Recrystallization and melting behavior of rolled tungsten under high heat flux loads

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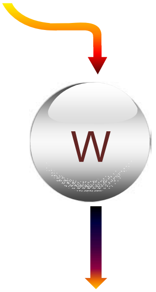
Outline

- Introduction
- High heat flux tests in GLADIS
- Recrystallization behavior after pulsed exposures
- Melt-layer characterization
- Summary/Outlook

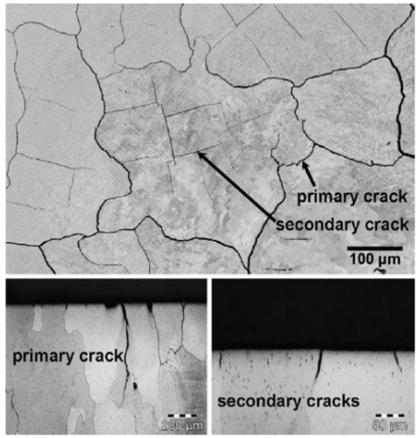
Introduction

High heat flux loads



high surface temperatures

Recrystallization & Grain growth



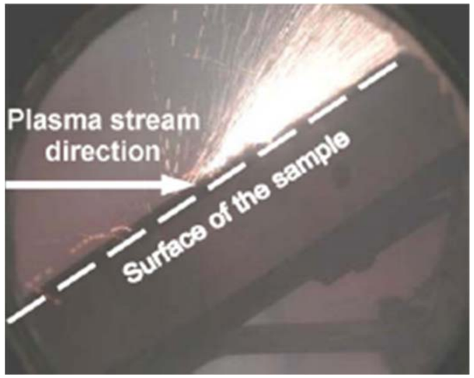
>> material embrittlement

>> crack formation

>> material degradation

! >> fatal destruction of the components

Melting



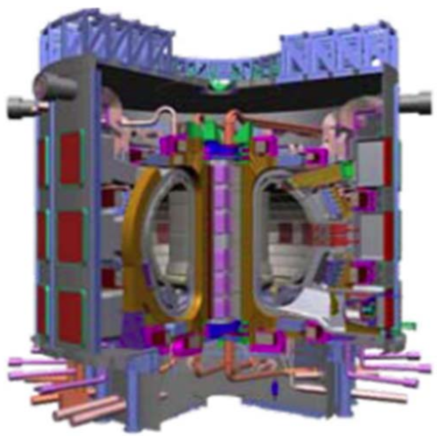
>> melt layer ejection

>> melt layer motion and redistribution

! >> severe erosion of PFCs

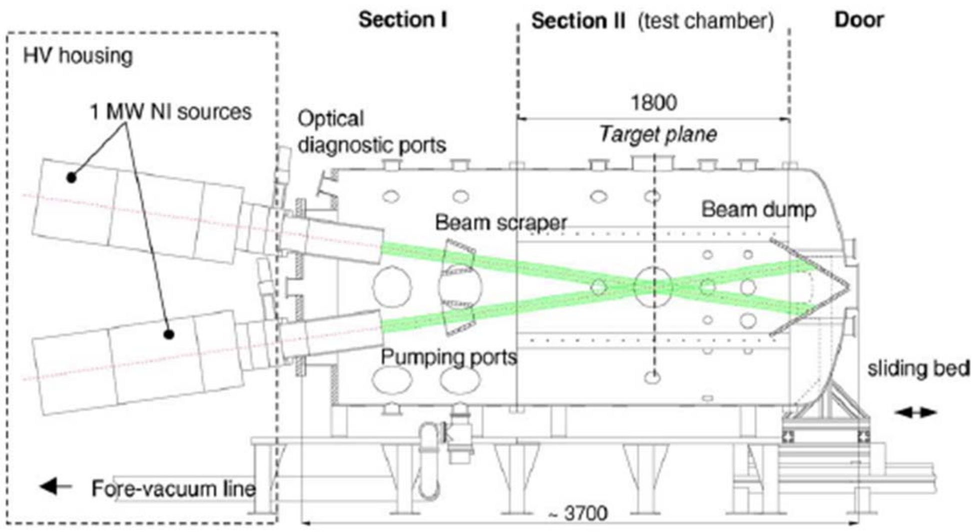
Fusion Engineering and Design.82 (2007) 1720–1729
Journal of Nuclear Materials 363–365 (2007) 301–307

HHF tests



Characteristics of Transients in ITER

Event	Repetition	Duration [ms]	Energy dump [MJ/m^2]	Power flux [GW/m^2]
Disruption	Low	1-10	$10-10^2$	10^2
A giant ELM	>1 Hz	0.1-0.5	1-3	1-10
VDE	Low	10^2-10^4	20-60	0.01-0.1



High heat flux facility: GLADIS

Pulse length:

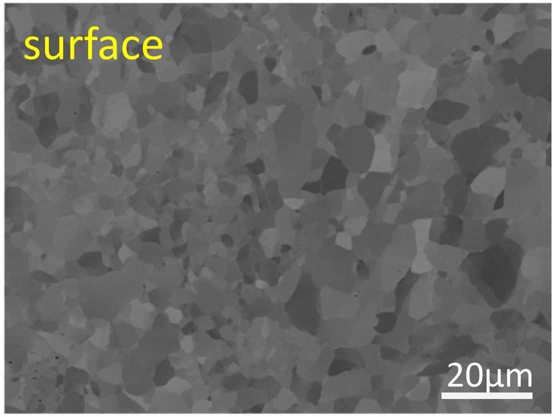
5 ms (100Hz) ~ 45 s, cycle rate 45-100/h.

