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

T. J. Renk, T. J. Tanaka, P. P. Provencio, C. L. Olson
Sandia National Laboratories, Albuquerque, NM

R. R. Peterson
Los Alamos National Laboratory, Los Alamos, NM

T. R. Knowles
Energy Science Laboratories, San Diego, CA

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Outline of Presentation

- IFE Threat Spectra: RHEPP-1 and Z as simulators to ion/x-ray threat to first wall
- Brief Summary of Z exposure results - tungsten
- Description of RHEPP-1 and and Heating/exposure Cycle
- Materials exposed on RHEPP-1 (ions):

  W and W alloys
    - Powder Metallurgy Tungsten (PM W)
    - Single Crystal W
    - Alloyed W - W25Re, W1%La

  Graphite/Carbon Fiber Composites (CFCs):

  'Engineered' Materials as an alternative to flat wall
    - Carbon fiber 'Velvet
    - W/Tac and W/HfC 'Foams'

- Conclusions

Summary of Exposure Results

- Ion and X-ray exposure forms key part of Laser IFE Direct Drive First-Wall Threat. RHEPP-1 ion beams (multi-pulse)and Z x-rays (single-pulse) can simulate this threat with good fidelity

- Z results (X-rays on tungsten): melt threshold at 1.3 J/cm^2; roughening threshold is grain-structure dependent, but < 1 J/cm^2

RHEPP Results:

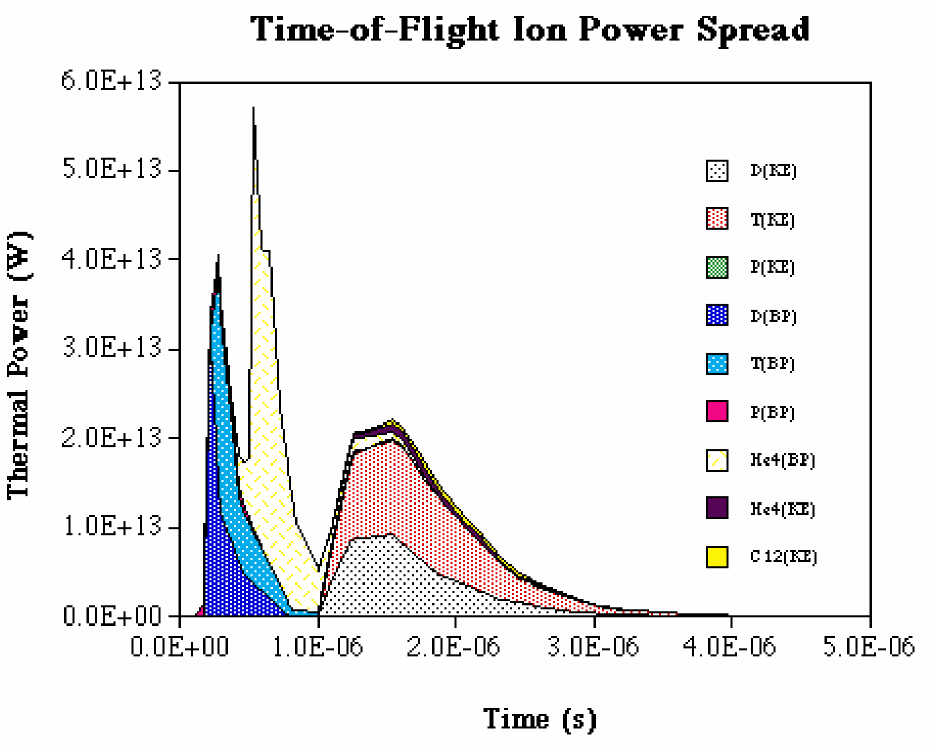
- For W materials, most serious issues are 1) Roughening below melt, evidently caused by thermomechanical stress, and 2) Stress cracking. Stress cracks deepen with pulse number, and may reach deep into interior. This is true regardless of melt. ‘Divit’ formation may indicate outright mass loss. Lower limit forPM W roughening is low ~ 1 J/cm^2.

- For Graphite/Carbon Composites (CFCs), good survivability at low fluence, but rapid loss above sublimation. Physical sputtering or radiation-induced sublimation?

- Engineered materials such as ‘Velvet’ or ‘Foam’ are up-optimized so far, but may be an alternative surface design

- These results are also relevant to MFE W exposure due to Type I EL

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:**
  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, judged
  Significant Threat
- **X-rays: ~ 1 J/cm^2, up to 10 keV energies, judged less significant threat**
- **Z: up to 10 keV x-rays, good single-shot simulator**
- **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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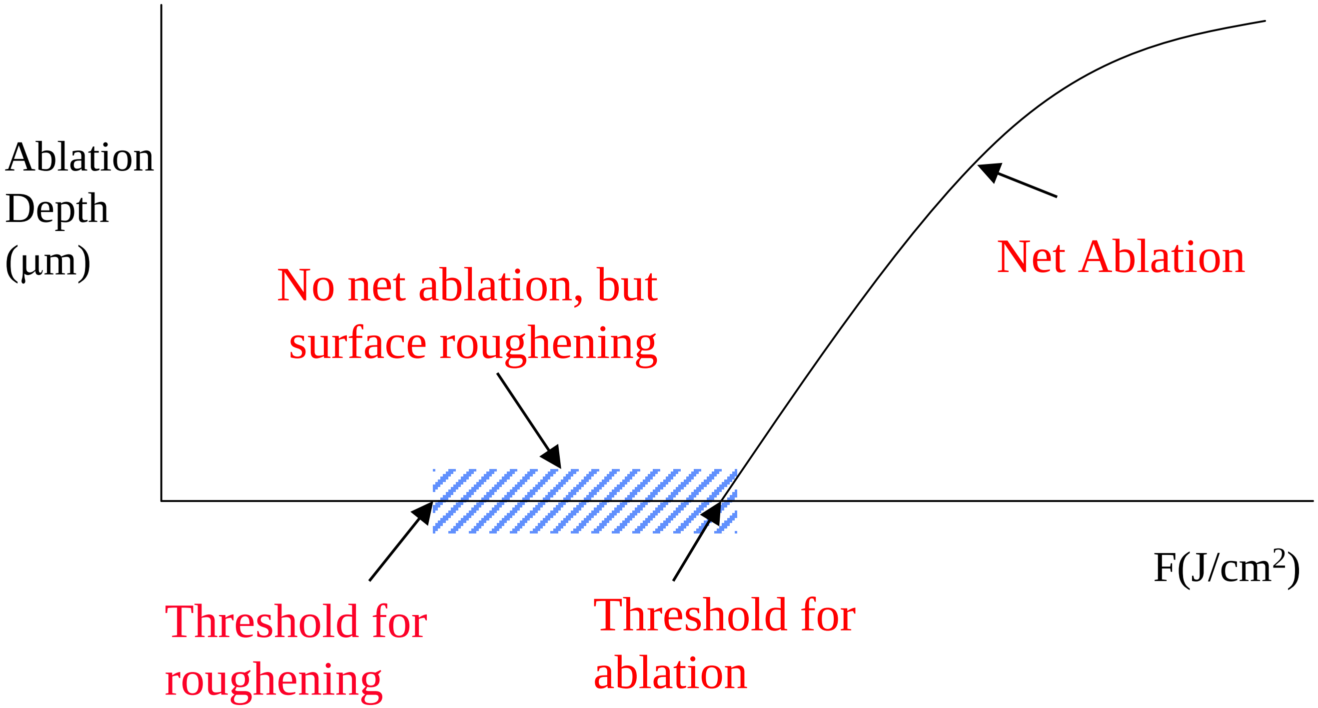
Regimes of IFE Materials Response Studies for x-rays and ions



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

Area of Interest understand roughening
find threshold for roughening

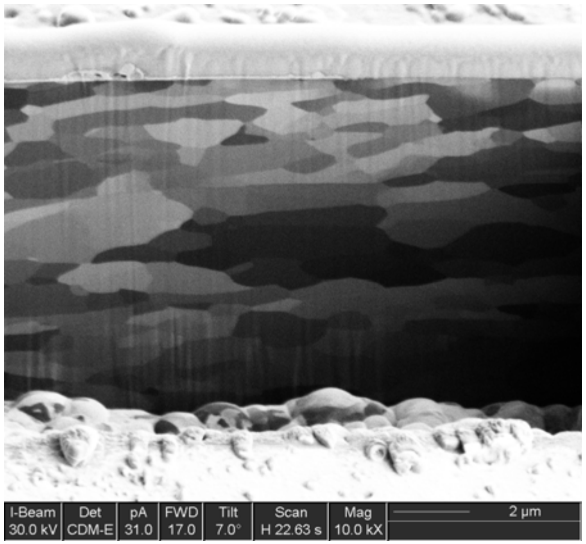
Z Results - PM W Melting/Roughening Thresholds

Tungsten Exposure on Z: Melting and Roughening Thresholds

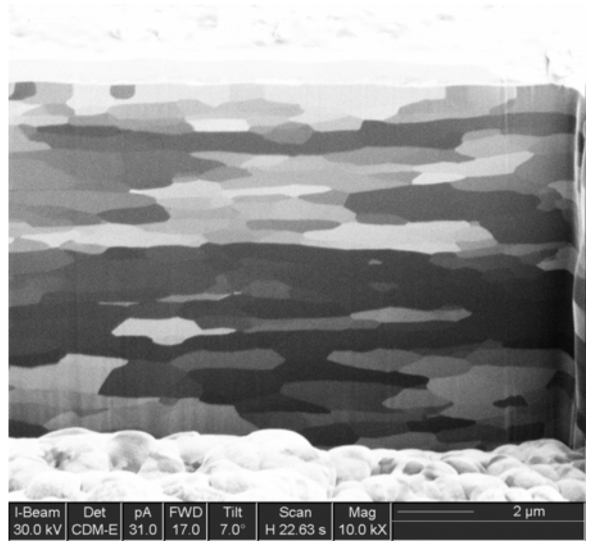
- Tungsten samples exposed to various fluence levels in Z machine with single shots.
  - Varied source-to-sample distance
  - Filter material: 8μm Be and 2μm Mylar
- Polished tungsten (Snead) prepared in 3 different ways:
  - single crystal
  - rolled powdered metal
  - chemical vapor deposition
- Latest samples preheated to 600° C
- Surfaces analyzed with
  - optical surface profilometer
  - Scanning electron microscope (with backscatter detector)
  - focused ion beam

Z Results - PM W Melting Thresholds

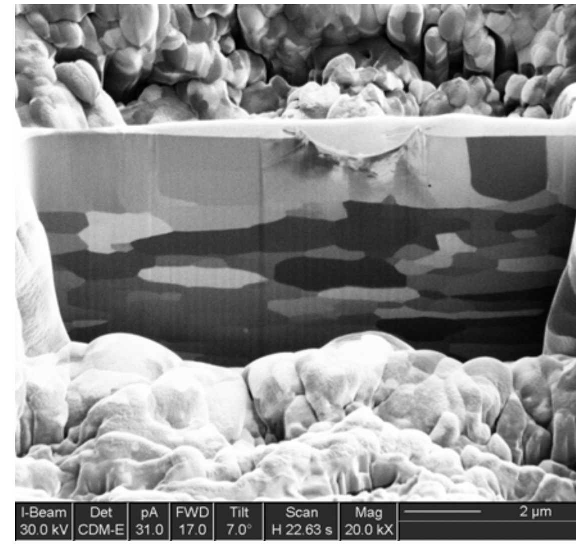
Single-pulse Z data shows no melting below 1.3 J/cm^2



