Thermo-mechanical properties of damaged tungsten surfaces

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Main thrust of the proposal

- Utilize the unique capabilities of the LANL IBML (Ion Beam Materials Laboratory)and UCSD PISCES Facility to damage the near surface regions of W targets

- Employ novel nanotechnology diagnostic techniques to interrogate the near-surface region to determine the thermal and mechanical properties of the thin damaged layer

IBML uses energetic ions to simulate neutron damage of plasma-facing materials

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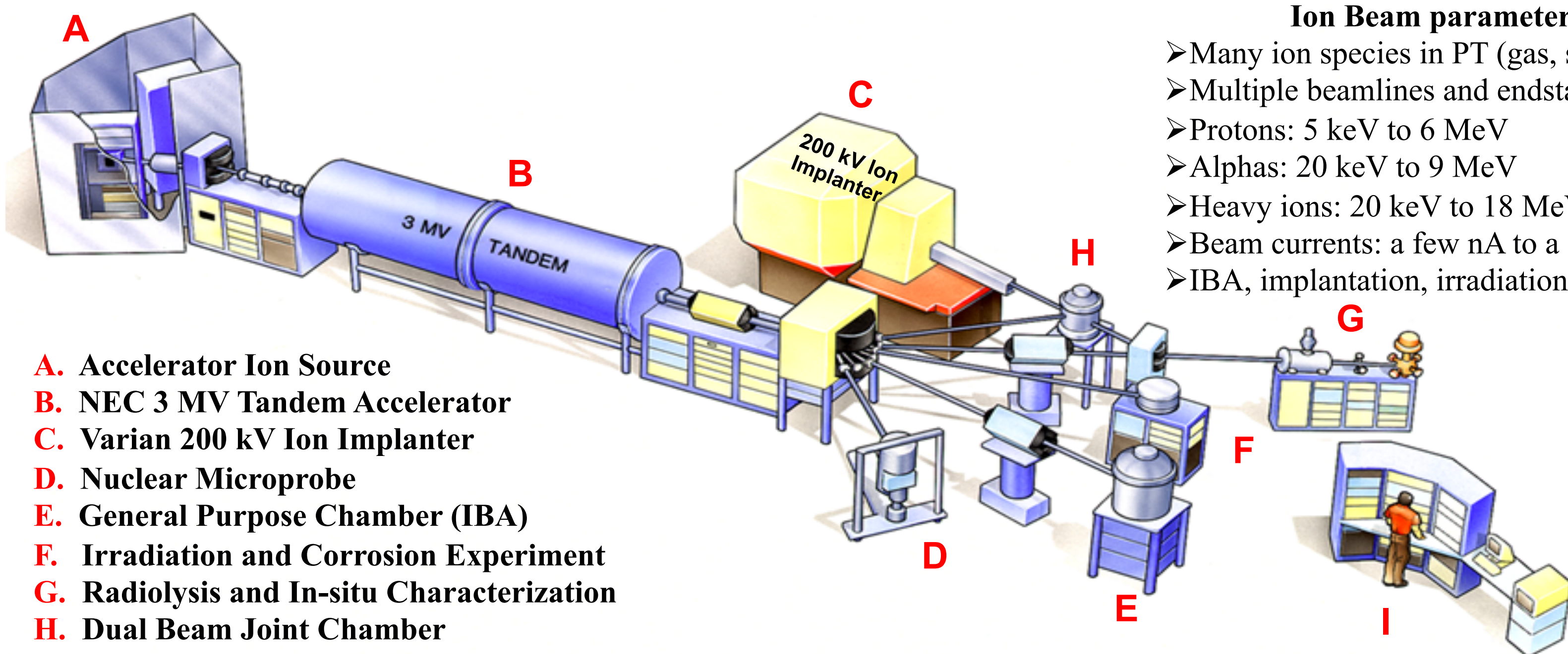
- A variety of heavy ions can impart surface damage to W targets
- Dual beam capability allows sequential and simultaneous He ion implantation
- Heated target holder allows damage annealing studies

Ion Beam parameters:

- Many ion species in PT (gas, sputter)
- Multiple beamlines and endstations
- Protons: 5 keV to 6 MeV
- Alphas: 20 keV to 9 MeV
- Heavy ions: 20 keV to 18 MeV
- Beam currents: a few nA to a few mA
- IBA, implantation, irradiation damage



A. **Accelerator Ion Source**
B. **NEC 3 MV Tandem Accelerator**
C. **Varian 200 kV Ion Implanter**
D. **Nuclear Microprobe**
E. **General Purpose Chamber (IBA)**
F. **Irradiation and Corrosion Experiment**
G. **Radiolysis and In-situ Characterization**
H. **Dual Beam Joint Chamber**
I. **Tandem Control Console**

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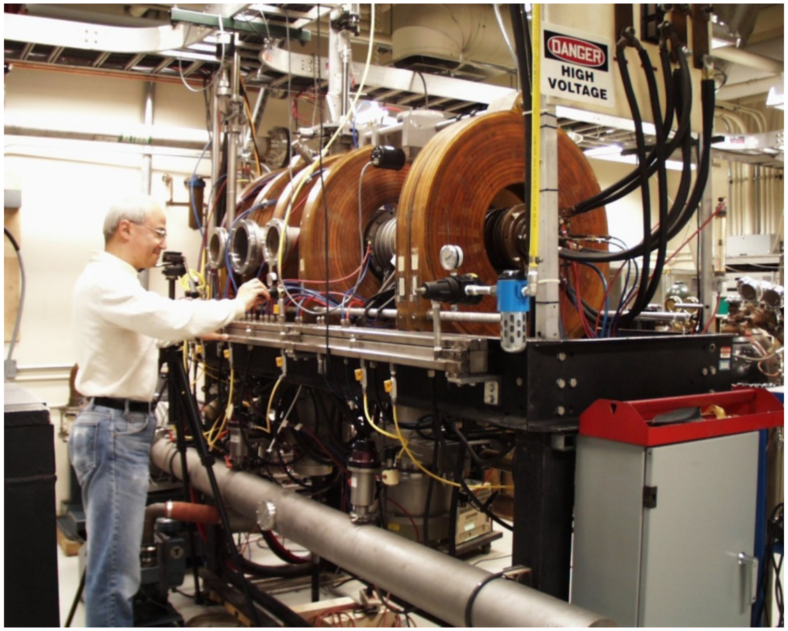
High flux plasma exposure occurs in PISCES-A

