TRILATERAL
EUREGIO CLUSTER

JÜLICH
FORSCHUNGSZENTRUM

Investigation of the Impact on Tungsten of Transient Heat Loads induced by Laser Irradiation, Electron Beams and Plasma Guns

Presented by
A. Huber

Institute of Energy and Climate Research – Plasma Physics, Forschungszentrum Jülich, Association EURATOM-FZJ, Germany

3rd International Workshop on Plasma Material Interaction Facilities for Fusion (PMIF 2012), Tsukuba, Japan, 27-31 August 2012

with thanks to many co-authors

A. Burdakov[2], M. Zlobinski[1], M. Wirtz[3], J. W. Coenen[1], J. Linke[3], Ph. Mertens[1], V. Philipps[1], G. Pintsuk[3], B. Schweer[1], G. Sergienko[1], A. Shoshin[2], U. Samm[1], A. Terra[1], B. Unterberg[1]

[1]Institute of Energy and Climate Research – Plasma Physics (IEK-4), Forschungszentrum Jülich, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany, www.fz-juelich.de/iek/iek-4

[2]Budker Institute of Nuclear Physics (BINP), Novosibirsk 630090, Russia

[3]Institute of Energy and Climate Research – Microstructure and Properties of Materials (IEK-2), Forschungszentrum Jülich, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany

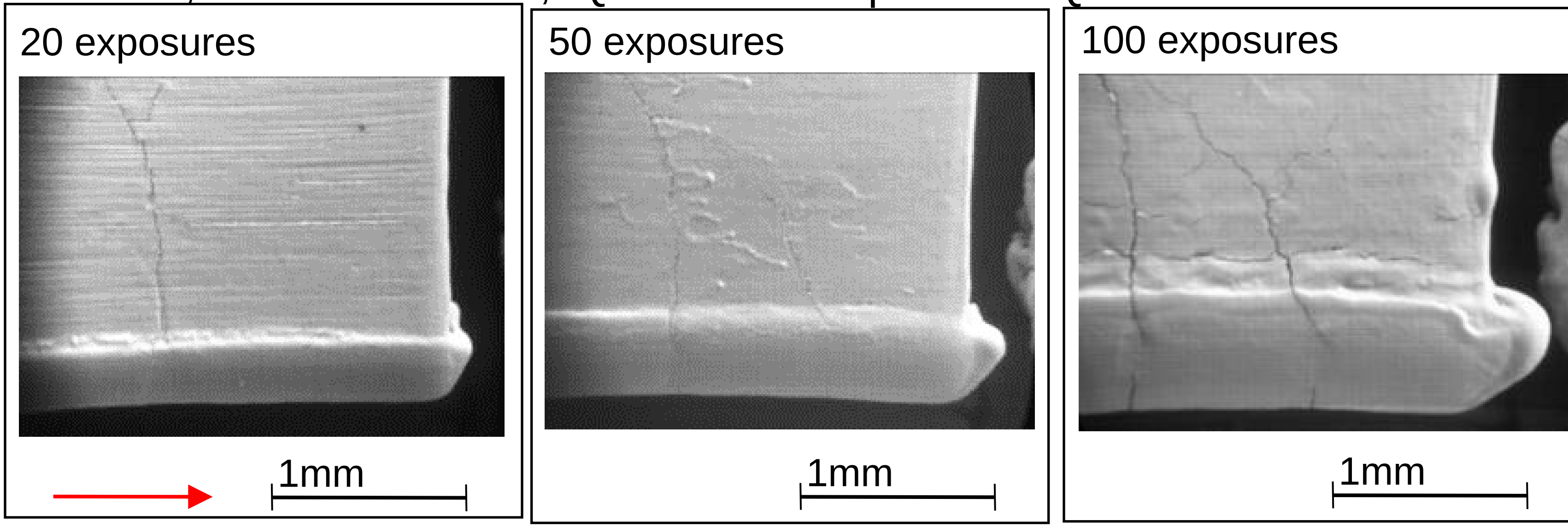
Outline

- **Motivation**
- **Methods for simulation of transient thermal shock events**
- **Comparison of different methods**
  - Parameters relevant to cracks
  - Surface Morphology after transient heat loads
- **Future Plans and experiments**
  - Laser heat load experiments (without plasma background)
  - Transient heat load experiments with plasma background.
- **Summary**

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

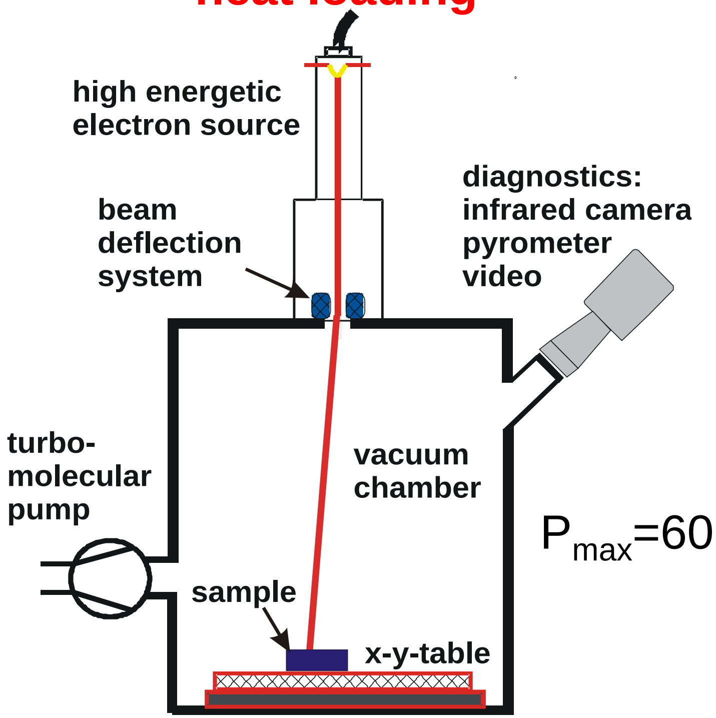
Estimates indicate that the ELM energy fluxes must remain below ~0.5 MJm^{-2} /ELM at the ITER divertor targets. This implies an ELM energy loss, ΔW_{ELM} ~ 1 MJ → ~0.3% of the stored energy in an ITER Q_{DT} = 10 burning plasma!

A. Loarte et al., “Power and particle fluxes at the plasma edge of ITER : Specifications and Physics Basis”, Nuclear Fusion… [Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)]

Methods

JUDITH 1 facility:

volumetric (several µm) heat loading



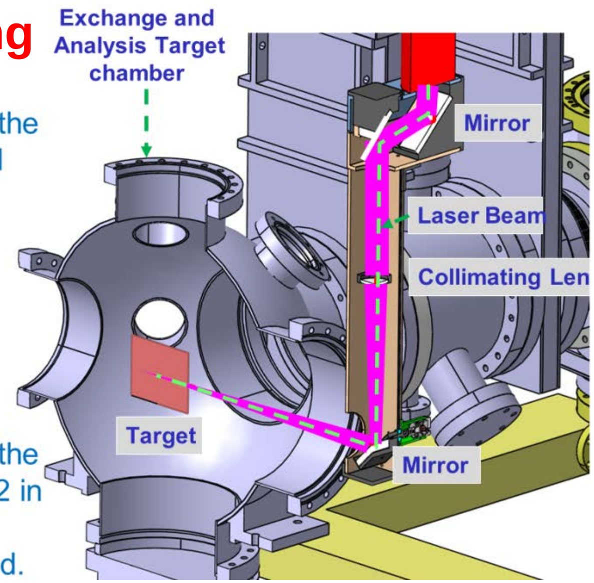
P_{max}=60kW

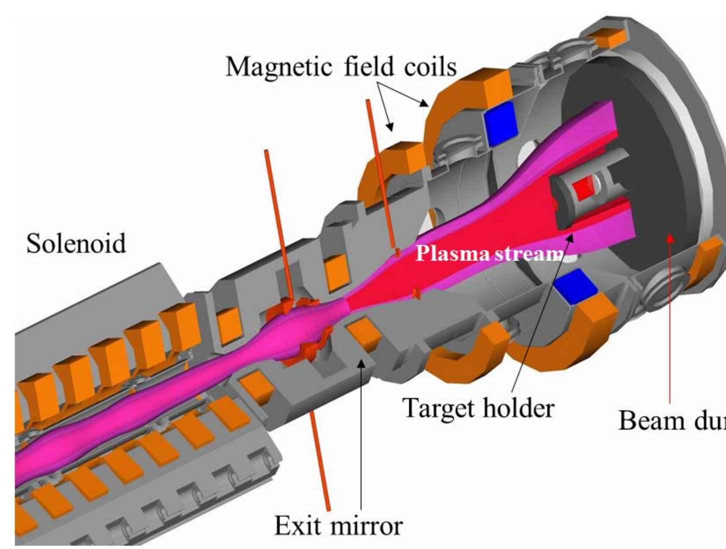
P= 0.19÷1.51 GW/m², pulse duration of 1ms. (ITER: max. W^{ELM}_{th}=0.5MJ/m²)

LASER System:

surface heat loading

- Measurements of the transient heat load without plasma background
- Measurements of the heat loads in PSI-2 in the presence of a plasma background.





JUDITH 1 facility:

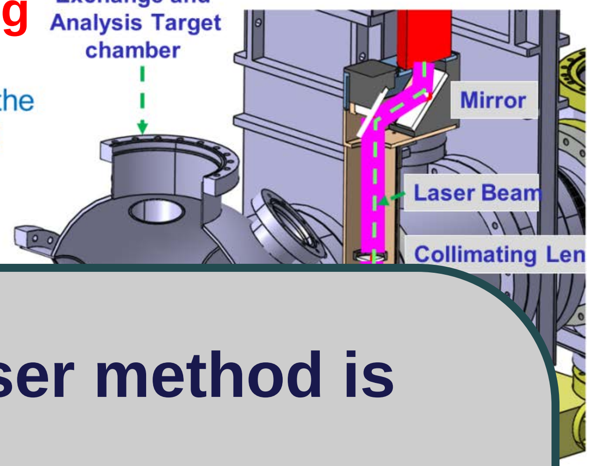
volumetric (several µm) heat loading

high energetic

LASER System:

