SAND2022-13846C

Exploring Thermal, Mechanical, and Electrical Shock via In-situ Electron Microscopy

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[1]Sandia National Laboratories (SNL)

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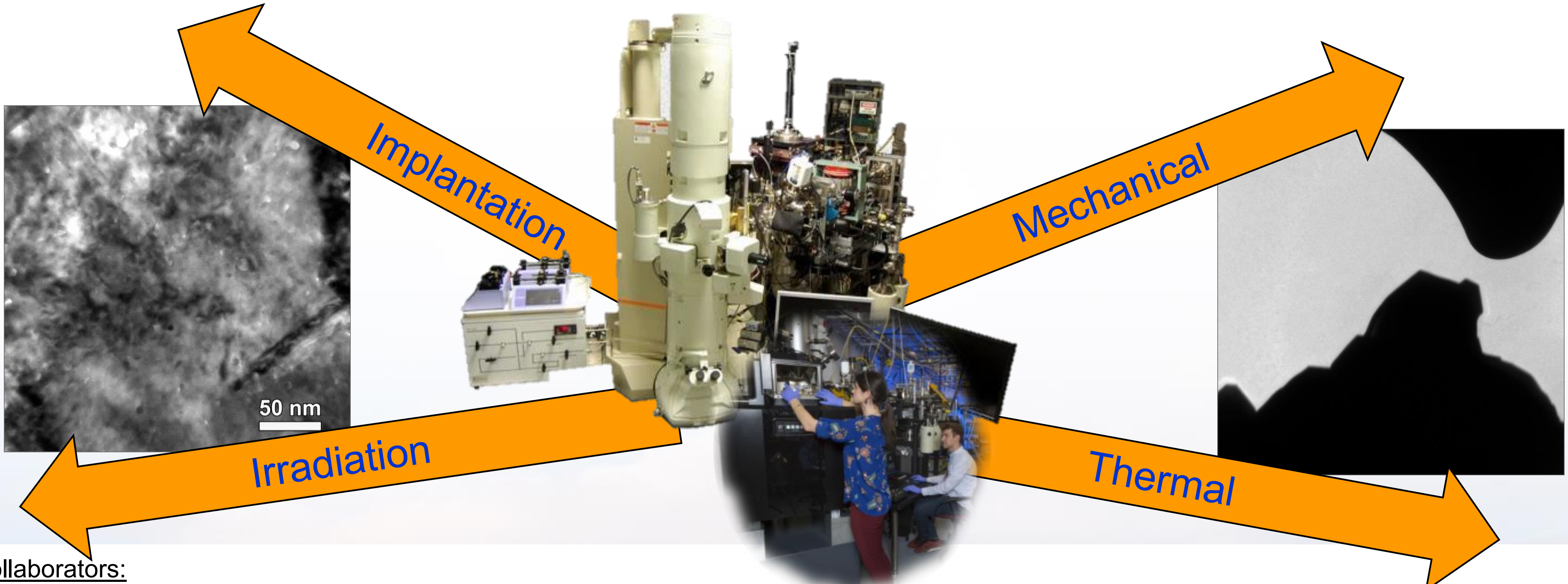

Collaborators:

- D.L. Buller, D.C. Bufford, S.H. Pratt, T.J. Boyle, B.A. Hernandez-Sanchez, S.J. Blair, B. Muntifering, C. Chisholm , P. Hosemann, A. Minor, J. A. Hinks, F. Hibberd, A. Ilinov, D. C. Bufford, F. Djurabekova, G. Greaves, A. Kuronen, S. E. Donnelly, K. Nordlund, F. Abdeljawad, S.M. Foiles, J. Qu, C. Taylor, J. Sugar, P. Price, C.M. Barr, D. Adams, M. Abere, L. Treadwell, A. Cook, A. Monterrosa, IDES Inc, J. Sharon, B. L. Boyce, C. Chisholm, H. Bei, E.P. George, W. Mook, Hysitron Inc., G.S. Jawaharram, S. Dillon, R.S. Averback, N. Heckman, J. Carroll, S. Briggs, E. Carnes, J. Brinker, D. Sassaki, T. Nenoff, B.G. Clark, P.J. Cappillino, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, L.R. Parent, I. Arslan. K. Jungjohann, & Protochips, Inc.

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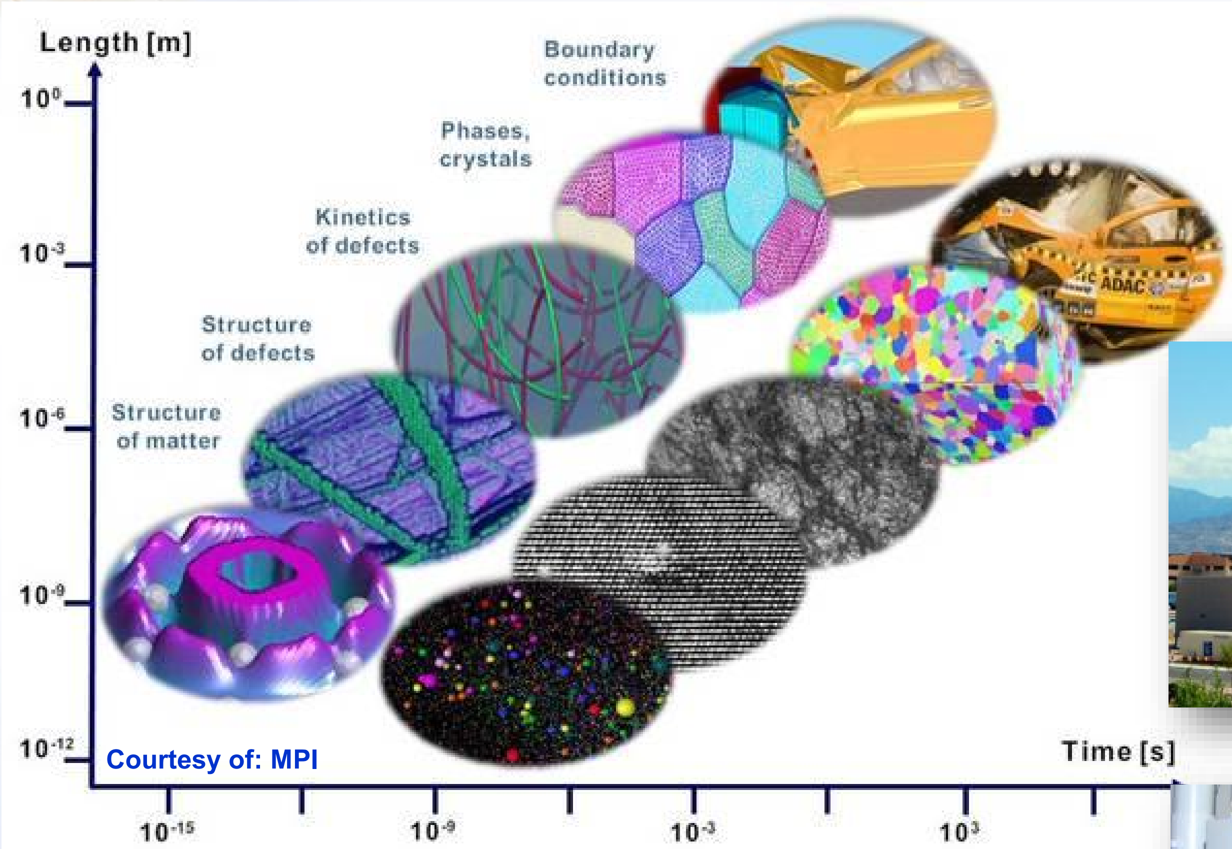
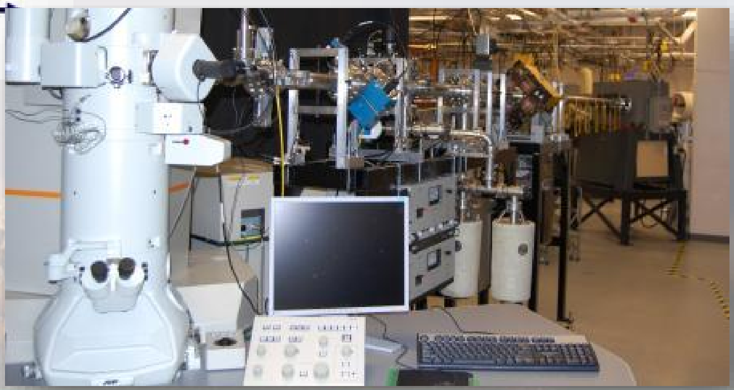
Investigating the nm Scale to Understand the km Scale Response of Materials in the Extremes



Courtesy of: MPI

Ion Beam Lab (IBL)

In situ Ion Irradiation TEM (I³TEM)

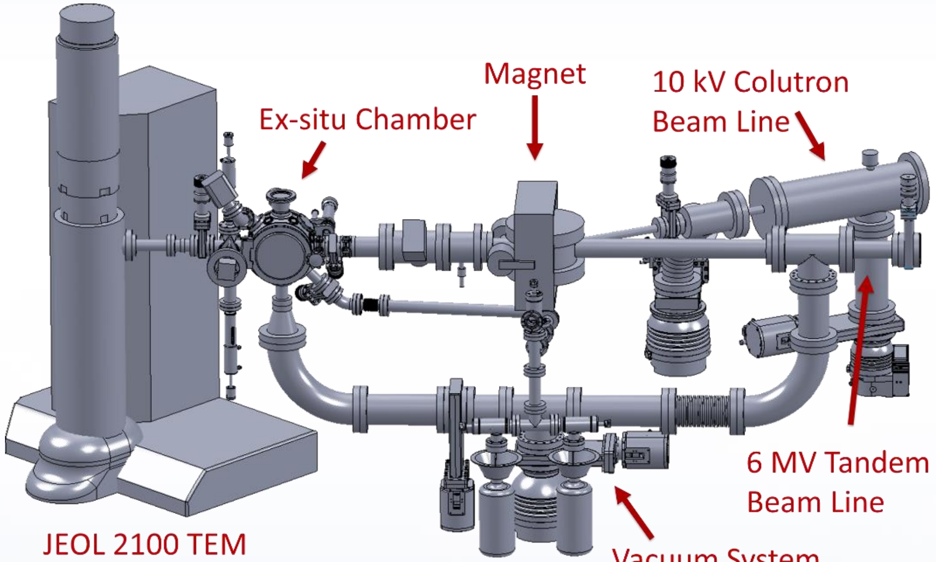


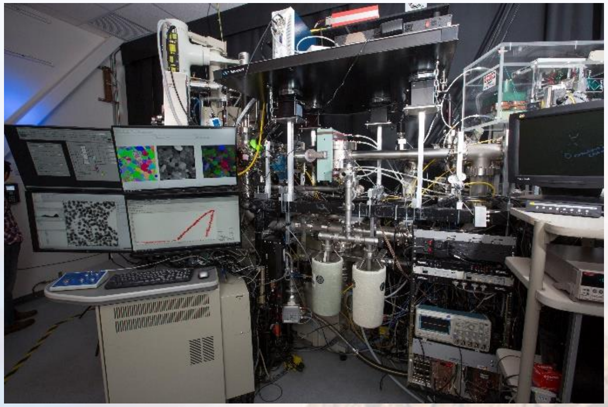
To develop predictive physics-based models, a fundamental understanding of the structure of mater, defects, an the kinetics of structural evolution in the environments of interest are needed

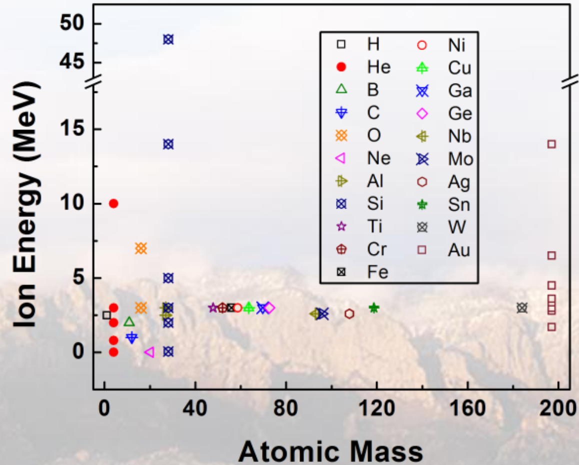
Sandia's Concurrent *In situ* Ion Irradiation TEM Facility

Collaborator: D.L. Buller

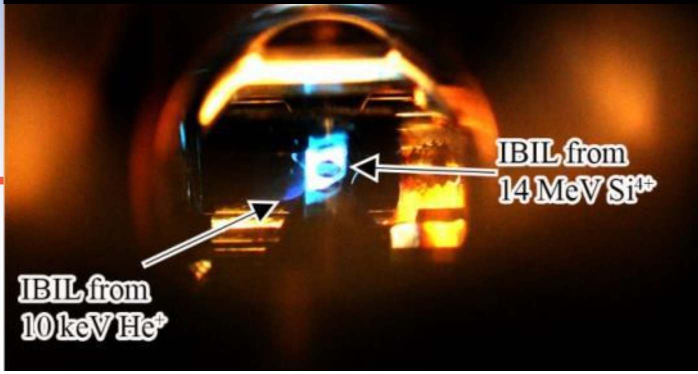
10 kV Colutron - 200 kV TEM - 6 MV Tandem

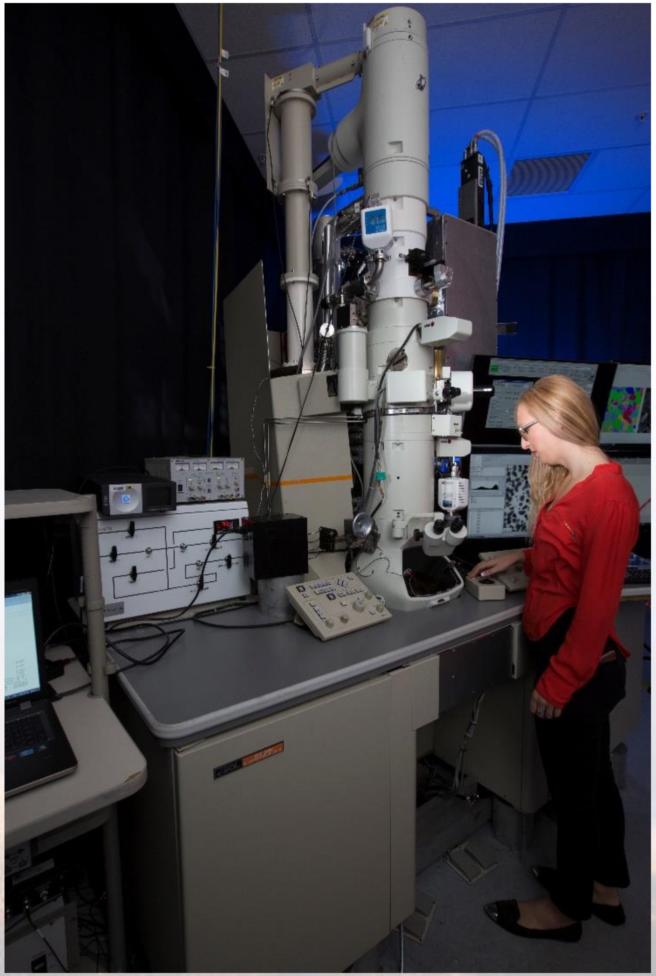






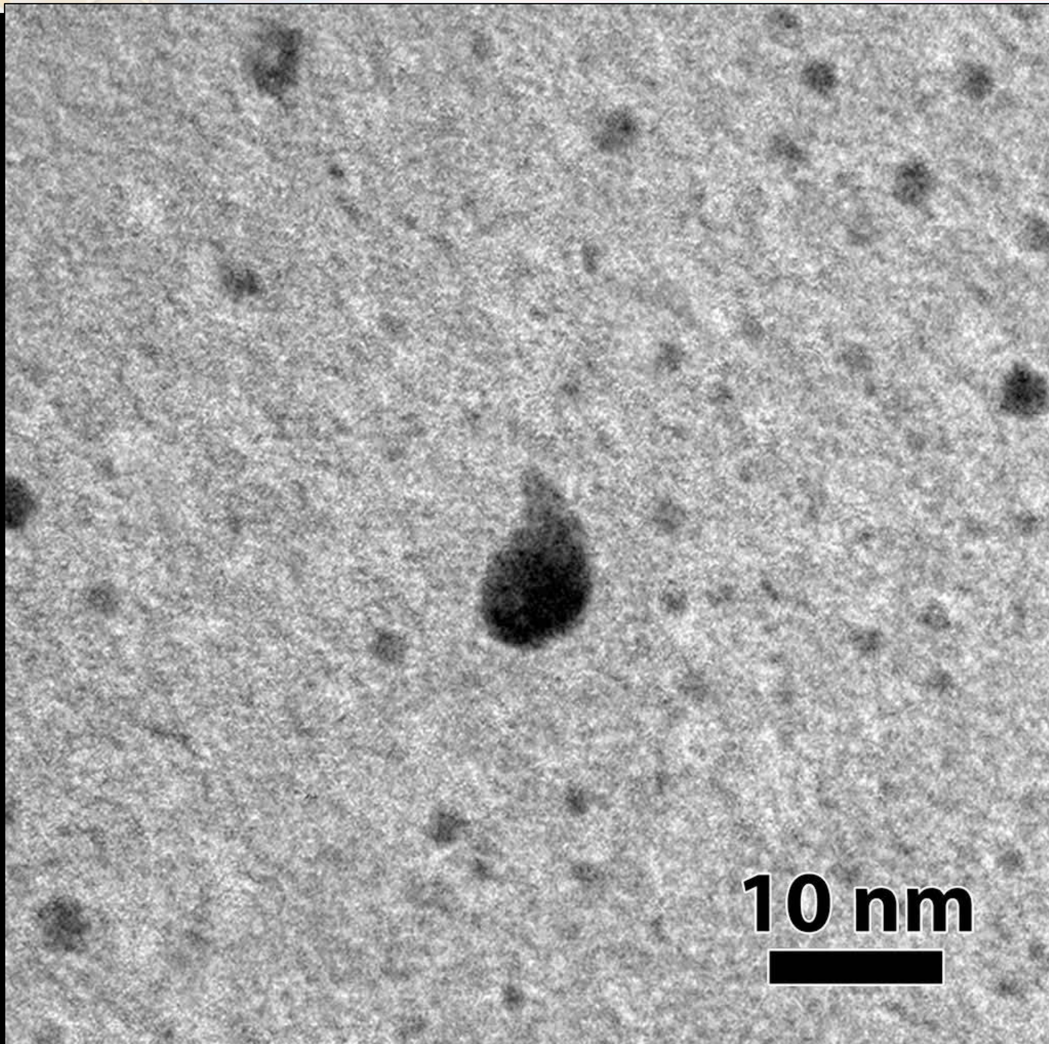
IBIL from a quartz stage inside the TEM

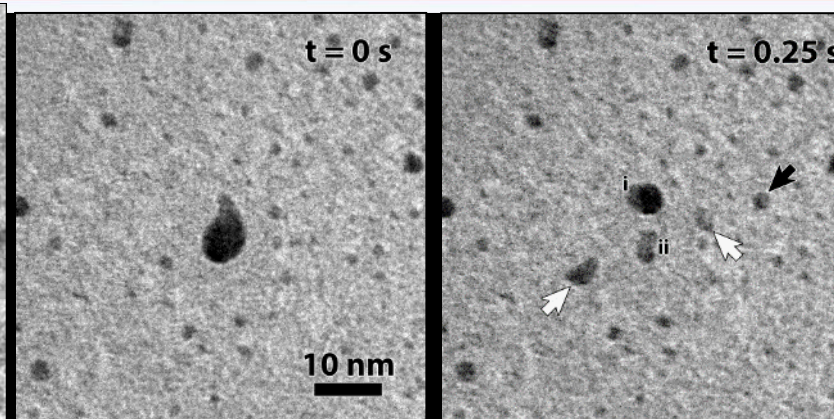


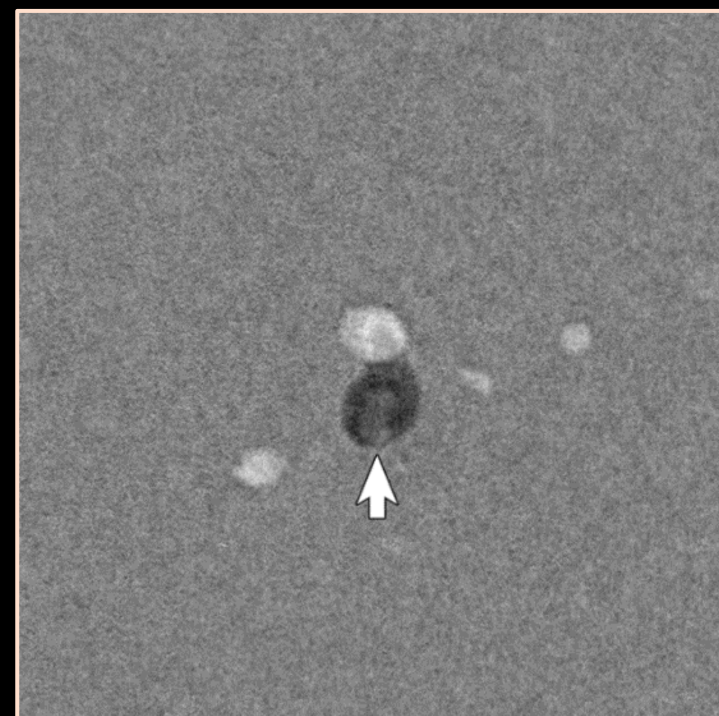


Single Ion Strikes:
46 keV Au^{1-} ions into ~5 nm Au nanoparticles

Collaborator: D.C. Bufford







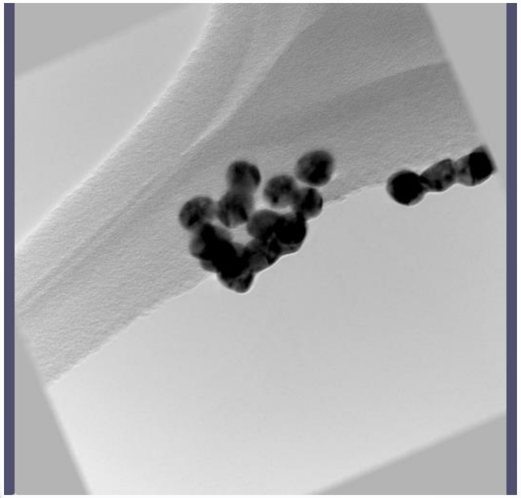
Electron Tomography Provides 3D Insight

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

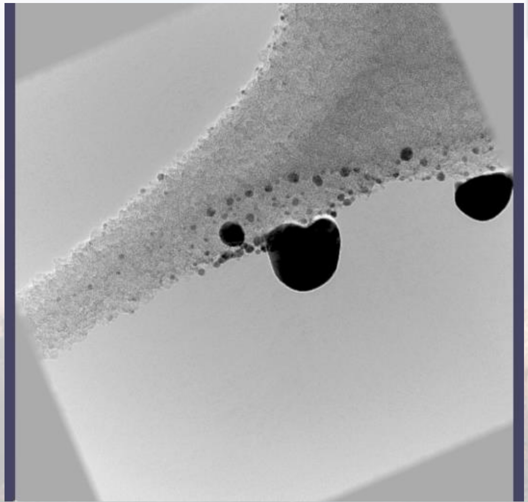
***In situ* Ion Irradiation TEM (I^3TEM)**

Hummingbird tomography stage

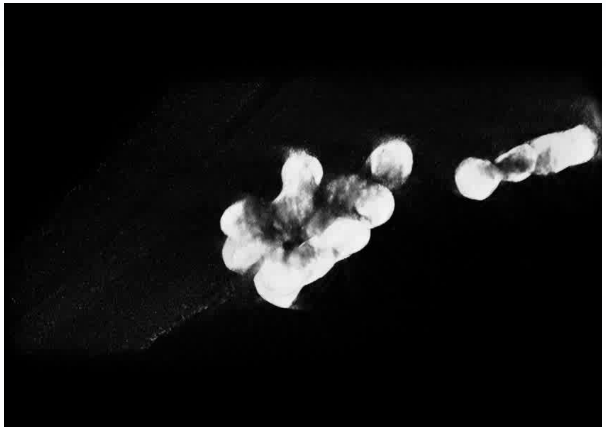
Aligned Au NP tilt series - unirradiated



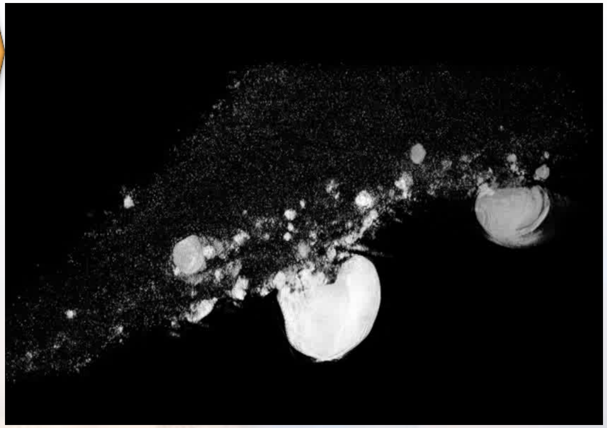
Aligned Au NP tilt series - irradiated



Unirradiated Au NP model



Irradiated Au NP model

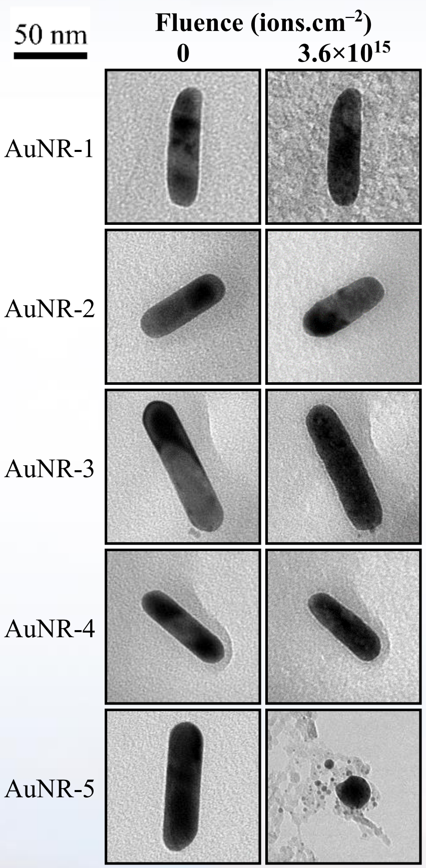


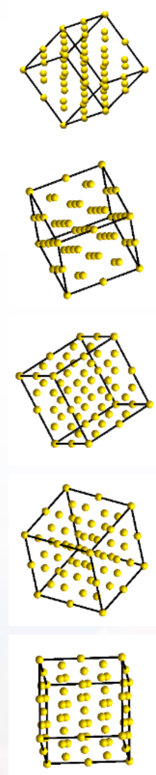
The application of advanced microscopy techniques to extreme environments provides exciting new research directions

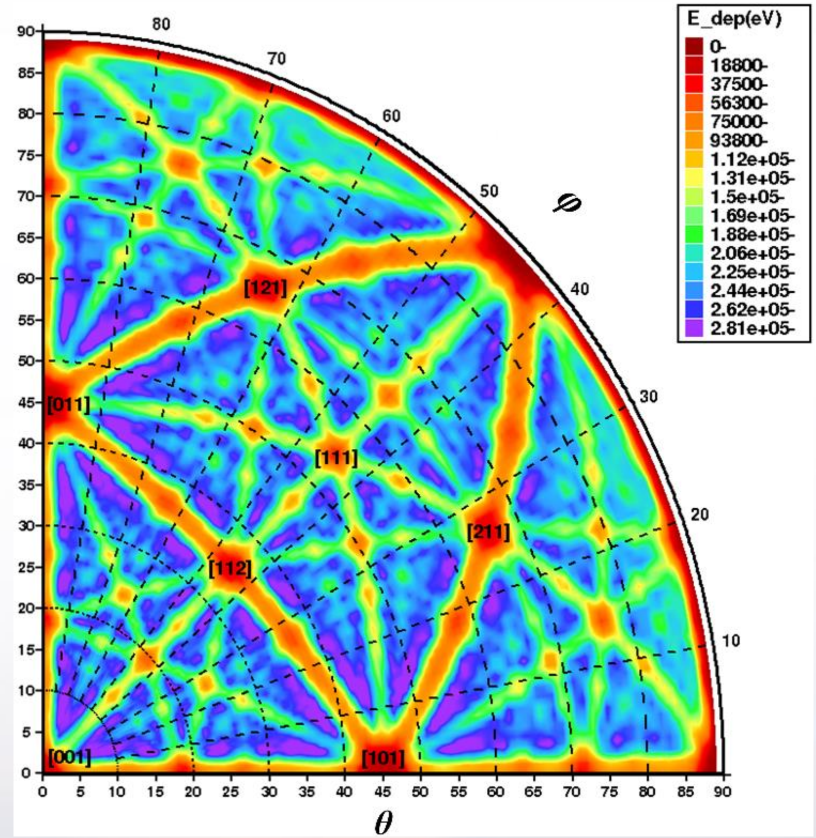
Exploring Radiation effects in Au Nanorods

Collaborators: J. A. Hinks, F. Hibberd, A. Ilinov, D. C. Bufford, F. Djurabekova, G. Greaves, A. Kuronen, S. E. Donnelly & K. Nordlund

	Fluence (ions.cm^{-2}) 0	Fluence (ions.cm^{-2}) 3.6×10^{15}	Sputtering ΔV (%)	Sputtering Atoms.ion^{-1}	Irradiation orientation: Model view	θ	φ
AuNR-1			+8.1%	–2.1		39.1°	21.9°
AuNR-2			+3.5%	–1.0		42.8°	13.7°
AuNR-3			+1.5%	–0.3		25.6°	30.1°
AuNR-4			–1.2%	0.3		59.6°	46.0°
AuNR-5			–89.7%	30.1		18.5°	75.4°







Direct Coupling of *In situ* Experiments and MD simulations Demonstrates Crystal Orientation Matters!

