Accelerated lifetime tests of ITER-like tungsten monoblocks in Magnum-PSI

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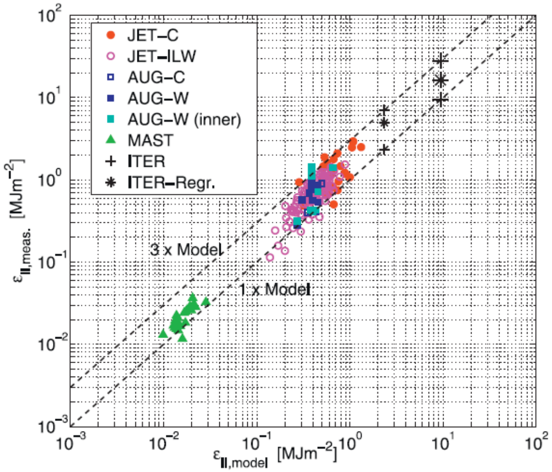
EUROfusion

DIFFER

NWO

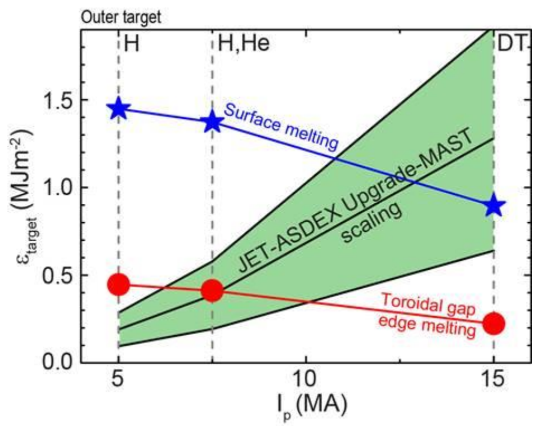
Expected lifetime limits for ELM-like loading in ITER

Multi-machine scaling now gives a good regression to estimate unmitigated type-I ELM-loads in ITER



T. Eich et al. *Nucl. Mater. Energy* (2017)

Taking this scaling and translating it into operational limits for the divertor implies that very strong ELM mitigation is required to avoid edge melting



J.P. Gunn et al. *Nucl. Fusion* (2017)
R.A. Pitts *Nucl. Mater. Energy* (2019)

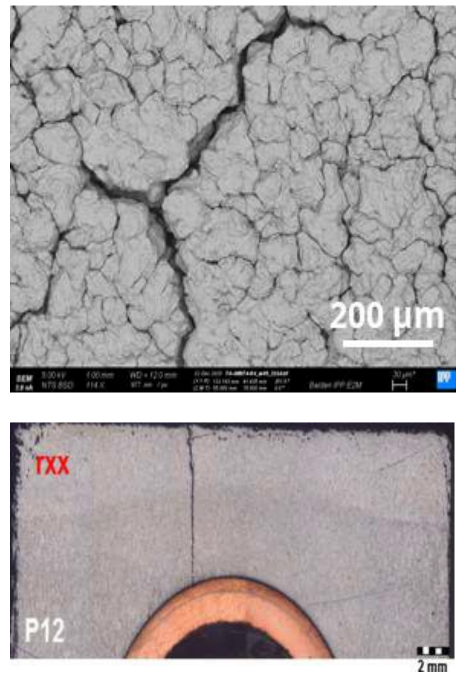
Avoiding surface damage fatigue implies even lower limits

PFCs are also vulnerable to surface crack-network development due to fatigue failure (~10^6 ELMs in ~100 DT shots ITER*)

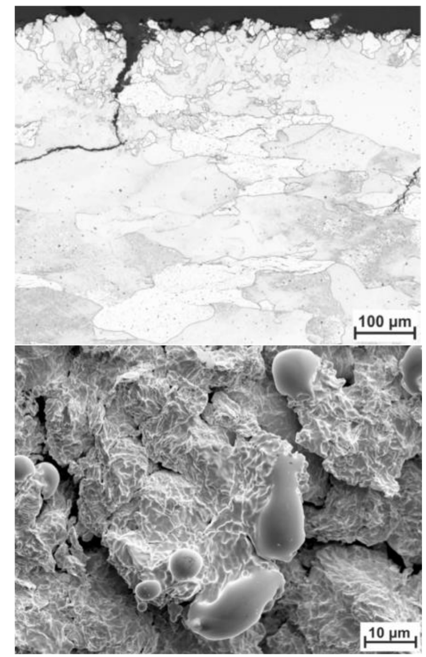
Threshold for this is significantly lower than toroidal gap edge melting

How significant is this damage for PFC performance?

- Risk to increase likelihood of macro-cracking through stress concentration?
- Can the strong roughening created increase erosion?
- Can the isolated grains caused by cracking be lost or melt?



Pintsuk et al. *Fusion Eng. Des.* (2013)



Wirtz et al. *Nucl. Mater. Energy* (2017)

*R.A. Pitts *Nucl. Mater. Energy* (2019)

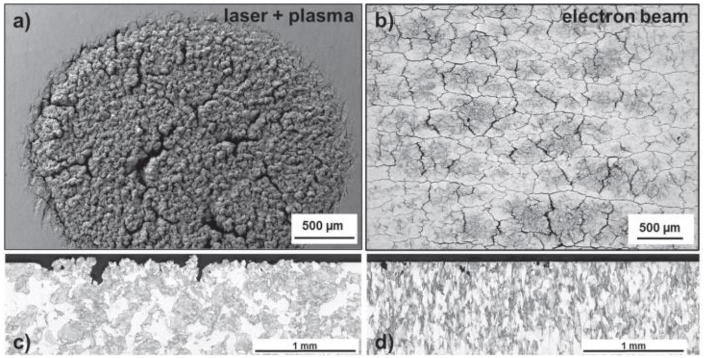
Influence of plasma on material behaviour

Most fatigue studies involve high-heat flux devices without considering plasma effects

However plasma loading and ELM loading both predominantly affect the surface region

Synergy may occur, increasing the damage level, when plasma loading is combined with transient loads (e.g*)

In particular, for high fluences of plasma, which are barely explored, the question is therefore:



* Wirtz et al. *Phys. Scr.* (2017)

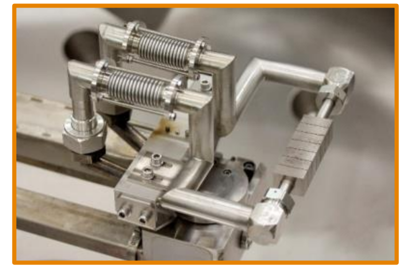
What is the influence of plasma loading on tungsten PFU fatigue limits?