surface heat loading

- Measurements of the transient heat load without plasma background

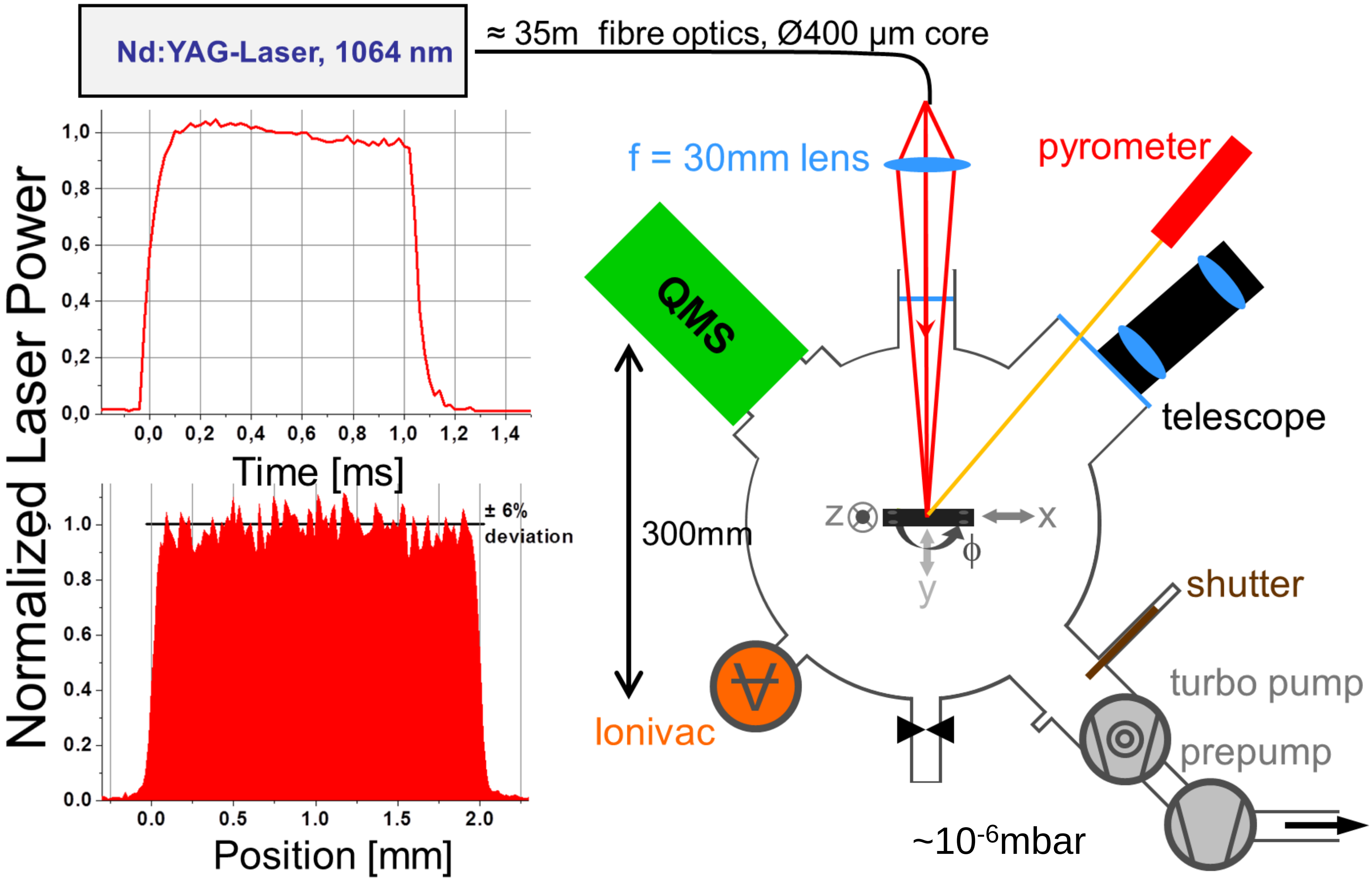


We wanted to know whether the laser method is comparable with the other ones

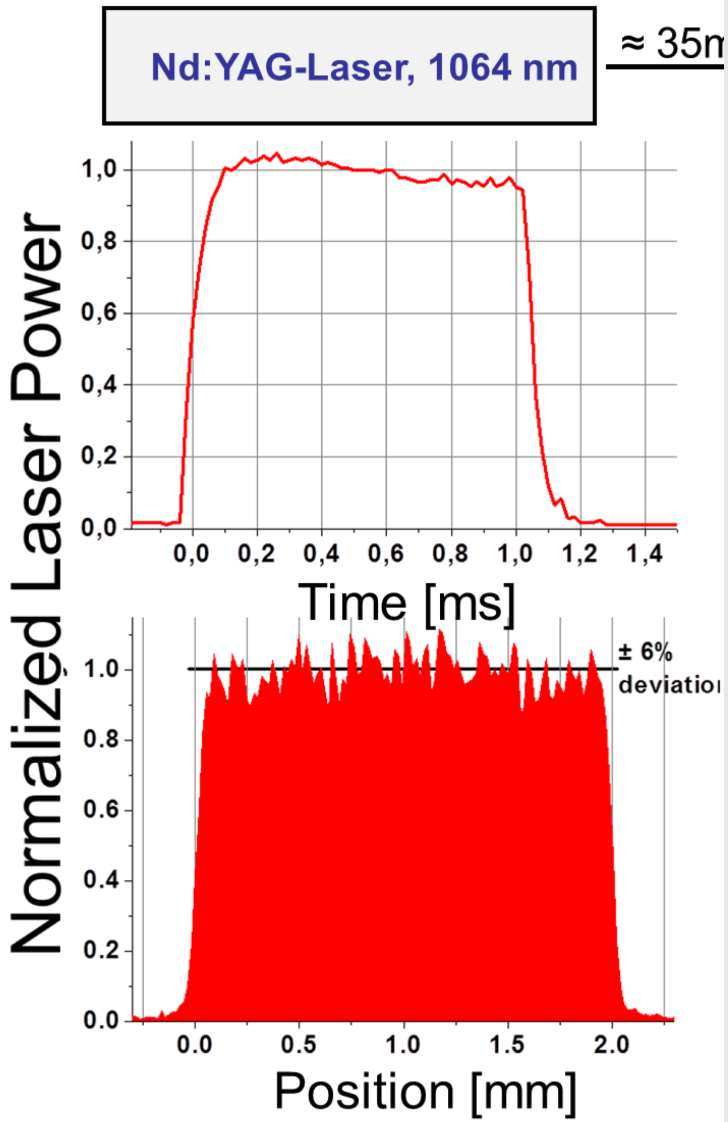
- the laser **pulse rate** can indeed be **much higher** and there is practically **no limit** to the overall **number of pulses**.

- Moreover, it is possible with the laser to **combine the transient heat loads with a steady state plasma exposure.**

Laser setup at Laserlab. Jülich



Laser setup at Laserlab. Jülich



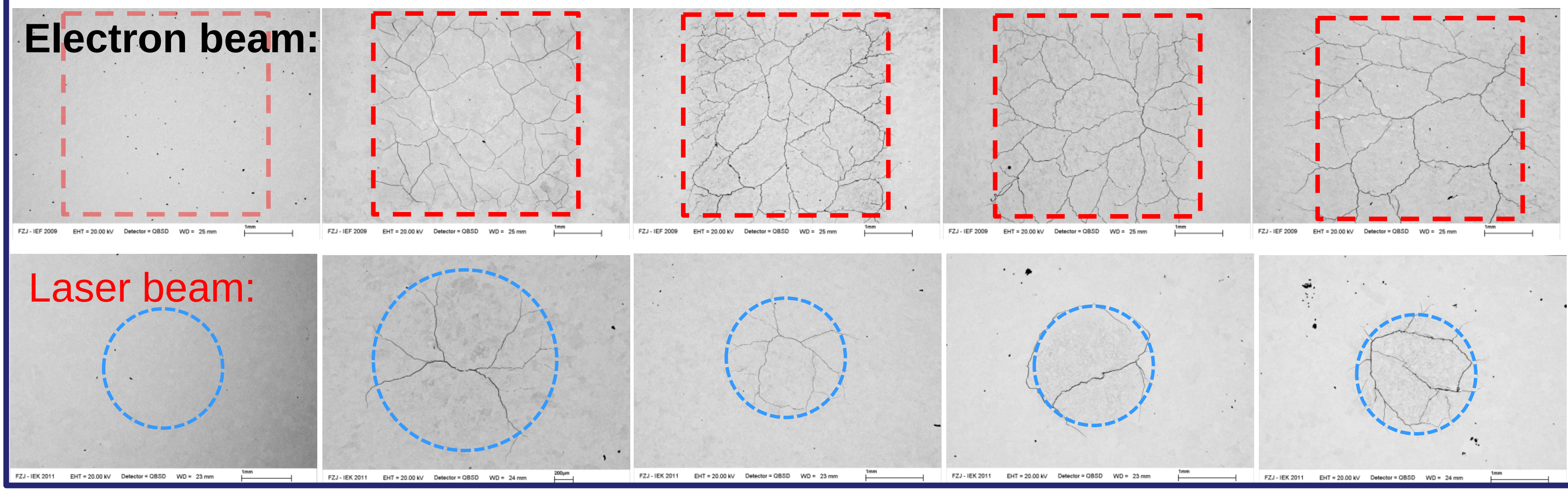
Standard settings for thermal loads:

1 ms pulse duration:
nearly square function

2 mm laser beam diameter
nearly hat top shape

0.5 Hz repetition rate
Heat power up to1.5 GW/m^2
heat flux factor: $I\sqrt{t} = 47$ $MW\sqrt{s}/m^2$)

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 !!!

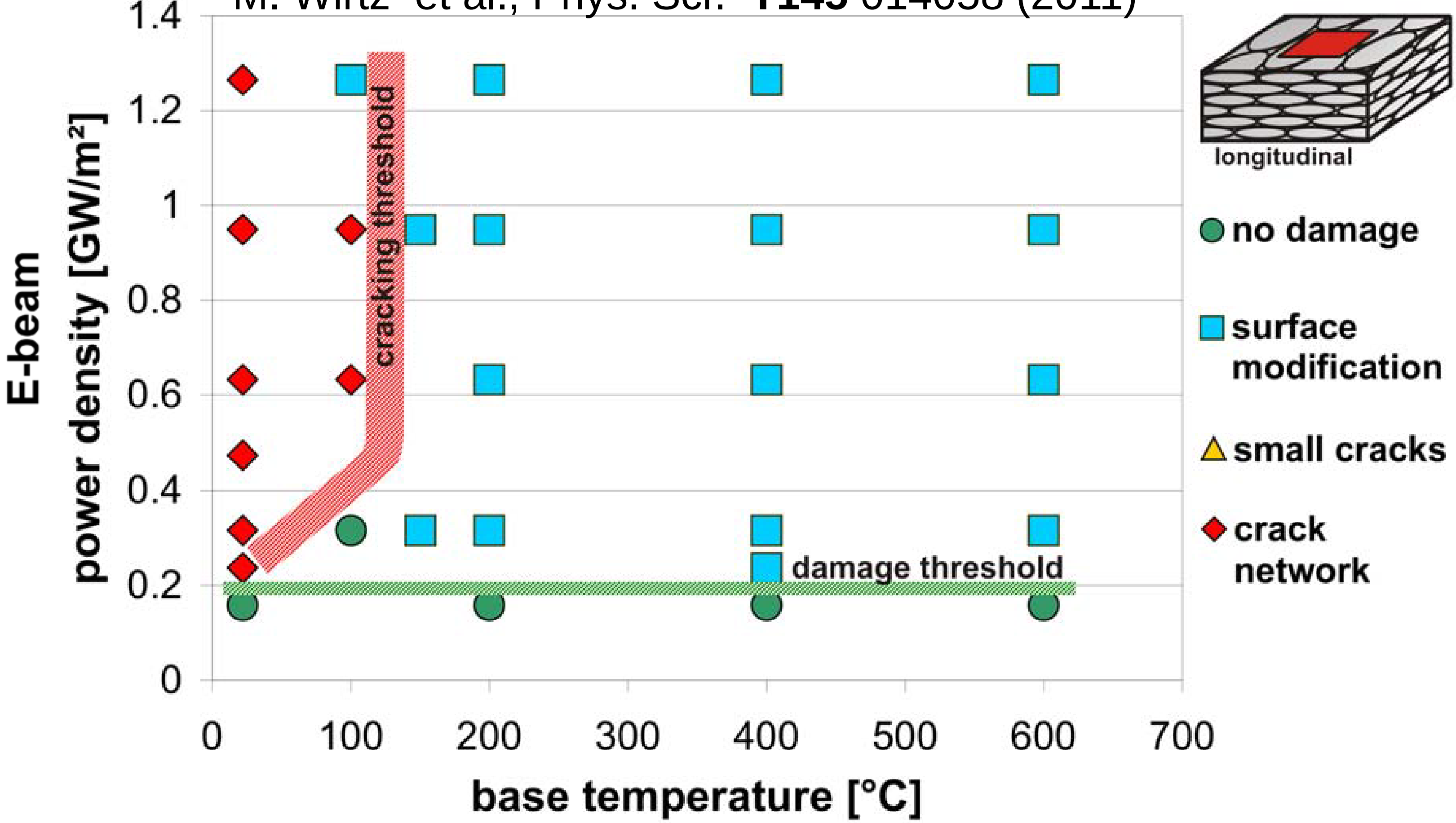
- At P= 0.19 GW/m² there are no cracks after repetitive electron as well laser loadings.
- Cracks network for P≥0.38 GW/m² for both methods

