Research status and issues of tungsten plasma facing materials for ITER and beyond

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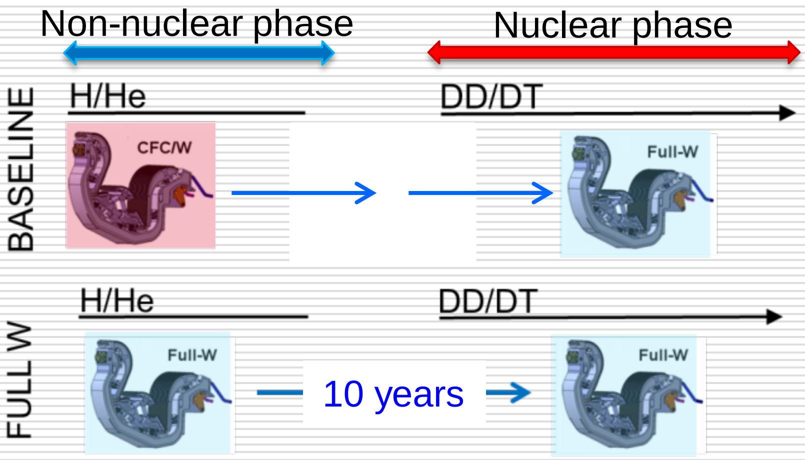
Divertor strategy of ITER

- ITER divertor options
  - Option 1 : Baseline (CFC/W)
  - Option 2 : Full W day 1



- Discussions at ITPA DIV/SOL on ITER divertor strategy
  - Heat fluxes
  - Fuel retention, fuel removal and dust production
  - Material issues (tungsten)
    - Transient heat pulse, Blistering, He induced structure, combined of these
  - Operational and scenario issues

Outline

- Heat flux conditions of ITER divertor
- Transient heat loading effects on melting and morphology changes
- Morphology changes by particle loadings
  - Blistering by hydrogen isotopes (H/D/T)
  - Helium effects
- Combined effects of heat and particle loading
- Conclusions

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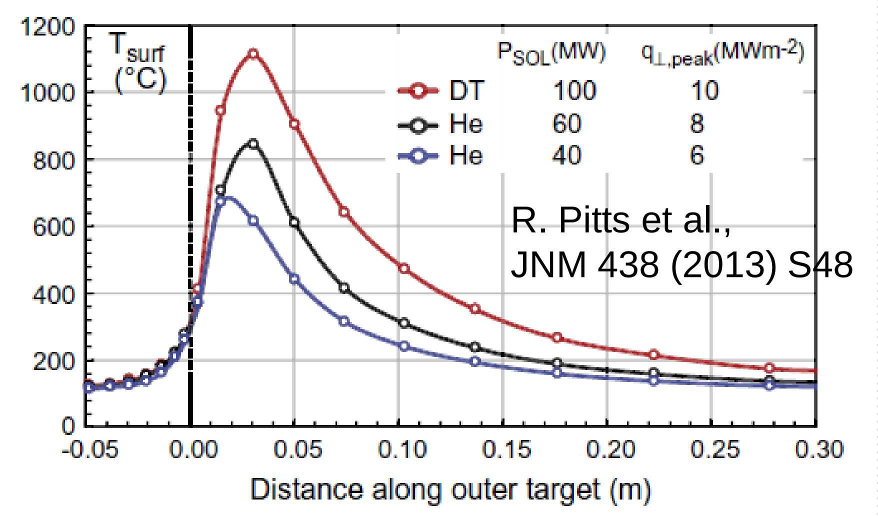
Steady-State (slow transient) heat flux to divertor

- 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



R. Pitts et al., JNM 438 (2013) S48

Temperature distribution on outer divertor

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)

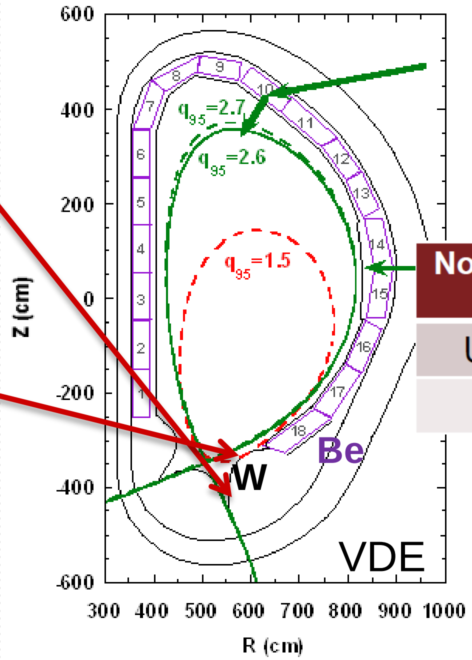
Disruption heat loading (Non-nuclear Phase)

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

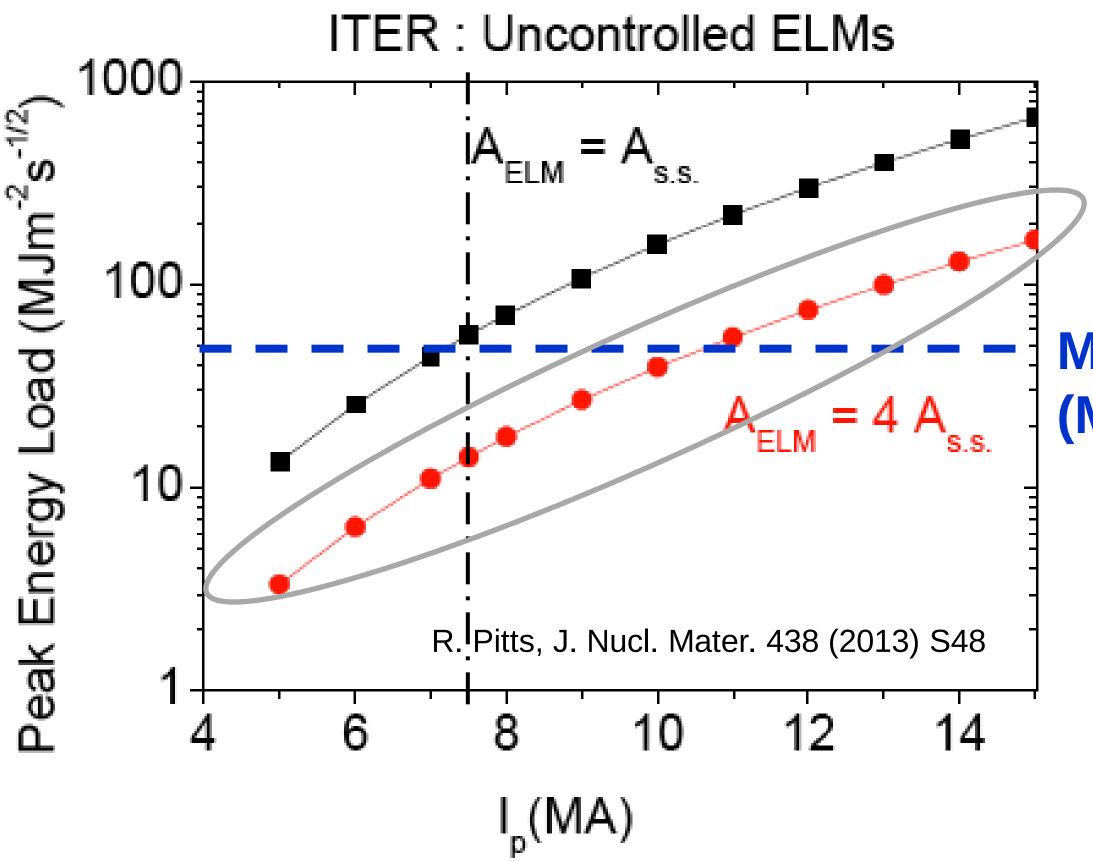
Melting threshold ~ 50 MJ/$m^{-2}s^{-1/2}$



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



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

Frequency : 1~10Hz
Pulse length : sub ms

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

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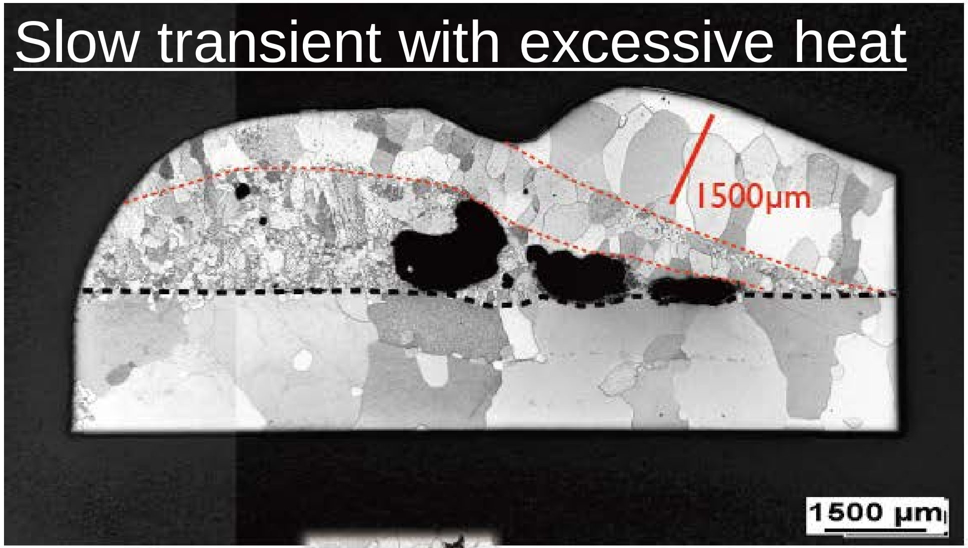
Melt Layer Structure