- PISCES-A device is used to facilitate sample sharing
- Simultaneous steady-state plasma exposure of damaged and undamaged targets to pure D, H, or He plasma, also quantified D/He mixed species plasma
- Γ_{ion} up to 5e22 ions/m^{2}s, T_e ~ 5-20 eV, T_{surf} = r.t. to 900°C
- TEM analysis for determination of surface changes
- TDS for post-exposure retention studies



Nanotechnology diagnostics can probe only the damaged surface region of targets

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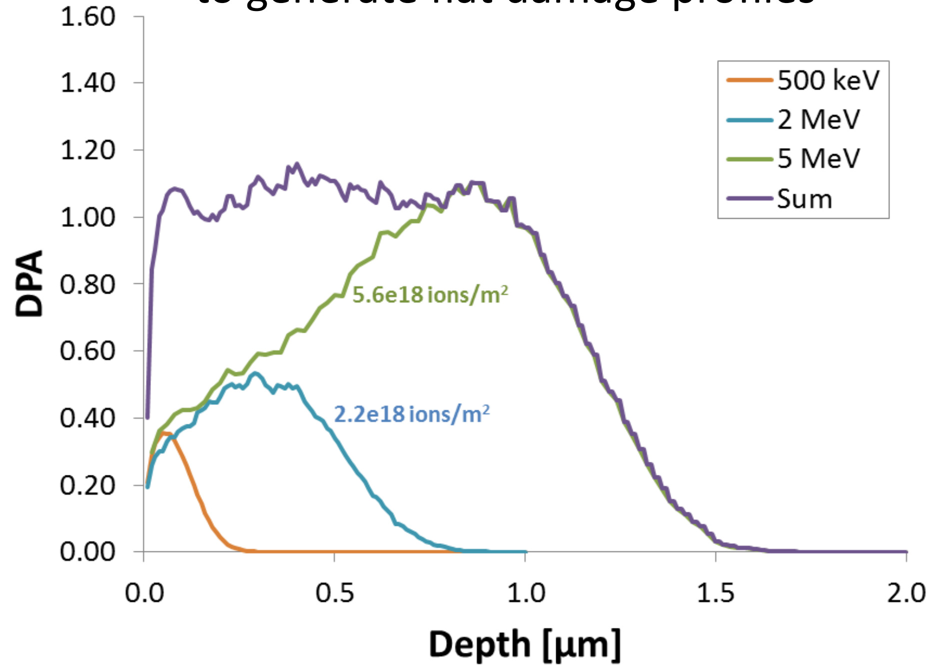
- Nanoindentation is used to measure changes in mechanical properties at the Center for Integrated Nanotechnologies (CINT) at LANL
- Nano3 Laboratory at UCSD provides clean room facilities for pattern deposition to measure thermal properties using a 3ω technique
- TEM analysis available at both locations

Multiple Cu^+ energies are overlaid to generate flat damage profiles

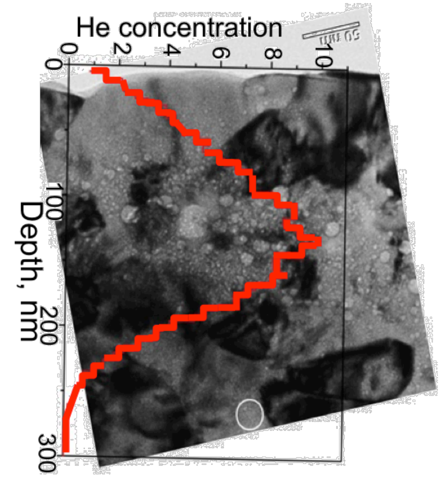


Research topics

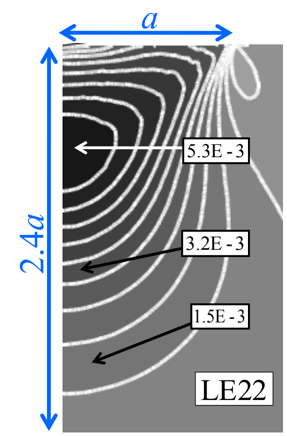
- Effects of room temperature damage with varying dose/dpa
  - Develop diagnostic procedures
  - Validate techniques against literature
- Inclusion of He in damage (sequential exposures @ rt)
  - Compare He ion beam damage to He plasma effects
- Influence of damage w & w/o He on D migration
  - Compare fluence dependences of He ion beam and plasma
- Vary temperature during damage to examine annealing [YR2]
- Simultaneous damage and He irradiation at a variety of temperatures to investigate He impact on annealing damage [YR3]

Using Indentation to Measure Radiation Damage

- The length scales in indentation (~ microns) are very complimentary to the size of the irradiation affected zone
- This makes indentation an ideal technique for measuring changes in local mechanical properties caused by irradiation



He profile (atomic %) on TEM of irradiated Ag



Strain fields under a spherical indenter

A series of differing indenter radii can be used to probe different depth scales

Indenter radius	Indentation depth (*h*)	Contact radius (*a*)	Indentation zone ~2.4*a*
1 µm	~10 nm	60 nm	144 nm
10 µm	~20 nm	250 nm	600 nm
100 µm	~40 nm	1,200 nm	2,880 nm
1000 µm *	>200 nm	12,800 nm	30, 720 nm

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Helium implanted W for nanomechanical testing
(~0.51 dpa, ~0.92 at%, ~18000 appm/dpa, ~500 nm)

