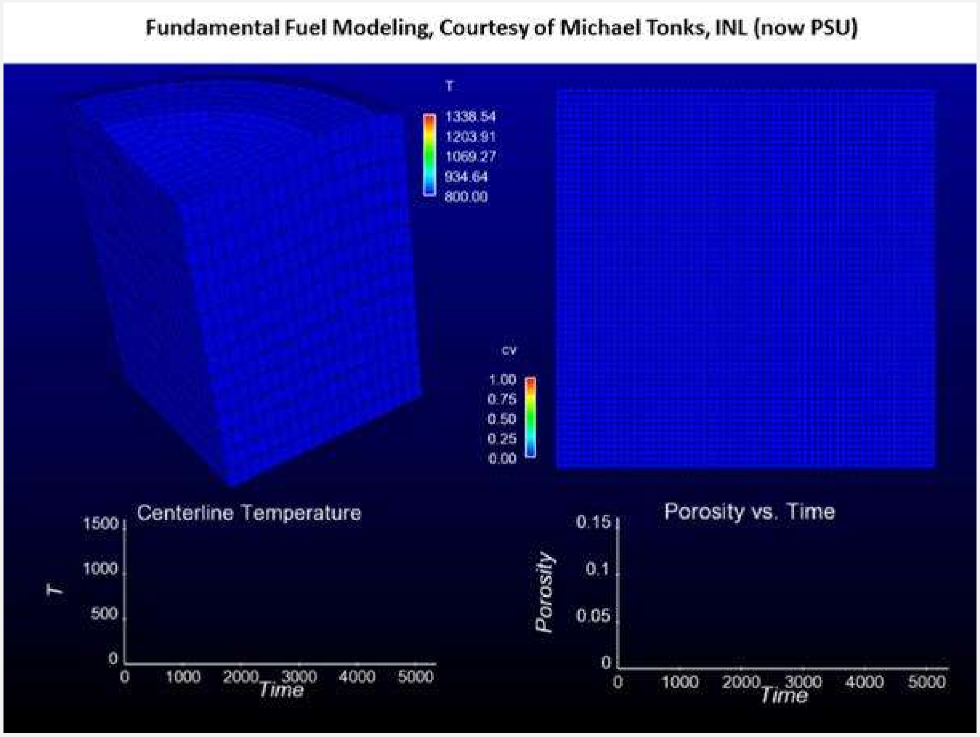

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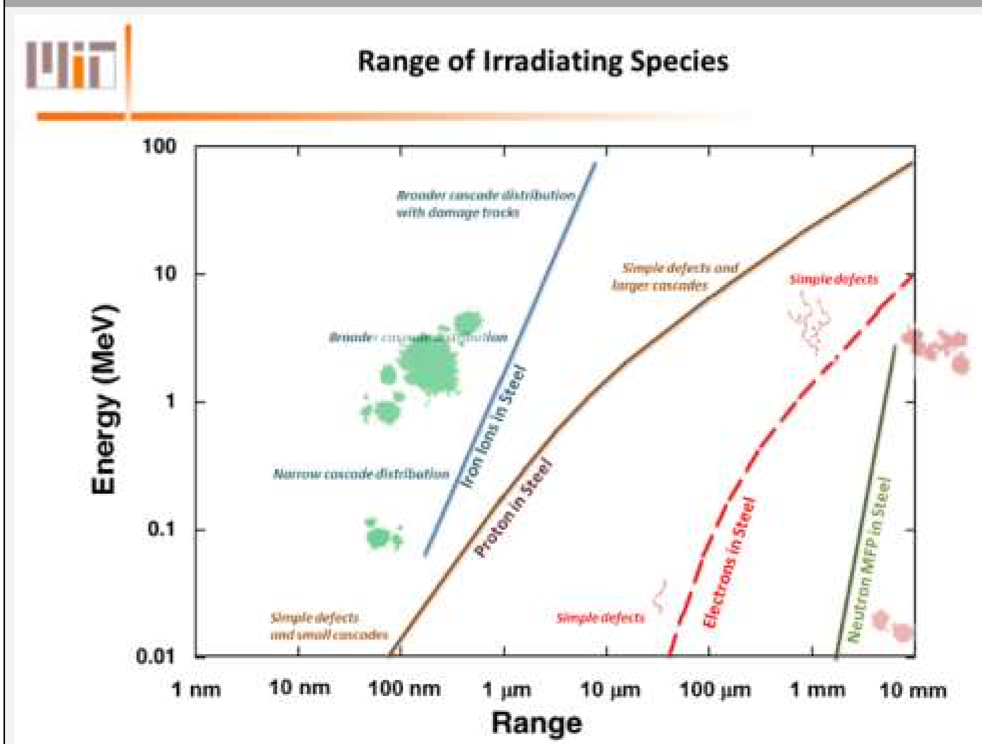

