SAND2015-10837PE

Survivability of first-wall fusion materials: relevance to IFE and MFE

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

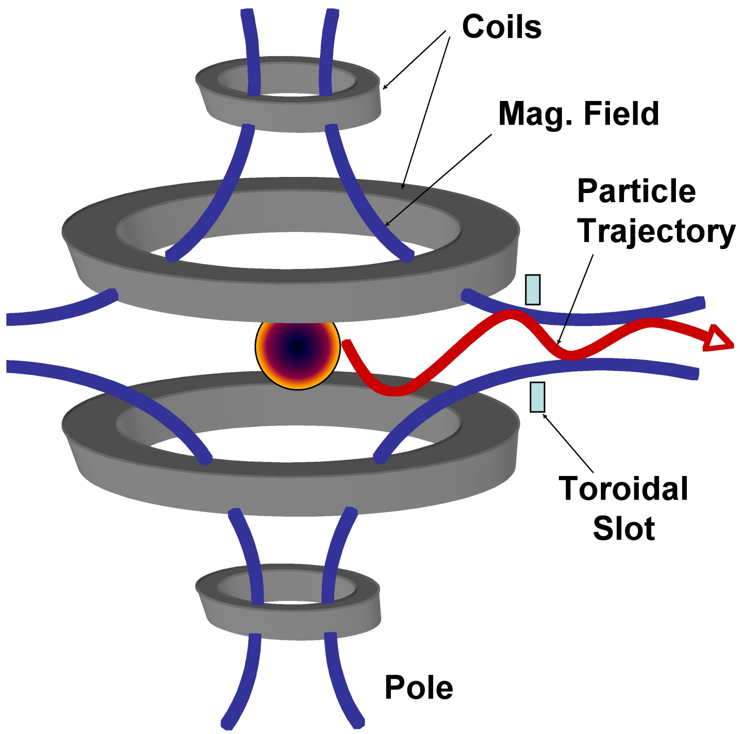
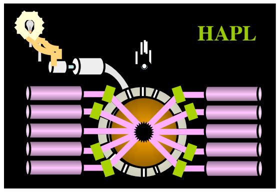


Image provided by R. Raffray, UC San Diego



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

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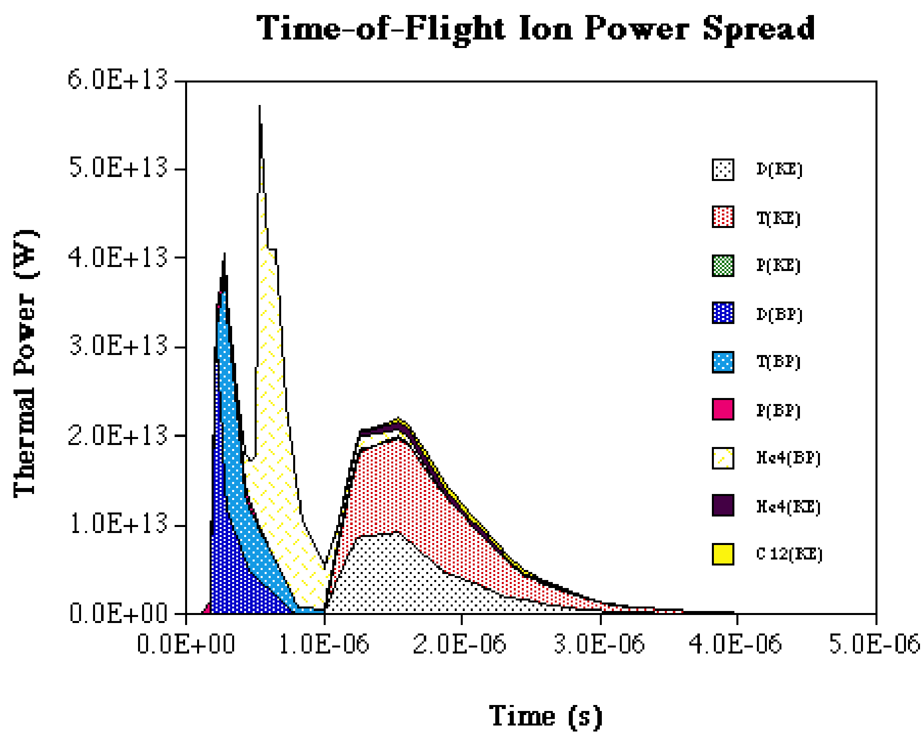
Laser IFE Direct Drive Threat Spectra (note: NIF is indirect drive)



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 *μ*sec 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$^{1/2}$

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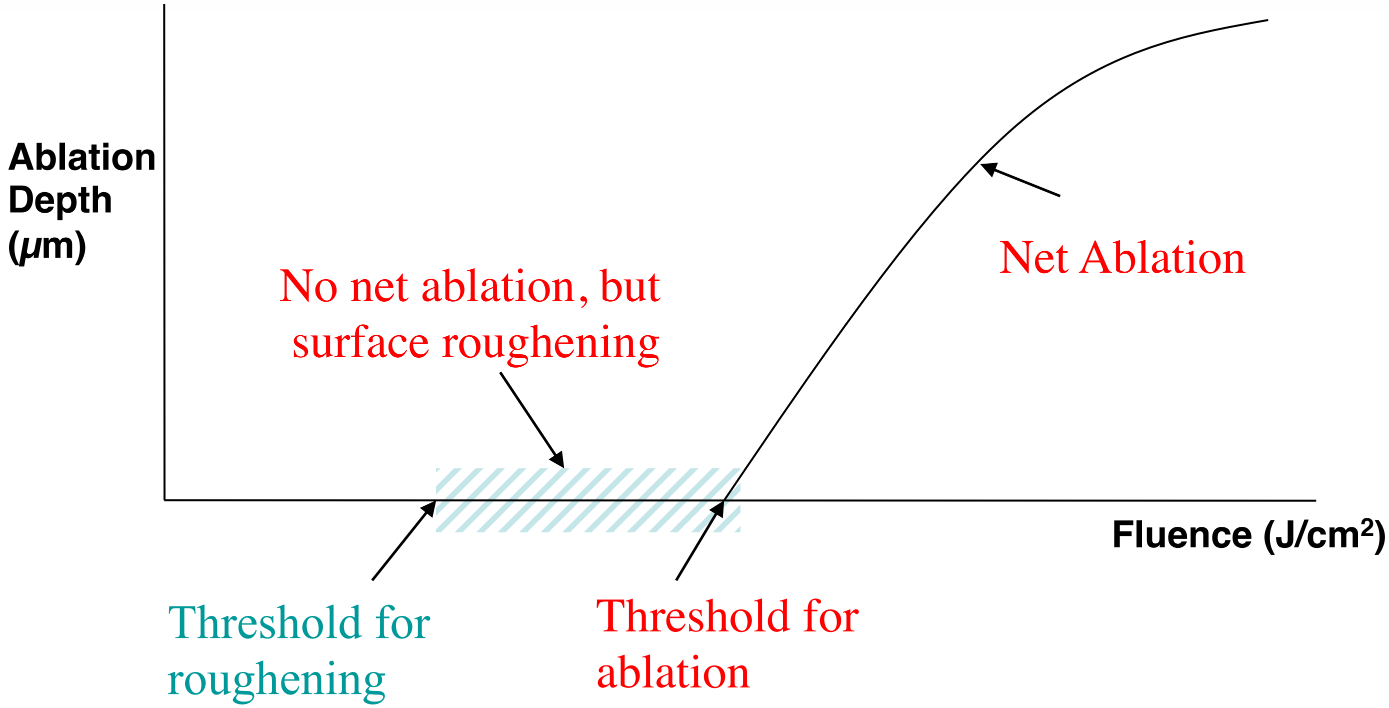
Regimes of IFE Materials Response to Ions



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)

Thresholds for Materials exposure to ions on RHEPP

6 J/cm^2 — Ablation threshold, tungsten

3 J/cm^2 — Ablation threshold, graphites, BUCKY code and experiment

2.0 J/cm^2 — Melting threshold, PM W Plansee, 600C, SIM and experiment

1.25 J/cm^2 — Roughening threshold, PM W Plansee, unheated

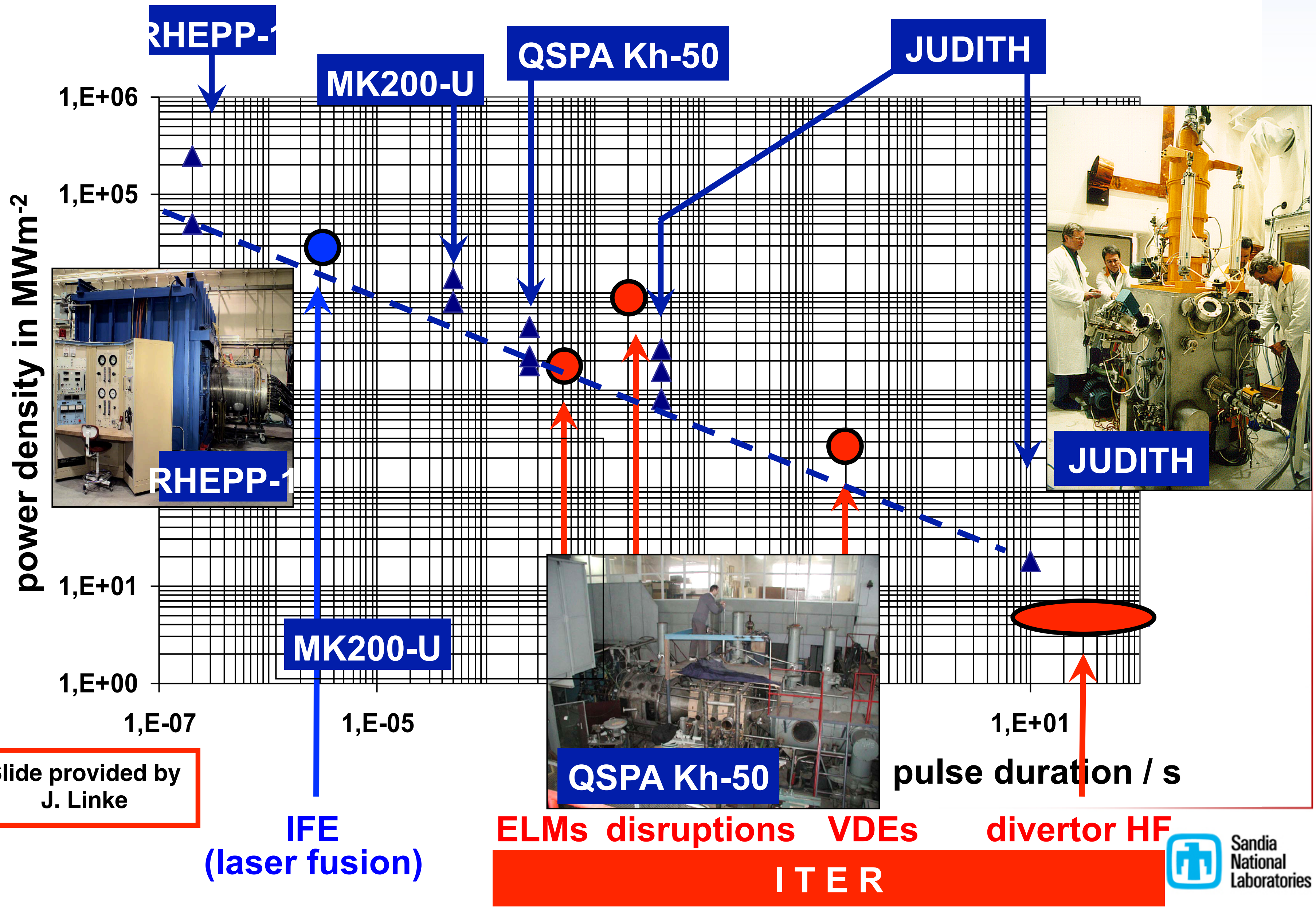
? Roughening threshold, Graphite

0

- General exposure conditions: MAP nitrogen beam, 150 ns pulsewidth, single shot.
- Roughening threshold for graphite (matrix) is unknown, but probably below 0.5 J/cm^2
- Roughening threshold for tungsten for He beam is below that for MAP Nitrogen
- Chart to left: '**PM W Plansee**' refers to random-grain Powder Met Tungsten provided by Plansee

Adding P*√t connects IFE with MFE simulation of short transient thermal loads

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft



Slide provided by
J. Linke

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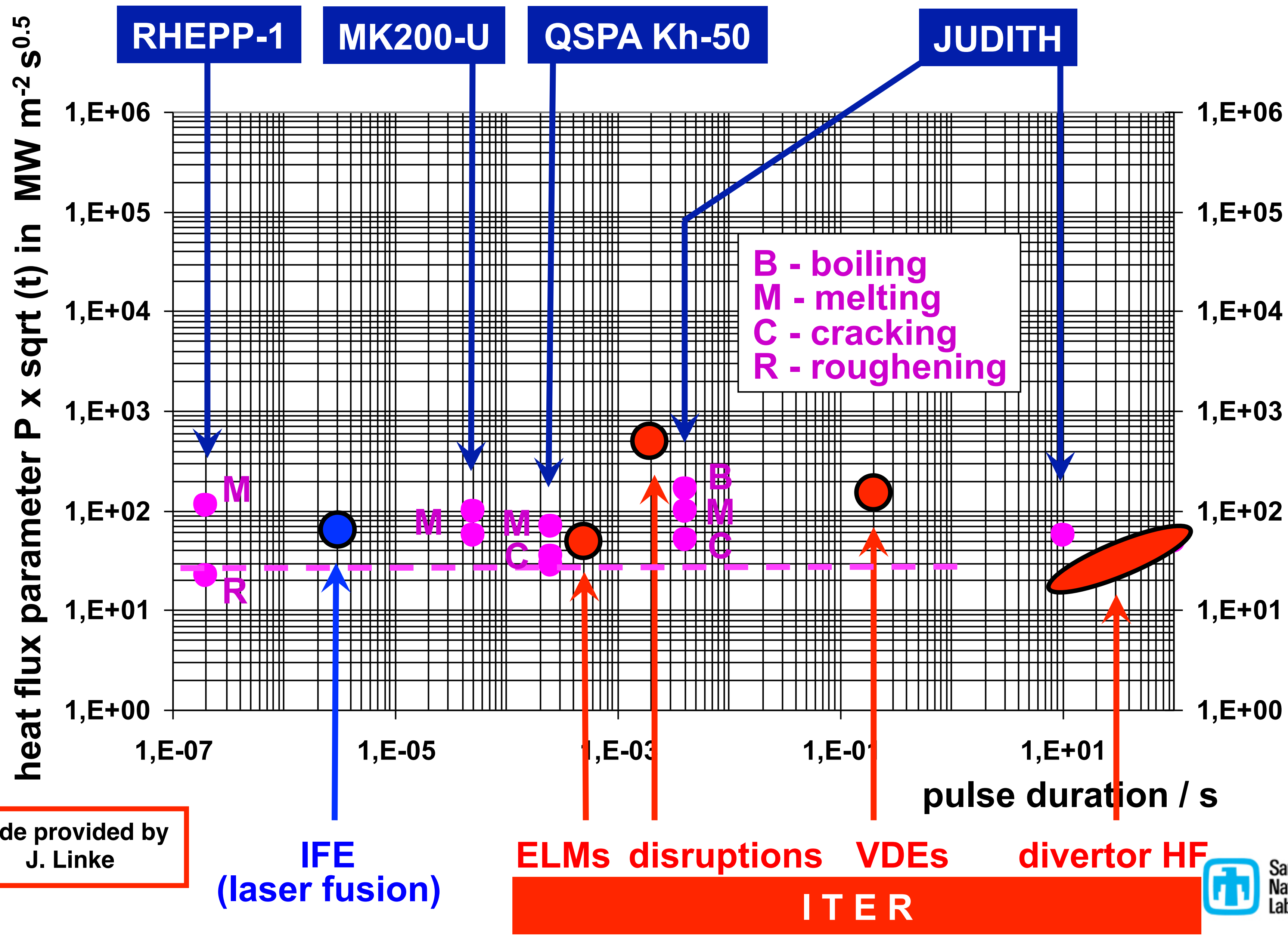
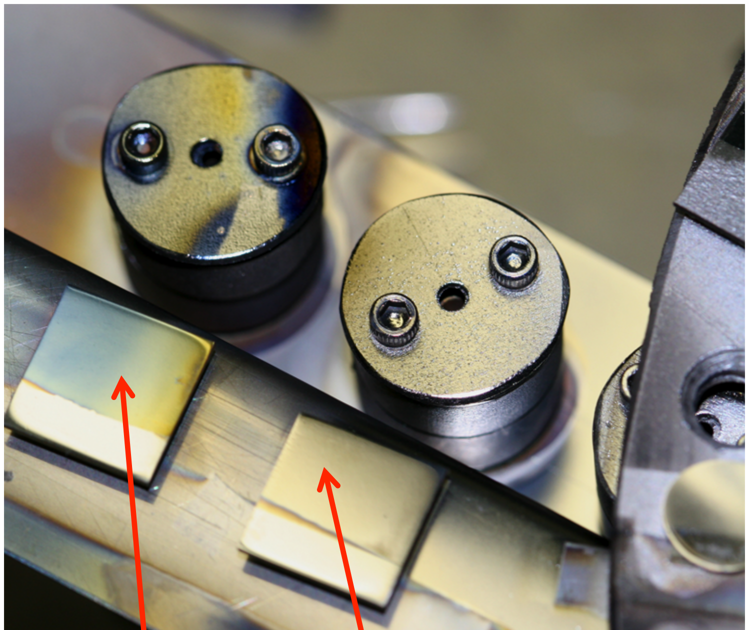
Performance of tungsten under short transient thermal loads. Confirms heat conduction dominates over direct energy deposition



Slide provided by J. Linke

RHEPP-1 Roughening Threshold, PM W, Multi-pulse, nitrogen beam exposure

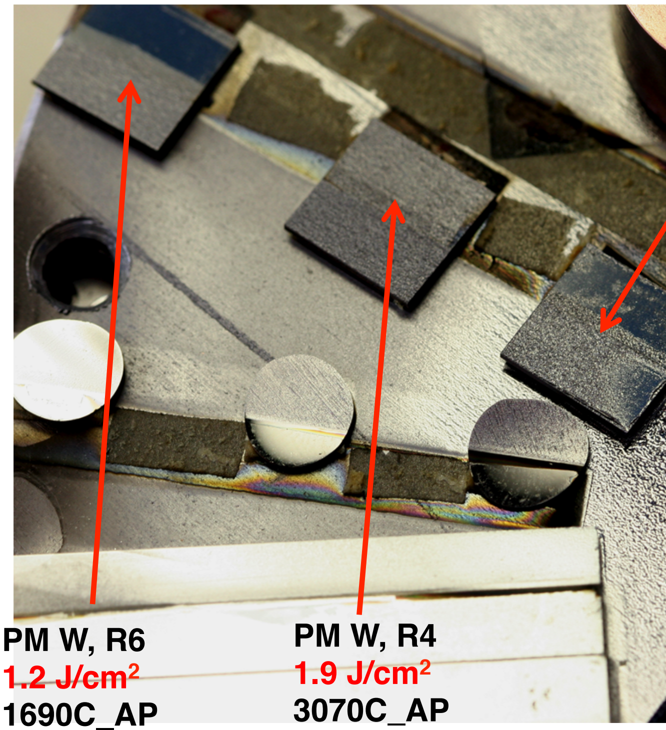
2000 shot series: PM W samples laid out radially from center. 10 and 8cm out are sub-threshold for roughening, 6cm is above. Note temperature excursions from modeling, based on fluence scatter from FCup data.



