Refractory Armored First Wall Development

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Government Labs
NRL
LLNL
SNL
LANL
ORNL
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Universities
UCSD
Wisconsin
Georgia Tech
UCLA
U Rochester
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UC Santa Barbara
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General Atomics
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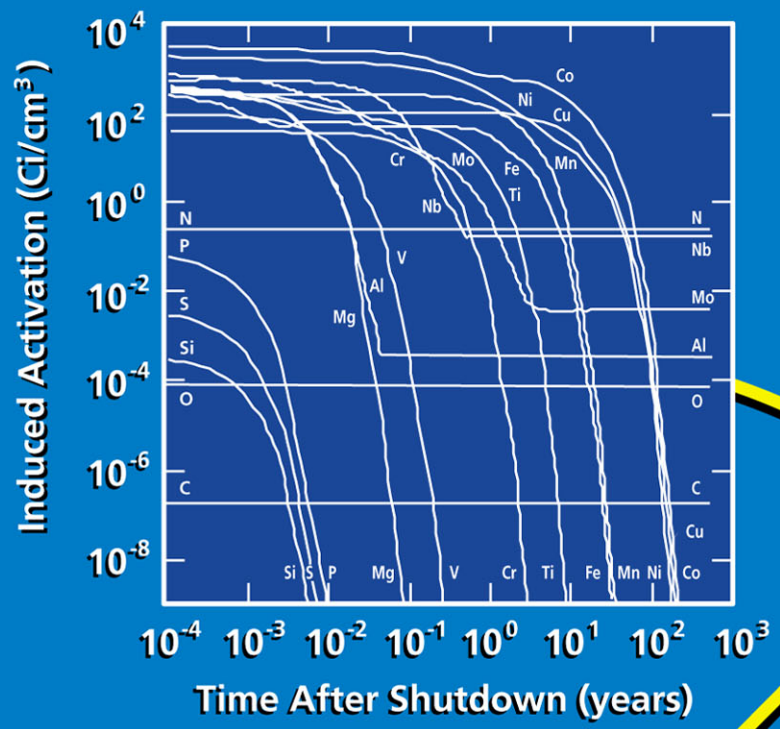
Coherent
Onyx
DEI
Mission Research Corp
Northrup
Ultramet, Inc
Plasma Processes, Inc
Optiswitch Technology
Plasma Processing, Inc

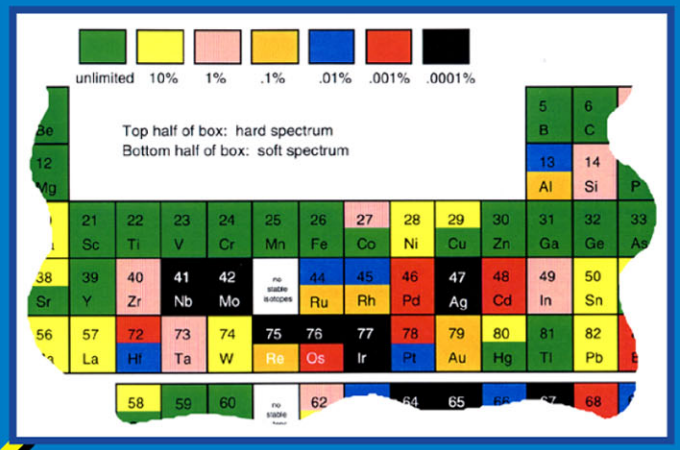
Leveraging and Focus of Program

Selection of structural materials is leveraging past and planned development carried out by the international MFE and other nuclear materials program assuming a “near term” time horizon.

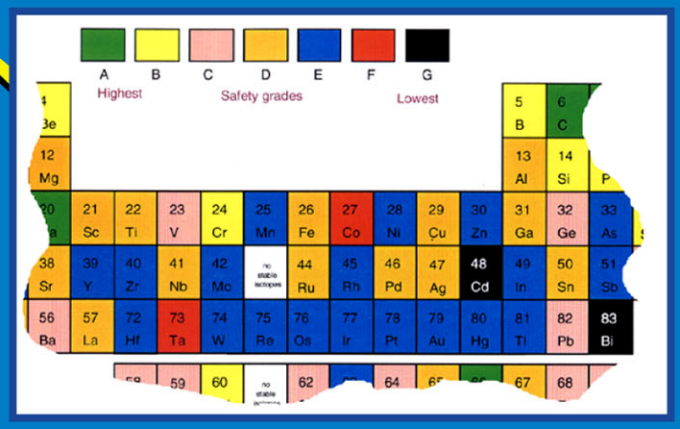
High Average Power Laser program is focused on key issues unique to IFE systems.

Structural Materials





Class C Waste Disposal



Safety

SiC

V Cr Ti Si

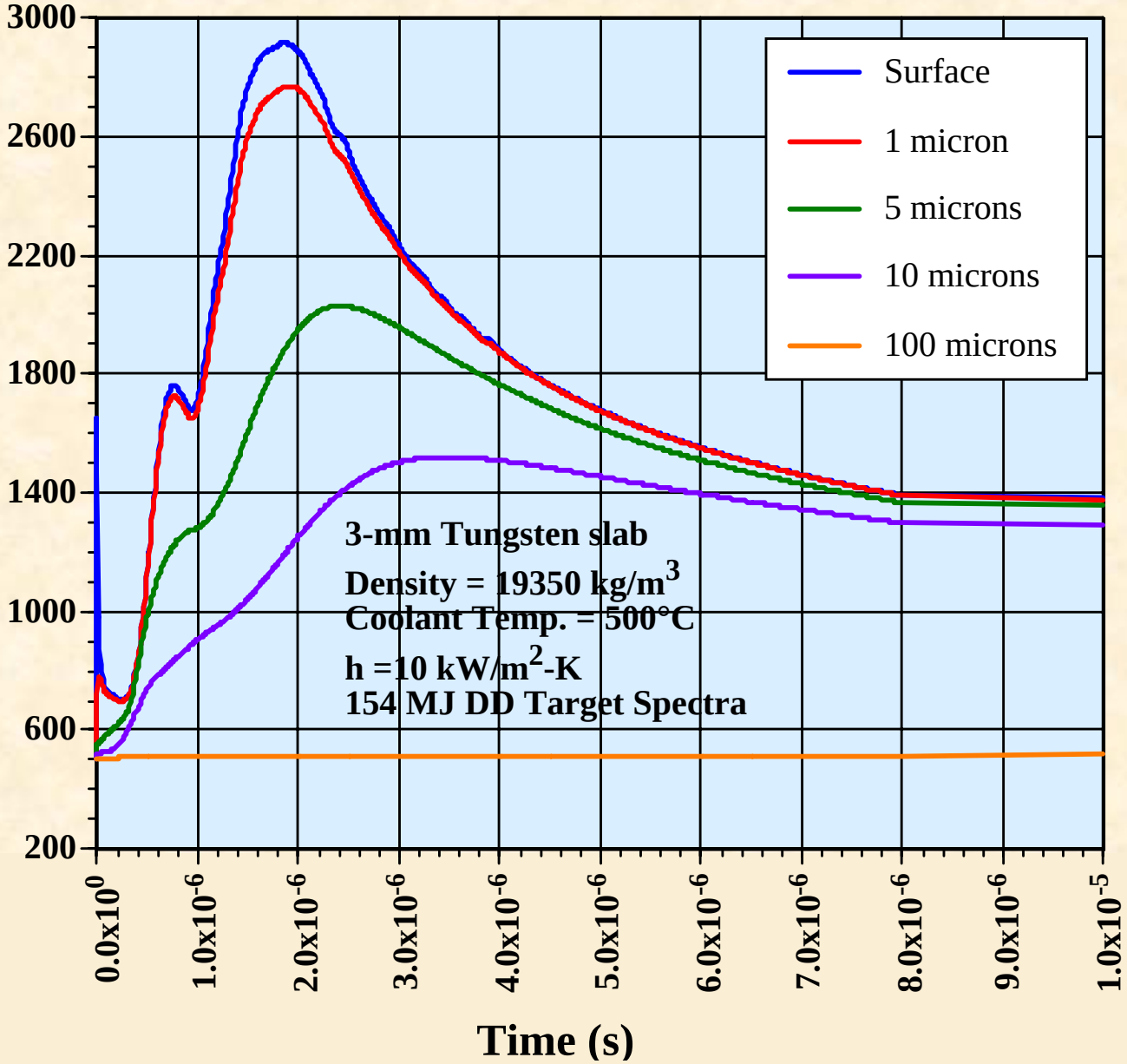
Fe Cr W V Ta

Temporal Distribution of Heat Flux

Instantaneous Heat Flux

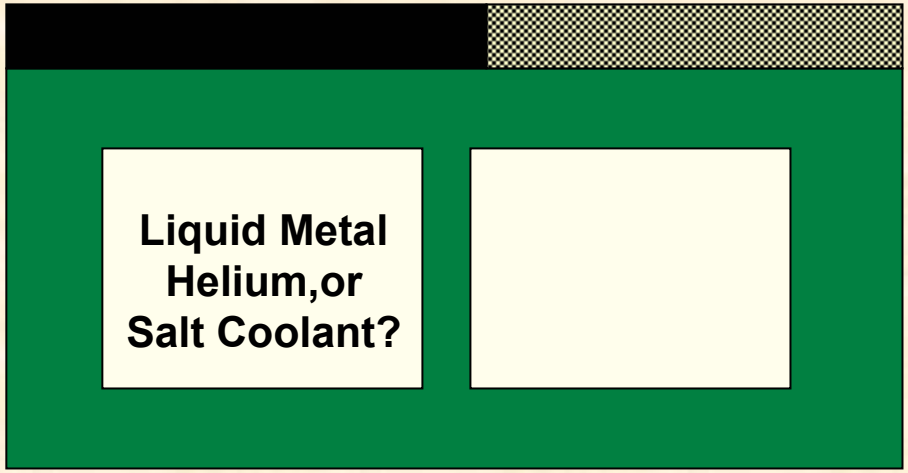
10 MW/m2 (MFE) = 10^4 MW/m2 (IFE)

Effect of Heat Flux on W-Armor Coated SiC



Candidate First Wall Structure W/LAF (W/SiC Backup)

Monolithic W *Porous W Structure*



Structure : LAF(~600°C max), ODS(~800°C) or SiC/SiC(1000-1300°C)

- ***It is assumed that MFE program will develop and qualify a low activation structural material.***

Development of Armor

fabrication process and repair
He management
mech. & thermal fatigue testing

Surface Roughening/Ablation

thermal fatigue
x-ray and ion irradiation effects

Underlying Structure

bonding (especially ODS)
high cycle fatigue
creep rupture

Armor/Structure Thermomechanics

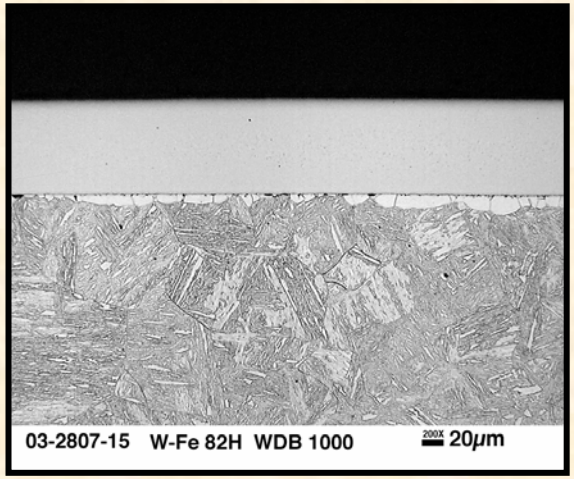
design and armor thickness
finite element modeling
thermal fatigue and FCG