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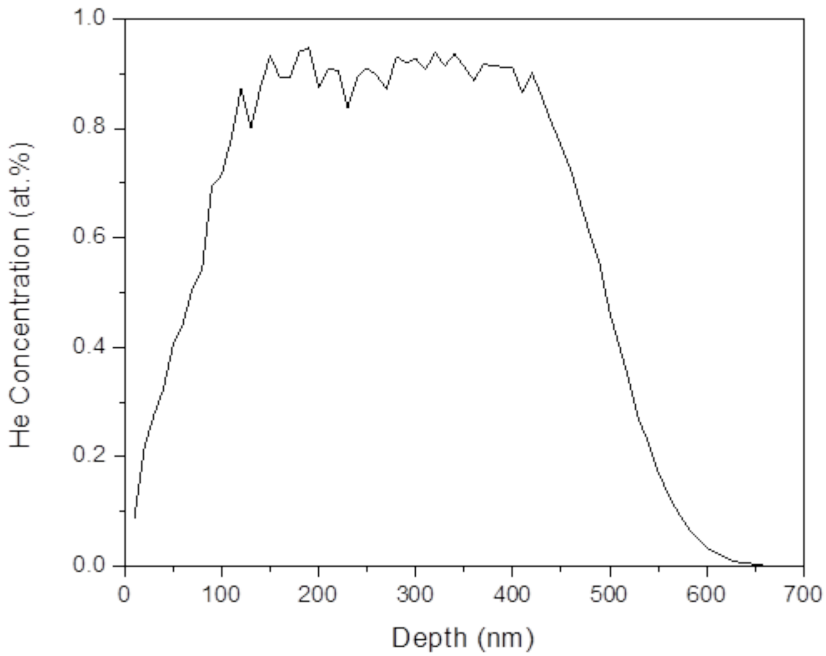
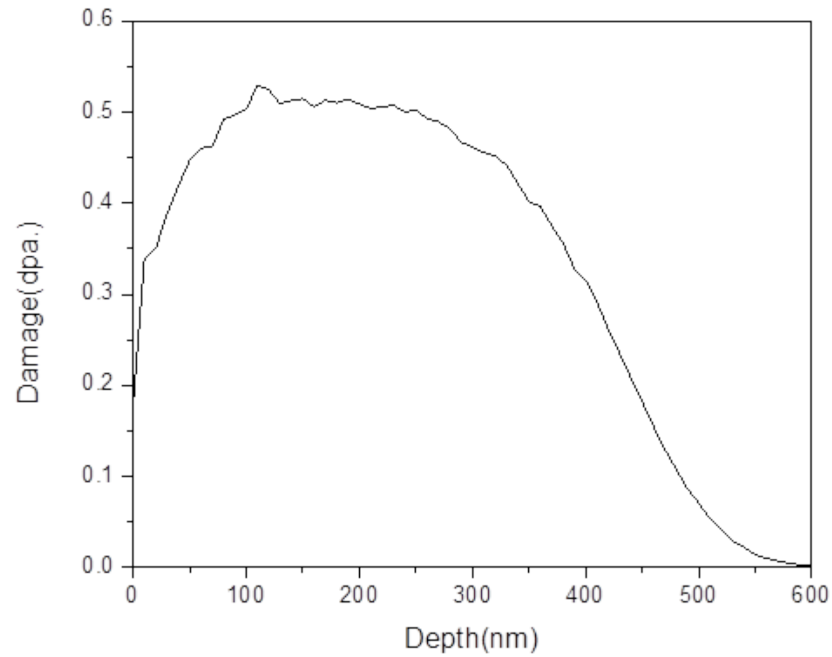
Multiple energies were used to generate a box-like profile
50 keV @$7.2x10^{15}$ ions/cm^2 100 keV @$8.0x10^{15}$ ions/cm^2
150 keV @$4.0x10^{15}$ ions/cm^2 200 keV @$2.0x10^{16}$ ions/cm^2





Indentation location on irradiated W sample

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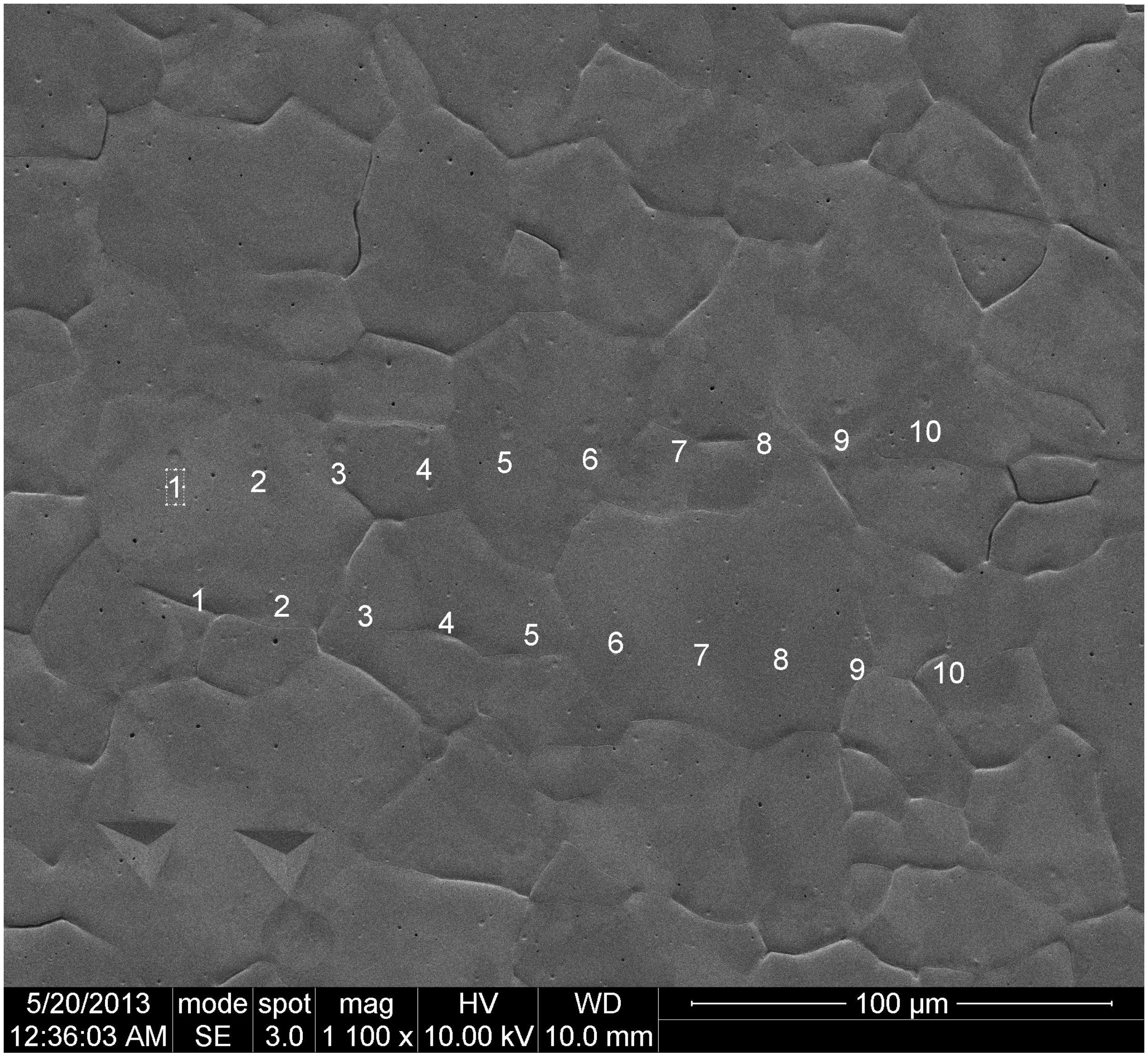