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



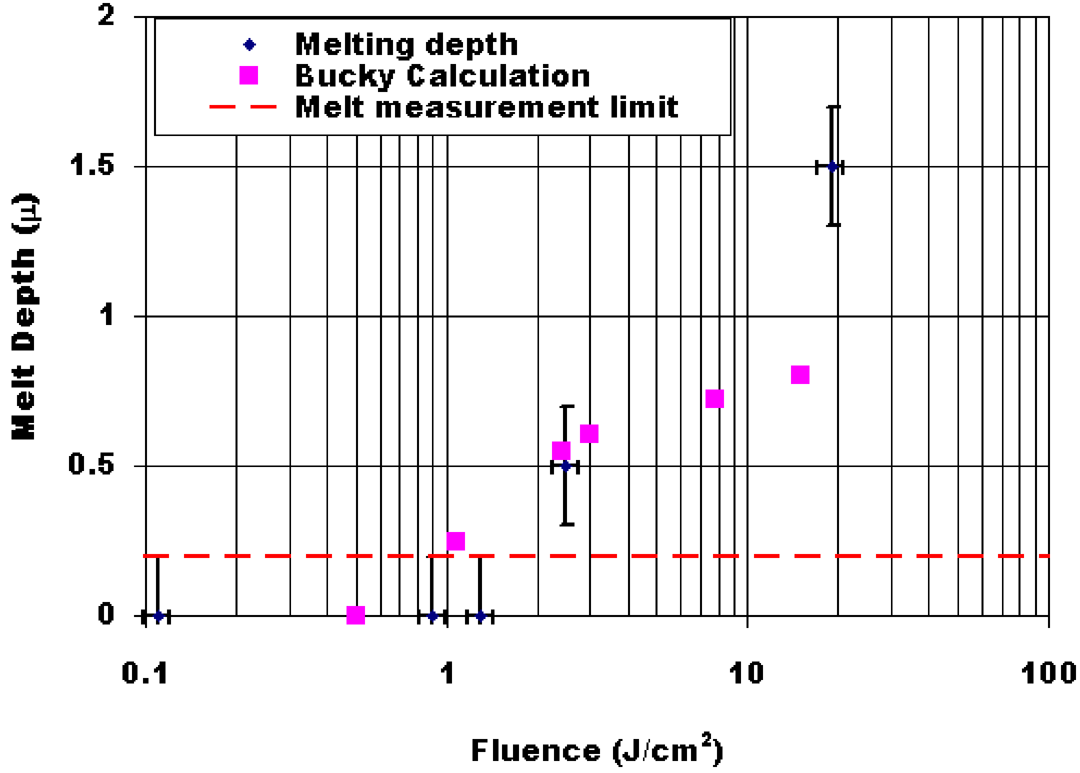
2.3 J/cm^2
2 m kimfoil
0.1 m Al
0.5 µ melting



19 J/cm^2
2 µ melting

- Unheated W
- Difficult to assess roughening with Z samples

Melt depth vs. Fluence on Z



- Experimental points (error bars) and BUCKY calculation (squares) using filtered fluence numbers.

- For melt depths < 0.2 µ (dashed line), melt depth < crystal grain size, so may or may not result in observable effect

Z Results - PM W Roughening Thresholds

Images from samples on Z from VEECO surface profiler

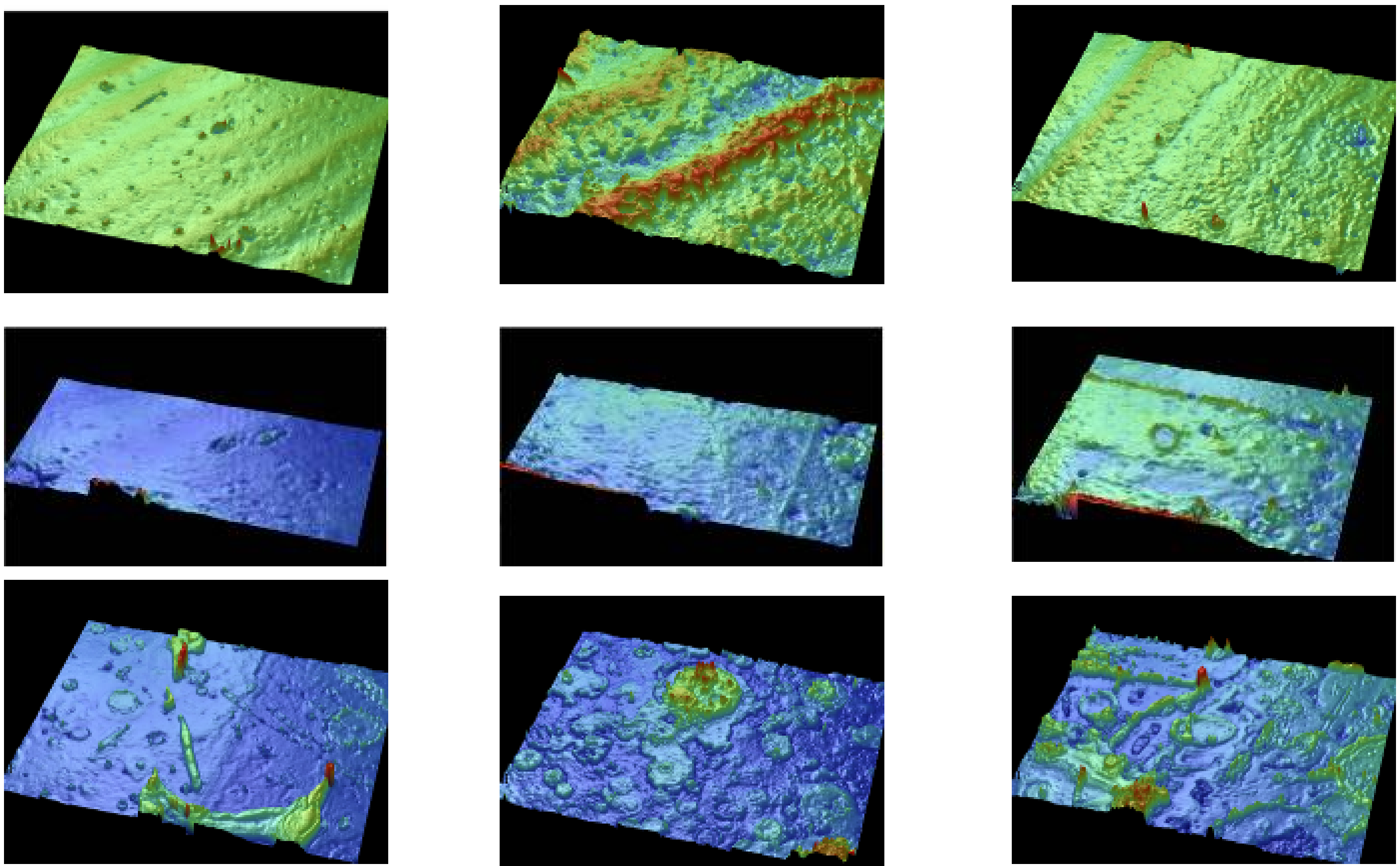
Single X | Rolled Powder | Chemical Vapor Dep

Fluence (J/cm^2)