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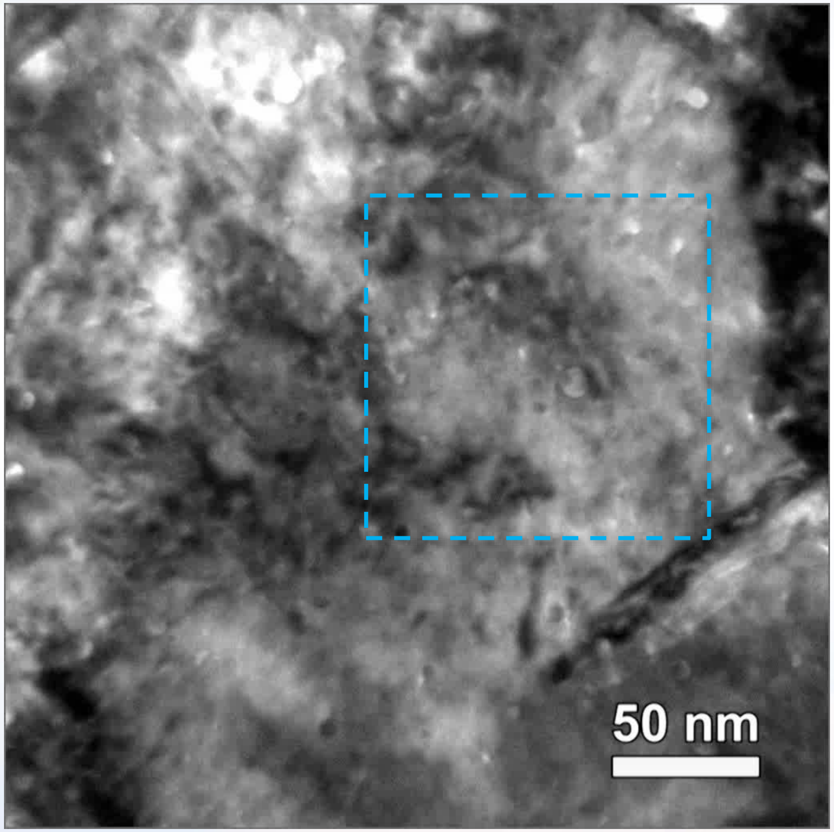
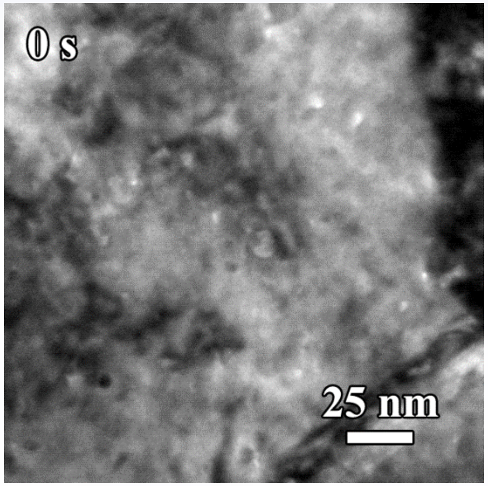
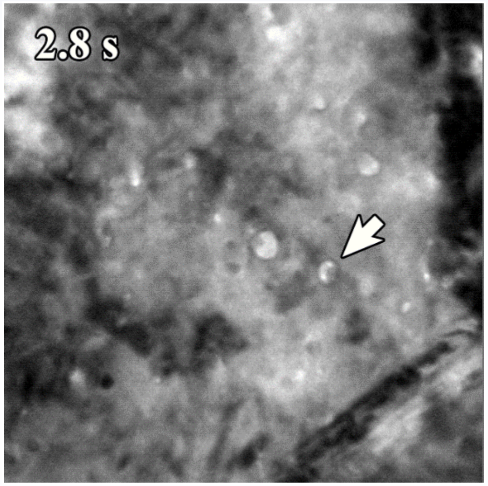
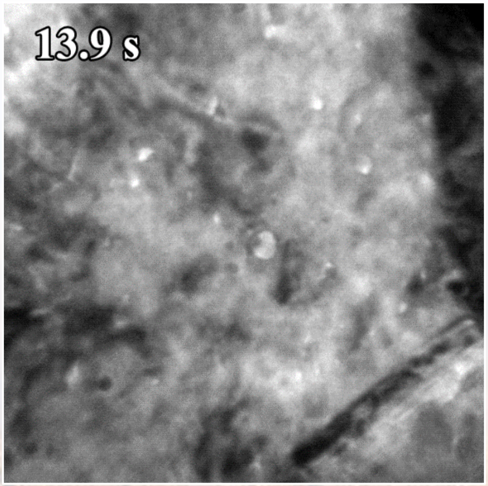
Simultaneous *In situ* TEM Triple Beam: 2.8 MeV Au^{4+} + 10 keV He^{+}/D_2^{+}

Collaborator: D.C. Bufford









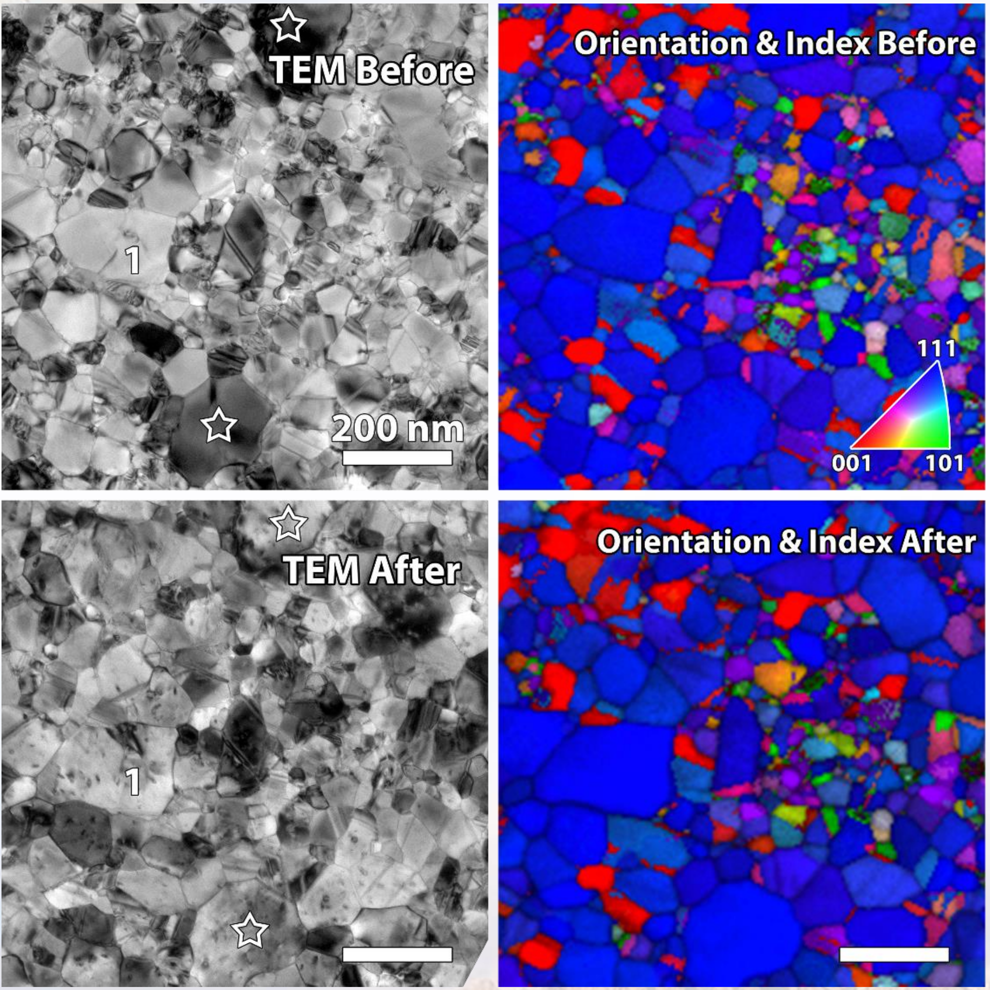
In situ triple beam He, D_2, and Au beam irradiation has been demonstrated on Sandia's I^3TEM! Intensive work is still needed to understand the defect structure evolution that has been observed.

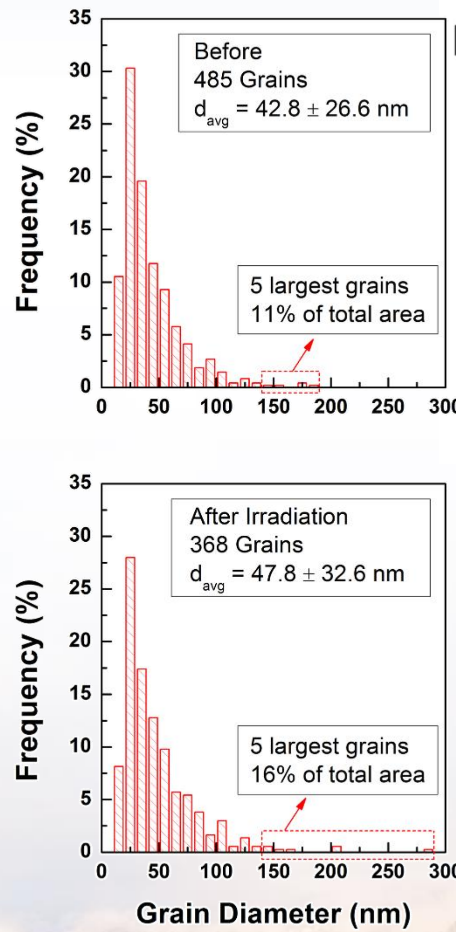
Speed x1.5

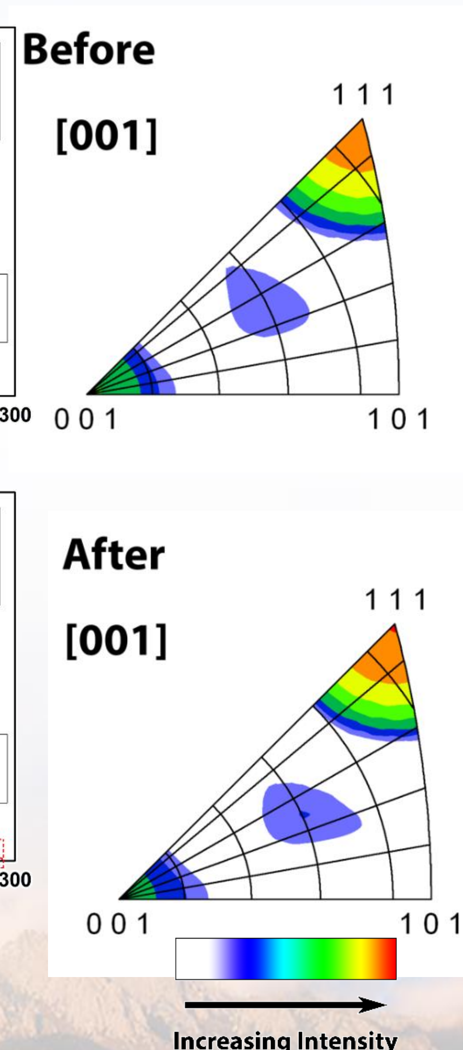
- **Approximate fluence:**
  - Au 1.2 $\times 10^{13}$ ions/cm^2
  - He 1.3 $\times 10^{15}$ ions/cm^2
  - D 2.2 $\times 10^{15}$ ions/cm^2
- **Cavity nucleation and disappearance**

Quantifying Grain Boundary Radiation Stability of Nanocrystalline Au

Collaborators: D.C. Bufford, F. Abdeljawad, & S.M. Foiles





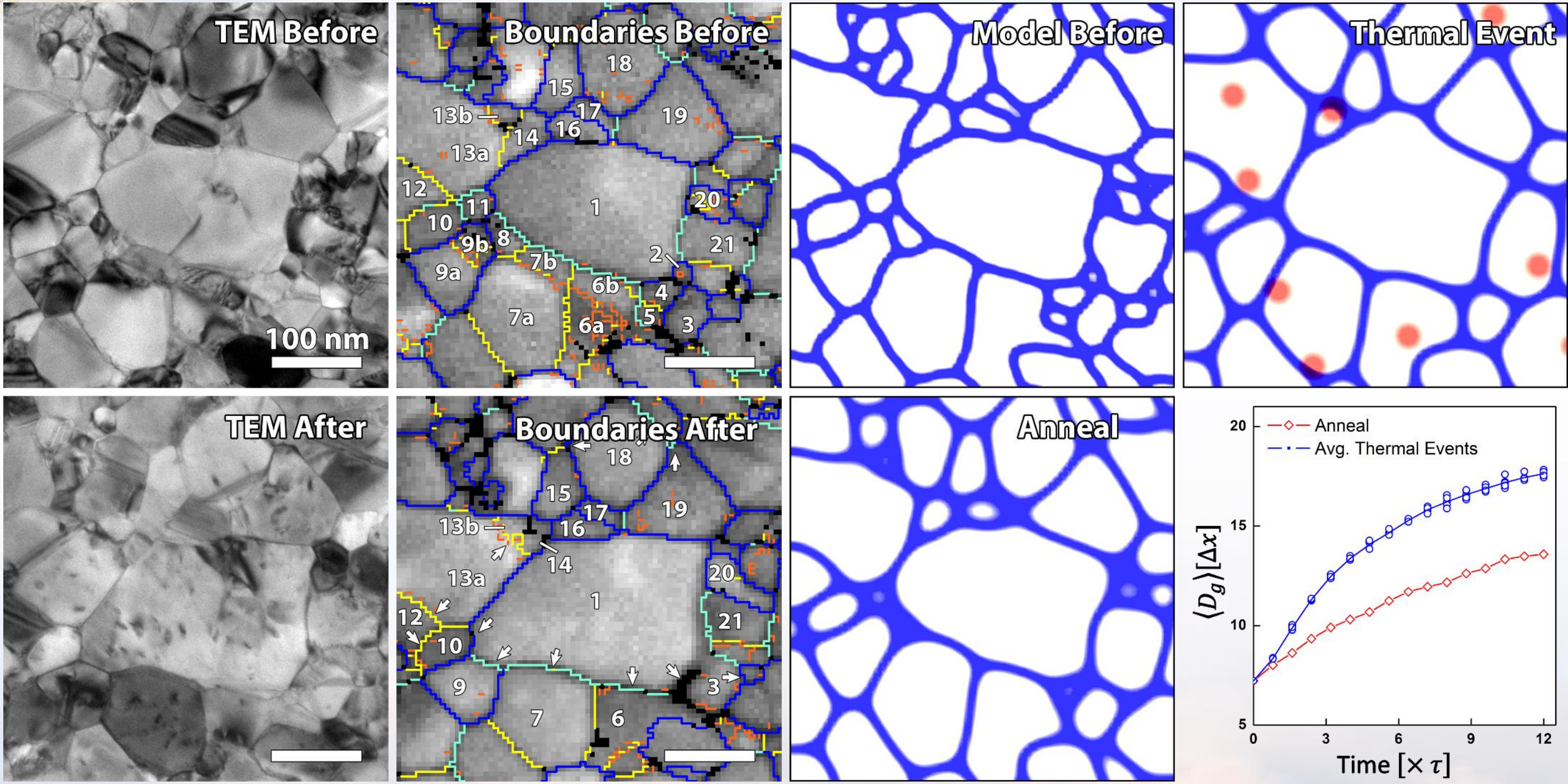


10 MeV Si

Any texture or grain boundary evolution can be directly observed and quantified

Direct Comparison to Mesoscale Modeling

Collaborators: D.C. Bufford, F. Abdeljawad, & S.M. Foiles



Because of the matching length scale, the initial microstructure can serve as direct input to either MD of mesoscale models & subsequent structural evolution can be directly compared.

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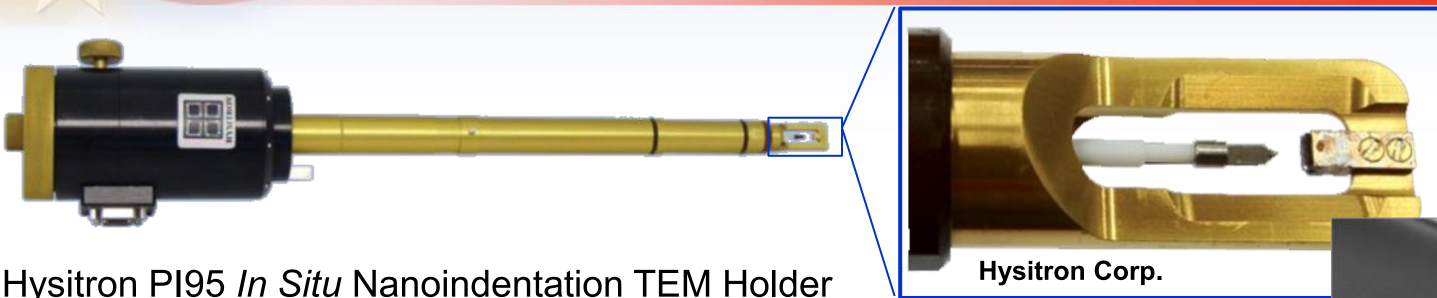
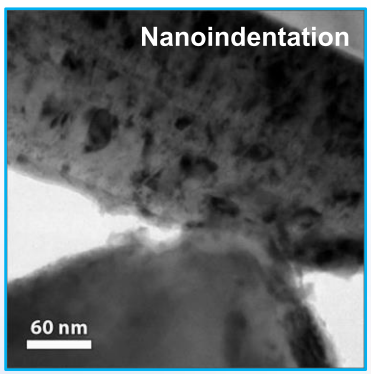
In situ Quantitative Mechanical Testing

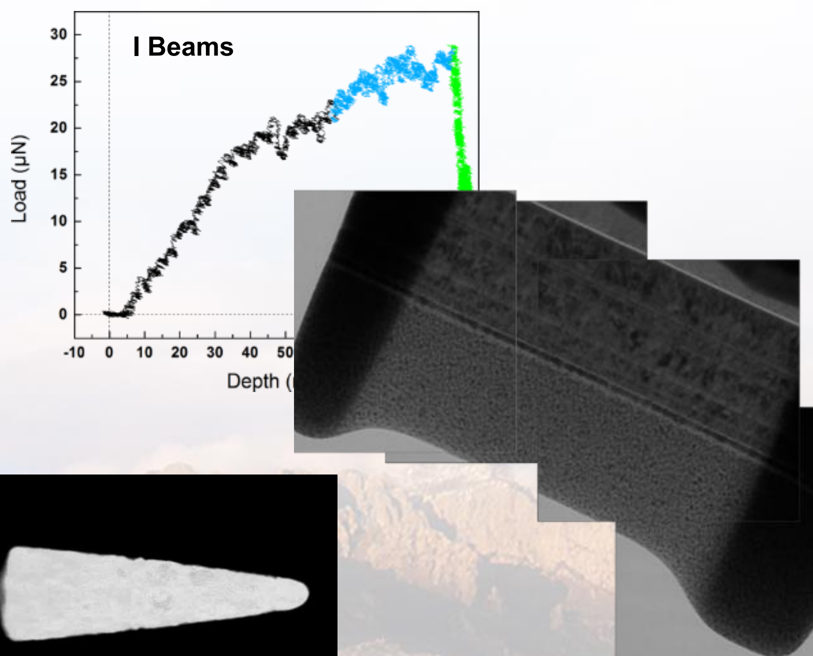
Contributors: J. Sharon, B. L. Boyce, C. Chisholm, H. Bei, E.P. George, P. Hosemann, A.M. Minor, & Hysitron Inc.

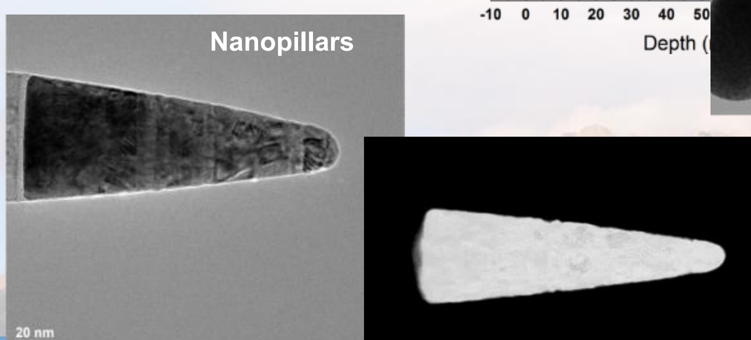


Hysitron PI95 *In Situ* Nanoindentation TEM Holder

- Sub nanometer displacement resolution
- Quantitative force information with μN resolution
- **Concurrent real-time imaging by TEM**



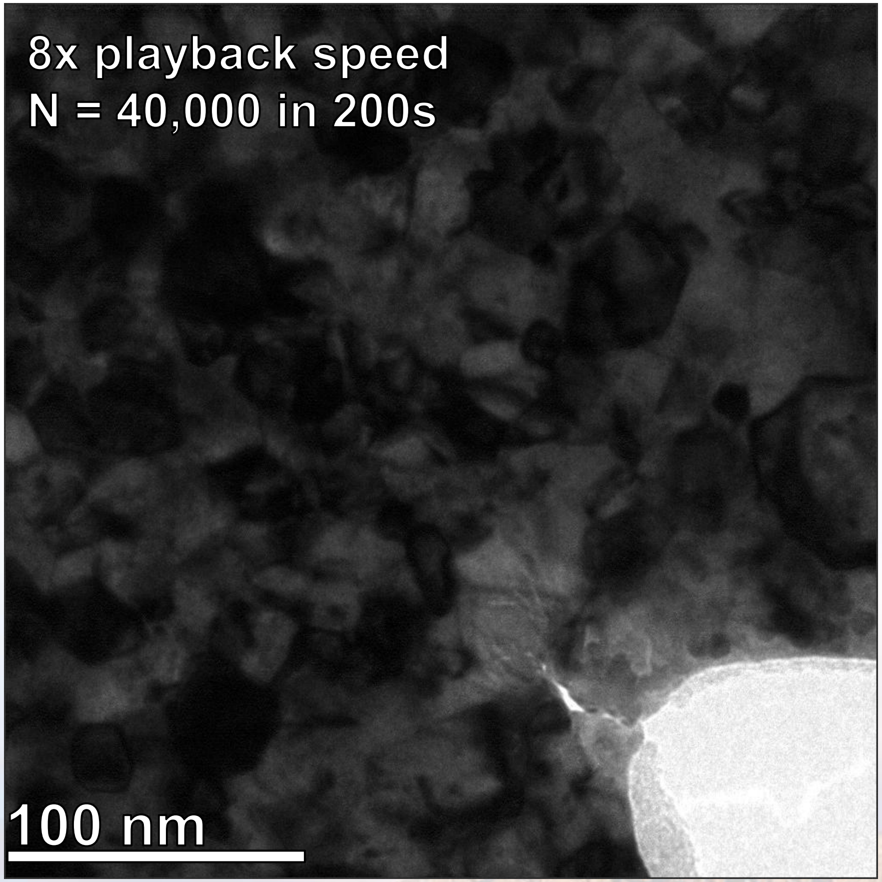




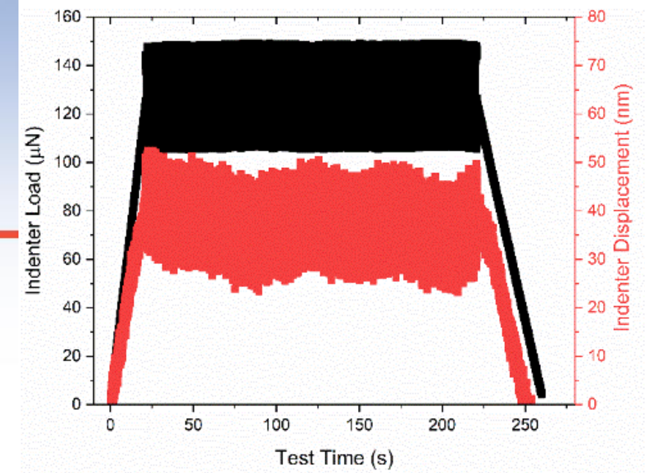
Fatigue Failure in Real Time?