Irradiated vs. Unirradiated Tungsten: Preliminary Indentation Results

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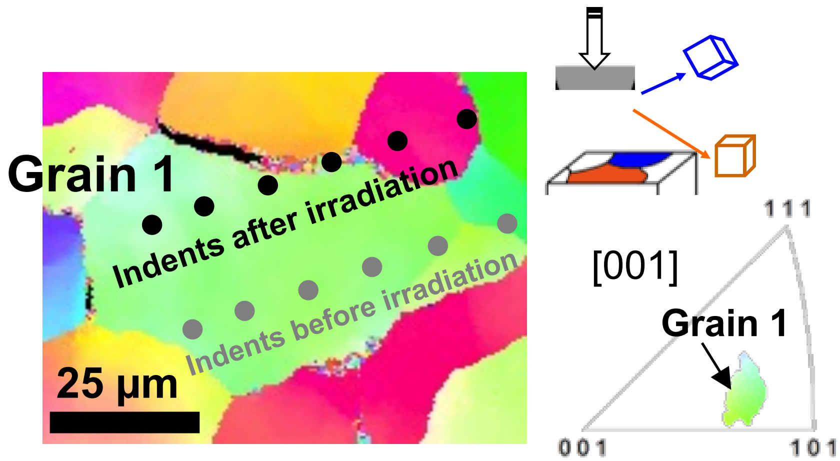
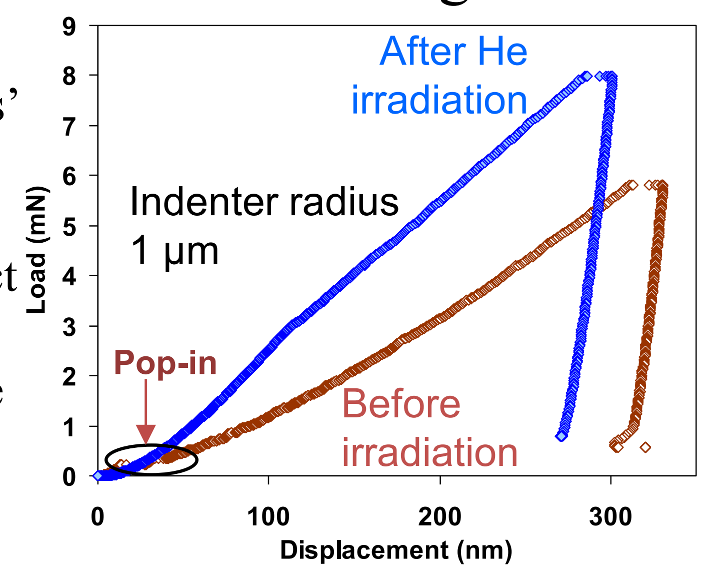
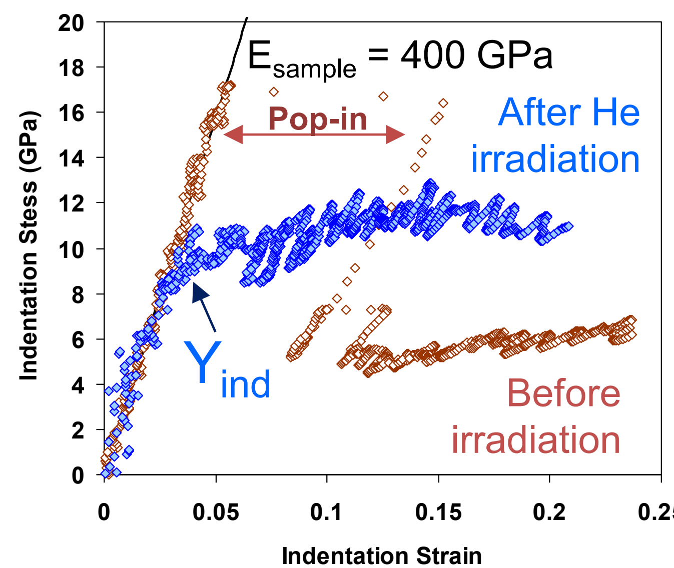


Tungsten Grain 1	Modulus, GPa	Hardness GPa
Before irradiation	373±24	5.36±5.3
After He irradiation	376±44	8.82±1.4

Irradiation induced hardening is measured using Stress-Strain analysis

Lack of 'pop-ins' after irradiation indicates significant defect density in the indentation zone





