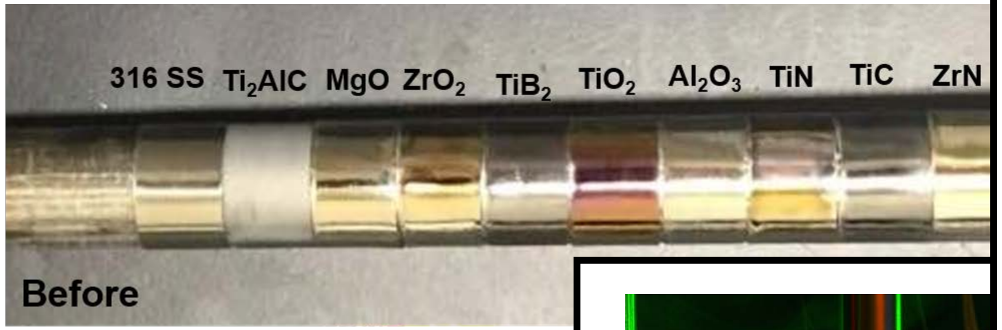
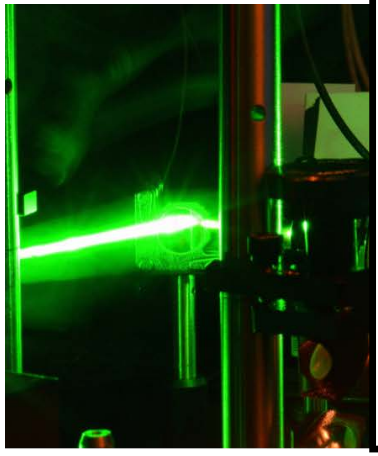
MIT-MNM: Mesoscale Nuclear Materials

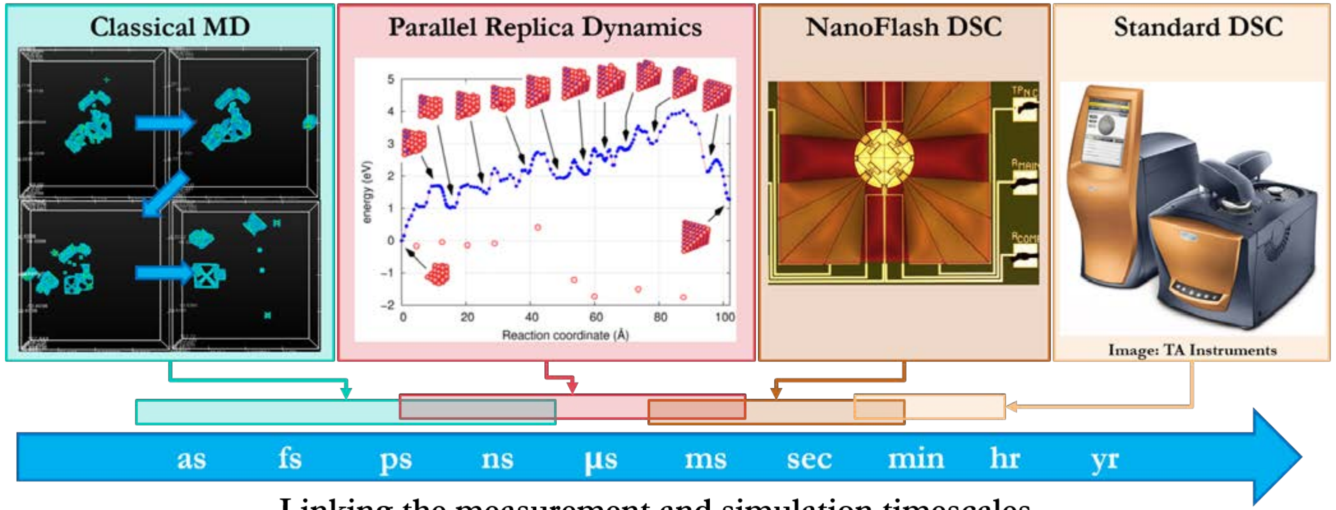
Our group focuses on science-based, industry-ready solutions to the longest and most deleterious issues facing large-scale energy production, with a particular emphasis on nuclear power.



Fouling-Re

Stopping stickiness by tuning optic





Linking the measurement and simulation timescales

The Stored Energy Fingerprints of Damage

Crafting a universal, measurable unit of damage to determine dose to nuclear structures, remaining reactor lifetime, and historical uranium enrichment

NDE of Radiation-Induced Material Properties

Measures swelling & stiffening *in situ*, reduces experiments from years to weeks

Designing the Ultimate Fouling Resistant Material

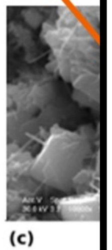
Max Carlson, Ittinop Dumnernchanvanit, Robert Simpson, Reid Tanaka, Alex Slocum, Michael Short

Designing Fouling-Resistant Materials

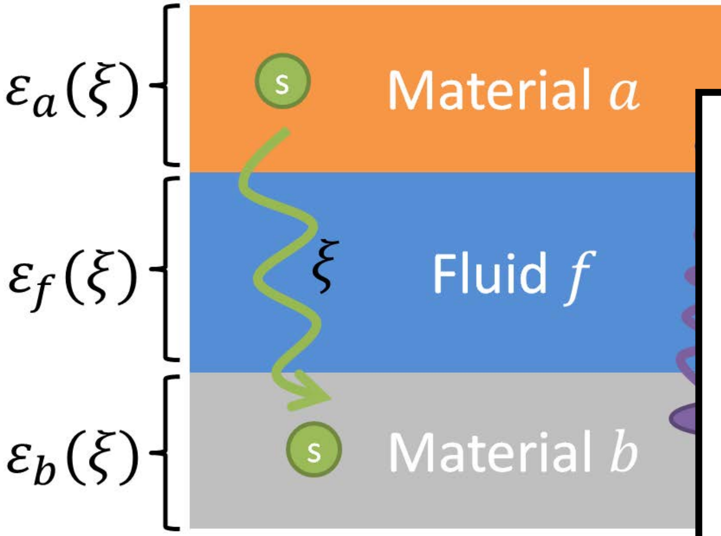
The Pr… …D) [1]

Corrosion …
as CRUD…

CRUD
constitu…
phases



The Origin: Electron Fluctuations [2]



- Fouling controlled by *van der W…*
- *Virtual photon amplitudes* deter… induced-dipole adhesion interac…
- Matching *either* material & the f… eliminate VDW forces & fouling

…ptoms and Cost: Power Shifts, Corrosion [2]

…uced Power Shift (CIPS)

Accelerated Corrosion (CILC)

The Theory & Solution: Match Optical Properties [3]

Matching coating index of refraction to the fluid provides a *foulant-agnostic* solution to CRUD, in nuclear, geothermal, and beyond!

$$A_{afb}^{TWA} \approx \frac{3\pi\hbar\nu_e}{4\sqrt{2}} \frac{\left(n_a^2 - n_f^2\right)\left(n_b^2 - n_f^2\right)}{\sqrt{\left(n_a^2 + n_f^2\right)\left(n_b^2 + n_f^2\right)}\left(\sqrt{\left(n_a^2 + n_f^2\right)} + \sqrt{\left(n_b^2 + n_f^2\right)}\right)}$$

Hamaker constant of VDW force → $A_{afb}^{TWA} = 0$ when $\begin{cases} n_a = n_f \\ \text{or} \\ \boldsymbol{n_b = n_f} \end{cases}$