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

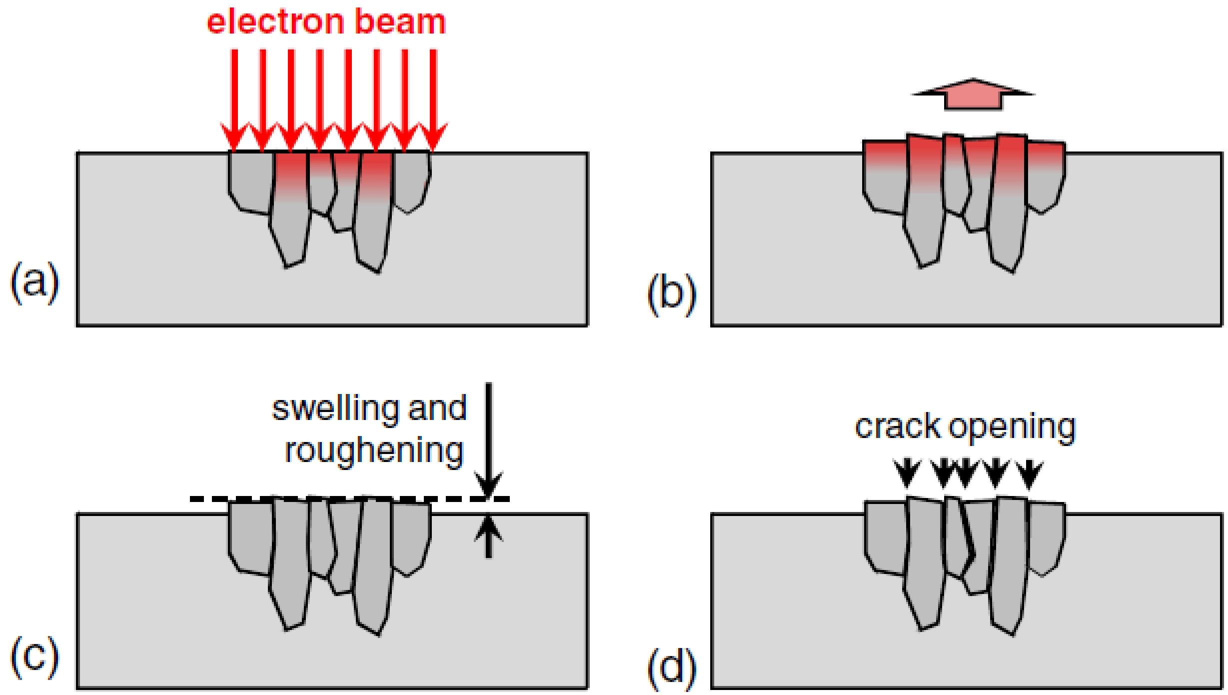
Thermal shock response of W-UHP L after 100 thermal shock events

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.

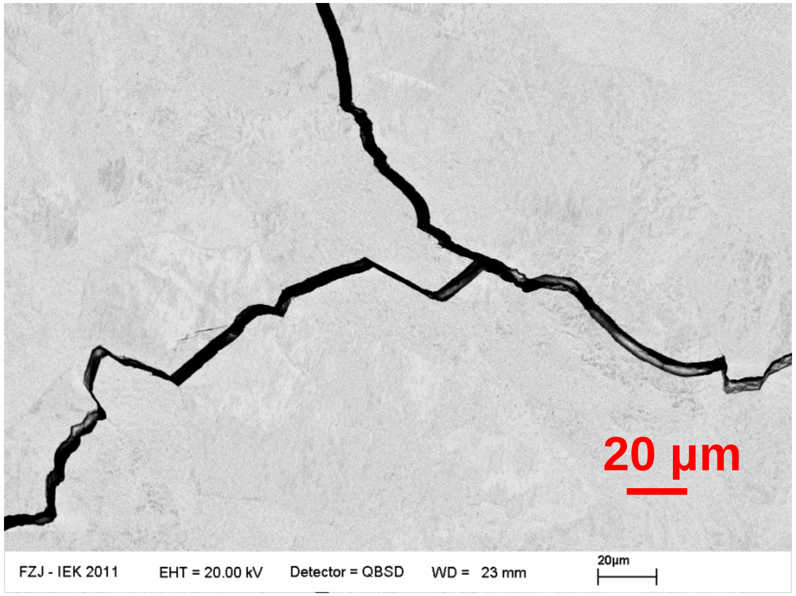
Mechanism of crack formation

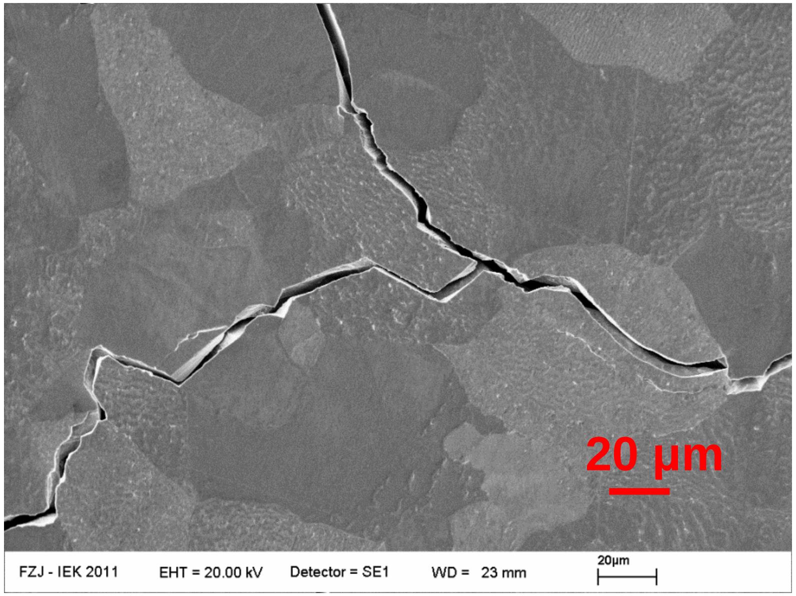


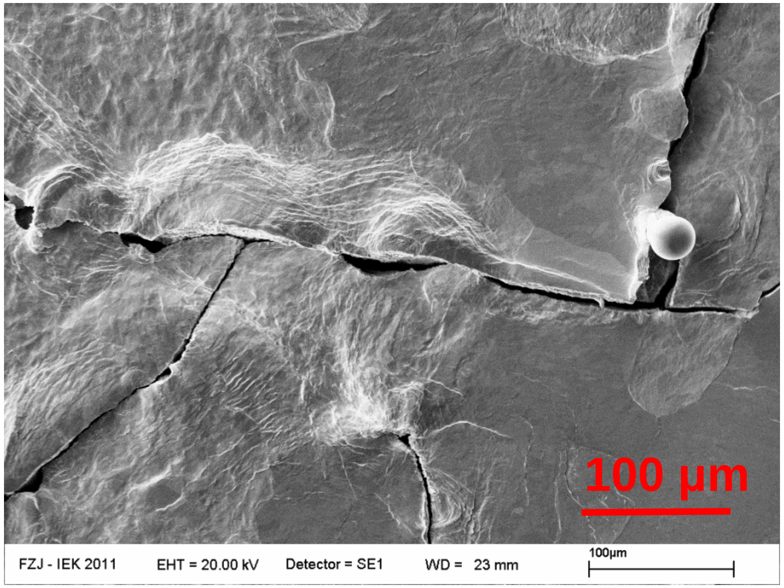
J. Linke et al. Nucl. Fusion 51 (2011) 073017

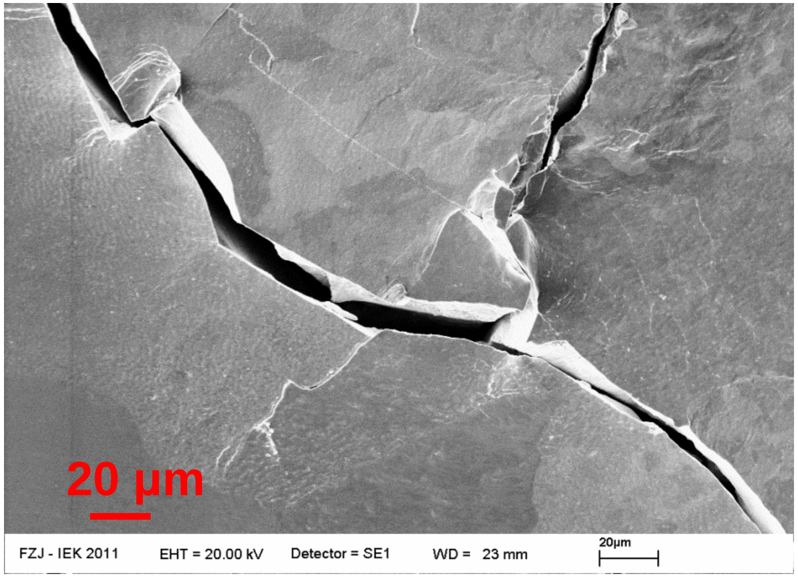
Cracks with an orientation parallel to the heated surface =>
subsequent delamination effects =>
overheating, melting and complete loss of the detached layer.

Cracks in high magnification





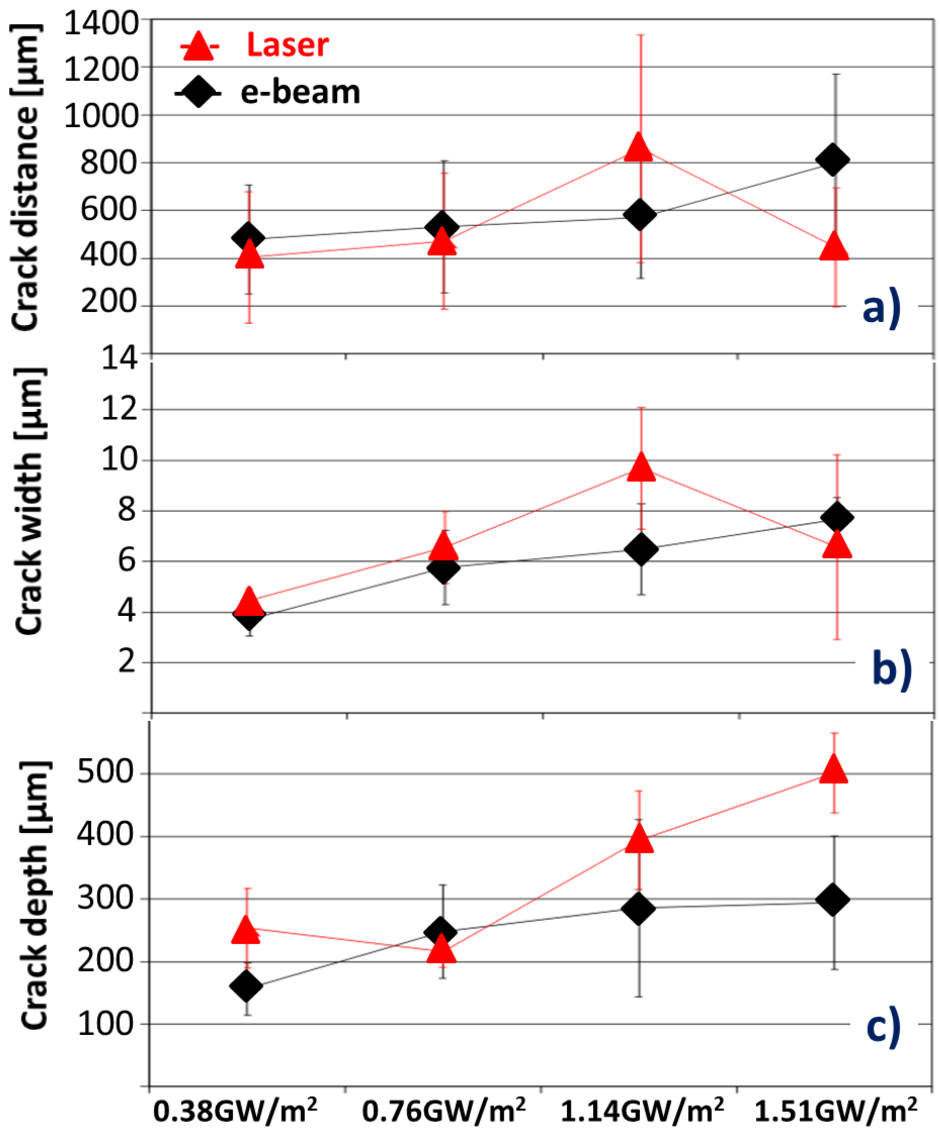




Crack formation: Electron vs. Laser beam

- Independently of loading methods, all observed crack parameter values increase with power density.
- Cracks extend perpendicularly to the irradiated surface to a depth of 100-500 µm.
- The observed crack width varied between 4 and 10µm.
- The cracks form a network with a distance between cracks in the order of 0.4-1.0 mm.