Modeling Irradiation Effects

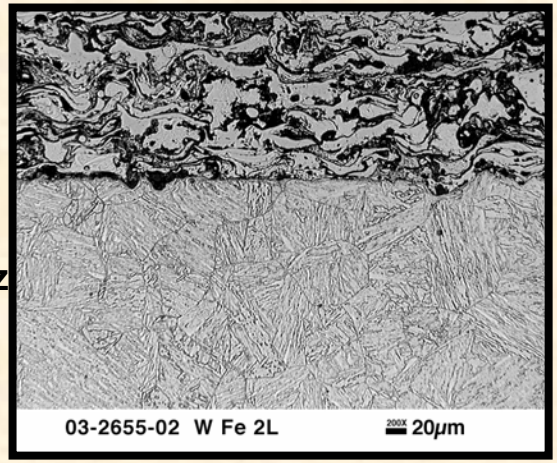
swelling and embrittlement

Fabrication Process : W/F82H

- **Two processes for bonding low activation ferritic to tungsten are considered: *Diffusion Bonding and Plasma Spray*:**



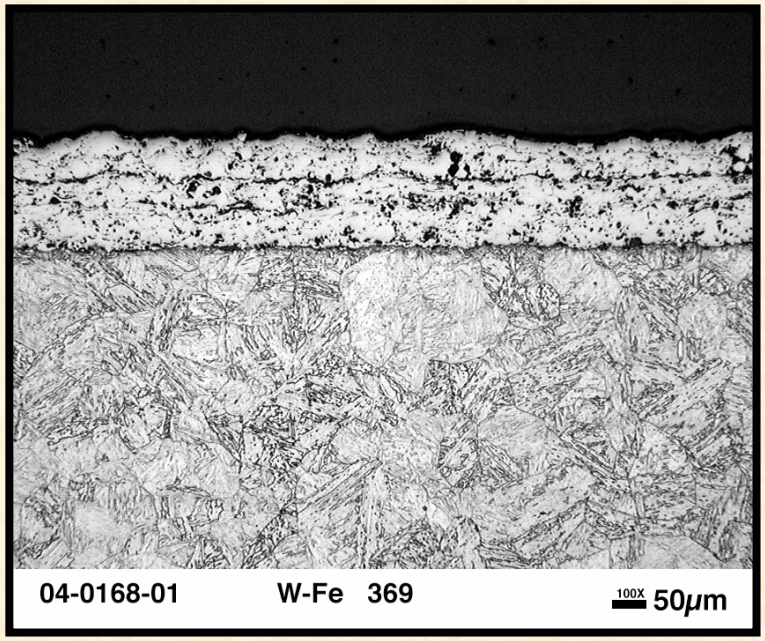
I. Diffusion-bonded tungsten foil (.1 mm thickness)
- **Allows the best possible mechanical properties and surface integrity**
- **Tungsten will remain in the un-recrystallized state**
- **No porosity**



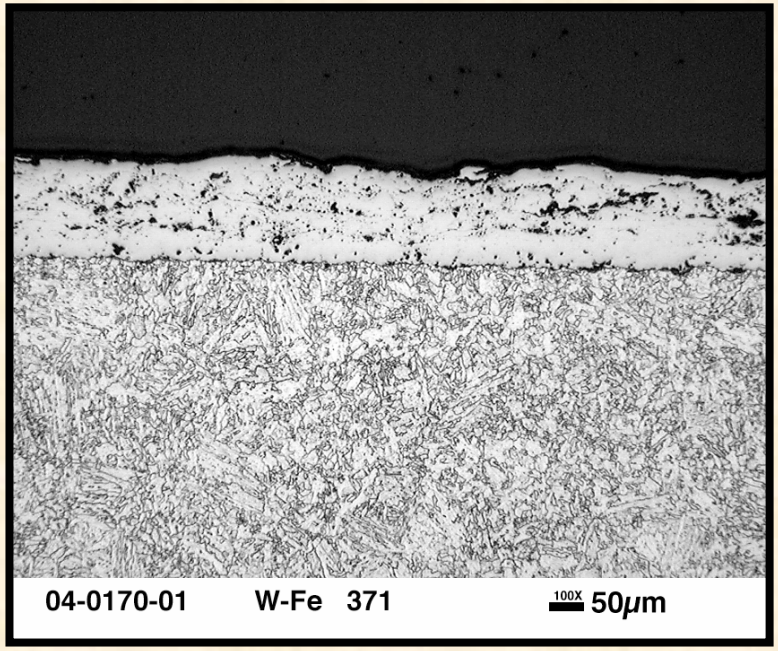
II. Plasma-sprayed tungsten transition coatings
- **Allows for a graded transition structure by blending tungsten and steel powders in an intermediate layer to accommodate CTE mismatch.**
- **Resulting microstructure is recrystallized but small grain siz**
- **May be spayed in vacuum or under a cover gas (wall repair)**
- **Variable porosity**

VPS Tungsten on F82H Steel : Post-Spray Treatments

As Sprayed



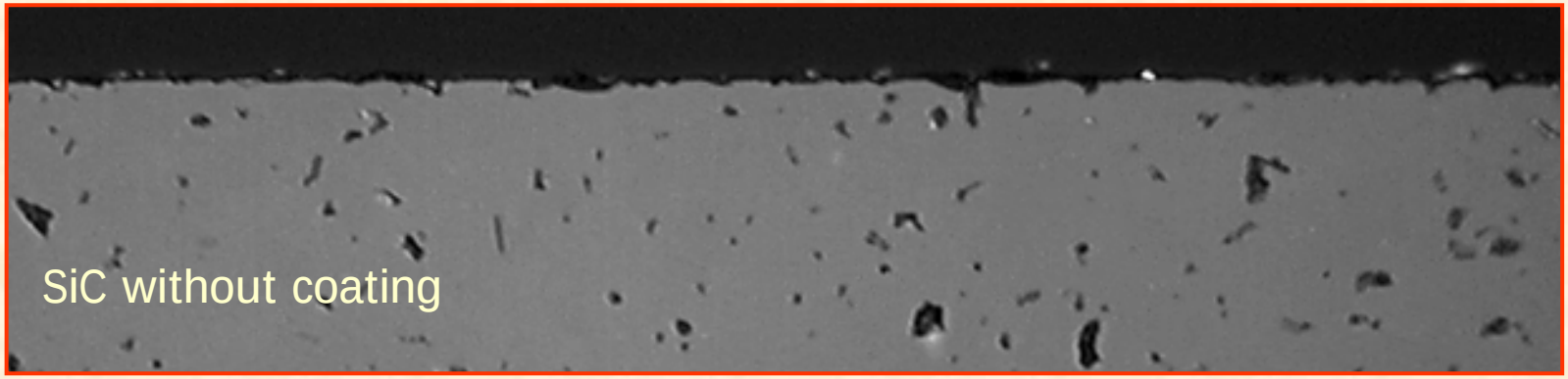
Hot Isostatic Pressing



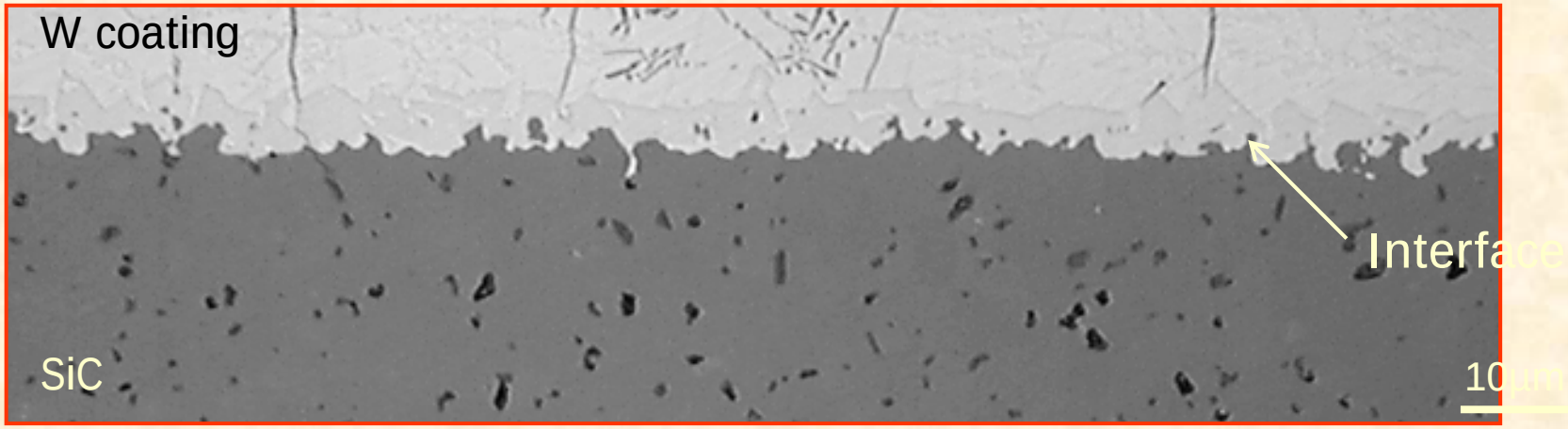
- **Post-spray hydrogen anneal at 800°C/4hrs provides stress relief. Annealing limited to 800°C due to steel substrate. Temps of 1700°C required for sintering VPS W coatings may be achieved with IR processing.**

- **Post spray hot isostatic pressing 800°C / 35ksi achieved some densification of the coating (enhancing thermal conductivity.)**

Fabrication Process : W/SiC



Tungsten Powder **IR processing**



SiC was removed by sublimation of the surface of the SiC prior to ordering the W powder melt. Rough interface was formed.

