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Investigation of the Impact on Tungsten of Transient Heat Loads applied by Laser Irradiation

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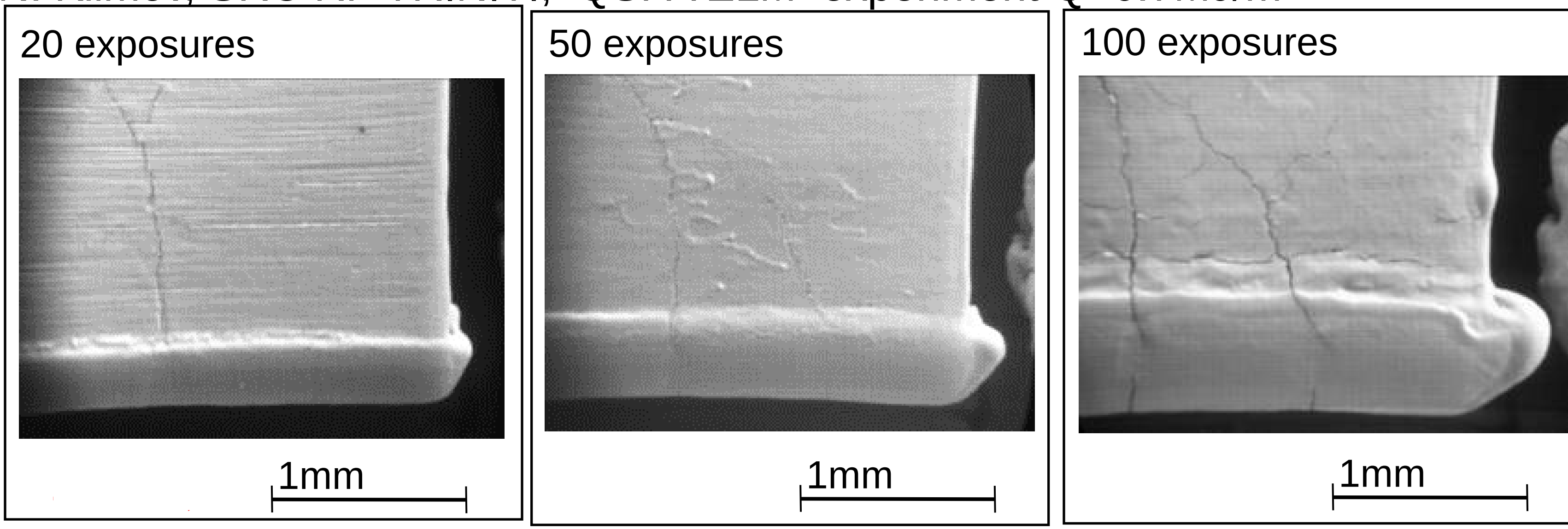
Outline

- **Motivation**
- **Methods for simulation of transient heat loads**
- **Surface Morphology after transient heat loads:**
  - o ELMs simulations study on ITER-like W samples (grains ⊥ to the irradiated surface) at different base temperatures of the W samples.
  - o Dependence of the surface modification on the frequency of the transient heat loads: 0.1Hz vs 10Hz (1000pulses).
  - o Surface modification dependence on the number of transient heat pulses
- **Summary**
- **Recent experiments**
  - oTransient heat load experiments with plasma background

Motivation

N. Klimov, SRC RF TRINITI, QSPA ELM experiment $Q=0.7 MJ/m^2$

Pure tungsten

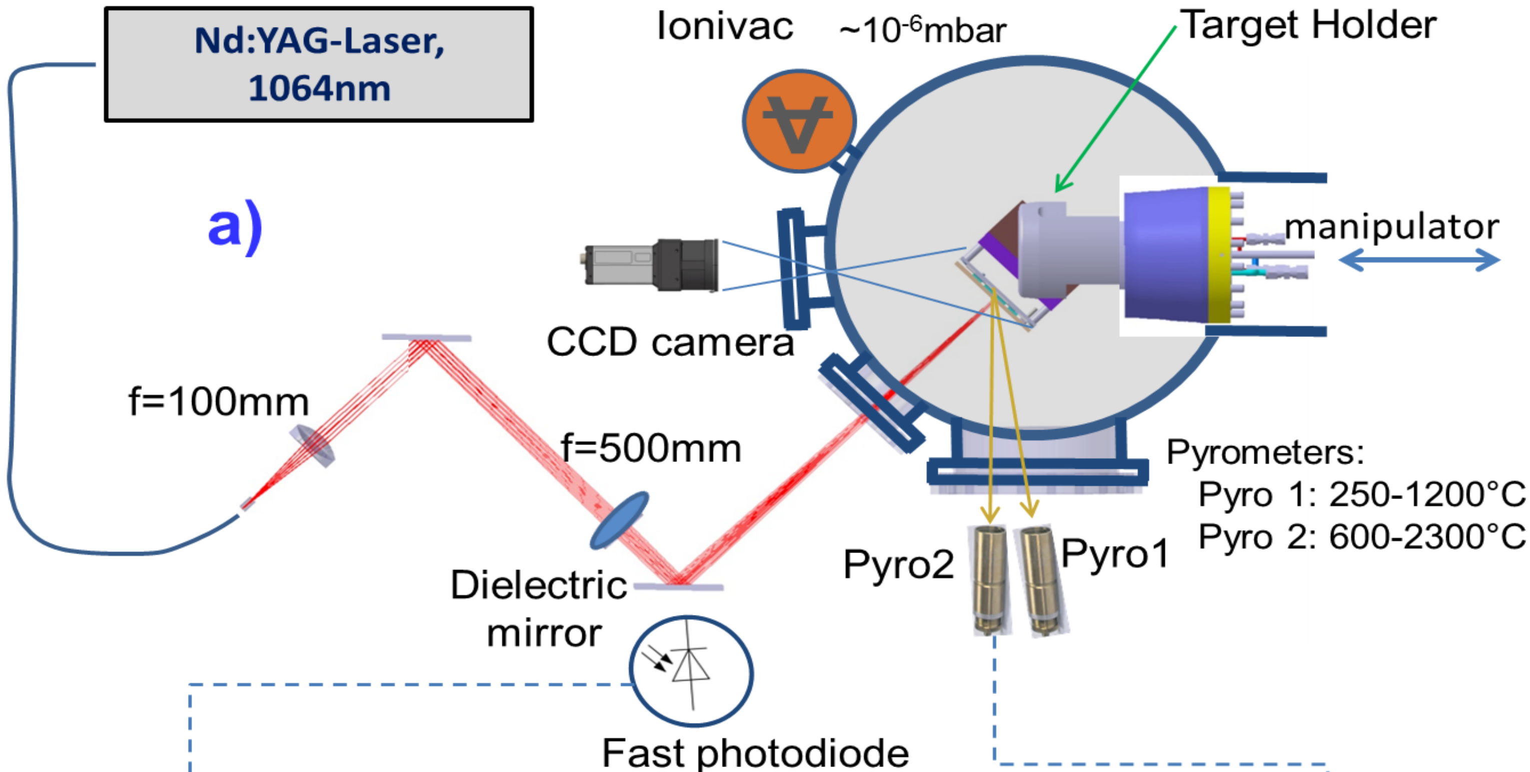


20 exposures 50 exposures 100 exposures

Strong Erosion for Energies beyond 0.5 MJ/m^2 for 0.5ms heat pulse duration

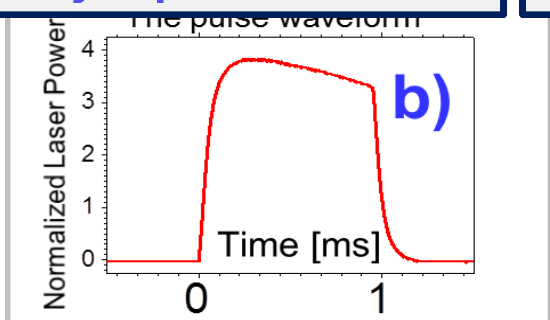
Simulation of heat and particle loads of such ELMs in laboratory devices is mandatory to determine the impact on Plasma-Facing Materials and the underlying physical processes.