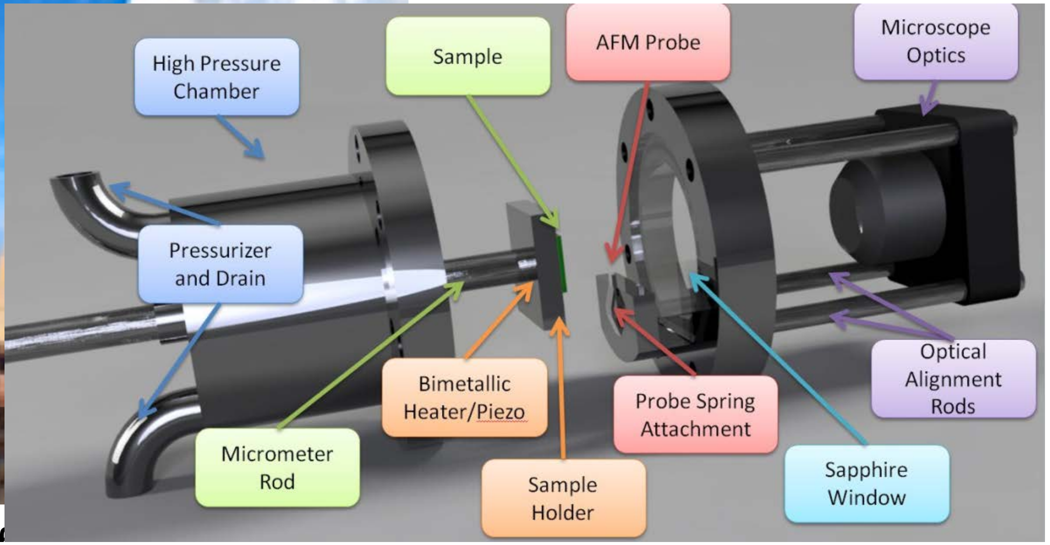
[1] Gaston, Short et al, *Ann. Nucl. Ener.*, 84:45-54 (2015)
[2] Gaston, Short et al, *Ann. Nucl. Ener.*, 84:45-54 (2015)
[3] Carlson, Slocum, Short. In *Active Matter*, MIT Press (2017)

Testing Fouling-Resistant Materials

What's Next for Fouling Resistant Materials?

Slick surfaces for geothermal energy
in IDDP2 (world's deepest geoth

Lead test rods scheduled
commercial reactor

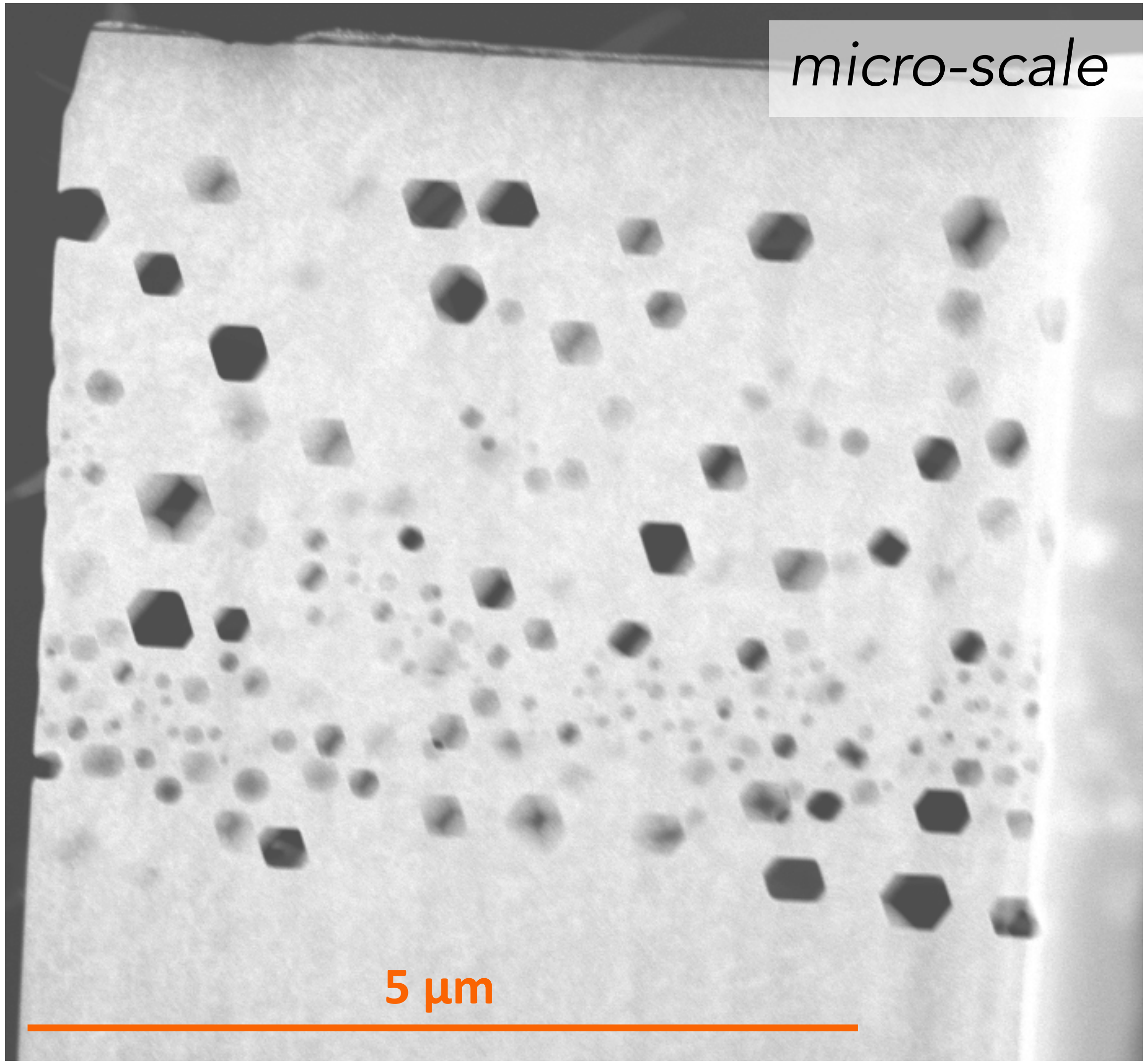


World's first high-T, hyperbaric AFM for direct force confirmation at reactor/geothermal conditions