Structural Materials Testing under the HAPL Program

- **Testing of structural materials is in two areas:**

  1) Testing of armor integrity

  - thermal fatigue testing

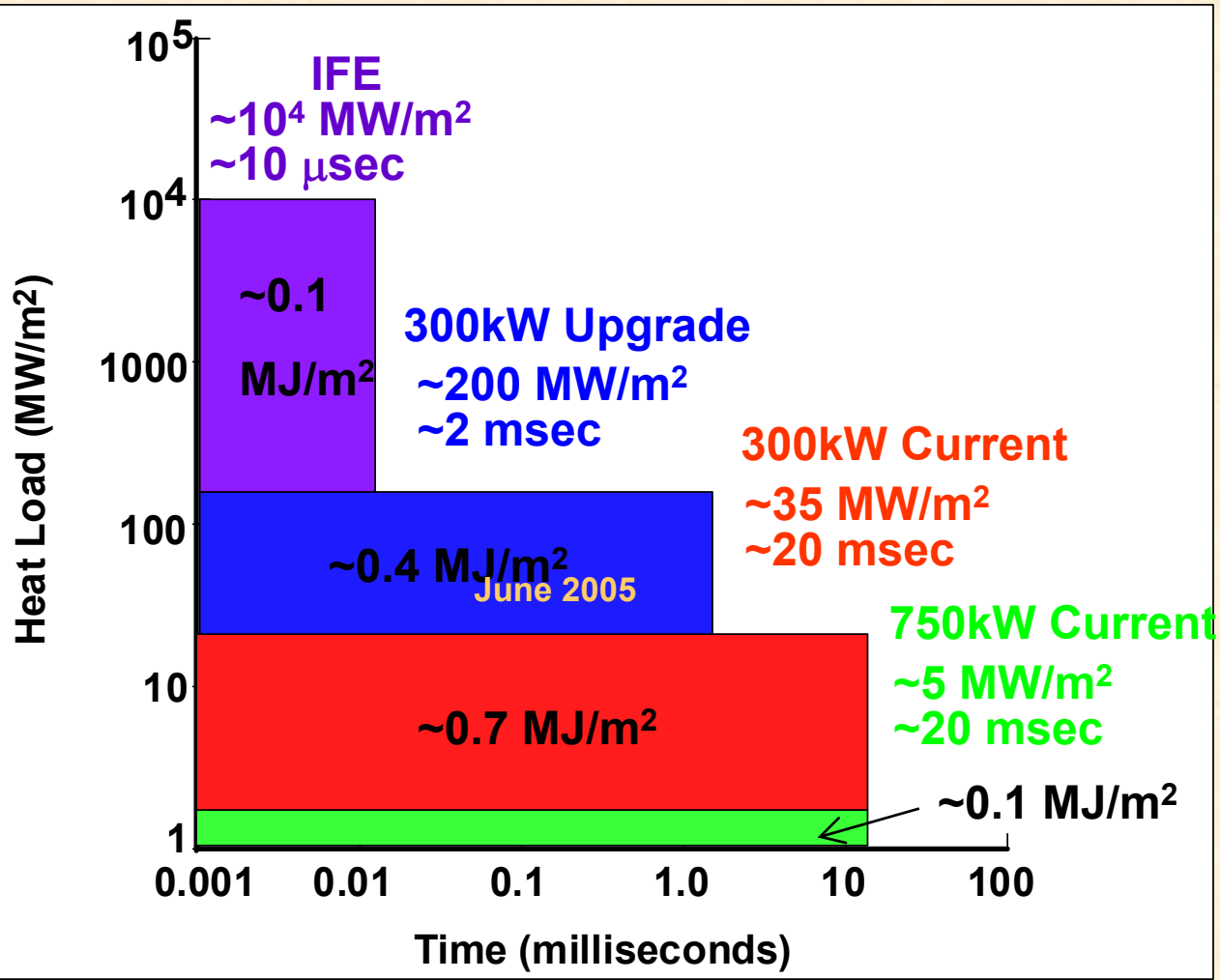
  - long-term thermal stability

  2) Response of base material to specific IFE threats

  - high cycle pulsed heating
  laser (UCSD)
  x-ray (LLNL, SNL)
  ions (SNL, *next talk*)

  - effect of high-dose ion implantation (ORNL, UCLA, UNC)

IR Thermal Fatigue Facility is an enabling technology for coating durability studies. Coupon and subscale component testing are possible.



Specimen Size (cm^2)	
300kW Upgrade	10
300kW Current	10
750kW Current	300

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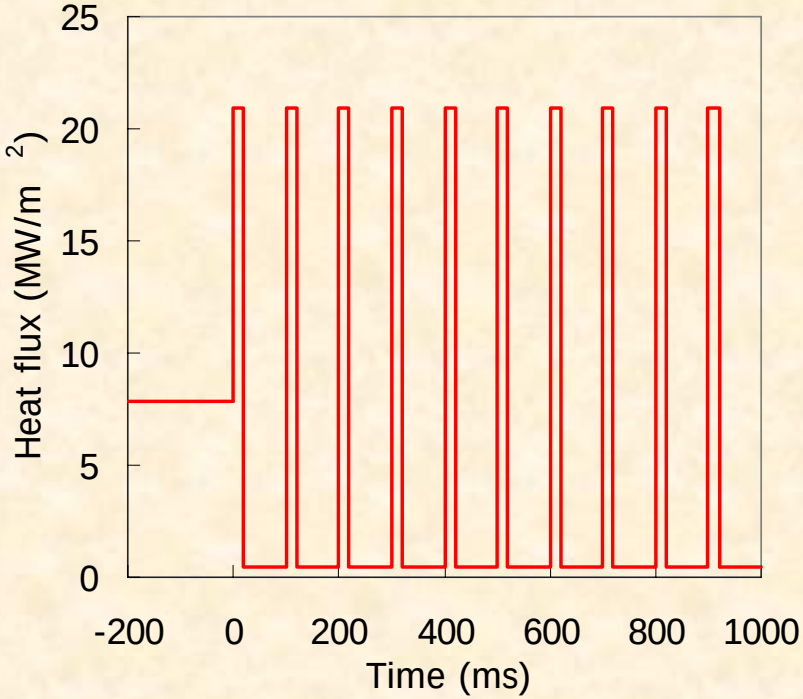
Thermal Fatigue Testing



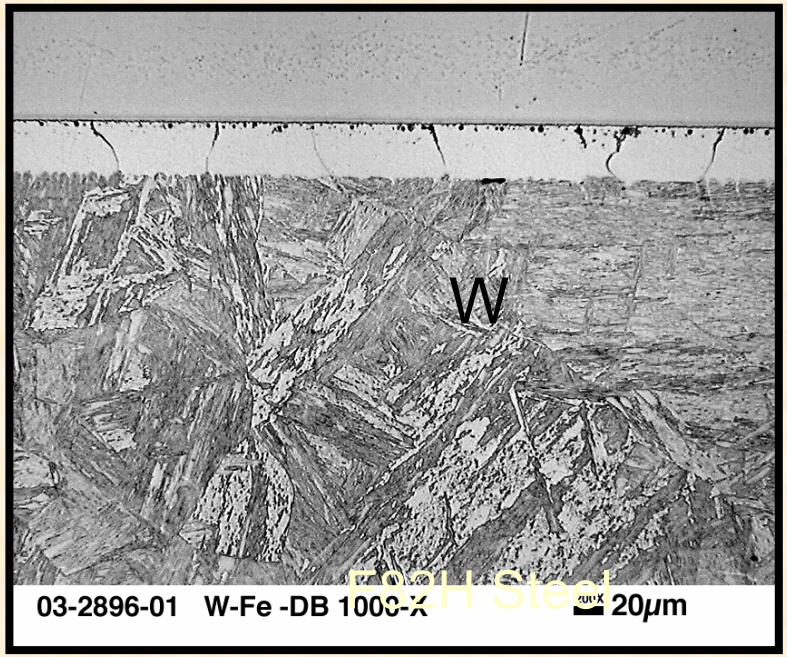
Rep rate: 10Hz
Max. flux: 20.9MW/m^2 (20ms)
Min. flux: 0.5MW/m^2(80ms)
Duration: 1000 cycles
Substrate temp. (bottom): 600 ºC

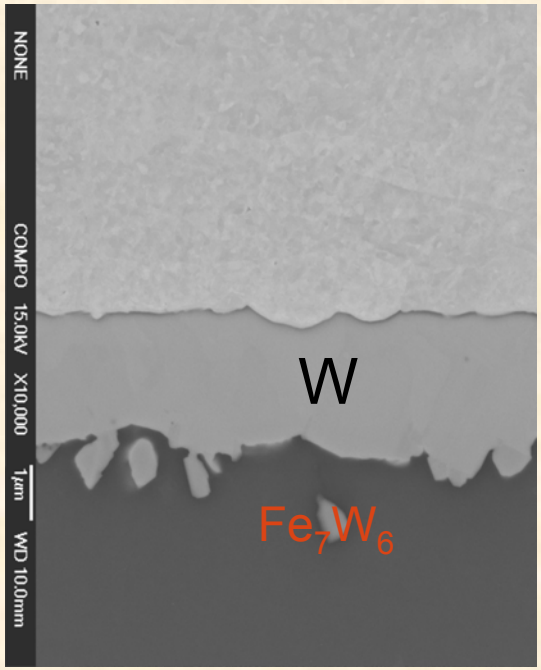
Substrate material: F82H steel
Coating material: tungsten (100µm-thick)
Specimen size: 25 x 25 x 5 (mm)

ORNL Thermal Fatigue Facility : 10 Hz, 20 MW/m^2

QuickTime™ and a
DV/DVCPRO - NTSC decompressor
are needed to see this picture.

Thermal Fatigue Results





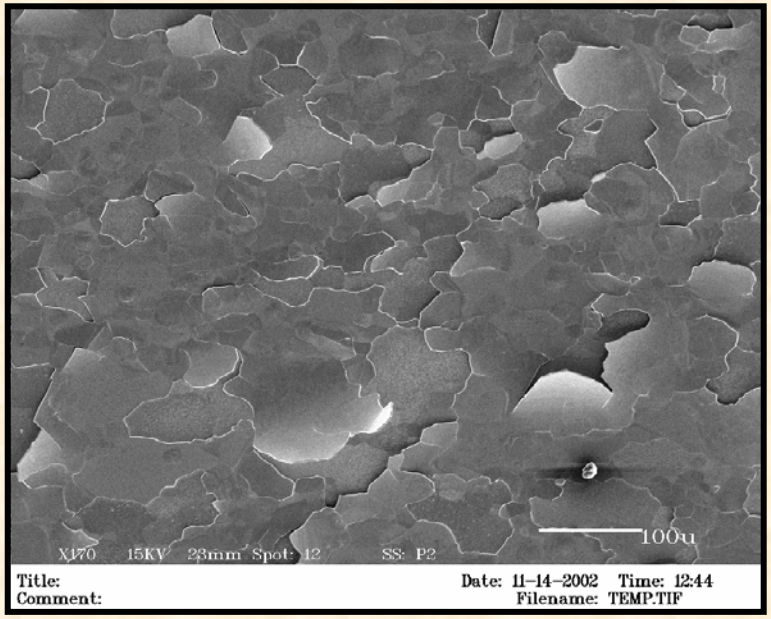
Test conditions: Preheat to 600ºC + 1000 cycles of IR Pulse.

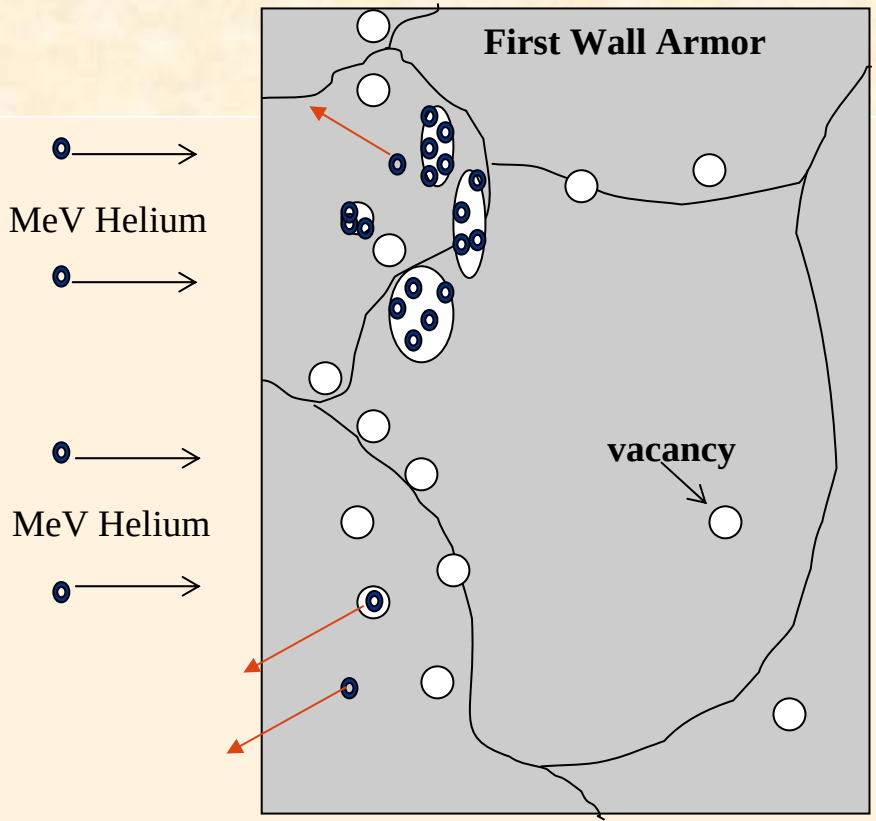
- **Coating are well adhered (do not spall.)**
- **XRD of intentionally spalled coating confirmed interfacial compounds Fe_7W_6 and Fe_3W_3C for over-temperature experiments.**
- **Long-term thermal stability studies are underway.**