PM W, R10
0.2 J/cm2
270C_AP
Hi 415C
Lo 145C

PM W, R8
0.6-0.9 J/cm^2
1290C_AP
Hi 1960C
Lo 535C

These PM W appear unaffected



PM W, R6
1.2 J/cm^2
1690C_AP
Hi 2278C (5%)
Lo 1175C (5%)
R_a ~ 2.5 μm

PM W, R4
1.9 J/cm^2
3070C_AP
Hi 3650C
Lo 2100C
R_a ~ 4 μm

These PM W are very rough

PM W, R2
3.5 J/cm^2
4300C_AP
Melt Duration 159 ns
Melt Depth 0.8 μm
R_a ~ 6-10 μm

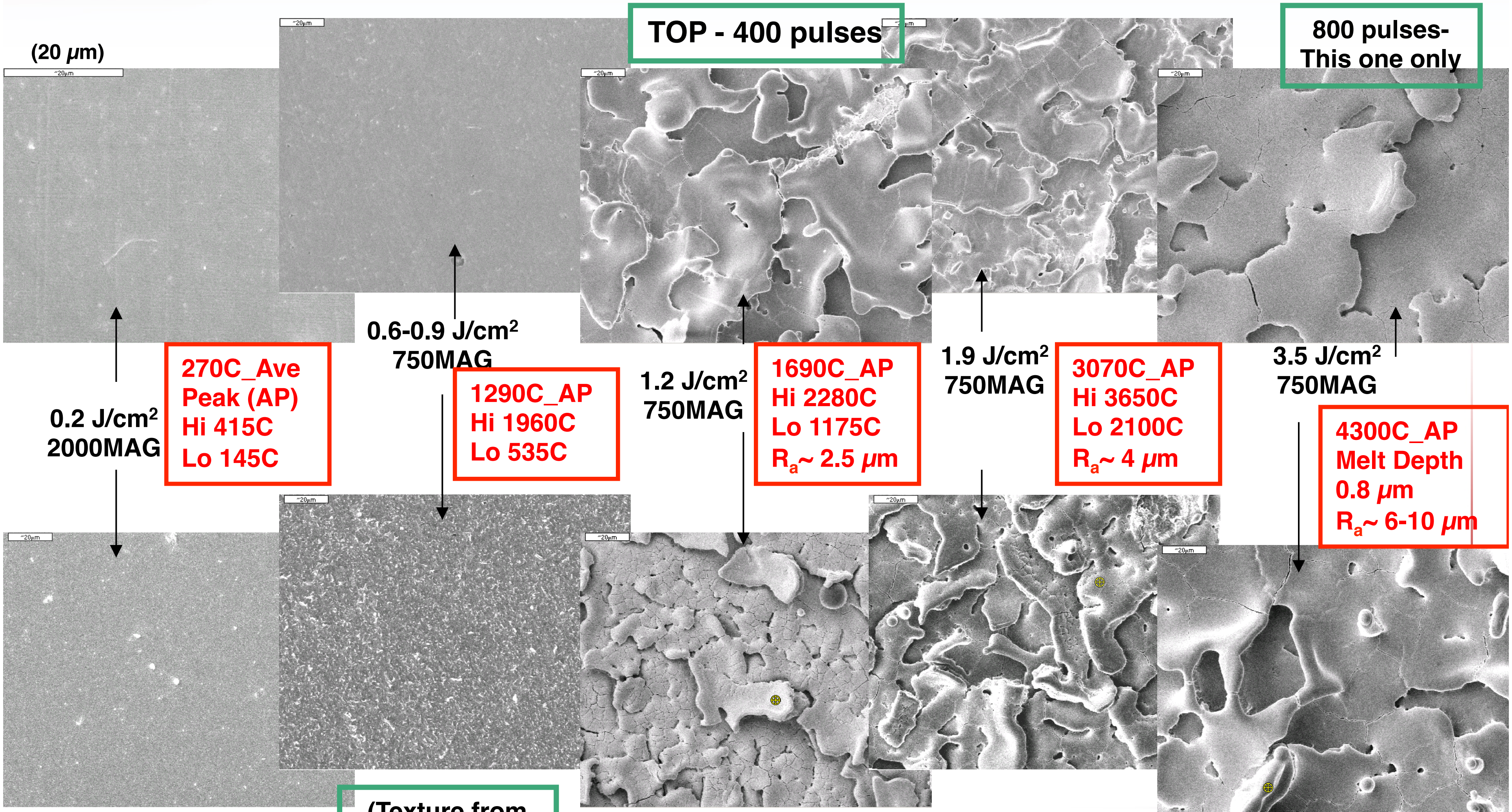
BEAM CENTER

R6 = 6 cm from Beam center

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

RHEPP-1 Roughening Threshold, PM W, Multi-pulse, nitrogen beam exposure

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



All samples initially Room Temperature (RT)

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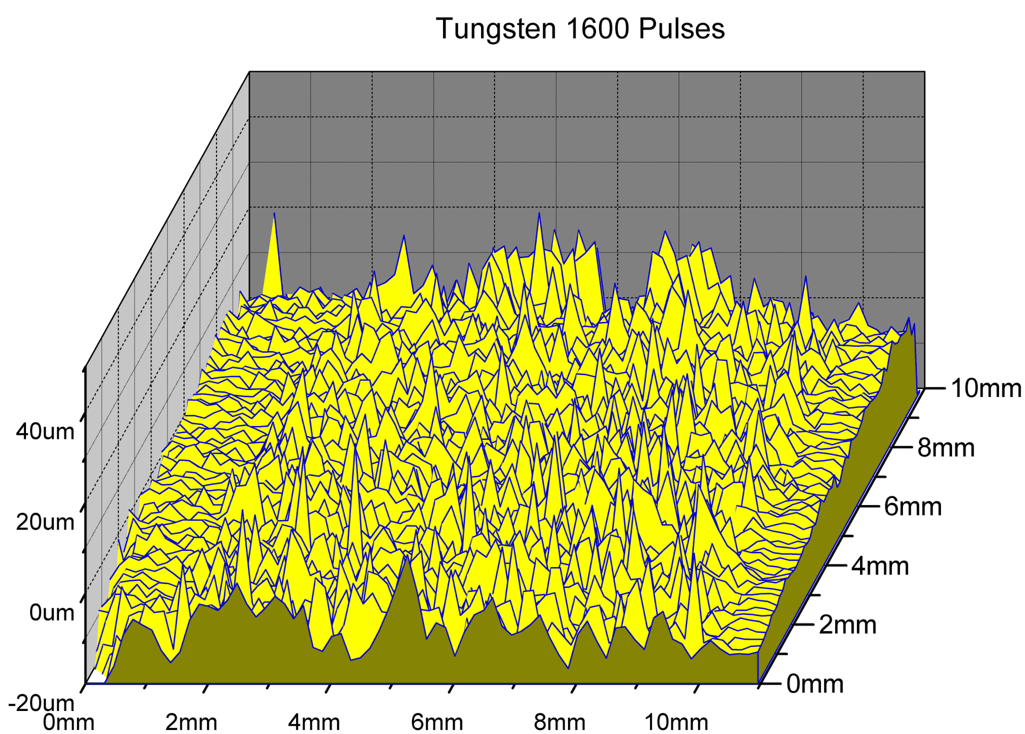
Is this erosion from melting? No. PM Tungsten after 1600 pulses (non-melting): Mostly mountains



- **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 micro-cracking not visible here**
- **Hypothesis: Thermal expansion from heating, plastic deformation**

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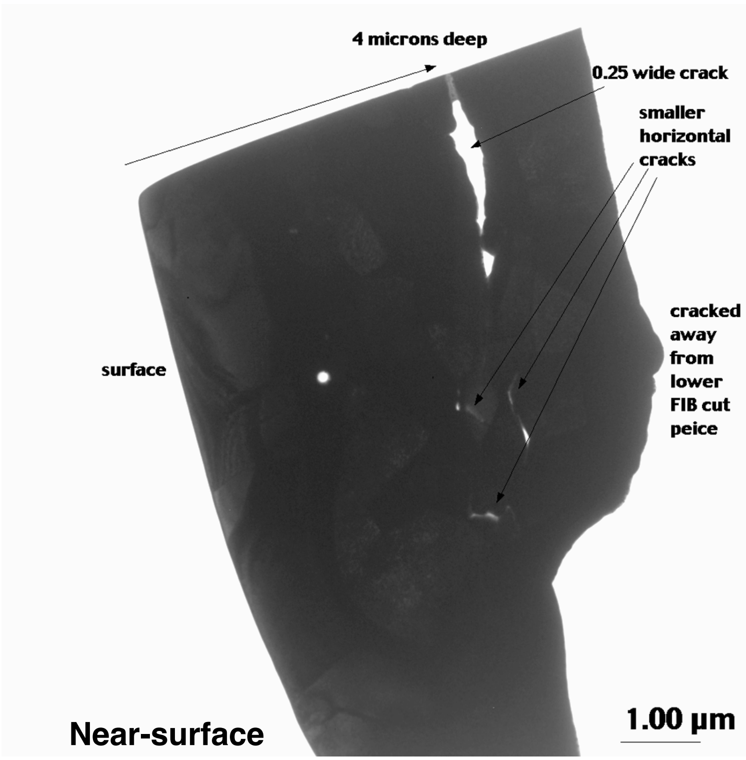
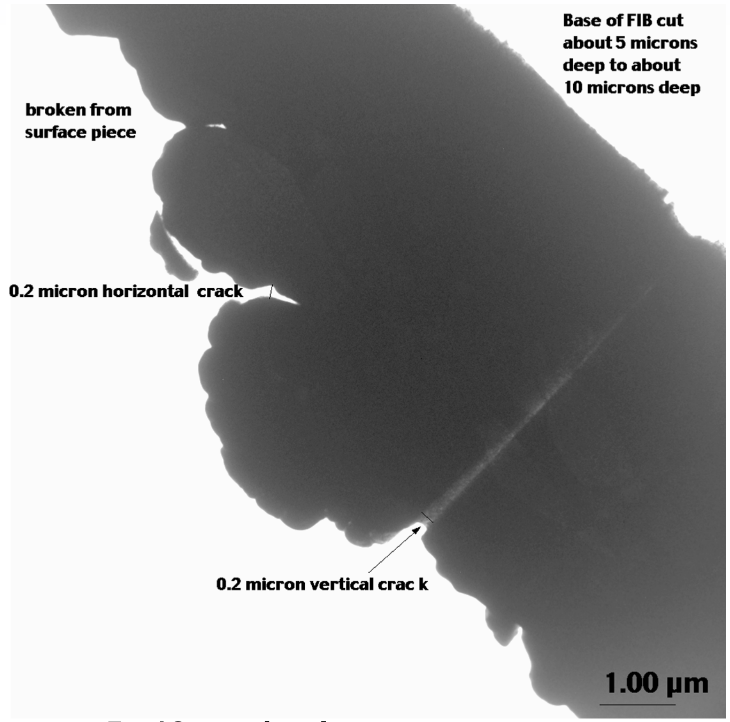
FIB-XTEM of 1000-pulse W at 2.25 J/cm^2 (ave): Deep horizontal/vertical cracking without melt



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. If deep enough to reach steel substrate, wall will fail

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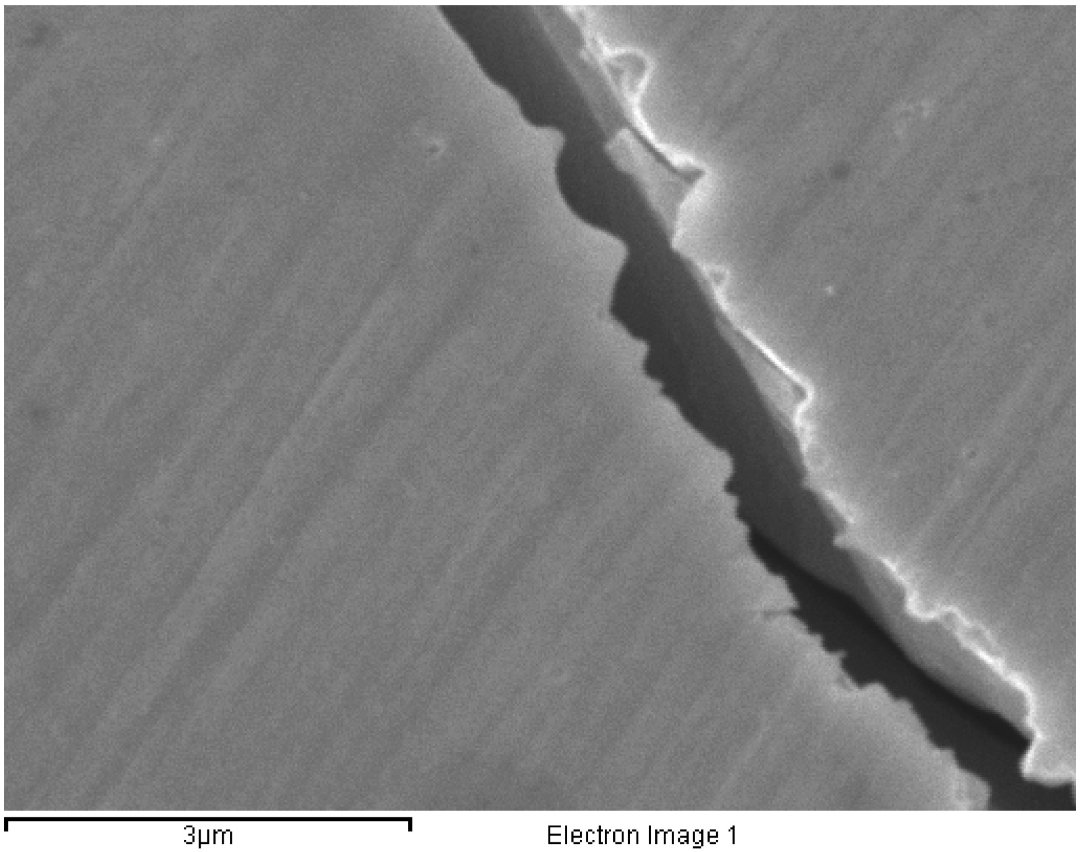
Evidence of lack of melt on Single Crystal Surface: 15,000X SEM

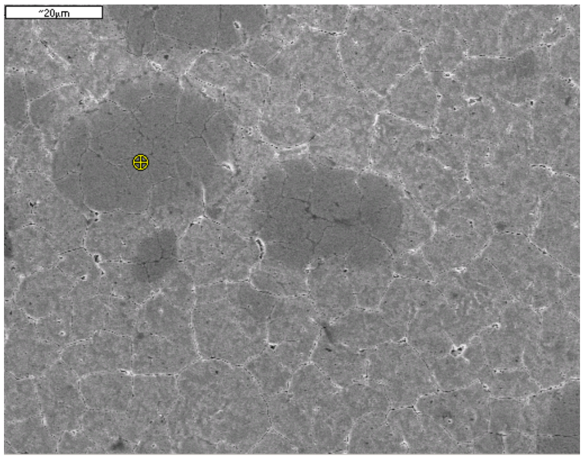


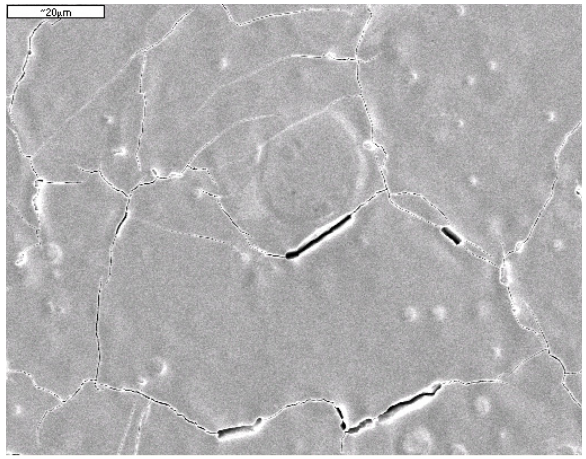
- Surface of Single-Crystal Tungsten, heated 510°C, after ~ 800 exposures at various fluences
- SEM at 15,000 magnification shows Clean Break along crack - stress cracking only
- Away from crack, surface is unaffected by Helium beam exposure

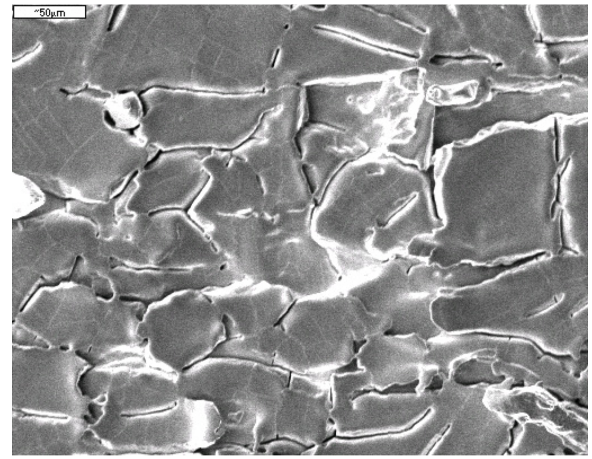
RHEPP-1 Ion Exposure

Three Forms of tungsten, treated at about same fluence: Its all about the grains.