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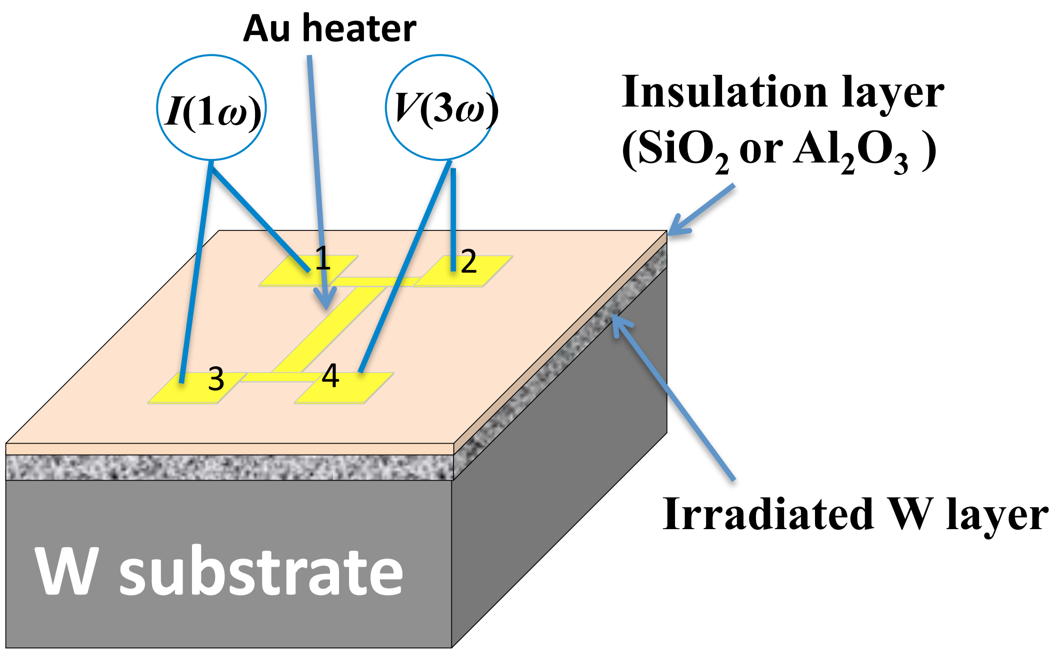
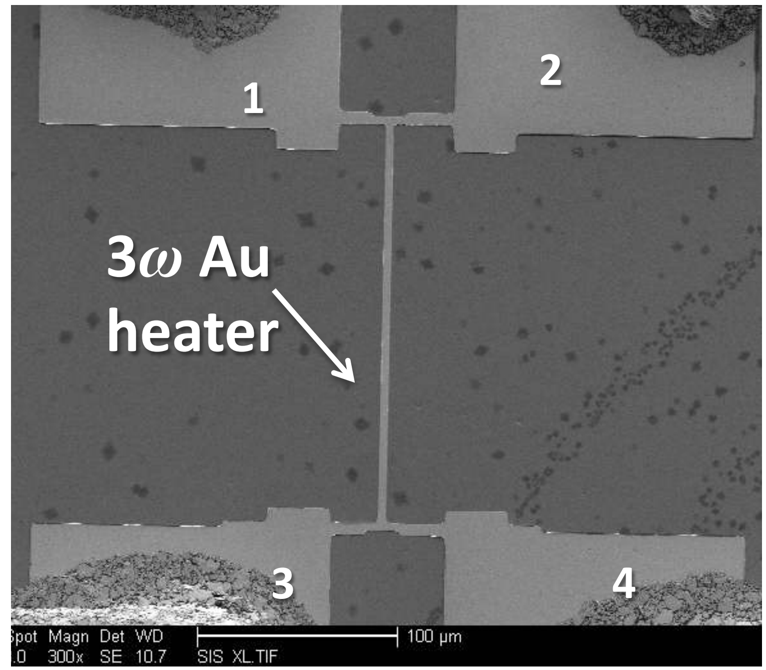
Thin Film Thermal Conductivity Measurement

3ω method





- Apply $I(\omega)$
- T oscillates at 2ω by Joule heating ($Q = I^2R$)
- R oscillates at 2ω ($R=R_o+\alpha T$)
- Can measure T rise from $V(3\omega)$
  - $V_{3\omega} = I(\omega)R(2\omega)$

3ω Data Reduction Method

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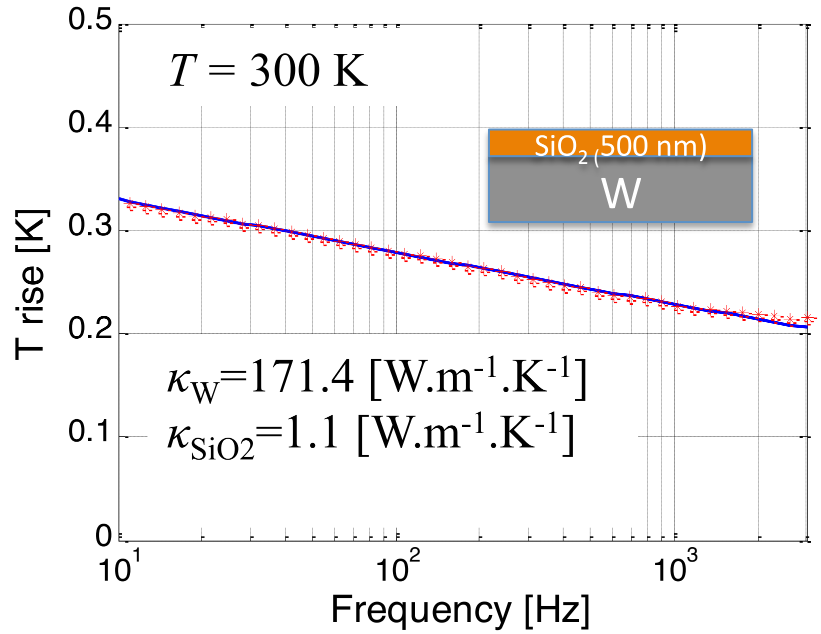
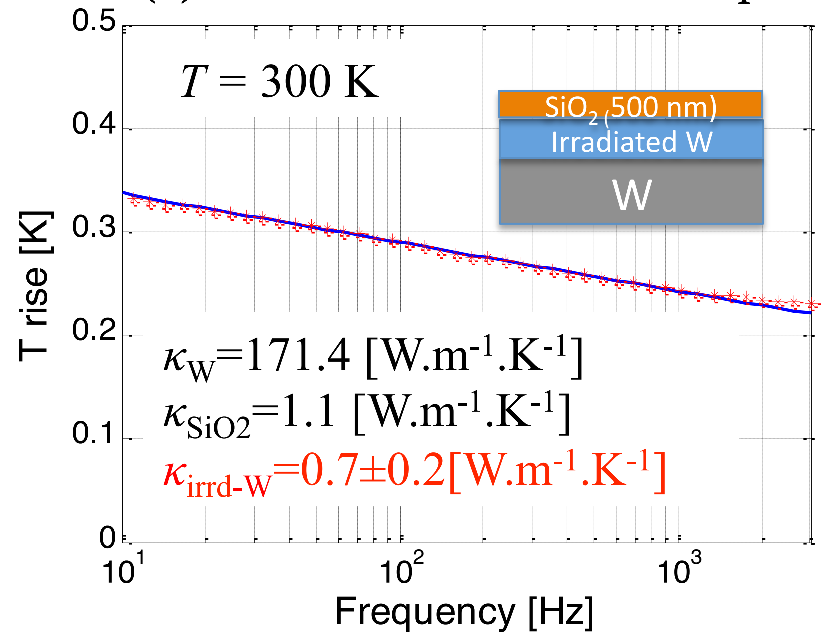
(1) Reference sample