1

Slow transient with excessive heat



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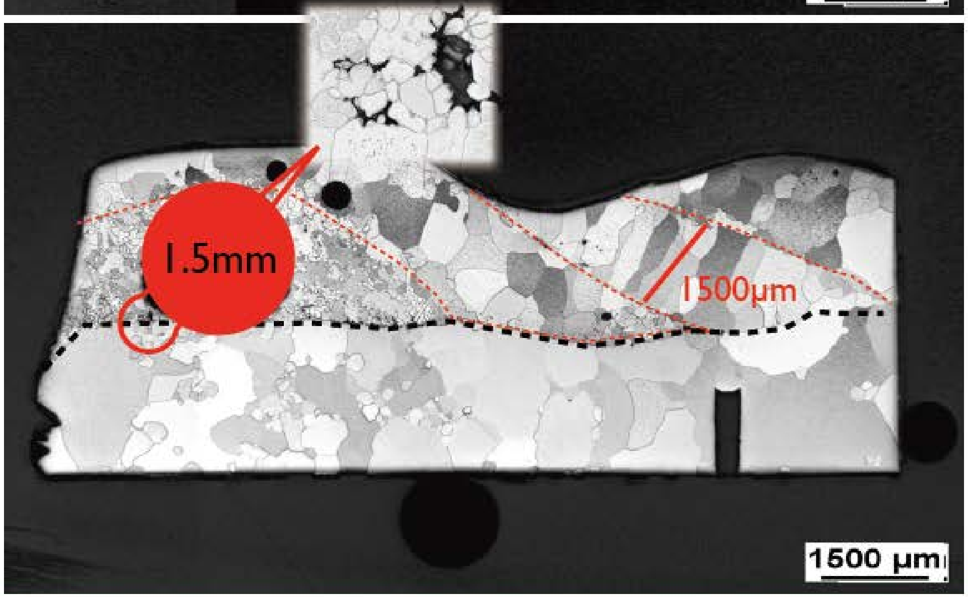
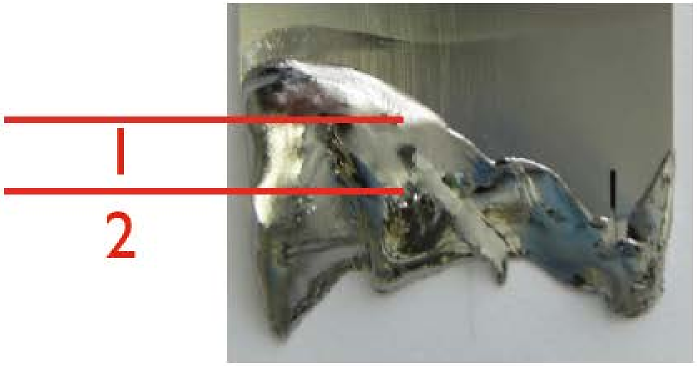




TEXTOR exp. :

several tens of MW/m² for ~3 s.

Melt layer thickness can reach up to 1.5 mm

Power-handling capability significantly degraded

unacceptable

Slight melting (Disruption, Giant ELM)

- Is slight melting acceptable?
  - Acceptable step height for ITER W monoblock (~0.3 mm)
  - **Bridging** by melt layer could cause fracture of cooling tube.
  - **Droplet ejection** could occur.
  - **Plasma shaping** may **not** occur.

Only "very slight melting" could be acceptable

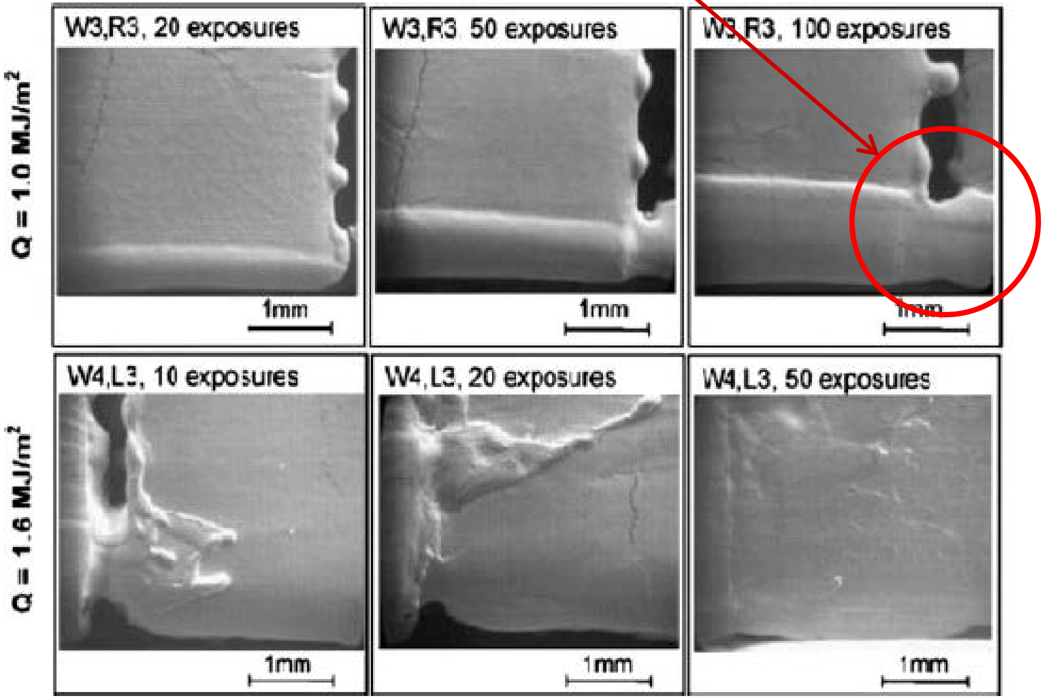
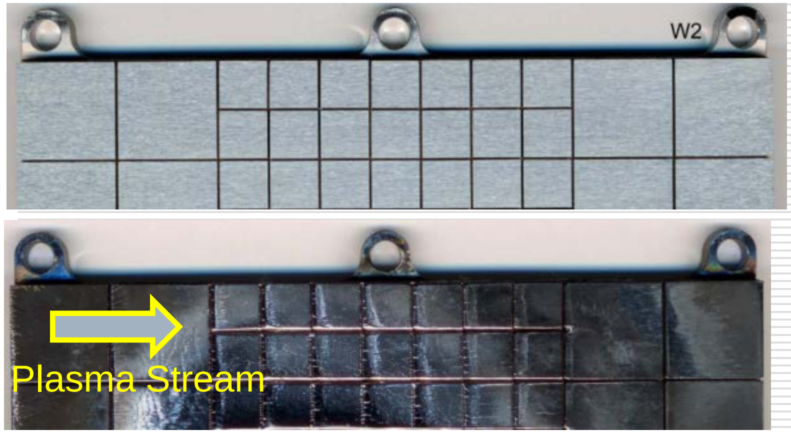

W3,R3, 20 exposures
W3,R3, 50 exposures
W3,R3, 100 exposures
W4,L3, 10 exposures
W4,L3, 20 exposures
W4,L3, 50 exposures

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

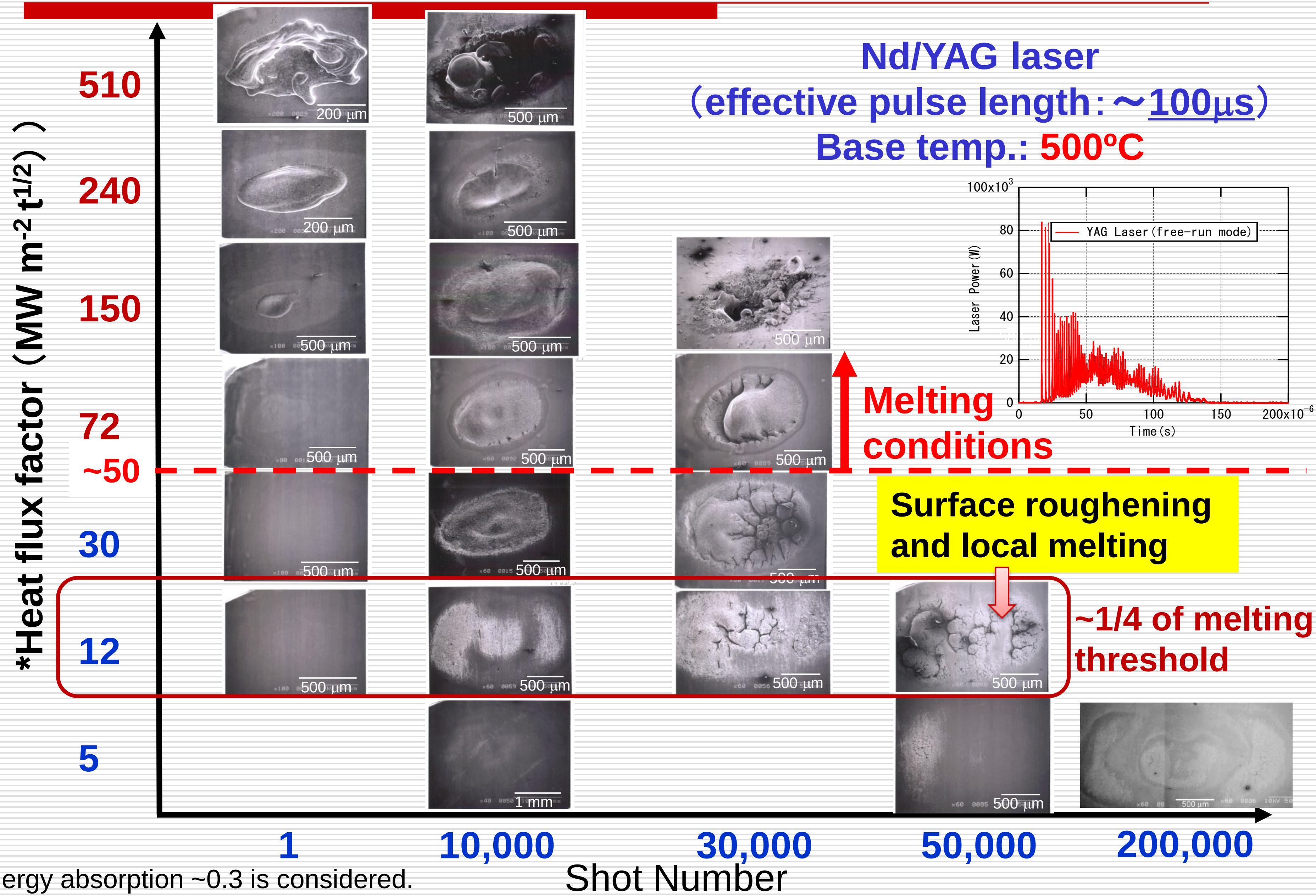
B. Bazylev et al., J. Nucl. Mater. *390-391 (2009)810-813*



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

Plasma Gun exp. (QSPA)

High cycle heat pulse effects



Nd/YAG laser

（effective pulse length：～100μs）

Base temp.: 500ºC

Melting conditions

Surface roughening and local melting

~1/4 of melting threshold

*energy absorption ~0.3 is considered.

