LA-UR- 10-06769

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Title: Radiation Damage from Atomic to Meso-Scales in Extreme Environments

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Intended for: IAEA Fusion Energy Conference, Daejon, Korea Rep. of, October 11 - 16, 2010

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LA-UR-10-xxxxx

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Los Alamos National Laboratory

Los Alamos, NM USA

Fusion Materials Irradiations at MaRIE's Fission Fusion Facility

MaRIE: Matter-Radiation Interactions in Extremes

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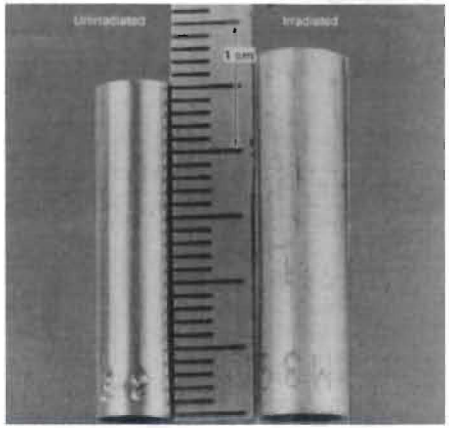
IFE Technologies Satellite Meeting

October 15, 2010

Abstract (see LA-UR-10-06527)

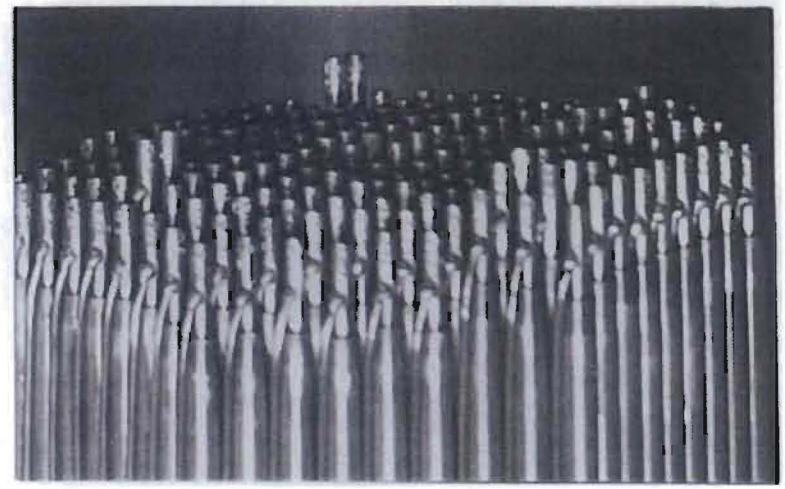
- Overcoming radiation damage degradation is a key rate-controlling step in fusion materials development. New science, approaches, and facilities are needed at multiple scales. Understanding is needed at the atomic scale of the behavior of materials subject to extreme radiation doses and mechanical stress in order to synthesize new materials that can tolerate such conditions. Current computational and experimental research into radiation-tolerant materials will be described. Plans for future irradiation facilities and science are also described. The Matter Radiation Interactions in Extremes (MaRIE) concept is a National User Facility to realize the vision of 21st century materials research and development. The Fission and Fusion Materials Facility (F3) segment of MaRIE proposes to use the present proton linac at Los Alamos with a power upgrade to drive a spallation neutron source that can provide the required radiation environment. Importantly, F3 would also provide the capability for in-situ measurements of transient radiation damage, using unique x-ray and charged particle radiography diagnostics. Coupled with integrated synthesis and characterization capability, these would reveal not only the atomic scale origins of radiation effects but also their meso-scale consequences. The mission of the facility would be to study material science in radiation extreme environments to provide predictive capability of material performance to allow certification of new nuclear systems. It is not intended for large-volume component testing. The radiation environment possible will be described.

Why does a plasma physicist care about radiation damage?

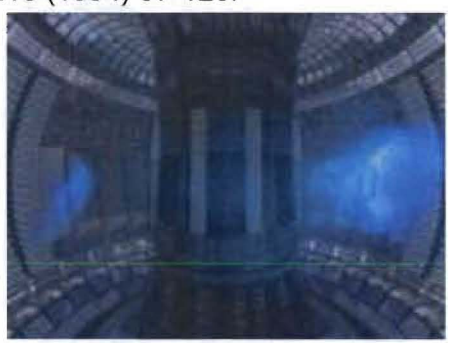


Steel pre & post irradiation[1]

1 L. K. Mansur, J. Nucl. Mater., 216 (1994) 97-123.



D9 irradiated to 2.1 10^{23}n/cm^2 (E>0.1MeV)

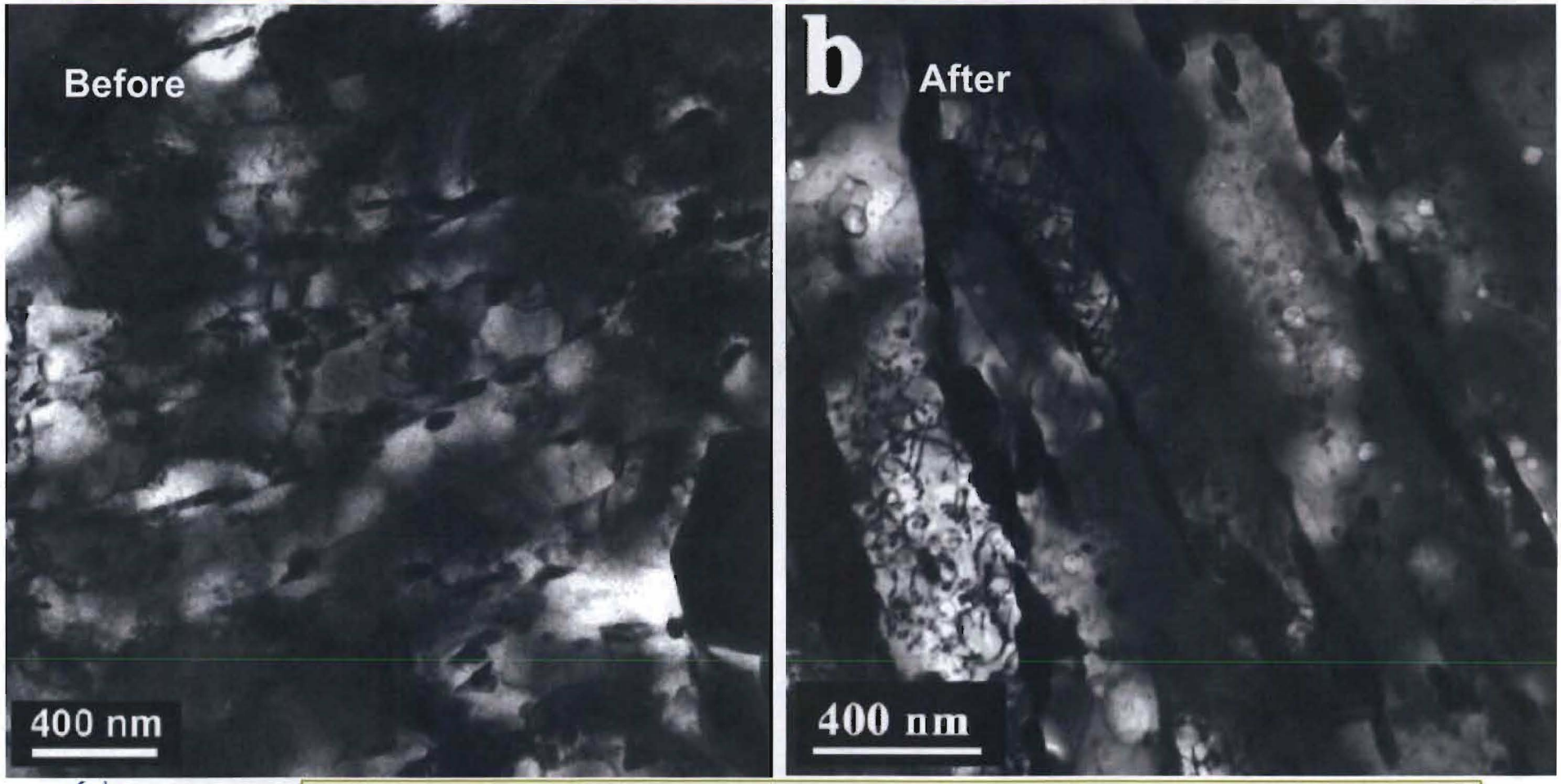


Fusion reactor

Control of materials in the extreme environment of a fusion reactor is rate-limiting for energy development.