0

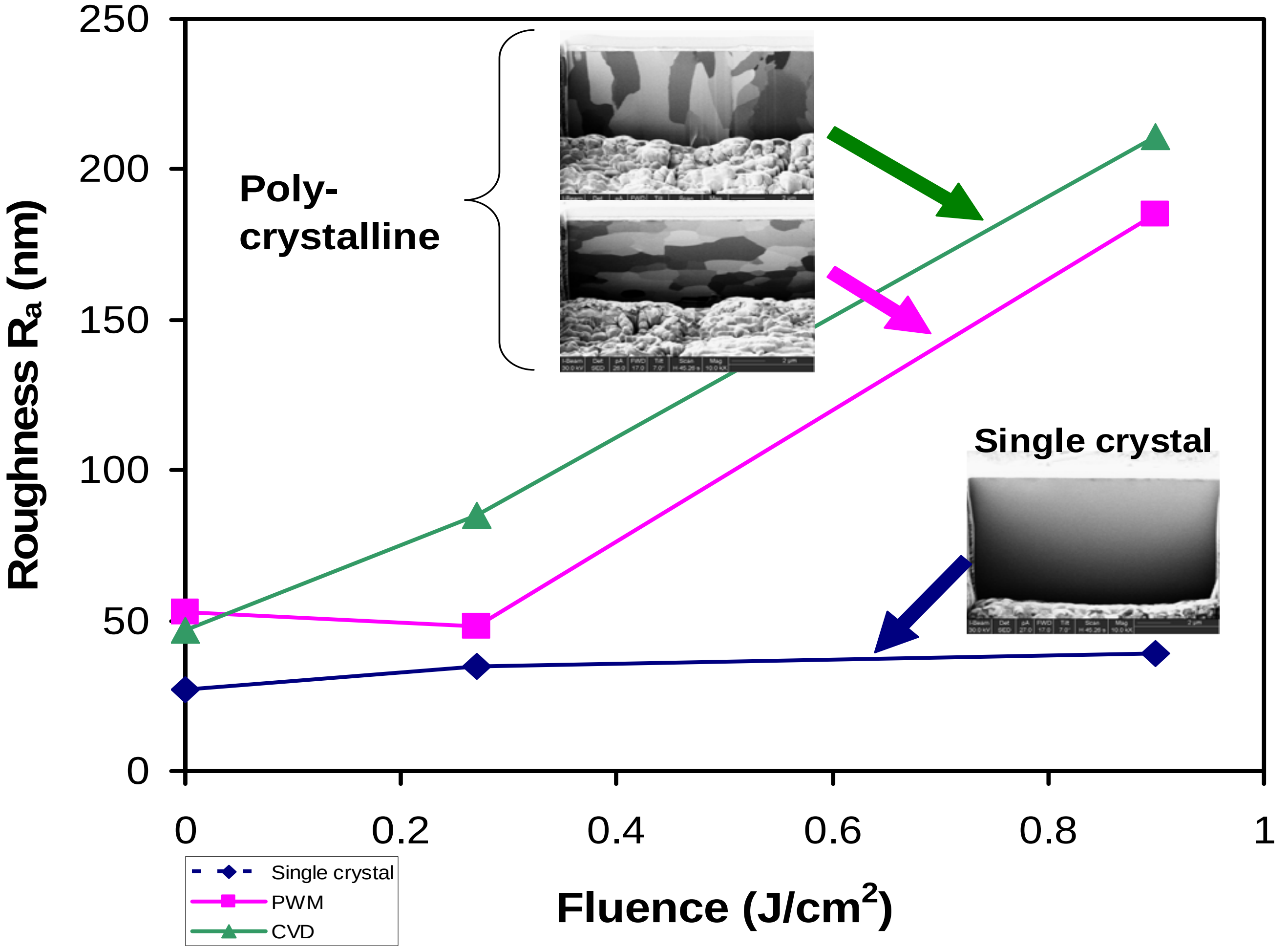
0.27

0.9



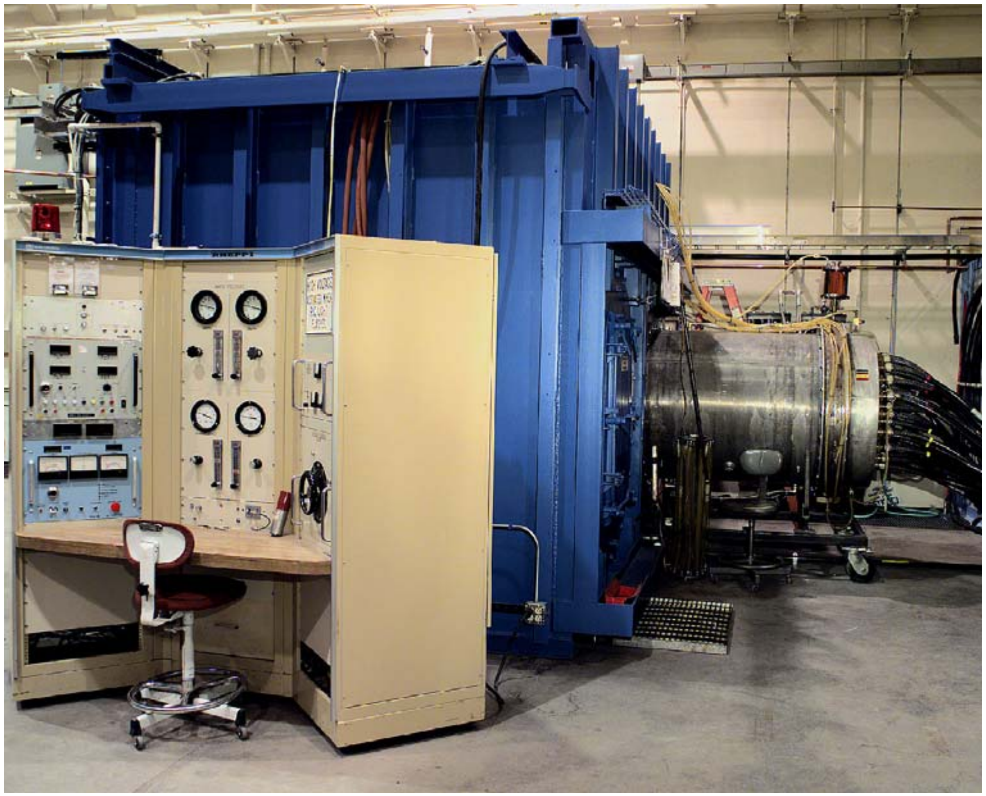
Z Results - PM W Roughening Thresholds

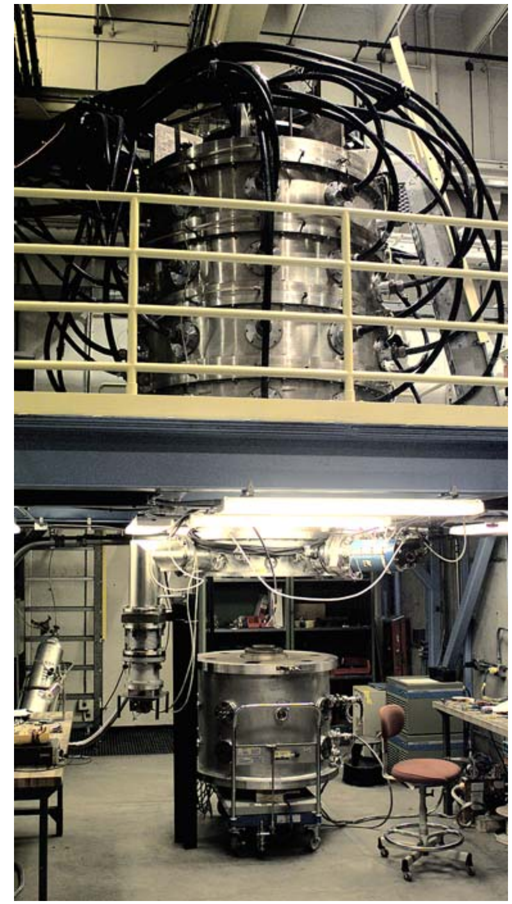
Roughening Depends on Fluence and Grain Boundaries



Roughening threshold: ~0.9 J/cm^2 - single crystal, and ~<0.3 J/cm^2 for polycrystalline tungsten

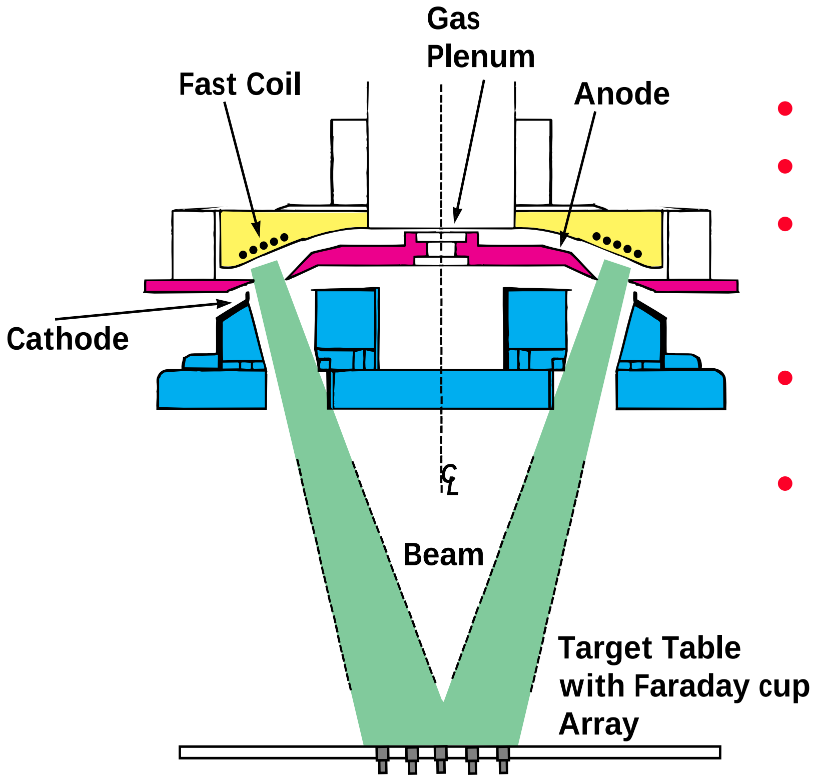
RHEPP-1 combines Repetitive High Energy Pulse Power with a robust and versatile ion source: MAP





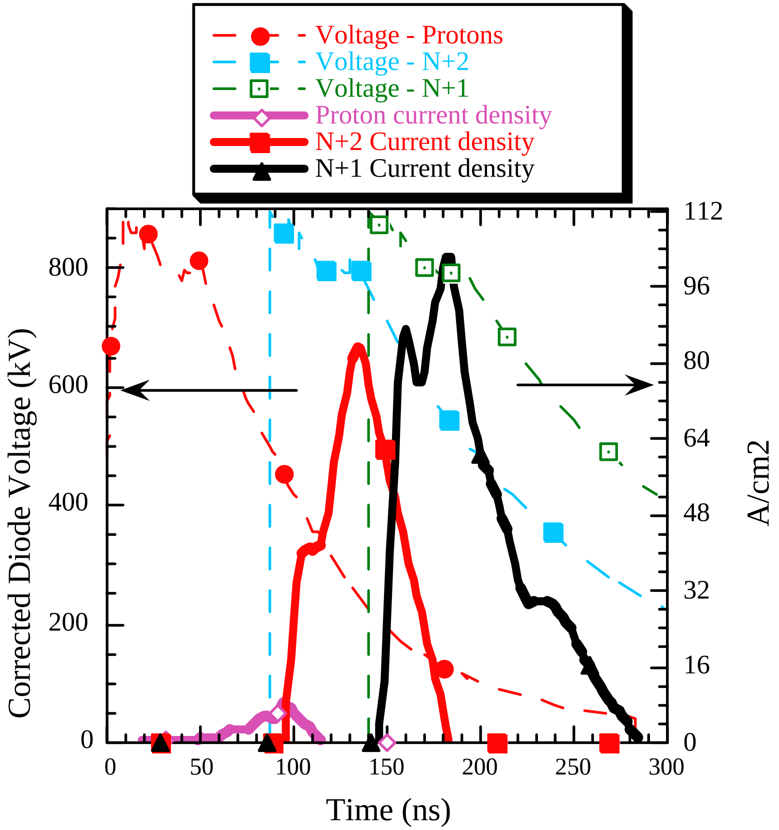
Left: Marx tank with pulse-forming line
Right: 4-Stage LIVA and treatment chamber

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

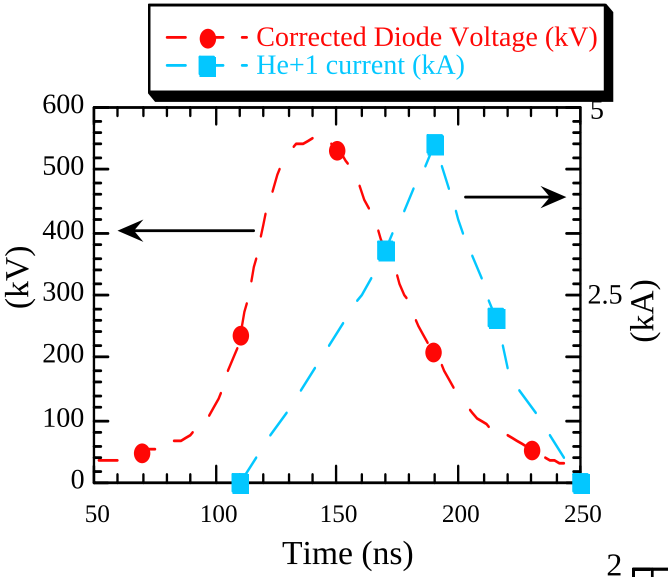
Nitrogen injection into MAP produces 3-component beam of mostly N++, N+



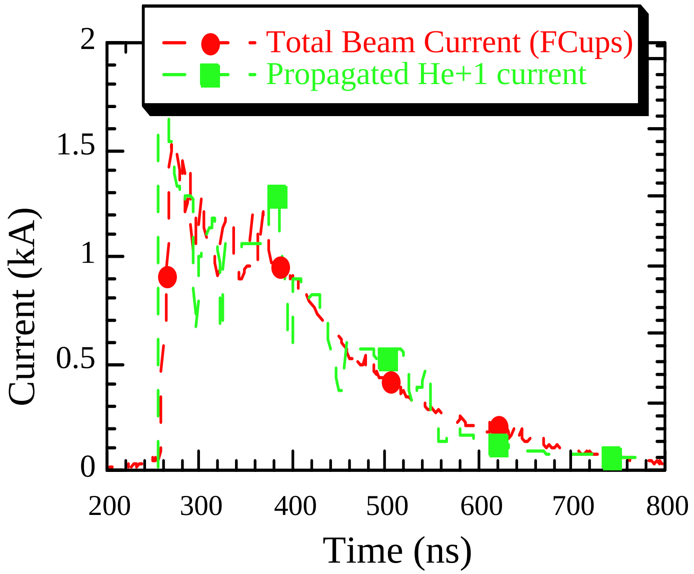
Shot 31661

- Beam predominantly N++ and N+ after small proton pulse at front
- Peak voltage = 850 kV
  Peak current density (total) ~145 A/cm^2
- Total fluence = 7.9 J/cm^2 - 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

He beam (HE^{+1}) pulsewidth is longer than N or C beam



- He current lags voltage, leading to debunching
- Current pulse width at 63 cm is almost 0.5 μsec long
- Beam here was intentionally attentuated
- He range in W (TRIM) ~ 0.9 μm
- Range similar to N beam because singly charged