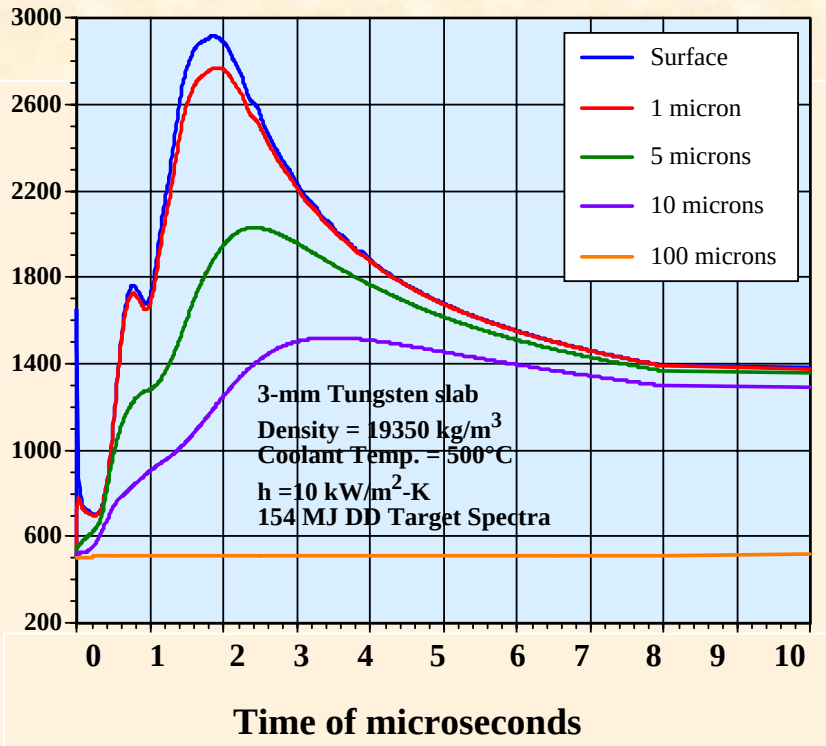
Helium Management

At room temp. growth of He bubbles beneath the surface causes blistering at ~3 x $10^{21}/m^2$ and surface exfoliation at ~$10^{22}/m^2$.

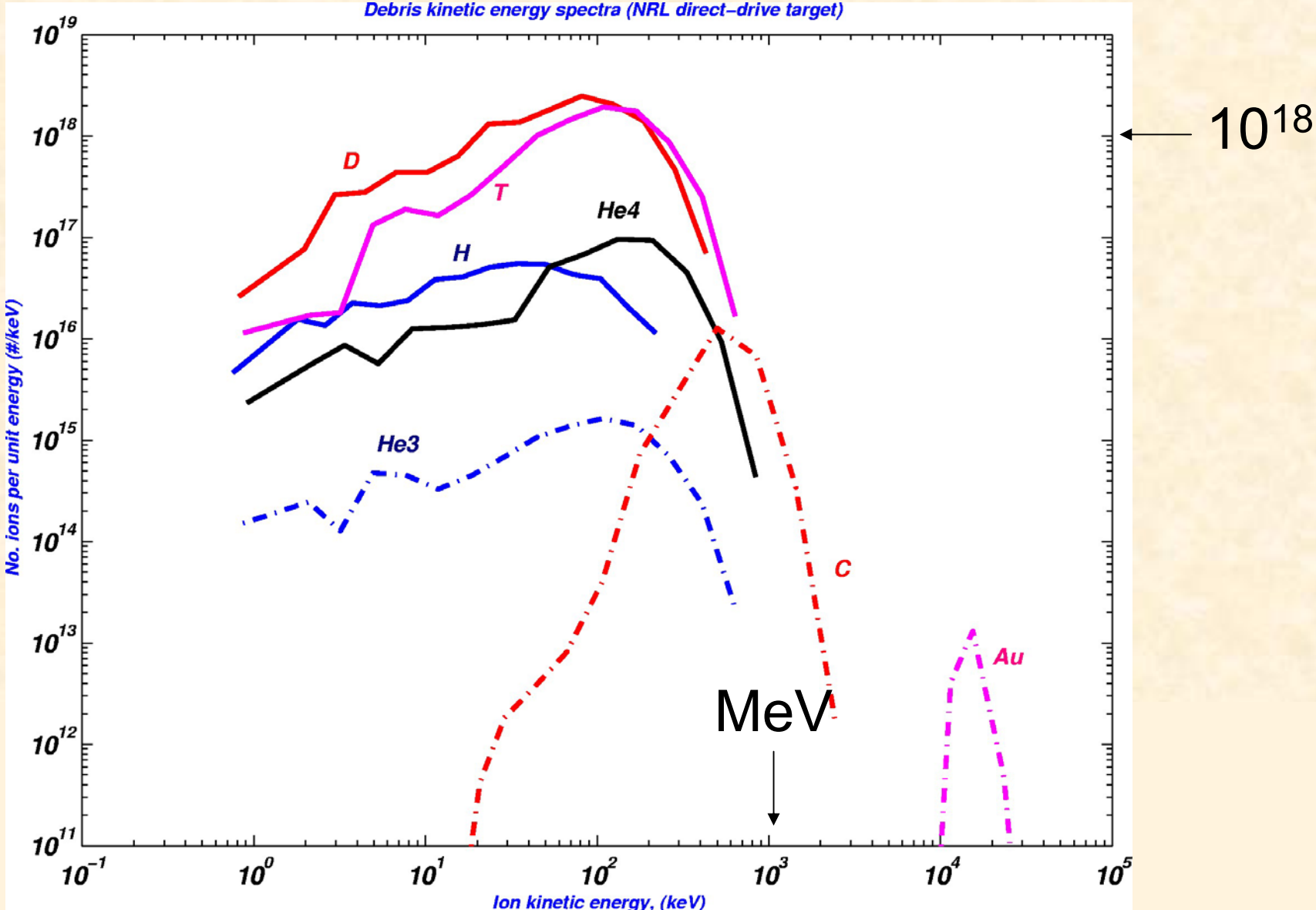
For IFE power plant, MeV He dose >>> $10^{22}/m^2$.



