Laser Inertial Fusion Dry-Wall Materials Exposure to X-rays and Ions*

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16th ANS Topical Meeting on the Technology of Fusion Energy
Madison, WI
September 14-16, 2004

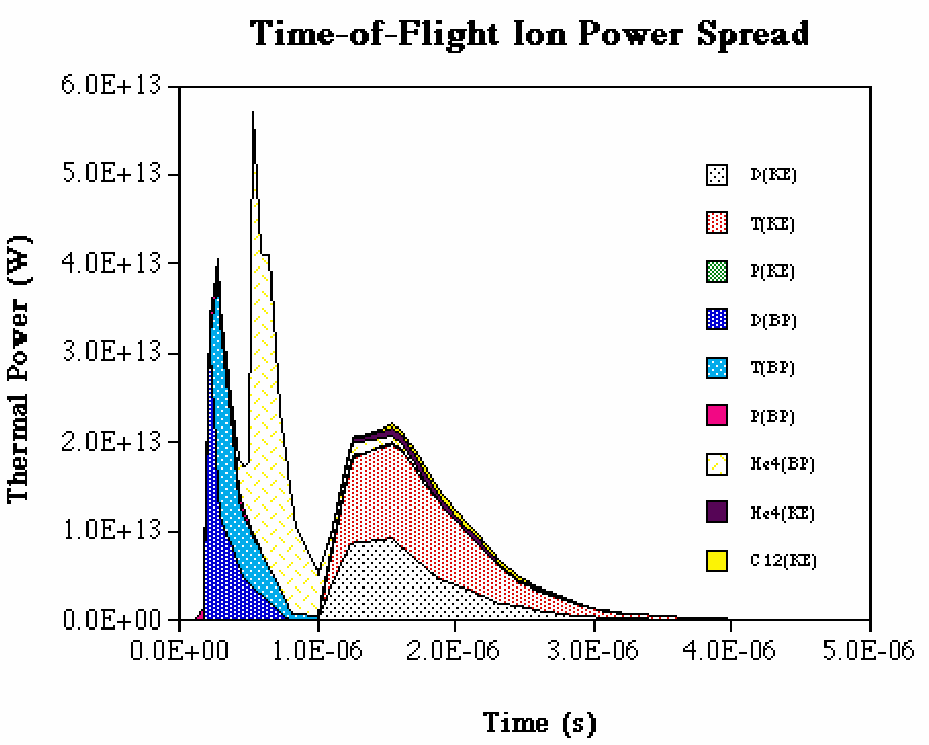
***Supported by NRL by the HAPL program by DOE NNSA DP**

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Outline of Presentation

- IFE Threat Spectra: RHEPP-1 can simulate ion threat to first wall
- Description of RHEPP-1 and and Heating Cycle
- W and W25Re:
  - Roughening as indicator of fatigue/stress
  - Powder Met W form is worst for roughening
  - Surface is raised, with possible exfoliation and deep stress cracking
  - Evolved effects take hundreds of pulses to develop
- Graphite/Carbon Composites:
  - Sublimation loss may be main problem – physical sputtering?
- 'Engineered' Materials as an alternative to flat wall
  - Carbon fiber 'Velvet
  - W/Tac and W/HfC 'Foams'
  - Plasma-sprayed W
- Conclusions

Laser IFE Direct Drive Threat Spectra



Simulation: Thermal Power to Wall from 154 MJ Yield
Wall Radius: 6.5 m

- For Direct-drive Laser IFE:
  1-2% x-rays
  30% ions (50-50 fusion and 'debris)
  ~70% neutrons
- Ions: several MeV, ~ 0.5 μsec each, 8-20 J/cm^2 fluence
- X-rays: ~ 1 J/cm^2, up to 10 keV energies
- RHEPP-1: 800 keV He, higher for N^{+2} , 100-300 ns pulsewidth
- RHEPP-1 energy delivery too short, but otherwise good fidelity with reactor ion threat

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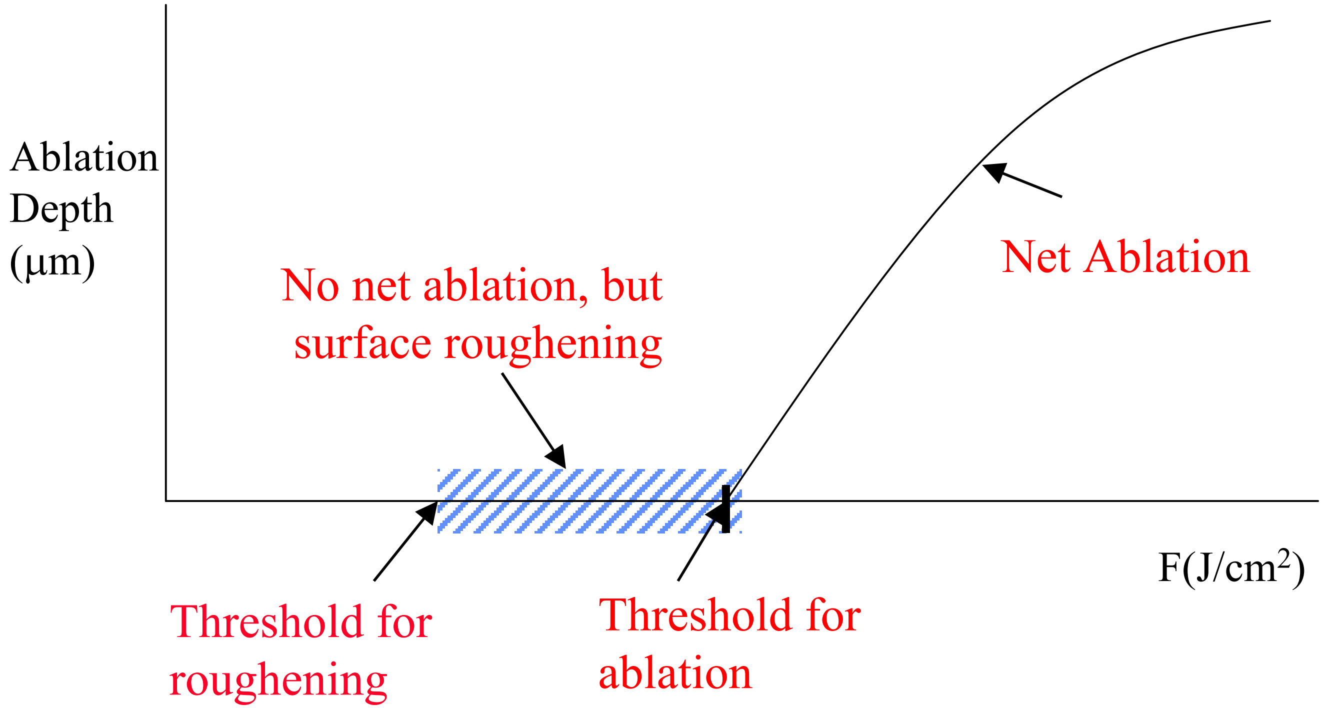
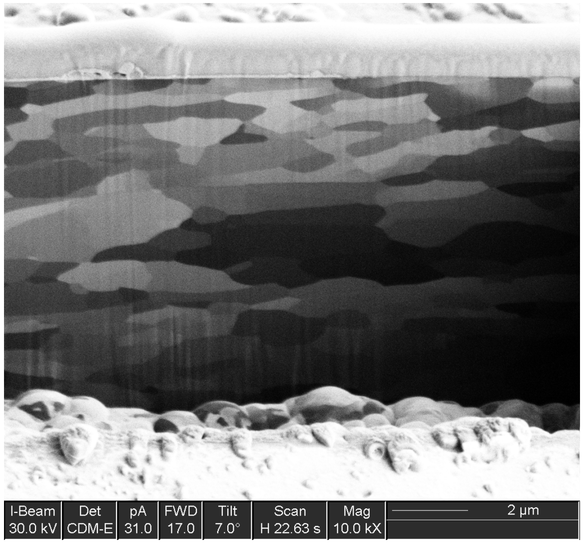
Regimes of IFE Materials Response Studies for x-rays and ions

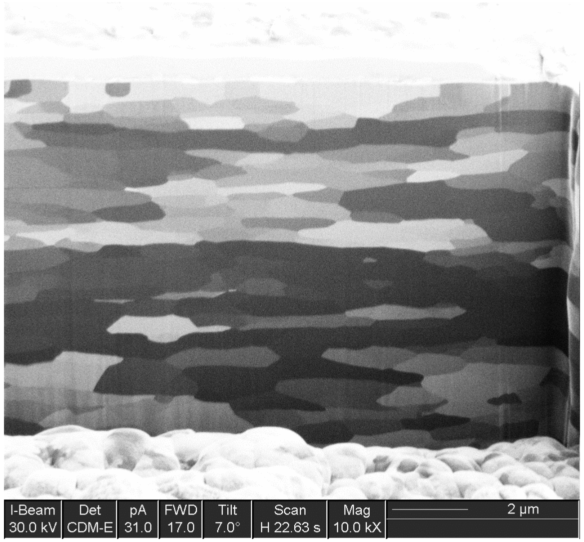


Goals (for each material):
- examine net ablation to validate codes
- find threshold for ablation
- understand roughening
- find threshold for roughening

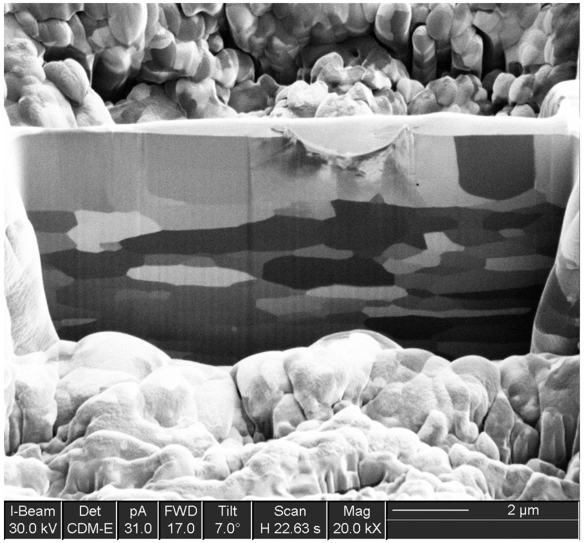
Single-pulse Z data shows no melting below 1.3 J/cm^2



