Pulsed heat load effects on plasma facing materials

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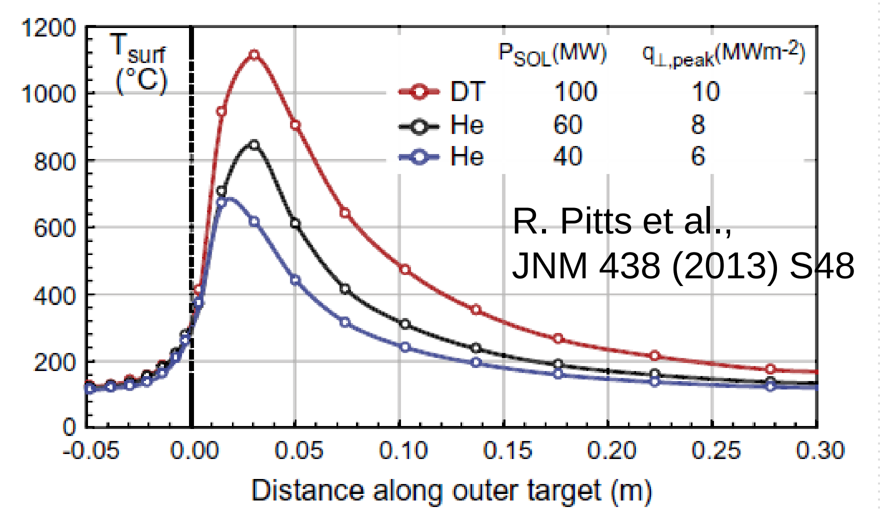
Outline

- Heat loading to divertor and its effects on tungsten
  - Steady-State, Slow transient, Pulse (ELMs, disruption)
- Repeated pulsed heat load effects
- Melt layer dynamics
- Vapor shielding
- Helium induced structure on tungsten and its response to pulsed heat
- Summary

Heat loading to divertor

Steady-State (slow transient) heat flux to divertor

- Non-nuclear phase（H, He）
  - Peak Power（$q_\perp$）: ~**7** MW/m^2 (SOLPS, no cooling gas injection)
- Nuclear phase（DT）
  - $q_\perp$~ **10** MW/m^2（SOLPS, Cooling gas & Detached plasma)
    - Plasma detachment reduces heat flux by 75 %
    - Without detachment, heat flux would be too high
    - Surface temp. below $T_{recrystallize}$~1200 °C
  - An important issue : stable detached plasma operation
- Slow transients
  - ~ **20** MW/m^2, 10 s
    - Test condition for W divertor
  - Surface temp. **> 2000 °C** recrystallization

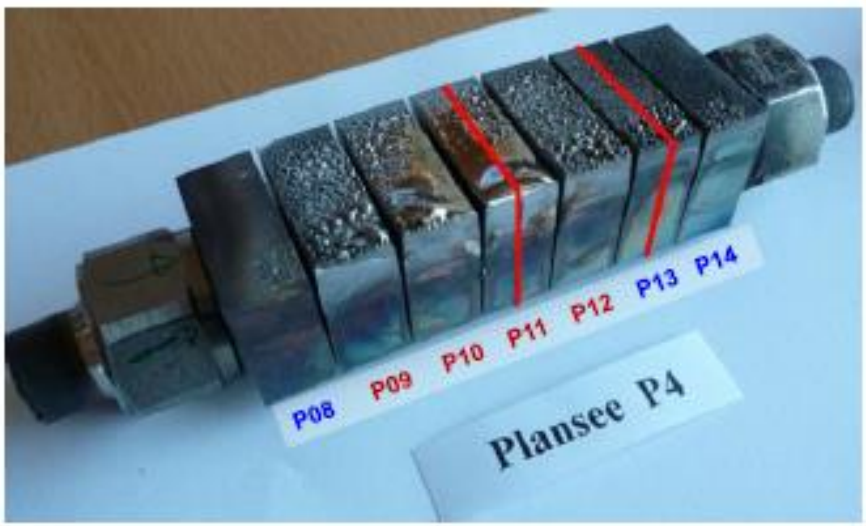


Temperature distribution on outer divertor

ITER W monoblocks under extreme heat

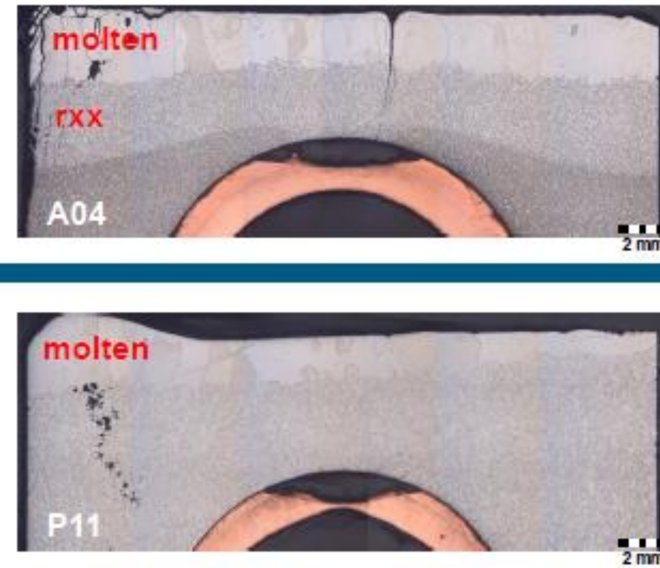
Heat Flux Conditions

F) 1000 cycles at 10 MW/m^2 +
1000 cycles at 20 MW/m^2 +
CHF (27-30 MW/m^2)



acceptable heat flux＜ 27 MW/m^{-2}

LOADING CONDITION "F"



- **recrystallization**
  → HRP (5-7 mm)
- **melting** (2-3 mm)
- **cracking** → HRP®

G. Pintsuk et al., 27th SOFT(2012)

Heat flux factor

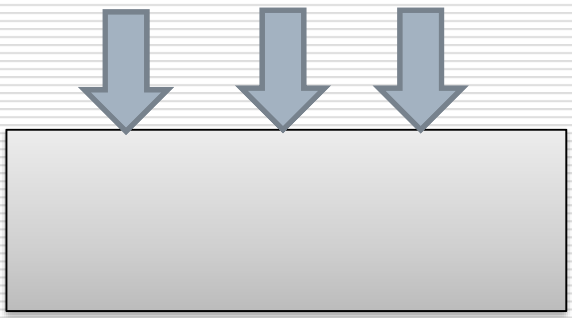
This is the number proportional to surface temperature rise as uniform heat flux is irradiated onto semi-infinite surface.

Useful criteria for surface damage evaluation.

Unit: $\mathrm{MW\ m^{-2}s^{0.5}}$ (or $\mathrm{MJ\ m^{-2}s^{-0.5}}$)

→ ~ 50 $\mathrm{MJ\ m^{-2}s^{-0.5}}$: melting threshold of tungsten

$$\boxed{Heat\ flux\ factor} \sim \Delta T = P\sqrt{\frac{4}{\pi k \rho C}}\sqrt{t} \sim P\sqrt{t}$$



ΔT: Surface temperature change

P : Heat flux

t : time

k : Thermal conductivity

ρ : Density

C : Specific heat

Transient heat loading（Disruption/VDE）

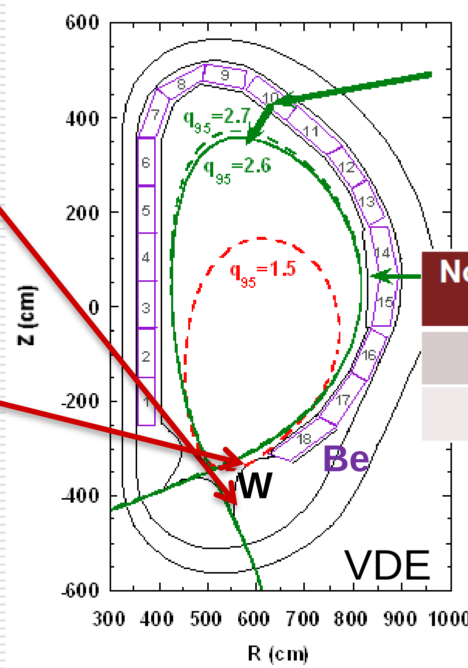
- Disruption
  - Even in H/He discharges, melting could take place.
  - Pulse length : ~1 ms
- Effects on divertor
  - Disruption（unmitigated）could melt the vertical target of divertor
  - VDE（unmitigated）could melt baffle (W) and lower first wall (Be)

Disruption heat loading (Non-nuclear Phase)

Heat flux factor

I_p MA	Mode	P_{IN} MW	W_p MJ	$E_{transient}$ MJ	λ_q m	$q_\perp$ MJ m^{-2}	ε MJ m^{-2}s$^{-1/2}$
7.5	L	20	26	13 → 26	0.02	0.22 → 2.86	4.1 → 74.3
7.5	L	30	30	15 → 30	0.02	0.25 → 3.30	4.5 → 84.9
7.5	H	40	75	25 → 38	0.01	0.83 → 8.3	15.2 → 213
15	L	8	35	16 → 35	0.01	0.52 → 7.69	9.4 → 199
15	L	18	52	26 → 52	0.01	0.86 → 3.43	15.7 → 295
15	L	28	73	37 → 73	0.01	1.21 → 11.4	22.2 → 406
15	L	40	85	43 → 85	0.01	1.39 → 18.7	25.5 → 483

R. Pitts, J. Nucl. Mater. 438 (2013) S48

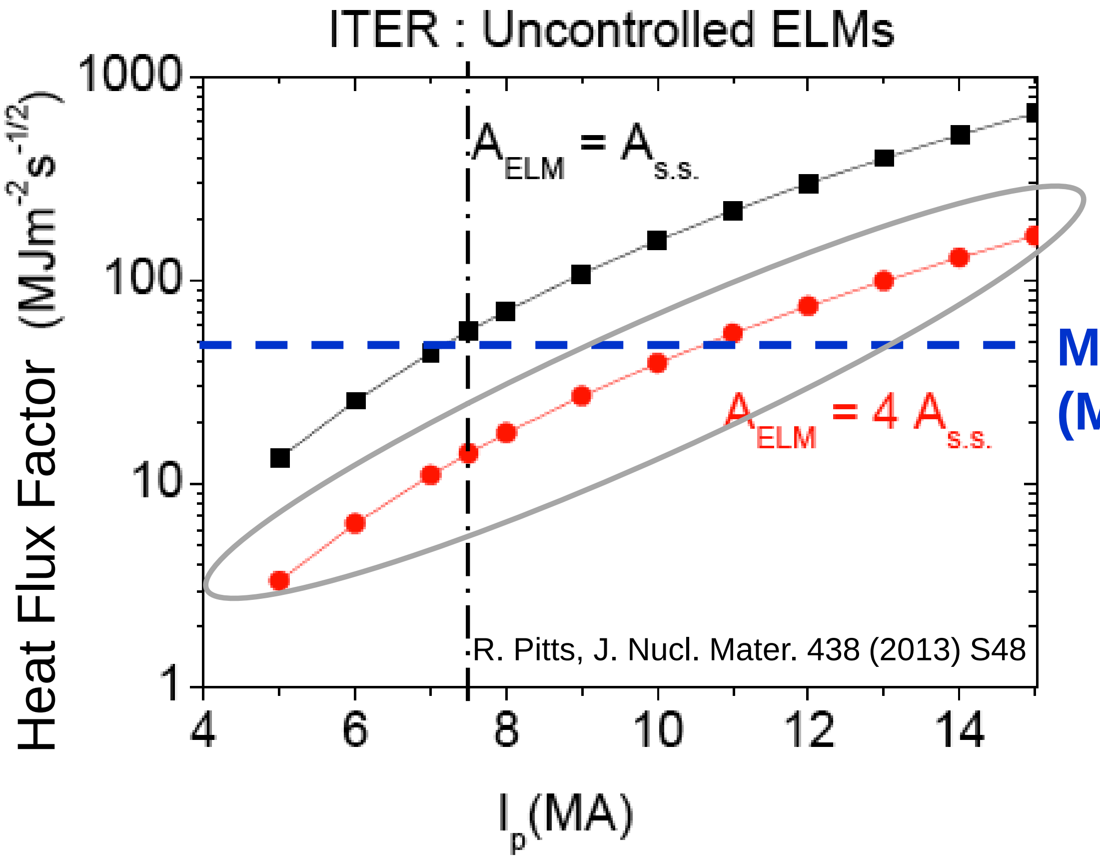


Melting threshold ~ 50 MJ/m^{-2}s$^{-1/2}$

Non-active phase disruptions	Major Disruption	Downward VDE
Unmitigated	~300	~50
Mitigated	~1400	~300

Shot No. in a non-nuclear phase

ELM energy in the non-nuclear phase of ITER



Frequency : 1~10Hz

Pulse length : sub ms

Melting Threshold (MT)

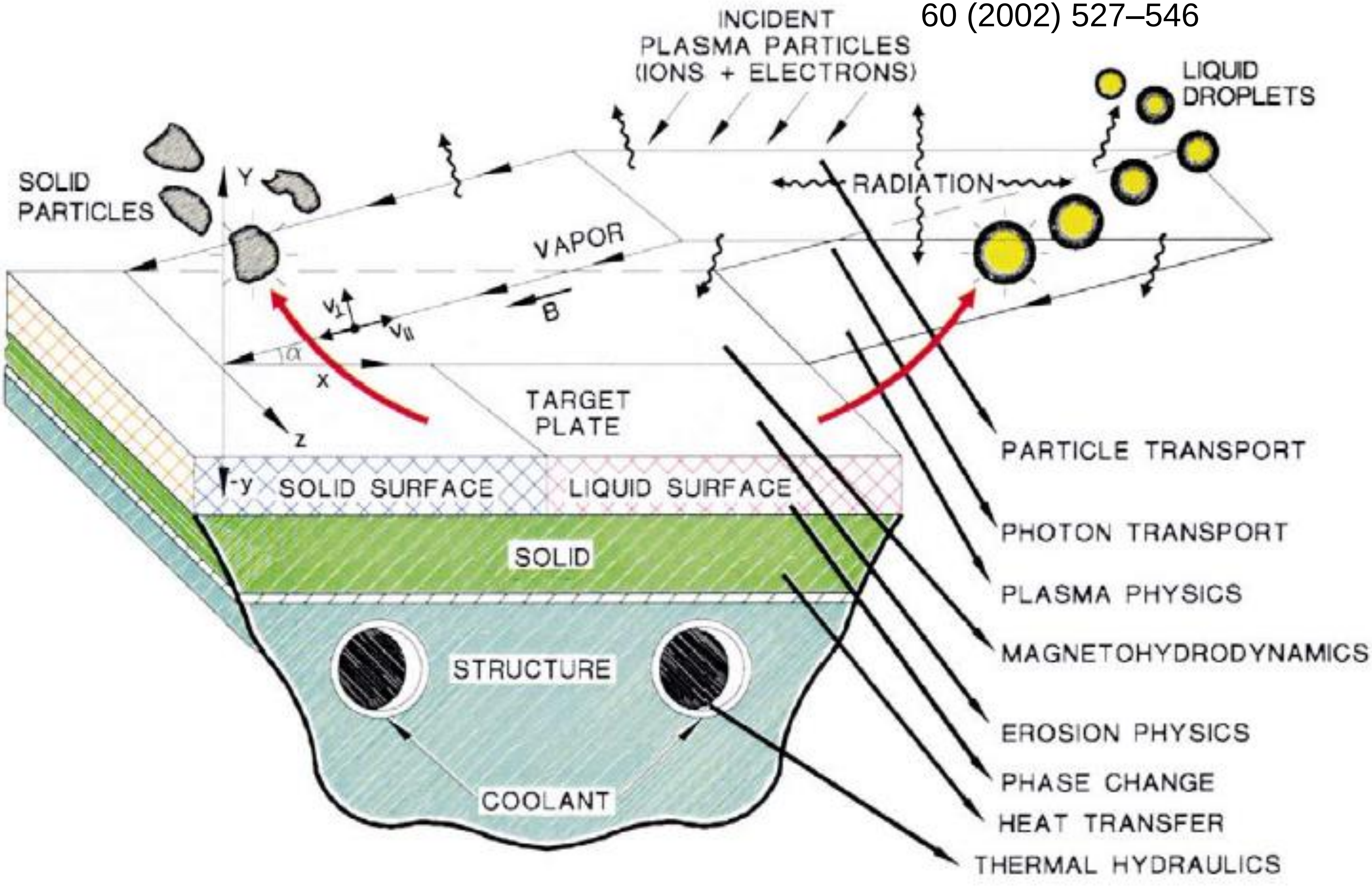
For the non-nuclear phase of ITER,

Half I_p (7.5 MA) : ELM energy density could be roughly 1/5 of **MT**
(considering possible broadening)

Full I_p (15 MA) : ELM energy density significantly exceeds **MT**
-> unacceptable, needs proper mitigation

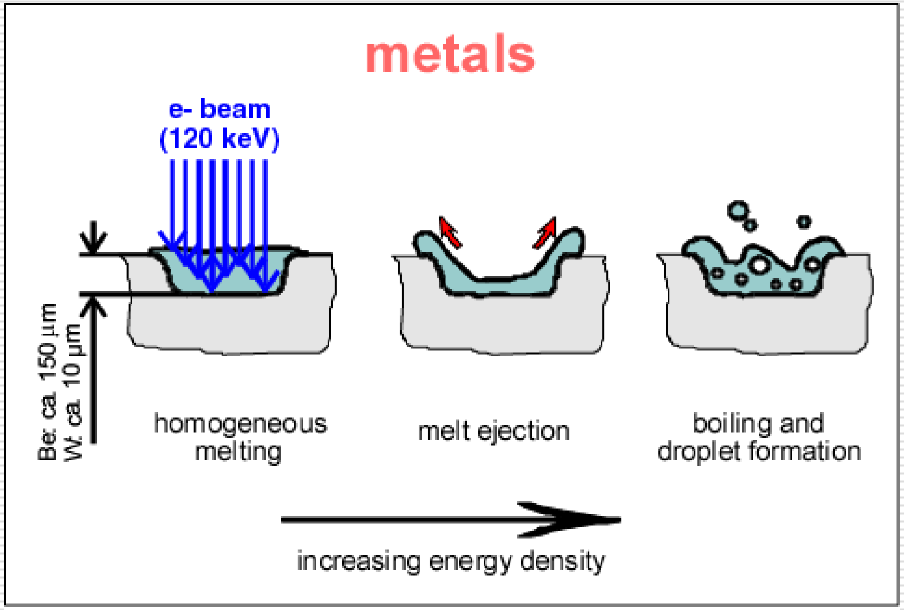
Interaction between intense pulsed heat and W

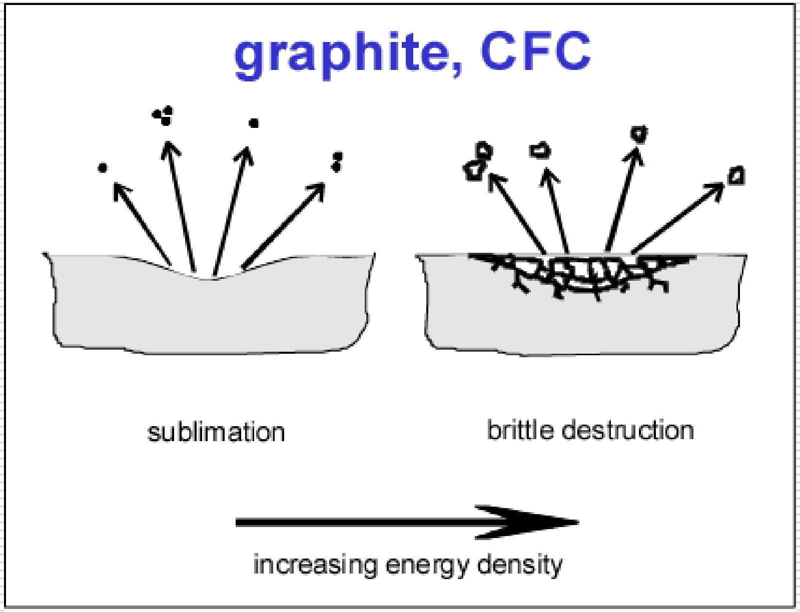
A. Hassanein, Fusion Eng. Des. 60 (2002) 527–546



Pulsed heat loading effects on materials

from J. Linke





FOR METALS:

Splashing

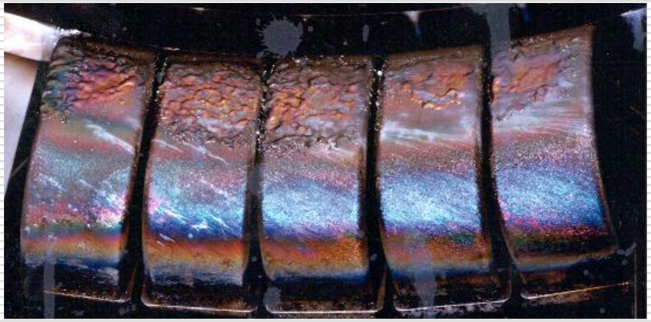
Formation of droplets

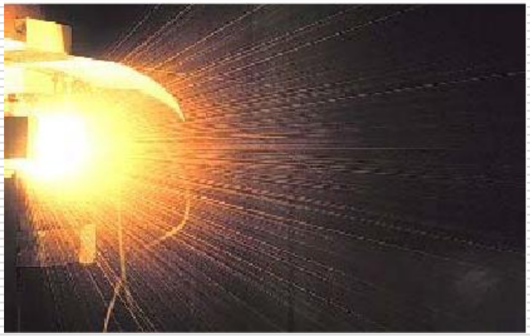
Formation of dust

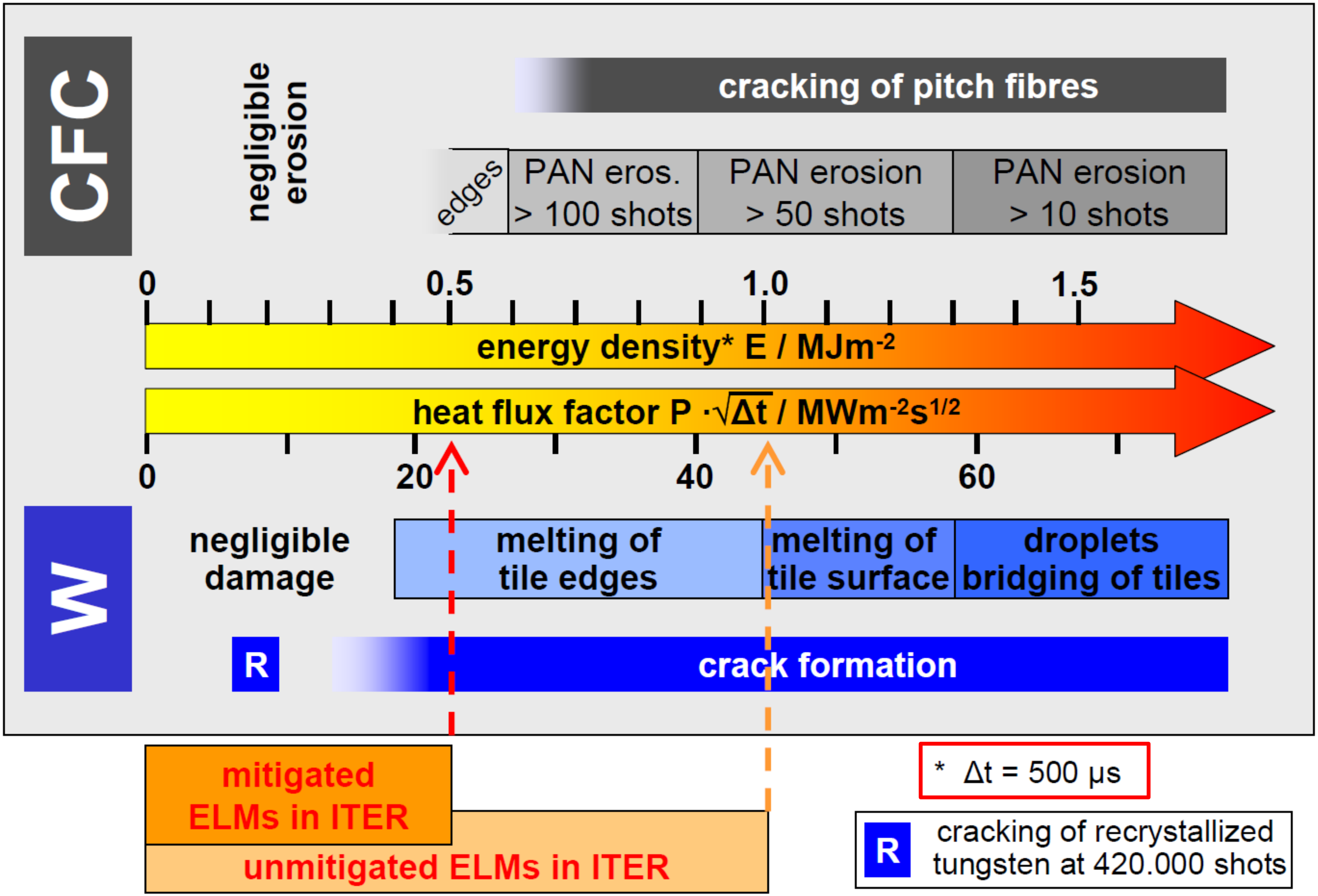
FOR CARBON:

Above a certain power load (threshold) emission of debris

➾ *BRITTLE DESTRUCTION*







J. Linke, Presented at ICFRM13 (2007)

Repeated pulsed heat load effects

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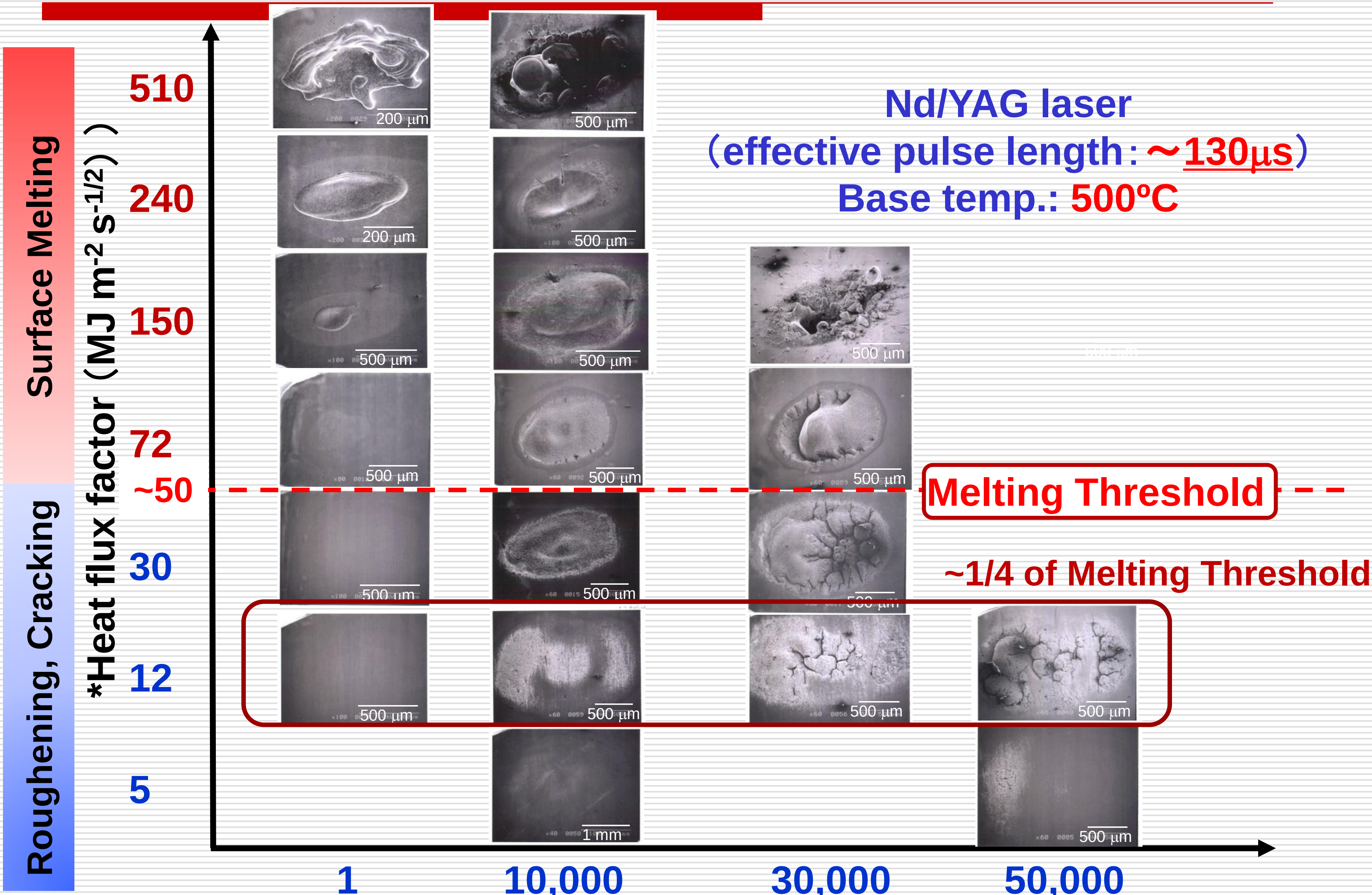
Surface modification by repeated heat pulses (pure W)



*energy absorption ~0.3 is considered.