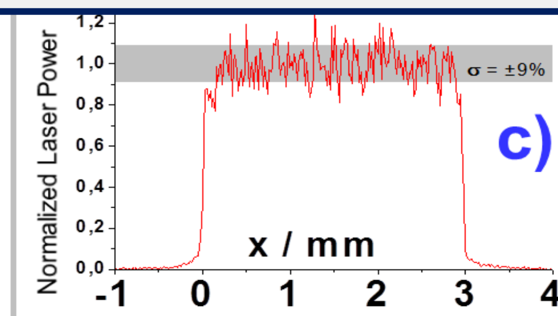
Experimental Set-Up

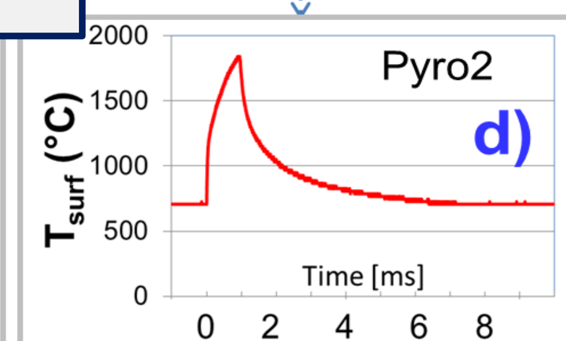


1 ms pulse duration:
nearly square function

3 mm laser beam diameter
nearly hat top shape







Exchangeable target holder with thermocoax heater

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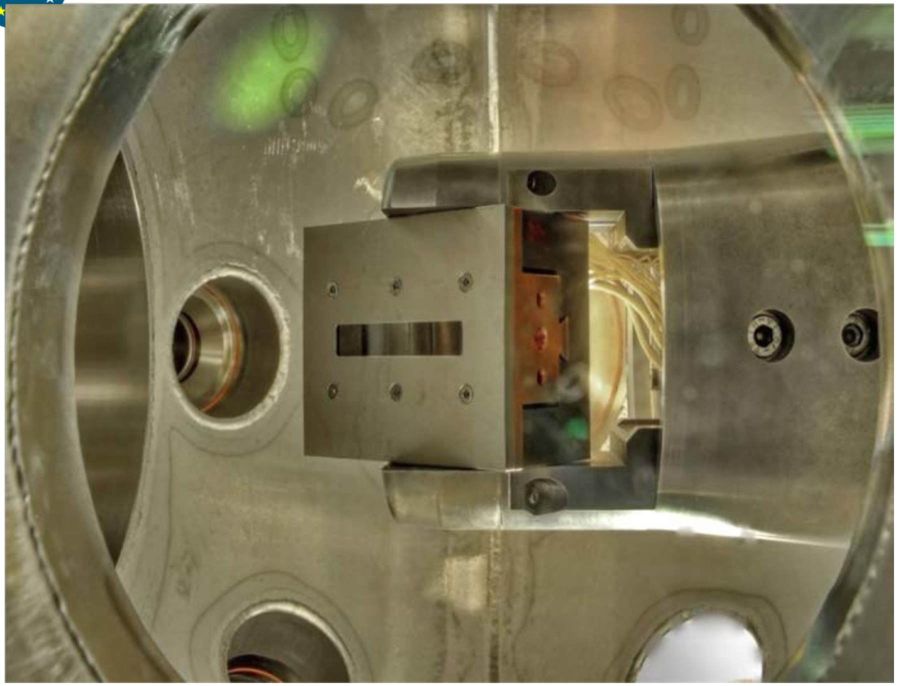
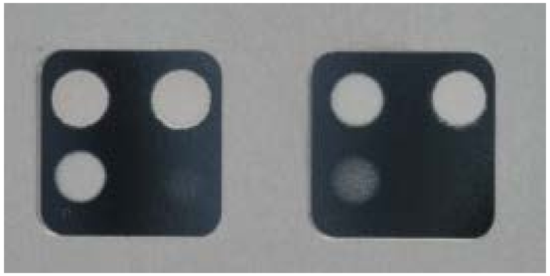


1000  100

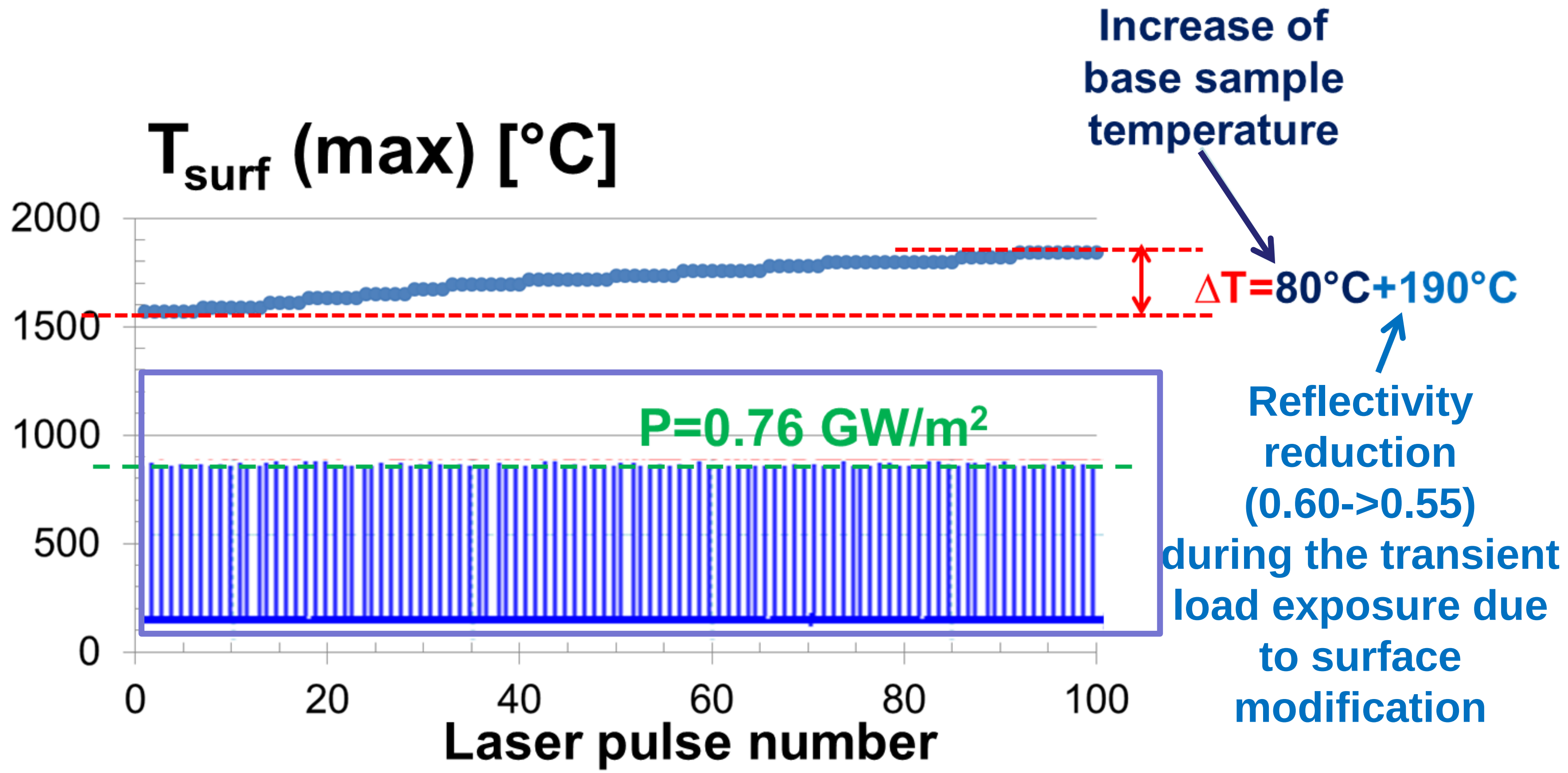
Pulses

W samples exposed to 1000 and 100 laser beam pulses each at power densities between 0.19 G W/m² and 0.90 GW/m²

Experimental settings for thermal loads:

- ITER-grade Tungsten (sample size: 12 × 12 × 5 mm³):
  - grain oriented ⊥ to the loaded surface; grain length ≈100µm, width of ≈40µm
- loaded area: ø = 3.1 mm: **nearly hat top shape**
- 1 ms pulse duration: **nearly square function**
- Repetition rate 0.5 Hz-10 Hz; base temperature: RT and 400 °C
- power density: 0.19 up to 0.9 GW/m²; heat flux factor: $P\sqrt{t} \leq 28.5\ MWm^{-2}s^{1/2}$)

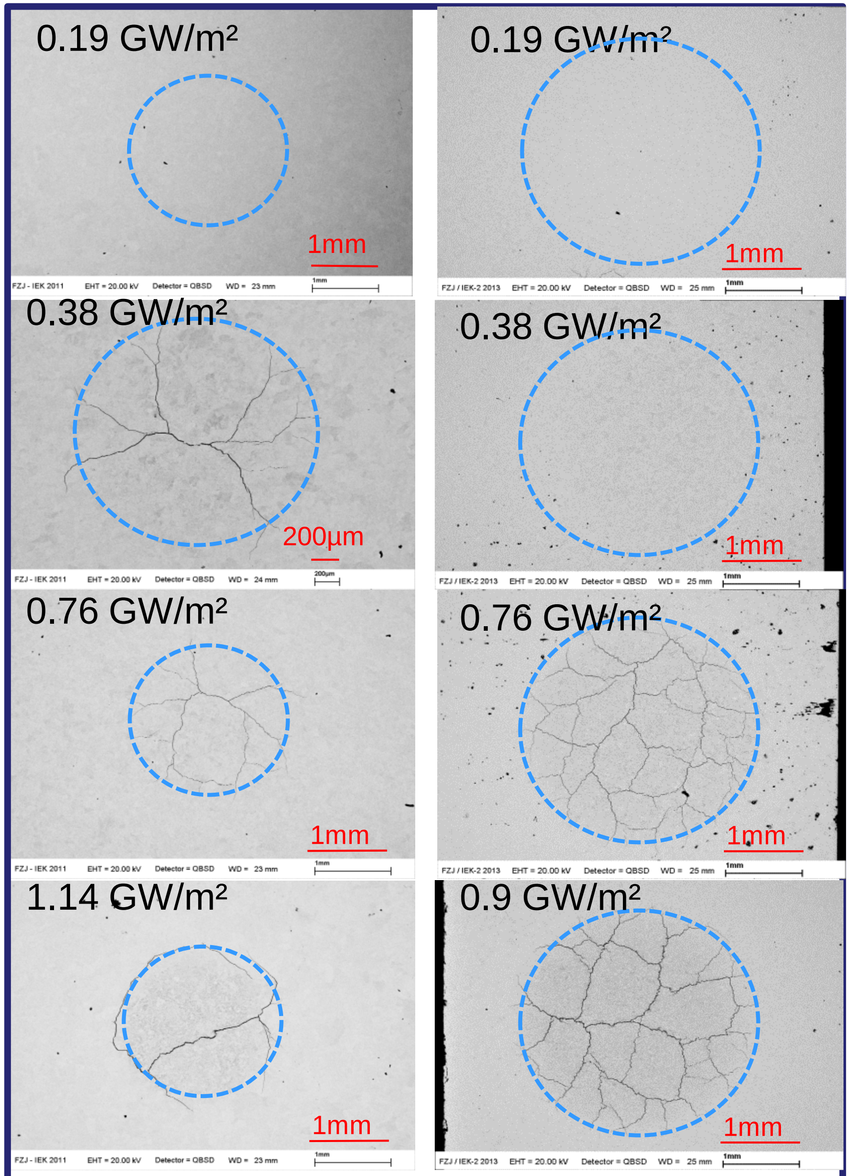
Surface Temperature of the W samples exposed each to 100 laser pulses



Two one-colour pyrometers with temperature ranges 250-1200°C and 600-2300°C monitored the surface temperature of the spot centre during the laser pulse with a time resolution of 15µs.