1.3 J/cm^2
2 m kimfoil
2.5 m Be
0.1 m Al
No melting



2.3 J/cm^2
2 m kimfoil
0.1 m Al
0.5 μ melting



19 J/cm^2
2 μ melting

- **Unheated W**
- **Difficult to assess roughening with Z samples**

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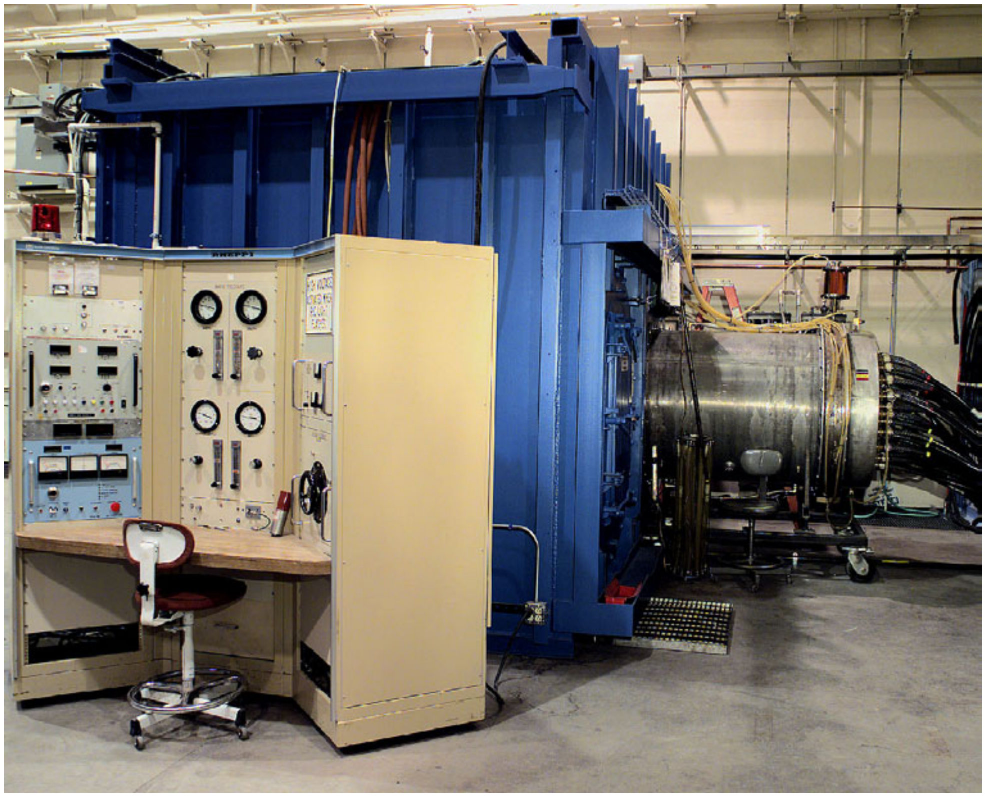
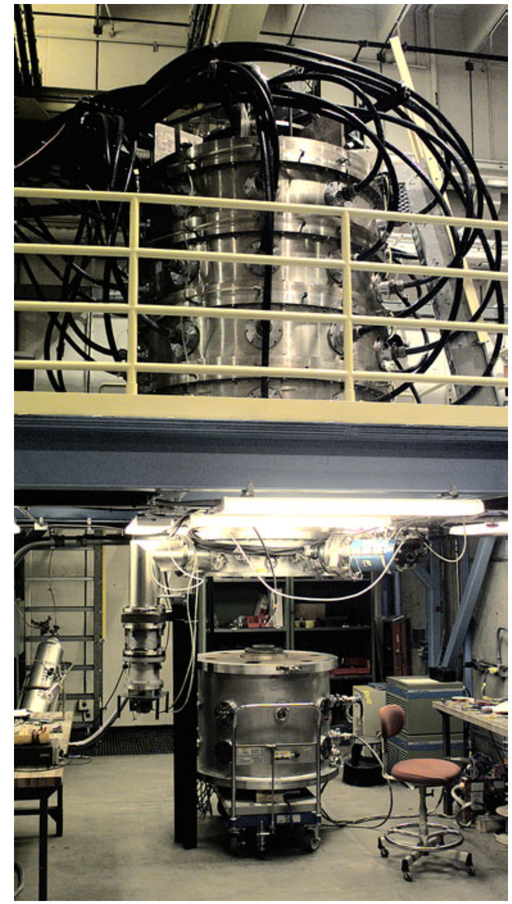
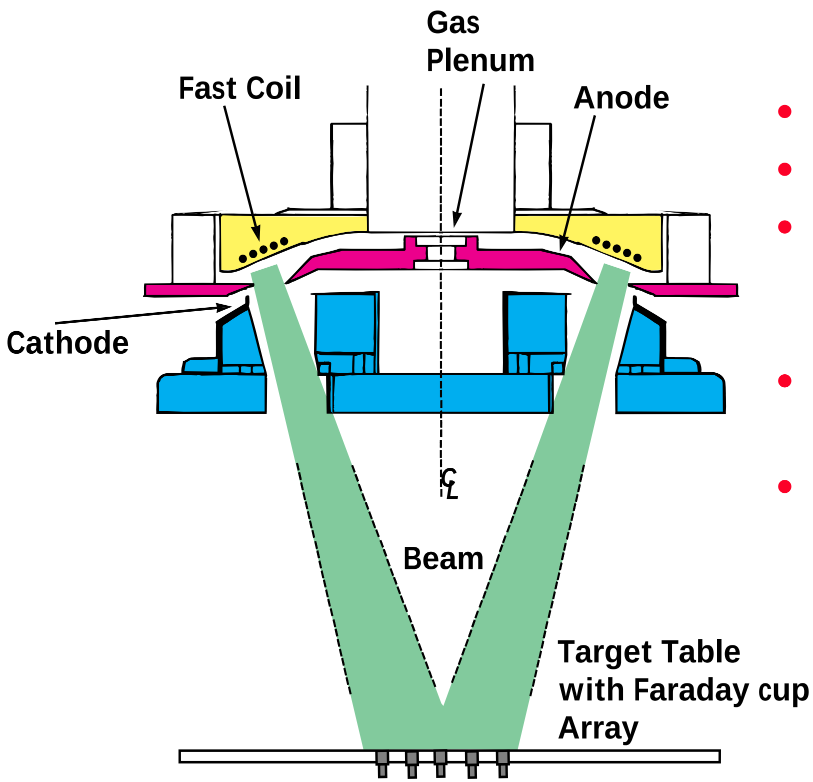
RHEPP-1 combines Repetitive High Energy Pulse Power with a robust and versatile ion source: MAP





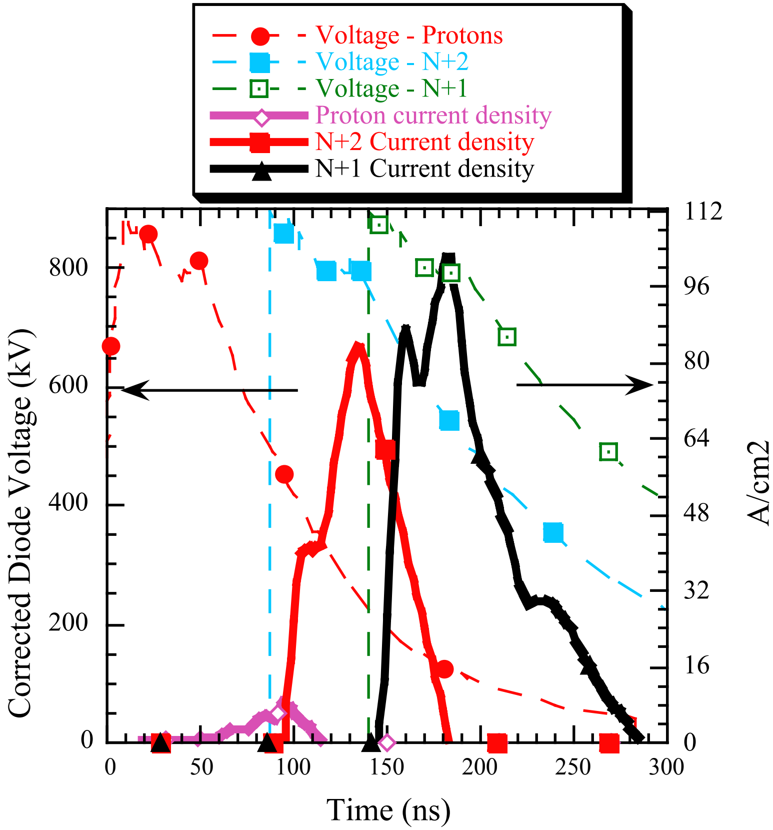
Left: Marx tank with pulse-forming line
Right: 4-Stage LIVA and treatment chamber

The MAP (Magnetically Confined Anode Plasma) Ion Source is used for surface modification experiments on RHEPP-1



- 600-800 kV
- < 250 A/cm^2
- Beams from H, He, N_2, O_2, Ne, Ar, Xe, Kr, CH_4
- Overall treatment area ~ 100 cm^2
- Diode vacuum ~ 10^{-5} Torr