Investigation using Magnum-PSI to reach high fluences and high cycle number simultaneously

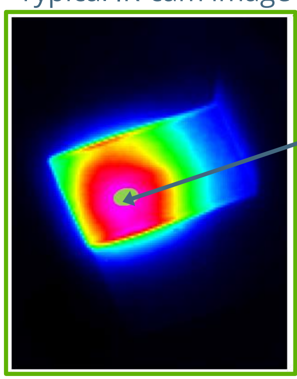
Take advantage of steady-state operations of Magnum-PSI with superconducting magnet

Use a high-power welding laser to recreate up to 10^6 ELM-like loading events (1 ms)

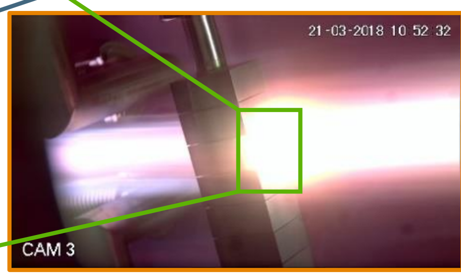
ITER monoblock mock-up chain mounted in Magnum-PSI

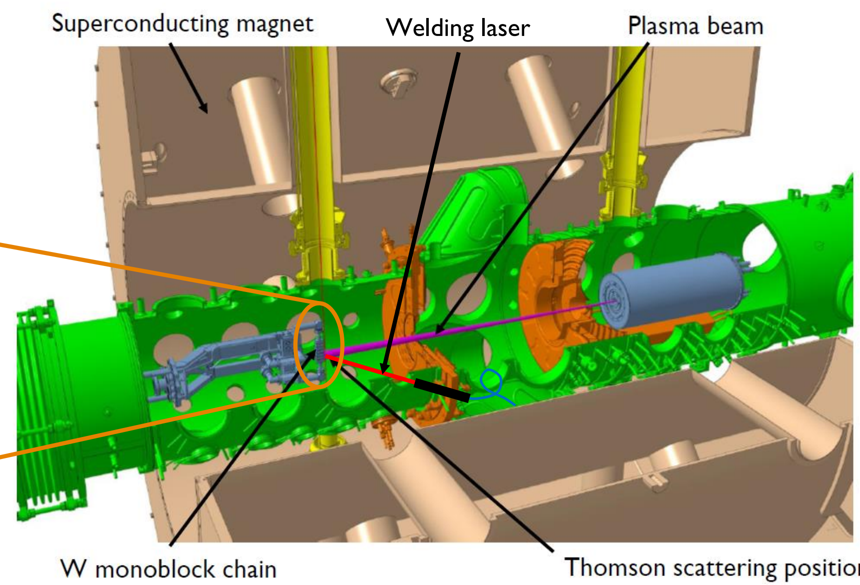


Typical IR-cam image

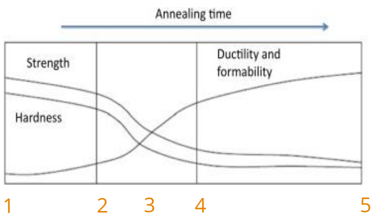


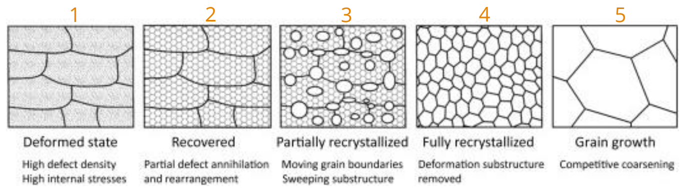
T.W. Morgan et al., *Phys. Scr.* (2020)





Plasma and laser loading conditions





Raabe, *Physical Metallurgy* (2014)

Vary base temperature to investigate evolution of different microstructures

T_{base}	750 °C 1	1150 °C 2	1500 °C 4
Gas species	H, H+He (6.5 ion%) H+Ne (8 ion%) H+He+Ne (6.5+8 ion%)	H, H+He (6.5 ion%) H+Ne (8 ion%)	H, H+He (6.5 ion%) H+Ne (8 ion%)
Γ_{peak} $(m^{-2}\ s^{-1})$	~3-3.5×10^{24}	~1.5-2.1×10^{24}	1.2-4.3×10^{24}
Φ_{peak} (m^{-2})	~2-2.5×10^{28}	1-1.4×10^{28}	0.8-2.8×10^{28}
Laser HFF $(MW\ m^{-2}\ s^{0.5})$	2.6-12.9	3.7-5.8	3.7-5.8
Laser N_{pulses}	10^4-10^6	4×10^5	4×10^5