Transient Heat Loads by Laser Irradiation

W-UHP **ITER-like**

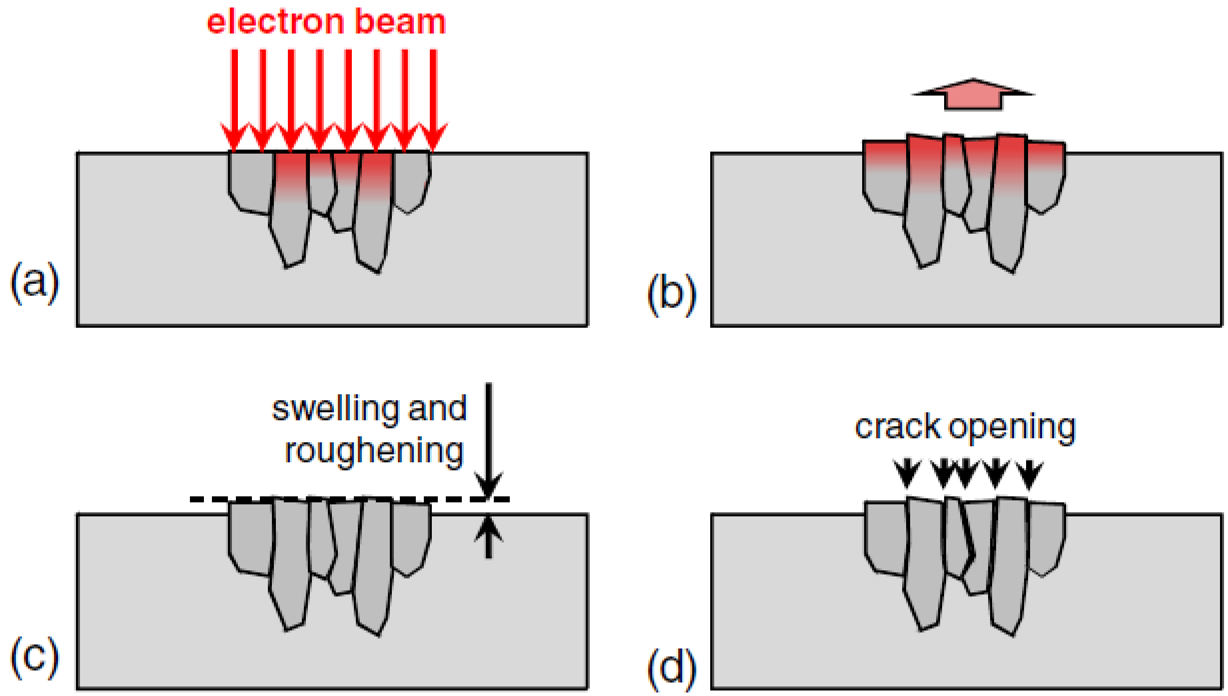


W-UHP vs ITER-like tungsten samples

after 100pulses of laser beam exposure at room temperature.

- The ITER-grade W sample demonstrates a higher resistance to thermal shock damage than high purity tungsten; the damage threshold is located between 0.38 and 0.76 GW/m²

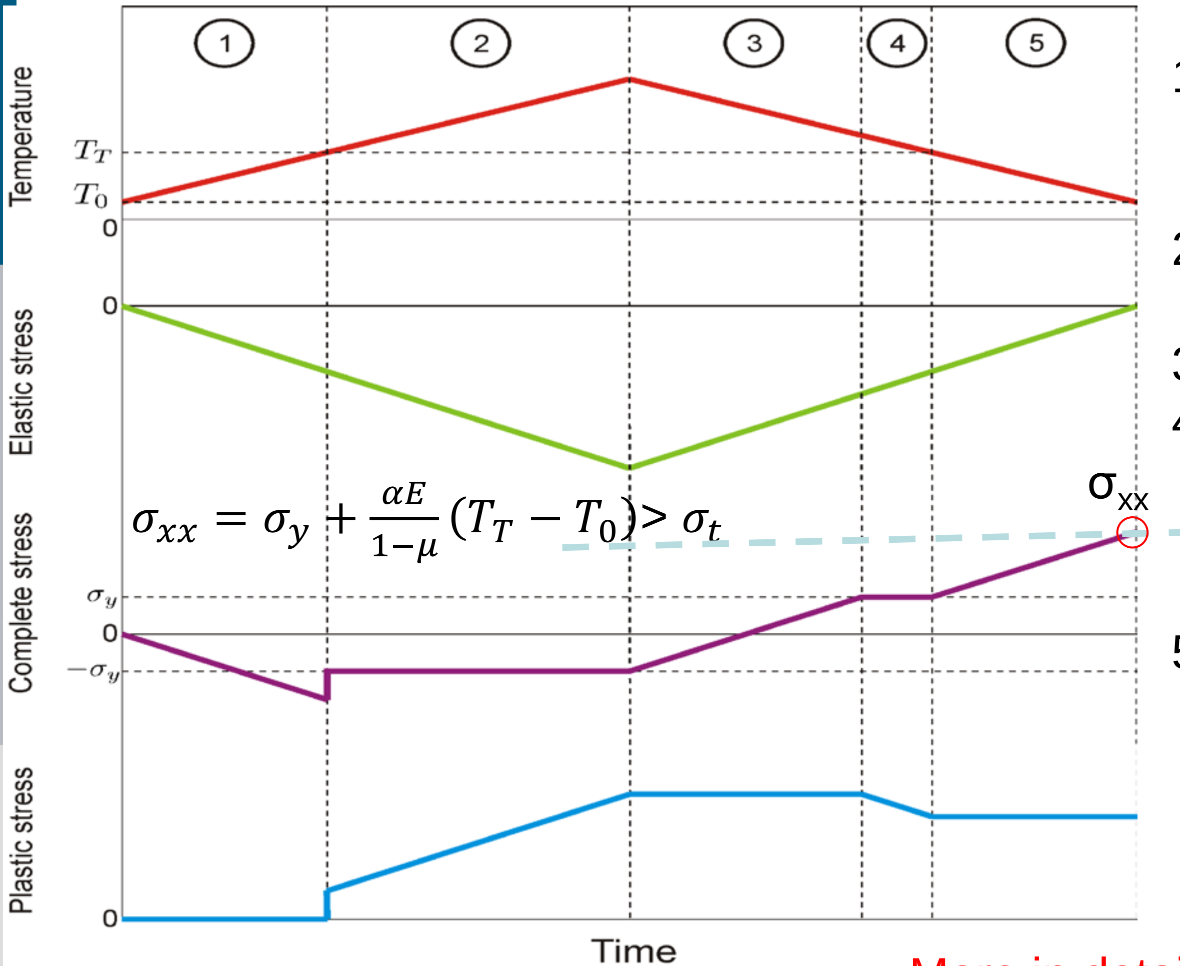
Mechanism of crack formation



J. Linke et al. Nucl. Fusion 51 (2011) 073017

Cracks with an orientation parallel to the heated surface => subsequent delamination effects => overheating, melting and complete loss of the detached layer.

Schematic image of the elastic and plastic stresses changing during the heating-cooling cycle



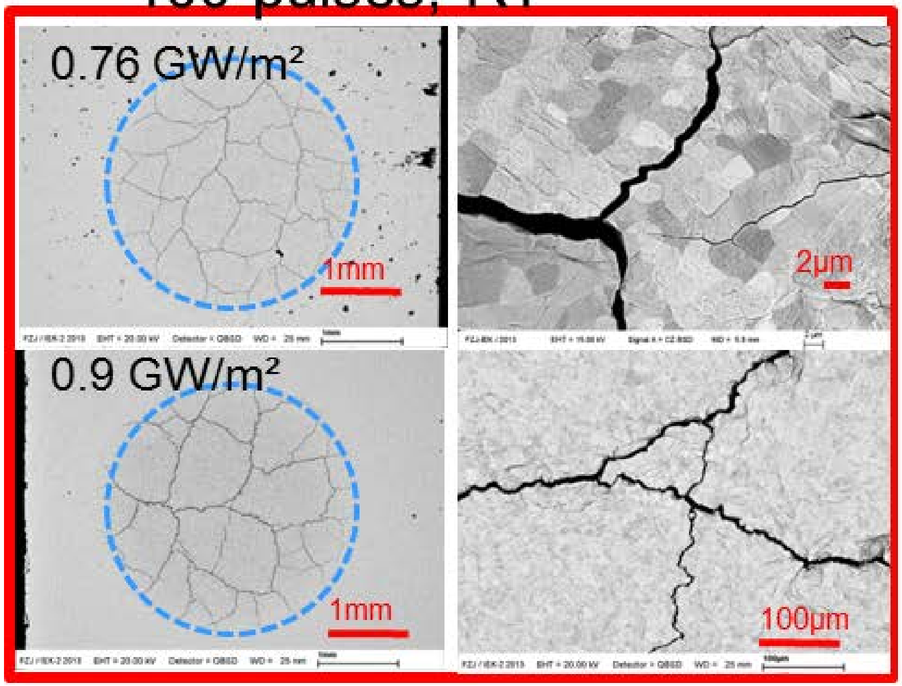
1. Increase of elastic compressive up to T_T=DBTT
2. appearance of plastic deformation
3. Decrease of elastic stress
4. the reversed complete stress causes opposite plastic deformation reducing plastic stress.
5. temperature becomes lower than DBTT. Consequently, the complete stress rises above σ_y

