Exploring the Effects of Ion Irradiation: Single Ion Strikes to Macroscopic Property Changes

SAND2016-2329PE

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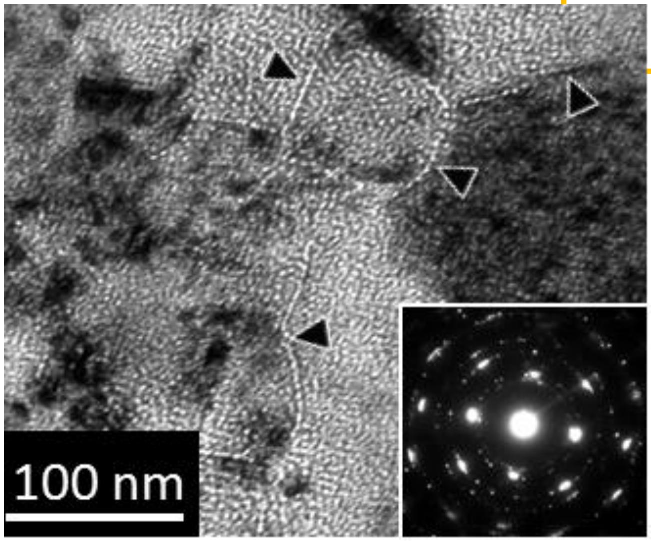
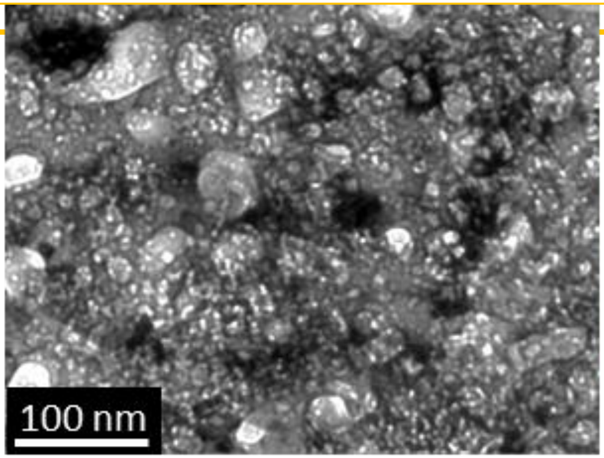
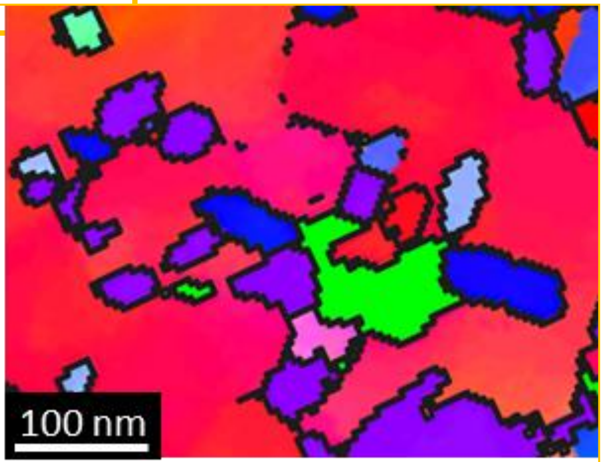
March 11, 2016







My Research Experience

BOISE STATE UNIVERSITY

RUHR
UNIVERSITÄT
BOCHUM

RUB

Sandia National Laboratories

NORTHWESTERN
UNIVERSITY

Outline

Sandia National Laboratories

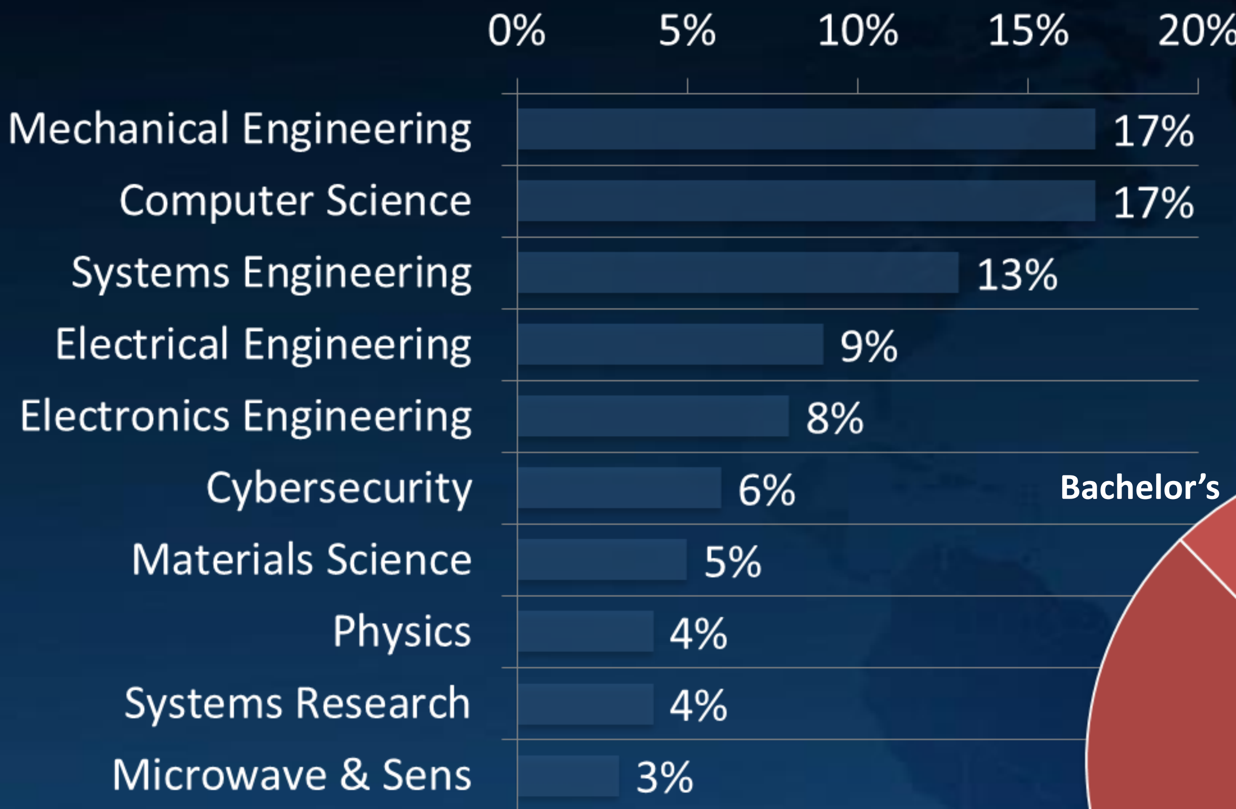
- Sandia Information
- Radiation-Solid Interactions
- Physical Effects of Radiation: “Radiation Damage”
  - Dislocation loops
  - Stacking Fault Tetrahedra
  - Voids and Bubbles
  - Radiation Induced Segregation
- Macroscopic effects
  - Mechanical Effects
  - Magnetic Effects

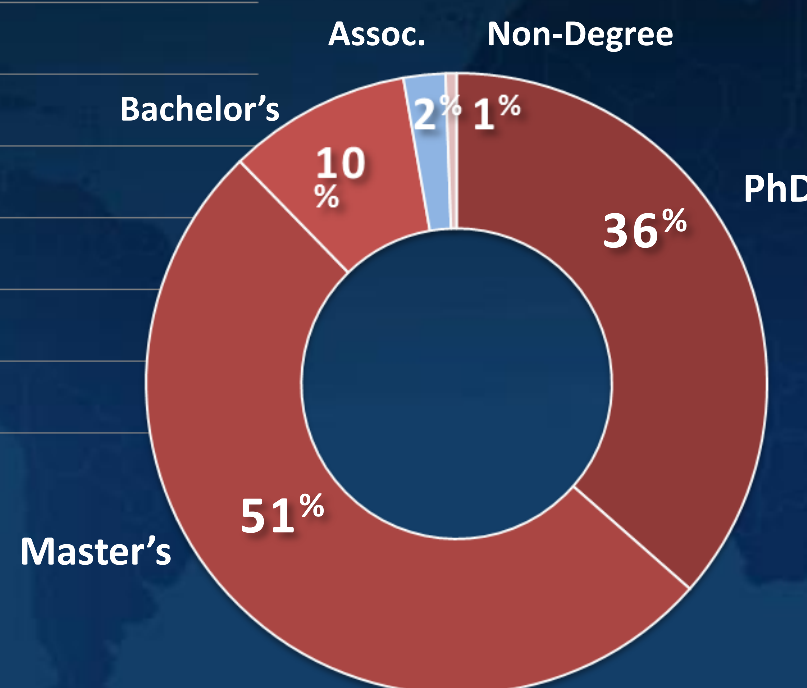
National Laboratories

Sandia has two main locations

Sandia's Impact Video

R&D by Discipline & Degree





Top 10 job descriptions shown, Regular exempt non-management employees only

Living in Albuquerque

Sandia National Laboratories

Life in Albuquerque

- Albuquerque is the largest city in New Mexico with a population of over 500,000
- Affordable housing, reasonable cost of living
- Minimal traffic congestion

Watch:
Sandia New Mexico Video

Albuquerque Environment

•High desert climate with 278 annual days of sunshine

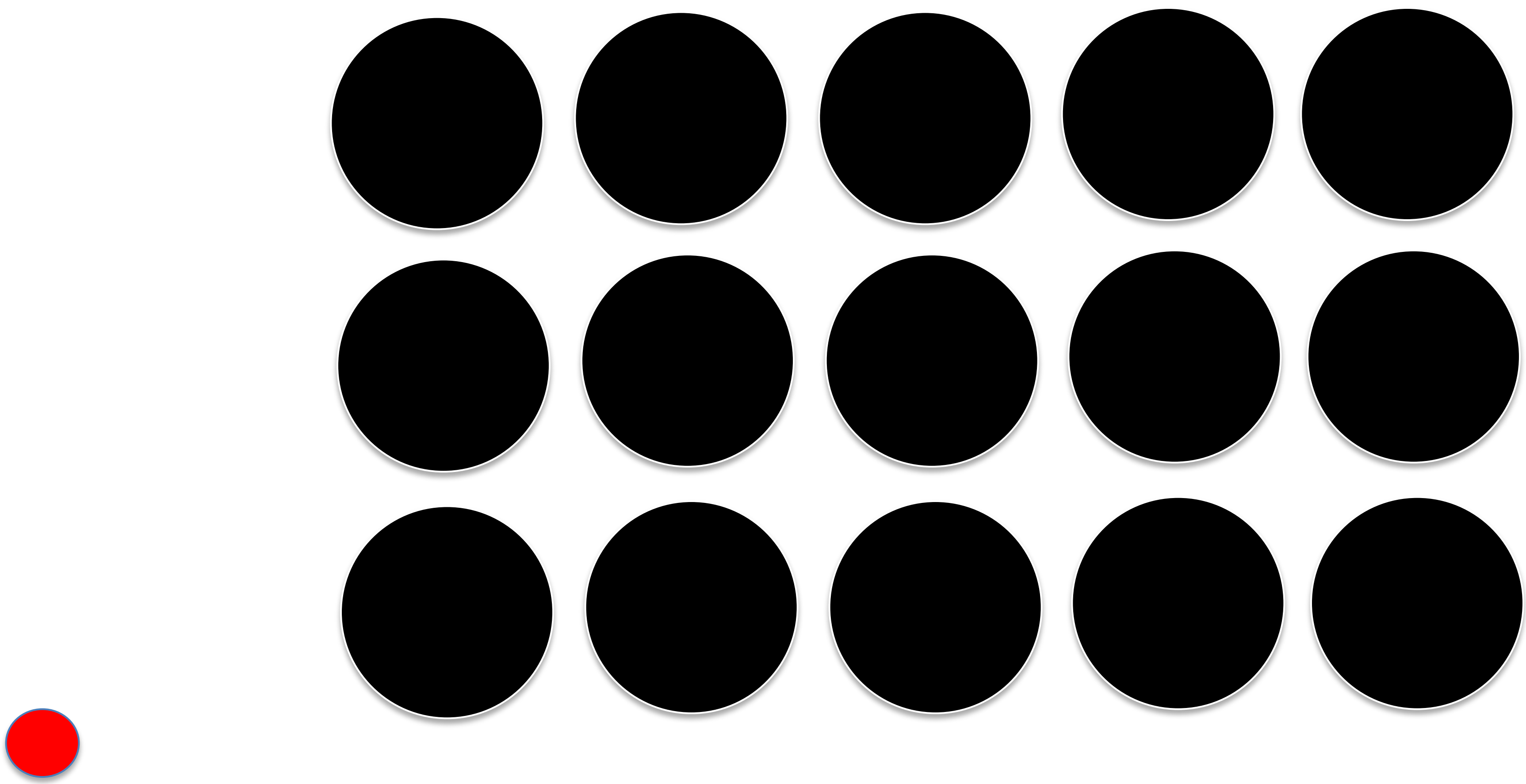
•Average temperatures between 78˚ and 40˚

•Wide-open spaces

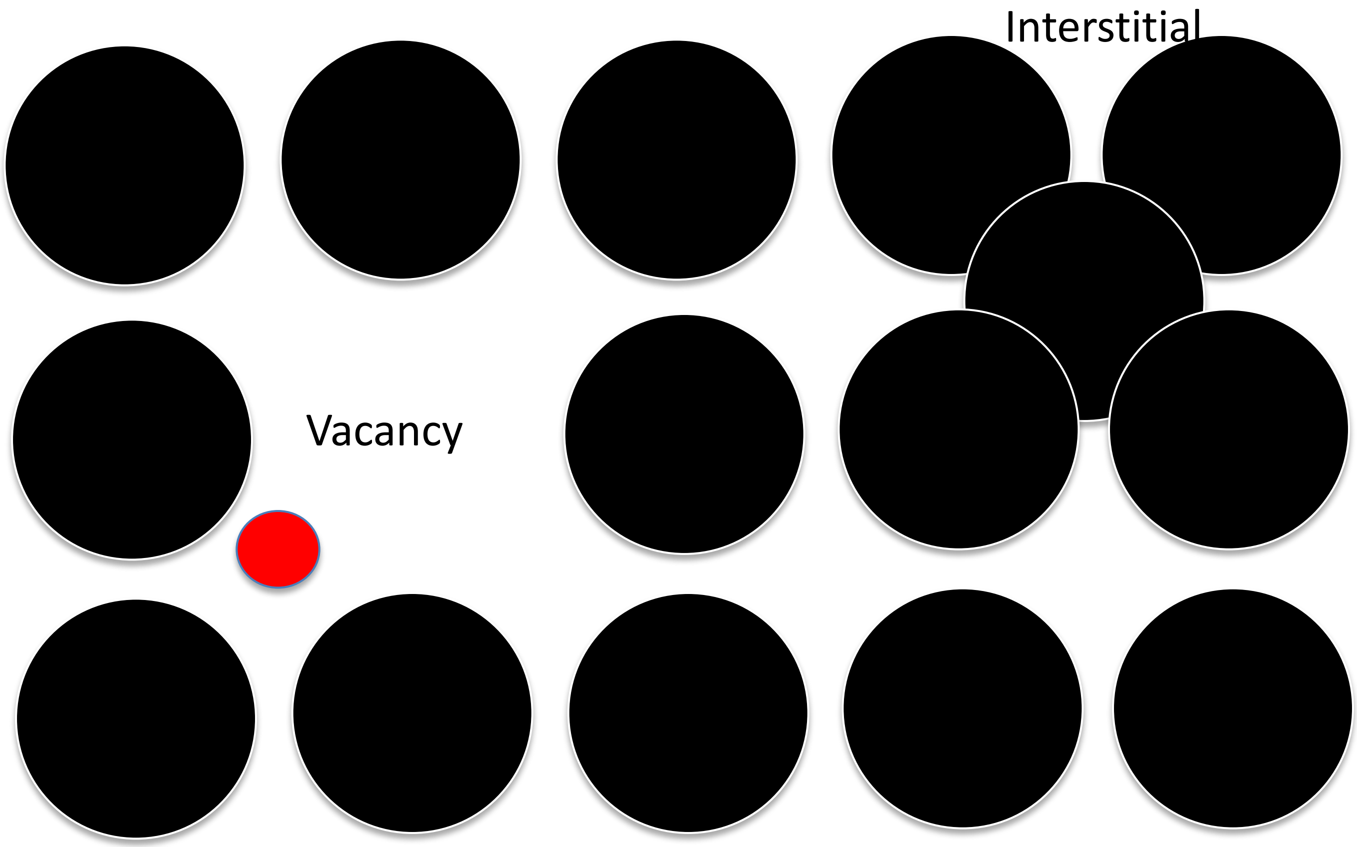
Things to Do

- Outdoor recreation - Ski, snowboard, hike, etc.
- Santa Fe – rich culture
- International Balloon Festival
- Explore Indian pueblos and our Hispanic heritage
- Green chile – NM Cuisine
- Museums, Parks, Sports

