IFE First-Wall Materials Response to Repeated High-Energy Pulsed Ions*

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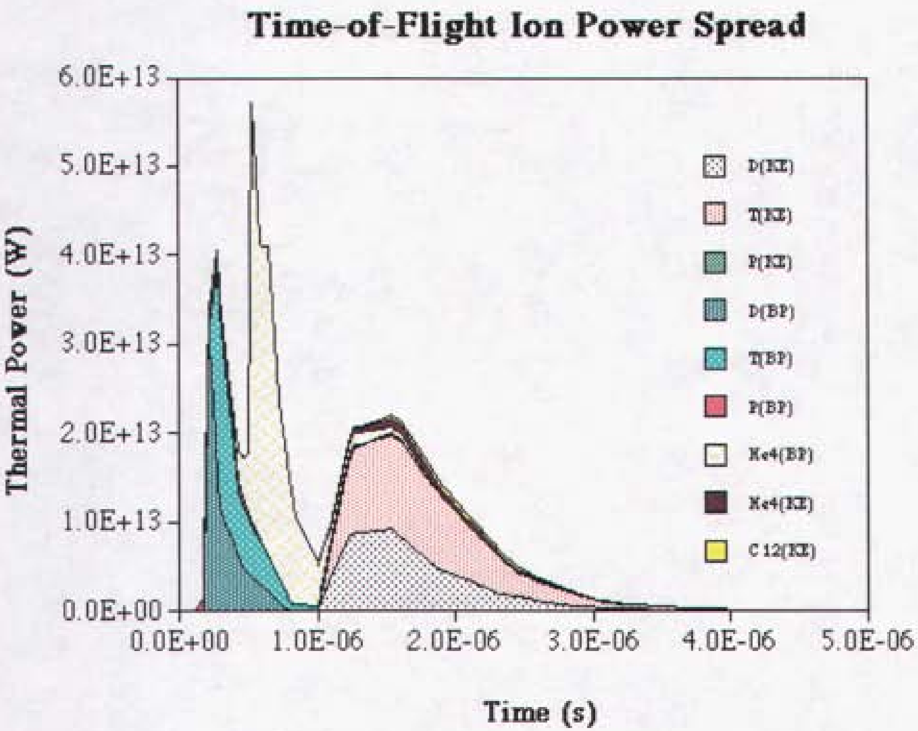
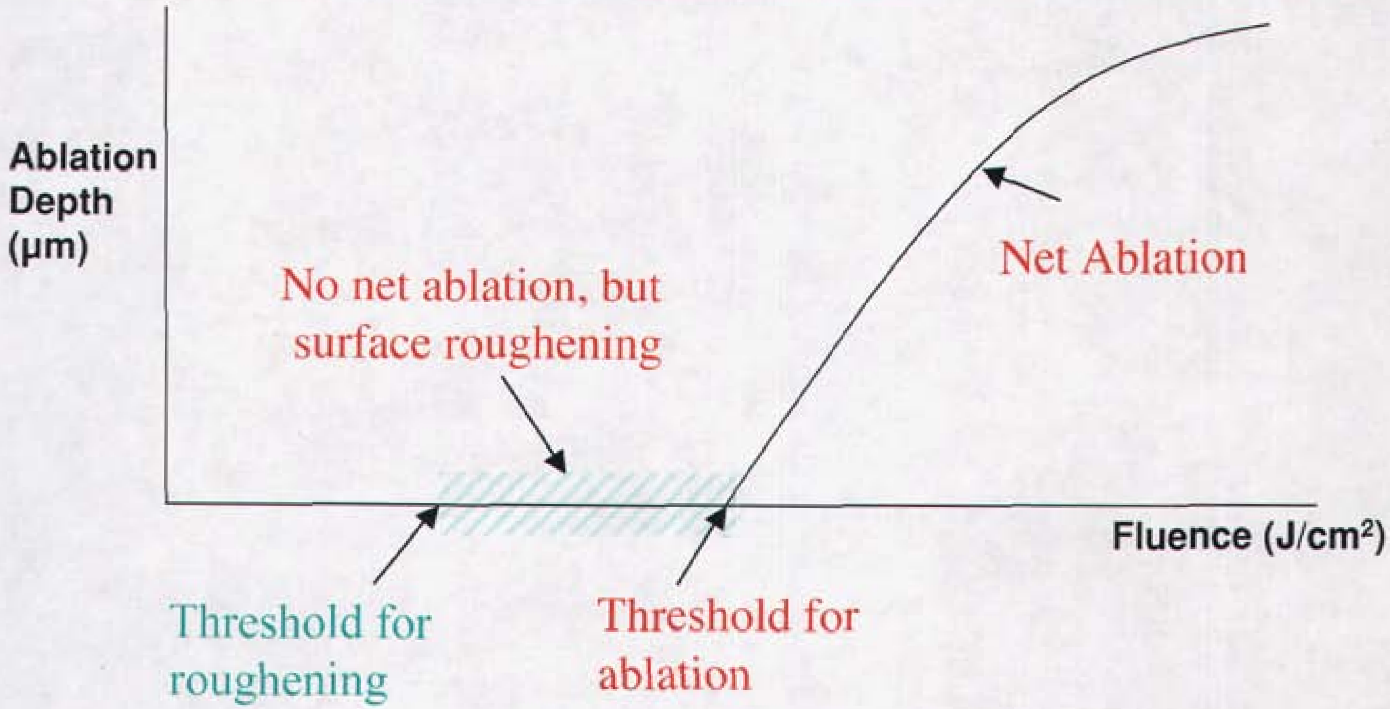
Laser IFE Direct Drive Threat Spectra



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/cm² fluence, judged Significant Threat
- X-rays: ~ 1 J/cm², up to 10 keV energies, judged less significant threat
- RHEPP-1: 700 keV N, higher for N^{+2}, 100-150 ns pulsewidth
- RHEPP-1 energy delivery too short, but otherwise good fidelity with reactor ion threat

Regimes of IFE Materials Response to Ions



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

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

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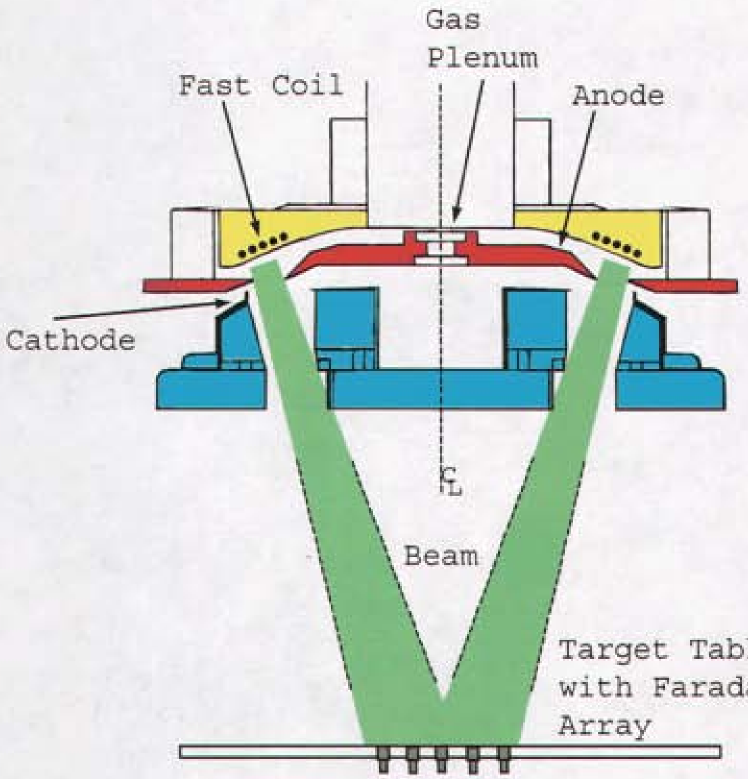
Overall View of RHEPP-1 vacuum chamber and treatment area



- 600-800 kV. Pulse Width ~ 100-200 ns
- < 250 A/cm^2
- Beams from H, He, N_2, O_2, Ne, Ar, Xe, Kr, CH_4
- N beam reported on here
- Overall treatment area ~ 100 cm^2
- Diode vacuum ~ 10^{-5} Torr