More in detail in the talk by A. Arakcheev

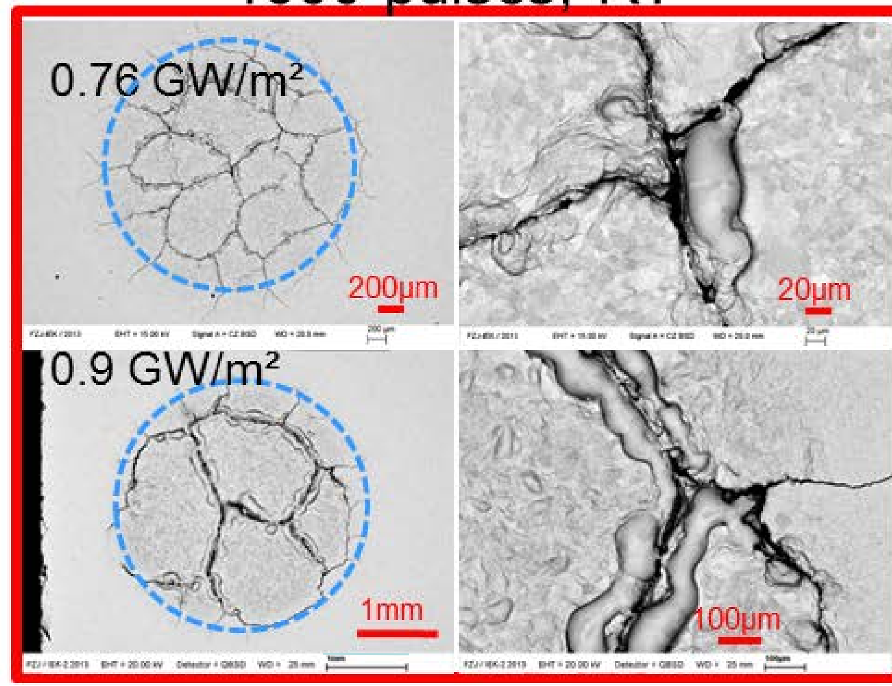
The present model do not describe the strain hardening (due the plastic deformation) that could lead to the accumulation of the stresses during the cycled heat loads

Impact of Transient Heat Loads applied by Laser Irradiation on ITER-grade Tungsten

100 pulses, RT



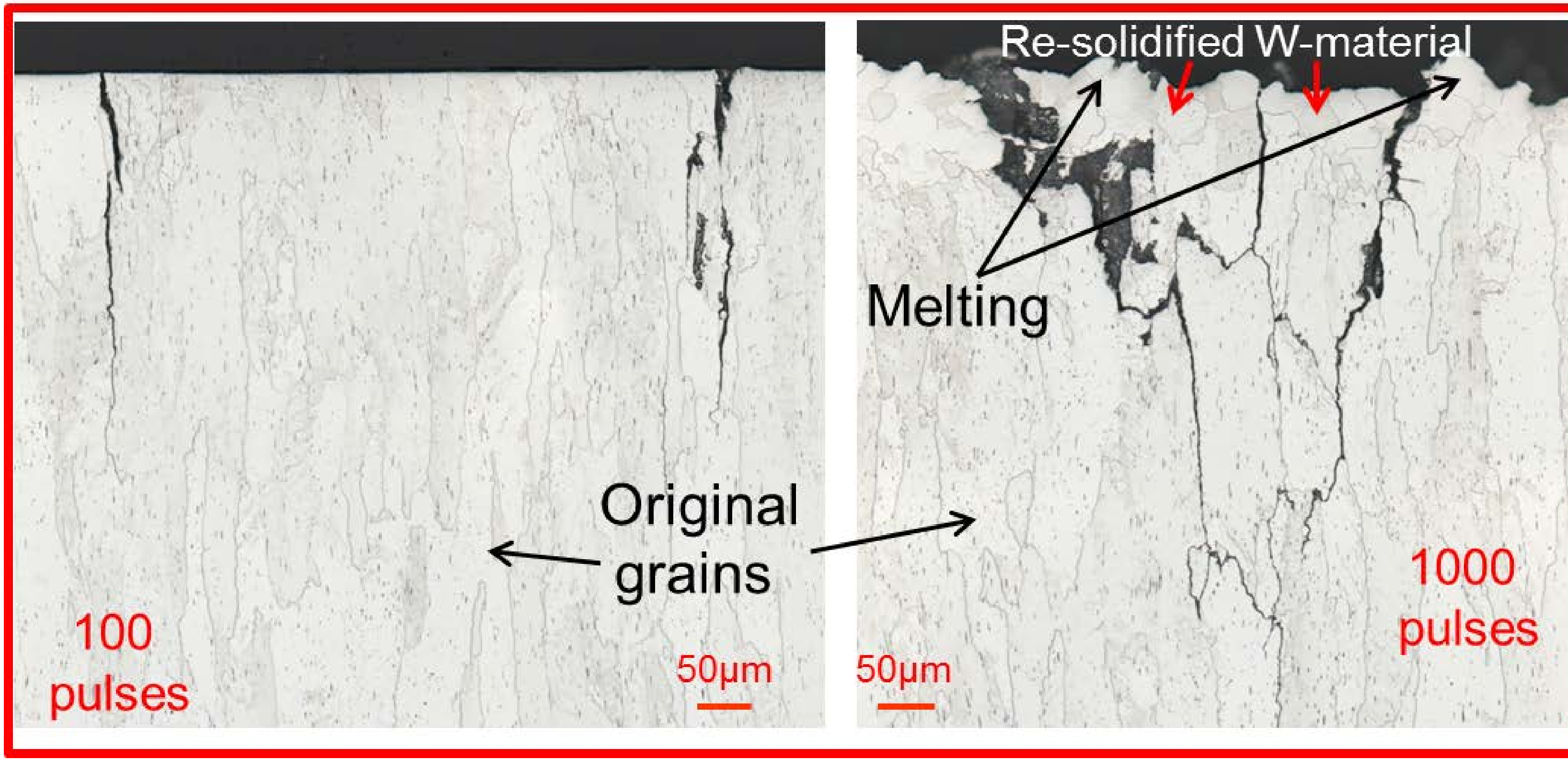
1000 pulses, RT



- The ITER-grade W sample demonstrates a higher resistance to thermal shock damage than high purity tungsten; the damage threshold is located between 0.36 and 0.76 GW/m^2
- For power densities above 0.76 GW/m^2 the, continued cycling up 1000 pulses after crack formation results in erosion of crack edges by melting.

Impact of Transient Heat Load Pulse Numbers on the damage threshold

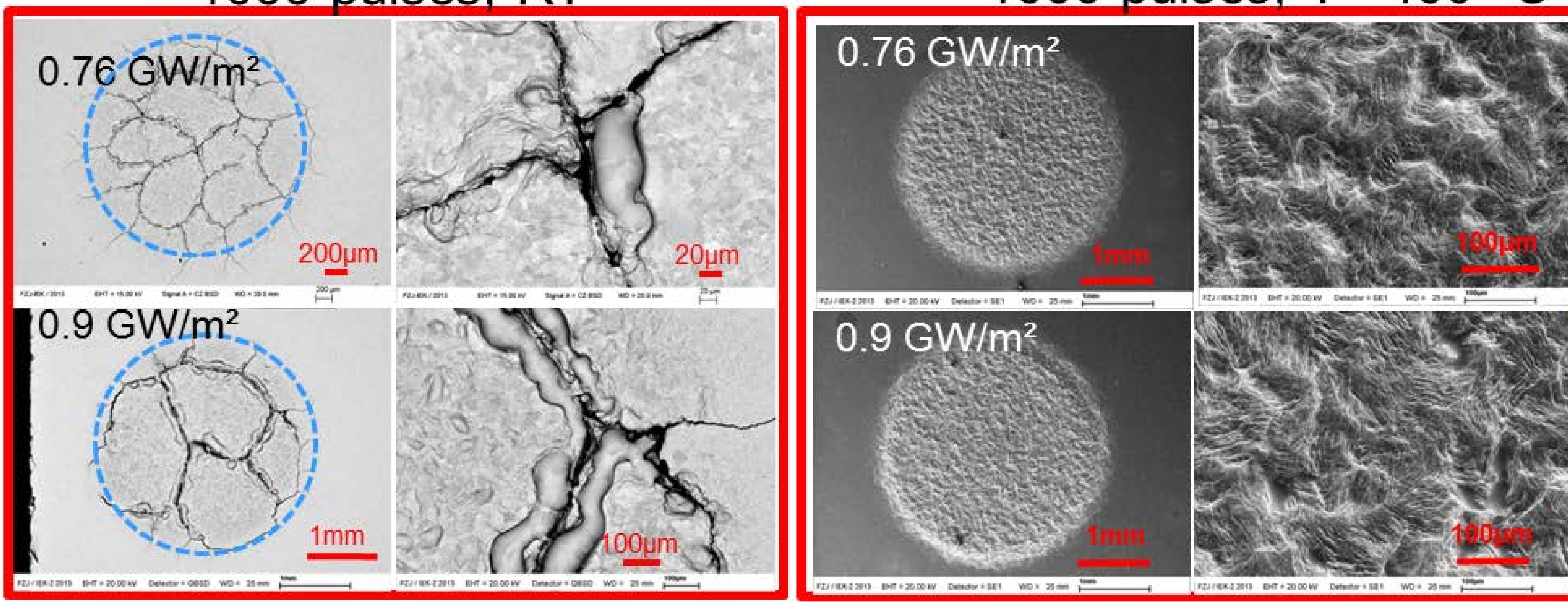
RT, P = 0.76 GW/m^2



- At high pulse numbers the friction at crack edges can cause erosion and high cumulative plastic deformation leading to a reduced heat transfer capability or even thermal isolation of the protruding parts of the W material, which can melt.
- For the ITER-grade W, typical cracks occur at grain boundaries.