Nitrogen injection into MAP produces 3-component beam of mostly N++, N+



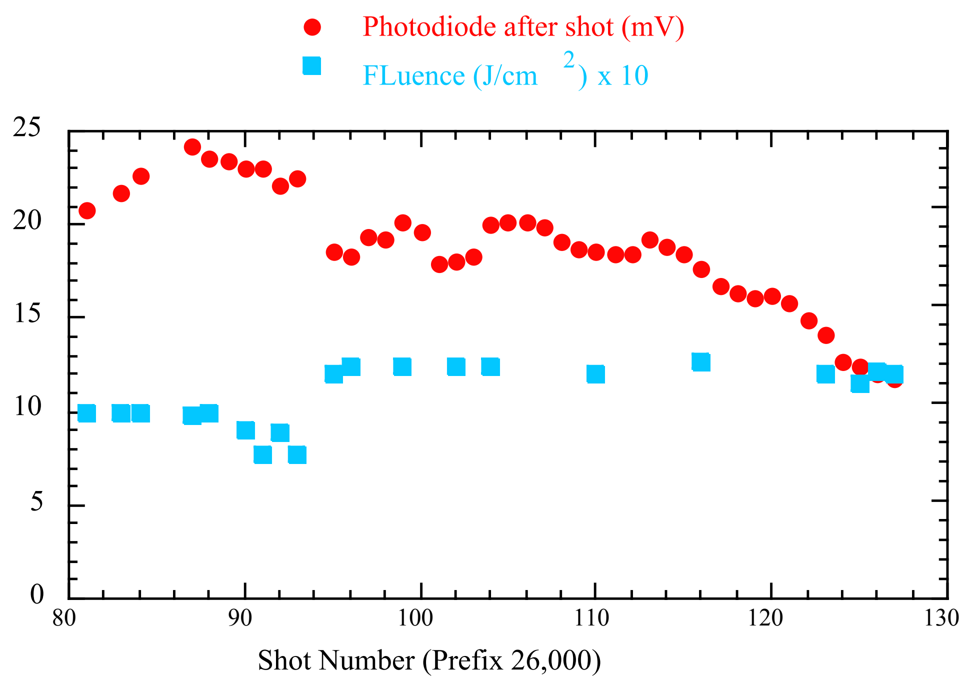
Shot 31661

- Beam predominantly N++ and N+ after small proton pulse at front
- Peak voltage = 850 kV
  Peak current density (total) ~145 A/cm²
- Total fluence = 7.9 J/cm² - will ablate almost all materials
- Total pulse width ~ 200 ns
- Ion range (TRIM):
  - N+ 0.9 μm, N++ 1.2 μm
- Oxygen, Neon beams similar

Geometry for extended exposure series

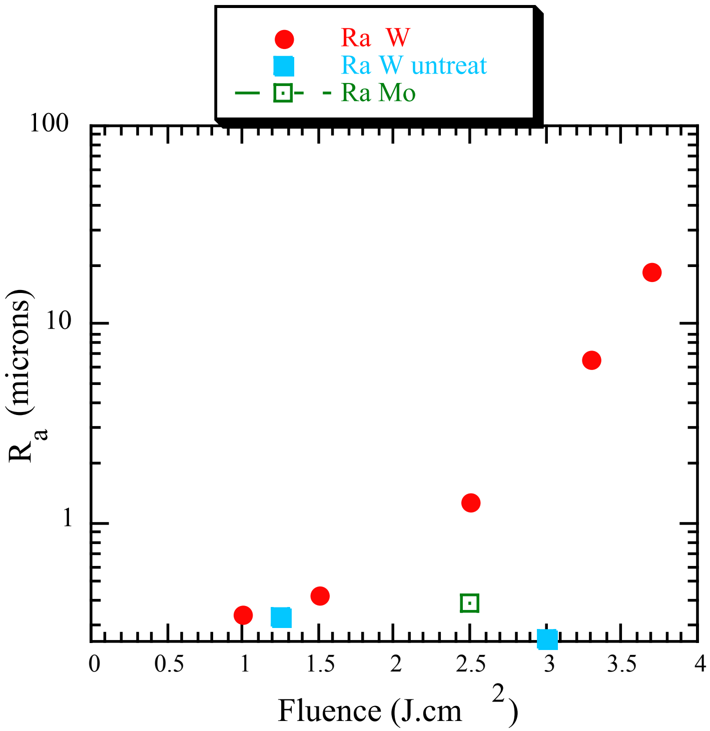
- Photo shows plate with heated samples on right, unheated strips on left
- Samples shot 200X or 400X, Ra measured by 1-D Dektak, then reloaded for another set, until maximum is reached
- SEMS, WYCO 2-D profilometry after series completion

Tungsten roughening (Room Temperature): Detailed History of Reflectometer measurements



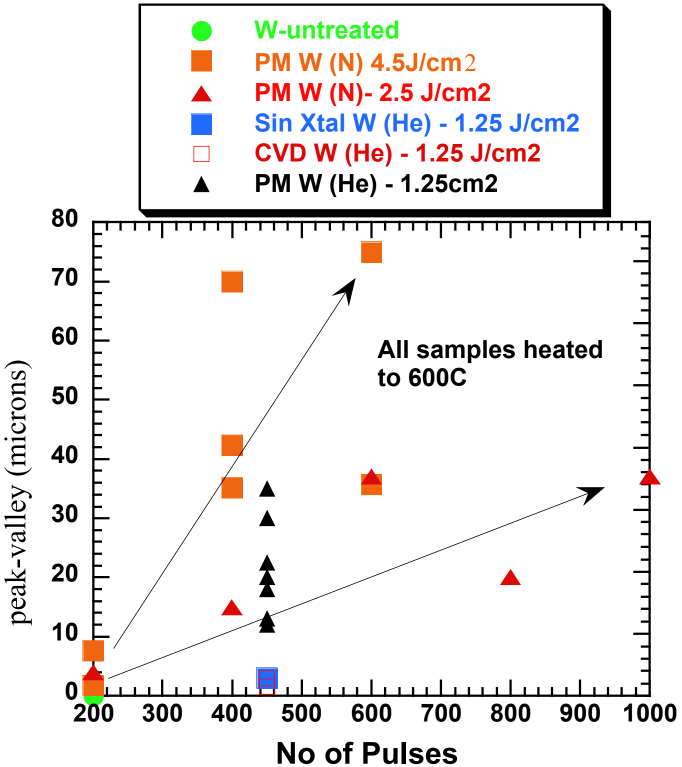
- Polished W exposed to N beam: 0.6 <dose< 1.25 J/cm^2 (53 shots)
- Reflectometer photodiode signal (red) plotted as function of shot number (26081 - 26127)
- Initial exposure at 1 J/cm^2 or less: photodiode remains above 20 mV
- Note progressive signal decrease after shot 26,112. Fluence is ~ 1.25 J/cm^2

400 shot Map N shots on Tungsten (Room Temperature): Roughening only above threshold



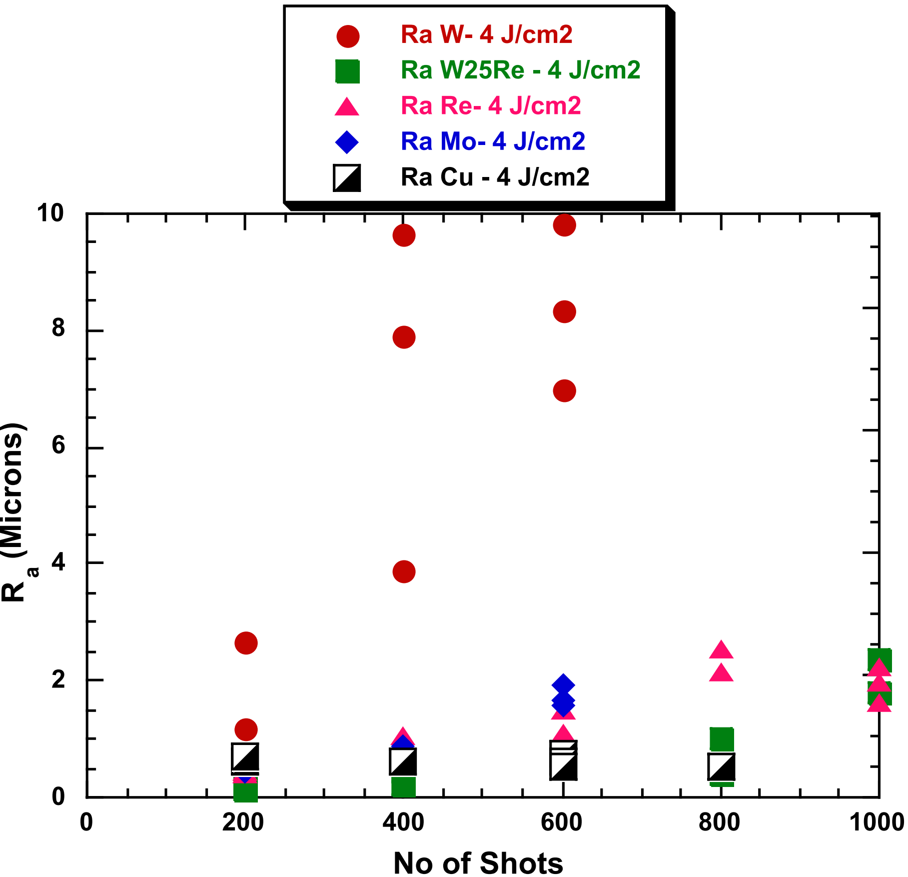
- Polished W exposed to 400 shots N beam: 1.0 < fluence < 3.7 J/cm^2
- Room Temp (RT) exposure
- Roughening occurs above 1.25 J/cm^2, consistent with single-shot reflectometer roughening threshold
- Powder Met Mo (one point at 2.5 J/cm^2): roughness stays near unexposed value
- Above threshold, roughening is a severe function of fluence. Maximum R_a exceeds 22 µm, with P-V height above 70 µm
- Roughening threshold evidently lower for He beam