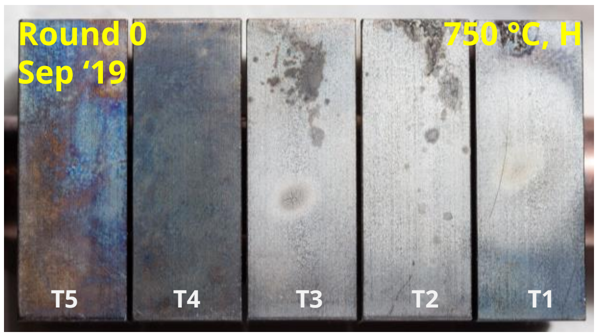
Including He ash or seeding impurity

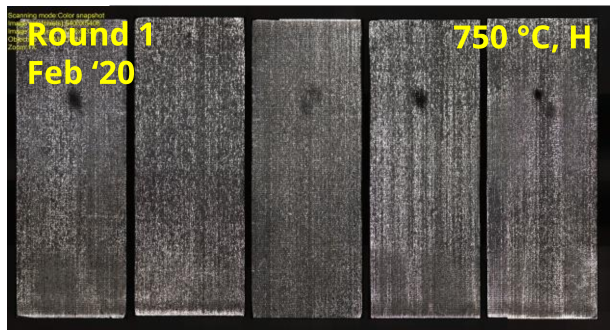
Achieve high flux/fluence

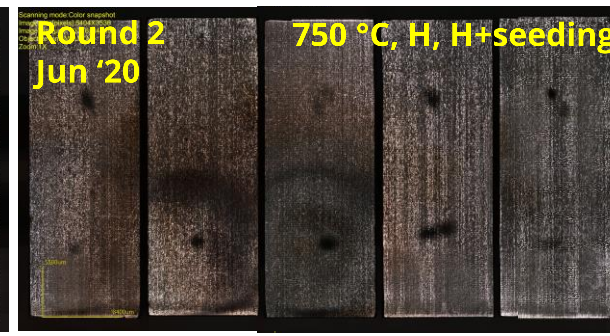
Investigate wide parameter range

Investigate close to fatigue crack limit

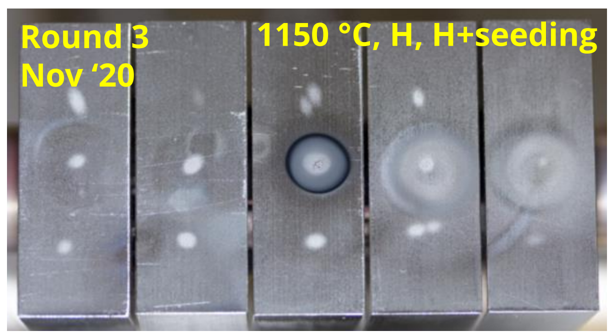
Exposure rounds

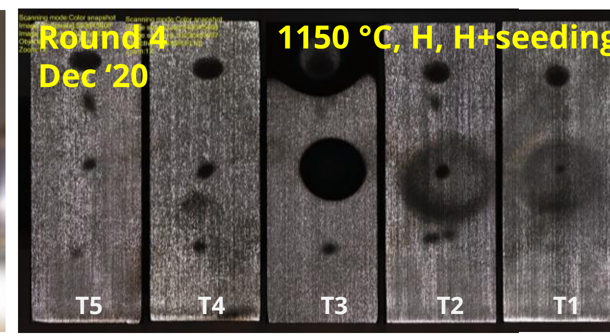






Oxidation issues: switch to alternative block





Exposures carried out in 5 rounds with characterization in-between

Goal to position plasma+laser on pre-characterized positions

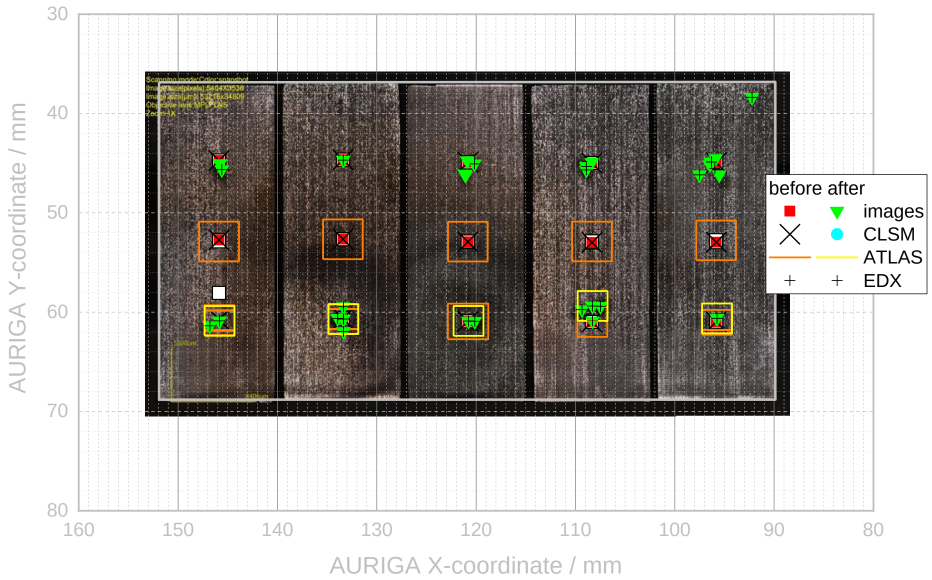
Pre-characterization and post-mortem analysis

Characterization using AURIGA at IPP Garching (large scale samples)

Pre- and post- characterization to compare influence of loading

- Large areas mapped with CLSM:
  - Overview of surface
  - Surface roughness determination
- Medium resolution SEM images acquired for macroscopic area by ATLAS-tool
- Details examined with SEM (and FIB)
- Surface elemental composition from EDX

Characterization status following round 2



Results overview

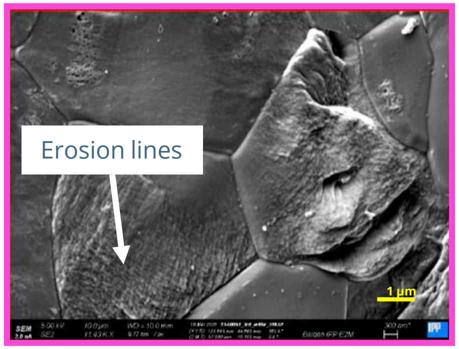
Part 1: What is the influence of H-plasma on ELM-like fatigue damage?

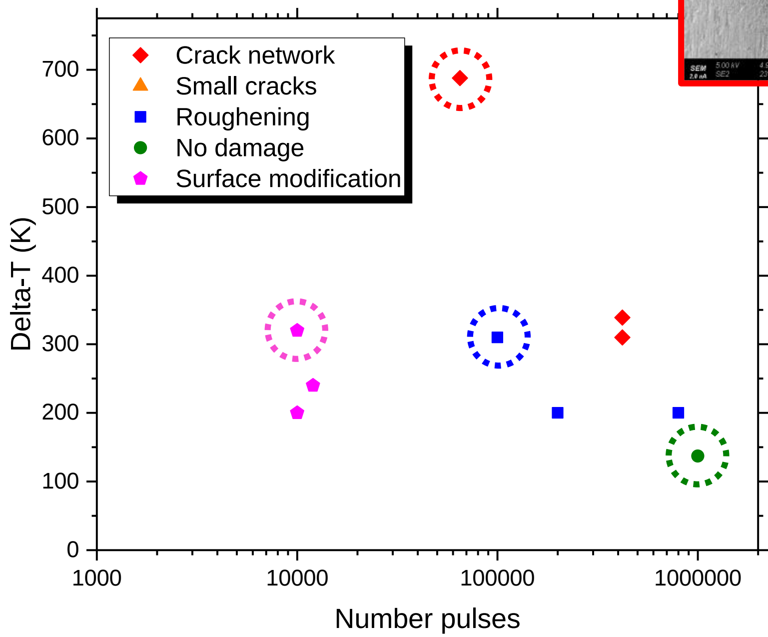
Part 2: What is the influence of surface temperature on ELM-like fatigue damage?

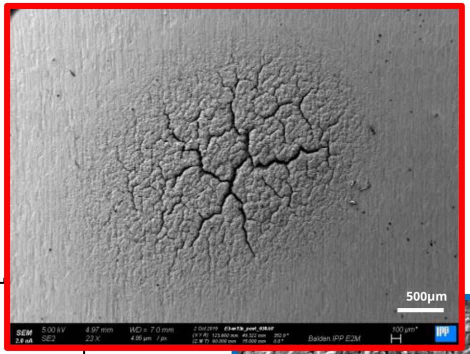
Part 3: What is the influence of plasma impurities on ELM-like fatigue damage?

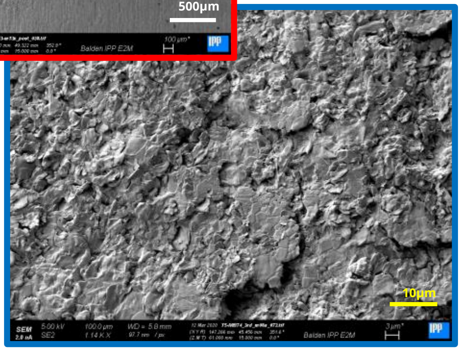
Part 1: What is the influence of H-plasma on ELM-like fatigue damage?