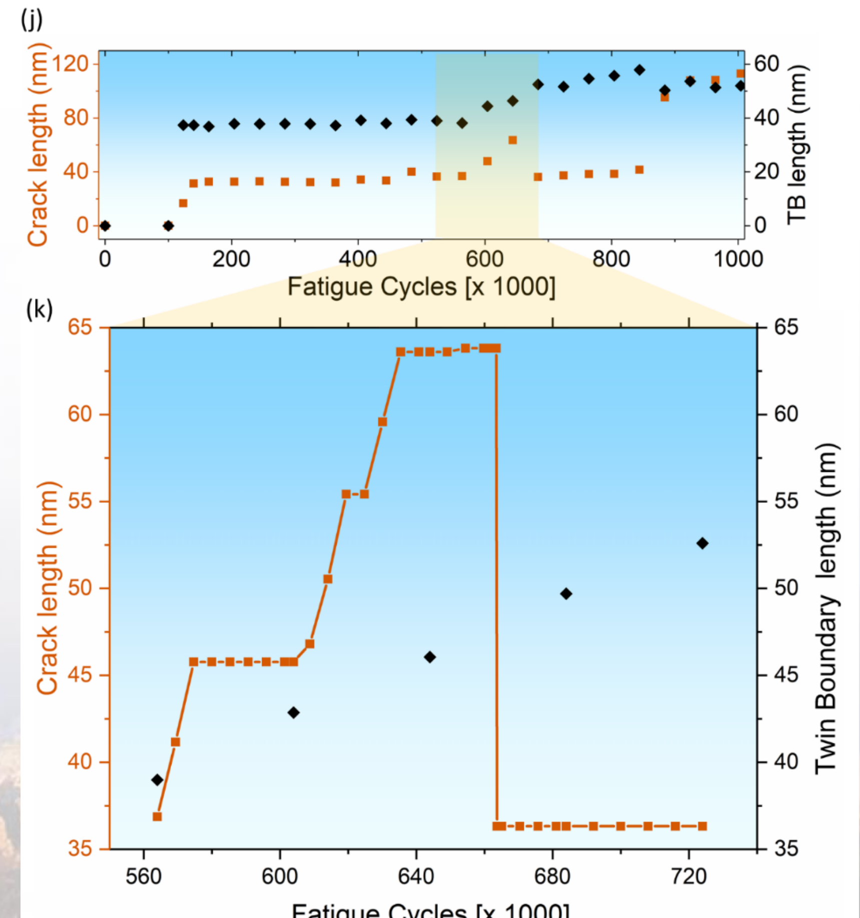
Collaborators: C. Barr, B. Boyce, & W. Mook

- Mean load: 135 uN; Amplitude load: 35 uN
- 200 Hz, 200s test (15 fps 1k x 1k camera)



~ 2 pm/cycle

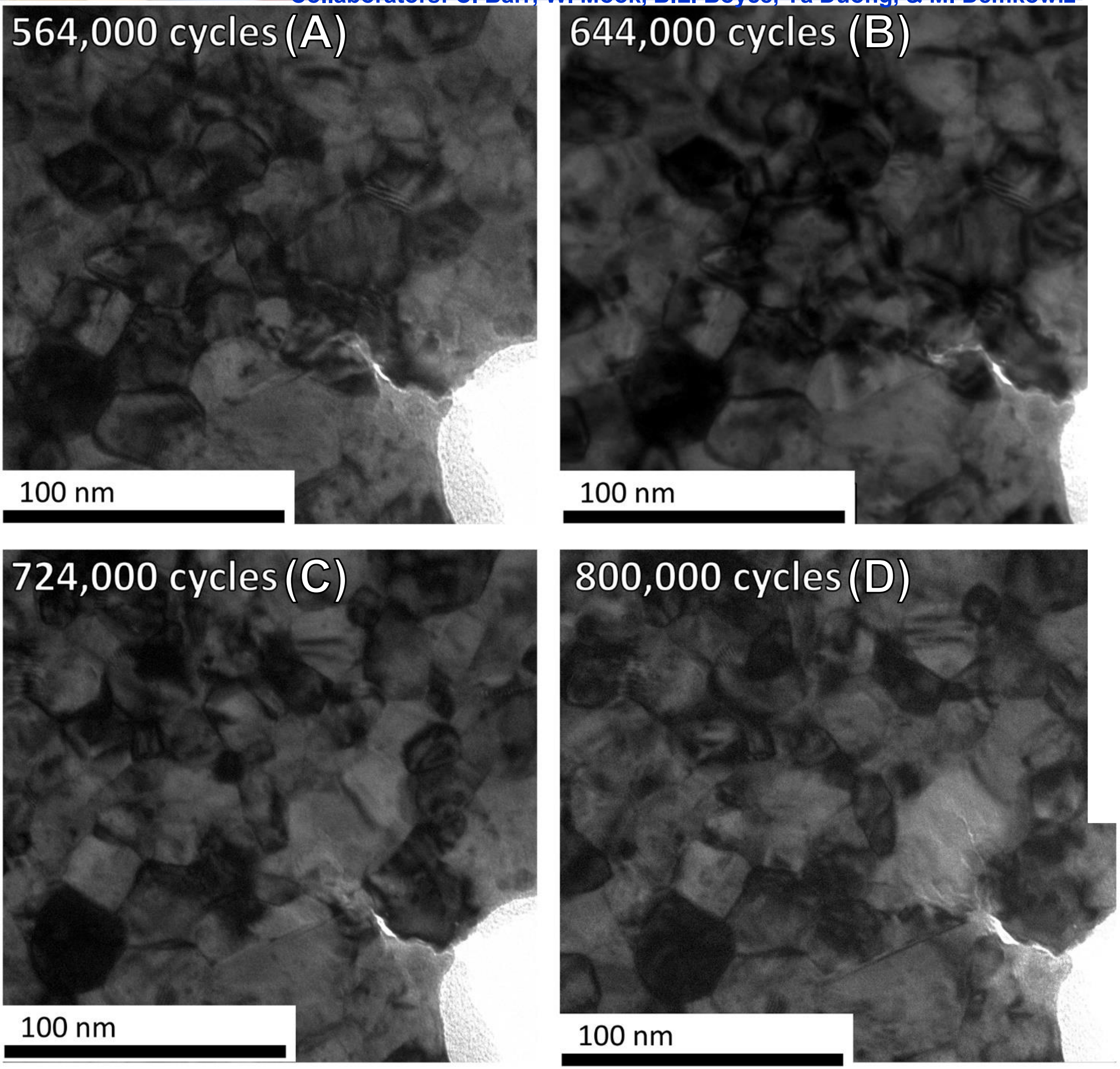


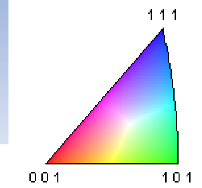


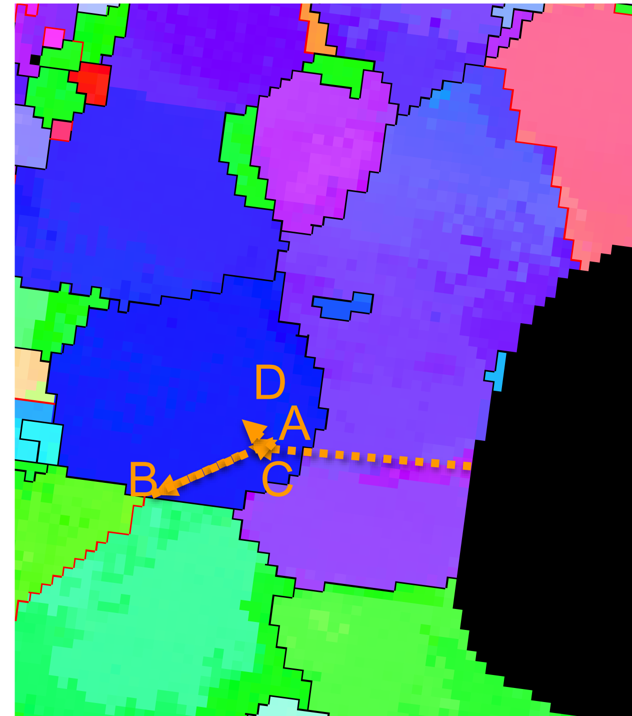
- da/dN = 1.7×10^{12} m/cycle
- Non-linear crack extension rate
- Crack propagation path changes “direction”

Crack Propagation, Closure, and Re-Direction

Collaborators: C. Barr, W. Mook, B.L. Boyce, Ta Duong, & M. Demkowiz

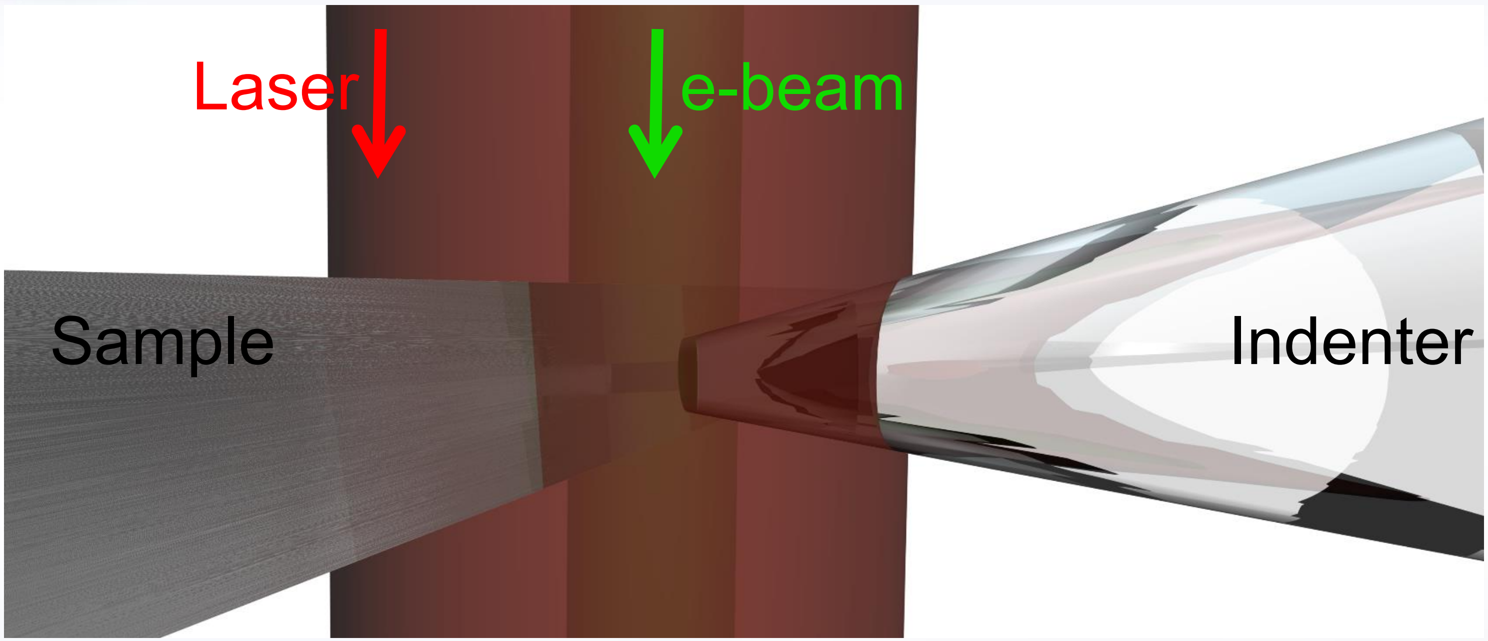


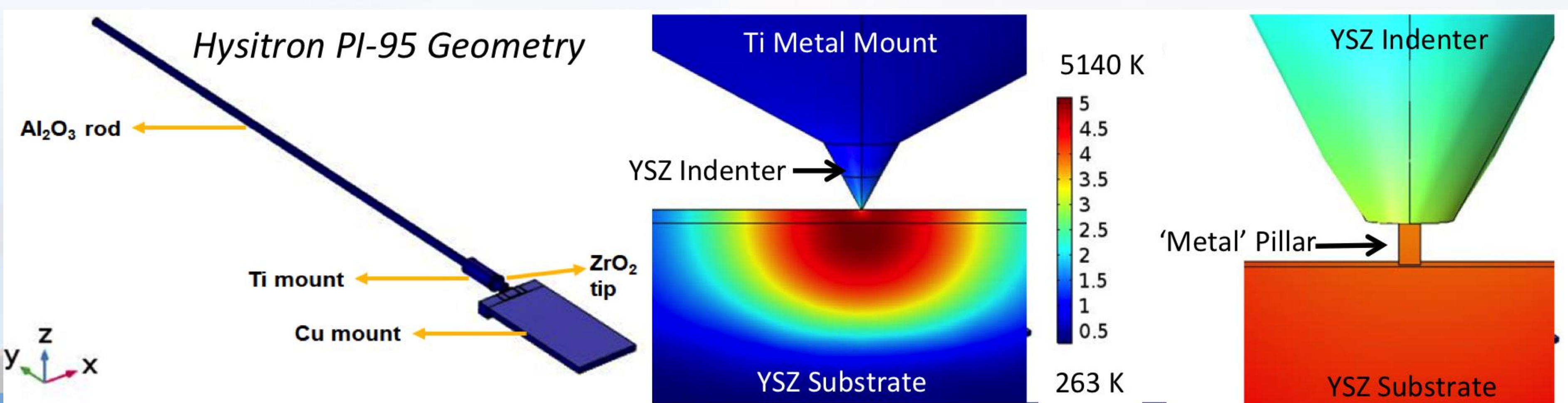




Can we Combine Laser Heating with Mechanical Testing?

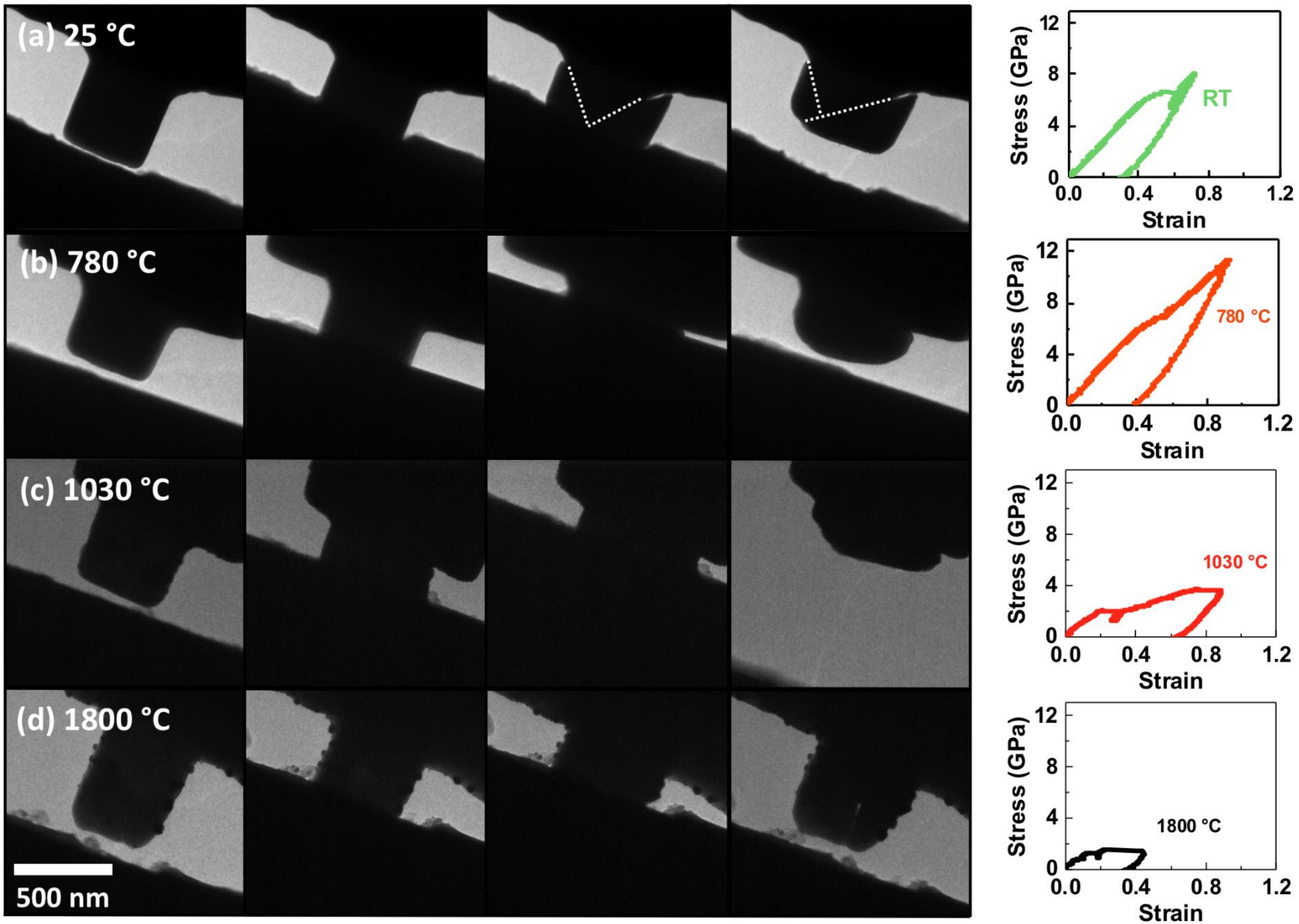
Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon





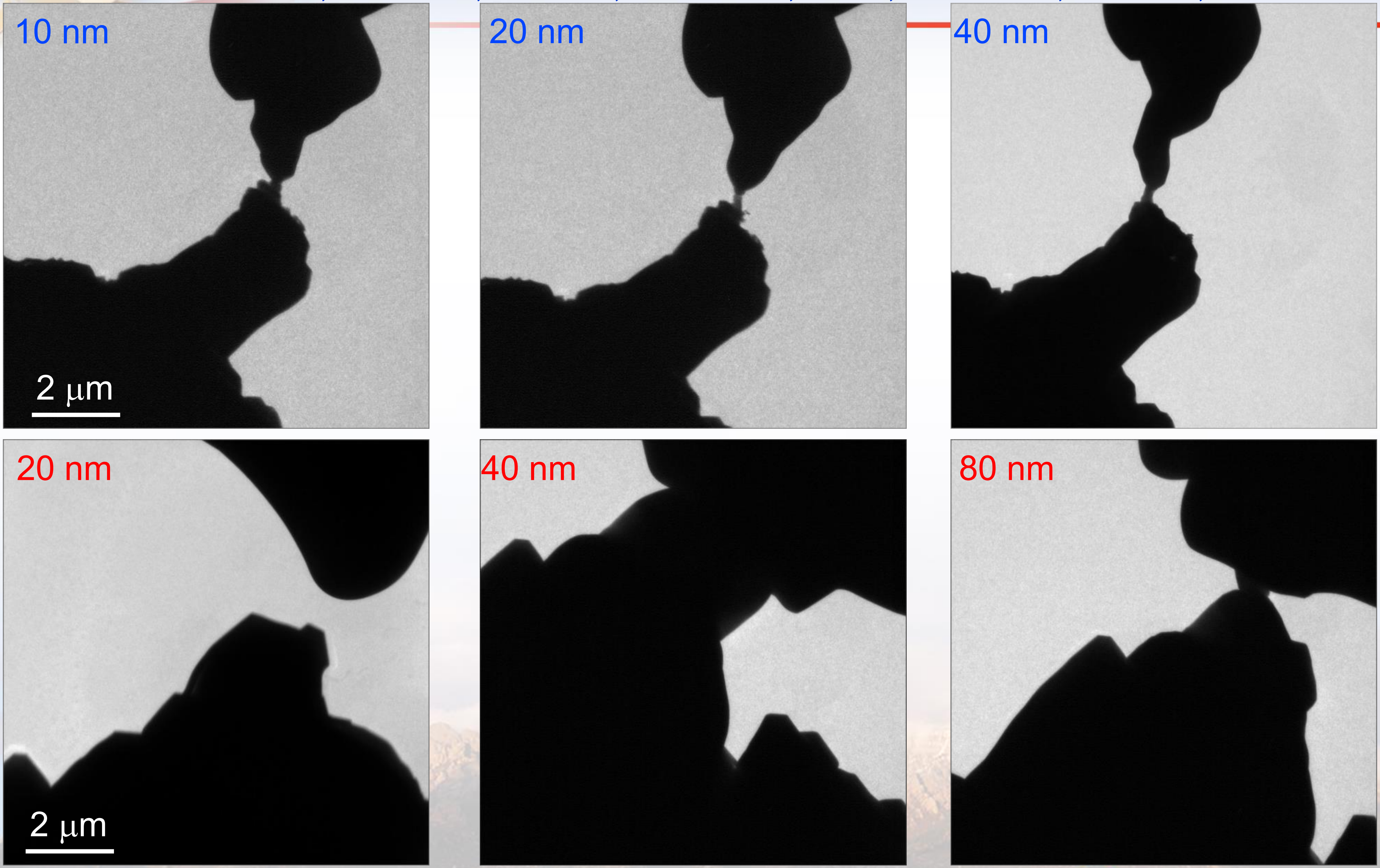
High Temperature Stress-Strain

Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon



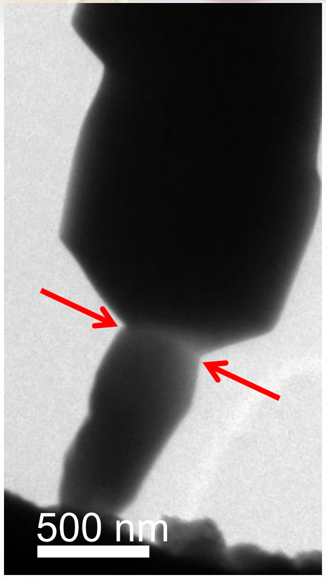
Pushing the Laser Limit - 1604 °C and 2056 °C ScSZ-ScSZ

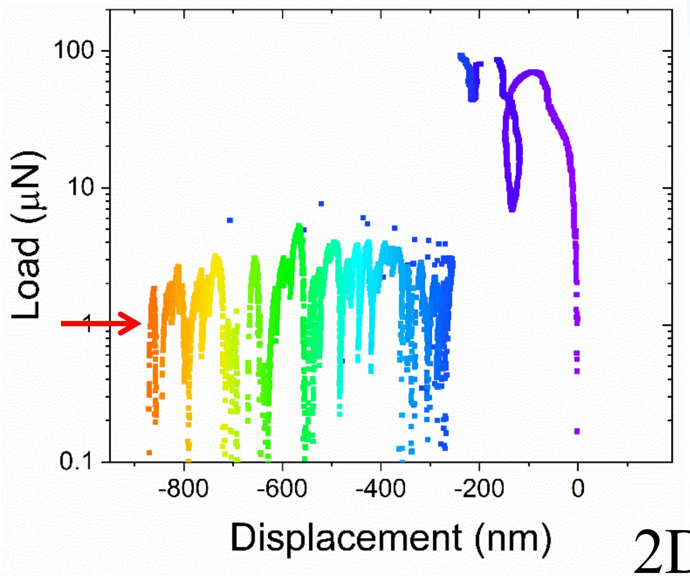
Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon

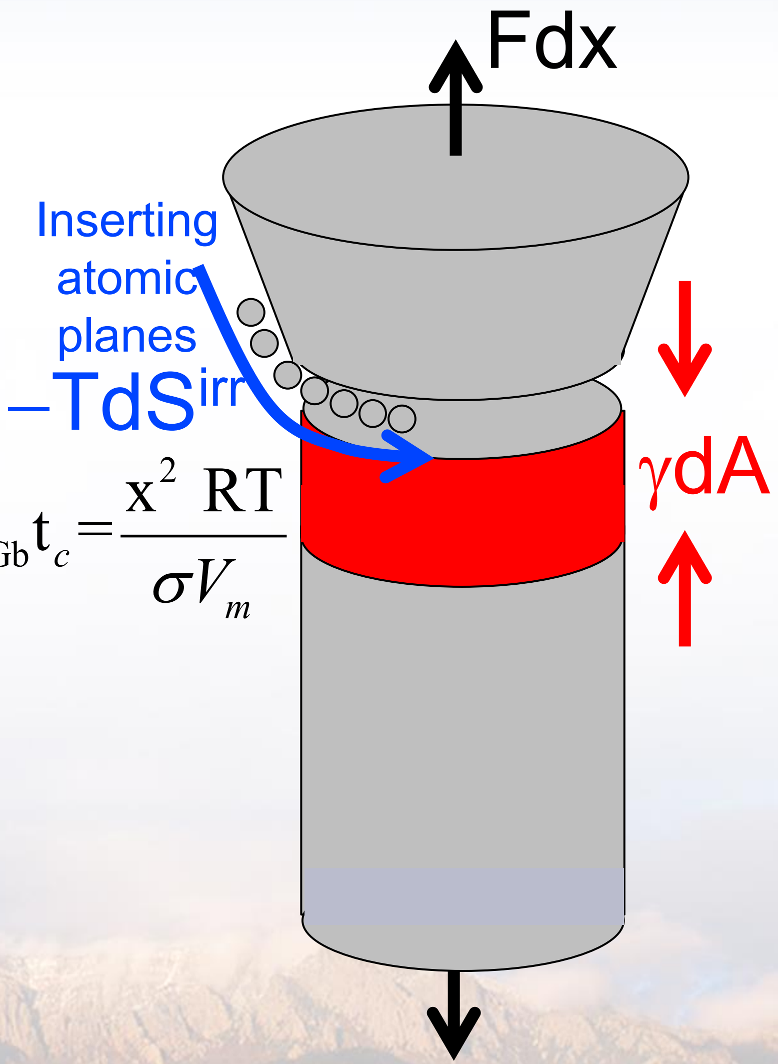


Mechanism for Fiber Growth

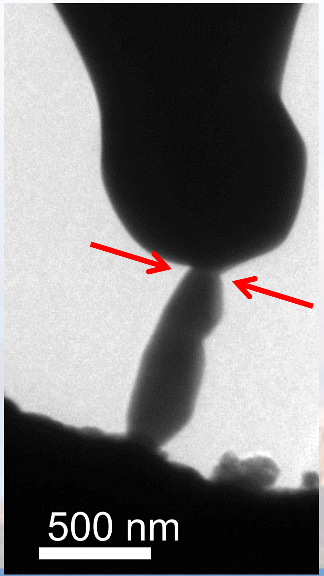
Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon

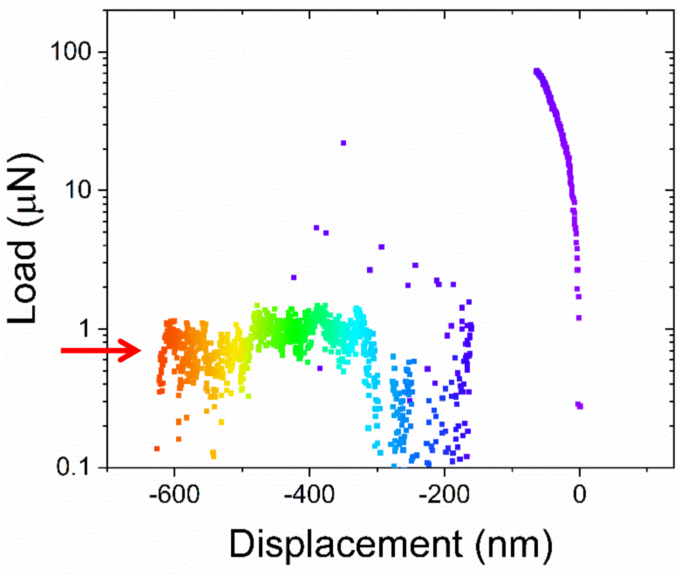






$$2D_{Gb}t_c = \frac{x^2\ RT}{\sigma V_m}$$



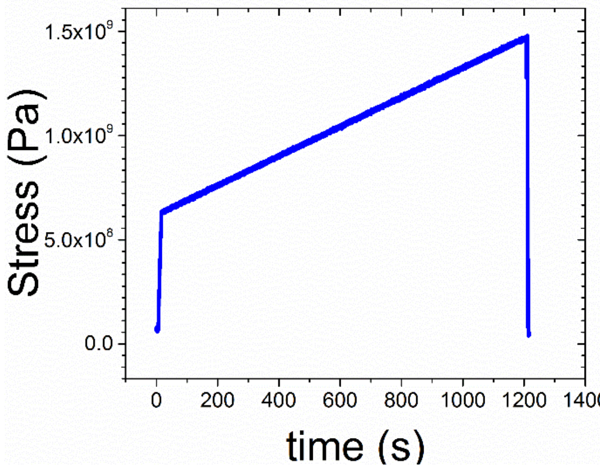


In situ TEM Ion Irradiation + Mechanical Testing = *In situ* TEM Irradiation Creep

Contributors: G.S. Jawaharram, S. Dillon & R.S. Averback

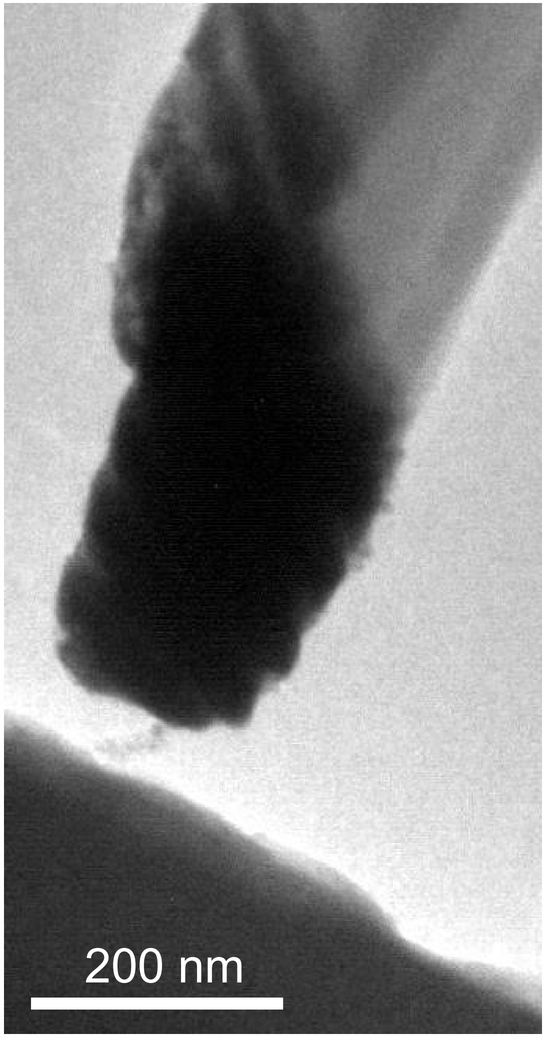
Controlled Loading Rate Experiments

4 MeV Cu^{3+}
10^{-2} DPA/s

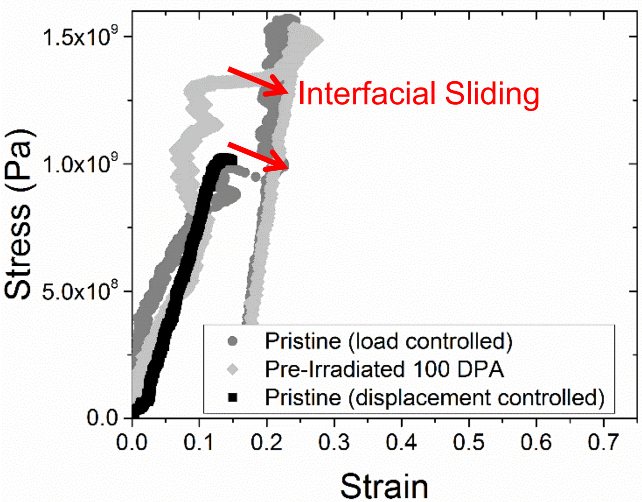


In-situ TEM radiation creep is feasible!

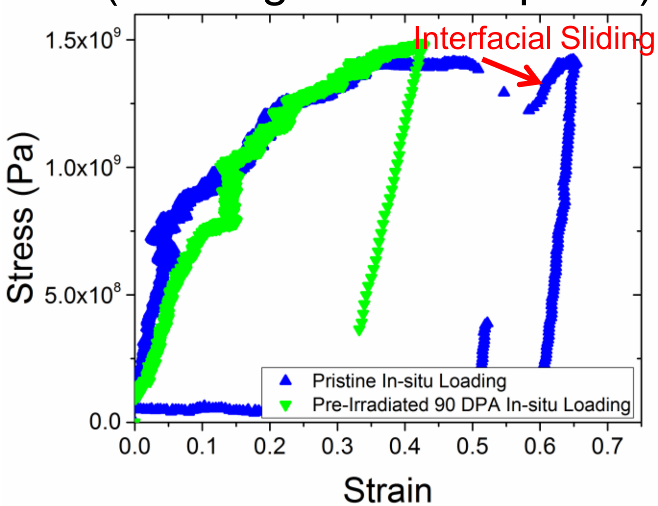
50 nm Cu-W multilayer
20 Min



No Irradiation
(Loading rate 0.6 Mpa s^{-1})



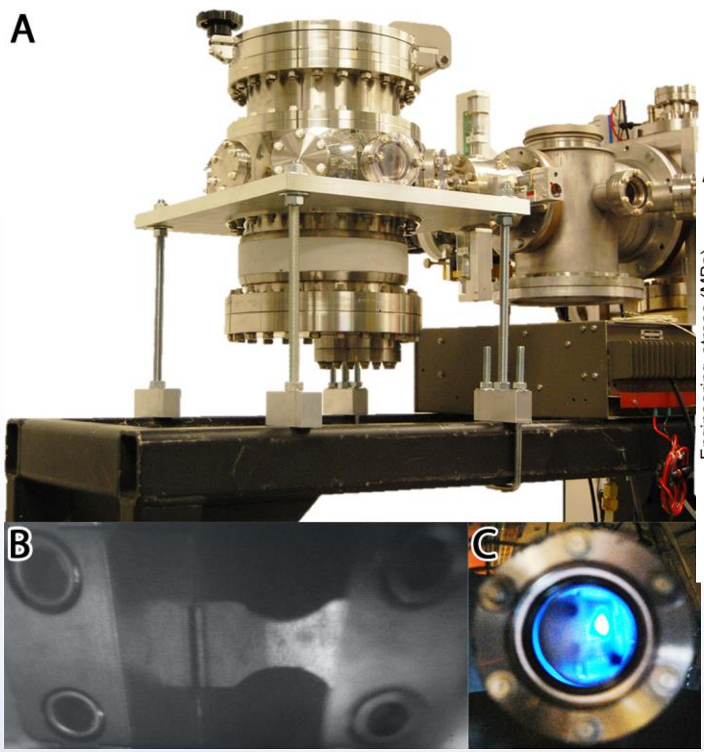
Irradiation Creep
(Loading rate 0.6 Mpa s^{-1})

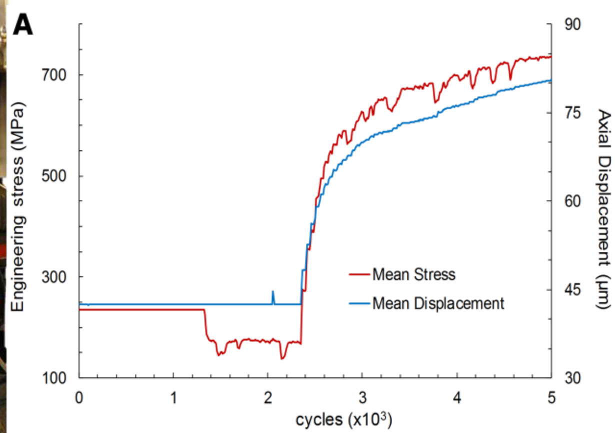


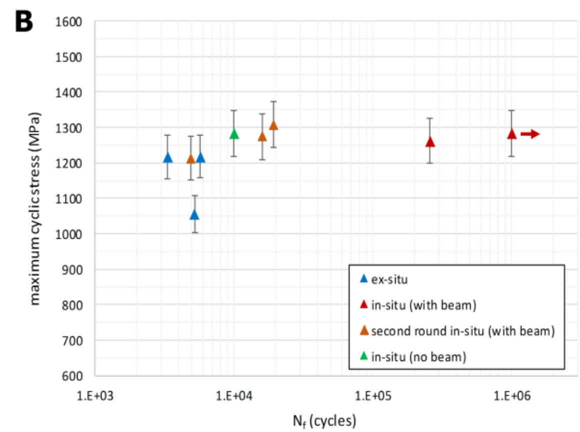
Ex situ Mechanical Testing End Station

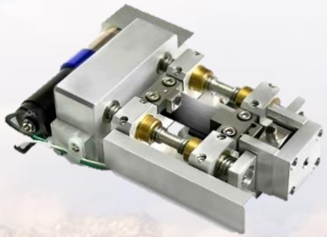
Collaborators: D. Buller, B. Boyce, J. Carroll, P. Price, C. Taylor, B. Muntifering, S. Briggs, N. Heckman, J.A. Scott

- Combined three individual mechanical testing in tandem beamline end station
- Limited (optical, IR only) imaging capabilities
- Have successfully collected preliminary data using this system



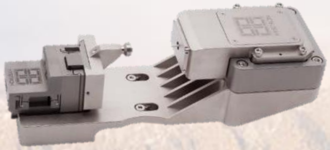


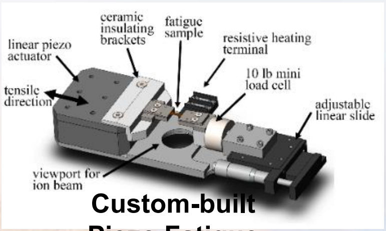




MTI Fullam Straining Heating

Hysitron PI85 Nanoindenter



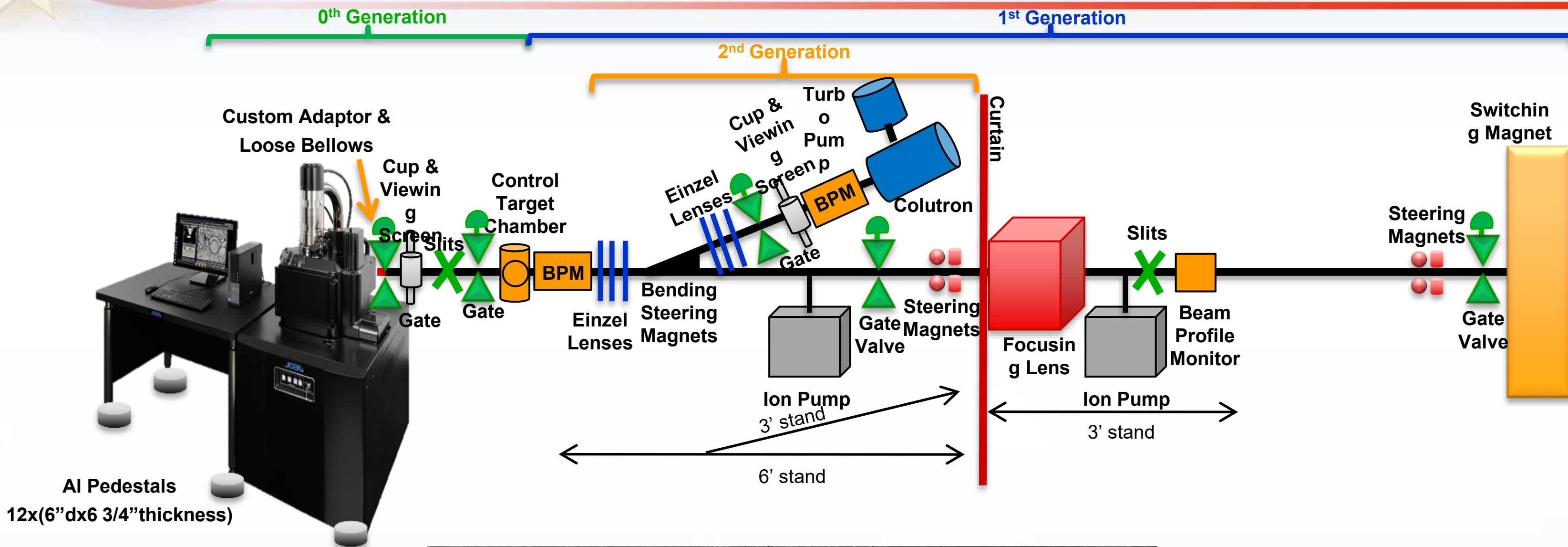


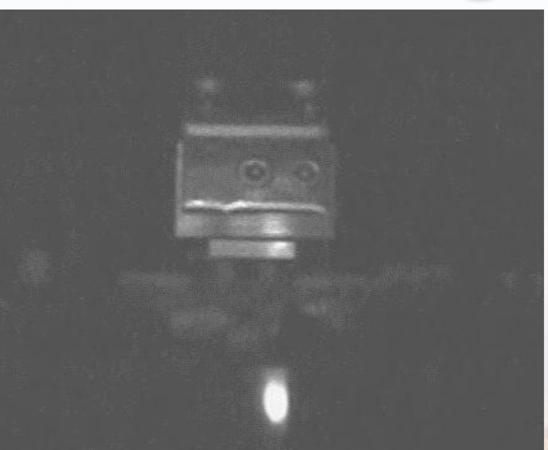
Custom-built Piezo Fatigue tester

Gatan Cryostage

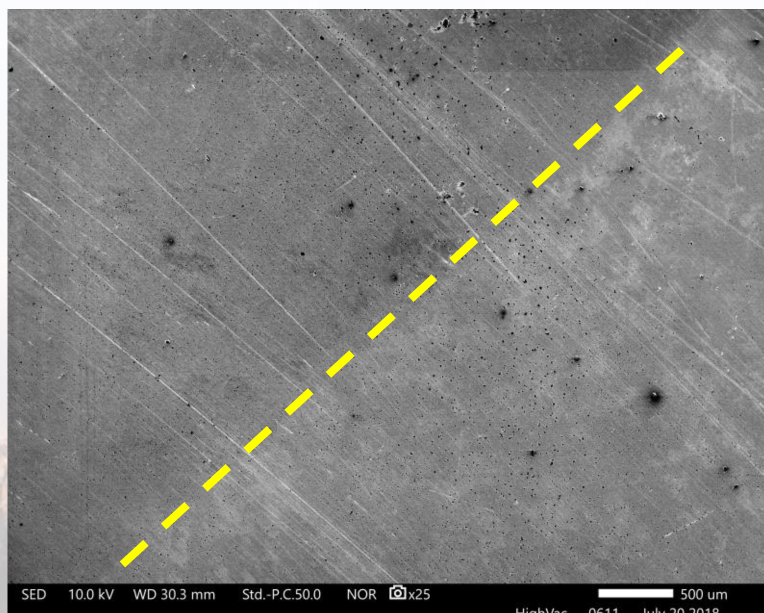
Heavy Ion Design and Proof of Concept

Collaborators: D. Buller, B. Boyce, J. Carroll, P. Price, C. Taylor, B. Muntifering, S. Briggs, N. Heckman, J.A. Scott





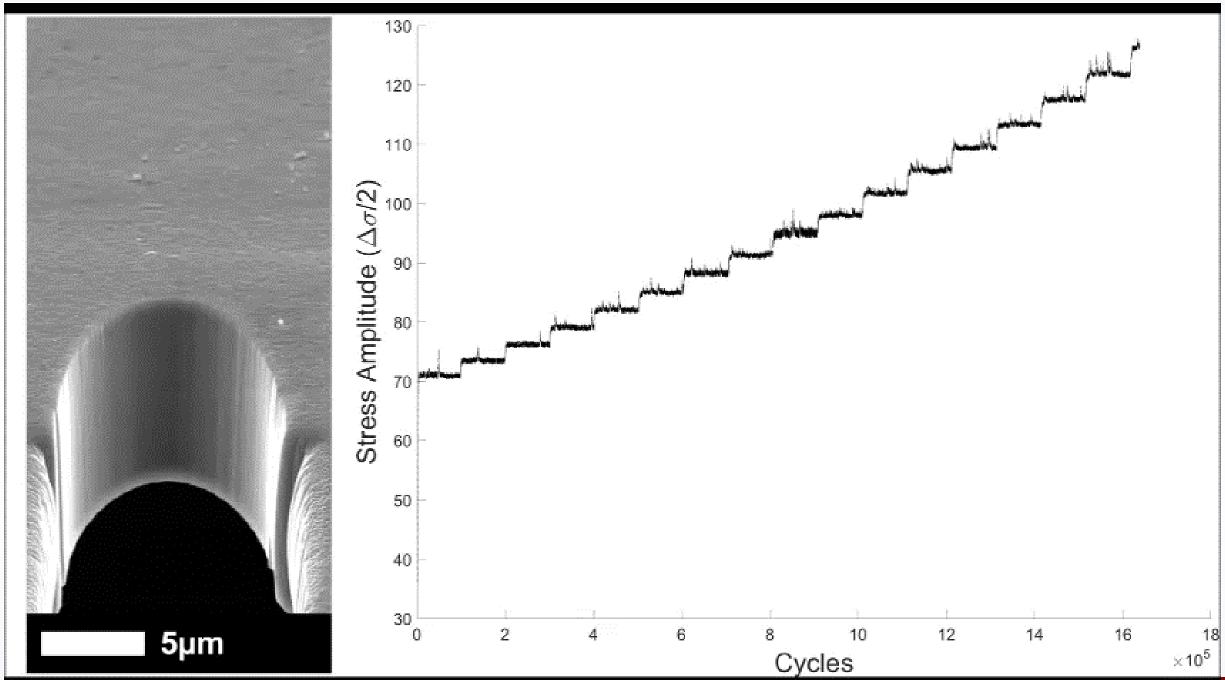
First Beam into SEM on April 6th, 2018



I³SEM planned for multiphase development. Ultimate plan is for multiple accelerators being attached for dual or triple beam experiments.

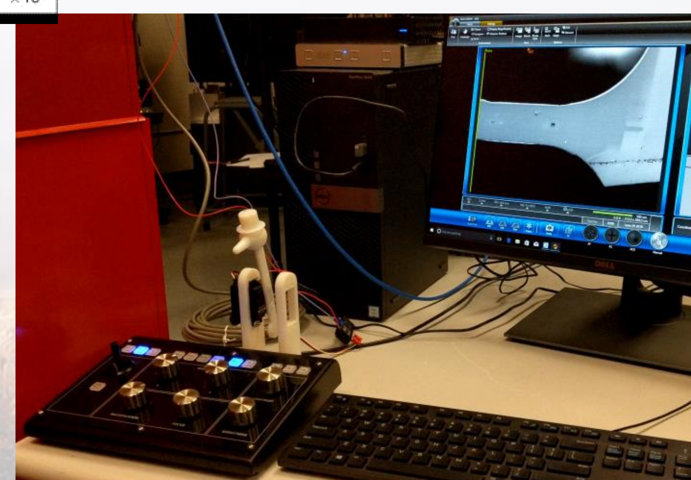
In situ High-cycle Fatigue

Collaborators: .N. Heckman, B.L. Boyce,

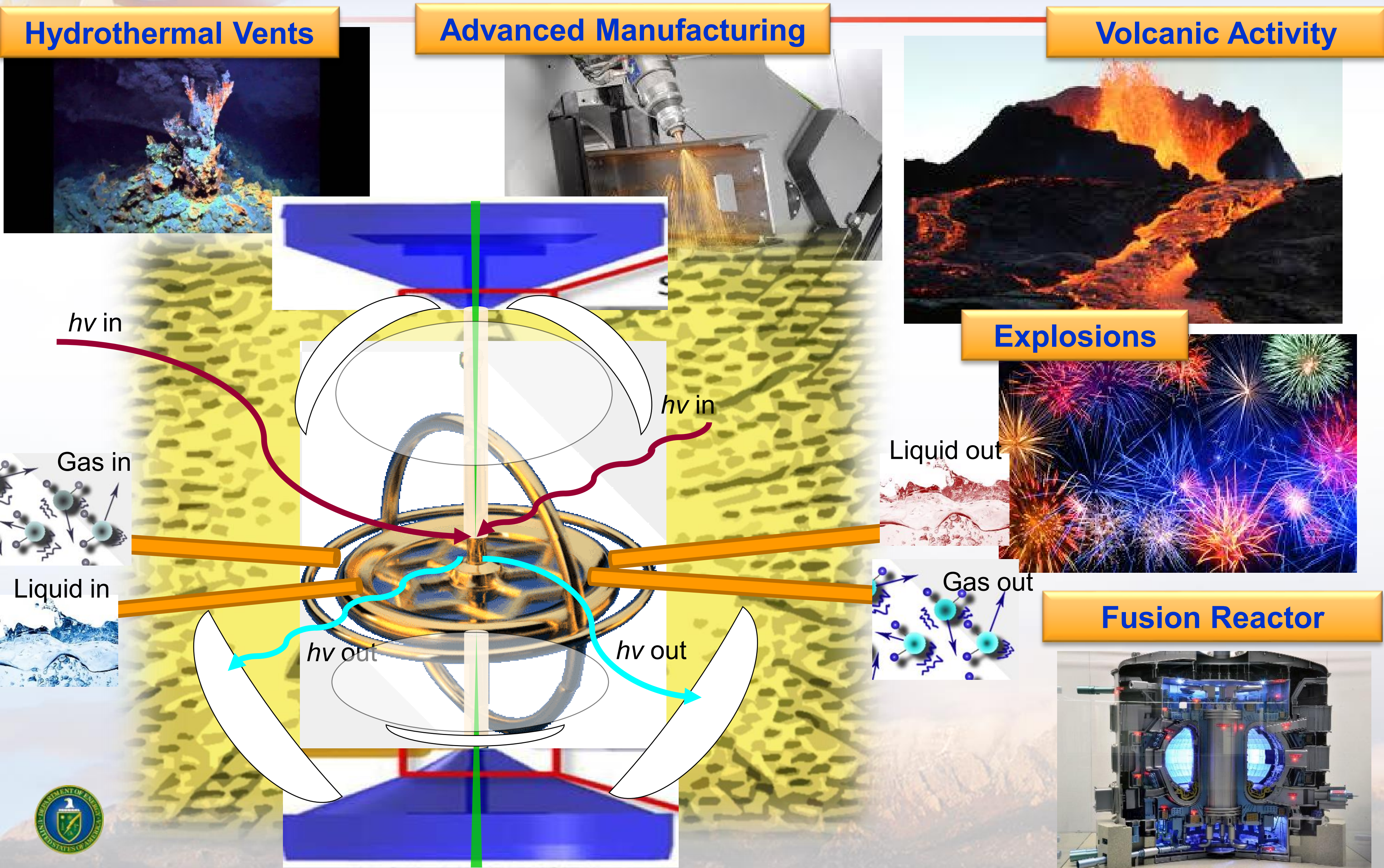


- Nanocrystalline Ni-40Fe, 10-60 nm grain size, 10 µm notch, imaged at 60˚
- Cycled at 30 Hz, 4000 cycles between images

Direct insight into crack propagation and failure during cyclic loading



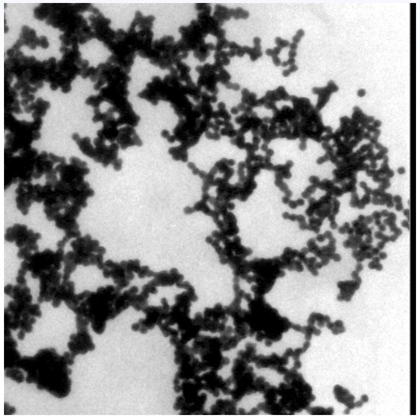
Future Vision:
Testing Greater Extremes in the TEM

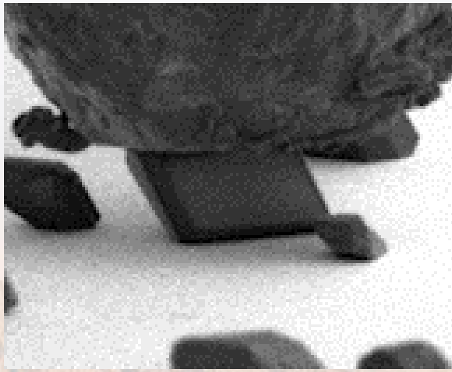


Unconventional *In situ* Microscopy Creates a Wealth of Possibilities

- Plethora of extreme environments that have not been fully explored.
- Utilizing the TEM as an experimental chamber provides a range of nanoscale extreme environments.
- Combining extreme conditions opens up the ability more complex real world applications.
- ACOM and other analytical techniques coupled with in situ observations provides a nice bridge to MD and mesoscale modeling.
- If you would like to hear about the I^3SEM let me know

The future is bright and fastly approaching for coupled *in situ* TEM





Collaborators:

D.L. Buller, D.C. Bufford, S.H. Pratt, T.J. Boyle, B.A. Hernandez-Sanchez, S.J. Blair, B. Muntifering, C. Chisholm , P. Hosemann, A. Minor, J. A. Hinks, F. Hibberd, A. Ilinov, D. C. Bufford, F. Djurabekova, G. Greaves, A. Kuronen, S. E. Donnelly, K. Nordlund, F. Abdeljawad, S.M. Foiles, J. Qu, C. Taylor, J. Sugar, P. Price, C.M. Barr, D. Adams, M. Abere, L. Treadwell, A. Cook, A. Monterrosa, IDES Inc, J. Sharon, B. L. Boyce, C. Chisholm, H. Bei, E.P. George, W. Mook, Hysitron Inc., G.S. Jawaharram, S. Dillon, R.S. Averback, N. Heckman, J. Carroll, S. Briggs, E. Carnes, J. Brinker, D. Sassaki, T. Nenoff, B.G. Clark, P.J. Cappillino, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, L.R. Parent, I. Arslan, K. Jungjohann & Protochips

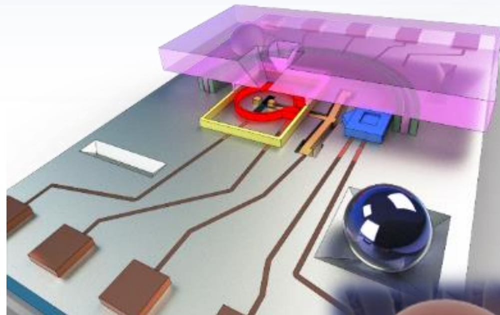
This work was partially funded by the Division of Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.