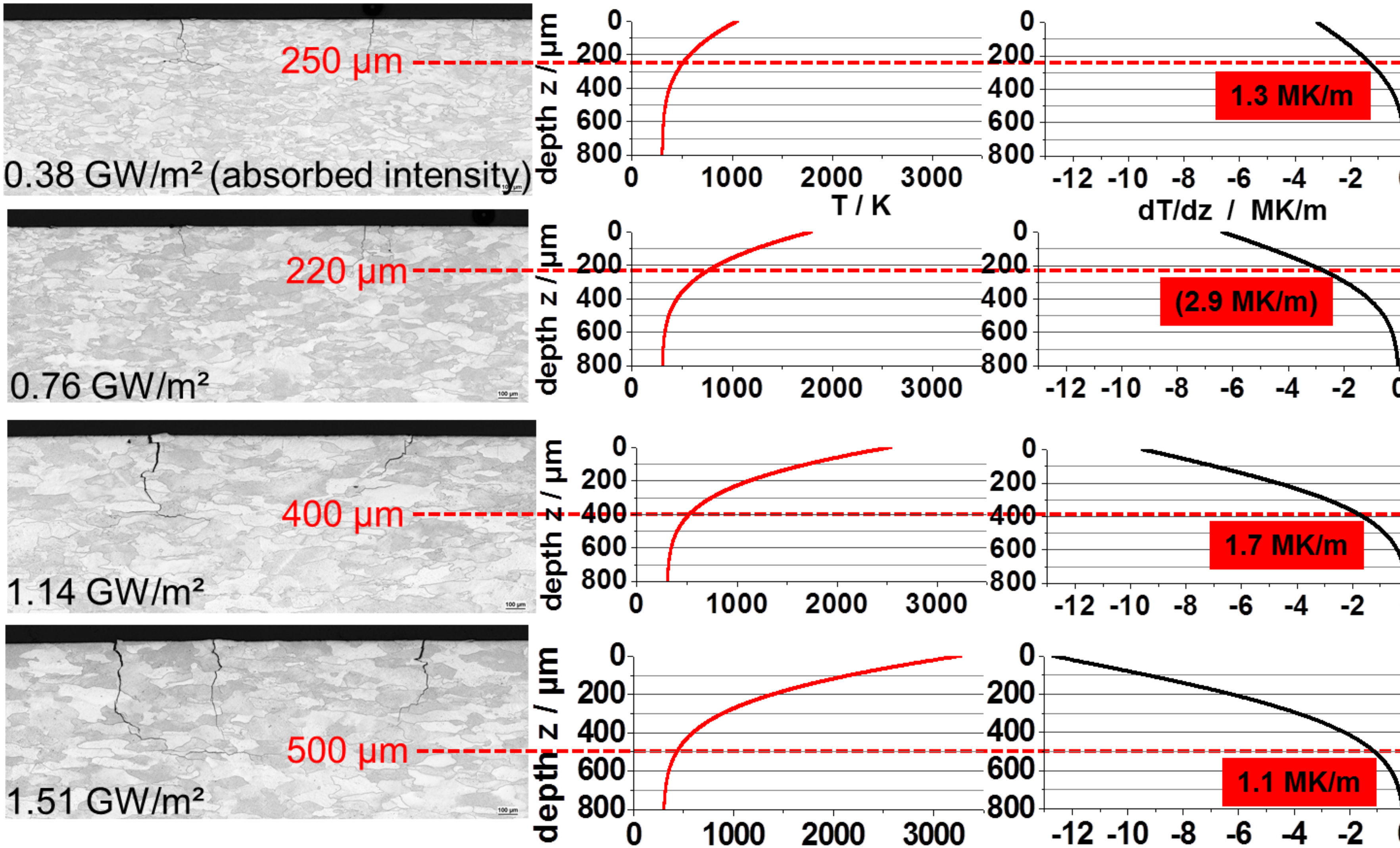
Cracking patterns parameters are very similar !!!



Crack depth

100 laser pulses of 1 ms, 2 mm diameter, 0.5 Hz, polished W (Plansee)

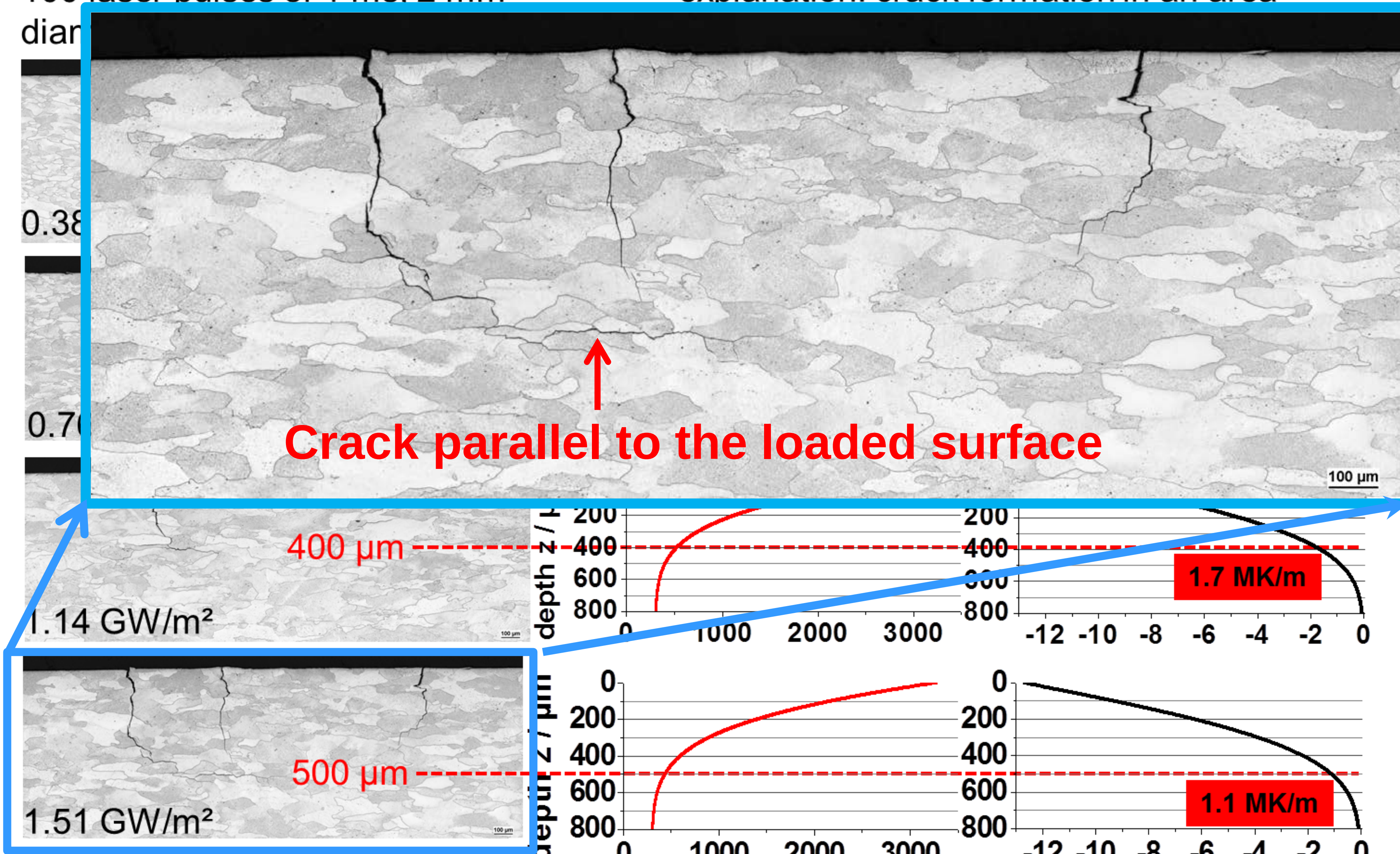
explanation: crack formation in an area with temperature gradient < -1.3 MK /m



Crack depth

100 laser pulses of 1 ms, 2 mm
diam

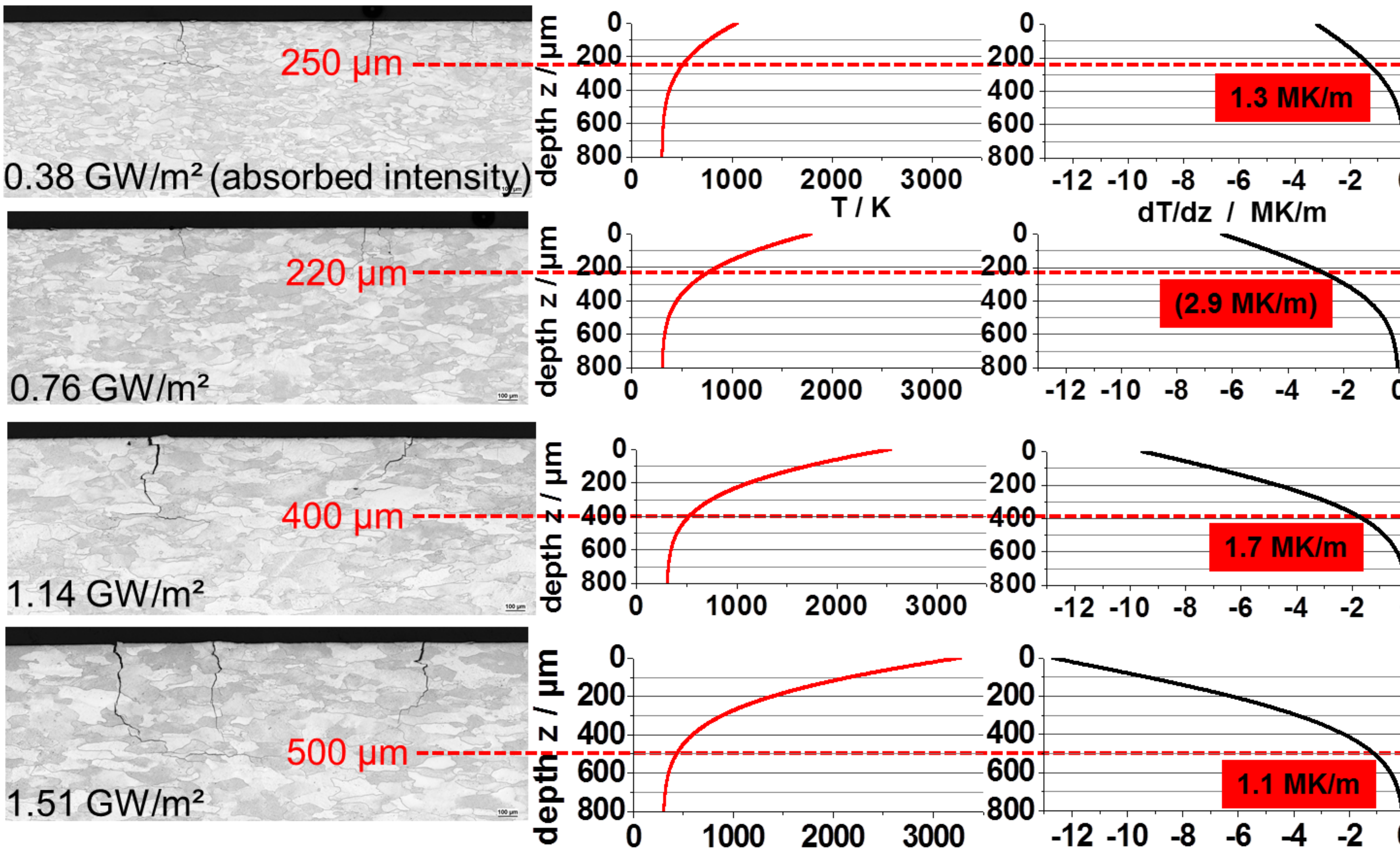
explanation: crack formation in an area



Crack depth

100 laser pulses of 1 ms, 2 mm diameter, 0.5 Hz, polished W (Plansee)