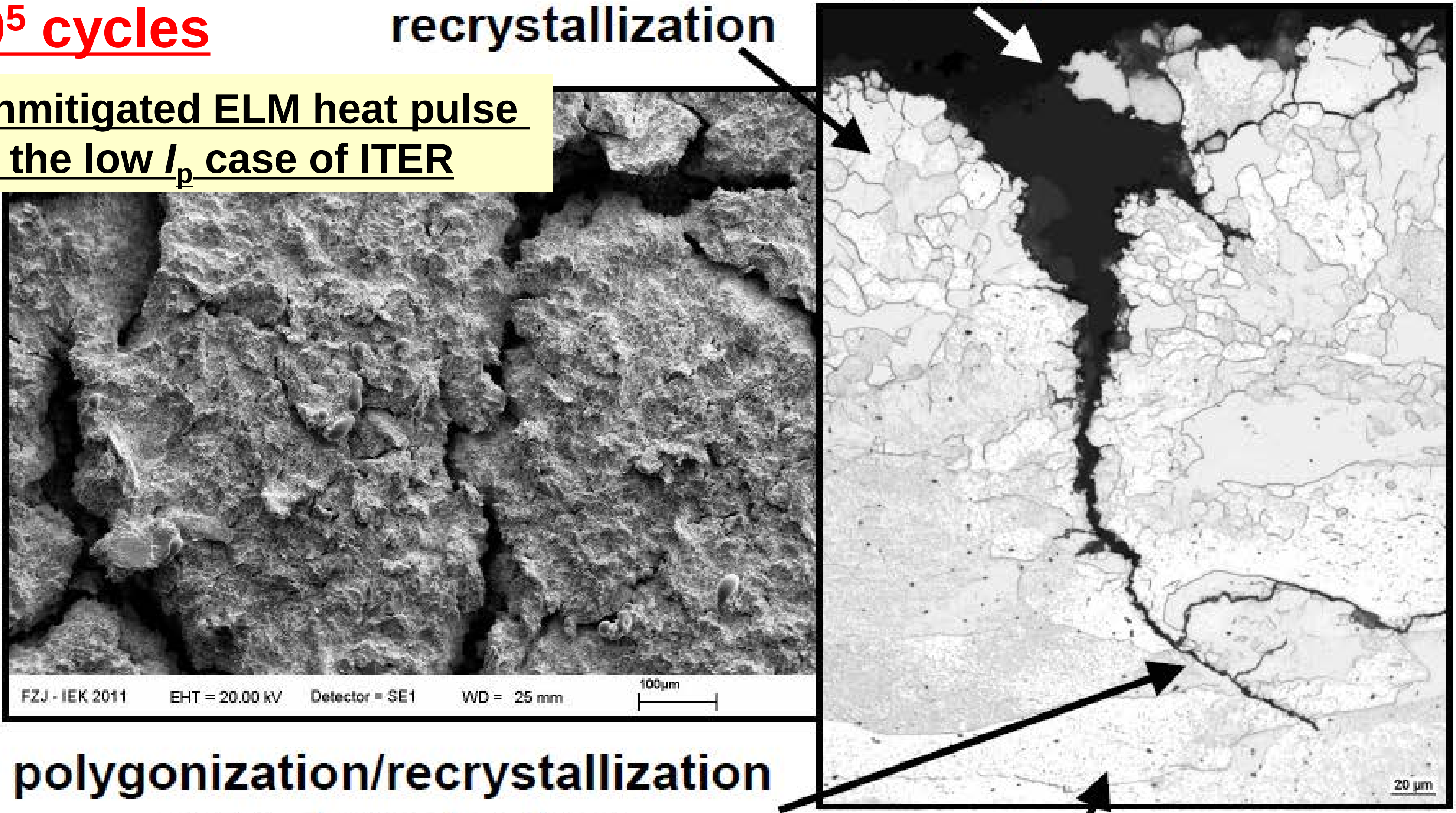
ELM simulation using e-beams with high repetition rates in JUDITH 2

Pulse energy : 1/5 of E_{MT}

10^5 cycles

Unmitigated ELM heat pulse
In the low I_p case of ITER

Unacceptable?



polygonization/recrystallization around crack edges

After J. Linke (FZJ)

To avoid surface morphology change, supression to 1/10 of MT (~6 $MJm^{-2}s^{-0.5}$) is necessary

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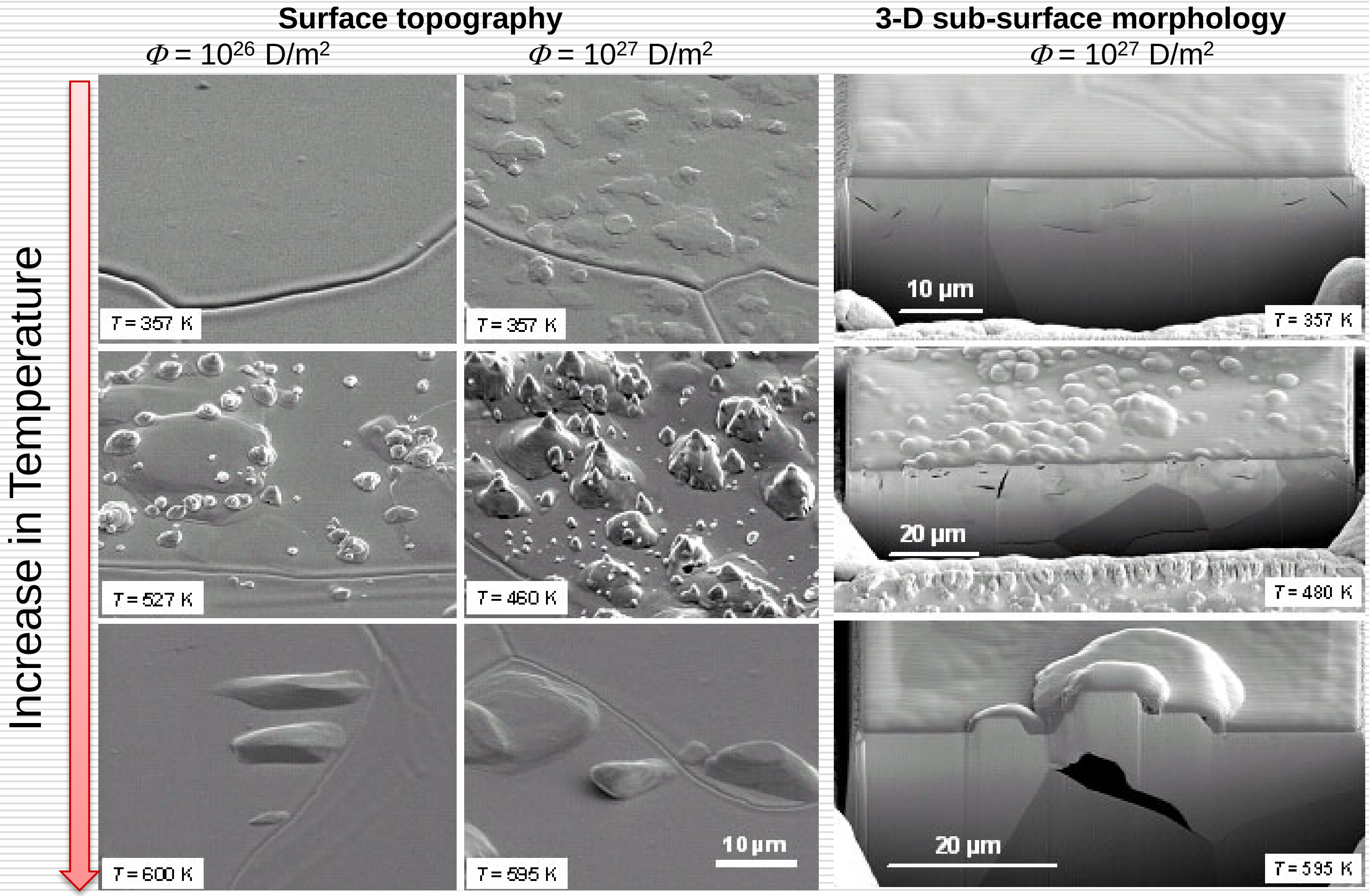
Blistering by hydrogen isotope ions

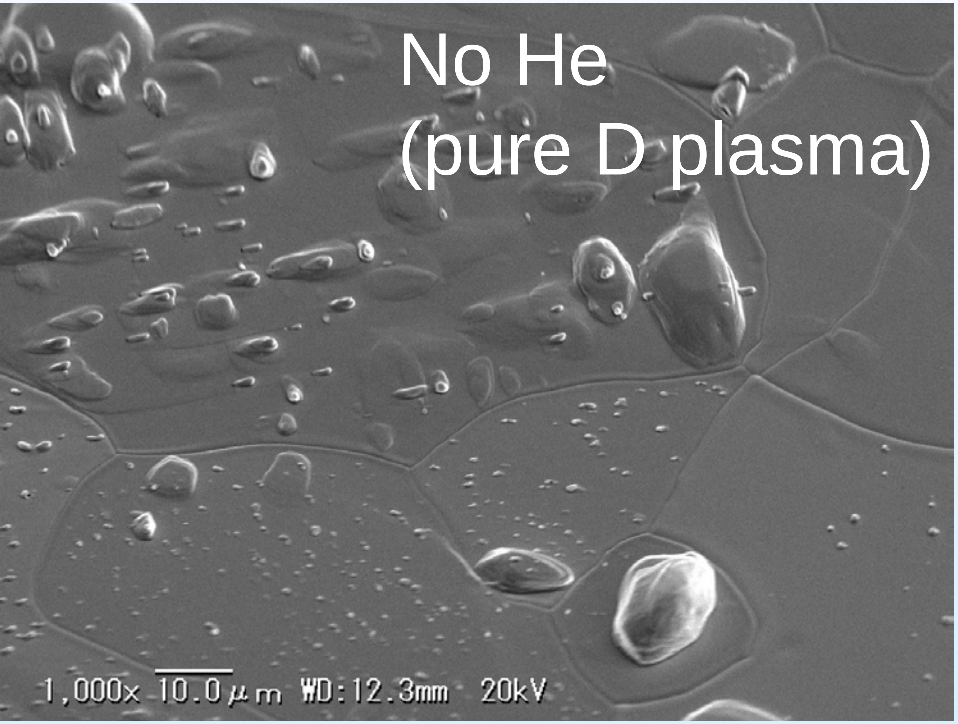
- Formation conditions
  - Fluence >10^{24} m^{-2}, Temperature < (500-600) °C
- Blistering **disappears above ~600 °C**