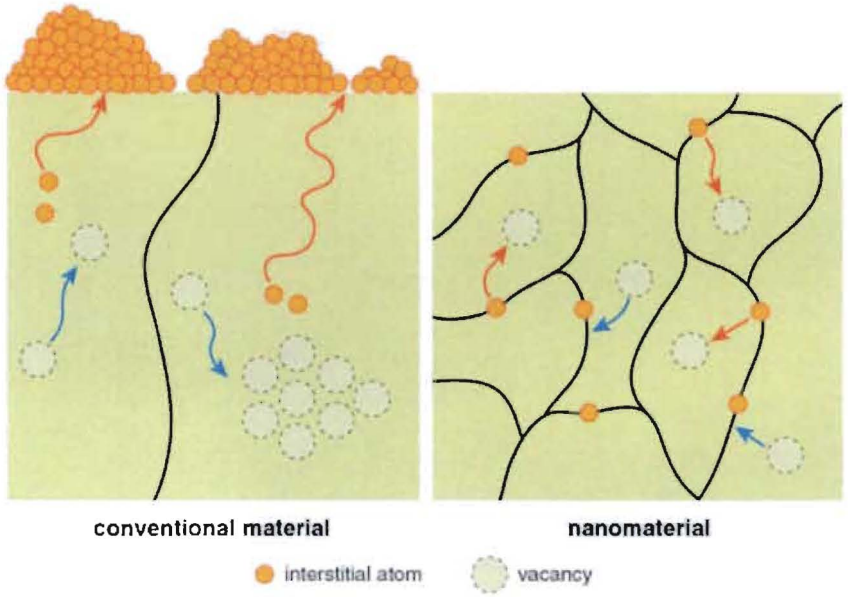
Dose ⇑ H, He ⇑ Temp. ⇑

Current state-of-radiation-damage-art is post-irradiation examination (such as HT9 steel after 155 dpa at 443 °C)

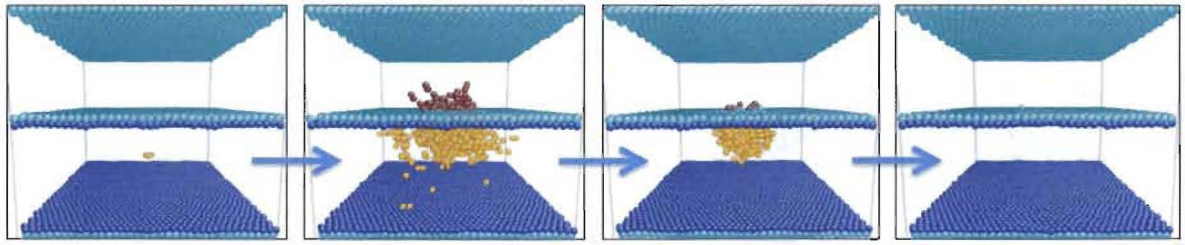


Why is HT9 steel resistant to swelling? How do we design new materials with such resistance?

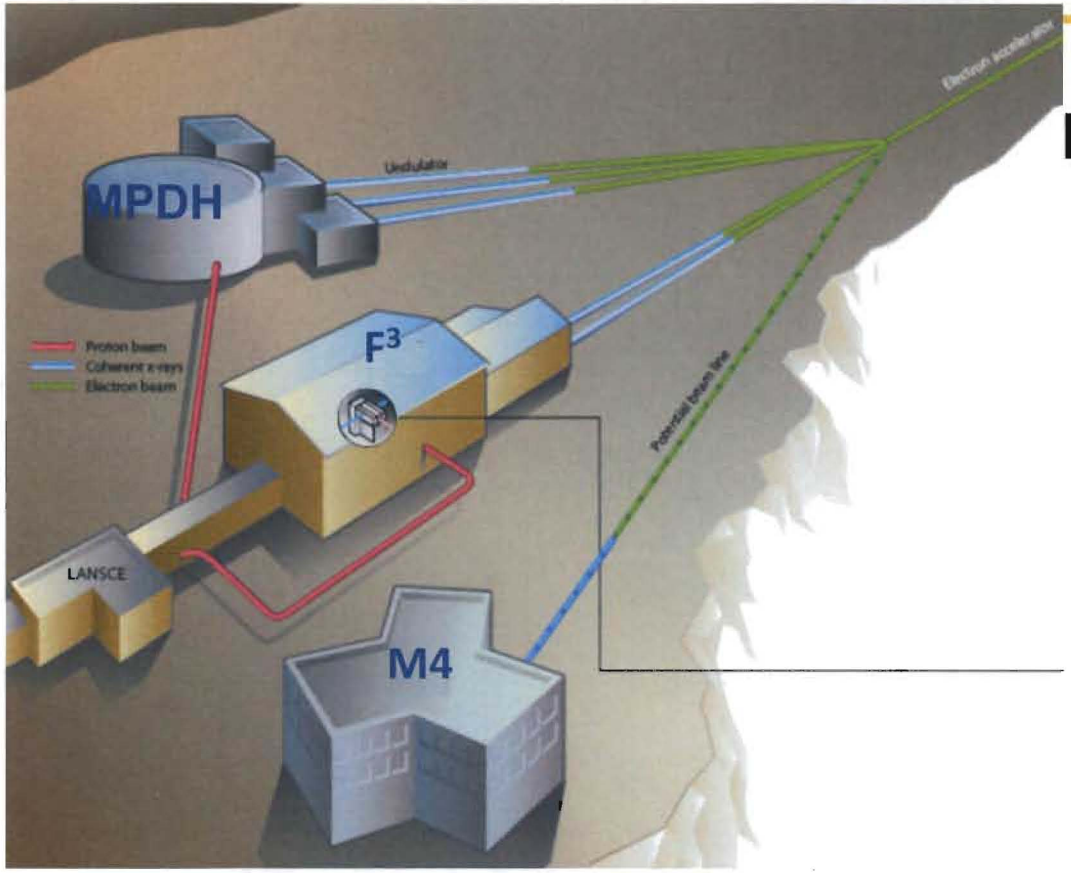
Nanomaterials demonstrate resistance to radiation damage, possibly because of "super-sinks" for defects at crystalline interfaces



The time sequence (left to right) of radiation damage evolution near a super-sink interface formed by joining copper and niobium in a ***molecular dynamics*** *simulation. Unlike in pure crystalline materials, the radiation-induced damage is completely absorbed by the interface. Similar effects are seen in post-irradiation examination of irradiated materials. Blue are interface Cu, gray interface Nb, yellow high-energy Cu, and red high-energy Nb in the CuNb nanocomposite material. All perfect fcc and bcc atom environments removed for clarity*



MaRIE, a signature facility concept at Los Alamos National Laboratory to revolutionize the control of materials in extremes