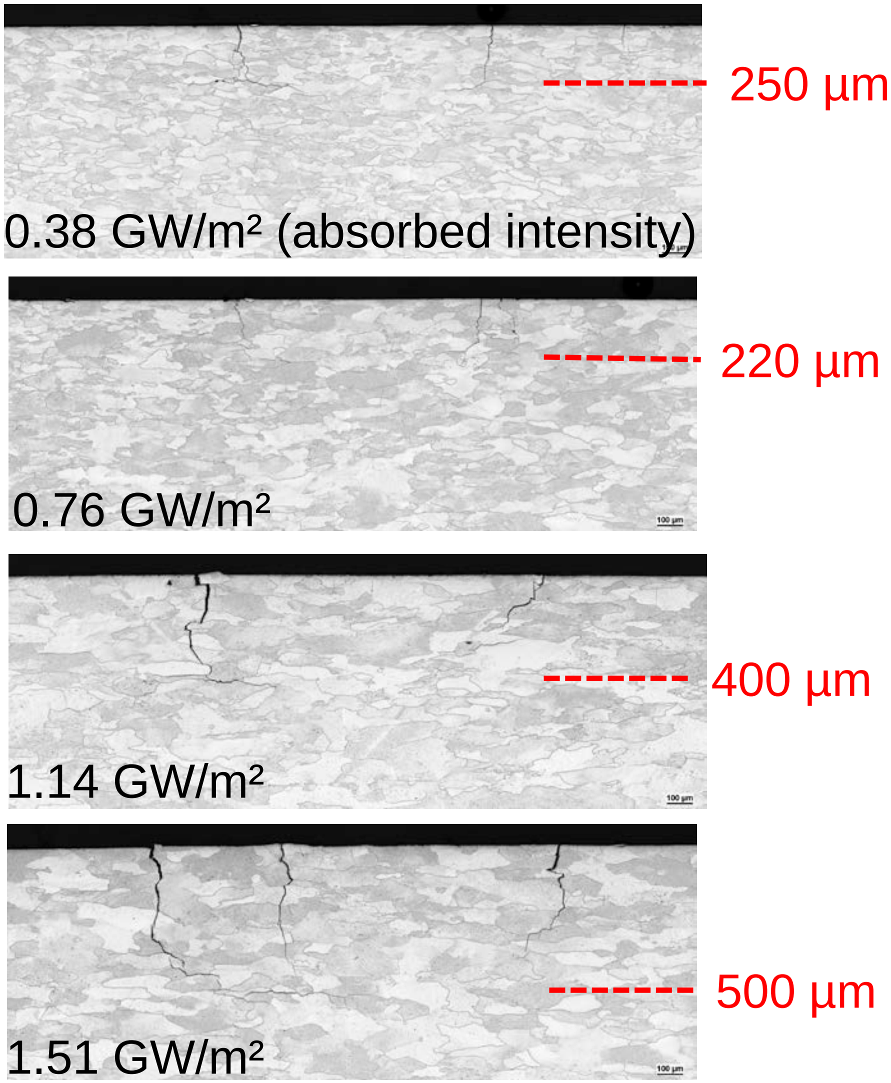
explanation: crack formation in an area with temperature gradient < -1.3 MK /m

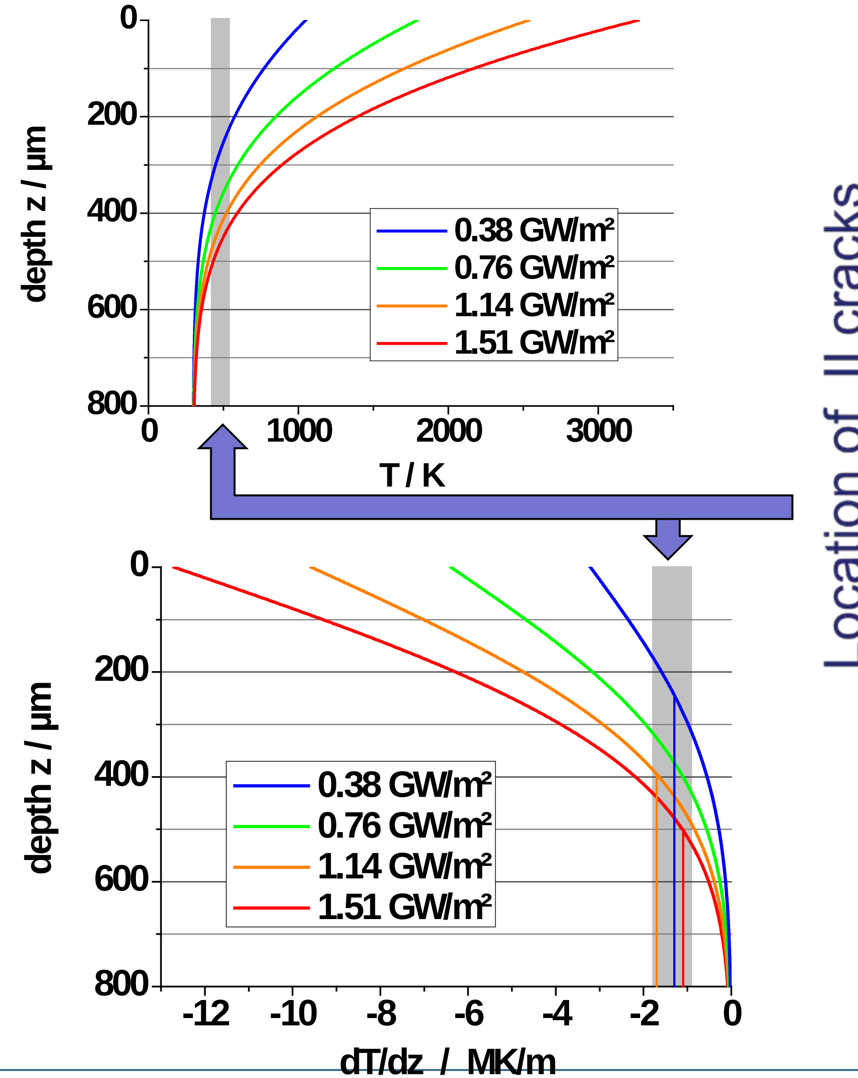


Crack depth

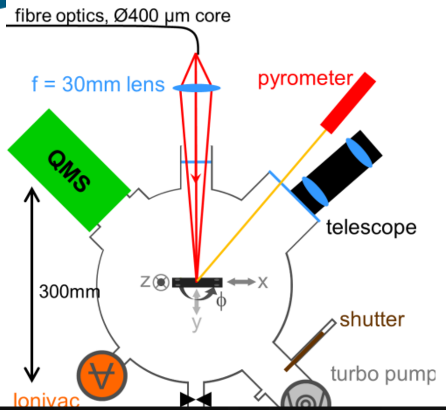
100 laser pulses of 1 ms, 2 mm diameter, 0.5 Hz, polished W (Plansee)

explanation: crack formation II to the surface in an area with T ~500 K –around DBTT – and a temperature gradient of 1.3-1.7 MK/m.