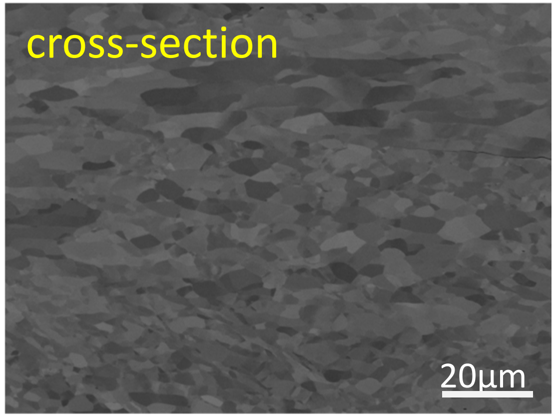
Power flux:

3-55MW/M^2 (with one 1.1 MW neutral beam)

Experimental

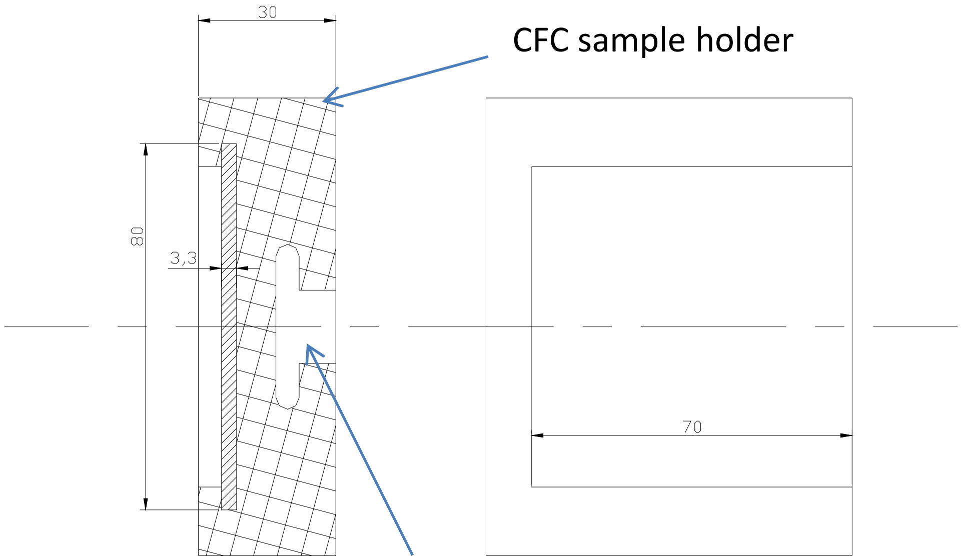
- Raw material
  - Pure tungsten (>99.95wt.%)
  - Rolled to 3.3mm
  - Microstructures

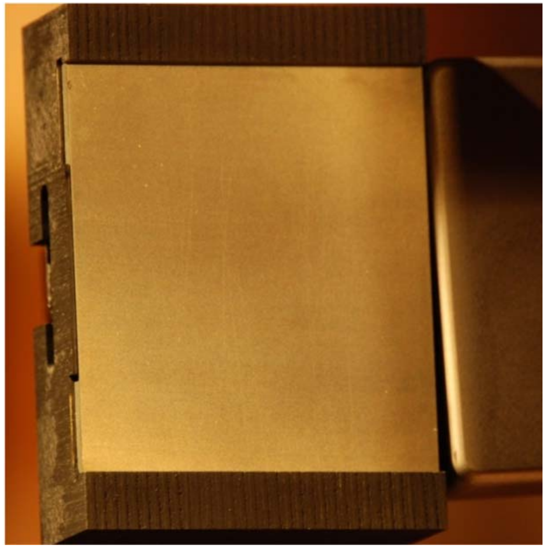




Rolling Direction

- Sample installation





Sample surface ⊥ the beam axis

Stepwise tests

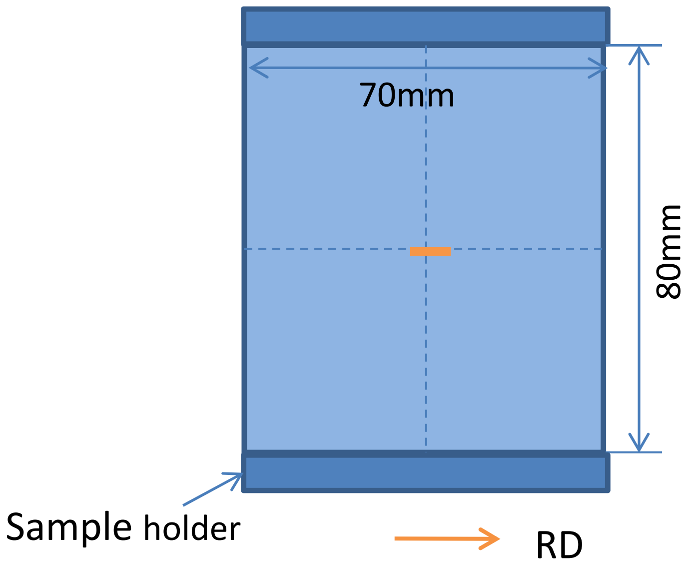
Power density (MW/m^2)	pulse train	Duration(s)	Results
23	1st	0.5	
	2nd	1.0	
	3rd	1.5	Little melt spot in the center
	4th	1.8	Serious melting on the surface