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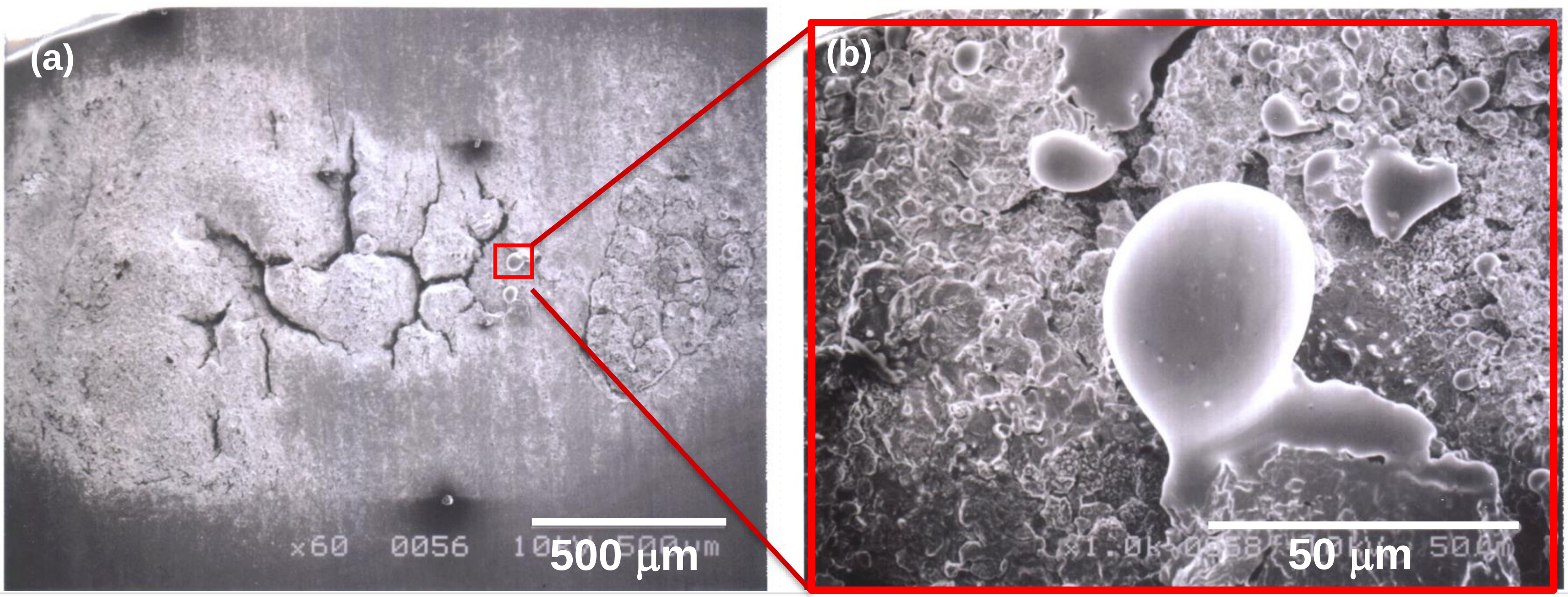
Surface modification by high cycle pulsed heat

- Surface roughness, cracking and local melting appeared after high cycle pulsed heat loading

For JET

c_W=5*10^{-5} density change
→ equivalent W mass
with r=80μm, 41.3μg



Heat flux factor : 12 MJ/m^2/t$^{0.5}$
Cycle number : 30,000

High cycle transients heat load tests - effect of recrystallization -

JÜLICH FORSCHUNGSZENTRUM

JUDITH 2

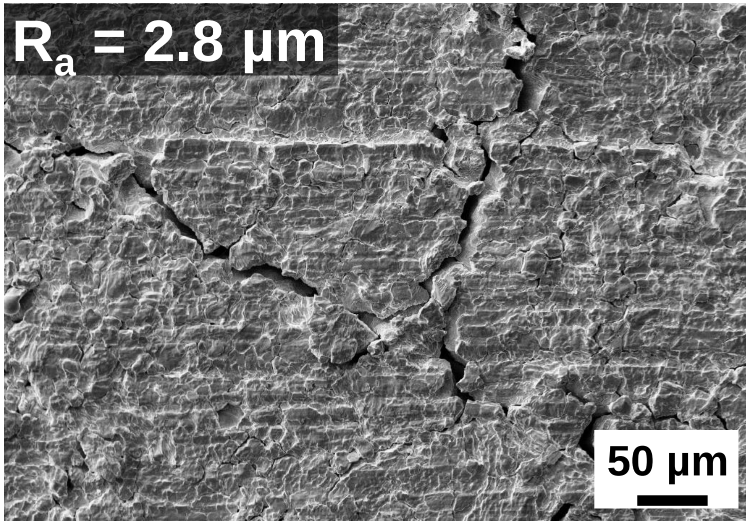
T_{surf} = 1500 °C

P = 0.2 GW/m²

effect of recrystallization

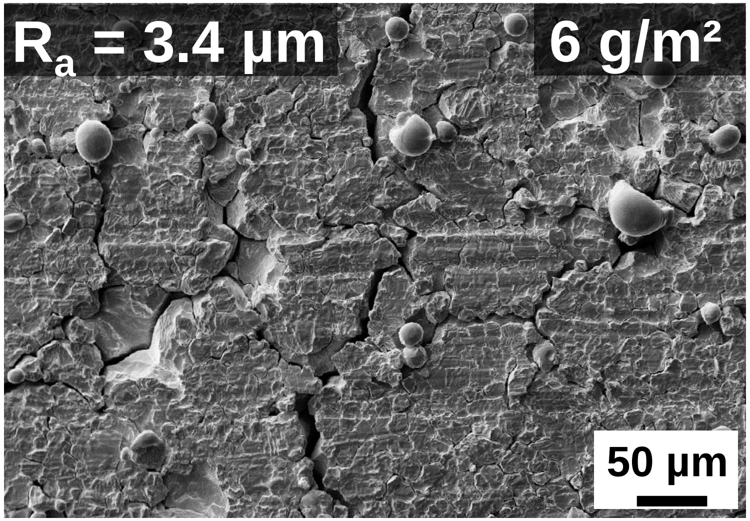
P = 0.6 GW/m²

18,000 pulses

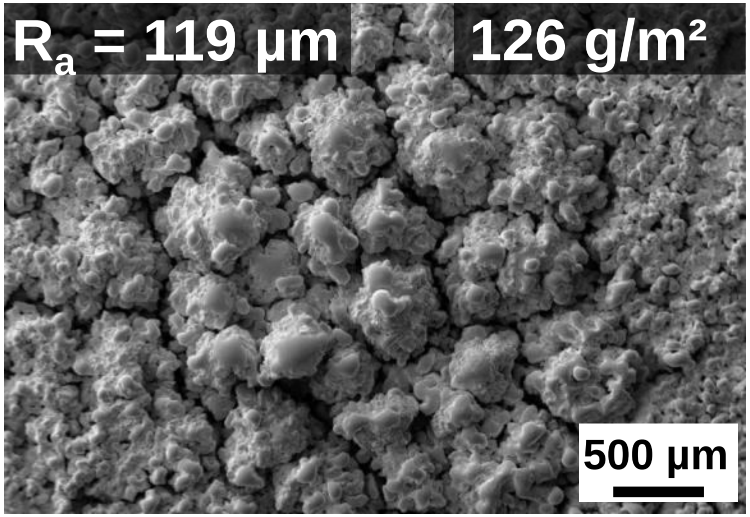


max./avg. depth ~ 150/110 µm

100,000 pulses



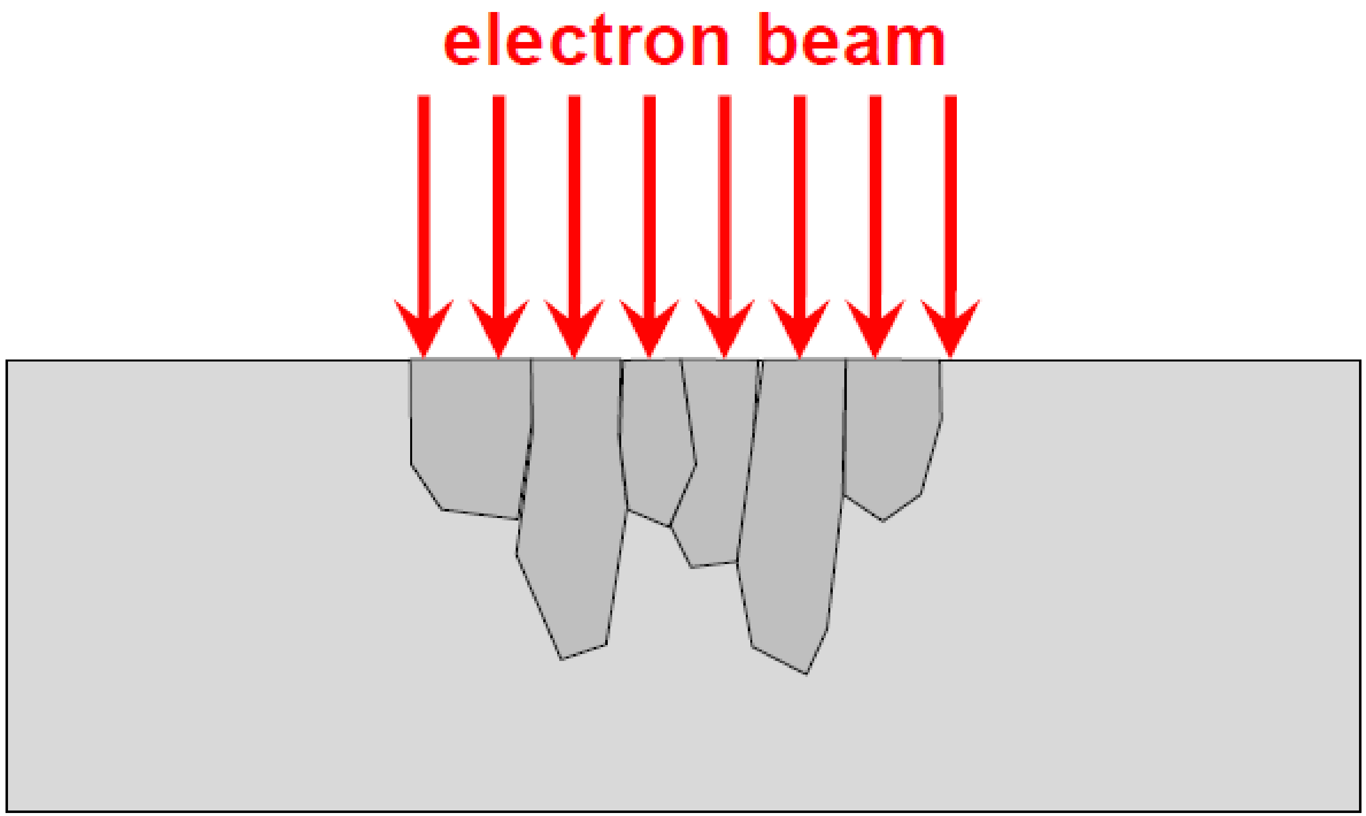
max./avg. depth ~ 420/180 µm



max. depth ~ 930 µm

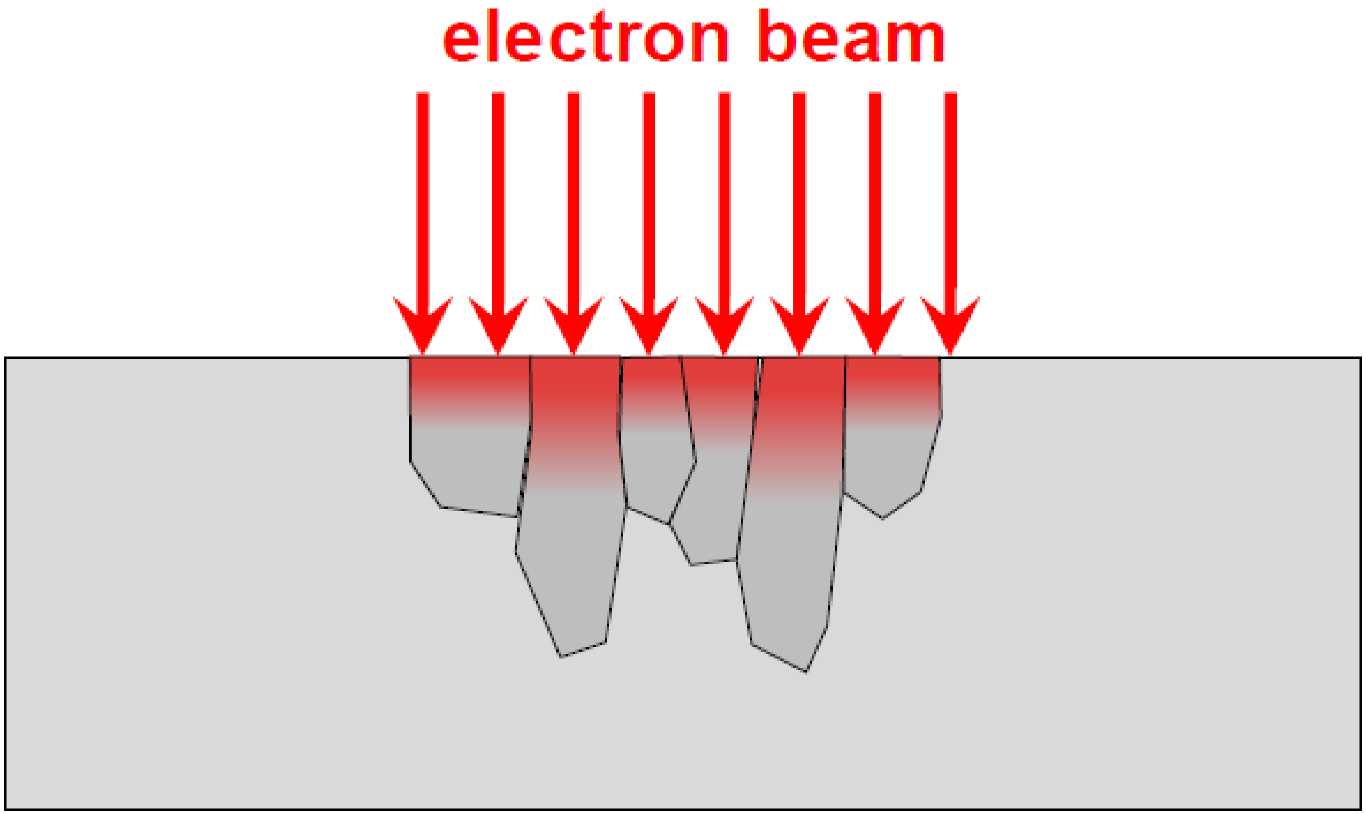
Transient thermal loads on metallic wall materials

from J. Linke



Transient thermal loads on metallic wall materials

from J. Linke

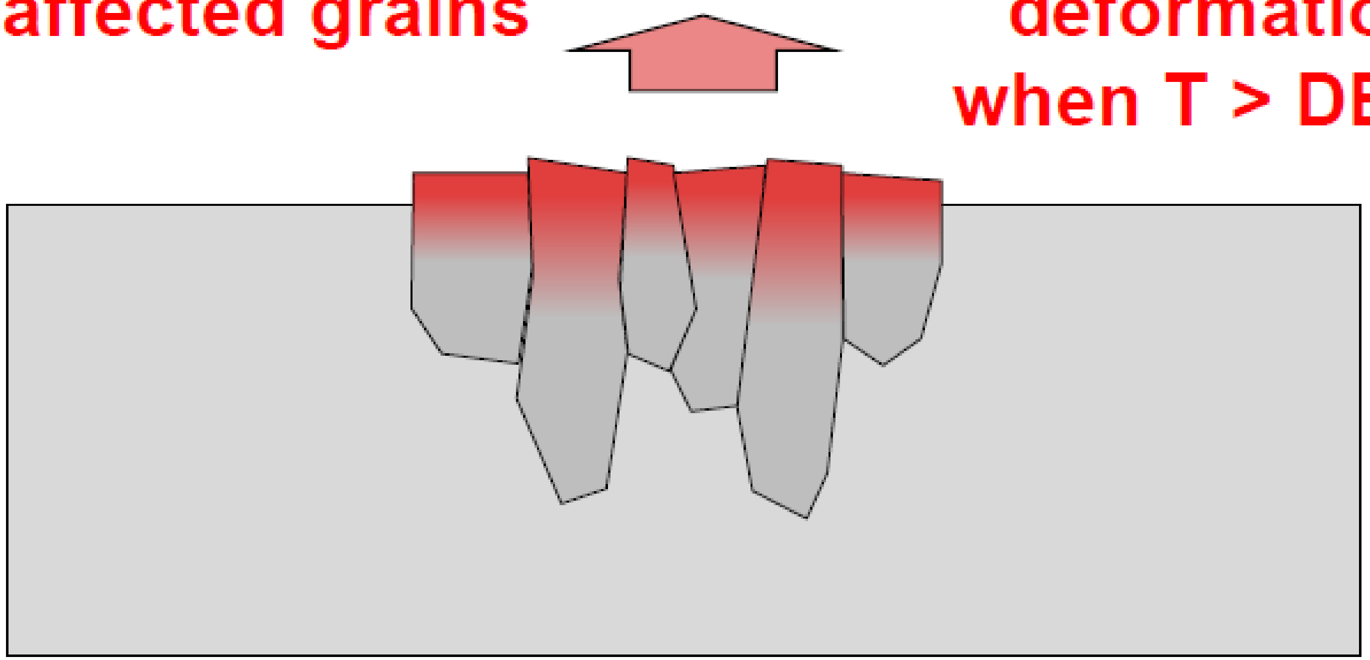


Transient thermal loads on metallic wall materials

from J. Linke

thermal expansion of heat affected grains

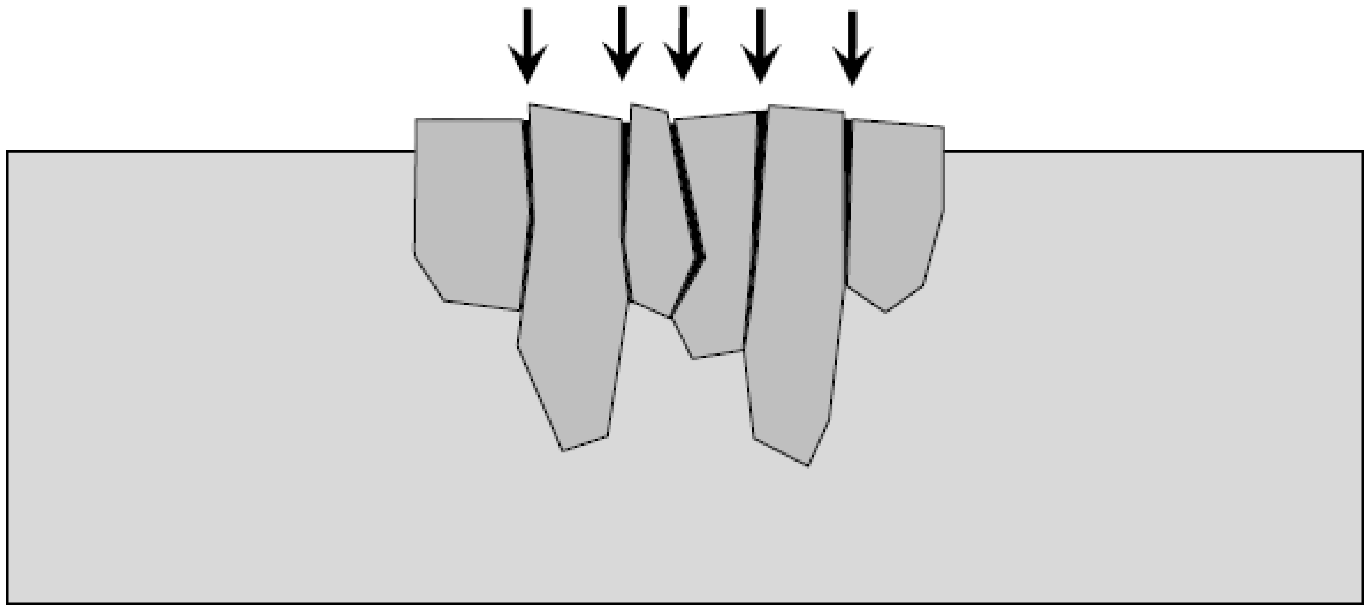
→ plastic deformation when T > DBTT



from J. Linke

Transient thermal loads on metallic wall materials

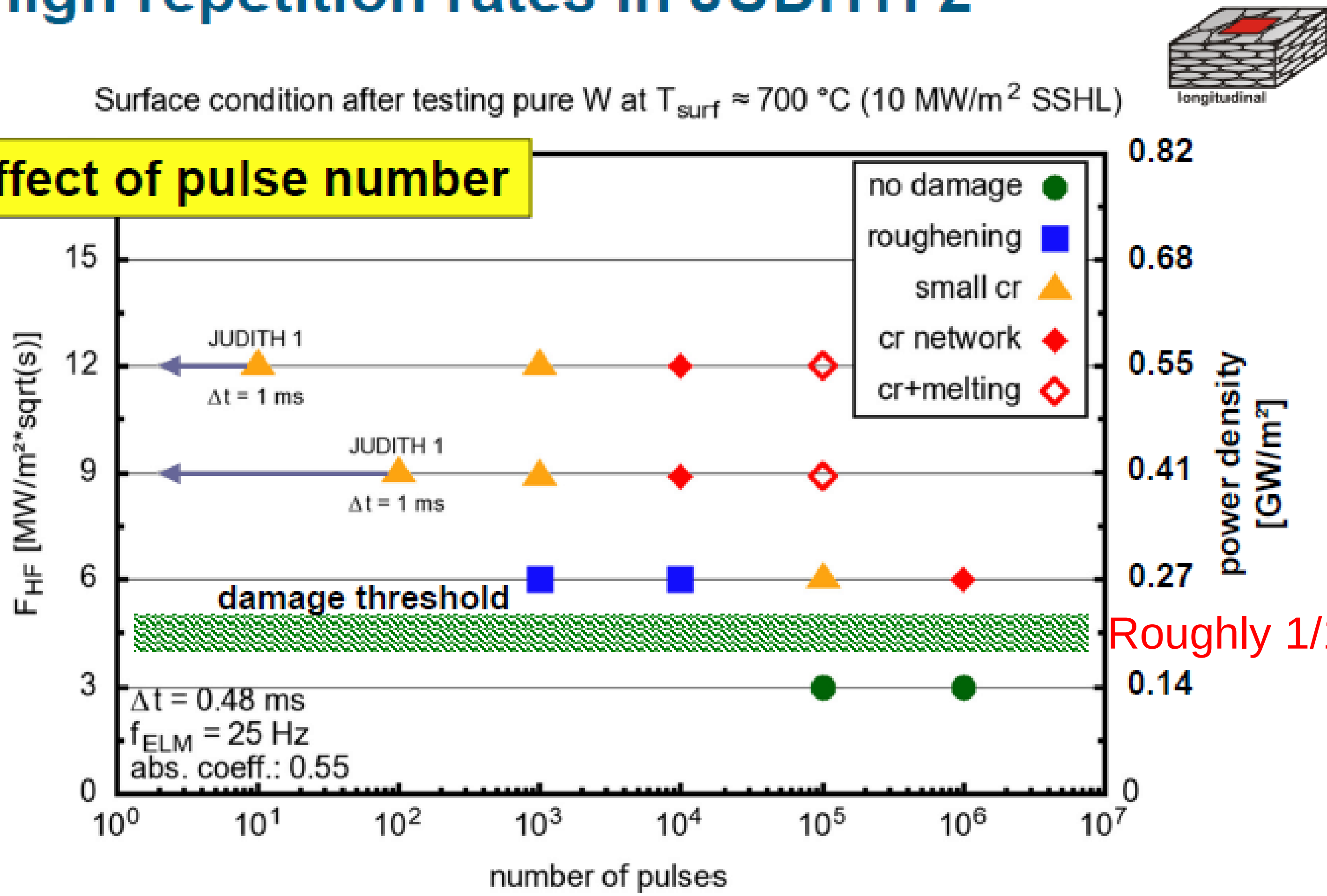
contraction during cool-down:
→ cracking along grain boundaries



ELM simulation using e-beams with high repetition rates in JUDITH 2

Surface condition after testing pure W at $T_{surf} \approx 700$ °C (10 MW/m^2 SSHL)

effect of pulse number



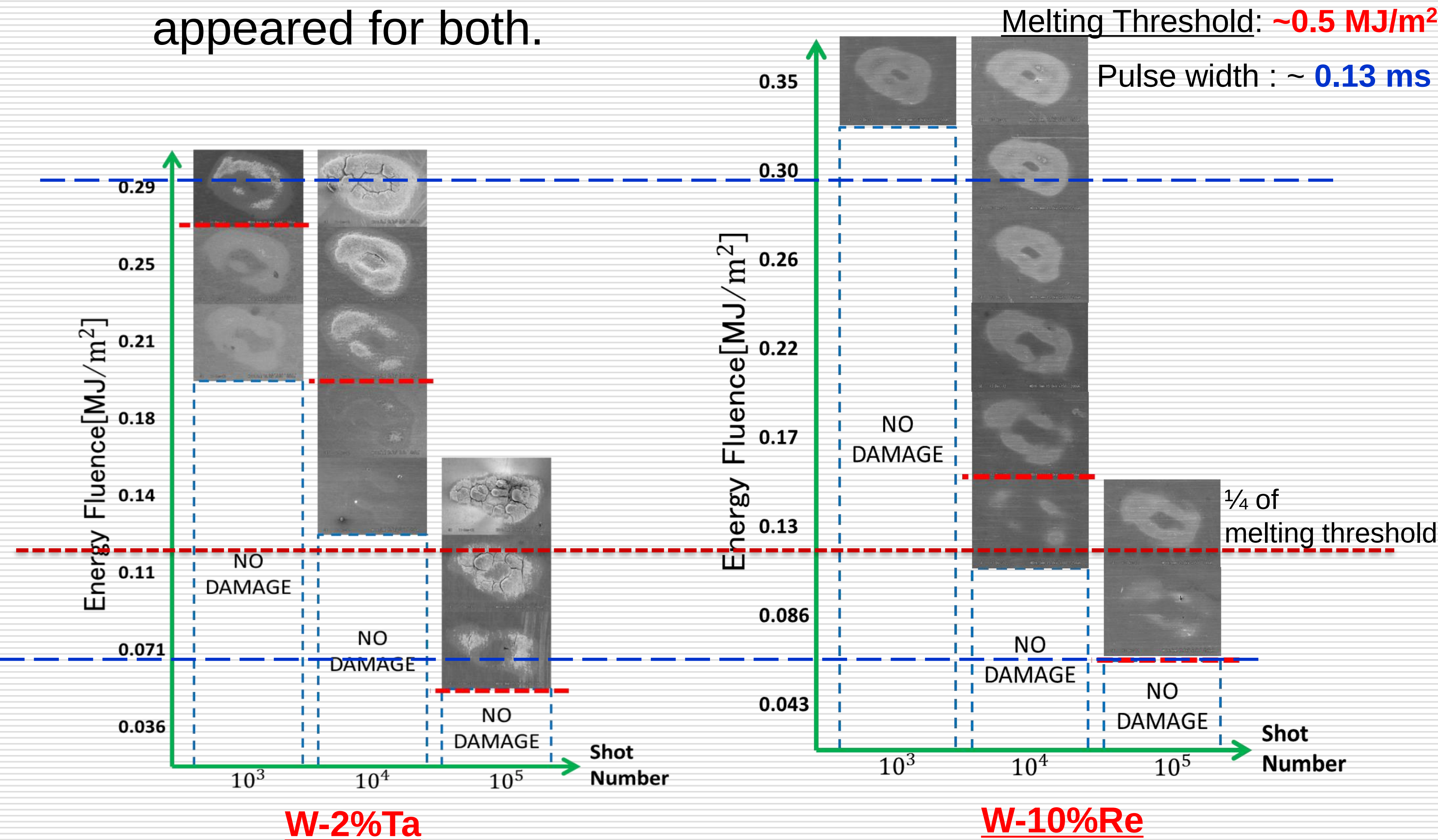
Roughly 1/10 of MT

Th. Loewenhoff et al., Physica Scripta T145 (2011) 014057

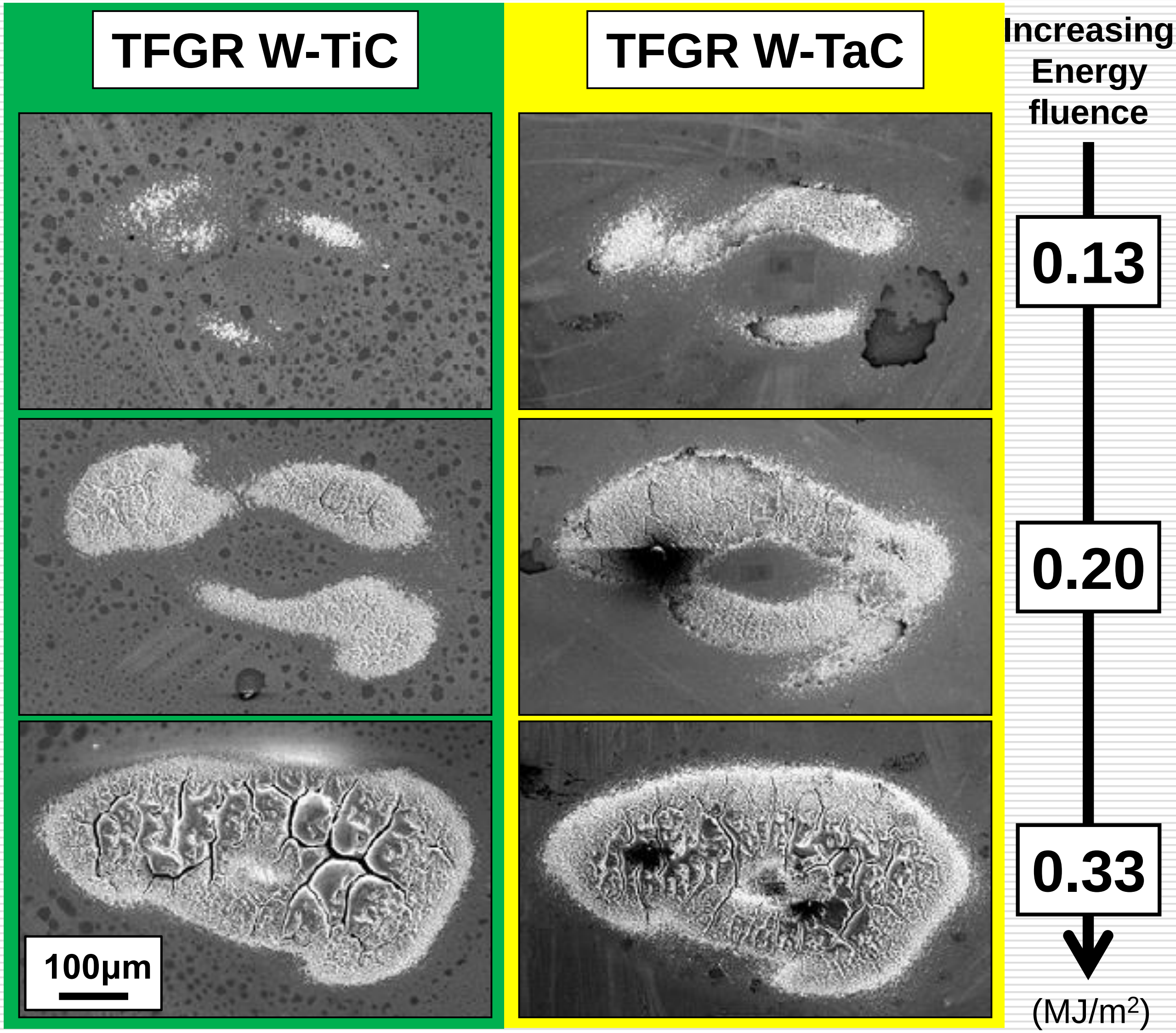
Particle ejection by surface cracking and local melting could determine the acceptable level of ELM heat flux

Effects of high cycle pulsed loading on W alloys

- Less damage for W-10%Re than W-2%Ta, but damage appeared for both.



High cycle pulsed heat effect of TFGR-W



TFGR-W
Toughened, Fine grained Recrystallized W.