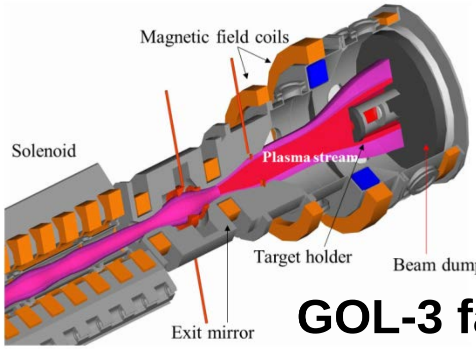




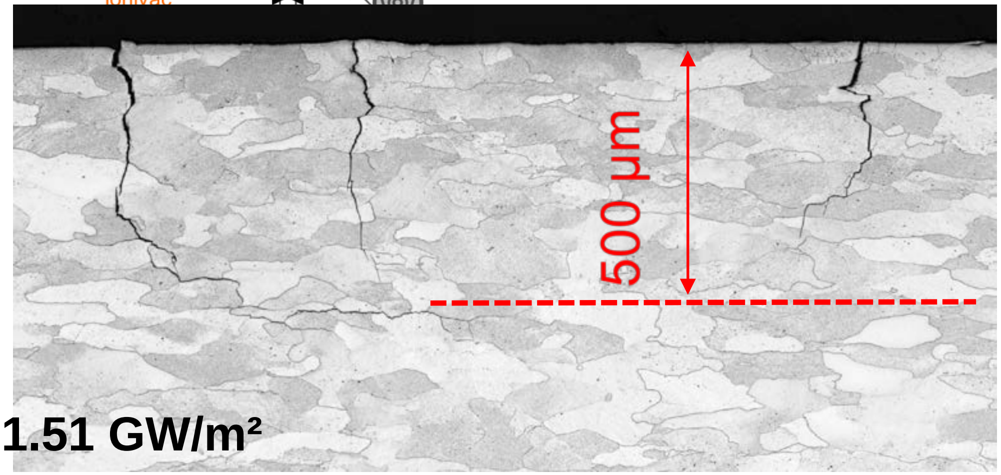
Crack depth



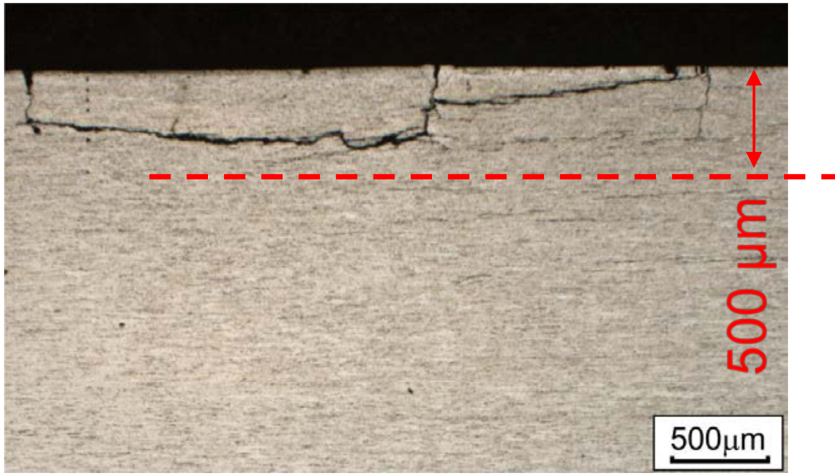
Laser irradiation



GOL-3 facility



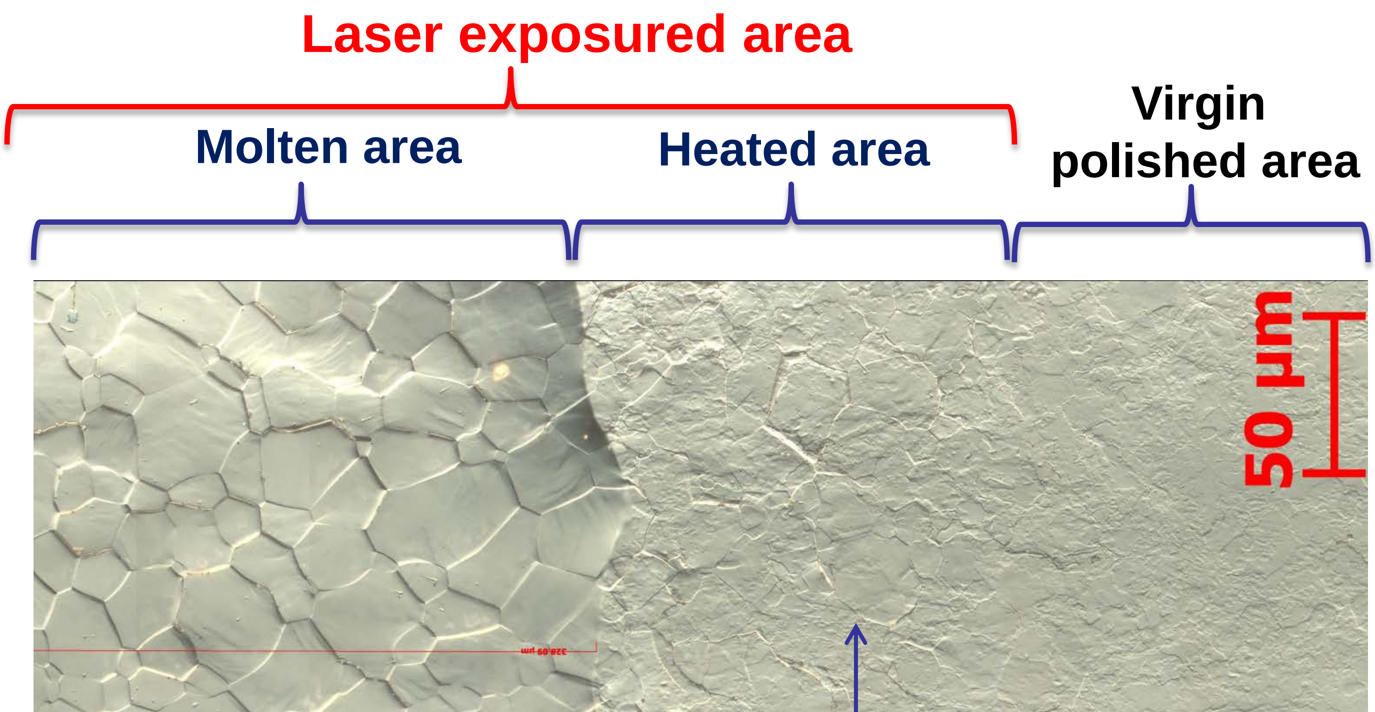
100 laser pulses of 1 ms, 2 mm diameter, 0.5 Hz, polished W (Plansee)



Crack propagation in the surface layer of the irradiated tungsten sample in GOL-3 2MJ/m^2

Similar crack parameters have been observed by transient heat loads simulations in the linear plasma device GOL-3

Roughening due to Laser heating



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

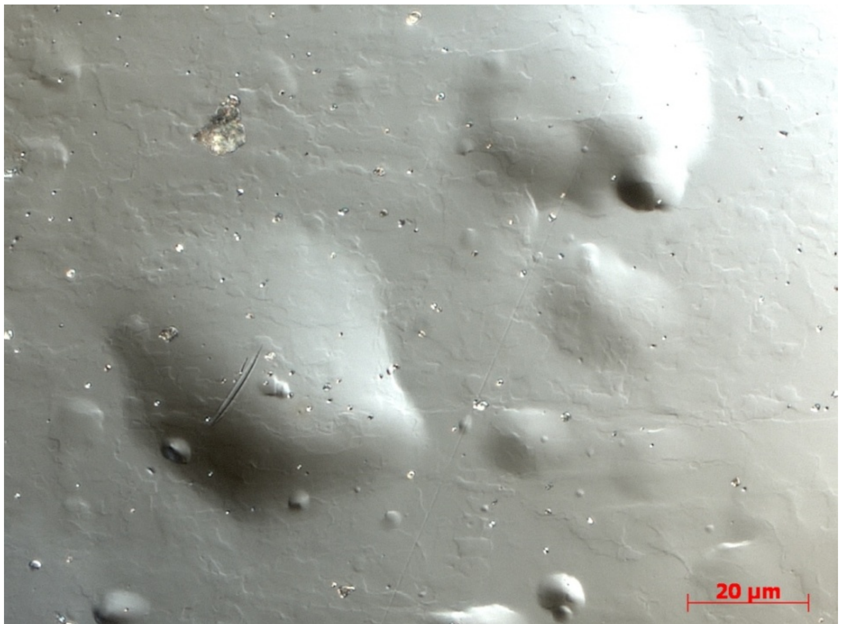
DIC optical microscopy

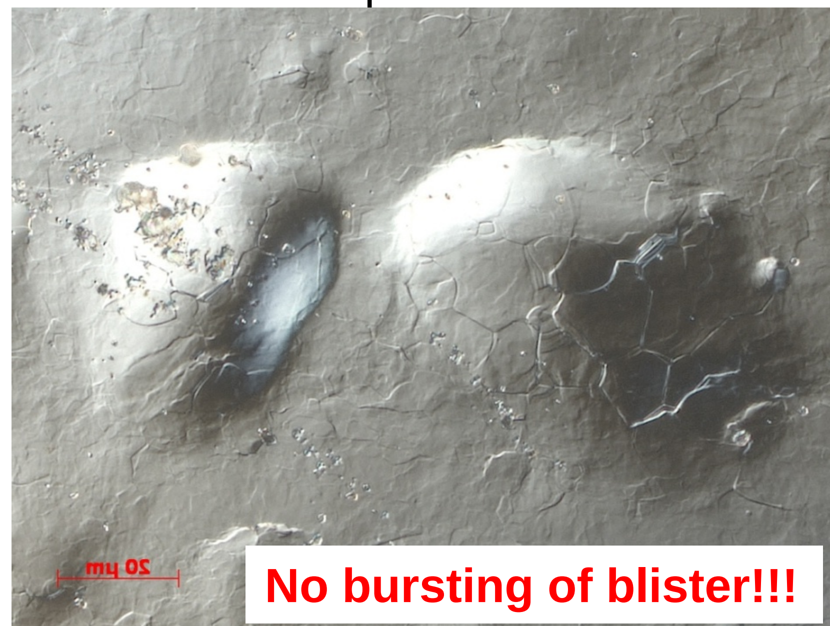
- Roughness increased by thermal shock loads: rougher in the melted area
- Roughness formation is independent of the loading methods.
- At P= 0.19 GW/m^2 there are no formation of roughness structure
- Beyond 0.2 GW/m^2: the surface roughening increase up to 2µm with P↑

blister behaviour

Before laser pulse: W with blisters due to D implantation: (fluence $6x10^{24}/m^2$, 480 K) up to 1 µm blister height

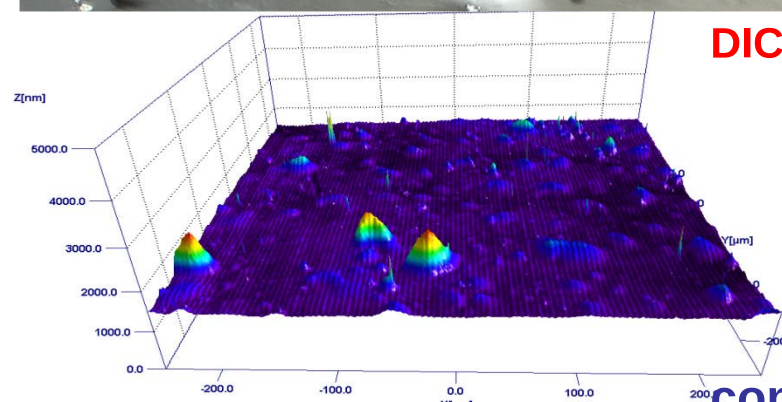
After laser heating pulse ($500MW/m^2$, 3ms duration, 2 pulses): blisters grow up to 4 µm, grain swelling due to thermal expansion

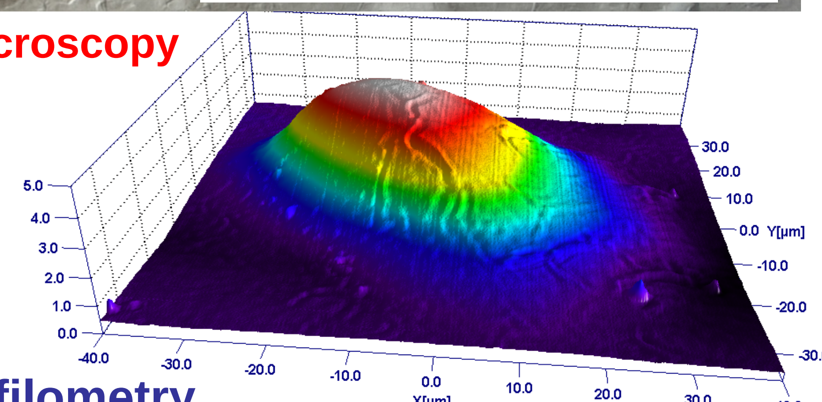




No bursting of blister!!!