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

Materials Modification Laboratory

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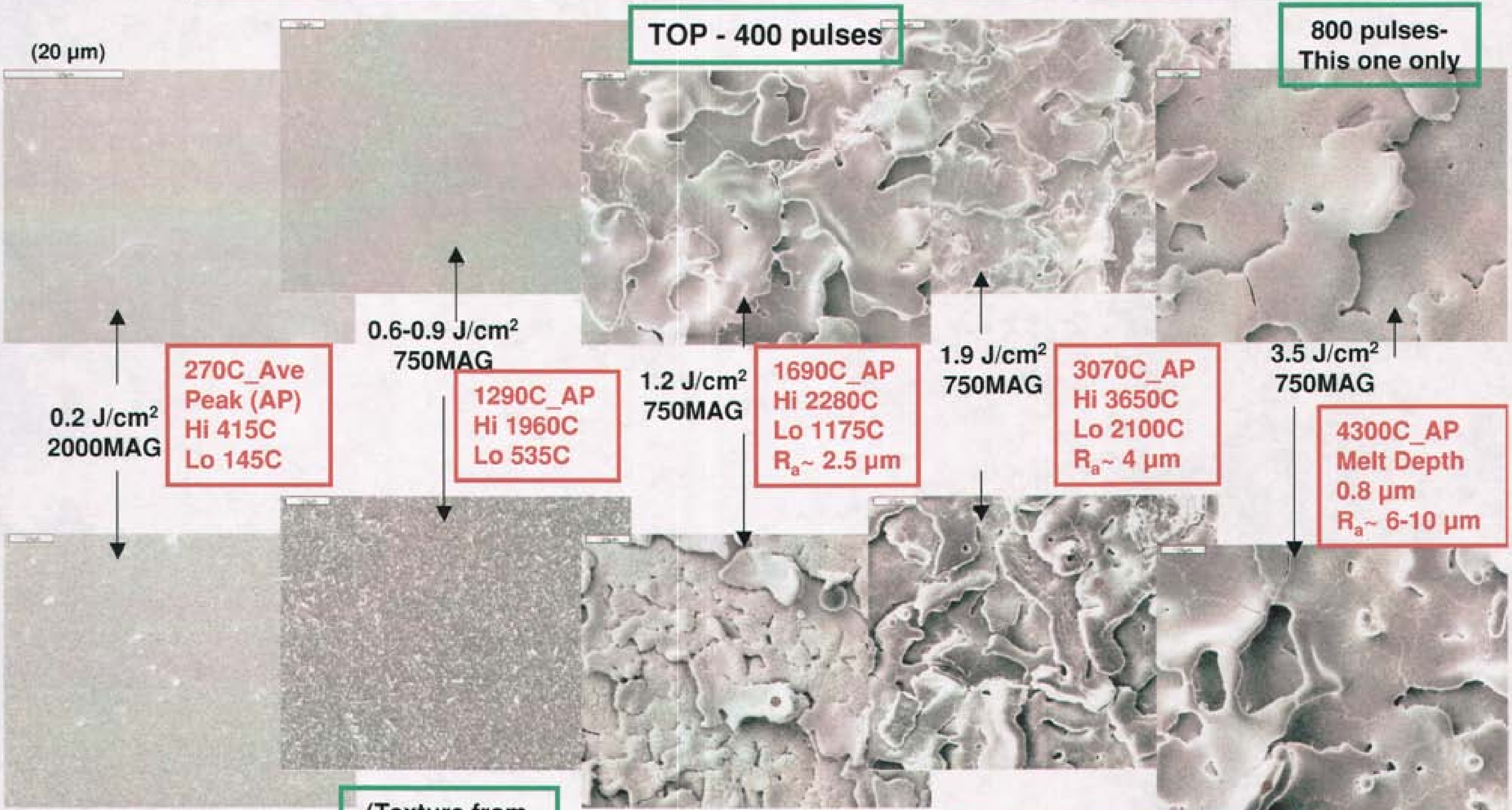
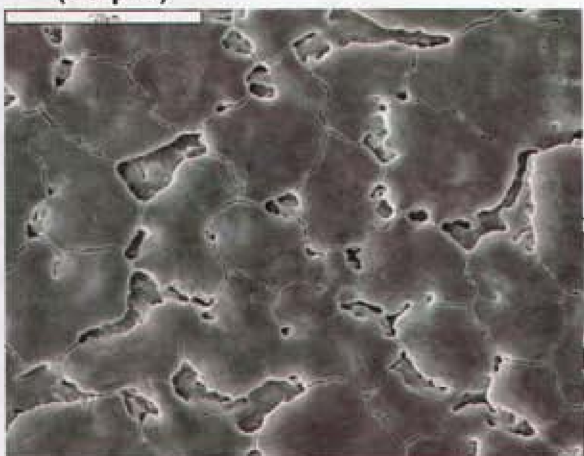
SEMs of Polycrystalline (PM) Tungsten Roughening: Threshold at ~ 1 J/cm², roughening saturates after ~ 400 pulses



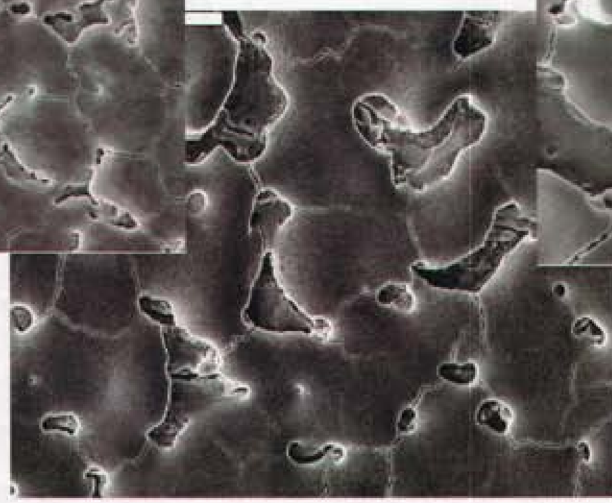
All samples initially Room Temperature (RT)

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

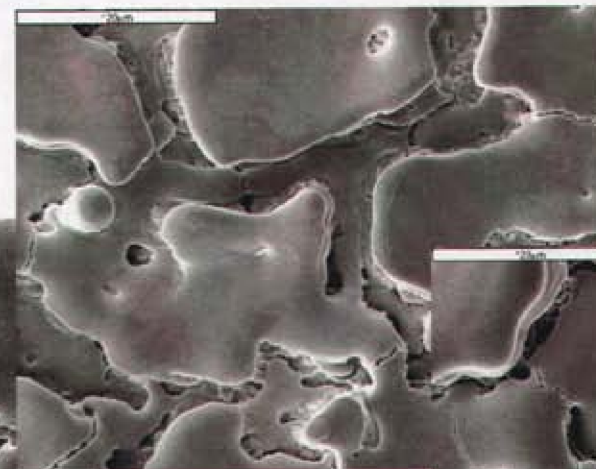
(20 μm)



