SAND2007-5752C

Materials Issues in Inertial Fusion Energy (IFE) First-wall Experiments - Response of Wall Materials to Repeated Pulses of High-energy Ions*

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Presentation Outline

- IFE Threat Spectra and Relation to MFE Conditions: RHEPP-1 can simulate ion threat to first wall
- Description of RHEPP-1 and Sample Exposure Setup
- Tungsten and Tungsten alloys: Brittleness leads to thermomechanical distress
- Graphite/Carbon Composites:
  Sublimation loss may be main problem – physical sputtering?
- 'Engineered' Materials as an alternative to flat wall
- Conclusions and Follow-on Work

In an IFE Reactor, the First-wall is subjected to a Programmed High Fluence of Energetic Ion pulses (3 x 10^8/year)

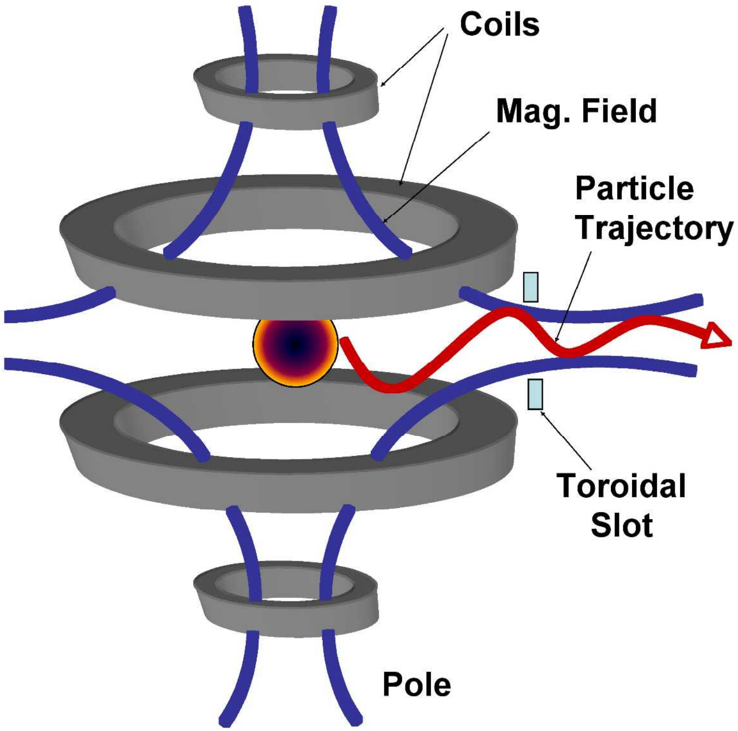
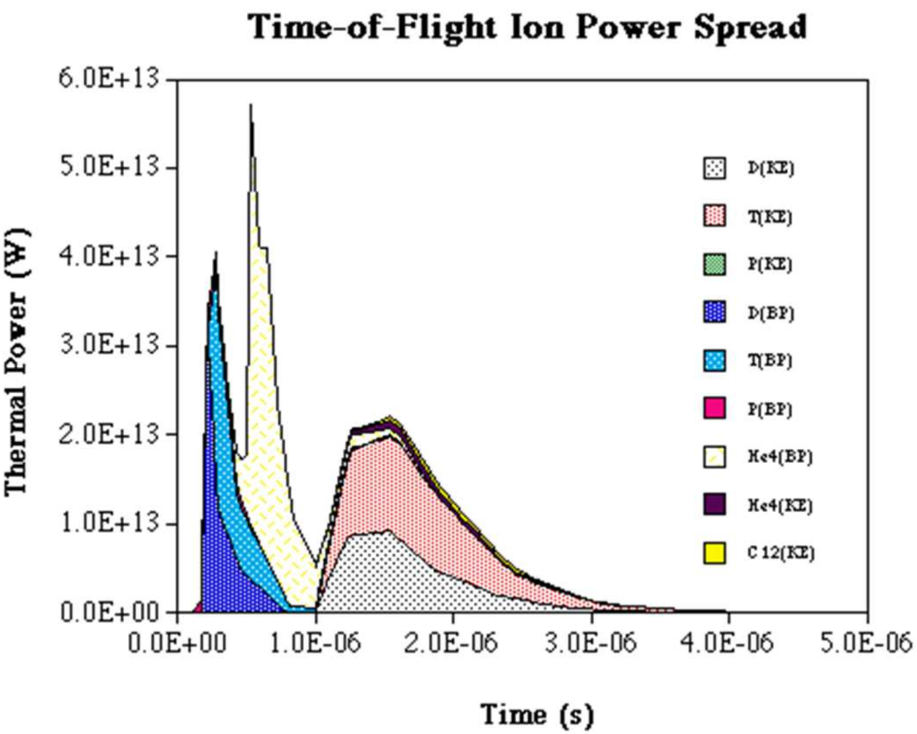


Image provided by R. Raffray, UC San Diego

- Unlike MFE, no Steady State phase, only 'transient' events.

  Level per pulse is known, ~ few MeV ions normal to surface. At 10 Hz operation, 3e8 pulses per year
- At 10 nm erosion/pulse, 3 METER thickness lost per year. So NOTHING can be lost per pulse. Melting should be avoided as well.
- Biggest threat below Melting is Thermomechanical stress
- Leading Geometry: Spherical w/ or w/o gas fill
- Backup Geometry (LEFT): Cusp with 'beam dump' on axis
- Leading materials: tungsten and W alloys, SiC

Laser IFE Direct Drive Threat Spectra



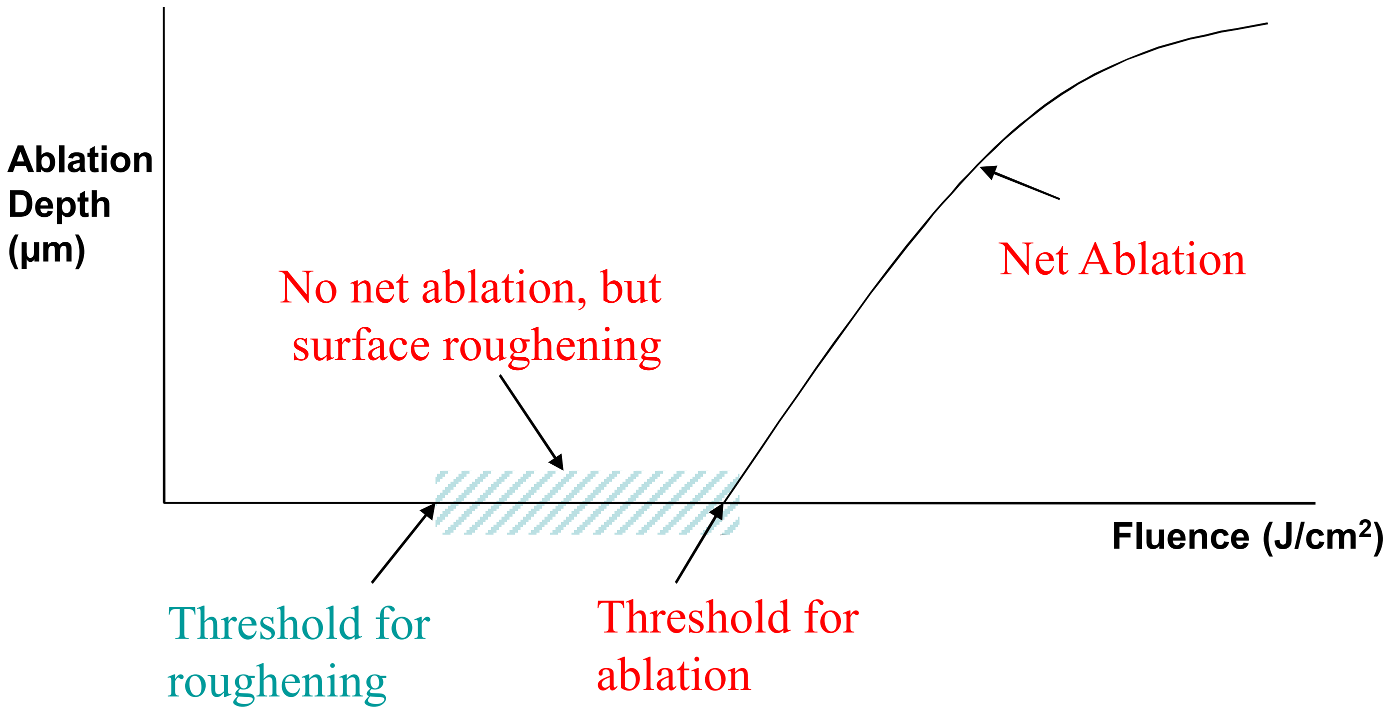
Simulation: Thermal Power to Wall in Ions from 154 MJ Yield. Wall Radius: 6.5 m

- **For Direct-drive Laser IFE:**
  ~70% neutrons, 1-2% x-rays
  30% ions (50-50 fusion and 'debris')
- **Ions: several MeV, ~ few μsec each,**
  8-20 J/cm^2 fluence, judged Significant Threat
- **X-rays: ~ 1 J/cm^2, up to 10 keV energies, judged less significant threat**
- **RHEPP-1: 700 keV N, higher for N^{+2} , 100-150 ns pulsewidth, 75-95 GW/m^2**
- **RHEPP-1 energy delivery too short, but otherwise good fidelity with reactor ion threat**

F=P*√t: High Heat Flux conditions with Heat Diffusion effect included. *Comparison*:

ITER ELMs (est):
22.4 - 67.1 MW m^{-2} s$^{1/2}$
RHEPP-1:
33 - 112 MW m^{-2} s$^{1/2}$

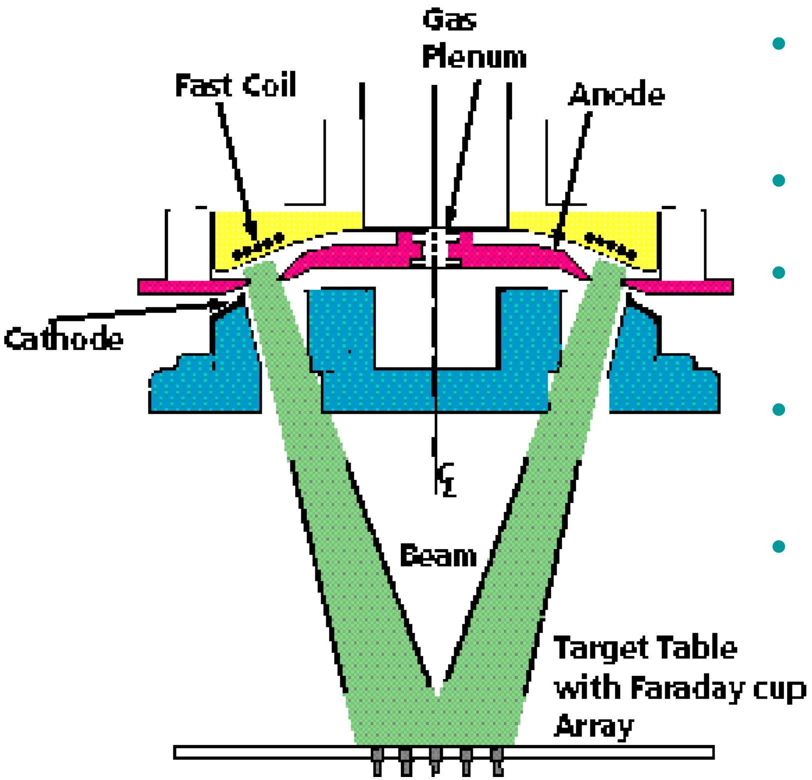
Regimes of IFE Materials Response to Ions



Goals (for each material): examine net ablation to validate codes; find threshold for ablation — **DONE**

Area of Interest: Understand roughening. Is there mass loss? Find threshold for roughening (Fluence/pulse, No. of pulses)

Overall View of RHEPP-1 vacuum chamber and treatment area

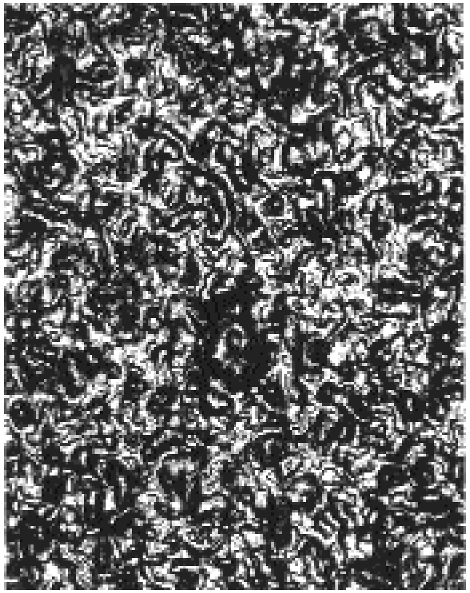


- 600-800 kV. Pulse Width ~ 100-200 ns
- Up to 250 A/cm^2
- Beams from N_2, Ar, He used here
- Overall treatment area ~ 150 cm^2
- Diode vacuum ~ 10^{-5} Torr

Tray shown here replaced by 'scalloped' holder that avoids Beam center

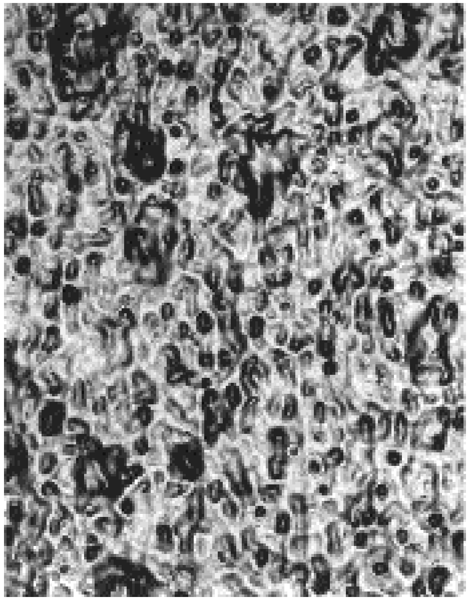
Not all ions are created equal: Surface morphology changes on SS303 samples depending upon treatment ion(s)

Proton Beam 25 pulses



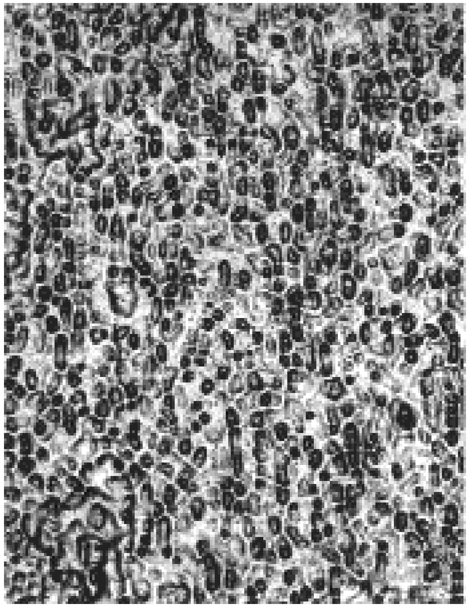
Modeling (Fe):
Max Temp: 1658K
'No' melting