Impact of Transient Heat Loads applied by Laser Irradiation on ITER-grade Tungsten

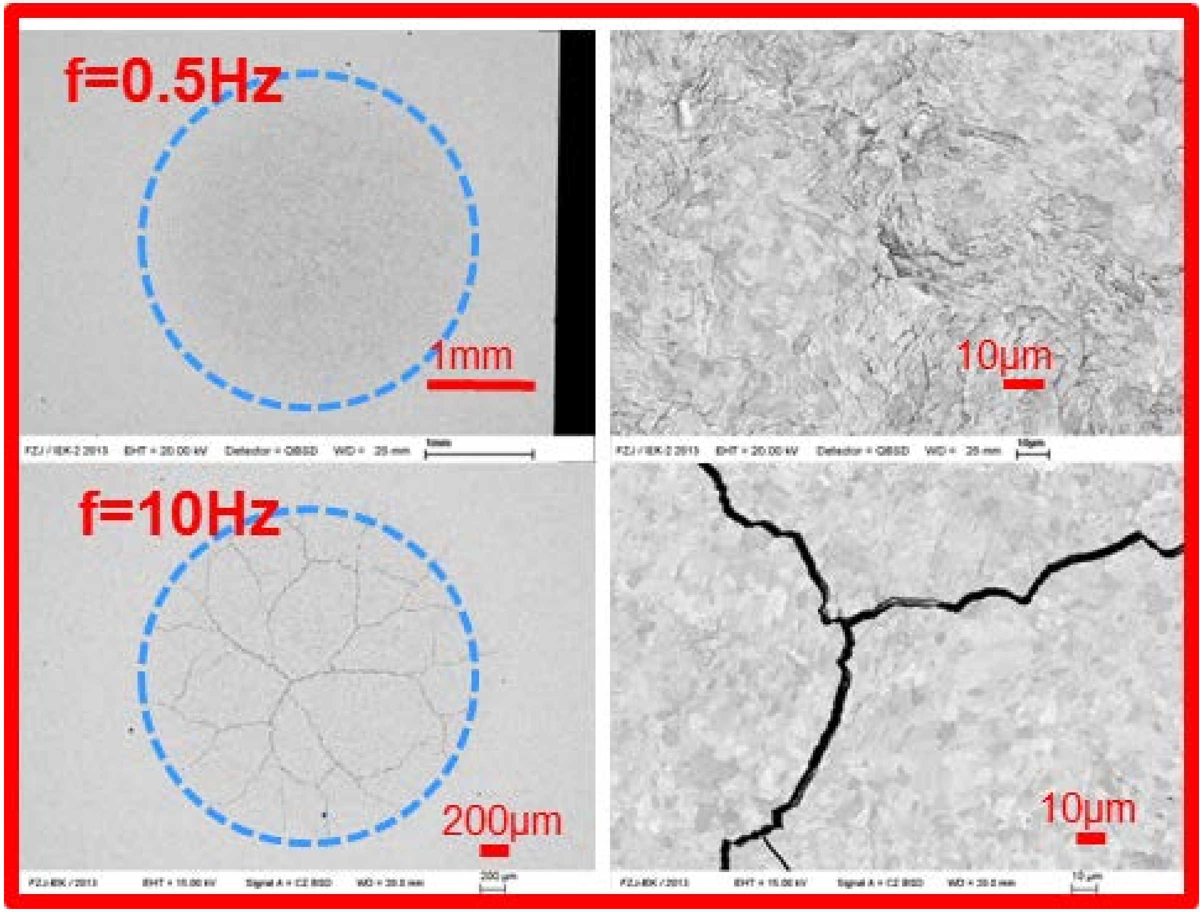
1000 pulses, RT | 1000 pulses, T= 400 °C



- For power densities above 0.76 GW/m^2 the, continued cycling up 1000 pulses after crack formation results in erosion of crack edges by melting.
- At the base temperature of 400 °C the formation of cracks is suppressed.
- Due to grain orientation, no cracks parallel to the loaded surfaces have been observed during the thermal shock loading of the ITER–grade W.

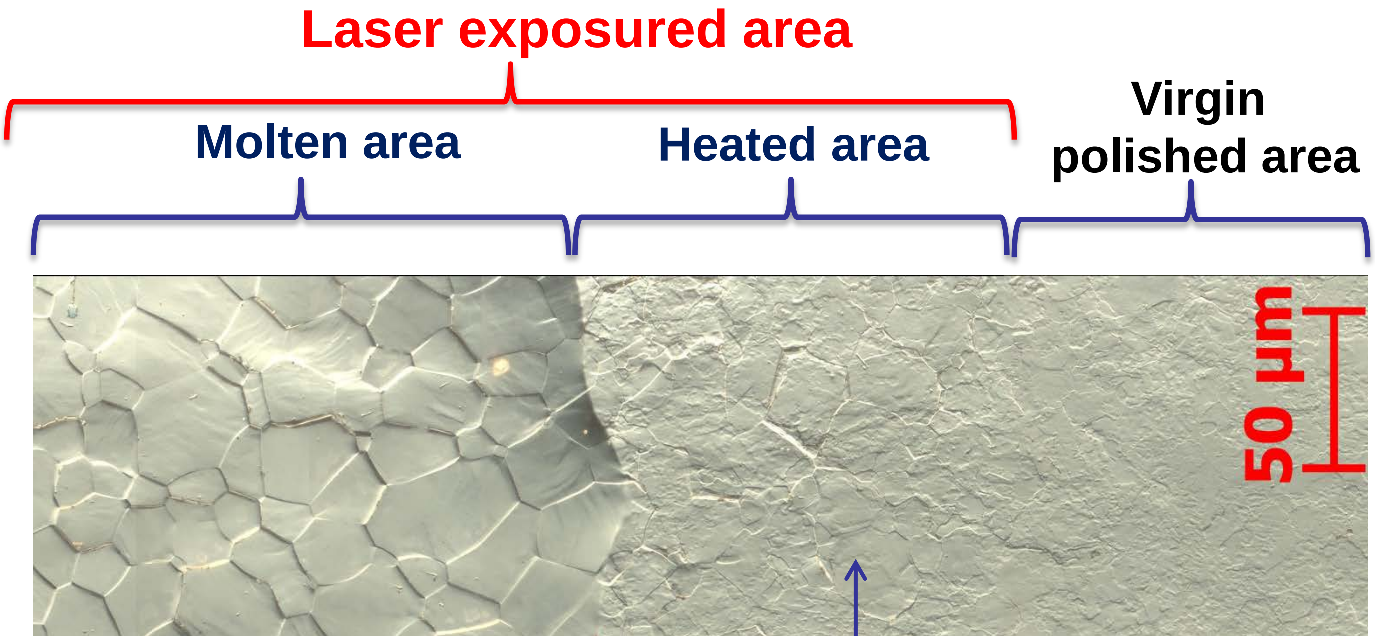
The dependence of the surface modification on the frequency of the transient heat loads

1000 pulses, RT, P = 0.38 GW/m^2



- An increase of the frequency of the heat cycles to 10 Hz may effectively decrease the damage threshold

Roughening due to Laser heating

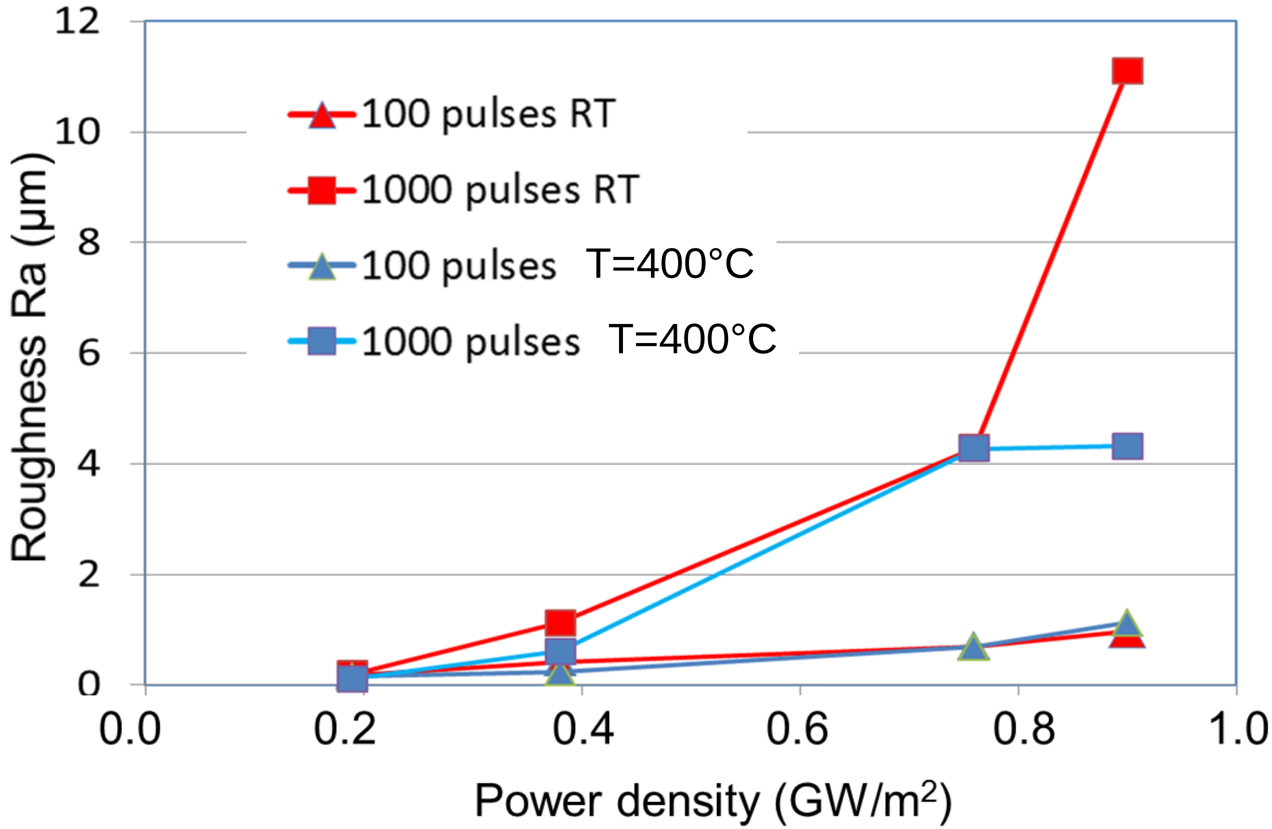


Polycrystalline, rolled tungsten
(Goodfellow, 99.95 wt.% purity)