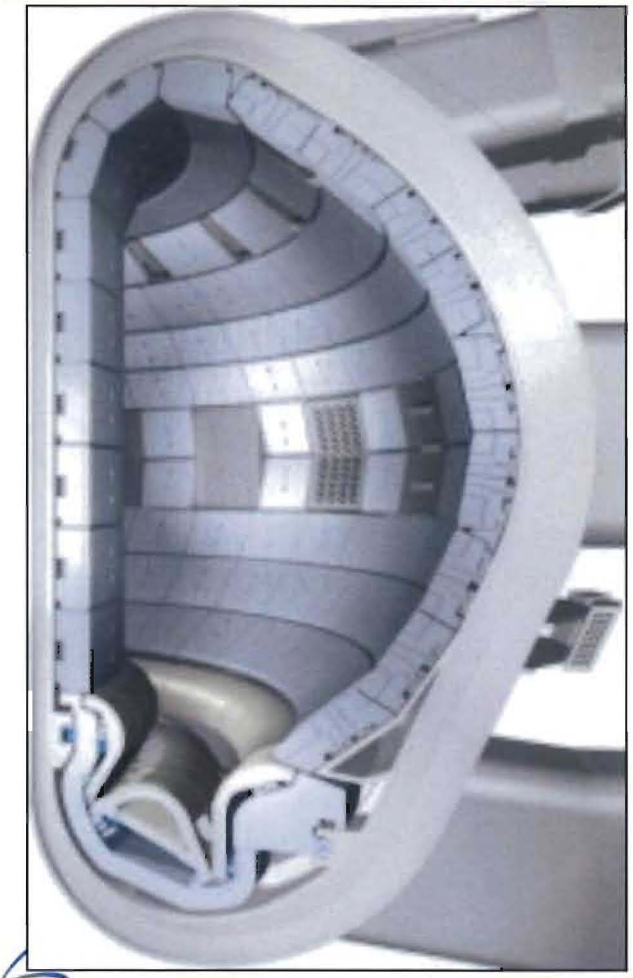


Matter-Radiation Interactions in Extremes (MaRIE)

- MPDH – Multi-probe diagnostic hall
- M4 – Making, measuring, modeling materials (synthesis and characterization)
- **F^3 Fission, fusion (materials) facility**

MaRIE will provide unique co-located tools necessary to realize transformational advances in materials performance in extremes

Office of Fusion Energy Science is beginning to focus on the materials issues of fusion technology



ITER Fusion first wall

High level goal –

Materials in a fusion environment

Plasma/surface interactions: survival, renewal, cracking, annealing, fuel retention

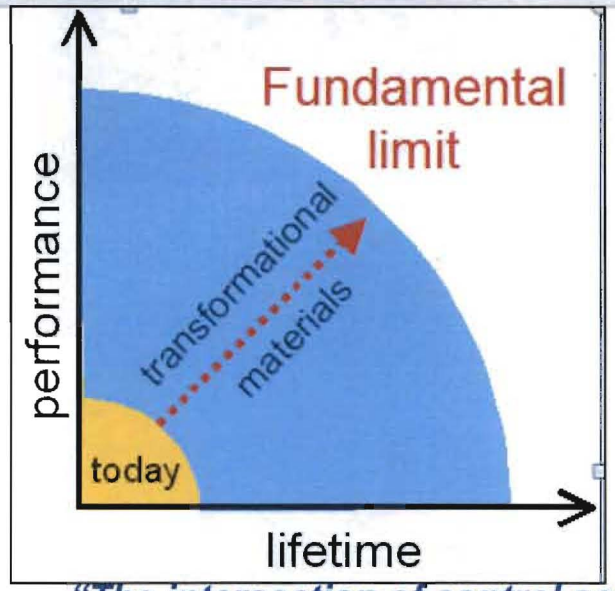
Nuclear effects on structures effects of > 100 dpa on structure integrity, helium creation in situ, and time evolving properties

.... requires the launching of a vigorous materials and nuclear science program that will be part of defining and constructing a fusion nuclear science facility, and will fill gaps en route to a DEMO

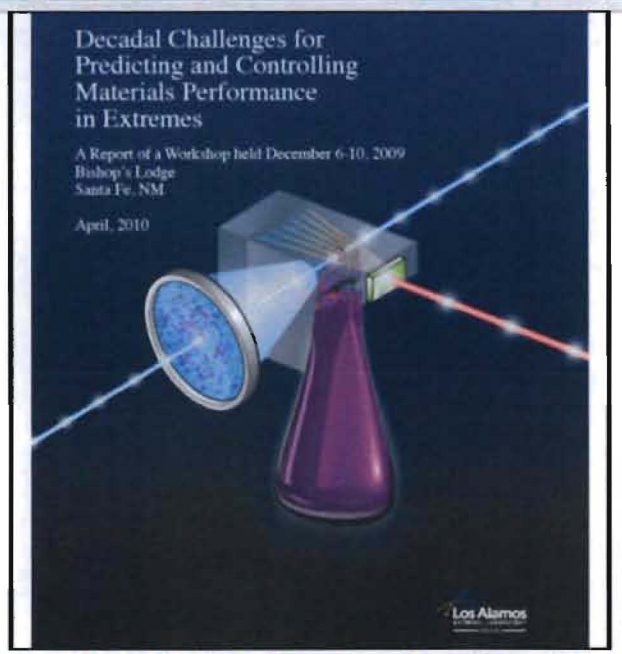
Radiation as well as dynamic extremes are of significant interest to both basic science and energy security

"Materials by design" ....