Nitrogen Beam 25 pulses



Modeling (Fe):
Max Temp: 2593K
Melt depth: 0.7 µm

Argon Beam 25 pulses

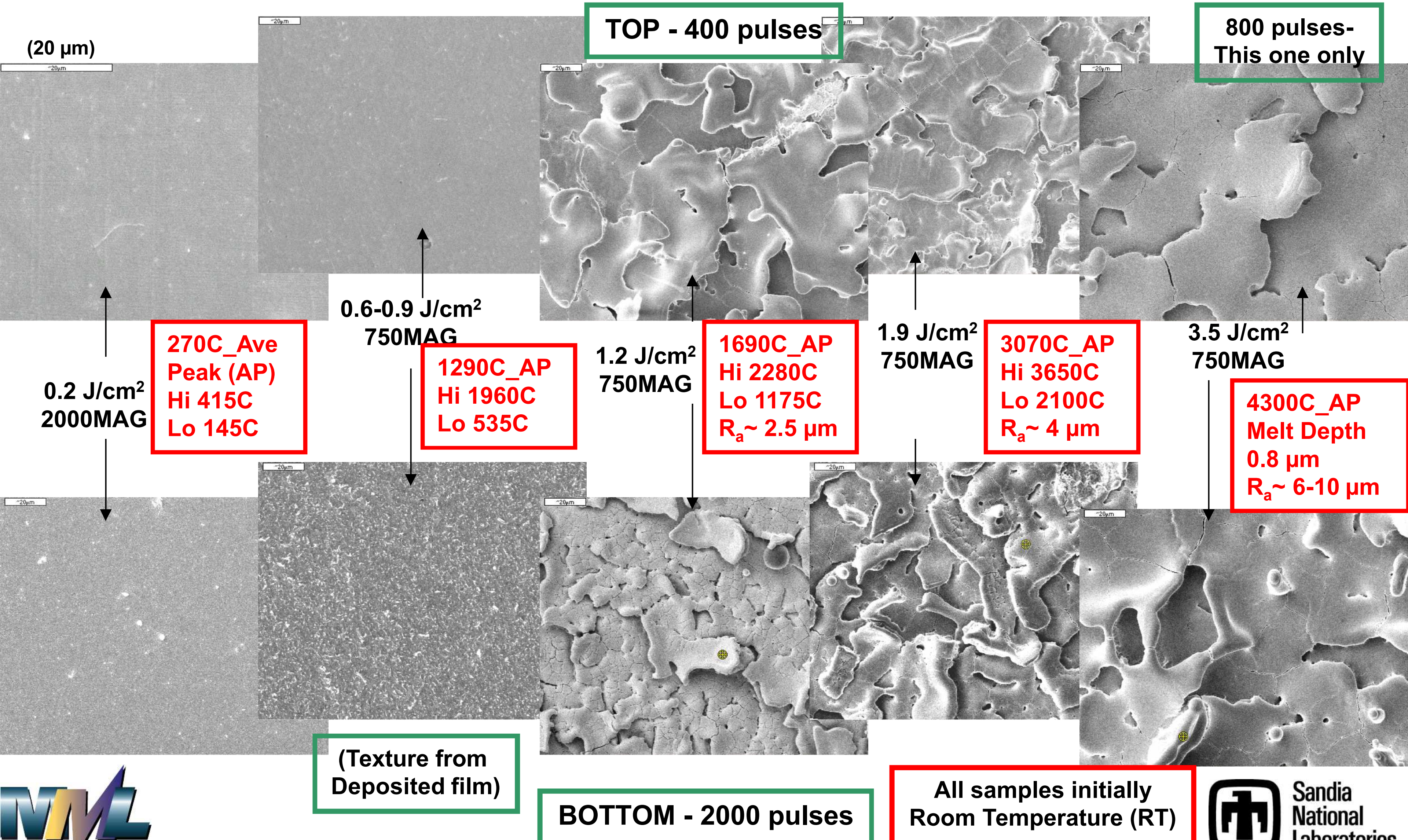


Modeling (Fe):
Max Temp: 2072K
Melt Depth: 0.45 µm

- SS303 exposed to 25 shots three different ion beams @ 2 J/cm^2
- 'Finer' surface features with Nitrogen, Argon in micrographs
- Periodicity ~ 50 µm for N, Ar surface, ~ 70 µm for proton-treated surface. Main contribution to morphology - sulfur

Tungsten Materials

SEMs of Polycrystalline (PM) Tungsten Roughening: Threshold at ~ 1 J/cm², roughening saturates after ~ 400 pulses



All samples initially Room Temperature (RT)

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The 2000-exposure surfaces were exposed to as much as 350 GW/m^2 average power over 100 ns

0.2 J/cm^2
2000MAG
(20 µm)

270C_Ave
Peak (AP)
Hi 415C
Lo 145C

0.6-0.9 J/cm^2
750MAG

1290C_AP
Hi 1960C
Lo 535C

1.2 J/cm^2
750MAG

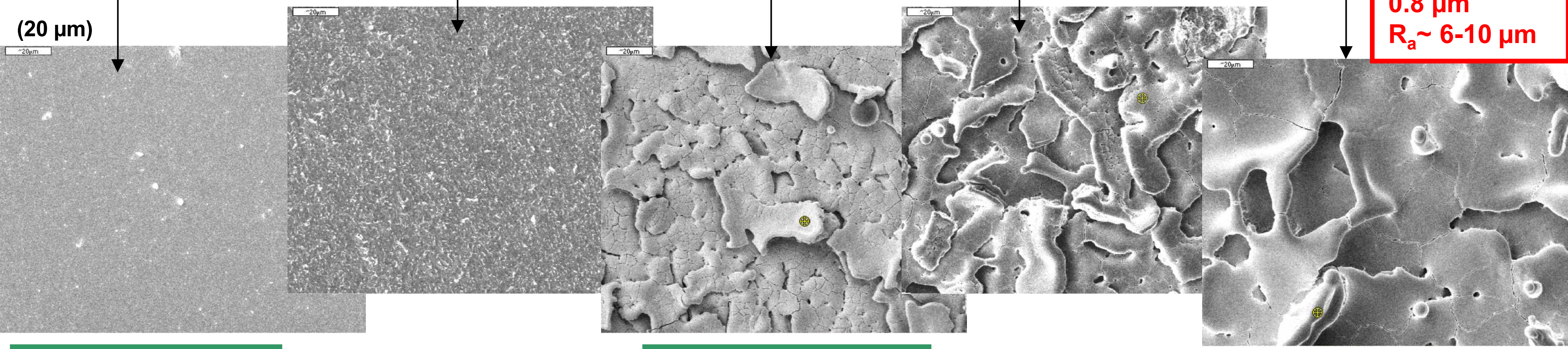
1690C_AP
Hi 2280C
Lo 1175C
R_a~ 2.5 µm

1.9 J/cm^2
750MAG

3070C_AP
Hi 3650C
Lo 2100C
R_a~ 4 µm

3.5 J/cm^2
750MAG

4300C_AP
Melt Depth
0.8 µm
R_a~ 6-10 µm



20 GW/m^2/pulse
2 kJ/m^2/pulse

120 GW/m^2/pulse
12 kJ/m^2/pulse

350 GW/m^2/pulse
35 kJ/m^2/pulse

- 700 kV for 100 ns @ 15A/cm^2 = 1 J/cm^2
- Only the rightmost surface above melted on each pulse
- Maximum cumulative dose 70 MJ/m^2

All samples initially
Room Temperature (RT)

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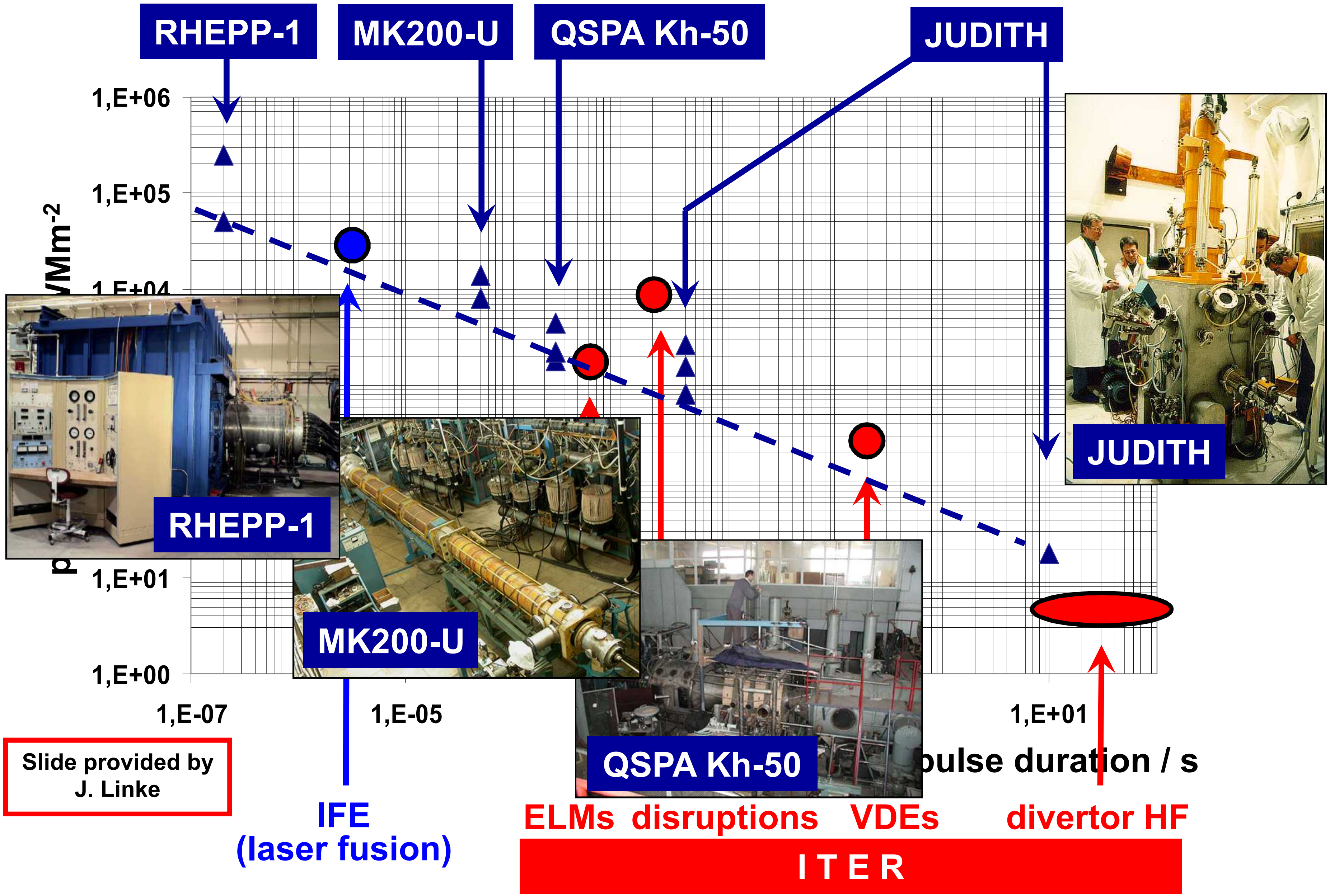
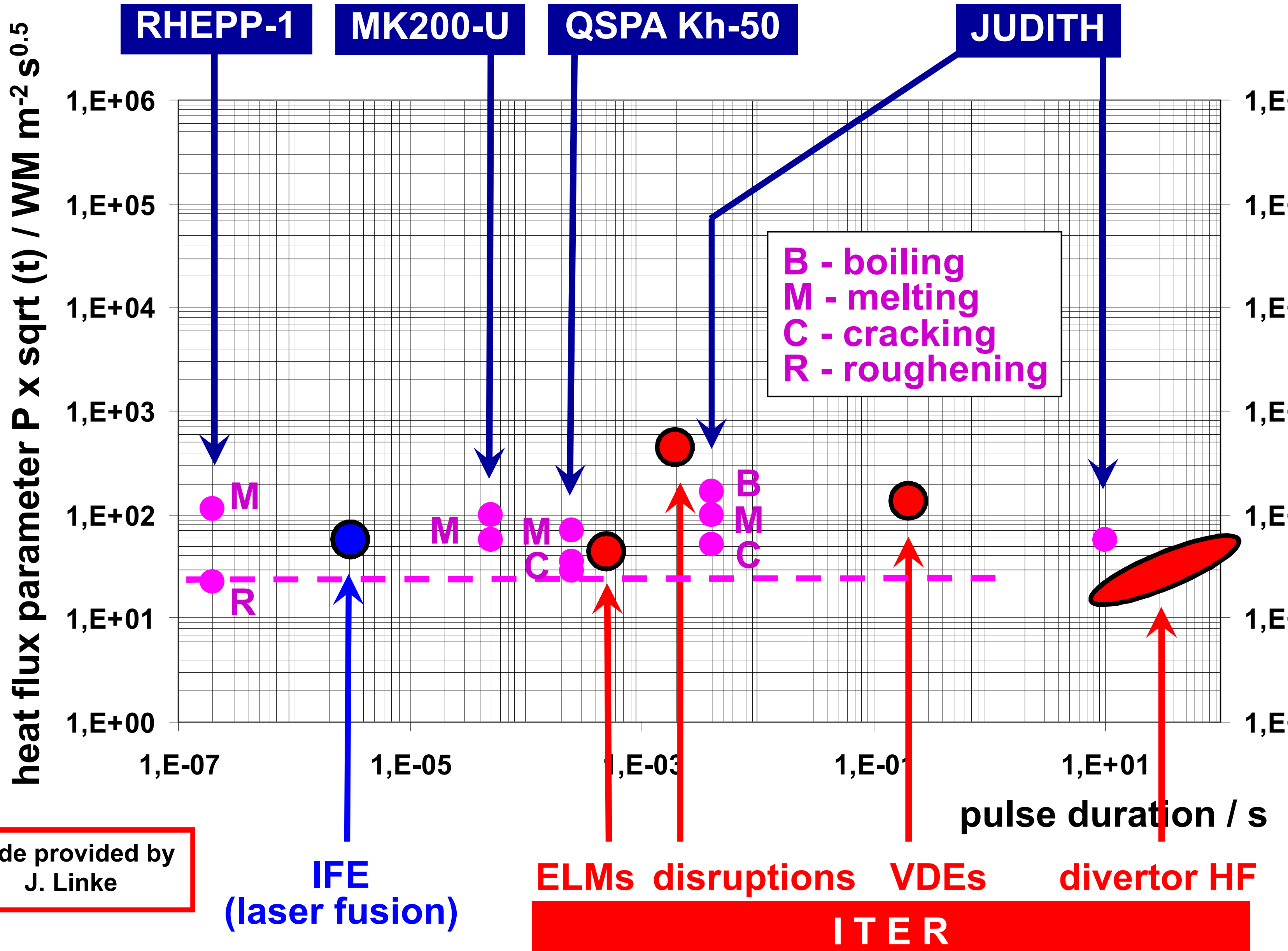
Simulation of short transient thermal loads



Slide provided by
J. Linke

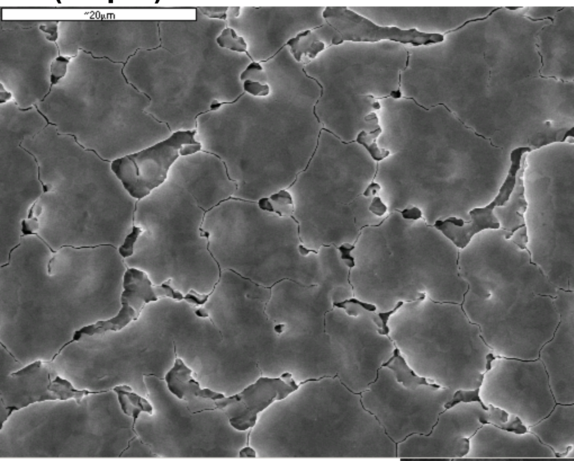
Performance of W under short transient thermal loads



Slide provided by J. Linke

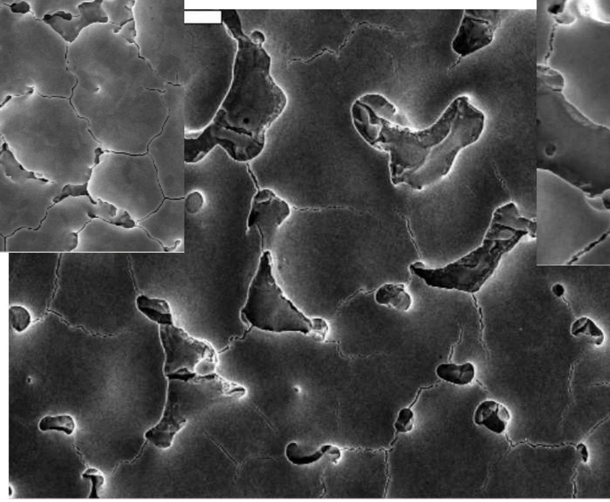
SEMs of lightly deformed PM Tungsten (non-melt): appears stress cracking starts, then exfoliation, forming 'valleys'