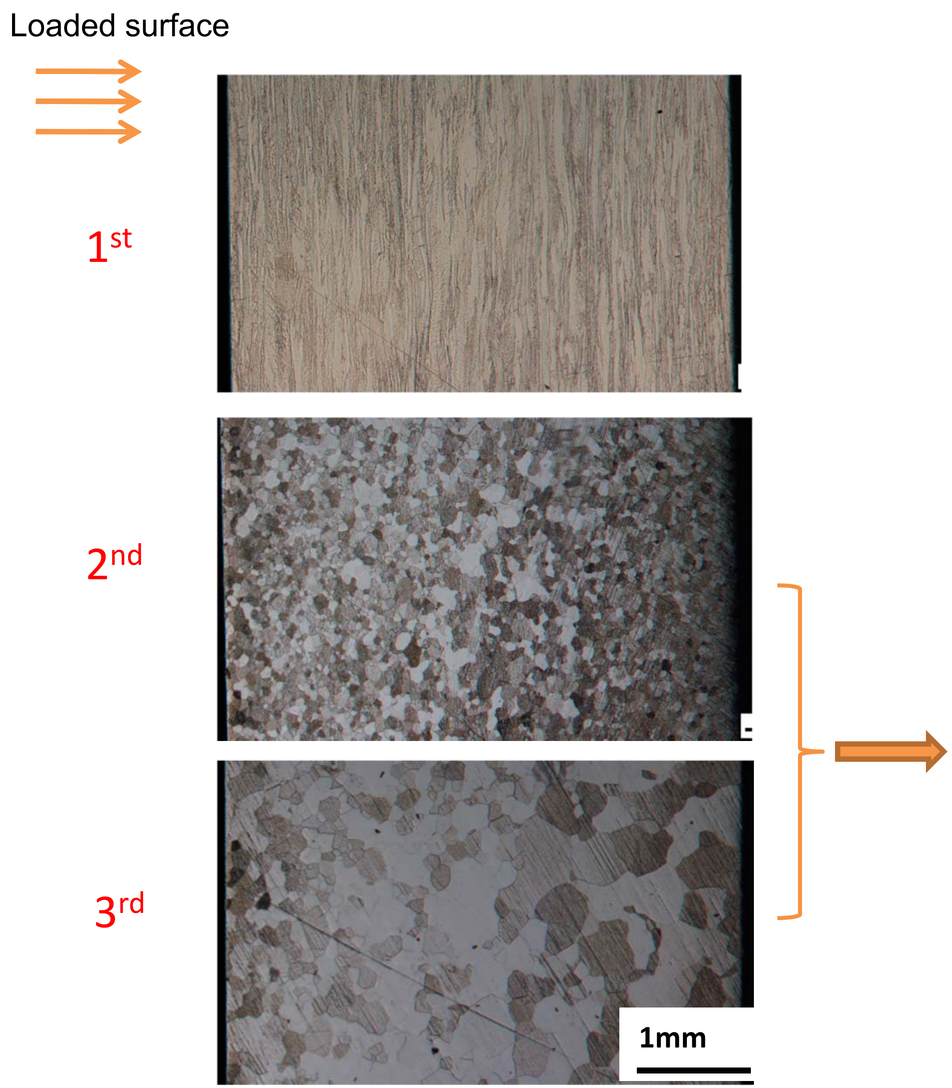
Melting threshold
28.53$MWm^{-2}s^{-1/2}$

Before each pulse, the sample was cooled to room temperature.

Recrystallization--up to melting

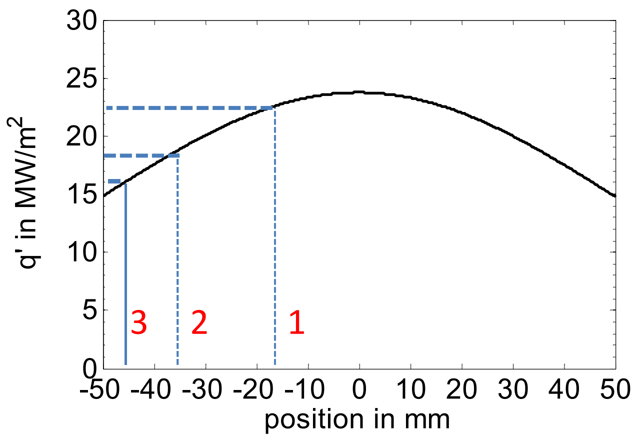
Power density (MW/m^2)	pulse train	Duration(s)
23	1st	0.5
	2nd	1.0
	3rd	1.5

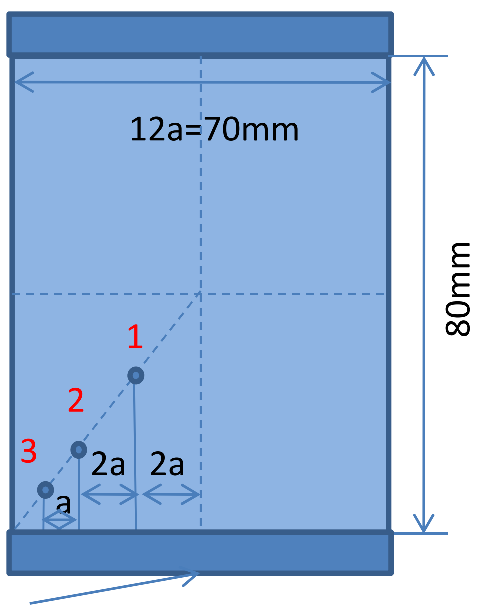




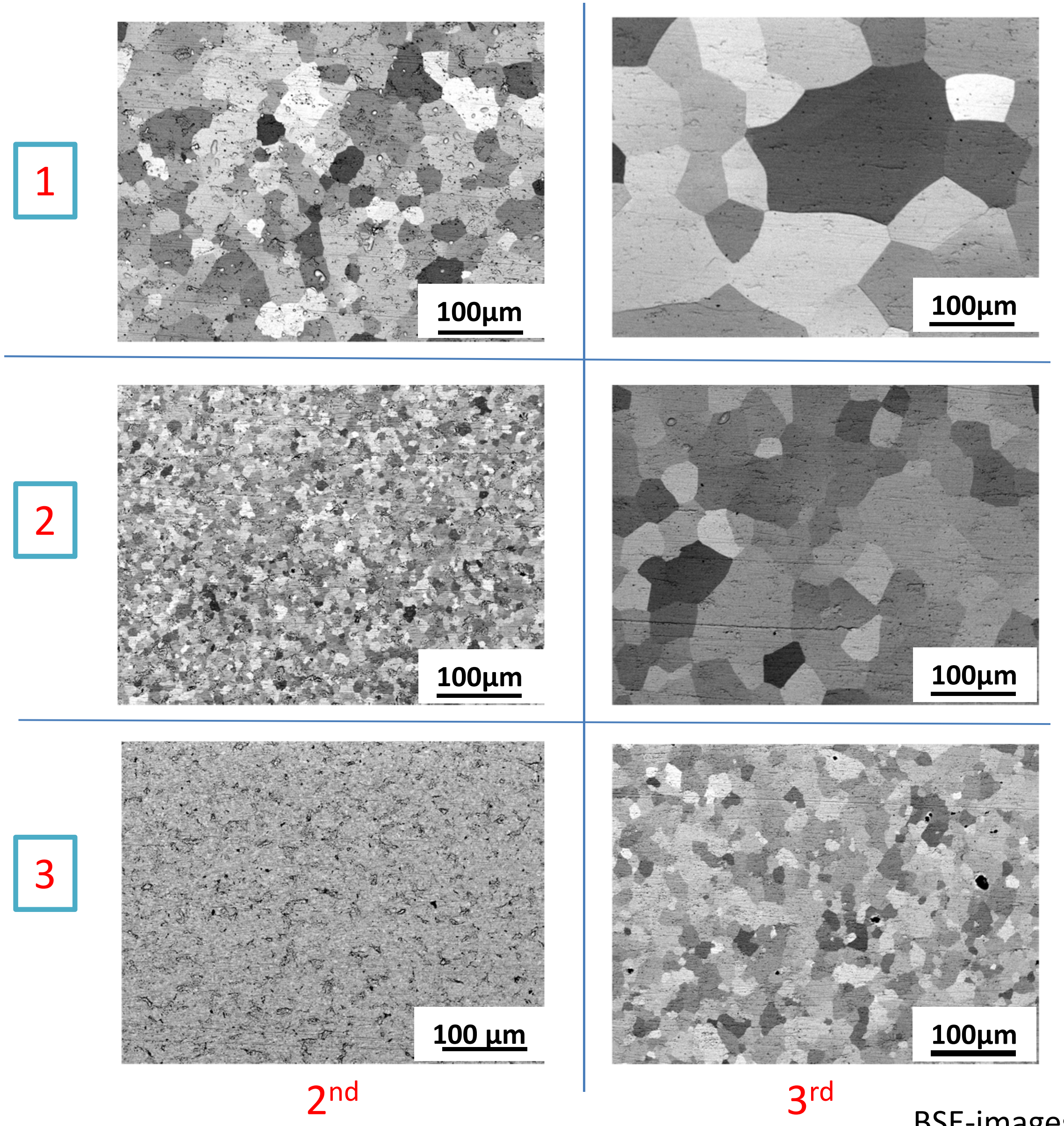
LM-images of cross-section after the three pluses