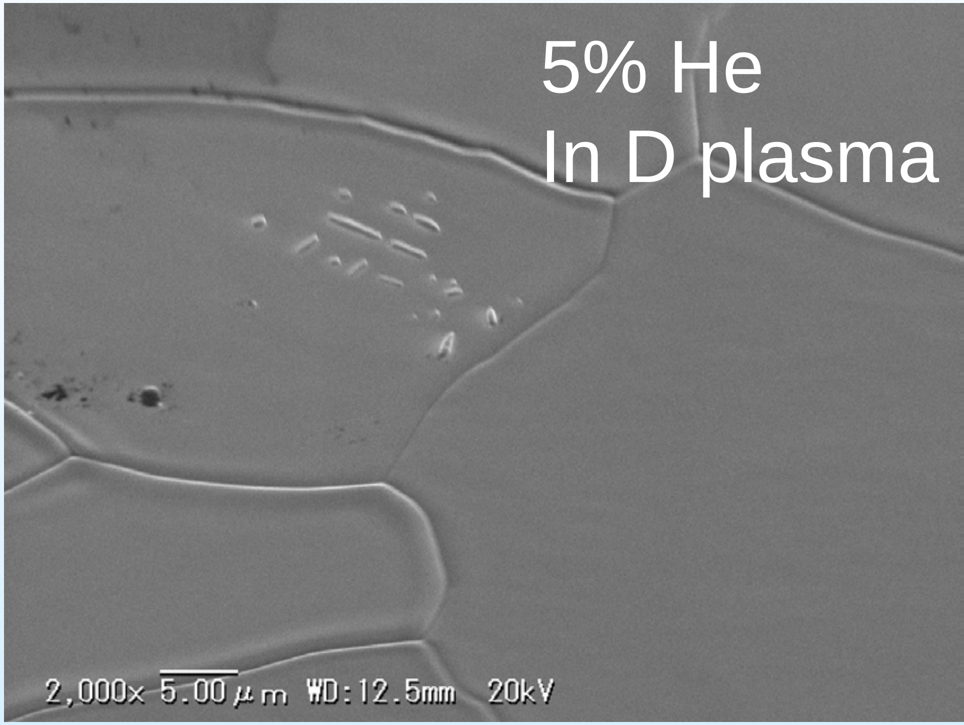
V. Alimov presented at ICFRM14 (2009)

W surfaces exposed to pure and helium-seeded D plasmas,

$\Phi = 10^{27}$ D/m^2



Pure D plasma
T_{exp} = 533 K



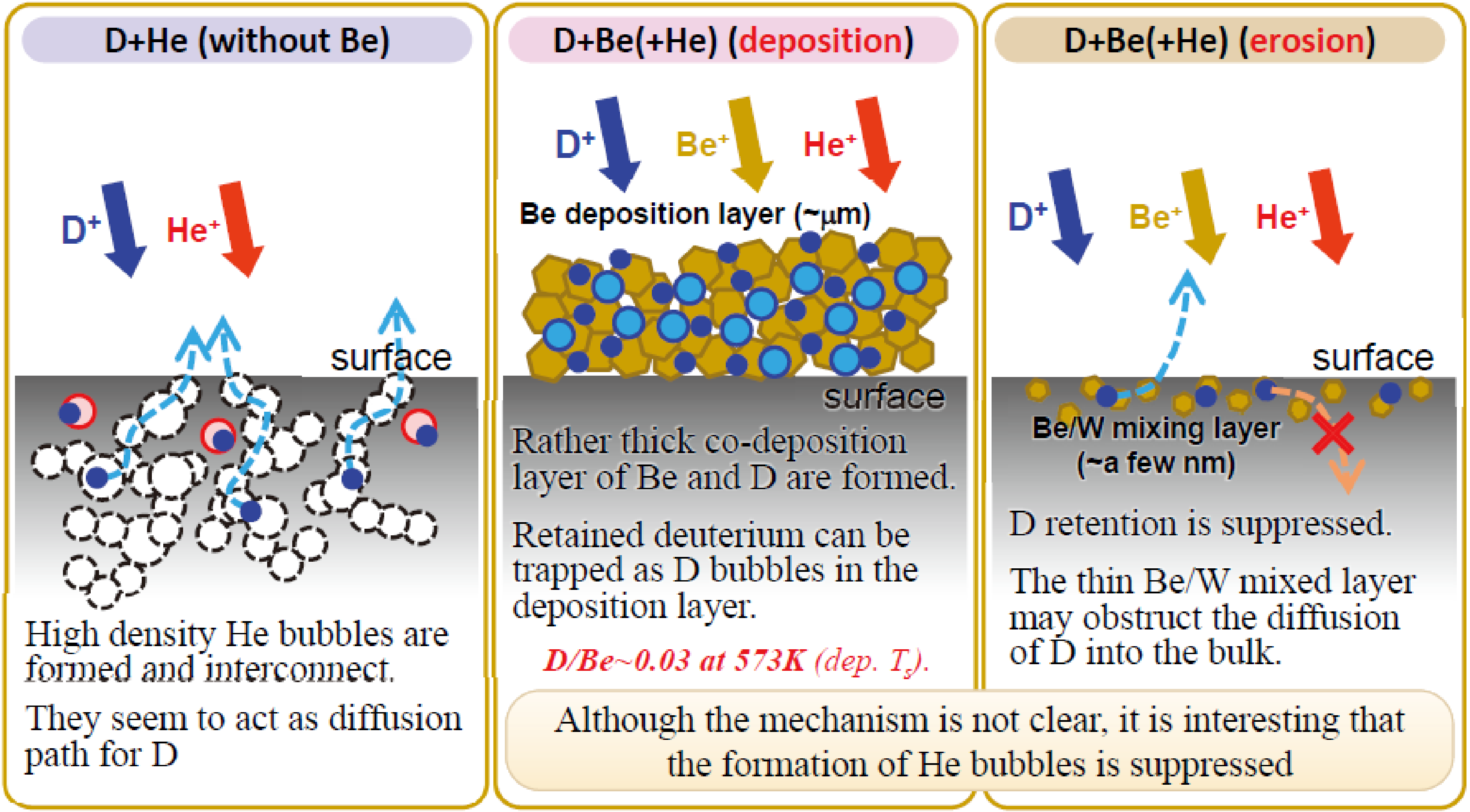
Helium-seeded D plasma (5% He ions)
T_{exp} = 533 K

He seeded plasma suppresses blistering (many observations).
→ no blistering for He plasma and DT (burning) plasma

Effect of mixed plasma exposure

Discussion

● D, ⬢ Be , ○ He bubble



High density He bubbles are formed and interconnect.

They seem to act as diffusion path for D

Rather thick co-deposition layer of Be and D are formed.

Retained deuterium can be trapped as D bubbles in the deposition layer.

D/Be~0.03 at 573K (dep. T_s).

D retention is suppressed.

The thin Be/W mixed layer may obstruct the diffusion of D into the bulk.

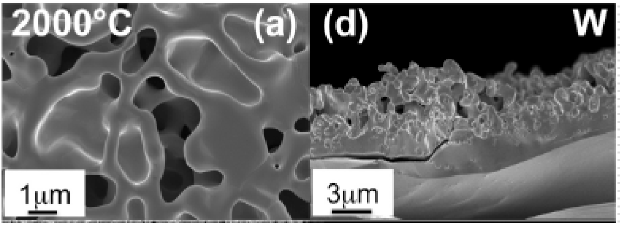
Although the mechanism is not clear, it is interesting that the formation of He bubbles is suppressed

In all cases, retention and blistering are suppressed. Blistering unlikely in ITER.

19th PSI, M. Miyamoto (2012)

He effects on W

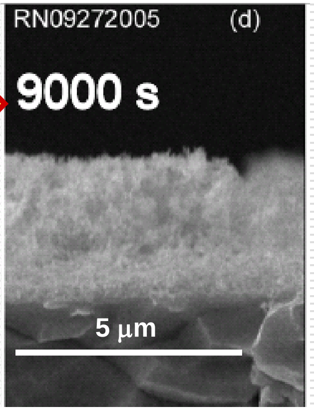
- **High temperature (> 1700 °C)**
  - Large **He holes** and **thick tendril** formation with recrystallization



PiLOT PSI

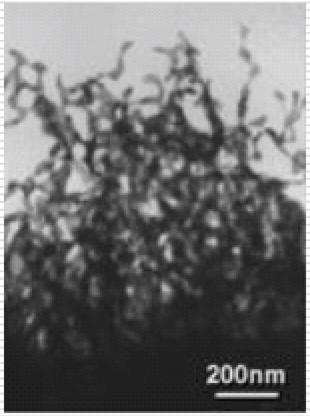
T ~ 2000 °C

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



PISCES (UCSD)

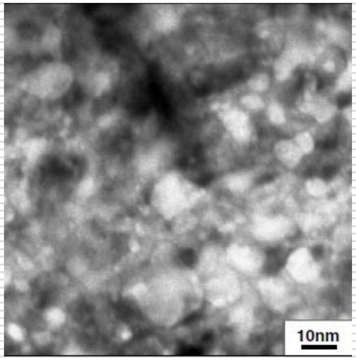
T ~850 °C



NAGDIS (Nagoya U.)