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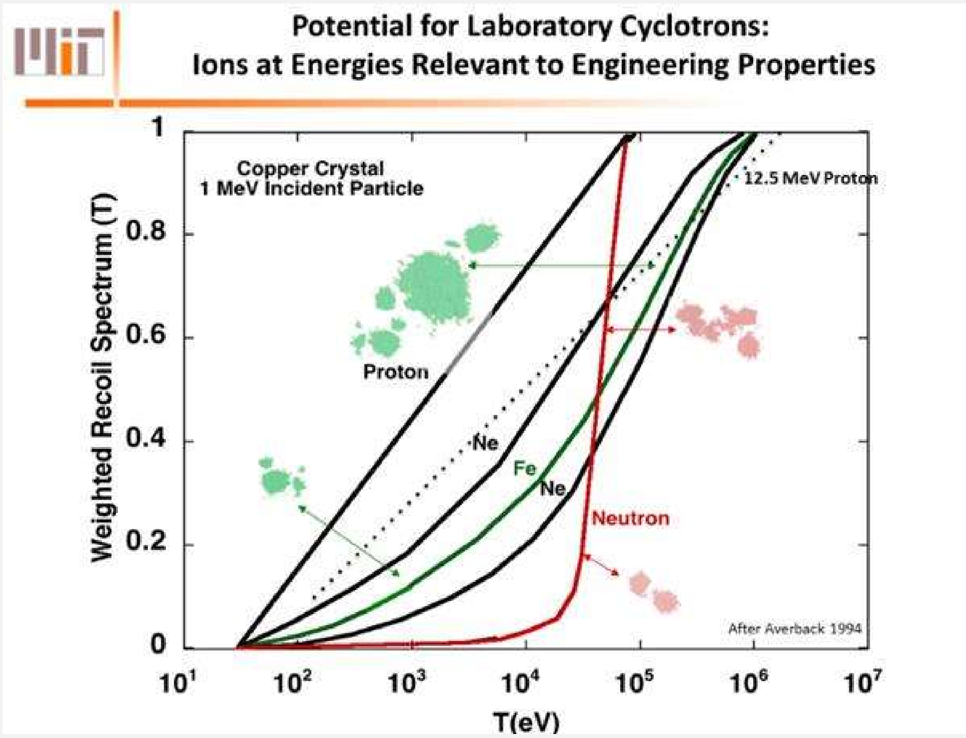