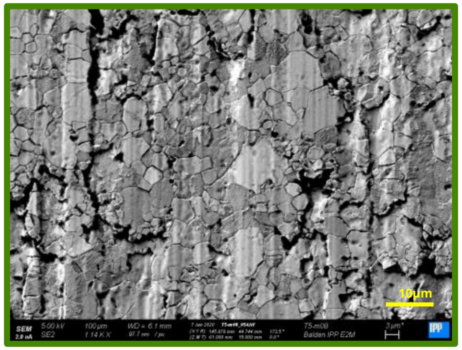
Summary of damage (H, T_{base} =750 °C)









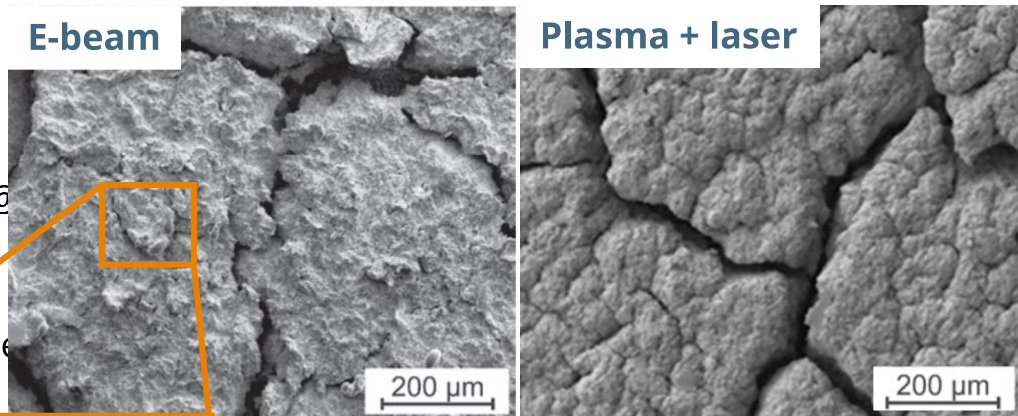


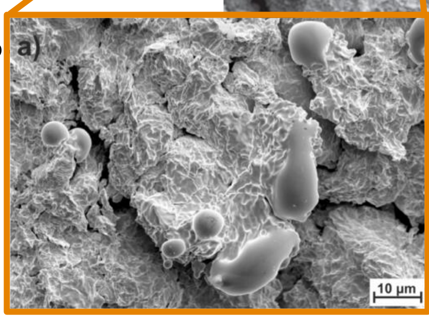
Comparison to E-beam loading

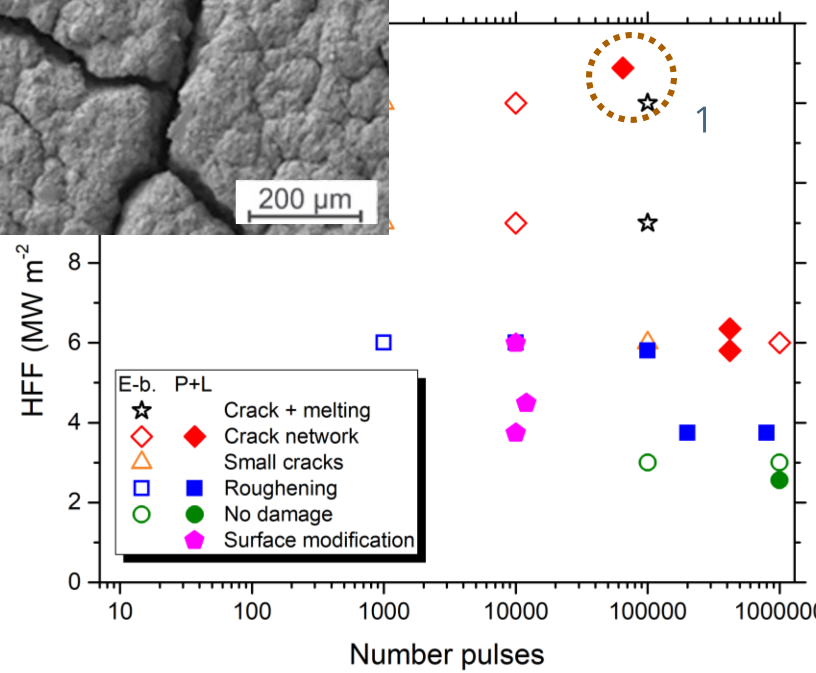
E-beam data @
longitudinal*

Generally quite

P

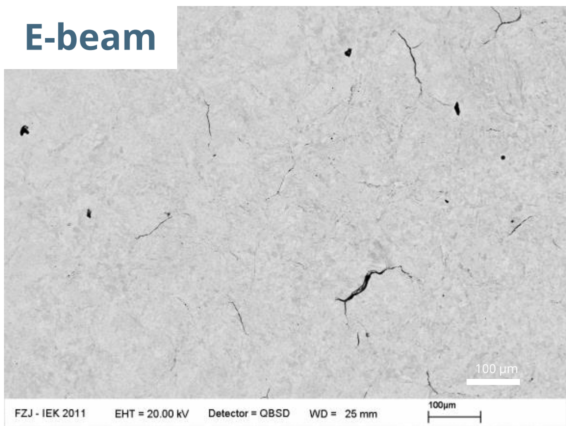


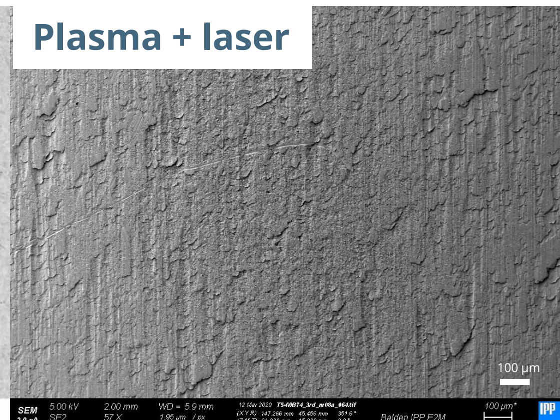




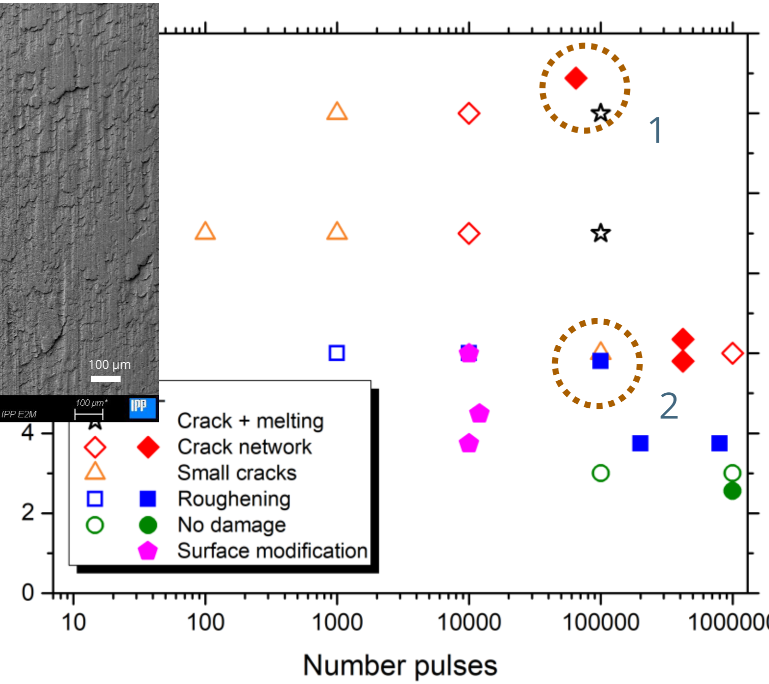
*Loewenhoff et al. *Fusion Eng. Des.* (2012)

Comparison to E-beam loading





2. Roughening vs small cracks seen with e-beam: not seen due to polished vs as-received surfaces?