Sandia's User and Position Opportunities

D. Hanson, W. Martin, M. Wasiolek

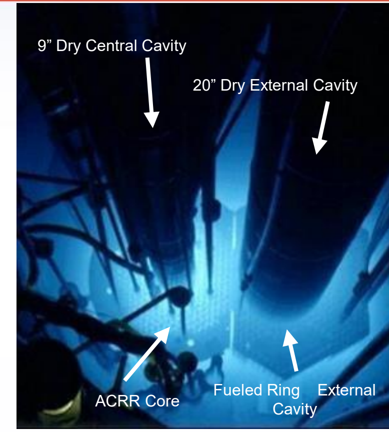
www.cint.lanl.gov

- Spring and Fall proposals for 18 months
- Rapid Access proposal anytime for 3 months



www.nsuf.inl.gov

- Three proposal a year for 9 months



Core Facility - SNL

Gateway Facility - LANL

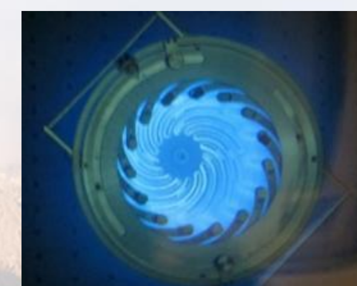
Position Oppurtunities at:

https://www.sandia.gov/careers/

Post-doc = 671121

Grad Student = 670865

Undergrad Student = 670864



This work was partially funded by the Division of Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of EnergyThis work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.

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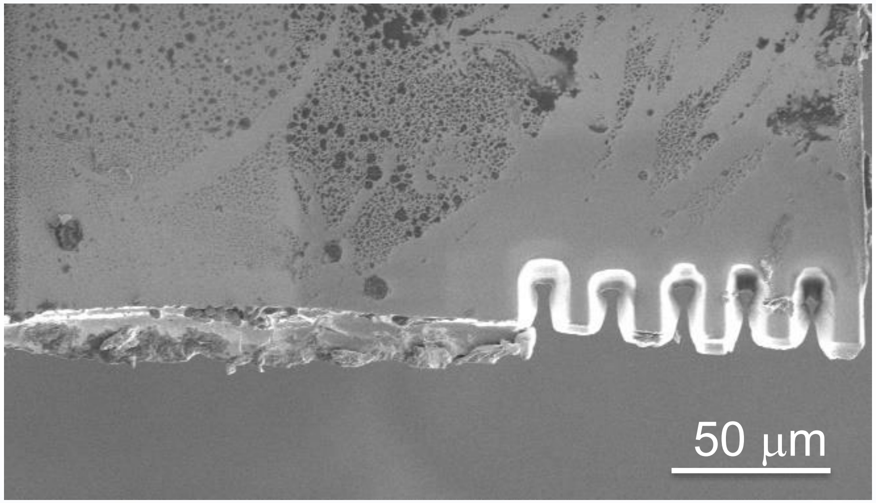
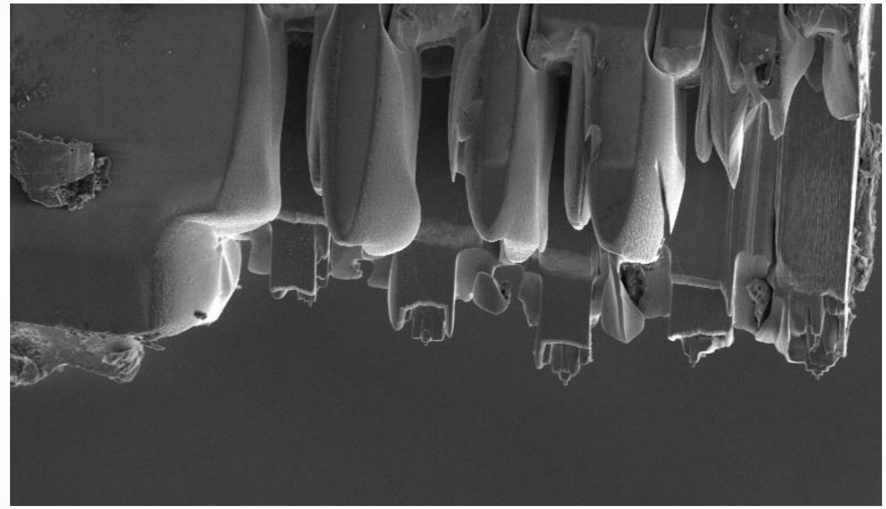
Back-up Slides

Temperature Upper Bound

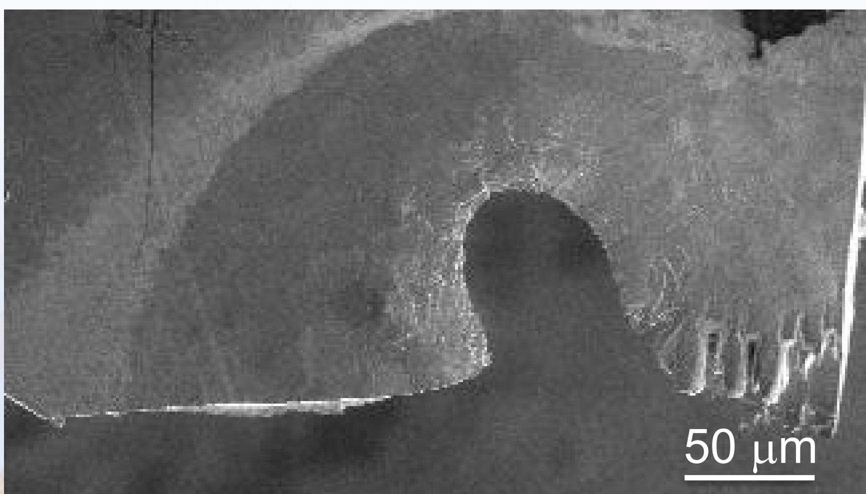
Before

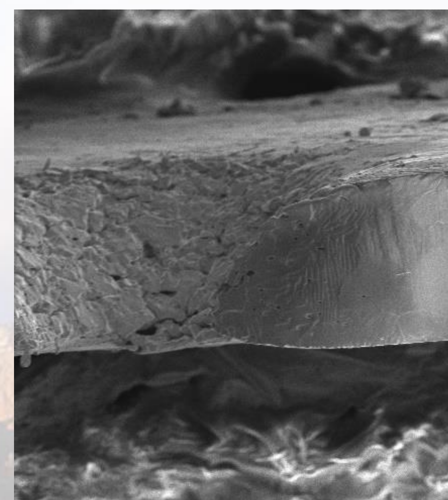
Sc_2O_3 doped ZrO_2

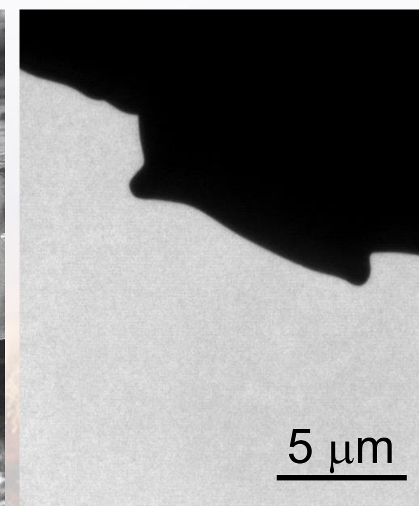




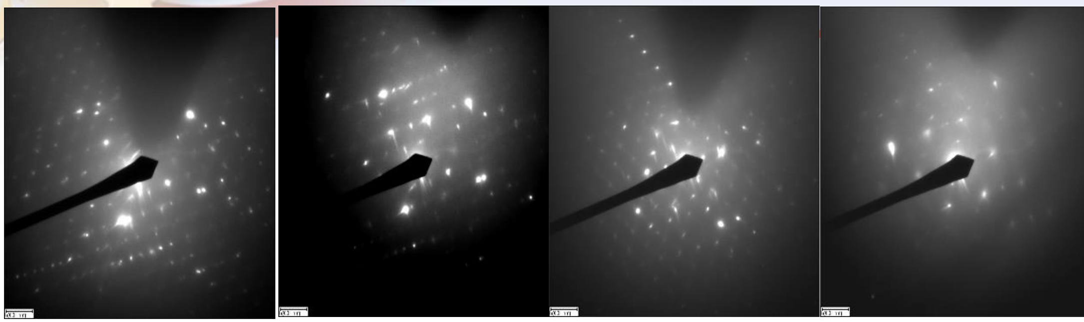
After



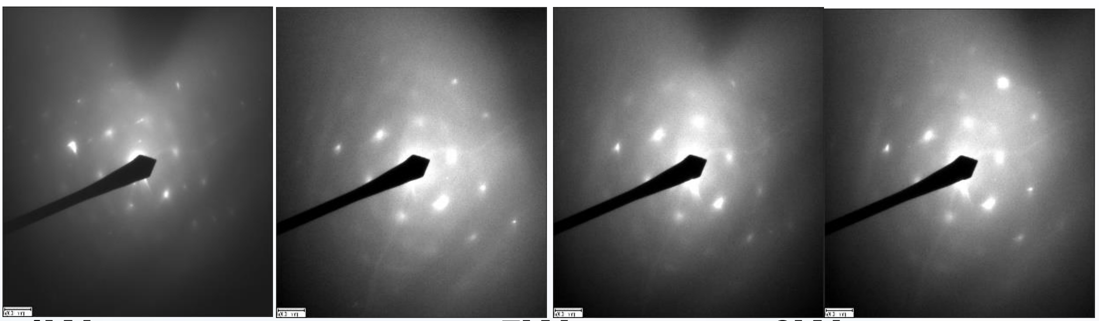




Diffraction for Temperature Calibration

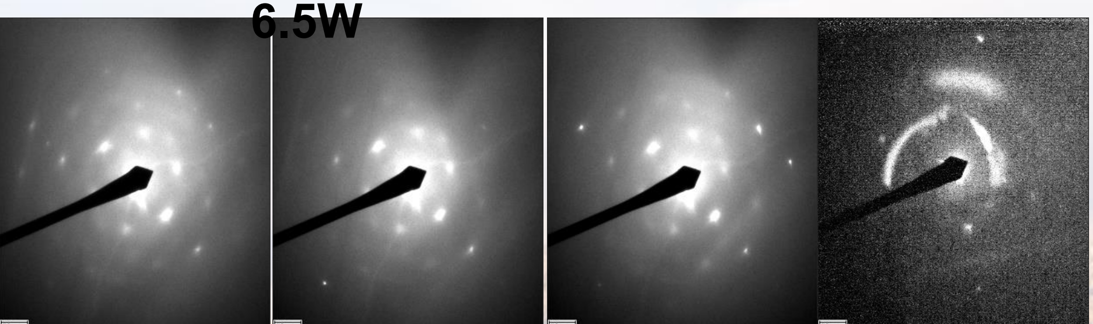


2W (β) 3W heating 3.5W (β)



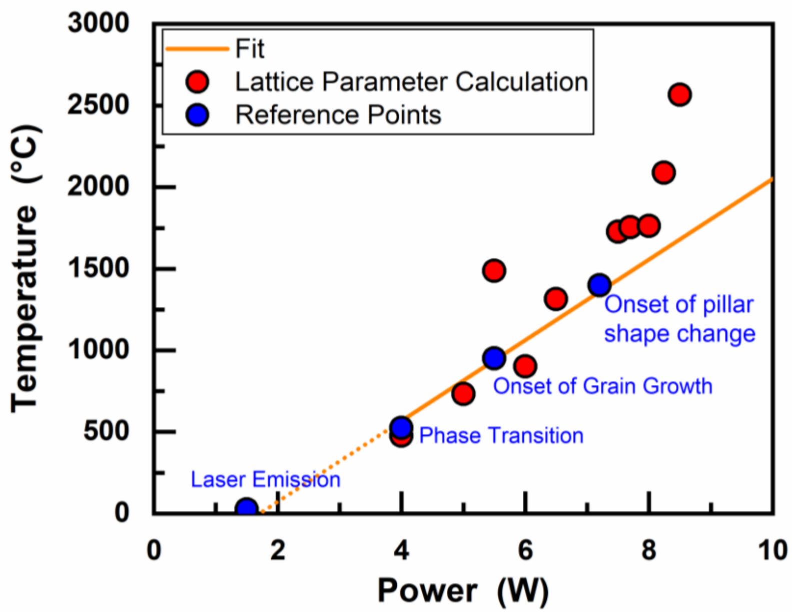
4W 5W 6W

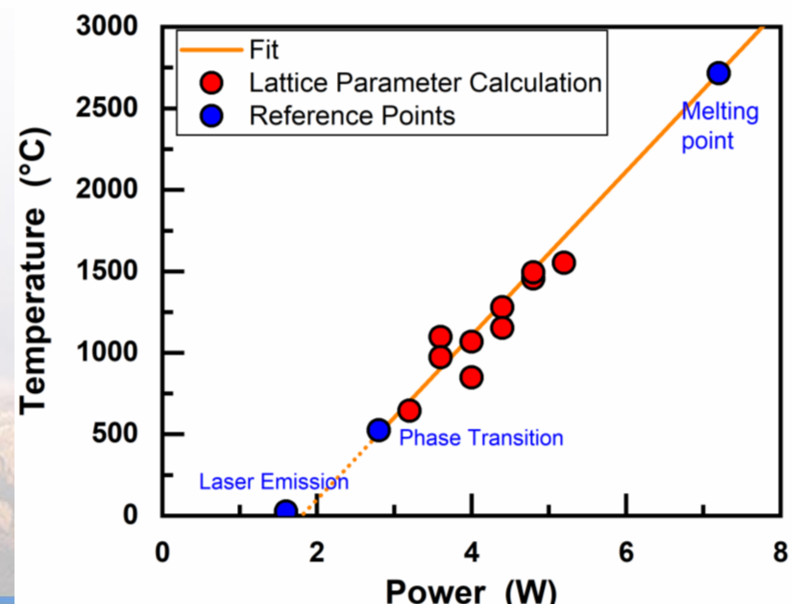
6.5W



7.7W 8W 8.5W

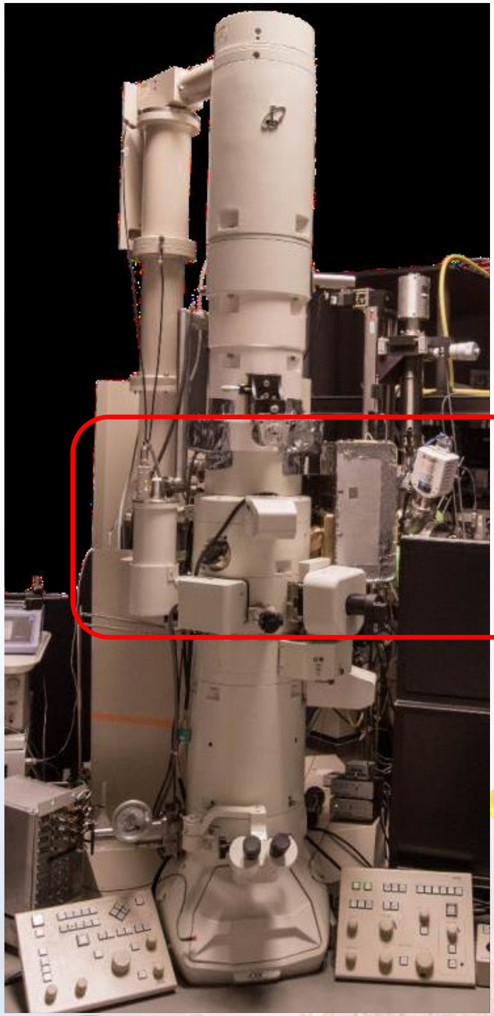
9.5W

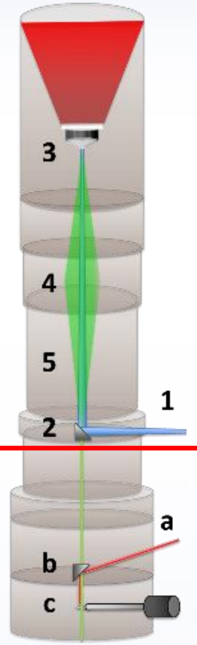




In-situ Specimen Drive Laser System

Collaborator: P. Price, A. Monterrosa, D. Adams, M. Abere, & IDES Inc.





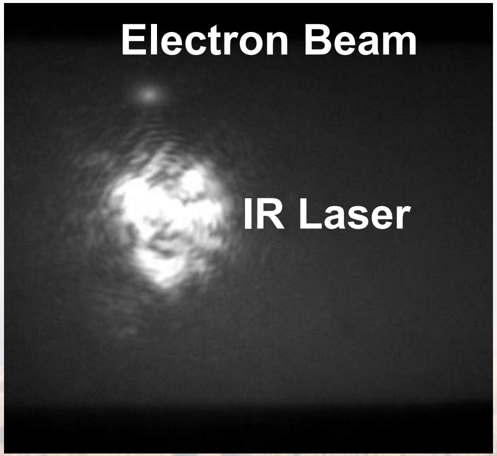
Specimen Drive Laser

a. Adjustable power 1064 nm infrared specimen (IR) drive laser

b. IR laser is reflected directly onto the specimen with metal mirror

c. Heat specimens in *in situ* holders, which otherwise would not be possible

- Laser capabilities:
  - 2-20 Watts
  - Pulsed or continuous operation
  - 50 μm diameter spot size
  - Positioning mirror, which can be used during laser operation



Laser Alignment TEM Holder

- Phosphor screen
- Borescope
- CCD camera
- Precise alignment of the laser to the electron beam

IDES INTEGRATED DYNAMIC ELECTRON SOLUTIONS

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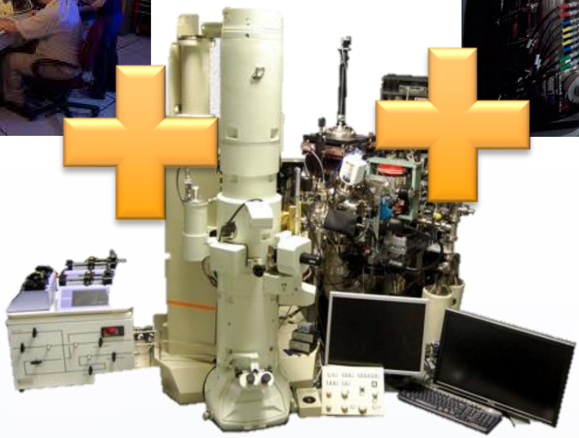
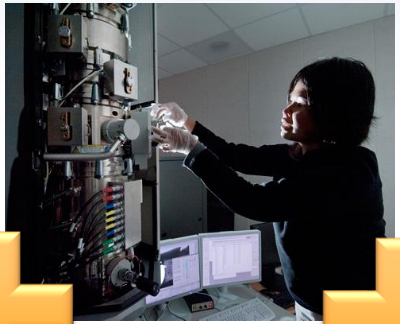
Cautionary Tale:
"Johannes Factotum"

- 1592 Robert Greene *Groats-Worth of Wit*





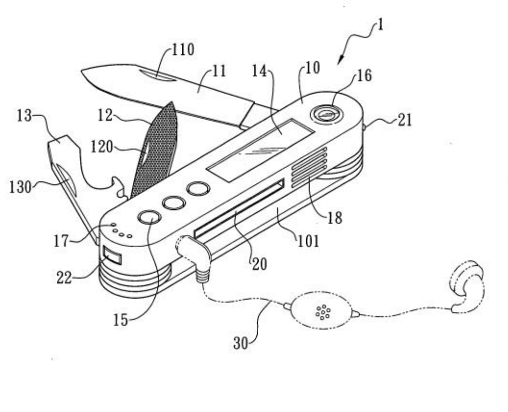


FIG. 3

M.-H. Yeh, "Knife Strucutre" US20060087845 A1

Chimera, Bellerophon and Pegasus, Athenian black-figure siana cup C6th B.C., Musée du Louvre

Can a tool do everything & Do anything well?

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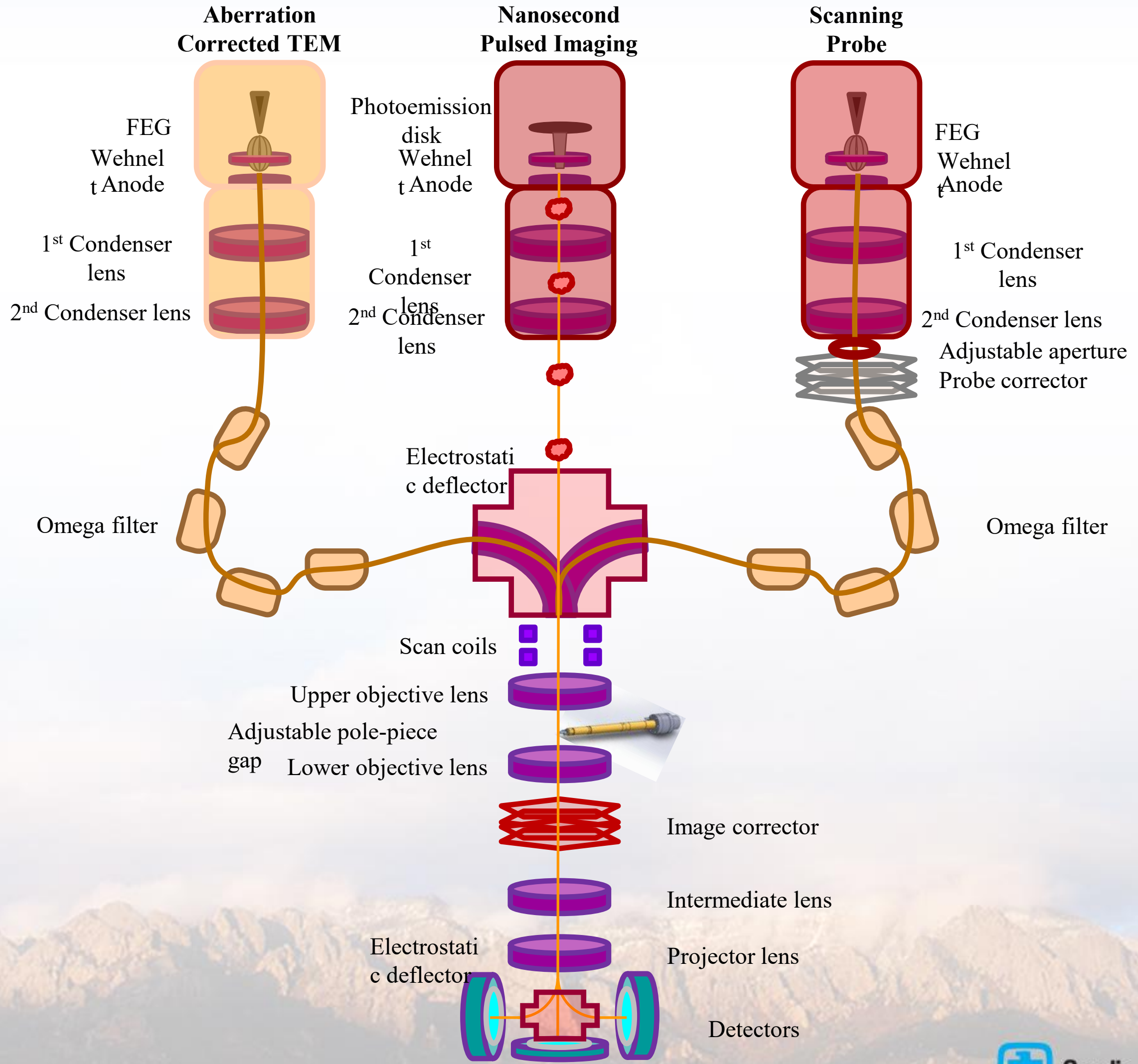
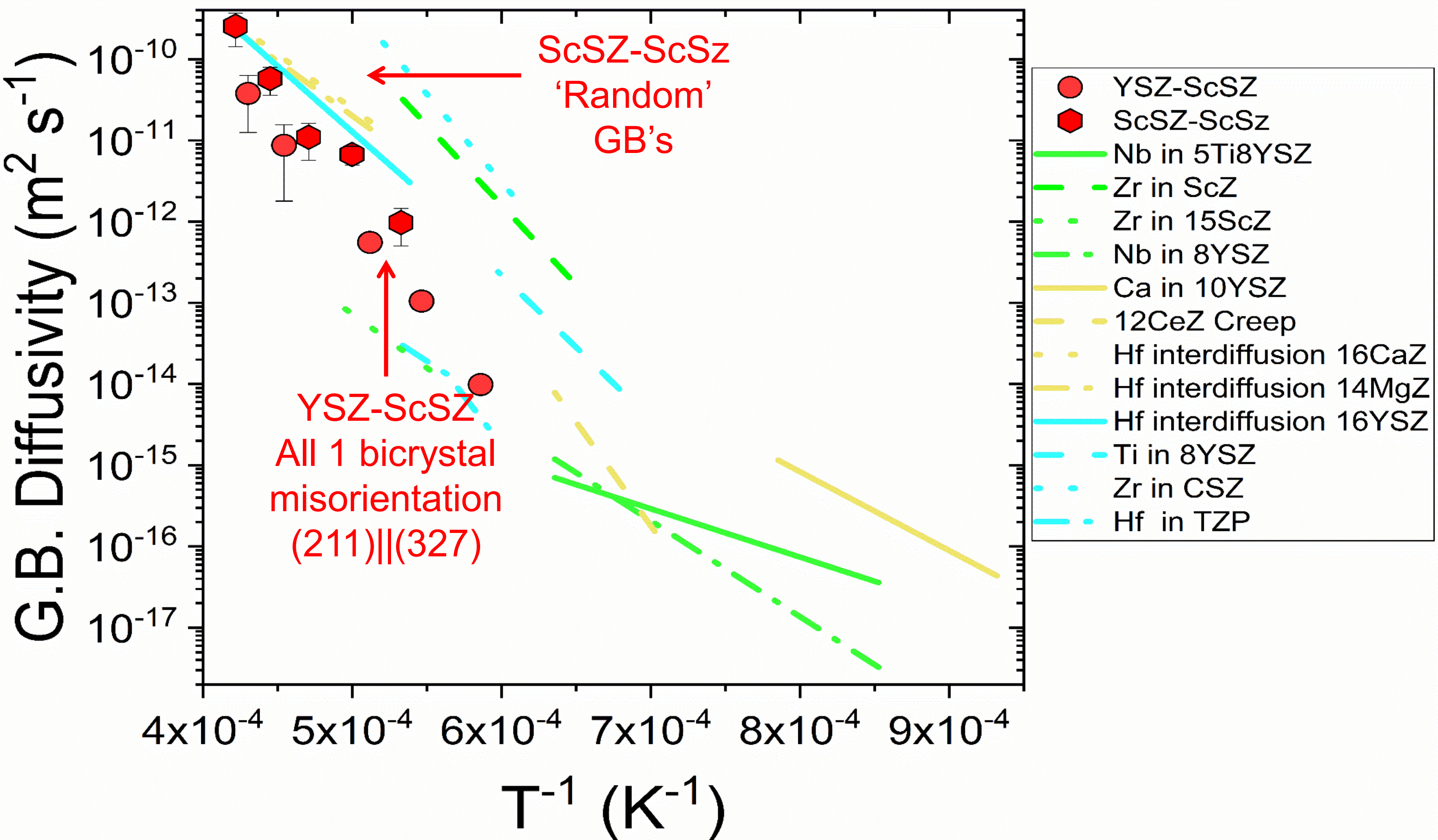
Is An Integrated (Chimera) TEM Possible?