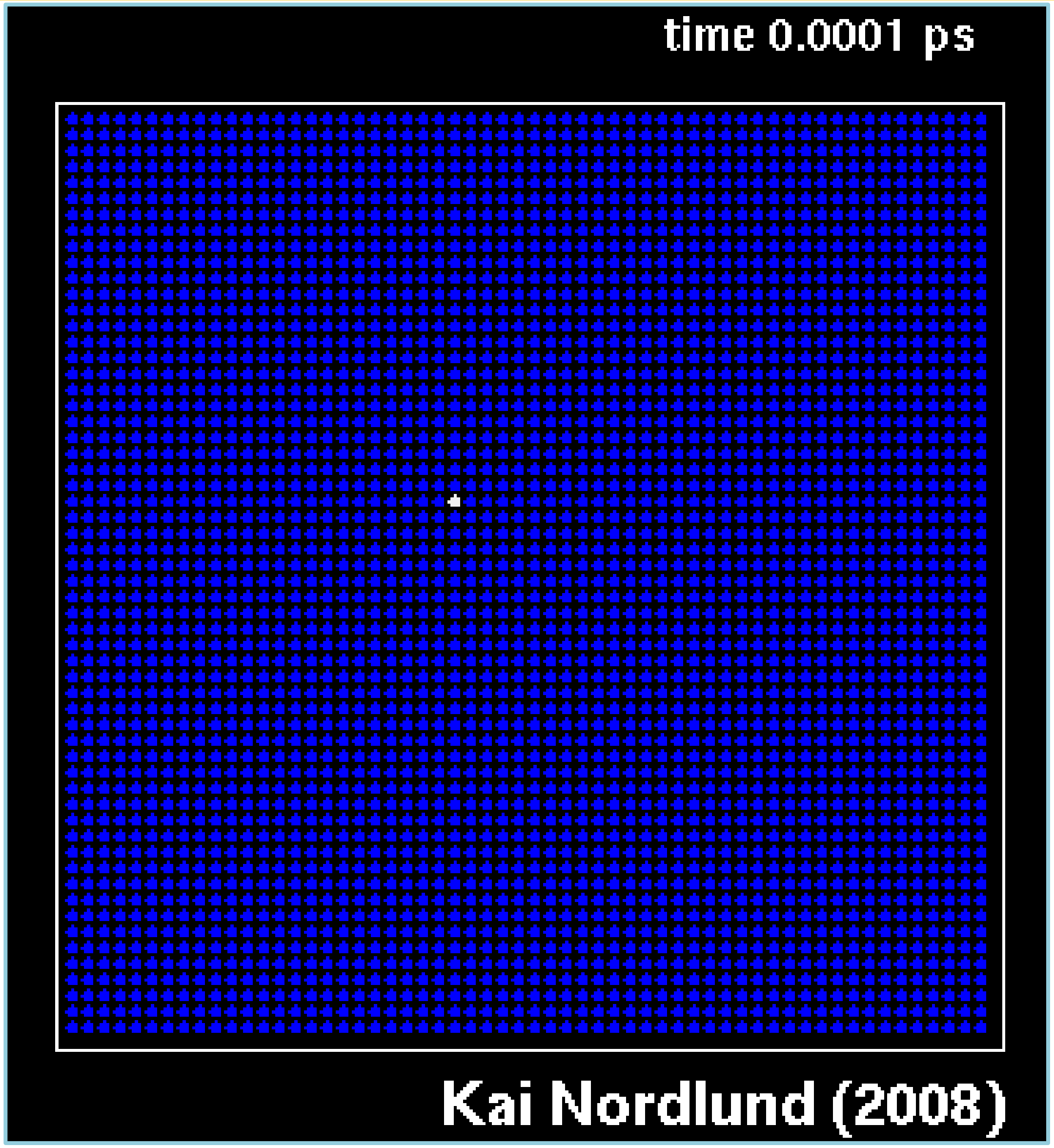
Radiation-Solid Interactions



Radiation-Solid Interactions

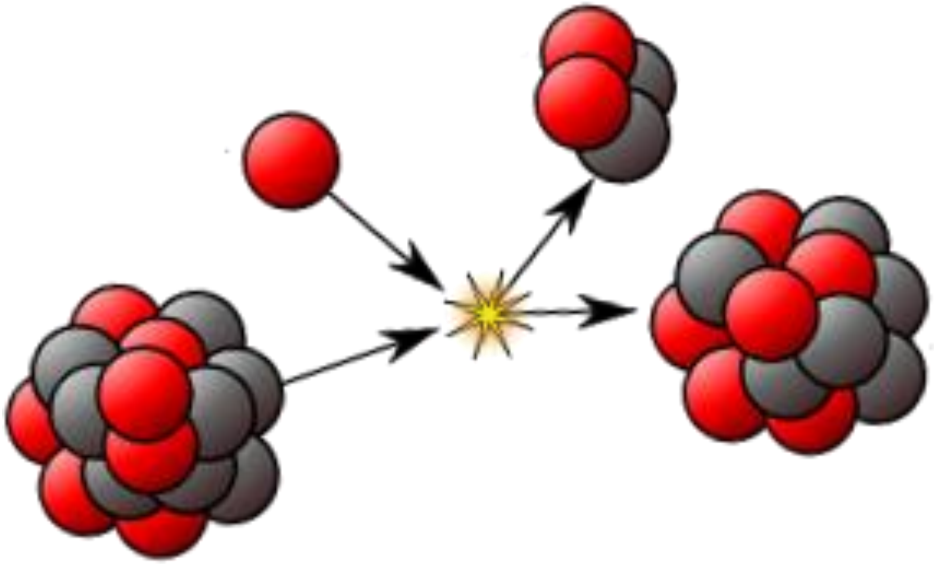


Radiation-Solid Interactions



Collision cascades may result in stable defects

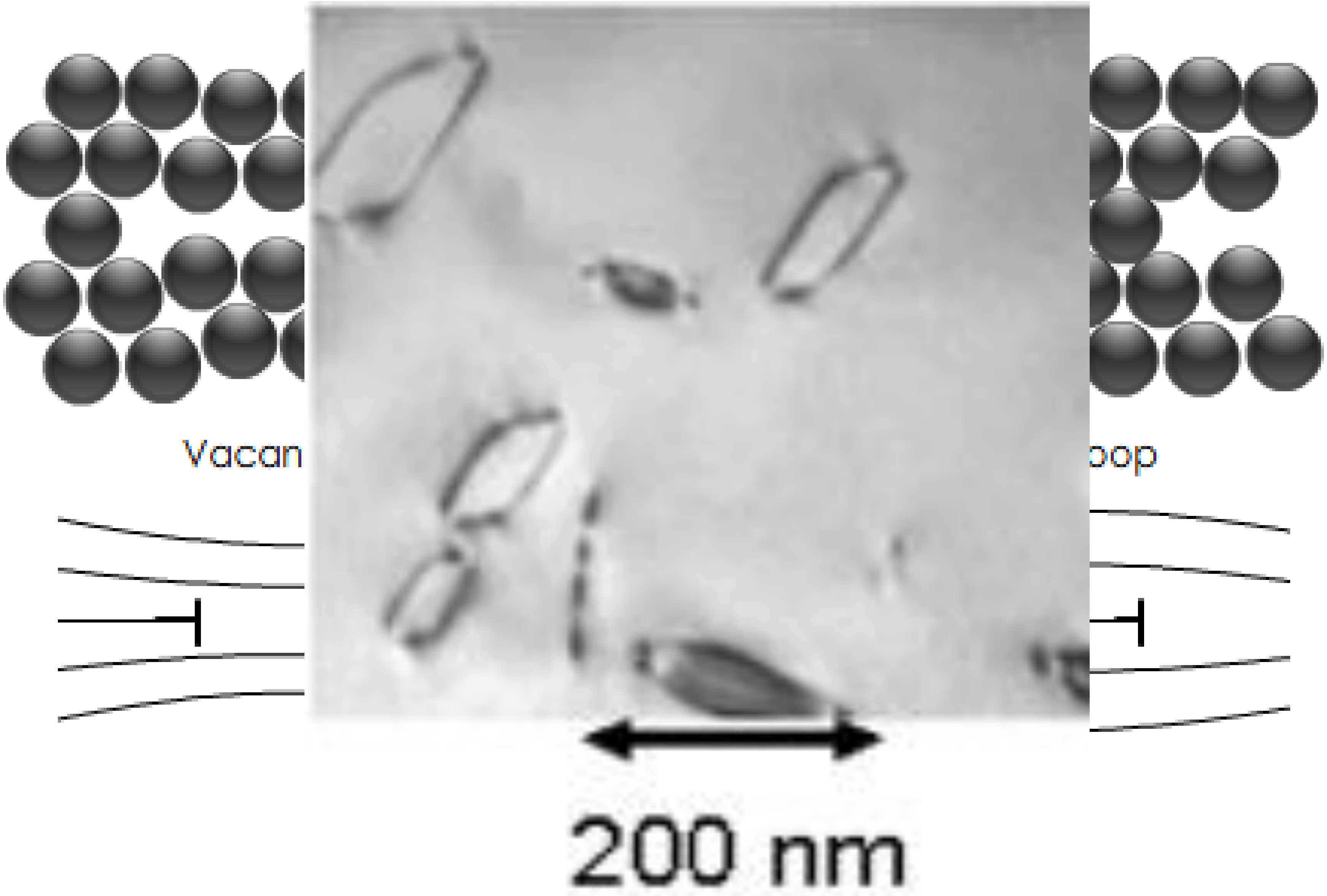
Nuclear Transmutation



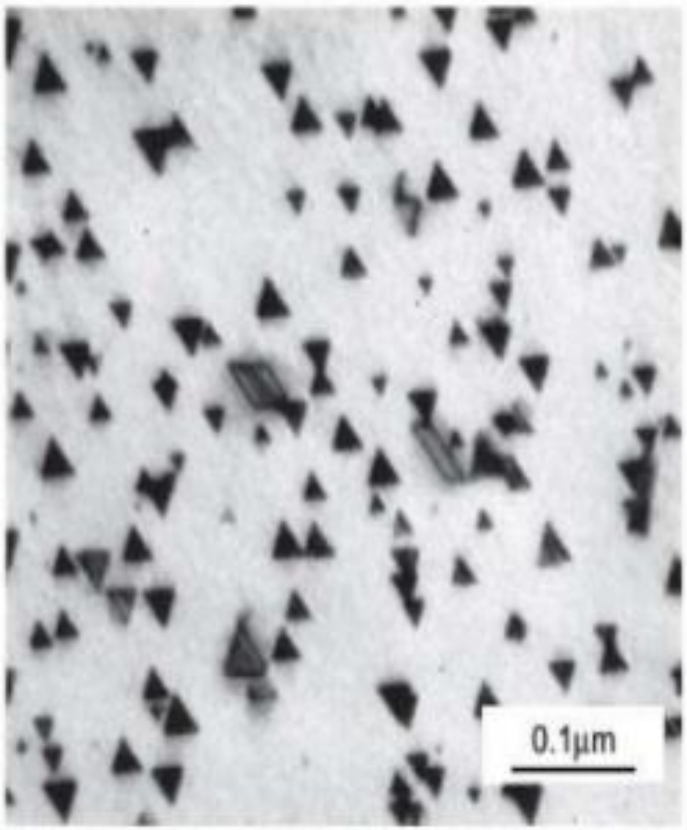
- (n , p)
- (n , α)

The conversion of one chemical element or an isotope into another

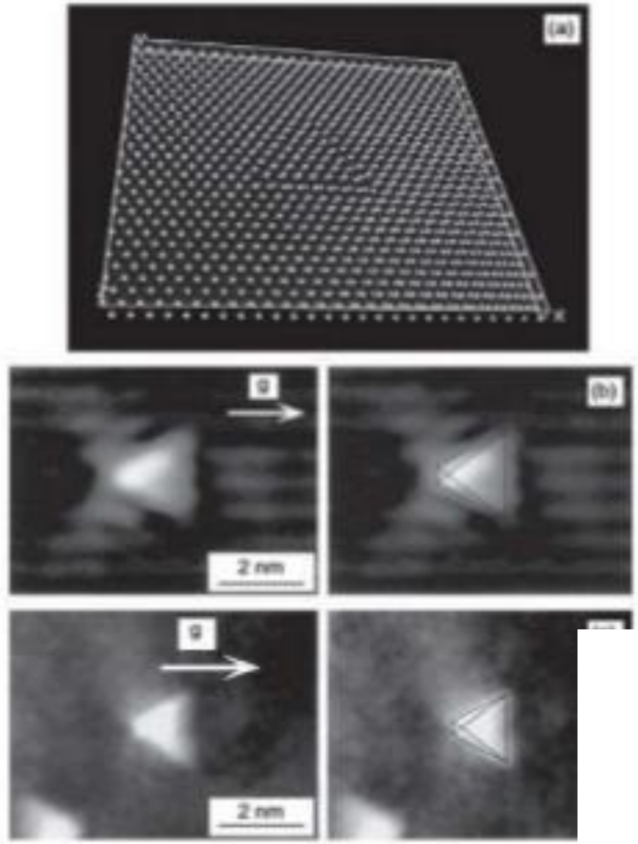
Microstructural Defects: Dislocation Loops