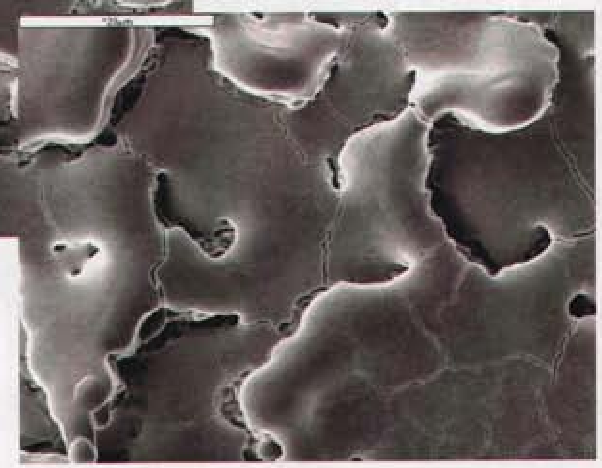
400 pulses



800 pulses



1200 pulses

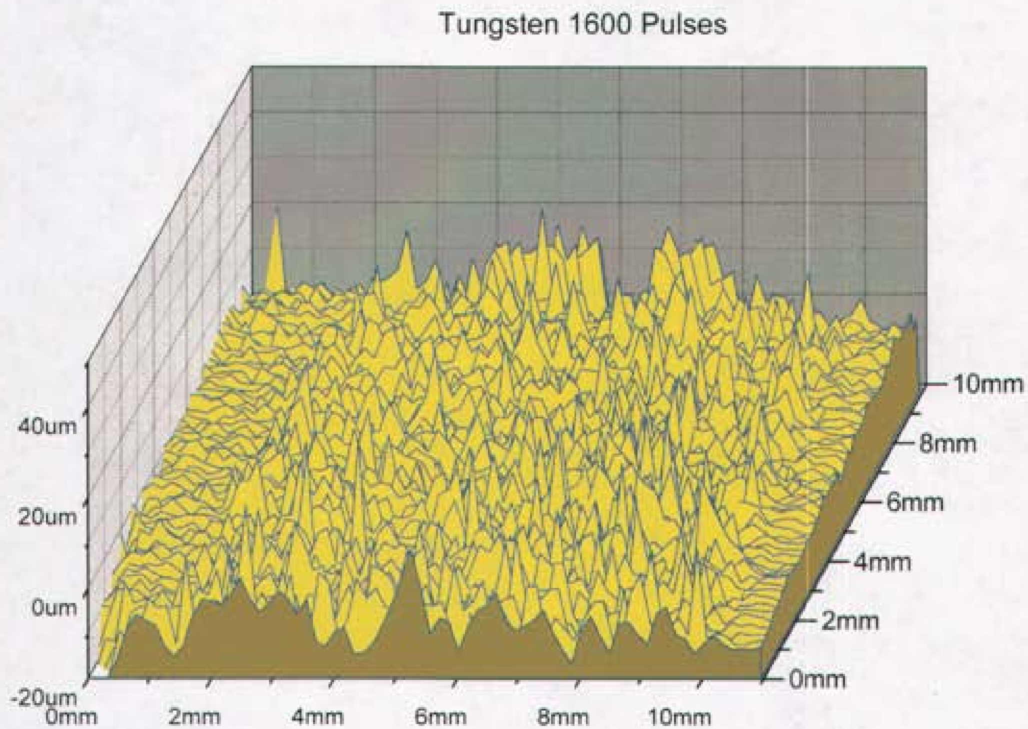


1600 pulses

All images 2000X

- Heated PM Tungsten (600C) exposed to Nitrogen beam at ~ 1.5 J/cm^2 - peak temp ~ 3300K
- Rounded 'knobs' are actually high points. **Surface rises during treatment.**

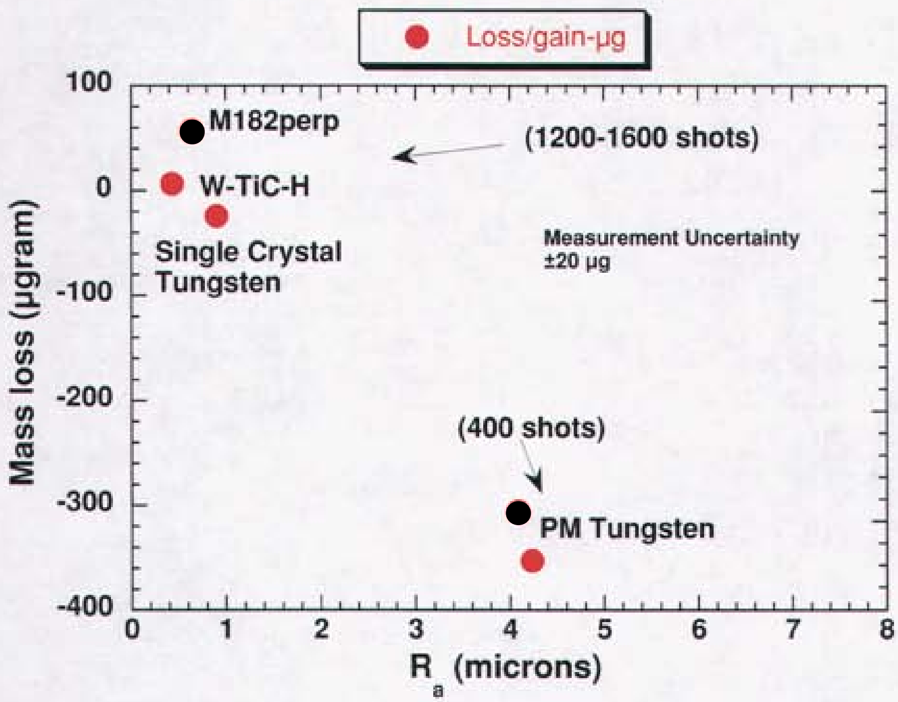
PM Tungsten after 1600 pulses (non-melting): Mostly mountains up to ~ 30 μm height



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

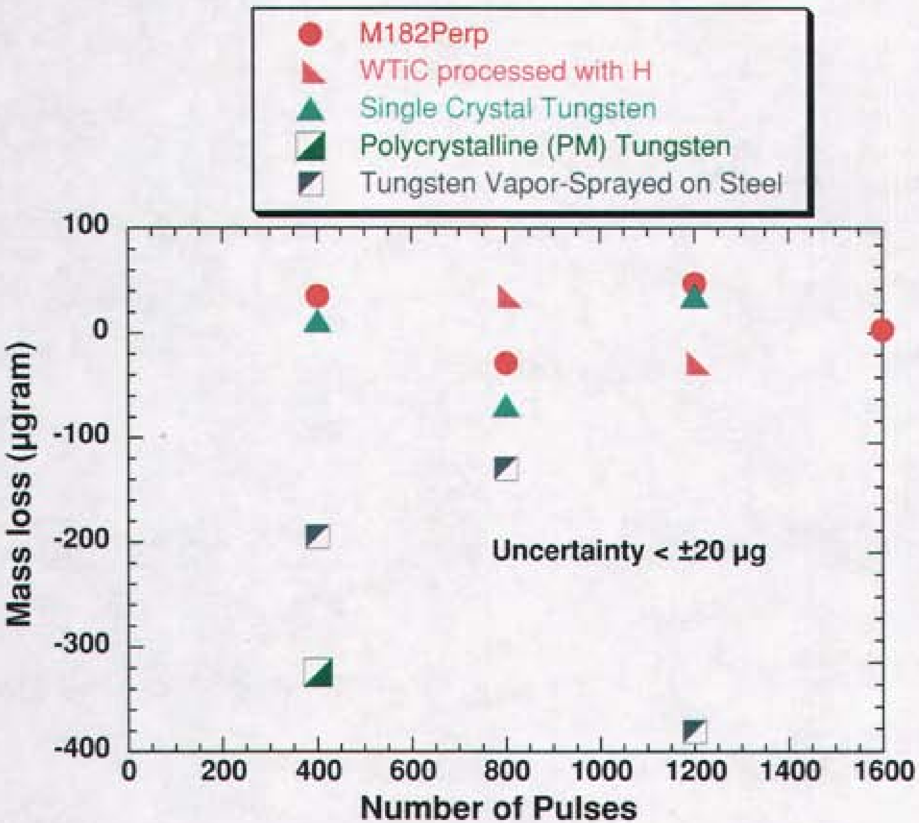
- Heated/treated PM Tungsten examined with NEXIV laser interferometry
- Comprehensive line-out scan: max height 30 μm, min height < 10 μm compared to untreated
- Very deep microcracking not visible here
- Hypothesis: mountains are due to CTE expansion that does not recover

SNL 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 Surface Roughness Ra ~ 4 µm
- M182Perp, W-TiC-H, and Single Crystal Tungsten remained < 1 µm Ra, and suffered little mass loss.