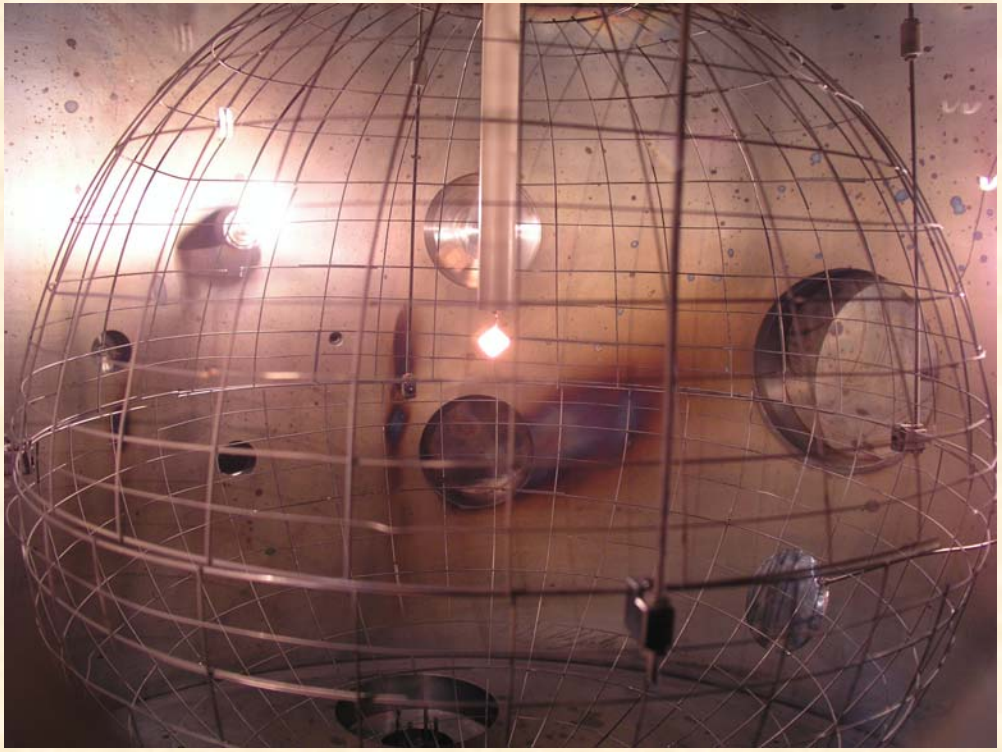


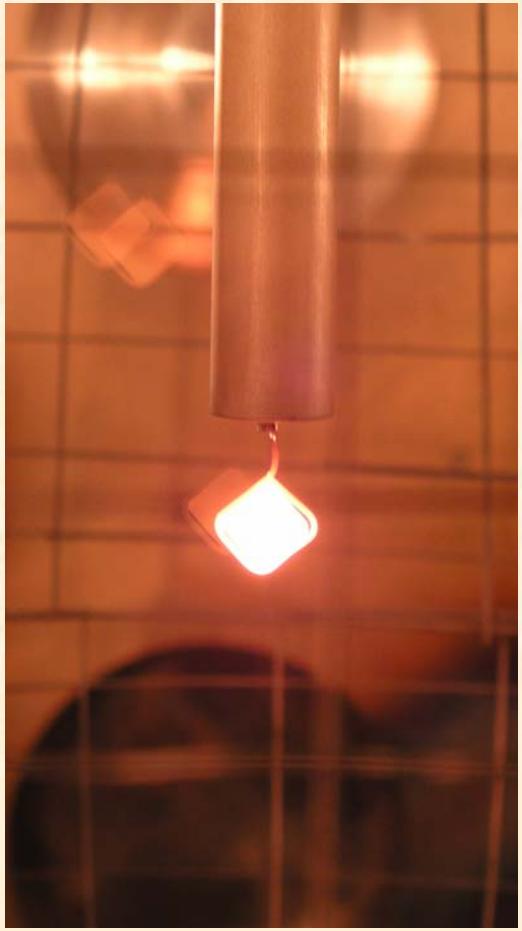


Spectrum of slow debris ions in the IFE reactor



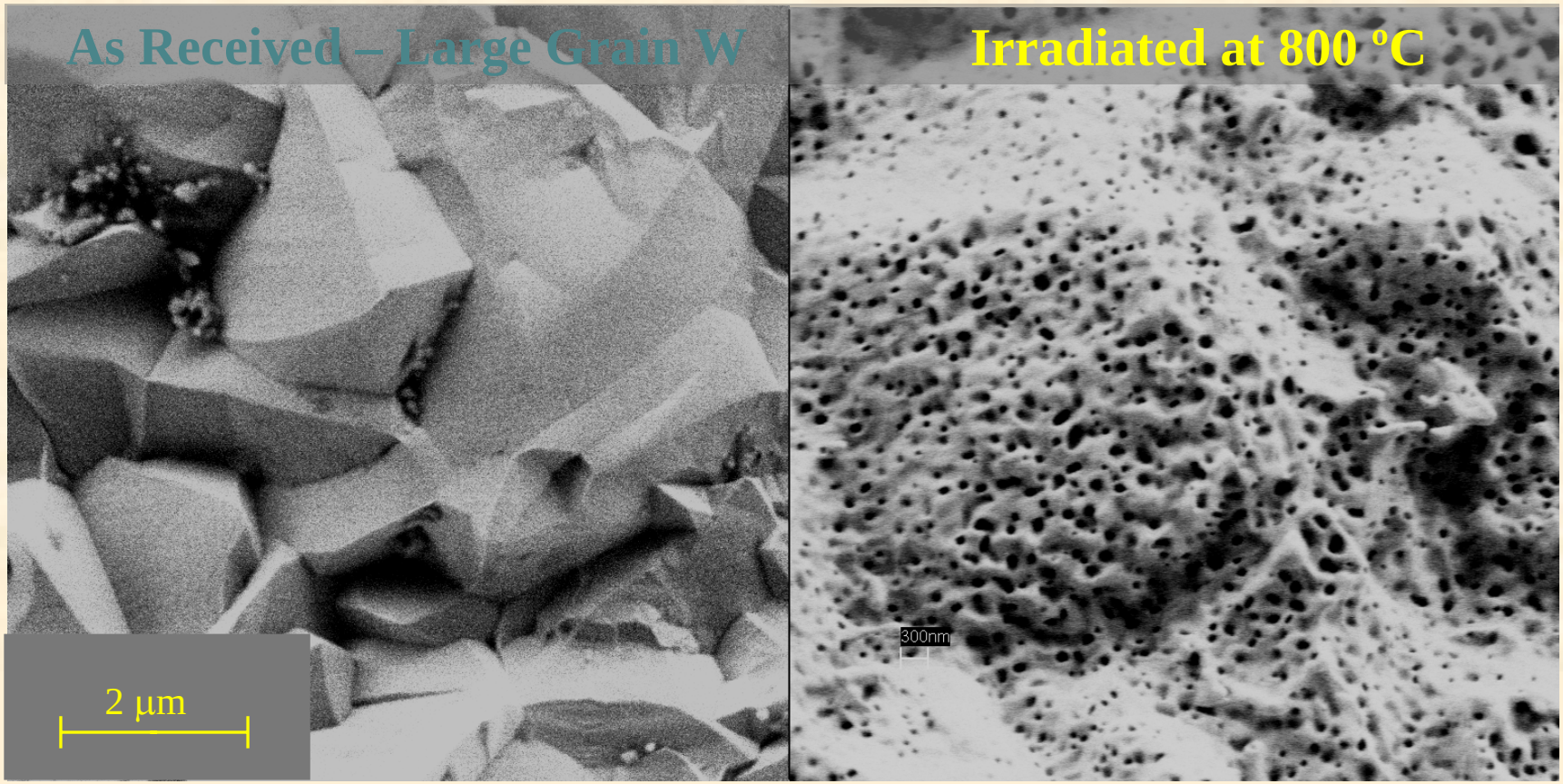
UW IEC Chamber
Capability of High-Temperature Implantation at 10-100 kV

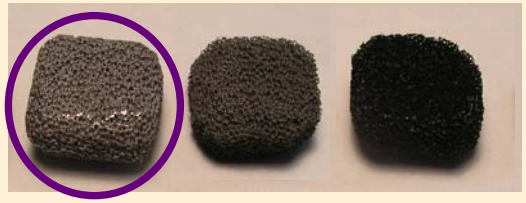




D^+, 20 kV, 5 mA
2 mtorr, 1100 °C

High Temperature He^+ Implantation Resulted in Porous Surface Structure in Large Grain W-coated TaC

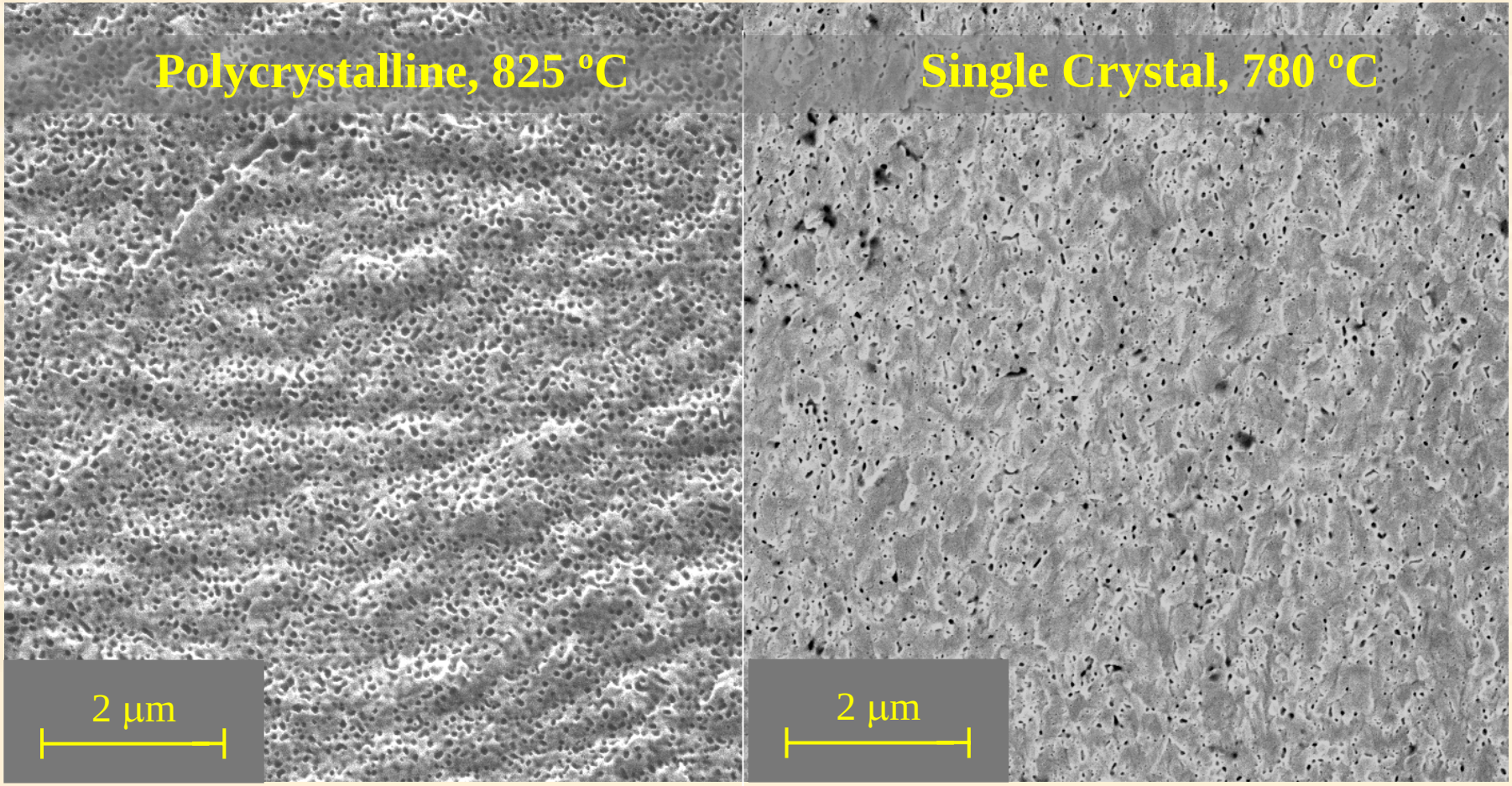




Large Grain W-coated TaC Sample Irradiated at 800 °C with a $6x10^{17}$ He^+/cm^2 Fluence

Ref. HAPL Chamber Operation for ~8 hours

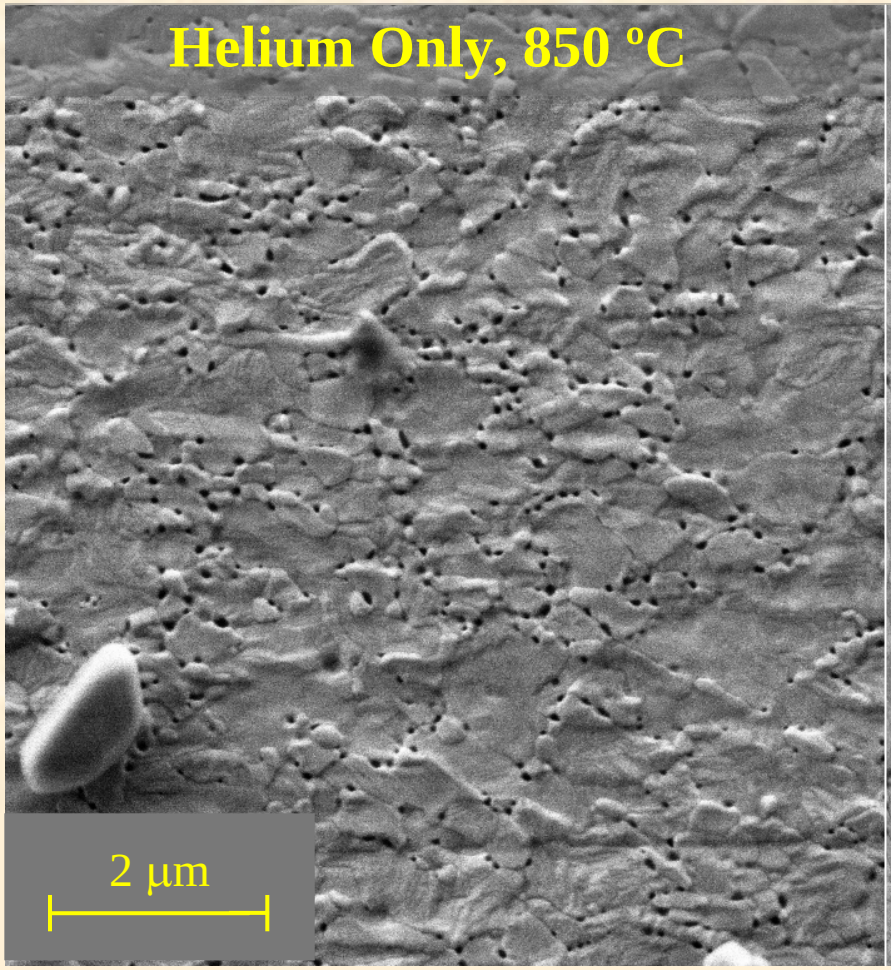
Effect of Microstructure on Pore Formation