Thresholds for Materials exposure to ions on RHEPP

6 J/cm² **Ablation threshold, W**

3 J/cm² **Ablation threshold, graphites, BUCKY and expt**

2.0 J/cm² **Melting threshold, PM W, 600C, SIM and expt**

~ 1 J/cm² **Roughening threshold, PM W, unheated**

? Roughening threshold, Graphite

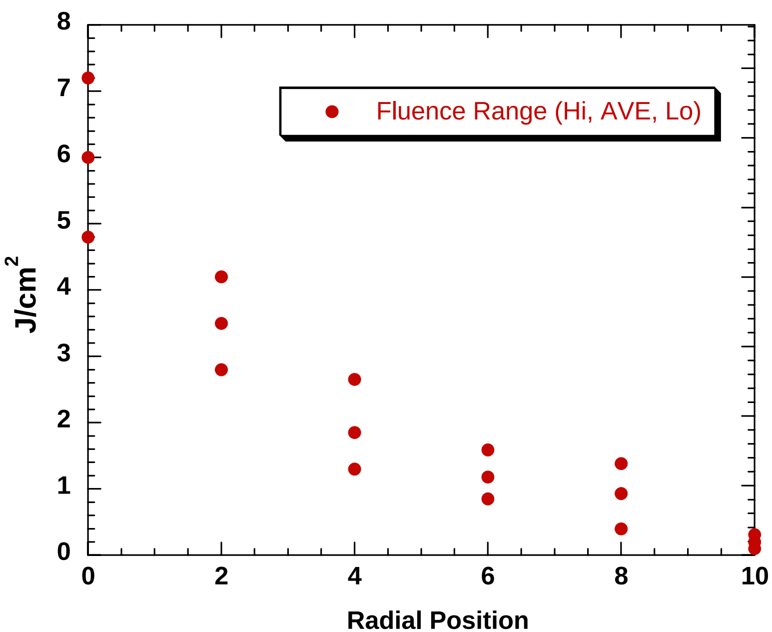
0

Based on AVERAGE fluences from RHEPP

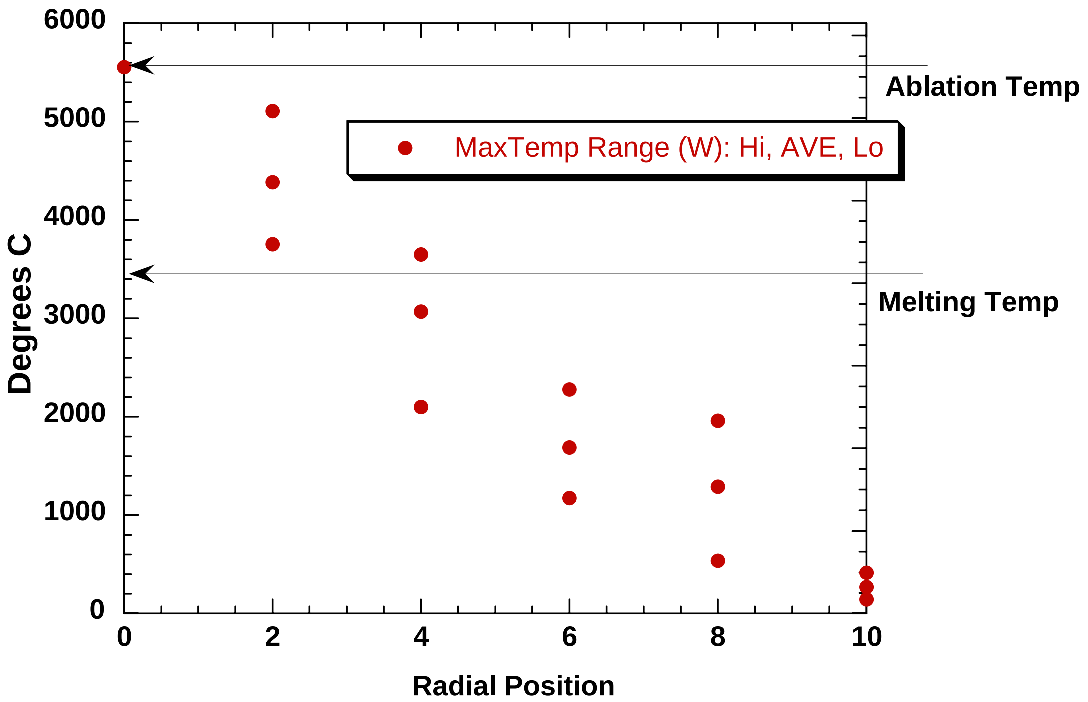
- General exposure conditions: MAP nitrogen beam, 150 ns pulsewidth, single shot.
- Roughening threshold for graphite (matrix) depends upon graphite
- Roughening threshold for W for He beam is below that for MAP N
- Roughening threshold, unheated, for
  - W25Re: 3.5 J/cm^2
  - Re: 1 J/cm^2

RHEPP-1 Surface Roughening

Range of Fluences, MaxTemps (W) for RHEPP-1



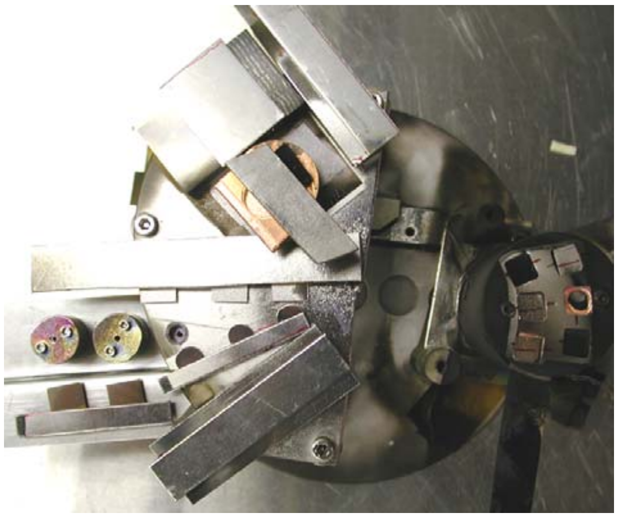
Fcups averaged over 10 or 40 pulses



TEMP simulations (SIM CODE)
Based on Fcups (Room Temp)

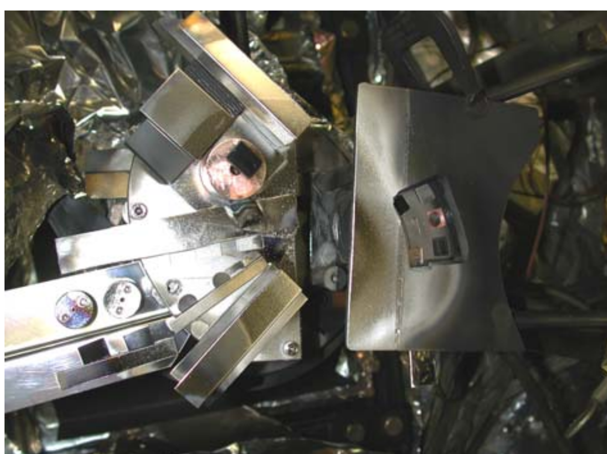
RHEPP-1 Ion Exposure

Setup for current 2000 pulse Series: Metals and graphite, RT and 520C Roughening and fatigue propagation study



Before

Heated



After 400 pulses

- Goals: Test below-melt response, explore if roughening saturates, study crack propagation, 2000 pulses total
- Upper Photo: 6-element heated samples (right), RT samples (left). Heated samples below melting, RT below/above
- Heated samples: CFC NB31, PM W (Snead), W25Re, graphite R6650, Sing XtalW(Snead), WC. C samples from FZ Julich (Linke). Velvet added later
- Samples shot 400X, then SEM, Dektak (Renk/Tanaka), then reloaded for another 400 shots.
- RT samples: PM W, Sing Xtal W, NB31, R6650, Ti-6Al-4V, W25Re, Re

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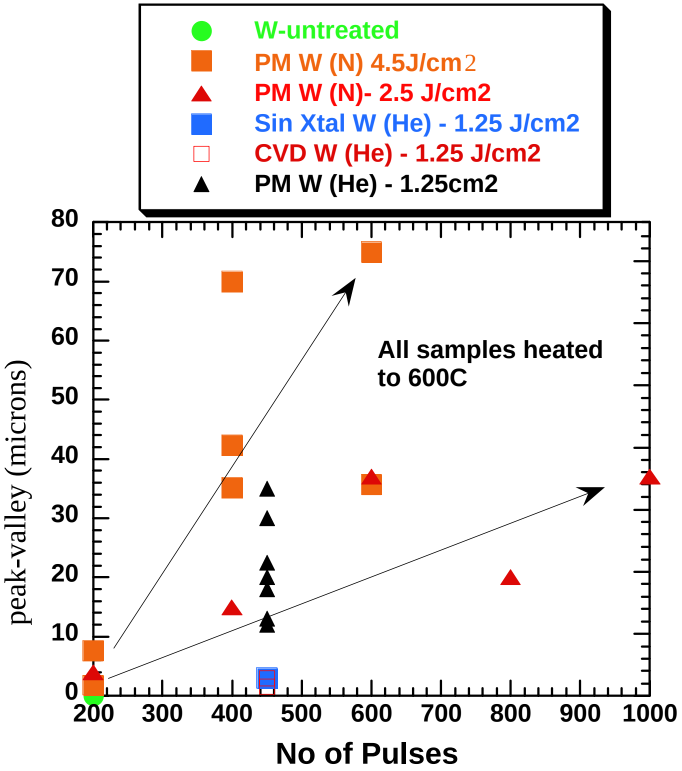
RHEPP-1 Surface Roughening

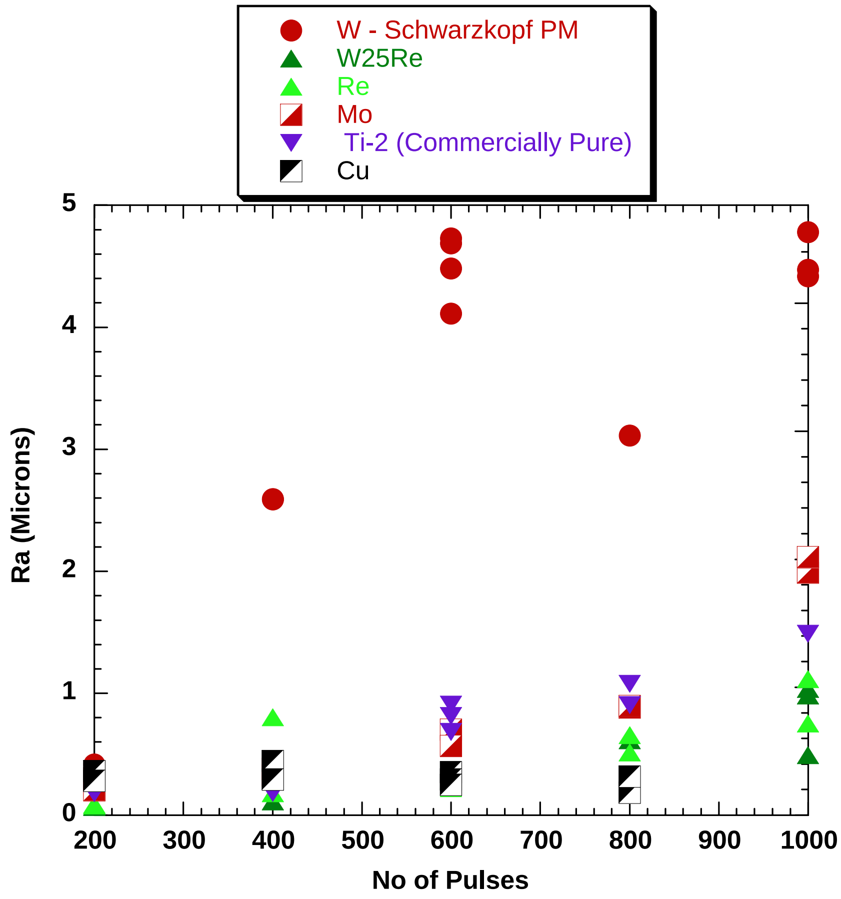
Surface Roughening: Develops over many pulses Increases with fluence/shot number; PM W the worst



- Roughening increases ~ linearly with pulse number
- Roughening increases with fluence per pulse
- Very little surface relief happens until after 200 pulses
- 4.5 J/cm² 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?

RHEPP-1 Surface Roughening

Evolution of R_a Roughness at 2.5 J/cm^2, various metals : PM W is worst, then everything else. Cu does NOT roughen

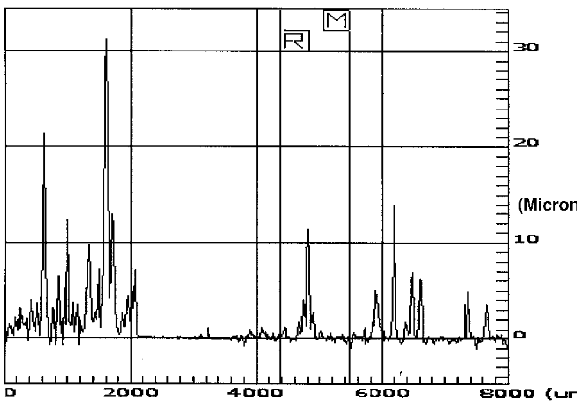


- 2.5 J/cm^2 is near or above melt for most metals shown
- Polished W and Mo are heated to 550-600C
- MO reaches 2 μm Ra at 1000 shots, but Cu remains very flat
- Ti-2, Mo roughen steadily to 1000 shots
- W Peak-Valley exceeds 35 μm at 600 shots, then plateaus. Is this a saturation point?