DIC optical microscopy

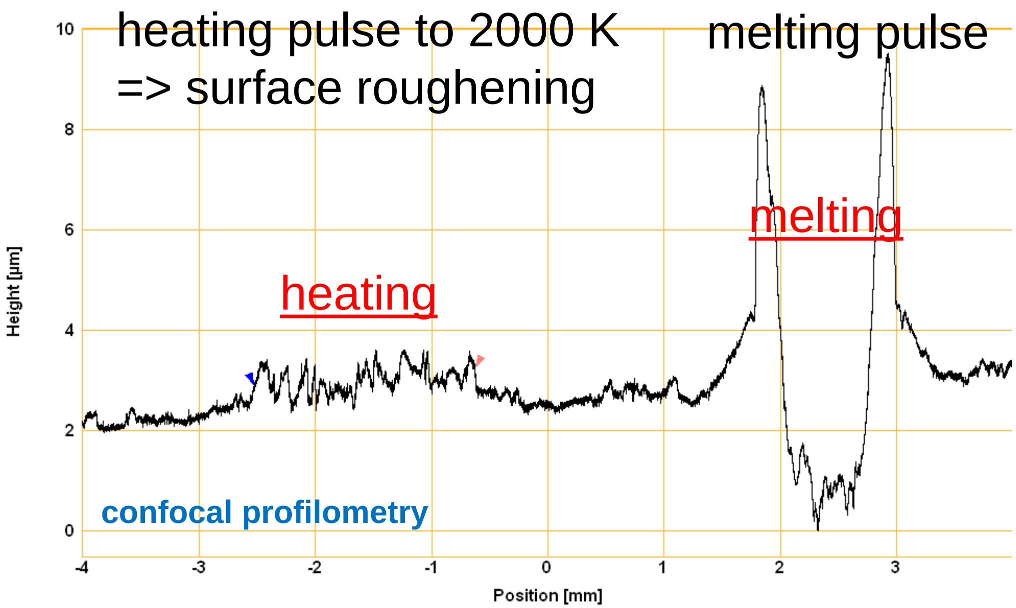


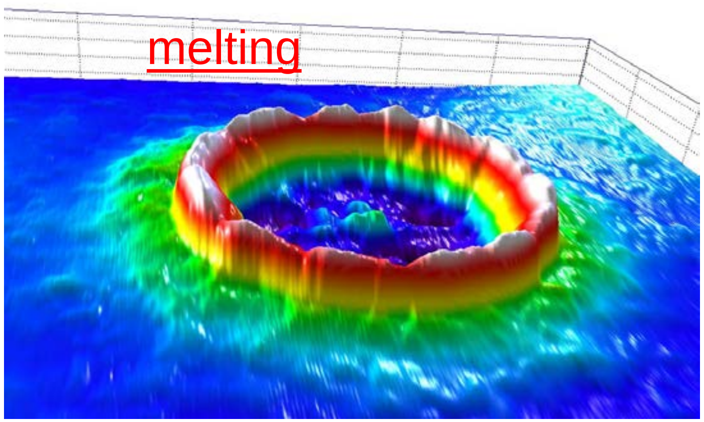


confocal profilometry

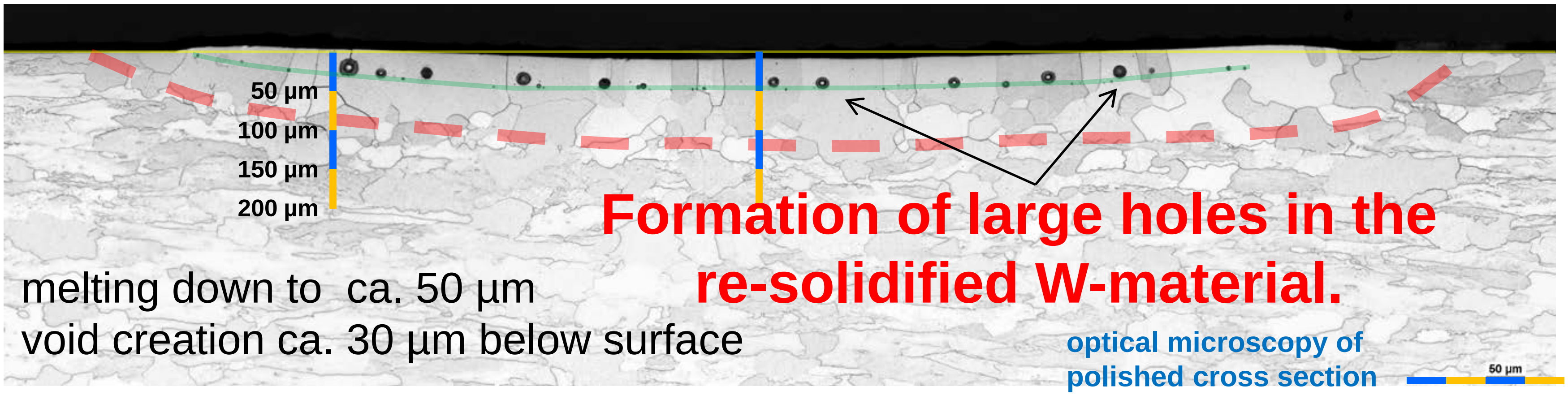
Surface Morphology after Laser Pulse

Surface profile of polished W after heating pulse (left) and melting pulse (right)





confocal profilometry

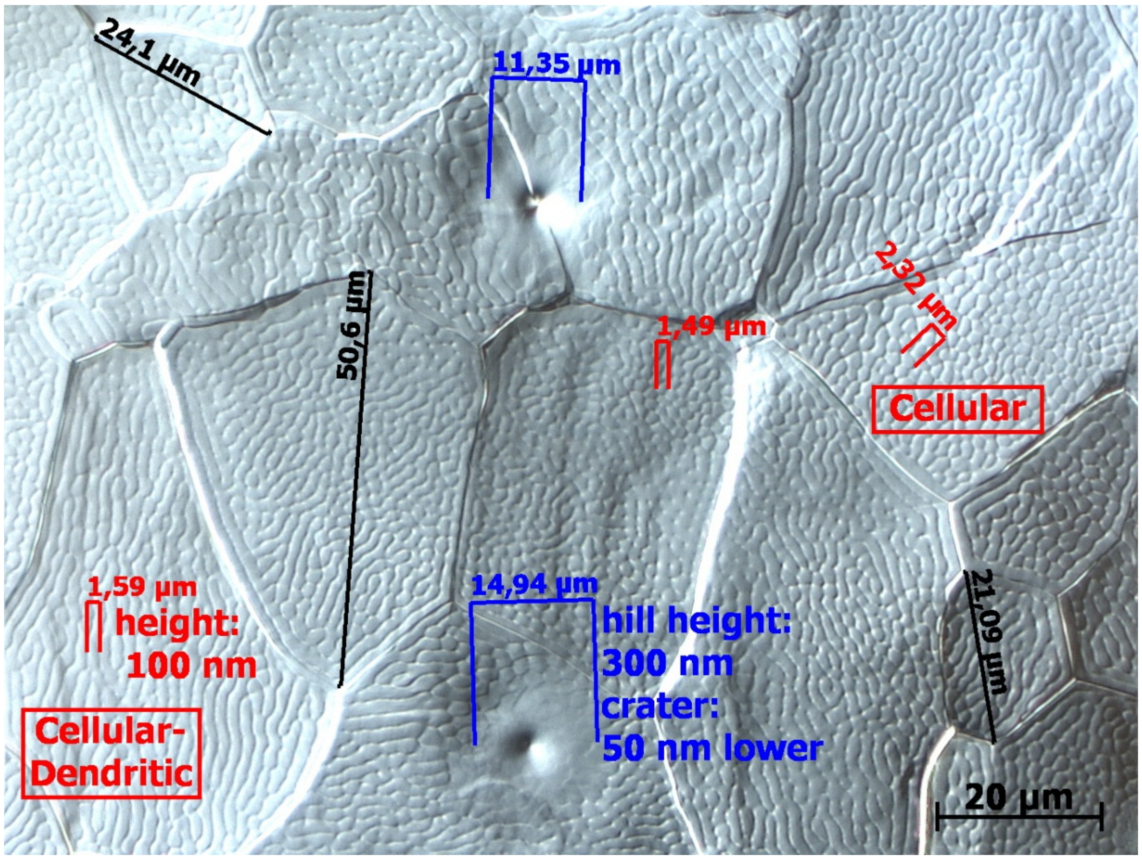


Formation of large holes in the re-solidified W-material.

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

optical microscopy of polished cross section

The area after the melted laser pulse



DIC optical Microscopy

- **The surface exhibits predominantly cellular structures inside the grains (due to surface stresses)**

Rapid cooling of thin melted layers

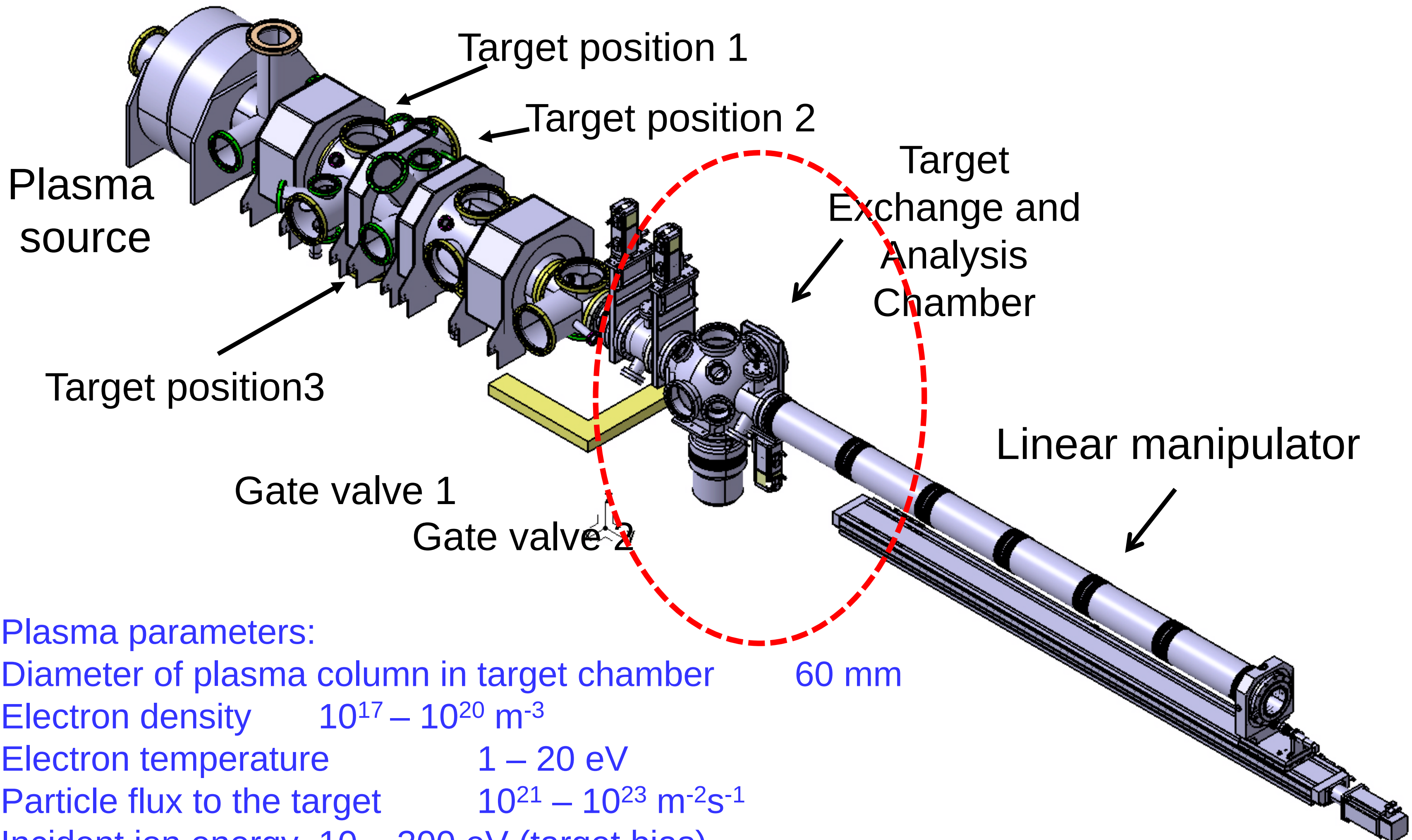
⇩

The surface material turns into a solid very quickly.