1,000X MAG	1,000X MAG	300X MAG







W-0.5%TiC 1.5 J/cm^2. Ra = 0.04 μm	M182Perp ~ 1.25 - 1.5 J/cm^2 Ra ~ 0.15 μm	M182Parallel ~ 1.3 J/cm^2 Ra ~ 4.5 μm

Two on right are SAME material

- **(LEFT) W-0.5%TiC (Kurishita) formed by Hot Isostatic Press (HIP) – strengthens grain boundaries**
- **(CENTER) M182Perp tungsten: grains vertical to surface. Bottom of grains protected. (RIGHT) M182Parallel – grain corners get lifted.**

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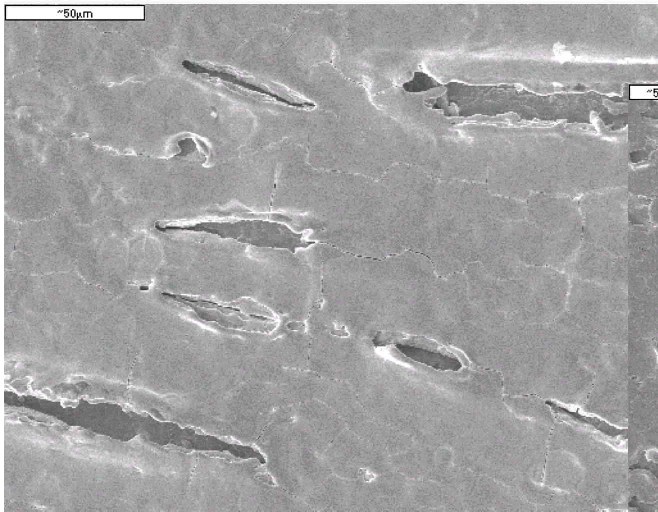
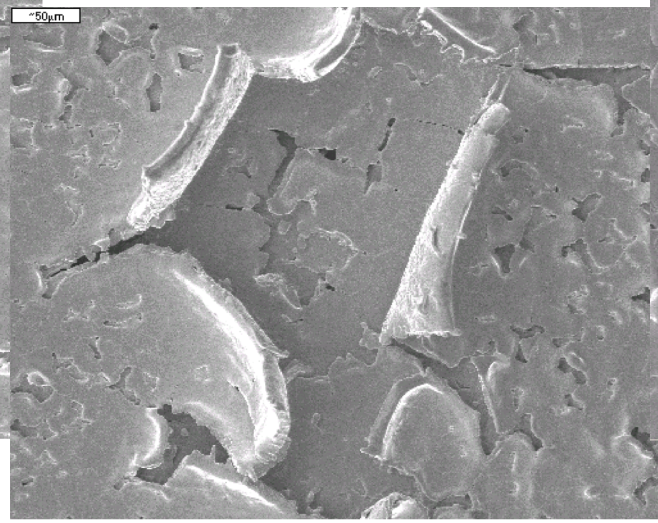
PM Tungsten exposed to Nitrogen (top) and Neon (bottom): Mass loss with N, not with Neon

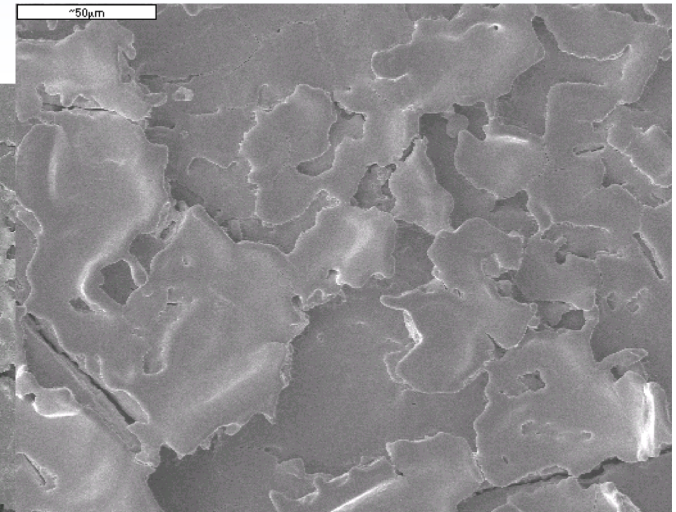
Top: Nitrogen



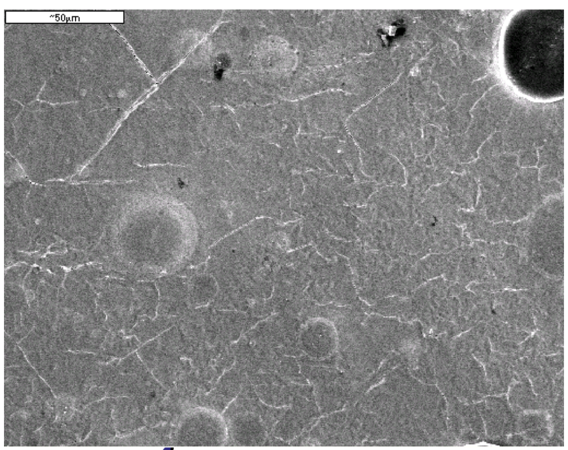
< 1.2 J/cm²



~ 1.2 J/cm²



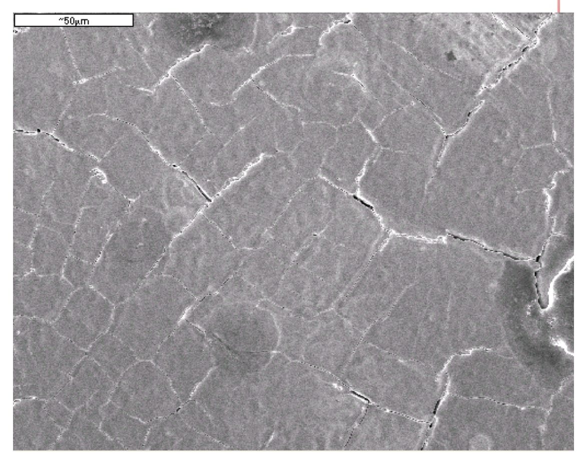
> 1.2 J/cm²



All images 500X Mag except above (250X)

Bottom: Neon

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



500X Mag

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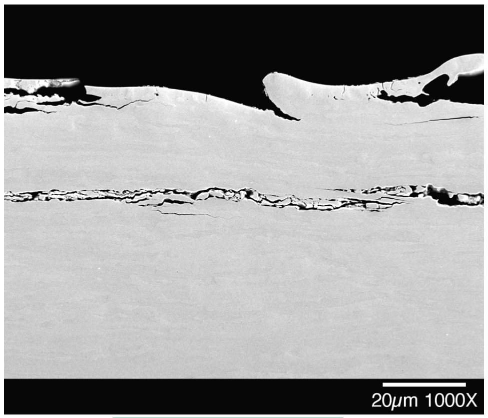
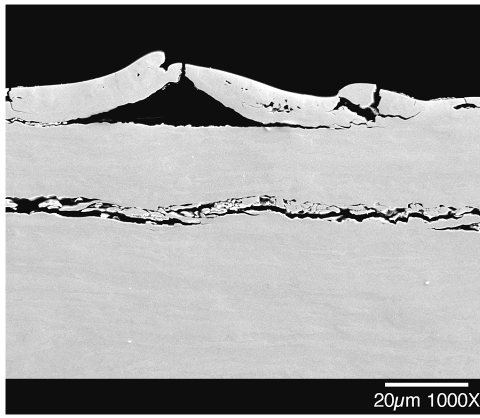
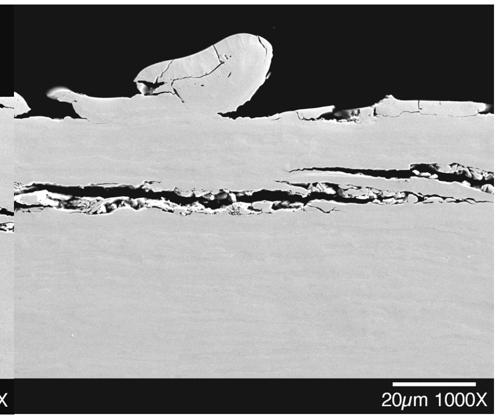
RHEPP-1 Nitrogen Beam

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



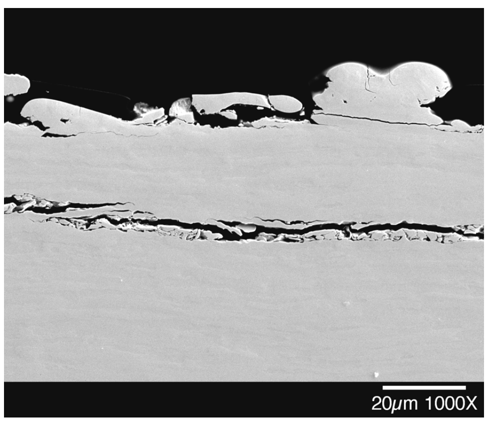


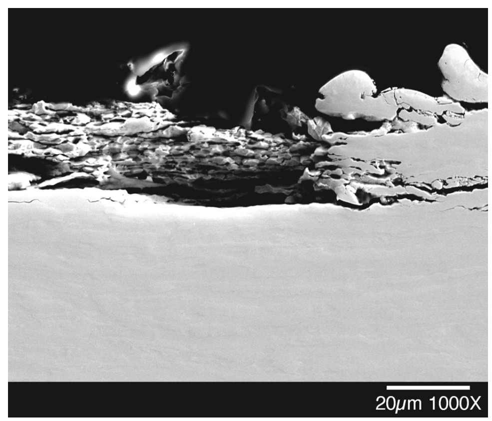


- Wholesale failure down to 20 μm level in last image

400 pulses

Increasing pulse number →





All images BEI 1000X MAG

→ 1600 pulses

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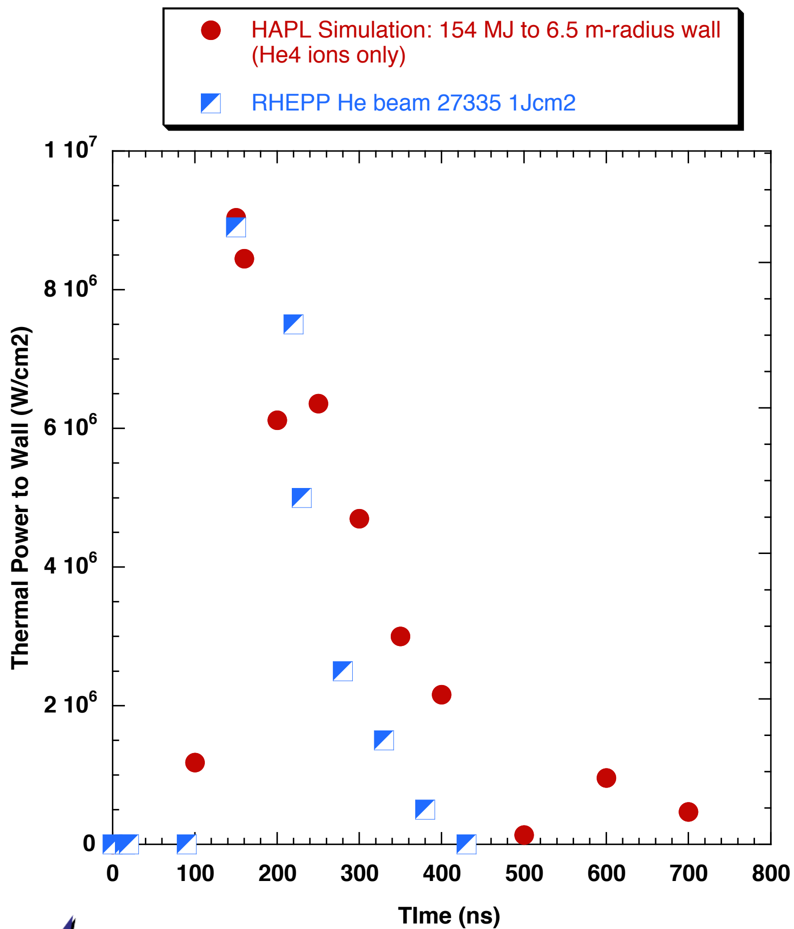
Helium beam exposure

The RHEPP helium beam well simulates IFE threat from both He ion and total Ion current



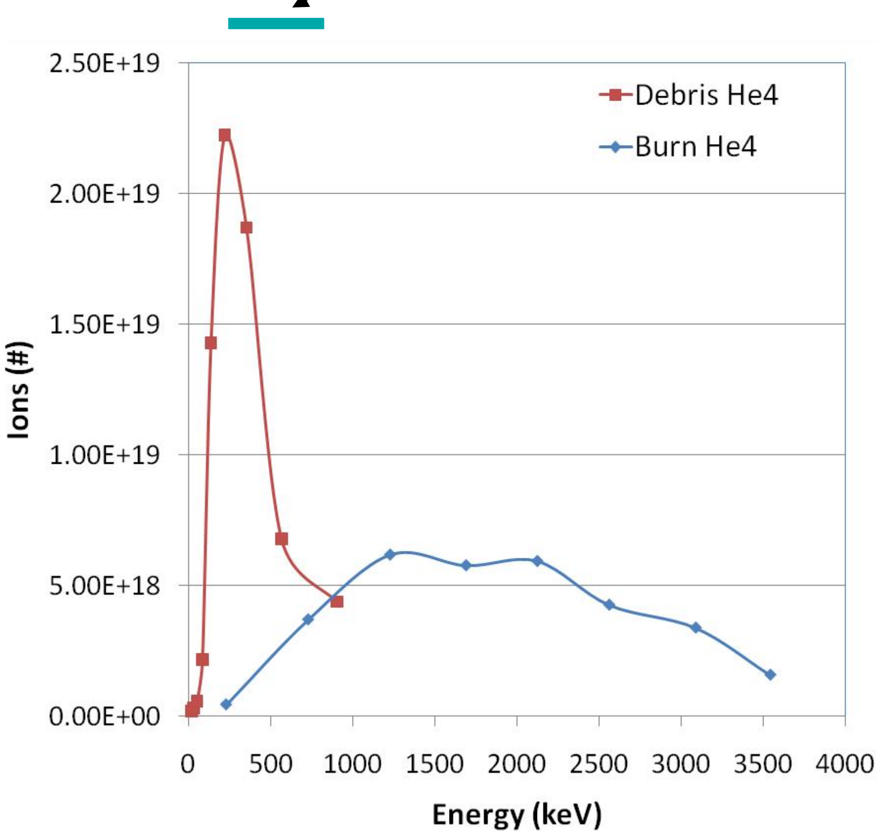
- RED: Simulation, 154 MJ IFE yield, at 6.5 meter wall radius, He_4 ions only
- BLUE: RHEPP pulse 27335, He beam, 1 J/cm^2 fluence, 9e6 W/cm^2 power density
- He component is ~ 1/3 of total ion pulse (fusion plus debris ions)
- Total pulsewidth ~ 1.5 μsec FWHM, vs ~ 80 ns Thermal Power FHWM for RHEPP
- RHEPP 1 J/cm^2 needs to be 3 J/cm^2 to include all ion effects. But shorter delivery increases *effective* RHEPP dose by 4x
- RHEPP He beam matches pulse heating time for reactor pulse, and 1-2 J/cm^2 matches overall power delivery to first wall expected for 154 MJ pulse

Energy Distribution of He^4 for 401 MJ Target

Raw data: http://aries.ucsd.edu/ARIES/WDOCS/ARIES-IFE/SPECTRA/

Range of RHEPP He ions

Thanks to Shahram Sharafat



COMPARISON:
Each RHEPP pulse delivers ~3e13 He^4/cm^2 to treatment surface at 2.25 J/cm^2 fluence. Max surface temp at 2.25J/cm^2 ~ 2350C

Total: Burn = 3.13e19 He^4/shot
Debris = 7.31e19 He^4/shot

He^4 Fluence (10 m radius chamber):
Burn = 2.49e12 He^4/cm^2
Debris = 5.82e12 He^4/cm^2
Total = 0.83e13 He^4/cm^2

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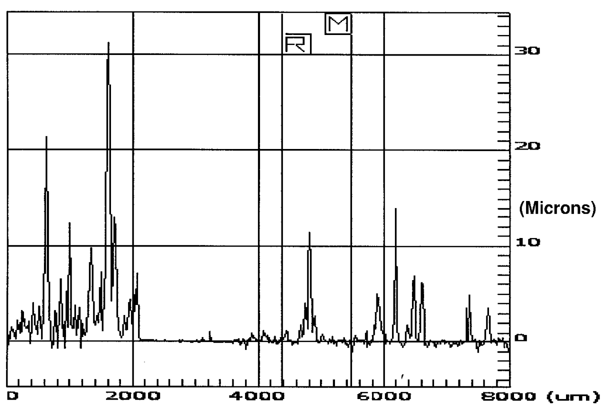
Presented at HAPL Meeting, Madison, September 2003

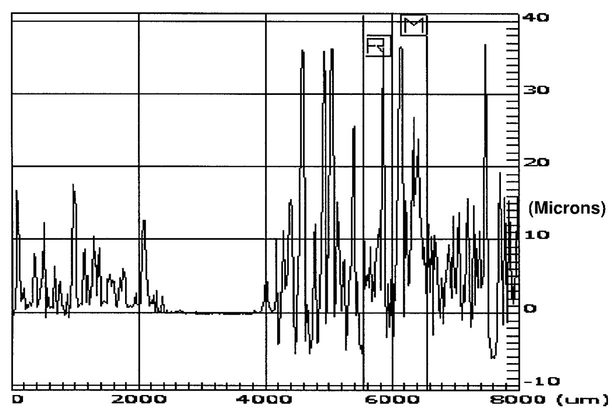
R_a as function of Number of Nitrogen pulses @ 4.0 J/cm^2
Helium actually roughens less than nitrogen

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

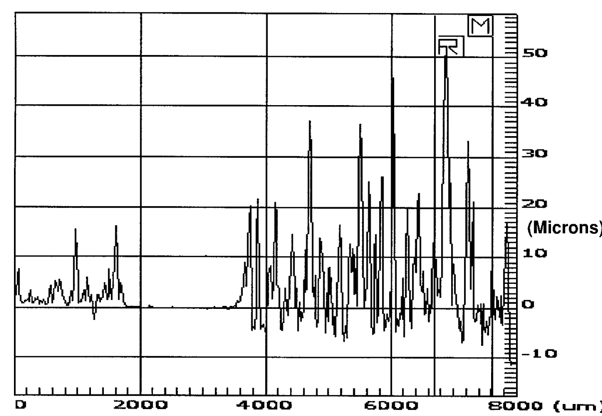
He Beam 1.3 J/cm^2 | **N Beam 4J/cm^2**



(He-450) (None) (N-200)



(He-450) (None) (N-400)



(He-450) (None) (N-600)

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

- Roughening of PM Tungsten: 450 pulses He @ 1.3 J/cm^2 roughens more than 200 pulses N @ 4 J/cm^2 (Melt)
- N-beam roughening catches up and passes at 400 pulses

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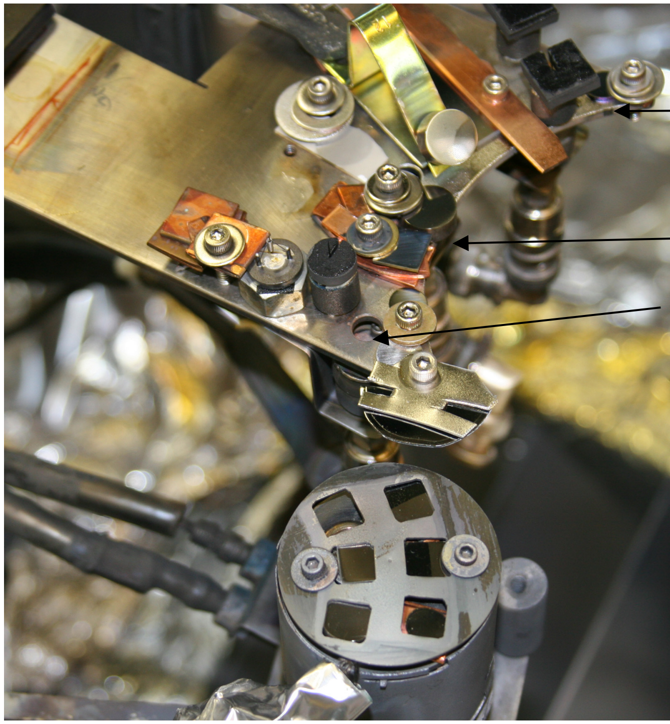
RHEPP-1 Roughening Threshold, PM W, Multi-pulse, helium beam exposure

Sample Setup for He1*_1600: four 400 shot series

Samples mounted before Start
Beam Center off to center Right

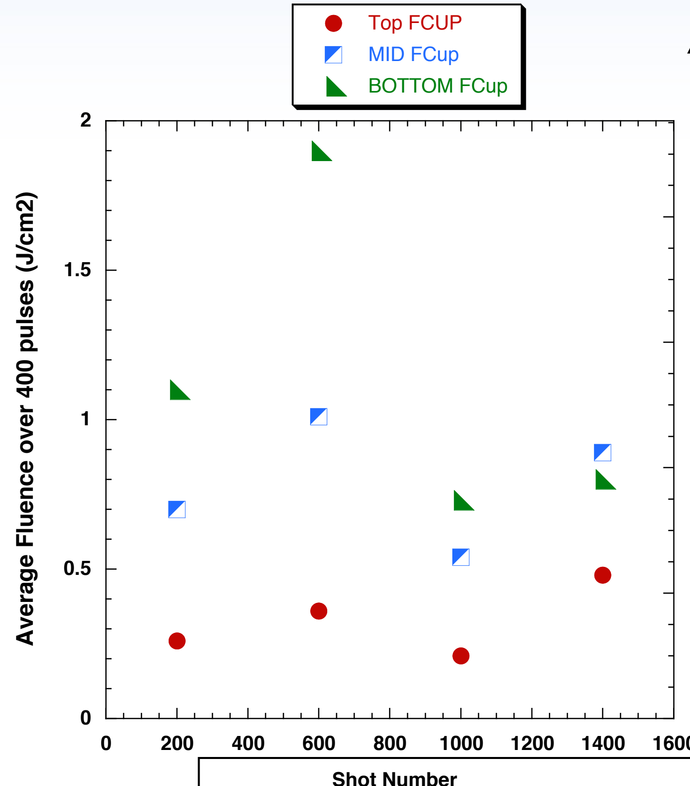


'TOP' FCup

'MID' FCup

'BOT' FCup

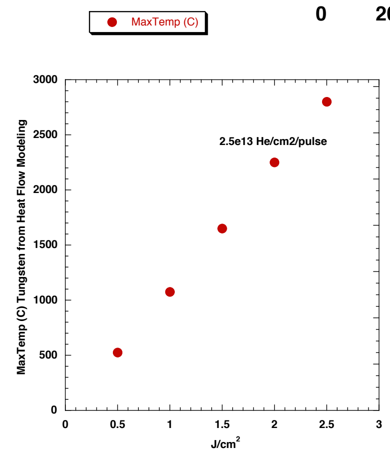
500°C Heater at bottom



Melt @ 3 J/cm^2

1100°C

500°C



MaxTemp Vs Fluence (from Heat-Flow modeling)