DIC optical microscopy

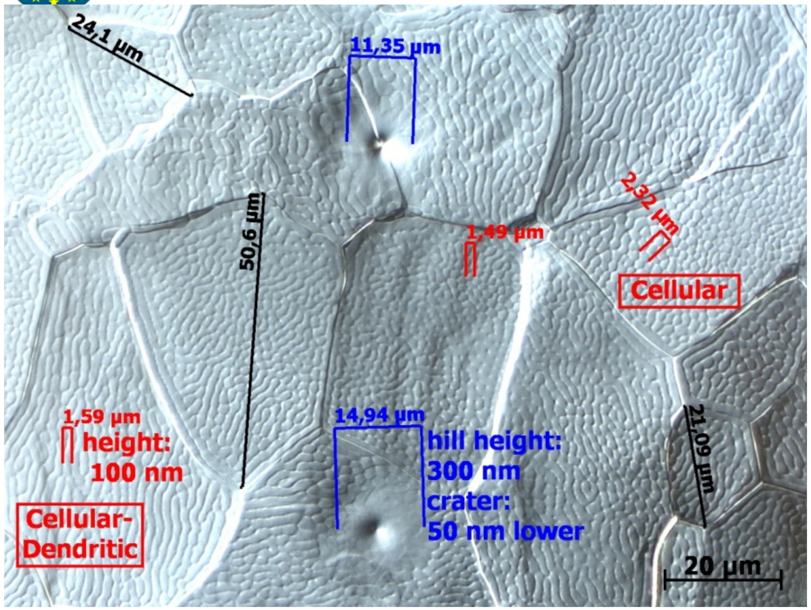
- Roughness increased by thermal shock loads: rougher in the melted area
- Roughness formation is independent of the loading methods.
- At P= 0.19 GW/m^2 there are no formation of roughness structure
- Beyond 0.2 GW/m^2: the surface roughening increase up to 2µm with increase of power density load

Power density dependence of the arithmetic mean roughness (R_a) after laser beam exposure.



- No dependence of the surface roughness *Ra* on the base temperature of the samples has been observed: *Ra* for the two base temperatures is almost the same except at 0.9 GW/m^2.
- Significant increase of the roughness Ra with the increased pulse numbers

Surface Morphology after Laser Melting Pulse



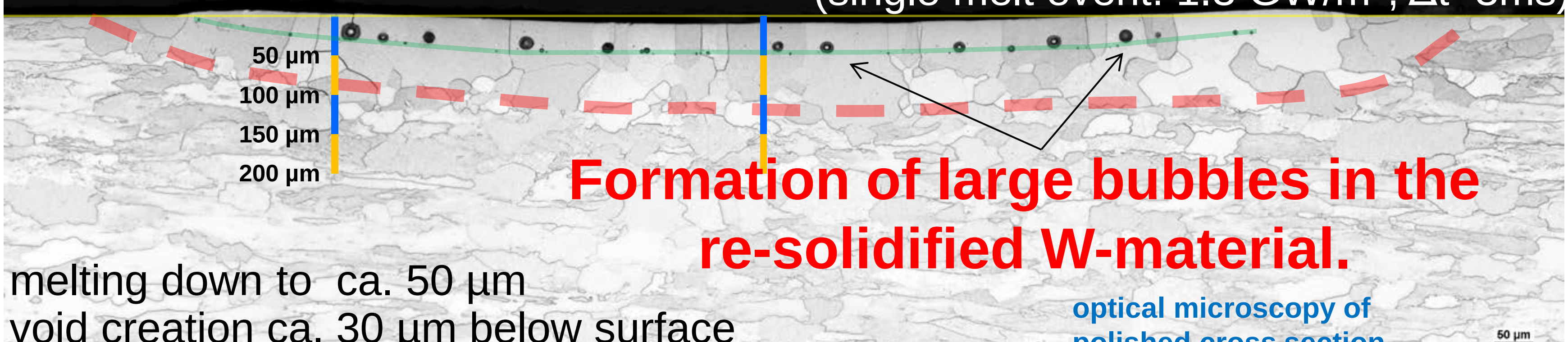
Surface Morphology after laser melt Pulse:

- predominantly cellular structures **inside** the grains (rapid solidification)
- formation of large holes in the re-solidified W-material

Surface roughness after heat loading

Metallographic cross sections of a molten W spot

(single melt event: 1.3 GW/m^2, Δt=3ms)



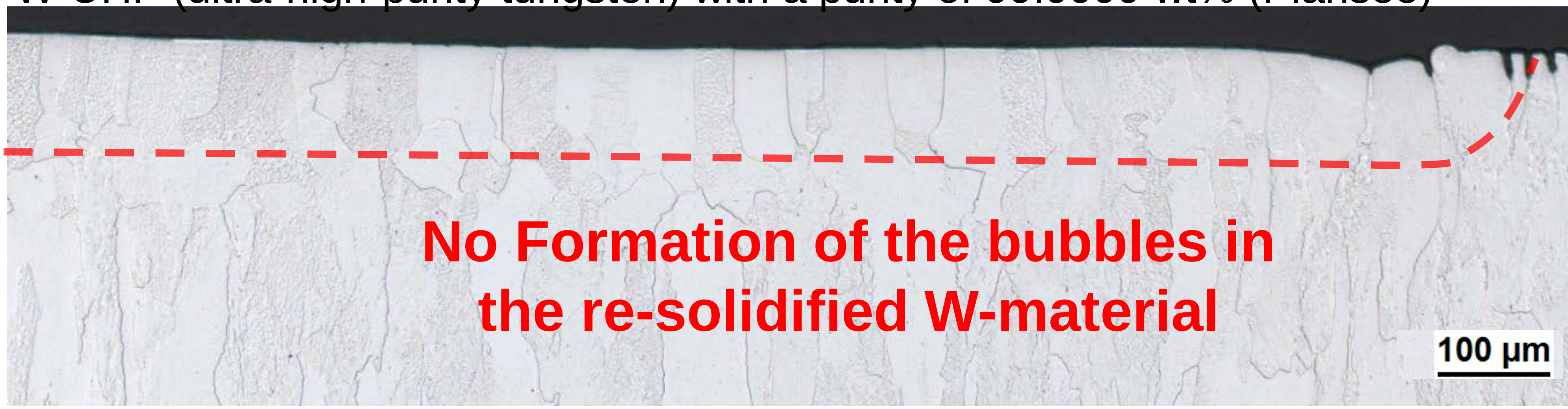
Formation of large bubbles in the re-solidified W-material.

melting down to ca. 50 µm
void creation ca. 30 µm below surface

optical microscopy of polished cross section

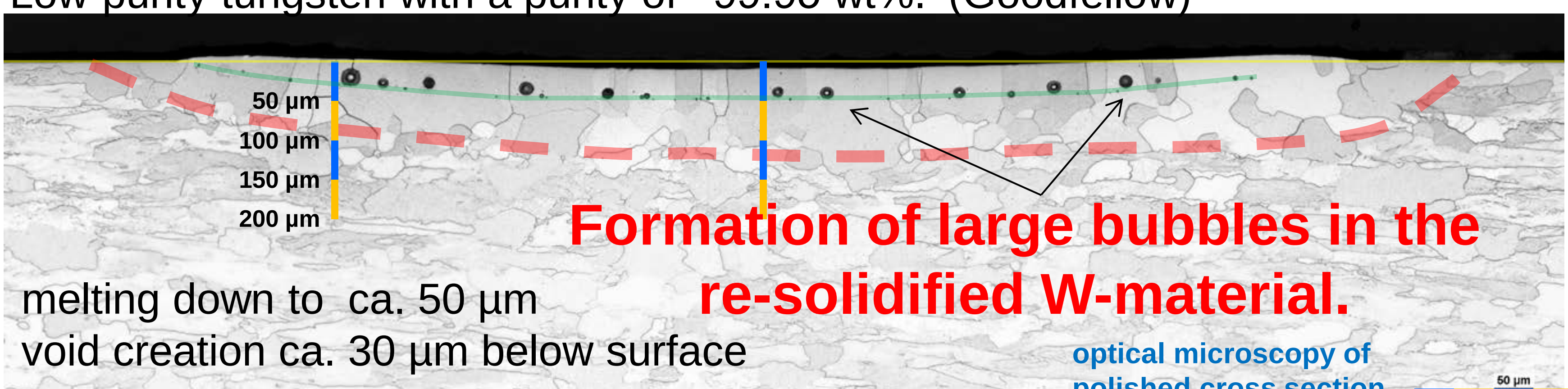
Surface Morphology after Laser Melting Pulse

W-UHP (ultra-high-purity tungsten) with a purity of 99.9999 wt% (Plansee)



The formation of the holes in the solidified W has been observed only in the Material with low purity => impurities => bubble formation

Low-purity tungsten with a purity of ≈99.95 wt%. (Goodfellow)