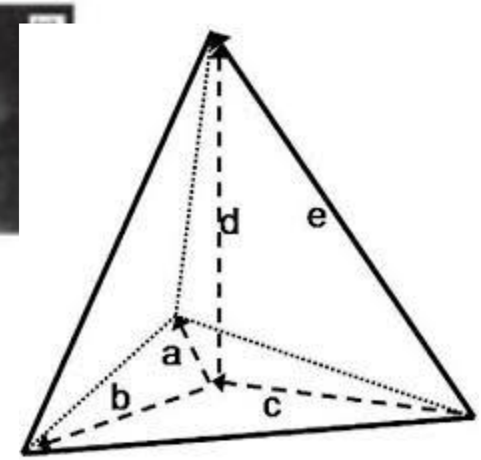
Microstructural Defects: Stacking Fault Tetrahedra



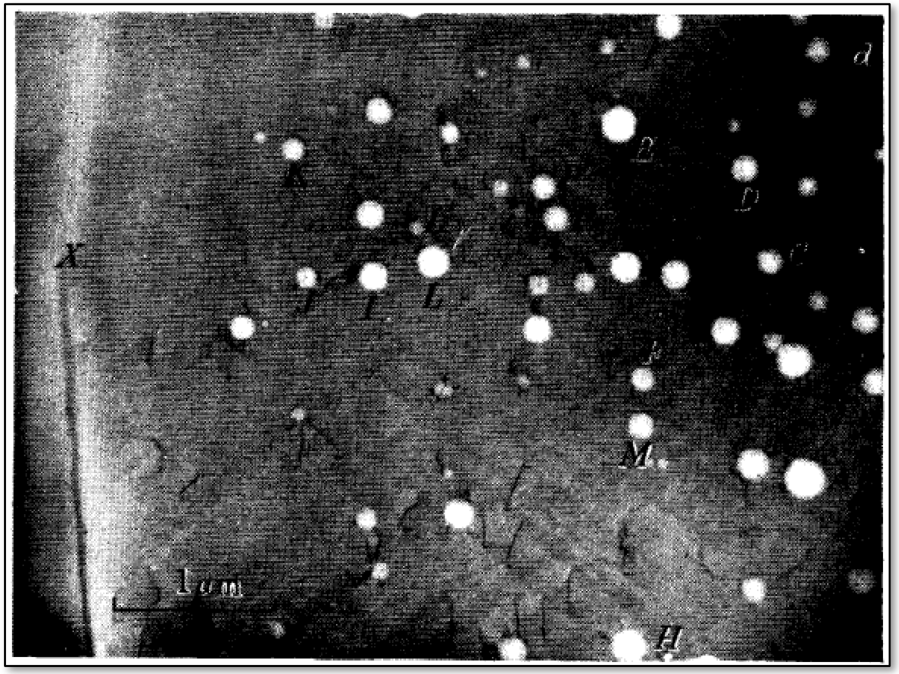
Transmission electron micrograph of tetrahedral defects in quenched gold.



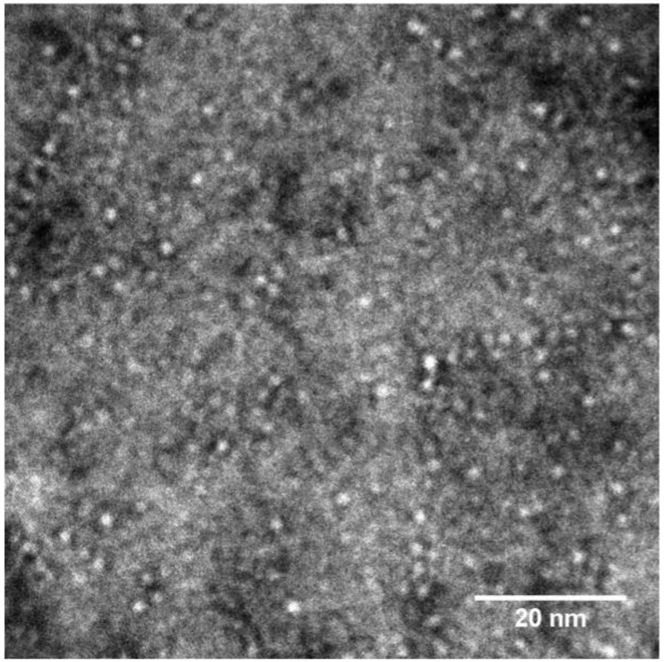
Stacking-fault tetrahedron in irradiated copper.



Microstructural Defects: Cavities

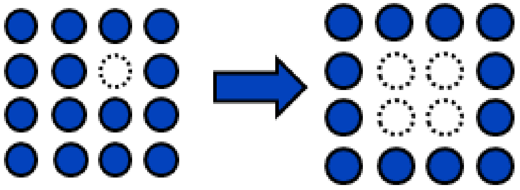


Voids



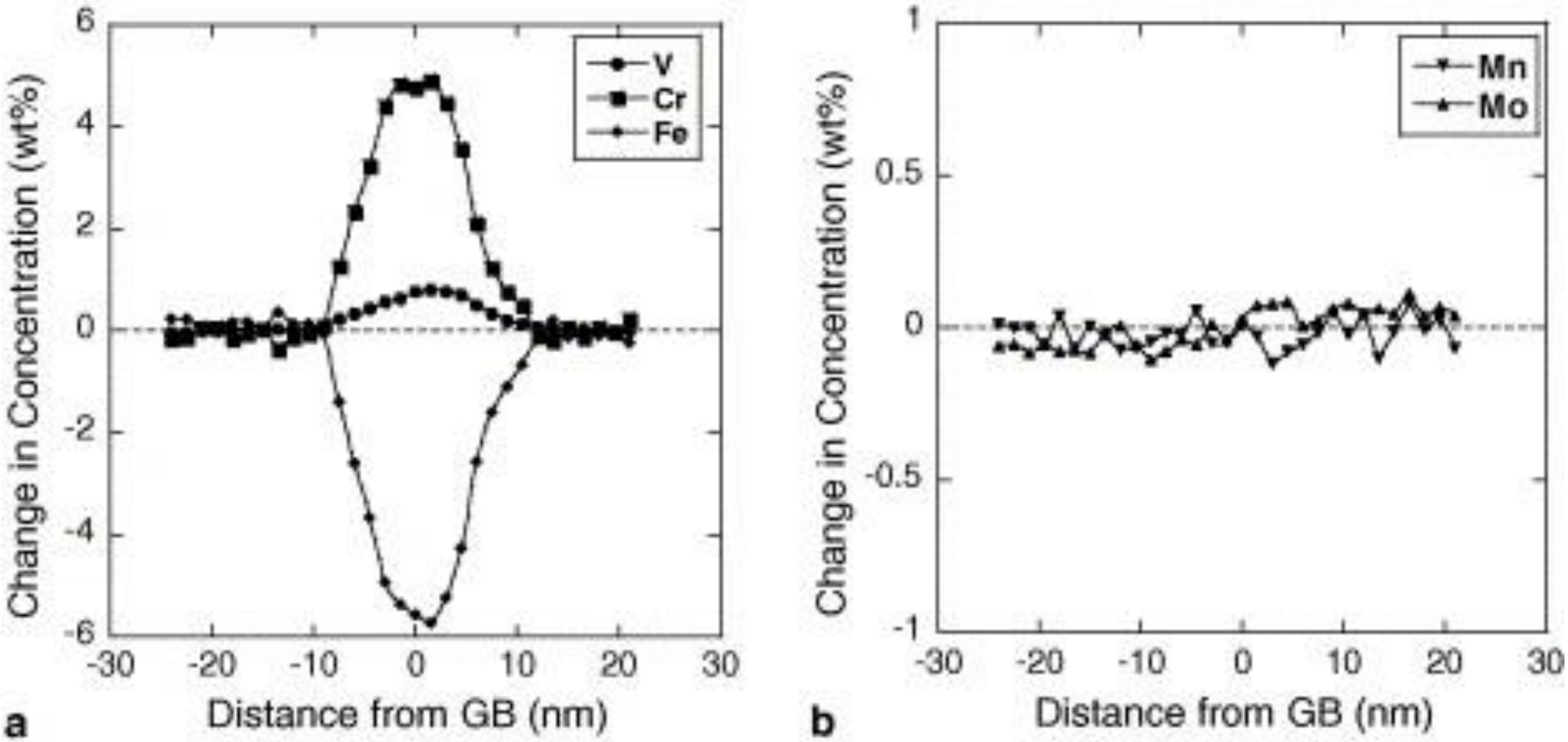
Helium Bubbles

Vacancy Diffusion Vacancy Clusters



Helium and hydrogen enhance cavity nucleation

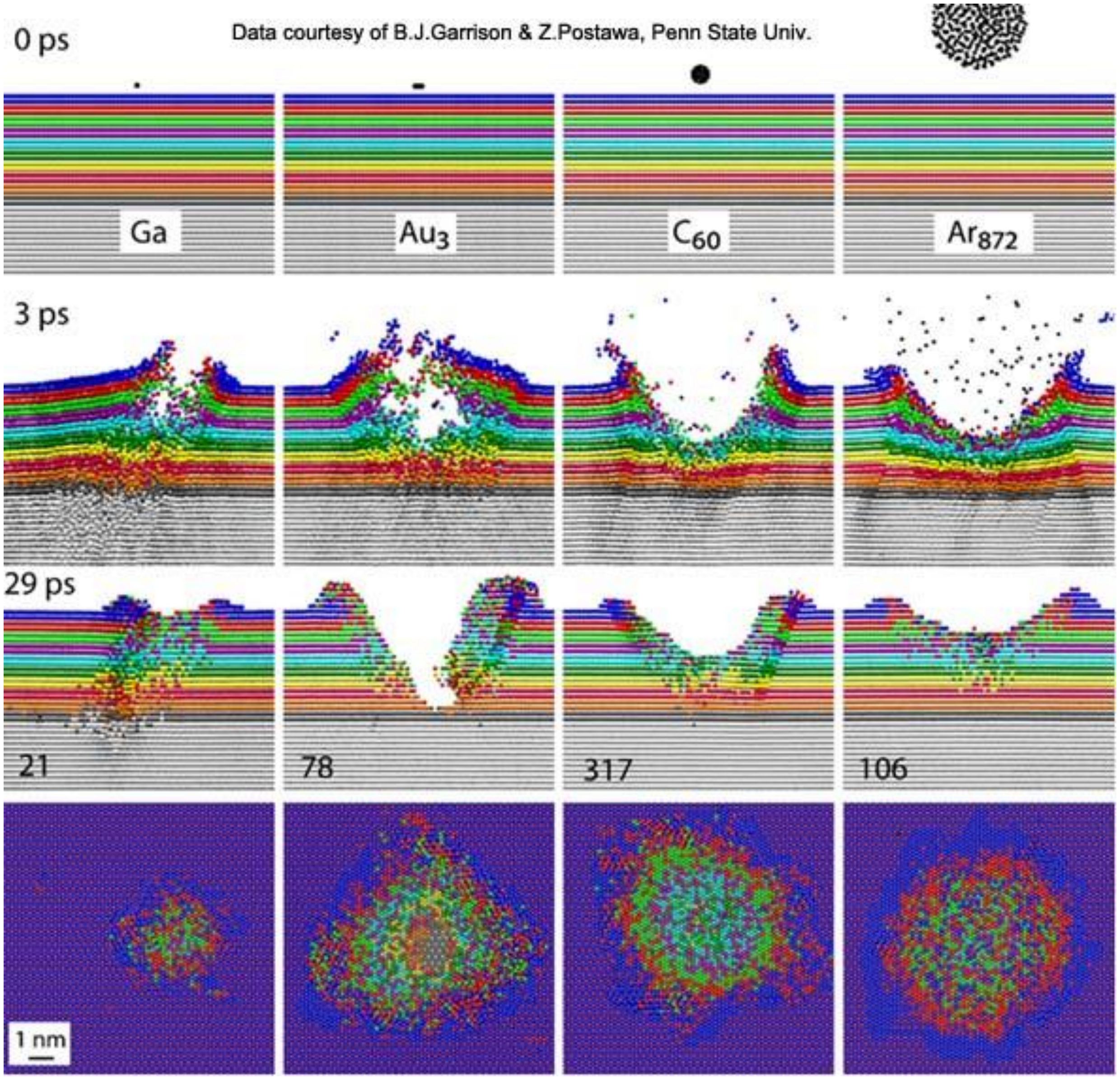
Radiation Induced Segregation



Change in concentrations with distance from the GB for T91 irradiated to 10 dpa at 450 °C with 2.0 MeV protons. (a) Fe, Cr, and V, and (b) Mn and Mo.

G Gupta. J Nucl Mater 2006

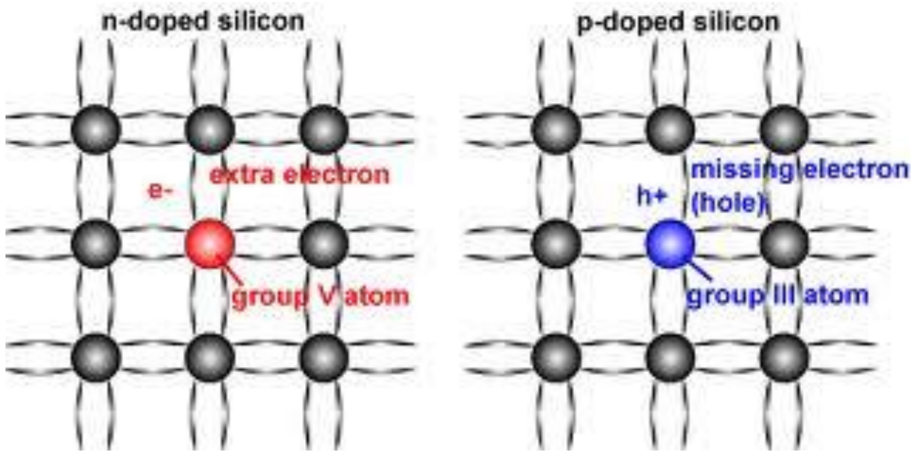
Radiation Induced Mixing

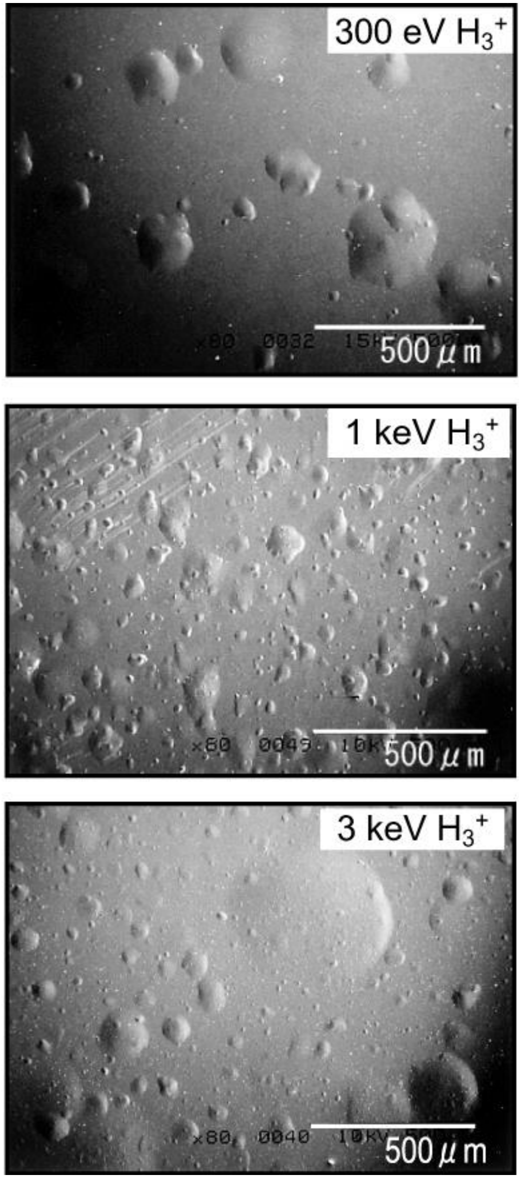


- Precipitation
- Dissolution
- Chemical Disordering
- Crystal Structure Transformation
- Amorphization