- 1 J/cm^2 ~ 1.25e13 He/cm^2/pulse
- Fluences and MaxTemps are Averages. ±30% variation in fluence, with outliers to ±50%
- Vacuum ~ Mid e-5 Torr (no Cryos)
- Heated samples not discussed – heating to 520°C doesn't affect results
- 520°C may be below DBTT

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‘Porosity’ evidence in images different from nitrogen

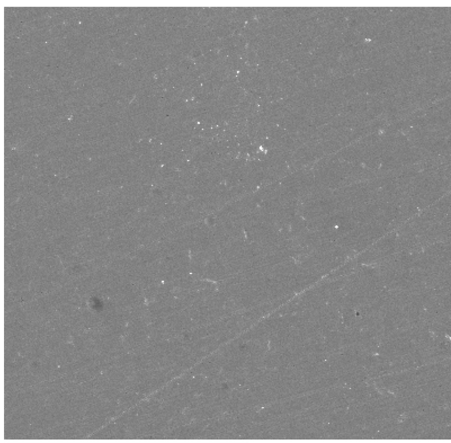
Polycrystalline Tungsten He exposure behavior - 1600 pulses

All samples initially Room Temperature (RT)

All images 1000X magnification

Ave 0.8 J/cm²/ pulse

~1000°C Average MaxTemp

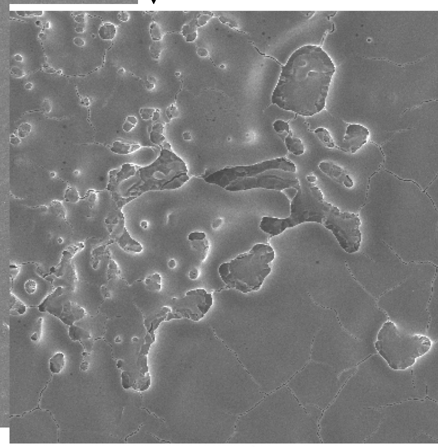


(50 μm)

400 pulses

Ave 1.4 J/cm² /pulse

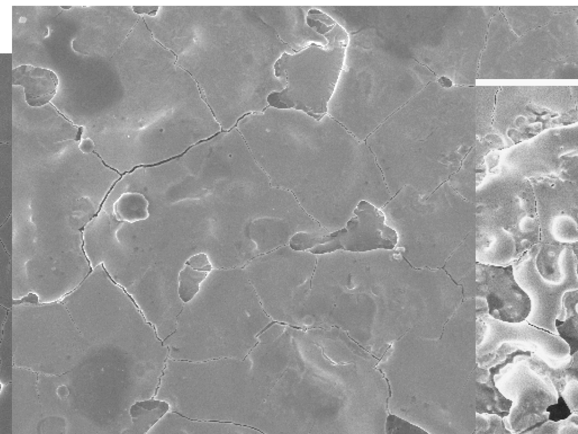
~1500°C Average MaxTemp



800 pulses

Ave 0.6 J/cm² /pulse

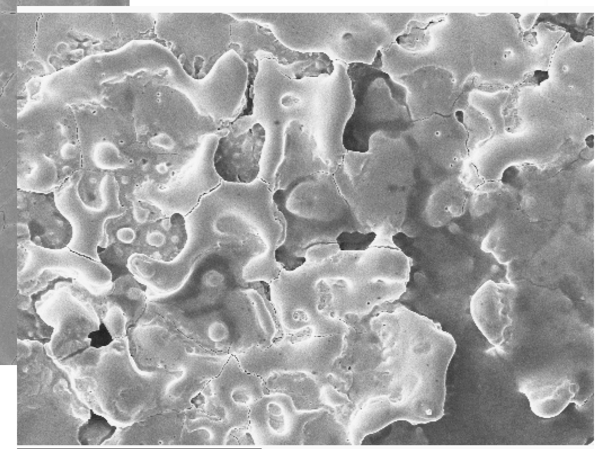
~600°C Average MaxTemp



1200 pulses

Ave 0.85 J/cm² /pulse

~1050°C Average MaxTemp



1600 pulses

Ra ~ 1.5 μm

(Est) total He implantation ~ 1.8e16 /cm²

- Average maximum surface temperature < 1500°C
- No effect 1st 400 pulses: below threshold
- Using √t scaling: 0.8 J/cm² equivalent of 0.4 MJ/m². Consistent with QSPA plasma exposure of tungsten PFCs (ref: A. Zhitukhin et al, JNM 363-365 (2007) 301-307
- Final 400 pulses @ 0.85 J/cm2: probable cumulative mass loss

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RHEPP-1 Roughening Threshold, PM W, Multi-pulse, helium beam exposure

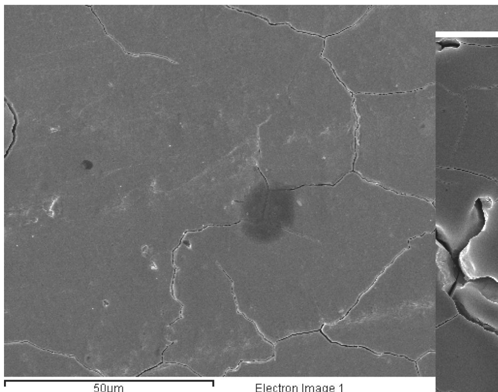
Pulsed Power Sciences, Sandia National Laboratories
TJR 9/27/2008

M184(P) oriented grain tungsten - 1600 pulses

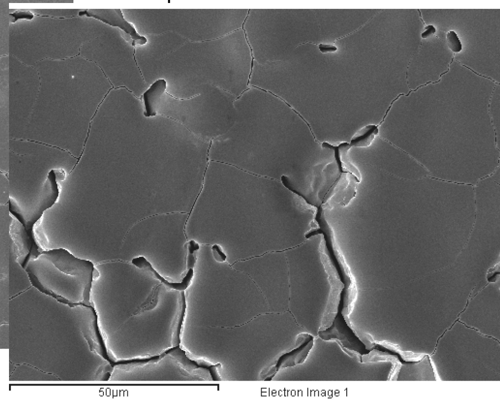
All samples initially Room Temperature (RT)

All images 1000X magnification

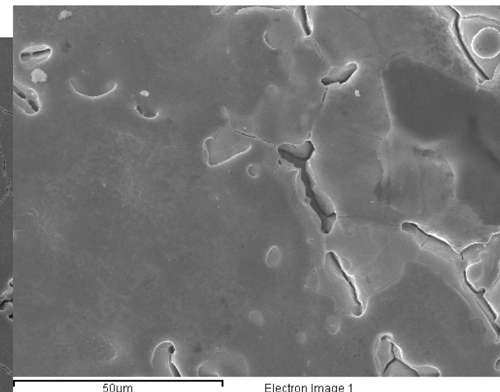
Ave 0.8 J/cm^2/ pulse ~1000°C



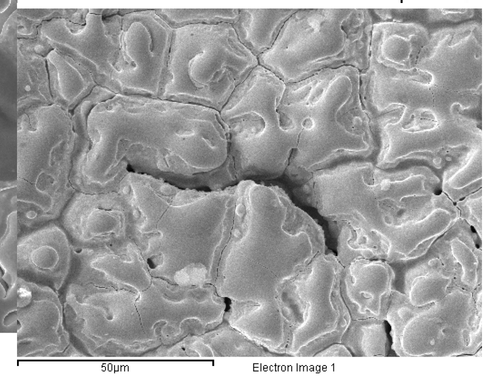
Ave 1.2 J/cm^2/pulse ~1300°C



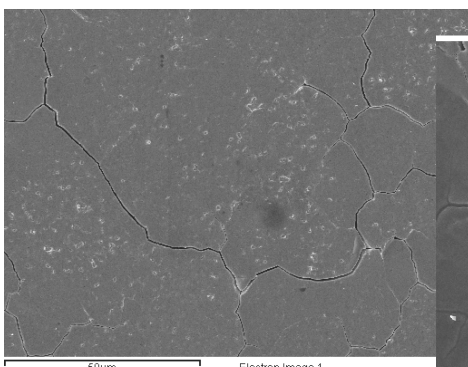
Ave 0.6 J/cm^2/pulse ~600°C



Ave 0.85 J/cm^2/pulse ~1050°C

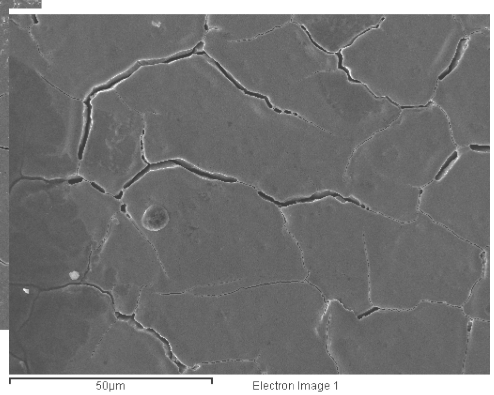


400 pulses

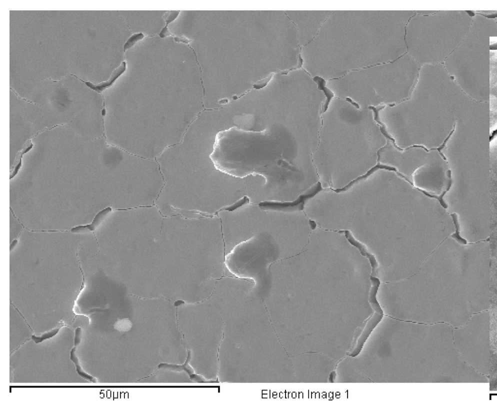


(50 µm)

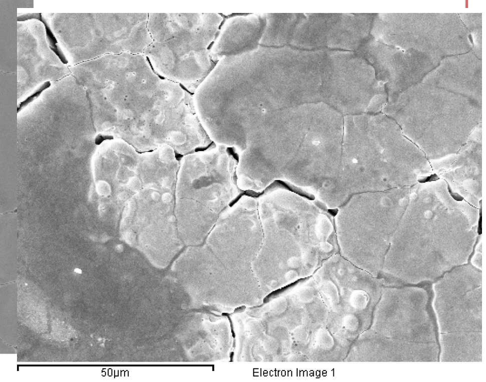
800 pulses



1200 pulses



1600 pulses



- Bottom Row: improved performance.
- R_a (TOP) ~ 1.5 µm, (BOT) ~ 0.26 µm – SMOOTHER SURFACE

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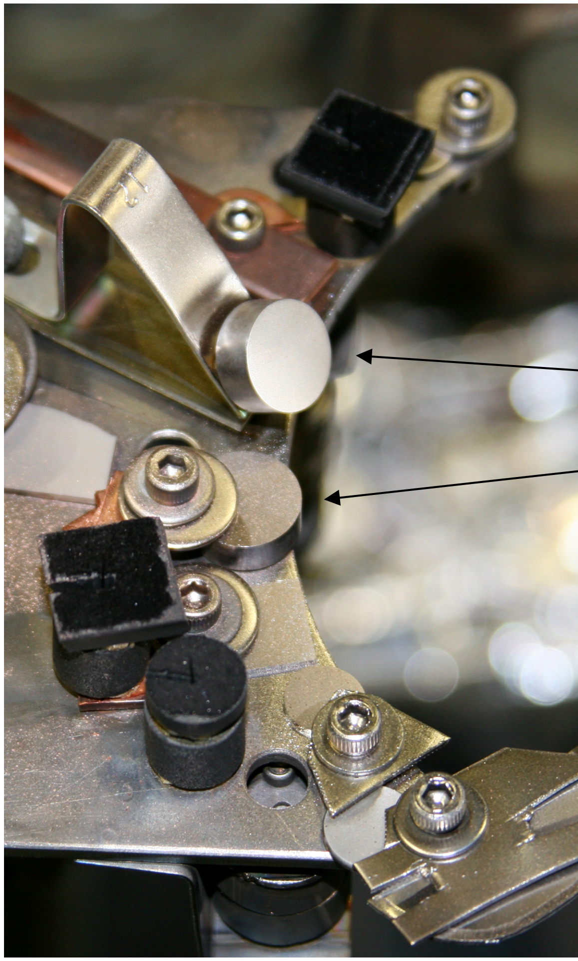
RHEPP-1 Roughening Threshold, PM W, Multi-pulse, helium beam exposure

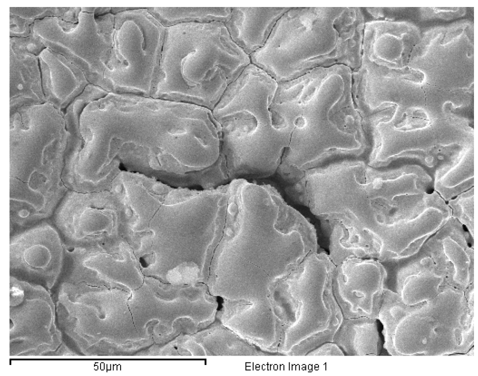
Bottom Row from last slide: Same M184p material tilted at 55° to beam

- 55° tilt reduces effective fluence in half
- Does this lead to longer-term survivability?
- Helium looks to cause more roughening than nitrogen beam

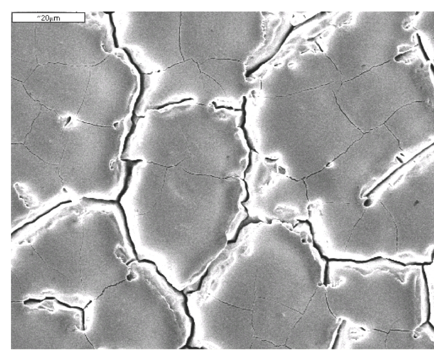


M184p 'Tilt'