(2) He Plasma Irradiated sample



1. Fit the experimental data (triangle symbols) to a 2D heat transfer model (solid line)
2. Obtain parameters for the reference sample (κ of W substrate & SiO_2 layer)
   - The obtain κ values agree well with the literature values. (κ_W=174 W/m-K, κ_{SiO2}= 1.1-1.2 W/m-K, see J. Appl. Phys. **81** (6) 2590 (1997))
3. Apply the parameters from the reference sample to the fitting of the irradiate sample to obtain the only unknown parameter, namely, κ of the irradiated layer.

Thermal Conductivity of Plasma(He)-Irradiated Tungsten

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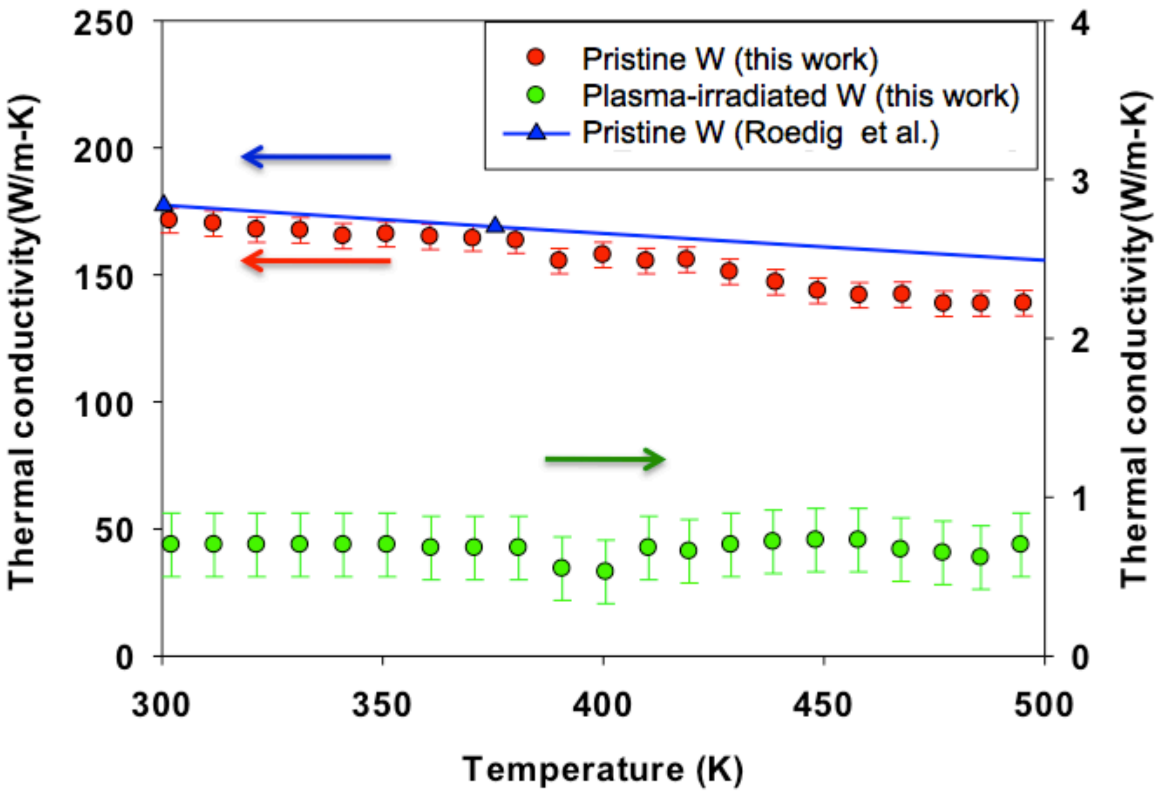

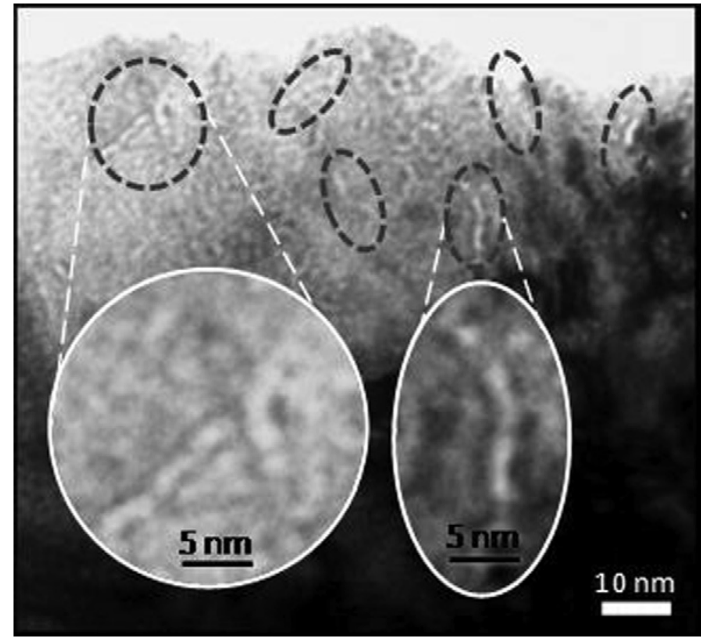

M. Miyamoto et al., JNM 415 (2011) S657

• κ of plasma-irradiated W (0.7±0.2 $W.m^{-1}K^{-1}$) is much lower than that of pristine W, presumably due to the defects formed during the irradiation.