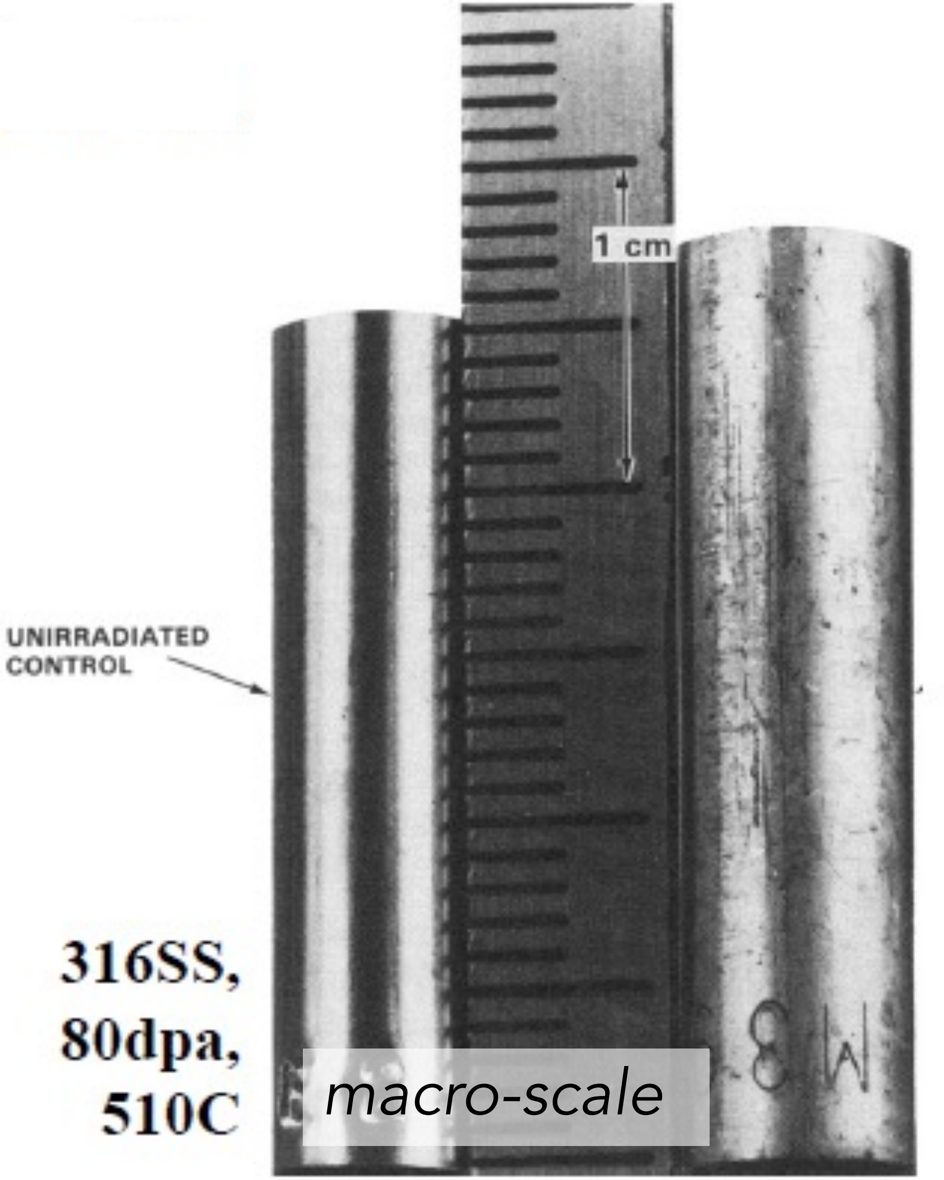
[1] Gaston, Short et al, *Ann. Nucl. Ener.*, 84:45-54 (2015)
[2] Gaston, Short et al, *Ann. Nucl. Ener.*, 84:45-54 (2015)
[3] Carlson, Slocum, Short. In *Active Matter*, MIT Press (2017)
[4] Dumnernchanvanit et al, Short. *J. Nucl. Mater.*, In Press (2017)

Radiation Does *Crazy* Things to Materials

Example: Radiation Void Swelling



Pure Cu
35 MeV Cu^{6+}
400°C



Calculating Radiation Dose with DPA…

Flux of particles at energy E_i

$$\frac{DPA}{sec} = \int_0^{E_{max}} \Phi(E_i) * \sigma_D(E_i)\,dE_i$$

Calculated radiation damage dose rate (**D**isplacements **P**er **A**tom)

Probability that each particle at energy E_i does radiation damage, and how much *primary* damage it does

…Just Doesn't Cut It! We Need to Measure.

Ions and Lasers: Exploring new, rapid diagnostics for nuclear materials

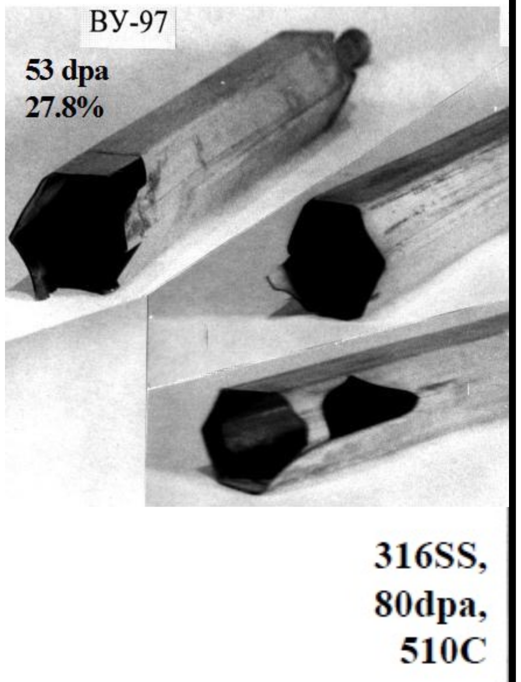
SSGF
STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP
NNSA
National Nuclear Security Administration
SUTD-MIT INTERNATIONAL DESIGN CENTRE (IDC)
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY

Cody A. Dennett, Sara E. Ferry, Penghui Cao, Kangpyo So, Michael P. Short (MIT), Khalid Hattar (Sandia National Lab)

We Need Faster Void Swelling Data

Problem: Void Swelling
Down All Types of Fissio

Neustroev et al., 1998



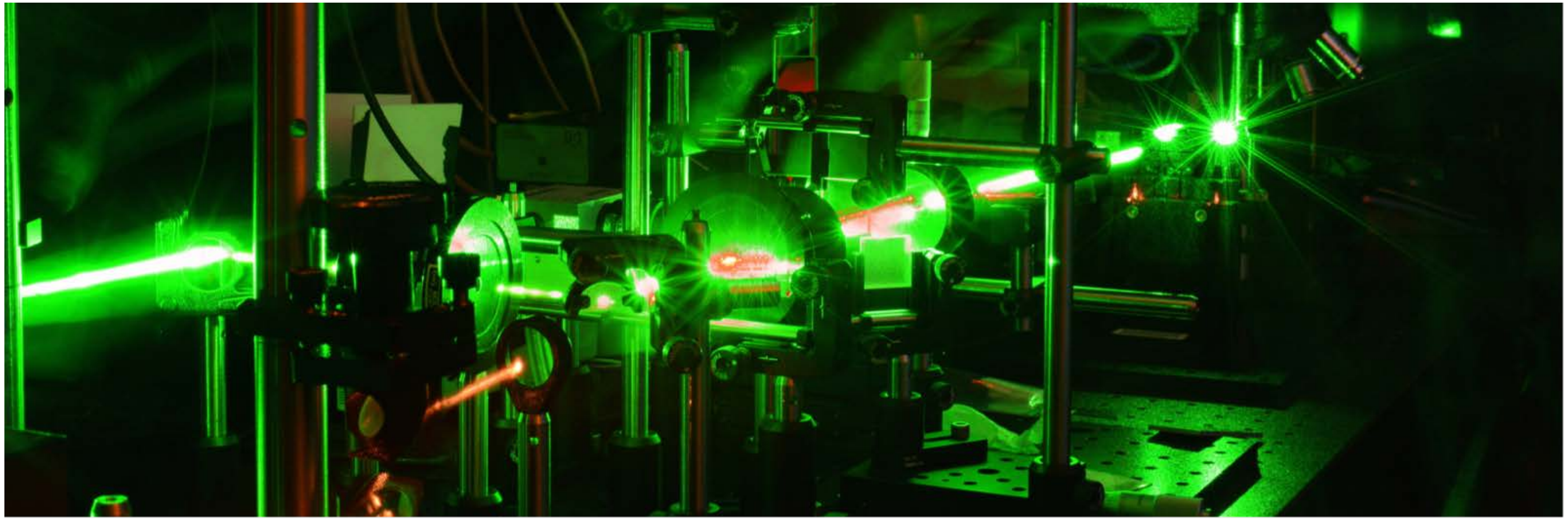
Left: Fuel failure upon reloading i
Right: Void swelling of 316SS i