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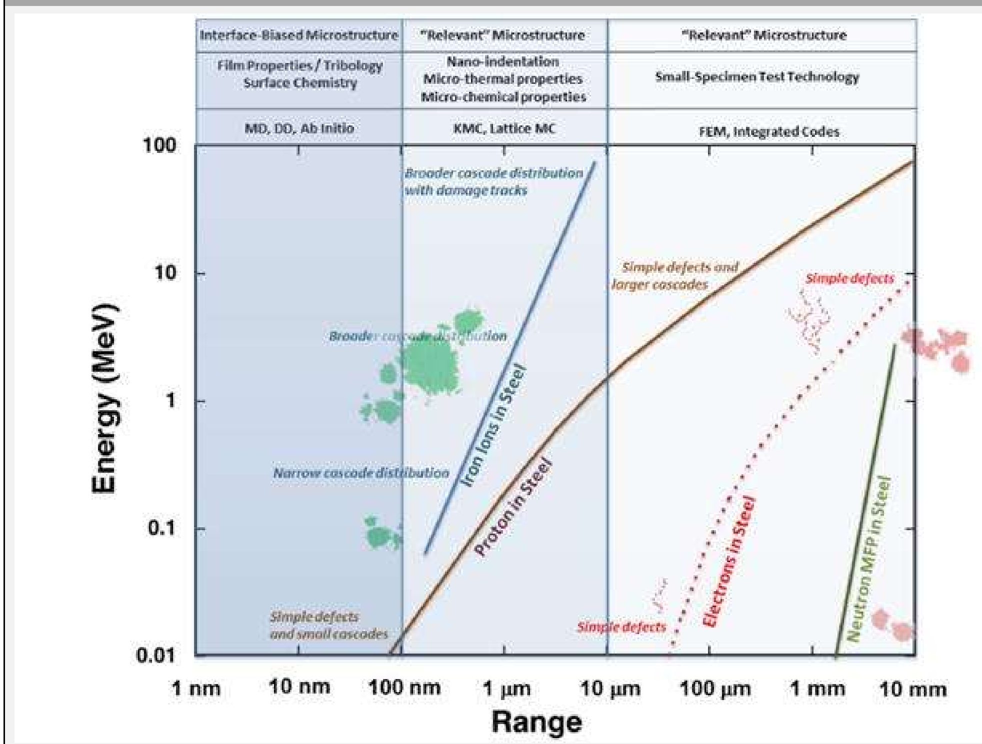
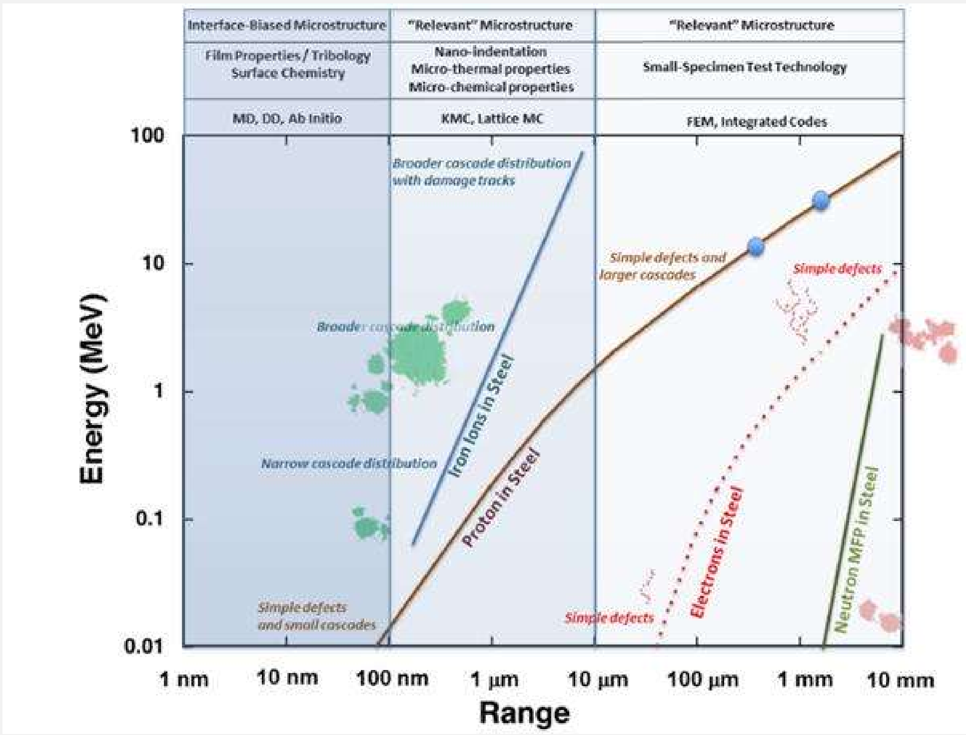