Trends in W roughening: Increases with fluence/shot number; PM W the worst



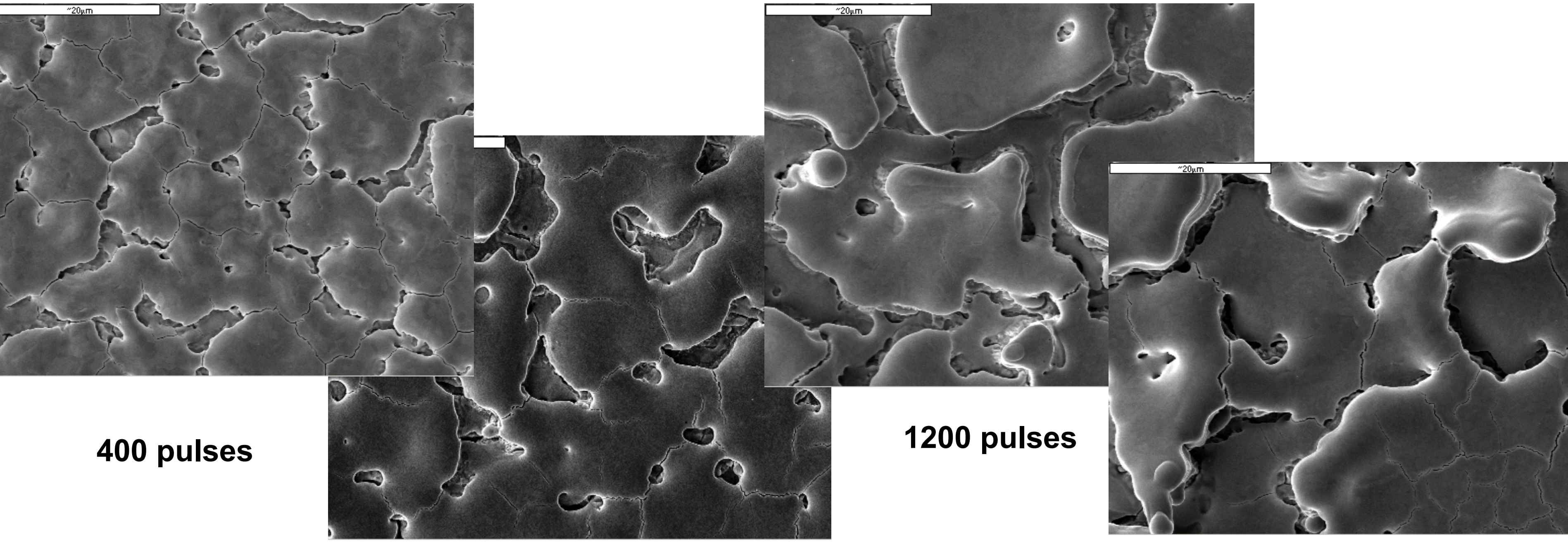
- Roughening increases ~ linearly with pulse number
- Roughening increases with fluence per pulse
- Very little surface relief happens until after 200 pulses
- 4.5 J/cm^2 is between melt and ablation for W
- He beam roughens more than N (black points)
- CVD, SingXtal (actually, everything) roughens less than PM W
- W Peak-Valley exceeds 70 μm at 600 shots
- Is W roughening reaching saturation?

Evolution of R_a Roughness at 4.0 J/cm²: WPowderMet, then everything else. Cu does NOT roughen



- 4 J/cm² is near or above ablation level for most metals shown
- Polished W and Mo are heated to 550 - 600C
- W roughens beyond 10 μm R_a at 400-600 shots (only 600 taken)
- W25Re, Re reach 2 μm R_a at 1000 shots, but Cu remains below 1 μm
- Ti-2 (not shown) roughens steadily to 1000 shots
- W Peak-Valley exceeds 70 μm at 600 shots
- Is W roughening reaching saturation?

SEMs of PM W (non-melt): appears stress cracking starts, then exfoliation, forming valleys



400 pulses

800 pulses

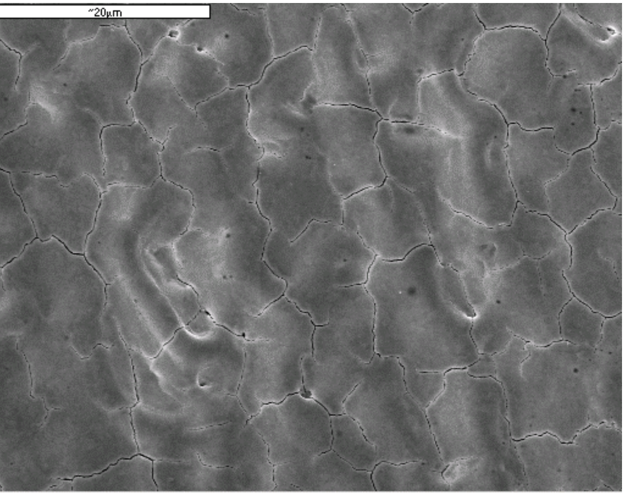
1200 pulses

1600 pulses

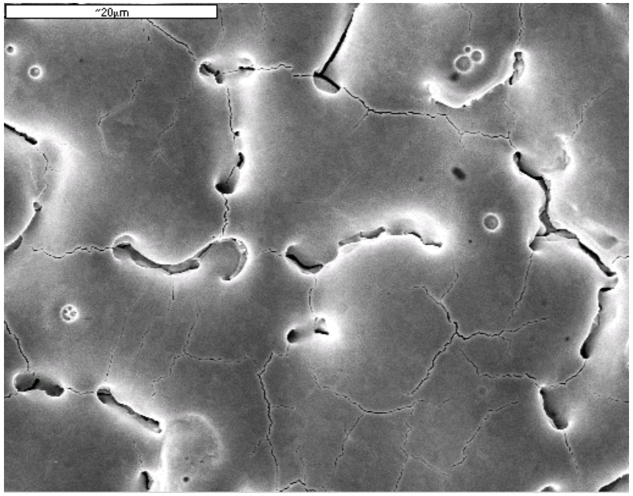
All images 2000X

- Heated PM W (600C) exposed to N beam at ~ 1.5 J/cm^2 - peak temp ~ 3300K
- Rounded ‘knobs’ are actually high points. But does average surface height rise or fall?

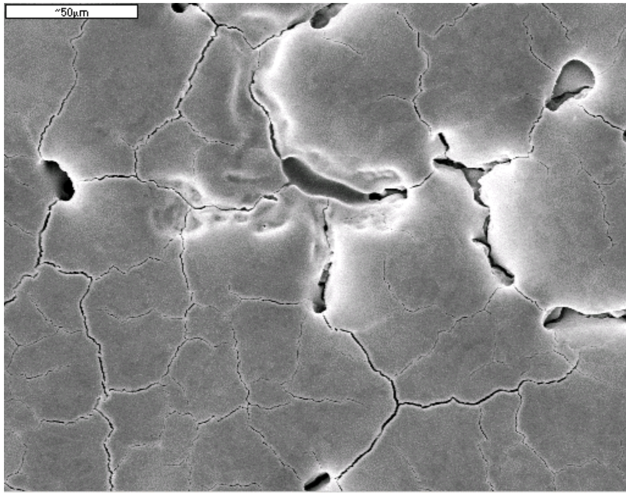
SEMs of W25Re (short-melt): appears Similar but attentuated roughening compared to PM W



400 pulses



800 pulses

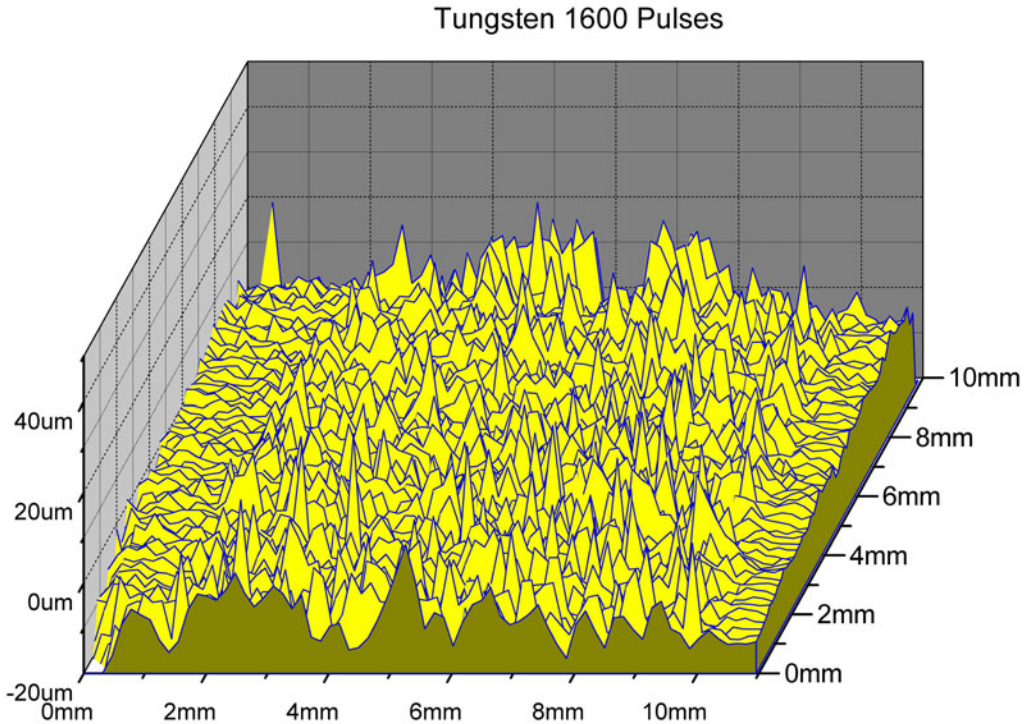


1200 pulses

All images
2000X

- Heated W25Re (600C) exposed to N beam at ~ 1.5 J/cm^2 - peak temp ~ 3300K. Sample experienced short melt time

PM Tungsten after 1600 pulses (non-melting): Mostly mountains



- Heated/treated PM W examined with NEXIV laser interferometry
- Comprehensive line-out scan: max height 30 μm, min height < 10 μm compared to untreated
- Very deep microcracking not visible here

