Evolution of tungsten degradation under combined high cycle ELM and steady state heat loads

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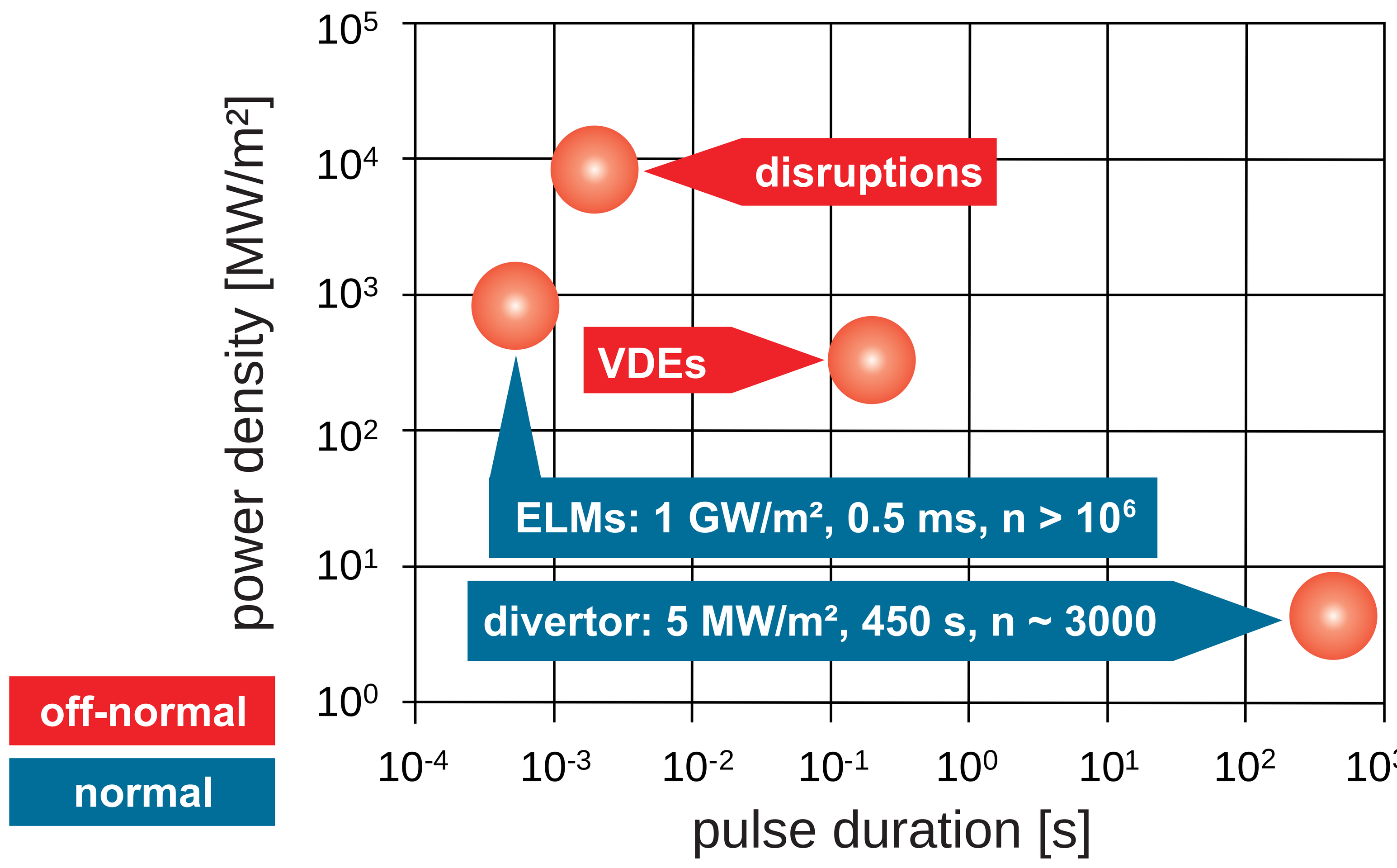
Introduction