T ~ 1100 °C

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



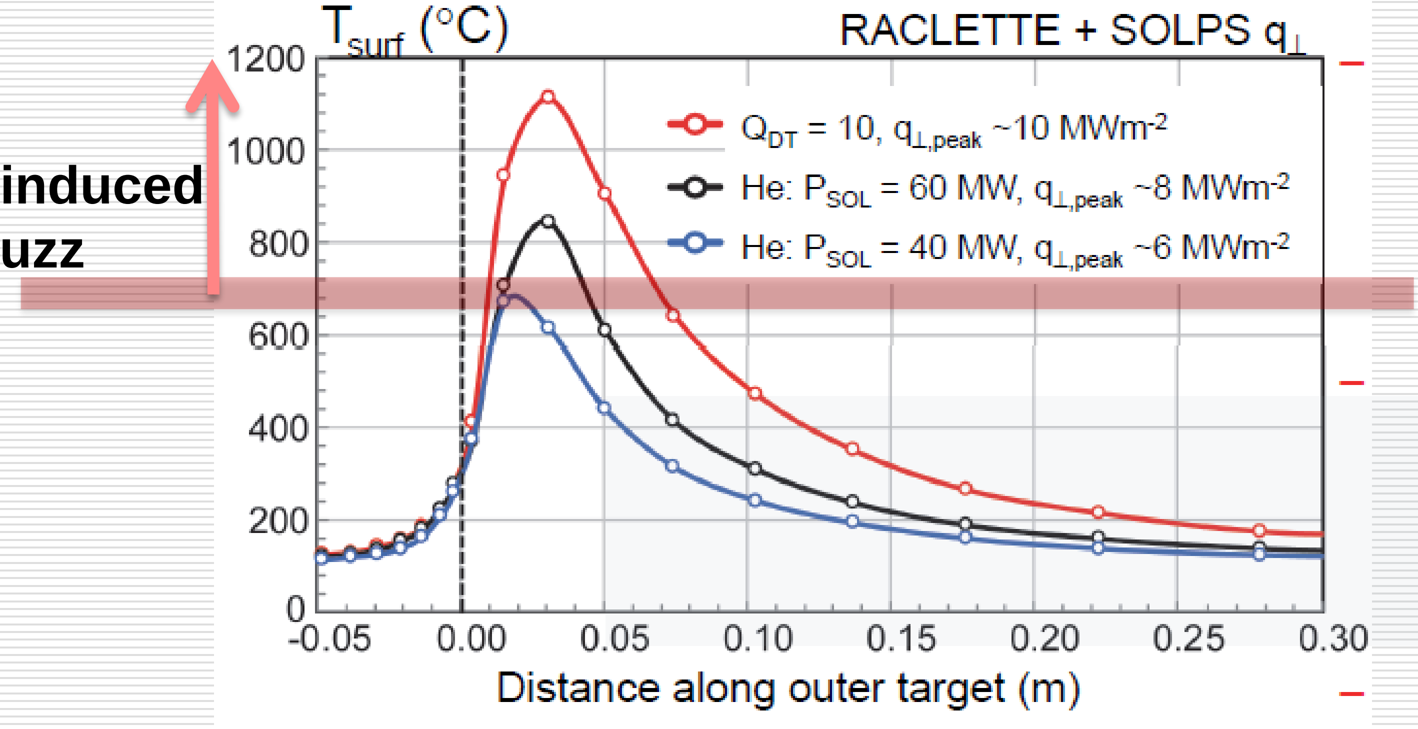
PISCES (UCSD)

T $\leq$ **600 °C**

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)**.

Formation area of W fuzz



He induced
W fuzz

20th PSI,
R. Pitts et al.

Calculation for 8 mm W mono-block thickness

For non-nuclear phases, peak temperature will be **about 800 °C or less.**

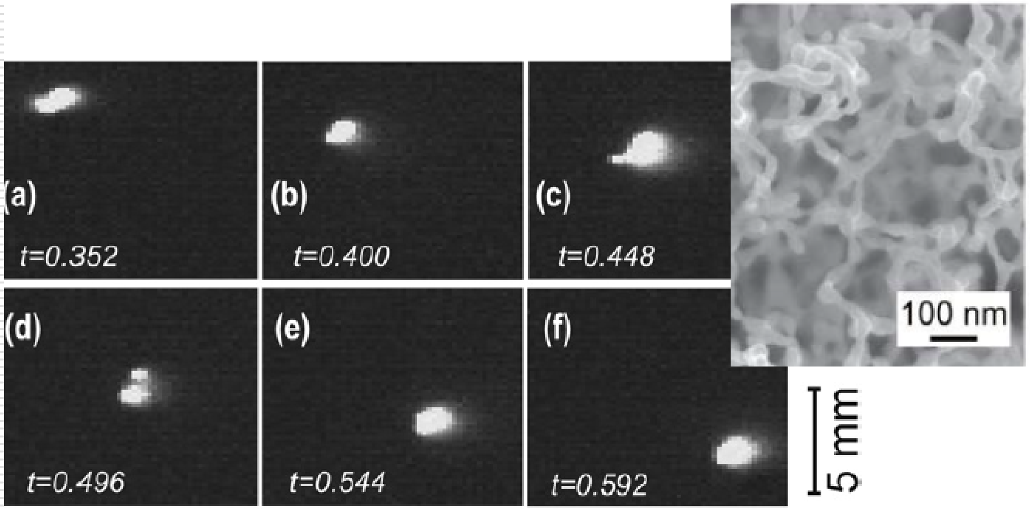
W fuzz : very limited area near the strike points.

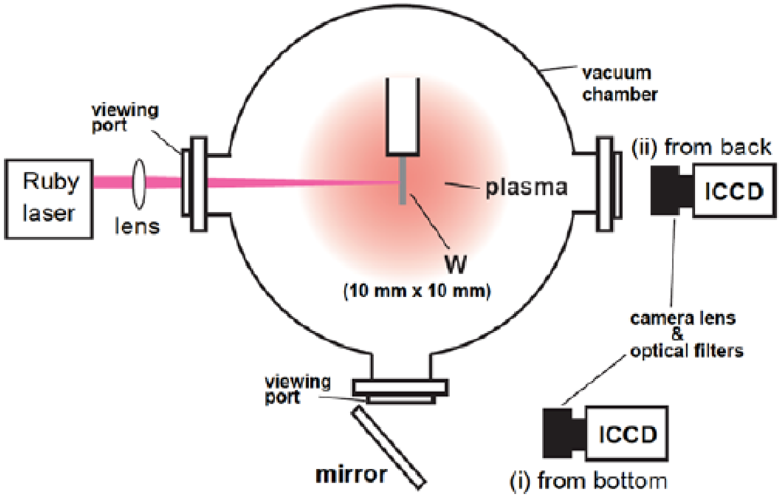
For nuclear phases,

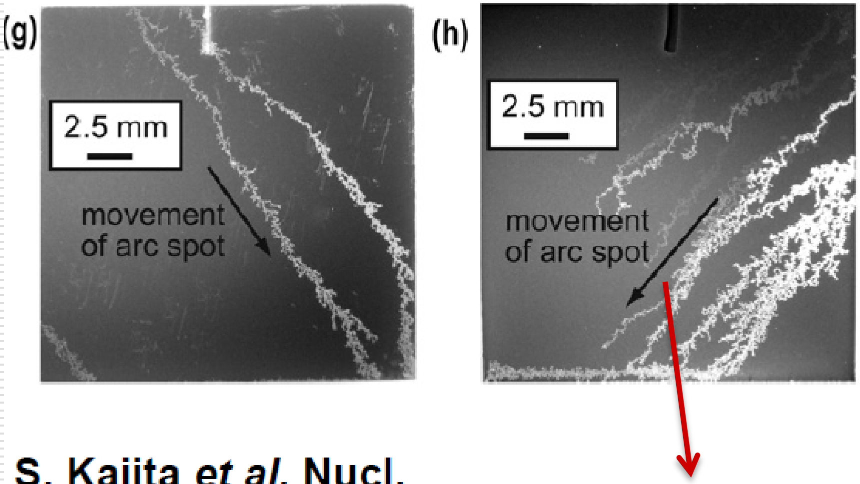
W fuzz : limited area also, because it could not grow in detached plasmas.

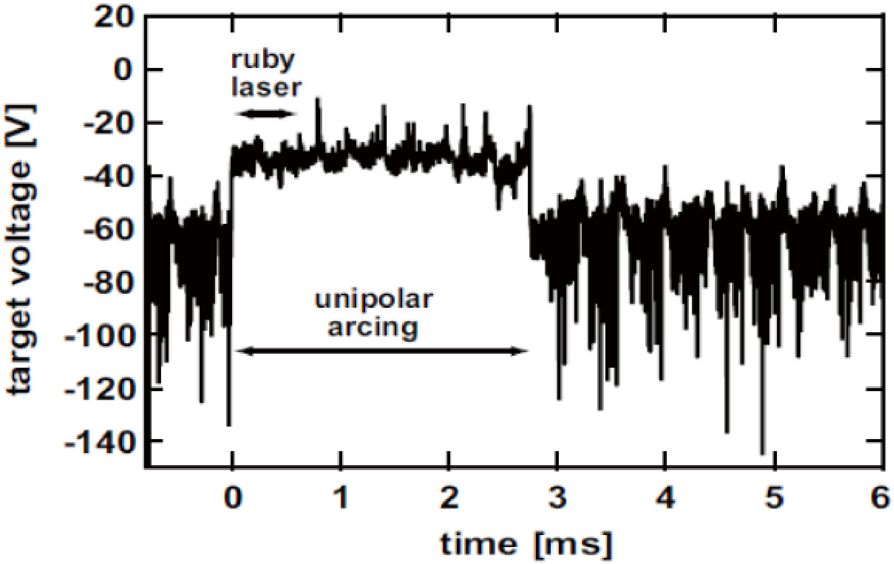
Critical evidence of unipolar arc (UA)