1. Need to get >1-MeV protons to get the depth that will allow mechanical testing on small samples.

Slide 13



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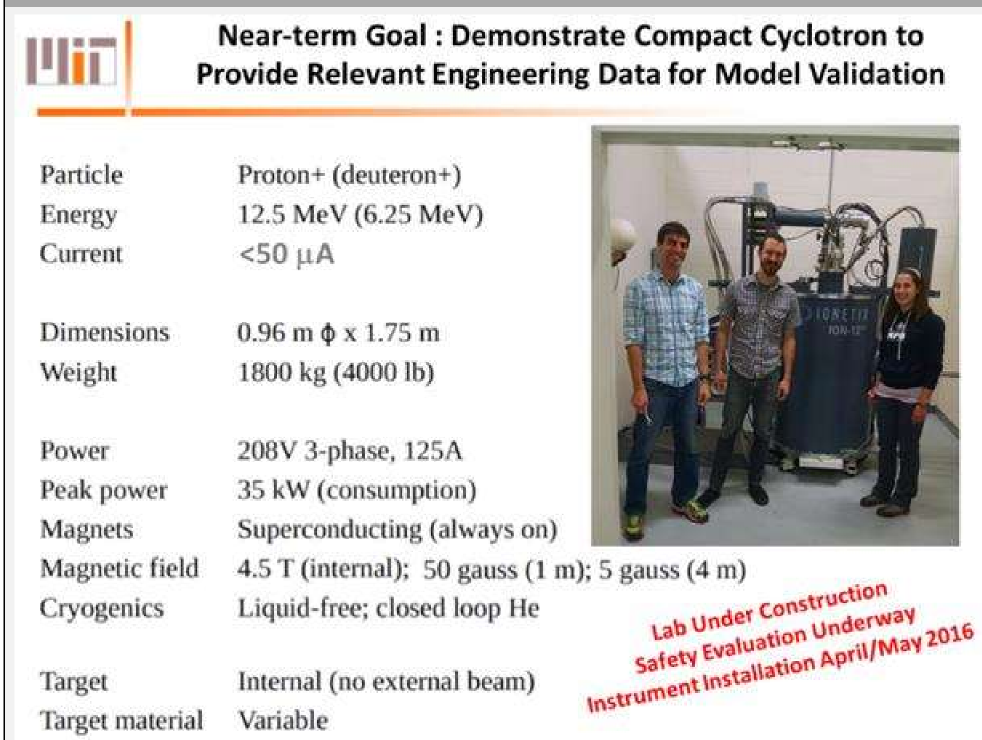
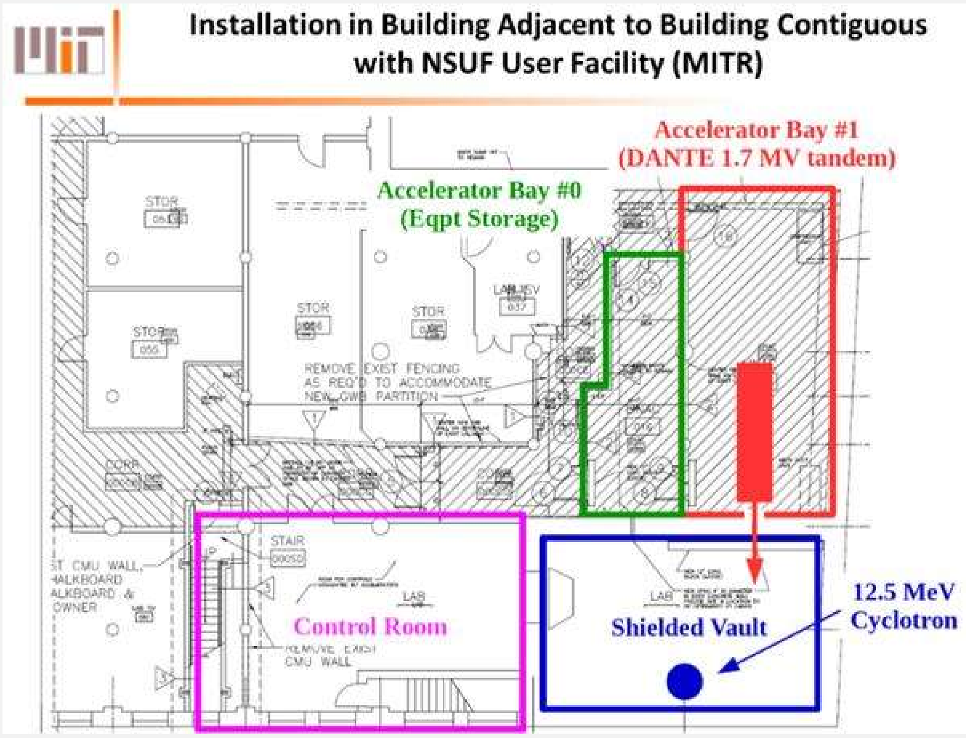