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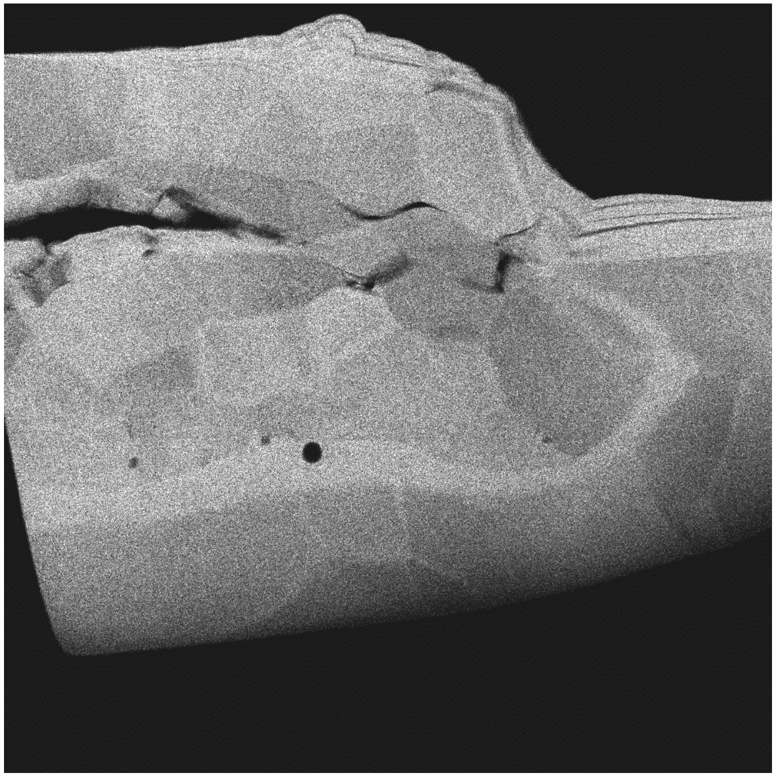
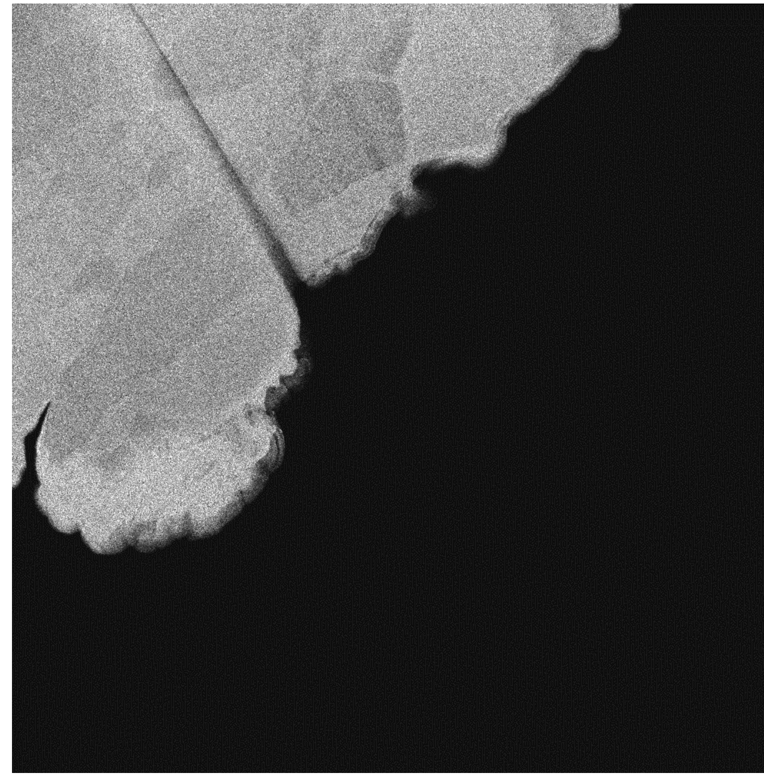
FIB-STEM of 1000-pulse W at 2.25 J/cm² (ave): No melting or recrystallization evident



Near-surface

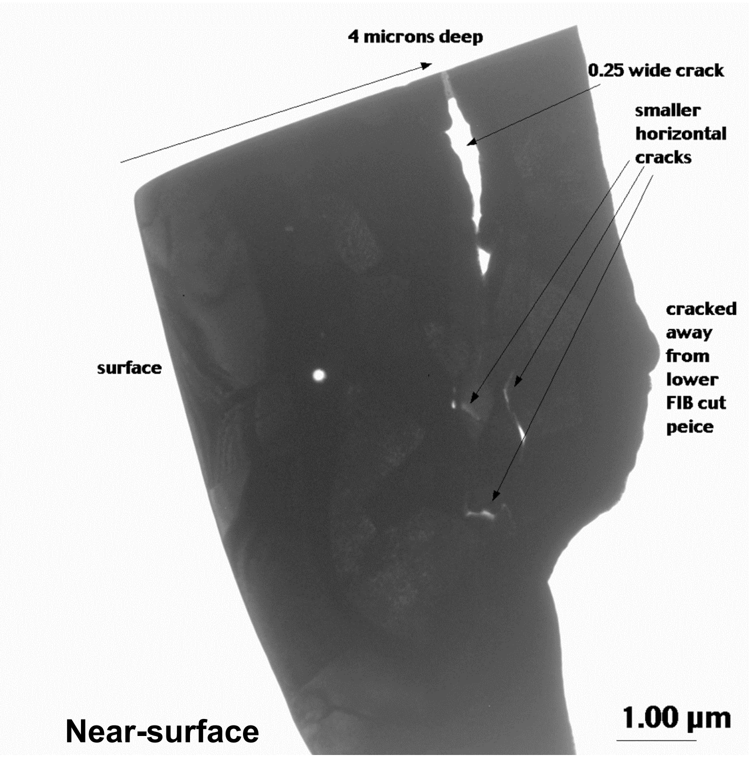


5 - 10 μm depth

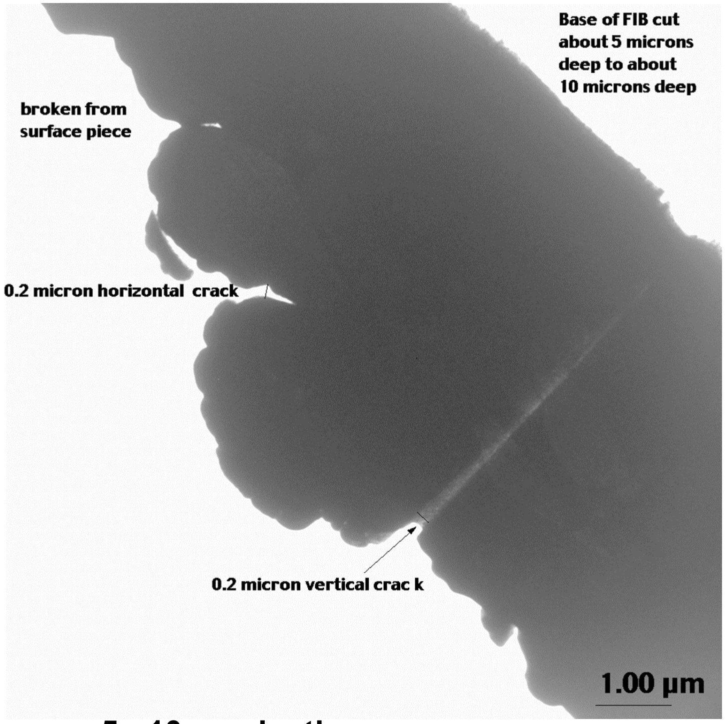
Simulation results:

Melt Depth: 0.2 μm
Melt Duration: 91 ns
MaxTemp: 3752K (from 600C)
R_a = 2.3 - 4.5 μm

FIB-XTEM of 1000-pulse W at 2.25 J/cm^2 (ave): Deep horizontal/vertical cracking without melt



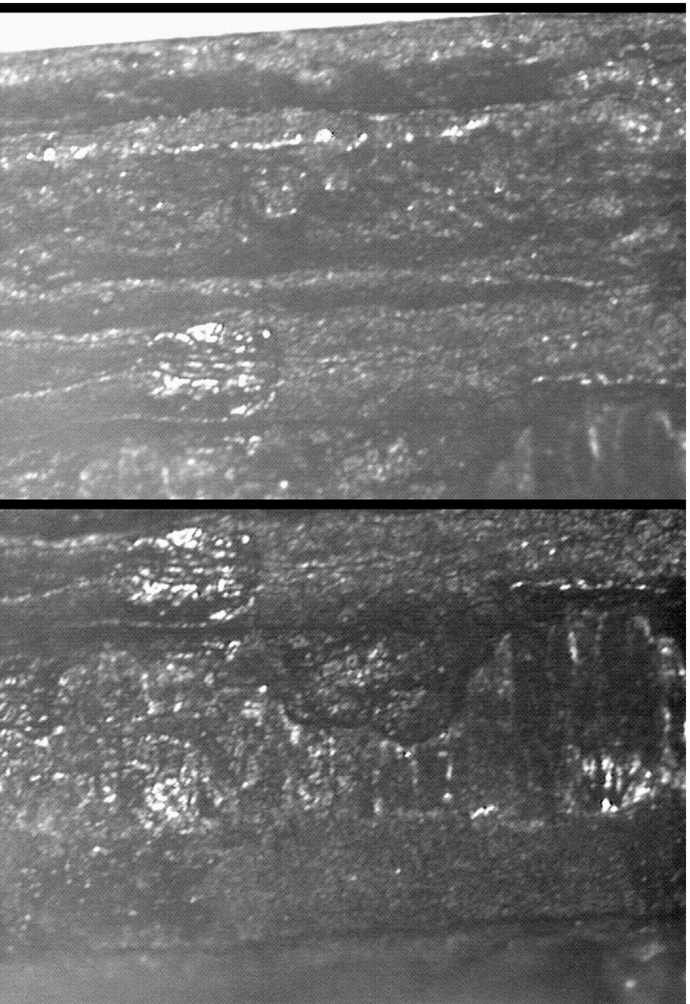
Near-surface



5 - 10 µm depth

- Polished Powder Met W exposed to 100 shots N beam @ 2.25 J/cm^2 ave /pulse, ~ melting temperature at surface. No melt layer observed.
- 600°C exposure
- Sample cracking horizontally/vertically down to 10 µm depth
- Suspect fatigue-cracking