Other Radiation Effects

- Compositional Changes
- Sputtering
- Grain Growth
- Texture Changes
- Blistering and Exfoliation

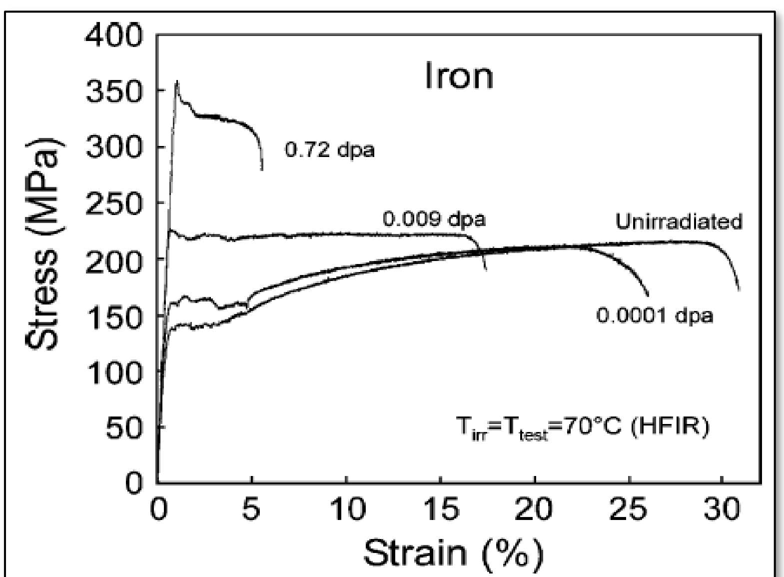




Radiation Effects on Mechanical Properties

- Yield Strength
- Ultimate Tensile Strength
- Ductile-Brittle Temperature Transition
- Young's Modulus
- Hardness
- High-Temperature Creep Rate

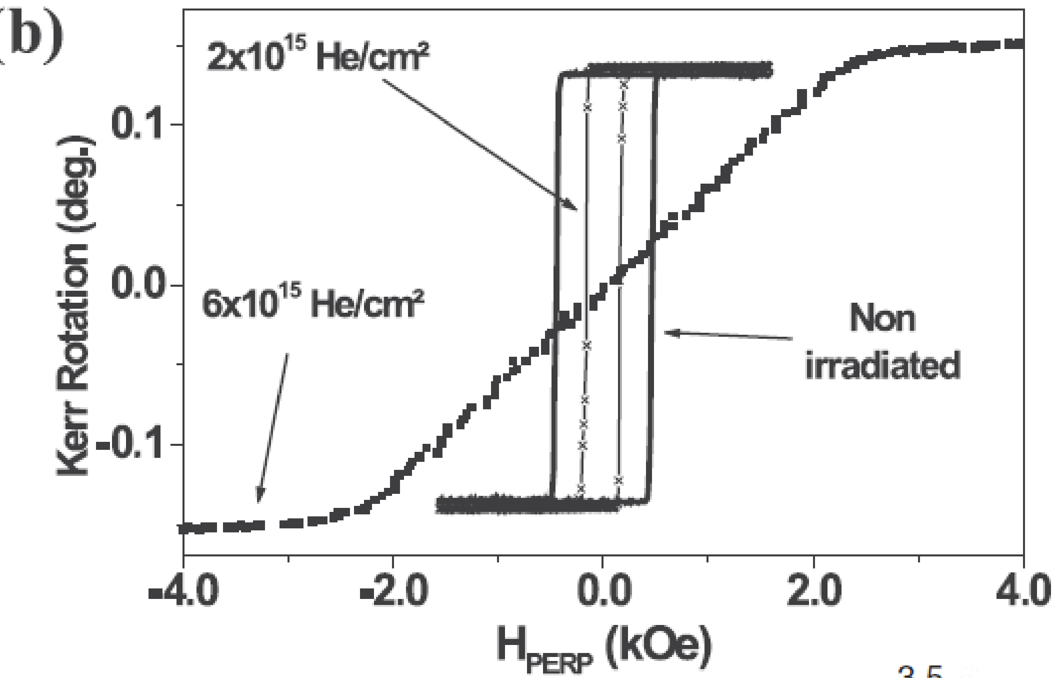
- Ductility
- Stress-Rupture Strength
- Density (swelling)
- Impact Strength
- Thermal Conductivity
- Electrical Conductivity



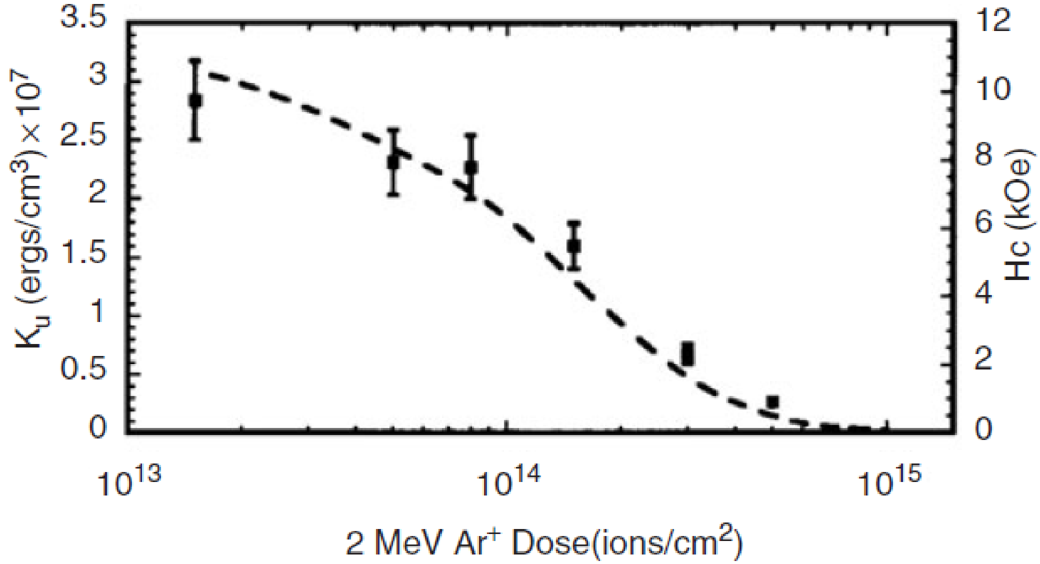
Eldrup et al. (2002)

Mansur (1994)

Radiation Effects on Magnetic Properties



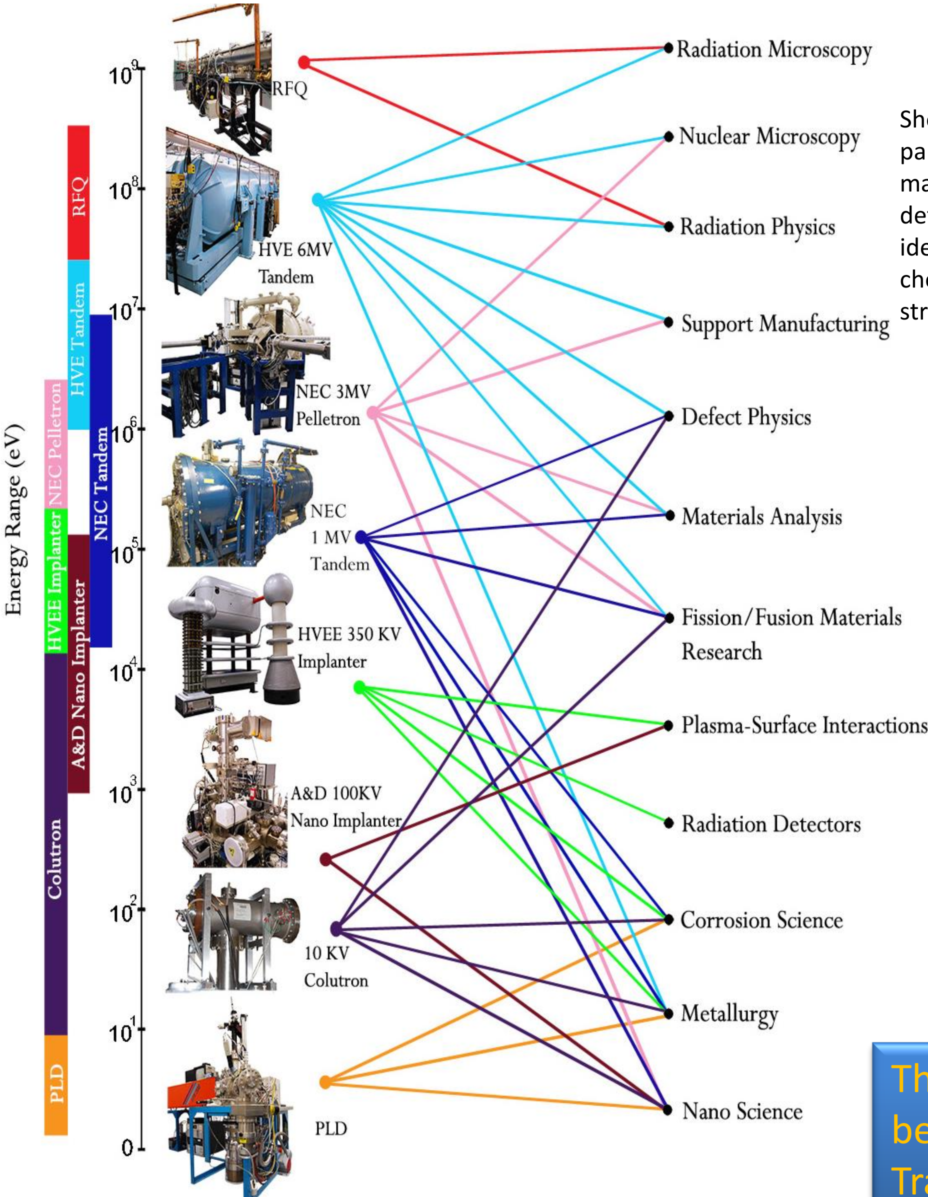
Hysterisis loops of Pt(2.8)-6x[Pt(0.6nm)-Co(0.3nm)]-Pt(6.5 nm)-SiO_2 multilayer. Irradiated with 30 keV He^+ ions.



Anisotropy and Coercivity of Co-Pt multilayer samples as a function of 2 MeV Ar^+ Fluence

J. Fassbender. J Phys D. 2004

Sandia’s Ion Beam Laboratory

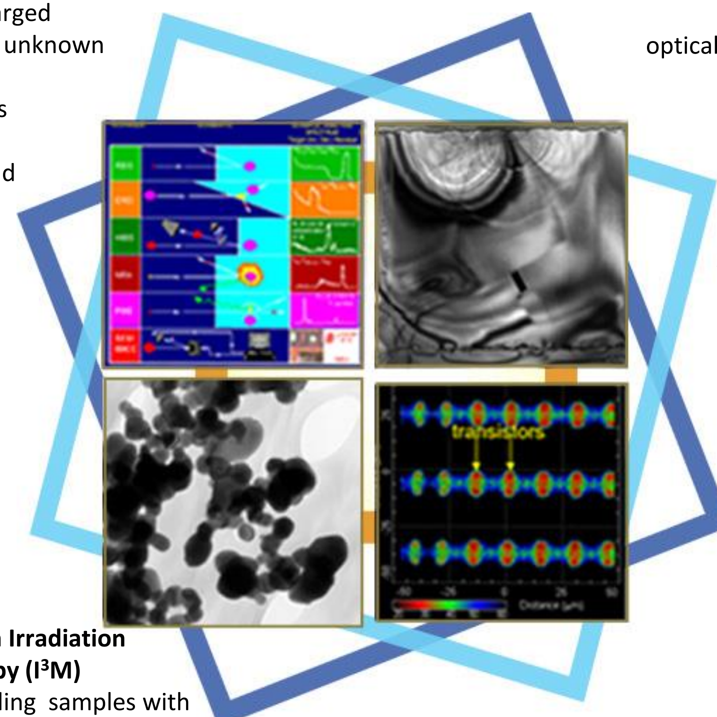


Ion Beam Analysis (IBA)

Shootingacharged particle at an unknown material to determine it’s identity, local chemistry, and structure.

Ion Beam Modification (IBM)

Changing the optical, mechanical, and chemical properties of materials via ion implantation to meet technological needs



***In Situ* Ion Irradiation Microscopy (I³M)**

Bombarding samples with various particles and observing the changes in real time to understand how materials will behave in extreme environments.

Radiation Effects Microscopy (REM)

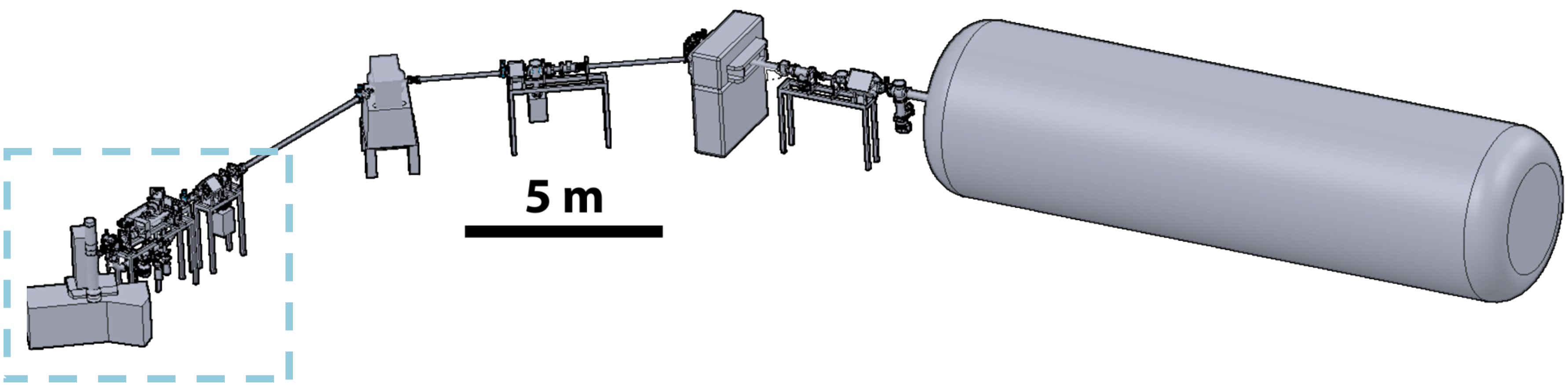
Using ion emissions to determine the Radiation hardness of microelectronics, identifying potential weaknesses.