Mass Loss with Shot Number: M182Perp, WTiC-H, Single Crystal W show almost no loss



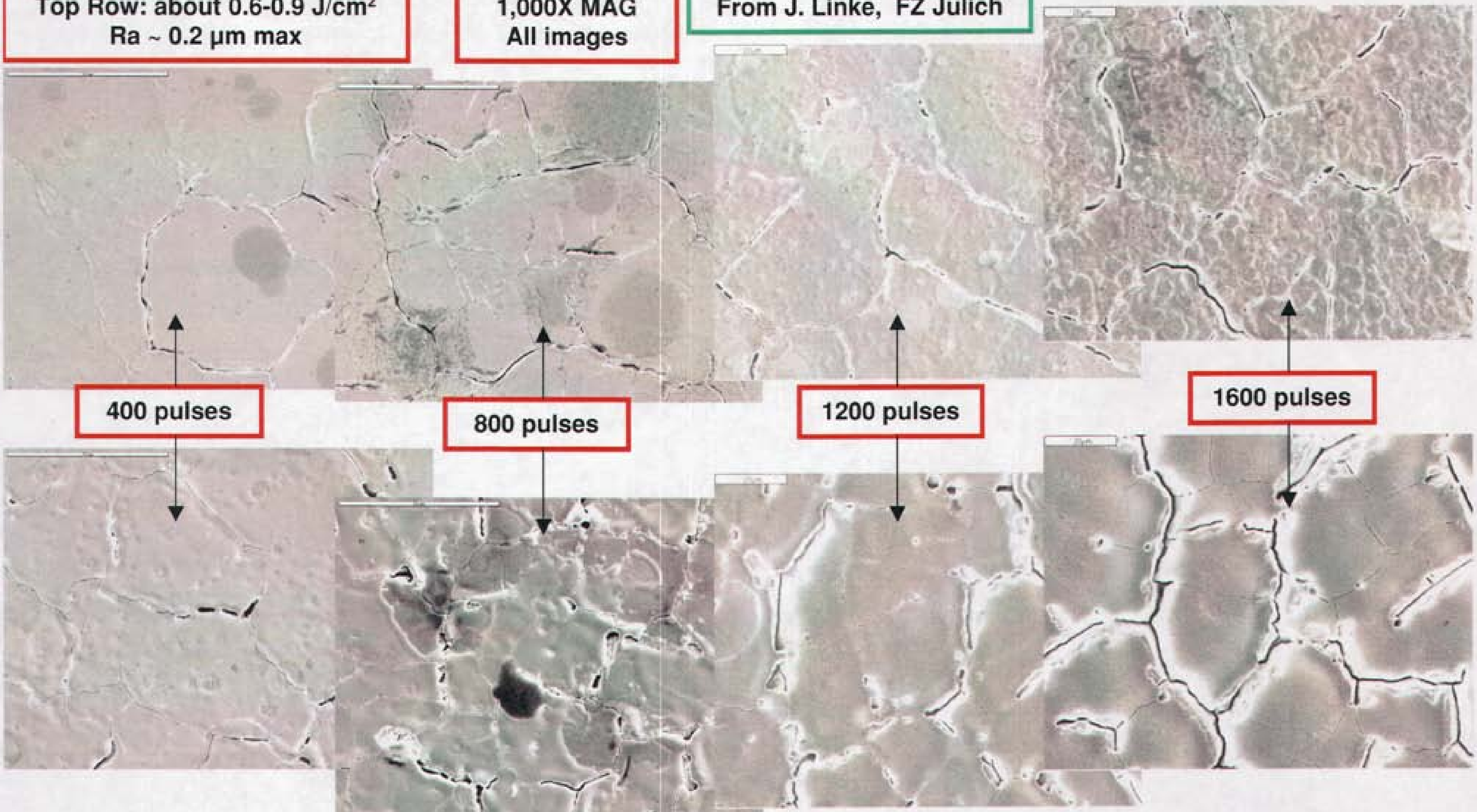
- Mass loss for PM Tungsten only for 400 pulses - exposure terminated
- Vapor-Sprayed Tungsten (on Ferritic Steel) loses up to 400 μg per 400 pulses
- Mass Gain due to entrained material (Cu) from diode region

SEMS of Tungsten M182 perp after 1600 pulses: Little topology change below 1 J/cm^2, some roughening w/ pulse number at ~ 1-1.2 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

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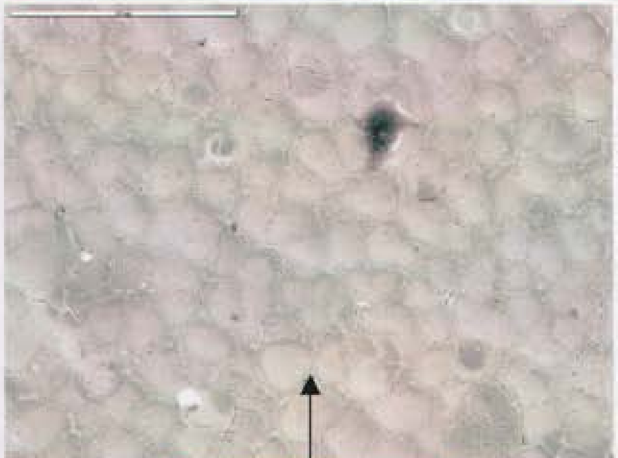
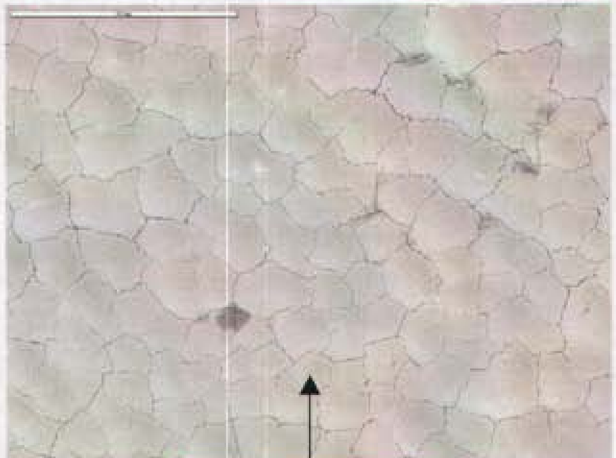
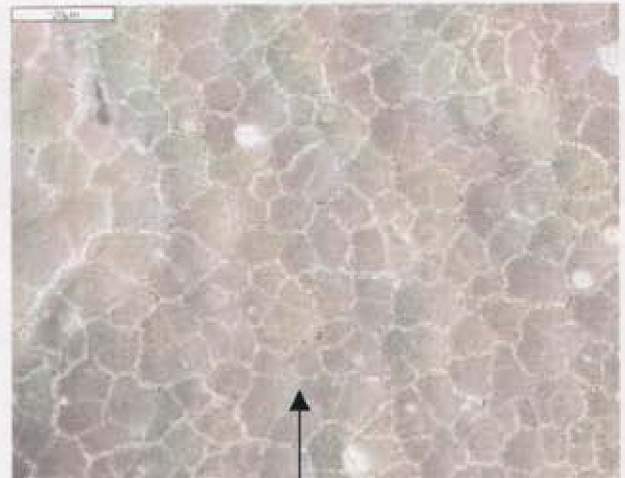
W-TiC-A 'pre-stressed*' 2.5 cm-wide sample (SEMs): (presumed) stress-relief seems to restrict grain corner exfoliation

Top Row~ 1.0 J/cm Ra ~ 0.16 µm

From H. Kurishita (Tohoku U.)