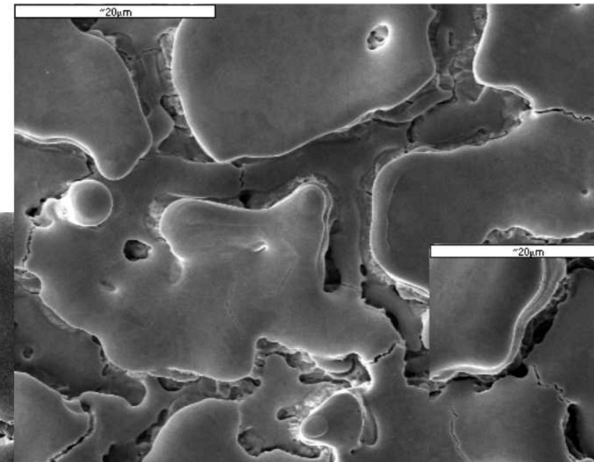
(20 μm)



400 pulses

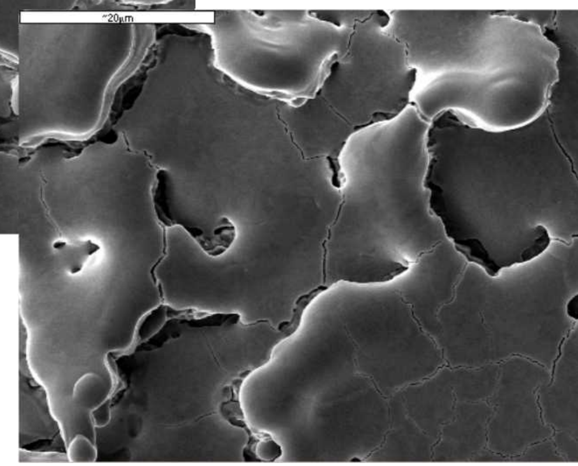
800 pulses





1200 pulses

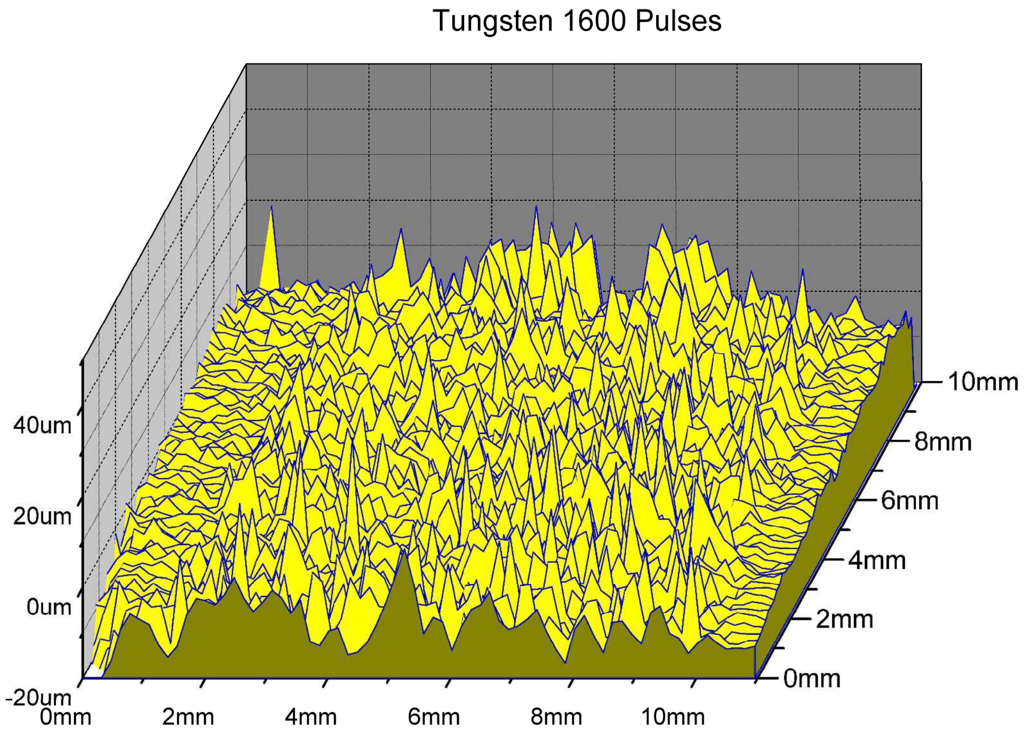
1600 pulses



All images 2000X

- Heated PM Tungsten (600C) exposed to Nitrogen beam at ~ 1.5 J/cm² - peak temp ~ 3300K
- Rounded 'knobs' are actually high points. **Surface rises during treatment.**

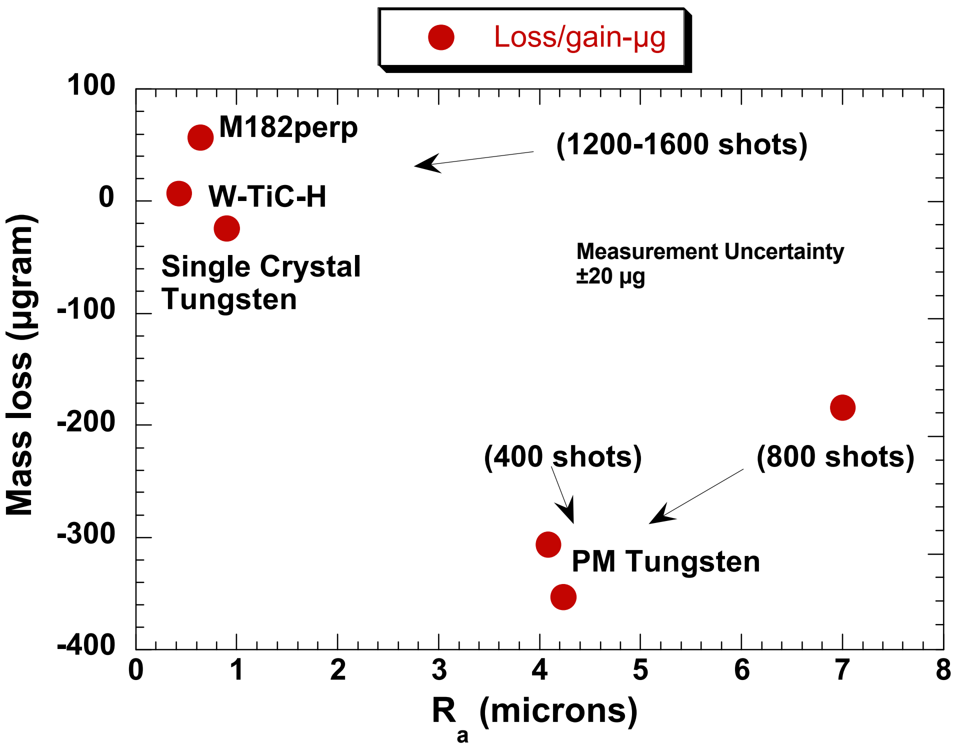
PM Tungsten after 1600 pulses (non-melting): Mostly mountains up to ~ 30 μm height



Cannot confirm mass loss by height study. Must weigh before/after exposure

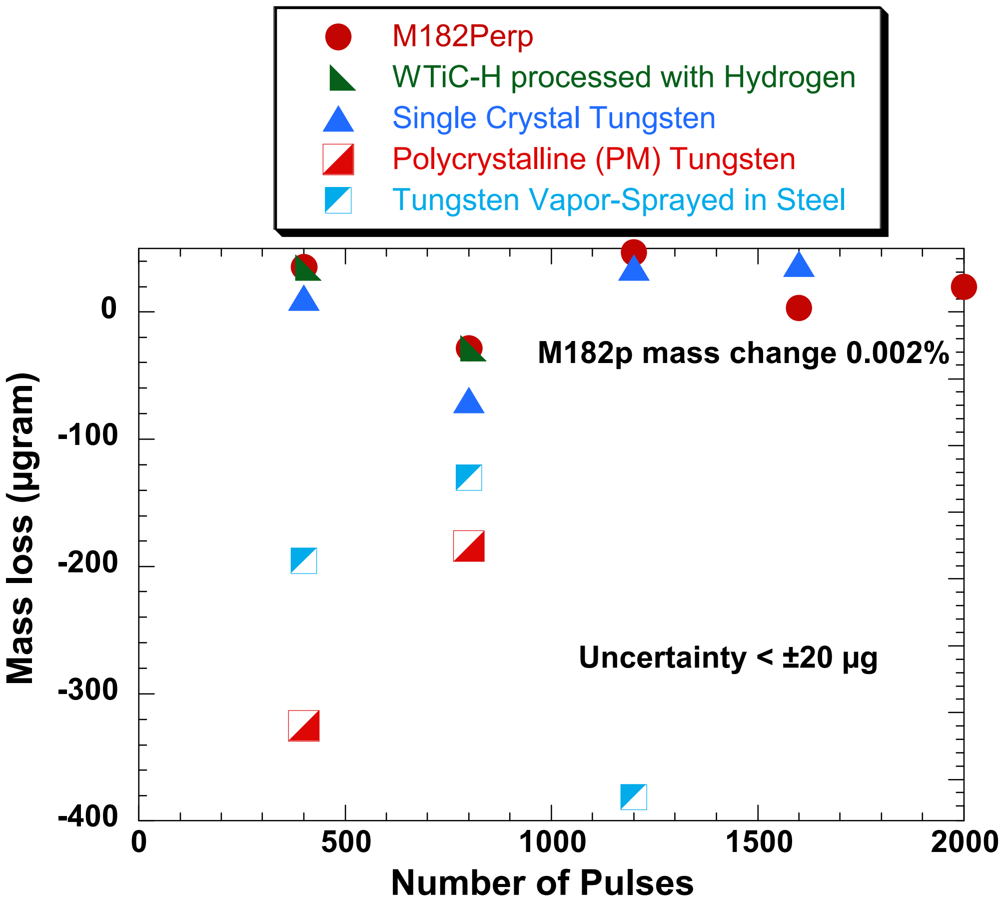
- **Heated/treated PM Tungsten examined with NEXIV laser interferometry**
- **Comprehensive line-out scan: max height 30 μm, min height < 10 μm compared to untreated**
- **Very deep microcracking not visible here**
- **Hypothesis: mountains are due to CTE expansion that does not recover**

Sandia Metrology weight measurements support connection between Roughening and Mass Loss



- Samples of each listed material exposed for multiple 400-shot series, and weighed pre-and post-shot
- Exposure level/pulse: 1.2 - 1.7 J/cm^2 Measurement Uncertainty < ± 20 µg
- Two samples of polycrystalline (PM) Tungsten lost ~350 µg in 400 pulses, with Ra ~ 4 µm; another 400 pulses produced even more roughening, -184 µm more mass loss
- M182Perp, W-TiC-H, and Single Crystal Tungsten remained < 1 µm Ra, and suffered little mass loss.

Mass Loss with Shot Number: M182Perp and Single Crystal W show almost no loss



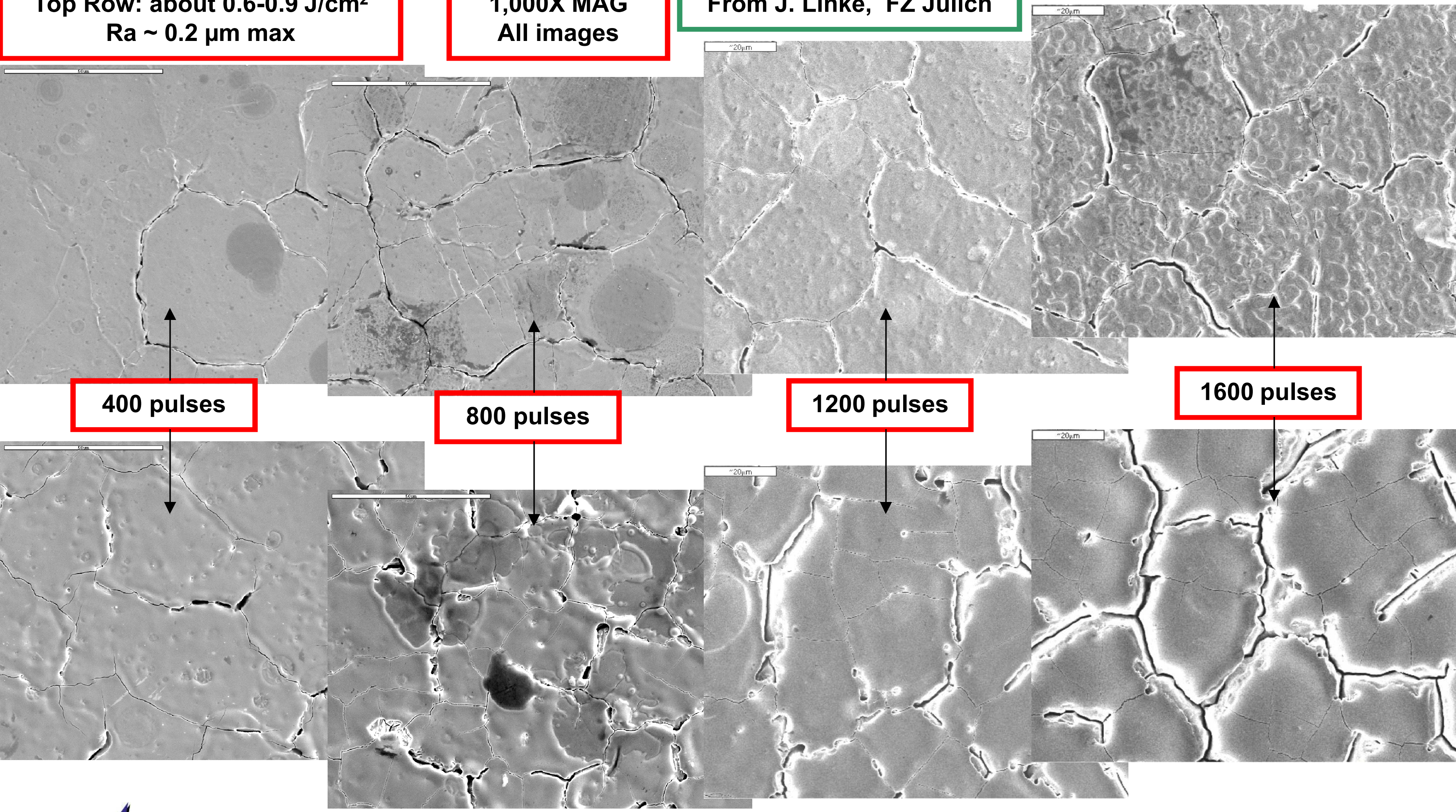
- **Mass loss for PM Tungsten terminated after 800 pulses - 350 and 184 µg loss on two 400 shot sets**
- **Vapor-Sprayed Tungsten (on Ferritic Steel) losses up to 400 µg per 400 pulses**
- **Mass Gain due to entrained material (Cu) from diode region**

SEMS of Tungsten M182 perp after 1600 pulses: Little topology change below 1 J/cm^2, some roughening w/ pulse number at ~ 1-1.5 J/cm^2