The IBL has a unique and comprehensive capability ion beam set including and *In situ* Ion Irradiation Transmission Electron Microscopy.

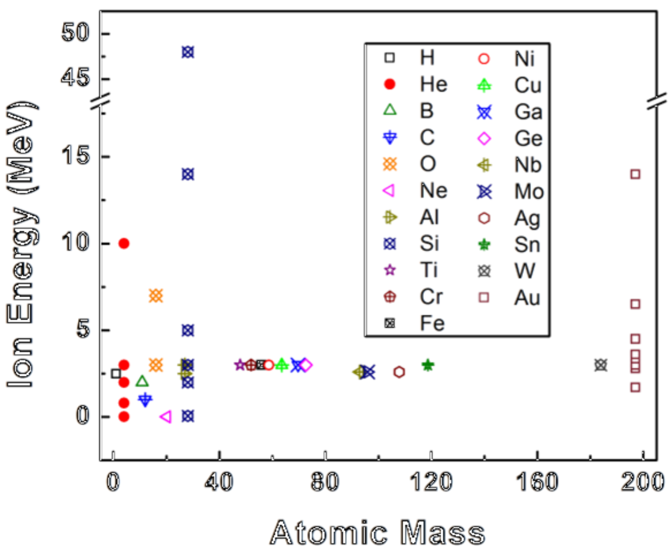
Sandia's I^{3}TEM Facility

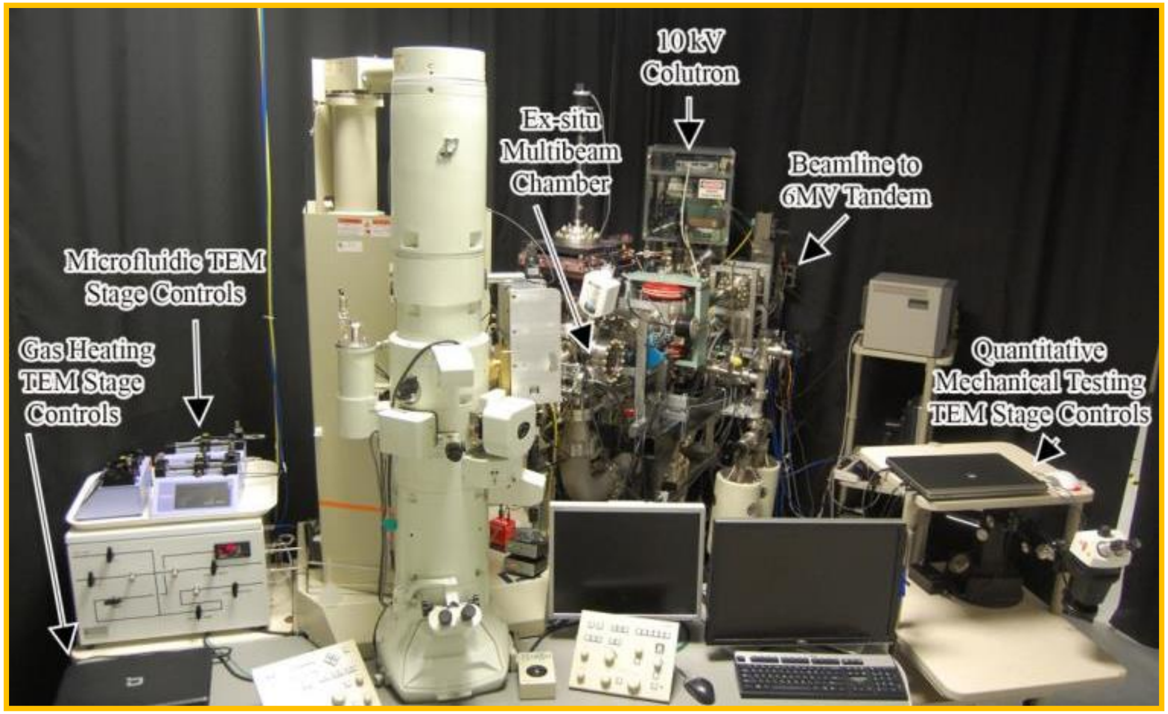
10 kV Colutron

6 MV Tandem



Sandia's I³TEM Facility





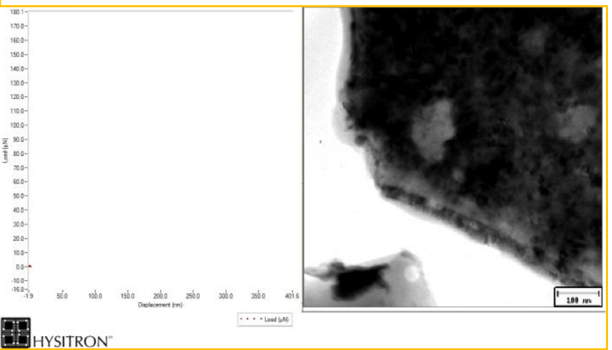
200 kV JEOL 2100 TEM

Heavy Ion Irradiation + Gaseous Implantation
Control ratio of dpa and gas species implantation and characterize coupling effects

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

Radiation & Potential Synergistic In- Situ Capabilities

Mechanical Effects



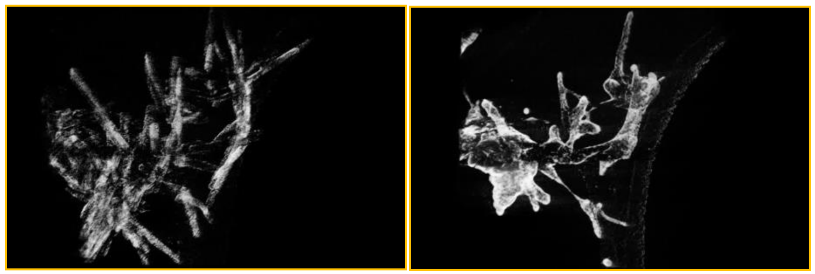
Hysitron PI95 TEM Picoindenter
Gatan 654 Straining Holder
Allows for direct correlation of dose and defect density with resulting changes in strength, ductility, and defect mobility

Environmental Effects

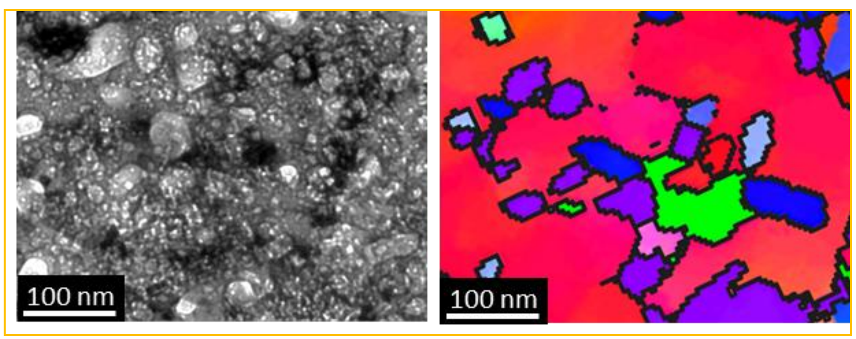
Protochips Liquid and Gas Flow
Study the material in different environments (flowing, mixing, temperature)

Structural Effects

Hummingbird Tomography Stage
Gatan 925 Double Tilt Rotate
Morphology changes as a result of radiation damage

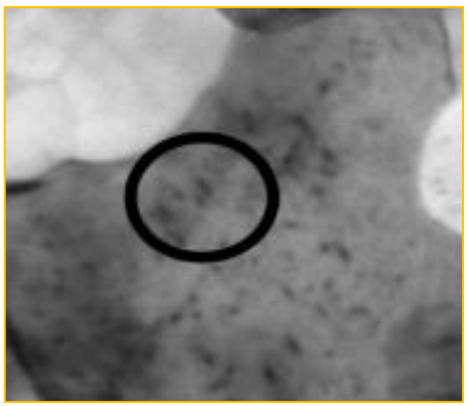


Nanomegas ASTAR
Grain structure changes as a result of radiation and implantation



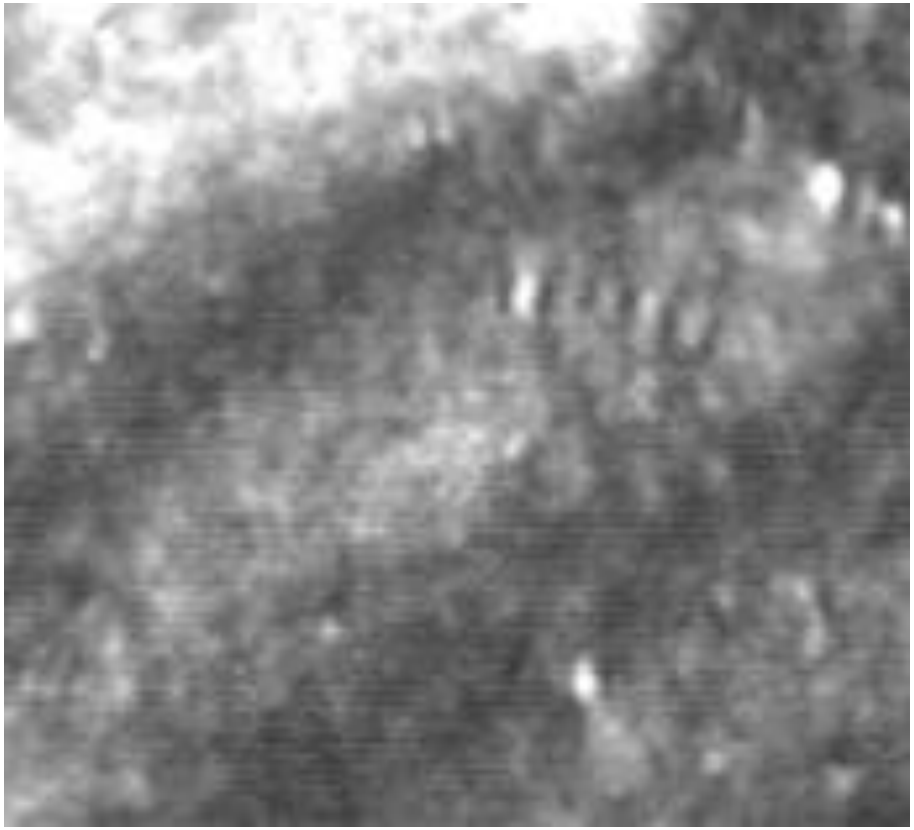
Thermal Effects

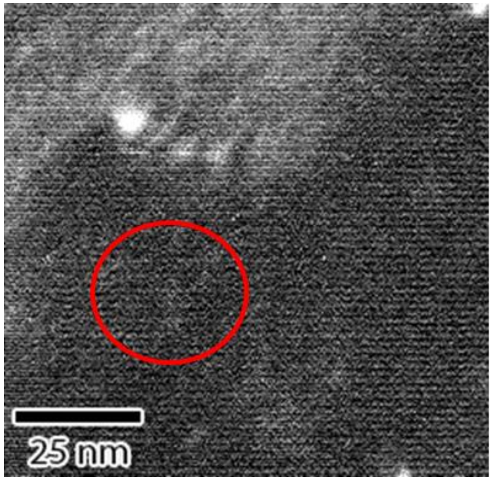
Hummingbird Heating Stage
Coupling effects of temperature and irradiation on microstructural evolution up to 800°C

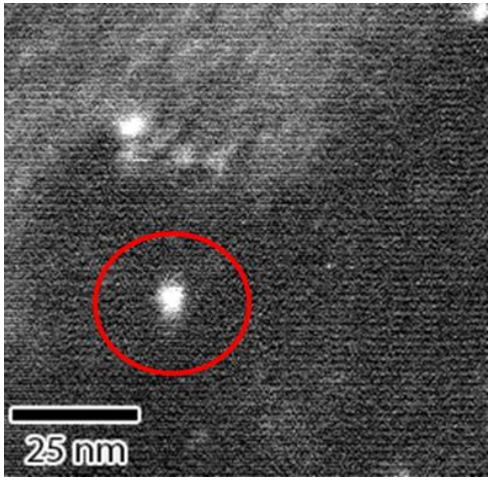


The application of advanced microscopy techniques to characterize synergistic effects in a variety of extreme environments