Issue: Experiments Take Too Long [5]

Damage (dpa)

This study would have taken 500 years in a reactor, ~1 year in an ion accelerator. ***Not fast enough!***

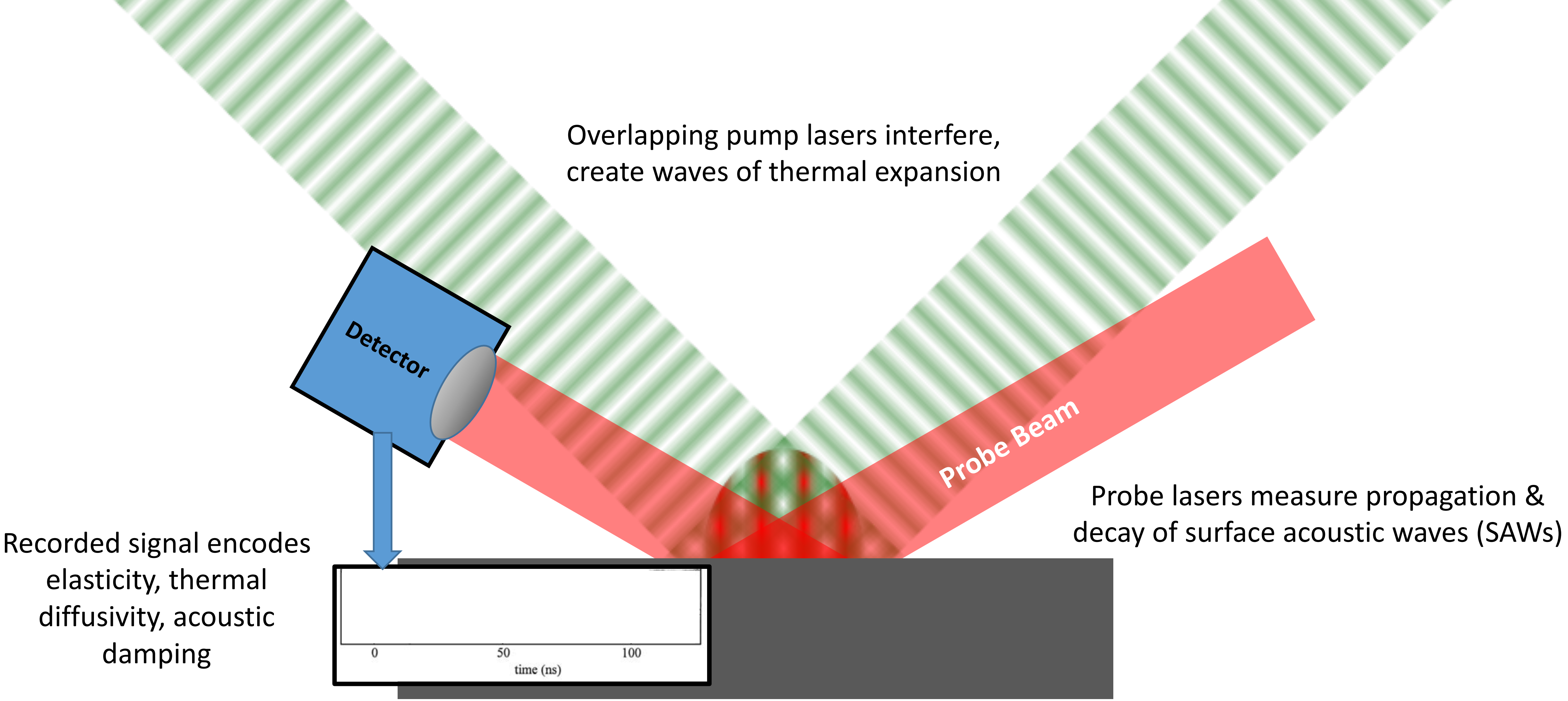
Our Solution: Transient Grating Spectroscopy as a Nuclear NDE Tech.



Chosen as the optimal technique to speed up radiation material science measurements [6]

[5] Short, Yip. *COSSMS*, 19(4):245-252 (2015)

How TGS Works



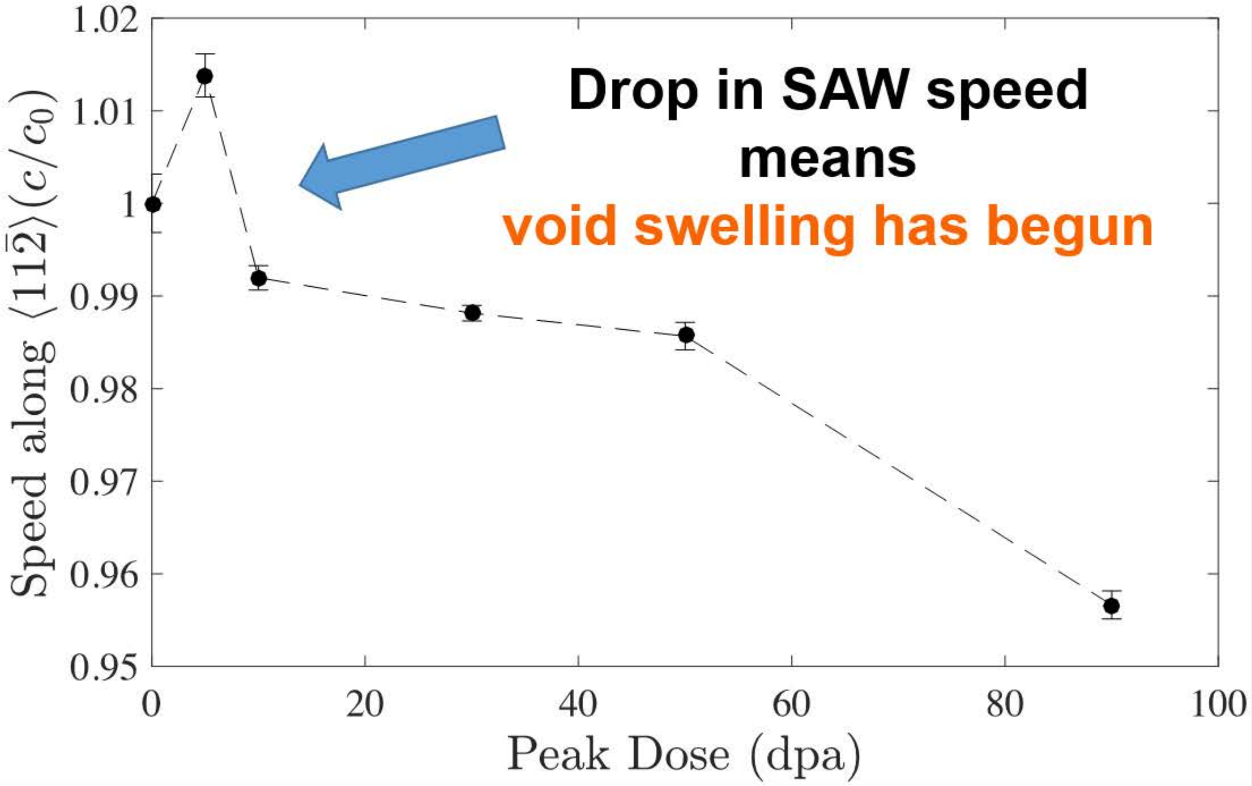
Proved that TGS Has Required Sensitivity, Speed, and Predictability