M184p



M184p – 1600 He pulses

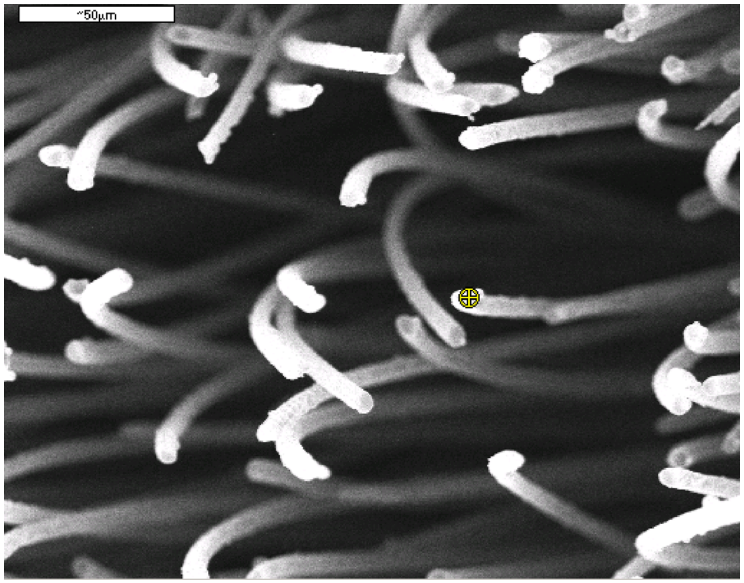


M182p – 1600 N pulses

RHEPP-1 nitrogen beam exposure

Alternate material: W-coated Carbon 'Velvet' survives 1600 pulses amazingly well

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

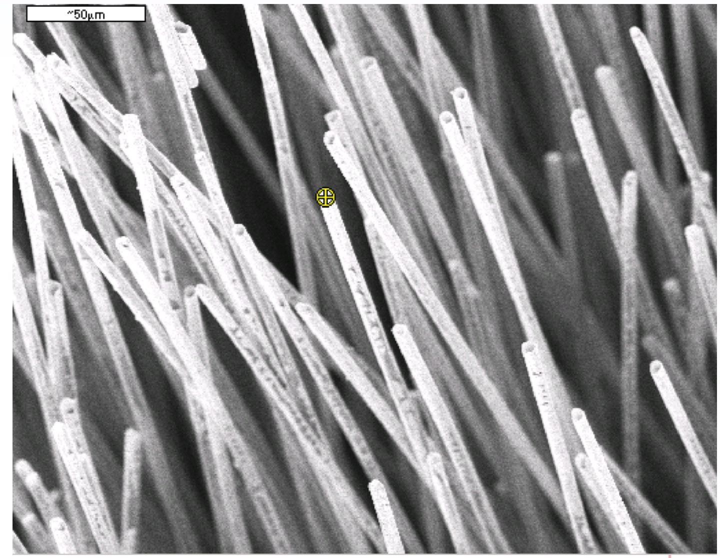


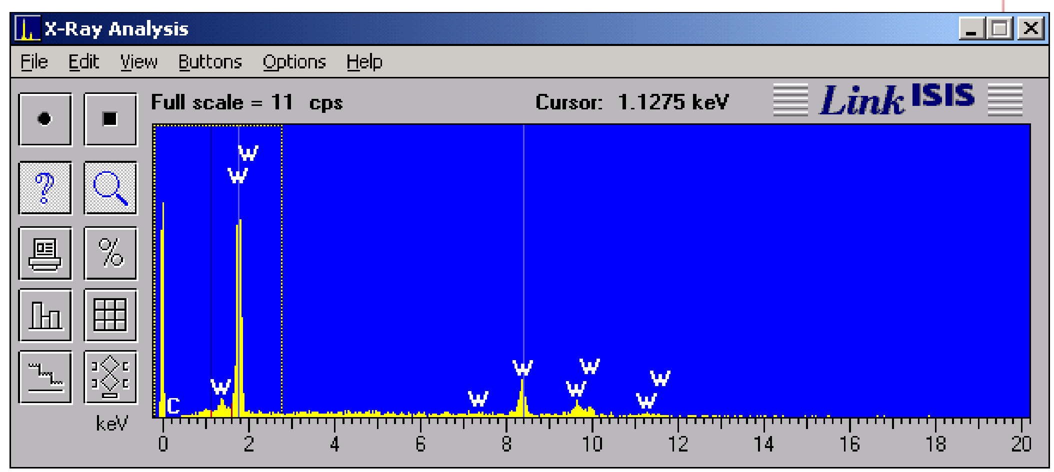
(ABOVE)
RT @ ~ 2.8 J/cm^2, 1600 pulses

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





EDS scan of tip (cross): W rich

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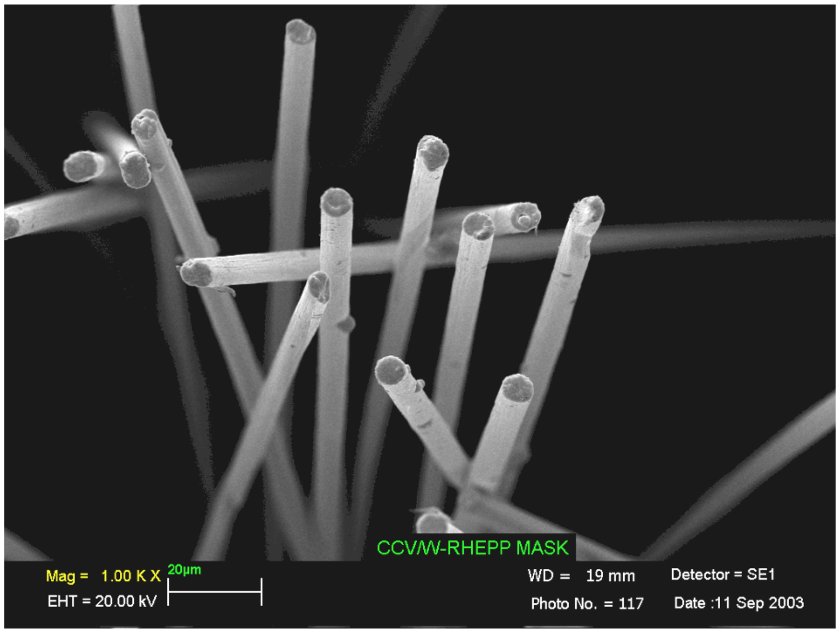
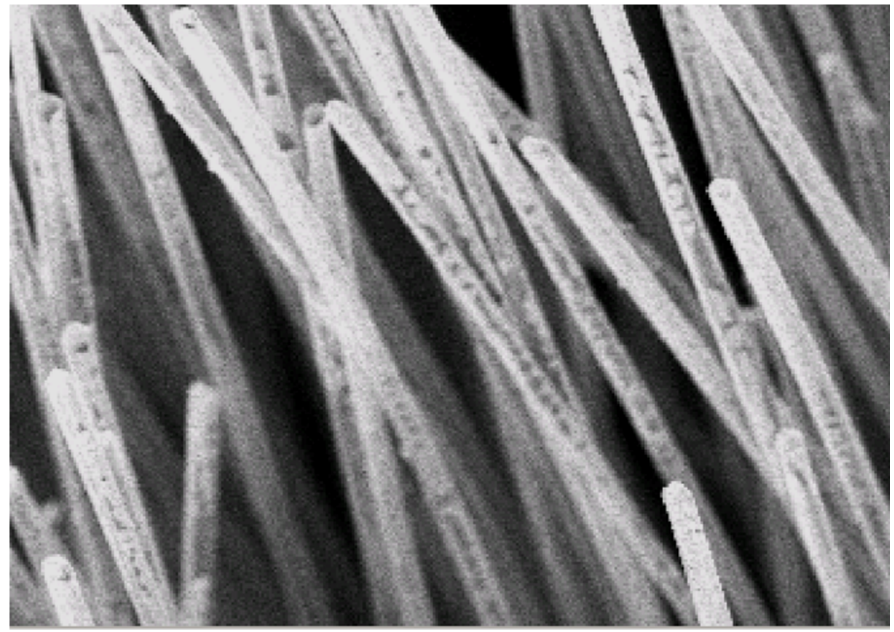
RHEPP-1 nitrogen beam exposure

Comparison of SEMs, exposed/unexposed velvet

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



Untreated Velvet Fibers



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

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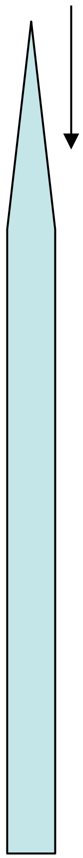
Needles and needle groups as a first wall

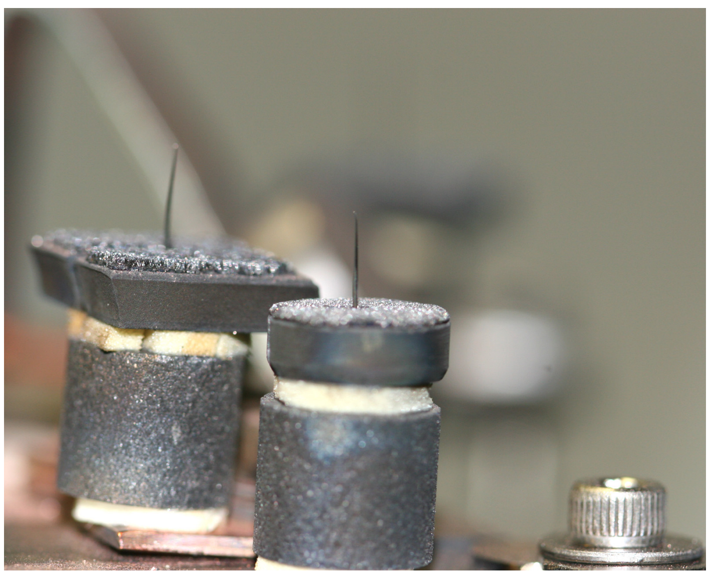
T.J. Renk, P. P. Provencio, T. J. Tanaka, J. P. Blanchard, C. J. Martin, and T. R. Knowles, *Survivability of First-Wall Materials in Fusion Devices: an Experimental Study of Material Exposure to Pulsed Energetic Ions*, Fusion Science and Technology **61** (2012)**,** 57-80.

'Needle' geometry minimizes full-exposure area, maximizes 'glancing blow' area, minimizes He penetration depth

Incoming Beam



Dimensions (Knowles W):
Tip Length 3000 μm
Radius 125 μm
Rtip 0.25 μm
Shaft 1.5 cm X 250μm diam



- **Design issues: overall length, tip geometry (sharpness, etc), assembly into groups**
- **Several designs investigated here:**
  - **Single Tungsten needle (Knowles-left)**
  - **Mo-coated W needle: ~ 0.25 μm Mo deposited by RHEPP**
  - **'Array' -more later**
  - **'Bundle' -more later**
- **Single W needles mounted in holder with carbon velvet at base to minimize blowoff**

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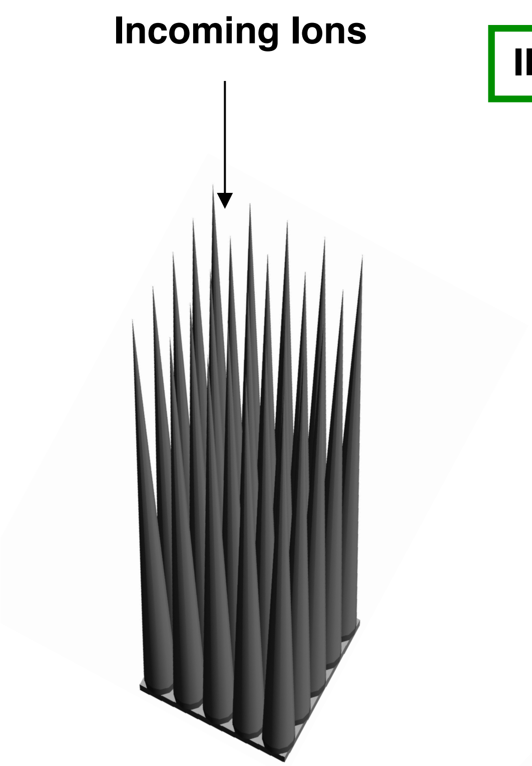
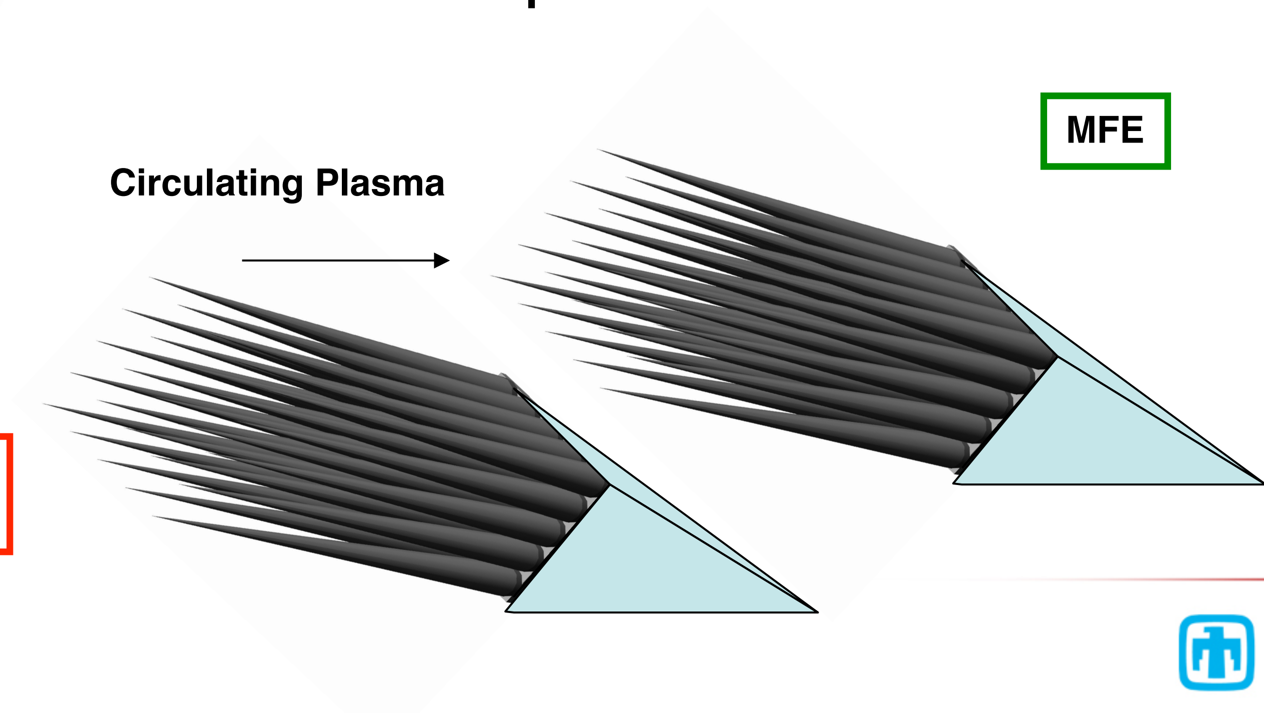
Arrays of Needles could be used in both IFE and MFE walls

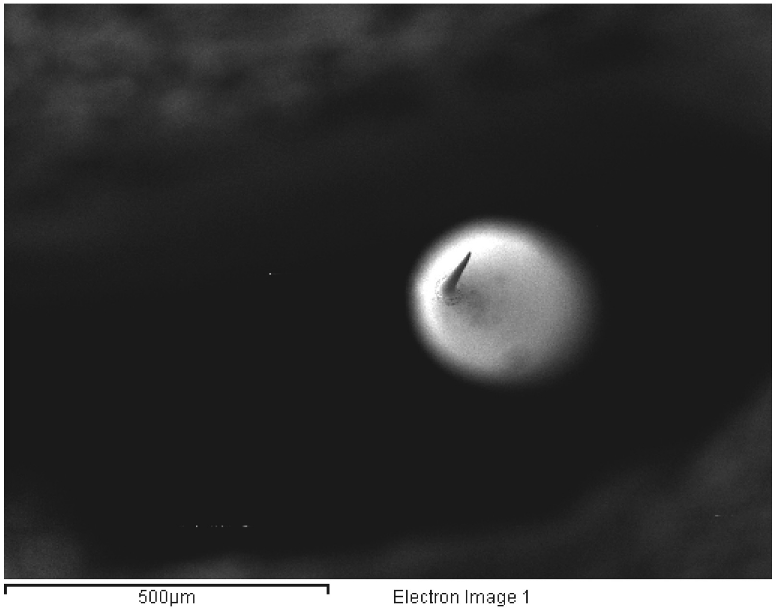


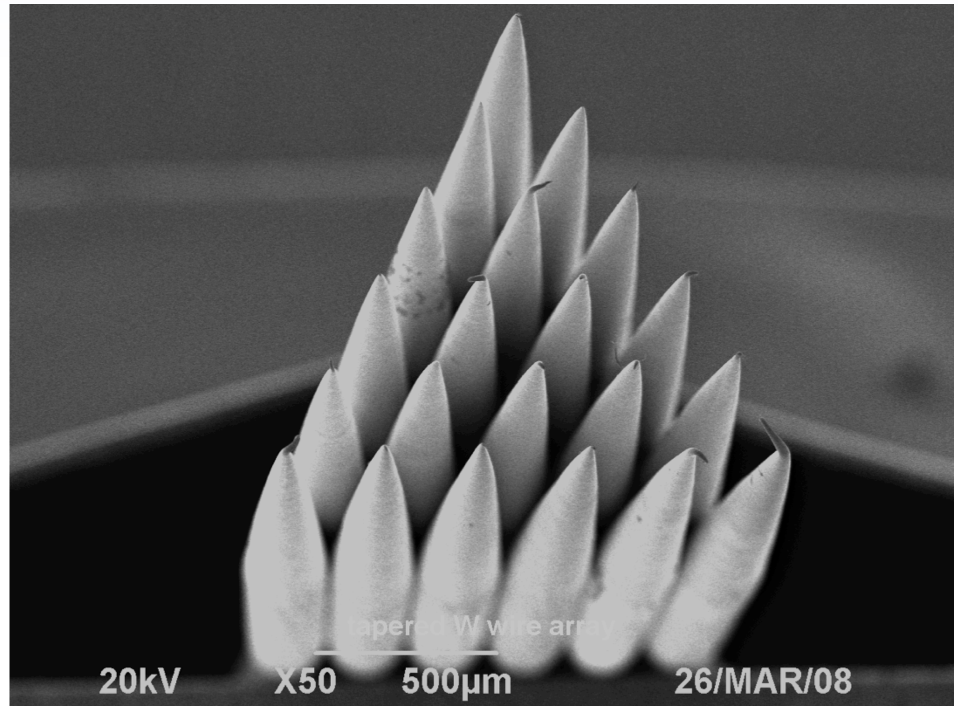
- Spacing, orientation aspect ratio to be determined
- MFE: arrays of needles on 'pedestals' facing circulating plasma direction



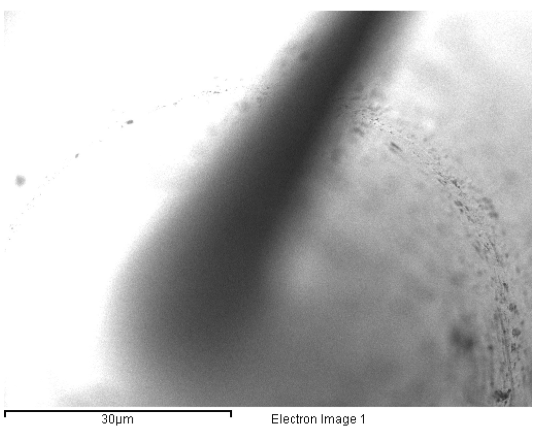
Dimensions (Knowles W):
Tip Length 3000 μm

Top SEM view: 400-pulse coated needle compared to virgin (right)





Treated 400 pulses. Diameter at 'bend' ~ 25 μm



(right) diameter at bend ~ 30 μm

Tip geometry identical to virgin needle at 400 pulses

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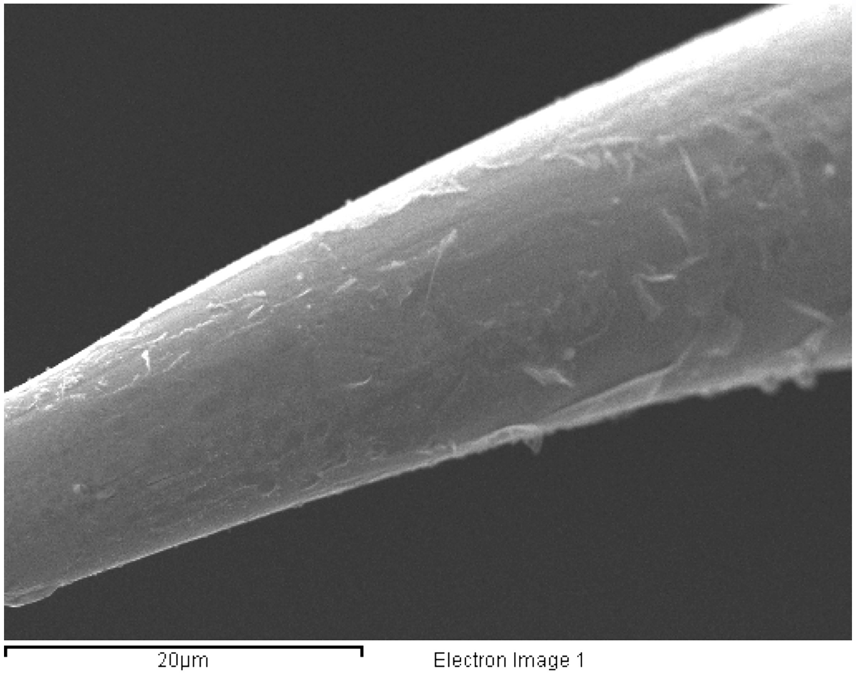
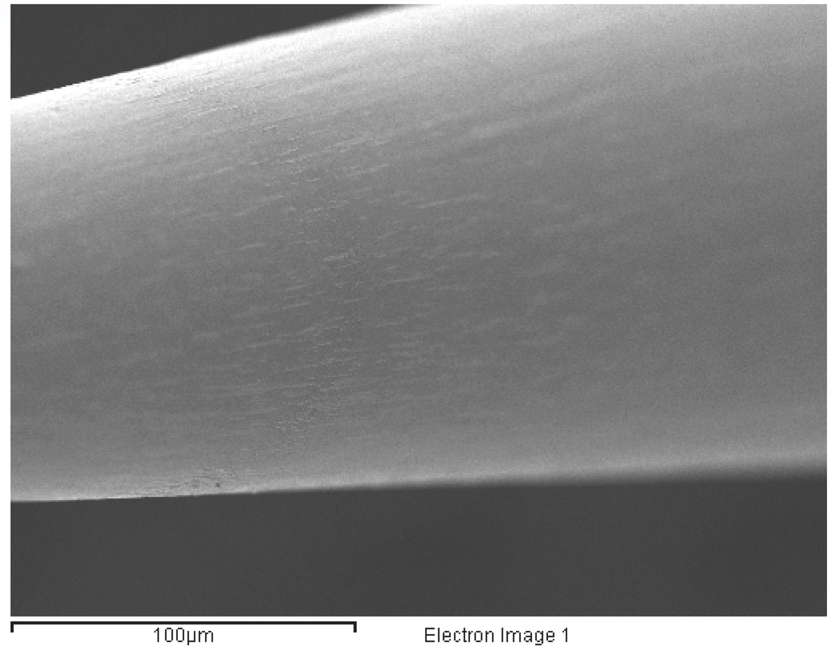
RHEPP-1 He Ion Exposure

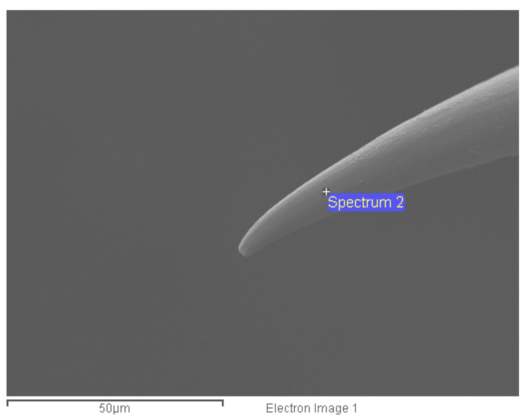
Mo-coated tungsten needle shows no sign of He bubble formation at 800 shots