http://www.sc.doe.gov/bes/reports/list.html

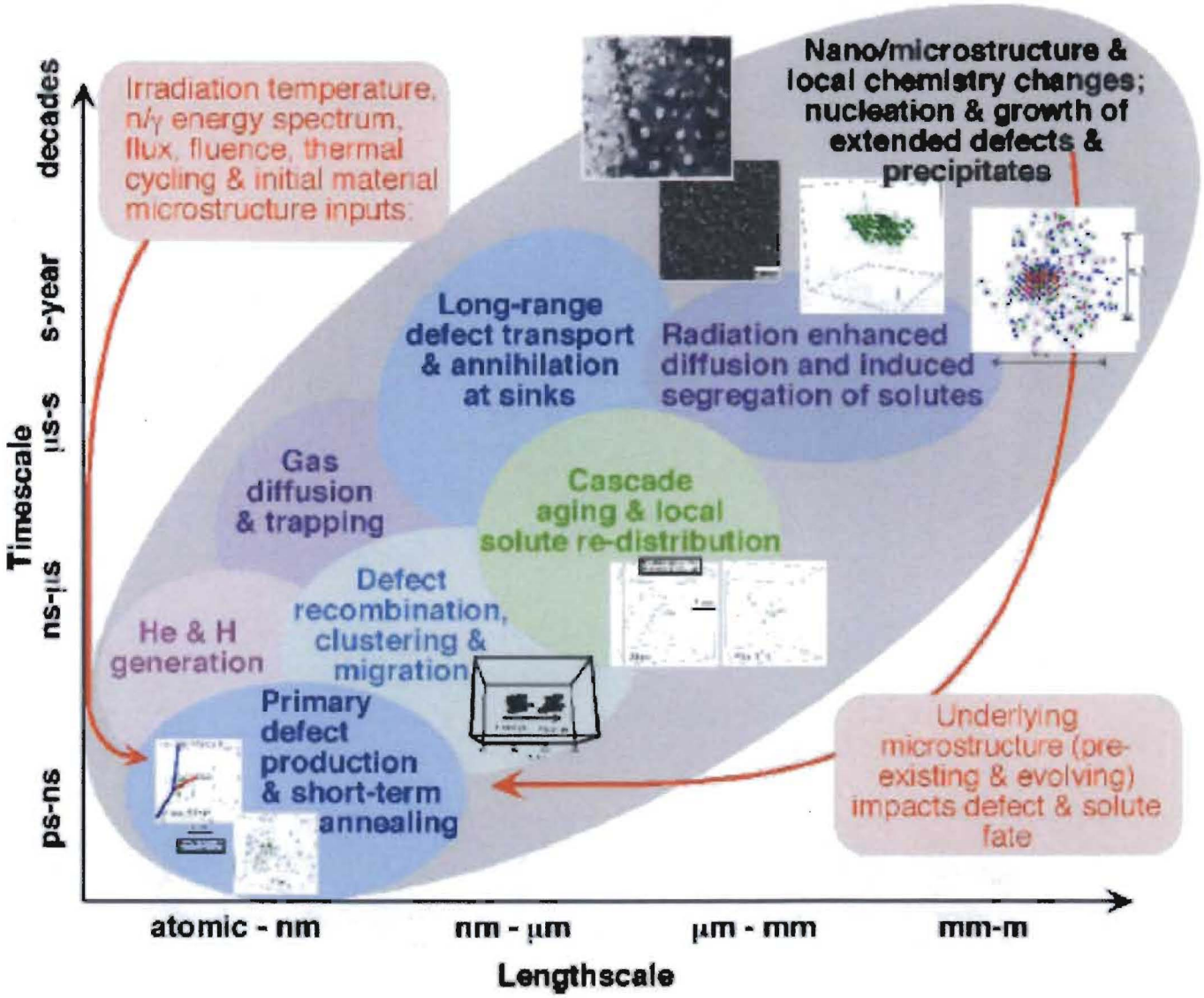


"The intersection of control science with high-functioning materials creates a tipping point for sustainable energy"



"The transition from *observation & validation* to *prediction & control* is a central mission challenge & the frontier of materials research"

Radiation effects times and length scales (after Wirth); the decadal frontier is predictive capability at the smallest scales



At the smallest scales the requirement moves towards the need for "in-situ" measurements in the radiation extreme

iii) "Ex situ" measurements

Specimens - disassembled MTS and in situ

Maximal spatial resolution ,

Measurement intervals defined by PIE schedule

ii) "Near in situ" measurements

Specimens - MTS irradiation portfolio

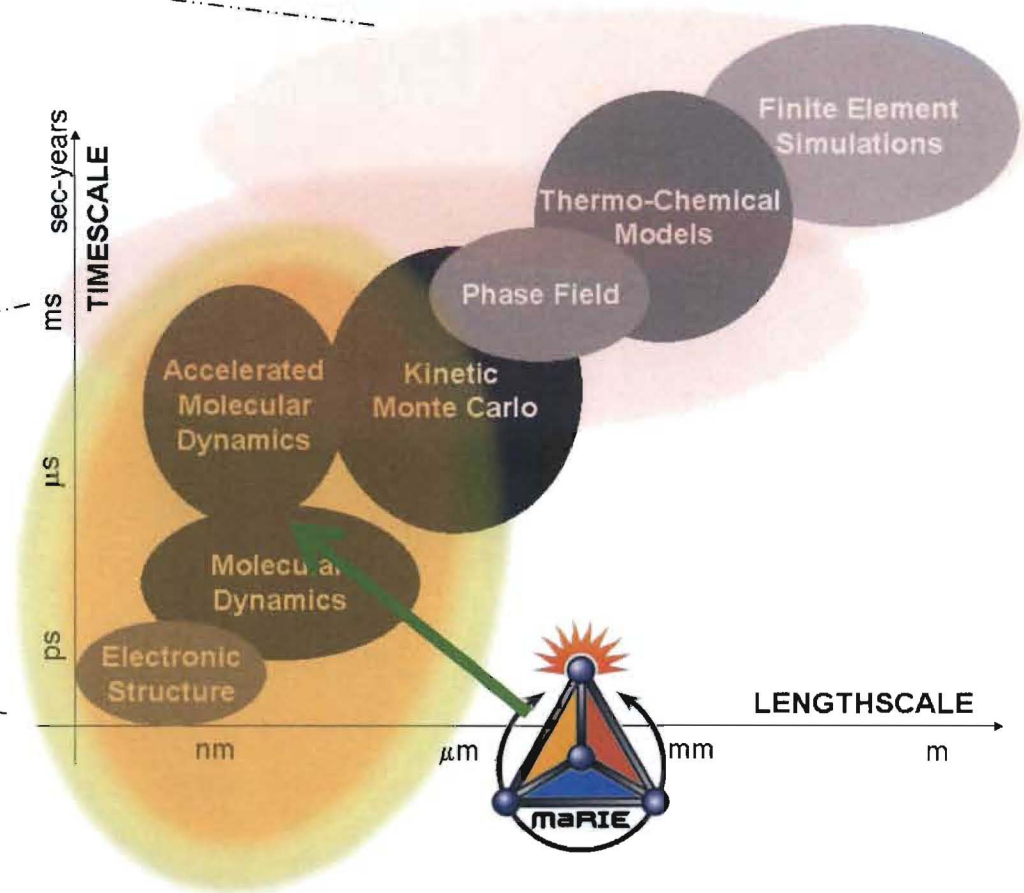
NDE examination during scheduled outages

i) "In situ" measurement

Specimens :- Custom design – model validation

Temporal resolution picoseconds to minutes,
Spatial resolution nm to mm

Measurement intervals picoseconds to hours.



LANL is a world leader in materials science, with significant relevant infrastructure investment

Center for Integrated NanoTechnology [CINT]

Metropolis Center for Modeling & Simulation

National High Magnetic Field Laboratory [NHMFL]

Plutonium Processing

Chemistry & Metallurgy Building

Dual Axis Radiographic HydroTest

SIGMA Building

Los Alamos Neutron Science Center [LANSCE]

The Los Alamos Neutron Science Center (LANSCE) provides a $1B investment currently used by many sponsors

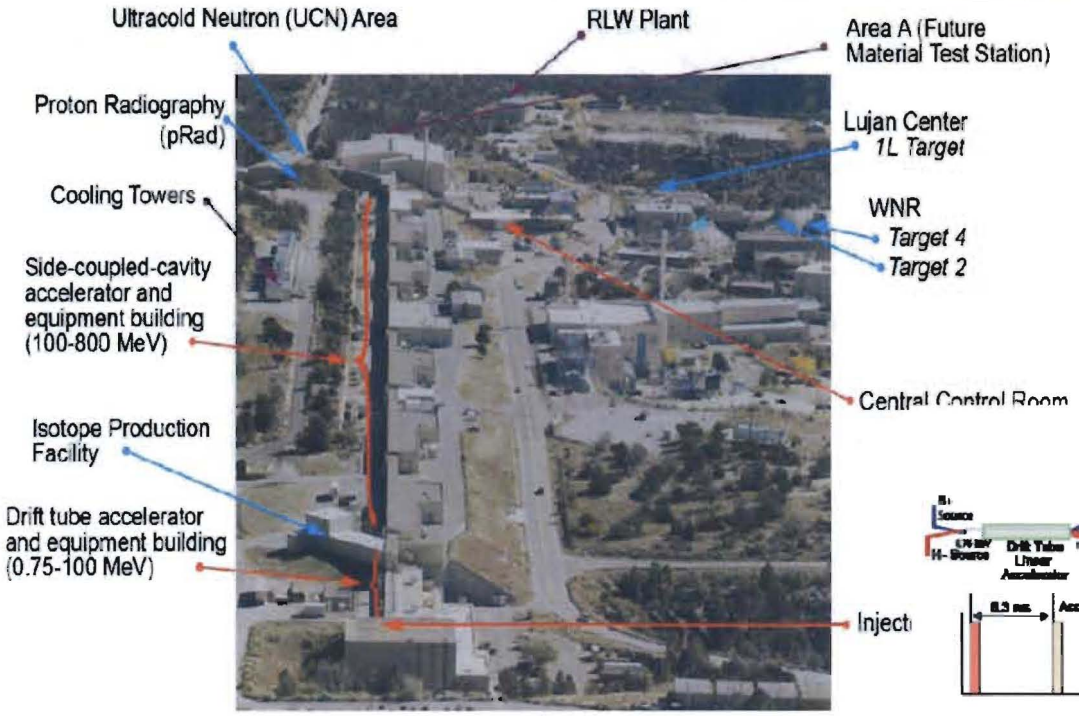


Figure 1. The LANSCE linac provides flexible time-structured beams from 100 800 MeV that serve five active experimental areas.