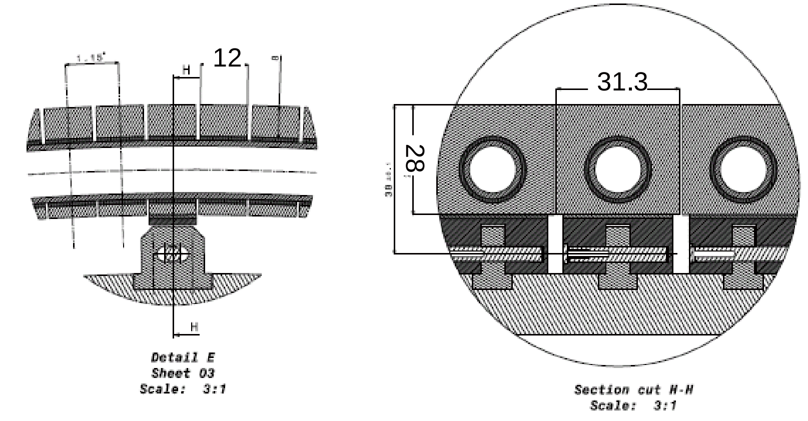
- Cracking seen for TFGR W under high cycle pulsed heat
- Threshold
  W-TiC > W-TaC
- → Cracking pattern is similar for these materials

Material	TFGR W
Shot No.	10,000
temperature	773 K
Energy absorption 27%	

Melting Threshold: **~0.5 MJ/m^2**

Surface damage effects on W (experimental)

1. Plasma gun exposure (U. Hyogo)
   - Pulse number : 20-100 shots
     - ~0.7 MJ/m^2
     - ~1.4 MJ/m^2
   - Pulse number : 25 shots
     - ~2.0 MJ/m^2
2. E-beam heat exposure (JEBIS)
   - 10 MW/m^2, 10 s, 300 cycle
     - Steady-state heat flux
   - 20 MW/m^2, 10 s, 300 cycle
     - Heat flux during slow transient
3. W samples
   - ITER Grade



Divertor mockup for ITER

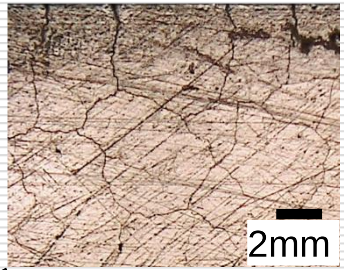
Surface damage effects on W monoblock performance

ELM simulated heat loading (plasma gun)*

pulse plasma energy

- 0.7 MJ/m²
- 1.4 MJ/m²
- 2.0 MJ/m²

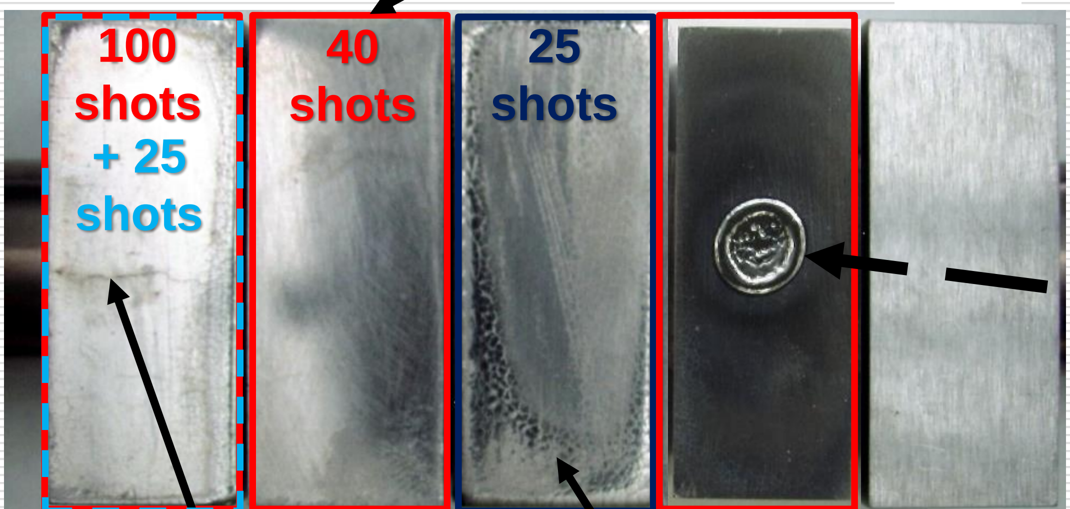
Pulse length 0.2-0.6ms



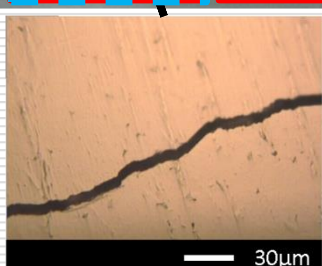
minor cracks

* Univ. Hyogo

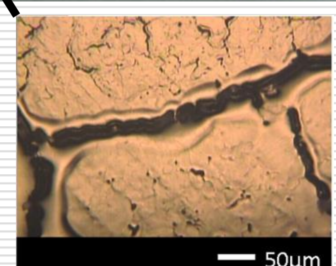
←12mm→



30mm



major cracks



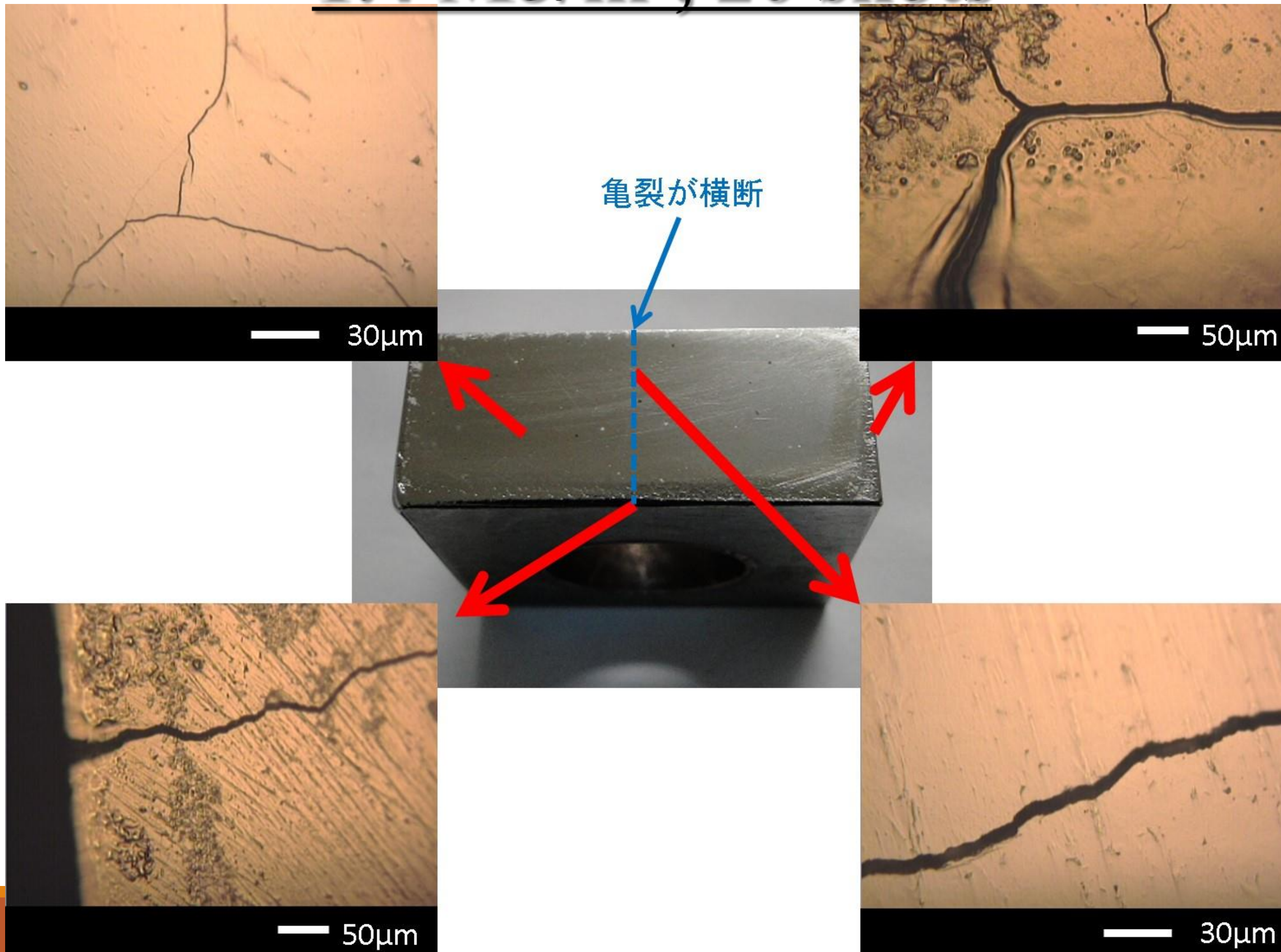
major cracks and melting

Disruption simulation (e-beam)

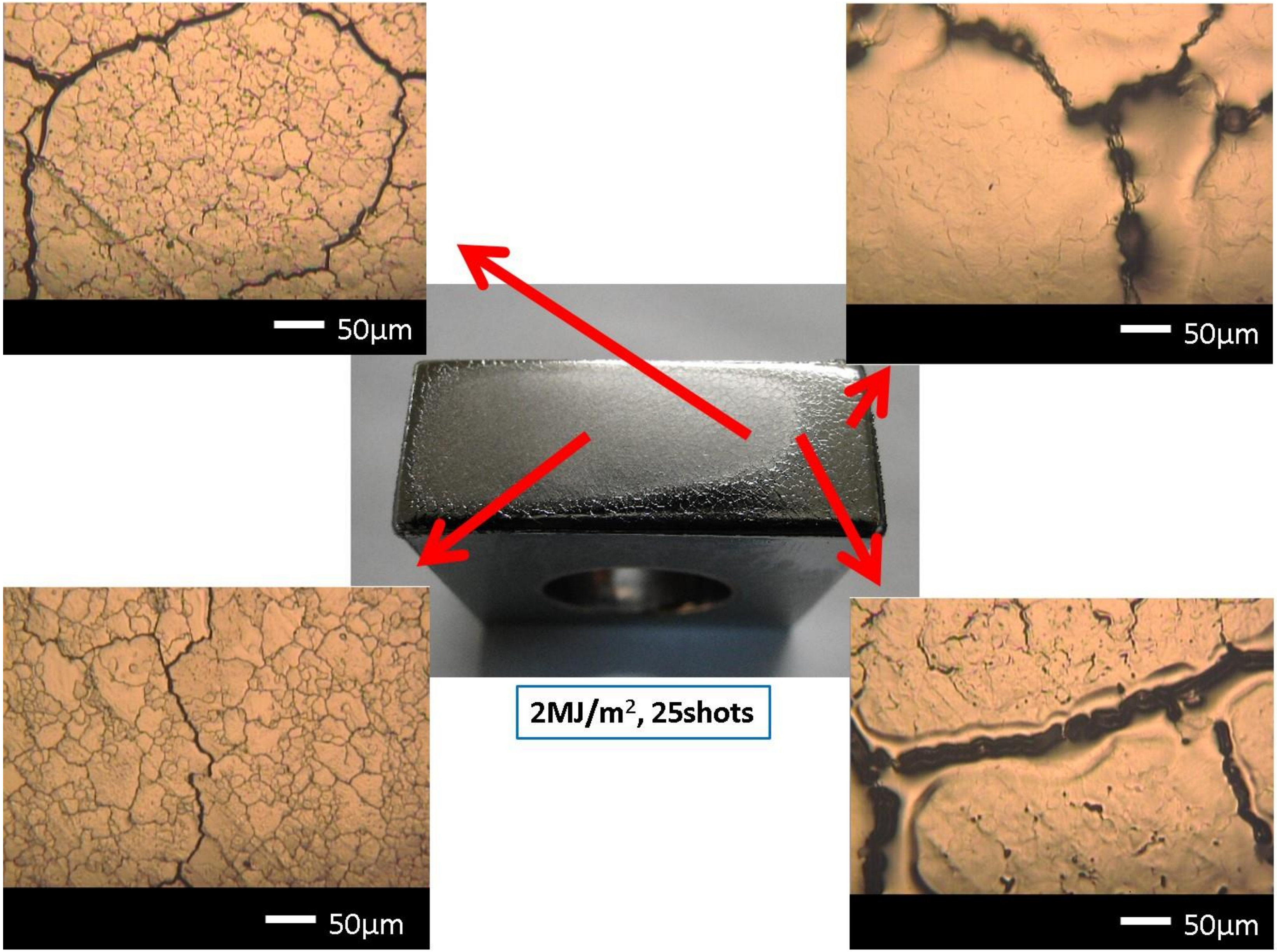
5 MJ/m^2, 1shots, 5 ms

Melting spot

Plasma gun : 0.7MJ/m^2, 100shots
1.4 MJ/m^2, 20 shots



2MJ/m^2, 25shots

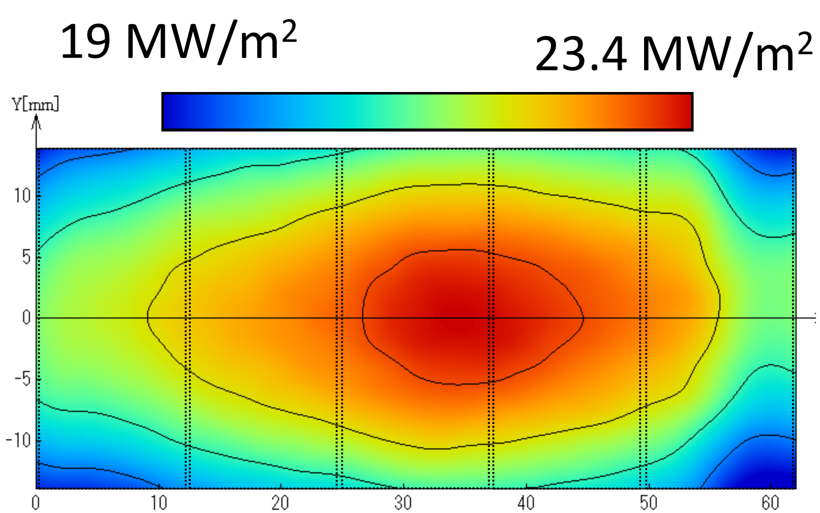


E beam heating conditions

E-beam (JEBIS, JAEA) under active cooling conditions

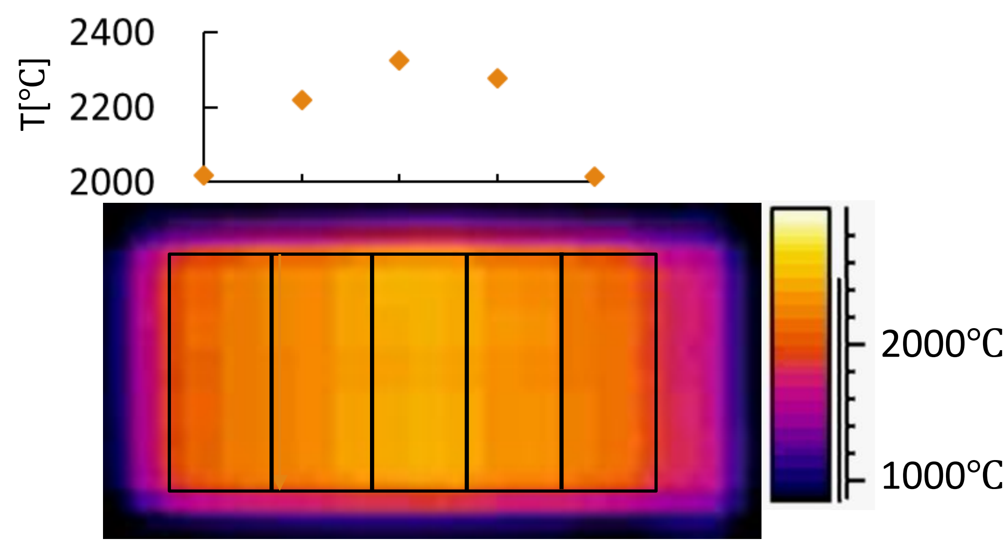
- **10 MW/m^2, 10 s, 300 cycle : No visible damage**
- **<u>20 MW/m^2, 10 s, 300 cycle</u> : Recrystallization**

◆ Heat flux distribution



- Over 20 MW/m^2 for 93% of total area

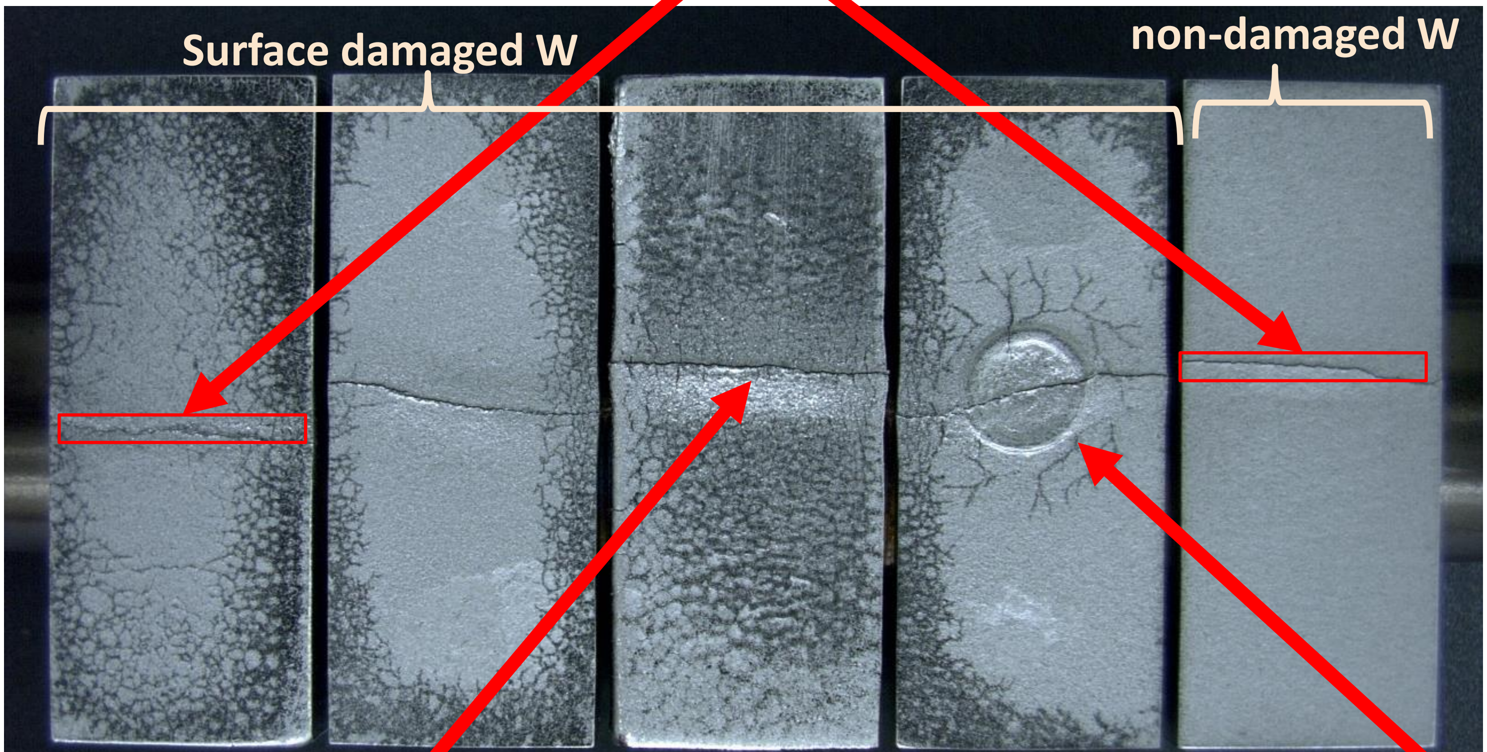
◆ Surface temperature distribution

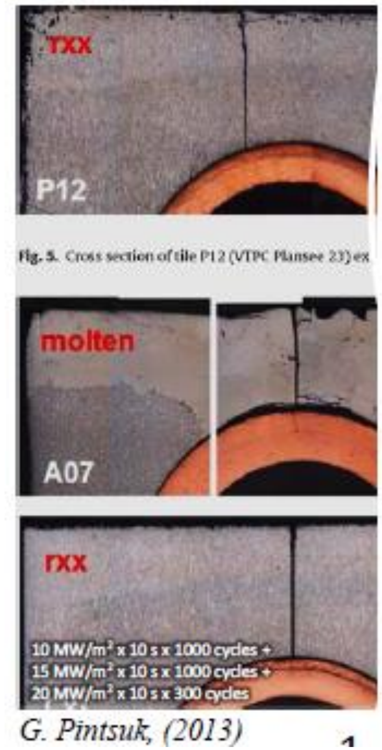


- >2000 °C
→<u>Recrystallization</u>

Surface morphology after 20 MW/m^2, 300shots

Grain ejection (only near large cracks)





Longitudinal (major) cracks : appeared on all W in this experiment

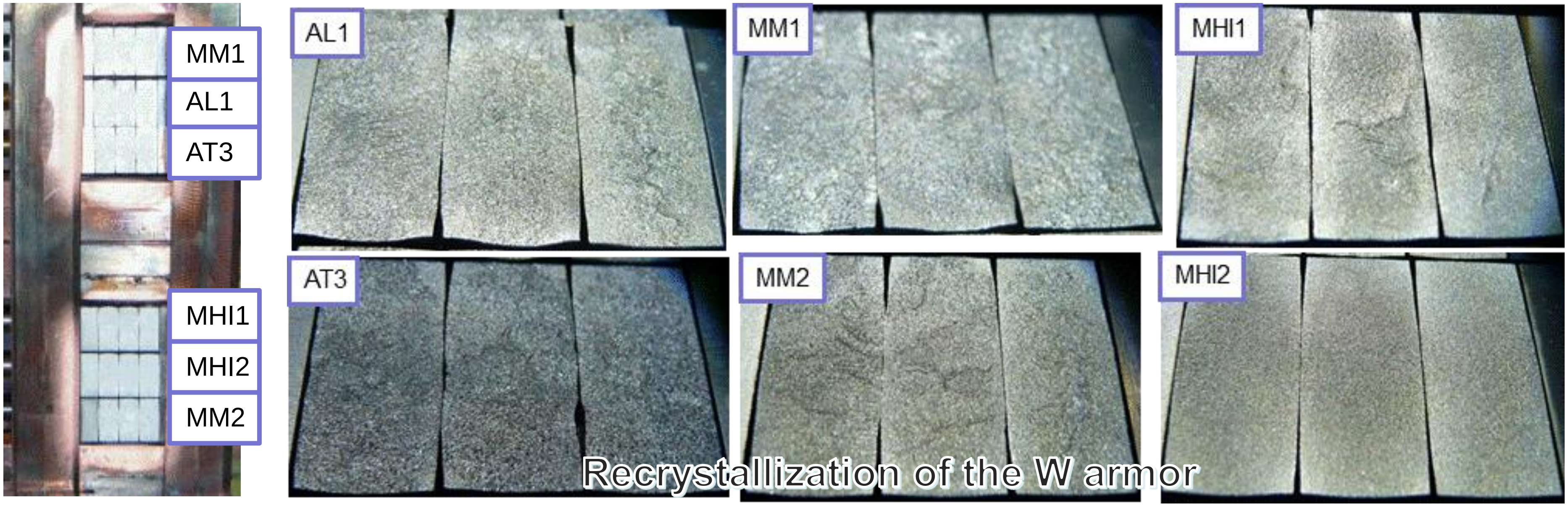
But, for surface damaged W : appeared earlier : < 18 cycles

For non-damaged W : > 100 cycles

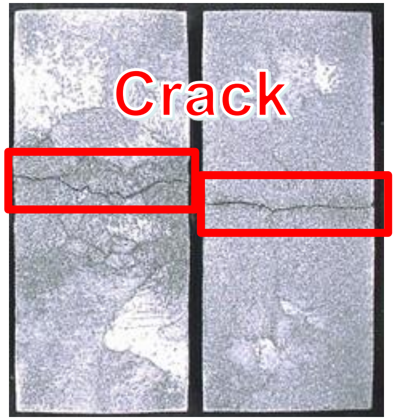
→ surface damage enhanced major crack formation

Cracks around resolidified layer

High heat flux test of small-scale mock-ups

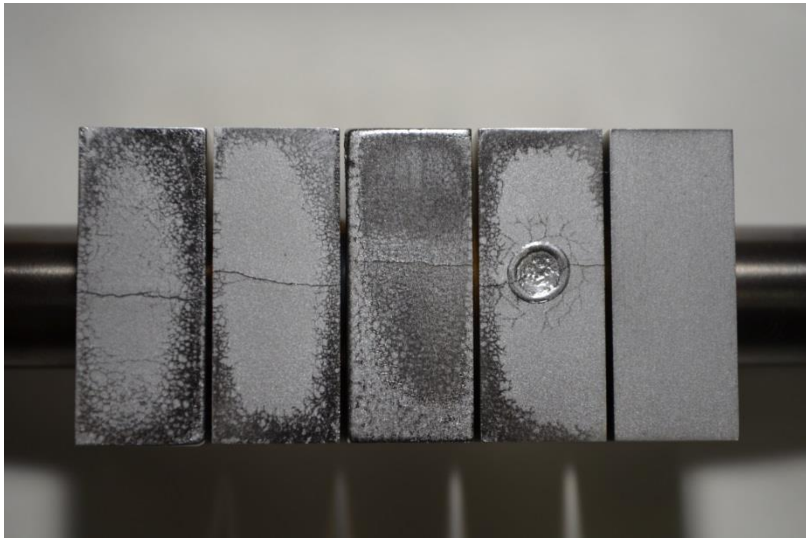


- All W monoblocks of 6 small-scale mock-ups withstood
  - 5000 cycles at 10 MW/m^2 and <u>1000 cycles at 20 MW/m^2</u>.
- None of W monoblock showed macroscopic cracks along the tube axis (so-called, self-castellation) that often appeared in monoblocks after HHF test at 20 MW/m^2.
- Gaps of 0.5 mm in neighboring W monoblocks are bridged by deformation of W.



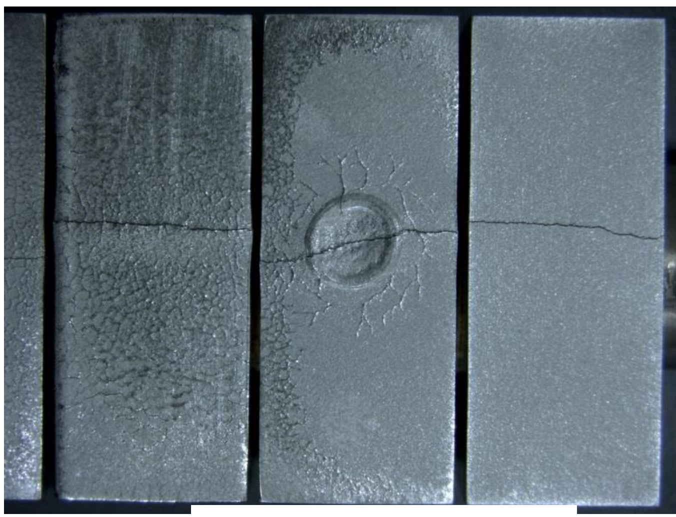
<u>Example of self castellation that JAEA's mock-up did not have.</u>

Surface morphology change : ~20 MW/m^2, 10 s

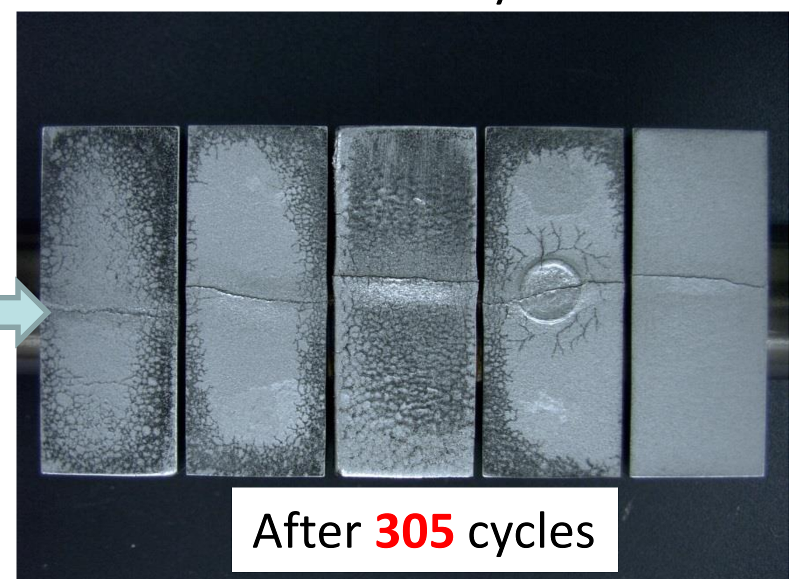


After 32 cycles

After 101 cycles



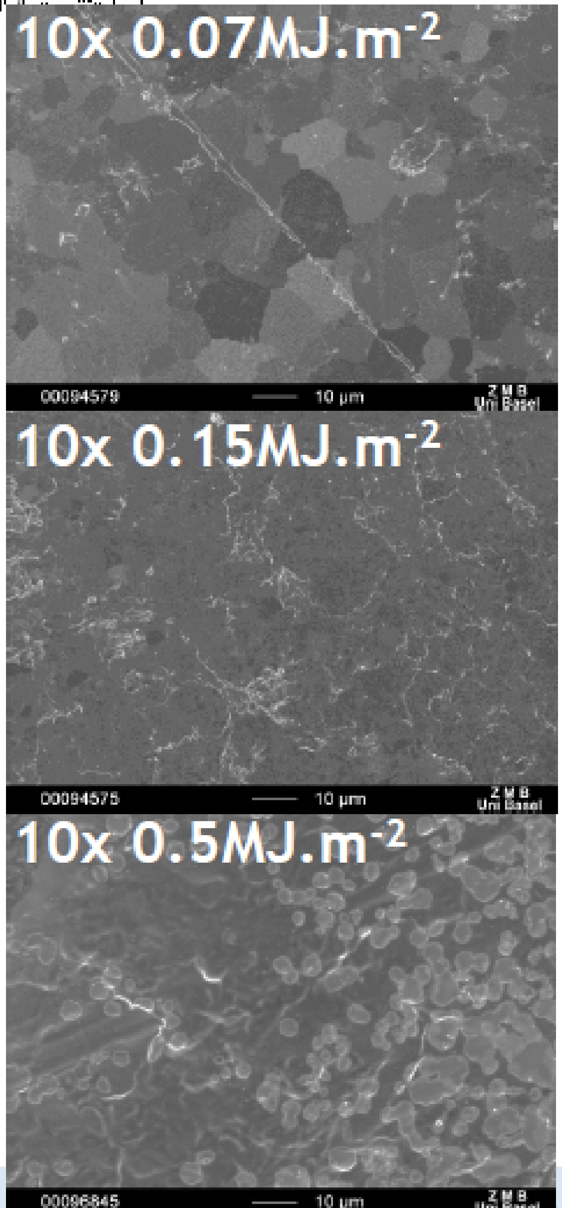
After 200 cycles



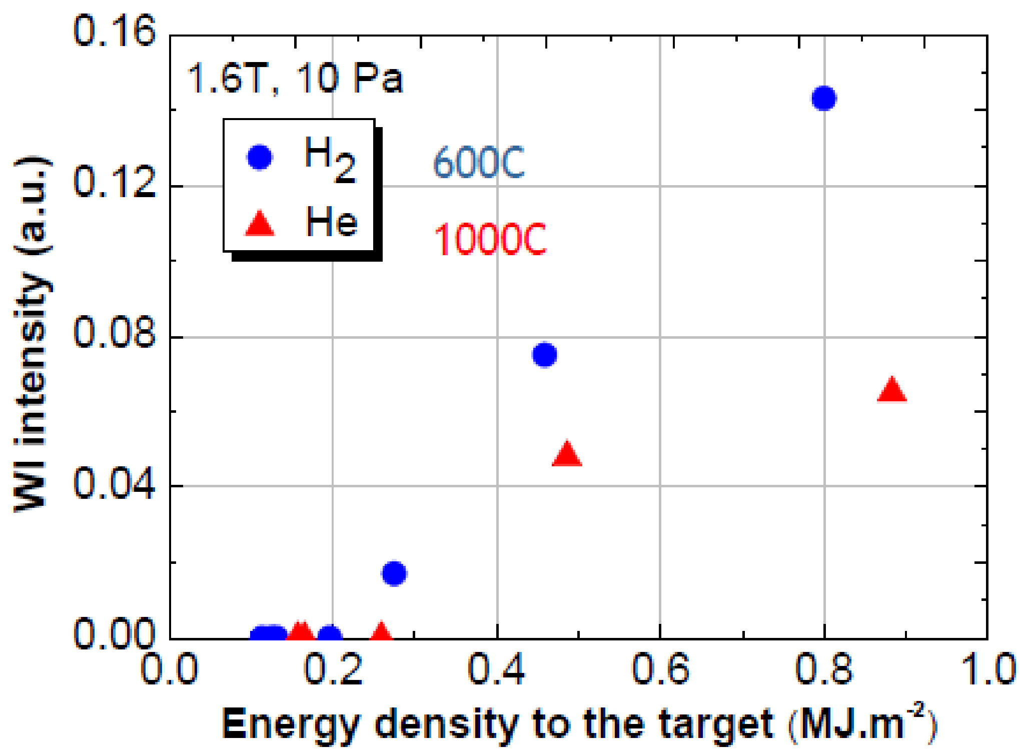
After 305 cycles

Surface damage becomes starting points of cracks, but its development largely depends on bulk material property.