Near tip



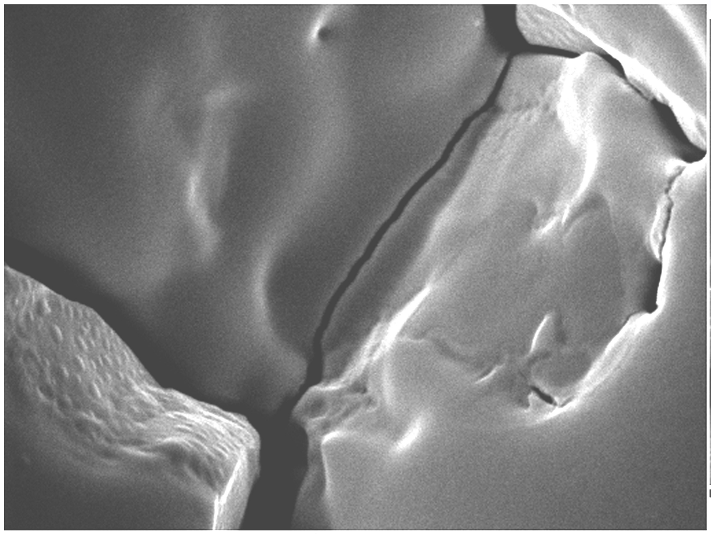
Where EDS shows Mo



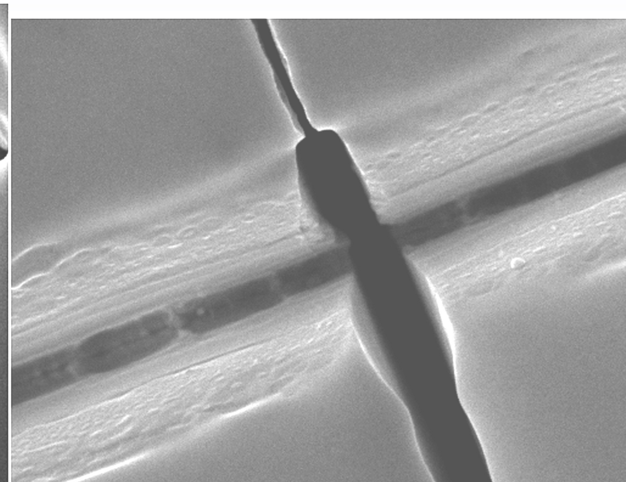
Tip may be blunted

RHEPP-1 He Ion Exposure

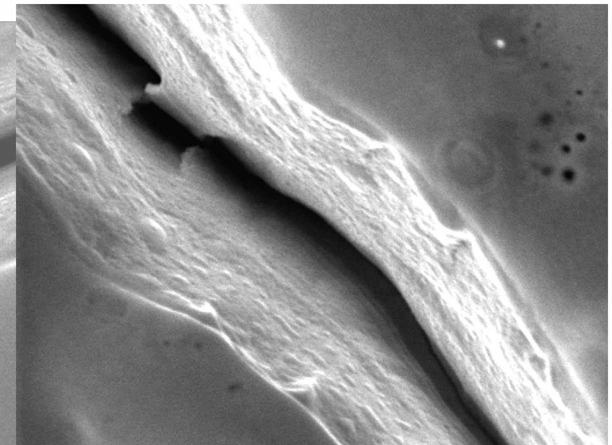
There IS evidence of He bubbles in both flat M184p and single crystal W, at ~ 1.2 J/cm^2



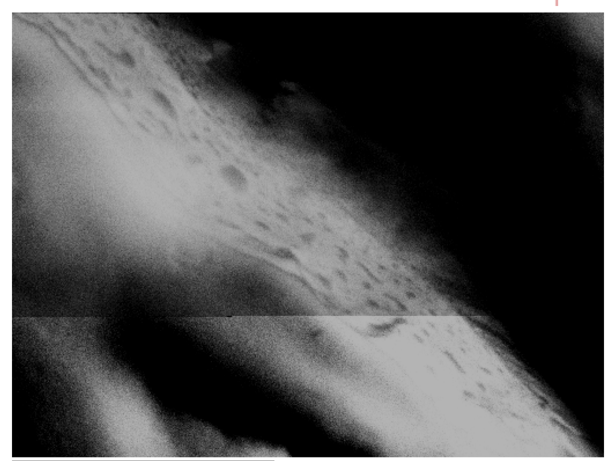
M184perp Room Temp



Single Crystal W RT



Single Crystal 520°C 1200x
Below: BSE image



- Structures occur at 400 pulses and up
- Mostly observed in cracks - consistent with ~ 1 μm He range in RHEPP
- More work is needed to assess exact nature of He retention
- NO EVIDENCE of He bubble/blister formation on needles - up to 1600 pulses

All Images
7500MAG

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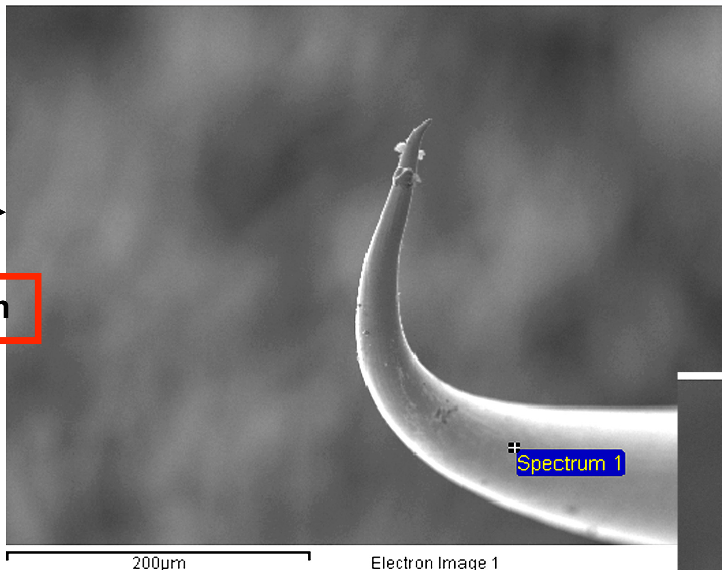
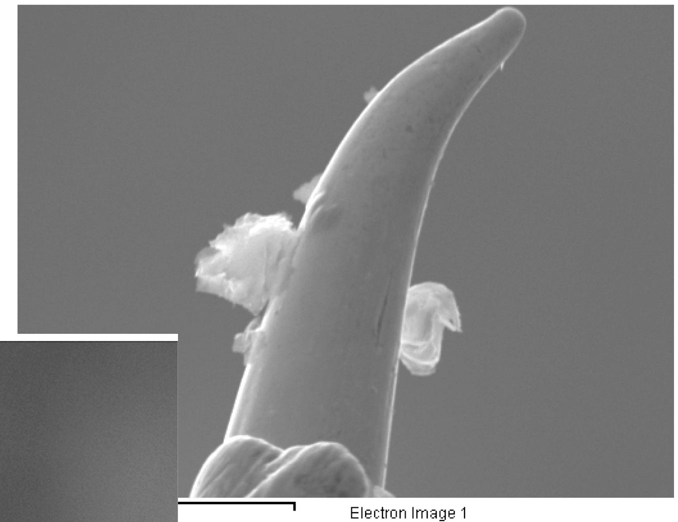
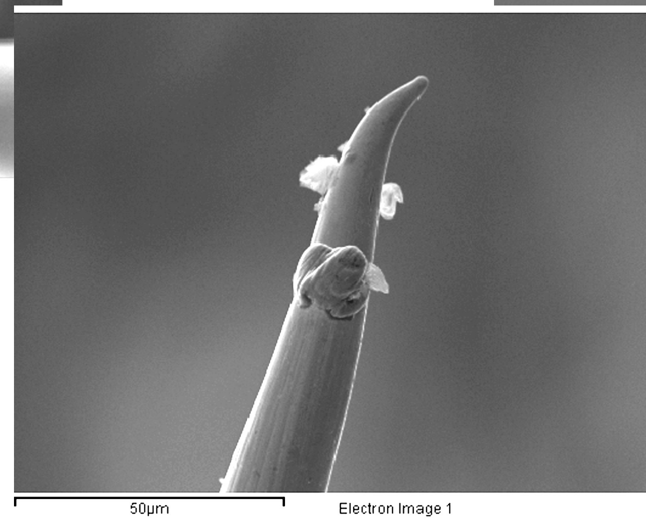
RHEPP-1 He Ion Exposure

Mo-coated W needle at 1200 pulses: markers are Mo coating, 90° bend

Beam







Diameter at 'bend' ~ 35 μm

Mo coating is peeling back from tip, but intact down shaft

Bent at tip: means full force hits bend. Also means tip cannot erode back In step-back fashion. This tip almost unaffected by beam

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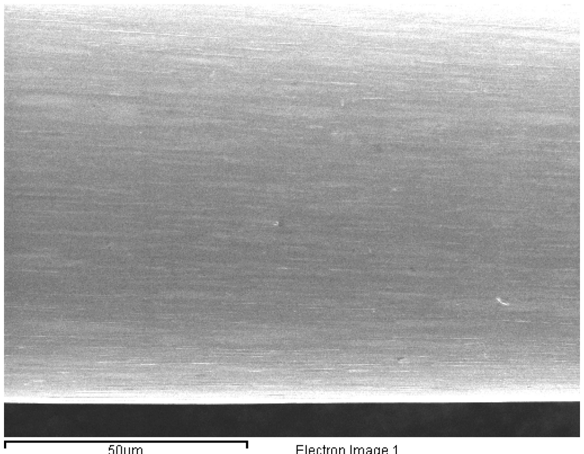
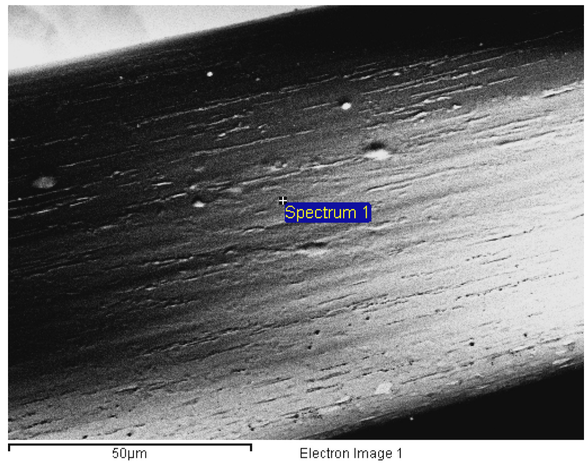
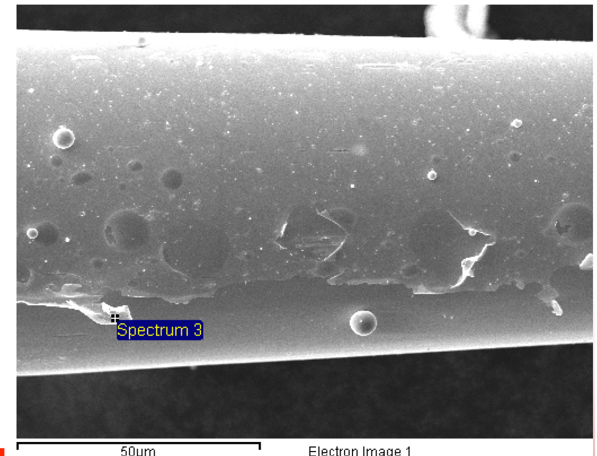
Tungsten needles compared - down shaft away from tip



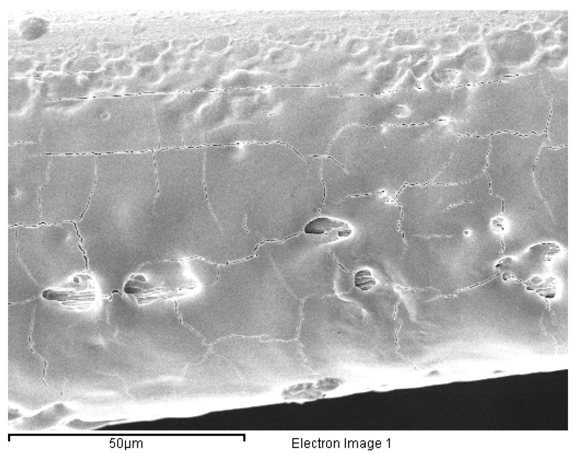
Virgin: 1mm from tip



Mo coated (BSE image): ripples are coating still intact after 1600 pulses. Confirmed by EDS



W needle-uncoated: 1600 pulses



W needle-flat - 400 pulses

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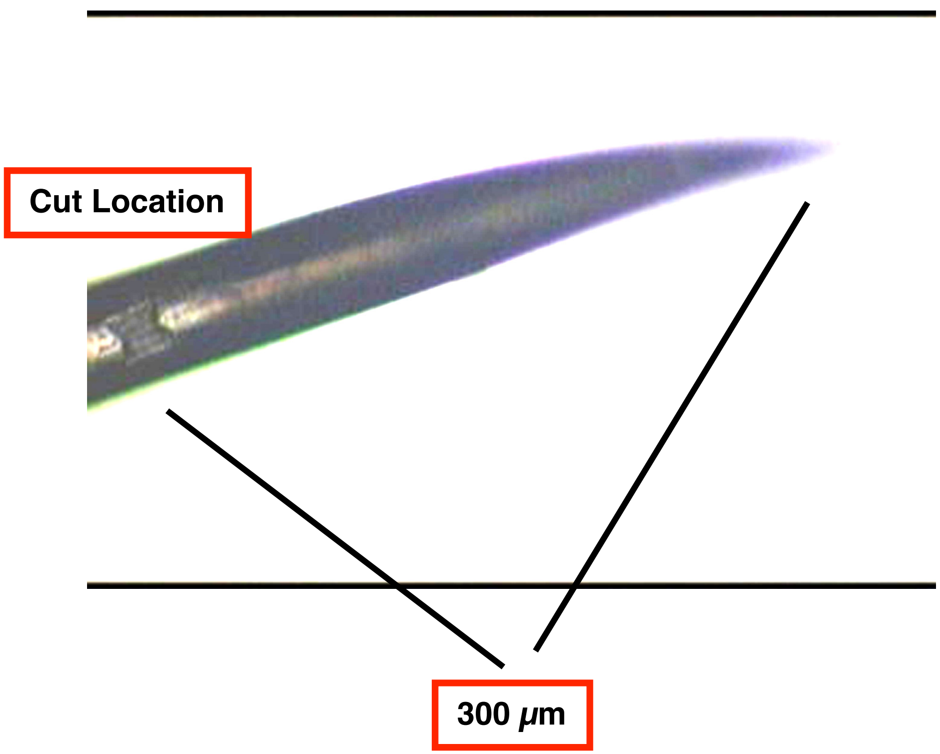
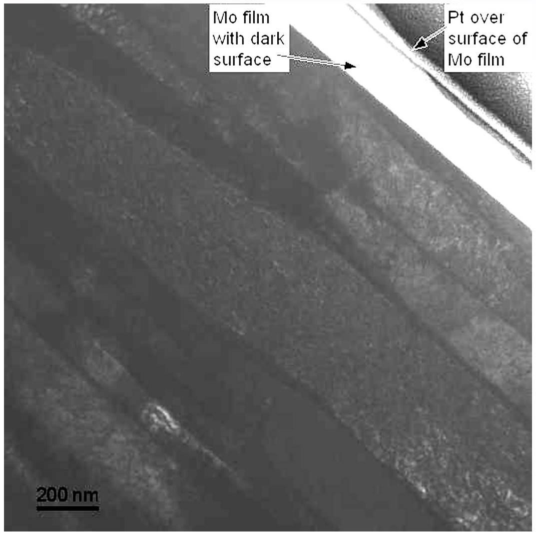
A FIB cut is made into the Mo-coated tungsten needle for XTEM

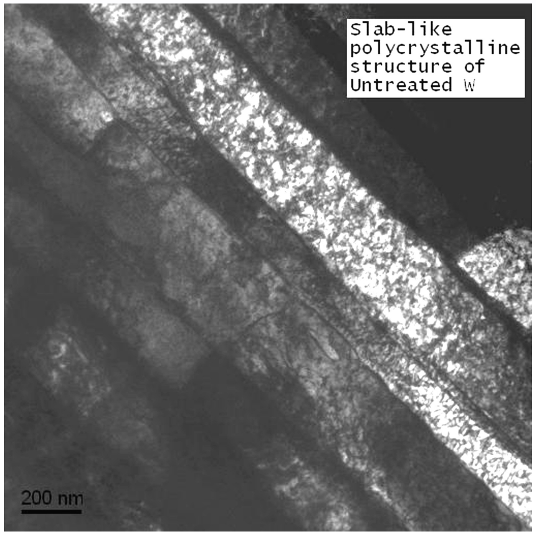


RHEPP-1 He Ion Exposure

FIB-XTEM: Mo-coated W needle survives 1600 pulses with no apparent effect vs uncoated untreated W needle



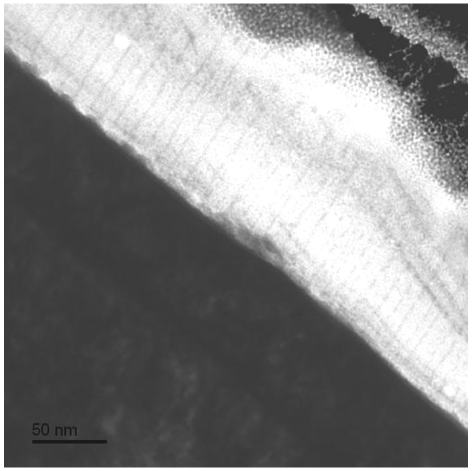
Mo coated - 1600 pulses

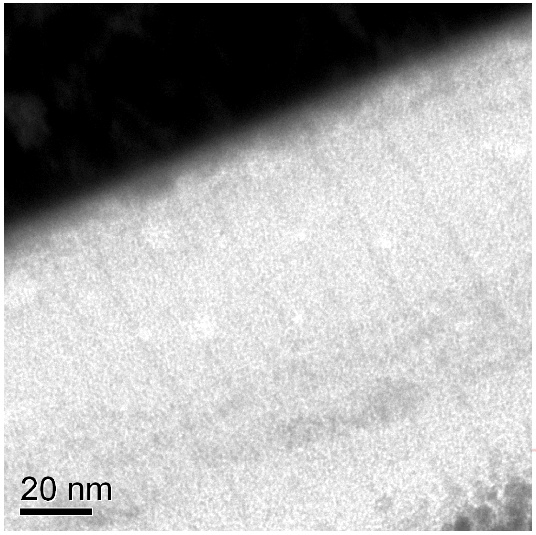


W needle uncoated virgin

- FIB cuts made in both needle surfaces 300 μm from tip
- Both XTEMS show fully dense tungsten with long oriented grains, no voids, no bubbles/blisters
- Close-up (bottom) shows columnar structure of as-deposited Mo - 200 nm thick - original thickness unknown
- No apparent effect from exposure