The importance of edge localized modes (ELMs)

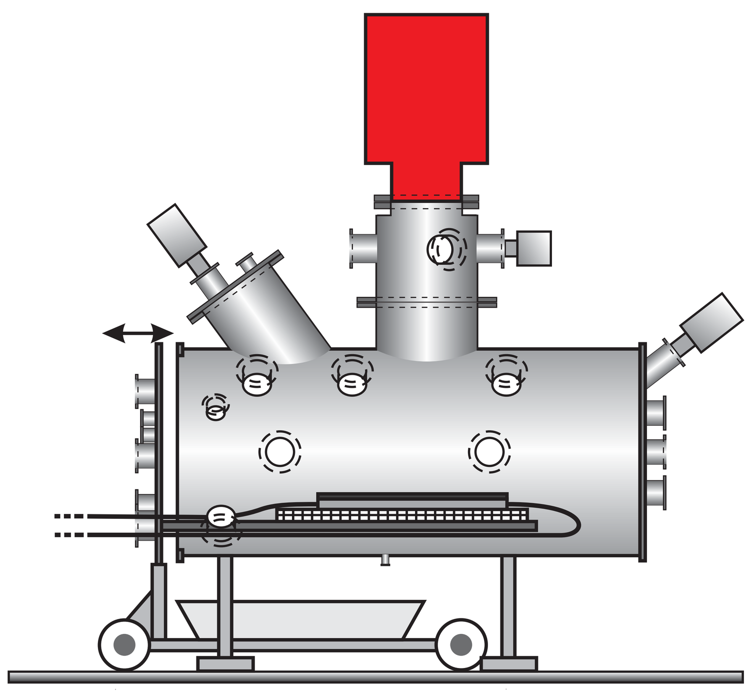
- ELMs occur in normal operation at a rate of ≥ 1 Hz
  → more than 10^6 events during estimated ITER divertor lifetime
- ELMs deploy ~0.5 MJ/m² in 0.2 – 0.5 ms pulses
  → high power density and high number of events can cause surface roughening, cracking & melting of plasma facing components
- heat loads during ELMs occur additionally to the steady state heat load of 5 – 10 MW/m² that results in different surface temperatures
  → synergistic effects of steady state and transient heat loads