Plasma-enhanced surface damage



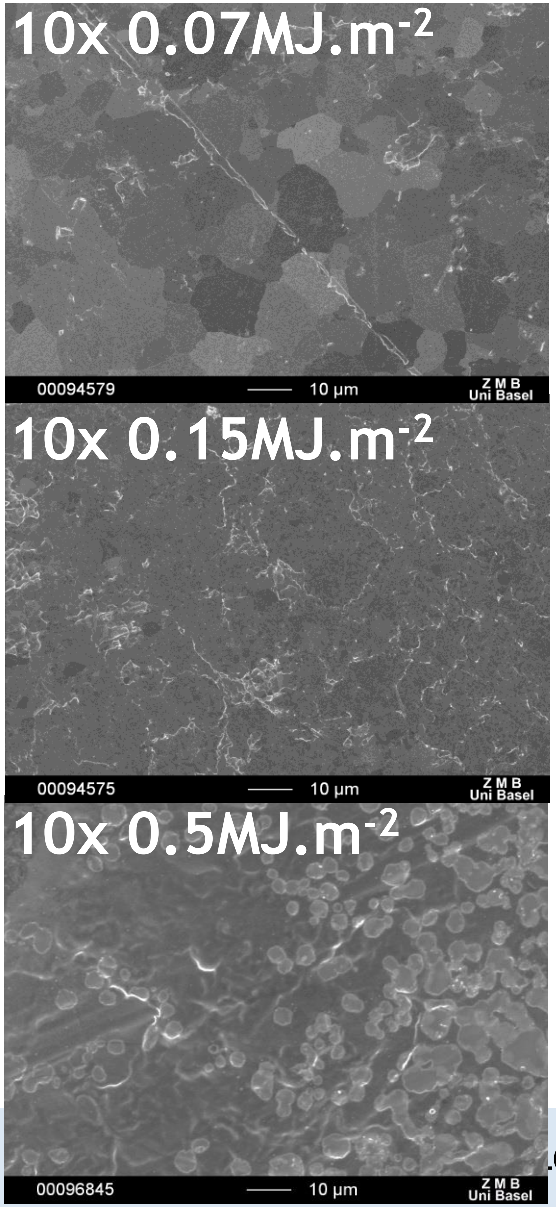
- Measured ablation threshold much lower than expected



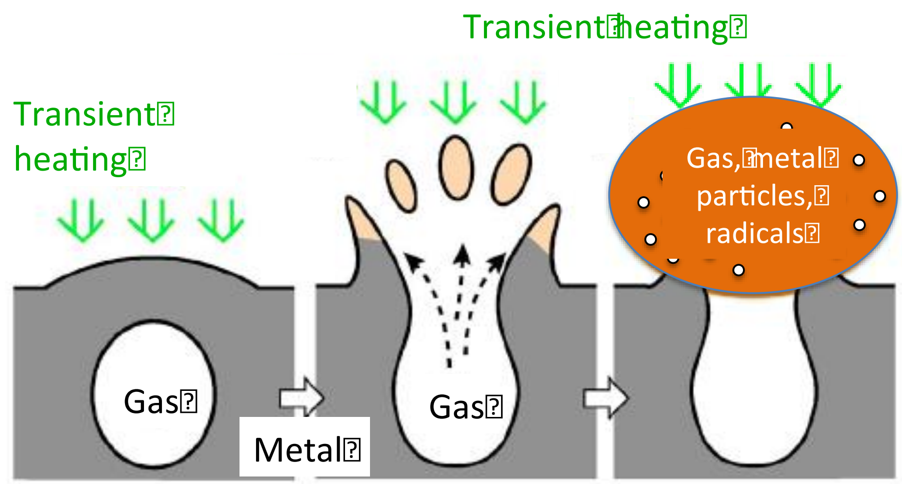
Plasma enhanced surface ablation

G. De Temmerman et al, IAEA FEC, 2010

Plasma-enhanced surface damage



- Synergistic effect:
  - Bubble formation due to high-flux plasma
  - Explosive release of material during transient



Re-definition of tolerable energy densitites in ITER might be necessary

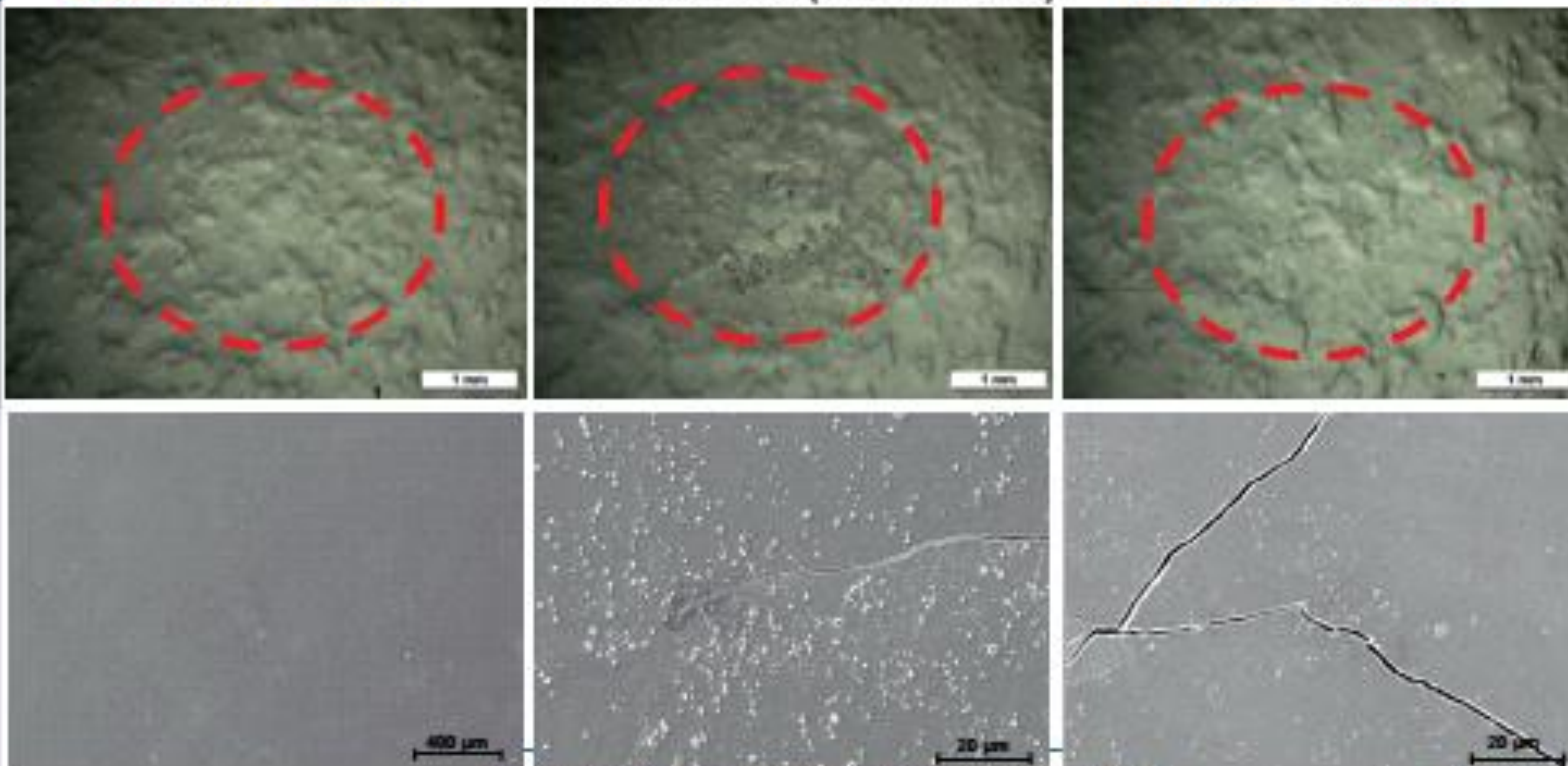
G. De Temmerman et al, IAEA FEC, 2010

Thermal shock and H-loading in PSI-2

Laser beam
1000 ELM-like events at RT
absorbed power density: 0.3 GW/m²
pulse duration: 1 ms (f = 0.5 Hz)

H-Plasma
biasing voltage: - 60 V
source current: 150 A
plasma flux: 2.5 – 4.0 × 10^{21} $m^{-2}s^{-1}$

Laser ⇒ H-Plasma | **Simultaneous (ΔT ≈ 100 °C)** | **H-Plasma ⇒ Laser**



J. Linke, IAEA-Seoul, 2015
Also PMIF/ICFRM (I. Steudel)

Synergistic effects of heat and particle loadings are important.

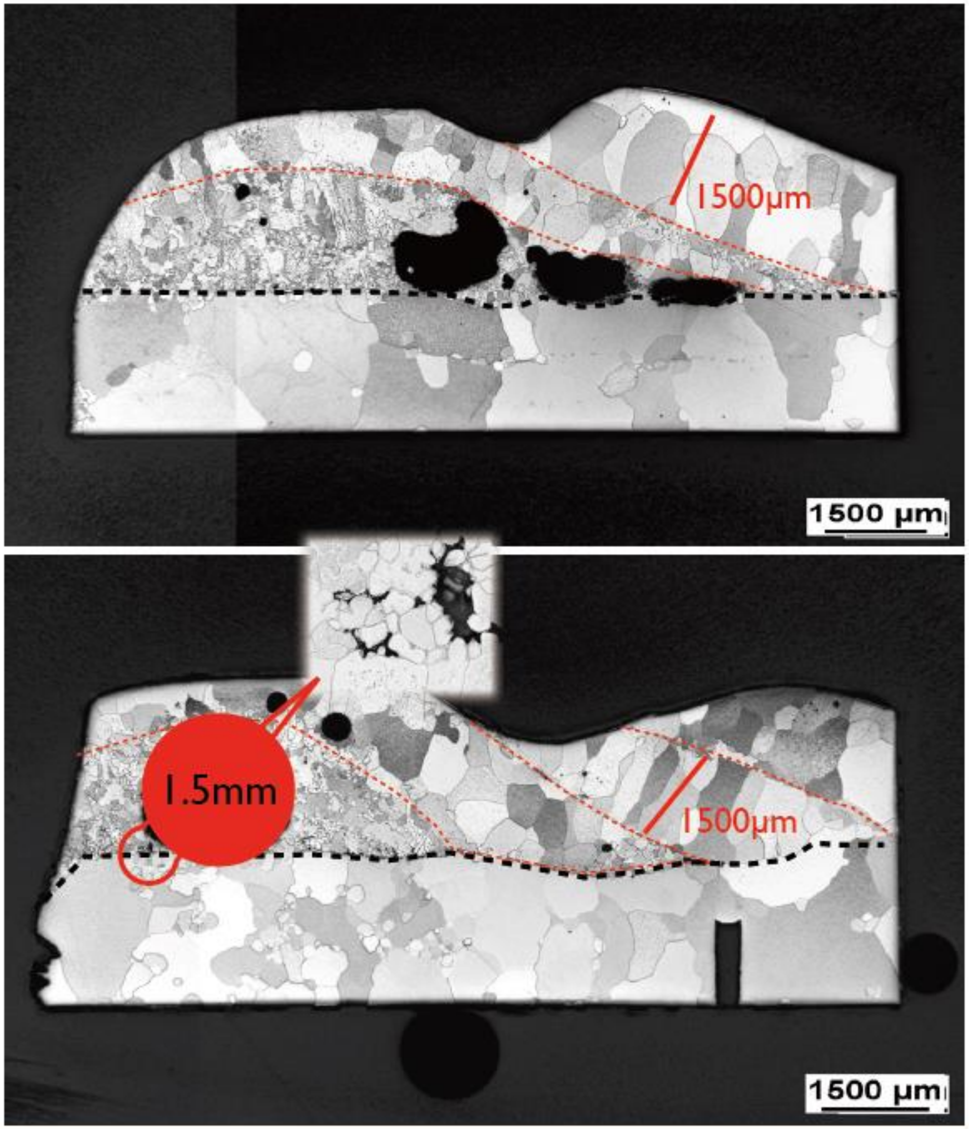
Remarks on surface damage by pulse heat

- **High cycle repeated ELM-like heat** (even 1/5 of the melting threshold) could cause surface roughening and local melting.
  - Further studies on cracking thresholds and impact on plasma performance are necessary.
  - This surface damage could determine the limit of pulse energy (and pulse number) by ELM.
- **Surface damage could be a starting point of large cracks** of W-monoblocks.
  - Further studies on crack propagation from surface damage for **crack-resistant W monoblocks**.
- **Combined plasma exposure** could reduce the damage threshold of pulsed heat. (need more investigation **with high flux plasma**)

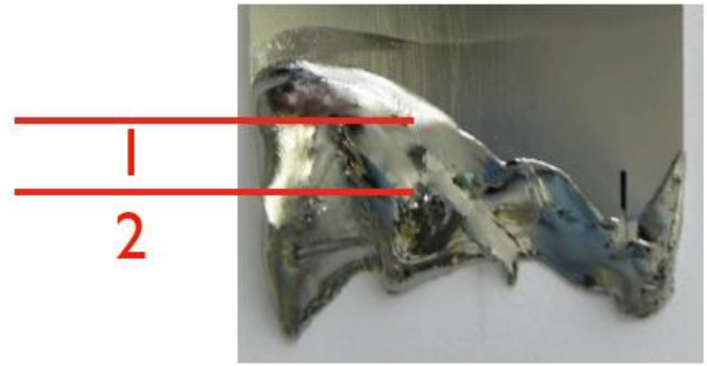
MELT LAYER DYNAMICS

Melt Layer Structure

1



2



tungsten: volume expands by 8% due to melting

Melt layer thickness can reach up to 1.5 mm

Power-handling capability significantly degraded

unacceptable

Slight melting

- Is slight melting acceptable?
  - Acceptable step height for ITER W monoblock (~0.3 mm)
  - Bridging by melt layer is serious, because it could eventually cause fracture of cooling tube.

Only "very slight melting" maybe acceptable

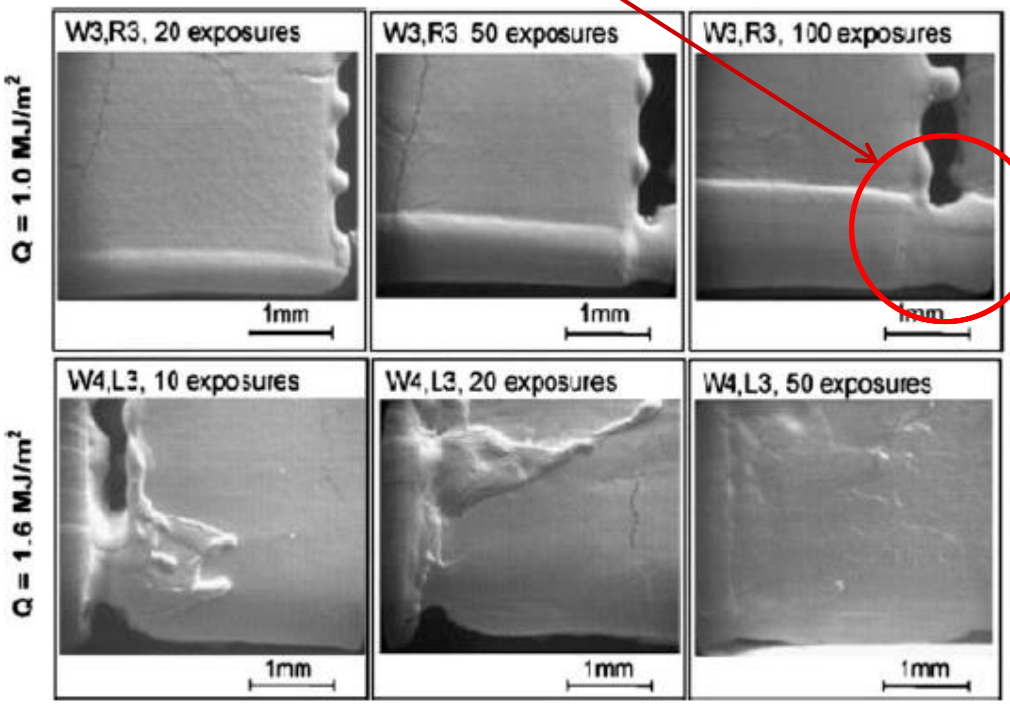


Fig. 1. The SEM view of the tungsten tile surface.

E = 1.0 MJm^{-2} Δt = 500 μs 100 pulses

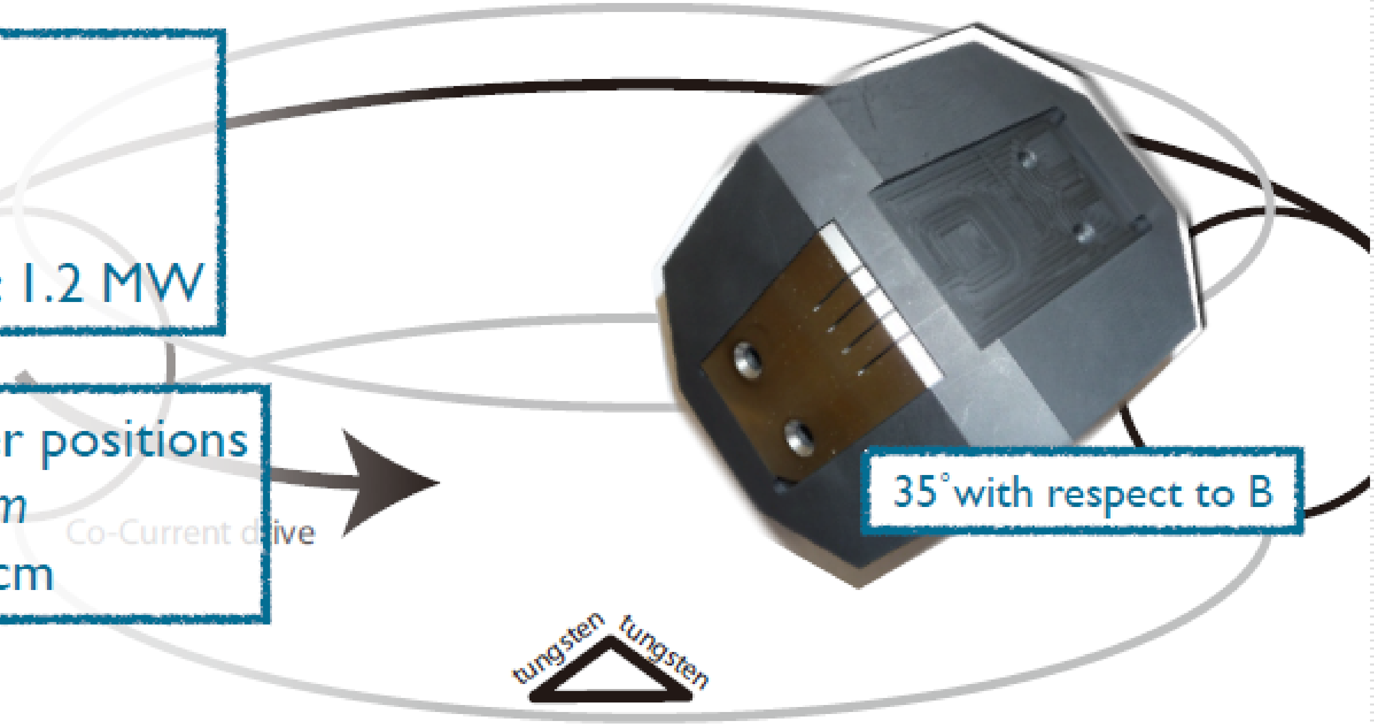
Plasma Gun exp. (QSPA)

B. Bazylev et al., J. Nucl. Mater. *390-391 (2009)810-813*

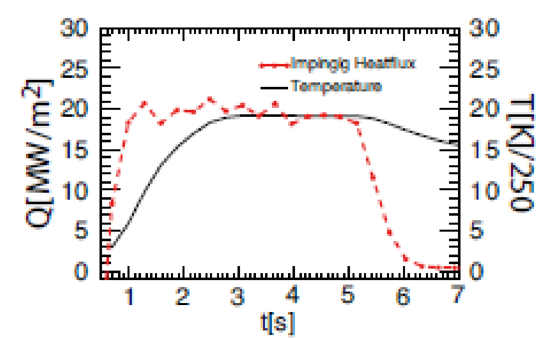
TEXTOR Setup

B_T=2.25 T
I_P=350kA
n_e=3.5 $10^{19}m^{-3}$
Co-Current NBI: 1.2 MW

Plasma and limiter positions
R=1.75m a=0.47m
Limiter 49cm-46cm

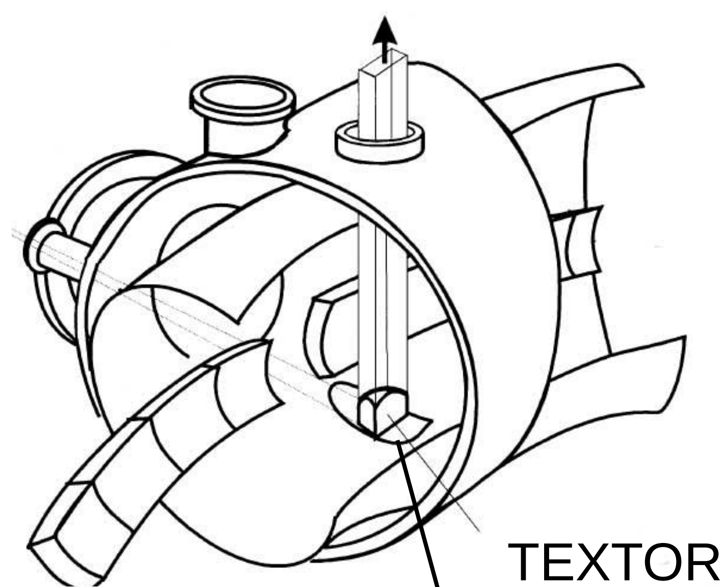


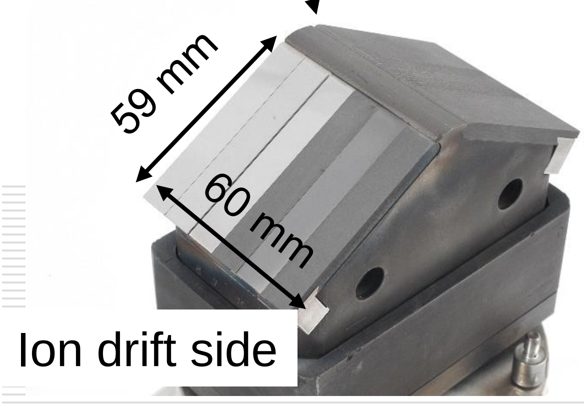
Typical heat-flux ~20MWm^2
Temperatures > 4500 °C

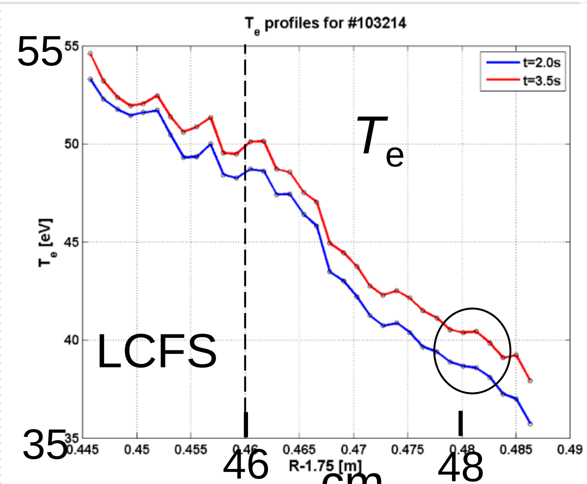


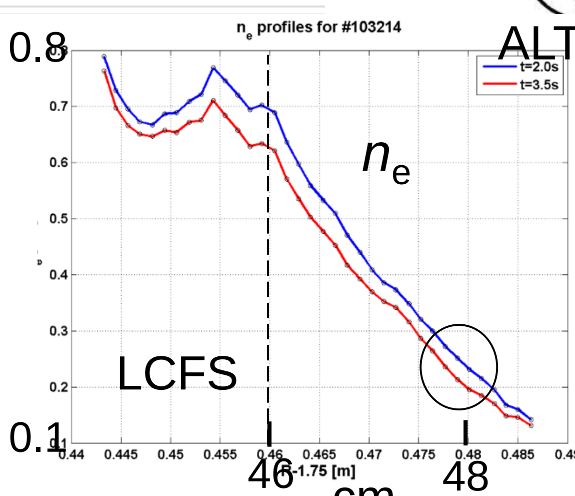
Experimental setup for test limiter exposure

- Roof limiter system
  - Samples on graphite roof limiter
  - Position : 46 cm (LCFS) ~ 47.5 cm
  - Base temperature : ~300 ºC
  - Standard ohmic plasma
    - I_p = 350 kA, $\bar{n}_e$ = 2.5 x 10^{19} m^{-3}
    - Bt = 2.25 T, Ohmic Power ~0.3 MW
  - Edge plasma Parameter (r =48cm)
    - T_e ~ 40 eV, n_e ~ 2.5 x 10^{18} m^{-3}

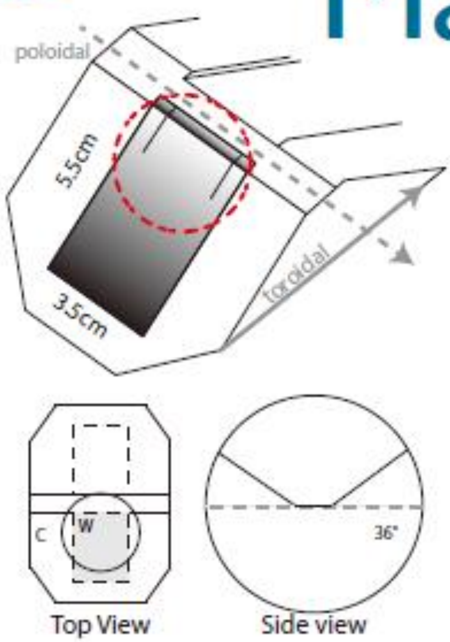


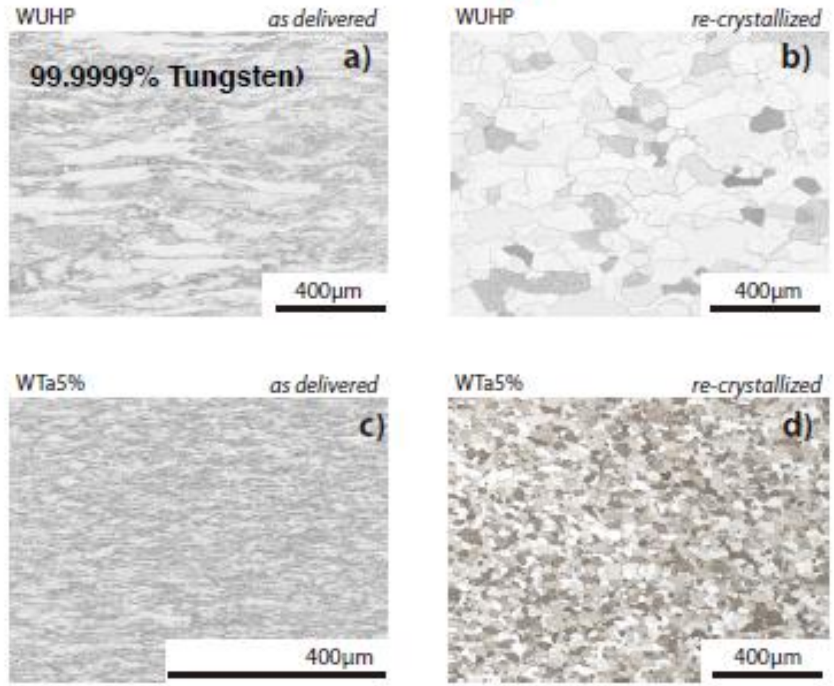






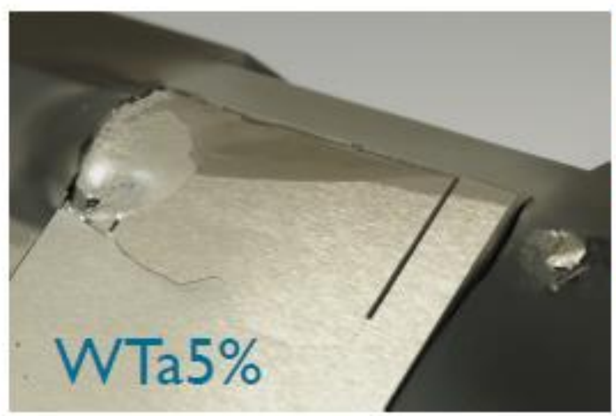
Material Exposure





Melt-layer ejection and material changes of three different tungsten materials under high heat-flux conditions in the tokamak edge plasma of TEXTOR Nuclear Fusion, 2011, 51, 113020

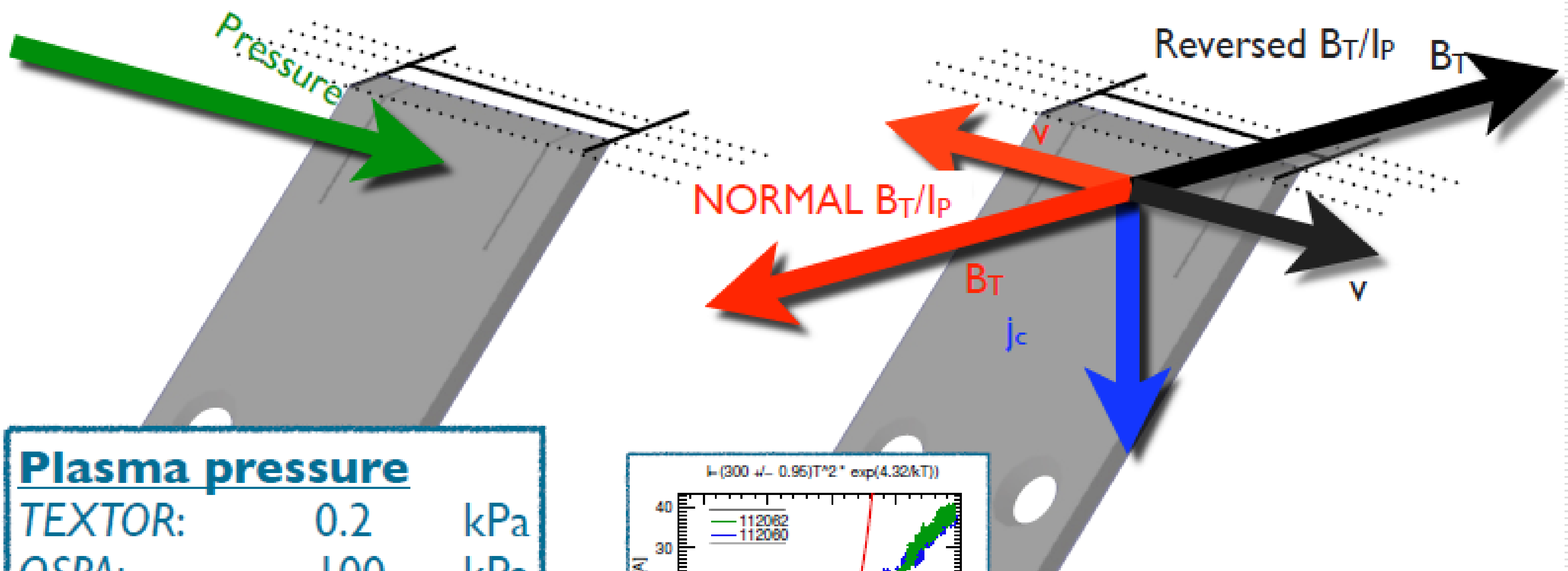
Tokamak plasma response to droplet spraying from melted plasma facing components Nuclear Fusion, 2012, 52, 013013