Recrystallization – power density & pulse length





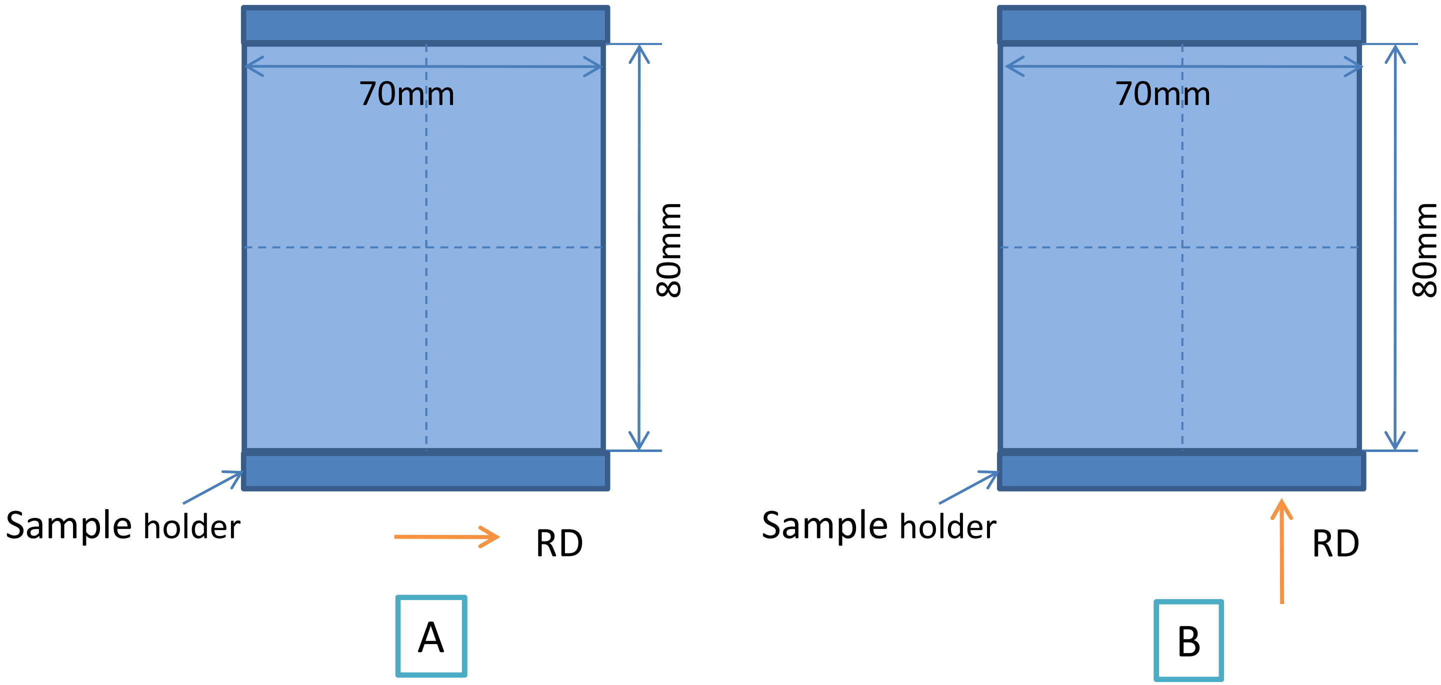
Sample holder



BSE-images

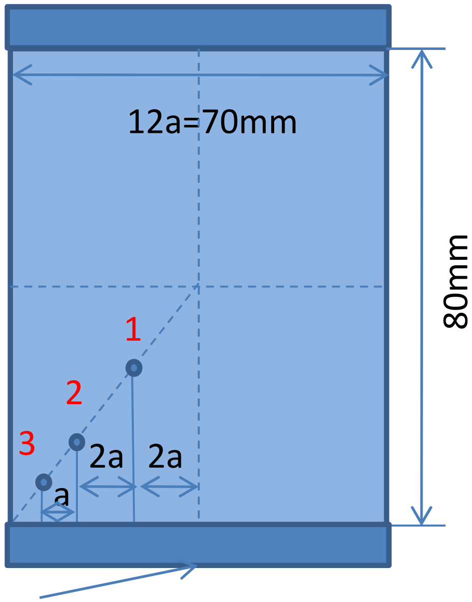
Recrystallization – different RD

Power density (MW/m^2)	pulse train	Duration(s)
	1^{st}	0.5
23	2^{nd}	1.0
	3^{rd}	1.5