https://www.greekmythology.com/pictures/Myths/Lernaean_Hydra/173982/chimera



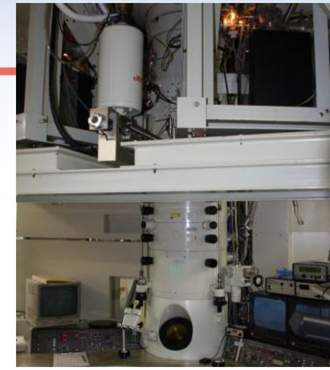
Calculated G.B. Diffusivity Compared to Literature

Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon



History of *In situ* Ion Irradiation TEM

Courtesy of: J. Hinks



1930s… | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s

1931
The invention of the TEM

1961
O^- emission reported from a TEM filament by Pashley, Presland, and Meneter at TI Labs, Cambridge, UK

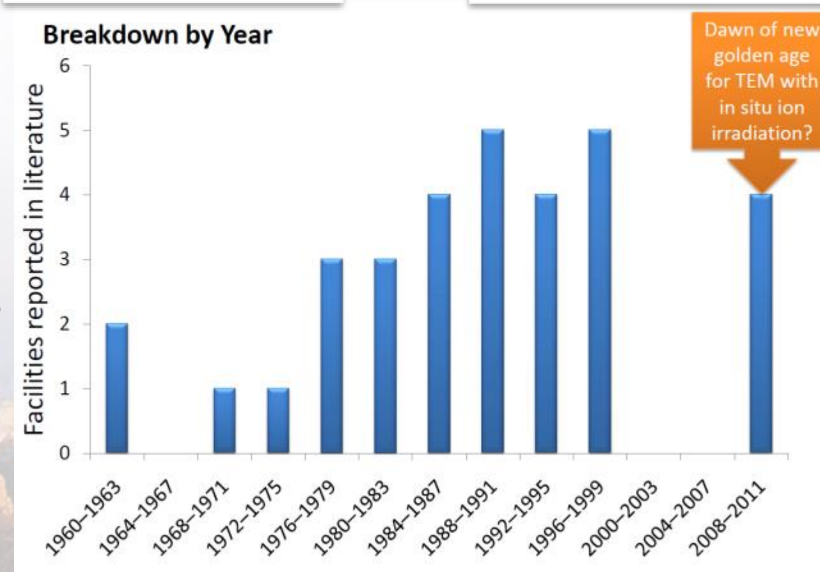
1968
First TEM beamline combination by Thackery, Nelson, and Sansom at AERE Harwell, UK

1976
First HVEM with ion irradiation at UVA, USA

1978
First in-situ ion irradiation experiments at ANL

1990s
First dual beam system developed at JAERI and NIMS, Japan

Workshop on Ion Irradiation TEM
Huddersfield, UK (2008)
Albuquerque, USA (2011)
Saporro, Japan (2013)
Paris, France (2016)
Huddersfield, UK (2018)
Ann Arbor, MI, USA (2020)

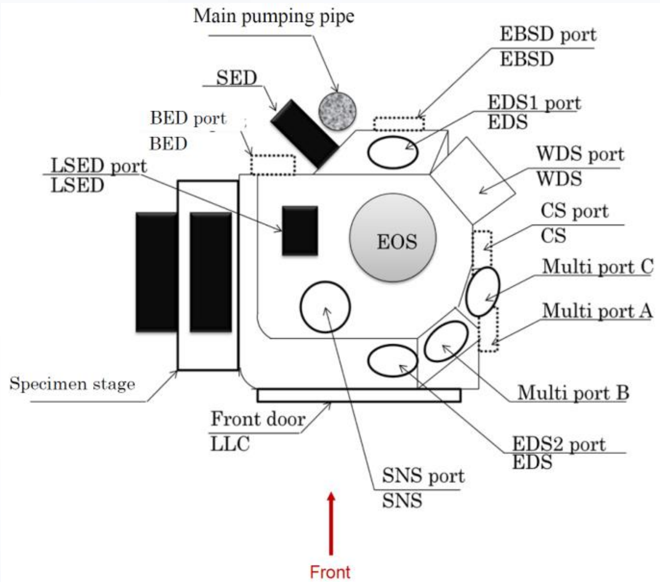


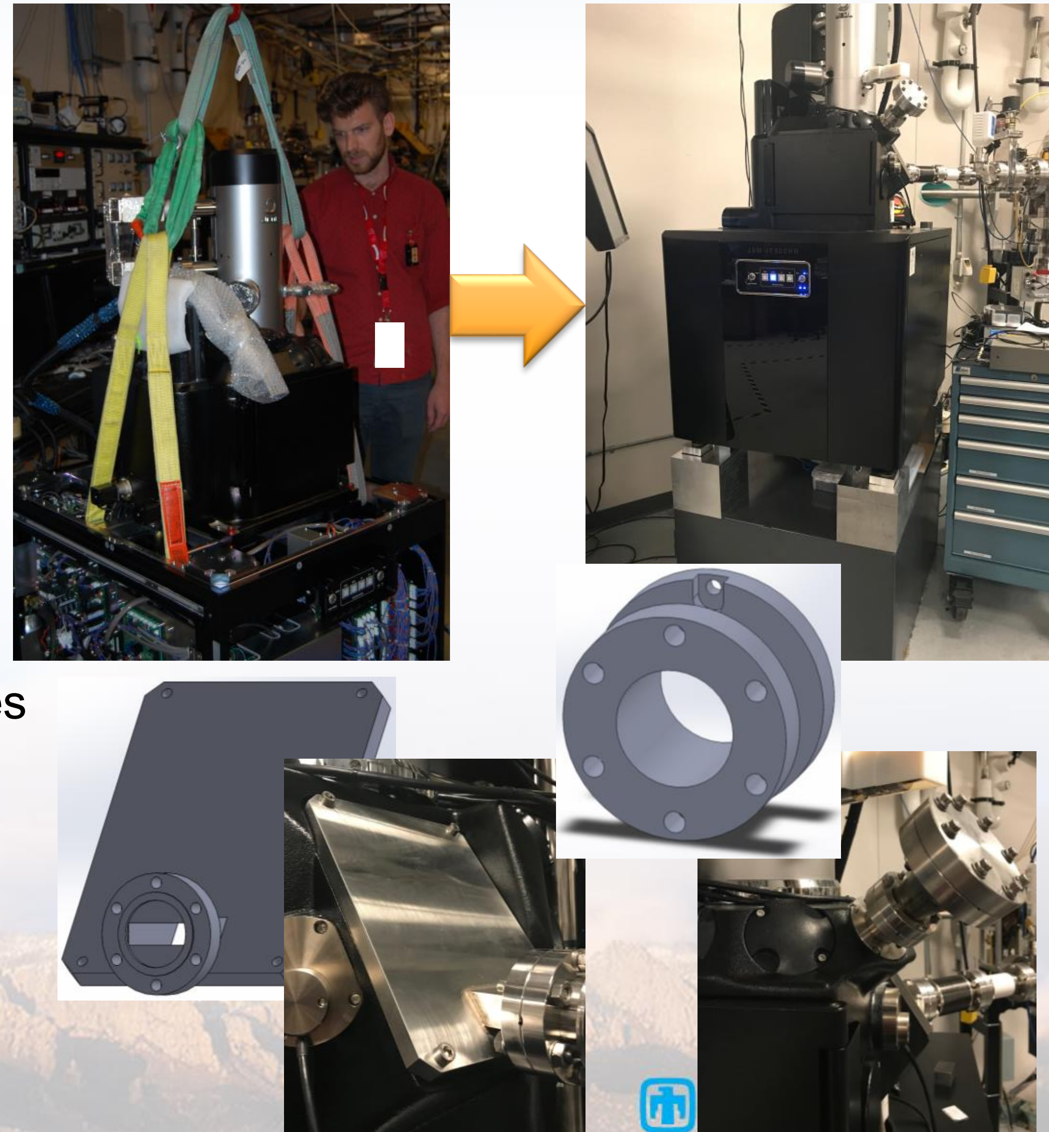
"The direct observation of ion damage in the electron microscope thus represents a powerful means of studying radiation damage"

D.W. Pashley and A.E.B. Presland Phil Mag. 6(68) 1961 p. 1003

I[3]SEM Design and Build

Collaborators: D. Buller, B. Boyce, S. Briggs, N. Heckman, J.A. Scott





- 500 eV - 30 kV FEG SEM w/ large chamber and low-vacuum capabilities
- Multiple chamber feedthroughs for connecting beamlines and instrumentation

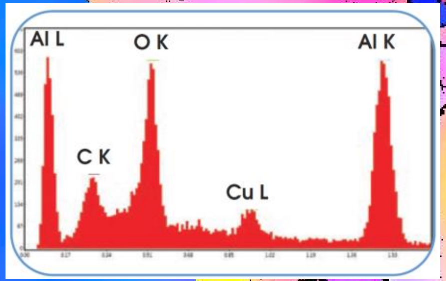
WDS port selected for primary mate to 6 MV tandem beamline

Recently Installed High Speed EBSD and EDS

- EDAX Velocity™ EBSD Camera
  - Capable of fast acquisition (> 3000 indexed points per second)
  - High signal-to-noise ratio, phosphor screen optimized for high speed collection

Enables study of grain growth/evolution during irradiation, heating and straining experiments

- EDAX Octane Elite EDS System
  - High light element sensitivity
  - High count & throughput rates



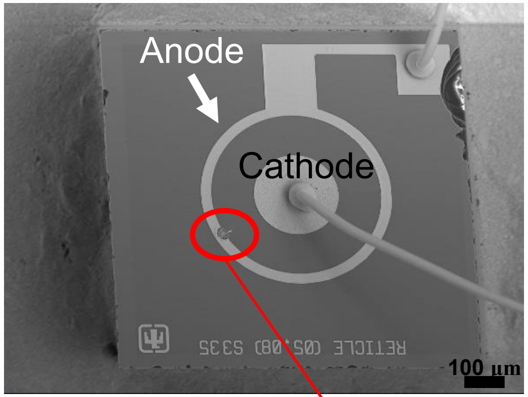
Allows for analysis of precipitates, solute segregation, and phase ID

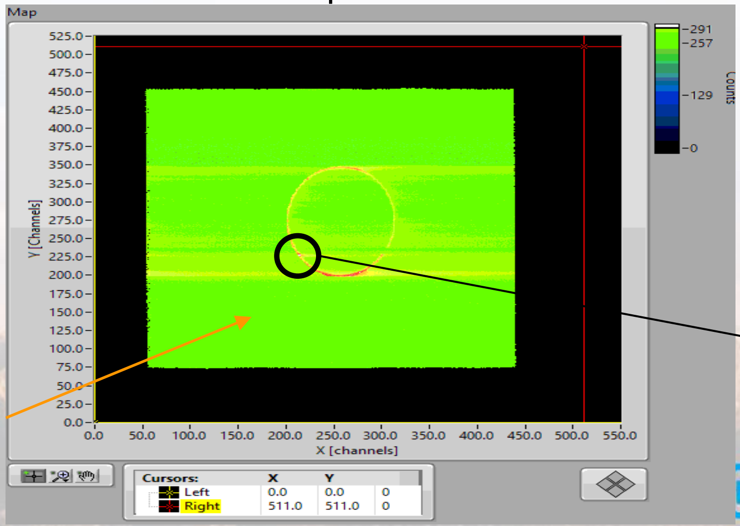
45 um

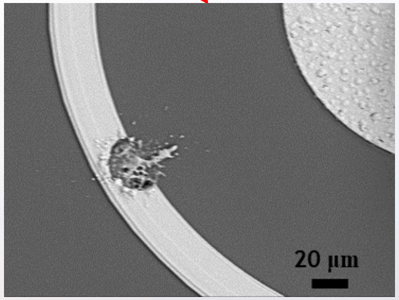
Electrical Characterization in the SEM

Collaborators: .S.A. Briggs, B. Doyle, A. Colon

- Device is biased at 400 V, SEM is rastered while monitoring EBIC signal
- Initial studies show a high EBIC signal around the inner perimeter of the anode
  - This is where the peak electric field is located (i.e. large $\frac{dE(r)}{dV_i}$ in Gunn Theorem)
- Crater after device breakdown with higher SEM probe current was near the location of an EBIC 'hotspot'. This shows the importance of using this technique towards screening devices







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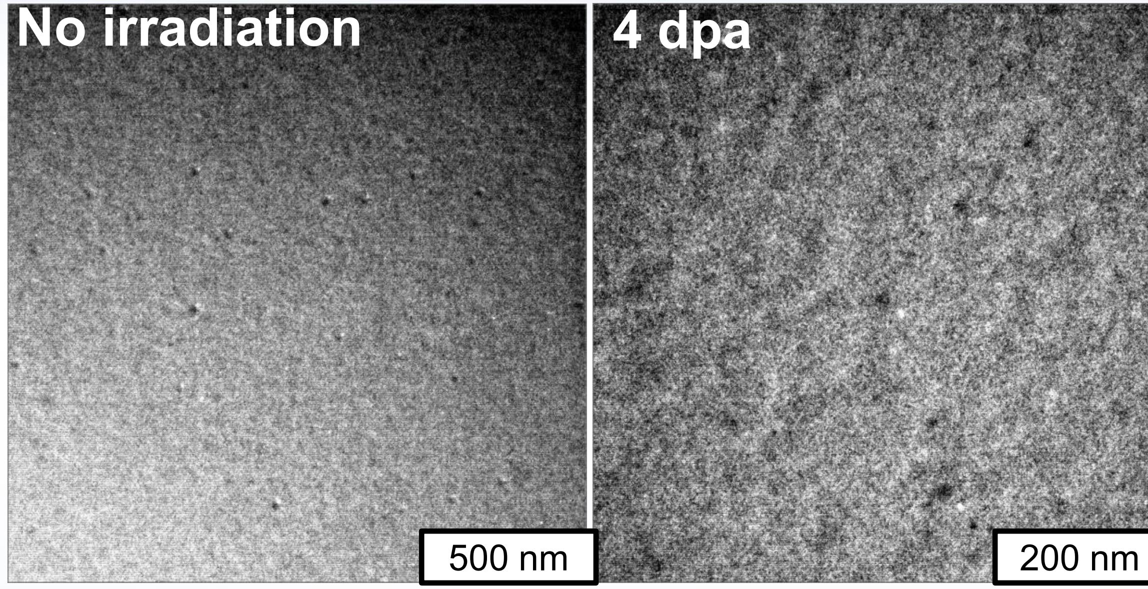
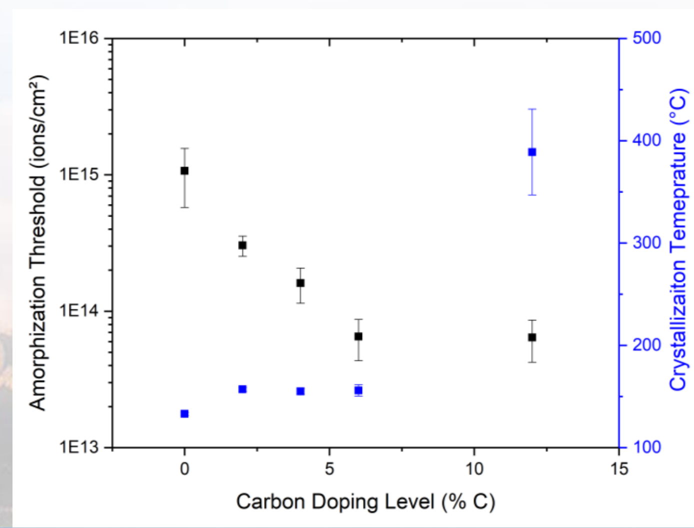
Radiation Tolerance in Phase Change Memory

Contributors: Trevor Clark, Eric Lang, Ethan Scott, and David Adams

- **90 nm-thick GST with 0-20%C**
- **Plan View:**
  - Anneal (5 ˚C/min)
  - RT irradiation (4dpa)
    - Anneal (5 ˚C/min)
  - 100 ˚C hold & irradiation (4dpa)
- **Cross section FIB lift-outs:**
  - RT Irradiation
  - 200 C & 300 C Hold
- **Irradiation Conditions**
  - 2.8 MeV Au^{4+} up to 4 dpa



GST 0 %C   Anneal 5°C/min from100-150 °C   15x speed



Amorphization and crystallization temperature are carbon dependent

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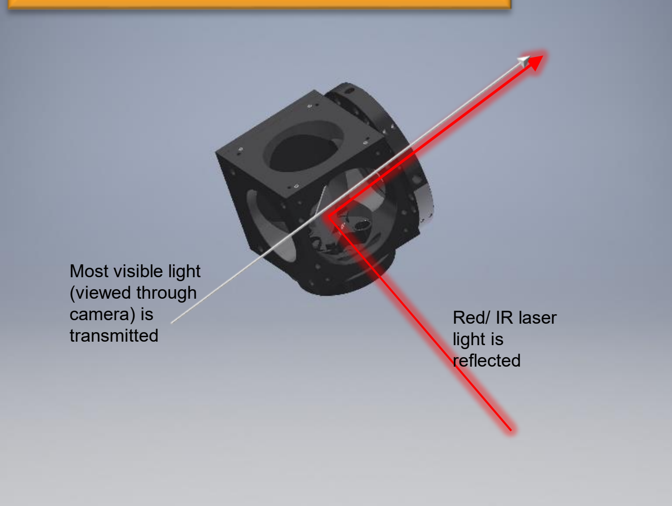
Further Additions Development

Collaborators: M. Abere, S.A. Briggs, E.A. Scott, P. Hopkins, J.P. Allain

Add Laser Capabilities

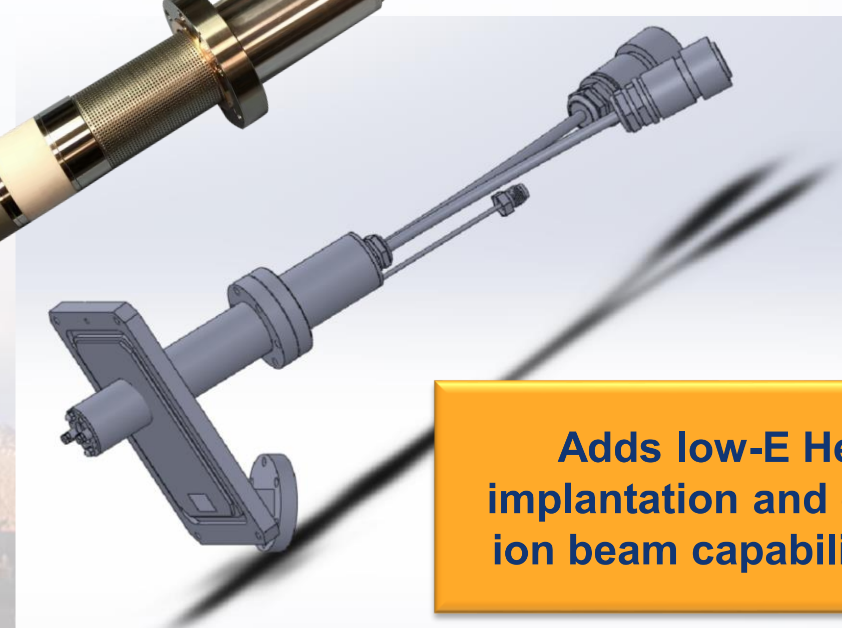
- Couple nearly parallel concurrent laser beam along the heavy ion beam path into the SEM.
- Current plans will use Quantel Big Sky laser with 1064 and 355 individually or simultaneously

Additional heating and ablation capabilities



Mate with a K&R KDC 10 Plasma Source

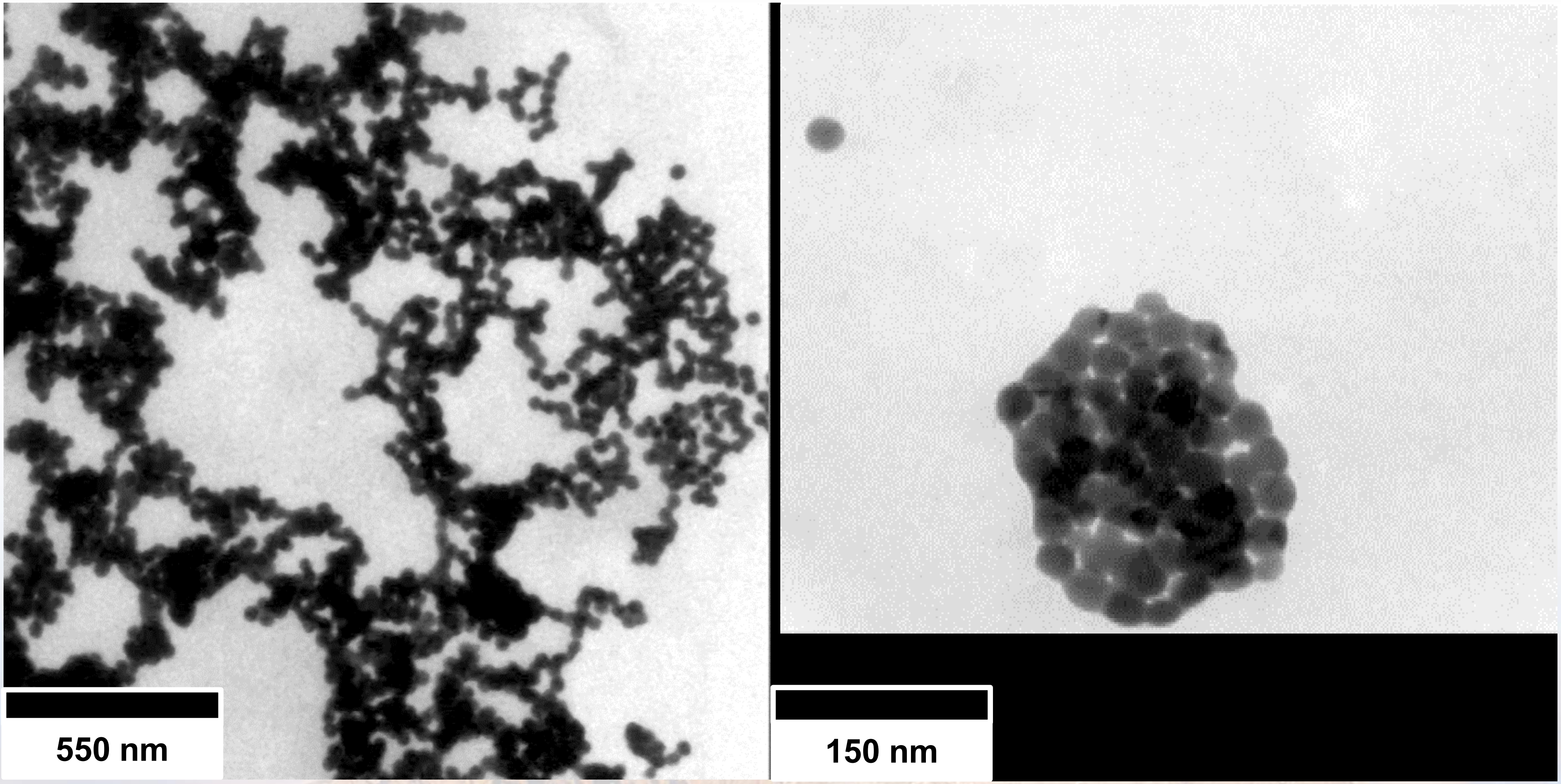
- 10 mA gas-fed source, energies from 100 eV to 1.2 keV
- Capable of running inert gases, some reactive gases (H, O_2), and mixtures



Adds low-E He implantation and dual ion beam capabilities

Complex Interaction Au NPs Exposed to Laser Irradiation

Contributors: P. Price, L. Treadwell, A. Cook, & IDES Inc.



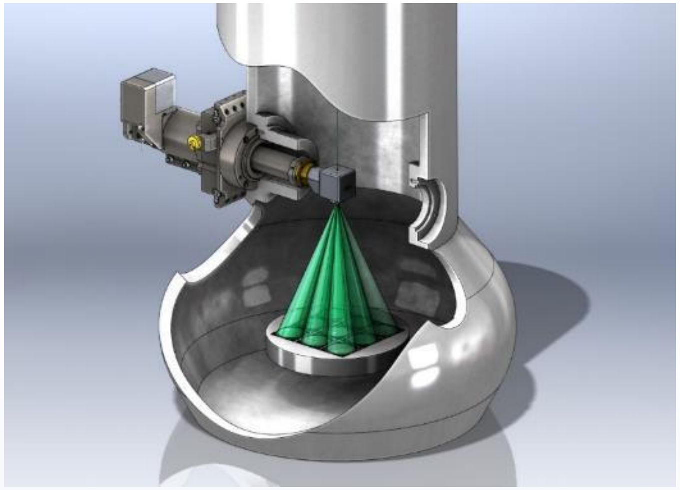
Speed = 2.5x

A Complex Combination of Sintering, Reactions, and Ablation Occurs

μs Resolution with a Standard Camera

Collaborator: P. Price, A. Monterrosa, D. Adams, M. Abere, & IDES Inc.