1. What is the timeframe for getting this operational? How long for the rest of the pieces?
2. [Lance Snead] The instrument will be operational within a month of delivery. Target design is underway. Construction of target thimble this summer. Irradiation late this year.

Slide 15



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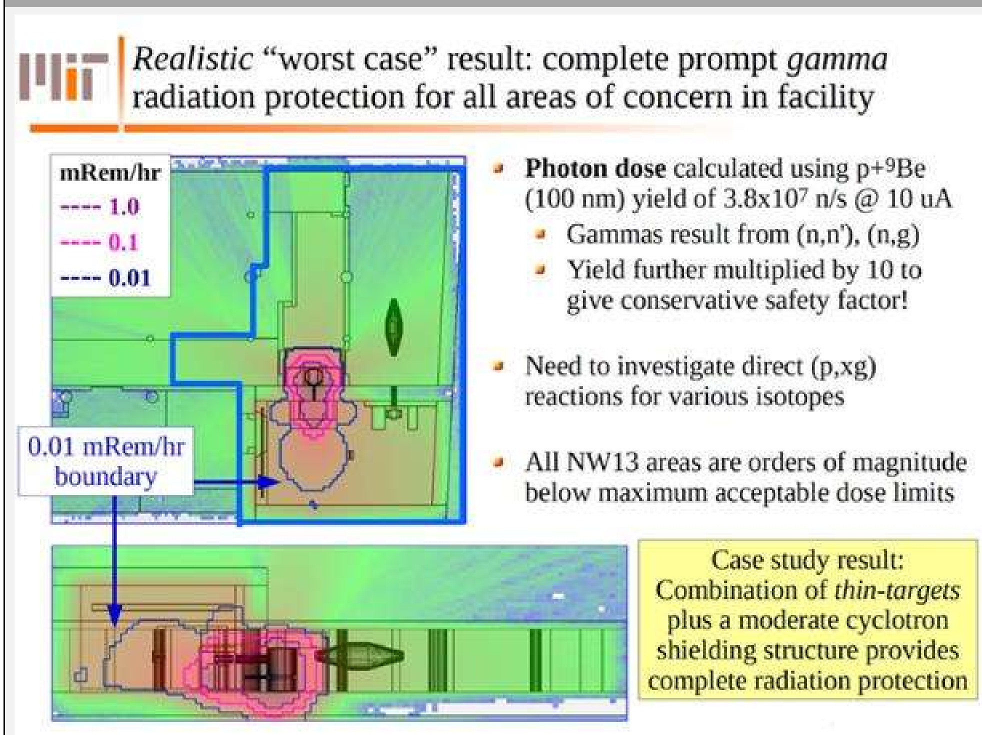
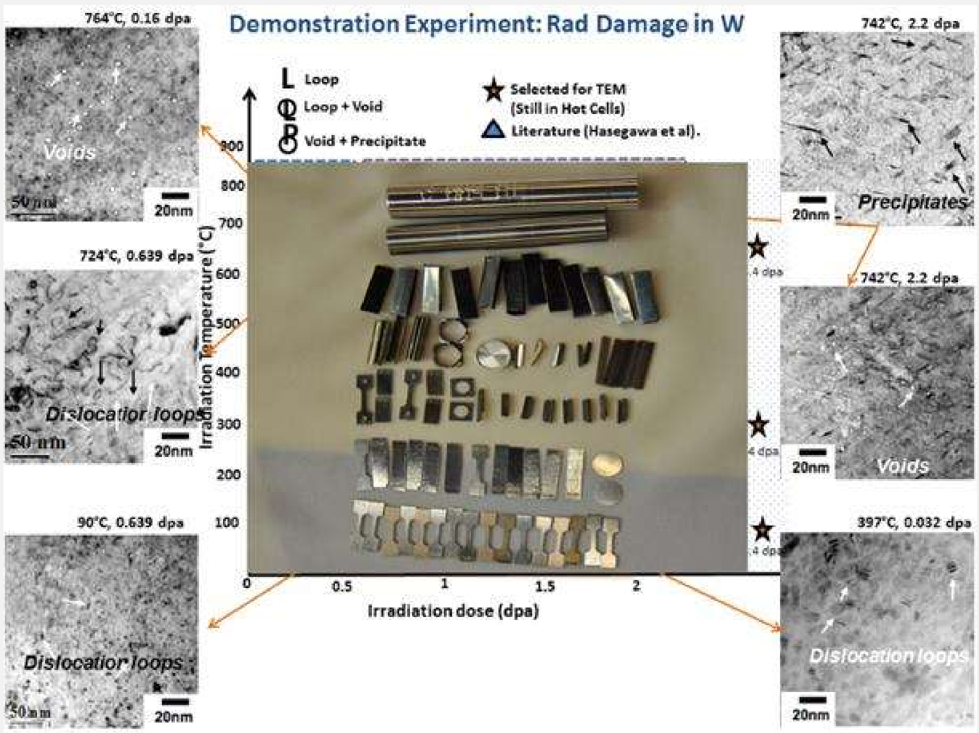
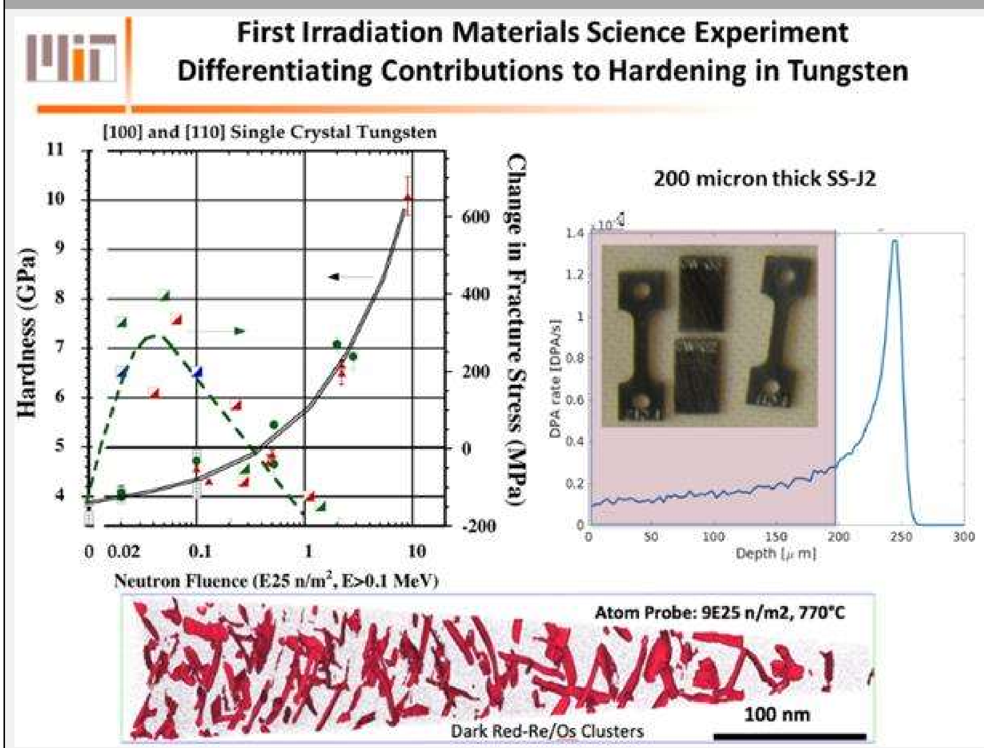