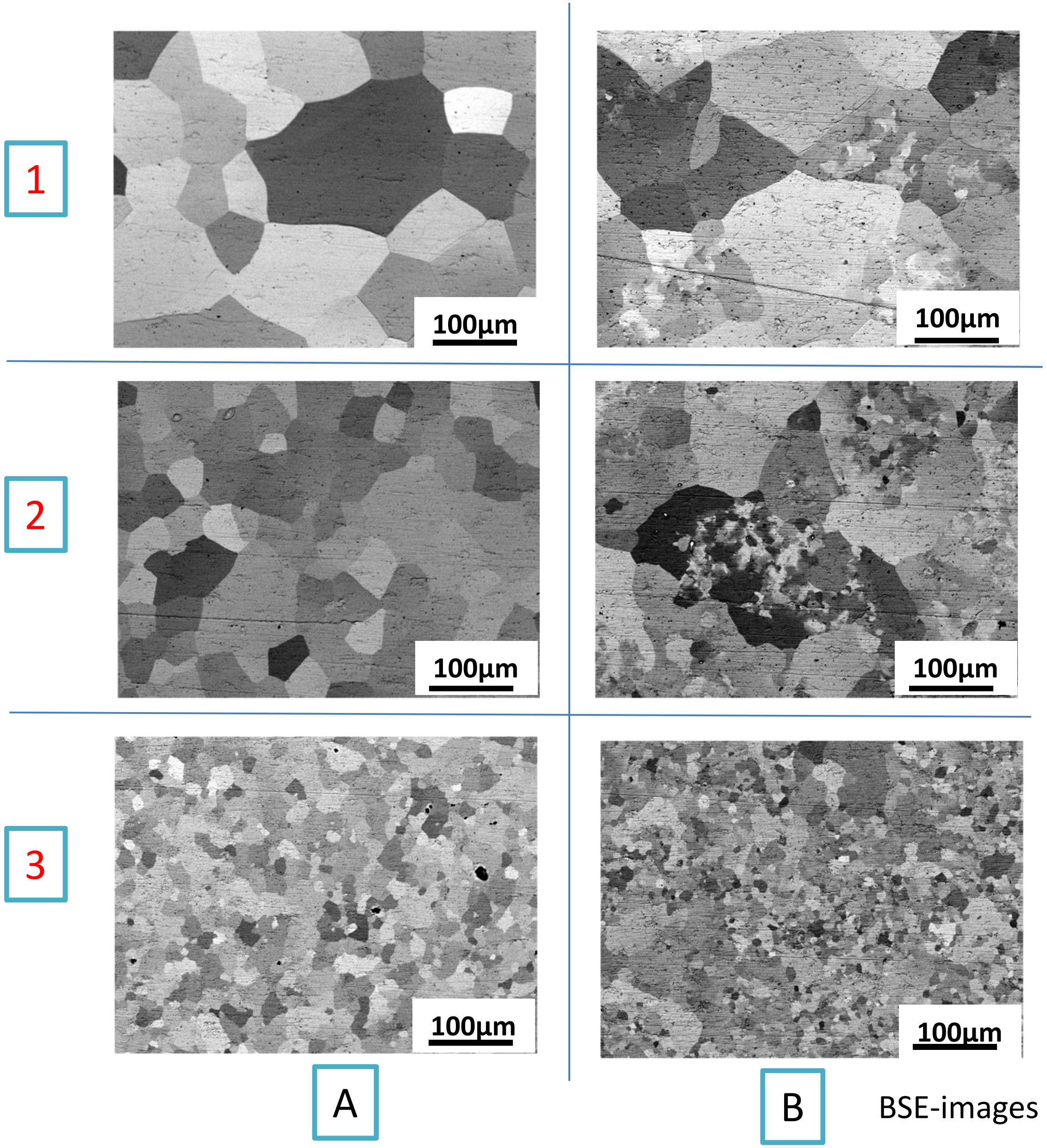


Recrystallization – different RD

	grain elongated direction	direction with better boundary thermal conductivity
A	→	↑
B	↑	↑



Sample holder



BSE-images

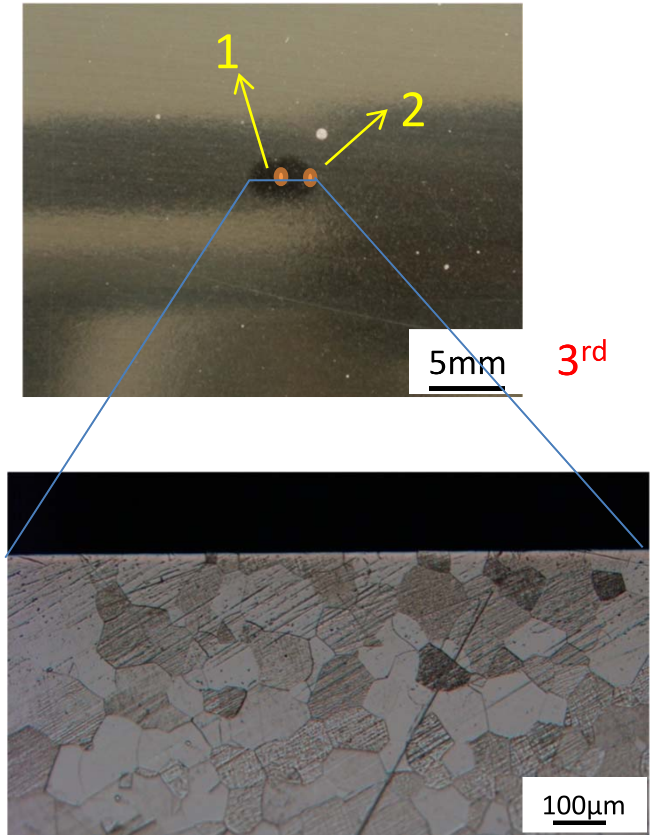
Melting

Power density (MW/m²)	pulse train	Duration(s)
23	1st	0.5
	2nd	1.0
	3rd	1.5
	4th	1.8