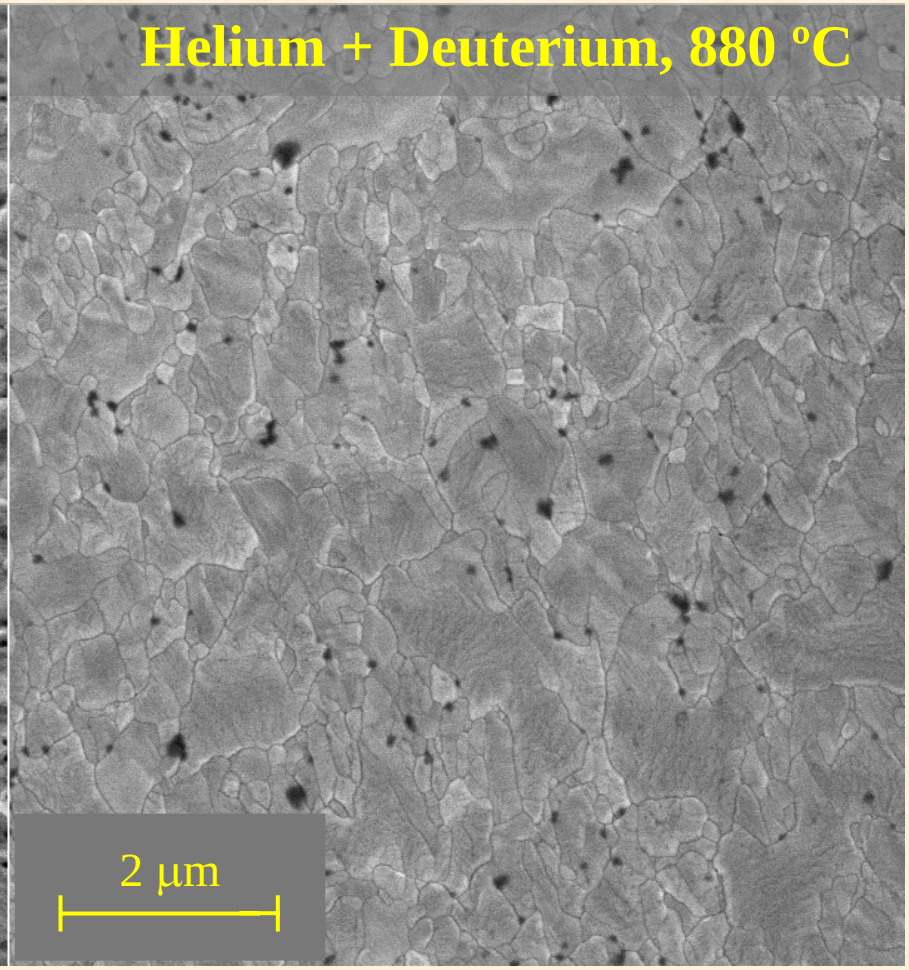


5.8×10^9 pores/cm^2 | 2.3×10^9 pores/cm^2

Tungsten Samples at 3×10^{18} He^+/cm^2

Effect of Simultaneous He and H Implantation



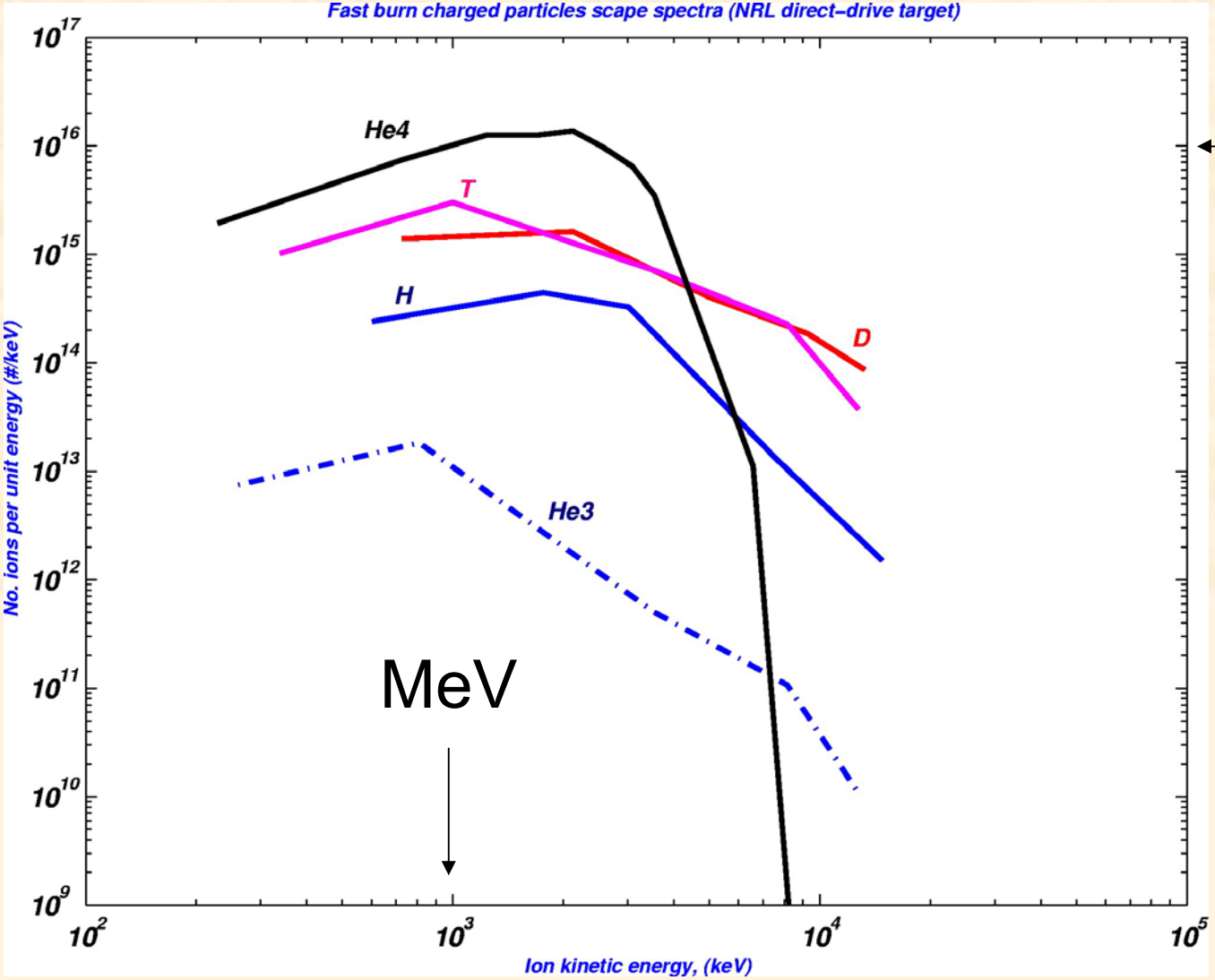


9.4×10^8 pores/cm^2

2.4×10^8 pores/cm^2

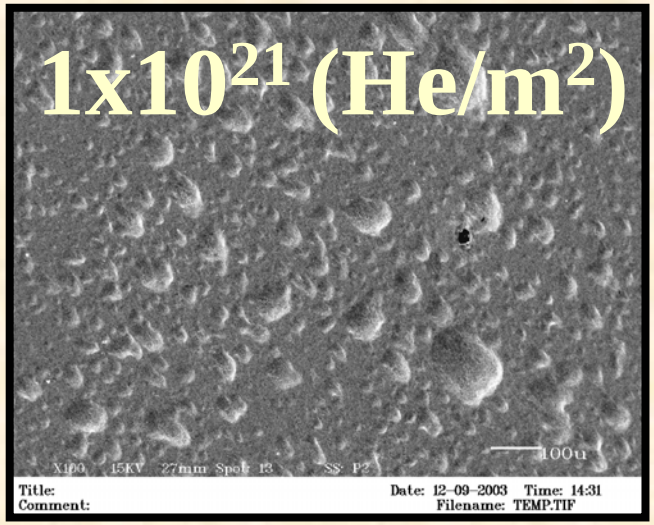
Polycrystalline Tungsten Samples at 1×10^{18} He^+/cm^2

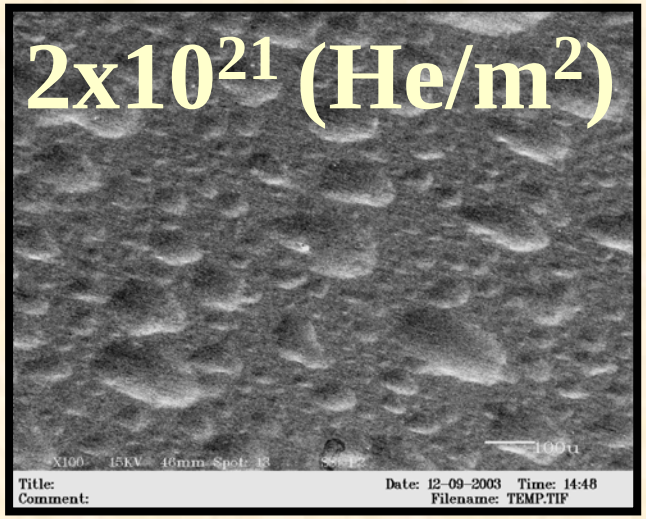
Spectrum of fast ions in the IFE reactor