Magnified Coated Treated





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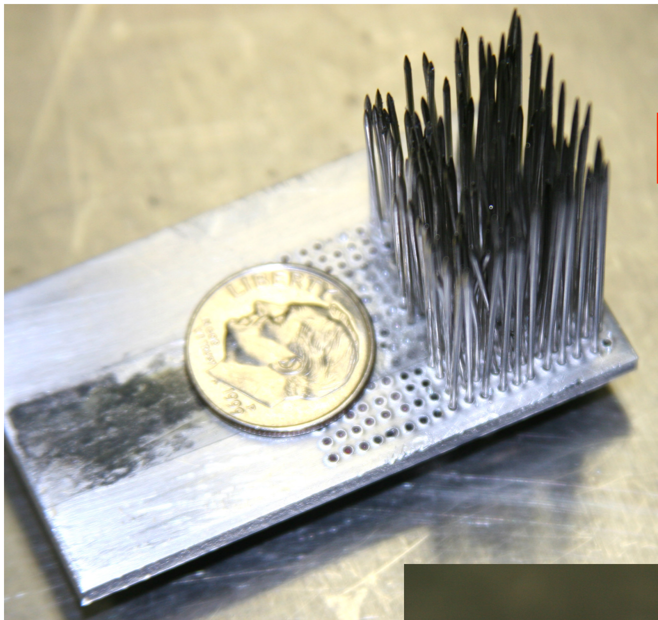
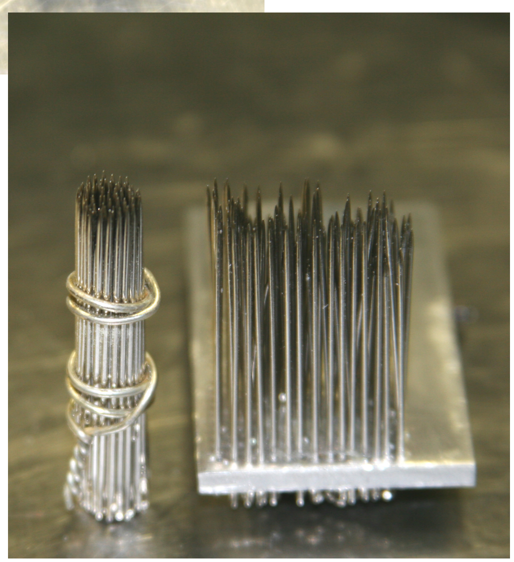
RHEPP-1 He Ion Exposure

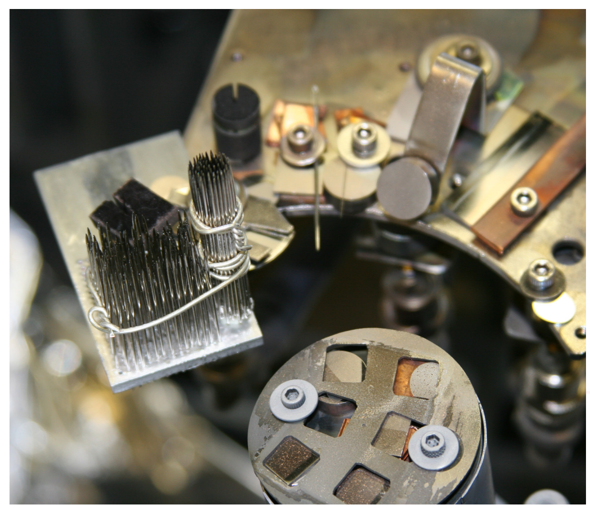
Two arrayed needle geometries investigated



Cost ~ $5

- Left: ‘Array’ - Sewing needles and dressmaker pins on Al-6061 substrate, mylar strip in center. Hole diameter 0.029in, 175 drilled into 1/8 in substrate 0.060in apart.
- Needle Composition; high carbon steel with Nickel plating
- Bottom Left: ‘Bundle’ - sewing needles tied together by wires
- Below: Arrays mounted before Shots 1201-1600





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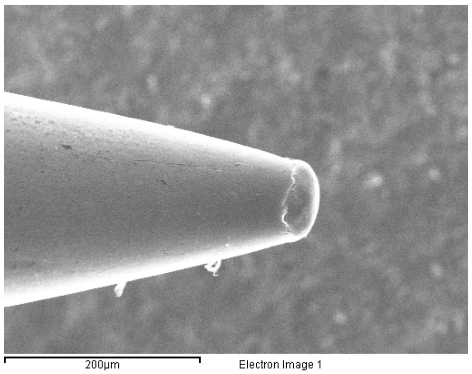
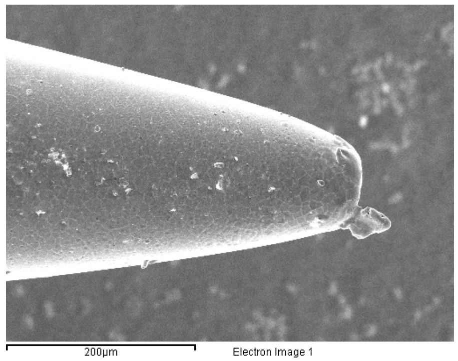
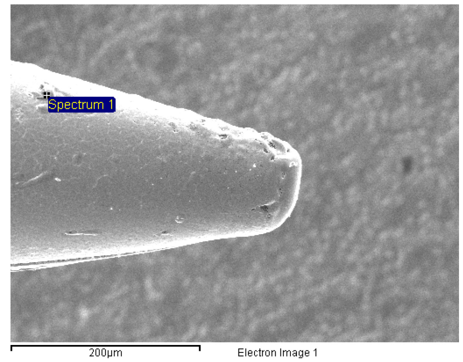
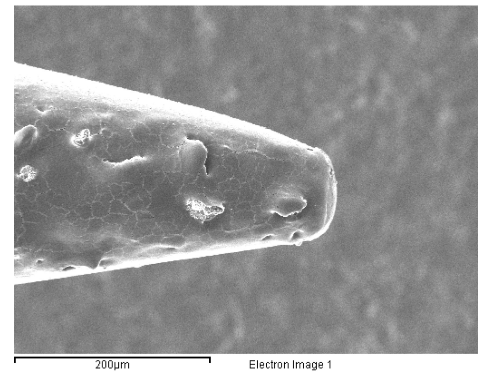
Comparison of Steel needles 400 pulses: virgin, in array, bundled, flat

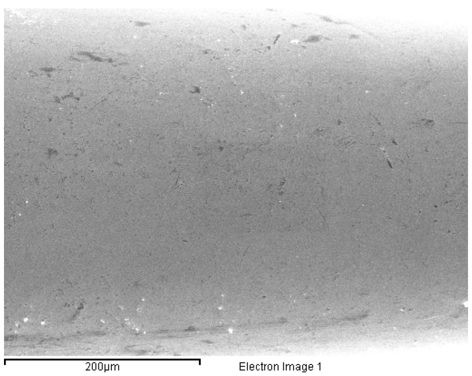
Virgin-Tip | **Tip in array** | **Tip in 'bundle'** | **Tip. flat**

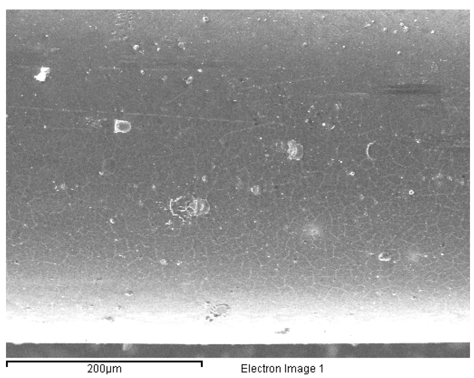


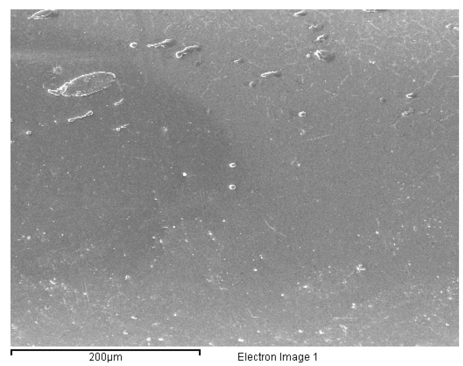


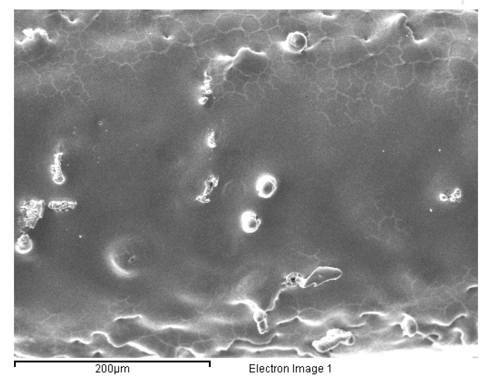












Virgin – 1mm from tip | **In array – 1mm from tip** | **In bundle – 2mm from tip** | **FLAT – 1mm from tip**

Away from tip, both bundled and array needle shows almost no effect from 400 pulses

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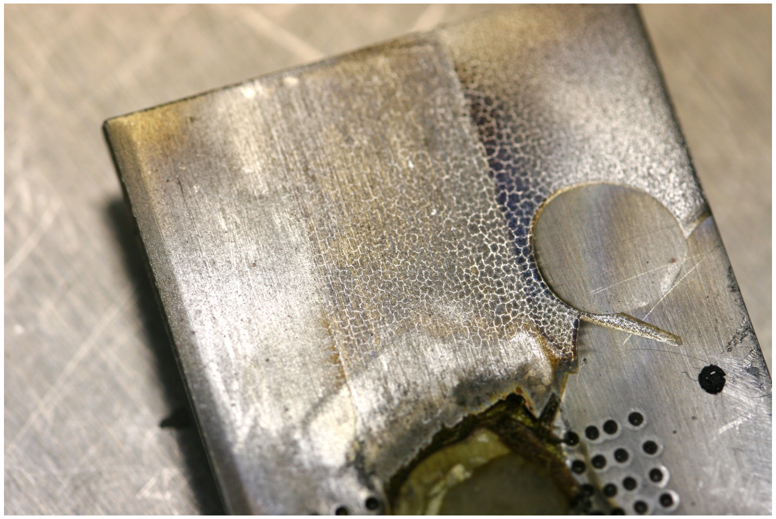
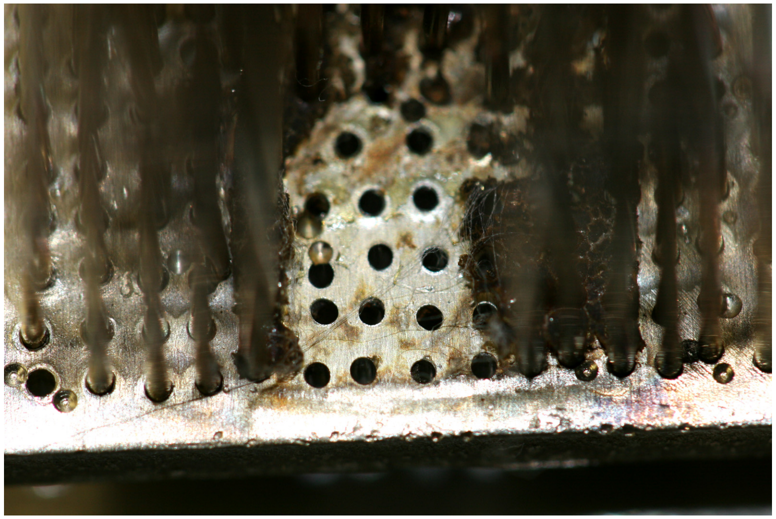
The needles protect the Al-6061 base very effectively: Mylar strip used as a marker



BACK of Al (no needles):
Mylar removed, Al melted



LEADING edge: Al heavily melted.
In needle ‘forest’, no Al damage

- Exposed mylar eroded away
- Inside the ‘forest’, complete protection of Al substrate, mylar partially intact

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Attempt to measure Mass Loss: 4 samples tested post-1600 show mass GAIN

Sample	Mass Gain (μg)	% Gain	μg/cm2
PM Tungsten	6.358	0.35	6.358
M184p FLAT	5.378	0.0532	5.378
M184p TILT	115.9	1.07	115.9
W/M Needle	2.768	1.72	(35.2)

- Gain occurs due to Cu adsorption from incoming beam
- M184p TILT gained by far the most mass
- PM tungsten AND M184P FLAT gained similar mass/cm^2
- On Areal basis, W/M Needle gained similarly with M184p FLAT
- Assume 116 μg on M184P tilt is entrained Cu. Then Pm tungsten LOST ~ 95 μg.
- Then needle area is consistent with < 1 μg gain. Actually gained 2.7 μg.
- Total data on W needles consistent with little or no mass loss due to 1600 exposures.

Summary – fusion materials exposure

- RHEPP pulsewidth similar to He_4 component in reactor, 1-2 J/cm^2 produces comparable power loading as 154 MJ pulse to 6.5 m-radius wall, comparable He implantation as 415 MJ pulse to 10m-radius wall.
- 'Needles' show promise as robust alternative to flat geometry. Little or no affect from 1600 He beam pulses.
  - CAVEAT: THE RHEPP IONS ARE NOT PARALLEL. Must investigate affective fluence compared to parallel ion path expected in reactor.
- Helium exposure of tungsten flats at up to 1600 pulses shows in all cases more surface roughening/signs of exfoliation than with comparable nitrogen pulses. Not Clear That Any of FLAT Materials RHEPP-tested will survive.
  - ROCK: effects here are NOT due to He entrainment, i.e. 1e18 cm-2 reported He blister formation threshold holds here, and results seen here are due to thermomechanical stress only. Then samples do not appear to be able to reach 1e18 cm-2 without unacceptable morphology change/weight loss.
  - HARD PLACE: effects seen ARE due to He entrainment, then threshold for pulsed He exposure is more like upper 1e15 cm-2.

Questions?

Backup Slides

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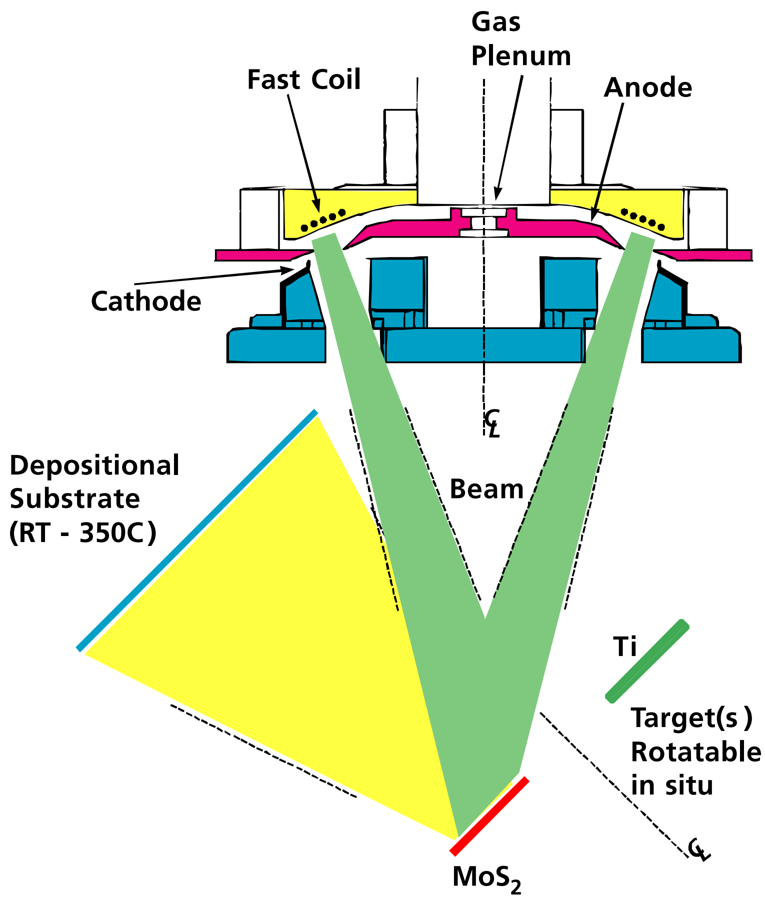
Ablation study of sub-range foils

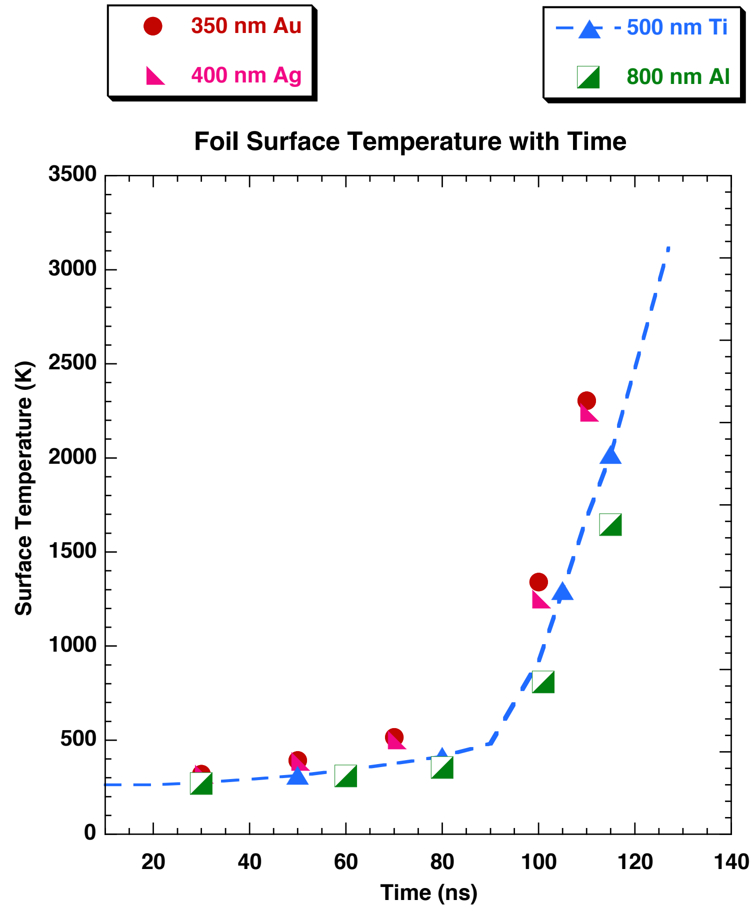
The RHEPP-1 nitrogen beam was used in sub-range foil ablation experiments



- High-energy pulsed ions (700 kV, 200 A/ cm^2) vaporize and redeposit material. Geometry as shown.
- Foils mounted on same ablation setup for mechanical rigidity. Normal 6-8 J/ cm^2 at beam center reduced by factor 0.707.
- Foils exposed:
  - 650 nm, 800 nm Al 2 - 6.4 to 11.5 cm (Lebow)
  - 400 nm Ag 4 cm
- Conditions DURING ablation not known: analysis of framing images MAY yield clues about ablation dynamics

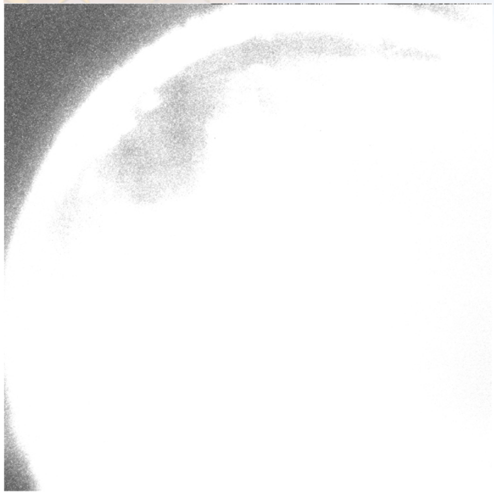
1-D Heat flow modeling: RHEPP nitrogen beam on sub-range foils

- **Purpose – predict thermal response of sub-range (for RHEPP) Au, Ag, Ti, Al. Look for fastest heating rate.**
- **Proton precursor to 90 ns, then Ni (++) heating starts**
- **Au heats from surface melting to ablation in ~ 15 ns**
  - **Ag not far behind**
  - **800 nm Al too slow**



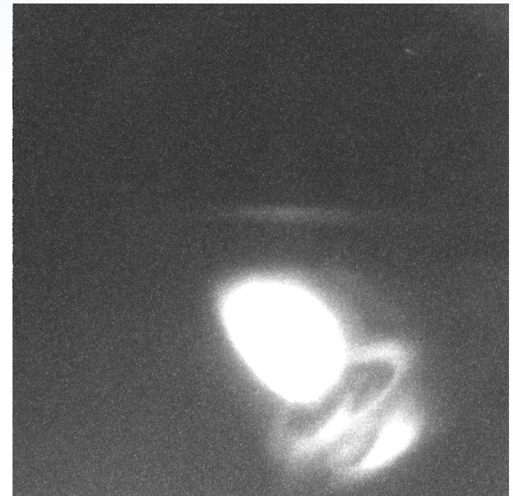
1st Experiment: plume evolution, solid titanium target