Different impurity content leads to strong changes in material behavior

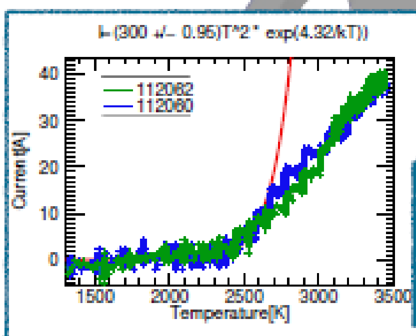
cf. 3D Melt layer modeling
B. Bazylev

Forces



Plasma pressure

TEXTOR:	0.2	kPa
QSPA:	100	kPa
ITER(ELM):	5-10	kPa



Thermo-electric emission

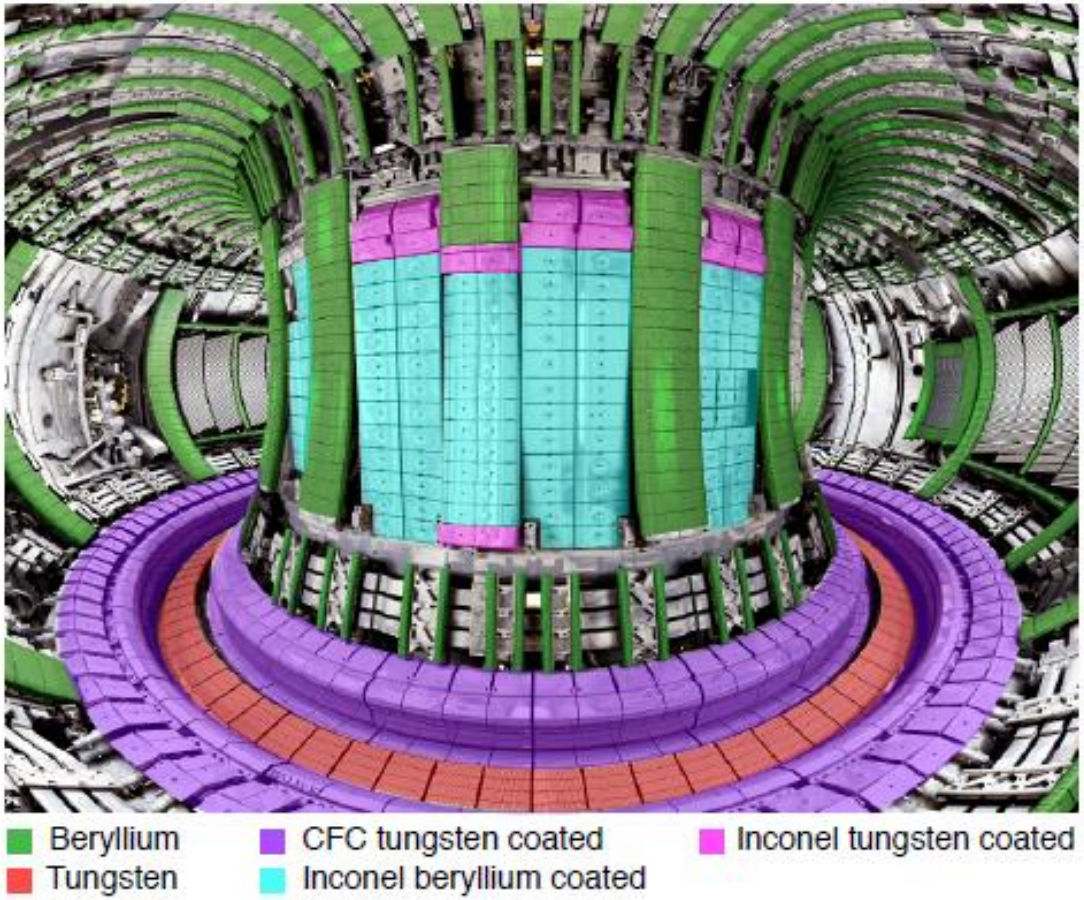
~3-4 cm^2 Emission-surface

Melting on both samples

jxB: 0.2-1mm melt ➠ ~600-4500 N/m^2

Dominant force under TEXTOR conditions is jxB

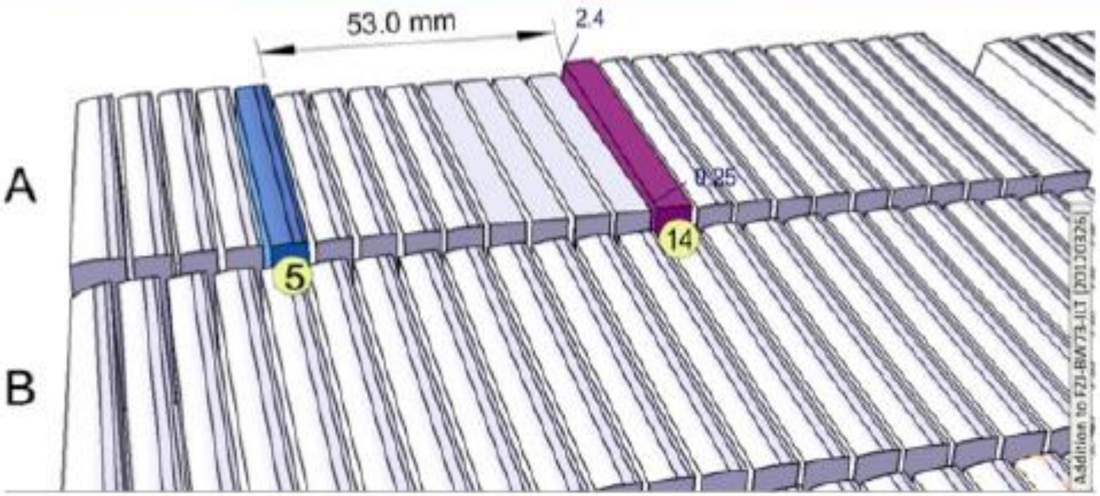
JET Abilities & ITER Input

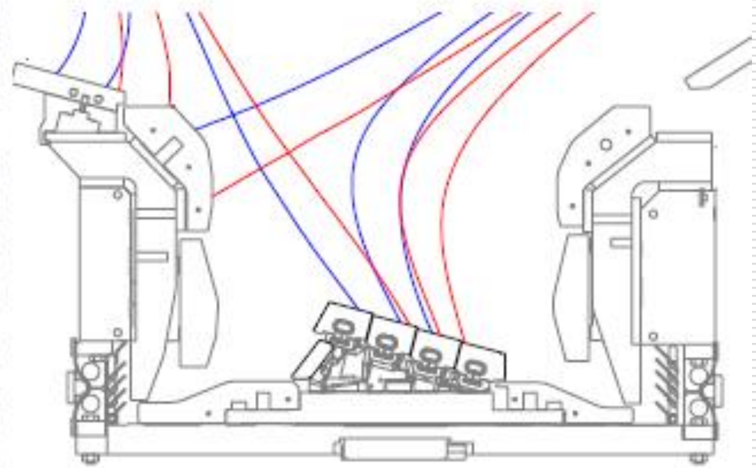


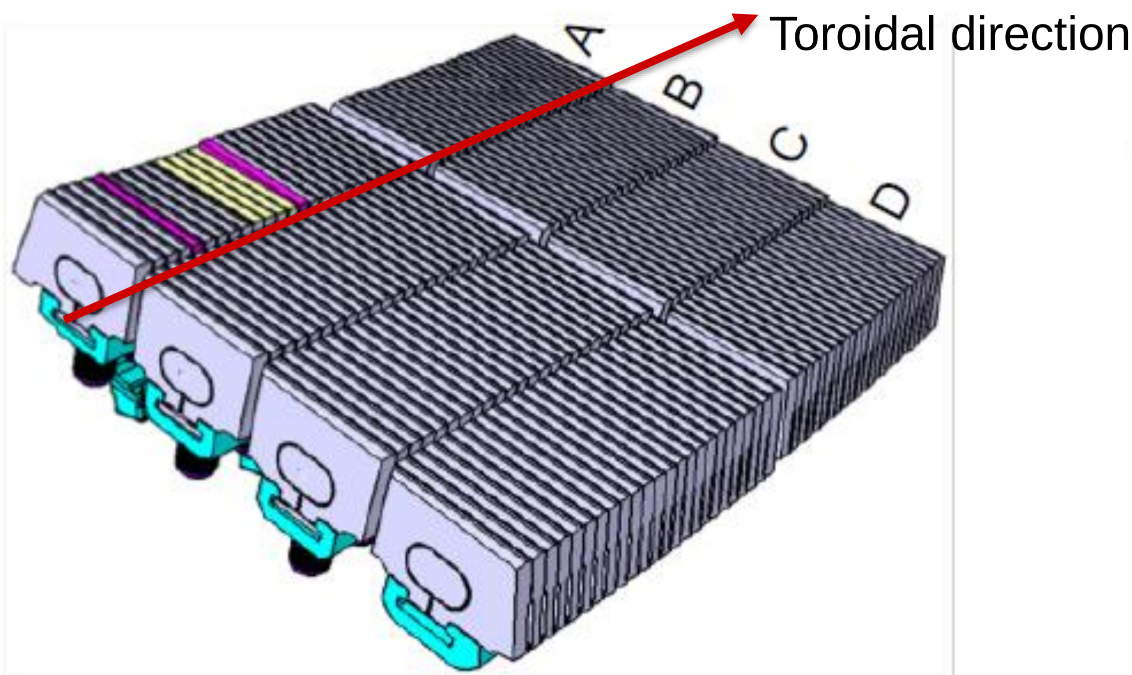
JET-ILW
W Divertor &
Be Main-Chamber

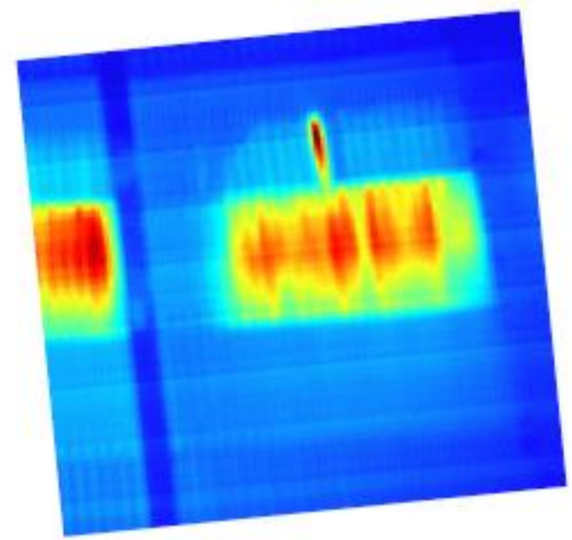
JET is the only operating device with sufficiently high ELM energy losses (>300kJ) to be able to produce transient damage under ITER relevant condition

The JET Melt experiments was meant to clarify issues of transient melting and its impact on operation

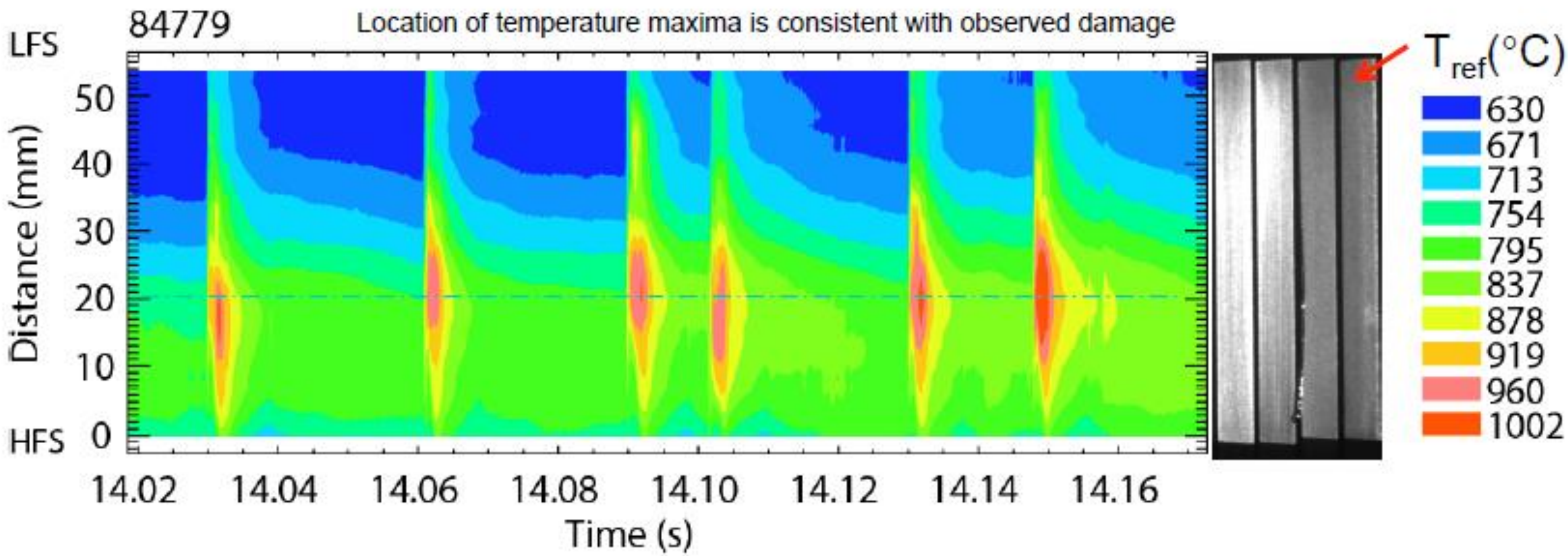

53.0 mm
2.4
0.25
A
B
5
14

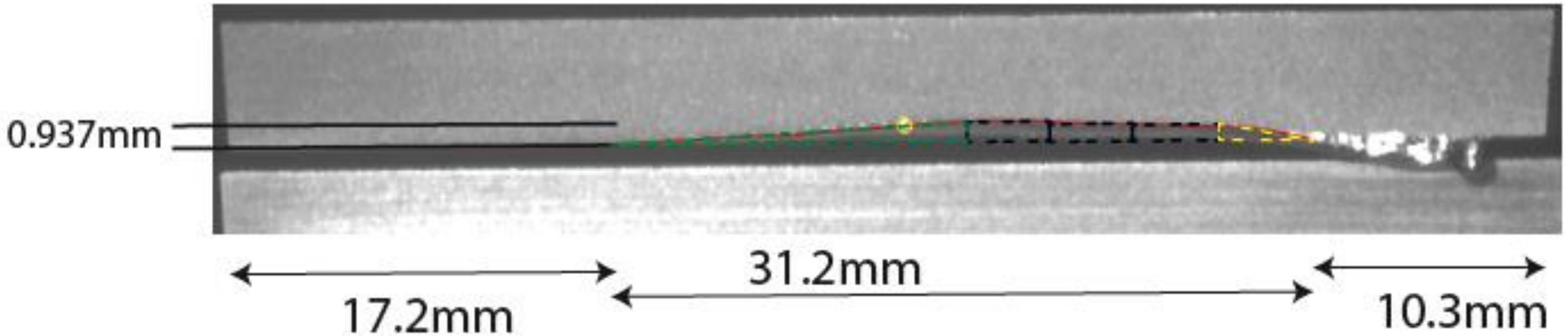



Toroidal direction
A
B
C
D



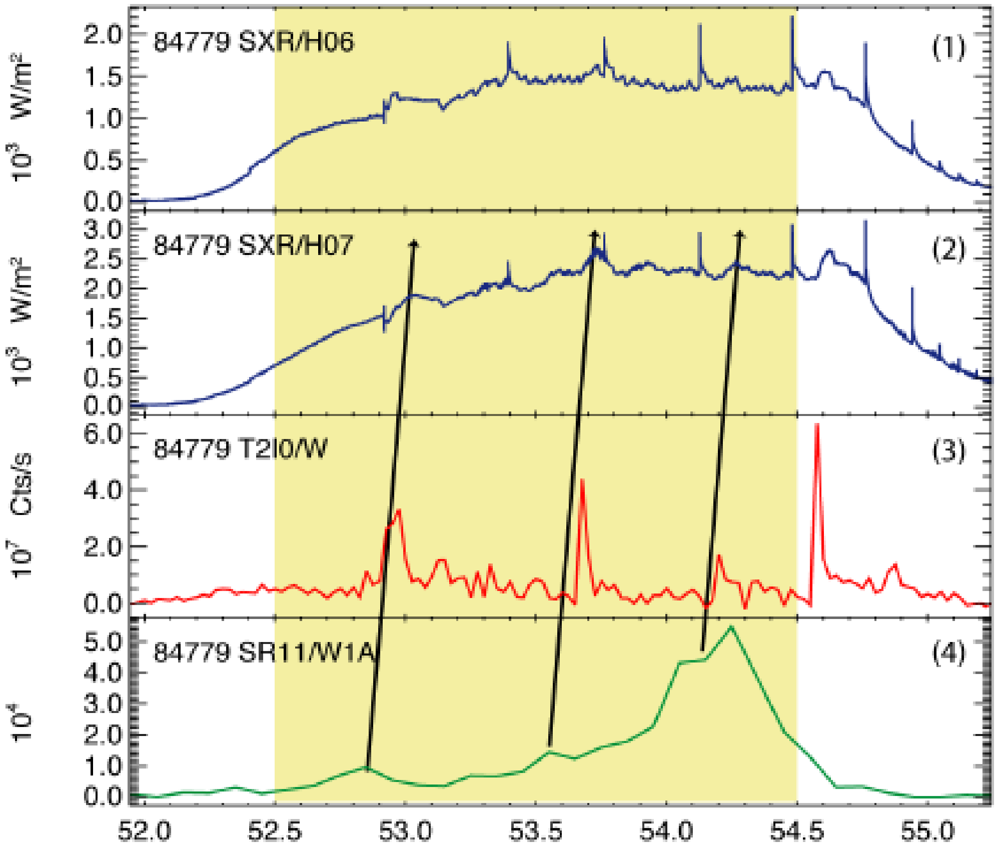
Melt Location





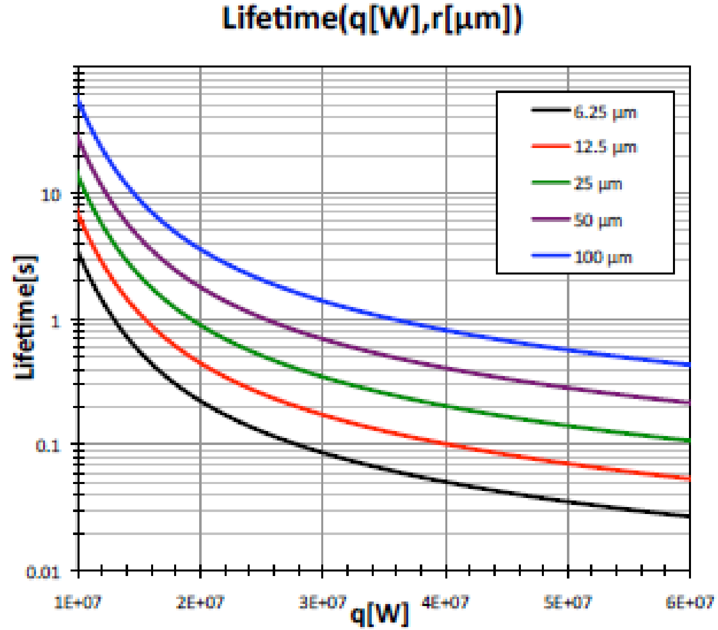
The final damage / material moved is roughly 6-7 mm³ from image analysis.

Localized Droplet Source Visible



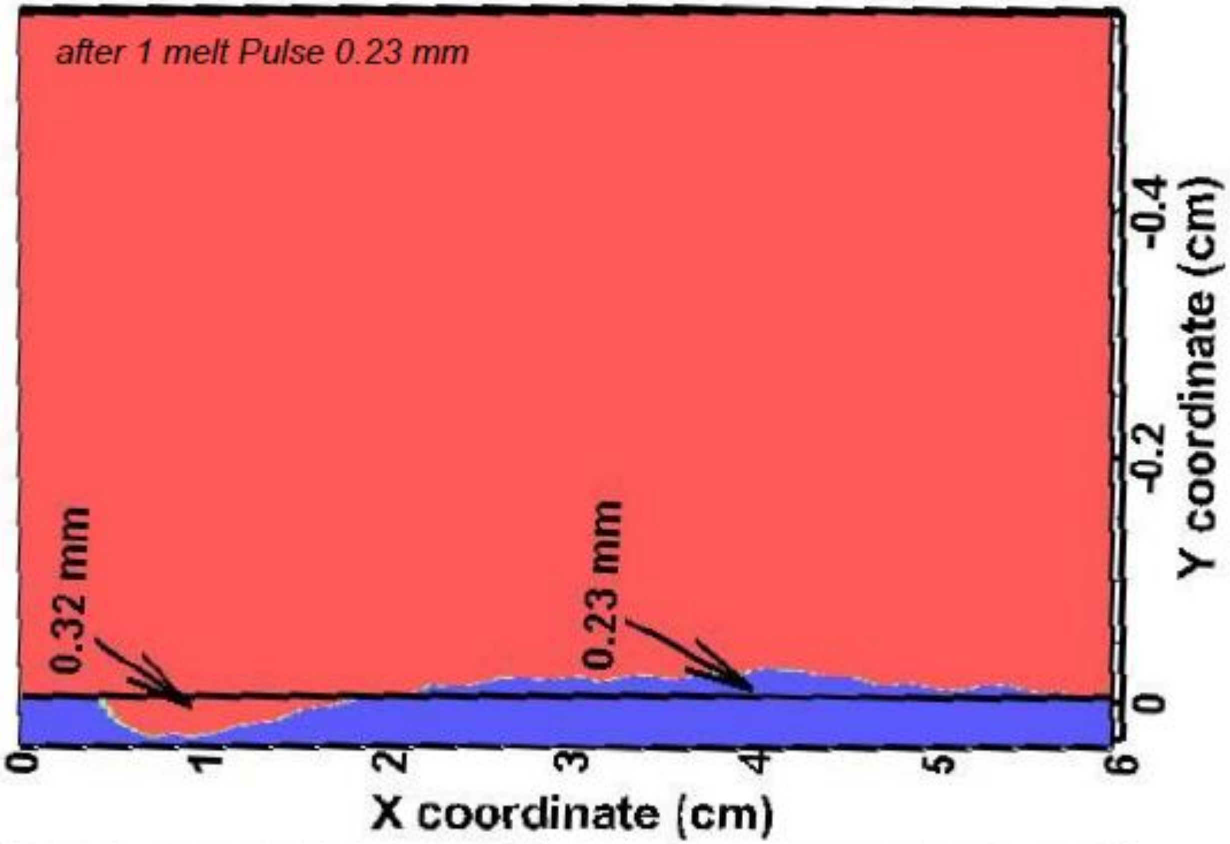
Local WI, KT2 (VUV), SXR show all 3 clear events

$c_W = 5 * 10^{-5}$ density change
→ equivalent W mass
with r=80μm, 41.3μg

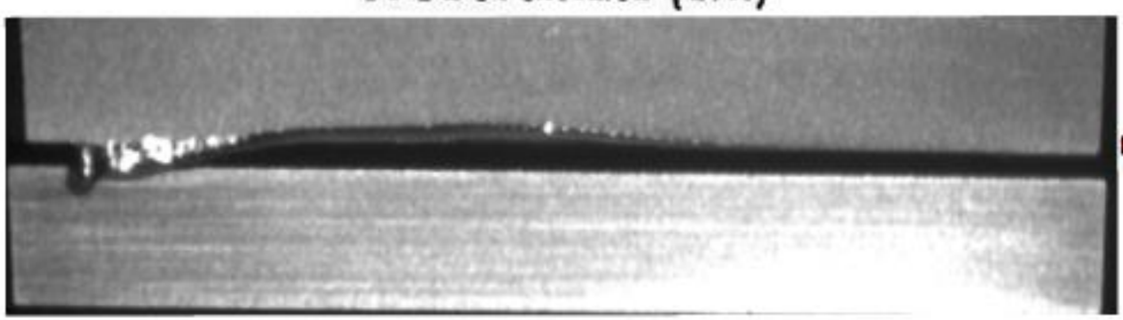


Tungsten droplets move from the divertor into the confined plasma with rather long lifetimes

Melt Layer Motion Matches



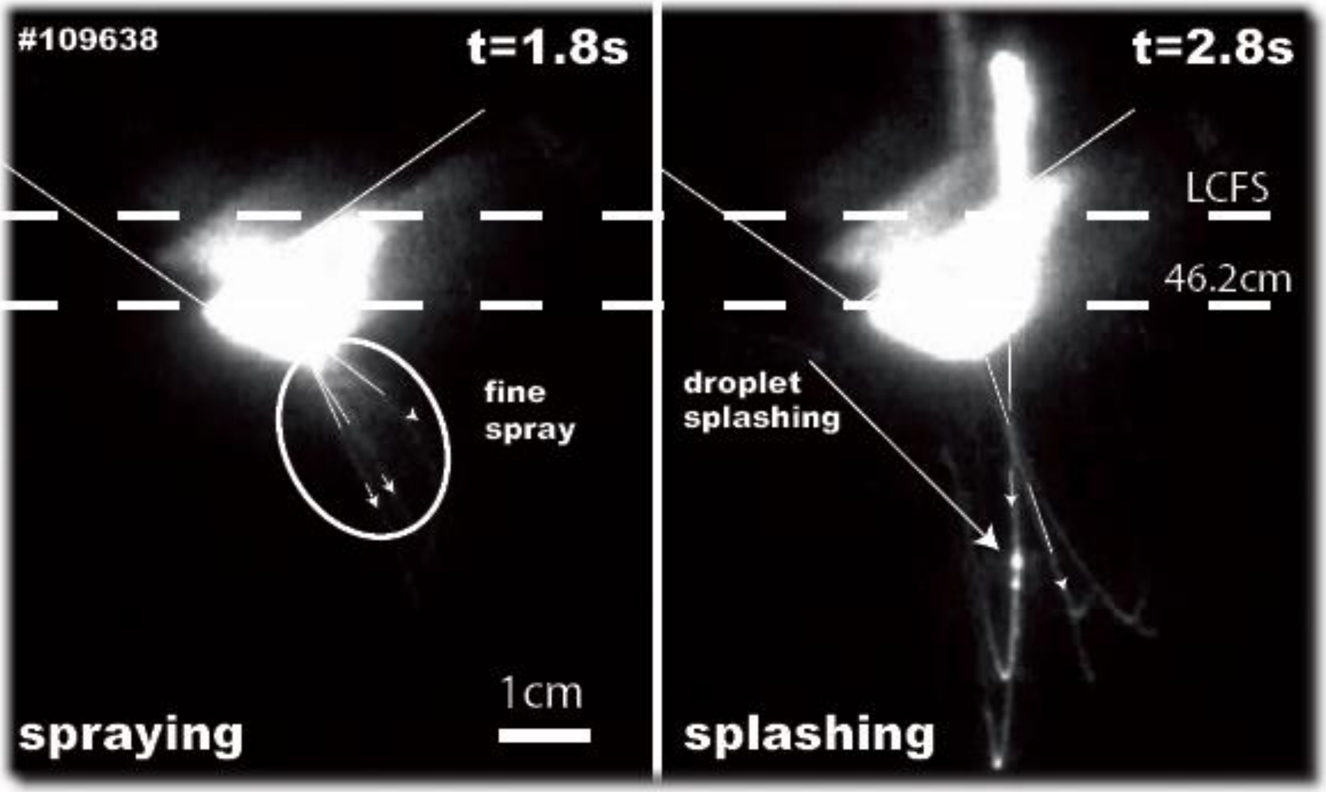
When the Temp. evolution in MEMOS is adapted to the measured data including mitigation factors the **melt layer motion is correctly modeled**



after 5 pulses 1mm

B.Bazylev

Spraying & Splashing



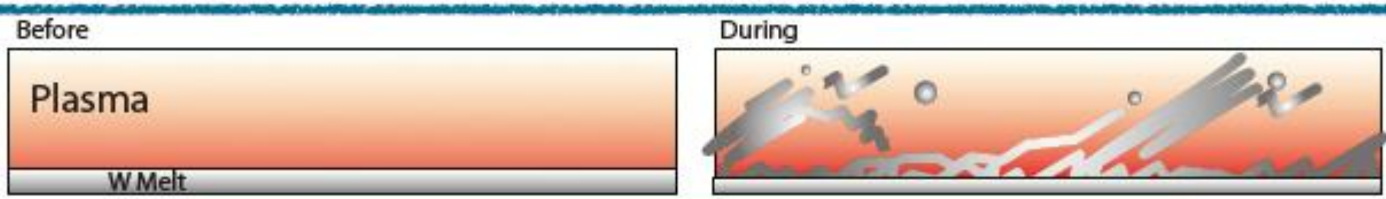
Due to boiling (mainly by impurities) and surface instability

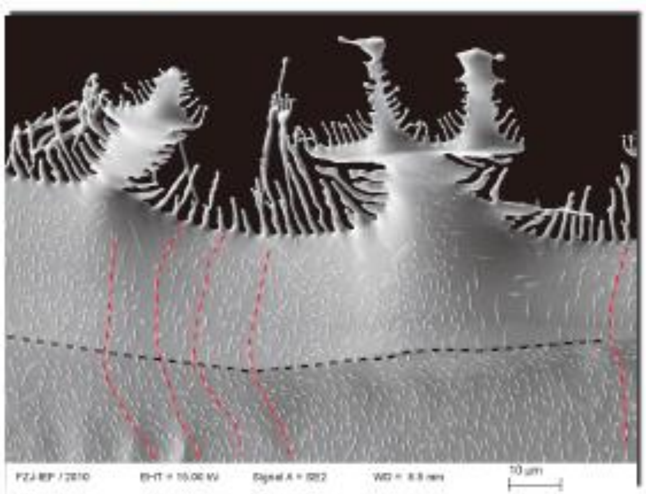
Droplet Production

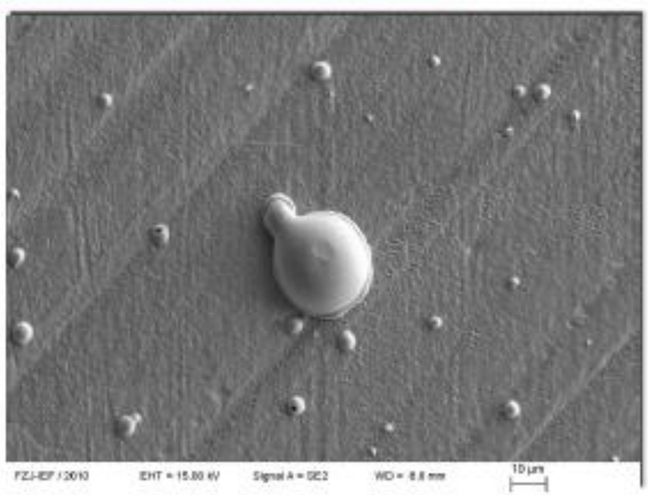
The most promising explanation for splashing seems a Kelvin-Helmholtz instability incorporating linear stability analysis and non linear modeling

Bazylev, B. et al. Fusion Engineering and Design, 2009, 84, 441-445
Experimental and theoretical investigation of droplet emission from tungsten melt layer