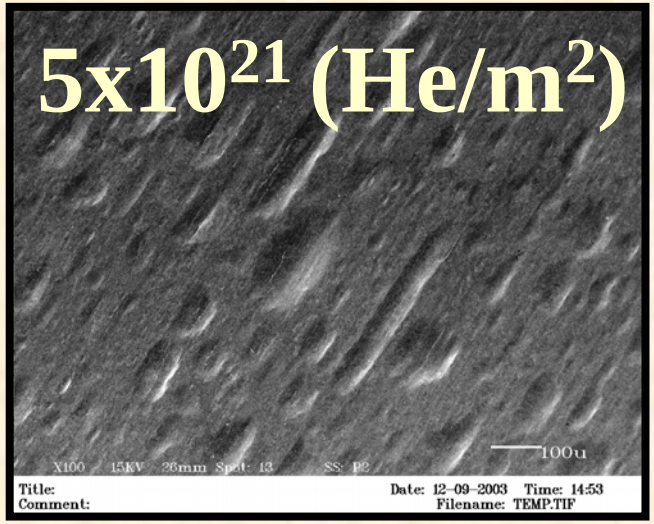


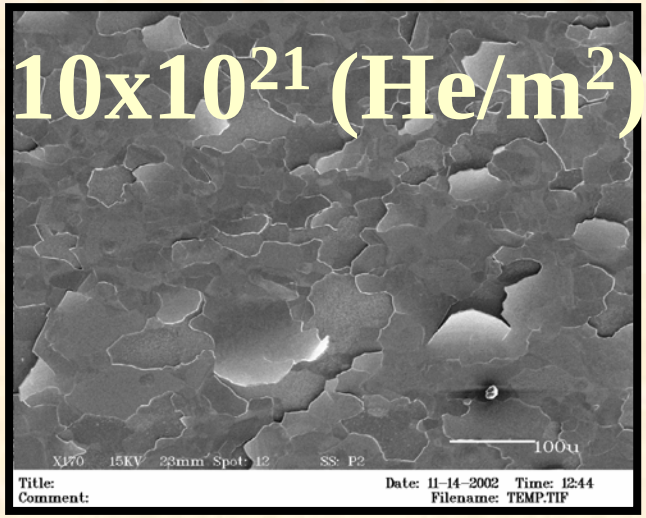
10^{16}

Spallation Problem



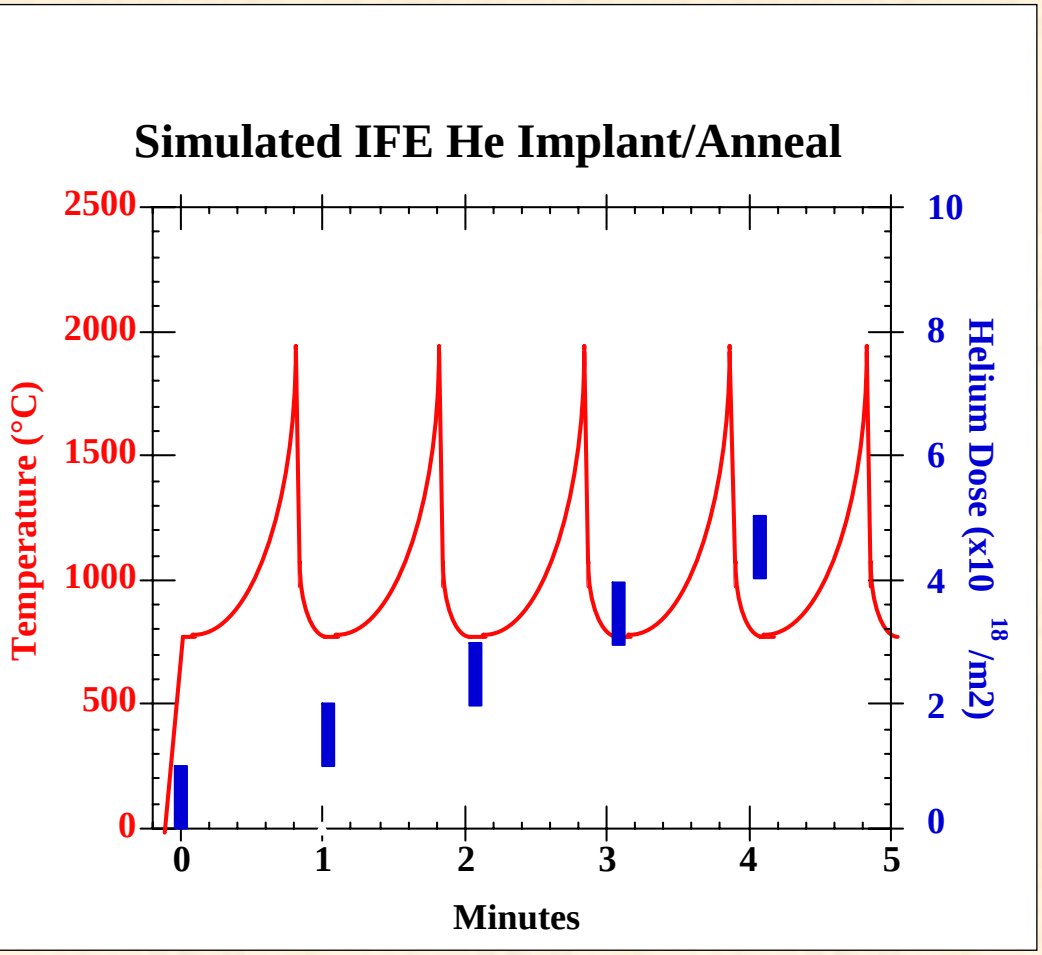


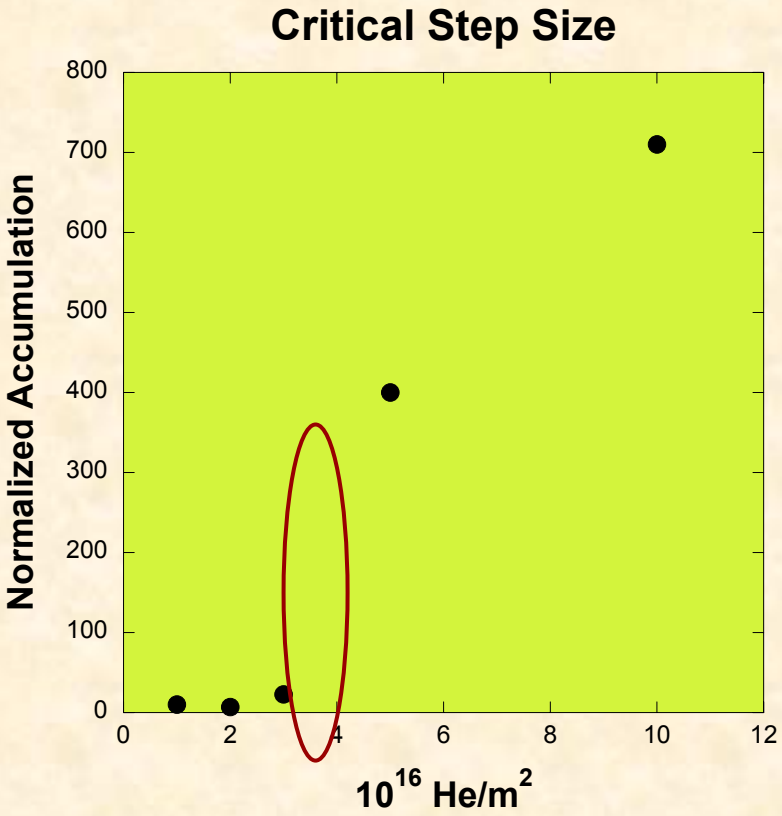


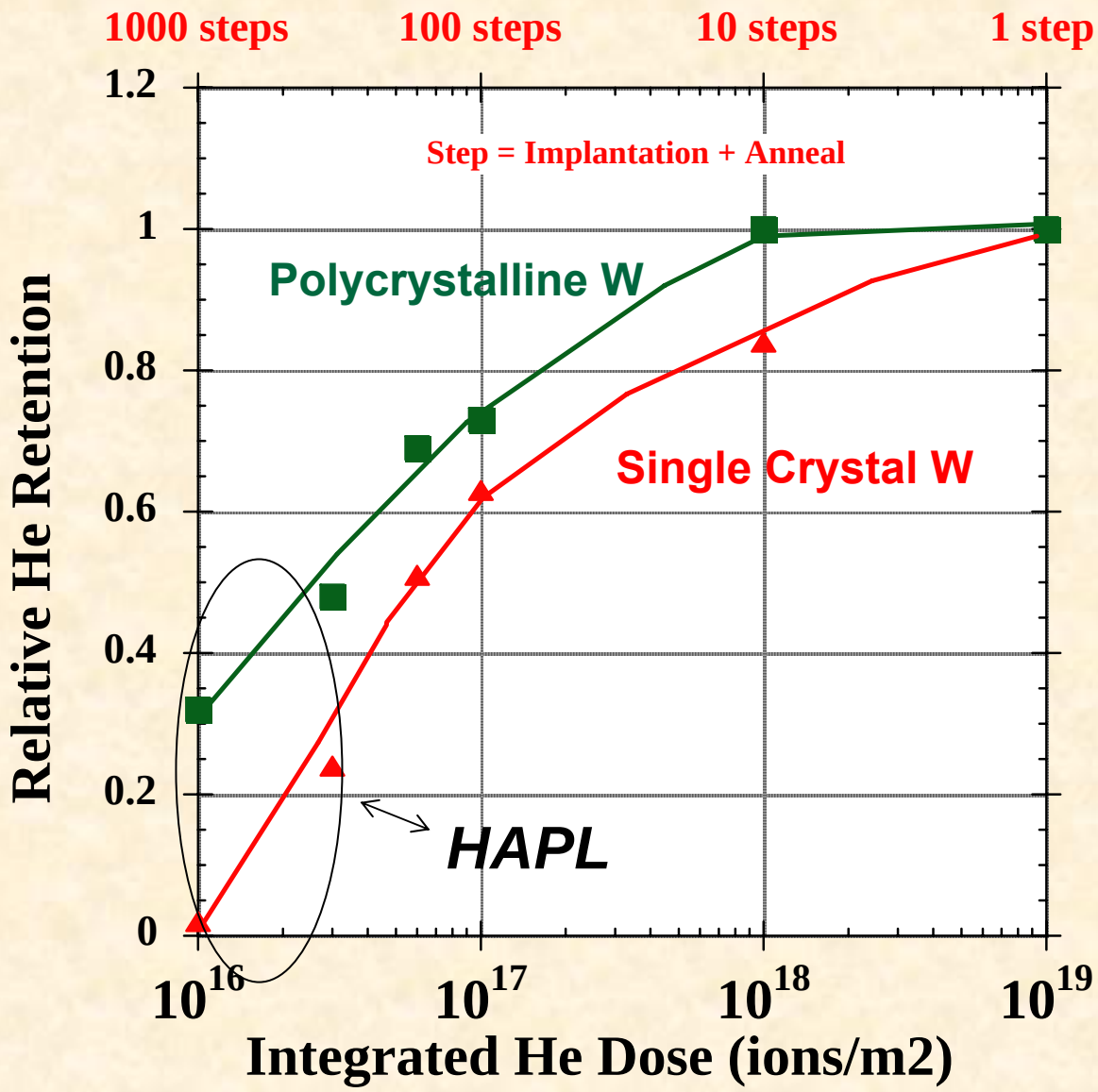


1.5 MeV He implanted polycrystalline W : 850°C,flash annealed to 2000°C.

Minimum Dose for Helium Accumulation Is IFE Below Threshold?

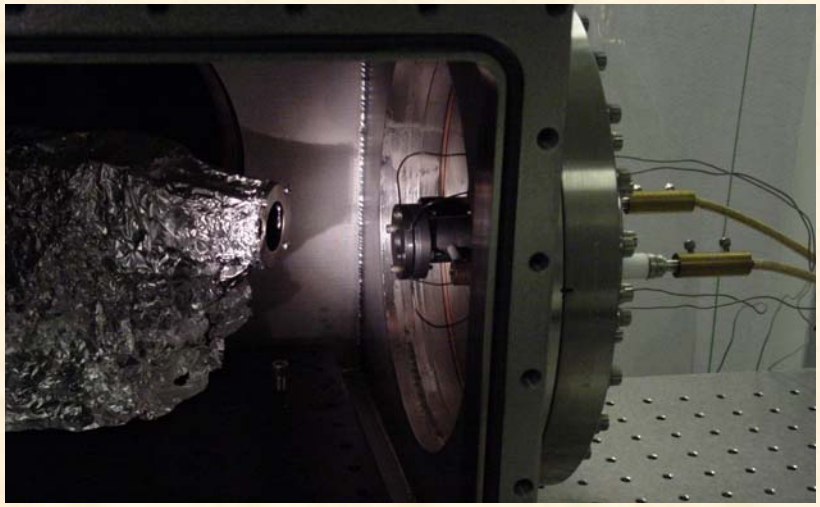





1000 steps
100 steps
10 steps
1 step
Step = Implantation + Anneal
Polycrystalline W
Single Crystal W
HAPL
Relative He Retention
1.2
1
0.8
0.6
0.4
0.2
0
10^{16}
10^{17}
10^{18}
10^{19}
Integrated He Dose (ions/m2)

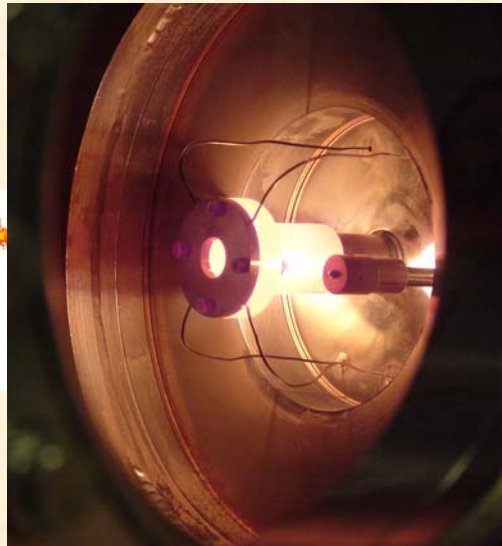
UCSD Dragonfire: High Cycle Laser Thermomechanical Testing Facility Developed for HAPL

- Laser pulse simulates temperature evolution.
- Capability to simulate a variety of wall temperature profiles.
- Repeatable and well-characterized source.
- Clean environment for careful measurements



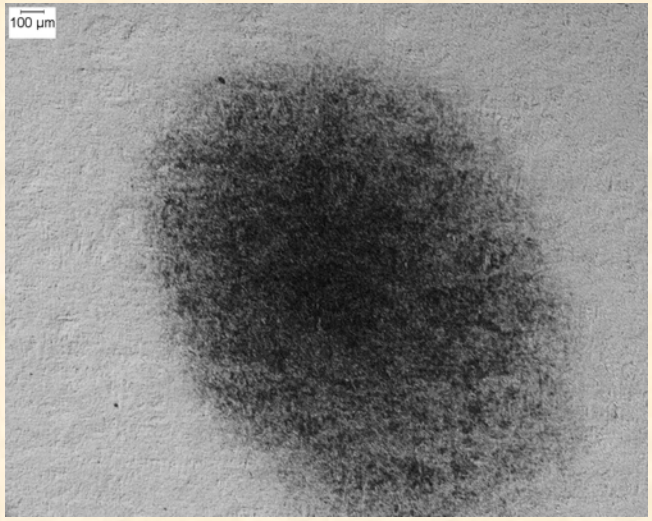
A suite of diagnostics:

- **Real-time temperature** (**High-speed Optical Thermometer)**
- **Per-shot ejecta mass and constituents** (**QMS & RGA**)
- **High rep-rate experiments** to simulate fatigue and material response
  - ✓Relevant equilibrium temperature (**High-temperature sample holder**)



Powder Metallurgy Tungsten Samples After Laser Irradiation

10,000 Shots



- Samples are polished to a “mirror-like” finish.
- The “damaged” area has a “dull” finish.
- A brown background is placed in the photograph to enhance contrast.