Ion Strikes in the TEM



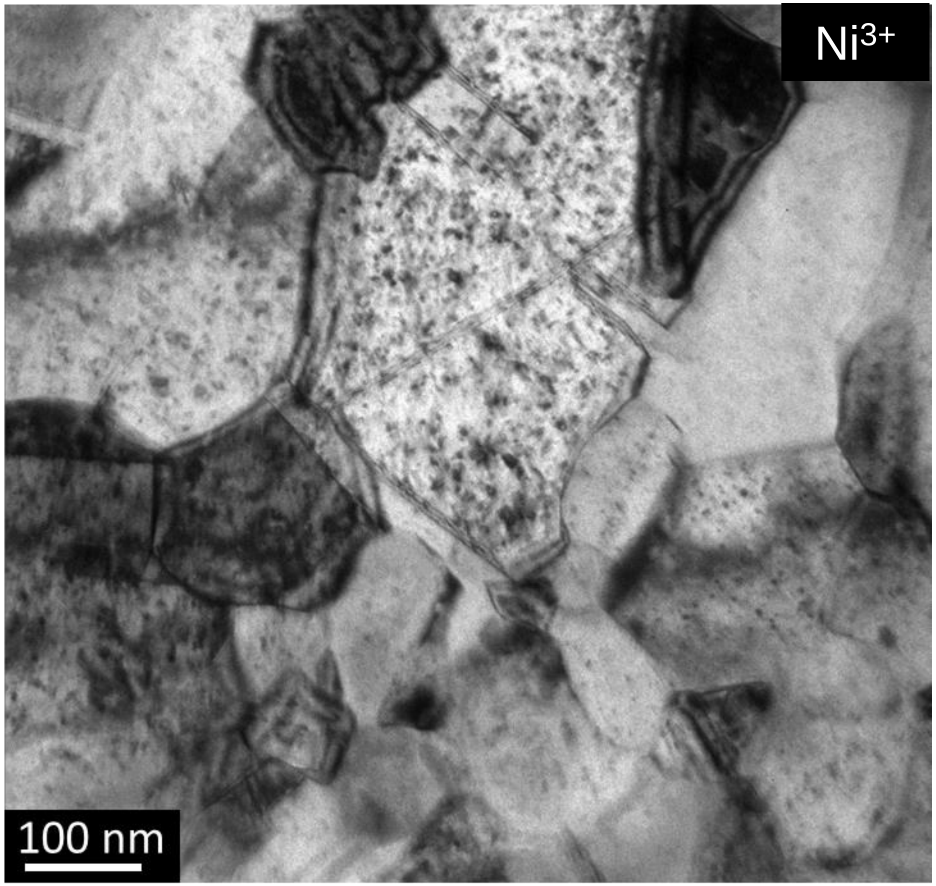


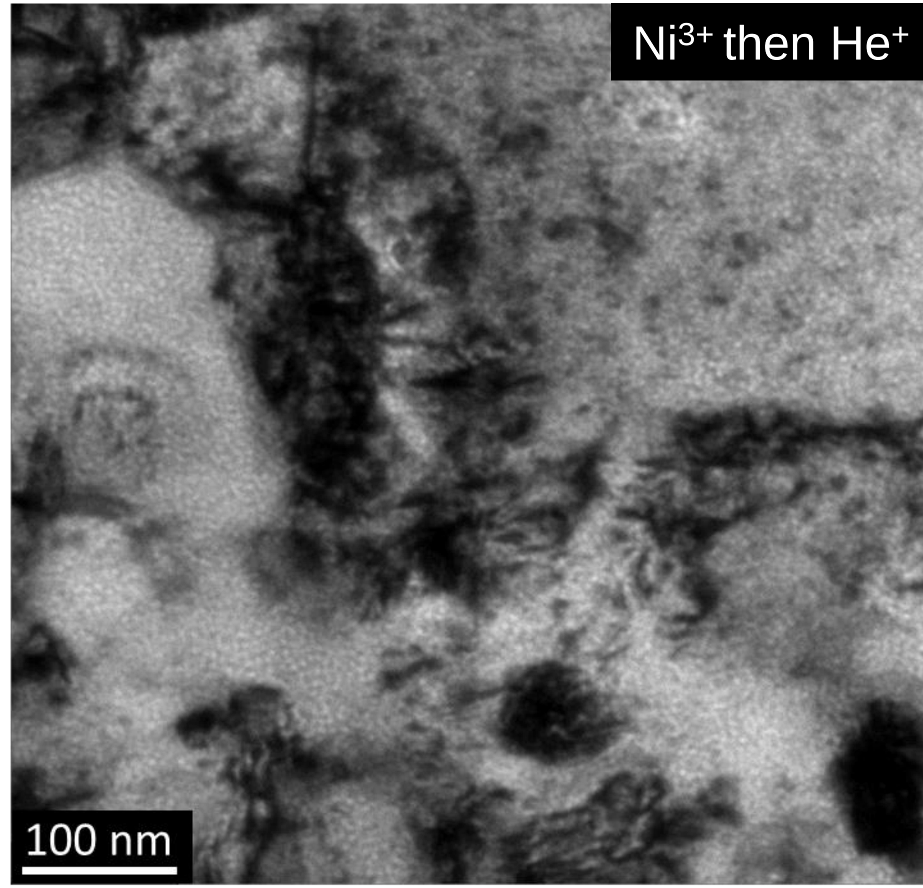


- 1.7 MeV Au^{3+} into Steel
- Single Ion Strikes Visible

Strikes appear in 1/30 s

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

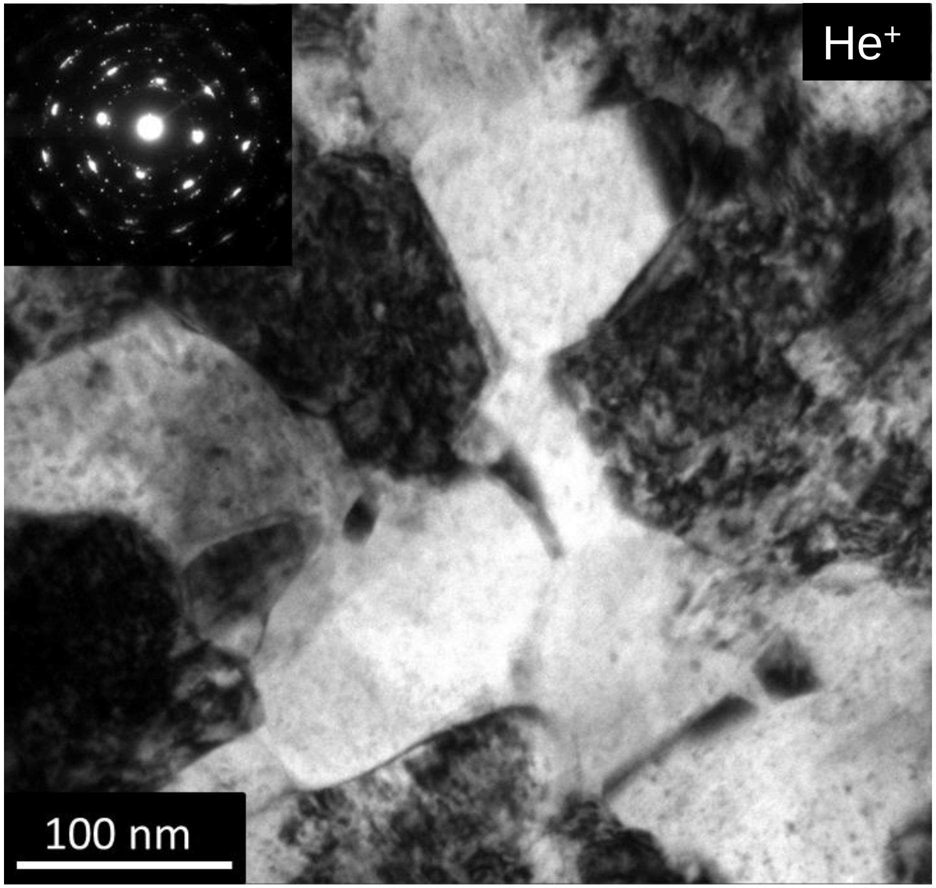




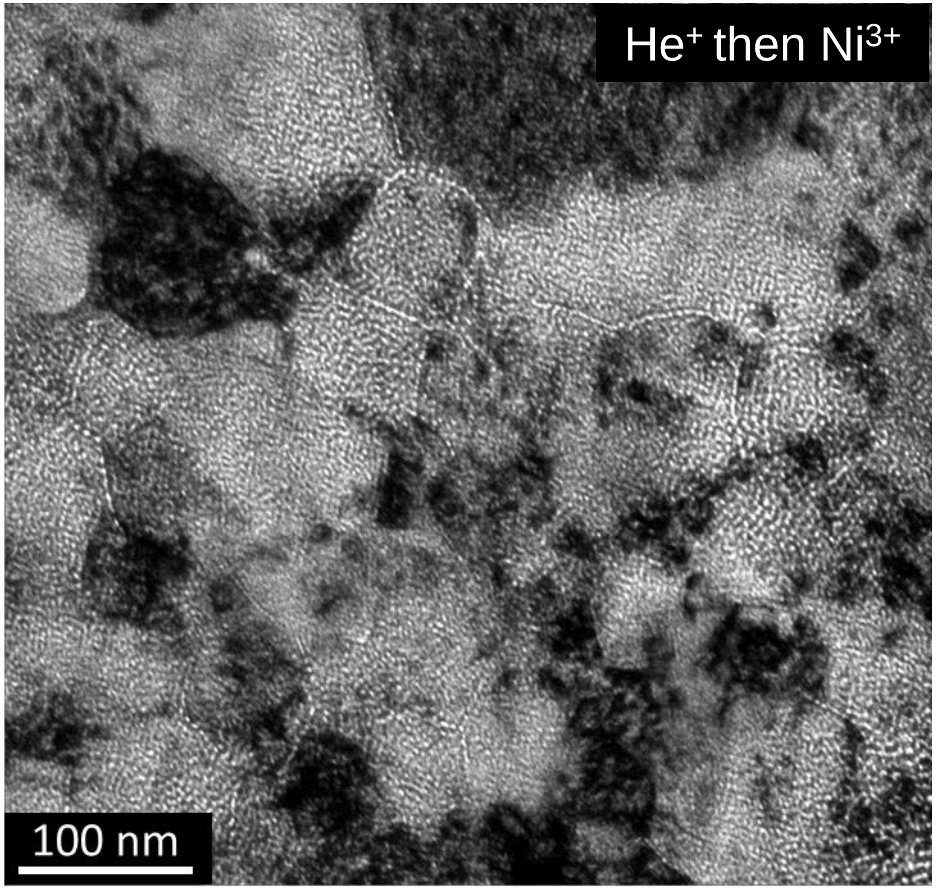
1.8 dpa Ni^{3+} irradiation
Dislocation loops and SFT are present

Additional $2x10^{16}$ He^{+}/cm^{2}
Evenly distributed nanometer size cavities

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

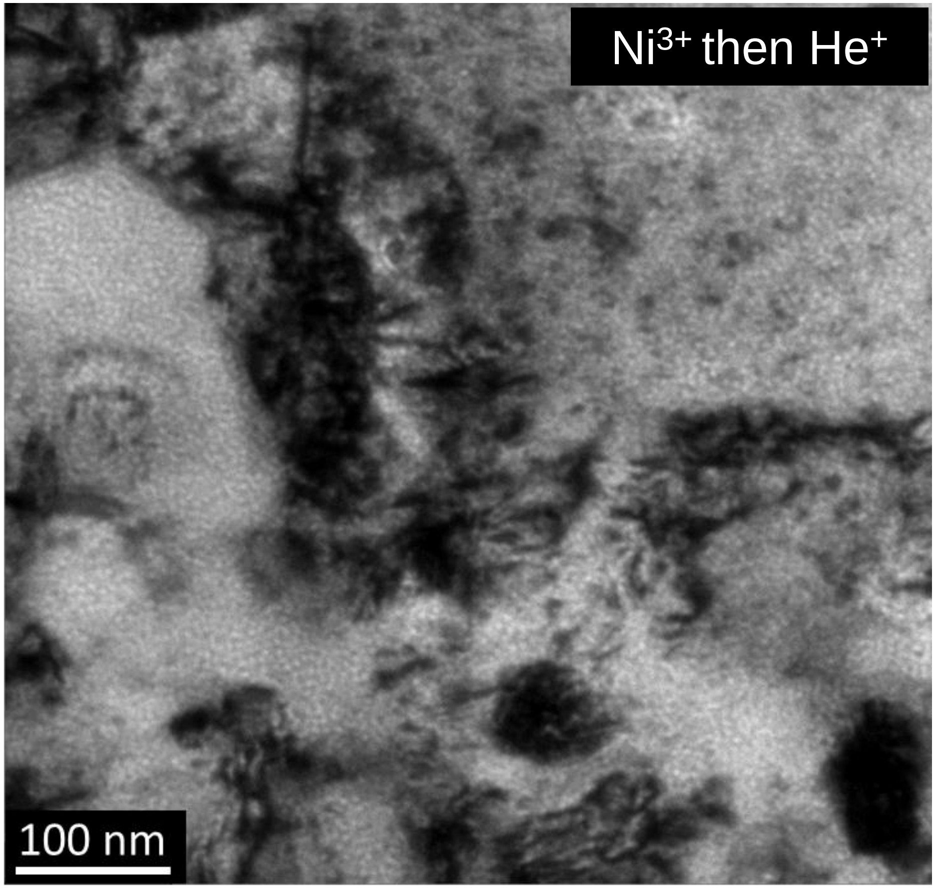


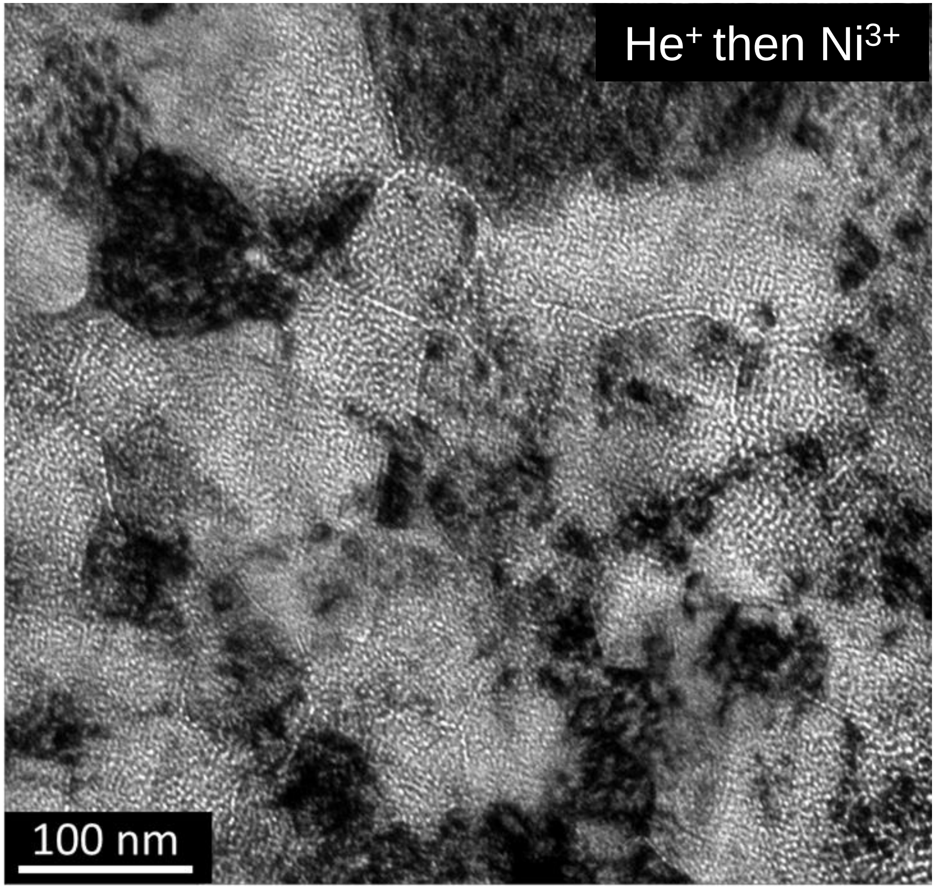
10^{17} He^+/cm^2
Visible damage



0.7 dpa Ni^{3+} irradiation
High concentration of cavities along grain boundaries