Top Row: about 0.6-0.9 J/cm^2
Ra ~ 0.2 μm max

1,000X MAG
All images

From J. Linke, FZ Julich



Bottom Row: ~ 1 - 1.5 J/cm^2
Ra ~ 0.35-0.45 μm

Little or no mass loss to 1600 pulses

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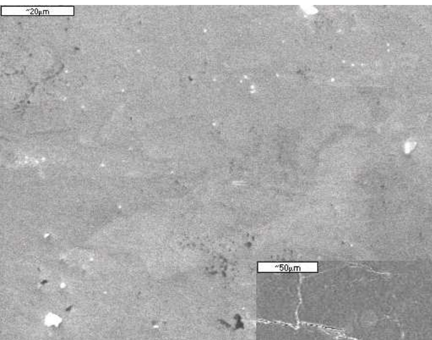
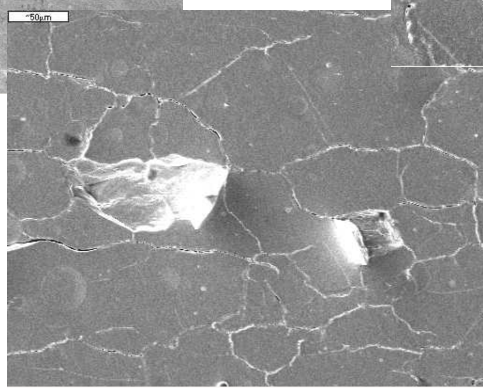
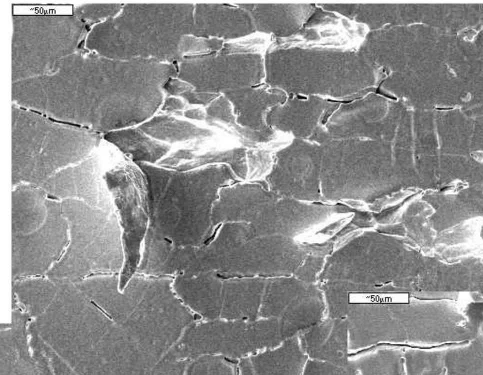
M182 Plansee Tungsten, cut with grains parallel to surface (SEMs): surface-lying grains become unzipped with increasing fluence

No Treat

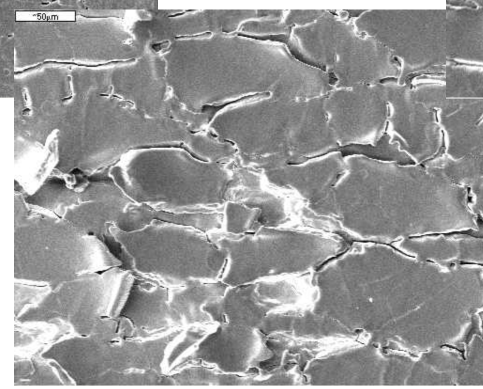


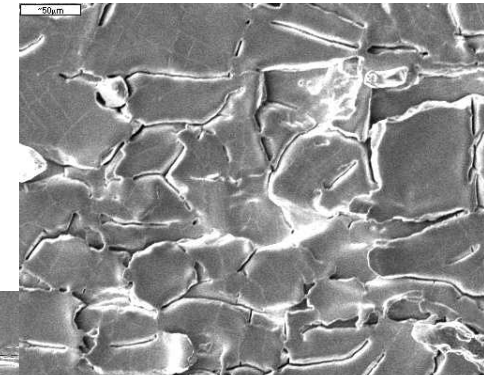
1,000X MAG





~ 0.7 J/cm^2





About 1.3 J/cm^2

All treated images 300X MAG.

R_a : reaches 4 - 4.5 µm at 1.3 J/cm^2 (same as PM Tungsten)
Only apparent AFTER 400 pulses (these images)

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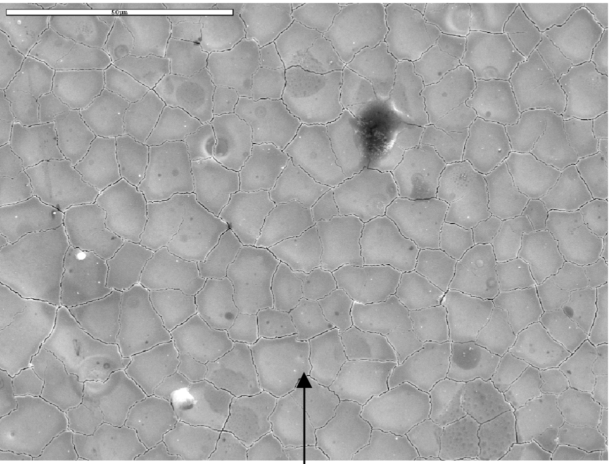
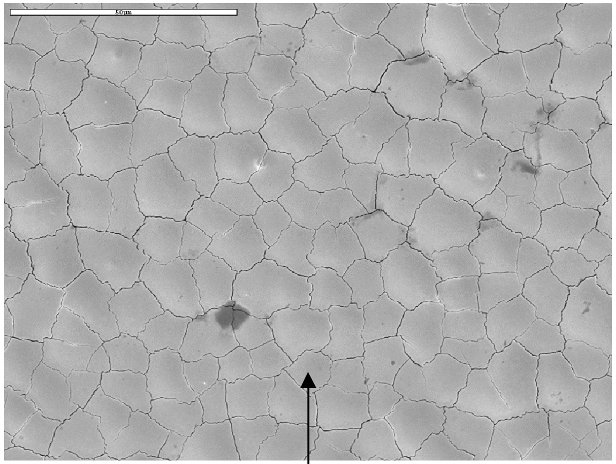
RHEPP-1 Ion Exposure

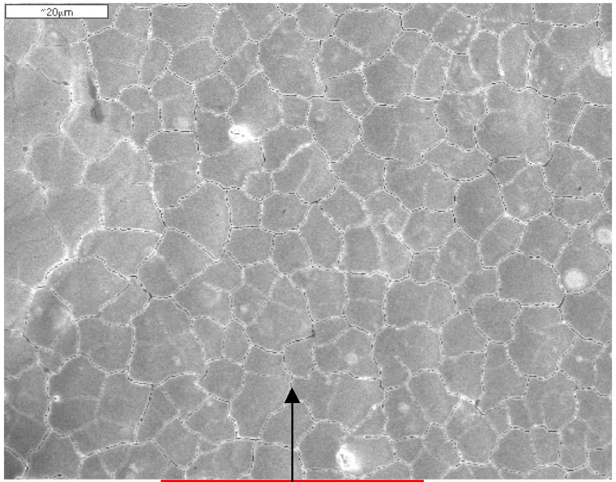
W-TiC-A ‘pre-stressed*’ 2.5 cm-wide sample (SEMs): (presumed) stress-relief seems to restrict grain corner exfoliation

Top Row~ 1.0 J/cm Ra ~ 0.16 μm

From H. Kurishita (Tohoku U.)



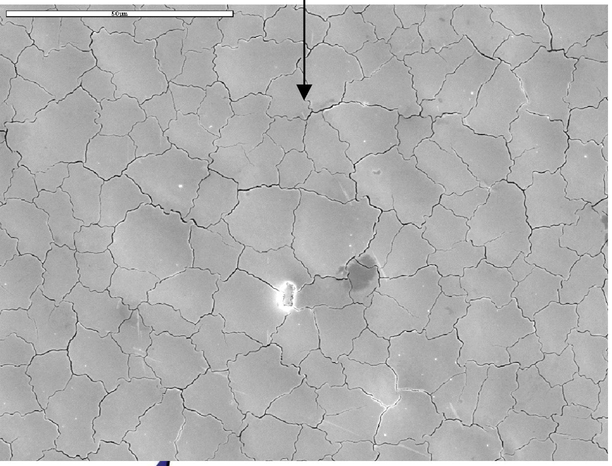


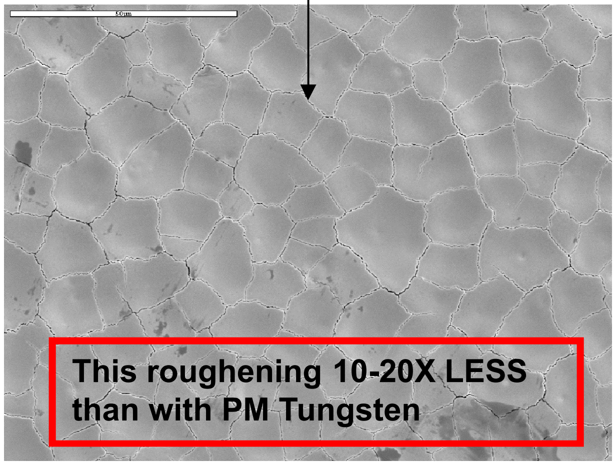


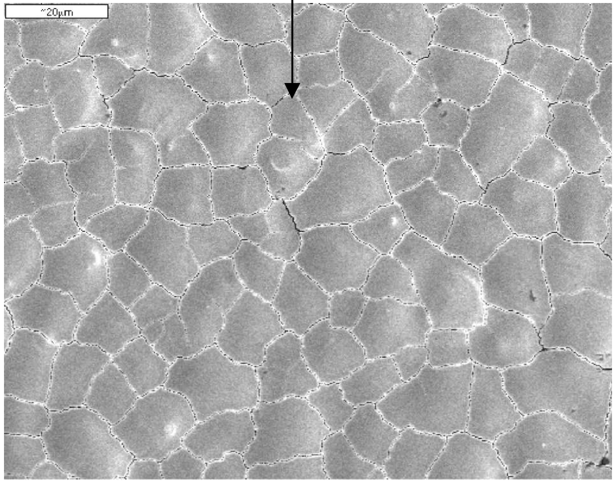
400pulses

800 pulses

1200 pulses







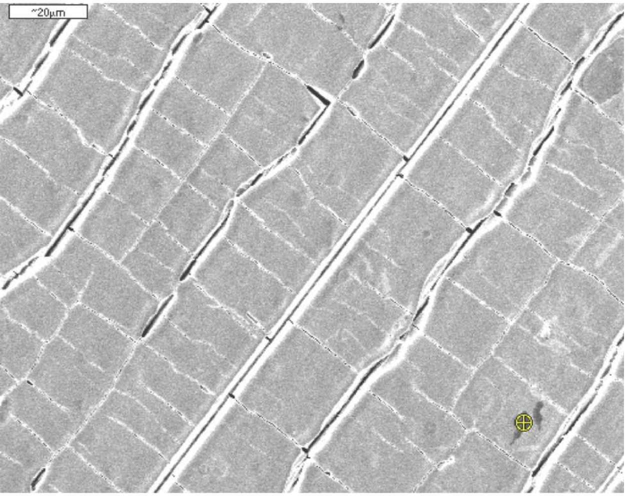
~ 1.4 J/cm^2

All images -
1,000X MAG

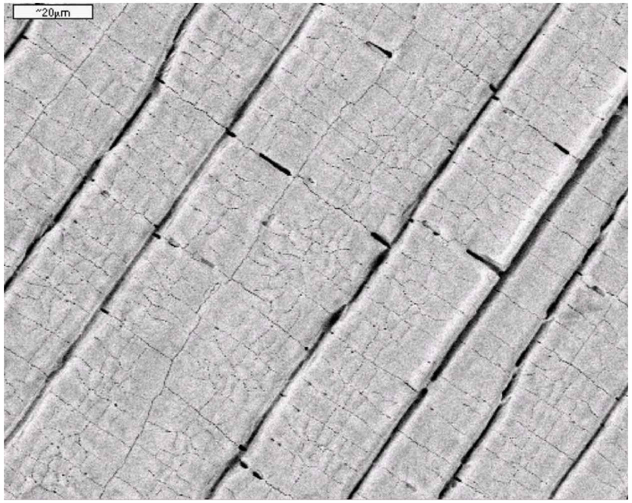
Right Two ~ 1.7 J/cm^2
Ra ~ 0.28 μm

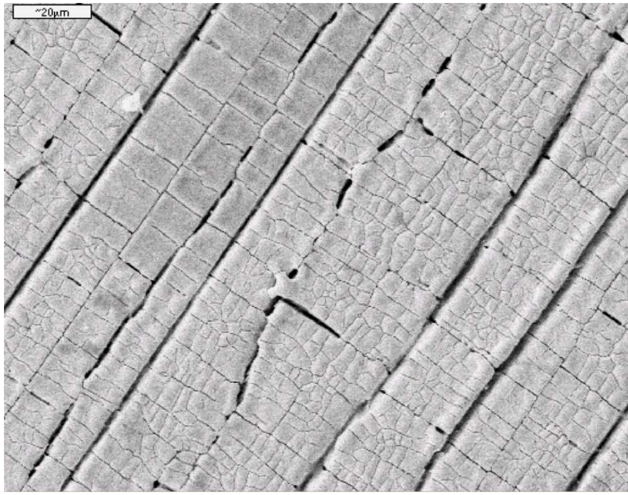
RHEPP-1 Surface Roughening

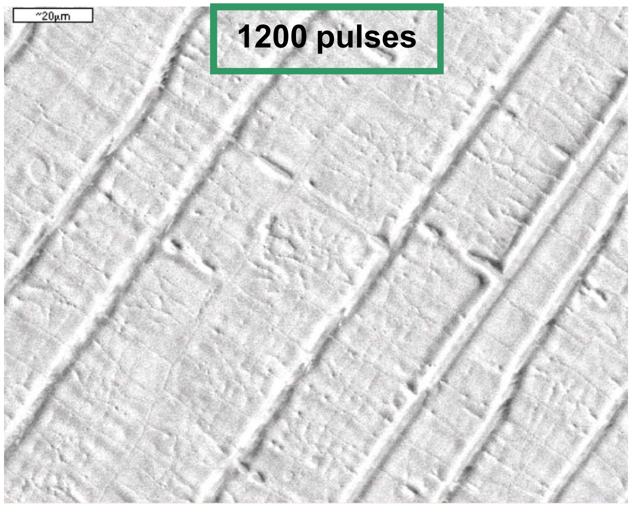
SEM, SingXtal RT, ~1.1 J/cm^2 : longitudinal cracks form, width stays constant, settling in between



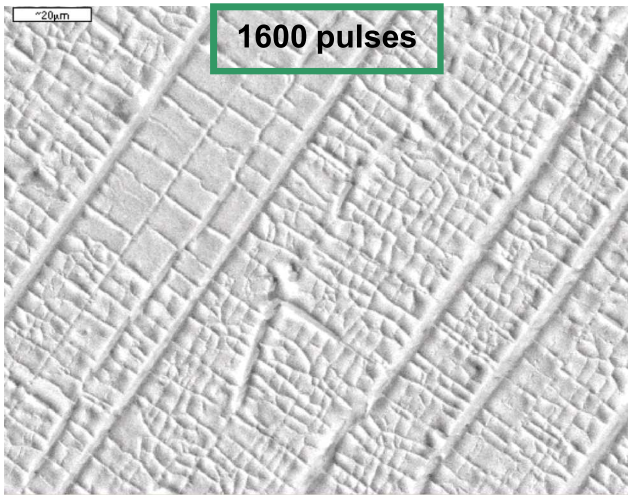
400 pulses







1200 pulses

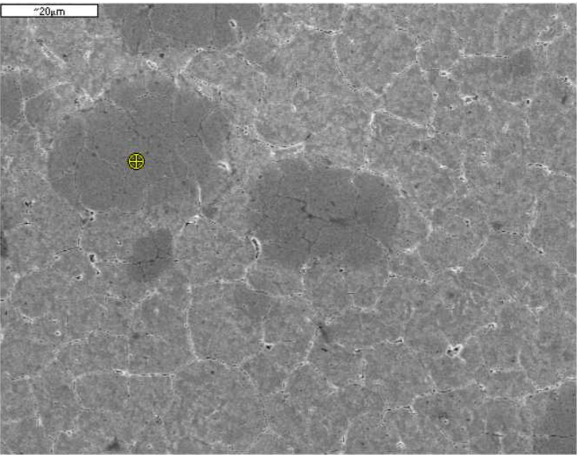


1600 pulses

BSE Images

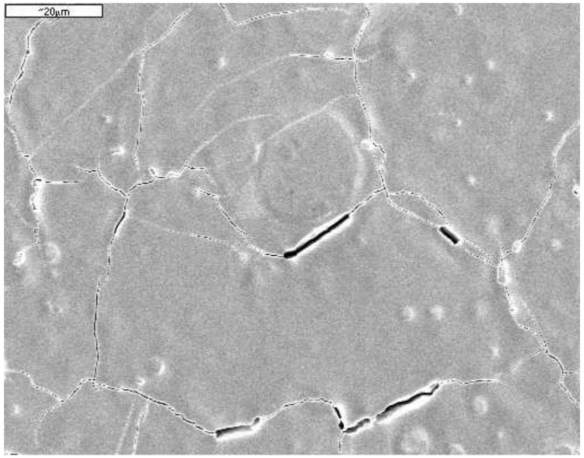
Three forms of Tungsten, treated at ~ same fluence (400 pulses): Grain-refinement/strengthening, or below-surface burial seem to restrict roughening/mass-loss.