- Isotope Production (NP)
- Neutron Scattering (BES)
- Proton Radiography and Neutron Cross-Sections (NNSA)
- Ultra-Cold Neutrons (NP)

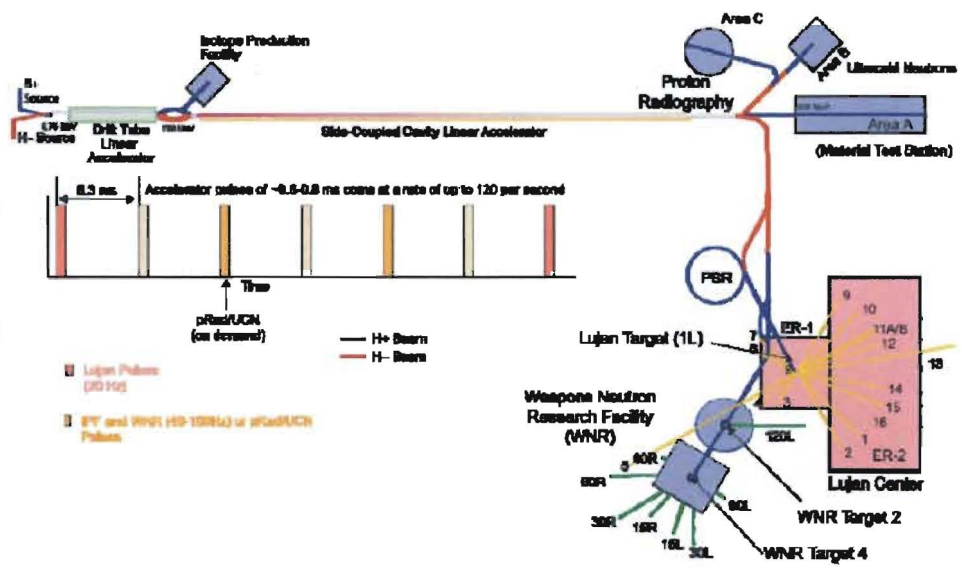
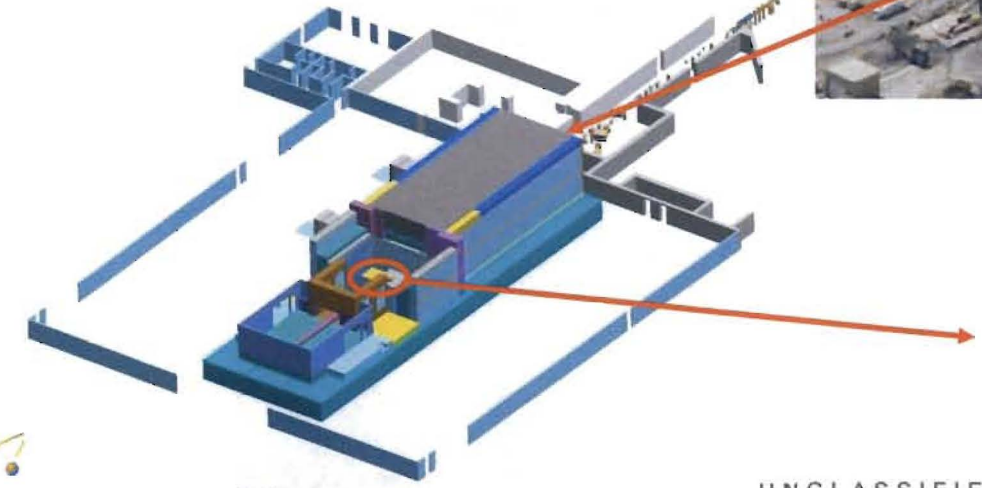
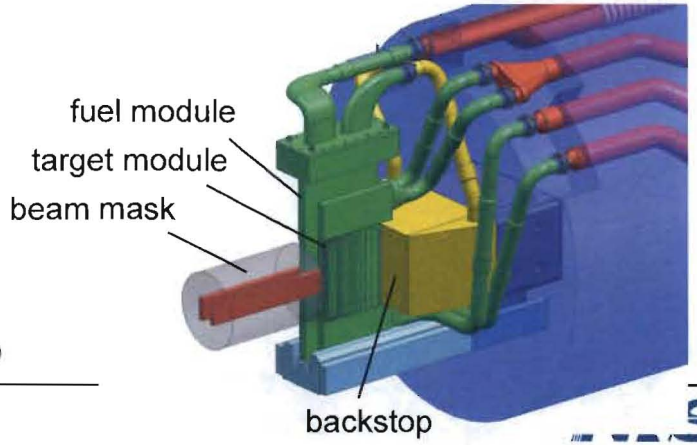


Figure 2. Schematic of the LANSCE National User Facility.

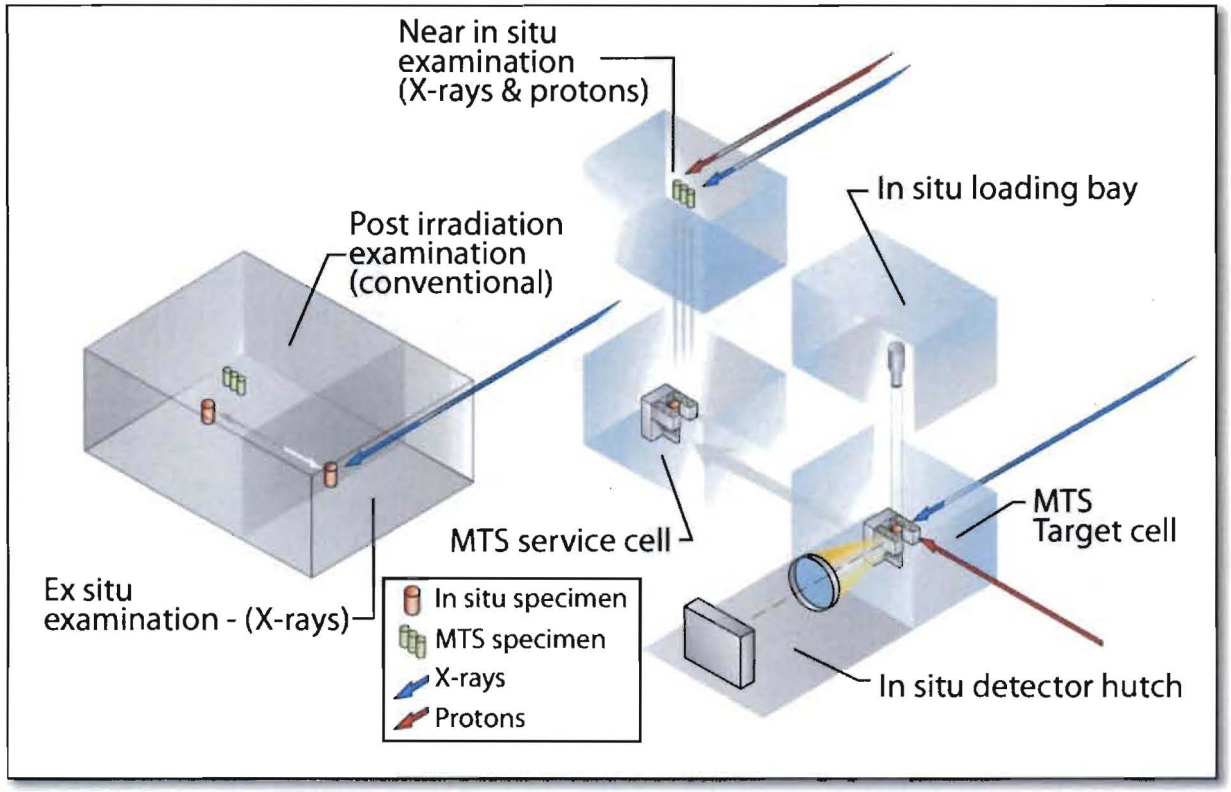
The Materials Test Station (MTS) is an Office of Nuclear Energy project to provide a fast spectrum fuel and materials irradiation testing facility

1-MW LANSCE proton beam delivered to MTS will produce 10^{17} neutrons per second and 10^{-6} dpa/s.