3. Surface modifications seen- plasma + laser

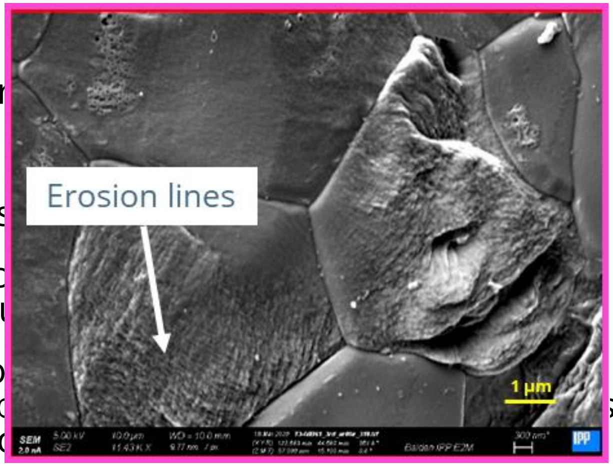


*Loewenhoff et al. *Fusion Eng. Des.* (2012)

Comparison to E-beam loading

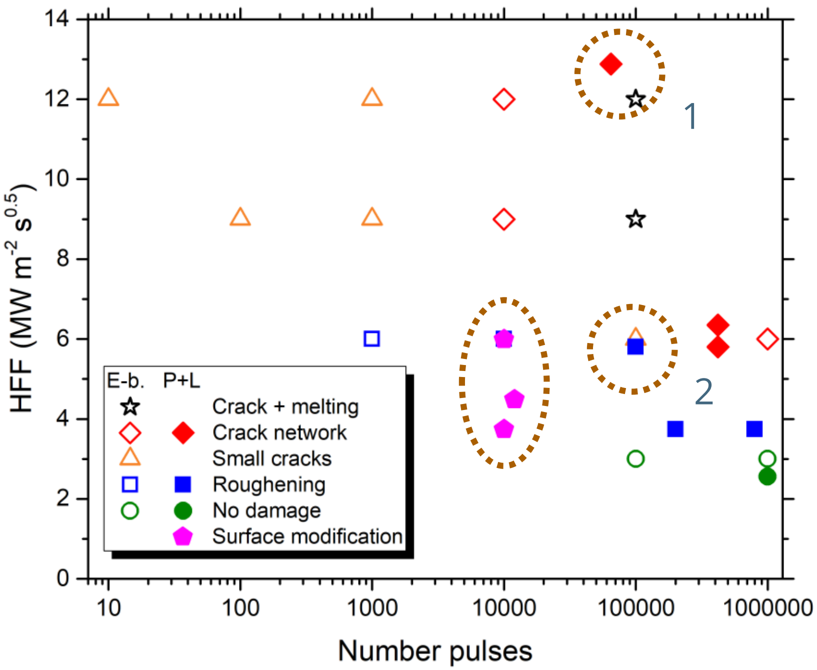
E-beam data @ base temp of 700 °C, IG W longitudinal*

Gener



Points

1. No
   rou
2. Ro
   e-b s-
   rec
3. Surface modifications seen- plasma + laser synergy? (not seen outside laser region)

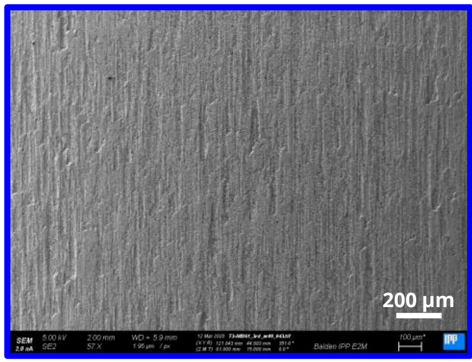


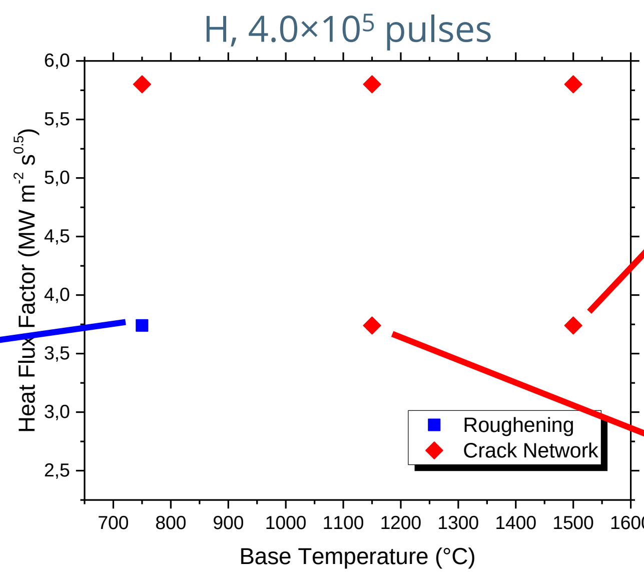
*Loewenhoff et al. *Fusion Eng. Des.* (2012)

Part 2: What is the influence of surface temperature on ELM-like fatigue damage?