Thermal loads on ITER wall / divertor

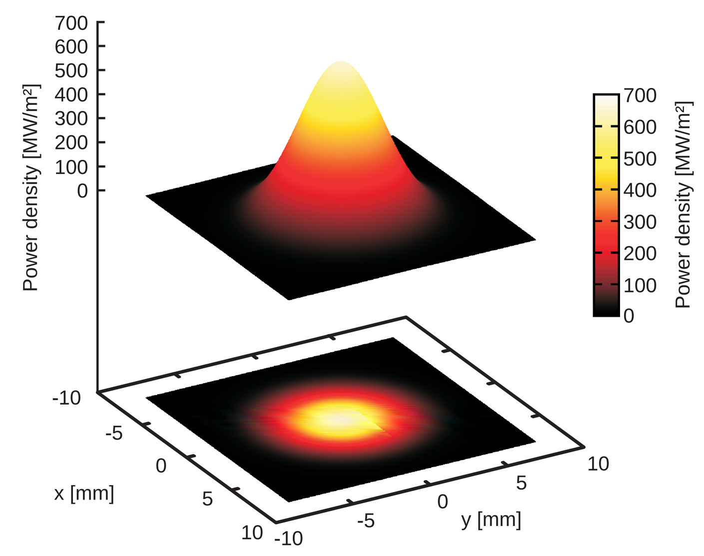


Experiment

Electron beam facility JUDITH 2



EB power distribution at 44 kW*

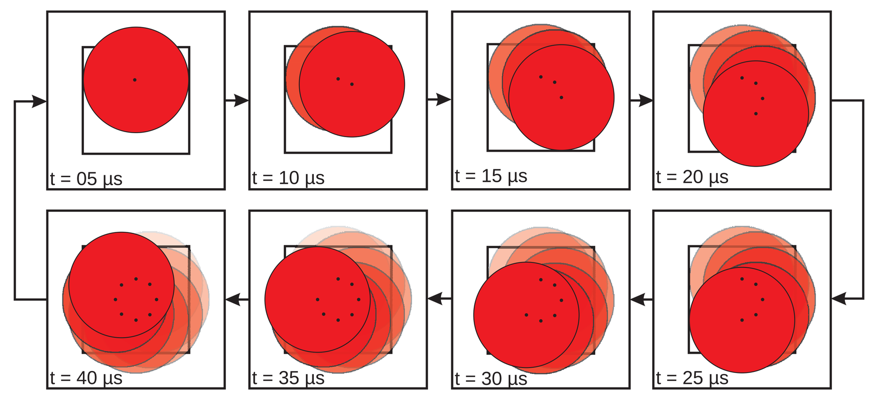


*with 45 % reflection (tungsten surface)

Layout data

- max. power 200 kW
- acceleration voltage 40 – 60 kV
- pulse duration 5 µs - CW
- EB diameter > 3 mm (FWHM)
- diagnostics: video & IR camera, fast pyrometer (Δt_{min} = 10 µs, T_{min} = 350 °C, T_{max} = 3500 °C)

EB guidance – circular pattern

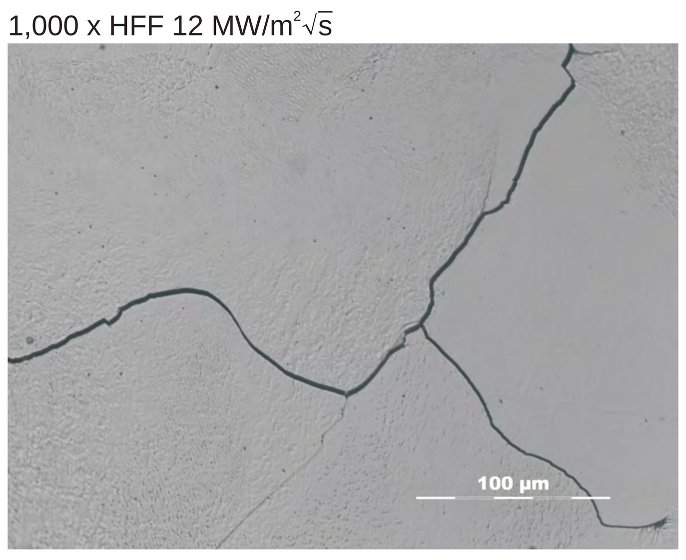


- EB is of Gaussian shape, while ELMs' footprints occur on a wider scale
  → use of circular loading pattern to increase „homogeneously" loaded area around centre
- pattern also increases stability with respect to beam width fluctuations
- test components: W tiles brazed to actively cooled copper cooling block