Se

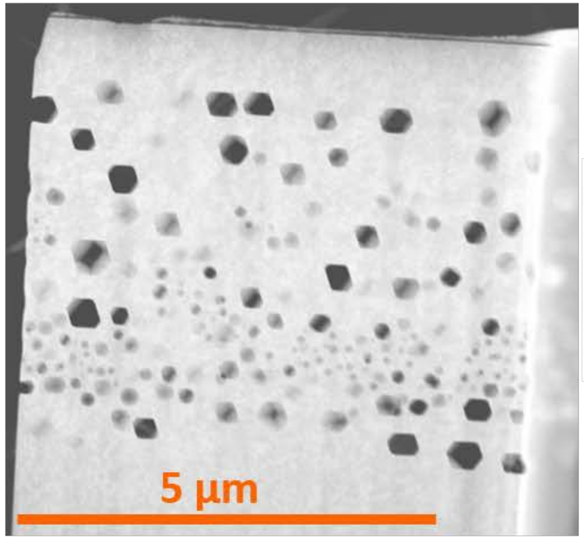
Fast: Acqu

Predictable: Excellent scaling between simulations and expts [6]

Impact: Detected void swelling onset in irradiated single crystal Cu with TGS [8]



Change in SAW speed with radiation dose along fast direction



Pure Cu
35 MeV
Cu^{6+}
400˚C

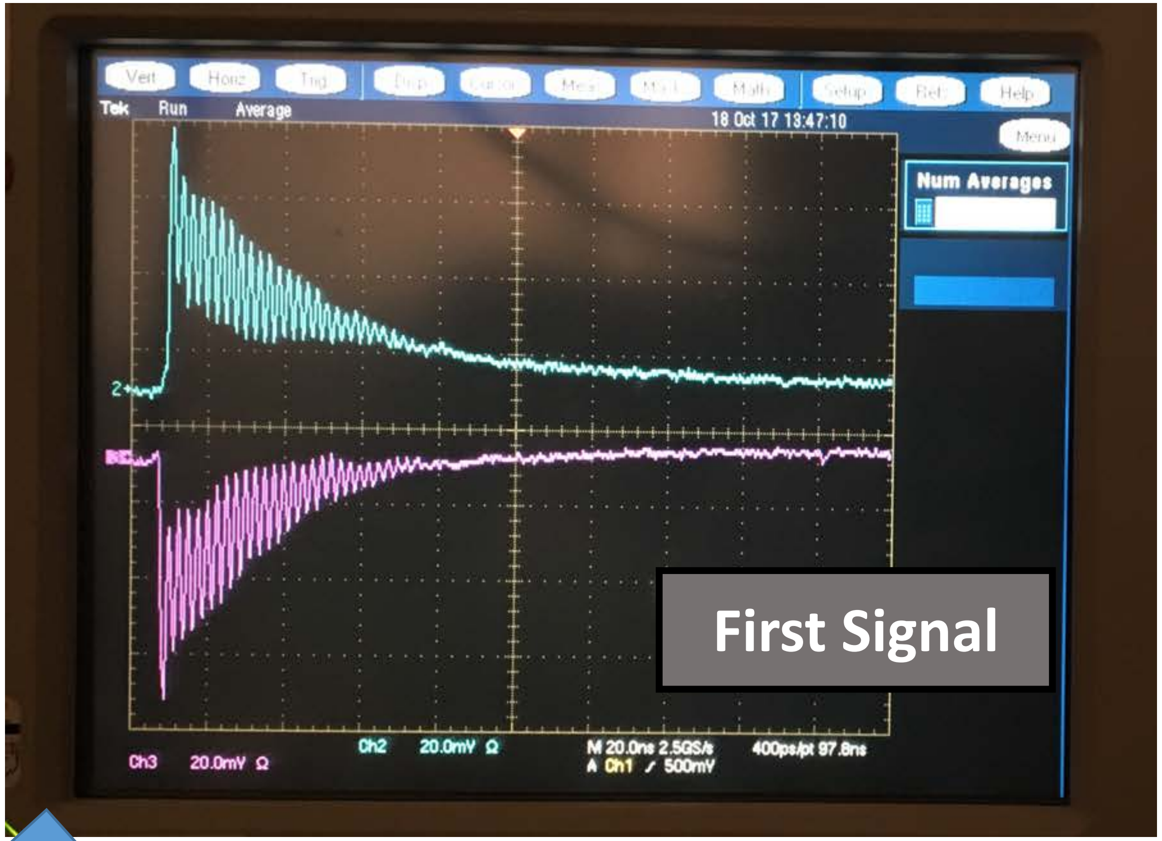
HAADF-STEM image of irradiated Cu

[5] Short, Yip. *COSSMS*, 19(4):245-252 (2015)
[6] Dennett et al., Short. *Phys. Rev. B*, 94:214106 (2016)
[7] Dennett, Short. *Appl. Phys. Lett.* 110:211106 (2017)
[8] Dennett et al, Short. *Acta Mater., Under Review* (2017)

Coming Soon!

Ion beam irradiation with *in-situ* DH-TGS

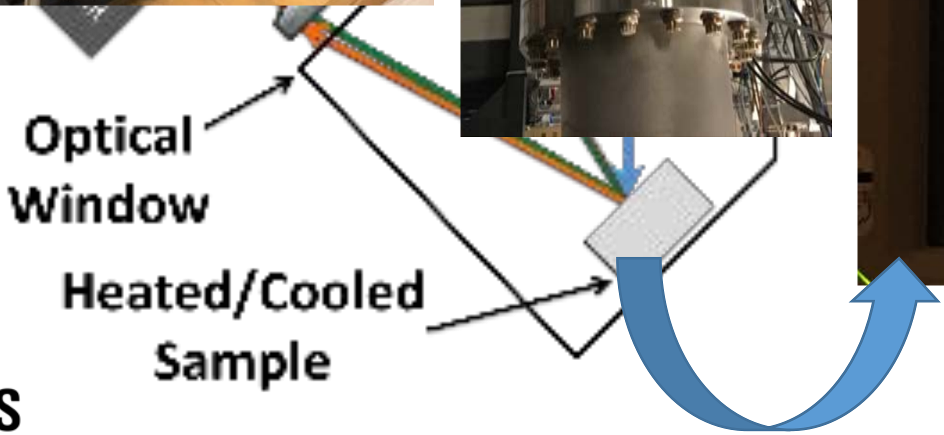
Ion Beamline

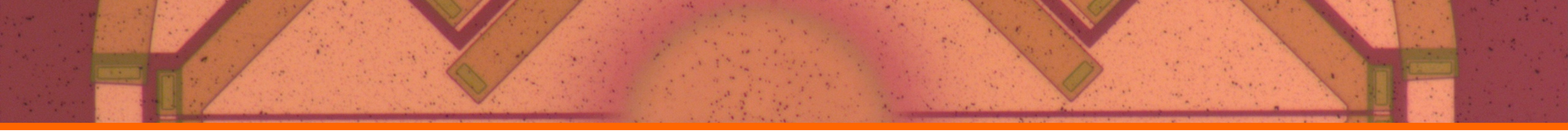


First DH-TGS signal measured on Oct. 19, 2017!!!