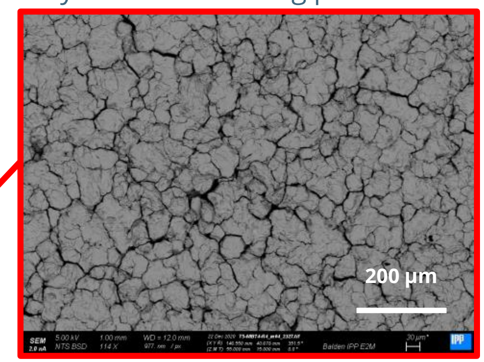
Increasing base temperature leads to decrease in fatigue cracking threshold (H plasma, 4.0×10^5 pulses)

As received microstructure

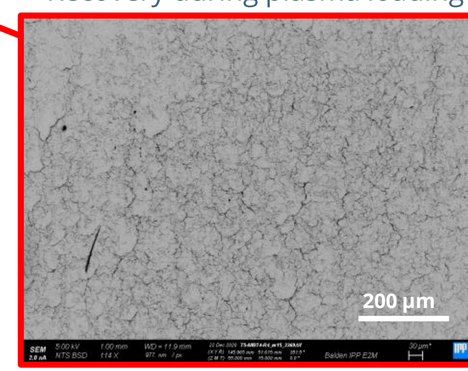




Recrystallization during plasma loading



Recovery during plasma loading



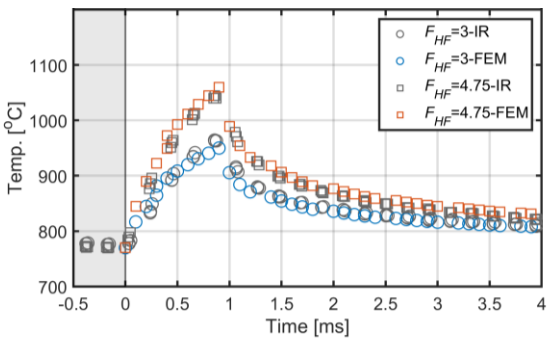
Relationship between plastic strain amplitude and fatigue cracking: Coffin-Manson law

How to understand this behaviour?

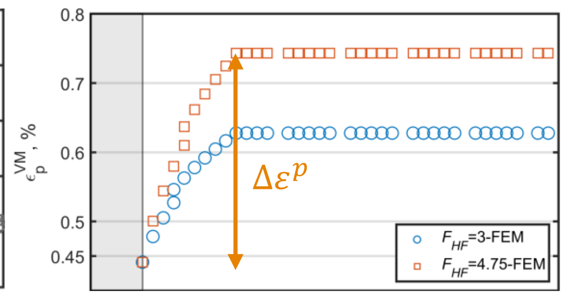
Coffin-Manson model* for samples undergoing uniaxial tension/compression loading tests relates the number of cycles to failure (N_f) to the plastic strain amplitude $\frac{\Delta\varepsilon^p}{2}$:

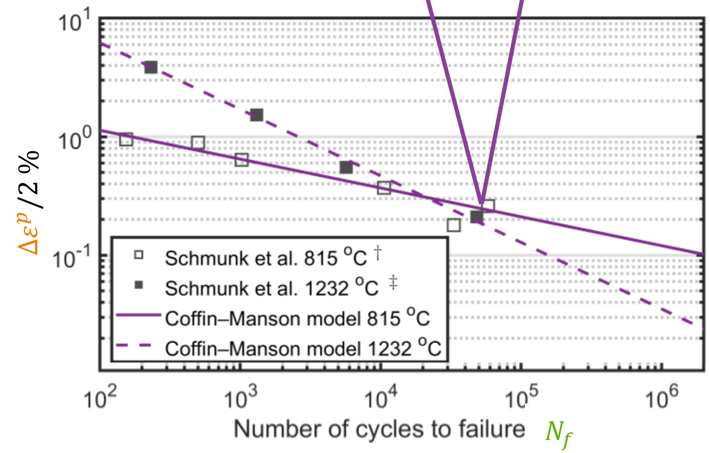
$$\frac{\Delta\varepsilon^p}{2} = \varepsilon_f'(2N_f)^c$$

Use FEM model to match IR temperature response



From FEM determine plastic strain amplitude corresponding to HFF



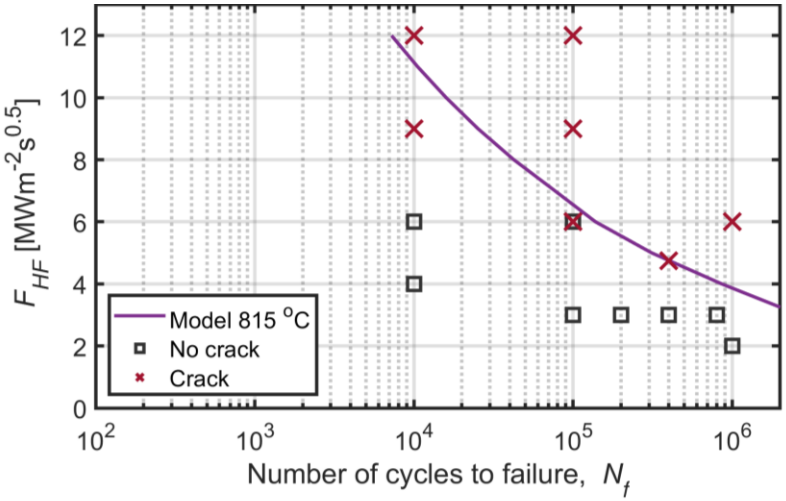


*Coffin Trans ASME (1954)
Manson NACA Report TN 2933 (1953)

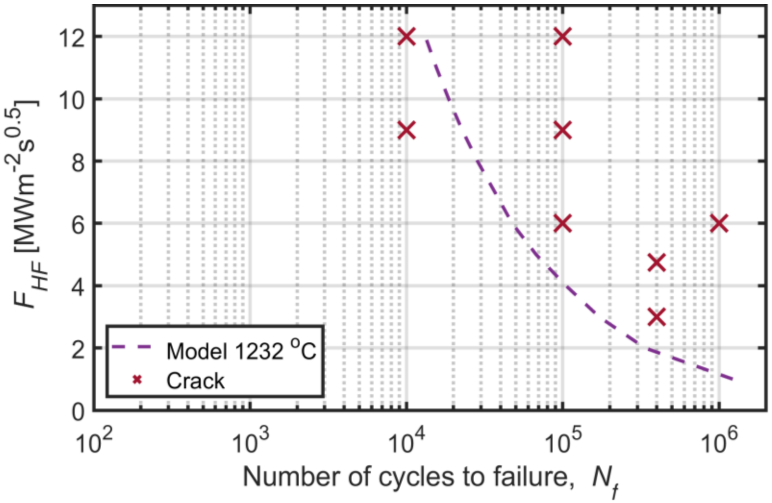
†Schmunk and Korth *J. Nucl. Mater.* (1981)
‡Schmunk et al. *J. Nucl. Mater.* (1984)

Observation of lower fatigue failure limit at recovery temperatures consistent with literature