3rd

4th

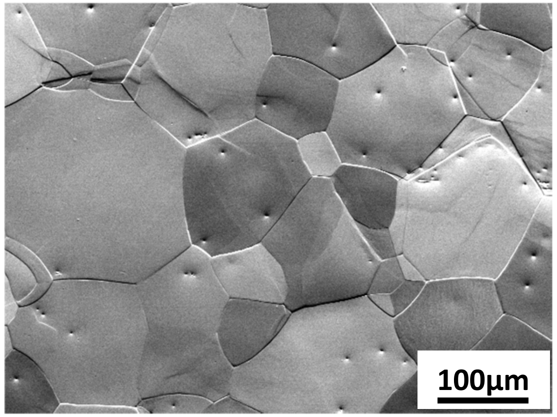
Melt layer characterization



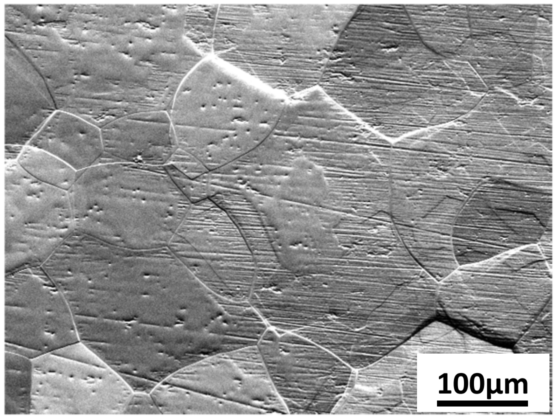
LM-image of cross-section

SEM-images

1



2

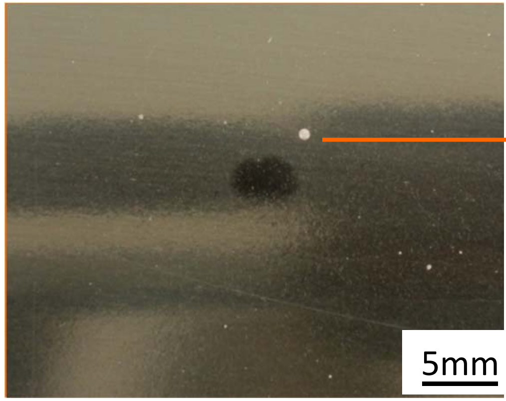


The microstructure characteristics have hardly changed after slight melting on the surface.

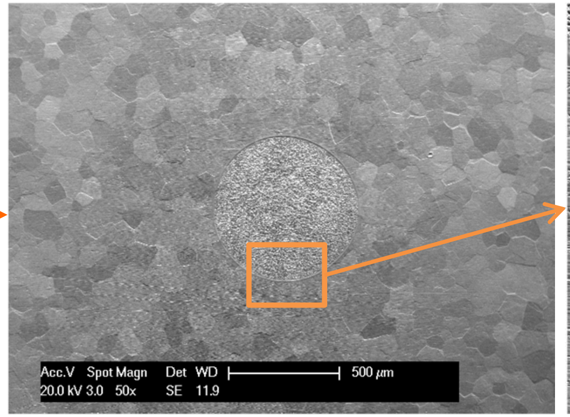
The specks on the melt surface come from the scratches on the original polishing surface.

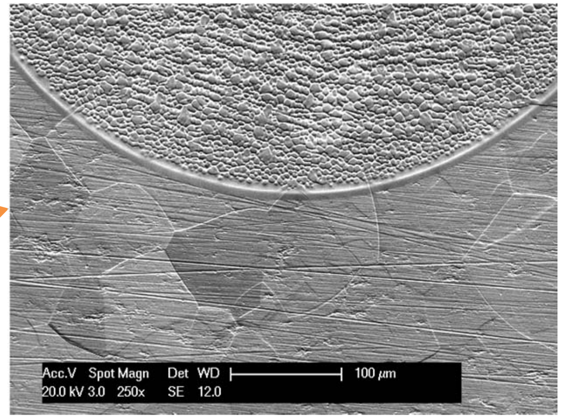
Melt layer ejection

deposited droplets



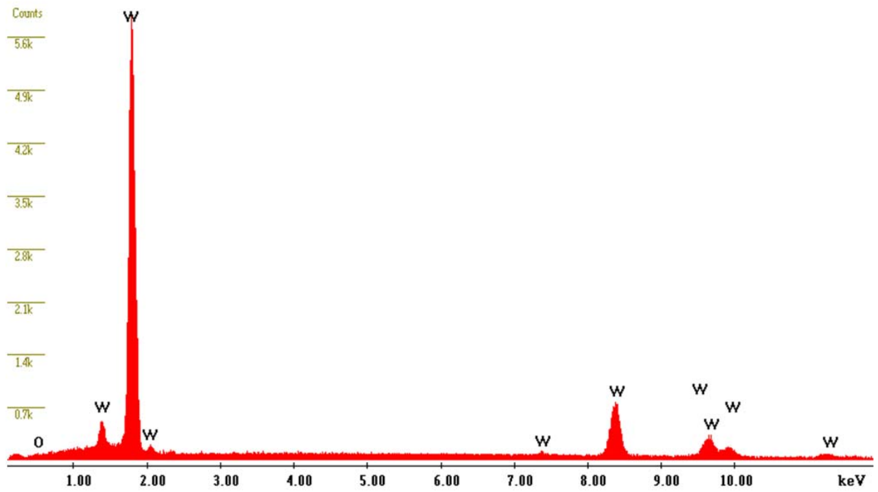
3rd





Droplets ejection under high heat flux loads

due to particles impact momentum?



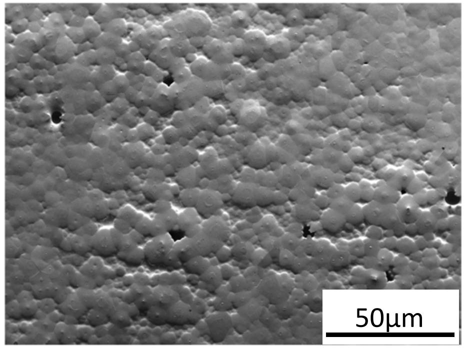
EDX for the deposited droplet

Melt layer characterization

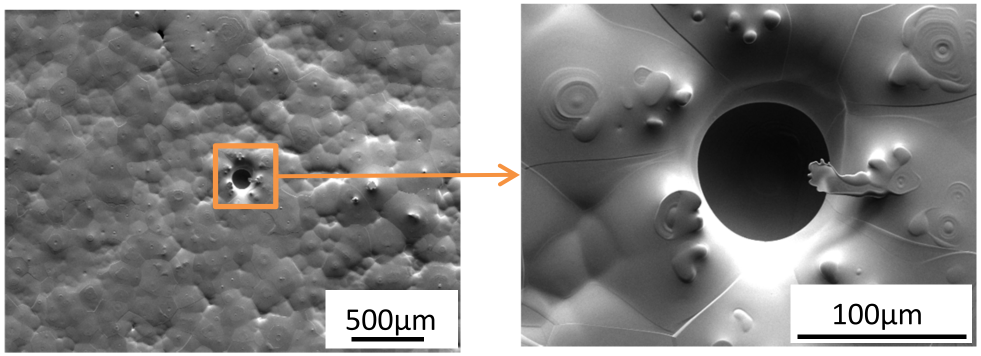
Power density (MW/m^2)	pulse train	Duration(s)
23	1st	0.5
	2nd	1.0
	3rd	1.5
	4th	1.8