Exposure = 100 ns

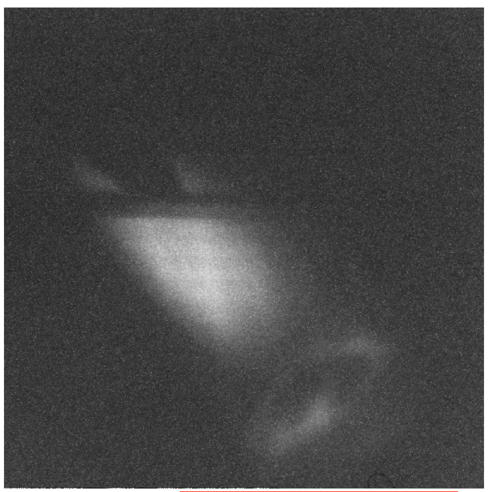


T = 0 sec (arbitrary)

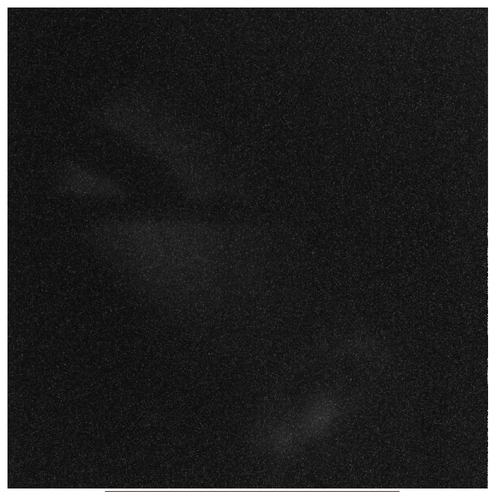
T = 2.35 μsec



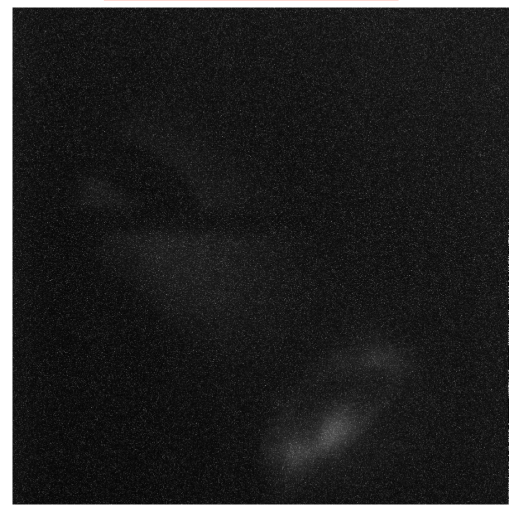
T = 7.35 μsec



T = 12.35 μsec



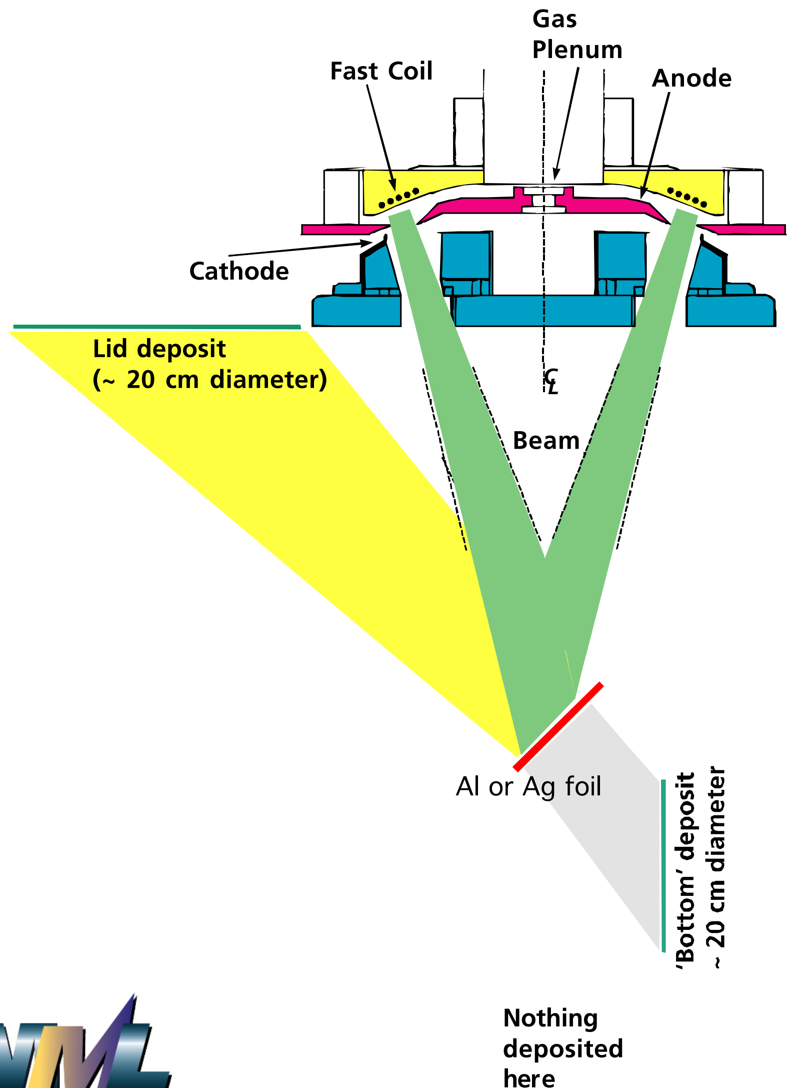
T = 17.35 μsec



T = 22.35 μsec

Note: 1) slowness of plume evolution, 2) 100 nsec exposure time

The RHEPP-1 nitrogen beam strikes foil at 45°, and film is deposited in both directions normal to foil plane



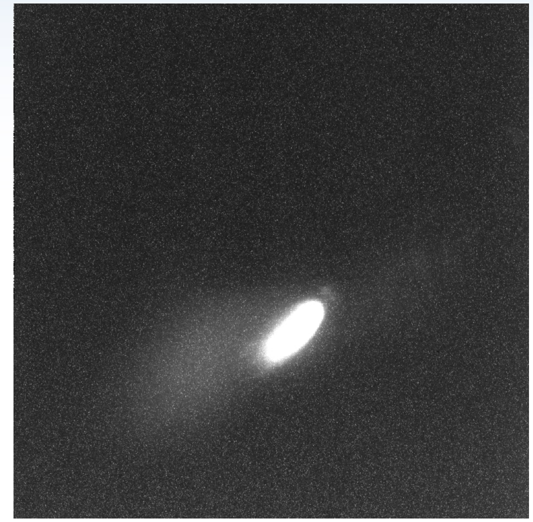
- **High-energy pulsed ions (700 kV, 200 A/cm^2) vaporize and redeposit material. Geometry as shown.**
- **'Lid' deposit at ~ 50-60 cm distance, 'bottom' deposit at ~ 20 cm distance. Si wafer mounted for 1-D dek-tak thickness profile measurements**
- **No deposition observed at tank bottom**
- **Foils exposed:**
  - **650 nm Al 11.5 cm diam (Lebow)**
  - **400 nm Ag 4 cm diam (Lebow)**

40 mm diameter Ag target, Shot 2039

Exposure = 5 ns

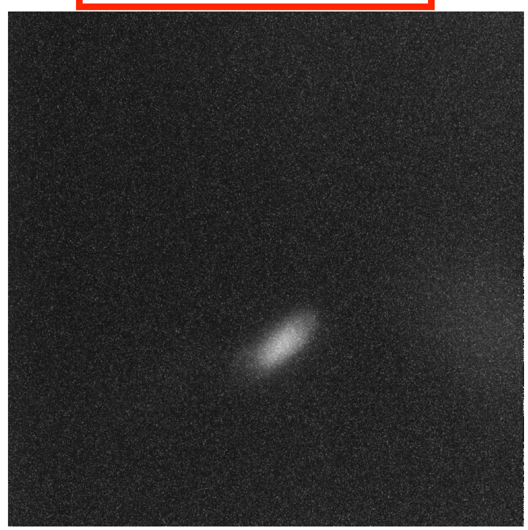
T = 4100 ns (arbitrary)

T = 4250 ns

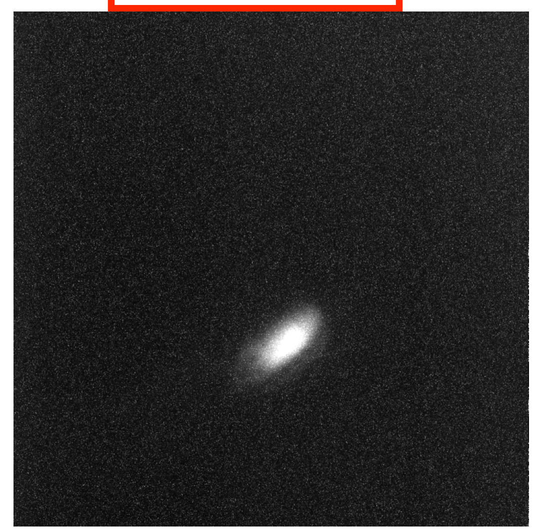


T = 4400 ns

T = 4700 ns



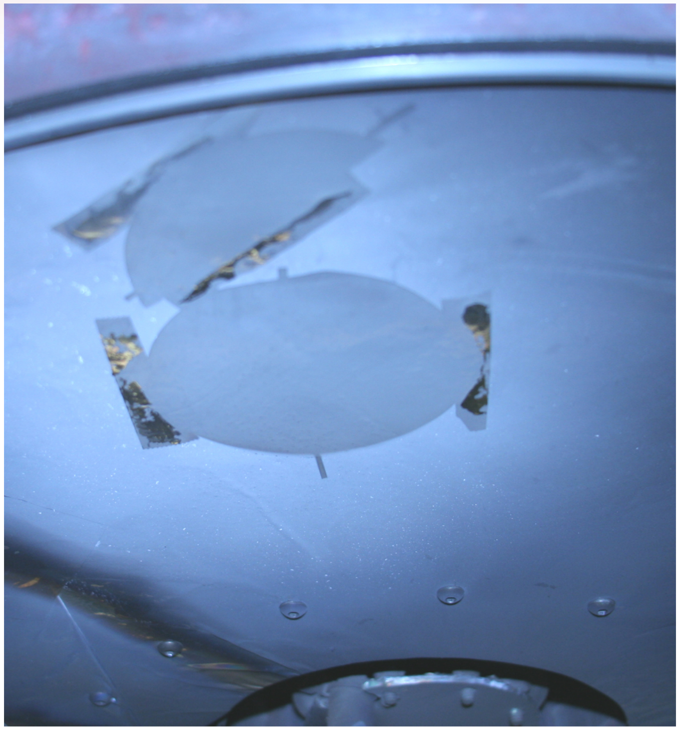
T = 4850 ns



T = 5000 ns

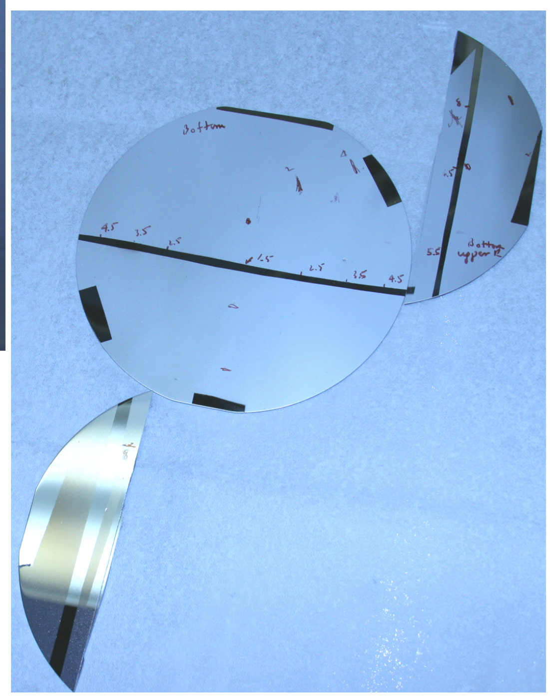
Note: 1) diameter shrinks with time, 2) 900 ns total time duration

Photos of Si wafers after 7 shots



Si wafers on top lid after shots

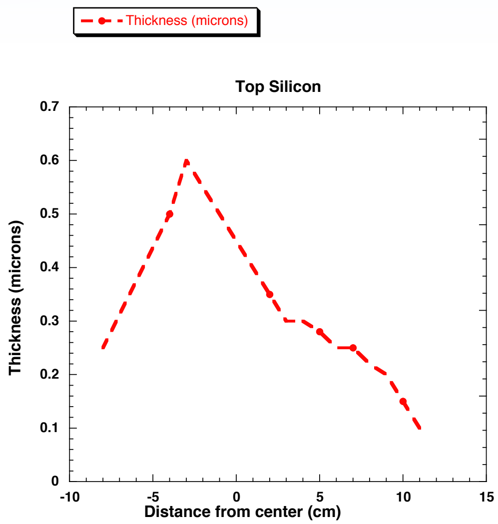
- (Left) Deposit on top lid
- (Bottom) bottom Si wafers demounted on bench
- (lower right) note cm-markers on close-up of film, heterogeneous appearance.

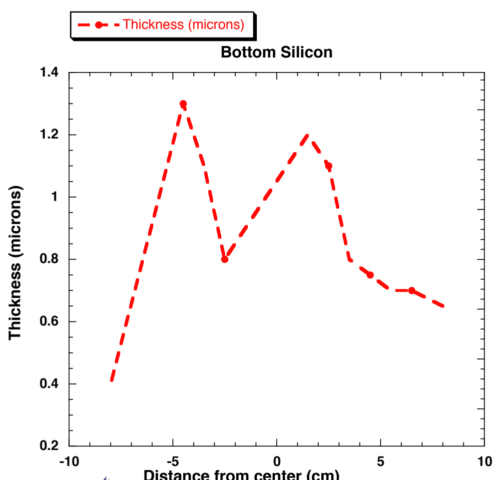


Bottom Si wafers on bench

Closeup, deposited material

The RHEPP-1 nitrogen beam strikes foil at 45°, and film is deposited in both directions normal to foil plane





- **1-D dek-tak thickness measurements made of both top and bottom depositions. Two chords measured from (approx) deposition center (left).**
- **'Smoothed profile overlaid, material inventoried using average thicknesses and $2\pi r\Delta r$ additions.**
- **Totals: 81 μm-cm^2 top, 181 μm-cm^2 bottom, 265 μm-cm^2 total. FIB-SEM of samples shows ~ 25-50% increase in thickness compared to dek-tak**
- **Total volume of 7 foils shot (not including He shot): 479 μm-cm^2. So between 70 and 85% of initial mass accounted for.**
- **Foil surface rough - typical R_A ~0.3 μm**

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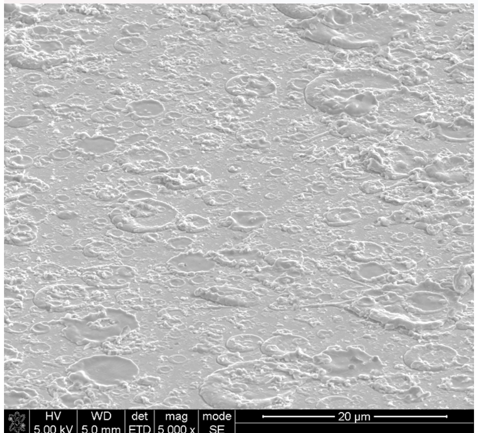
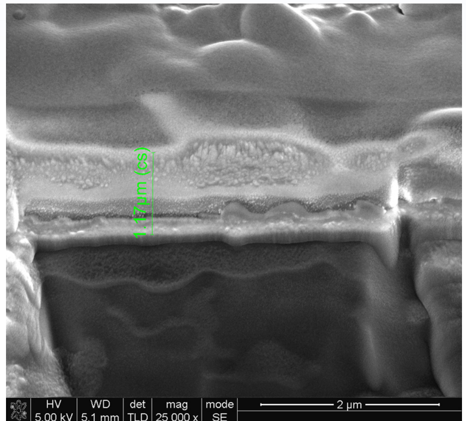
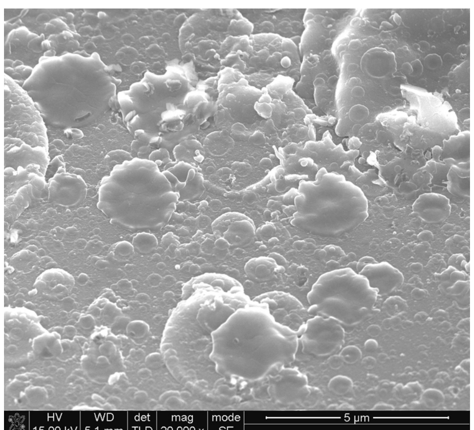
The RHEPP-1 deposited film appears to be formed of droplets, but film appears slightly porous to fully dense



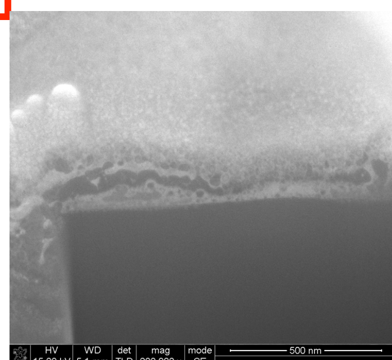
SEM, deposited material, 'top' 3 cm radius



FIB/XTEM, top 3 cm film

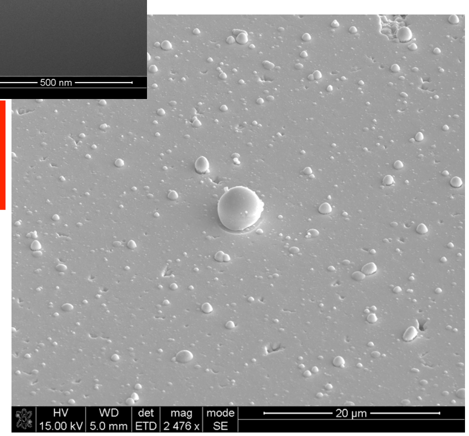


SEM, deposited material, 'top' 5 cm radius



FIB/XTEM, top 5 cm film

- 'Smoothed profile overlaid, material inventoried using average thicknesses and $2\pi r\Delta r$ additions.
- FIB-SEM of Top 3 cm radius point (right) shows twice the thickness as Dek-tak indicates. So 265 becomes 530.
- Total volume of 7 foils shot (not including He shot): 479 μm-cm^2. So about equal to deposited material.
- Surface of Ni film deposited from thick target is much smoother (below)
- SEM shows 'droplets' - indication from FIB is 'overlapped pancakes'
- EDX shows Al, O in film. Since we break vacuum every shot (unlike with films from solid targets), much more oxidation occurs.



SEM, Ni film from solid target

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Summary of sub-range foil shots

- **Extended timescale imaging: 40 mm Ag shows lighted image for 900 ns.**
- **Al (much larger diameter target) light shows much shorter duration.**
- **Deposited film measurements show twice as much film deposited from foils in 'transmission' direction, compared to 'reflected' direction. No material is deposited in direction of beam propagation.**
- **FIB cut and SEM images of film surface show 'droplety' appearance. Viewing of the cut indicates fully dense to slightly porous layer . This may be expected since the most of material is probably deposited in molten state. Measured thickness shows that dek-tak is off by factor ~ 2. Therefore, the two spots together account for roughly all the material in the foils.**