Irradiation / Implantation Sequence
Effect on Cavity Structure

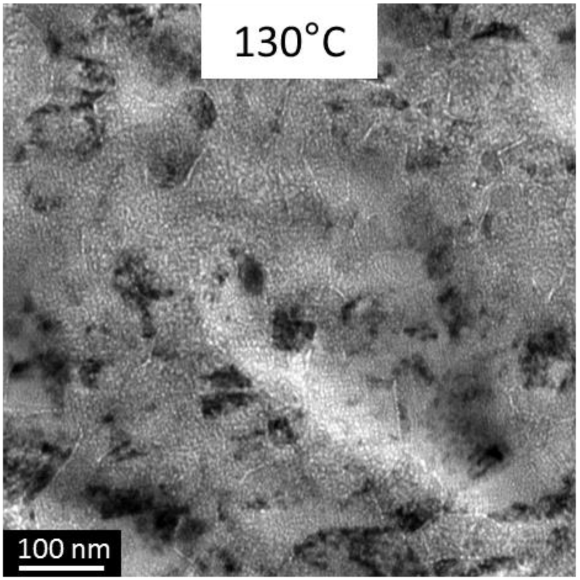


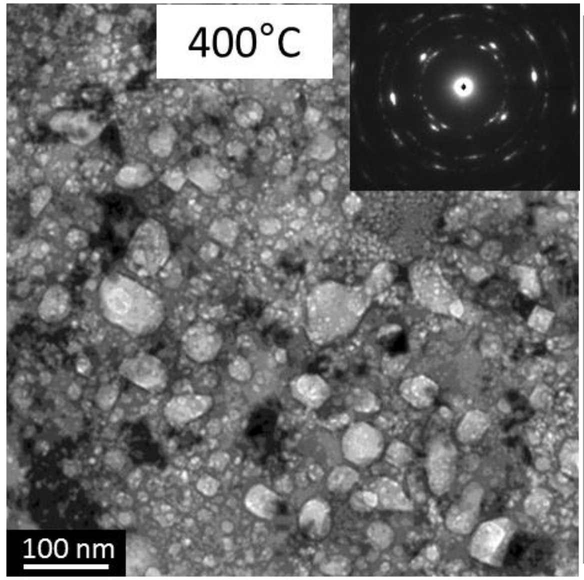


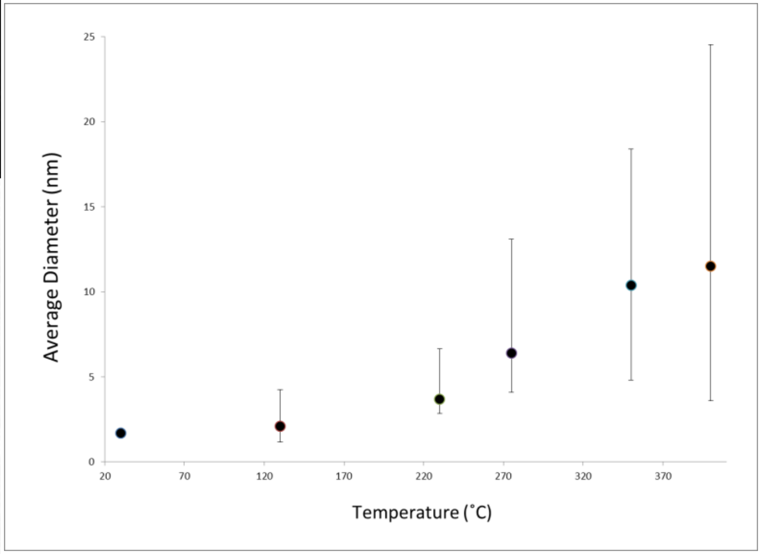
Evenly distributed cavaties over the entire grain structure

Apparent higher concentration of cavities along grain boundaries

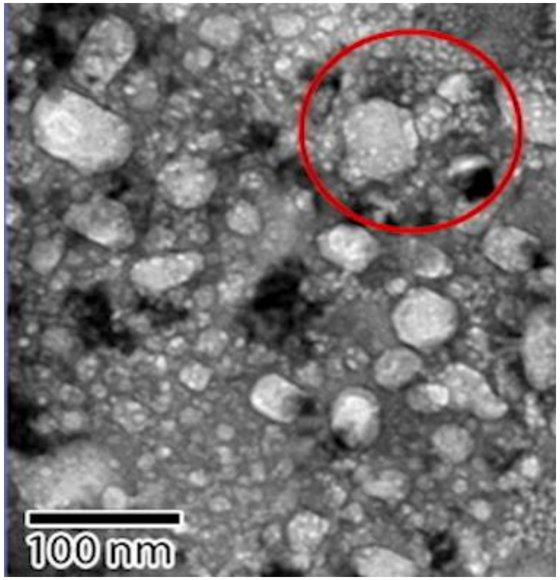
Cavity Growth during In-situ Annealing of 10 keV He^{+} Implanted and then 3 MeV Irradiated Ni^{3+}

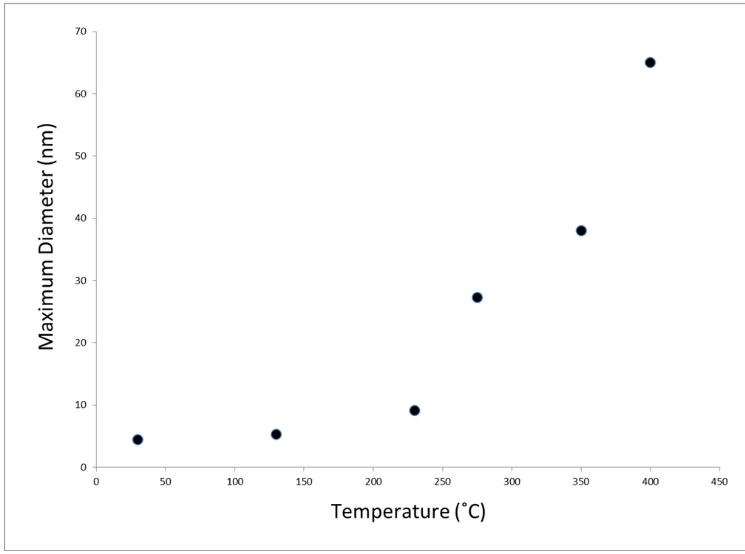






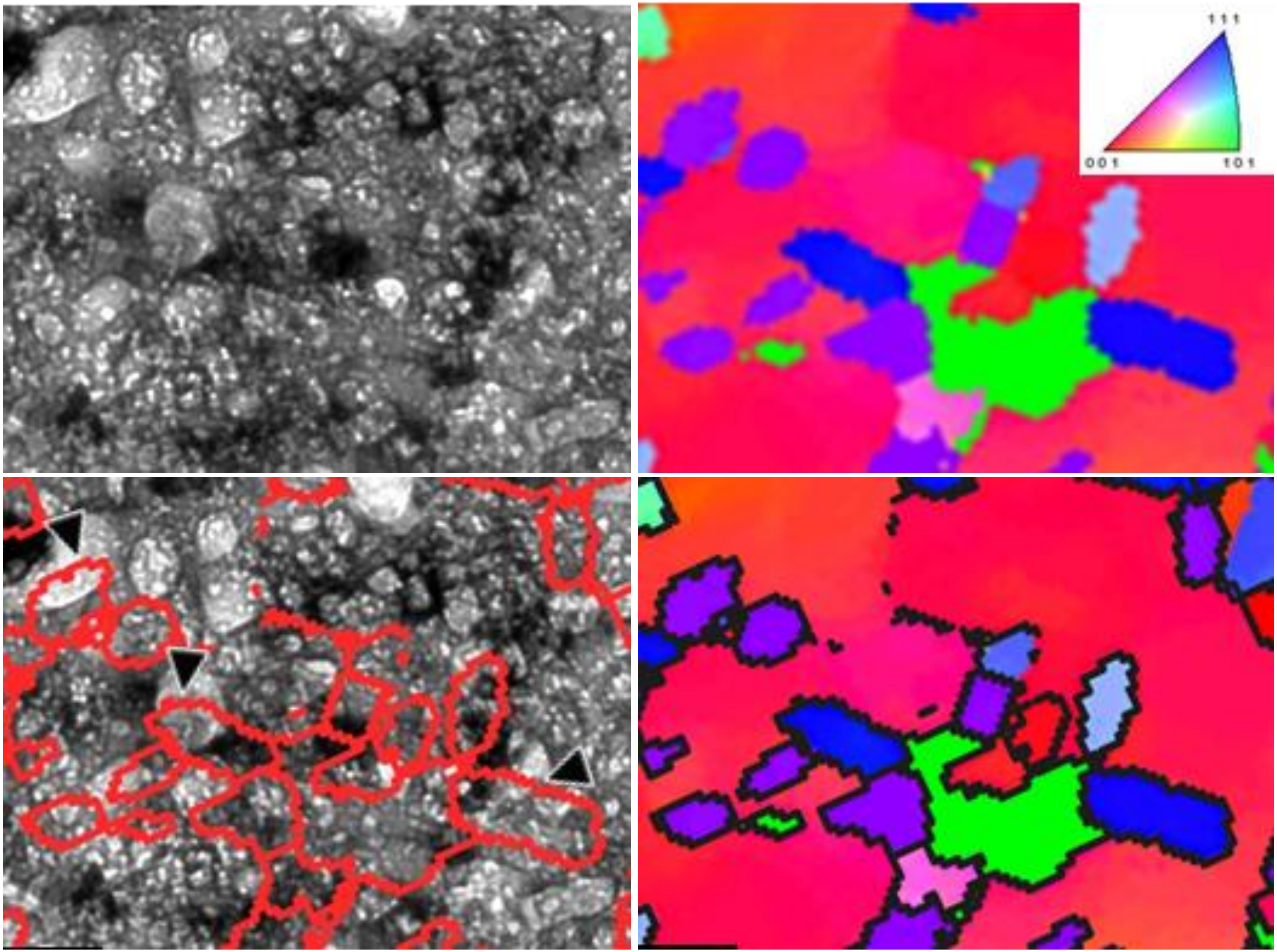
Bubble to cavity transition and cavity evolution can be directly studied





Precession Electron Diffraction Reveals Hidden Grain Structure

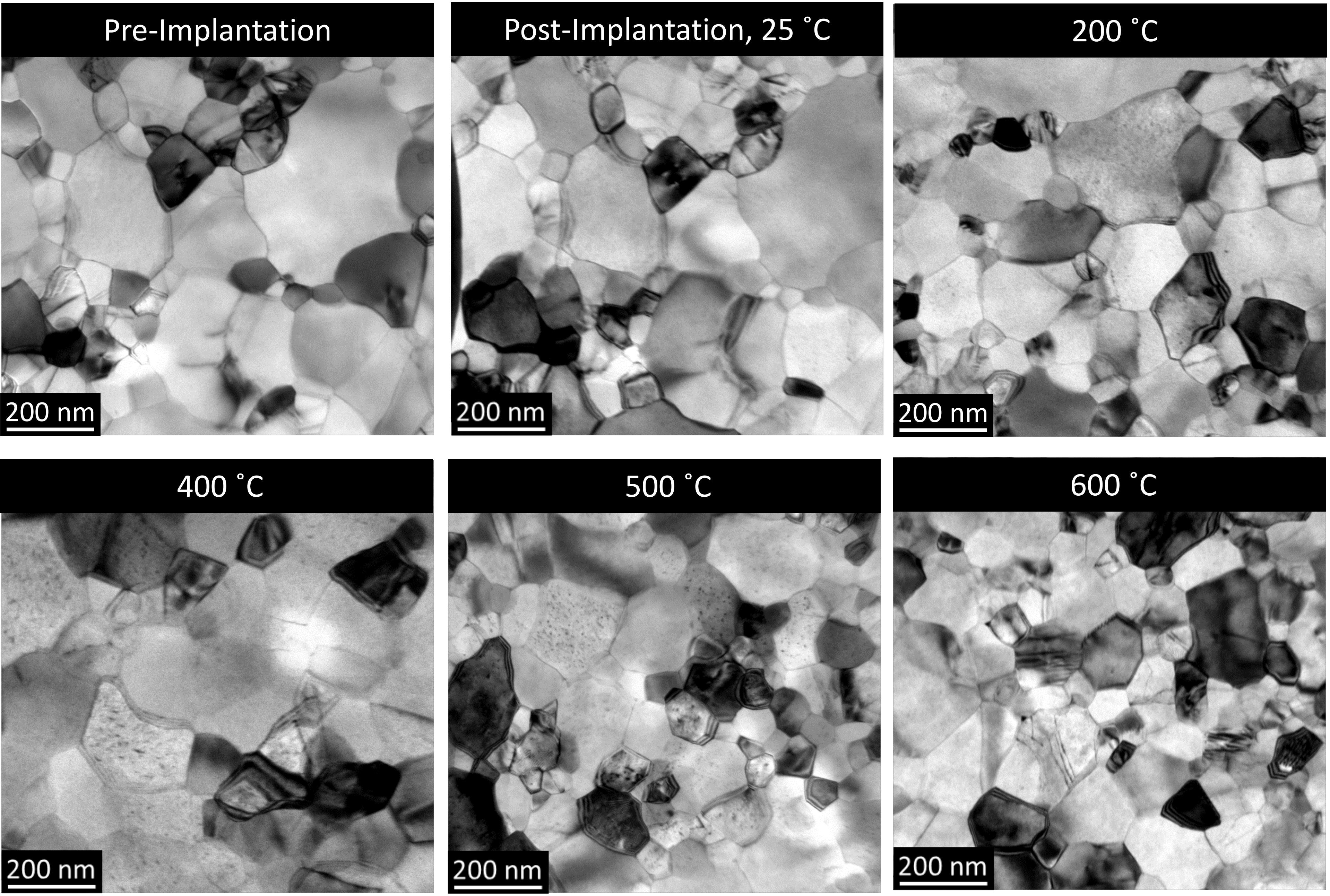
Cavities in helium implanted, self-ion irradiated, nc nickel film annealed to 400 ˚C