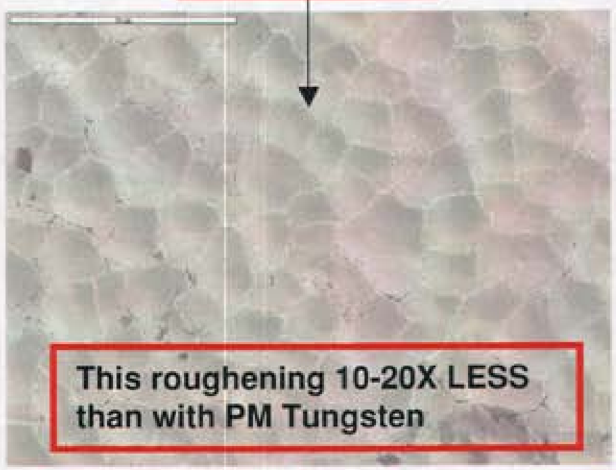


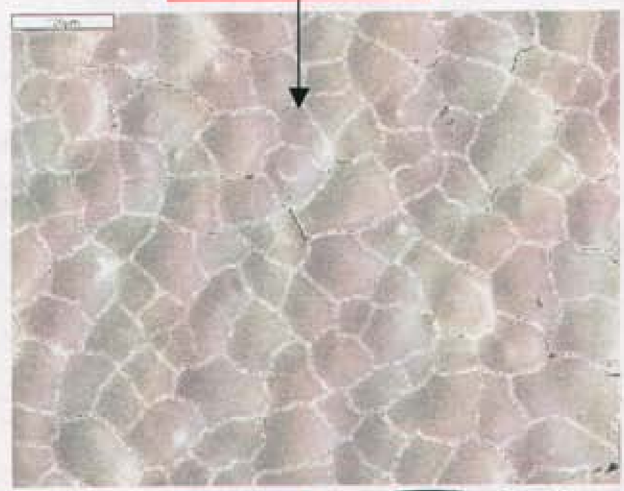


400pulses

800 pulses

1200 pulses





This roughening 10-20X LESS than with PM Tungsten

~ 1.4 J/cm²

All images - 1,000X MAG

Right Two ~ 1.7 J/cm²
Ra ~ 0.28 µm

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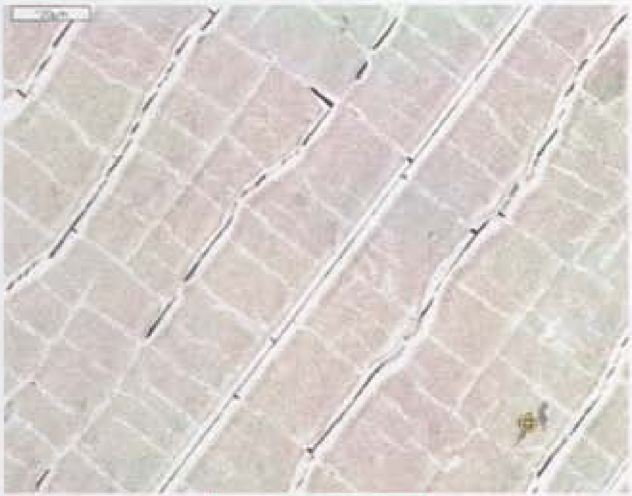
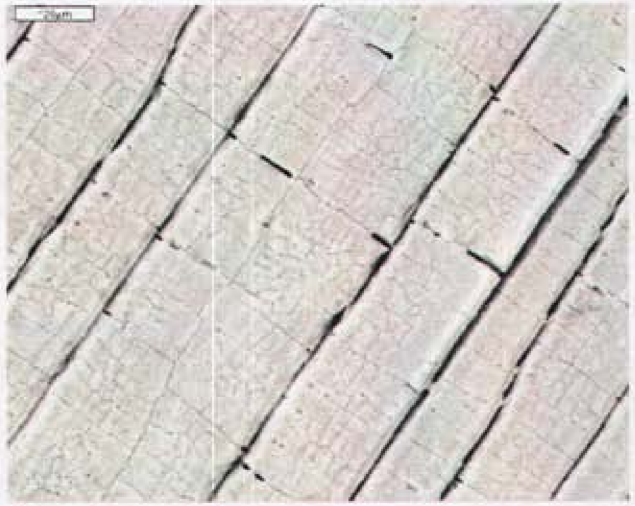
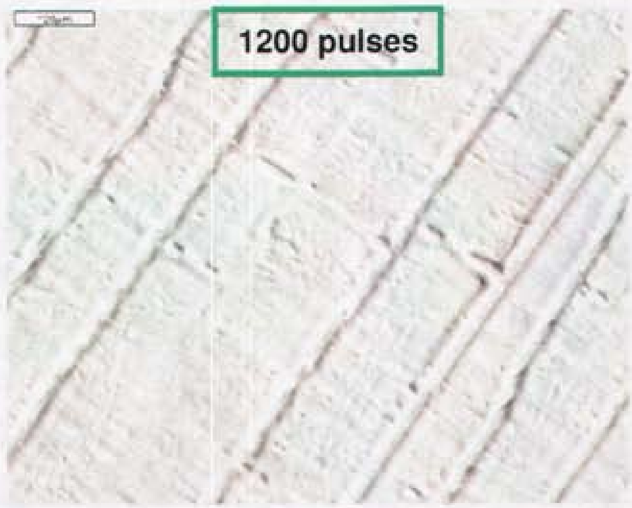
RHEPP-1 Surface Roughening, KS2000 Series

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

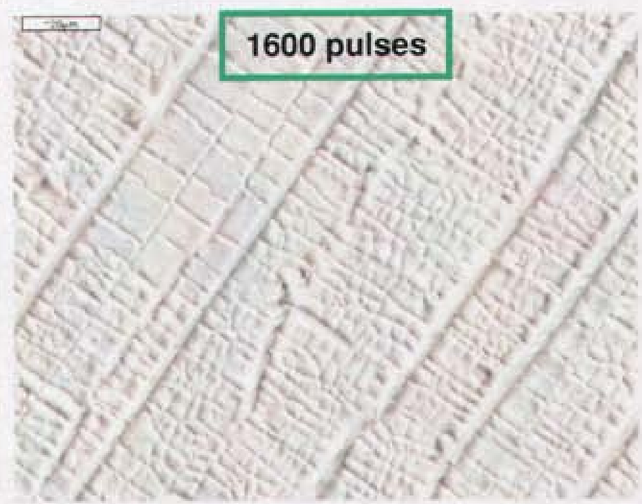


400 pulses





1200 pulses

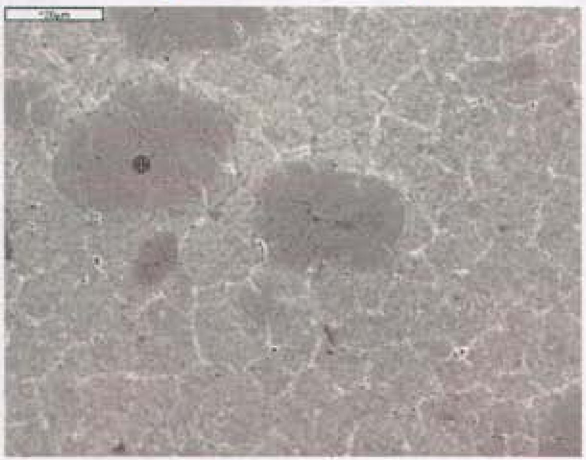


1600 pulses

BSE Images

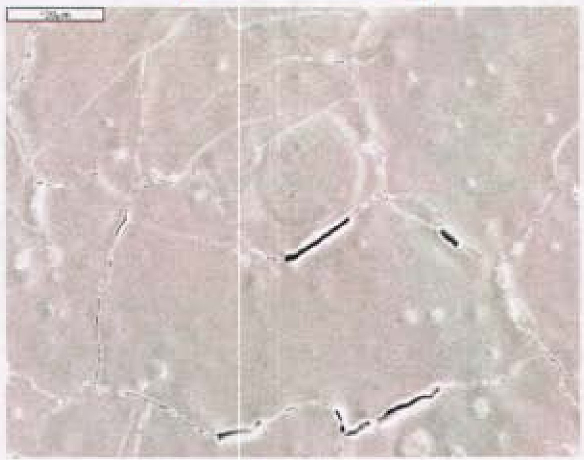
Three forms of Tungsten, treated at ~ same fluence (400 pulses): Grain-refinement/strengthening, or below-surface burial seem to restrict roughening/mass-loss.