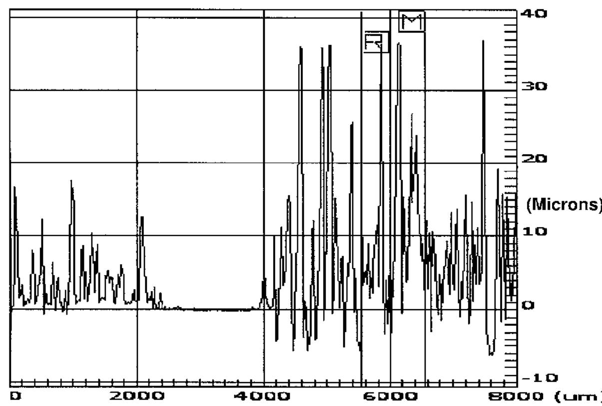
RHEPP-1 PM W Surface Roughening

R_a as function of Number of Nitrogen pulses @ 4.0 J/cm^2: (Right) - Roughness increases from 200-400-600 pulses

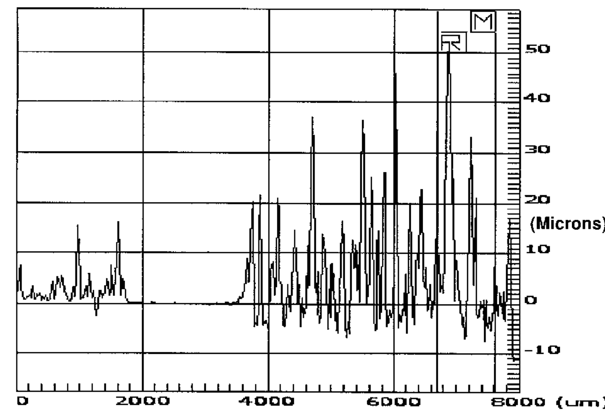
I-D 8 mm Profilometer Scans, 450x He (Left) and Nitrogen (Right)



(He) (None) **(N 200X)**



(He) (None) **(N 400X)**



(He) (None) **(N 600X)**

Ra ~ 1-3 µm
P-V ~ 10-30 µm

Ra ~ 1-3 µm
P-V ~ 5-15 µm

Ra ~ 4-9 µm
P-V ~ 20-35 µm

Ra ~ 7-10 µm
P-V ~ 50-70 µm

Left Side (He) same in ALL plots. Material: Snead PM W

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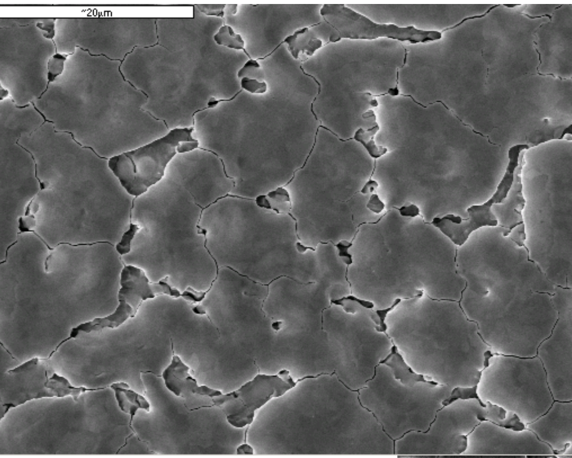
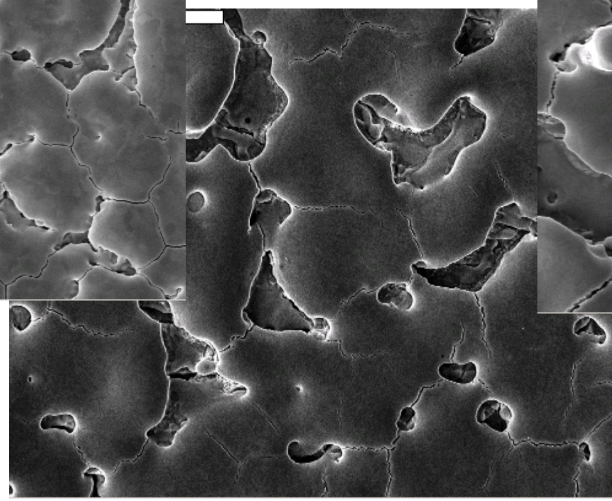
RHEPP-1 PM W Surface Roughening

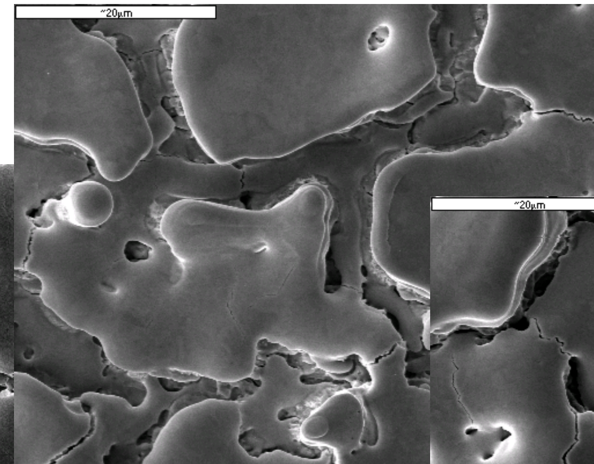
SEMs of PM W (non-melt): appears stress cracking starts, then exfoliation, forming valleys



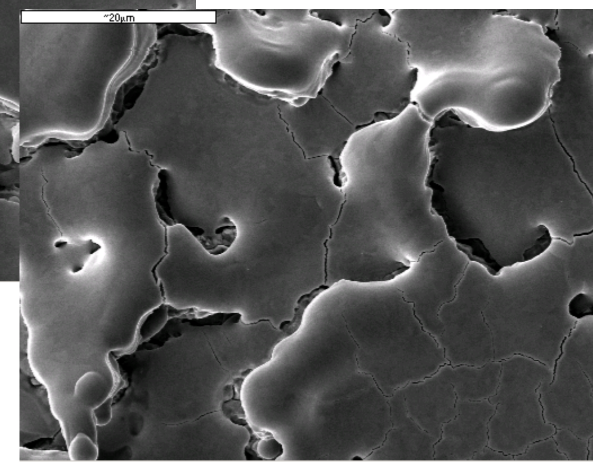
400 pulses



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?

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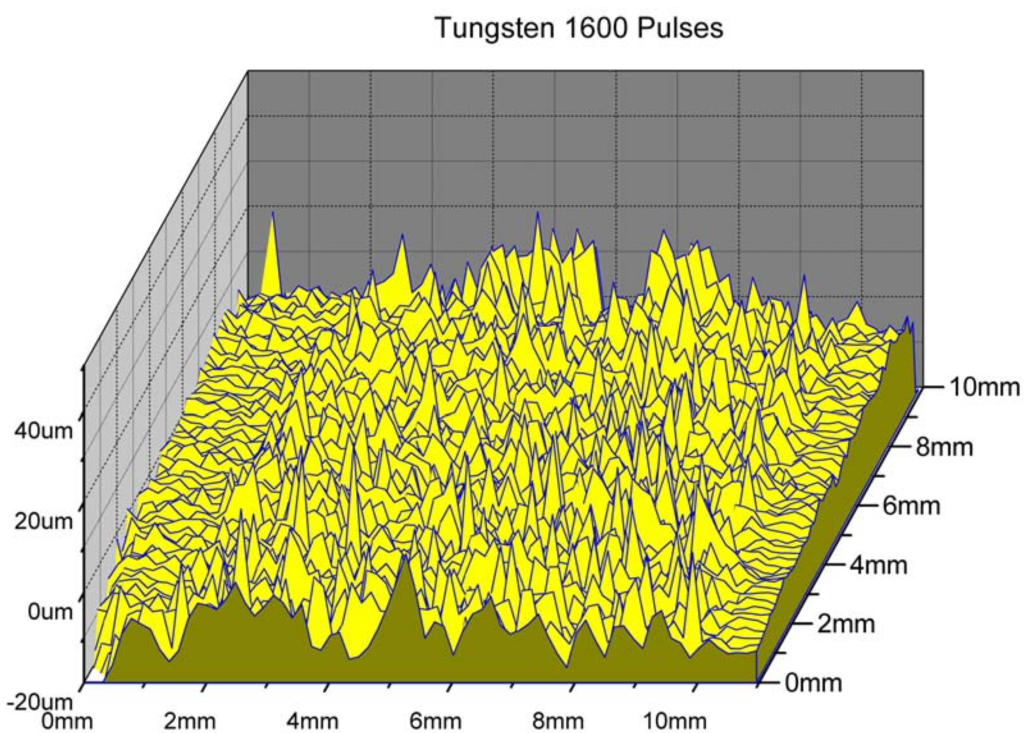
RHEPP-1 PM W Surface Roughening

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

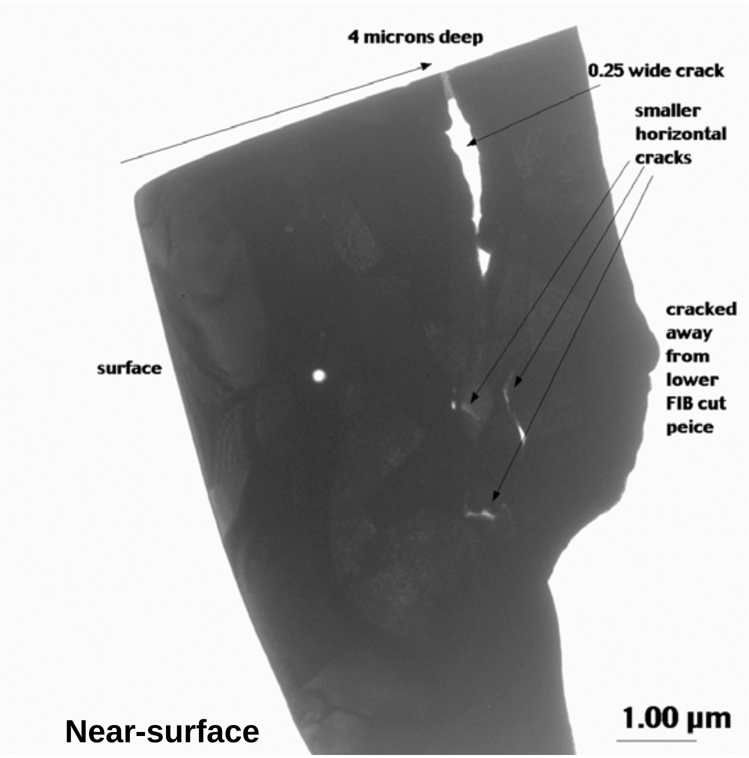


- Heated/treated PM W examined with NEXIV laser interferometry
- Comprehensive line-out scan: max height 30 μm, min height < 10 μm compared to untreated
- Very deep microcracking is present but not visible here

Exposure Conditions:
Ave 1.45 J/cm^2
Hi 1.71, Lo 1.19
MaxTemps: Ave 2900C
Hi 3275C, Lo 2450C