Comparison, treated W and W25Re, side view: ‘Laminated’ structure to 1mm depth on W, missing in W25Re



Photomicrographs, side view, 1600 pulses, surface temp to near-melt

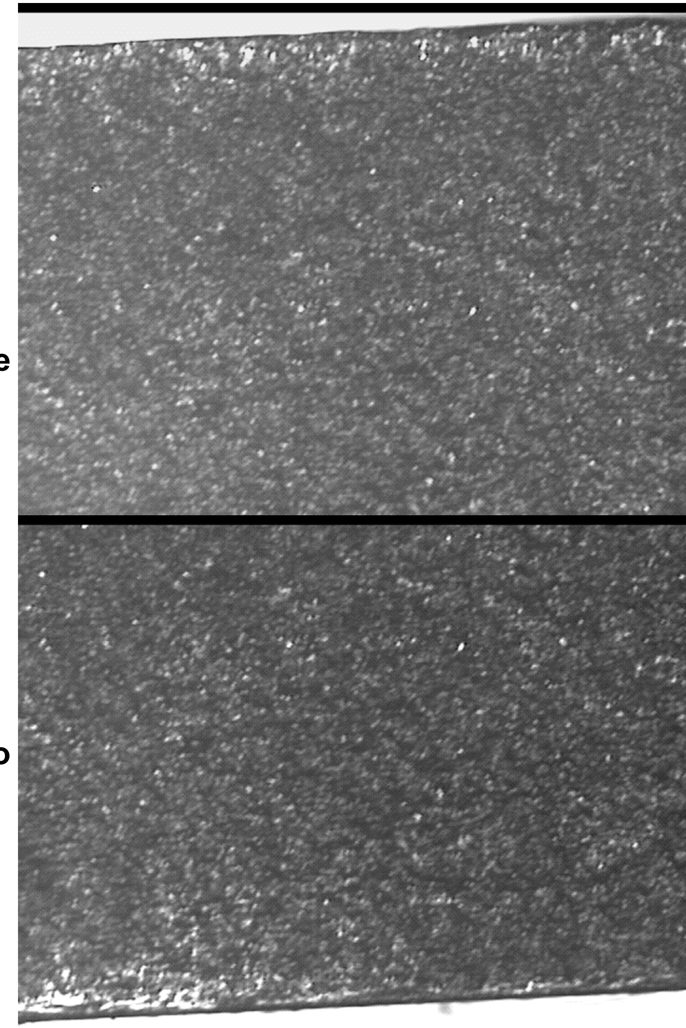
Surface to near-middle (~ 0.8 mm)

0.8 mm to ~ 1.5 mm

PM Tungsten

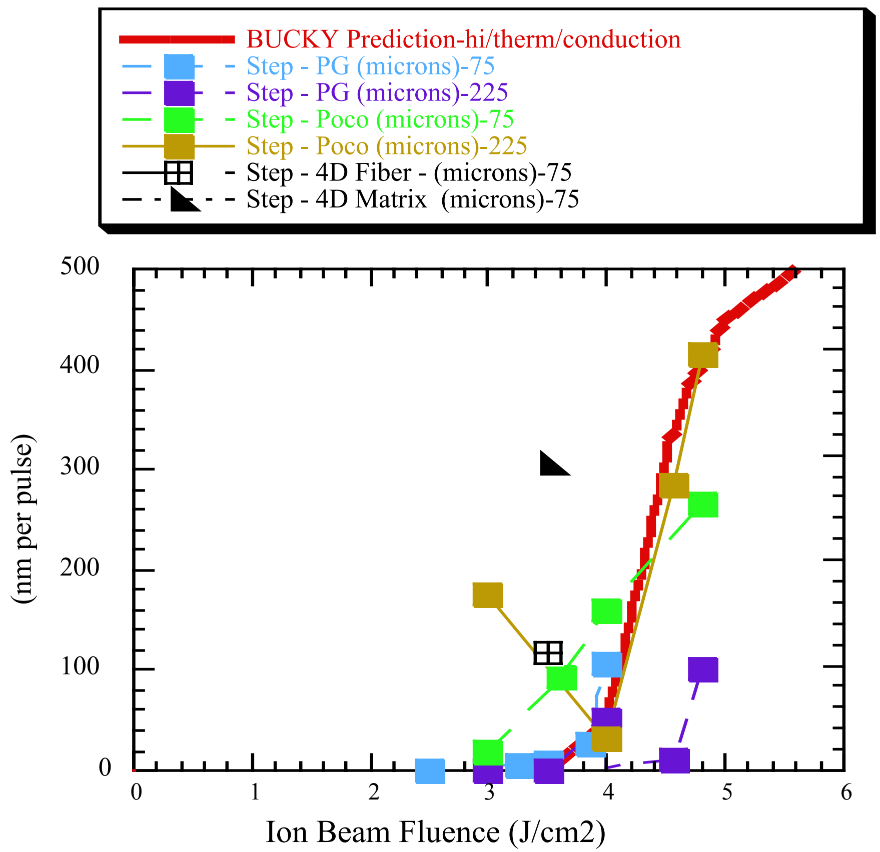
Surface to near-middle (~ 0.6 mm)

0.6 mm to ~ 1.2 mm



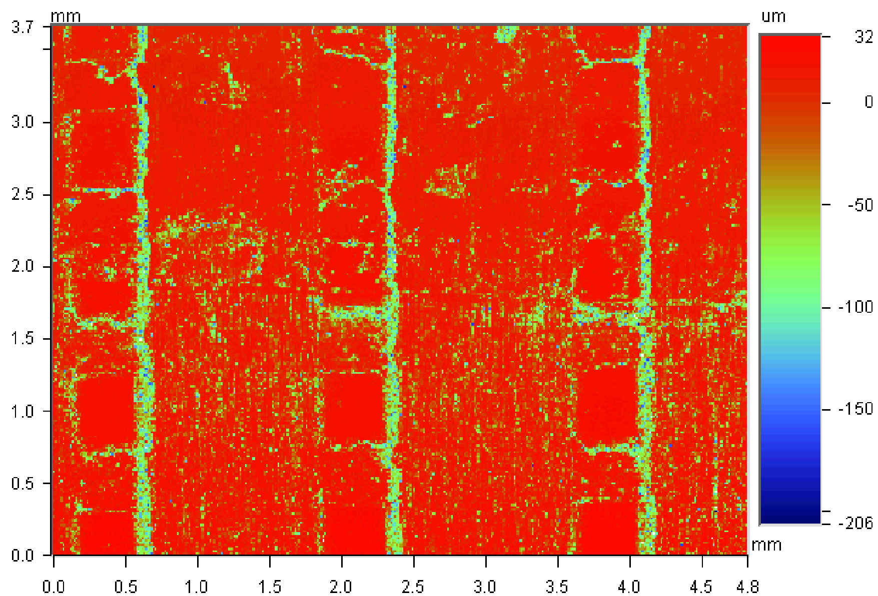
W25Re

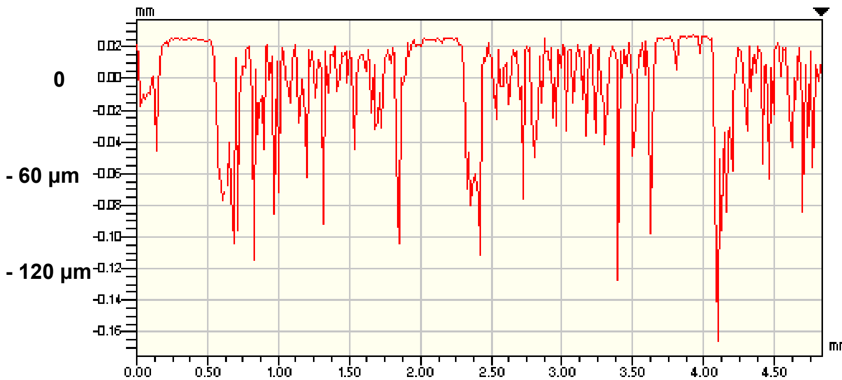
Response of graphite to mixed H - C beam qualitatively confirms BUCKY predictions



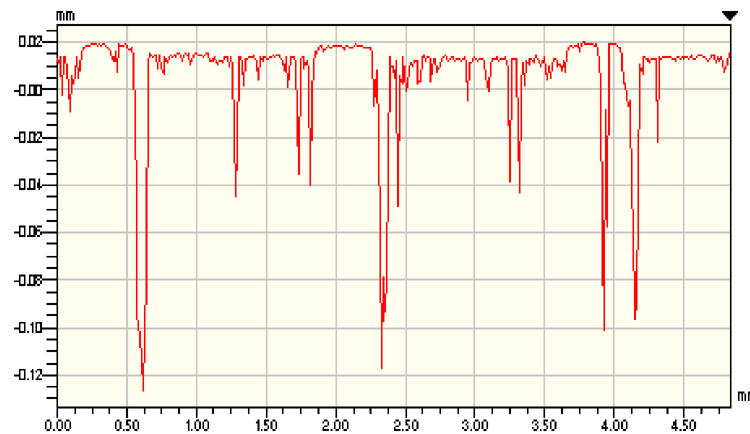
- Mechanically polished pyrolitic graphite (PG), Poco, and 4D carbon composite weave exposed to 75 pulses/225 pulses of 70% C /30% H beam at doses of 1.9 to 5 J/cm^2
- PG ablation threshold ~ 4 J/cm^2
- Poco ablation threshold ~ 3 J/cm^2
- Above threshold, rapid increase in ablated material per pulse with dose. Data scatter reflects uncertainty in dose
- Composite matrix ablates more than PG/Poco, fibers comparable (sample rough)

FMI-222 unheated CFC exposed to MAP N for 1000X at 1.6 J/cm^2: Significant erosion of matrix