1,000X MAG



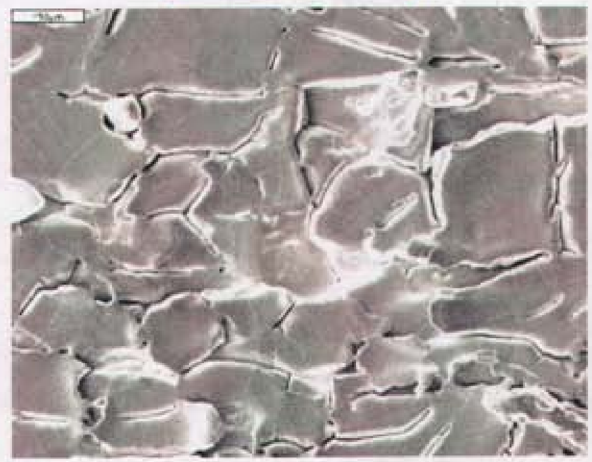
W-0.5%TiC 1.5 J/cm².
Ra = 0.04 μm

1,000X MAG



M182Perp ~ 1.25 - 1.5 J/cm²
Ra ~ 0.15 μm

300X MAG

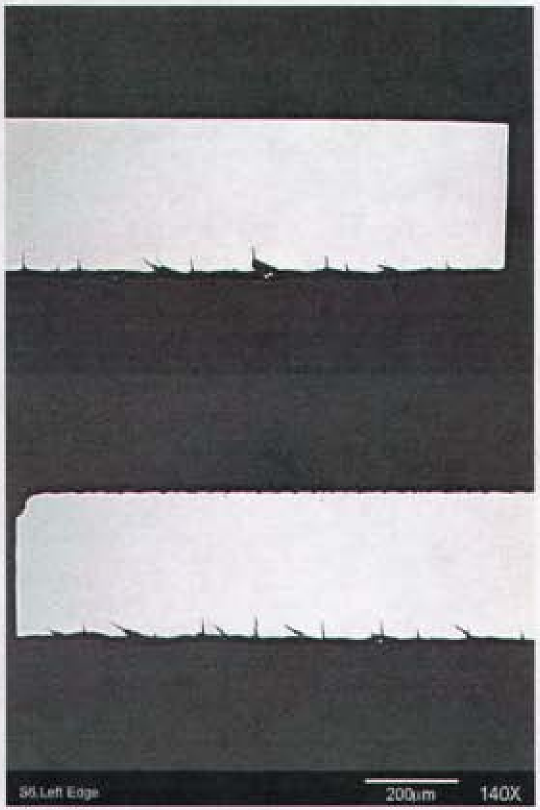


M182Parallel ~ 1.3 J/cm²
Ra ~ 4.5 μm

Two on right are SAME material

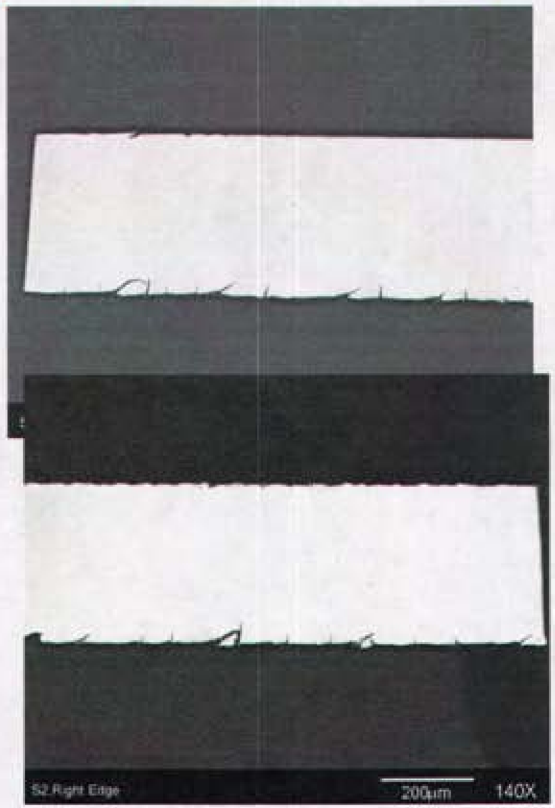
Single-Crystal Tungsten, 400 and 1600 pulses: No fatigue-cracking in-depth

1.2 J/cm² 400X Upper 1600X lower



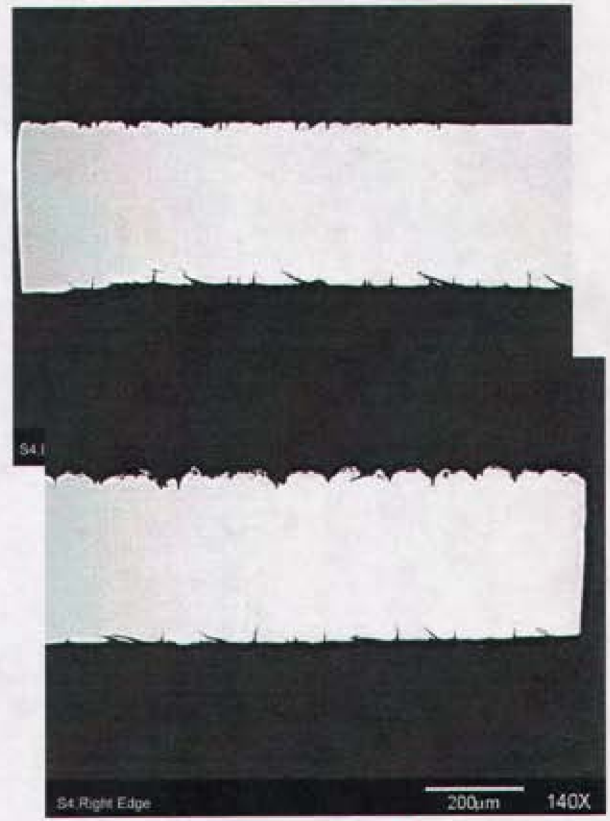
All 140X MAG

1.9 J/cm² 400 pulses



1600 pulses

3.5 J/cm² 400 pulses

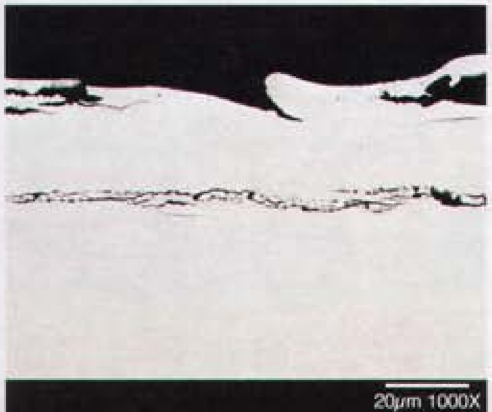


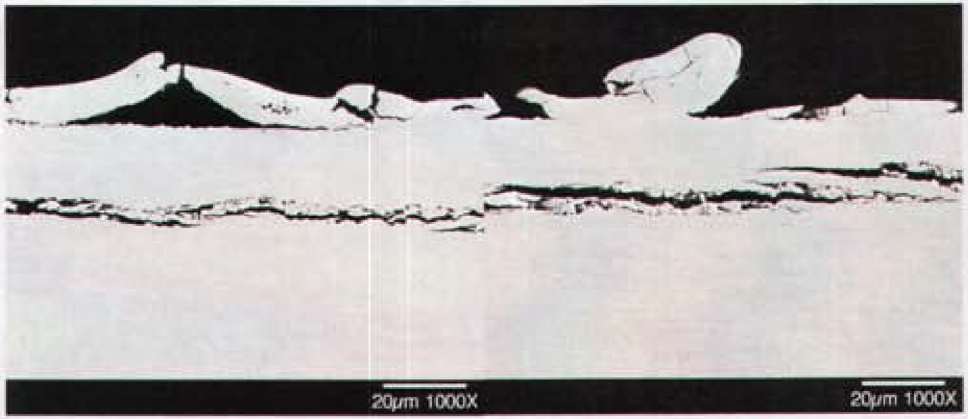
1600 pulses

Top surface is treated in all cases
Cuts on bottom surface look like sample prep

RHEPP-1 Surface Roughening

PM Tungsten, 1.9 J/cm² RT, sectioned SEMs (near Melt): Large distortions in near-surface zone