•Between 300 and 500 K, κ of the plasma-irradiated W is independent of the temperature, also indicating that the electron scattering is dominated by the defects rather than phonon.

Ref: M. Roedig et. al , J. of Nucl. Mater. **329–333** (2004) 766-770

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Thermal Conductivity of Ion-Irradiated Tungsten

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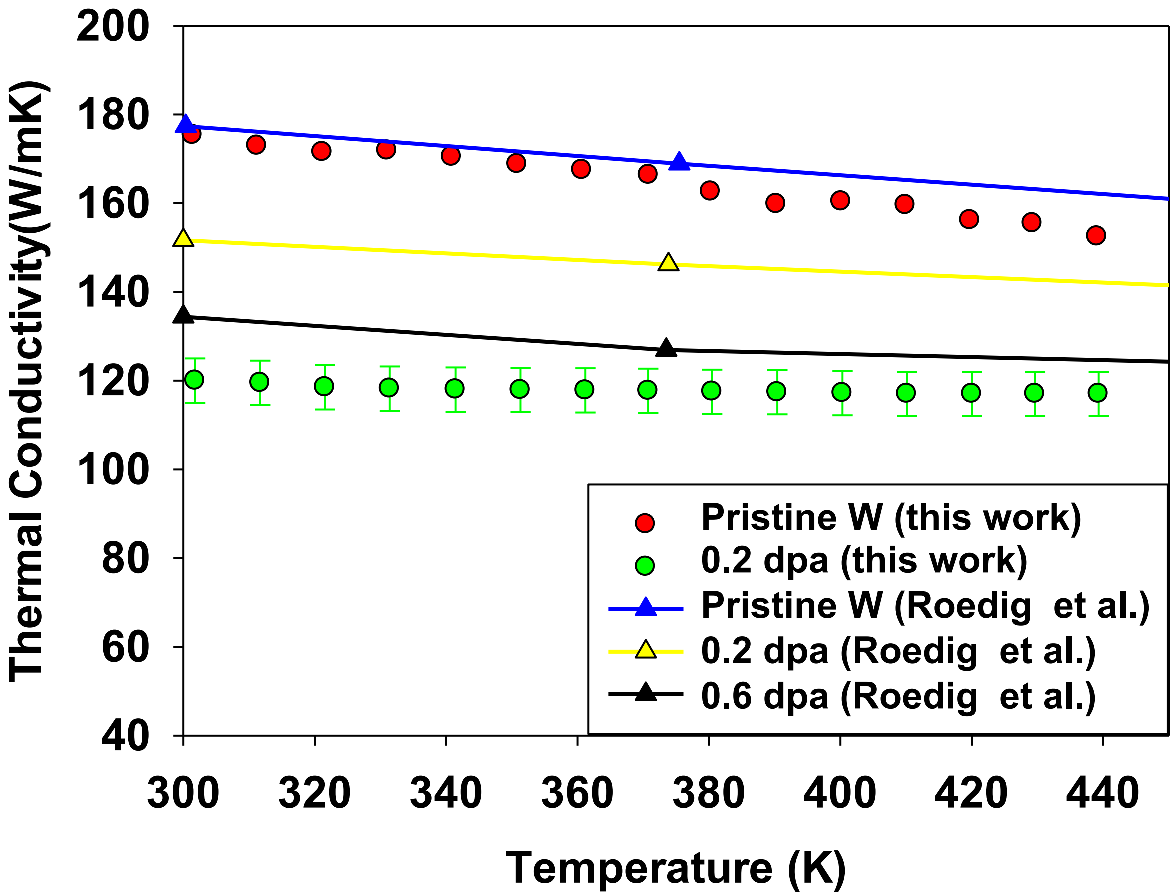

$\kappa_{irrd\_0.2dpa}$ = 120±5 [W.m^{-1}K^{-1}] (~30% lower than pristine W) and independent of temperature, indicating defect formation after ion irradiation of 0.2 dpa dose.

This value is somewhat lower than that what was reported in Roedig *et al.* (~150 W/m-K for 0.2 dpa irradiation), which used the laser flash method.

Ref: M. Roedig et. al , J. of Nucl. Mater. **329–333** (2004) 766-770

Plasma exposure is used to measure impact of damage on D migration

- Targets damaged with ions at LANL are brought to PISCES for plasma exposure
- After plasma, targets are returned to LANL for D depth profiling using NRA
- Finally, targets are returned to UCSD for TDS determination of total D content in the sample bulk