Under construction at

Sandia National Laboratories





The Stored Energy Fingerprints of Radiation Damage

Penghui Cao[1], Rachel Connick[1], Charles Hirst[1], Sara Ferry[1], Cody Dennett[1], Logan Abel[1], Ki-Jana Carter[1], Sean Lowder[1], Kevin Menard[2], Brian Turner[2], Mikhail Merezhko[3], Kira Tsay[3], Diana Merezhko[3], Oleg Maksimkin[3], Michael P. Short[1]

SUTD-MIT INTERNATIONAL DESIGN CENTRE (IDC)

[1] *Department of Nuclear Science and Engineering, MIT, USA*

[2] *Mettler-Toledo, Inc., Columbus, OH, USA*

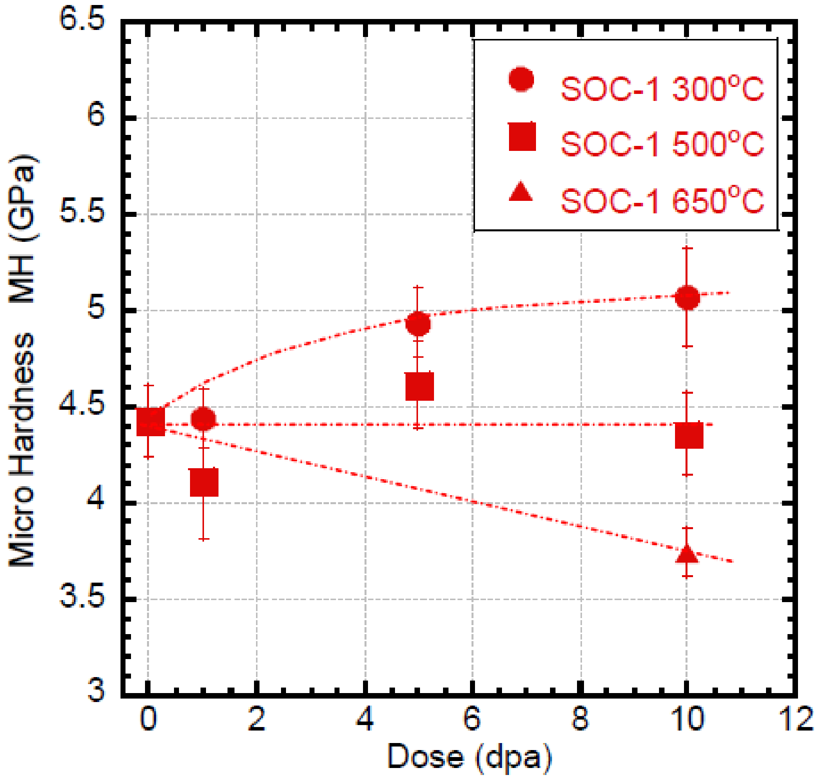
[3] *Institute of Nuclear Physics, Almaty, Kazakhstan*

NSF

CAREER Project

There Is *NO* Universal Unit of Damage

Problem: Can't Measure Damage!



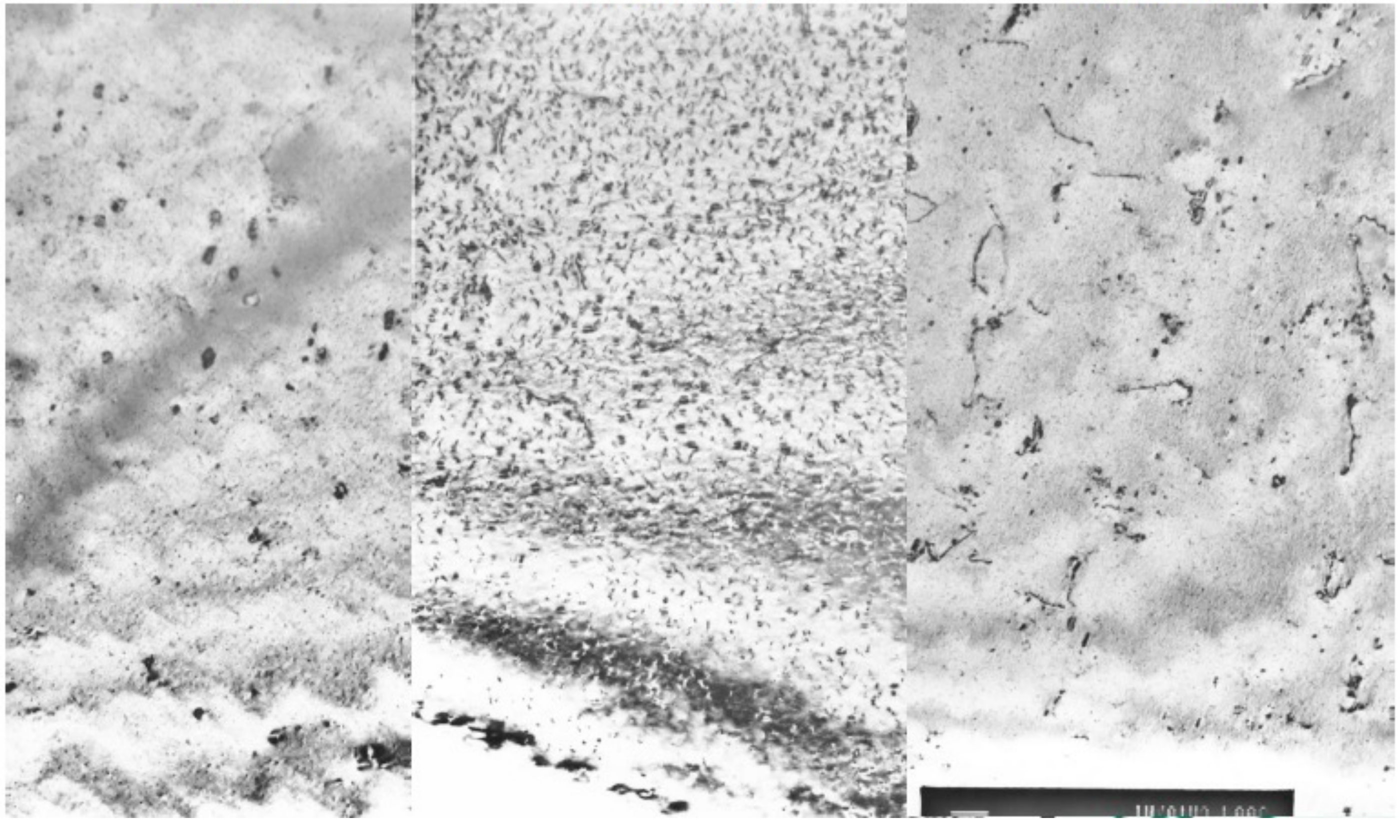
The "unit" of radiation damage, the DPA, is woefully inadequate. Can't be measured!

It Gets Worse: Looks Are Always Deceiving

Medium-high magnification, thin region

Medium magnification, thicker region

Low magnification, thickest region



Three people, one specimen in the TEM, three different results, all wrong

S. Ohnuki et al. "Japanese Facilities for High Fluence Irradiation." Michigan Ion Beam Workshop (2014).

S. J. Zinkle, Presentation, NATO Advanced Study Institute Course on Radiation Effects in Solids Erice, Sicily, Italy, July 17-29, 2004

Inspiration from the Manhattan Project

1943 Memo describing Eugene Wigner & Leo Szilard's discovery:

A series of wild letters from Franck and Barton to Hilberry on the Wigner effect. Don't see that these need change our program any. A new twist has been brought up--"the Szilard complication." According to this, energy is stored up in the graphite by neutron collision in a fashion analogous to cold working of metals or amorphous Zn.