Miloshevsky, G. et al, *accepted by Nuclear Fusion*, 2010
Modelling of Kelvin-Helmholtz instability and splashing of melt layers from plasma facing components in tokamaks under plasma impact

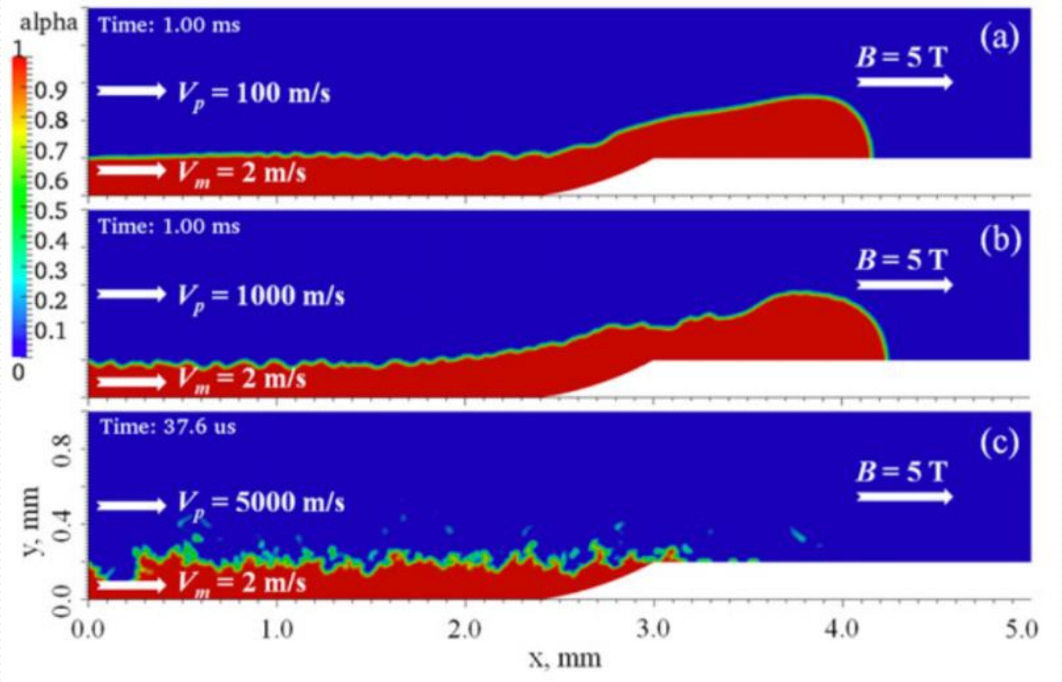






Tungsten Melt layer motion

G. Miloshevsky and A. Hassanein, NF**54** (2014) 043016



Kelvin-Helmholtz instability

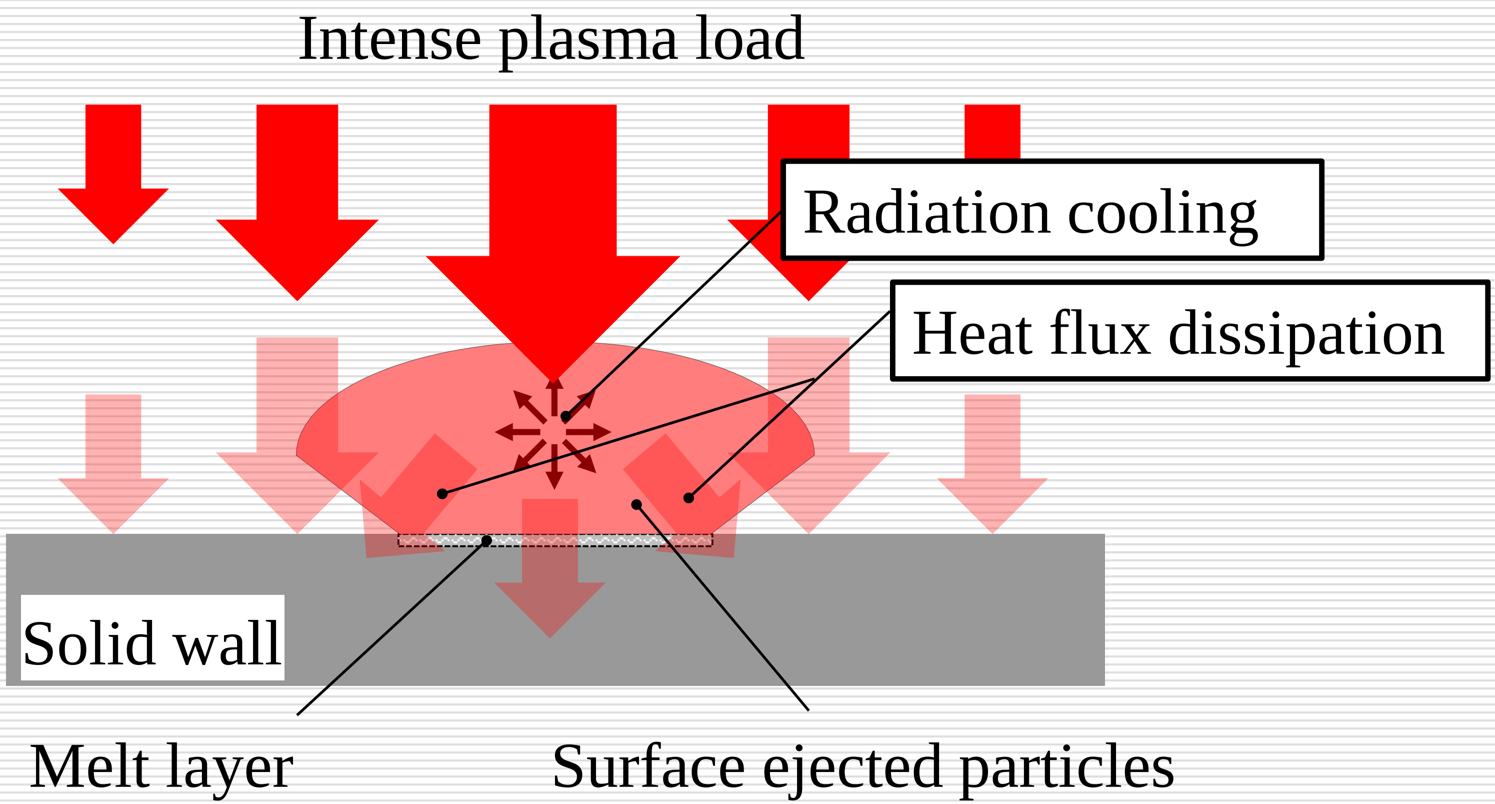
- 2D Volume of Fluid(VoF)-MHD model

➔ Two fluid simulation on plasma and melt layer

➔ Instability can be treated. Thus, droplet simulation is possible. ➔ Complex numerical method. Difficult to treat generation and motion of melt layer simultaneously.

VAPOR SHIELDING

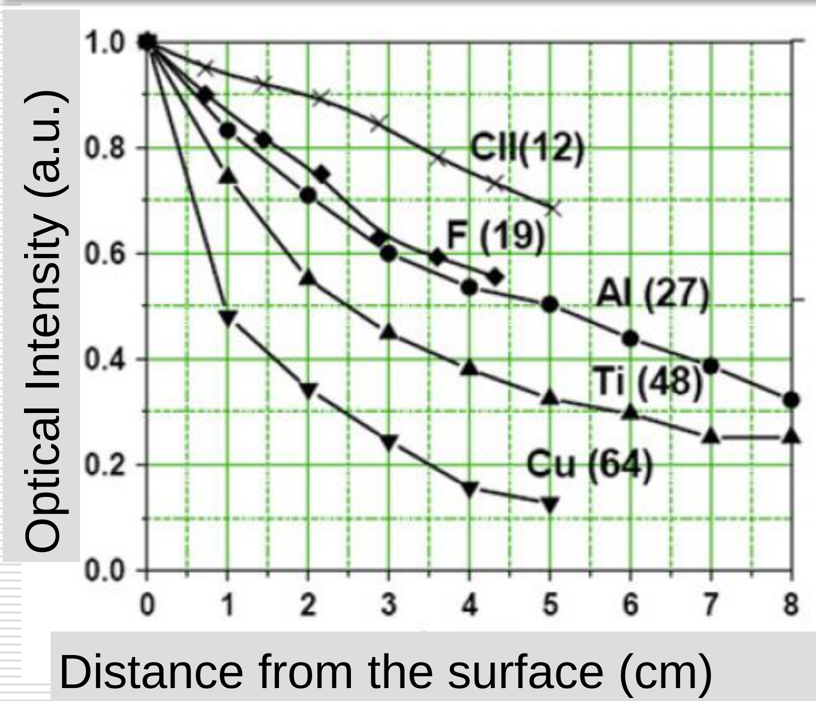
Vapor shielding at a flat surface

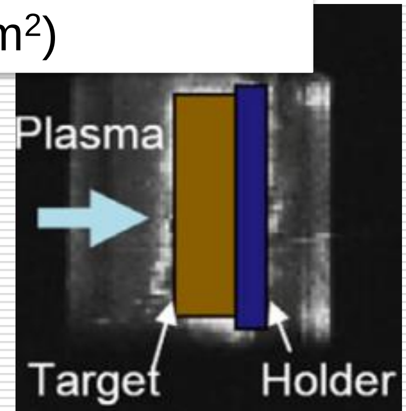


- Intense plasma load causes ablation/evaporation from the surface.
- Then, Vapor–Plasma interaction dissipates the localized heat flux to the surrounding area.

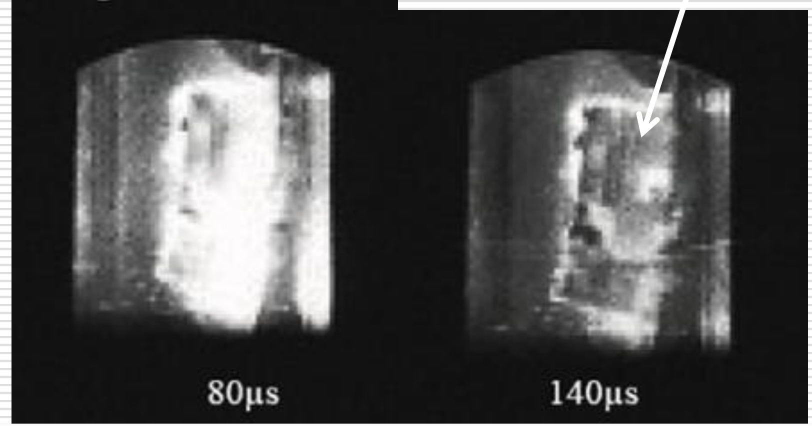
Formation of shielding layer

Line intensities from vapor of different materials
Irradiated by QSPA Plasma Gun (25MJ/m^2)





Carbon vapor reaches >5 cm
While W vapor stays <0.5 cm



High speed CCD images from shot to a W sample.

Thickness of vapor layer decreases as atomic number increases.

V. I. Tereshin and et.al., Plasma Phys. Control. Fusion, **49** (2007) A231

Graphite vapor shielding

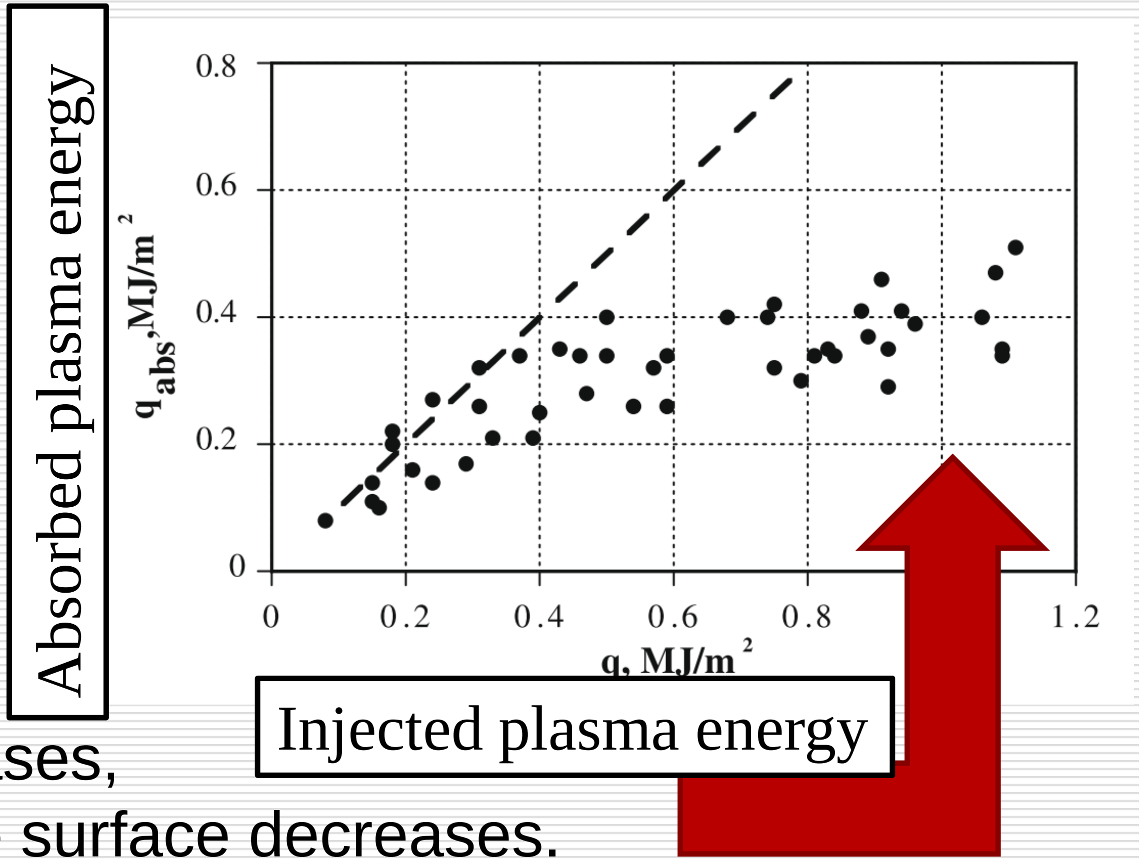
MK-200UG

τ=0.05 ms

E_i = 2-3 keV

n_e=(0.1-2)x$10^{20}$$m^{-3}$

q''=1-20 GW/m^2



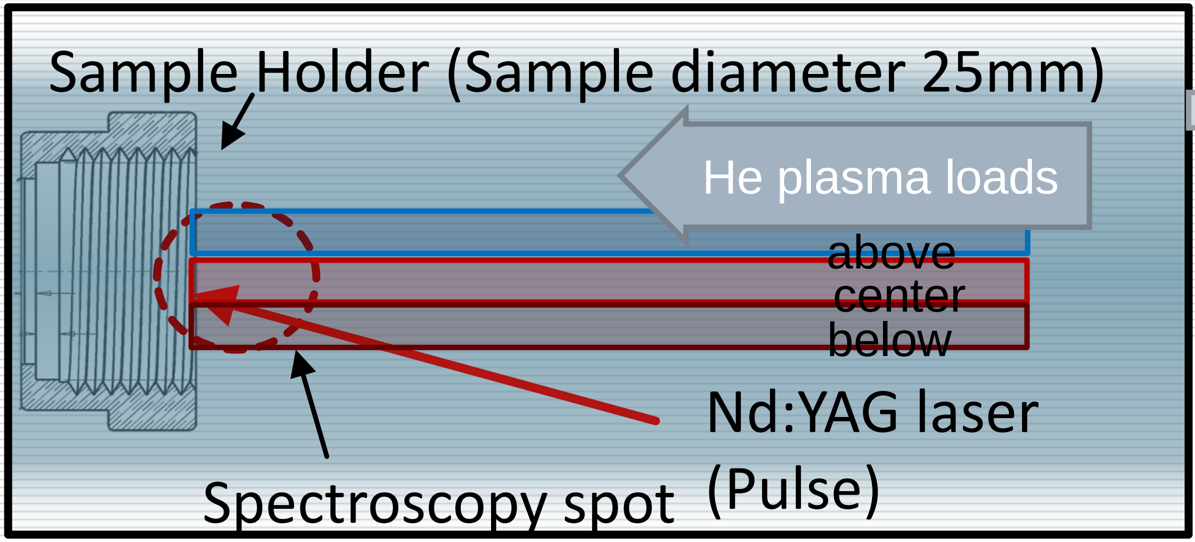
- As input power increases,
  power reaching to the surface decreases.
- Graphite does not melt. (sublimation ~ 3900 K)
  - ➔ Easily vaporized. Strong shielding effects.

V.M. Safronov et al. JNM,386, 744 (2009)

Experimental observation (PISCES)

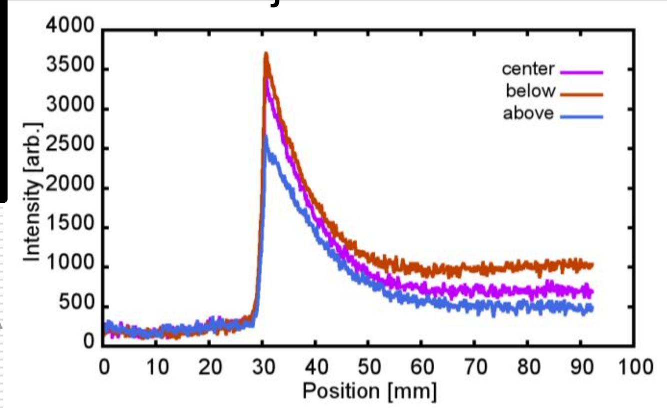
<u>Steady-state He plasma loads + Pulse Laser shot</u>

PISCES-B @ UCSD



High speed camera
w/ optical band-pass filter

Line intensity profile
of surface ejected materials



Decay length of surface ejected materials

$$f_{(x)} = I_{\mathbf{peak}} * e^{-\lambda\, x_{\mathbf{peak}}}$$

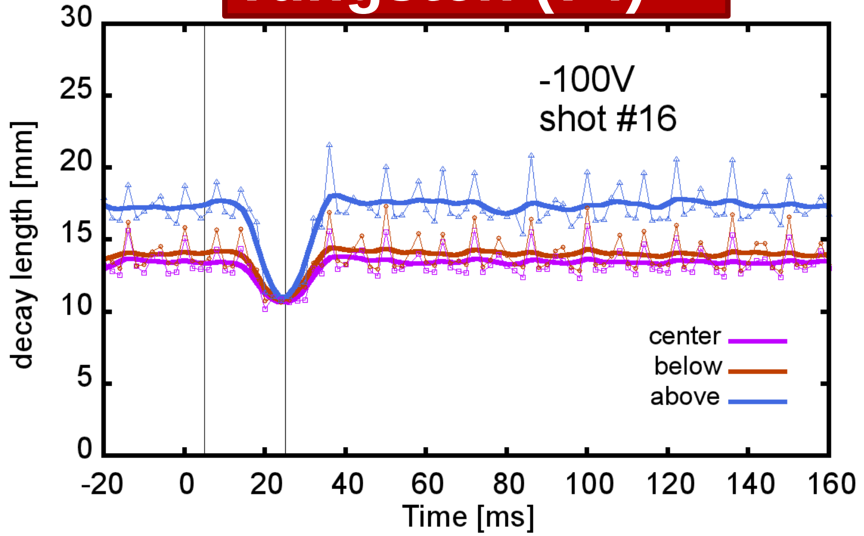
Laser caused evaporation results

Generation of slow ejected materials ➔ ***Shorter*** decay length ($V_{evaporate} < V_{sputtering}$)

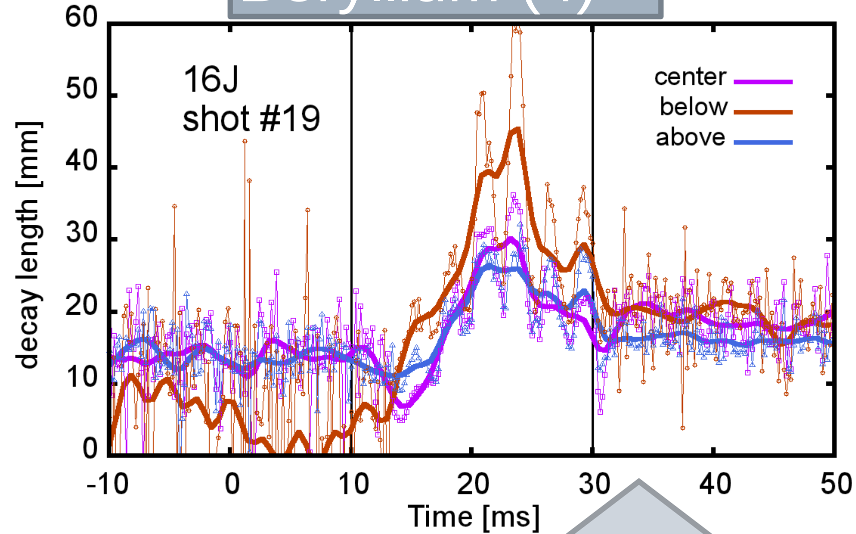
If massive vapor cools plasma down ➔ ***Longer*** decay length

Decay length analysis

Tungsten (74)



Beryllium (4)



Laser irradiations on

W sample: ***Decrease*** of decay length

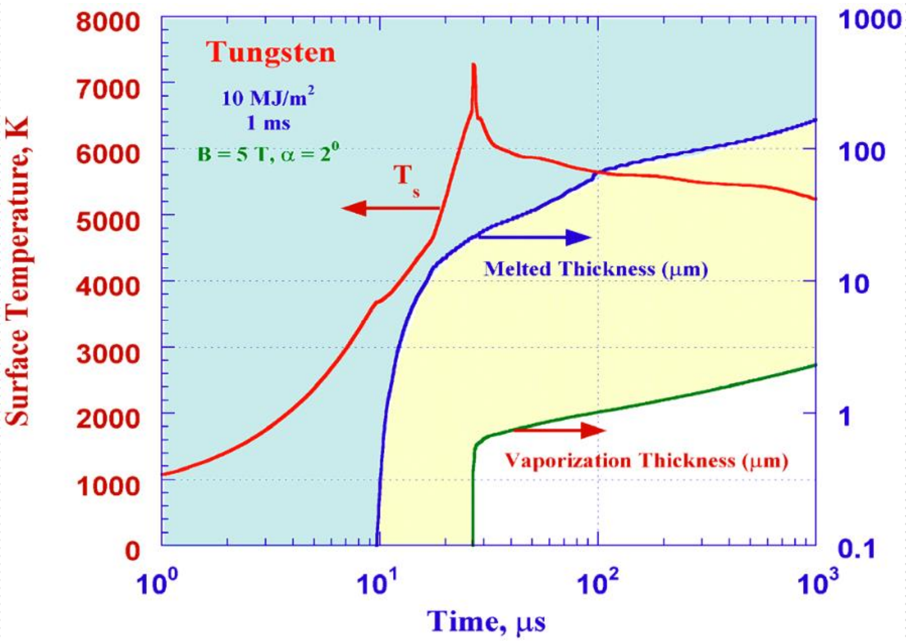
➔ Difference of V_{sput} and V_{evap}.

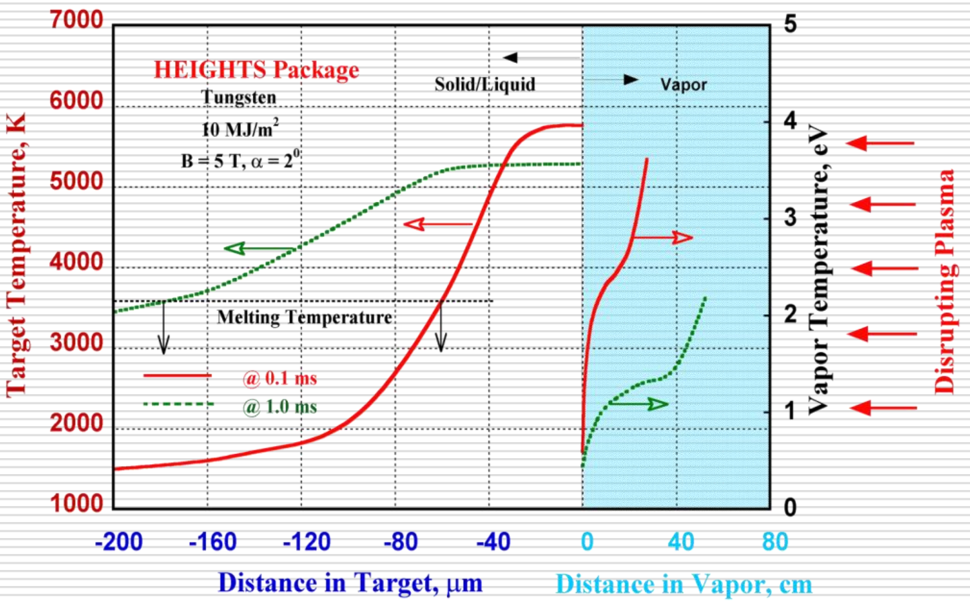
Be sample: ***Increase*** of decay length

➔ Plasma cooling, longer mean free path

Experimental observation of vapor shielding!!

HEIGHTS Predictions of Erosion due to Vaporization & Melting of Tungsten



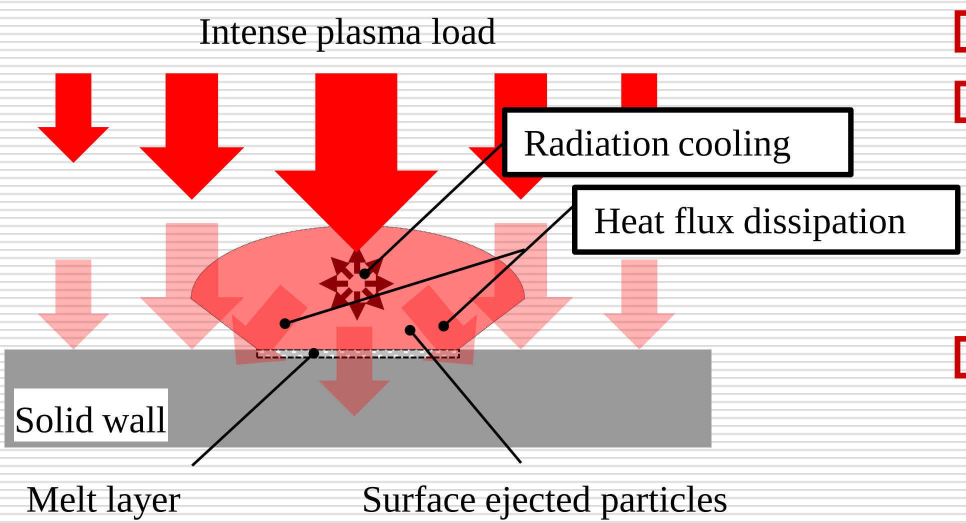


- ❑ Tungsten erosion due to vaporization ~ 1-2 μm
- ❑ Melt layer thickness ~200 μm at 1.0 ms
- ❑ Melt boiling can take place

Hassanein & Konkashbaev, *J. Nucl. Mater.* 233 (1996) 713

Hassanein & Konkashbaev, *J. Nucl. Mater.* 273 (1999) 326

Simulation approach



During vapor shielding,

- Vapor ejected from surface.
- Neutrals/Ions shield incoming flux via
  - Ionization
  - Line Radiation
- Energy transfer to the wall becomes
  - Surface recombination
  - Radiation
  - non-shielded flux

Simulation should includes

Motion of particles

Ionization and recombination

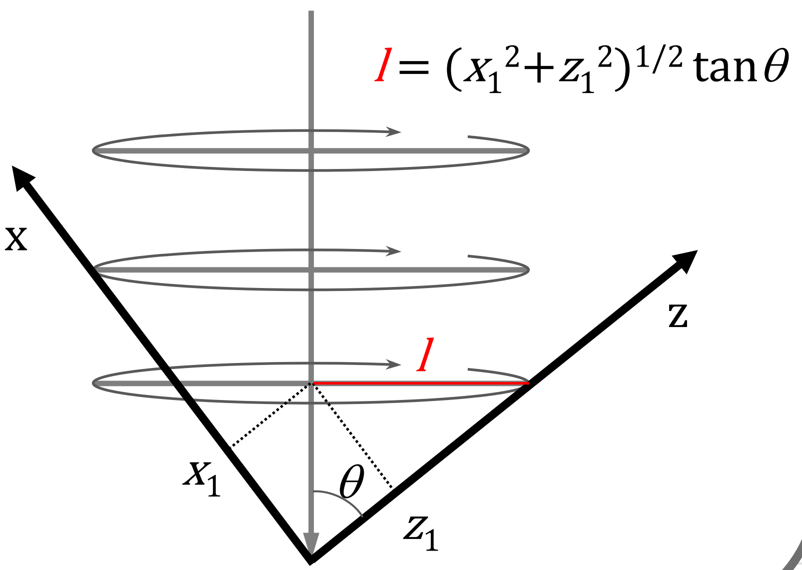
Radiation (transport)

Particle-In-Cell (PIC) simulation

W ion has a large gyroradius.

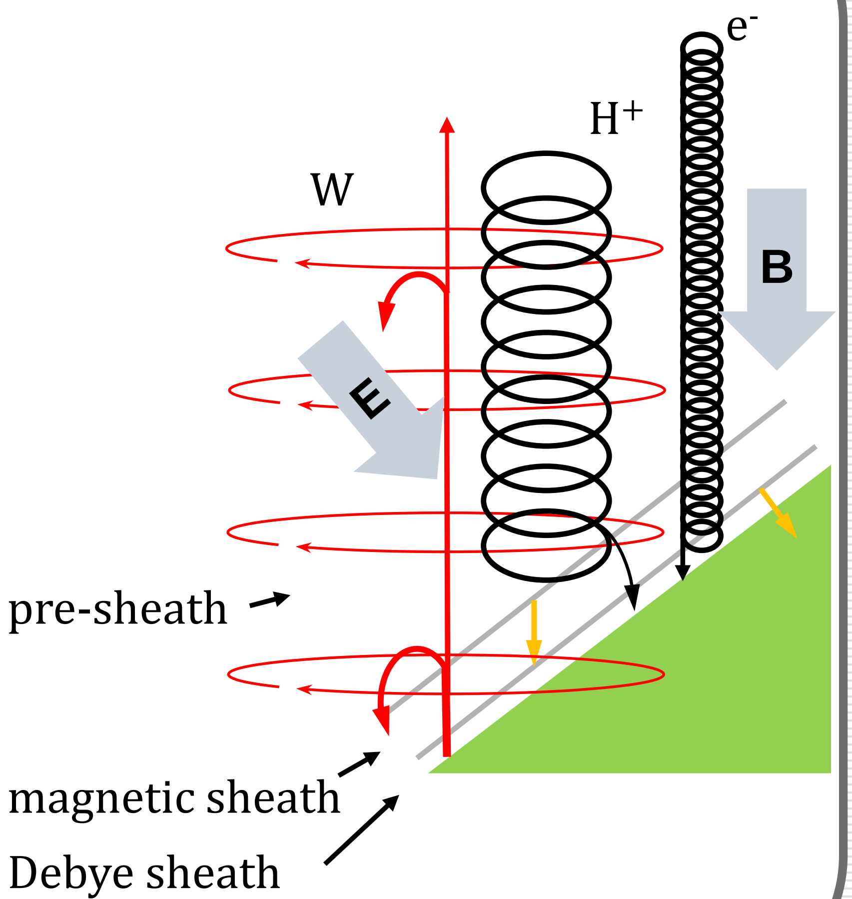
Tungsten prompt re-deposition

prompt



Tungsten should be treated by particle codes.