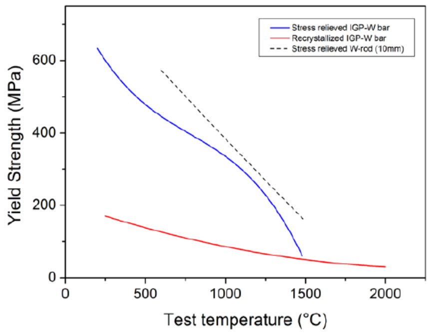
Damage map for data at 700-750 °C

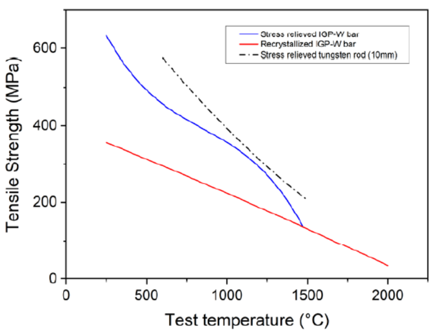


Damage map for data at 1150 °C



Why does fatigue failure limit decrease with temperature?





DEMO material property handbook: Appendix B- tungsten

Yield and tensile strength decrease with temperature

Due to higher dislocation mobility at higher temperatures

This increases ductility but also makes it easier to accumulate plastic deformation and creep in the plastic zone of the fatigue crack*

Therefore, fatigue damage may expect to be enhanced at higher temperatures

*Schijve J. (eds) *Fatigue of Structures and Materials* (2009)

Part 3: What is the influence of plasma impurities on ELM-like fatigue damage?

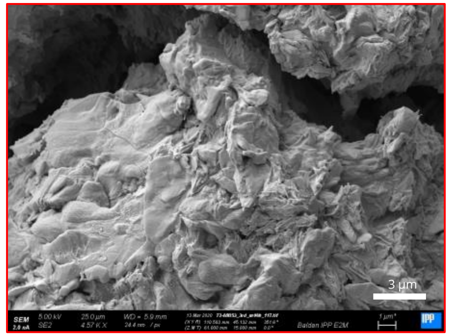
Overview of results (750 °C, $N \sim 4\times10^5$ pulses, ΔT=310 K)

Under this condition all surfaces formed a crack network ◆

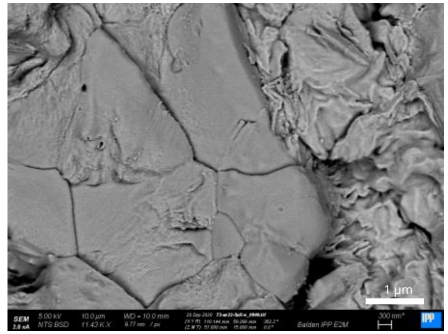
For H+Ne observe edge nanostructures

For H+He and H+He+Ne no obvious changes occur

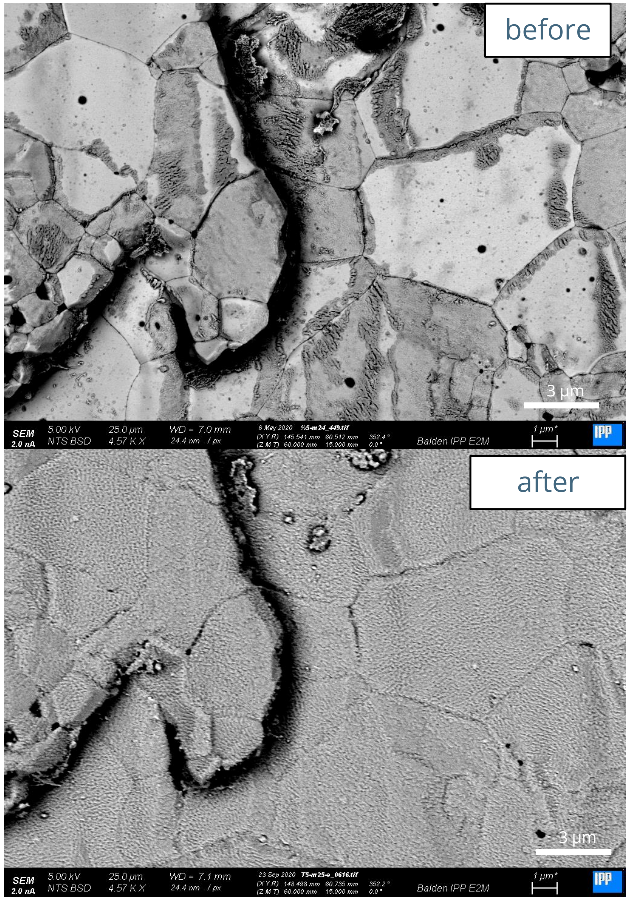
No fuzz or nanobubbles are observed (ion energy/ temperature too low)