4th

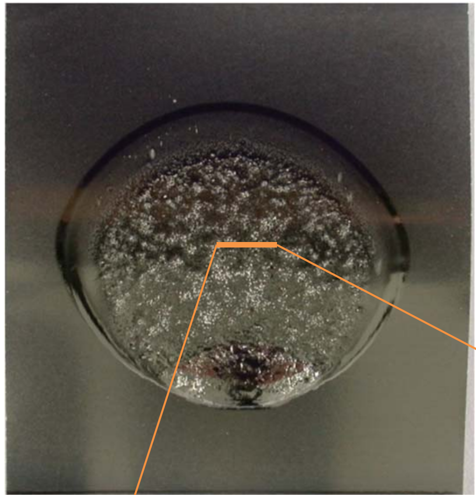
1



2



Melt layer -- bubbles



4th

Melt ejection leads to loss of parts of the melt layer.

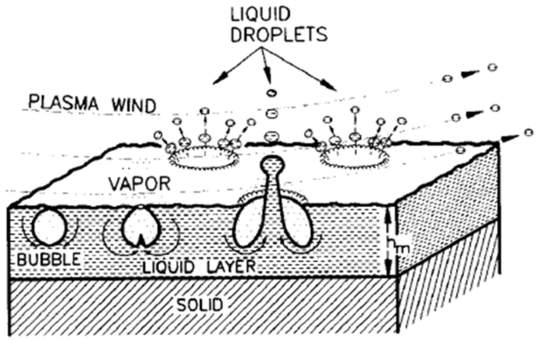
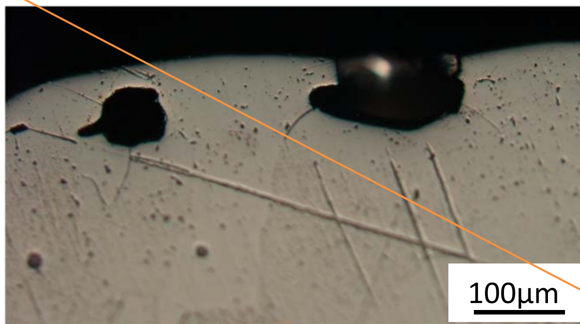
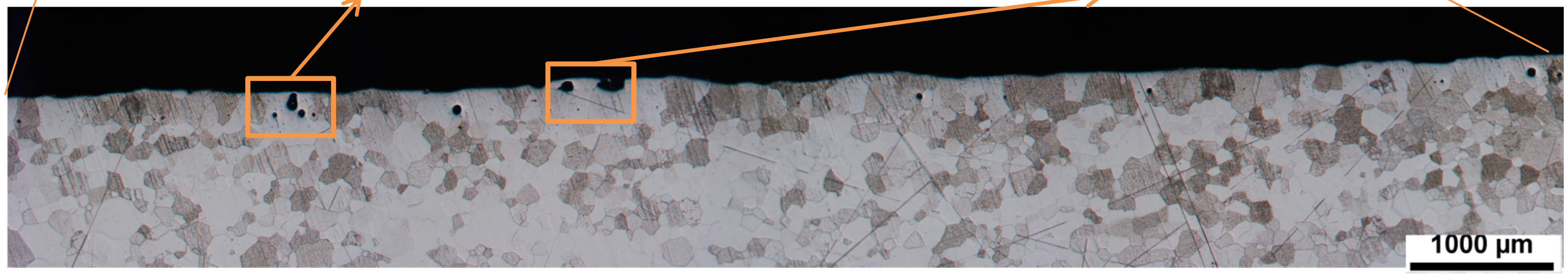


Fig. 4. Bubble growth, vaporization and loss by incident plasma wind.

A.Hassanein et al. J. Nucl. Mater. 241-243(1997)288-293

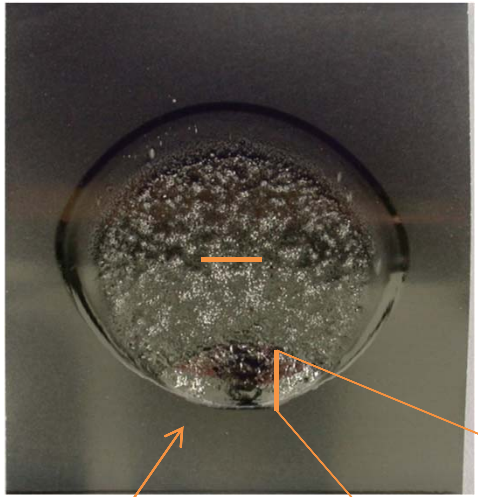


LM-images



Cross-section

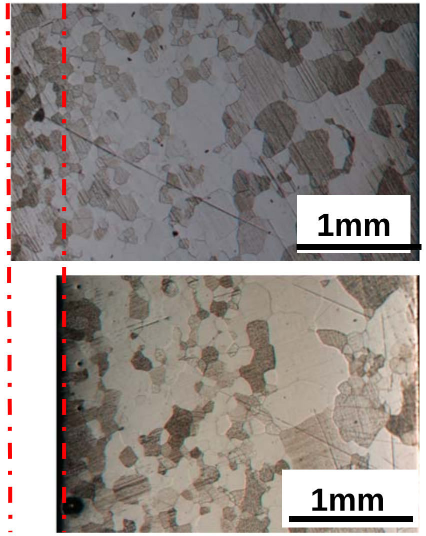
Melt motion & redistribution



Vertical motion under gravity

Melt layer erosion by melt layer motion.