The MaRIE Fission and Fusion Materials Facility would add capability to MTS, especially in-situ transient science

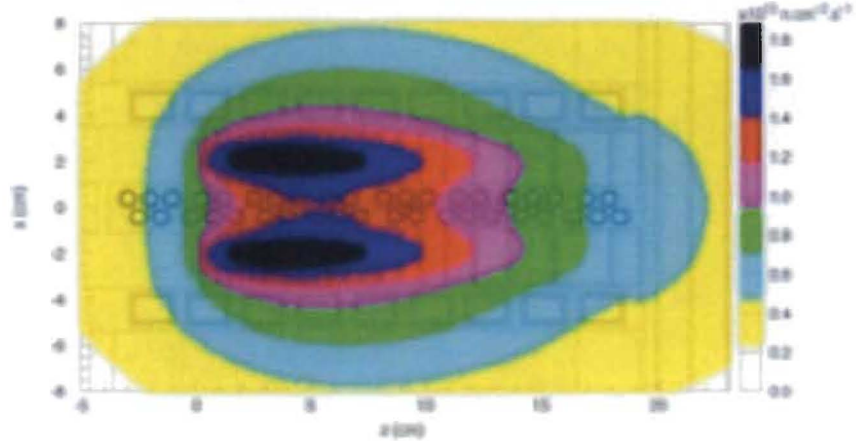


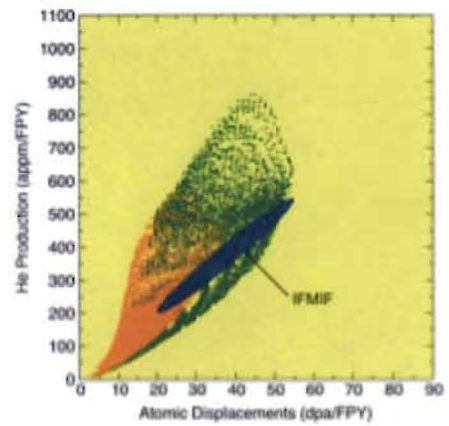
MaRIE F³ :- Fission Fusion Materials Facility

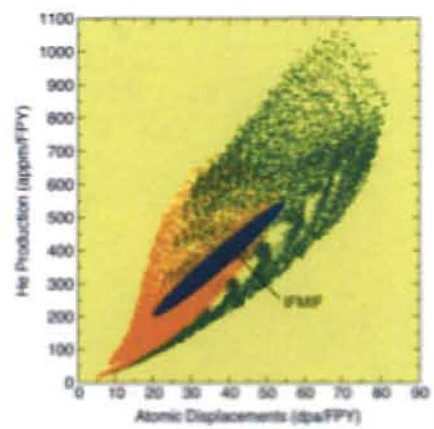
MaRIE F³ will augment a fast neutron irradiation facility with unique experimental capabilities to address basic and applied problems in radiation damage science for the fission & fusion communities

F^3 can provide relevant radiation environments in a time- and cost-effective way

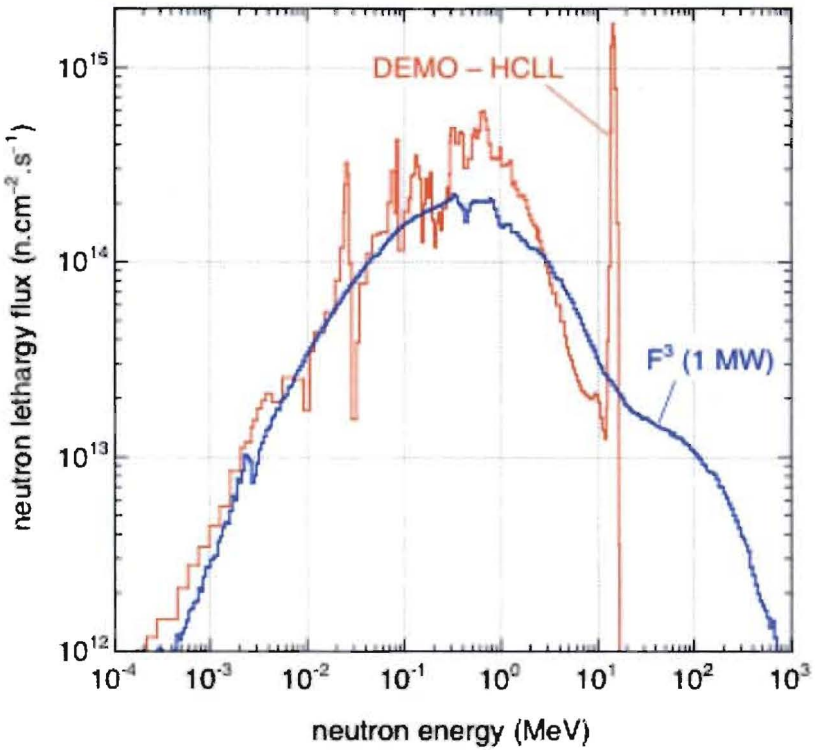
- Radiation Environment for the proposed Fission and Fusion Materials Facility.
  - a) Plan of the spallation neutron source, showing neutron flux contours at 1 MW level.
  - b) He production vs atomic displacements at 1.8 MW, with each point representing a volume element in the source. The proposed IFMIF design space is shown for comparison.
  - c) Same as b) but at 3.6 MW.



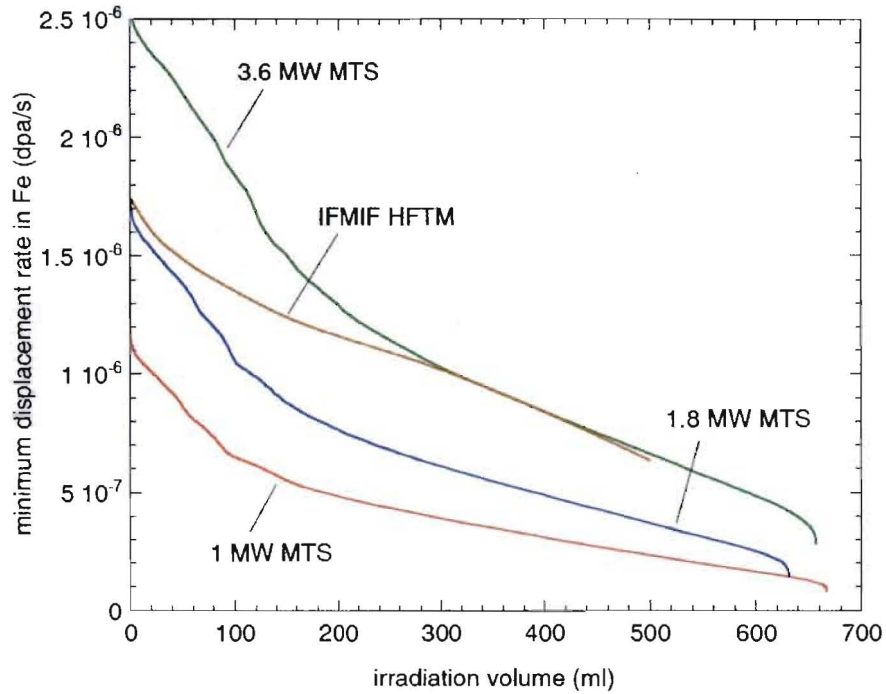




The neutron spectrum, primary knock-on spectrum, and displacement rates in F^3 provide fusion relevant conditions