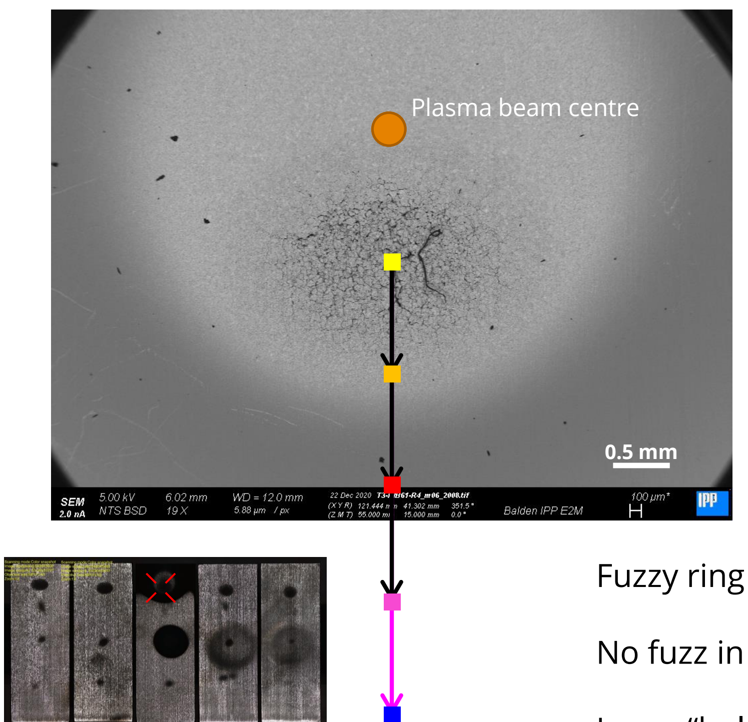
H

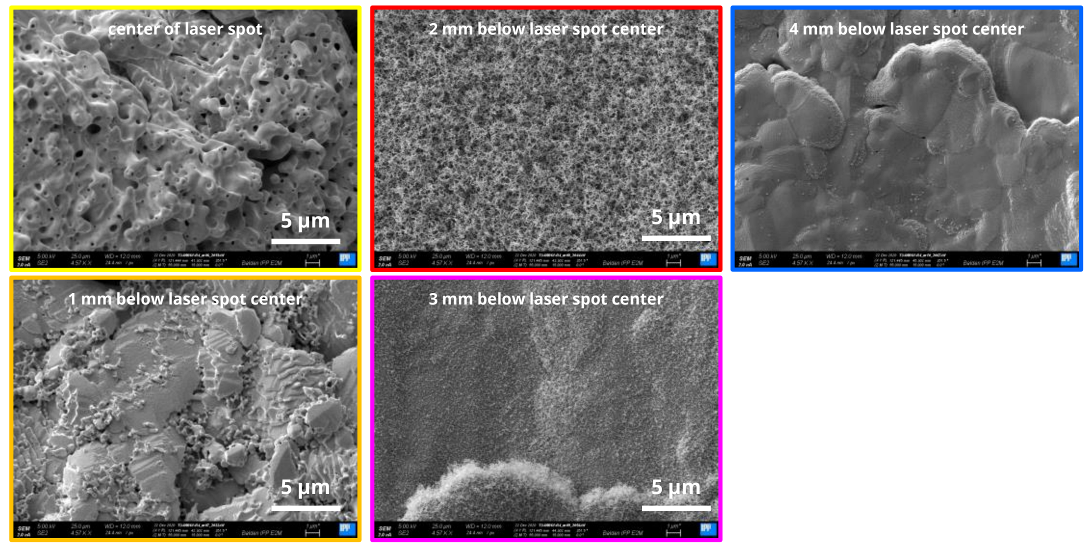


H+He



See more dramatic differences in surface at higher temperatures (H+He, 1500 °C, N~4×10^5 pulses, ΔT=310 K)





Fuzzy ring grown with thickest coverage around 3 mm from beam centre

No fuzz in centre region of plasma beam due to lower ion energy than at edge*

Large “holes” observed laser spot centre compared to “pre-fuzz” outside laser spot

*Costin et al. *Plasma Sources Sci. Technol* (2015)

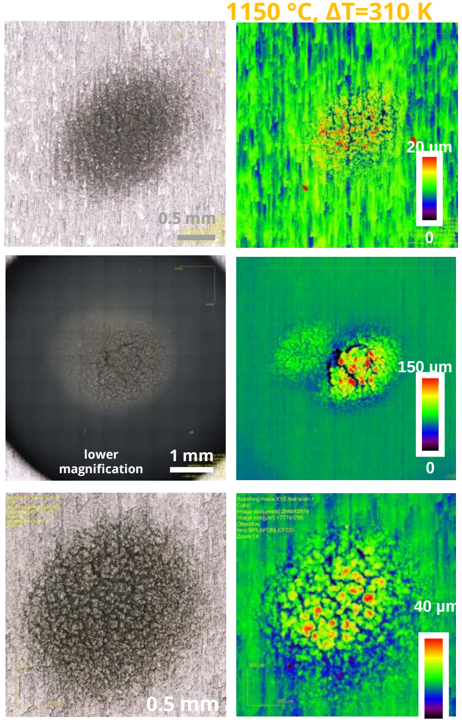
Overall addition of impurities increases surface roughening- concern for erosion?

1150 °C, ΔT=310 K

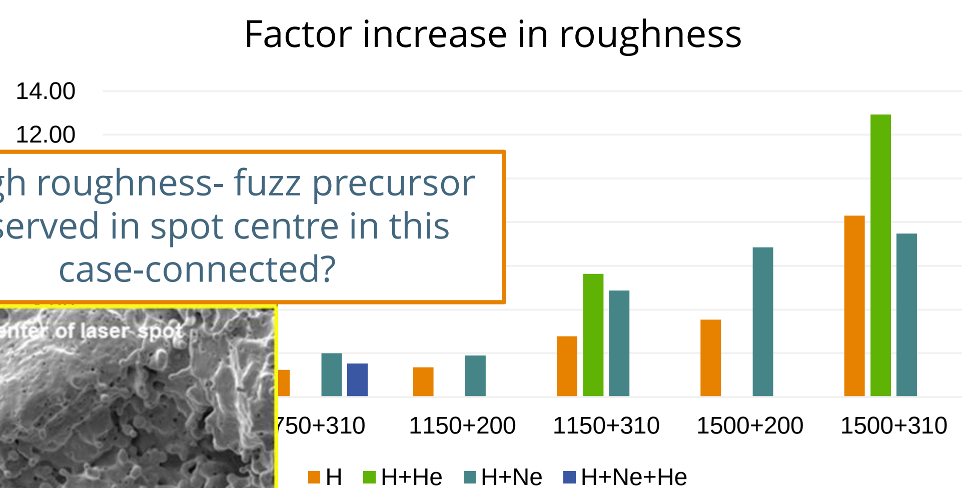
H

H+He

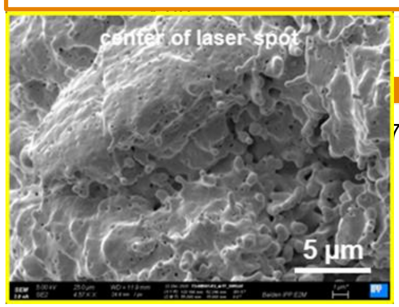
H+Ne



$$Sq = \sqrt{\frac{1}{A}\iint Z^2(x,y)\mathrm{d}x\mathrm{d}y}$$



v. high roughness- fuzz precursor observed in spot centre in this case-connected?



Conclusions

Summary

1. ITER monoblock mock-ups were exposed to ELM-like loading and simultaneous plasma loading
2. Up to 10^6 pulses were applied, while surface temperature and seeding impurities of He or Ne were also varied.
3. Comparison of plasma+laser data to e-beam at 700-750 °C shows broadly similar conclusions, but indicates additional effects due to plasma presence
4. Increasing surface base temperature leads to a decrease in resistance to fatigue cracking
5. Addition of impurities lead to more extensive surface modifications and strongly increase roughening due to cracking (more extensively for He than Ne)

Implications for ITER

1. No small melt areas were seen in plasma+laser crack networks, unlike for e-beam loading
   - Implies edges "rounded off" by plasma rather than remaining thermally isolated. Erosion/core pollution issue?
2. Fatigue lifetime damage threshold is lower at the "nominal" operating conditions than previously thought.
   - Almost impossible to avoid extensive surface cracking due to ELMs at the strikepoint locations, not just when the material is recrystallized but also at "normal" full power operation surface temperatures
3. Particularly for cases where seeding impurities are present, strong surface modifications occur and roughening is much more extensive
   - Very high roughness may modify sputtering rate and possibly leave surface more vulnerable to dust production or local overheating at the low incidence angles expected in ITER

Thank you!
Questions?