⇩

Rapid Solidification

Future plans for ELM simulation Experiments in PSI-2

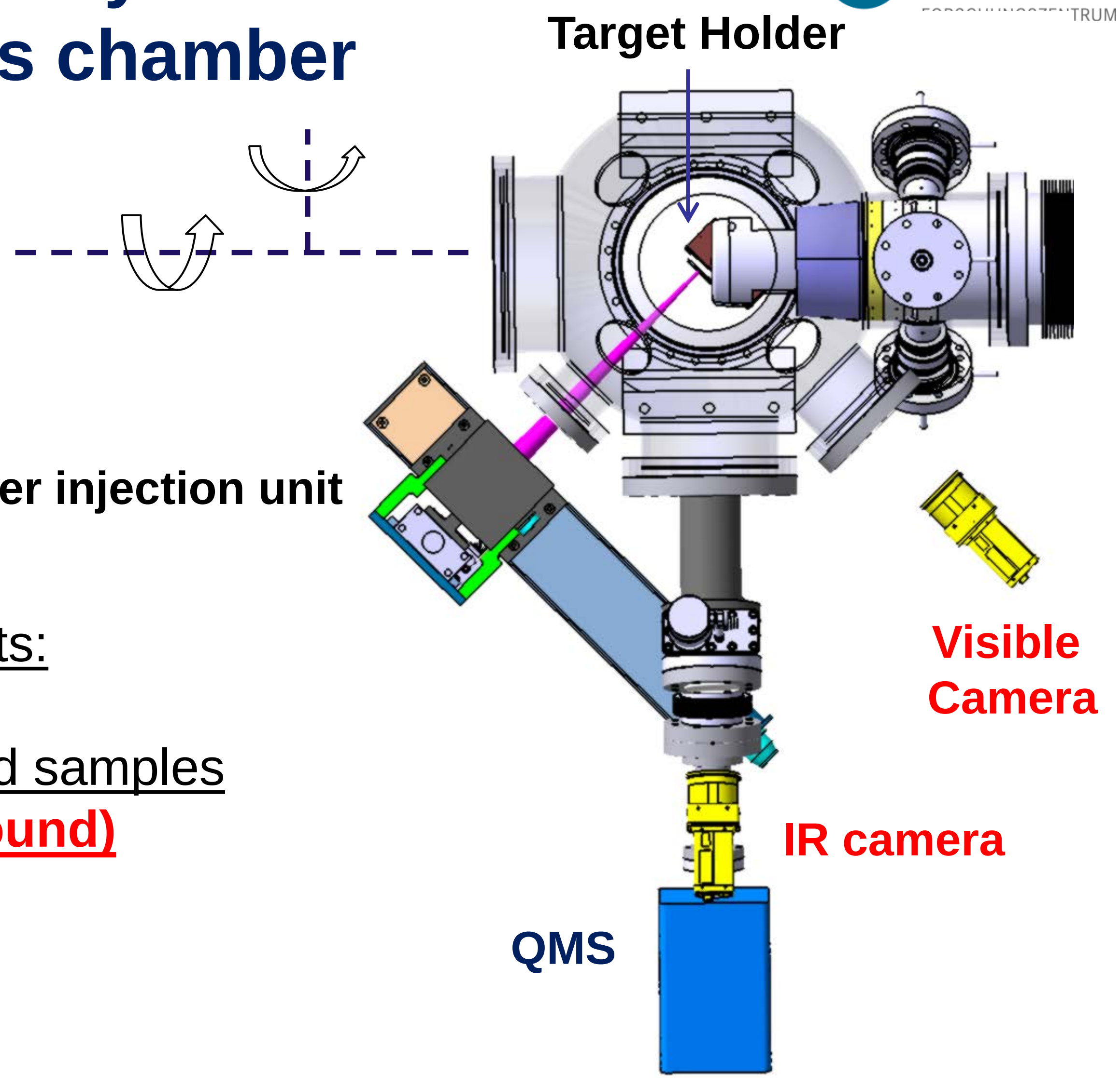


Plasma parameters:
Diameter of plasma column in target chamber 60 mm
Electron density $10^{17} – 10^{20}$ m^{-3}
Electron temperature 1 – 20 eV
Particle flux to the target $10^{21} – 10^{23}$ $m^{-2}s^{-1}$
Incident ion energy 10 – 300 eV (target bias)
Min. neutral gas pressure in target chamber 10^{-2} Pa

Laser exposure system at PSI-2 analysis chamber

Target Holder:

- rotatable
- heatable up to 600 ^{0}C
- with active cooling
- exchangeable



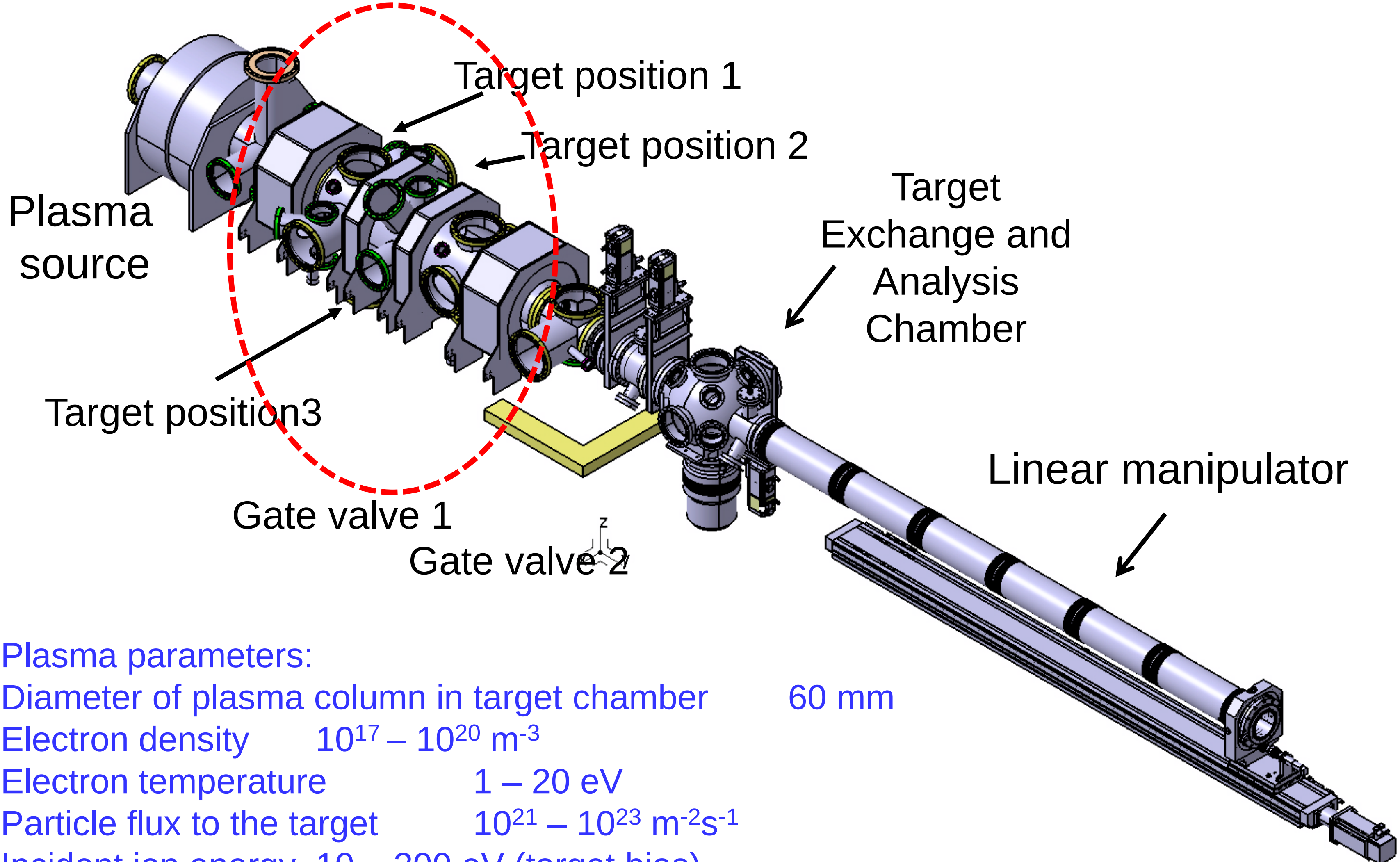
Laser heat load experiments:

- Unexposed and
- Plasma pre-exposed samples

(without plasma background)

Without breaking the vacuum in the plasma chamber the probes can be removed easily for post mortem analysis.

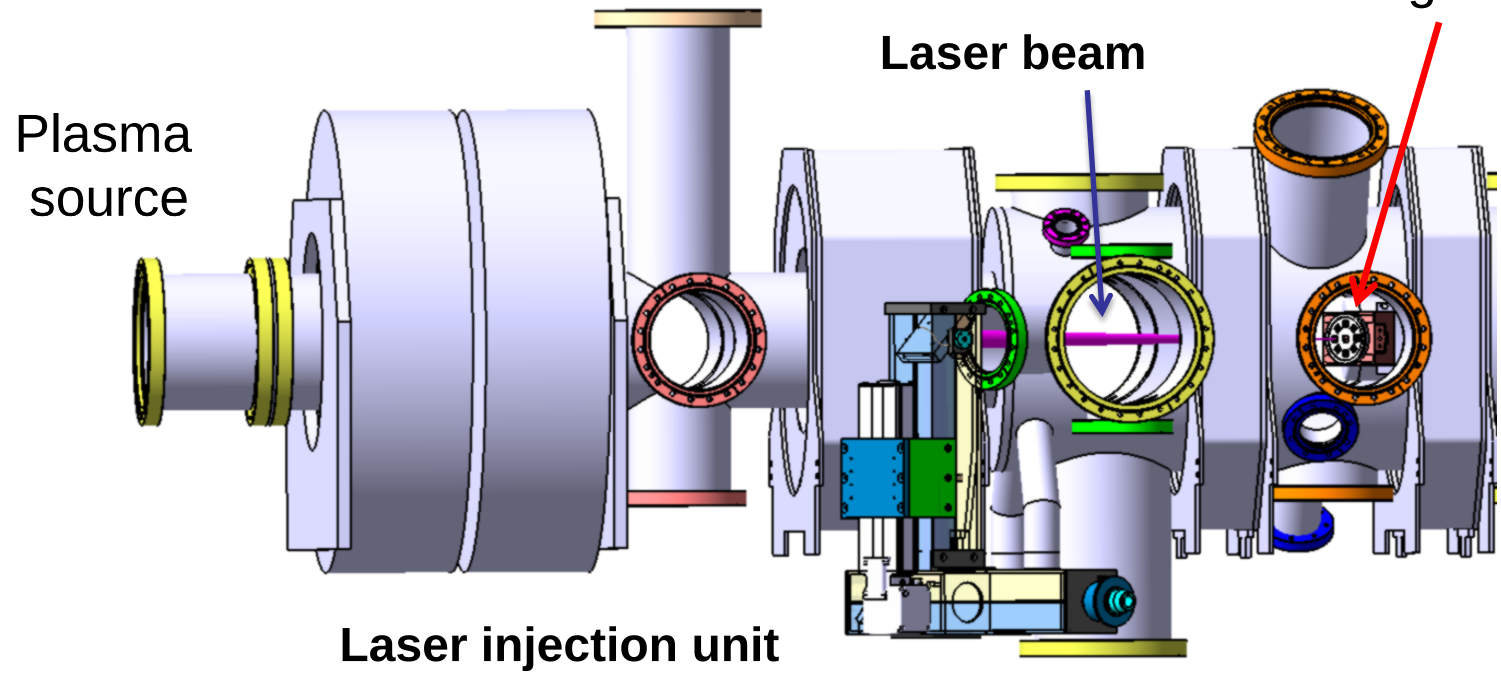
Future plans for ELM simulation Experiments in PSI-2



Plasma parameters:
Diameter of plasma column in target chamber 60 mm
Electron density $10^{17} – 10^{20}$ m^{-3}
Electron temperature 1 – 20 eV
Particle flux to the target $10^{21} – 10^{23}$ $m^{-2}s^{-1}$
Incident ion energy 10 – 300 eV (target bias)
Min. neutral gas pressure in target chamber 10^{-2} Pa

Laser exposure system at PSI-2

Target Holder:
- rotatable
- heatable up to 1600 ^{0}C
- with active cooling
- exchangeable



- Transient heat load experiments in the PSI-2 facility simultaneously to a steady state plasma exposure **(with plasma background)**.

Summary

- Volumetric loading with the electron beam (penetration depth in W in the µm range) has been compared with surface loading with the laser beam (22 nm light decay length) and plasma gun

- Results indicate that the different techniques show, in general, similar damage behaviours and the same damage thresholds

- The laser simulation is comparable to e-beam and plasma methods.

- Since the laser method is successful, one can use its advantages:
  - - no restrictions on pulse number (can be much higher than in other methods)
  - - can be applied simultaneously to a steady state plasma exposure

➢ Physics results:

- Independently of loading methods, observed crack parameter values increase with power density
- Cracks ⊥ to the irradiated surface: to a depth of 100-500 µm. width varied between 4 and 10µm, distance between cracks in the order of 0.4-1.0 mm.
- Cracks || to the loaded surface: formation in areas with T ~500K –around DBTT – and a temperature gradient of 1.3-1.7 MK/m.
- surface roughness after heat loading
- Surface Morphology after laser melt Pulse: predominantly the cellular structures, holes in the re-solidified W-material