1,000X MAG



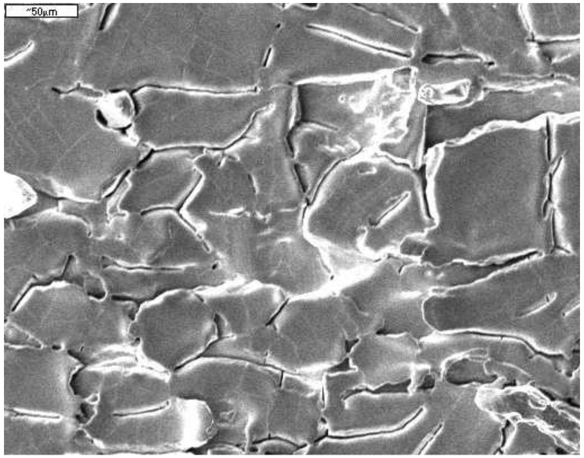
W-0.5%TiC 1.5 J/cm^2.
Ra = 0.04 µm

1,000X MAG



M182Perp ~ 1.25 - 1.5 J/cm^2
Ra ~ 0.15 µm

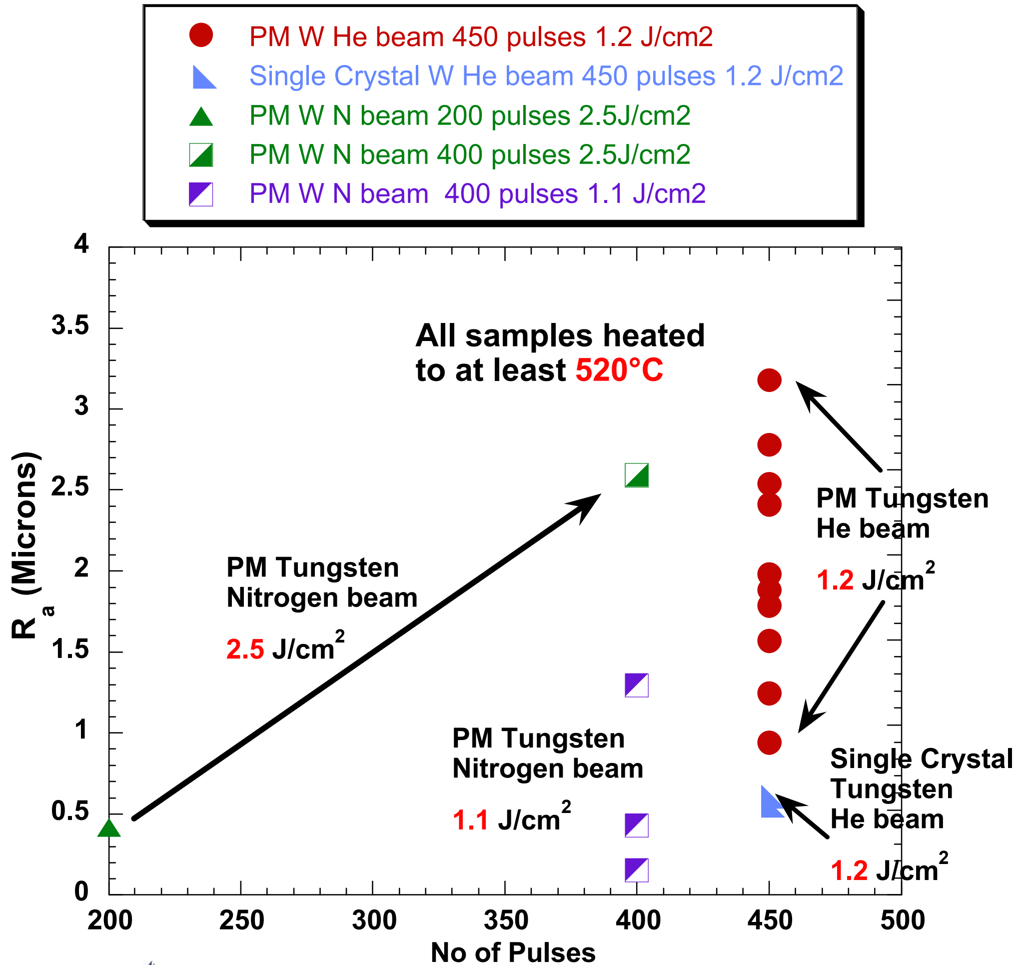
300X MAG



M182Parallel ~ 1.3 J/cm^2
Ra ~ 4.5 µm

Two on right are SAME material

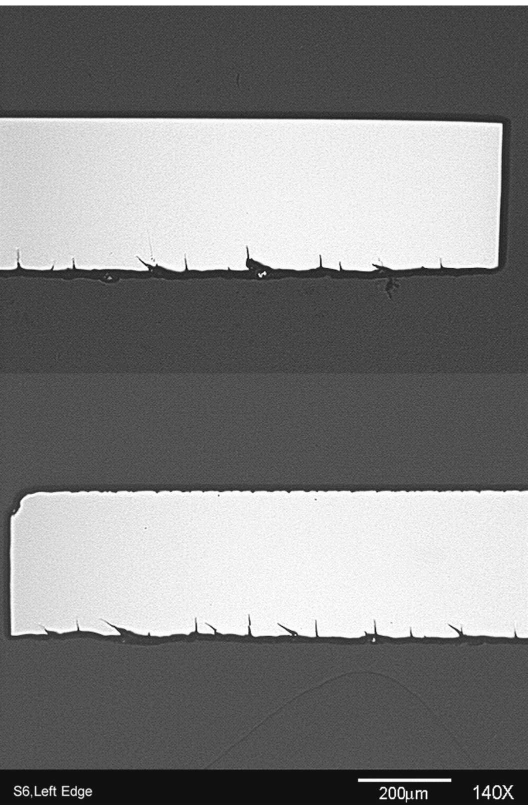
Comparison of R_a Roughness, PMW: He beam produces more roughening with the same fluence (~ 1.2 J/cm²)



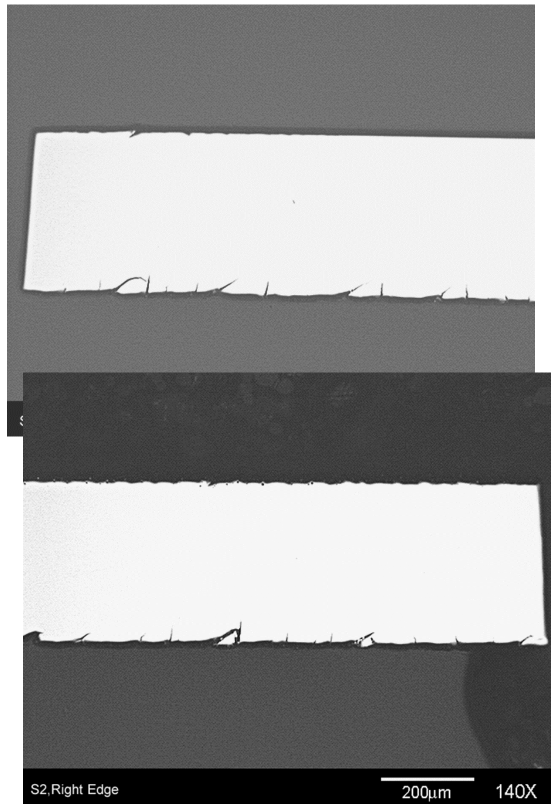
- Red Dots - PM W exposed to He beam, 1.2 J/cm², 450 pulses
- Purple Squares - PM W exposed to N beam, 400 pulses, 1.1 J/cm²
- He beam roughens PM W worse than N beam (note data scatter). Roughness similar to N beam at 2.5 J/cm² (above melt threshold)
- SingXtal W (pink triangles) shows much less roughening at 400 pulses

Single-Crystal Tungsten, 400 and 1600 pulses: No fatigue-cracking in-depth

1.2 J/cm² 400X Upper 1600X lower

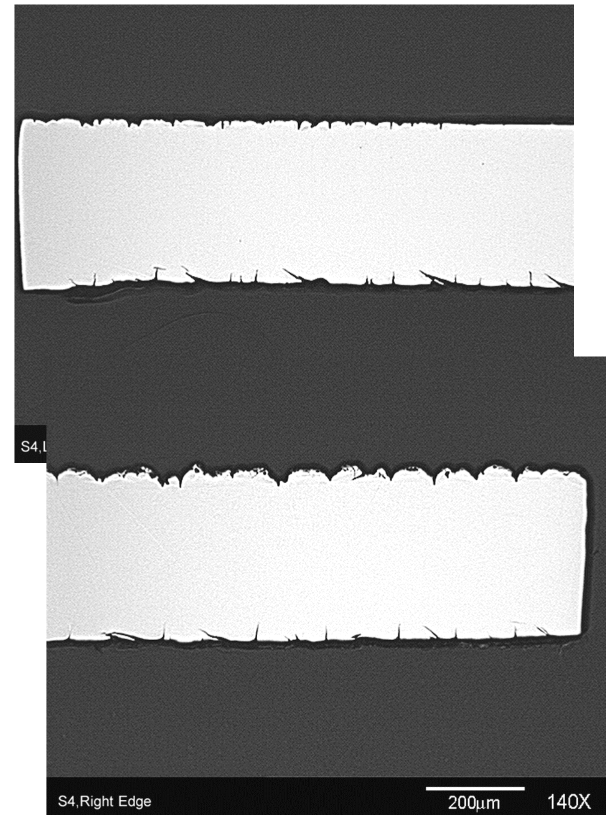


1.9 J/cm² 400 pulses



1600 pulses

3.5 J/cm² 400 pulses



1600 pulses

All 140X MAG

Top surface is treated in all cases

Cuts on bottom surface look like sample prep

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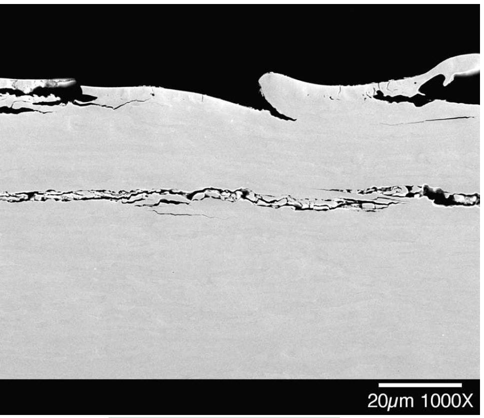
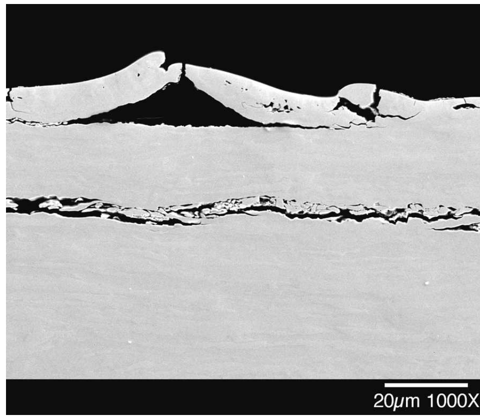
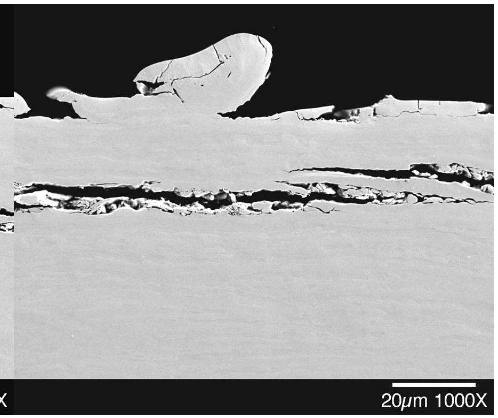
RHEPP-1 Surface Roughening

PM Tungsten, 1.9 J/cm^2 RT, sectioned SEMs (near Melt): Large distortions in near-surface zone



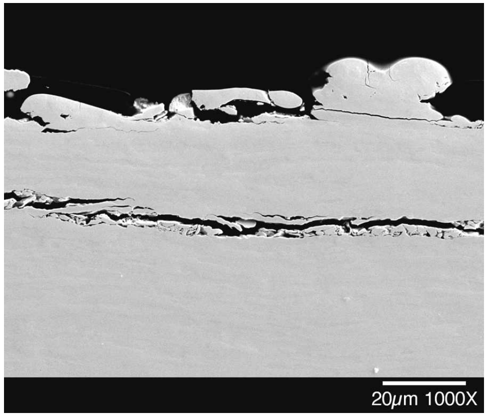


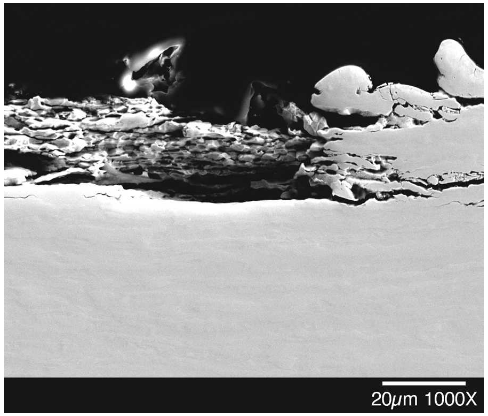


- Wholesale failure down to 20 μm level in last image

400 pulses

Increasing pulse number →





All images BEI 1000X MAG

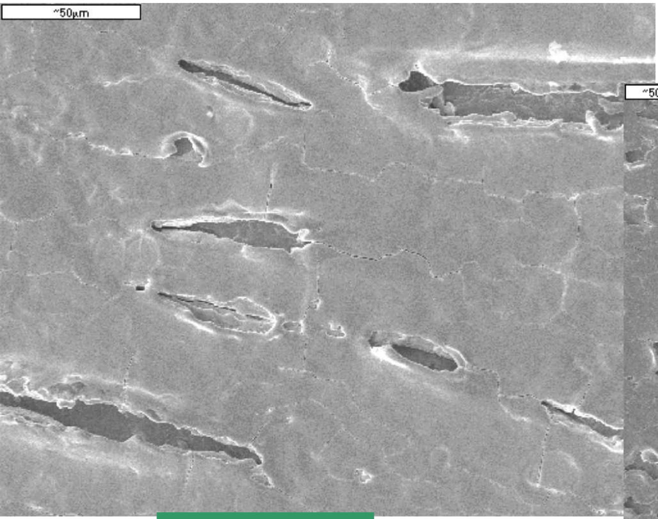
→

1600 pulses

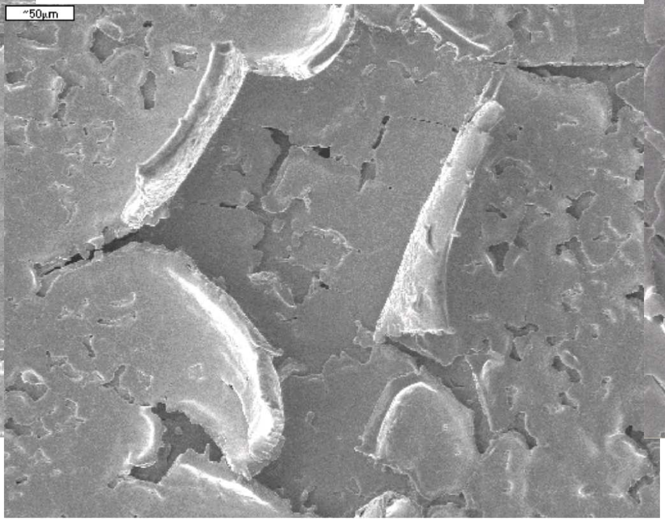
Pulsed Power Sciences, Sandia National Laboratories
TJR 04/16/2004