Summary

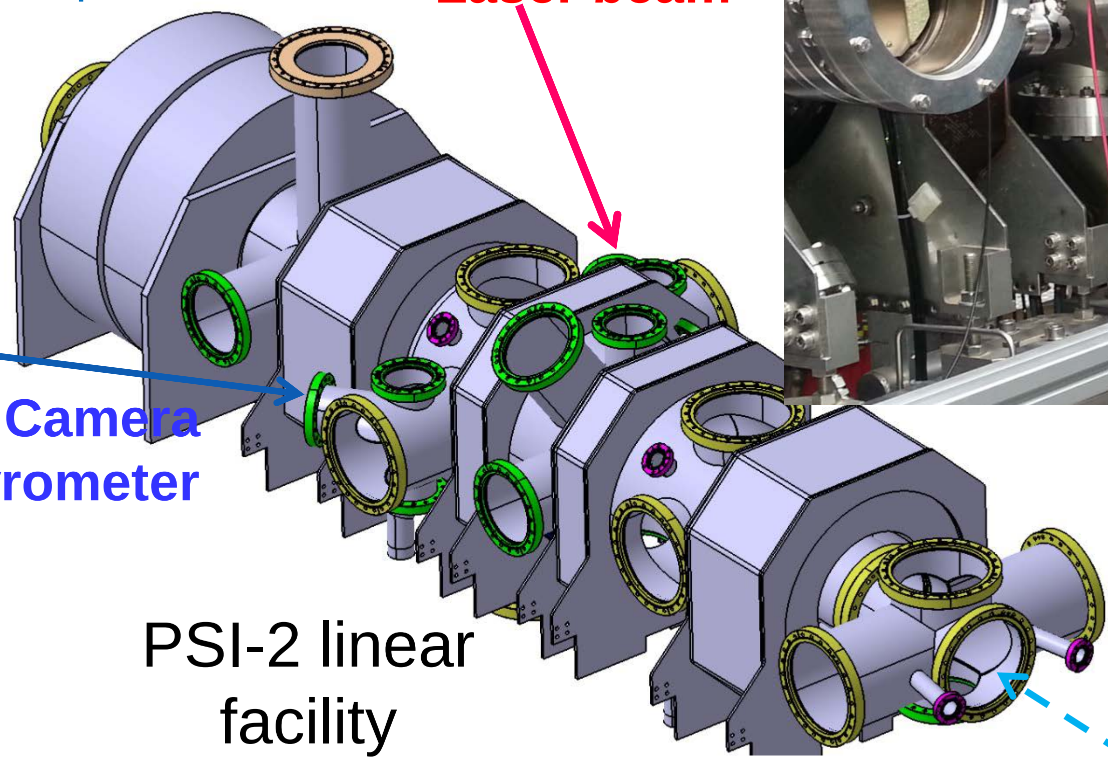
- To examine the performances of ITER-grade W under thermal shock loads, simulations were performed using the laser beam facility at Forschungszentrum Juelich.
- The observed damage threshold for ITER-grade W is located between 0.38 and 0.76 GW/m^2 .
- For the ITER-grade W, typical cracks occur at grain boundaries where the strength of the material is lower.
- Due to grain orientation, no cracks parallel to the loaded surfaces have been observed during the thermal shock loading of the ITER – grade W.
- Continued cycling up to 1000 pulses results in enhanced erosion of crack edges and crack edge melting.
- At the base temperature of 400 °C the formation of cracks is suppressed.
- An increase of the frequencies of the heat cycles to 10 Hz may effectively decrease the damage threshold.

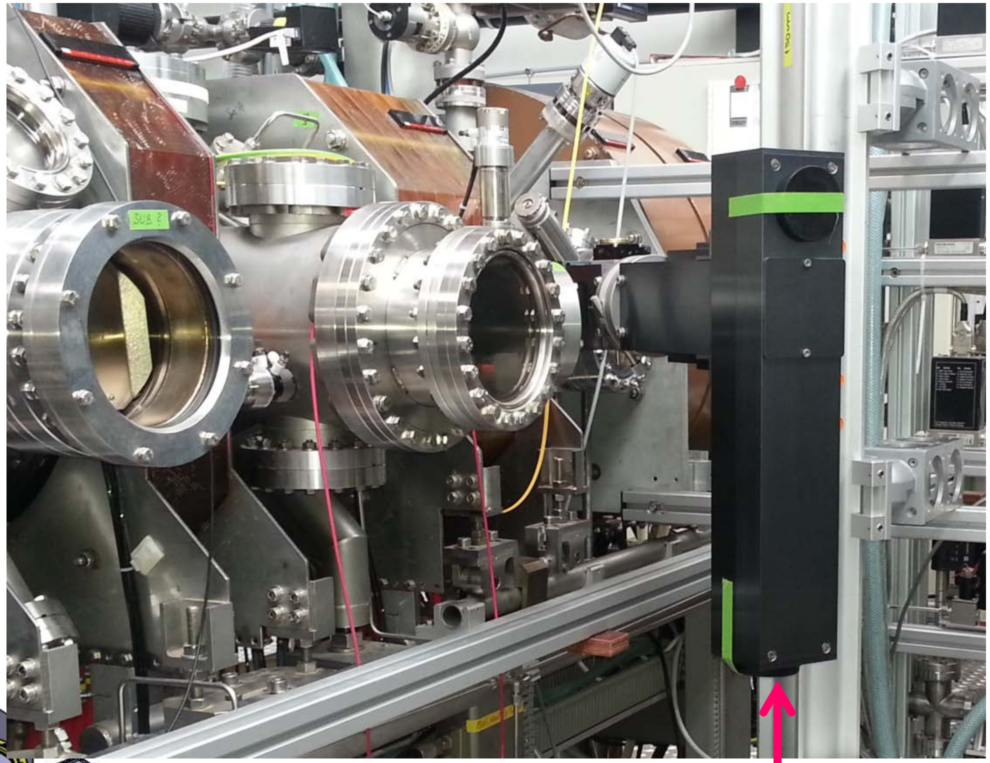
Recent experiments

Transient heat load experiments in the PSI-2 facility simultaneously to a steady state plasma exposure

Laser method advantages:

- no restrictions on pulse number
- can be applied simultaneously with a steady state plasma exposure





Experiment ready to start

First Results: modification of the surface roughness Ra

- Deuterium Plasma parameters: Particle flux $=2\times10^{17}cm^{-2}\ s^{-1}$, ion energy 60eV (biased sample), Flux Fluence = $4\times10^{20}cm^{-2}$

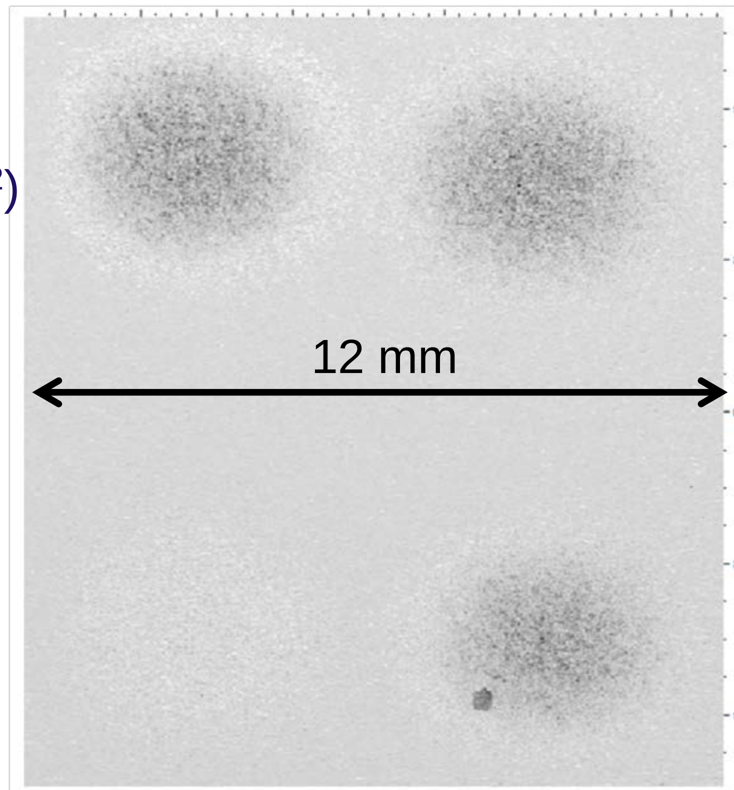
Laser absorbed power density = $0.76GW/m^{-2}$ (w/o correction on vacuum window transmission)
target roughness after plasma exposure Ra = 0.07µm

Laser → Plasma
(1000pulses, $0.76GW/m^{-2}$)

Roughness Ra=0.89µm

Laser + Plasma
(1000pulses, $0.76GW/m^{-2}$)

Ra=0.56µm



Plasma → Laser
(100pulses, $0.9GW/m^{-2}$)

Ra=0.26µm

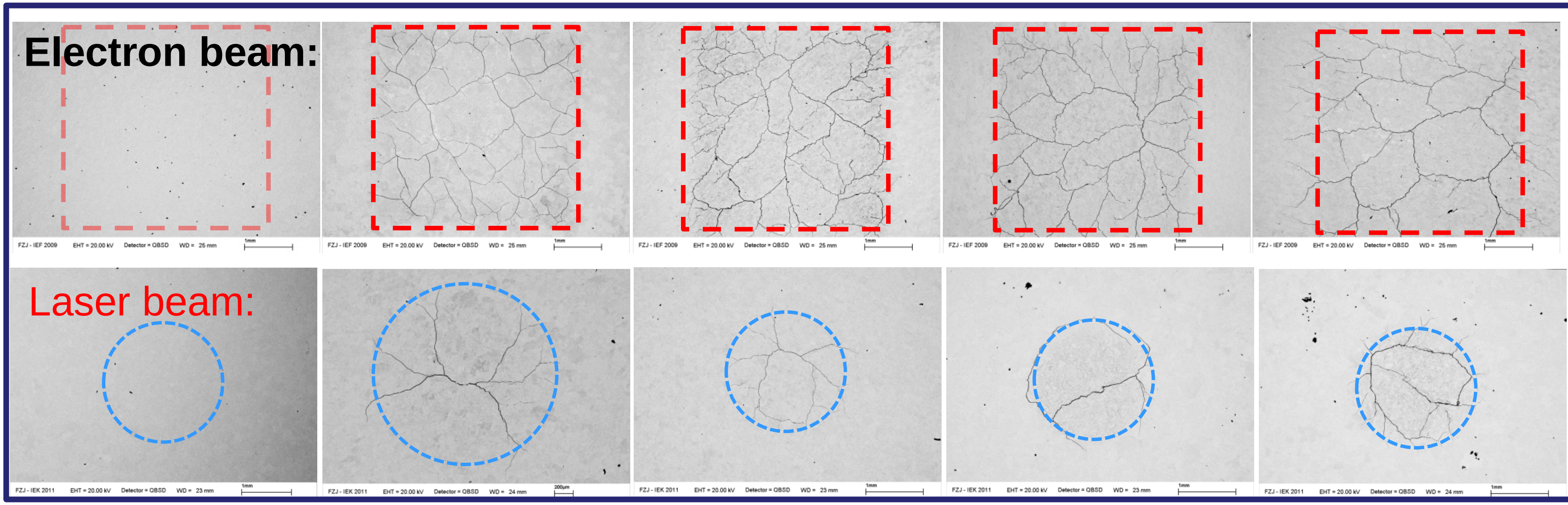
Plasma → Laser
(1000pulses)

Ra=0.50µm

Increased stresses due to implantation of the D ions

Reserved Slides

Crack formation: Electron vs. Laser beam



0.19 GW/m² 0.38 GW/m² 0.76 GW/m² 1.14 GW/m² 1.51 GW/m²
(absorbed intensity)

Cracking patterns are very similar !!!