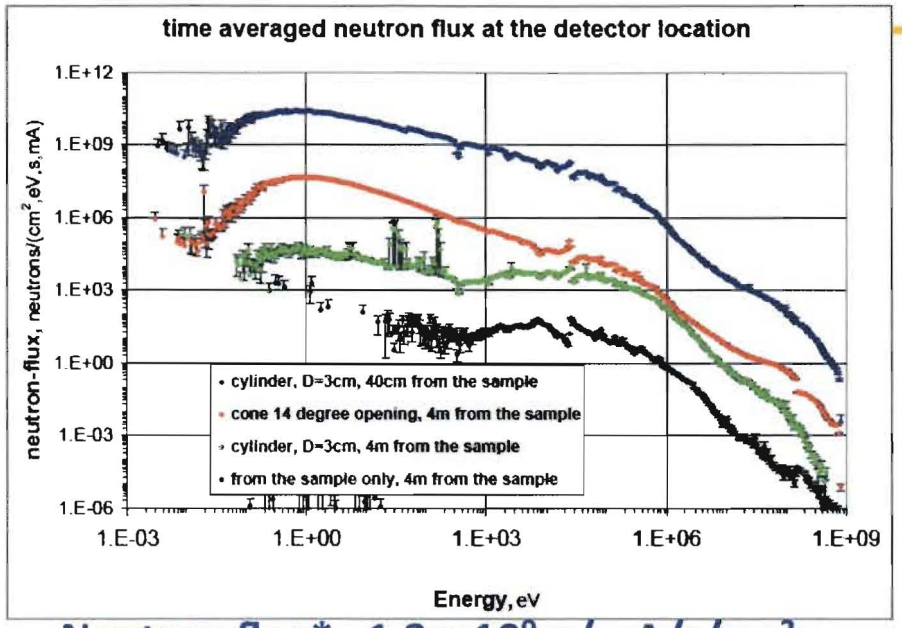


Neutron flux lethargy spectra for F3 and the DEMO HCLL

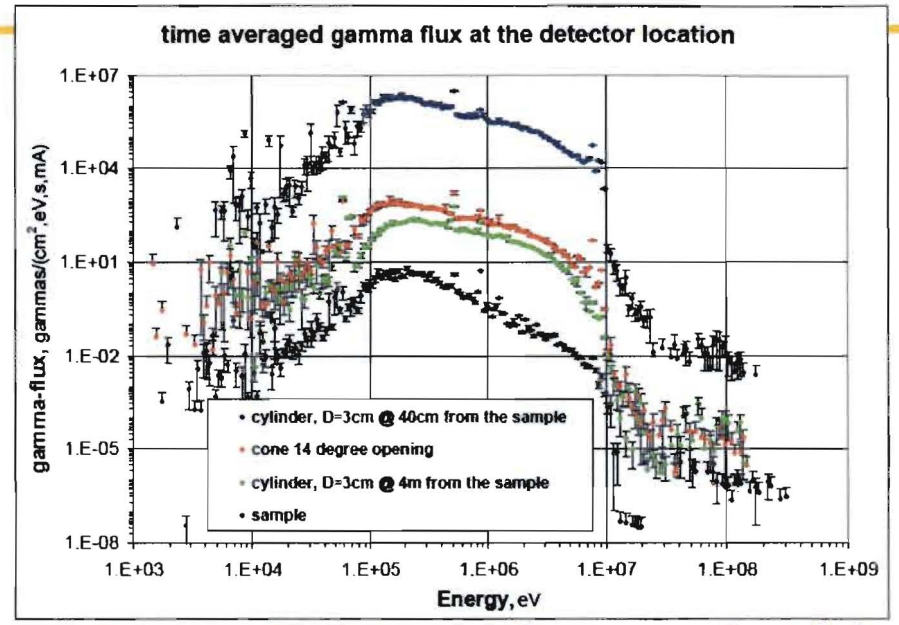


Displacement rate in iron as a function of volume for three different beam powers. The tallied volume includes only that for which the He/dpa ratio ranges from 8 to 13 appm/dpa

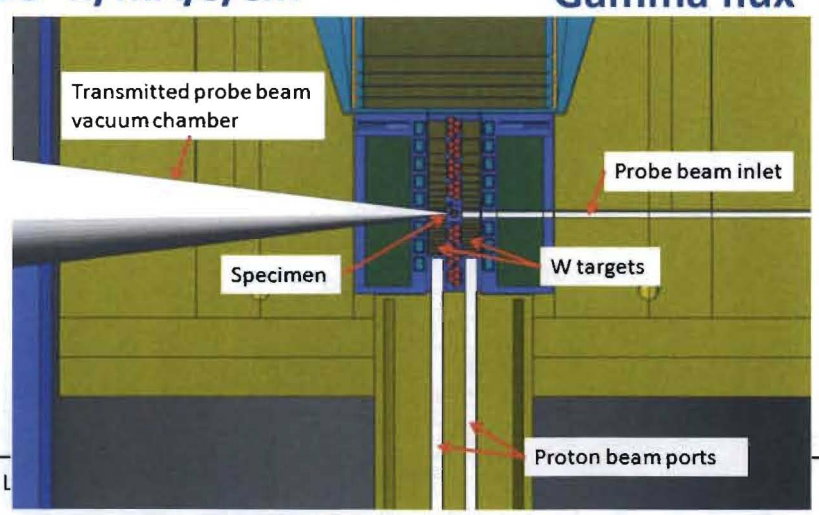
Technology challenge for in-situ science ; γ & neutron flux emerging from MTS



Neutron flux* 1.3 x 10^9 n/mA/s/cm^2



Gamma flux* 2.5 x 10^8 gammas/mA/s/cm^2



Top section view

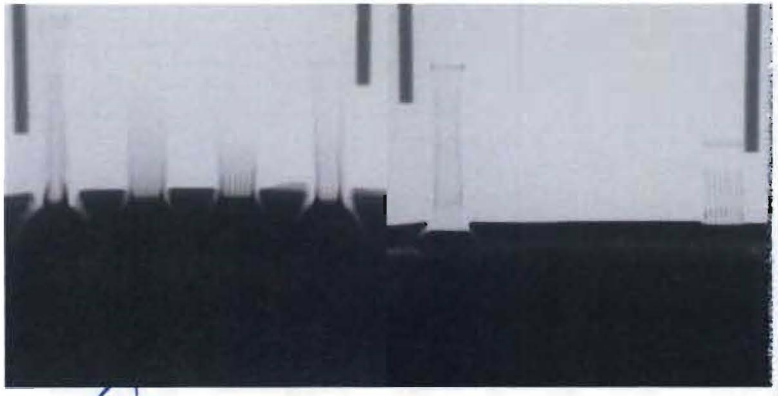
* 4 m from the sample, 3 cm ϕ, cylindrical view

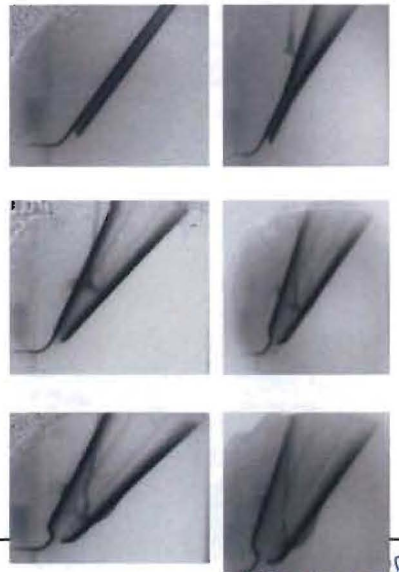
Proton Radiography is a growing tool internationally for materials science