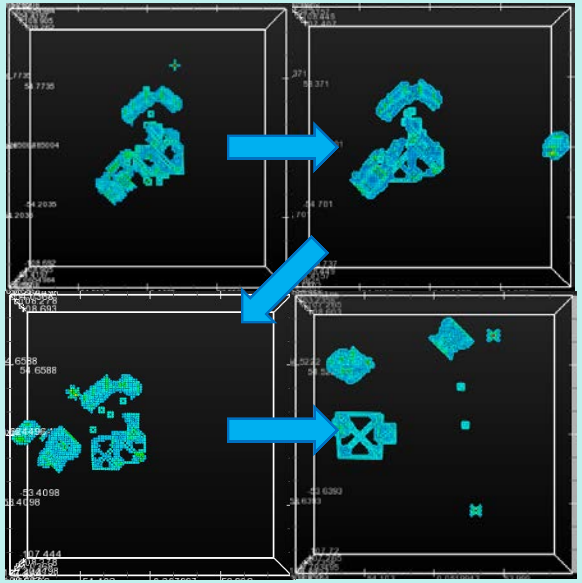
Retrieved from the Du Pont Manhattan Project archives by Andrew Engel and Cyril Milunsky (Mike's uncle)

Timescale Limitations To Overcome

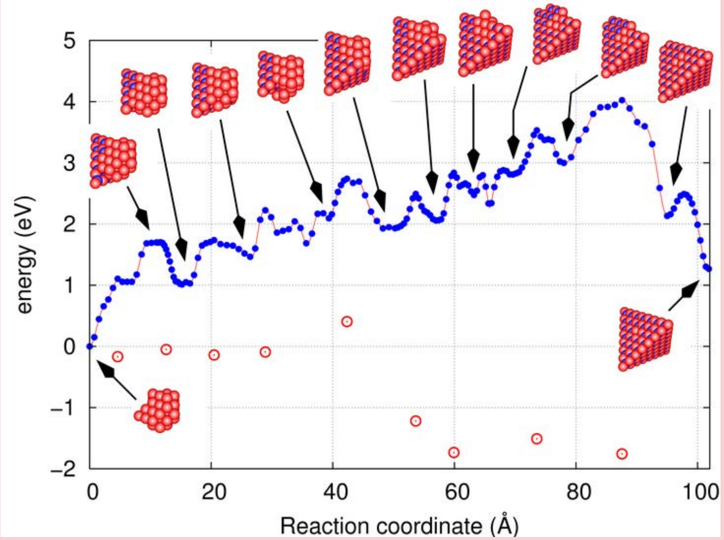
Allows us to "slow down" simulations to watch meaningful defect reactions