M Tungsten exposed to Nitrogen (top) and Neon (bottom): Surface remains intact with Ne, no mass loss

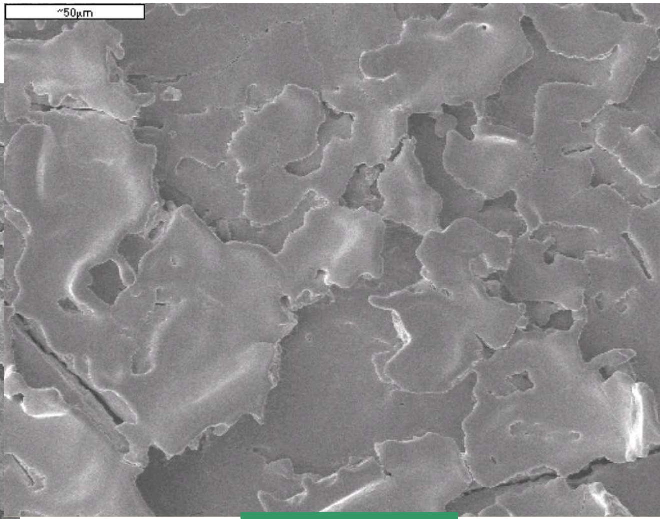
Top: Nitrogen



< 1.2 J/cm²



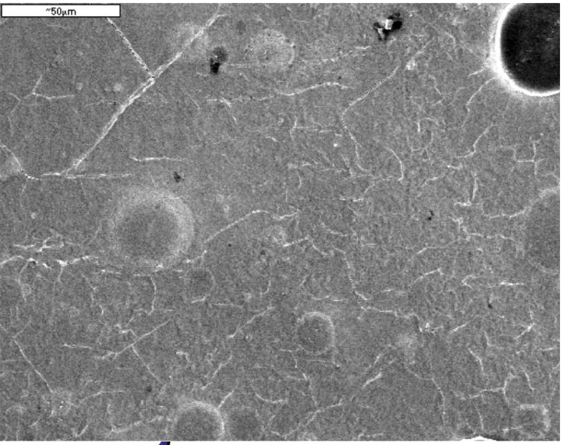
~ 1.2 J/cm²

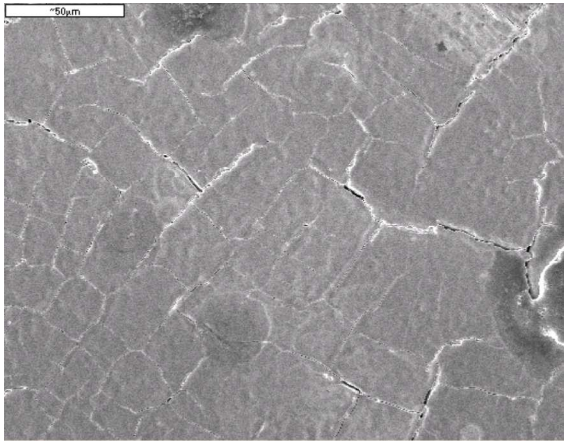


> 1.2 J/cm²

All images 500X Mag except above (250X)

Bottom: Neon





500X Mag

Mass loss: N -306.1 µg, Ne +167.4 µg
(gain due to entrained Cu)

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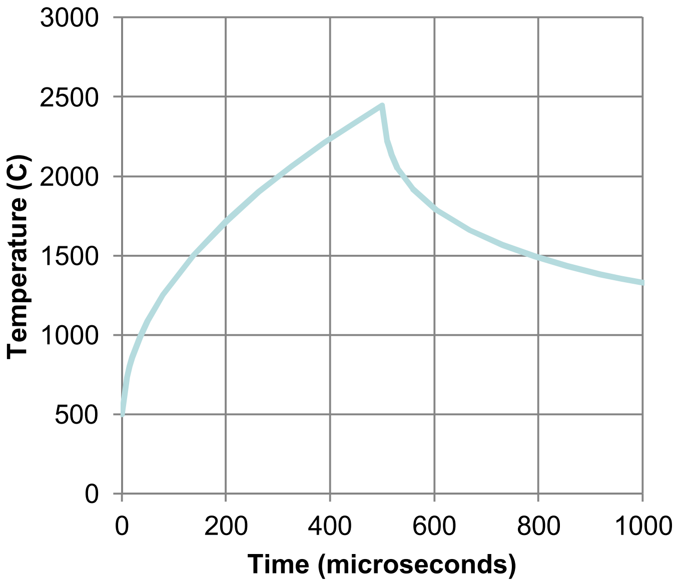
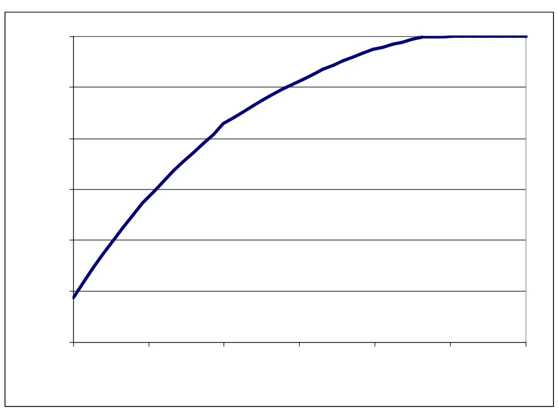
Fracture Modeling: Comparison of Tungsten exposed to IFE and MFE ELM Conditions





- 3 mm Tungsten on ferritic steel exposed to single heat pulse.

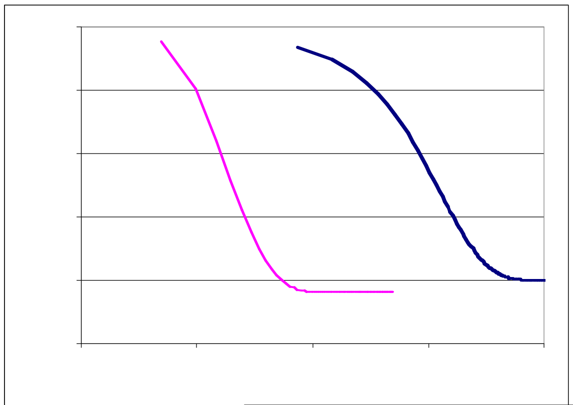
Fluence: 0.7 MJ/m^2 over 500 µsec.
$T_{initial}$ = 500C, Tungsten properties from ITER Material Properties Handbook.

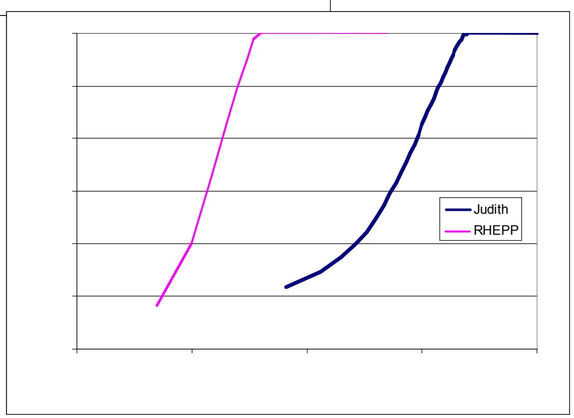
- Heat deposited at surface

- (Top Left): Surface temp reaches ~2500C

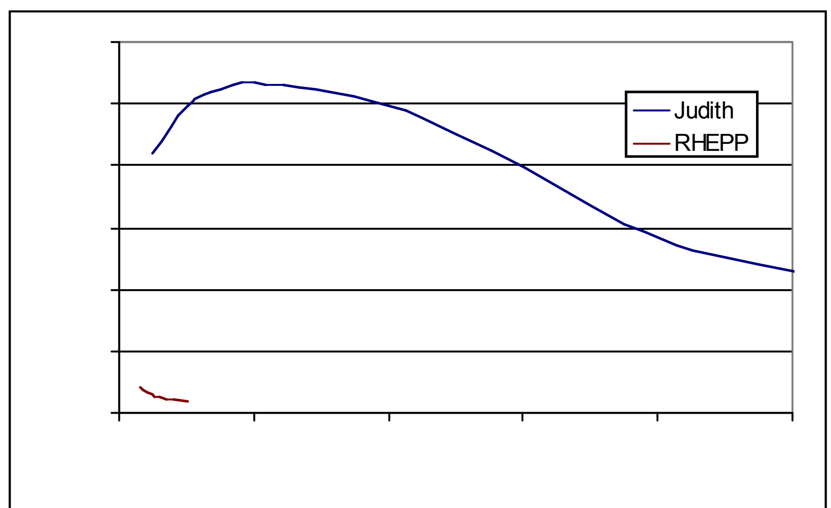
- (Bottom Left): Plastic Strain reaches 1%, gradient to >250 µm depth

Unlike RHEPP heating, the ELM-like pulse produces fracture stresses at the fatigue crack threshold after one pulse





- (Top Left) RHEPP pulses with fluence chosen to reach same surface maximum temperature - 2500C
- (Mid Left) Plastic Strain Curves: Both effects MUCH deeper for the ELM case
- Bottom: Stress Intensity for the ‘ELM’ case at 25 MPA-m$^{0.5}$ - at fatigue cracking threshold for tungsten (20-40 MPA-m$^{0.5}$). RHEPP at ~ 2 MPA-m$^{0.5}$
- This could explain why RHEPP thermomechanical effects take hundreds of pulses to develop.



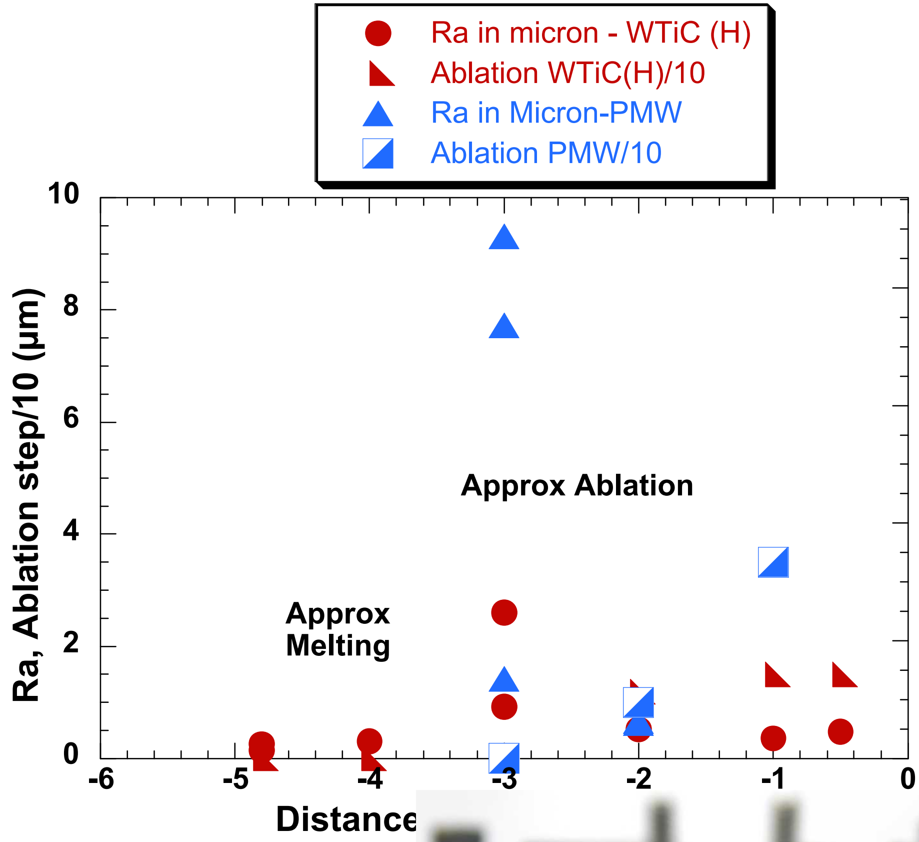
What if we allow the surface to melt? Will this smooth it out? Higher Fluence Test

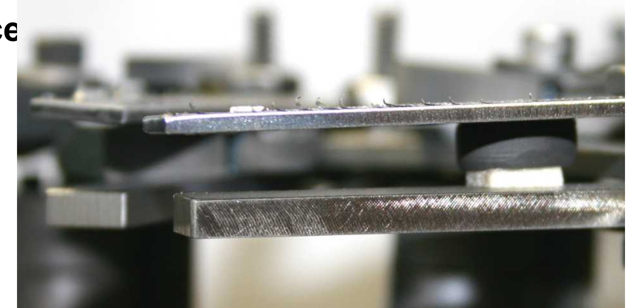
Samples mounted before Start
Beam Center off to Right

Nitrogen beam

- Samples mounted at Left:
  - M182Perp
  - W-0.5%TiC-Argon (Kurishita)
  - W-0.5%TiC-Hydrogen (Kurishita)
  - W25%Re
  - PM Tungsten
  - Single Crystal W
  - Mo
  - Nb
  - Cu 3 9s
  - Cu 5 9s
- ‘Normal’ exposure towards Left. Beam center at right (up to 10 J/cm^2)
- PM Tungsten strips used to mask samples
- Vacuum ~ 1e-5 Torr

Roughening behavior of W-0.5%TiC(H), PM W at high fluence: R_a highest at ablation onset. Melting leads to increased roughness