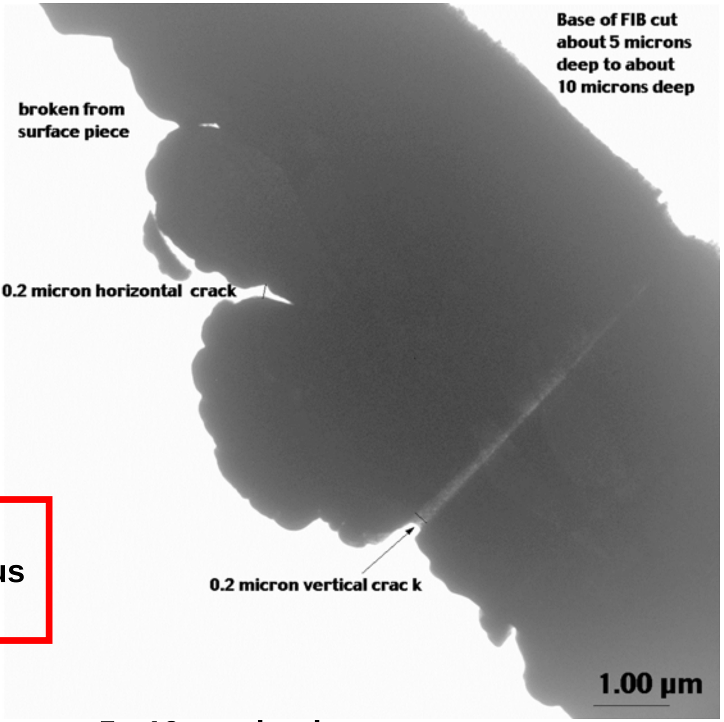
RHEPP-1 PM W Fatigue Cracking

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



Near-surface

Fatigue Cracking may be more serious than roughening

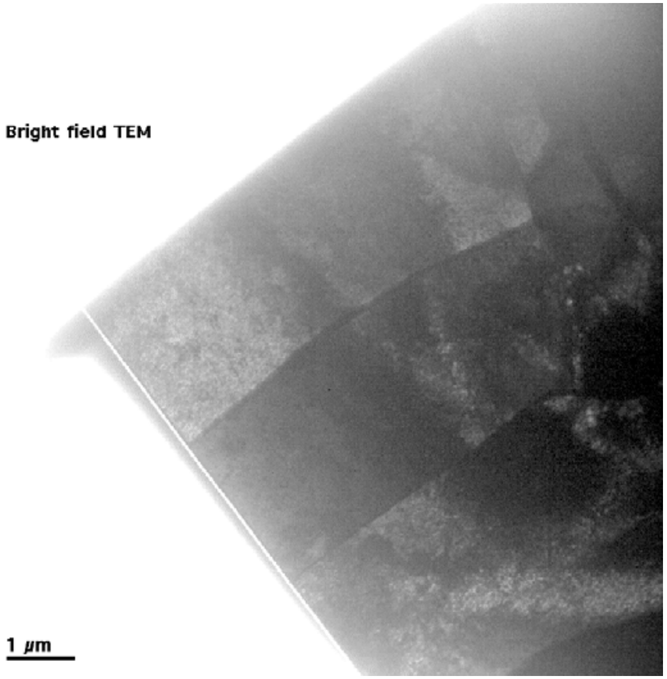


5 - 10 µm depth

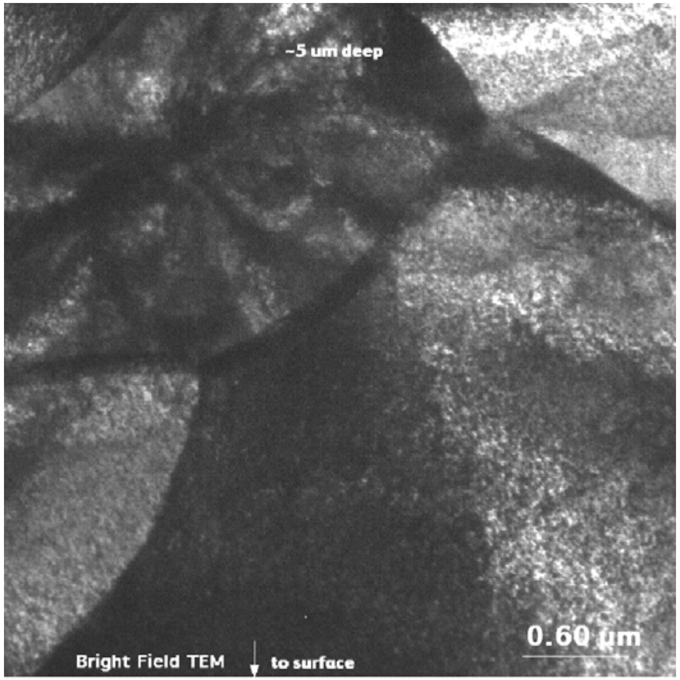
- Polished Powder Met W exposed to 100 shots N beam @ 2.25 J/cm^2 ave /pulse, ~ melting temperature at surface. No melt layer observed.
- 600°C exposure
- Sample cracking horizontally/vertically down to 10 µm depth
- Suspect fatigue-cracking

RHEPP-1 PM W Fatigue Cracking

Fatigue Cracking only evident after extended exposure - XTEM of 60X-treated PM W (right) show no cracking in depth



Bright-Field TEM image

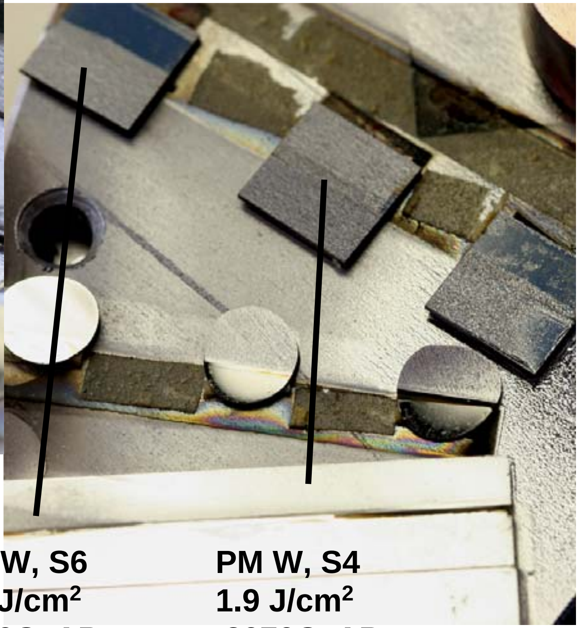


TEM image from 5 μm depth

60 pulses at ablation threshold:
No cracks

RHEPP-1 Roughening Threshold, W, Multi-pulse

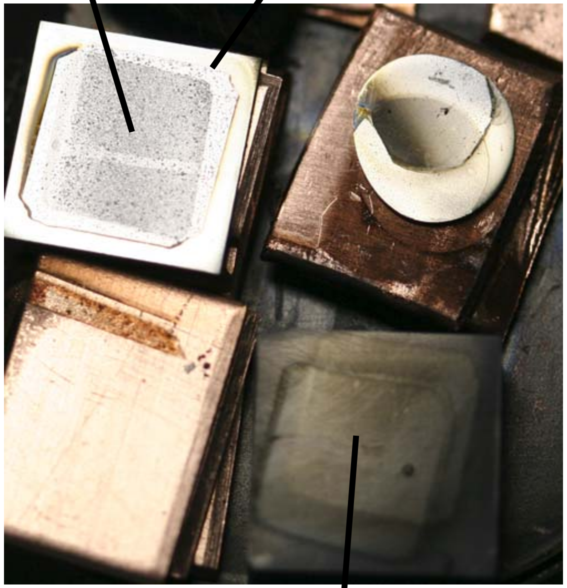
New 2000Series confirms multi-pulse roughening threshold for PM W at ~ 1 J/cm² (RT). R_a increases rapidly with fluence



PM W, N6
510C, 1.1 J/cm2
800 pulses

2272C_AP
Hi 2830C
Lo 1515C

(Collar) PM W, 400 pulses



PM W, S10
0.2 J/cm2
270C_AP
Hi 415C
Lo 145C
400 pulses

PM W, S8
0.9 J/cm^2
1290C_AP
Hi 1960C
Lo 535C
400 pulses

PM W, S6
1.2 J/cm^2
1690C_AP
Hi 2278C (5%)
Lo 1175C (5%)
800 pulses

PM W, S4
1.9 J/cm^2
3070C_AP
Hi 3650C
Lo 2100C
800 pulses

Graphite
R6650
400/800 pulses

These Snead PM W appear unaffected

These Snead PM W are very rough

AP = Average High Surface Temp
Hi and Lo occur on 5% of pulses

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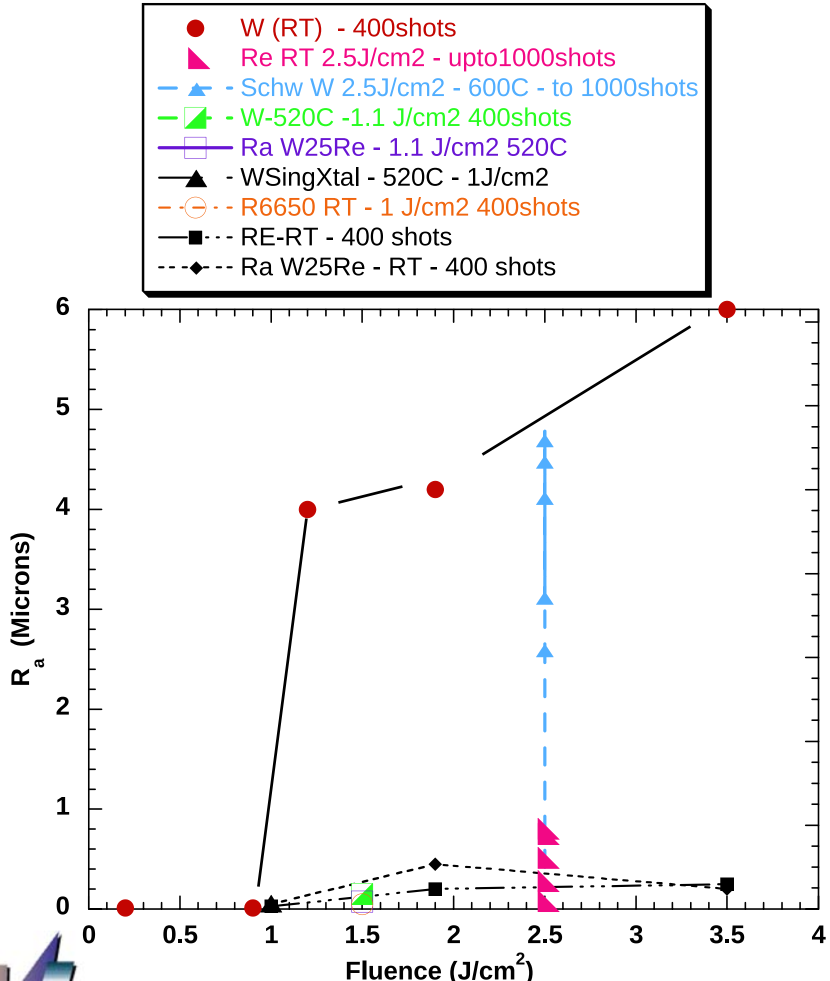
RHEPP-1 Surface Roughening, Current Series

Evolution of R_a Roughness , current series plus previous data: PM W RT roughening severe, heating helps, but trend w/shots is up

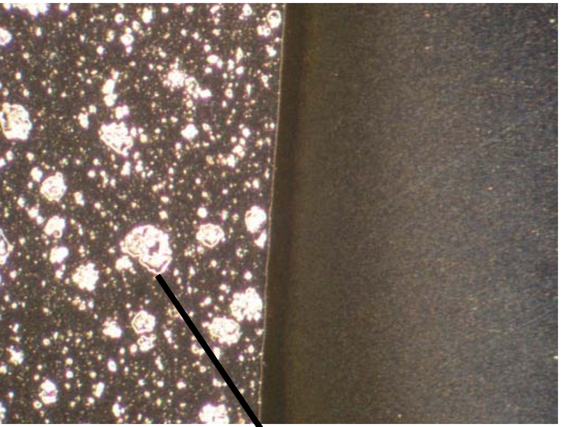


- **Red Dots - shows roughening threshold for PM W unheated - ~ 1 J/cm²**
- **Every other metal < 1 µm Ra up to 1000 pulses (Re shown)**
- **Heated PM W Snead at 1.1 J/cm² very smooth except for Divits**
- **Heated Shwarzkopf PM W @ 2.5 J/cm² reaches Snead RT roughness at 1000 pulses**

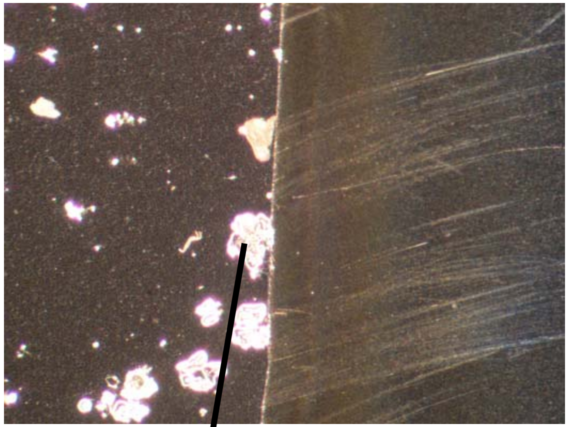
Note: Heated W, W25Re Ra does NOT include Divits

RHEPP-1 Surface Roughening

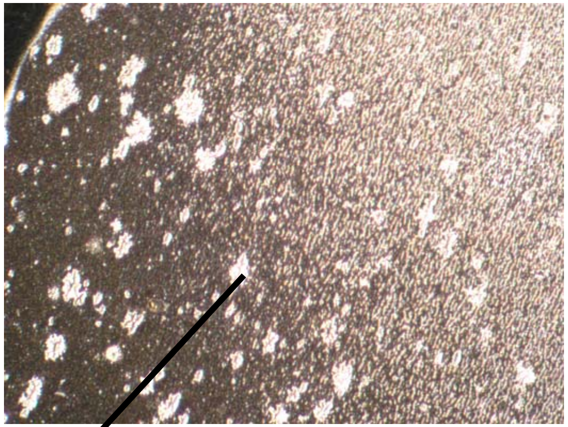
Current series, Optical Micrographs, surfaces after 400 pulses