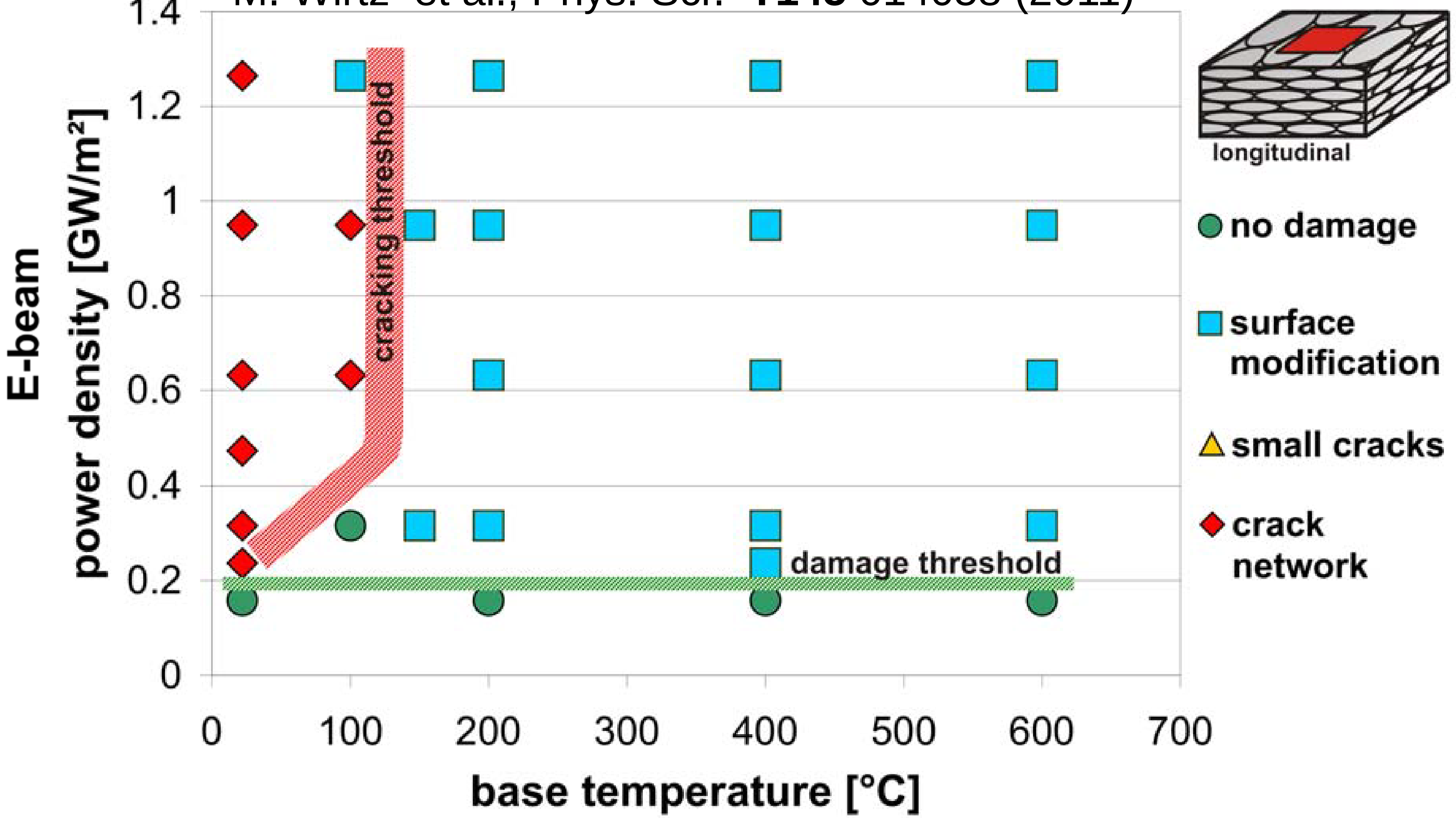
- At P= 0.19 GW/m² there are no cracks after repetitive electron as well laser loadings.
- Cracks network for P≥0.38 GW/m² for both methods

Samples:

- Industrially manufactured single forged tungsten grade W-UHP (ultra-high-purity tungsten) with a purity of 99.9999 wt%.
- The base temperature of W samples around room temperature

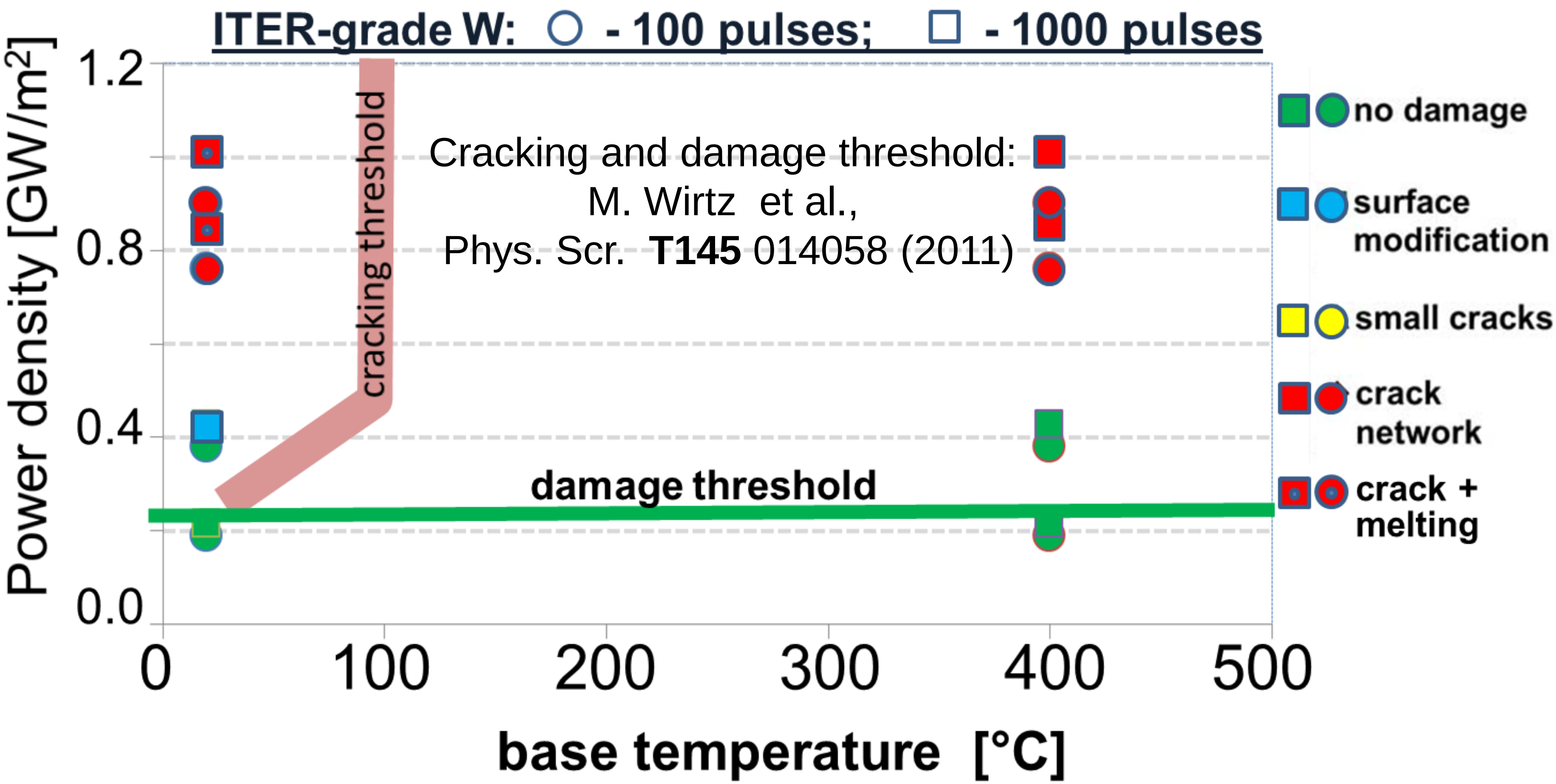
Thermal shock response of W-UHP L after 100 thermal shock events

M. Wirtz et al., Phys. Scr. **T145** 014058 (2011)



Below 0.16 GWm^{-2} no visible damage appears. Above a base temperature of 100 °C only surface modification occurs.

Thermal shock response after 100 and 1000 pulses



No visible damage below 0.19 GWm^{-2}.