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





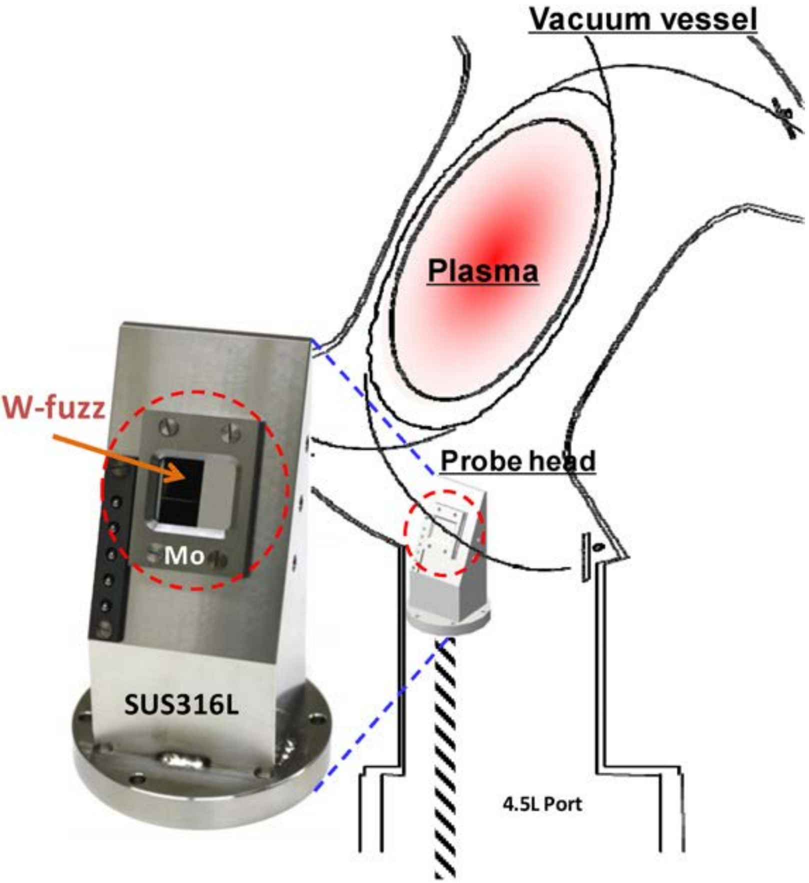




S. Kajita *et al.* Nucl. Fusion (Letter) (2009)

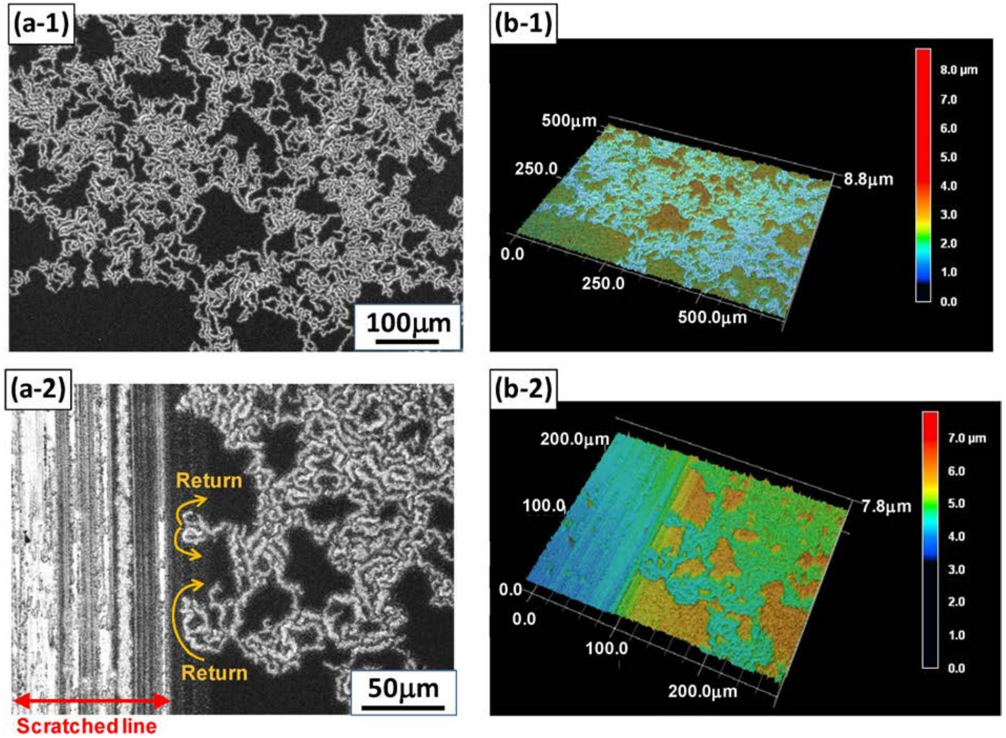
B x J direction

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.



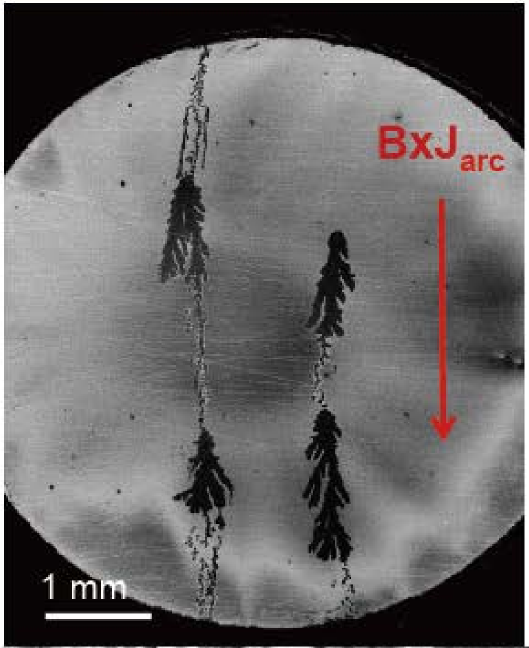
-Since the magnetic field direction was almost normal to the target, the motion was Brownian-like.

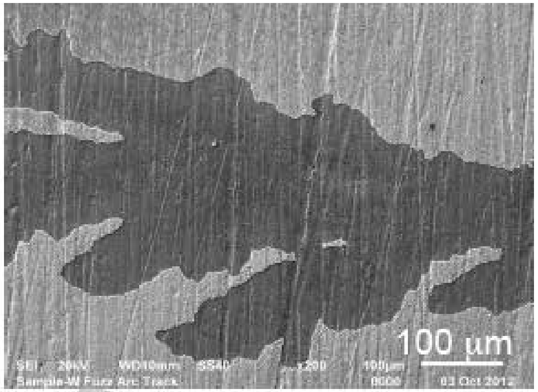
-This results strongly suggest that arcing can be easily initiated on W fuzz.

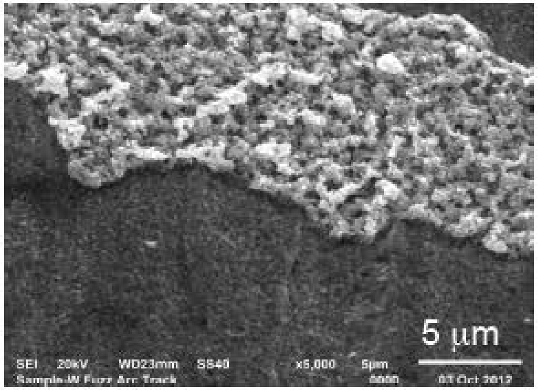
M. Tokitani *et al.* Nucl. Fusion 51 (2011) 102001.

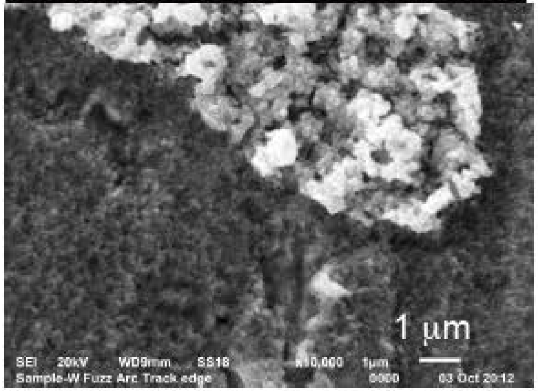
Arcs are Efficient in Removing Fuzz, after 3 VDEs

- 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

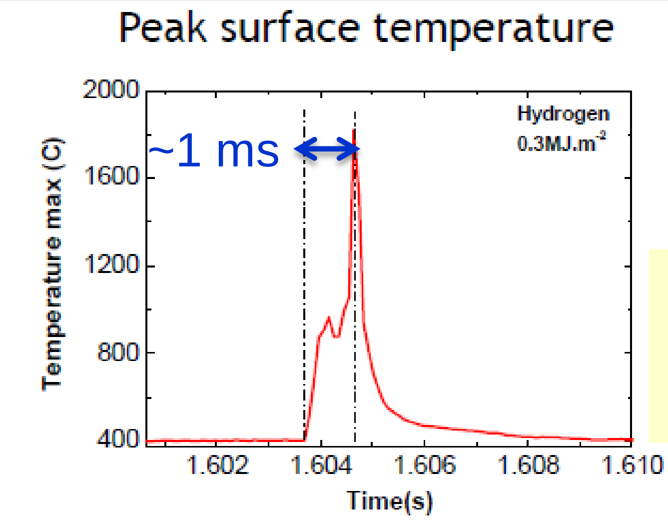
Conditions of arcing of W fuzz

- **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.
- Erosion rate

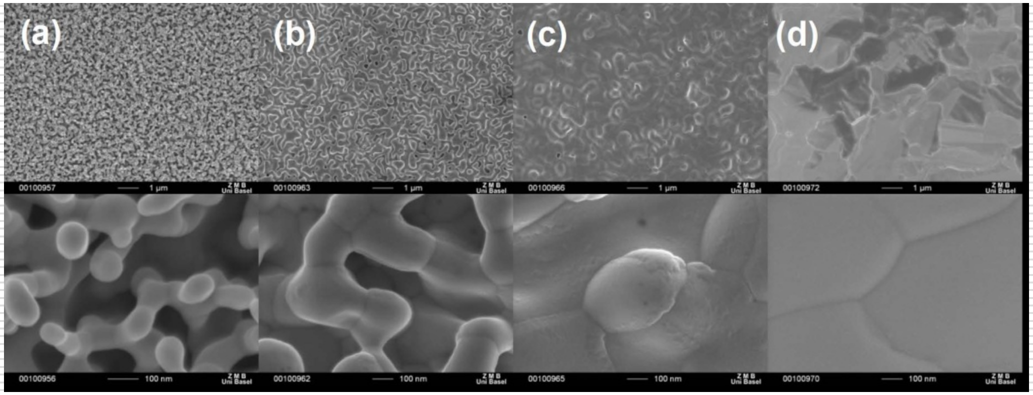
  *Kajita et al., Plasma Phys. Control. Fusion 54 (2012) 035009 (9pp)
  - According to Kajita*, ~10 µg / 1 ms per one arc track. But DIII-D exp. showed no W release by arcing.

    → **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.

Pulse plasma effects on W fuzz



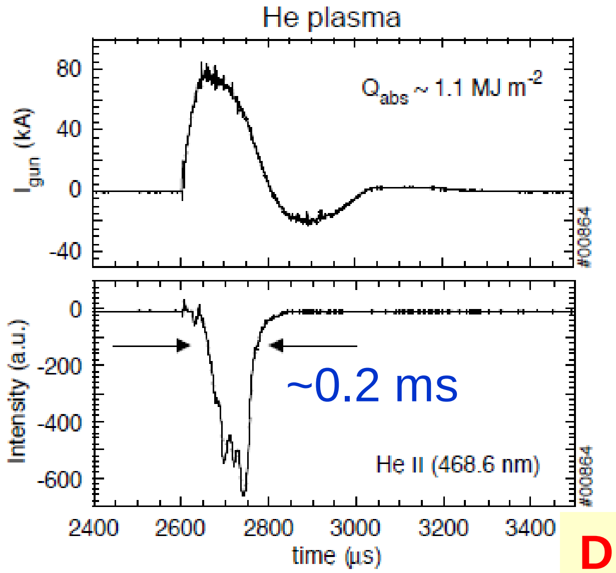
Simply W fuzz anneal out.
No W release.