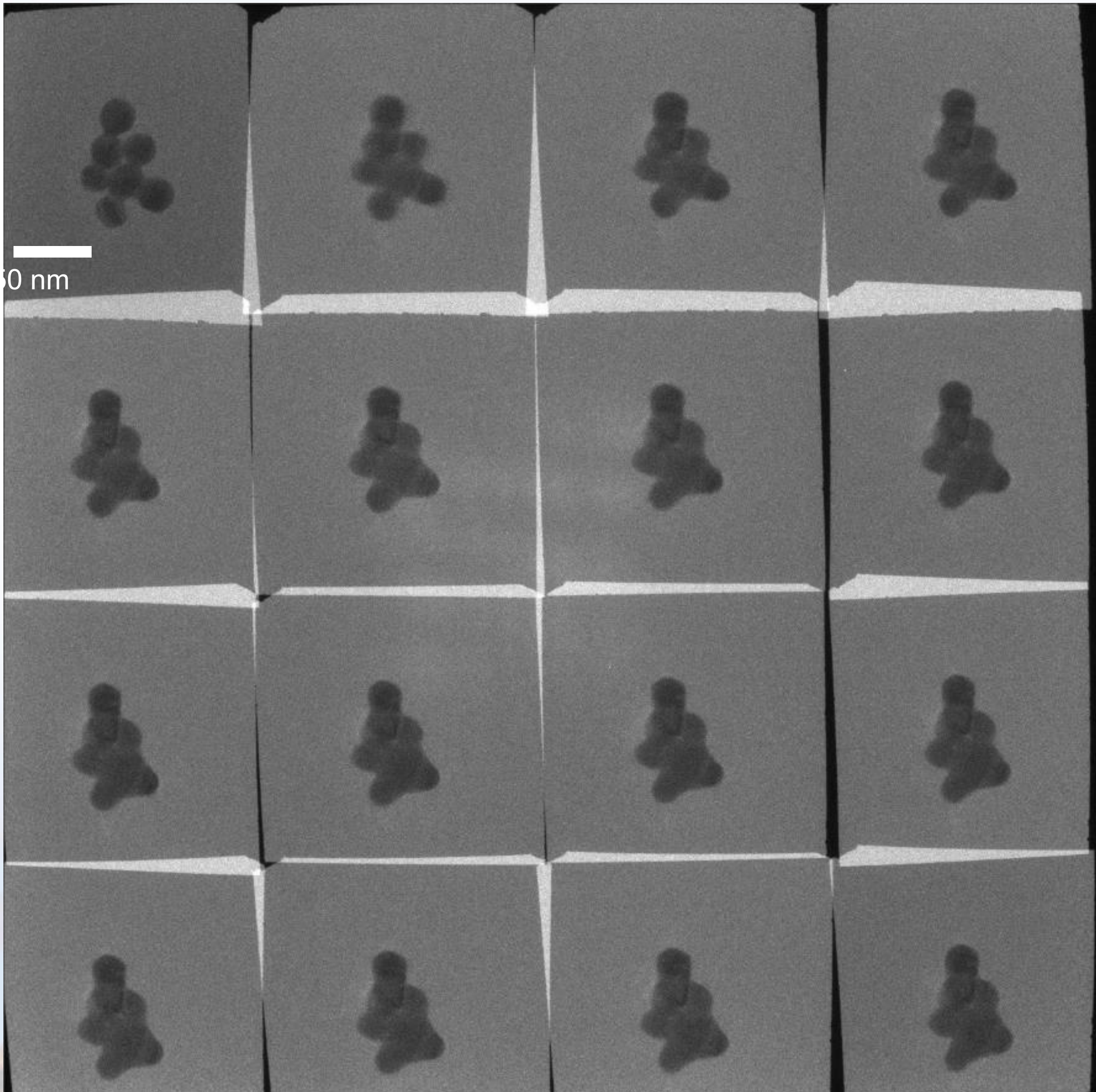
fs ps ns **μs** **ms** s

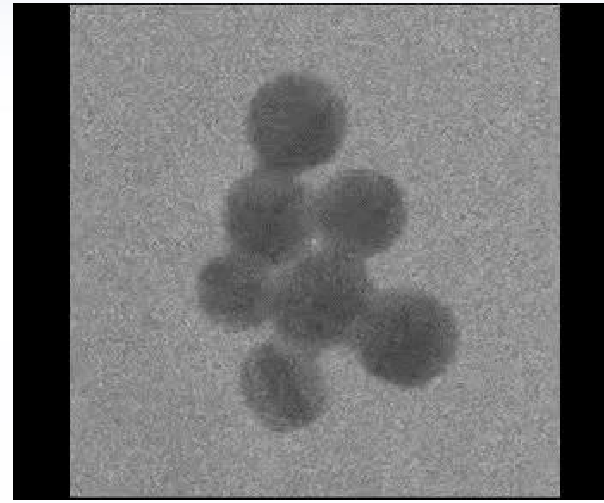


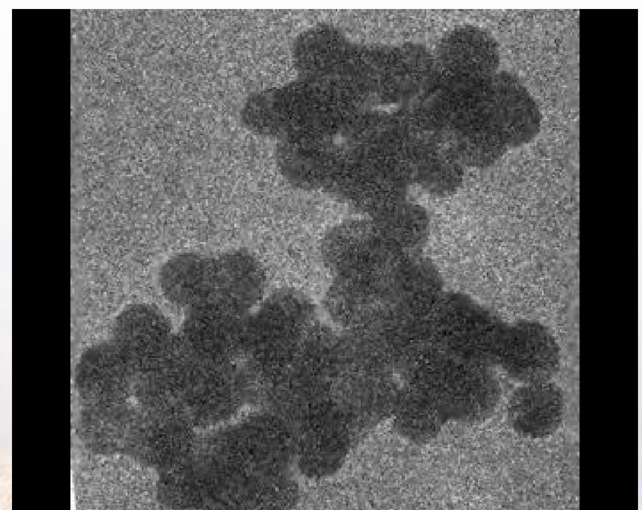
- **Electrostatic deflection of electrons**
- **4, 9, or 16 images per frame, spread over a large camera**
- **Any exposure time up to the limits of the camera**
  - Ultimate limit is beam current/brightness

1-to-1 Frame Capture (<5 ms per frame)
Sintering of 20 nm Au Nanoparticles

Collaborator: P. Price, A. Monterrosa, & IDES Inc.



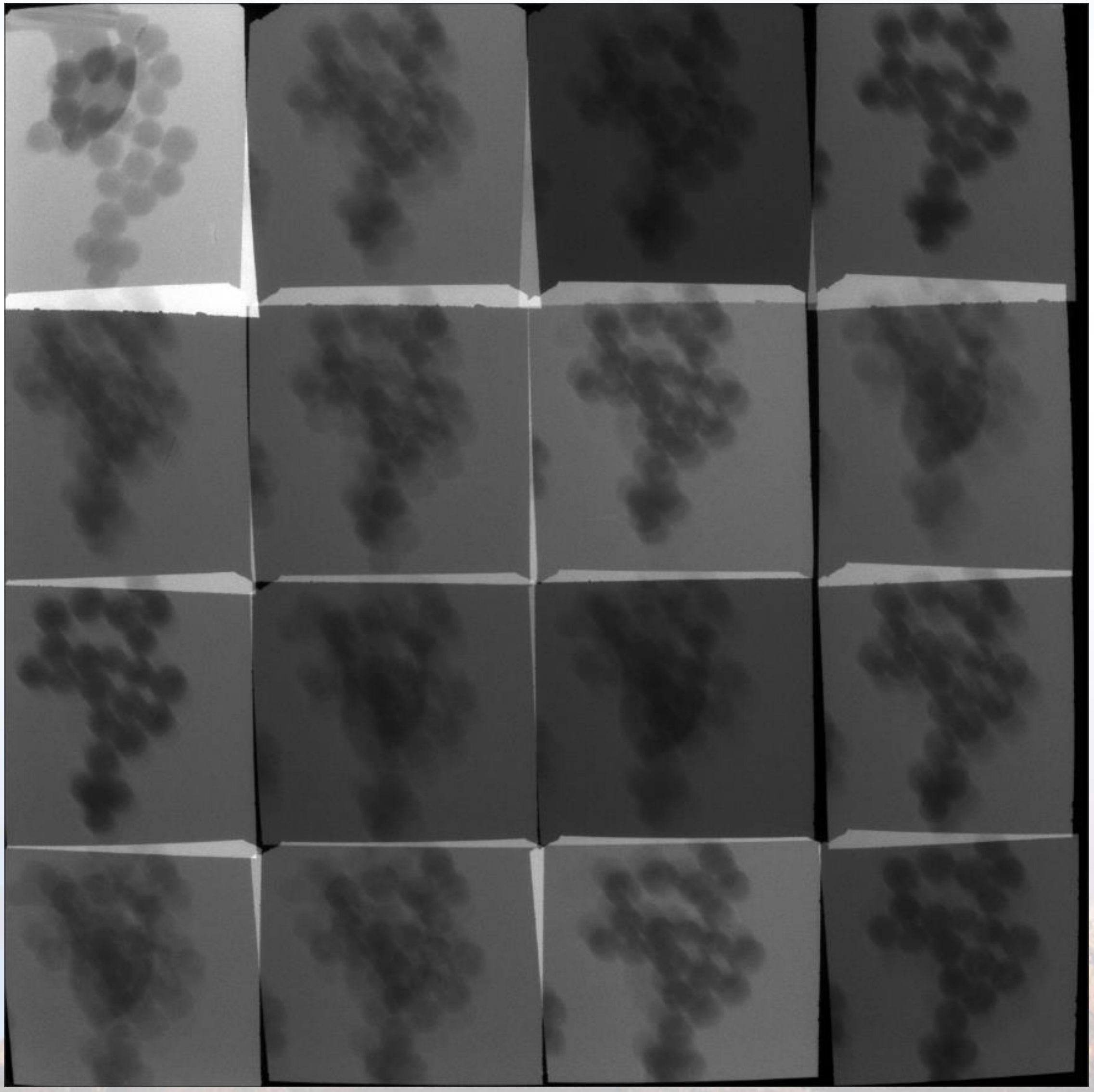


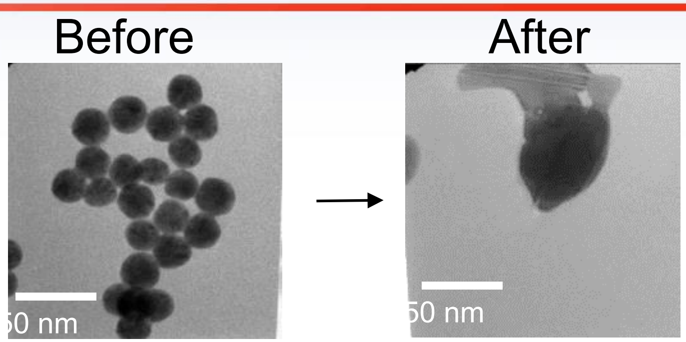


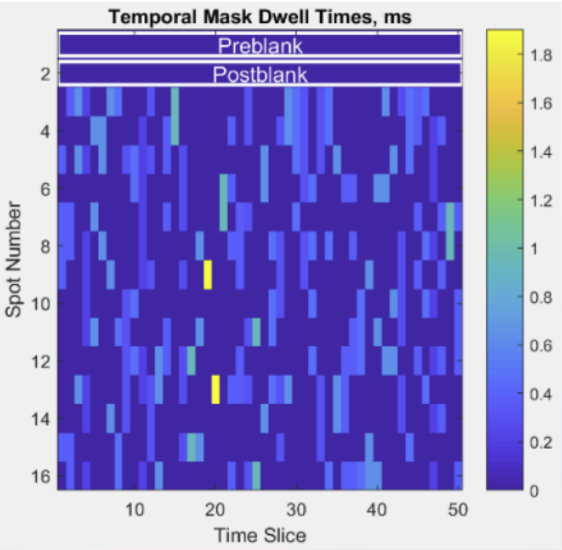
16 frames captured with <5 ms exposure per frame

Temporal Compressive Sensing to Improve Temporal Resolution

Collaborator: P. Price, A. Monterrosa, & IDES Inc.



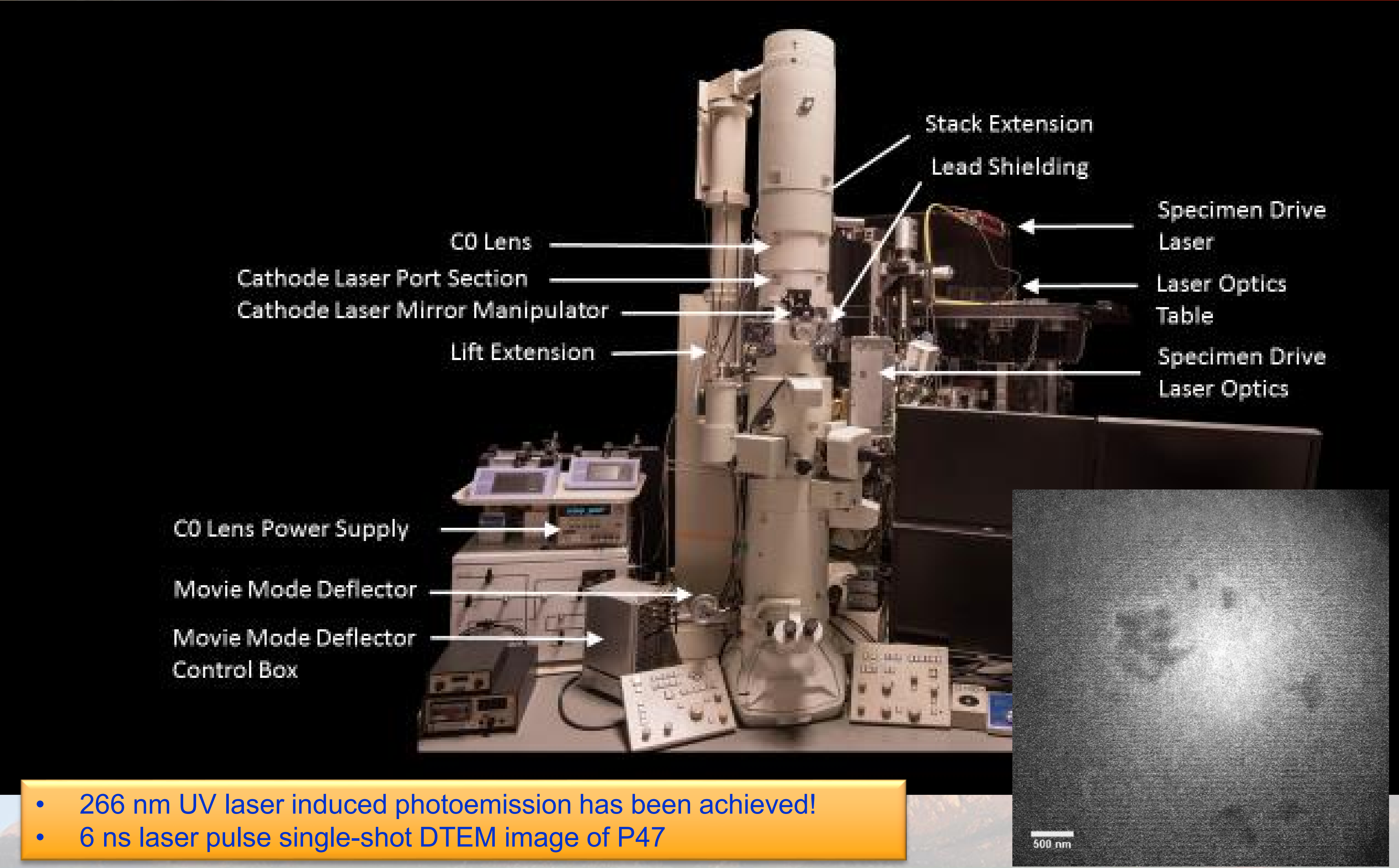




A pseudorandom exposure pattern can produce more than 100 frame movie from a single 4k x4k acquisition

Current Status of DTEM Conversion

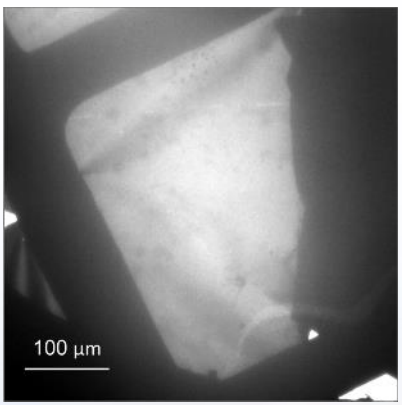
Collaborator: P. Price, A. Monterrosa, C.M. Barr, D. Adams, M. Abere, & IDES Inc.



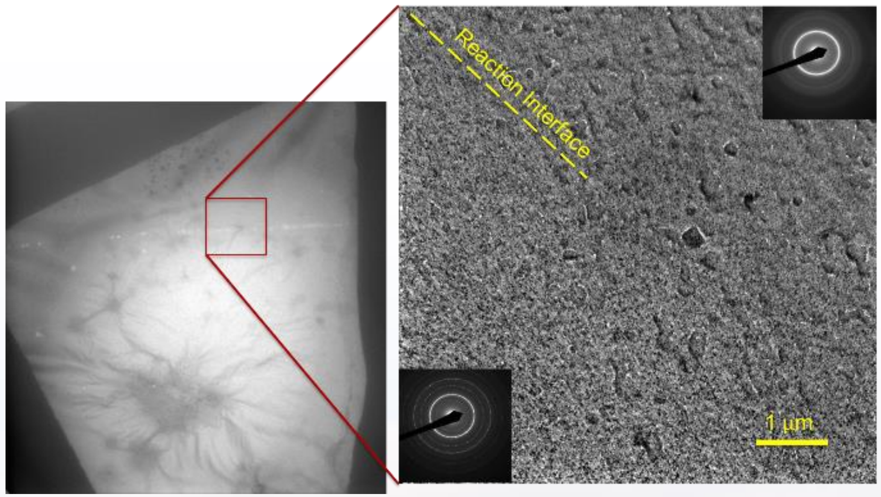
- 266 nm UV laser induced photoemission has been achieved!
- 6 ns laser pulse single-shot DTEM image of P47

DTEM of Reactive Multilayers

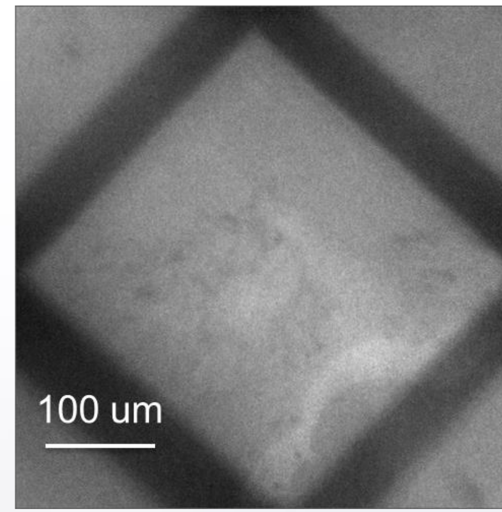
Reactive multilayers provide an excellent example of the capabilities of DTEM. Al/Co multilayer samples are ignited by the IR laser, and convert to a CoAl phase. The reaction front propagates across the sample at ~10 m/s. With a fast enough time resolution this wavefront can be captured.



Al/Co multilayer sample **before IR laser shot**



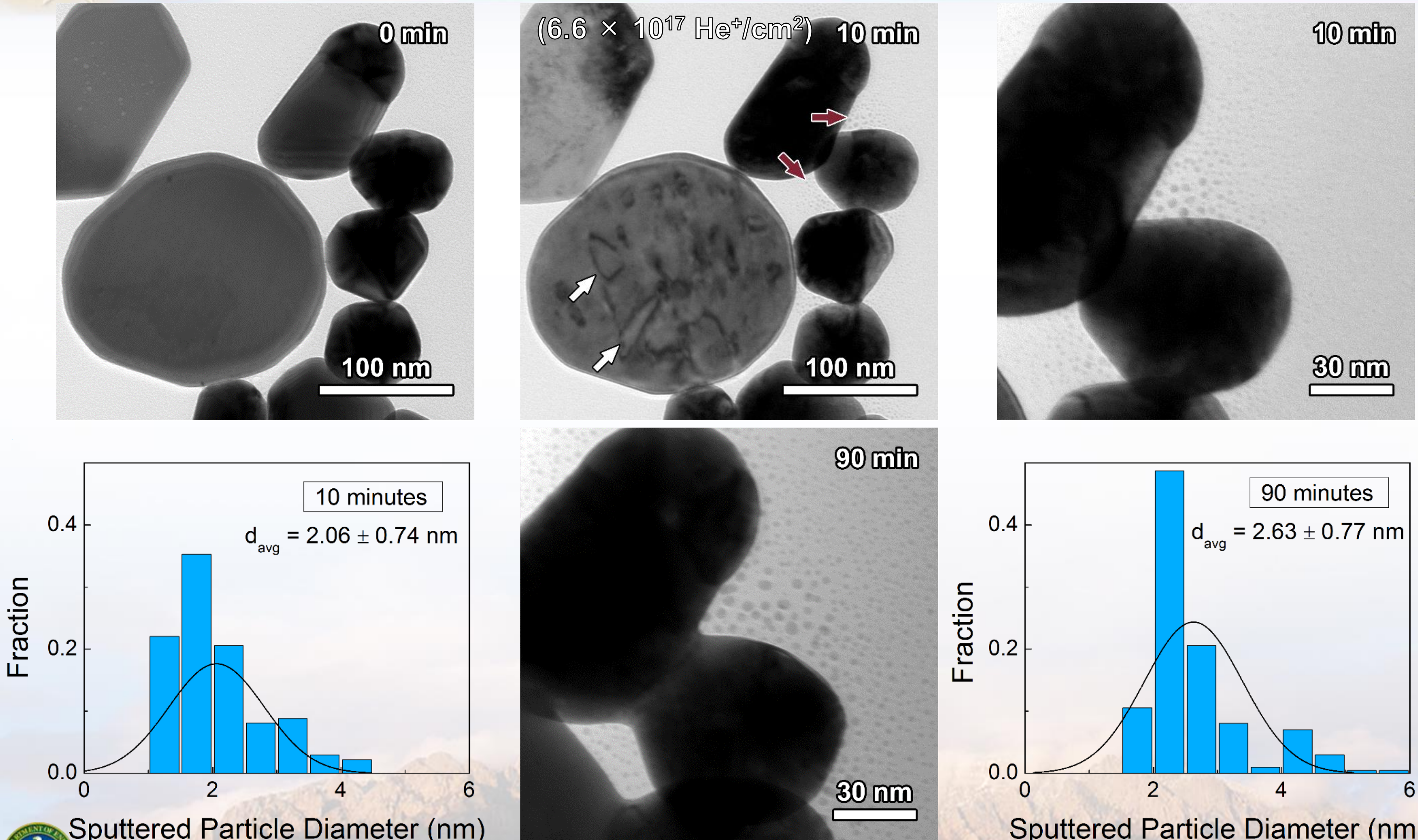
Al/Co multilayer sample **after IR laser shot** and closeup of reaction interface



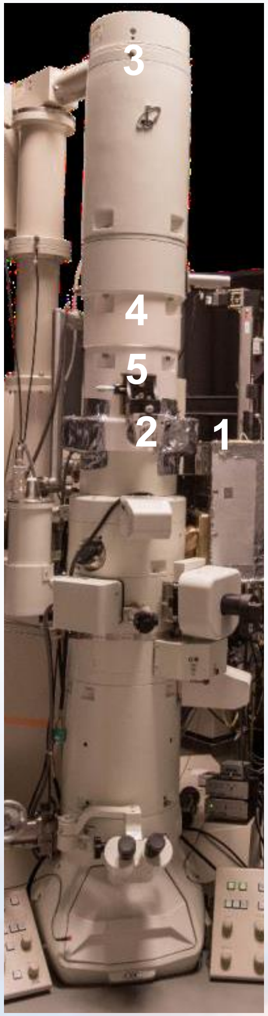
Single shot DTEM of unreacted Al/Co multilayer sample

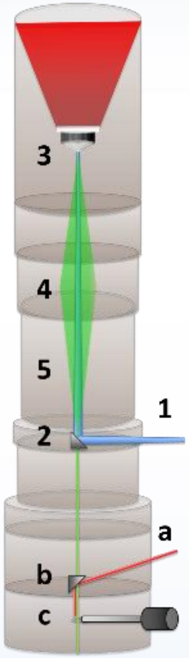
Formation of Dislocation Loops & Sputtered Particles due to He implantation

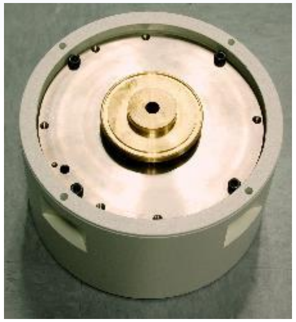
Collaborators: D.C. Bufford, S.H. Pratt & T.J. Boyle



Conversion of a Standard JEOL 2100 TEM to DTEM: Increase Current Density







C_0 Lens

Drift Section

UV Laser

A standard LaB_6 TEM has on average 1 or 2 electrons in the column at a given time!

Laser induced photoemission of electrons can increase nanosecond electron current by 6-8 orders of magnitude

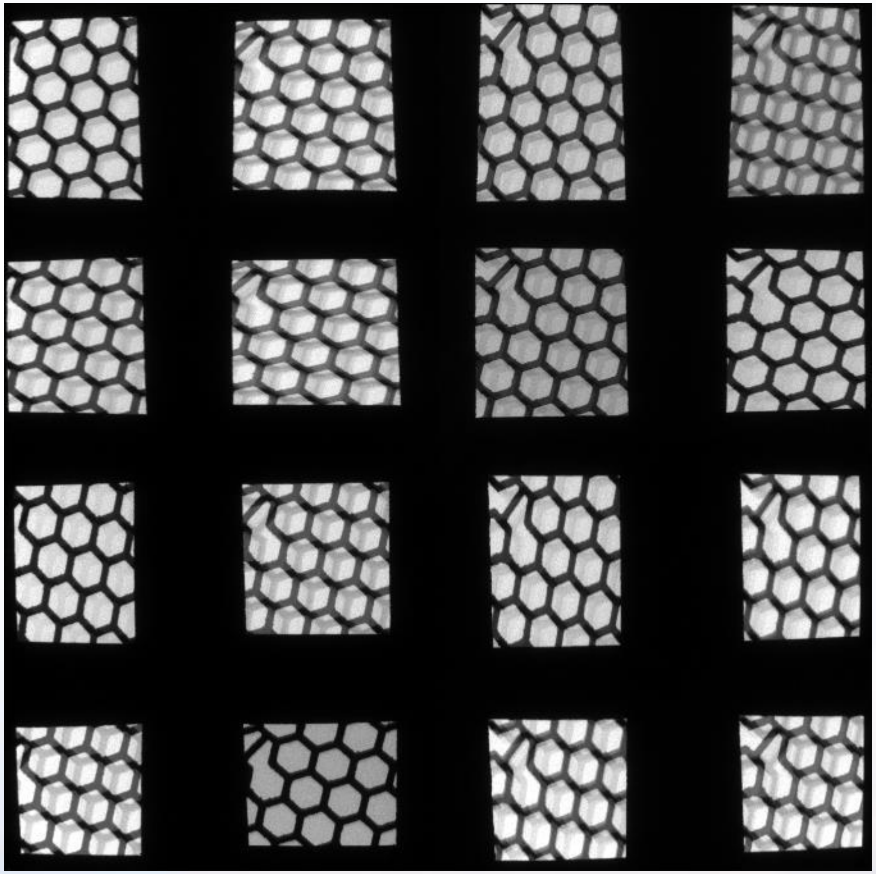
<u>DTEM Development</u>

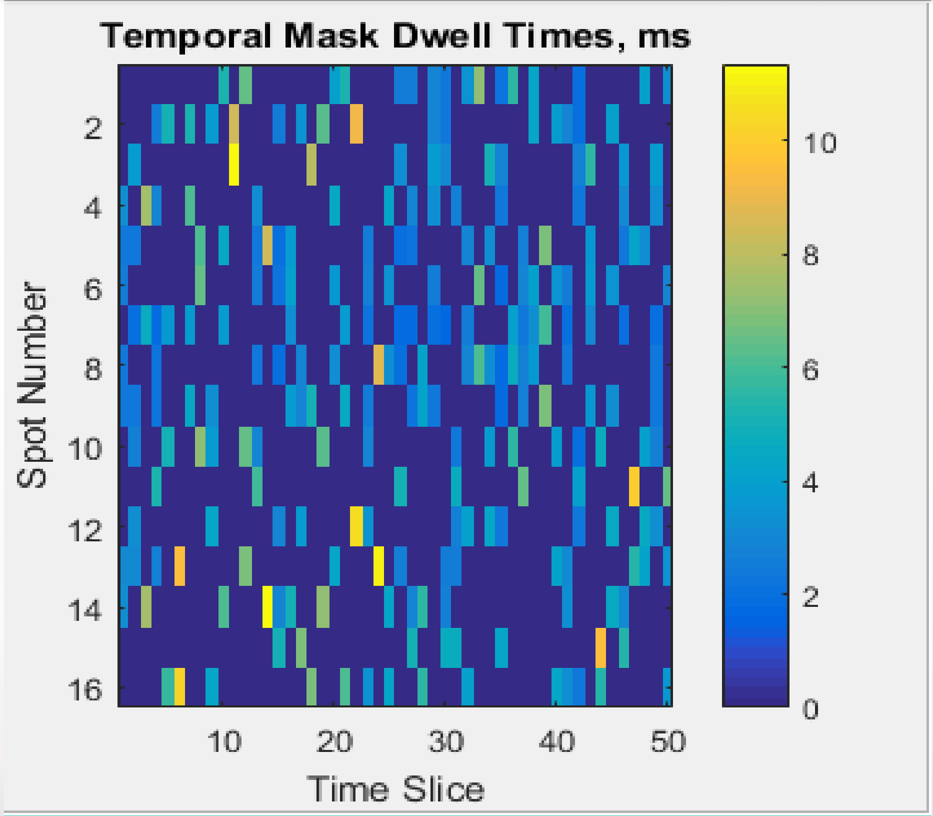
1. **Ultraviolet laser and optics system capable of producing nanosecond pulses**
2. **Adjustable molybdenum mirror assembly to reflect the UV laser up the column**
3. **Tantalum cathode disc filament**
4. **Addition of a C_0 lens and power supply to gather electrons increasing current to the specimen**
5. **Addition of a drift section to condense electrons from the C_0 lens**
6. **Lead shielding as needed to ensure safe operation of the instrument**

Movie Mode & Temporal Compressive Sensing

Collaborator: P. Price, A. Monterrosa, & IDES Inc.