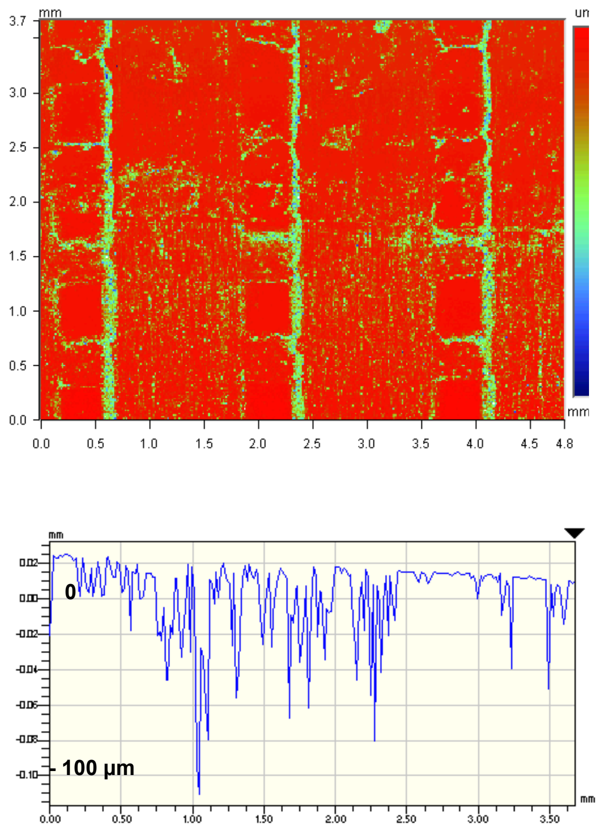
Treated at 1.6 J/cm^2



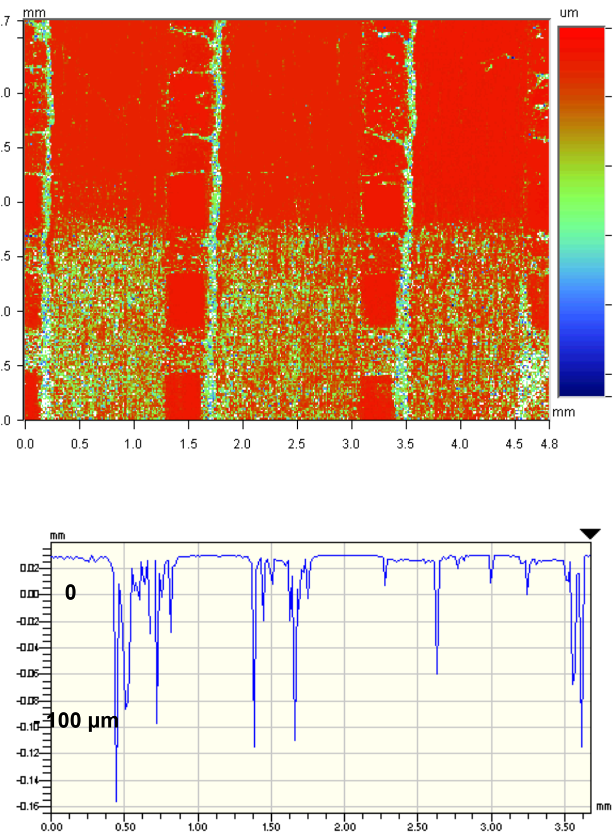
Untreated

FMI-222 Fiber ends appear ablation-resistant; Matrix loss ~ 0.3 µm/pulse at 4.0 J/cm^2:

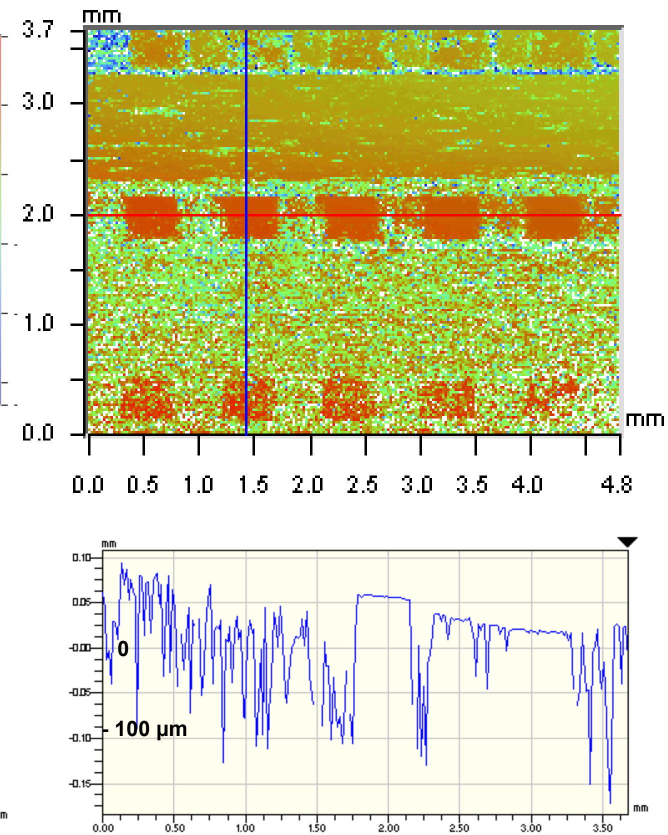
Treated at 1.6 J/cm^2 1000X



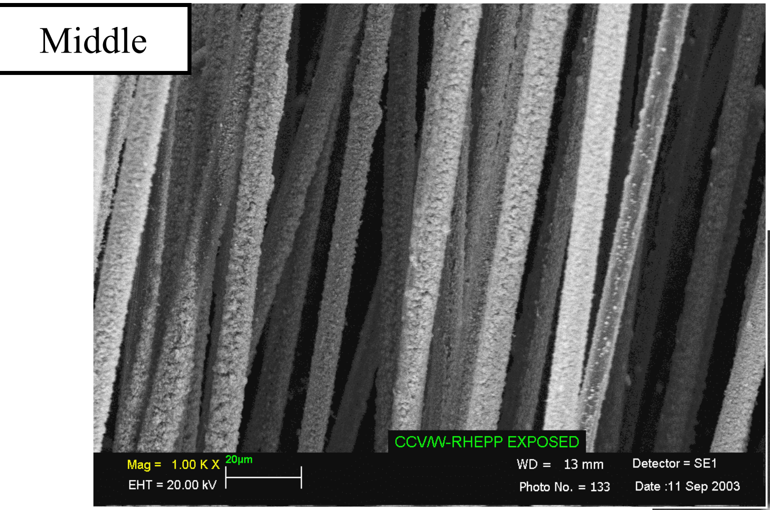
Treated at 2.6 J/cm^2 600X



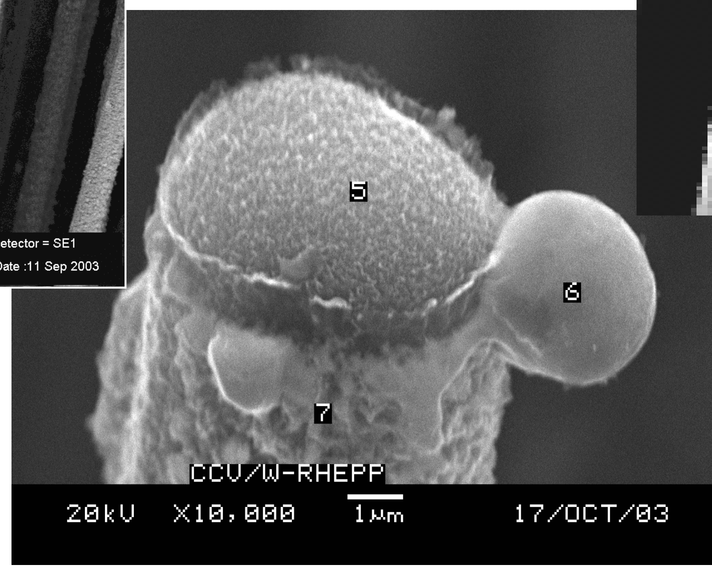
Treated at 4.0 J/cm^2 600X



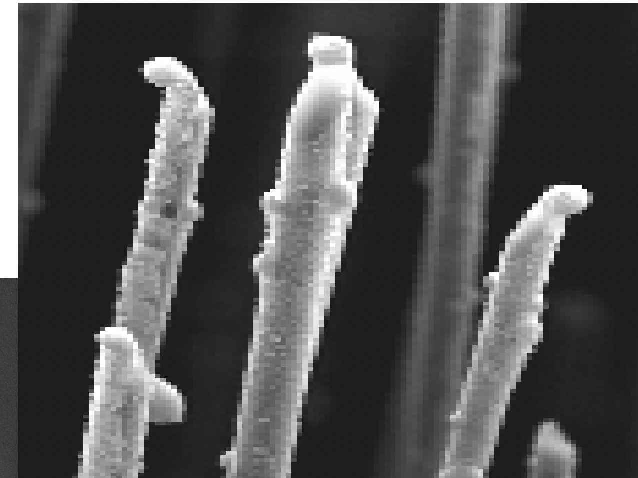
W-coated Carbon 'Velvet' exposure to ions: 1.6 μm W survives on sharp tips, 200 pulses at 6 J/cm^2