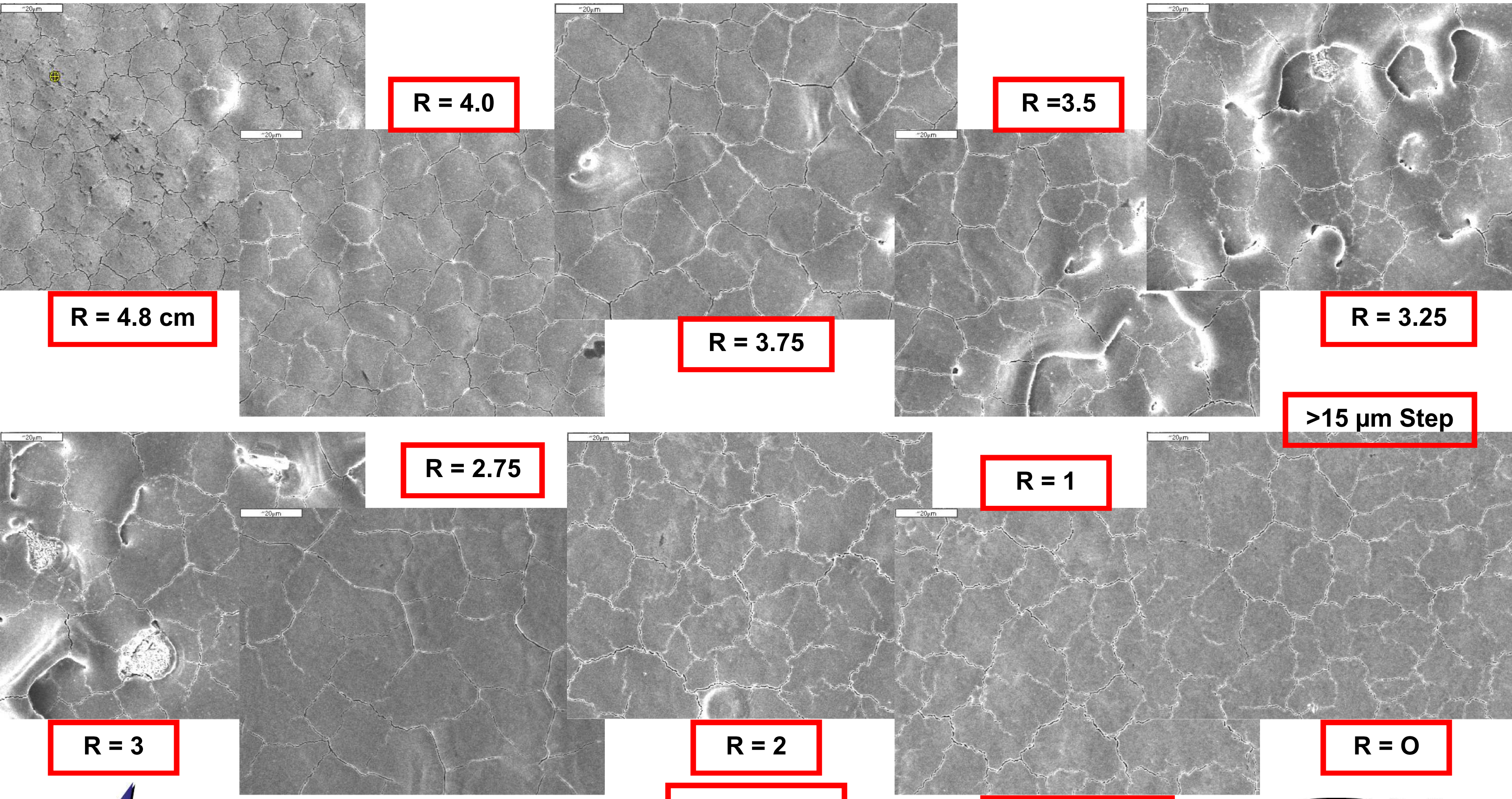




- Two each W-0.5%TiC (H) and PM Tungsten (Snead) samples exposed in fluence range from melting to above ablation threshold (per pulse).
- Sample melt leads to much higher roughness (R_a reaches 2.5 µm for WTiC, 9.5 µm for PM W)
- Roughness reduced beyond ablation threshold, but 15 µm (WTiC) to > 35 µm (PMW) material removed after 400 pulses
- Similar behavior for Mo, Cu, Nb. Ablation steps exceeding 35 µm observed (> 900Å/pulse removed)
- BIG surprise: W25Re. Hardly ANY roughening.
- (LEFT): 'fingers' protruding from W shield

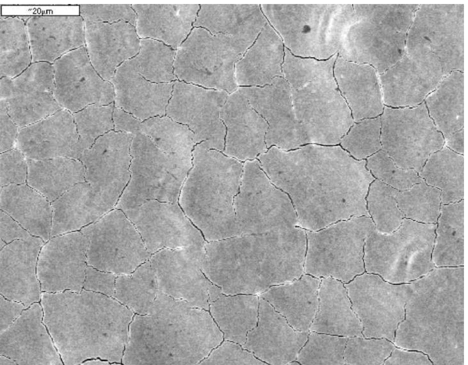
Nitrogen Beam

SEMs, W0.5%TiC (H), S4.8 to BEAM CENTER: Same roughness at both extremes, 15 µm Step at R = 1 cm (400 pulses)



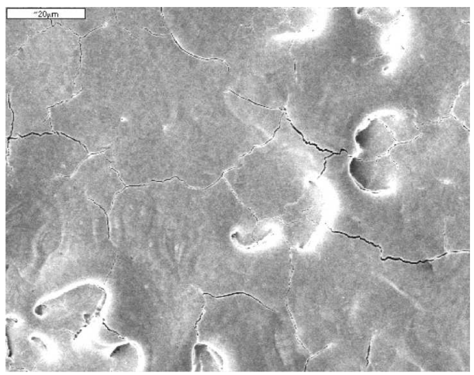
1000X Mag All Images

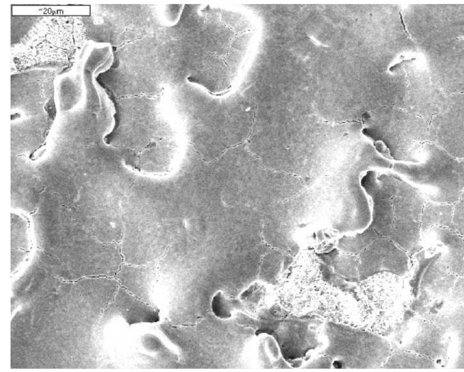
SEMs, W0.5%TiC - Argon:
More brittle destruction evident compared to WTiC (H)



R = 5 cm

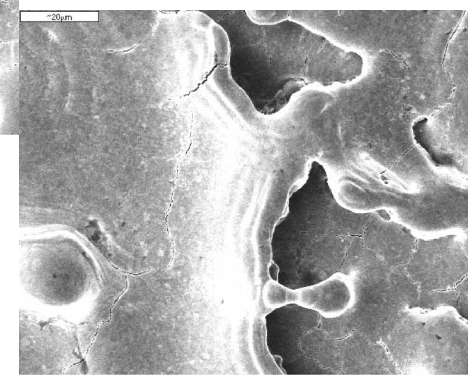
R = 4.5





R =4.25

R = 3.5

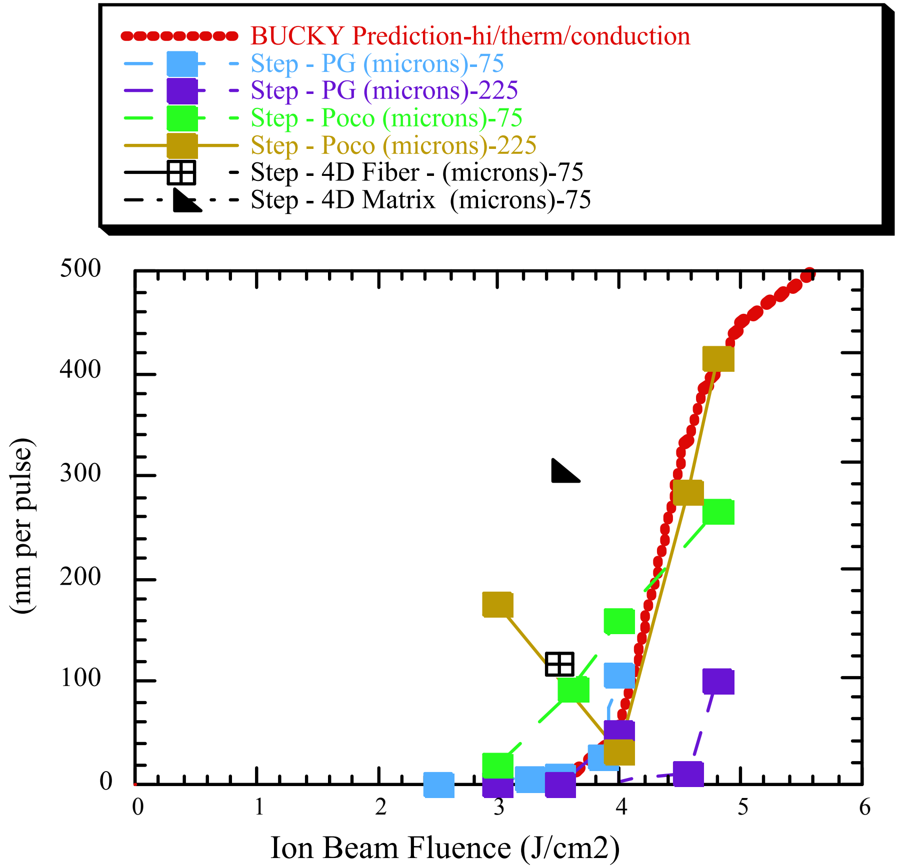


~ 2 μm Step

1000X Mag All Images

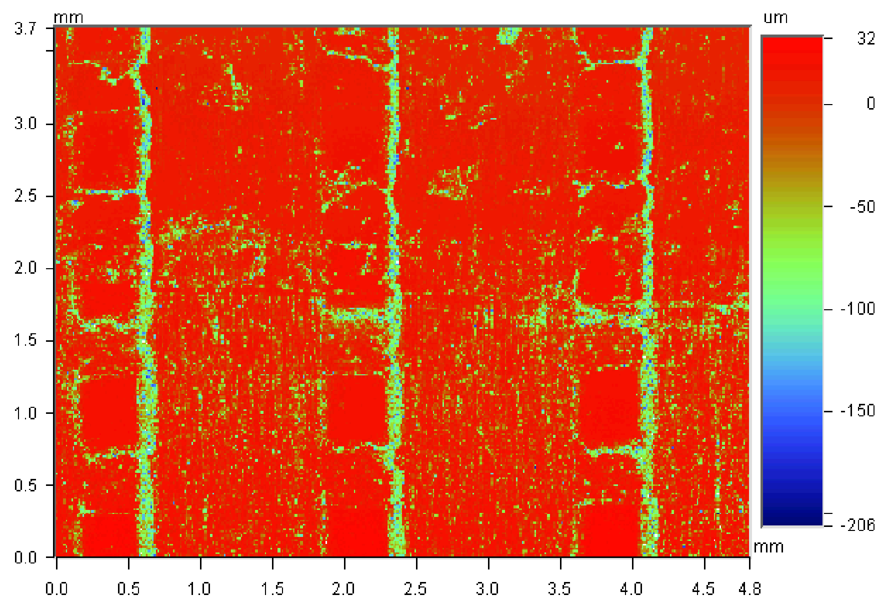
Carbon Materials

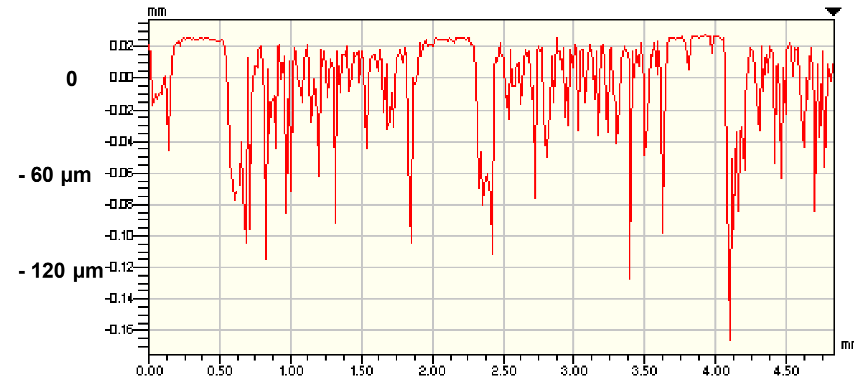
Early exposures with H - C beam qualitatively confirms BUCKY predictions of 3.5 J/cm^2 ablation onset



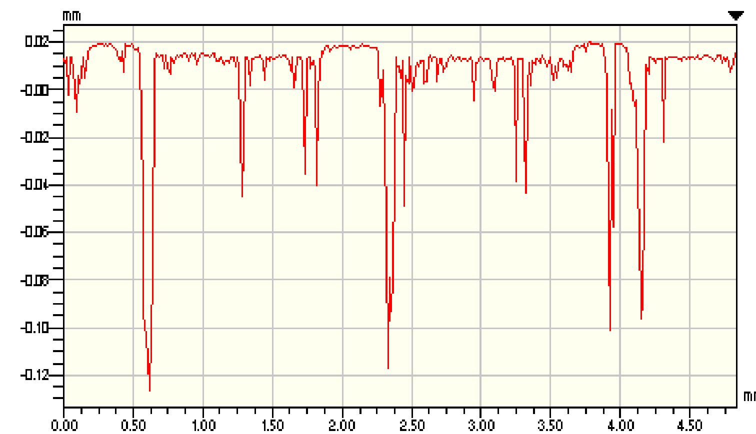
- **Mechanically polished pyrolitic graphite (PG), POCO, and 4D carbon composite weave exposed to 75 pulses/225 pulses of 70% C /30% H beam at doses of 1.9 to 5 J/cm^2**
- **PG ablation threshold ~ 4 J/cm^2**
- **Poco ablation threshold ~ 3 J/cm^2**
- **Above threshold, rapid increase in ablated material 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 1000 pulses at 1.6 J/cm^2: Significant erosion of matrix





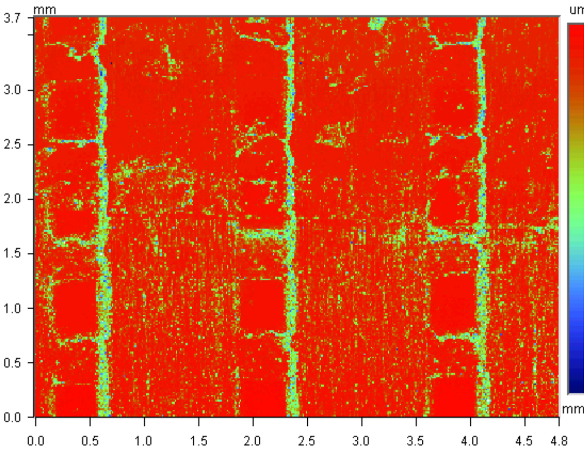
Treated at 1.6 J/cm^2

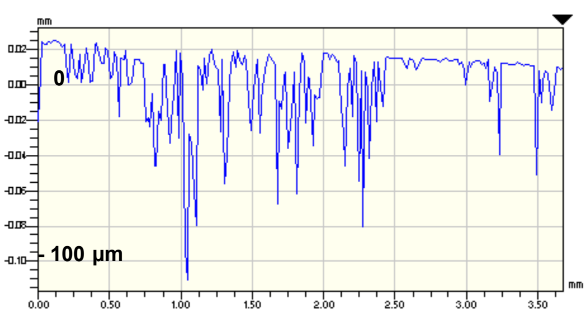


Untreated

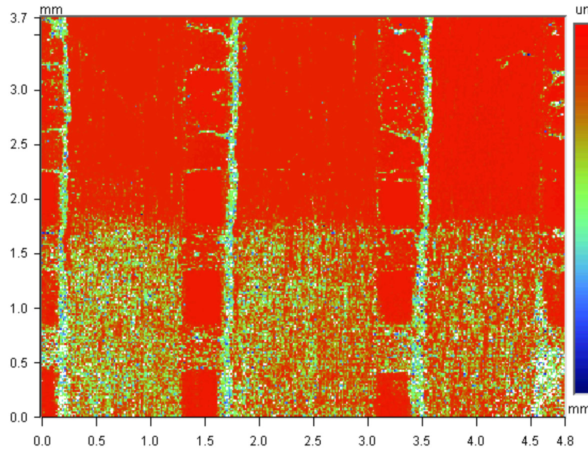
FMI-222 Fiber ends appear ablation-resistant; Matrix loss ~ 0.3 µm/pulse at 4.0 J/cm^2:

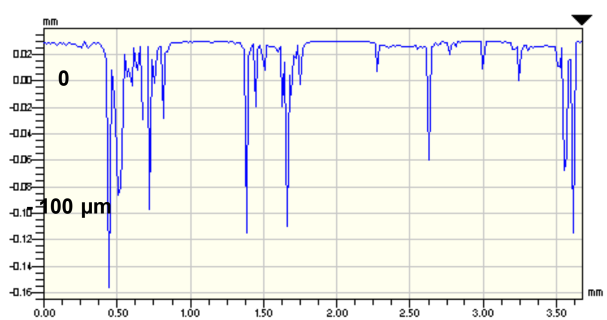
Treated at 1.6 J/cm^2 1000 pulses



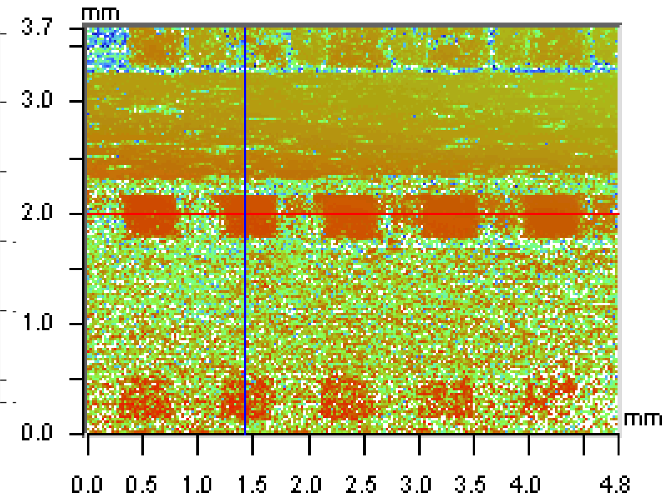


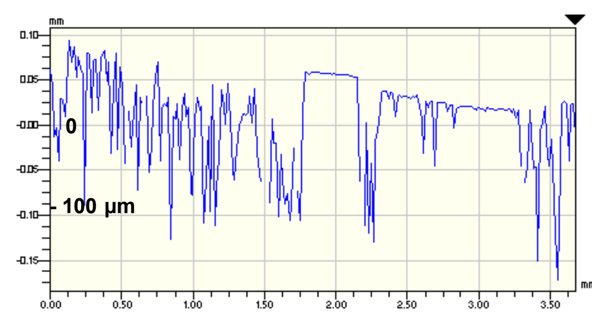
Treated at 2.6 J/cm^2 600 pulses





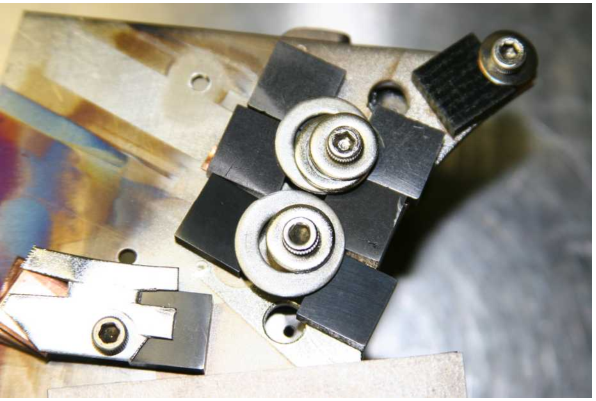
Treated at 4.0 J/cm^2 600 pulses

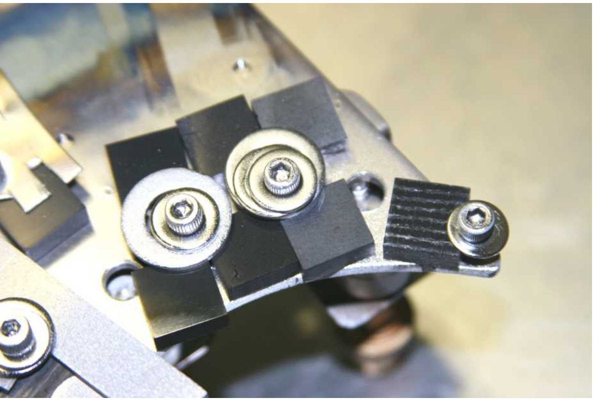




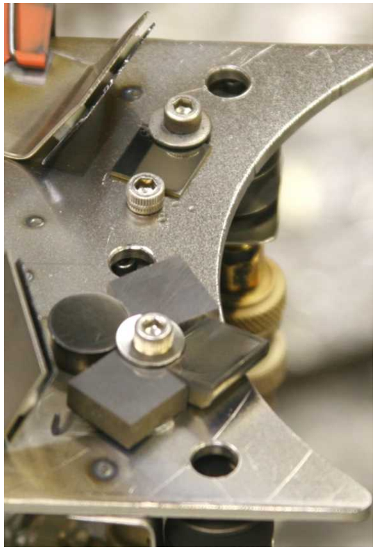
Several carbon samples from Juelich exposed to 400 pulses @ 1-1.25 J/cm2: All lose less mass than PM tungsten

Samples mounted (3, HI and LO) before Start, Beam Center off to Right



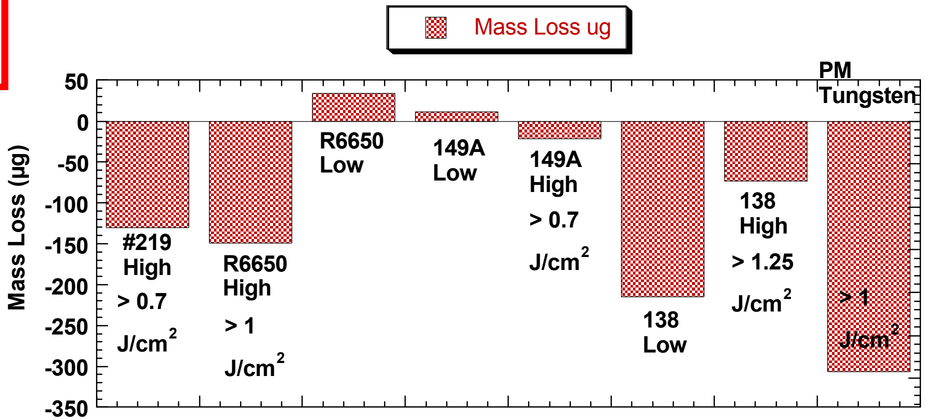


(Above) After 400 shots



(Above) REFERENCE PM Tungsten between screws

- Several C samples exposed at HI (above) PM W 1 J/cm² level, and LO (below), as per picture at left.
- Samples:
  - 219 - CFC, PITCH/PAN fibers, HI only
  - R6650 - isotopic fine grain graphite
  - 149A - Ti-doped RGTi from Russia
  - 138 - unidirectional perp CFC (MFC1) from Japan
- All these lost LESS mass at LO and HI than PM W after 400 pulses (below)
- Mass GAIN below due to Cu contamination due to Beam. Not known why 138 HI lost less mass than 138 Lo.



MAP Nitrogen

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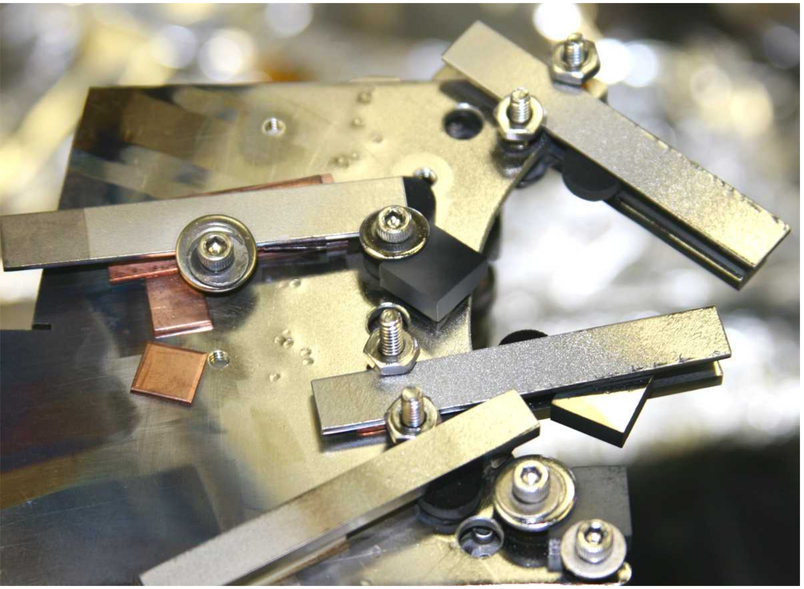
Higher Fluence exposure of Juelich Carbons: Beyond 1.3 J/cm² fluence/pulse leads to significant mass loss



Samples mounted for higher fluence compared to C400 (Below). Tungsten shields extend towards beam center (right)

Earlier C400 Series (from Previous Slide)

- **Samples:**
  - R6650 Repeat at 1.3 - 1.5 J/cm²
  - Pyrolytic Graphite cut perpendicular to C-Planes: 2 - 4 J/cm²
  - 149A - Repeat at 1.5 - 2 J/cm²
- **Results:**
  - R6650 roughened from 0.18 to 3 µm, 2 µm step even at 1.3 J/cm² (50Å ablative loss/pulse)
  - Pyrolytic: almost 4 µm step at 2 J/cm², beyond measurement ability at 4 J/cm²
  - 149A: roughened from 0.15 to 0.6 µm, mass loss likely but not confirmed

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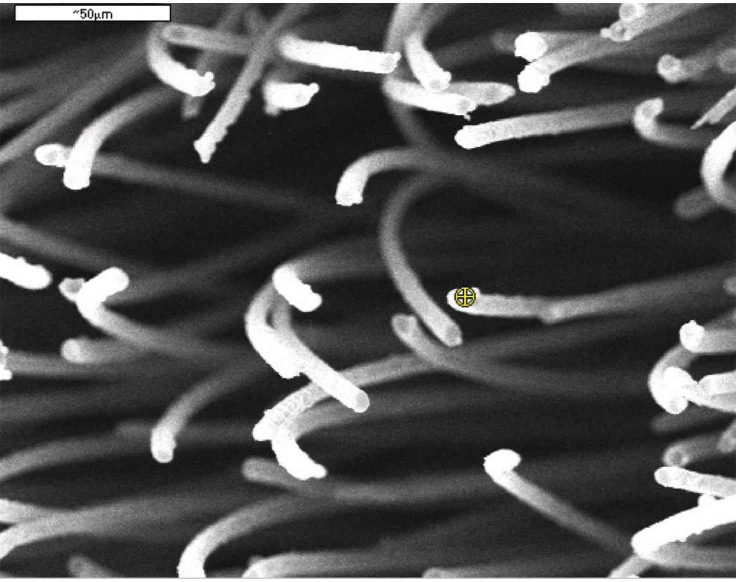
RHEPP-1 Surface Roughening

Tungsten-coated Carbon Velvet survives 1600 pulses amazingly well

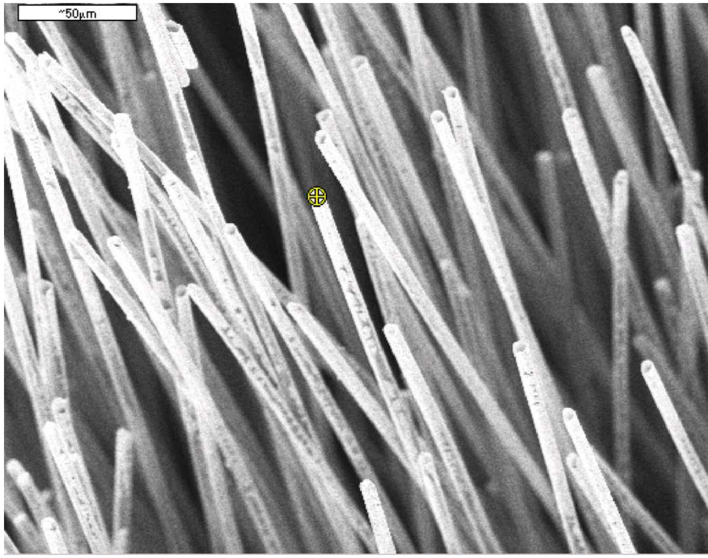
From T. Knowles, ESLI

Carbon PAN fibers w/ 1.6 µm W coating, 2% areal coverage



(RIGHT)
520C (nominal), 1600 pulses, 1.5 J/cm²/pulse

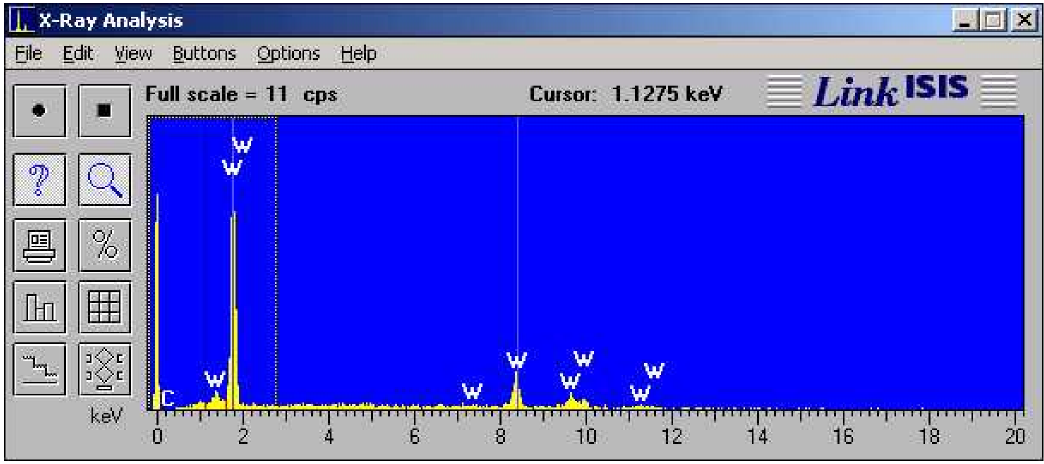
NOTE: W remaining on tips (see below) and sides



(ABOVE)
RT @ ~ 2.8 J/cm², 1600 pulses

NOTE: bent tips, flat ends have W removed, rounded ends still have W

This reinforces recent JUDITH result: Mechanical strength of PAN fibers may more than make up for their lower Thermal Conductivity compared to PITCH



EDS scan of tip (cross): W rich

Exposure Results Summary_1

- Tungsten:
  - Surface roughens due to thermomechanical stress, occurs BELOW the melt point. Relief develops over hundreds of pulses. Heating to 500C, i.e. above the DBTT, delays but does not stop this process.
  - Roughening Threshold for multi-pulse exposure ~ 1 - 1.2 J/cm^2 - corresponds to ~ 1400 - 1700C maximum surface temperature.
  - Grain size and orientation very important. Worst form is polycrystalline lightly-deformed, - develops high relief (5+ µm R_a, up to 100 µm P-V). This relief is linked to confirmed mass loss.
  - Deformed tungsten with grains perpendicular to surface (M182) suffers much less roughening, as does W-25Re alloy (not shown).
  - W-0.5%TiC (Kurishita) - fine grain Tungsten shows robust survivability, low roughening. Processing with Hydrogen seems to improve grain boundary strength compared to Argon, as predicted.

Exposure Results Summary_2

- Graphite:
  - Some forms of graphite, e.g. R6650, MFC-1, 149A, show little/no mass loss at 1 J/cm^2, I.e. at higher than roughening threshold for tungsten. This corresponds to surface temperature of 1800K, according to 1-D BUCKY modeling of high-thermal conductivity graphite.
  - Above this point, however, ablation/sublimation result in significant roughening and rapid mass loss.
  - These values are WELL below BUCKY modeling of sublimation threshold for high-conductivity graphite, - 3.5 J/cm^2.
- 'Engineered' surfaces like 'Velvet' may represent the best solution for surface survivability. Robust PAN fiber survivability consistent with recent JUDITH findings that use of PAN limits brittle destruction see in PITCH fibers.
- Fracture Modeling indicates 1) single RHEPP pulses are well below threshold for Tungsten surface cracking, and 2) single ELM-like pulses produce much deeper strain and are at or near the Tungsten fracture threshold

Future Work

- No Dry-wall solution yet for full-exposure condition, although some promising materials (M182p, W-coated Velvet, W25%Re). Cusp - configuration could allow SiC for Main Wall, replaceable materials at ion dump (equator)
- Although PM Tungsten roughening reaches saturation, no other form of tungsten has shown similar behavior. So we may not be able to show ultimate survivability in RHEPP experiments.
- Need to include He entrainment, possibly neutron effects, in same sample set
- Need to study diffusion of contaminants into wall materials. Auger measurements show C diffusion into 520° C heated tungsten deep into near-surface region (tens of microns)