- Optical microscope at low resolution
- “Black” areas appear black because of the “dull finish” (they appear as whitish to the naked eye)

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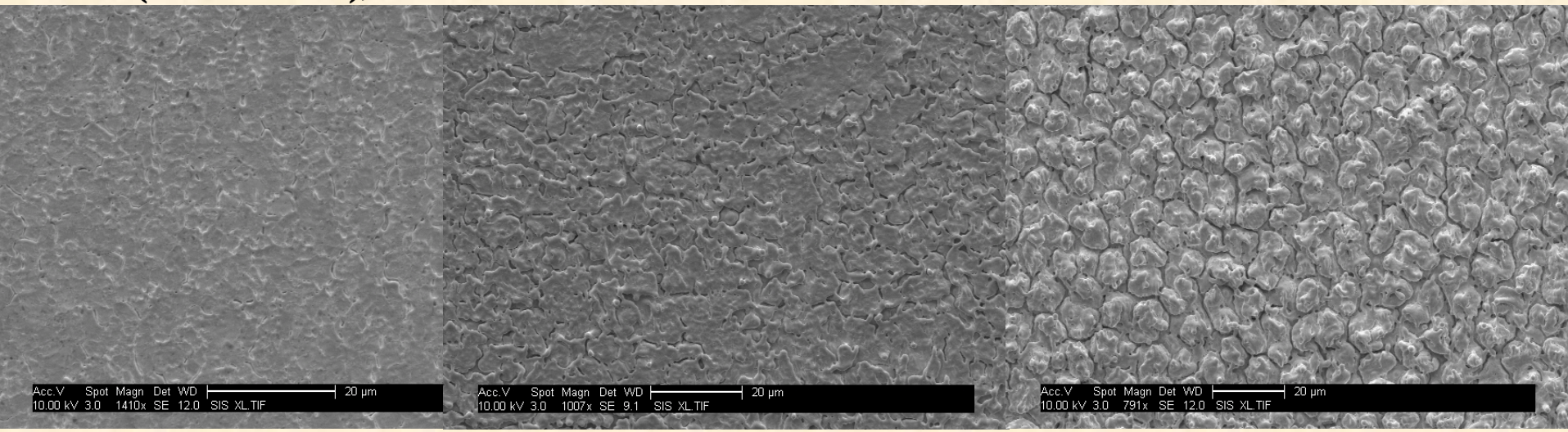
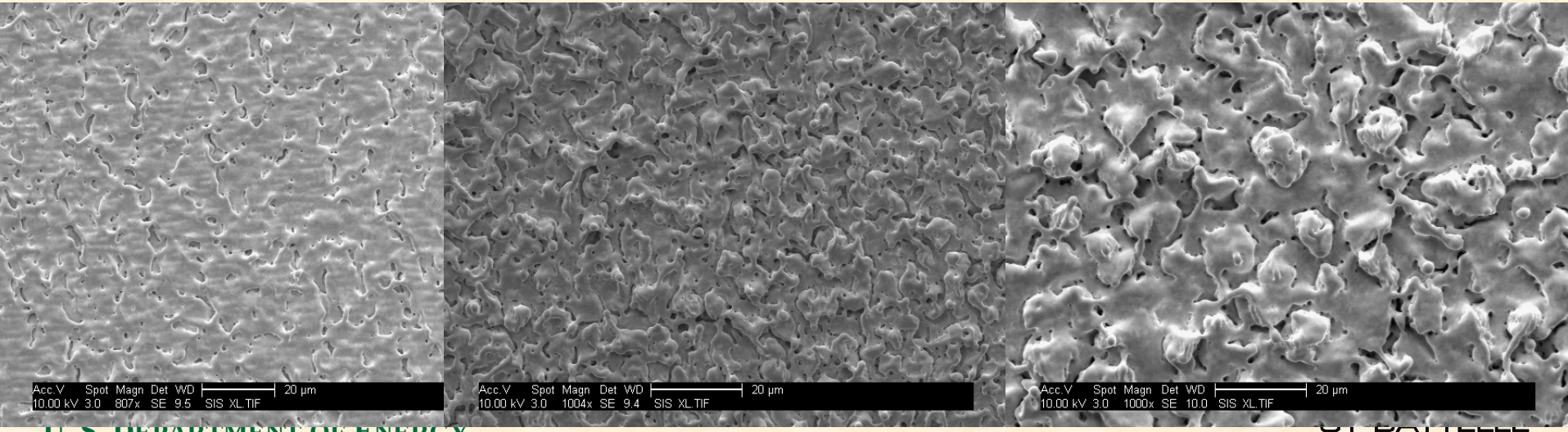
Effects of Shot Rate and Temperature Rise

370mJ (~2000°C ΔT), RT

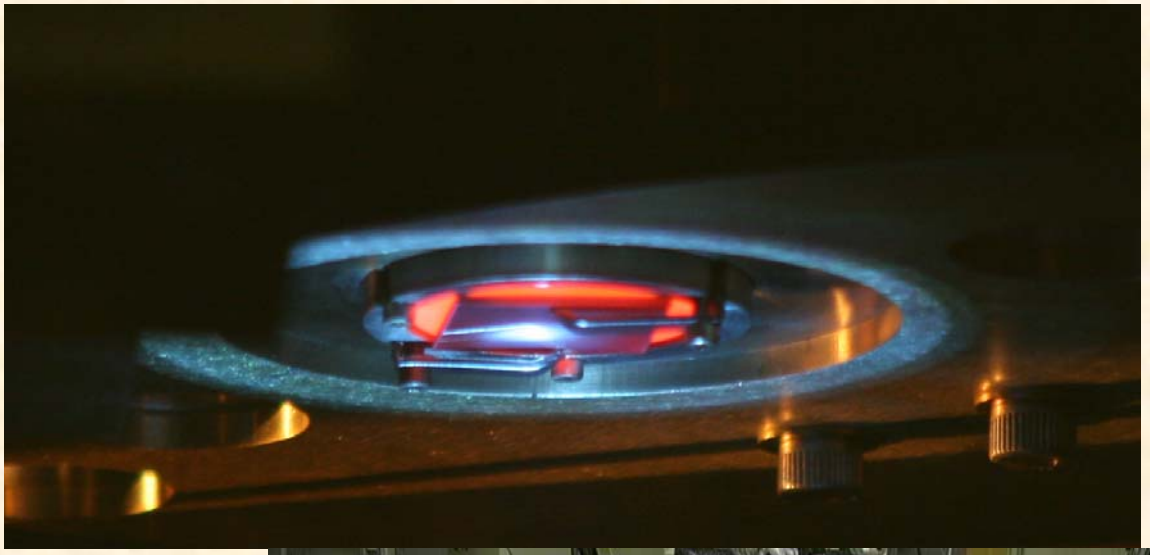


530mJ (~2500°C ΔT), RT



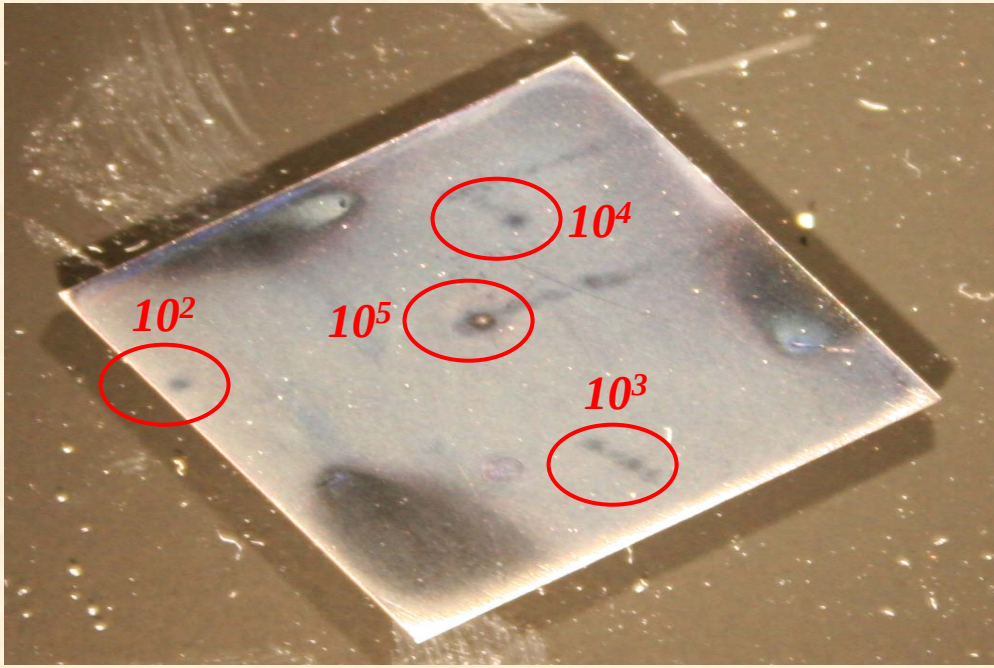
10^3 shots **10^4 shots** **10^5 shots**

XAPPER : High cycle x-ray testing



XAPPER

- **Powder met tungsten:**
  - Sample heated to 600 ºC
  - Hit with a fluence of *at least* 0.4 J/cm^2
  - Calculations indicate that each pulse would heat surface to *≥2000 K*
  - 10^2, 10^3, 10^4, 10^5 pulses placed on sample
  - Pre-irradiation roughness was 22.9±1.5 nm



- XAPPER tests are now underway. Discoloration indicate oxidation, however, no significant change in surface has been measured (at these pulse energy and cycle levels.)

Summary

moving towards an IFE first wall

- **The HAPL program has focused on unique, critical issues. For dry wall chambers, these issues were identified as:**

  - fabrication of refractory armored first wall, capable of intense gamma heating, thermal fatigue, and long-term thermal stability.

  - near zero ablation of the first wall surface.

  - management (transport) of high-energy implanted ions.