Speeds up DSC measurements to extract more power from tiny samples

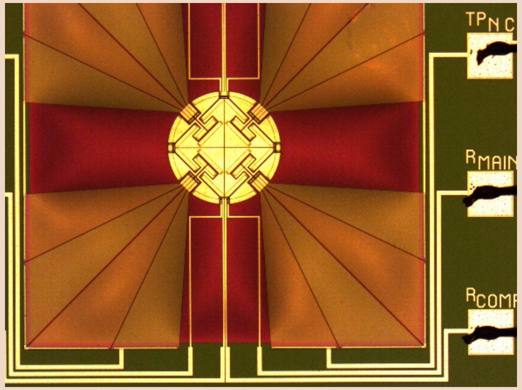
Classical MD



Parallel Replica Dynamics

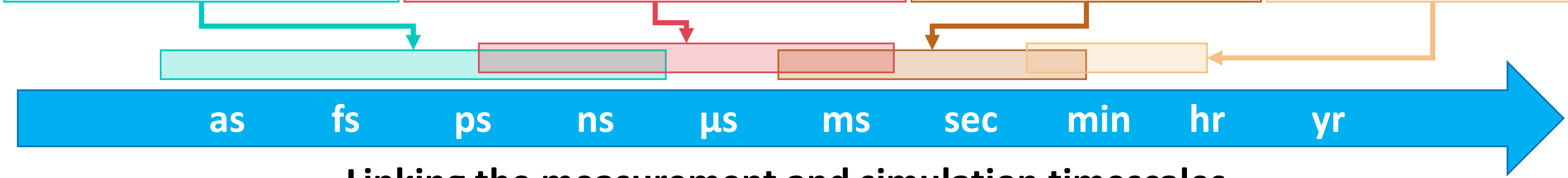


NanoFlash DSC



Standard DSC

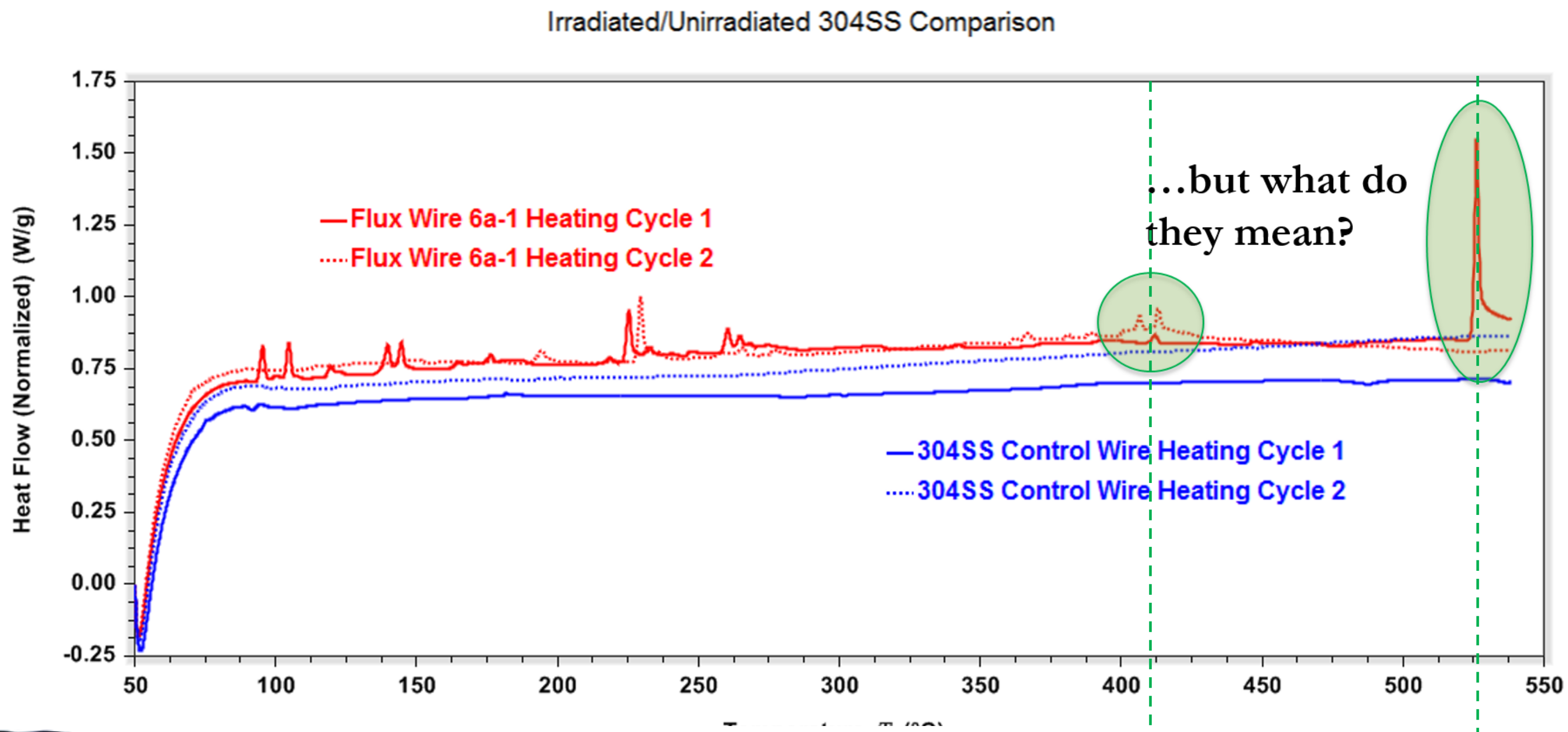
Image: TA Instruments



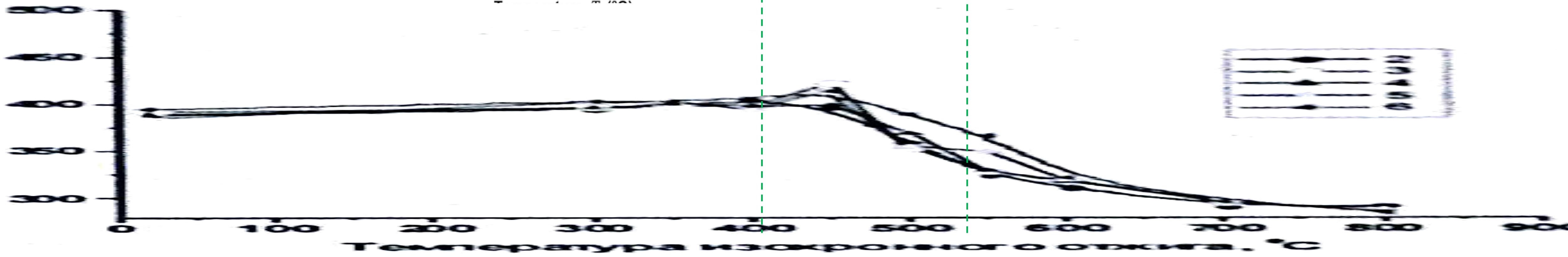
Linking the measurement and simulation timescales

[9] Cao et al., Short. *Phys. Rev. Lett., Submitted* (2017)

Initial Results Reveal *Radiation Induced Magnetism* - A Newly Observed Effect

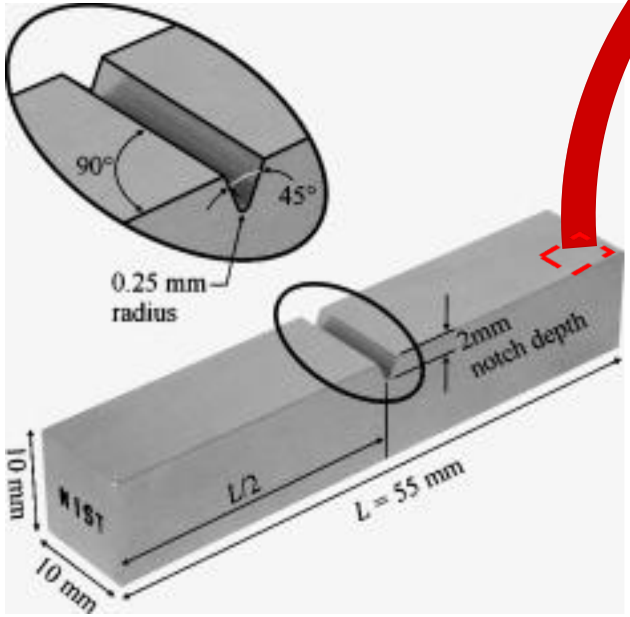


- DSC observed *energy storage* upon heating – phase transformation
- DSC curve (top) represents the *derivative* of the change in magnetism curve (bottom)

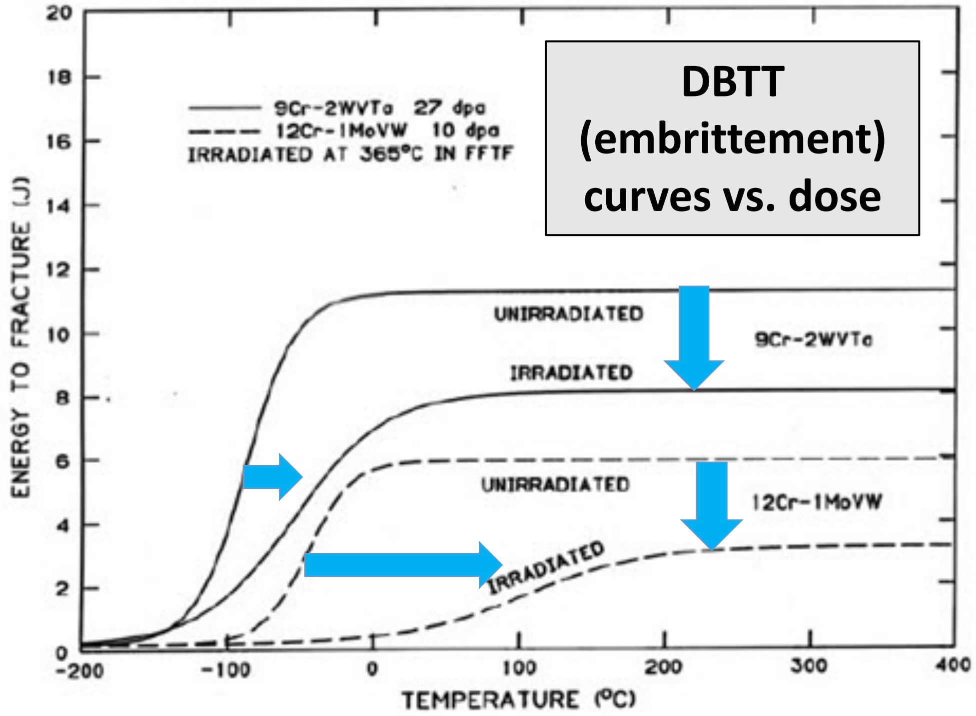


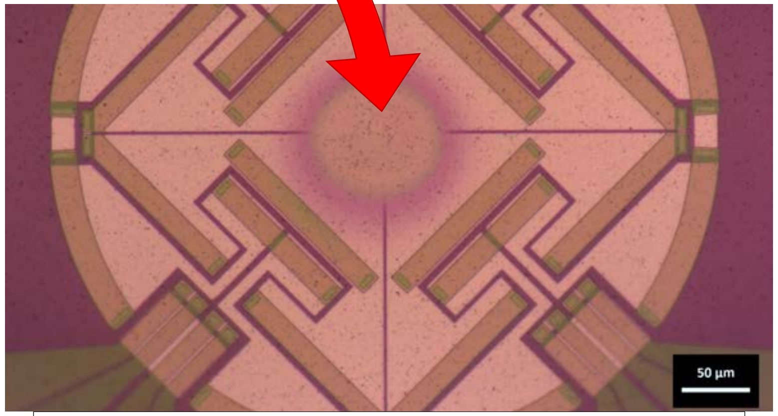
So… What Can We Do with nanoDSC?

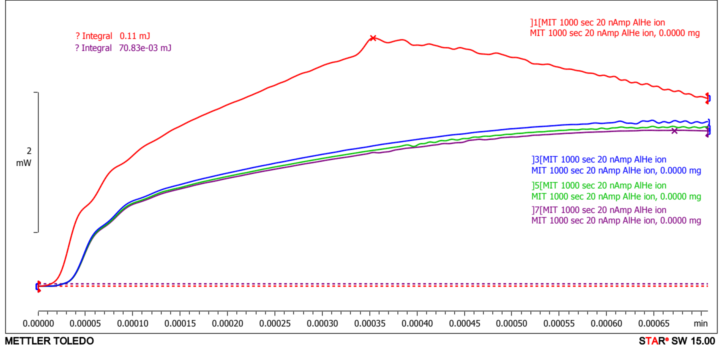
- Questions to Ask Ourselves:
  - What is the lowest dose that gives useful information?
    - Implications for basic science, reactor safety, and nuclear security



Charpy test coupon







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