thickness loss ~300µm

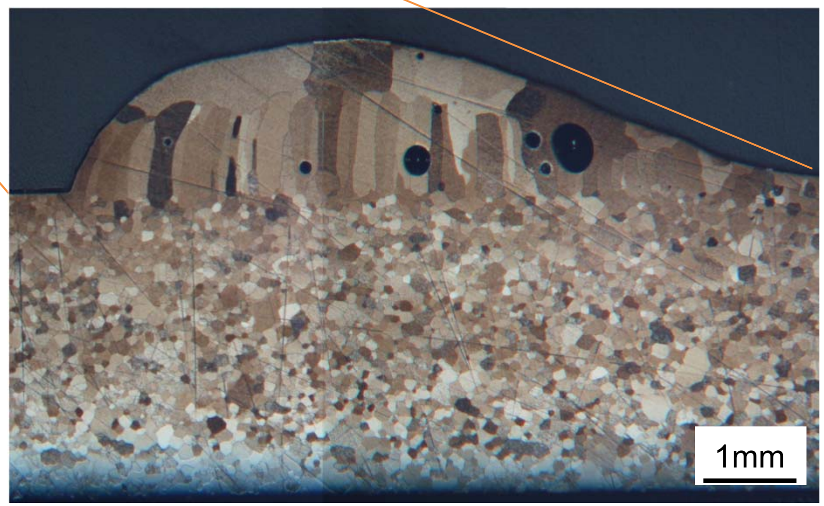


3^{rd}

4^{th}

LM-images of cross-section in the center of samples

Coarse columnar grains & bubbles



LM-image

Summary

- Recrystallization happens rapidly under pulsed high heat flux loads.
- The degree of recrystallization depends on the pulse duration, power density and the grain orientation.
- Melt layer motion and ejection are the main factors responsible for tungsten damage.
- The microstructures of resolified layer depend on the layer thickness which corresponds with the solidification rate.

Outlook

- Melt layer erosion of rolled tungsten will be further studied.

✓ Bubbles formation and boiling; (impurity measurement: SIMS, EDXS)

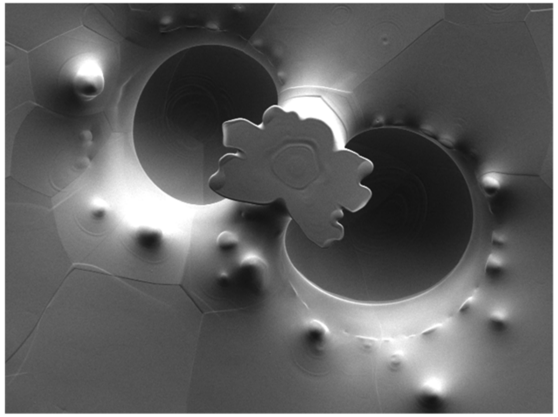
✓ Erosion during cyclic high heat loads. (e.g. 23MW/m^2,1.5s ×10)

- Different grade materials will be used to study the thermal behavior up to melting. (Cracks are expected.)

✓ Sintered W;

✓ Recrystallized W;

✓ W- 5wt.%Ta alloy;



Thank you for your attention!

IPP

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Parameters of the tests & responses of the samples

Power density (MW/m^2)	Pulse No.	Duration(s)	Response	
			Cracks	Melting
10	1	1.0	No	No
	2	2.0	No	No
	3	3.0	No	No
	4	3.5	No	No
	5	4.0	No	No
	6	4.5	No	No
	7	5.0	No	Yes
16.5	1	1.0	No	No
	2	2.0	No	No
	3	2.5	No	Yes

The interval between two pulses is 8mins.

Parameters of the tests & responses of the samples

Power density (MW/m^2)	Pulse No.	Duration(s)	Response	
			Cracks	Melting
23	1	0.5	No	No
	2	1.0	No	No
	3	1.5	No	Yes
30	1	0.25	No	No
	2	0.5	No	No
	3	0.5(Set Value is 0.75s)	No	No
	4	0.75	No	No
	5	1.0	No	Yes

The interval between two pulses is 8mins.

Sample No.	Power density (MW/m^2)	Duration(s)	Response
17	23	0.5	no melting
18	23	0.5, 1.0	no melting
13	23	0.5, 1.0, 1.5	melting
19	23	0.5, 1.0 , 1.5, 1.8	melting

Samples	Neutral beam	Surface temp. °C	Particle energy $\bar{E}$ [keV]	Implantation depth nm	Particle Flux ϕ [m^{-2} s^{-1}]	Pulse length s	No. of pulses	Incident fluence Φ [m^{-2}]	Erosion (calc.) µm
Long pulse loading, actively cooled									
2 MW m^{-2} heat flux:									
2 mm W-VPS on steel F82H	H	841	*8*	*60*	1.58E+21	27	121	5.17E+24	0.10
2 mm W-VPS on steel 316L	He	860	*16*	*30*	7.60E+20	27	734	1.51E+25	7.00
W bulk, AC 4	H	200	8	*60*	1.58E+21	27	772	3.30E+25	0.80
W bulk, AC 1	He	200	*16*	*30*	7.60E+20	27	734	1.51E+25	7.00
W bulk, AC 5	90H/10He	200	*8/17*	*60*	1.50E+21	27	769	3.12E+25	2.20
10 MW m^{-2} heat flux:									
W bulk, AC 2	H	850	15	*120*	4.03E+21	30	251	3.04E+25	0.70
W bulk, AC 3	90H/10He	850	*15/28*	*120*	3.85E+21	30	253	2.92E+25	2.00
Short pulse loading, adiabatically loaded									
10 MW m^{-2} heat flux:									
200 µm W-VPS on graphite	He	2150	33	*70*	1.90E+21	3.5	200	1.33E+24	0.60
200 µm W-VPS on graphite	H	2000	15	*120*	4.03E+21	3.5	105	1.48E+24	0.03
W bulk, W-30	He	~2100	33	*70*	1.90E+21	3.5	200	1.33E+24	0.60
W bulk, W-26	H	~2100	15	*120*	4.03E+21	3.5	105	1.48E+24	0.03

H. Greuner