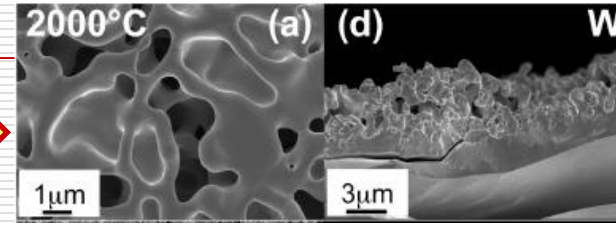
total



HE INDUCED STRUCTURE ON TUNGSTEN AND ITS RESPONSE TO PULSED HEAT

He effects on W

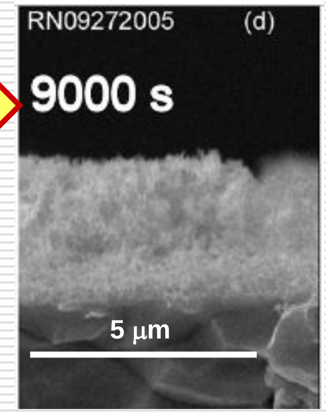
- **High temperature (> 1700 °C)**
  - Large **He holes** and **thick tendril** formation with recrystallization

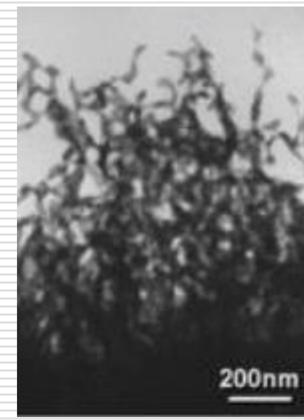


PiLOT PSI

T ~ 2000 °C

- **Medium temperature**
  - Nano-structure (**W fuzz**) formation





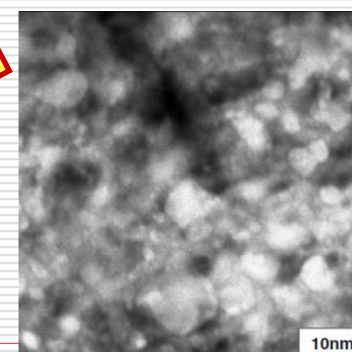
PISCES (UCSD) NAGDIS (Nagoya U.)

T ~850 °C **T ~ 1100 °C**

- **Low temperature (< ~700 °C)**
  - **Nanometric He bubble** formation (a few nm)
  - Hardening and reduction of thermal conductivity

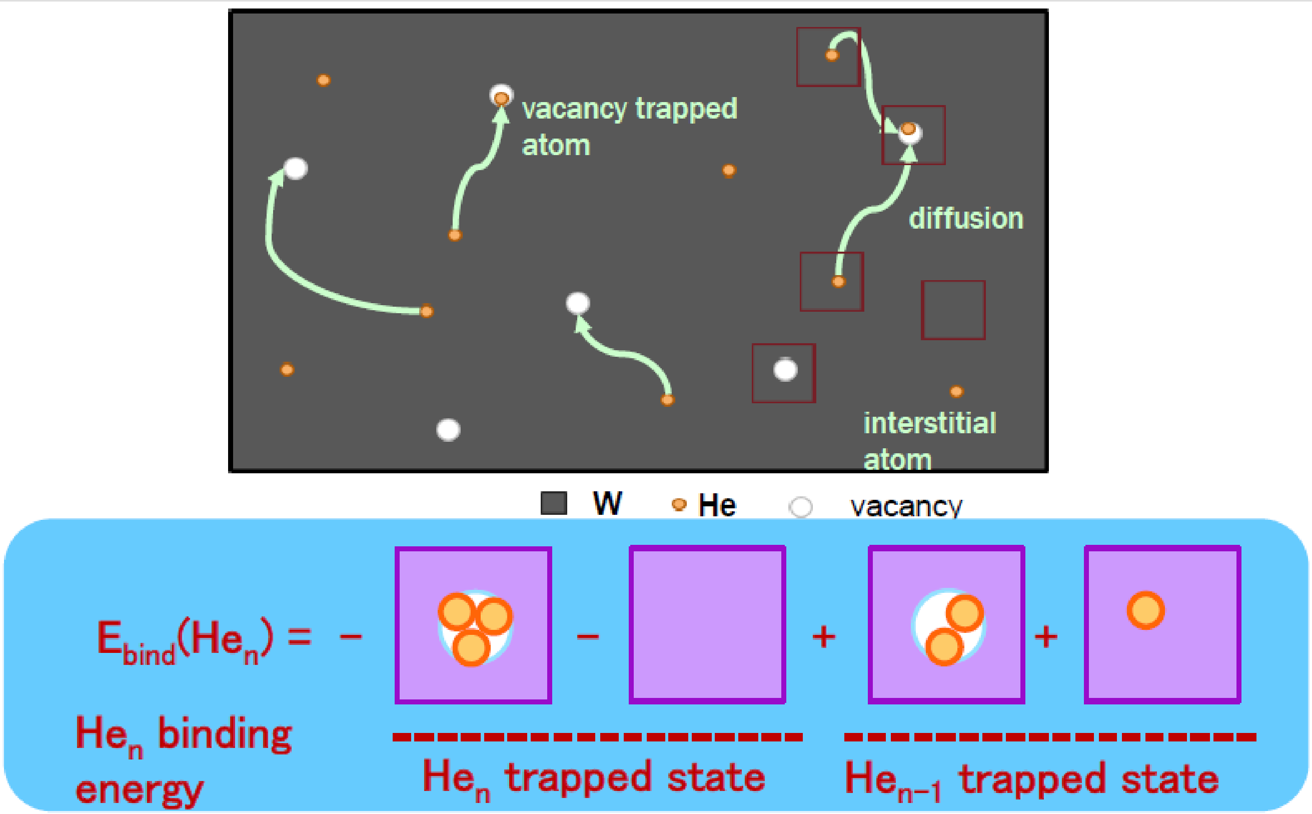
PISCES (UCSD)

T $\leq$ **600 °C**



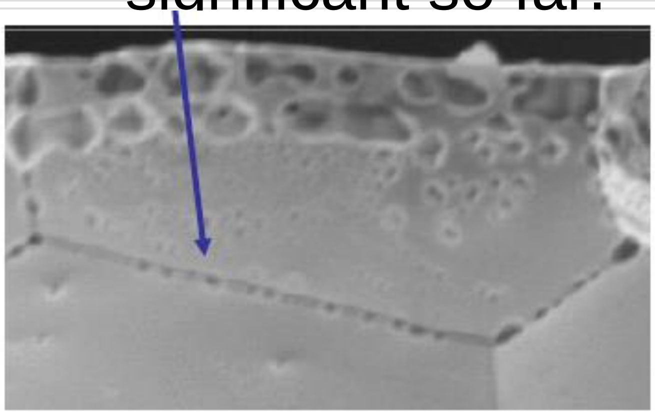
Why He makes bubbles in metals

- He atoms have closed electronic shell structure.
- He atoms prefer to stay in vacuum (or low electron density environment).
- He atoms strongly trapped in vacancies.
- He trapped vacancy attracts more He to grow to bubbles

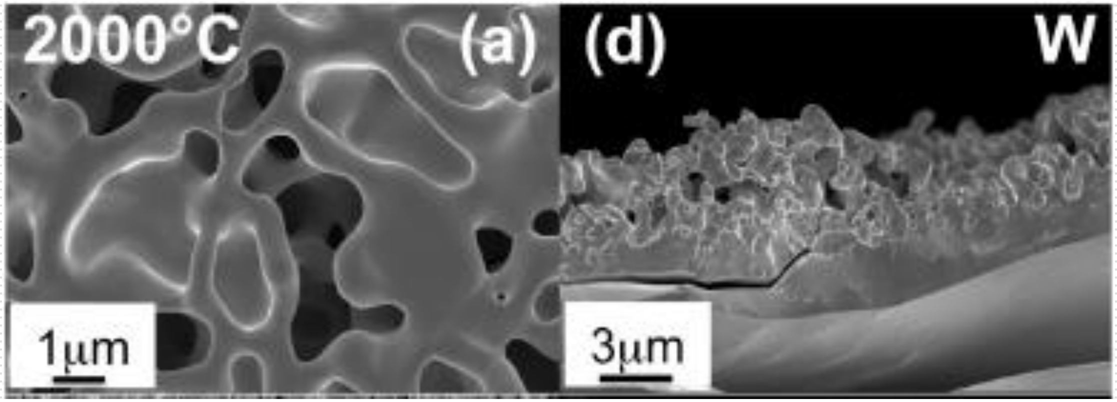


Surface He holes (> ~ 1700 °C)

- Porous structure reduces effective thermal conductivity and power handling capability.
- He bubbles are formed not only on the surface but also along grain boundary, which weaken adhesion of grains.
- In some preliminary experiments, grain ejection by plasma particle exposure was observed, but not very significant so far.



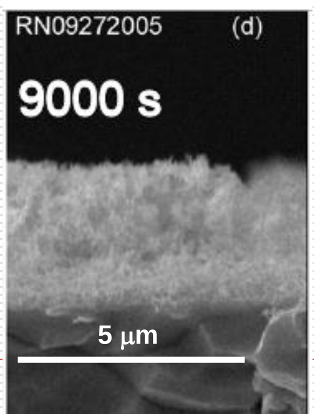
Results from NAGDIS



Results from MAGNUM

Present knowledge on W fuzz

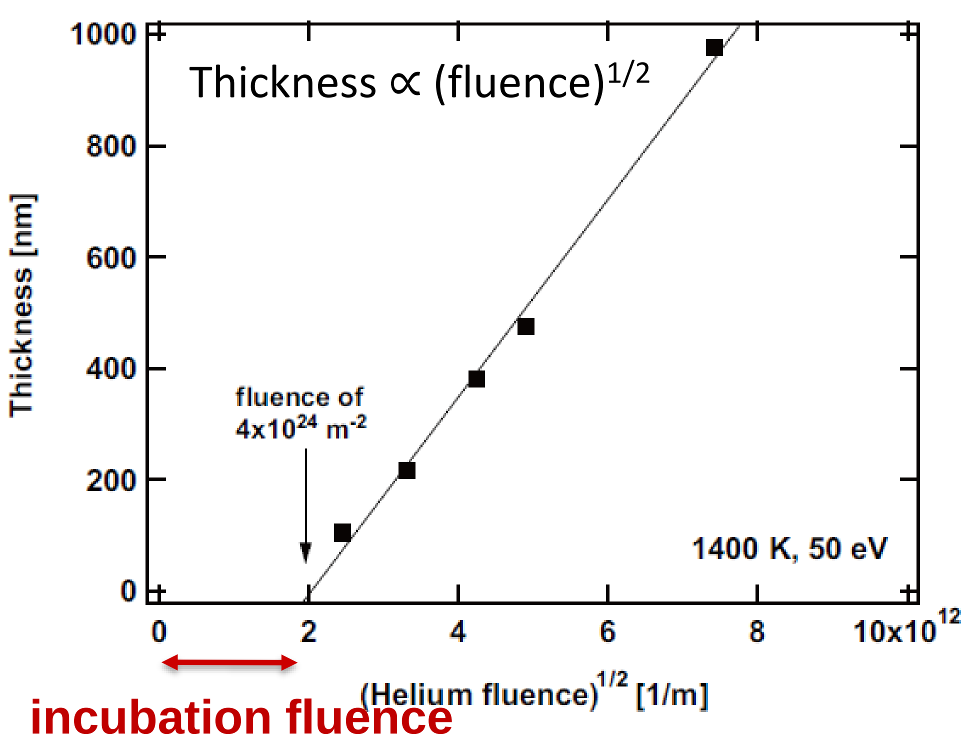
- **Formation conditions**
  - Temperature : **> 700 °C**, He flux : **> $5x10^{21}m^{-2}s^{-1}$**, an ion energy **> 20-30eV**.
  - The area of fuzz could be very limited near the strike points.
  - In detached plasmas, fuzz is unlikely formed because of very low ion energies (a few eV).
- **General properties and their effects**
  - Advantages: Low sputtering erosion. Resistant to pulsed heat loading, Reduction of secondary electron emission
  - Disadvantages: Erosion by **unipolar arcing** (leading to **Dust formation)**.

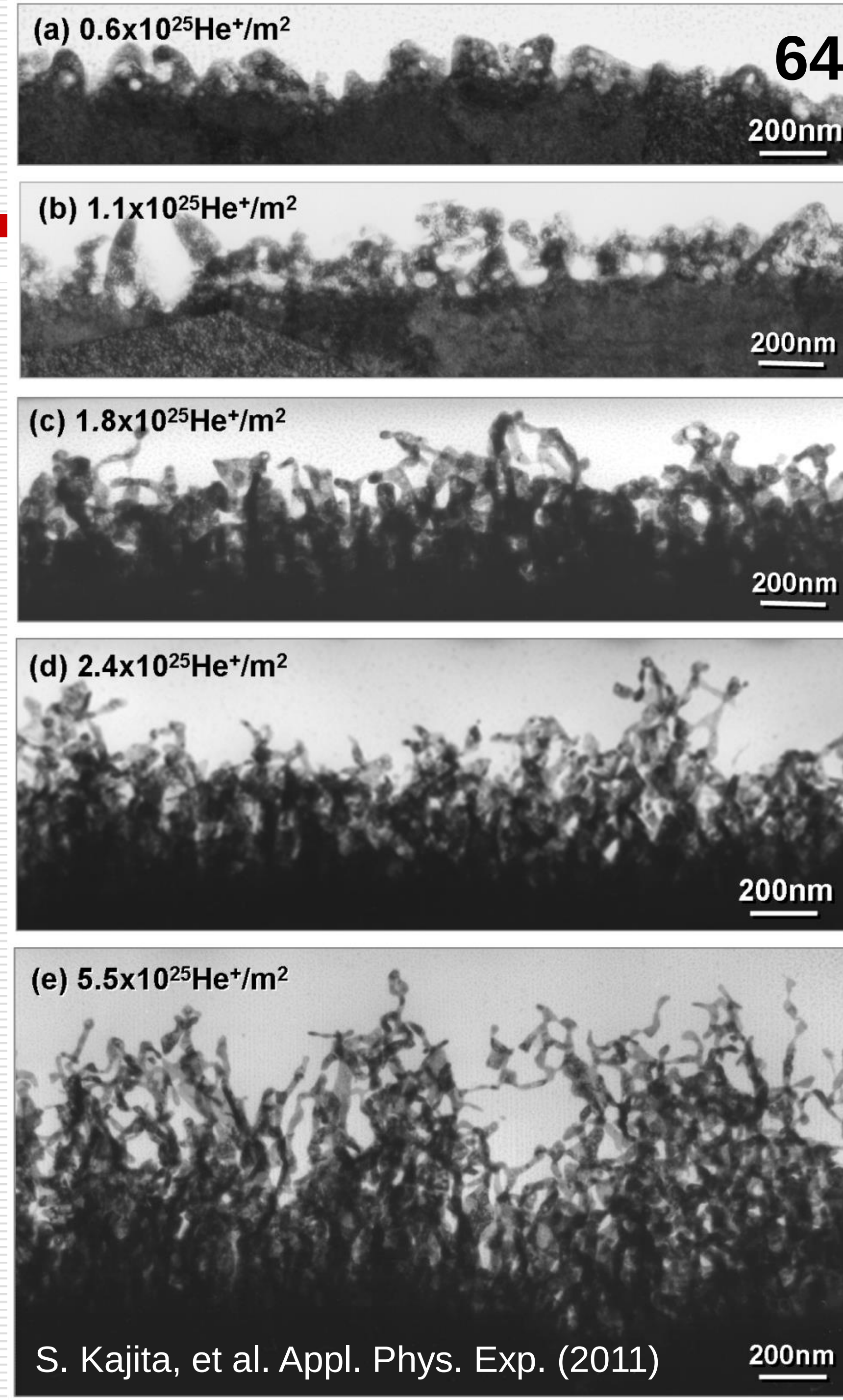


Growth of protrusions by helium irradiation

Irradiation were performed in the divertor simulator NAGDIS-II. The samples were analyzed FIB-TEM analysis.

sample：W, 1400K, 50eV-He plasma





S. Kajita, et al. Appl. Phys. Exp. (2011)

Four-step process of tungsten nanostructure formation

1. Penetration

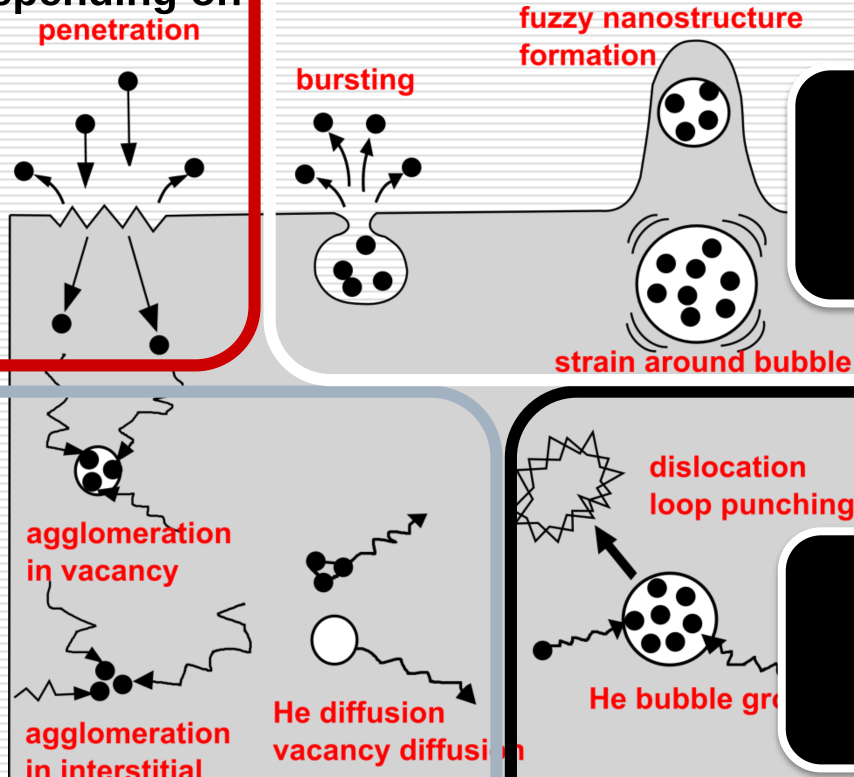
- Competition of penetration and sputtering
- penetration range depending on incident energy

BCA
Binary collision approximation

4. Fuzzy nanostructure growth

- Bursting on the surface
- Formation of fuzzy structure
- How does He-bubble play a role?

MD-MC
Hybrid simulation



DFT
First-principle calculation

2. Diffusion & agglomeration

- Agglomeration of He, differing from H
- Diffusion of He, differing from H

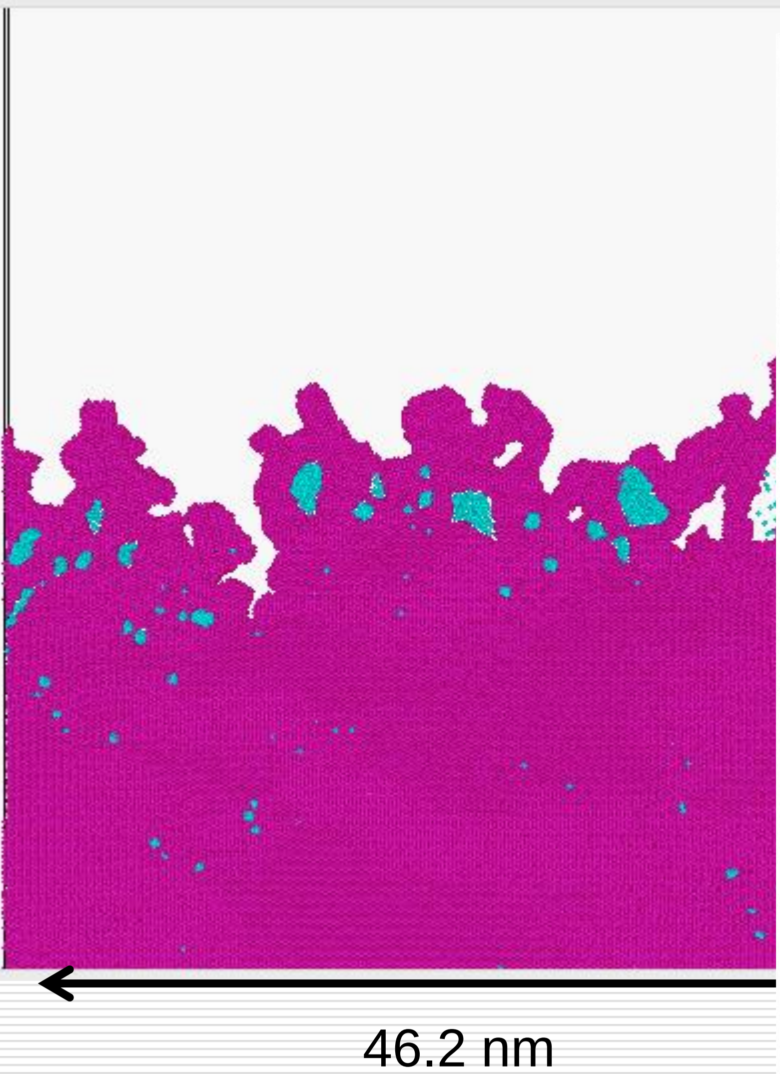
3. He bubble growth

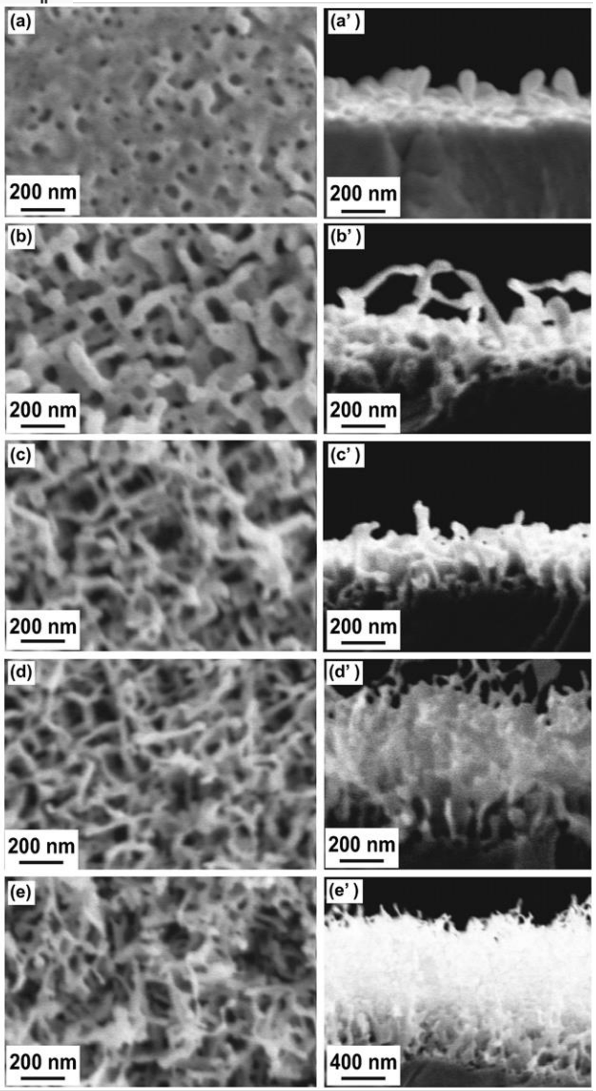
- Growth of He bubble to the size of 1nm or grater.
- Bursting and inter-bubble fracture of He bubble and Loop punching.

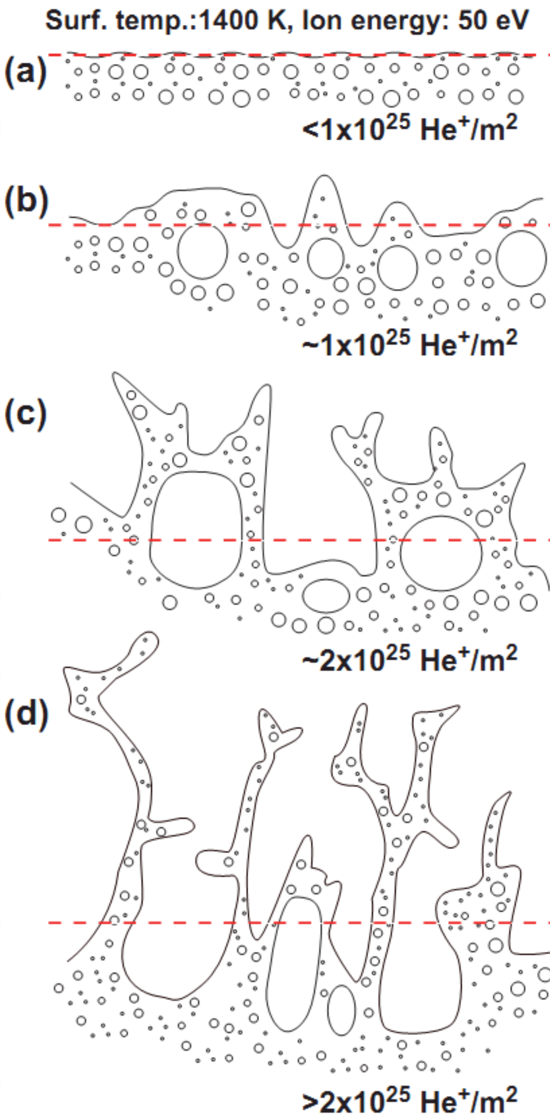
MD
Molecular Dynamics

Slide by A. Ito

Fuzzy Nanostructure Formation by MD-MC Hybrid Simulation







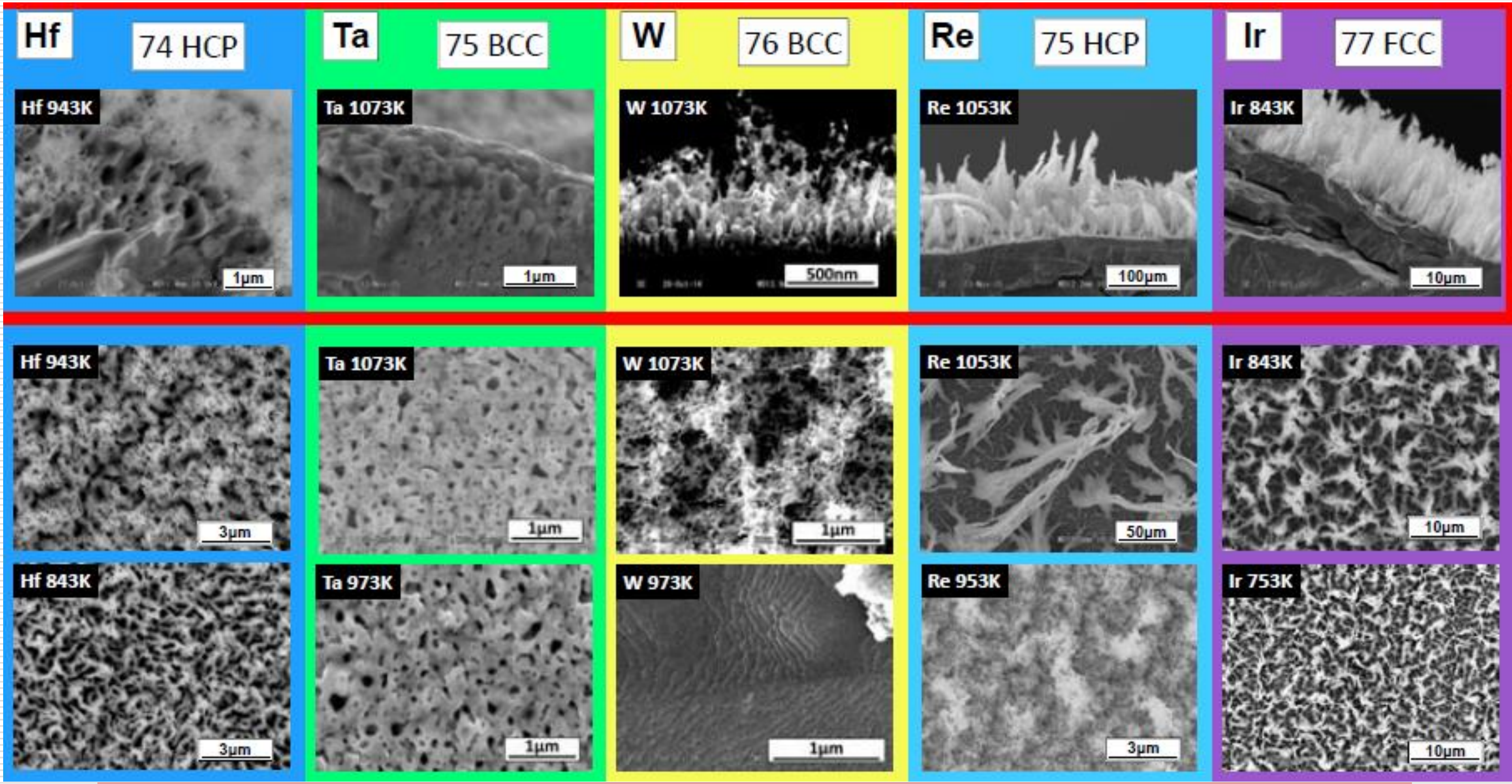
[1] A. M. Ito, et al, J. Nucl. Mater. 463 (2015) 109-115.
[2] A. M. Ito, et al, Nucl. Fusion 55 (2015) 073013.

*S. Kajita, et al., Nucl. Fusion. 49 (2009) 095005.

S. Kajita, et al., J.Nucl.Mater.418(2011)152-158.

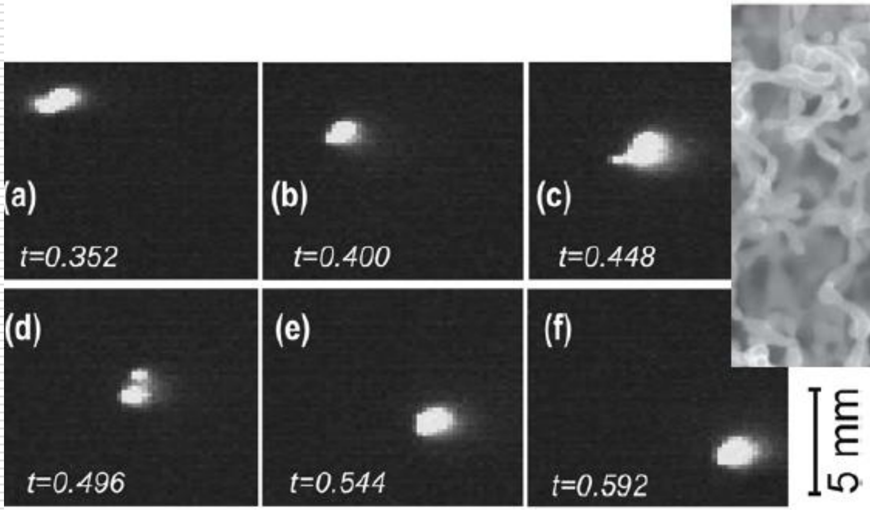
Fuzz structure on various refractory metals

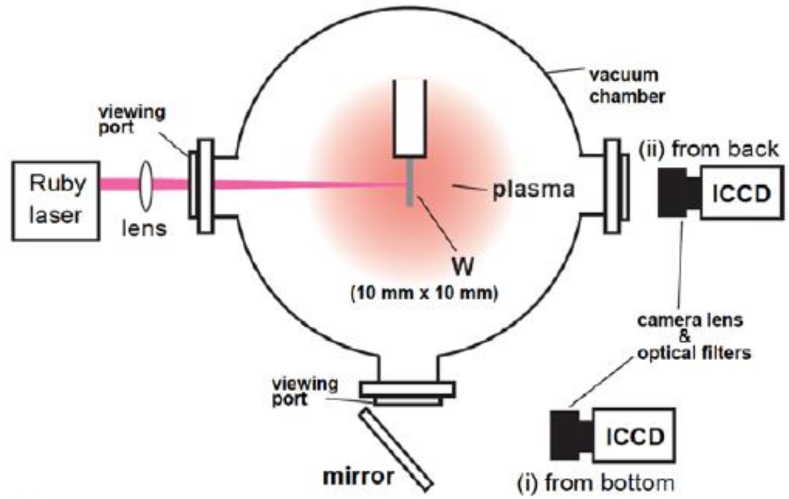
- He induced fuzz formation is relatively common.
- One exception is Ta.