Fiber sides, W-sputtered, after treatment

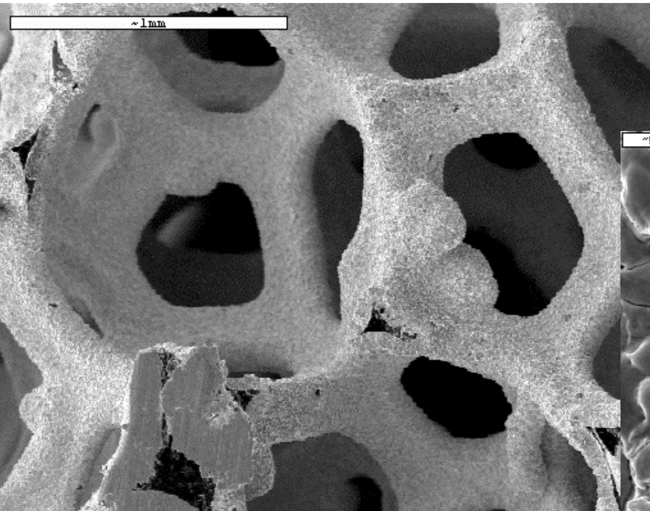


Flat tips, W balls up on side

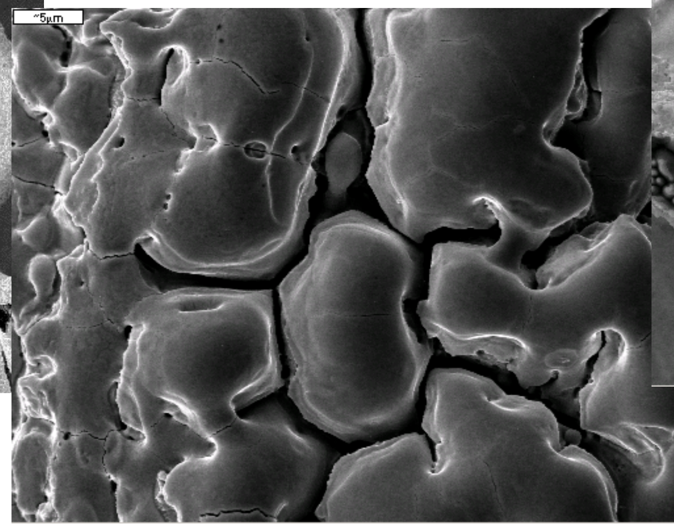


Tapered tips, showing W still in place

'Foam' (Ultramet) exposure to ions: W/TaC suffers erosional loss, W/HfC brittle failure

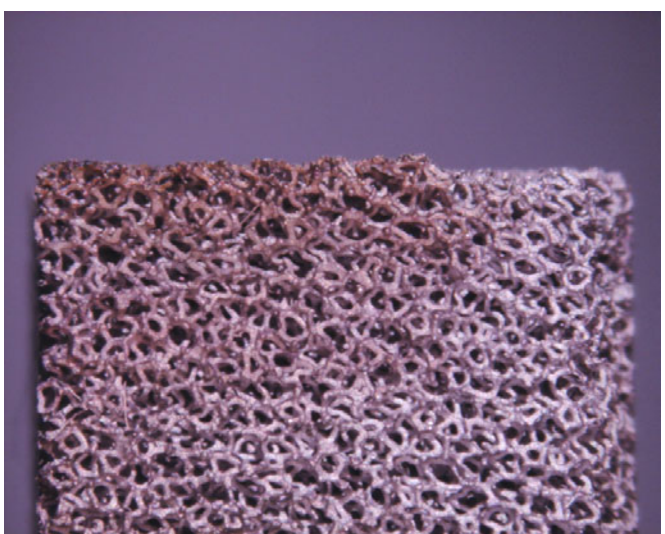


Foam geometry, untreated, 50X



W/TaC, after 1200 pulses, 2500X

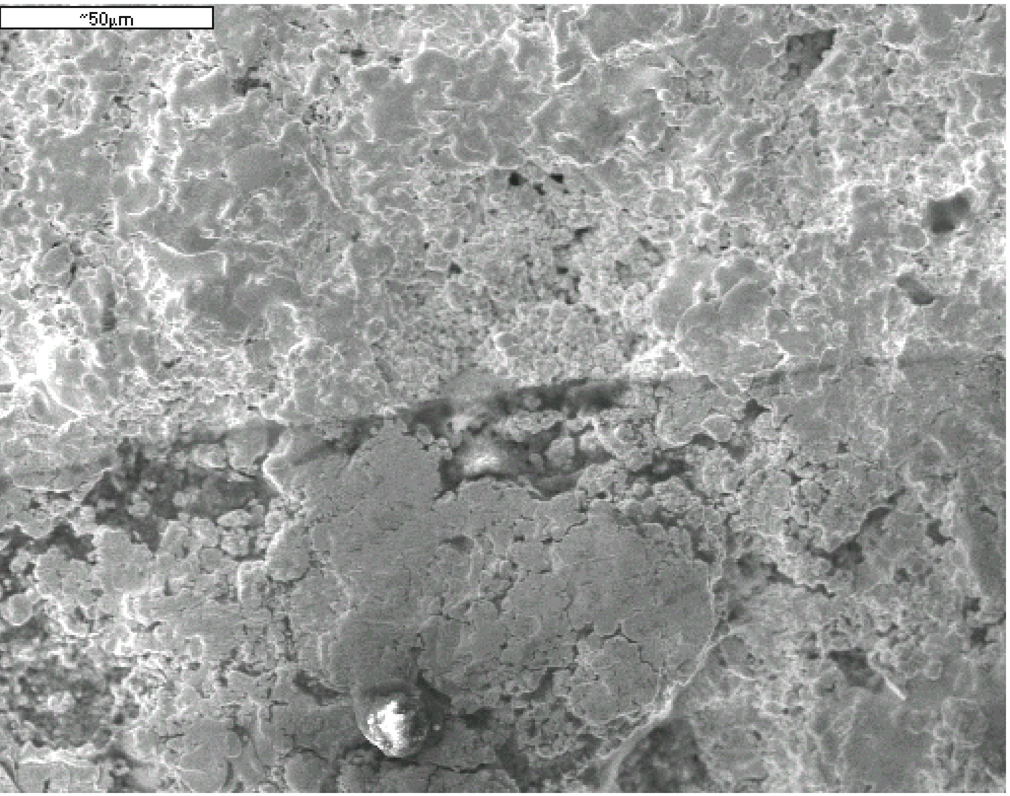
W/HfC, 800 pulses, 250X



Side view, W/TaC, after 800 pulses, showing EXPANDED height (left)

SEMs:
Thinner structures, better bonding may be necessary

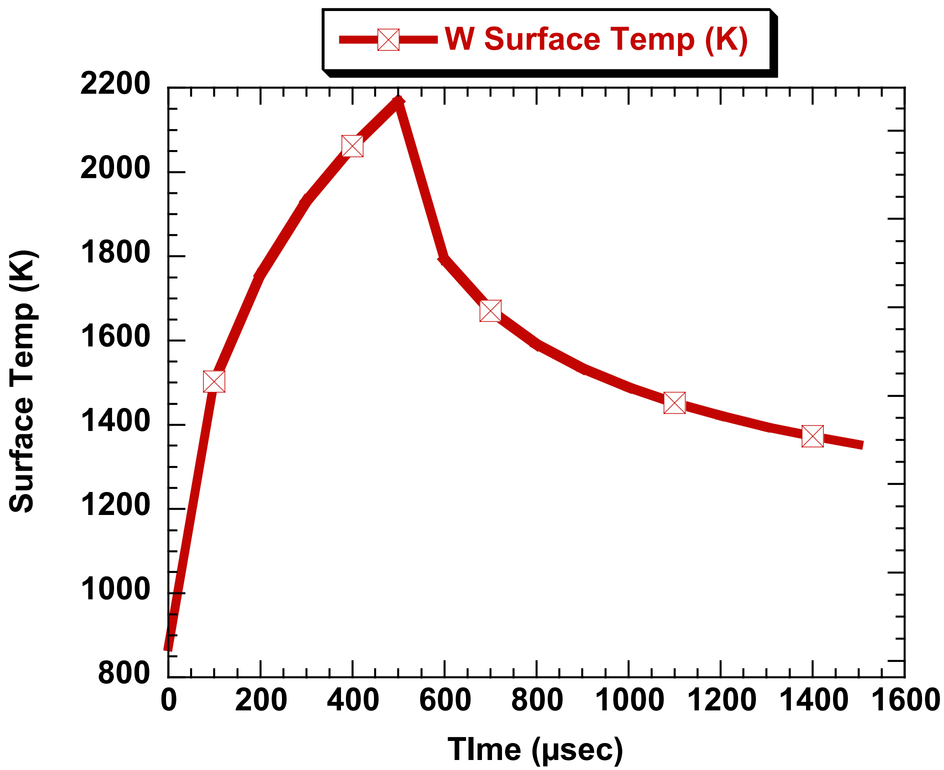
Plasma-sprayed W on Steel exposed to 400 Ion Pulses: Evidence of Mass-loss at low Fluence



454 W on Steel

- Plasma-sprayed W on steel (unheated) exposed to 400 pulses MAP N at average 1.4 J/cm^2
- SIM model prediction: 3000K max for surface temp
- Interface in middle, exposed at bottom
  - Dektak measurements not definitive – both sides too rough
  - Images indicate mass loss from treated side

SIM 'ELM' simulation: 3 kV protons on 600°C W @ 40 A/cm² for 500 μsec (60 J/cm²)



- This simulates estimated ELM deposition in H Mode tokamak discharge: 10 MJ over 5 m² for 500 μsec
- Pure W at 600 °C initial temp
- Constant flux of 3 kV protons at 40 A/cm² for 500 μsec
- Peak temp < 2200K after 500 μsec
- Peak temp less than SIM prediction for 1000 shot series
- Temp gradient < IFE case. Will fatigue cracking still occur?

Summary

- Ion exposure forms key part of Laser IFE Direct Drive First-Wall Threat. RHEPP-1 beams can simulate this threat with good fidelity
- For W materials, most serious issue is roughening, evidently caused by thermomechanical stress. Stress cracking is followed by erosion or exfoliation of material. Stress cracks deepen with pulse number, and may reach deep into interior. This is true regardless of melt.
- W25Re develops this topology less severely than W. But, along with Ti and Mo, still shows this behavior. Surface melting does not smooth the roughening, unless vaporization threshold is reached.
- Engineered materials such as ‘Velvet’ or ‘Foam’ may be an alternative surface design
- These results are relevant to MFE W exposure due to Type I ELMs