Up to 100 exposures can be acquired on a single camera frame giving *μs* temporal resolution

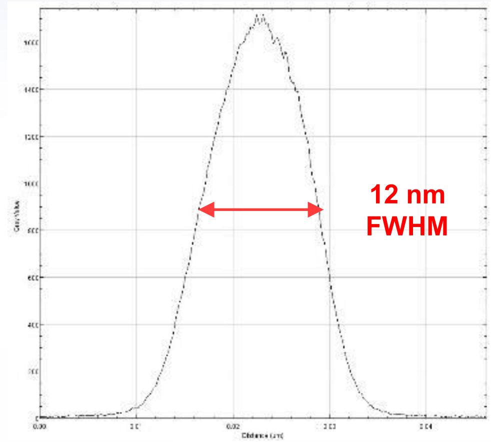


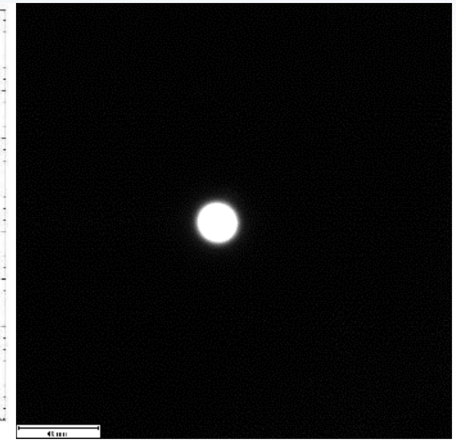


- **Electron intensity of a single exposure is randomly distrusted to multiple images within a single frame**
- **Record of random mask used to distribute exposure intensity is later used deconvolute images**

Tantalum Filament Exchange

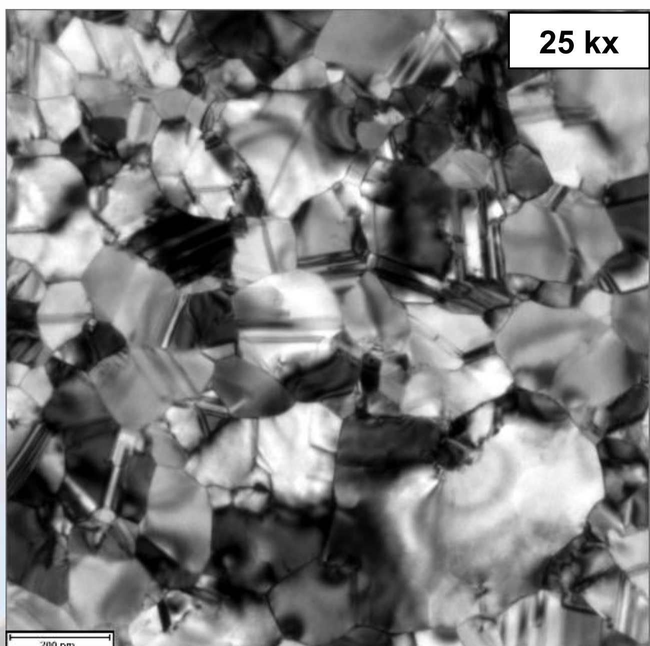
- **Changes with C_0 lens setting of 0V**
  - 50% reduction in electron
    - LaB_6 ~ 50 pA/cm^2
    - Ta ~ 30 pA/cm^2
  - Higher beam current at from source
    - LaB_6 ~ 7 μA
    - Ta ~ 23 μA
  - Increase in minimum spot size for precession
    - LaB_6 ~ 8 nm FWHM
    - Ta ~ 12 nm FWHM

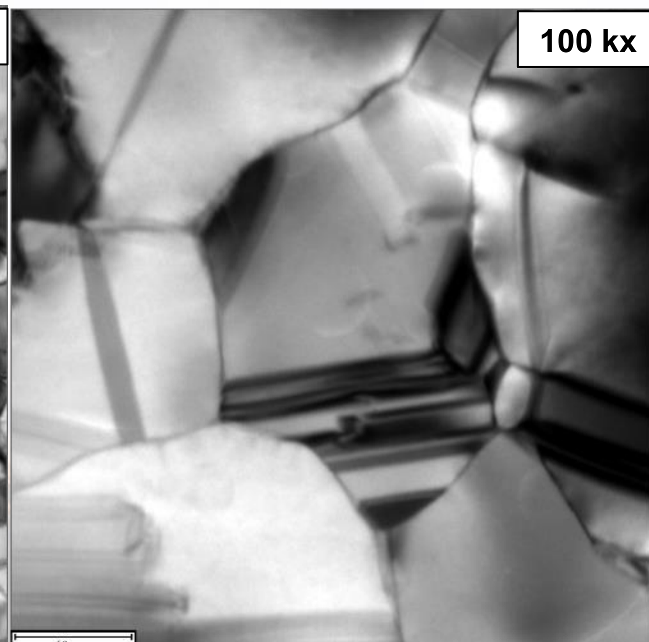




Above:

Smallest achievable spot size for precession with Ta cathode





Left:

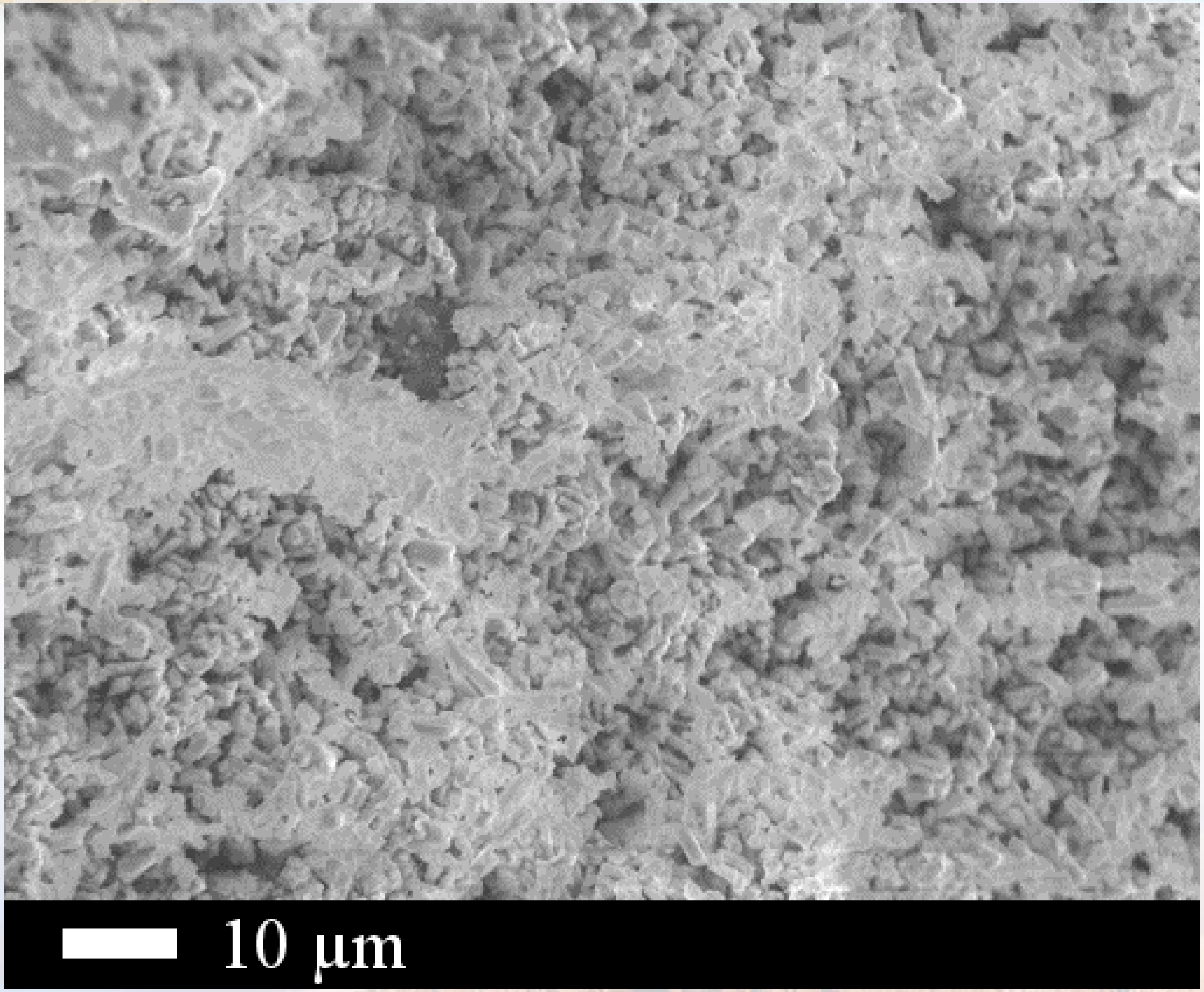
Bright field TEM images of nanocrystalline gold taken with Ta filament

Easily switch between DTEM and thermal emission with good resolution in minutes!

Filament exchange in as little as 90 min.

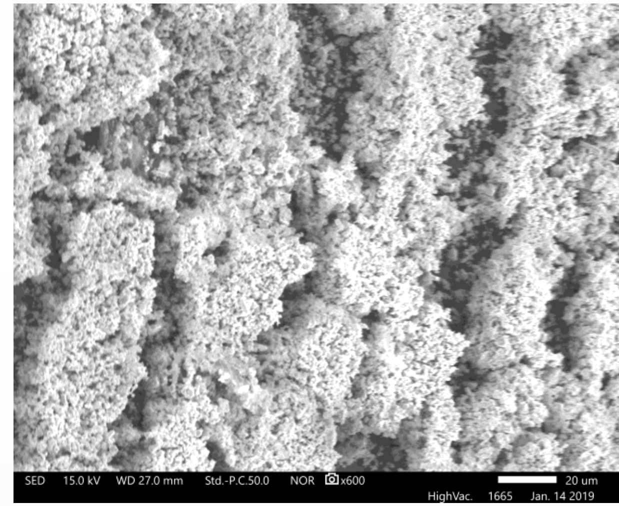
Heavy Ion Irradiation of Ceramics

Collaborators: D. Buller, N. Heckman, A. Monterossa, C. Bryan

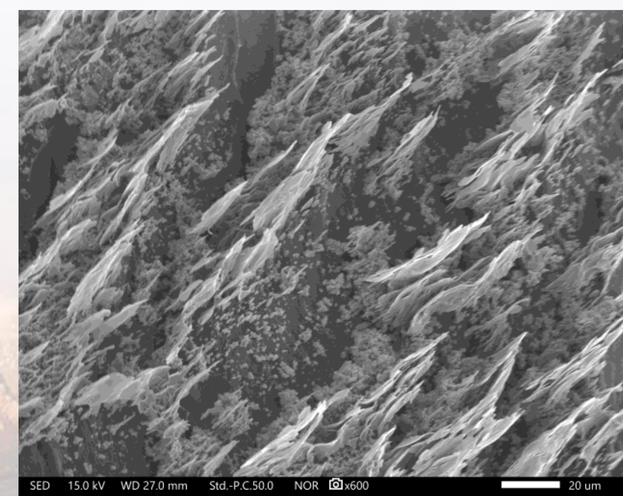


10 MeV Au into ZrO_x based waste form

Prior to Irradiation

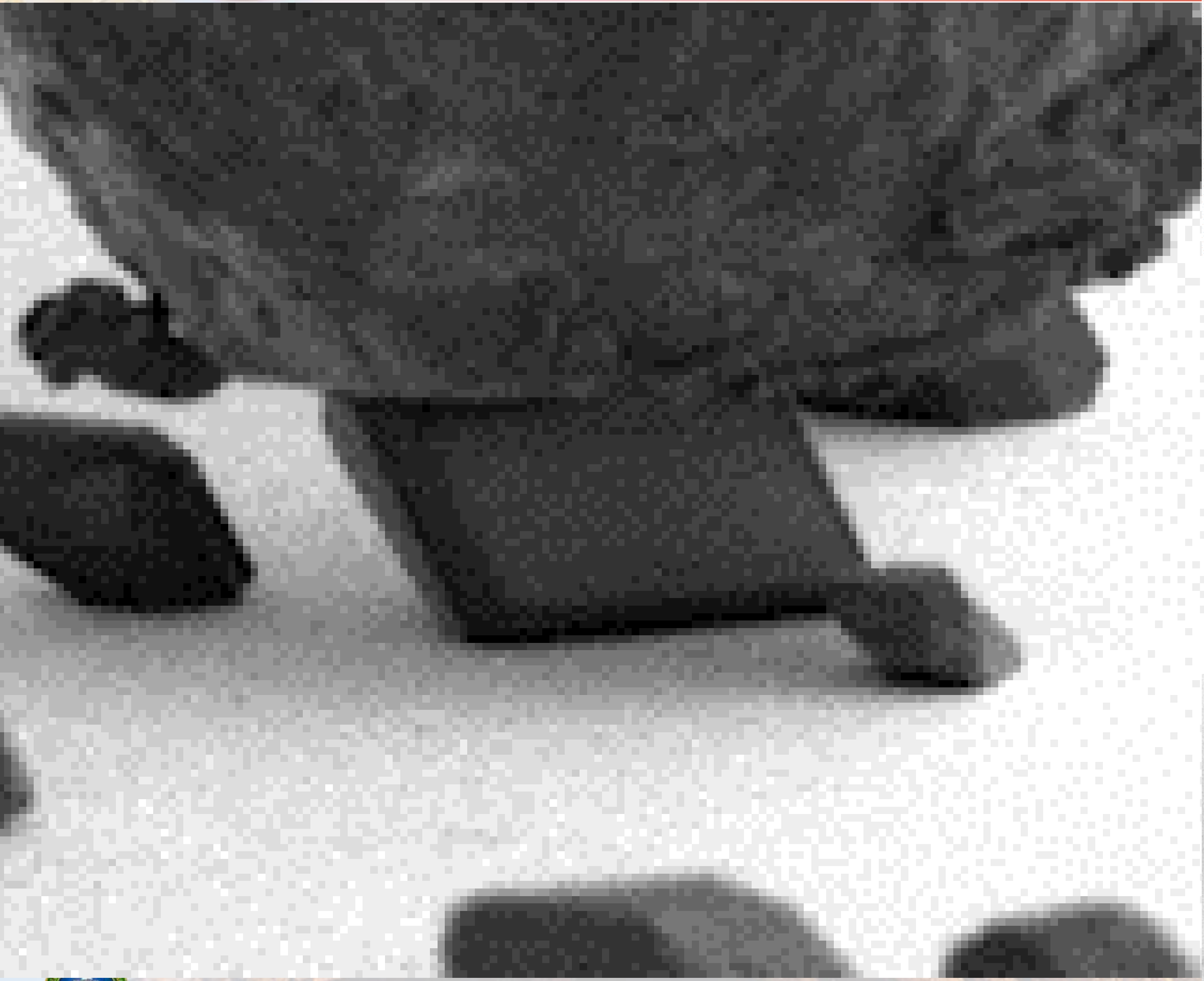


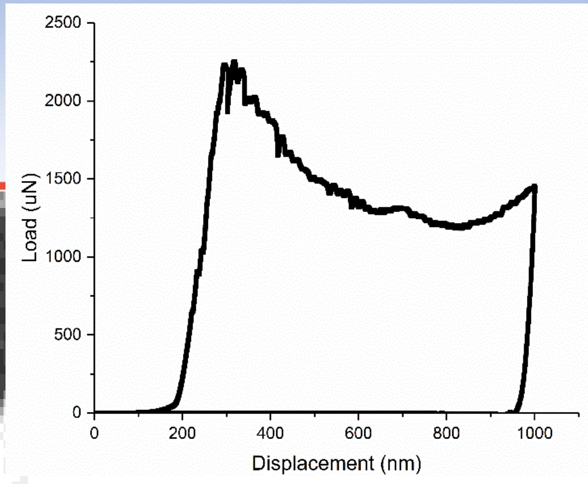
Post Irradiation

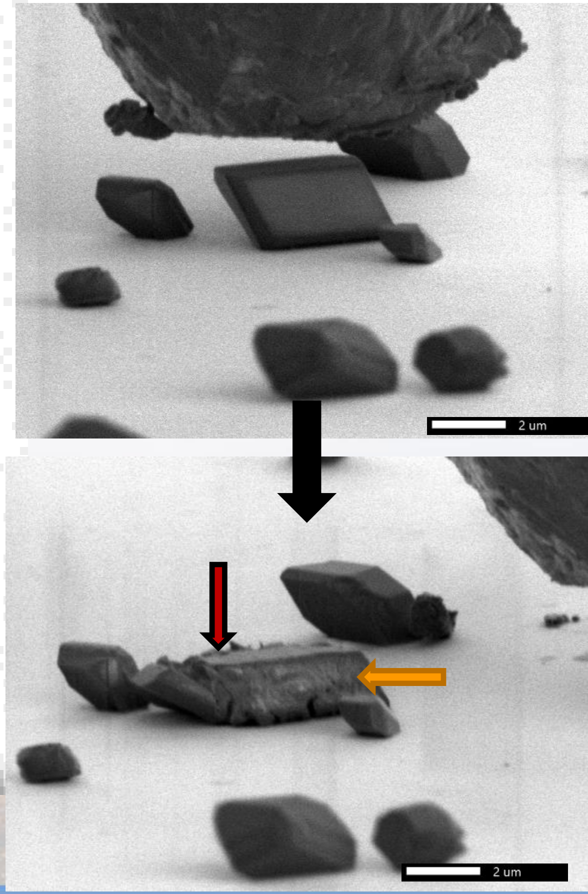


In situ Compression: Molecular Crystals

Collaborators: C.M. Barr, M. Cooper, D.C. Bufford, and J. Lechman



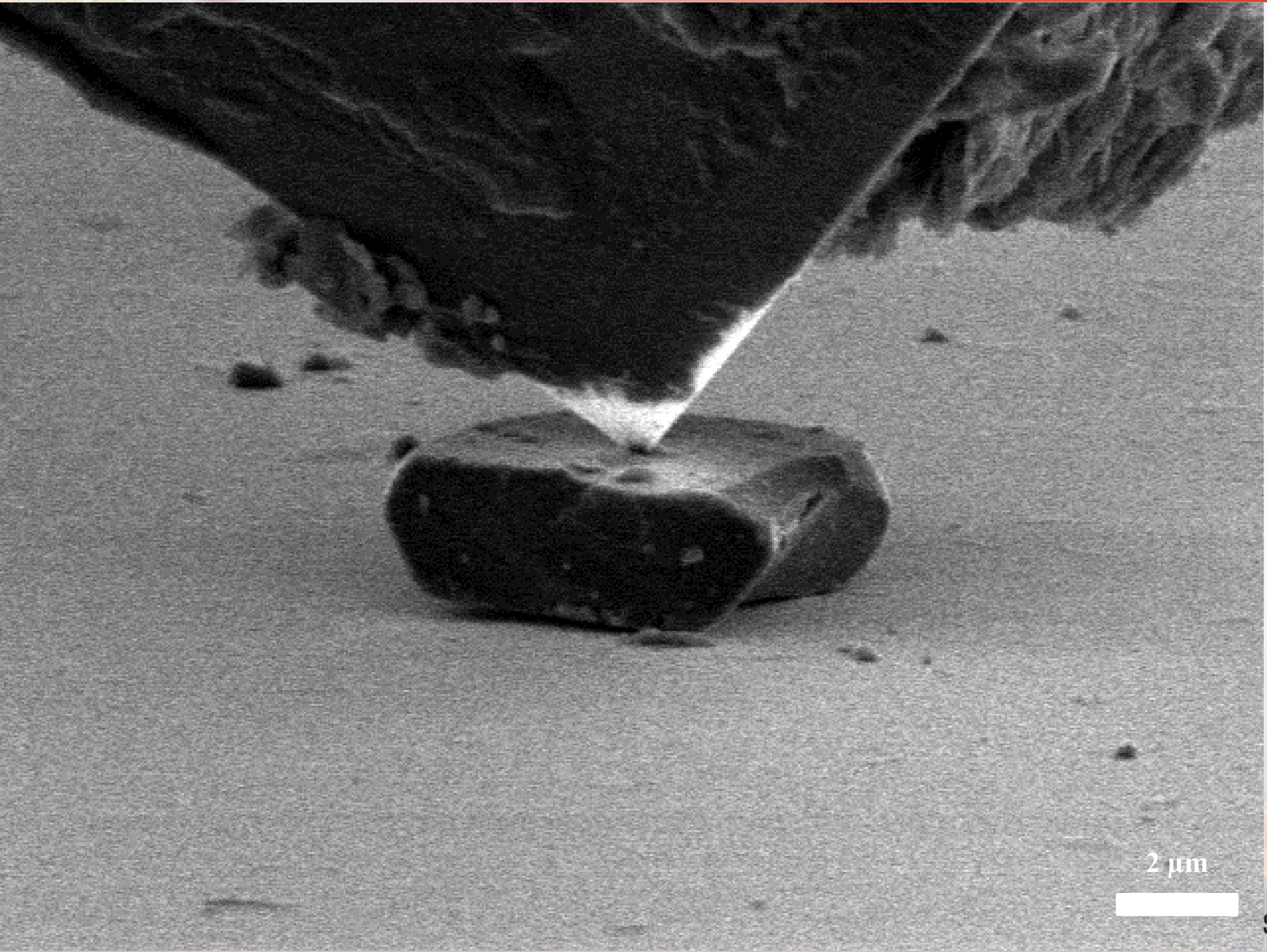




Displacement controlled fracture of molecular crystal

In situ Indentation: Ceramics

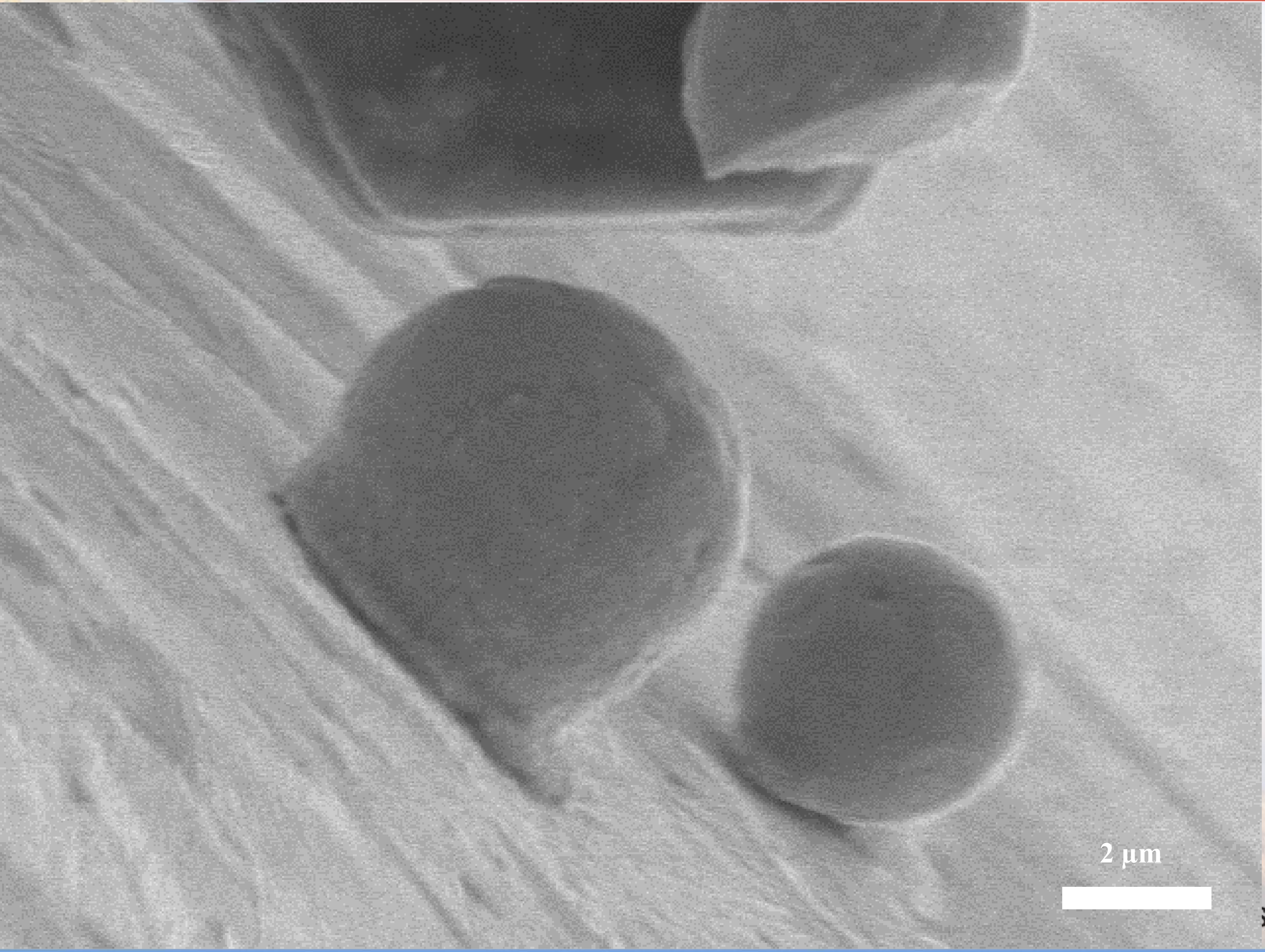
Collaborators: .N. Heckman, B.L. Boyce,



Alumina
30 mN peak load
3 mN/s load rate
1x speed

Angled *In situ* Compression: Steels

Collaborators: .N. Heckman, B.L. Boyce, B. Muntifering



Kovar
5 micron displacement
0.5 micron/s
1x speed