Plasma implanted D accumulates in damaged regions

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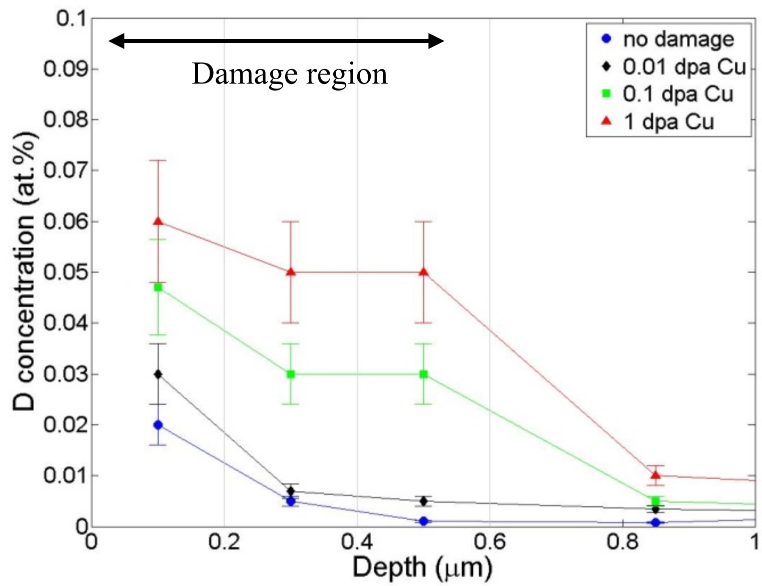
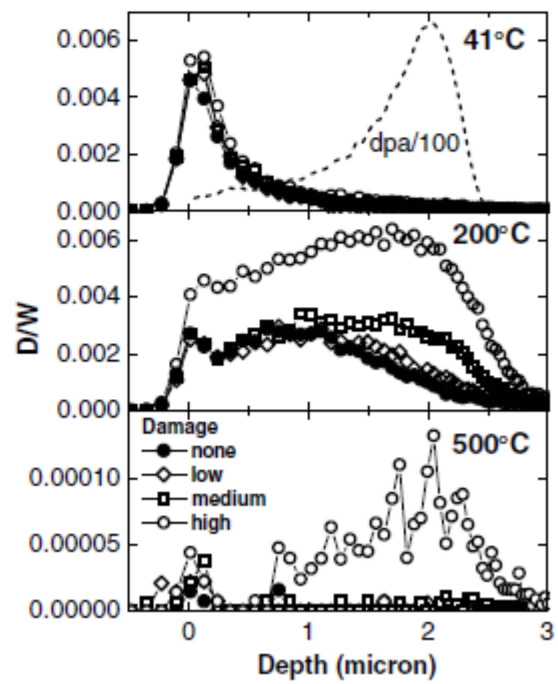
Retention increases with
increasing damage level



Retention behavior of self-damaged W and W damaged by Cu ions begins to deviate at around 1 dpa.



12 MeV Si^+
Low = 0.006 dpa
Medium = 0.06 dpa
High = 0.6 dpa

From: W. Wampler and R. Doerner, NF 49(2009)115023

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He plasma pretreatment requires large He^+ flux to inhibit D migration into the bulk, while high energy He^+ does not

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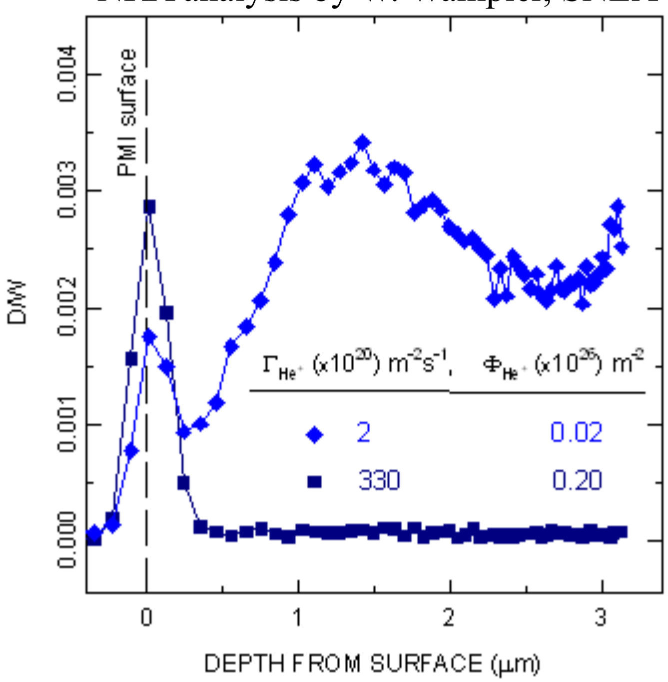
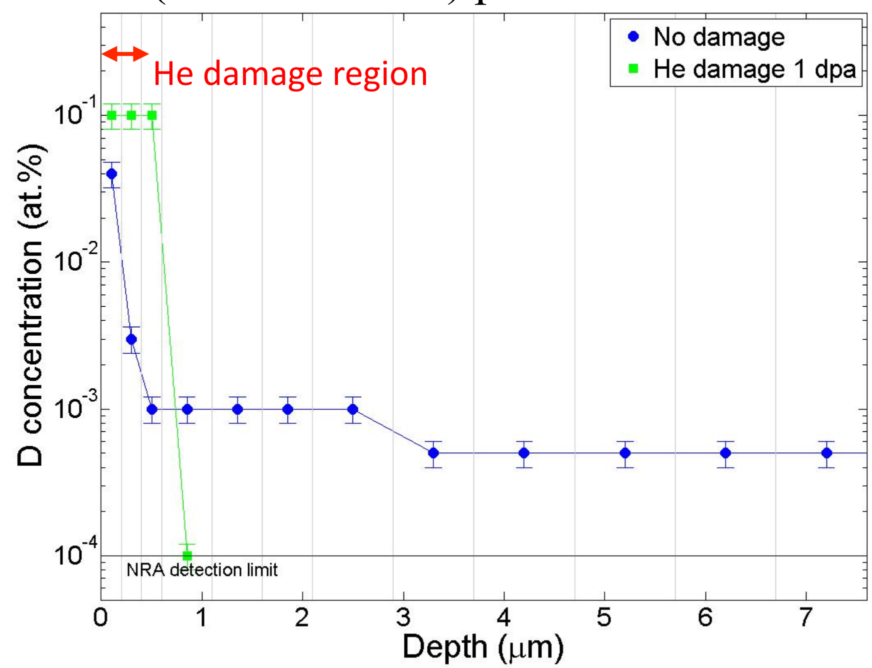
NRA analysis by W. Wampler, SNLA



200 keV He^+ to a peak 1 dpa ($5x10^{20}$ He^+/m^2) pretreatment



- Plasma ion energy was below W damage threshold, so helium concentration in W needs to be large enough to favor agglomeration and bubble growth (i.e. high flux necessary).
- 200 keV He ions can create and populate damage sites resulting in similar effects at much lower flux

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Status and summary

- 3 year project, year 1 recently completed
- Staffing, sample preparation and setup are all completed
- Initial results from nano-indentation and 3ω thermal measurements verify the capability of measuring the thermo-mechanical properties of thin damaged layers
- Preliminary results incorporating He into damaged regions seem to support basic principles of D/He interactions in tungsten and highlight the importance of helium production due to neutron bombardment