Demonstration Experiment: Rad Damage in W



Slide 18



1. Provides direct comparison of hardening with and without the transmutation product (difference between n and p irradiations).

Slide 19

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

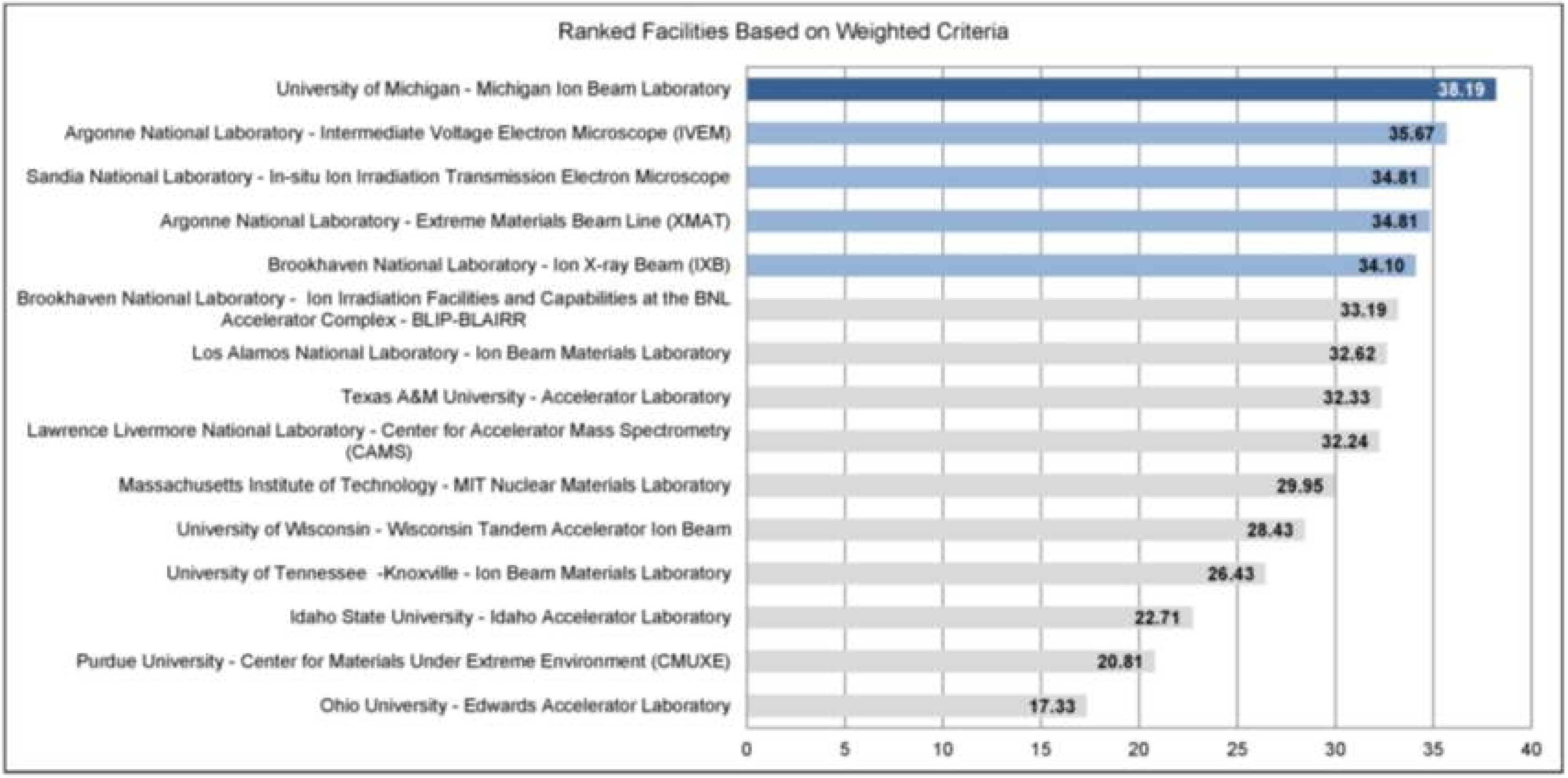
No.	C8: Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	Avg. Score	Std. Dev.	Number of Votes at Each Score (1-5)					
				0	1	2	3	4	5
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.95	1.00	0	1	1	2	11	6
6	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**