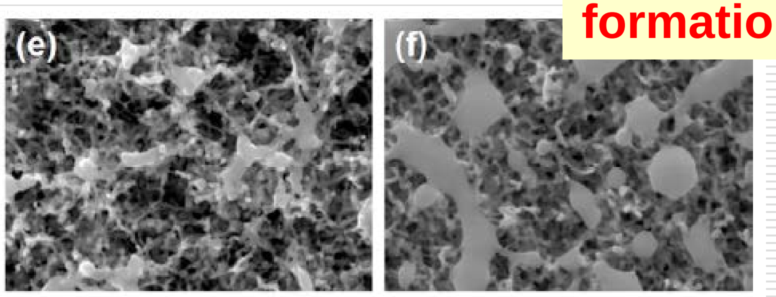
<0.1 0.25 0.35 0.5 MJ/m^2

Pilot PSI

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



Droplet formation



0.7 MJ/m^2 (partially)

1.1 MJ/m^2

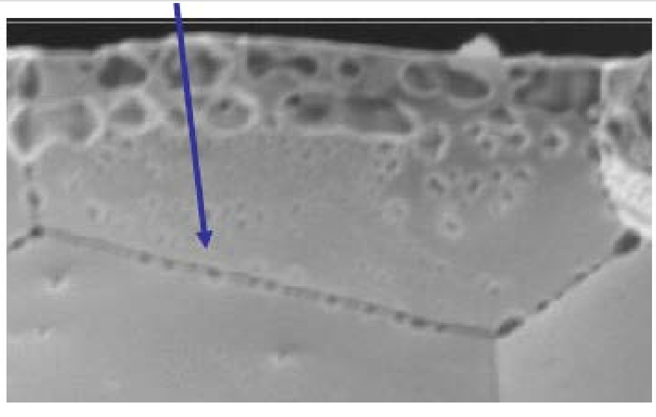
Plasma Gun (U. Hyogo)

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

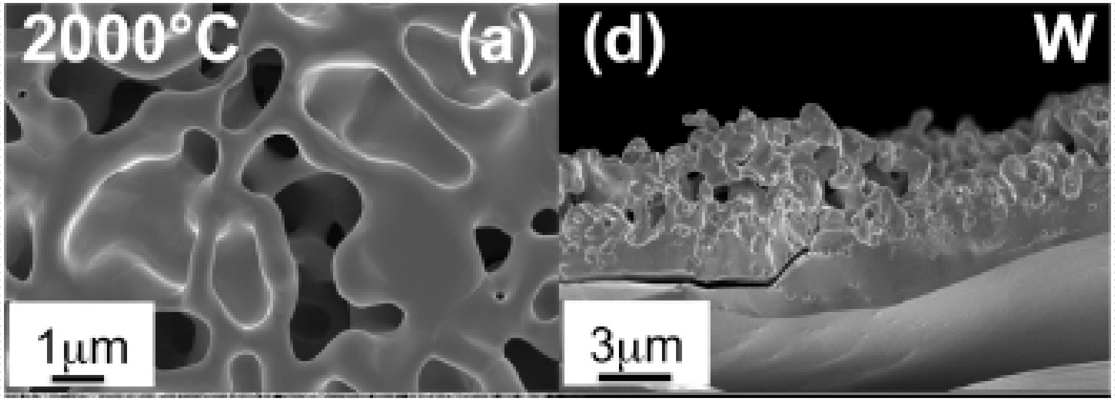
Difference could be due to pulse length and/or plasma Te → **need more investigation**

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. → **needs more investigation**



Results from NAGDIS



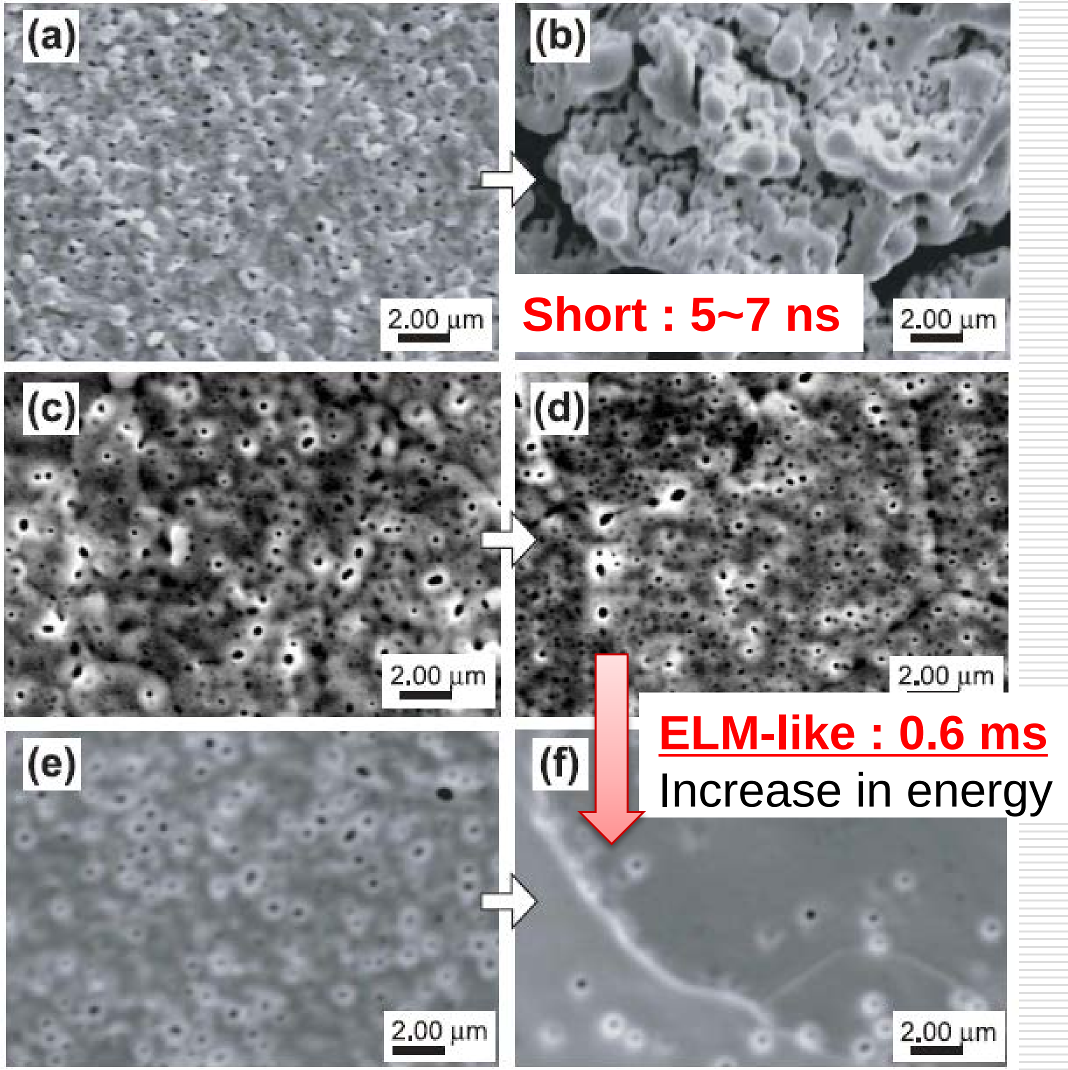
Results from MAGNUM

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

He exposed W → **Pulsed laser**



Short : 5~7 ns

ELM-like : 0.6 ms
Increase in energy

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

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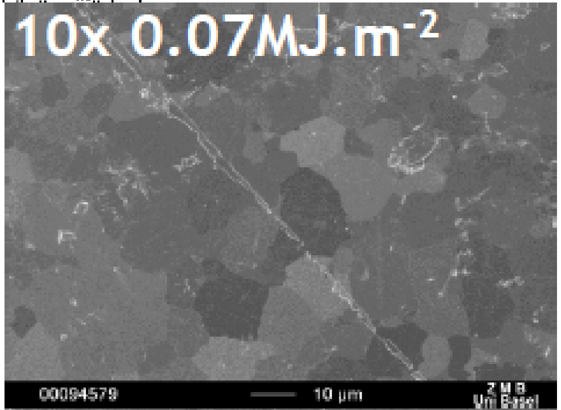
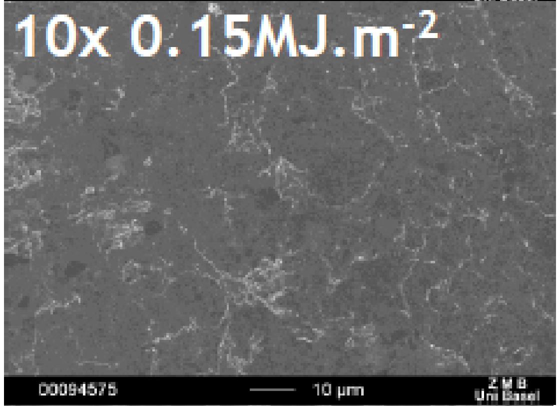
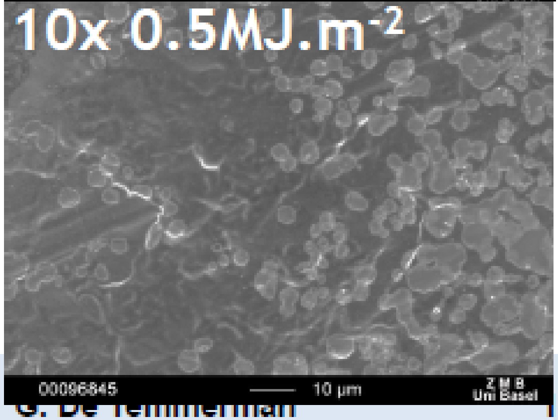
Plasma-enhanced surface damage