Cavities span multiple grains at identified grain boundaries

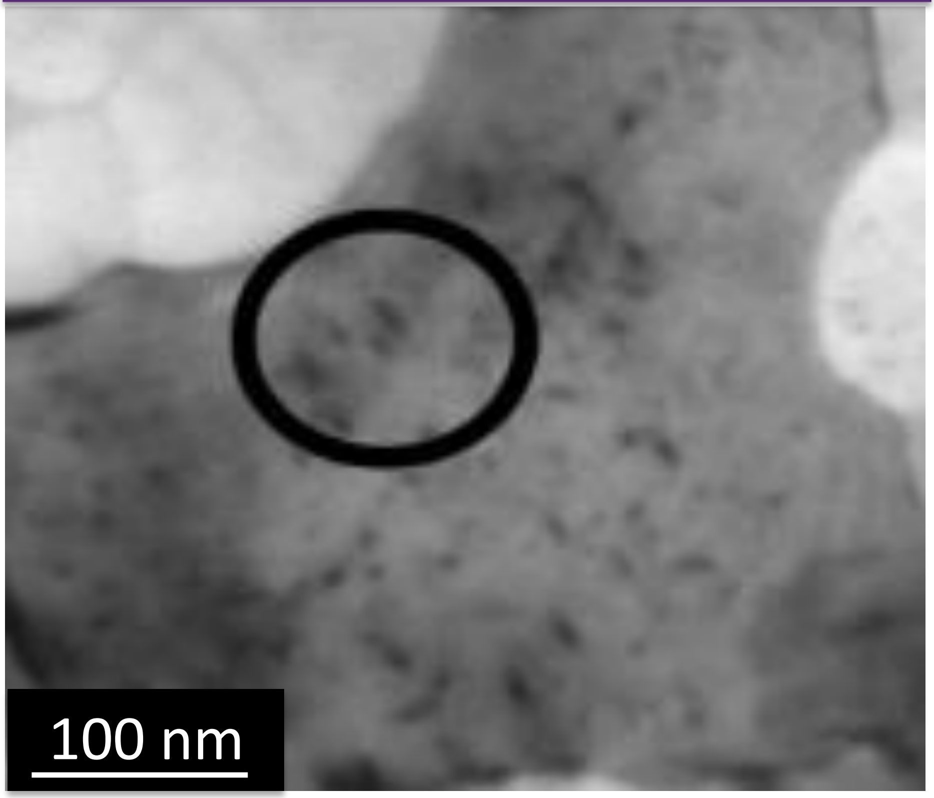
100 nm

Helium Implantation at Room Temperature

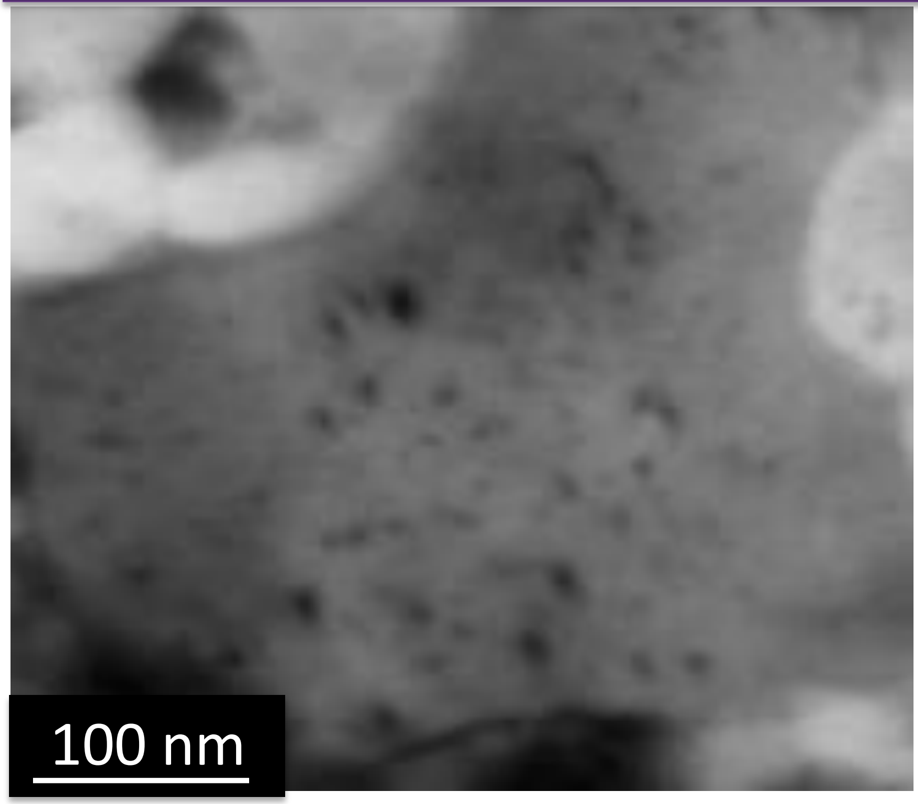


Dislocation Loop Mobility 500 ˚C to 600˚C

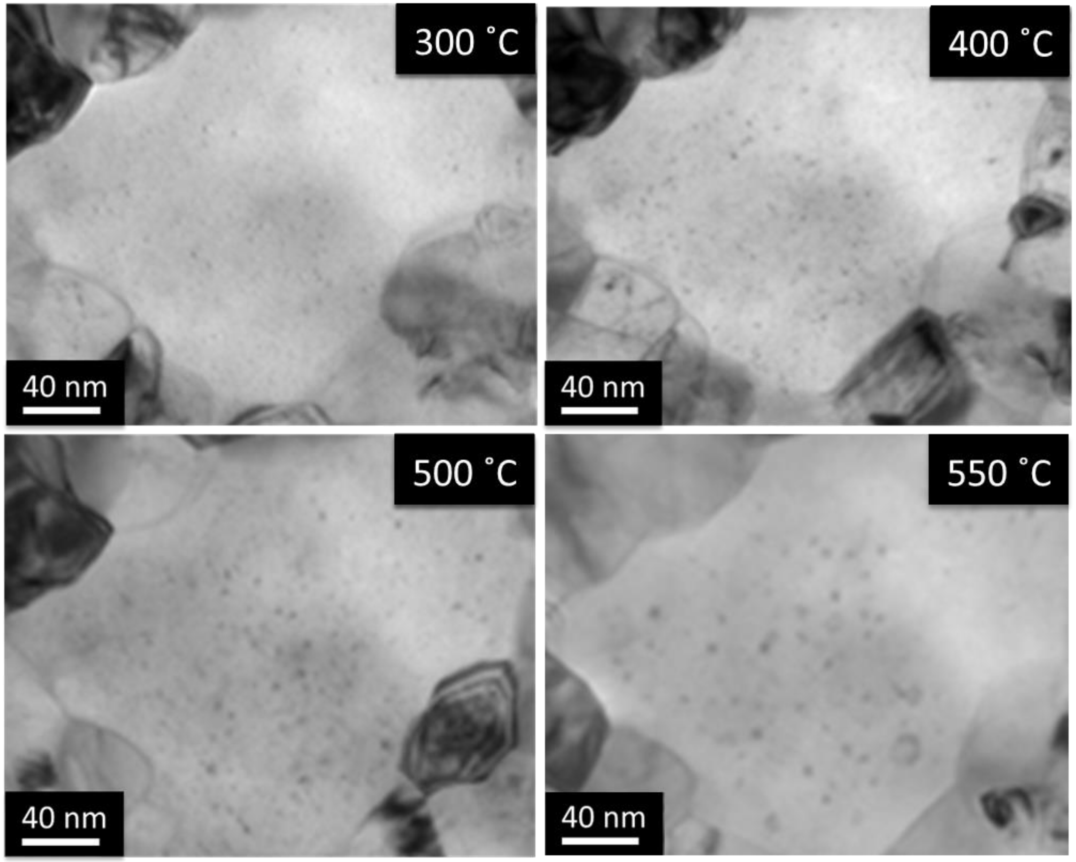
Dislocation Loop Coalescence

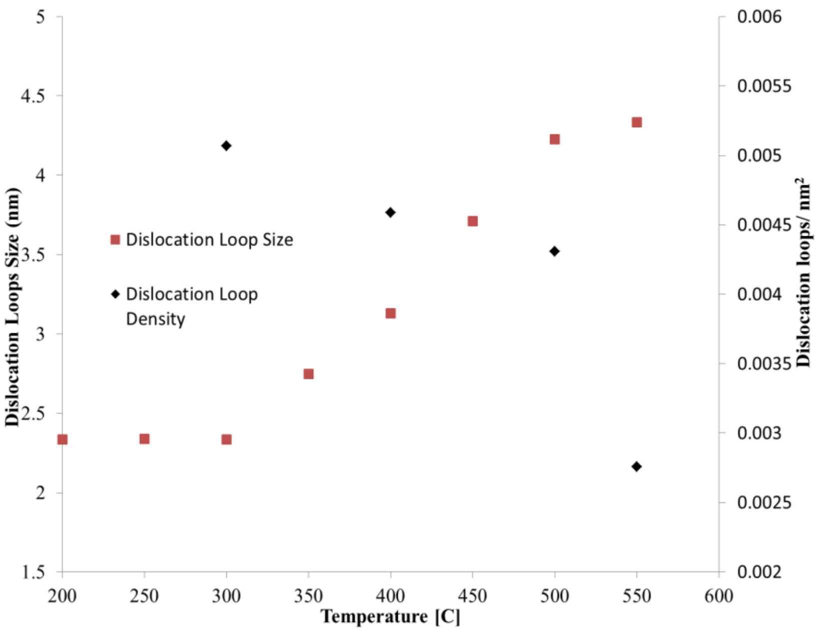


Dislocation Loop Migration to Surface



Defect Size & Density Evolution with Annealing

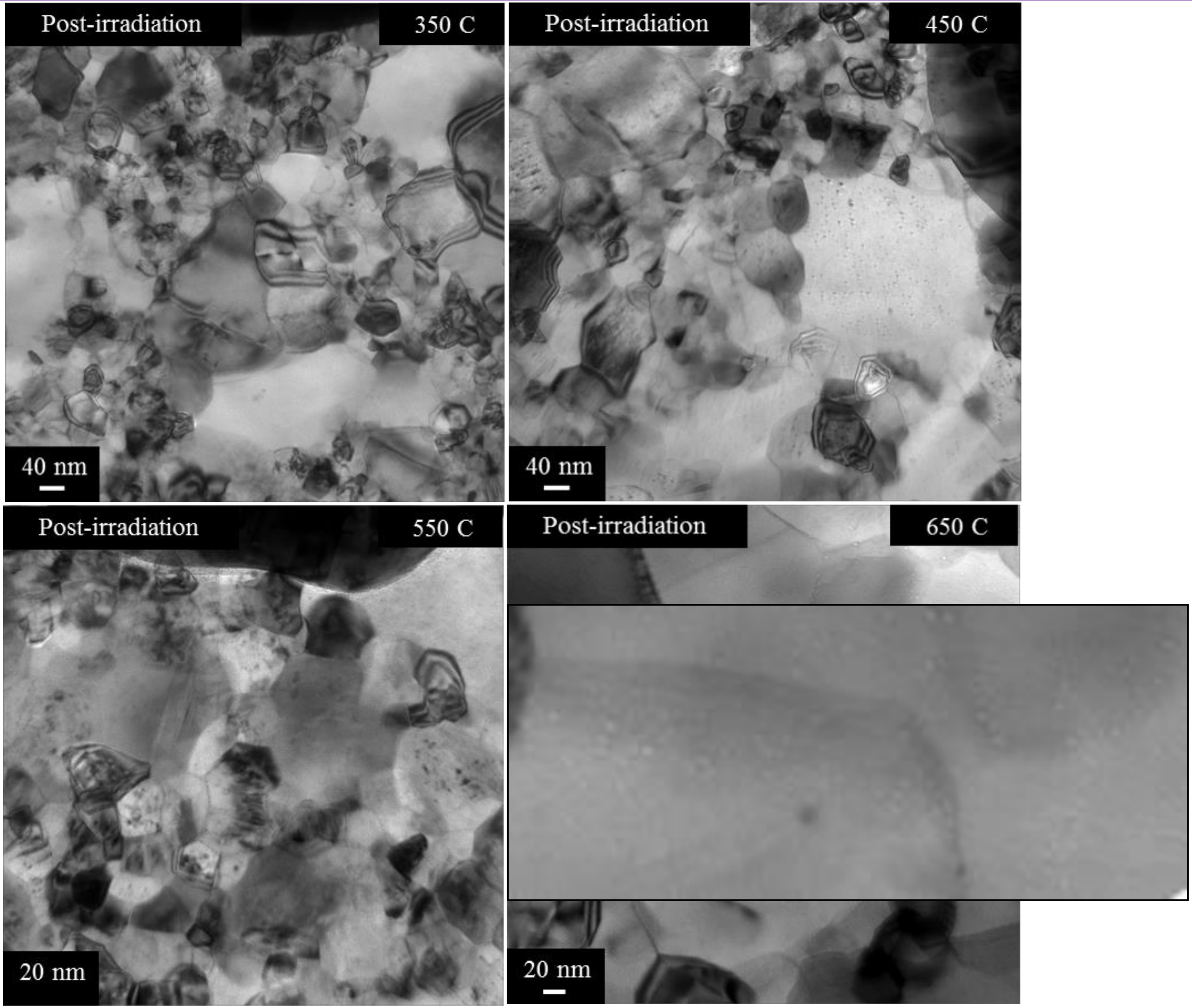




Defect Size Increases, Density Decreases

No visible Cavities

Elevated Temperature Helium Implantation



CINT Capabilities

Core Facility (SNL)

- TEM, SEM, FIB, XRD
- Low Temp Transport
- Scanning Probe Microscopy
- Ultra-fast Spectroscopy
- Molecular Beam Epitaxy
- Chem & Bio labs
- Molecular films
- E-beam lithography
- Photolithography
- Deposition & Etch
- Ion Irradiation

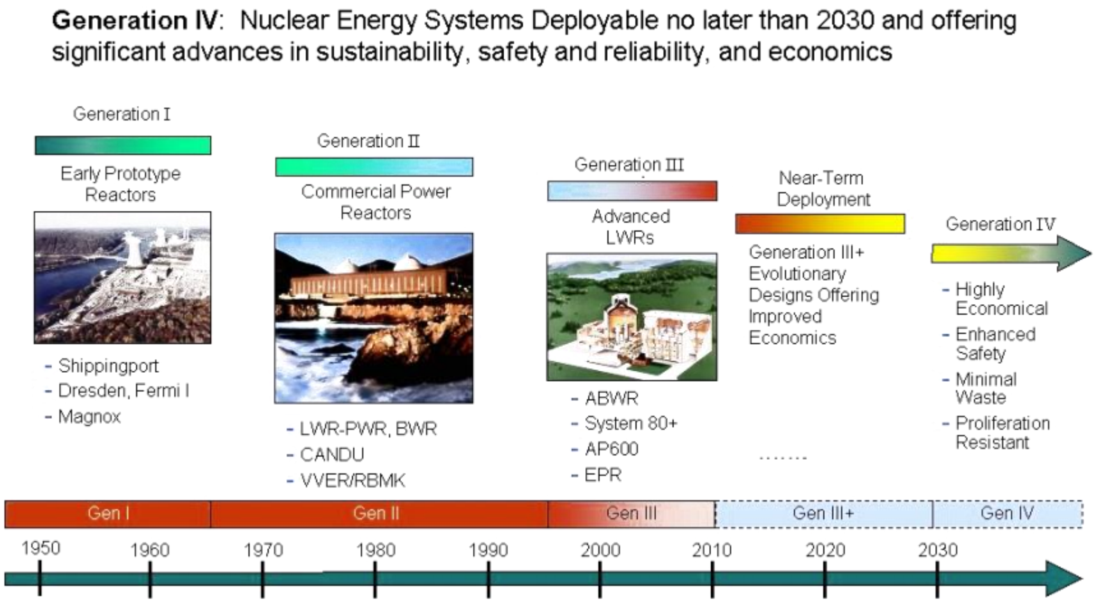
Gateway Facility (LANL)

- Biomaterials & Chem synthesis
- XRD, SEM
- UV-vis, ellipsometry
- Nano-indentation
- Nanoscale optical probes
- Microscopies
- Physical Synthesis
- Pulsed Laser Deposition
- Ultra-fast Spectroscopy
- Computer Cluster
- Visualization Lab

Many instruments/techniques in this talk available for use through CINT's competitive proposal-based system.

Summary

Radiation Effects



EPR reactor design (Gen III+)

ITER (fusion)

- Generation II reactor lifetime extensions: material aging
- Generation IV structural materials: safer, more radiation resistant
- Fusion materials: very high dose, helium bombardment

CINT: a DOE Office of Science National User Facility

"A DOE/SC user facility has unique world-class research capabilities and technologies which are available broadly to science community worldwide from universities, industry, private laboratories, and other Federal laboratories for work that will be published in the open literature."

The DOE/SC nanoscience centers are different from traditional user facilities

- Defined by a scientific field, not specific instrumentation.
- NSRC staff support user projects and conduct original research.
- Capabilities involve hardware plus research expertise.