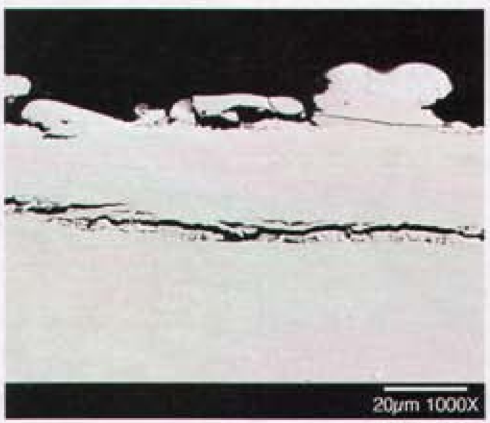


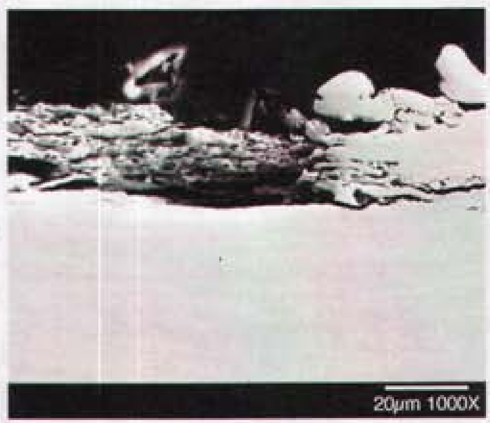


- Wholesale failure down to 20 μm level in last image

400 pulses

Increasing pulse number →





All images BEI 1000X MAG

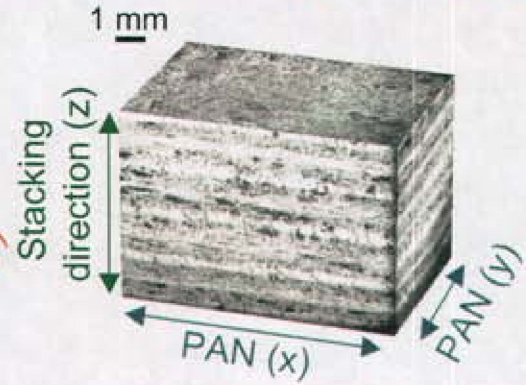
→ 1600 pulses

Preferential erosion of carbon-carbon composites

Forschungszentrum Jülich

Same type of preferential erosion under different conditions (particles, pulse duration, deposited energy)

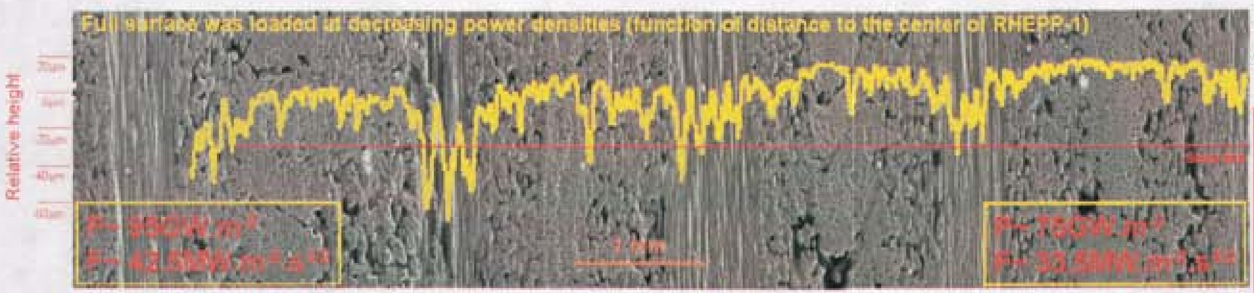
NB31 **(SNECMA, FR)**
3 directional
(orthotropic needled)



DMS704 **(DUNLOP, UK)**
2 directional (0°, felt, 90°)

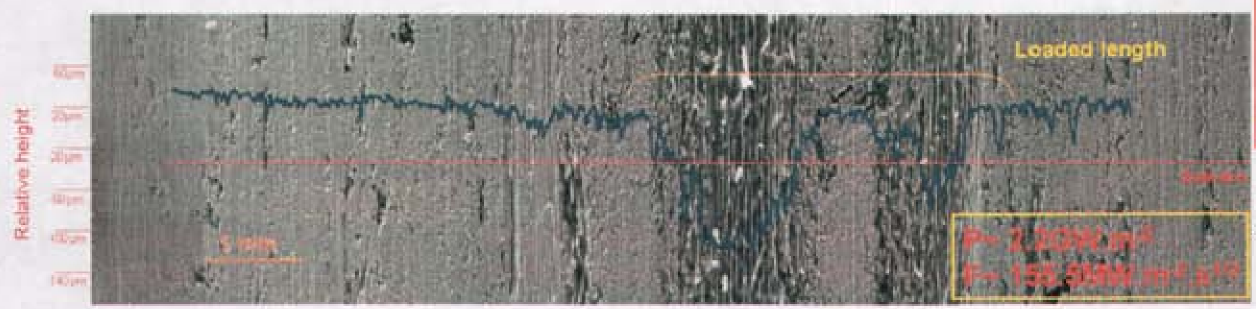
Electron beam loading in JUDITH facility:
120kV, 2.4 GW/m^2, 5 ms
Forschungszentrum Juelich, Germany

Ion beam loading in RHEPP-1 facility:
700kV, 75-95 GW/m^2, 200 ns
Sandia National Laboratories



DMS704 loaded in RHEPP-1 for 400 pulses

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 - 42 MW m^{-2} $s^{1/2}$



DMS704 loaded in JUDITH, single pulse

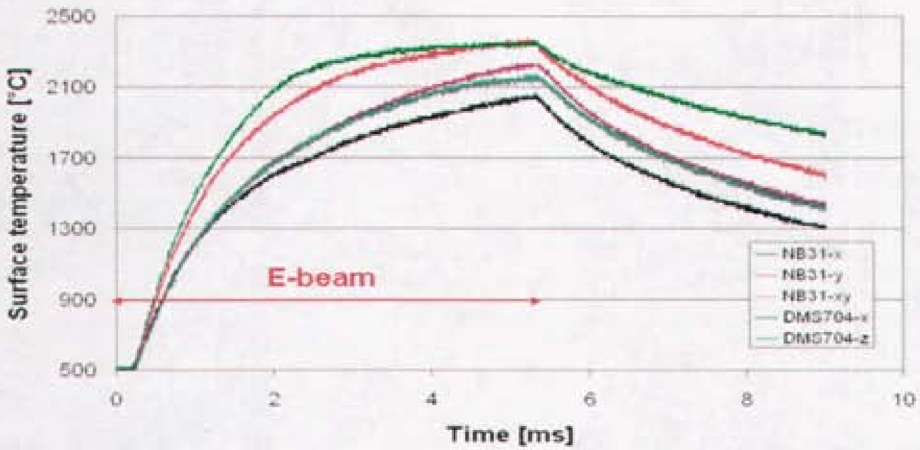
Preferential erosion can be reduced by aligning less fibers perpendicular to heat flow

Sketch of NB31-xy

- Pitch fiber (x)
- PAN fiber (y)
- Needled PAN fiber (z)

NB31-xy

NB-31, DMS704 mounted in different orientations and exposed to 5 JUDITH pulses each



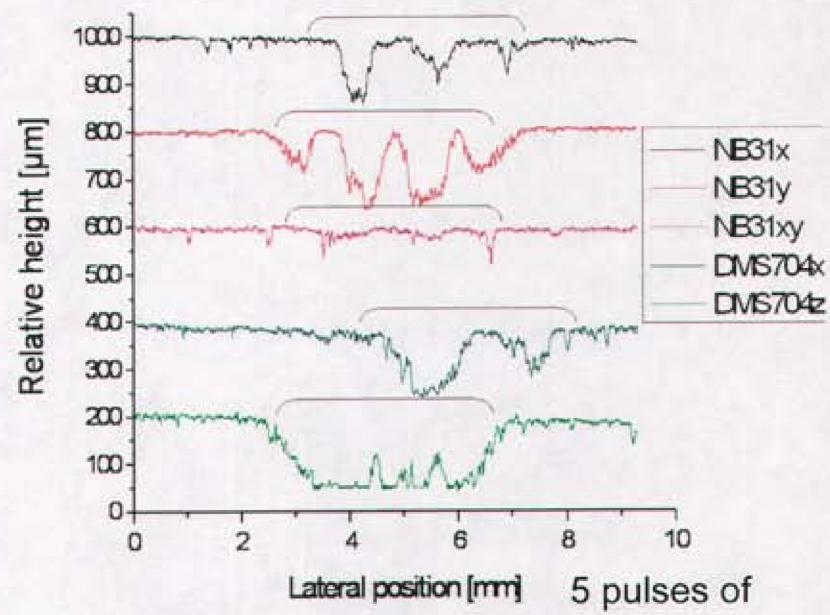
Results

- **Higher Measured Surface Temperature (left) and**
- **More Erosion (Below) in RED and GREEN directions with greater fiber alignment perpendicular to heat input**

Optimal material orientation is essential

This allows:

- Maintaining good thermal conductivity (x direction)
- Limiting of local overheating (y and z directions)
- More homogeneous mechanical attachment of all the fibers



5 pulses of $1.9\ GW.m^{-2}$, 5ms

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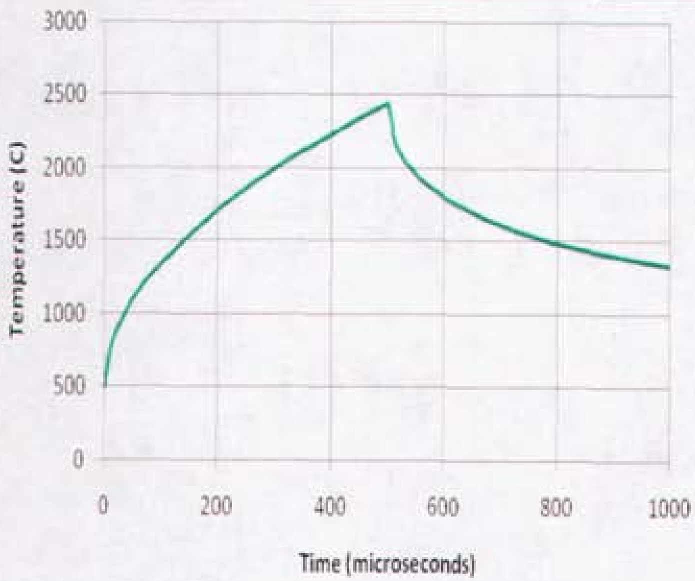
Fracture Modeling: Comparison of Tungsten exposed to IFE and MFE ELM Conditions



- 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

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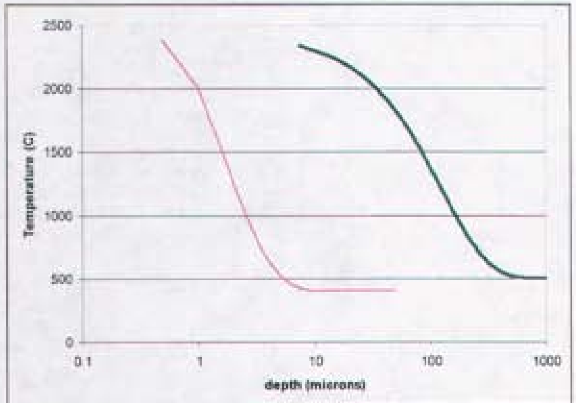
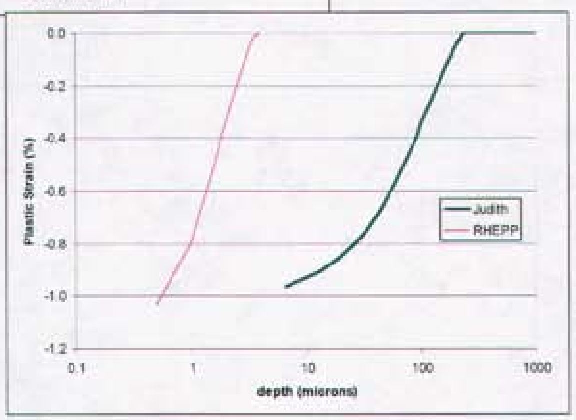
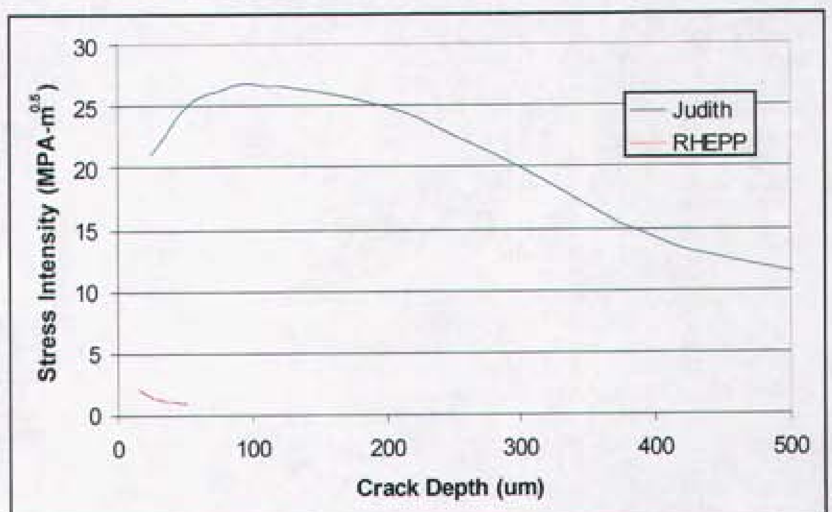
Unlike RHEPP heating, the ELM-like pulse produces fracture stresses at the fatigue crack threshold after one pulse





- (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.



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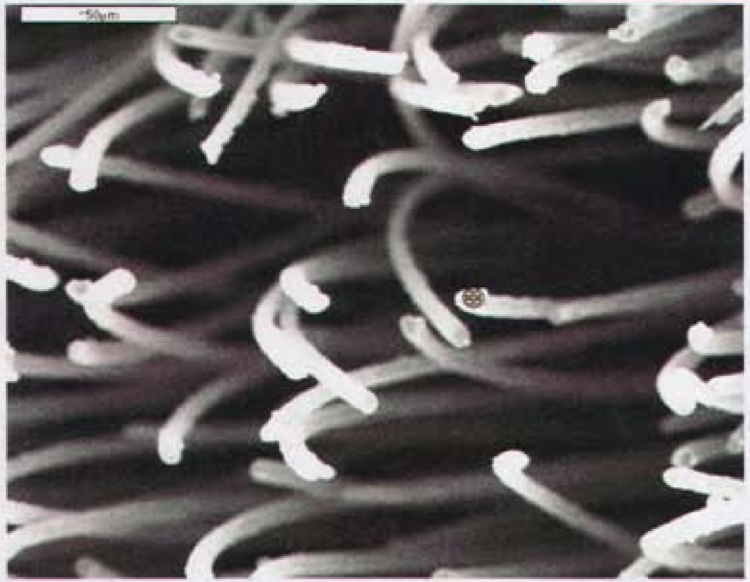
RHEPP-1 Surface Roughening

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



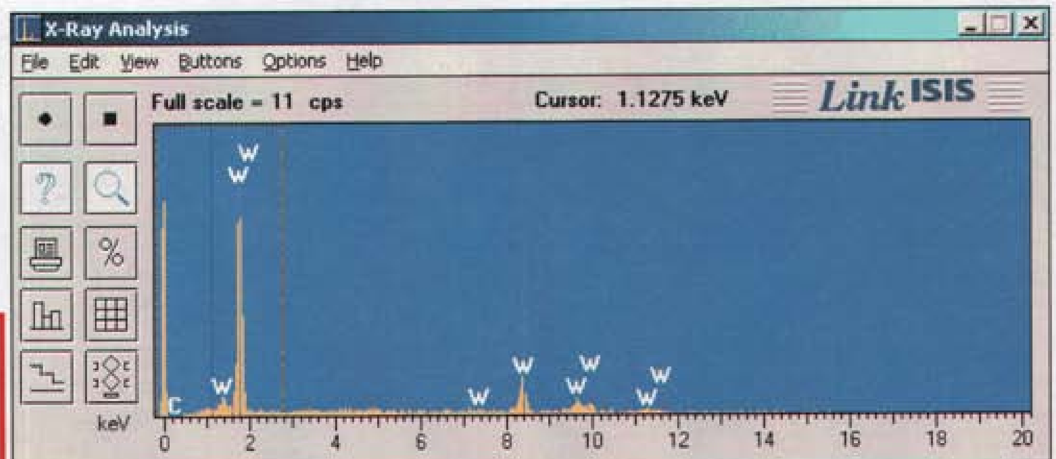
(ABOVE)
RT @ ~ 2.8 J/cm^2, 1600 pulses

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

(RIGHT)
520C (nominal), 1600 pulses, 1.5 J/cm^2/pulse

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

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:
  - CFCs perform best when fiber direction is oriented to conduct maximum heat below the surface, and when minimal fibers are parallel to surface, independent of whether they are PAN or PITCH fibers.
  - 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 (seen 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.