Los Alamos

Brookhaven

Russia





We have compared proton and x-ray radiography (tomography) of mock nuclear fuel pins as example of what could be done in-situ

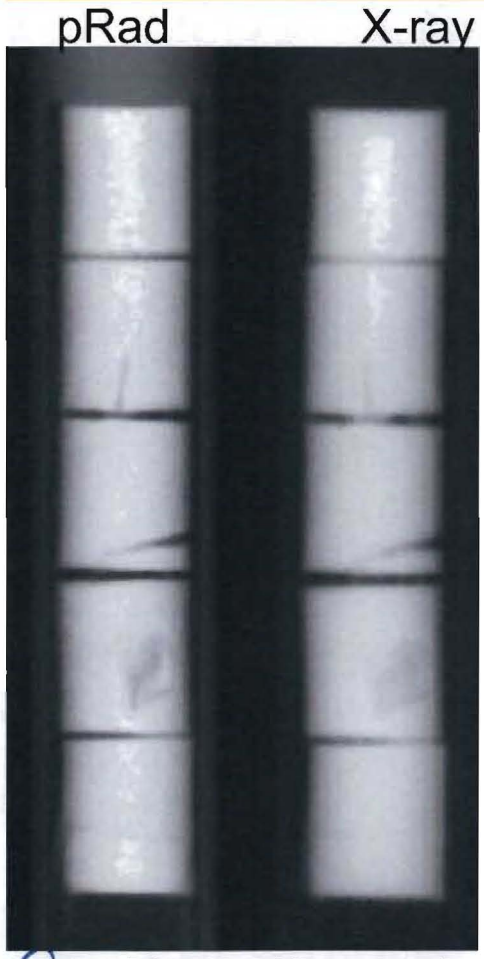


Figure 2) Areal density Left) proton radiography Right) X-ray radiography

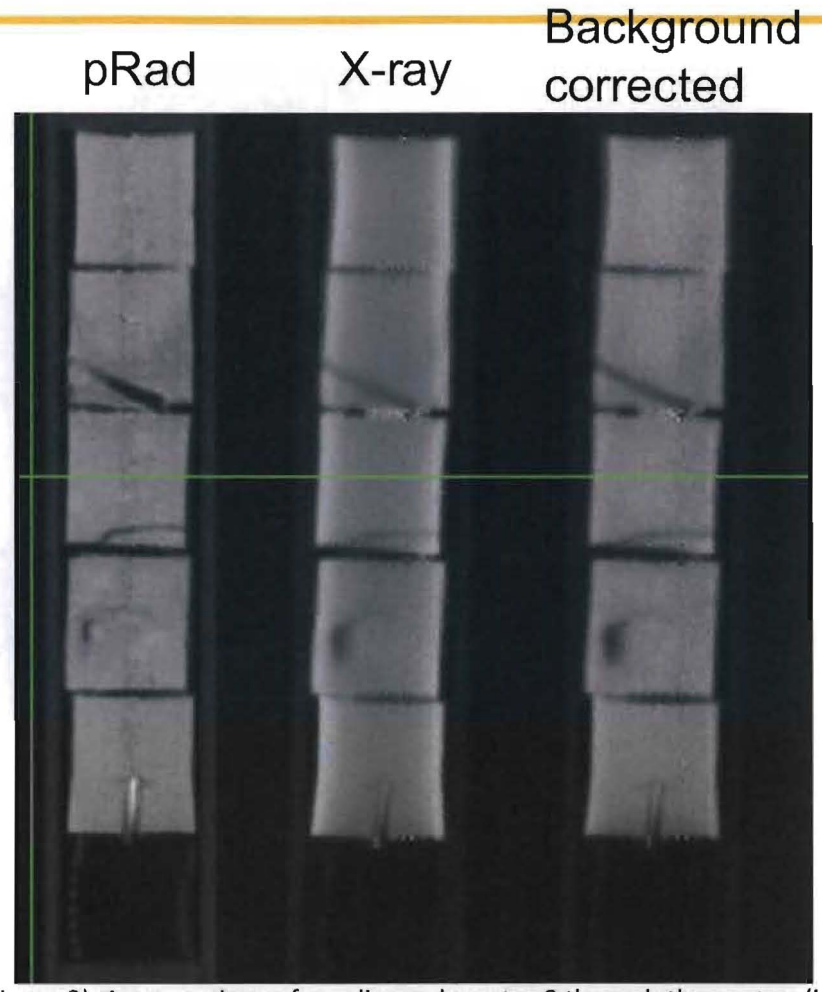
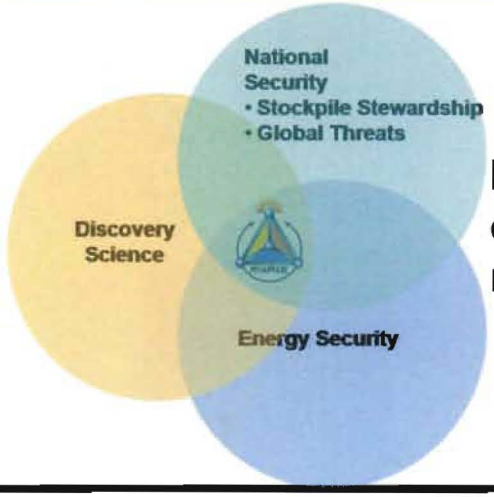


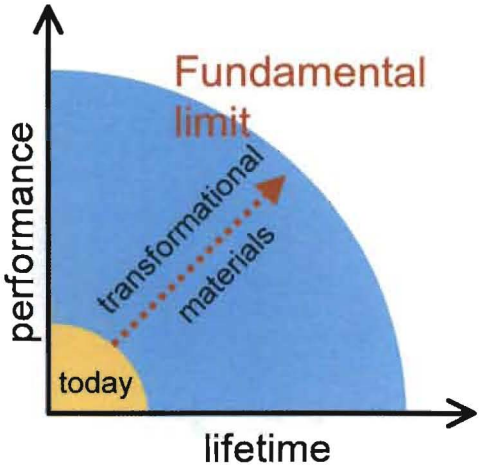
Figure 3) A comparison of x-y slices taken at z=0 through the proton (left), x-ray (center), and background corrected x-ray tomography

MaRIE: Revolutionizing Materials in Extremes



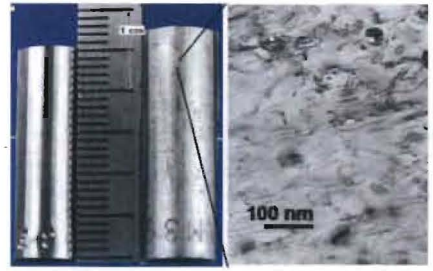
Materials in extremes challenges span multiple missions

MaRIE enables the transition from "observation" to "control"



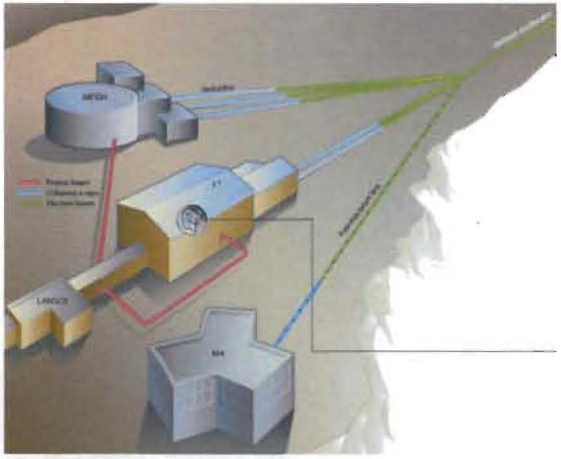
MaRIE will transform the science of microstructure, interfaces, and defects

Next-generation solar cell architecture



Radiation-induced swelling

MaRIE provides tools for transformational materials performance in extremes



MaRIE