Ranked Facilities Based on Weighted Criteria
University of Michigan - Michigan Ion Beam Laboratory
Argonne National Laboratory - Intermediate Voltage Electron Microscope (IVEM)
Sandia National Laboratory - In-situ Ion Irradiation Transmission Electron Microscope
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
Los Alamos National Laboratory - Ion Beam Materials Laboratory
Texas A&M University - Accelerator Laboratory
Lawrence Livermore National Laboratory - Center for Accelerator Mass Spectrometry (CAMS)
Massachusetts Institute of Technology - MIT Nuclear Materials Laboratory
University of Wisconsin - Wisconsin Tandem Accelerator Ion Beam
University of Tennessee -Knoxville - Ion Beam Materials Laboratory
Idaho State University - Idaho Accelerator Laboratory
Purdue University - Center for Materials Under Extreme Environment (CMUXE)
Ohio University - Edwards Accelerator Laboratory
38.19
35.67
34.81
34.81
34.10
33.19
32.62
32.33
32.24
29.95
28.43
26.43
22.71
20.81
17.33
0
5
10
15
20
25
30
35
40

Community Comments on Facility Rankings

Facilities	Any Comments
Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	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	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)	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	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	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	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	1. Not able to handle active materials.

Facilities	Any Comments
Extreme Environment (CMUXE)	2. No info provided on ability to handle radioactive material. 3. 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	1. That is BS! 2. Assuming that comment refers to the 0 in situ rating. If so, then agreed.
Texas A&M University – Accelerator Laboratory	1. Apparently not an accurate comment.
University of Michigan – Michigan Ion Beam Laboratory	1. 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	1. Not able to handle active materials. 2. Stated inability to handle radioactive materials. 3. Cannot handle radioactive material. 4. Cannot handle radioactive materials. 5. Cannot handle radioactive materials. 6. 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	1. We can handle 100 mR/hr on contact—there should be no standard deviation here. 2. UW-Madison supports DOE-NE through a vast number of NEUP projects. 3. 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 mm2
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 (H2, CH4, 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				
Characteriza-tion	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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