10x 0.07MJ.m^{-2}

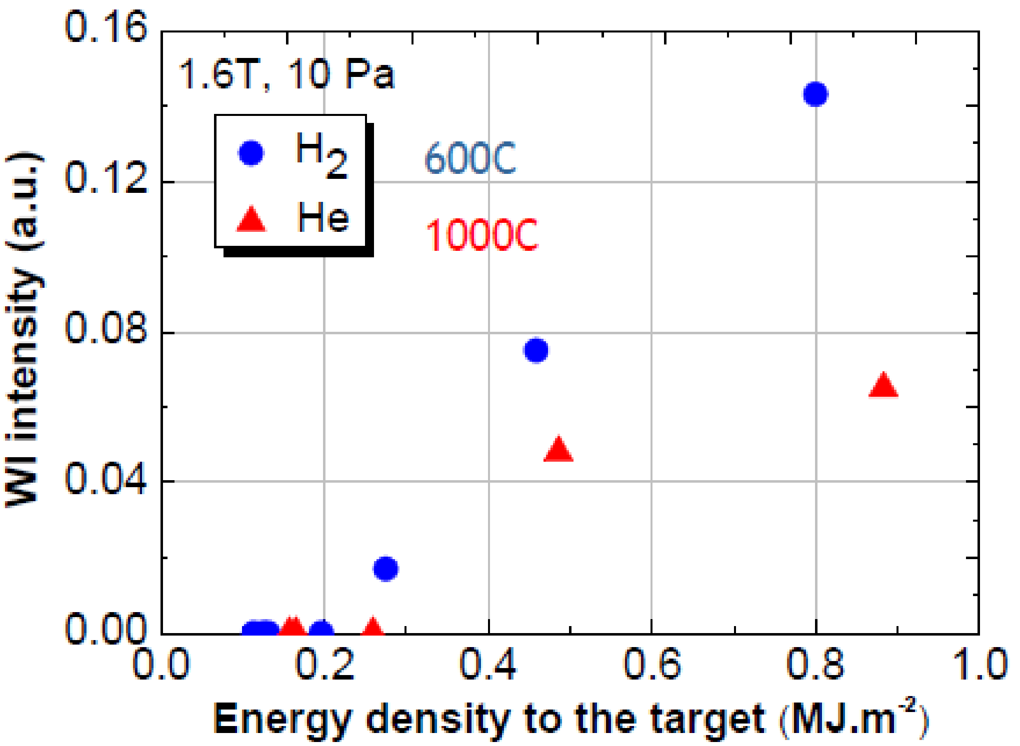


10x 0.15MJ.m^{-2}



10x 0.5MJ.m^{-2}

- Measured ablation threshold much lower than expected



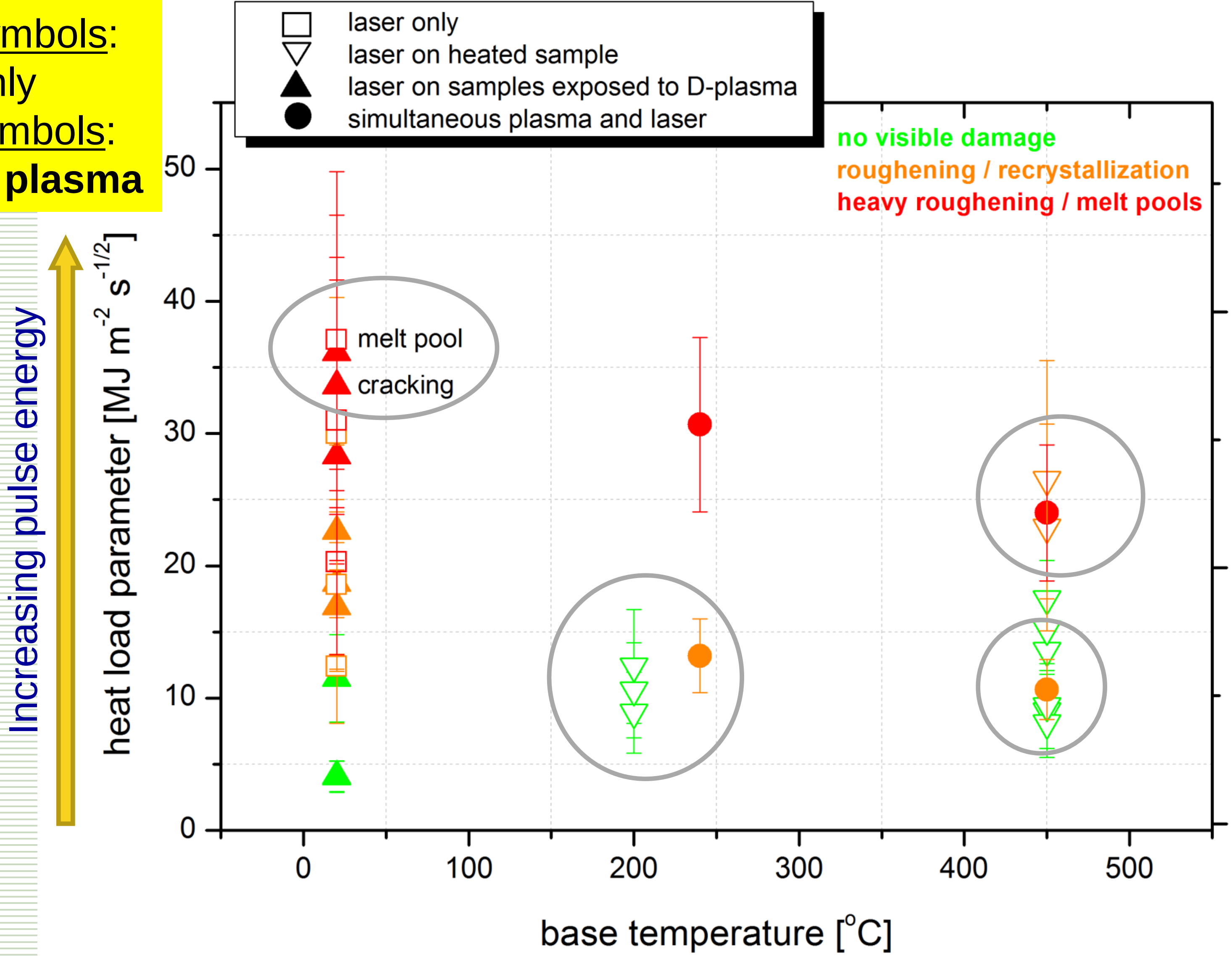
→ **Plasma enhanced surface ablation**

G. De Temmerman et al, IAEA FEC, 2010

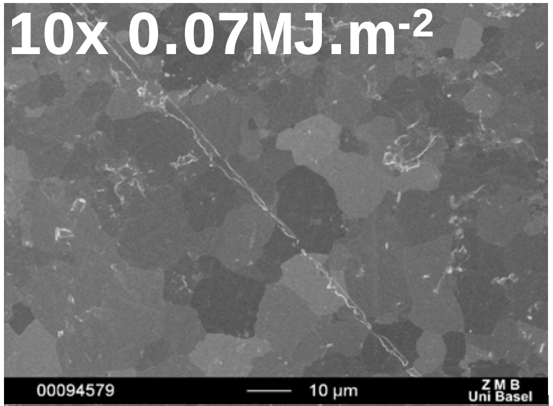
Comparison of damage - summary

Open symbols: Laser only

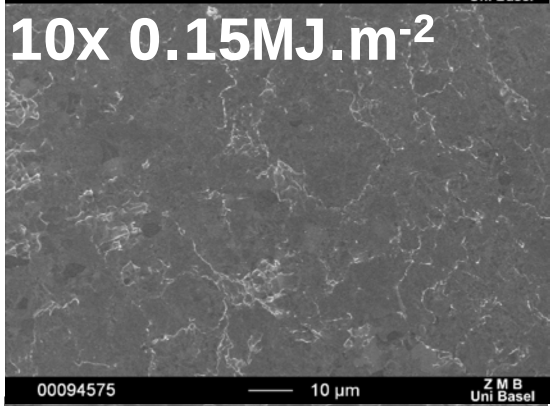
Filled symbols: **Laser + plasma**



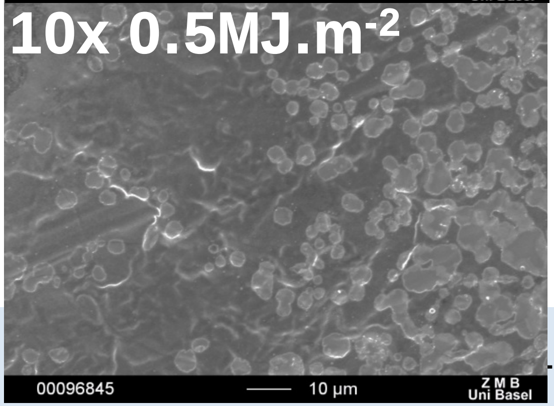
Plasma-enhanced surface damage



10x 0.07MJ.m^{-2}

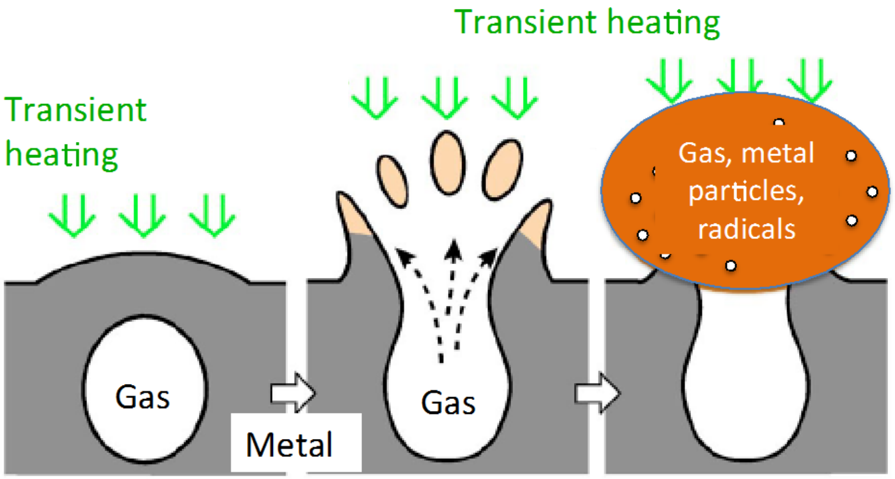


10x 0.15MJ.m^{-2}



10x 0.5MJ.m^{-2}

- ❑ 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

Conclusions 1 (particle loading)

- **H/D/T plasma exposure** (≤ 600 °C)
  - Blistering is not an issue in ITER (and DEMO).
  - Combination with pulsed plasmas could enhance erosion.
- **He nanometric bubbles** (< 700 °C)
  - Nanometric bubble layer slightly deteriorate thermal and mechanical properties, but itself is not an issue.
  - Combination with pulsed plasmas could enhance erosion.
- **W fuzz by He** (> 700 °C)
  - There are several preferable features (e.g. low sputtering erosion), but unipolar arcing could enhance erosion (need more investigation, especially in **magnetic confinement devices**).
  - Response to pulsed heat should be further investigated (Its impact on W fuzz is not still clear).
- **He holes** (> ~1700 °C, also recrystallization occurs)
  - Cracking and dust ejection could be an issue (need more investigation)

Conclusions 2 (heat loading)

- ☐ **Disruption/ELM**
  - Slight melting could be acceptable, but repeated melting causes brittle and uneven morphologies, **unacceptable**. → Clarifying melt layer behavior and its impacts on core plasmas are necessary
  - 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.
  - **Combined plasma exposure** could reduce the damage threshold of pulsed heat. (need more investigation **with high flux plasma**)
- ☐ **Surface repairment**
  - Some ELM-like heat pulse may alleviate He induced morphologies (W fuzz, He holes) →may be useful for temporal surface repairment (need more investigation)
- ☐ **Appropriate mitigation (control) of transients (slow transient, disruption/VDE, ELM) are mandatory.**