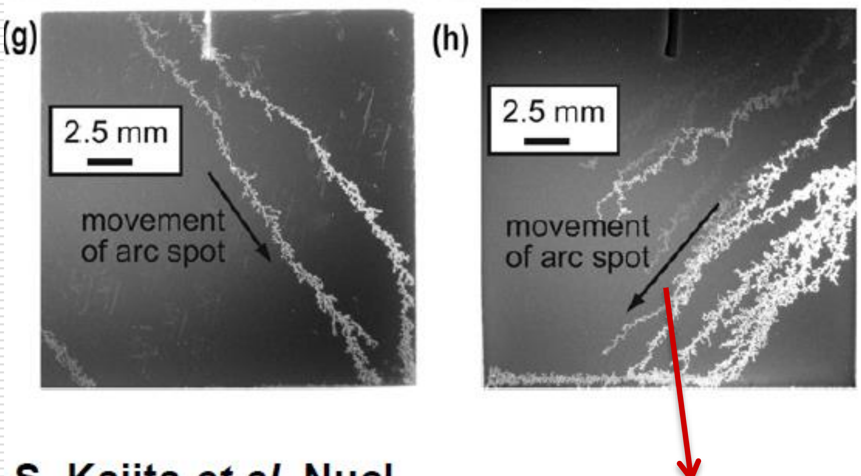


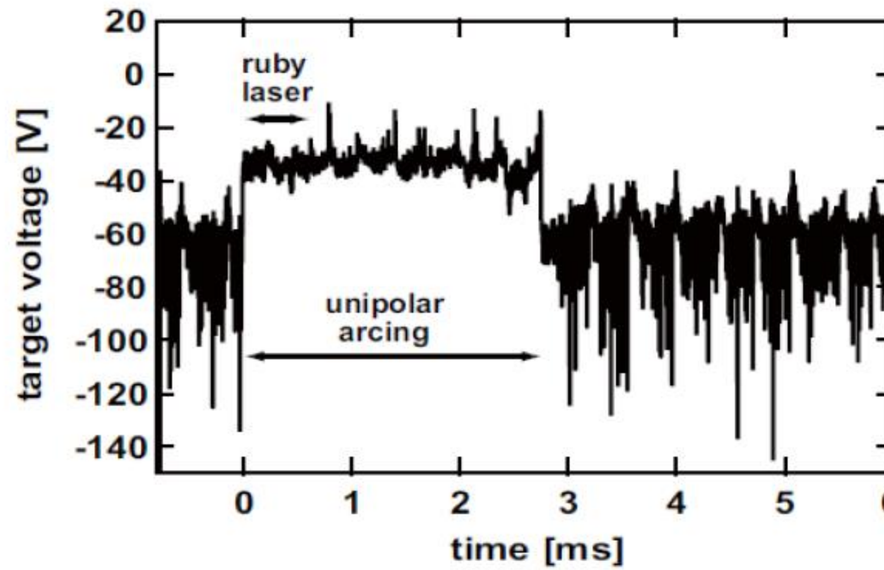
Critical evidence of unipolar arc (UA)

- Demonstration of ELMs on nanostructured W using laser.
- UA is confirmed from the jump of the floating potential.





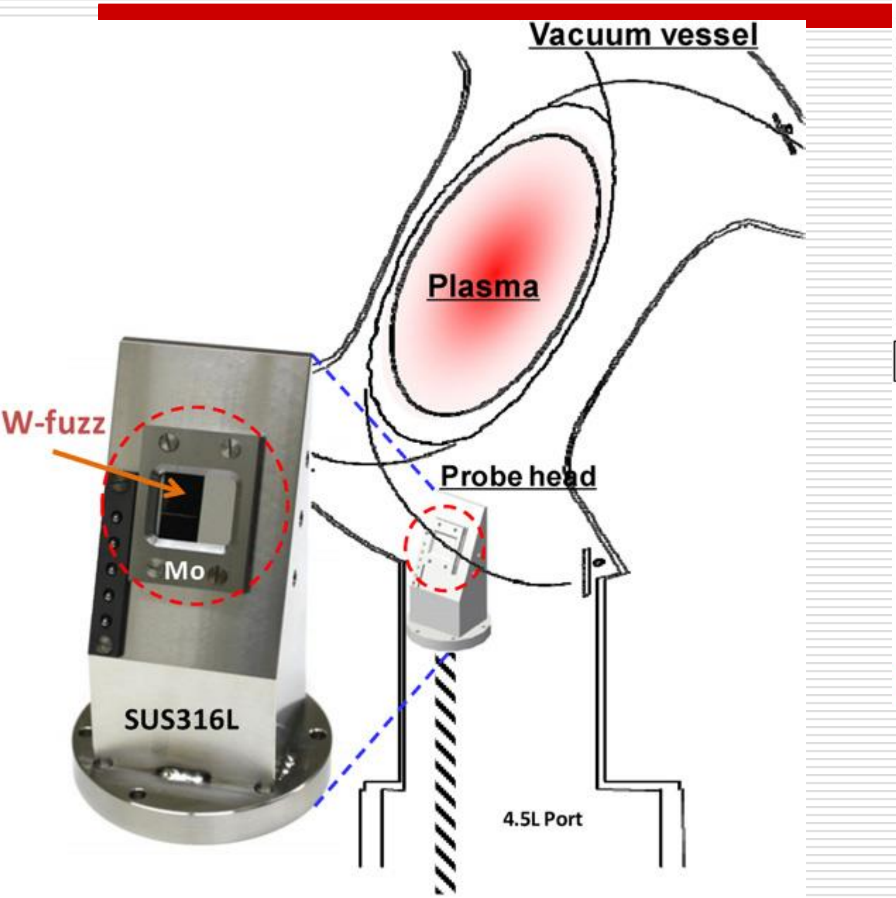


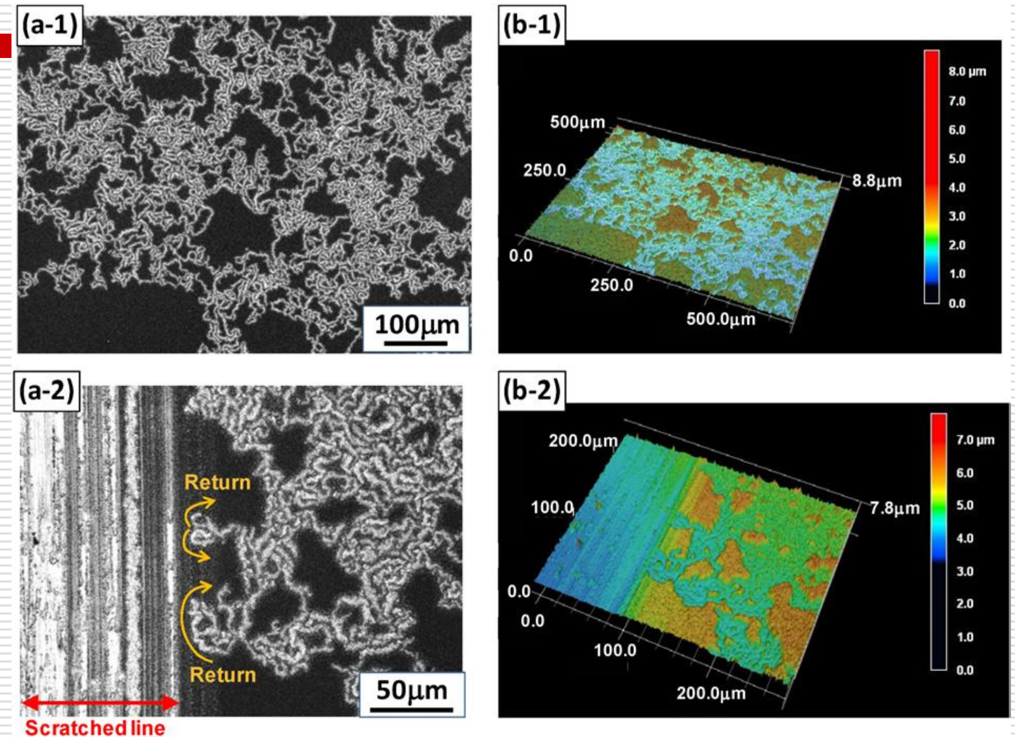


S. Kajita *et al.* Nucl. Fusion (Letter) (2009)

B x J direction

Arcing on premade fuzz-W in LHD





-Nanostructured W formed in the NAGDIS-II was installed in LHD.

-Arcing was initiated by the exposure to the LHD plasma, the duration of which was 2s.

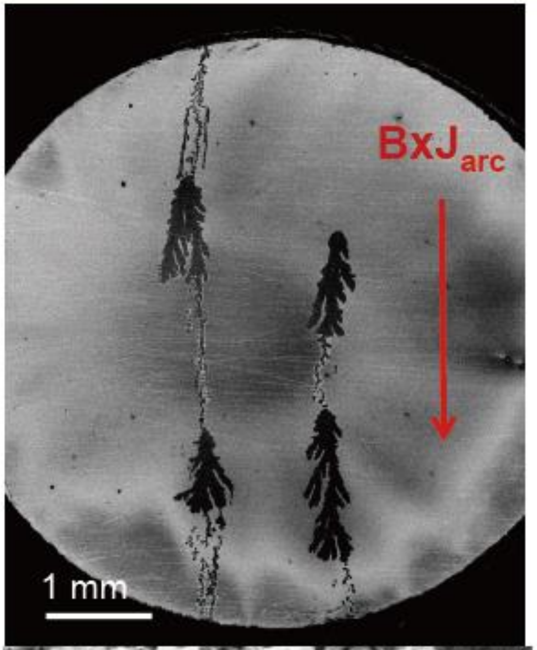
-Since the magnetic field direction was almost normal to the target, the motion was Brownian-like.

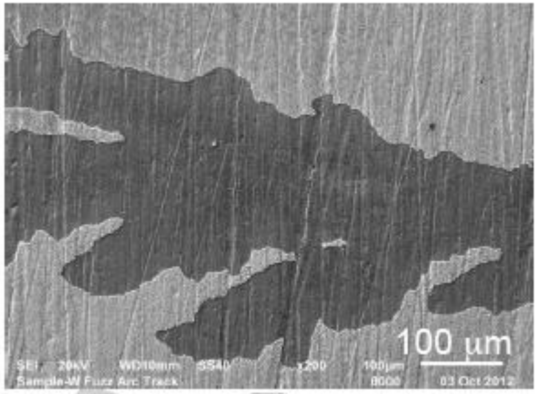
-This results strongly suggest that arcing can be easily initiated on W fuzz.

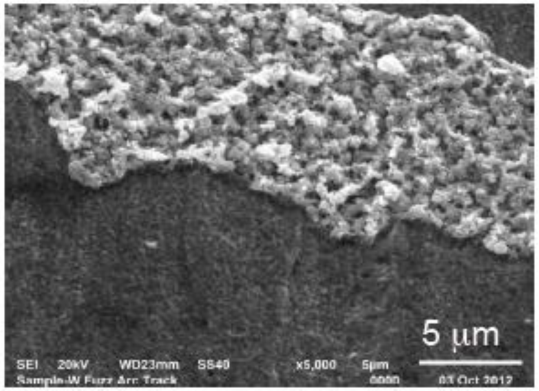
M. Tokitani *et al.* Nucl. Fusion 51 (2011) 102001.

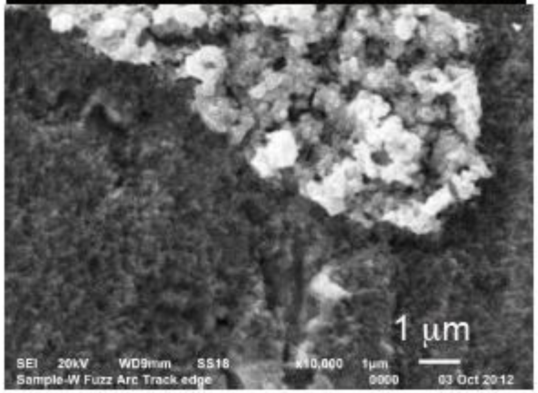
Arcs are Efficient in Removing Fuzz, after 3 VDEs

- Arc track shape consistent with motion in "retrograde" BxJ_{arc} direction
- At least one of the arcs starts on the fuzzy surface
- Traces split, affecting large areas
- Fuzz appears to be completely suppressed by arcing → **No release of W**



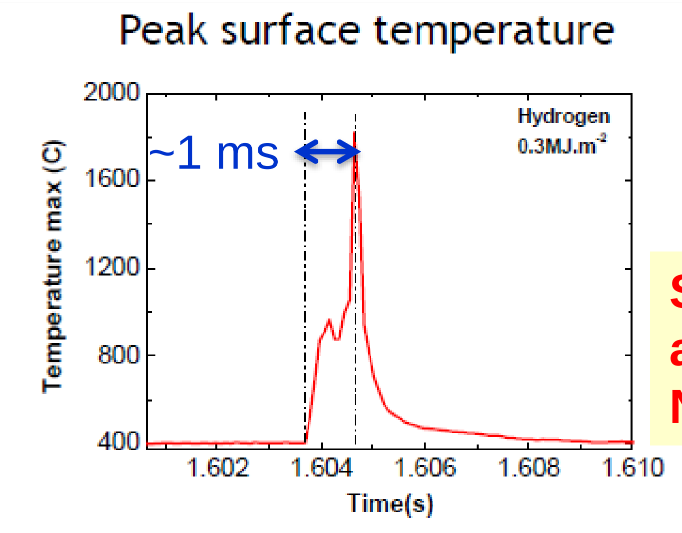




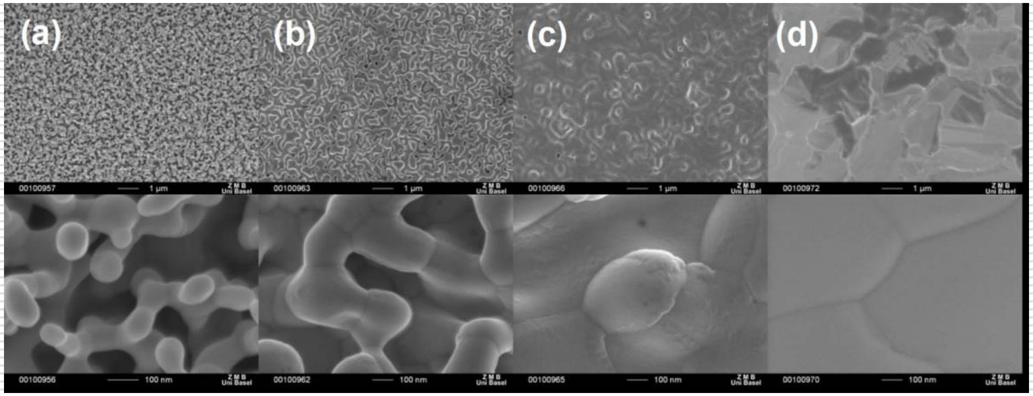


Arcing on premade W fuzz in DIII-D

Pulse plasma effects on W fuzz



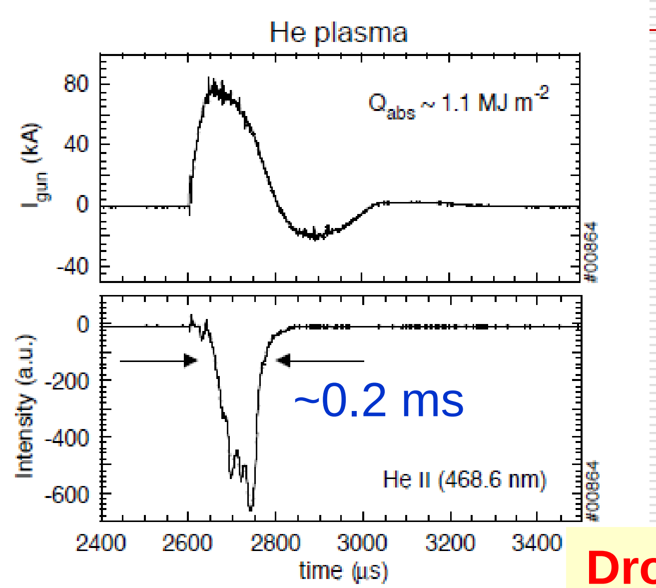
Simply W fuzz anneal out.
No W release.



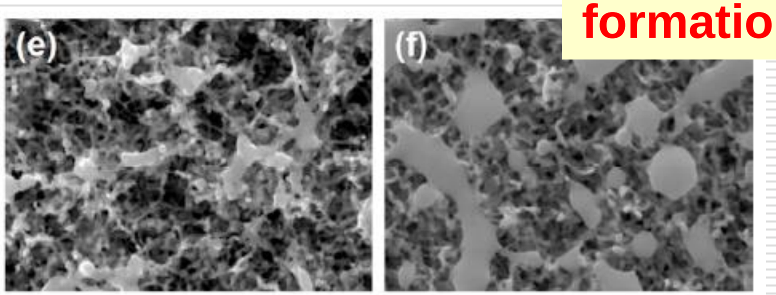
<0.1 0.25 0.35 0.5 MJ/m^2

Pilot PSI

(20th PSI, G. De Temmerman et al.)



Droplet formation



0.7 MJ/m^2 (partially) 1.1 MJ/m^2

Plasma Gun (U. Hyogo)

(D. Nishijima et al., J. Nucl. Mater. 434 (2013) 230)

Difference could be due to pulse length and/or plasma Te

Summary of arcing events of W fuzz

- **Experiences from various devices**
  - NAGDIS : arcing on fuzz with ion bias **over 70 V**
  - DIII-D : arcing on premade fuzz
  - C-Mod : No arcing probably due to low T_e (20-30 eV)
  - LHD : arcing on premade fuzz without heat pulse (T_e ~ 20 eV)
  - MAGNUM : No arcing on fuzz even with pulsed heat **(T_e~1-2 eV)**
- **Suggestion from these results**
  - **High ion bombarding energies** or **high sheath potential (high T_e)** could sustain arcing. But so far we do not understand the exact conditions of arcing in actual confinement devices.

*Kajita et al., Plasma Phys. Control. Fusion 54 (2012) 035009 (9pp)

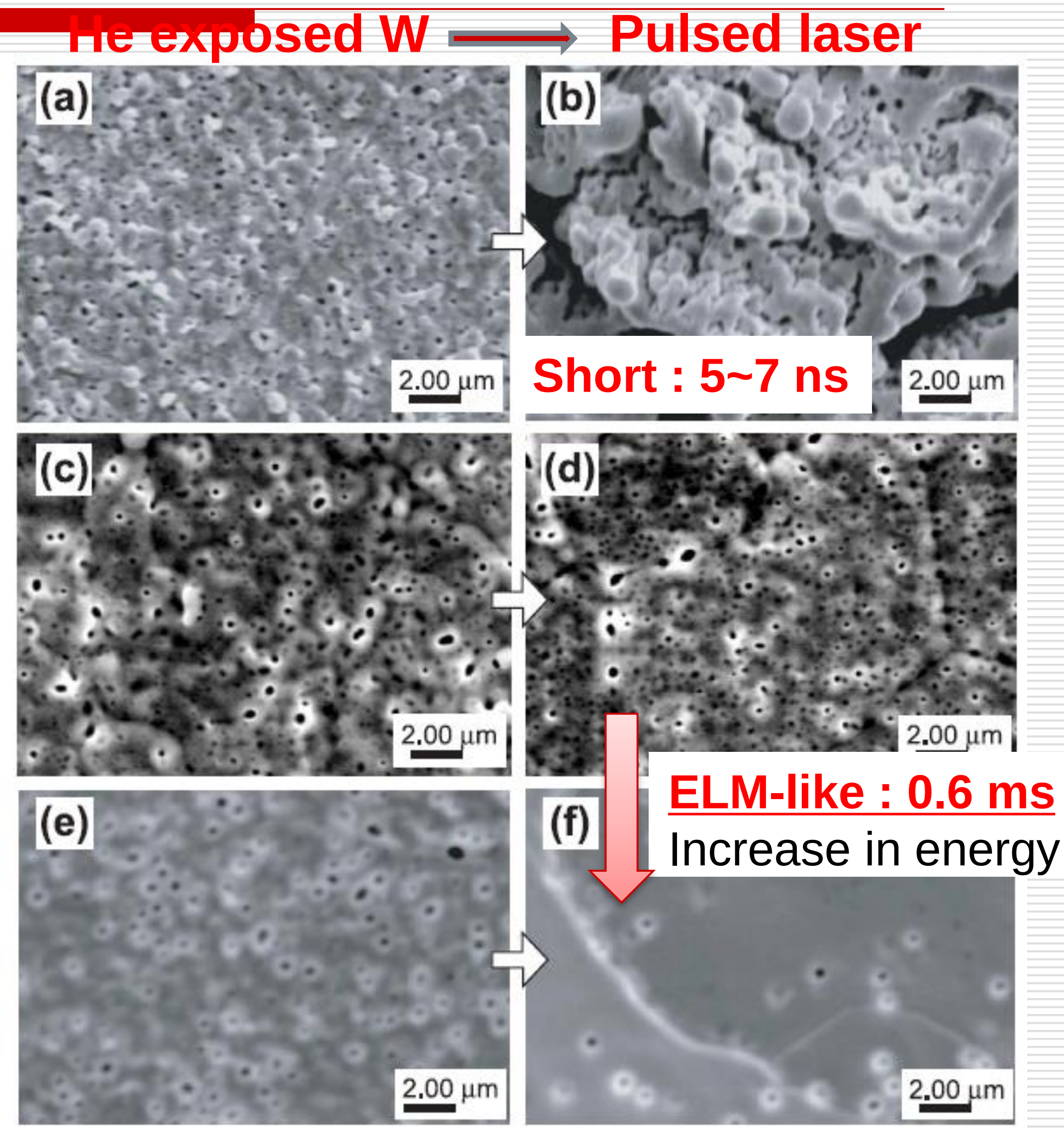
- Erosion rate
  - According to Kajita*, ~10 µg / 1 ms per one arc track. But DIII-D exp. showed no W release by arcing.

    → **needs more investigation**
  - Arcing may be an issue in terms of **core plasma contamination,** but **not** be an issue in terms of W monoblock lifetime.

Alleviation of He holes by pulsed heat

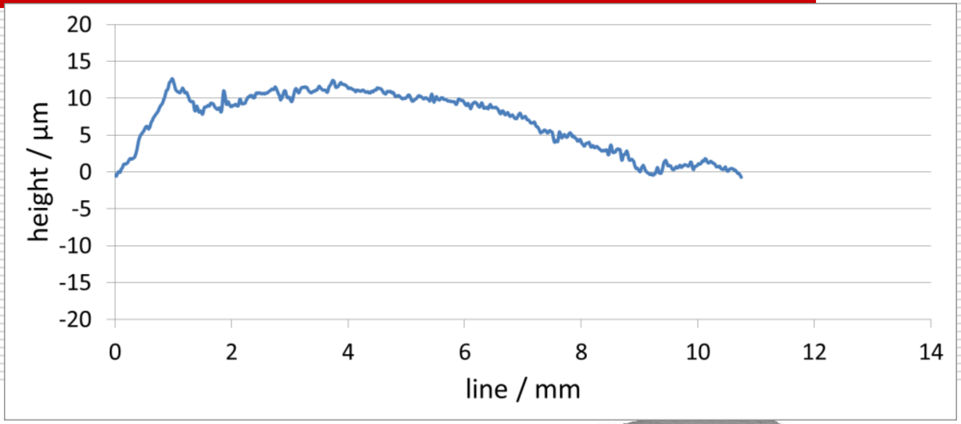
- He hole structure is irradiated by pulsed laser
- Pulsed laser
  - 5~7 ns (Nd/YAG)
  - 0.6 ms (Ruby)
- Short pulse (5-7 ns)
  - Roughness increased
- ELM-like (long) pulse (0.6 ms)
  - Smoothing occurred

Possibility of surface repairment

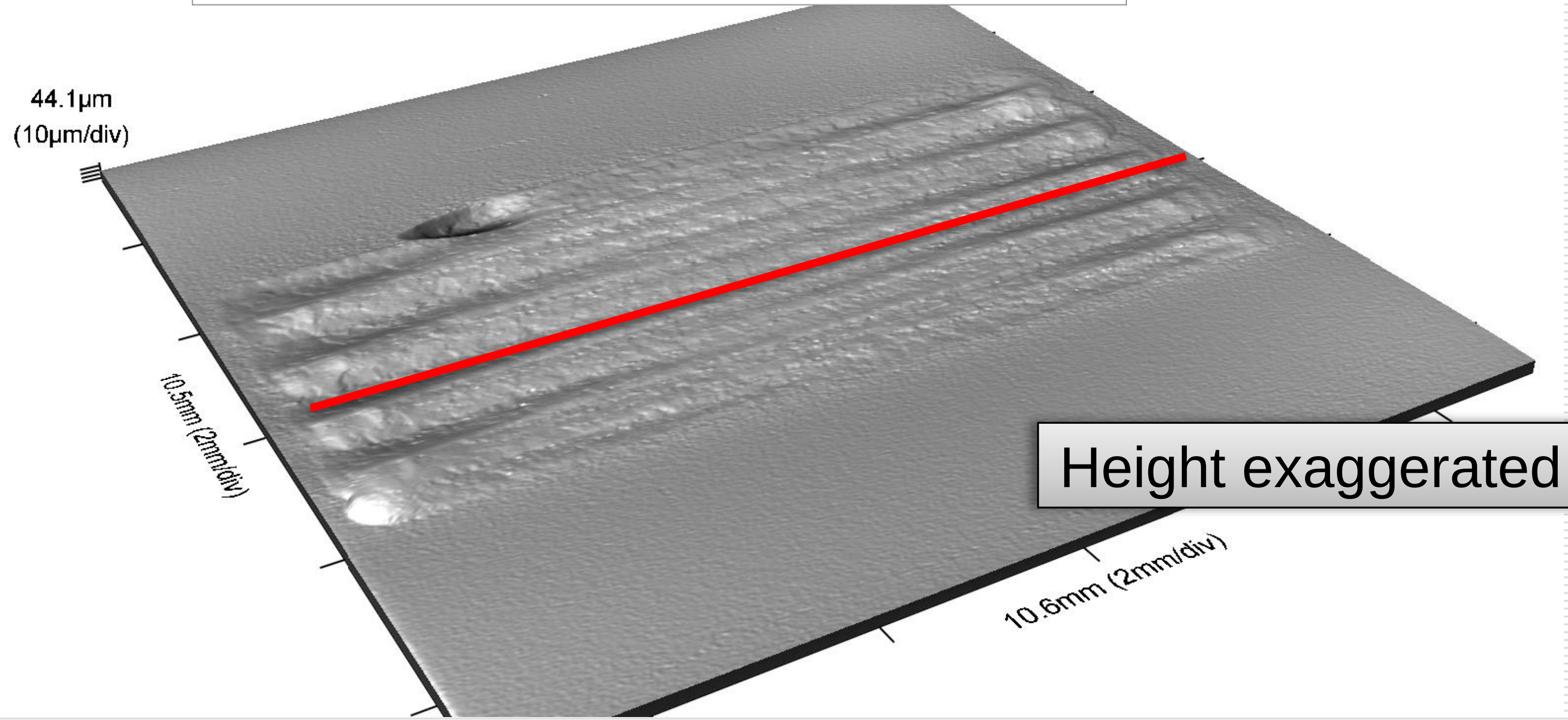


S. Kajita et al., PFR 2, 009 (2007)

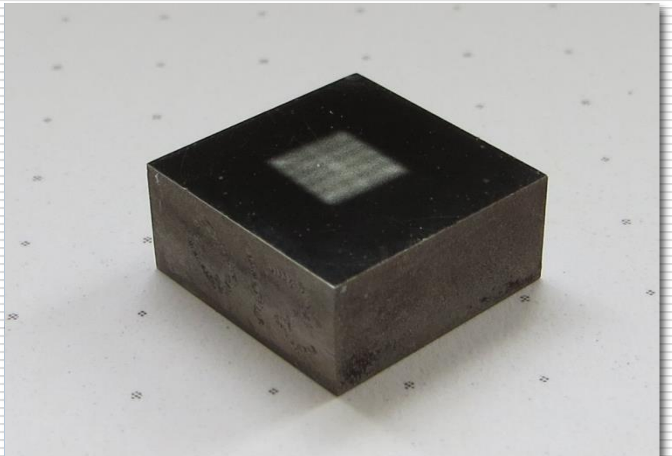
Laser annealing of tungsten surface



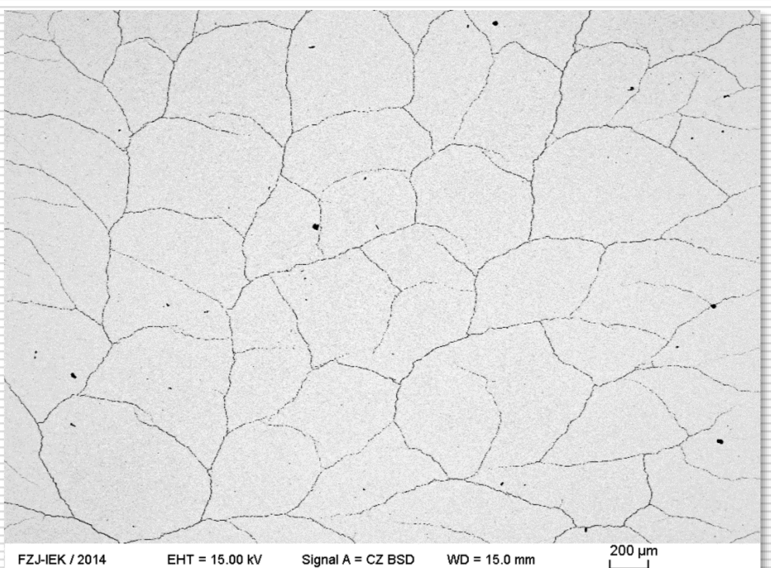
- Focal spot 0.8 mm
- Power 1 kW
- Velocity 5 mm/s
- 2 passes



Experiment for damage repair



- standard geometry: 12 × 12 × 5 mm^3
- polished to mirror finish
- loaded on 4 × 4 mm^2 area
- loading: 100 thermal shocks of 1 ms
- $L = 0.38\ GW/m^2$ ($F_{HF} = 12\ MW/m^2s^{1/2}$)
- purpose: create thermal shock crack network with well known parameters



Results of laser annealing

Cross section

- No cracks remained
- Flat surface
- Low grain boundary strength
- Full recrystallization

Summary

- W melt layer dynamics are dominated by **plasma pressure (plasma wind)** and **JxB force**.
- **Surface instability (ex. Kelvin-Helmholtz instability) and boiling (partly by impurities)** could cause droplet ejection.
- **Vapor shielding could mitigate surface damage** from intense plasma heat (caused by disruption). Comprehensive modeling of vapor shielding of tungsten walls are necessary (ex. PIC approach).
- He induced surface morphologies are very unique (Holes, fuzz, etc.) but **very vulnerable to pulsed heat**.
- Effects of arcing of fuzz on plasma performance are under investigation.
- Slight melting could somewhat **repair damaged surface**.