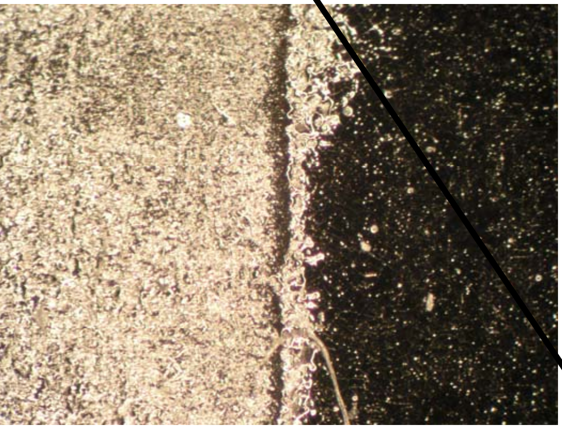
PMW, 1.2 J/cm2, 520C



W25Re, 1.2 J/cm2, 520C

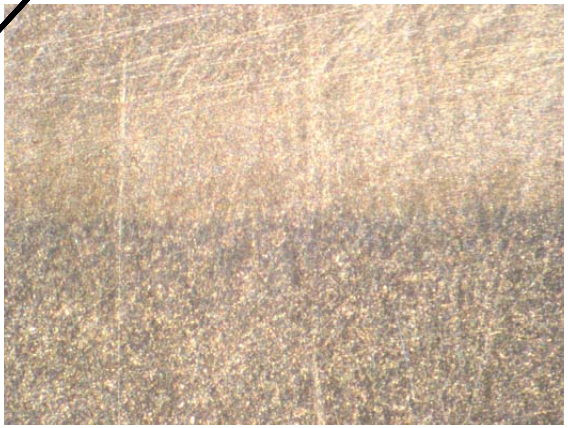


SingXtal W, 1.2 J/cm2, 520C



PMW, 1.2 J/cm2, RT

Re, 1.2 J/cm2, RT

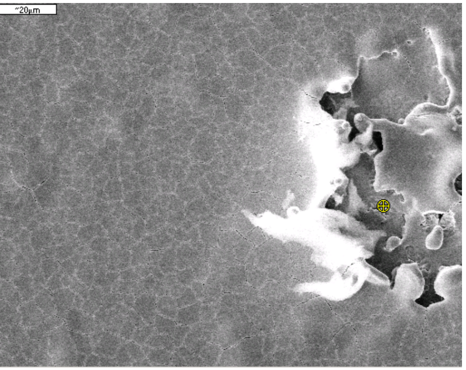


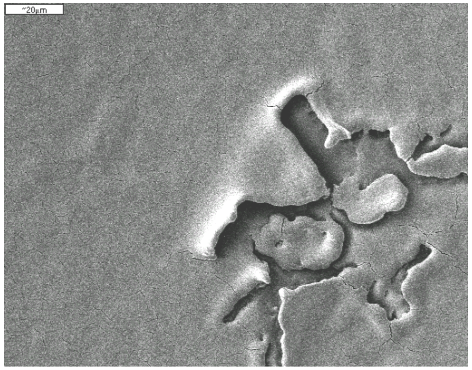
R6650 Graphite, 1.2 J/cm2, 520C

What are these?

RHEPP-1 Surface Roughening

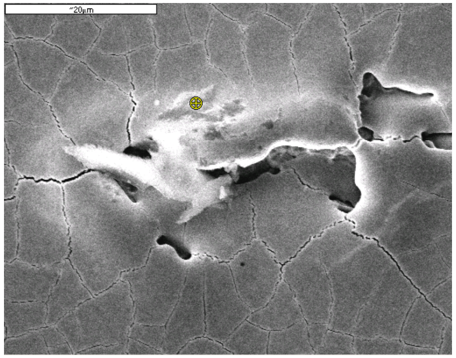
Heated W, W25Re, SingXtal smooth except for 'Divits'



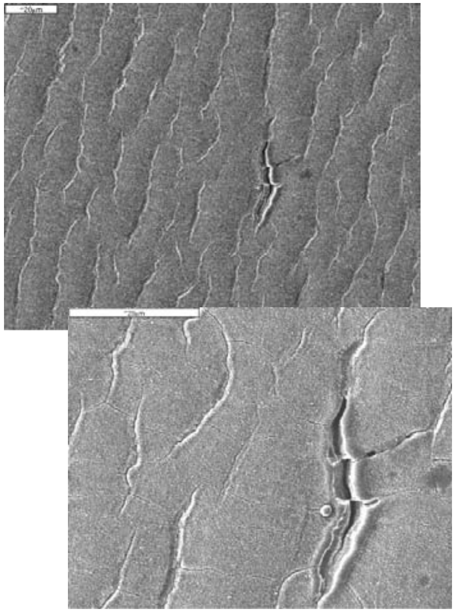


PMW, 1.2 J/cm2, 520C, 750Mag

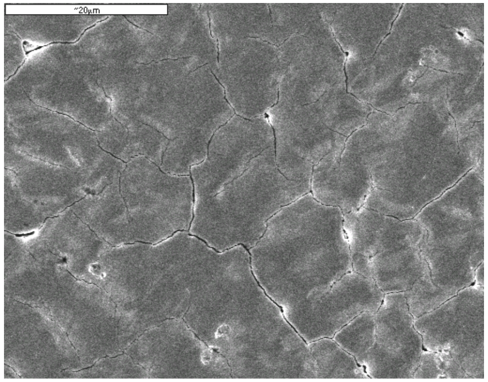
Divit Height ~ 10 µm



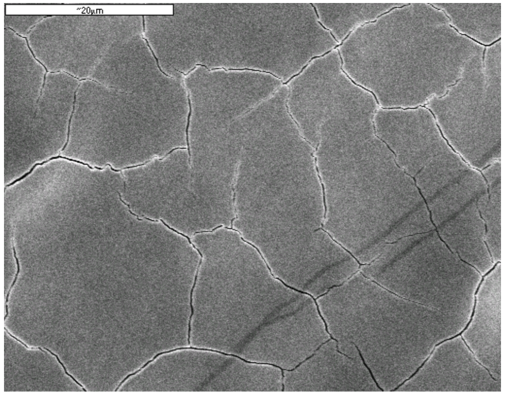
W25Re, 1.2 J/cm2, 520C, 2000Mag



SingXtal W, 1.2 J/cm2, 520C. 750Mag and 2000Mag



(Comparison) Re, 1.2 J/cm2, RT



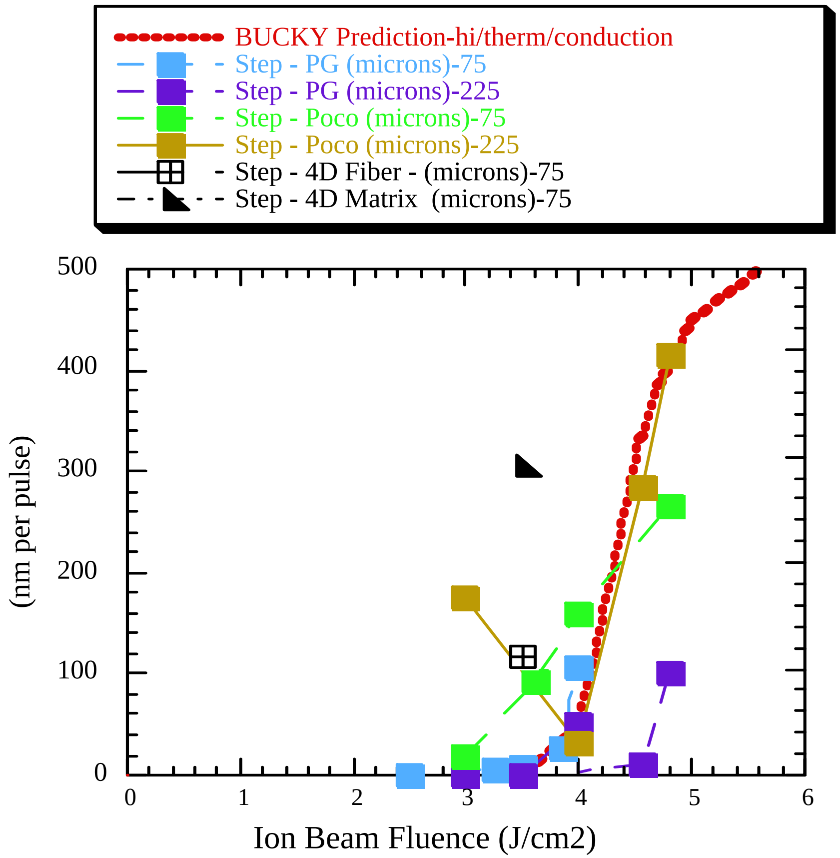
Re, 2 J/cm2, RT

Re RT: Microcracks, no Divits

PM W, W25Re, SingXtal W:
Tears in surface, opening below-grade
EDS: no contamination

RHEPP-1 Carbon Response

Graphite Response: Rapid material removal above sublimation point, consistent with BUCKY predictions

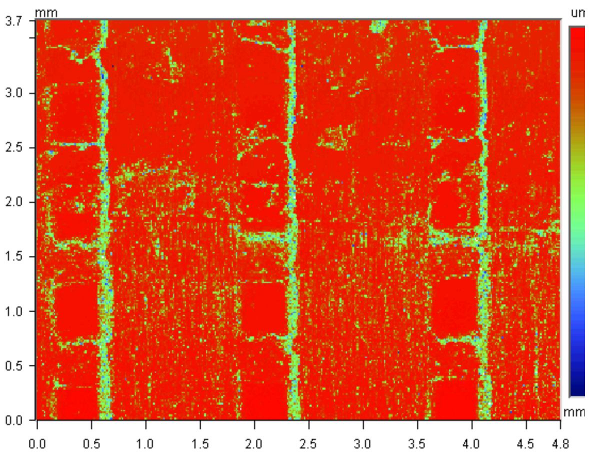


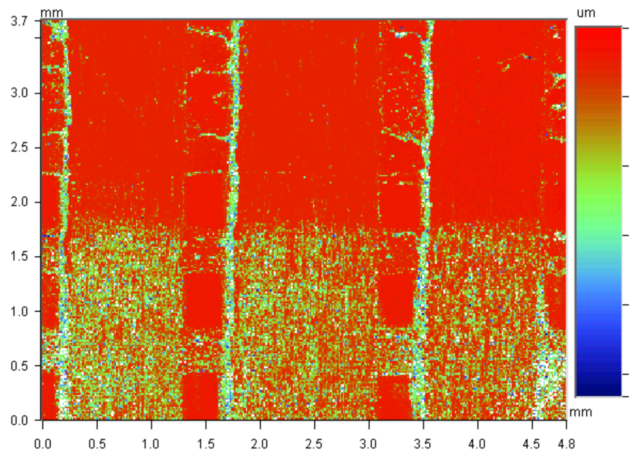
- Mechanically polished pyrolitic graphite (PG), Poco, and 4D carbon composite weave exposed to 75 pulses/225 pulses of 70% C /30% H beam at doses of 1.9 to 5 J/cm^2
- PG ablation threshold ~ 4 J/cm^2
- Poco ablation threshold ~ 3 J/cm^2
- Above threshold, rapid increase in ablated material per pulse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

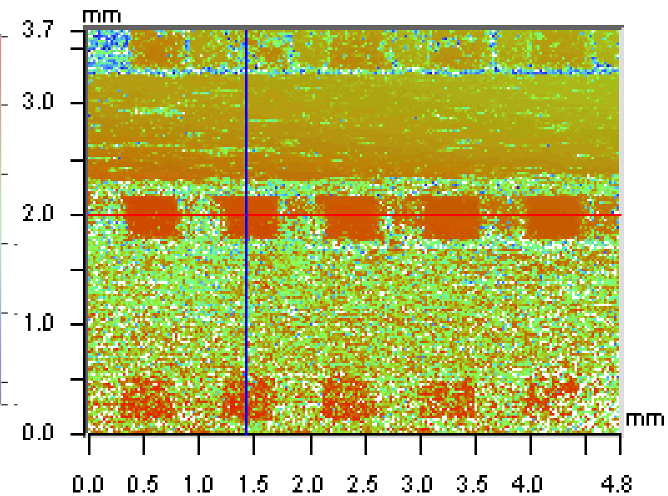
RHEPP-1 CFC Carbon Response

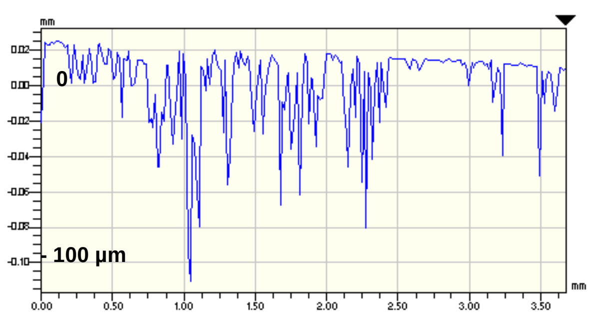
FMI-222 Fiber ends appear ablation-resistant; Matrix loss ~ 0.3 µm/pulse at 4.0 J/cm^2:

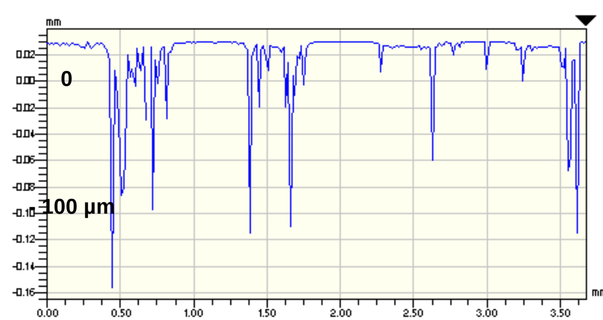
Treated at 1.6 J/cm^2 1000X | **Treated at 2.6 J/cm^2 600X** | **Treated at 4.0 J/cm^2 600X**

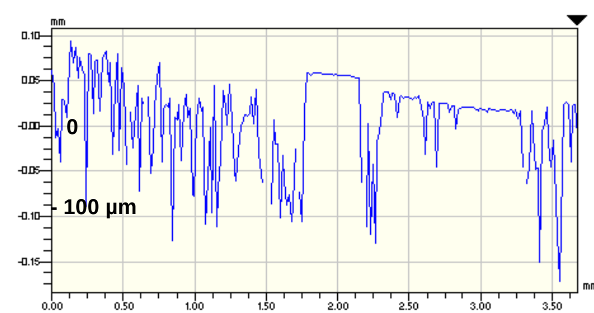






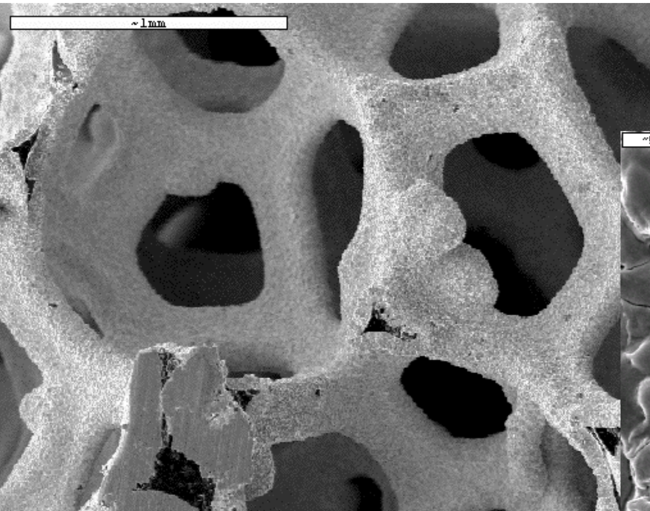




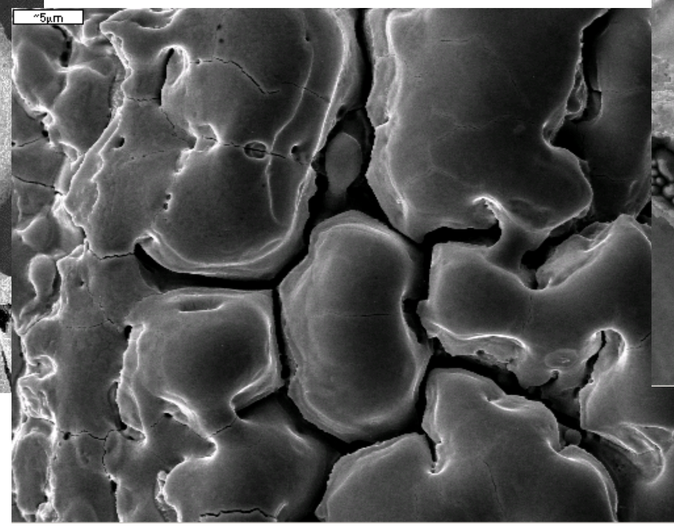


MIDDLE is approximately sublimation threshold

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

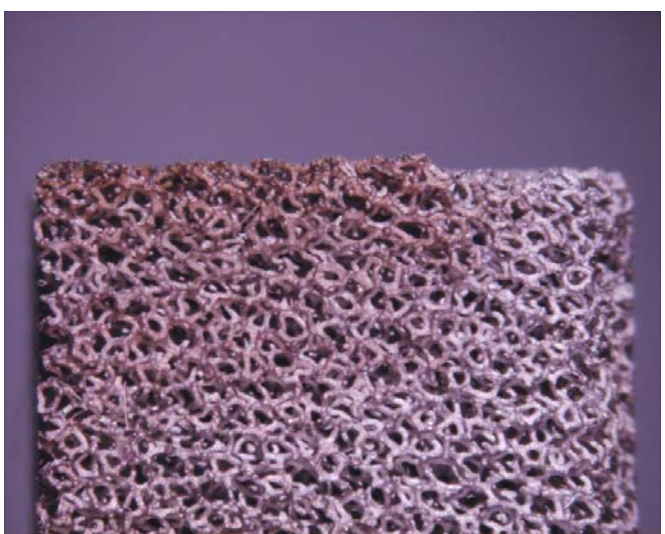


Foam geometry, untreated, 50X



W/TaC, after 1200 pulses, 2500X

W/HfC, 800 pulses, 250X



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

All exposures between 1 - 1.5 J/cm^2

SEMs:
Thinner structure, better
Bonding may be necessary

ESLI CCV/W Test Specimen

ESLI Carbon-Carbon Velvet (CCV) with sputtered-W Coating

Carbon fiber volume packing	1.9%
Sputtered-W film thickness	1.6 µm over area

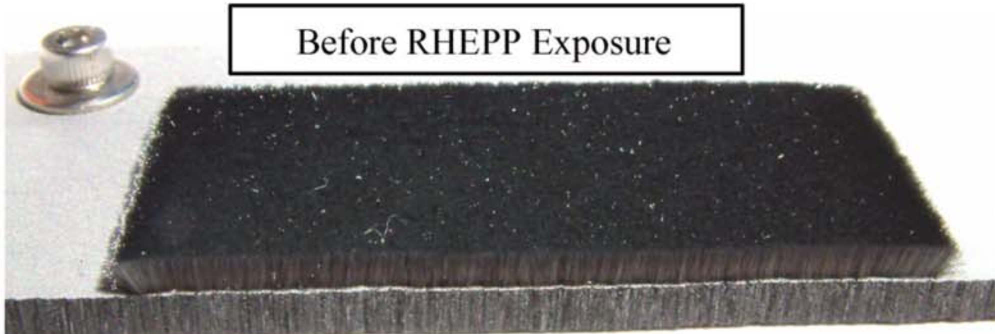
Thick (1.6 µm) caps on fiber tips; thin (<0.1 µm) film on fiber shafts (thickest at top)

Design for RHEEP incidence angle (0.3-0.5 radian)

Fluence distribution

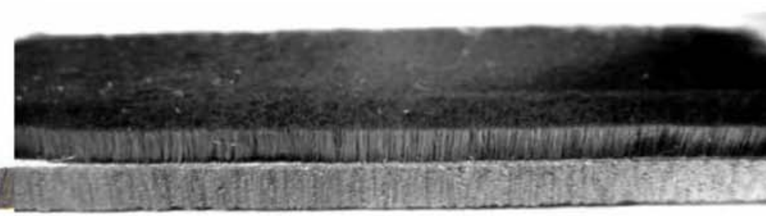
On flat fiber tops	100% of incident fluence
On fiber shafts	< 25% of incident fluence (max near top)
On graphite substrate	<5% of incident fluence

Before RHEPP Exposure



50 x 25 mm^2 fiber area
1/8” Graphite Substrate

After RHEPP Exposure

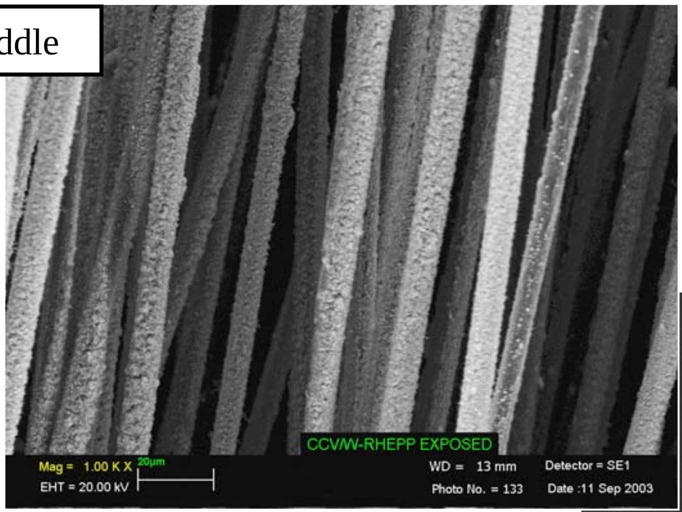


50 x 6 mm^2 fiber area exposed
(remainder masked by Ta foil)

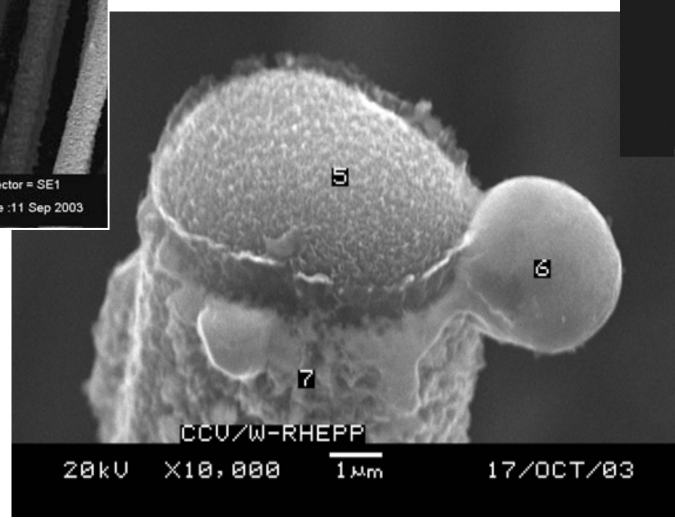
RHEPP-1 Carbon/W Velvet Response

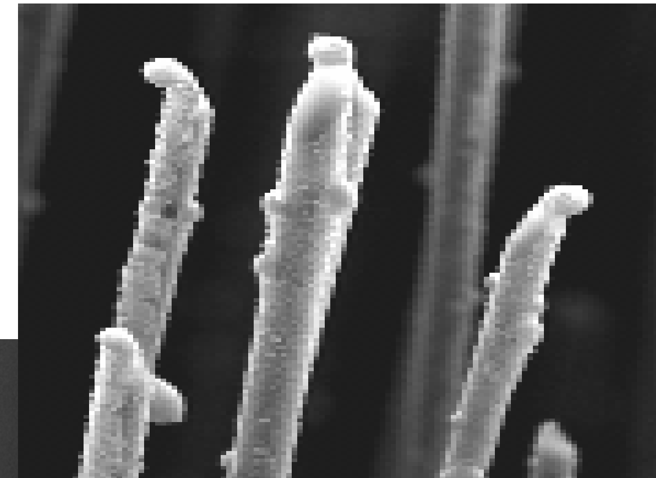
W-coated Carbon ‘Velvet’ exposure to ions: 1.6 μm W survives on sharp tips, 200 pulses at 6 J/cm^2

Middle



Fiber sides, W-sputtered, after treatment





Tapered tips, showing W still in place

1.6 µm W survives ablation-level Fluence on SOME tips

Materials Modification Laboratory

Sandia National Laboratories

Summary

- Ion and X-ray exposure forms key part of Laser IFE Direct Drive First-Wall Threat. RHEPP-1 ion beams (multi-pulse)and Z x-rays (single-pulse) can simulate this threat with good fidelity

- Z results (X-rays on tungsten): melt threshold at 1.3 J/cm^2; roughening threshold is grain-structure dependent, but < 1 J/cm^2

RHEPP Results:

- For W materials, most serious issues are 1) Roughening below melt, evidently caused by thermomechanical stress, and 2) Stress cracking. Stress cracks deepen with pulse number, and may reach deep into interior. This is true regardless of melt. ‘Divit’ formation may indicate outright mass loss. Lower limit forPM W roughening is low ~ 1 J/cm^2.

- For Graphite/Carbon Composites (CFCs), good survivability at low fluence, but rapid loss above sublimation. Physical sputtering or radiation-induced sublimation?

- Engineered materials such as ‘Velvet’ or ‘Foam’ are up-optimized so far, but may be an alternative surface design

- These results are also relevant to MFE W exposure due to Type I EL