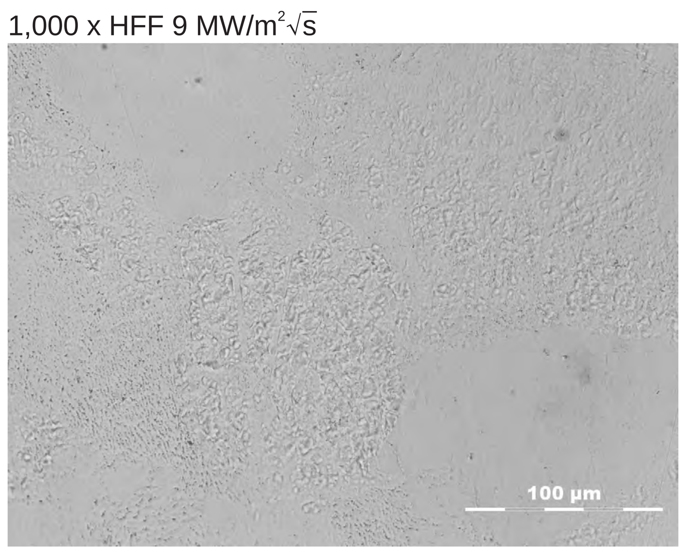
Results

Tests with pure tungsten tiles

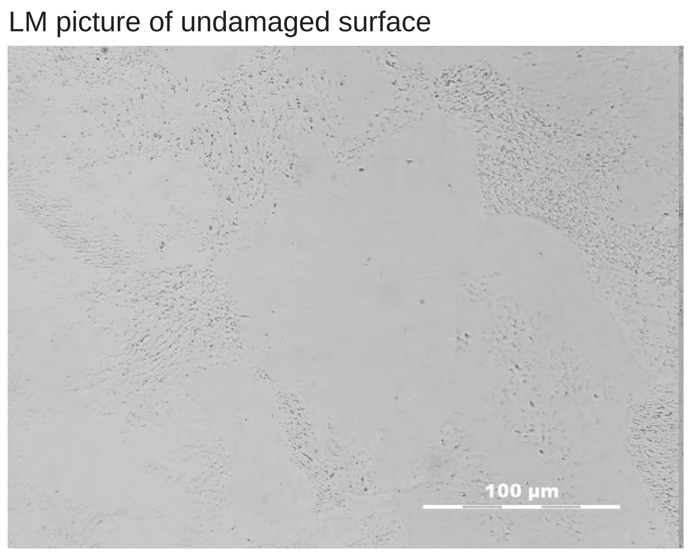
1,000 x HFF 12 MW/m²√s



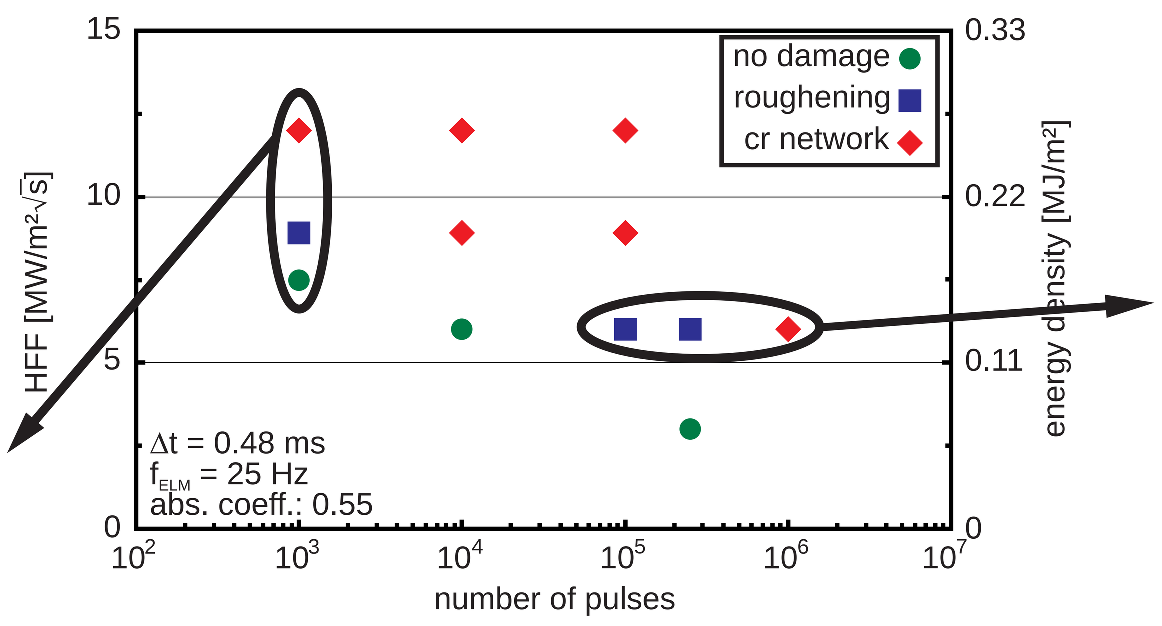
1,000 x HFF 9 MW/m²√s



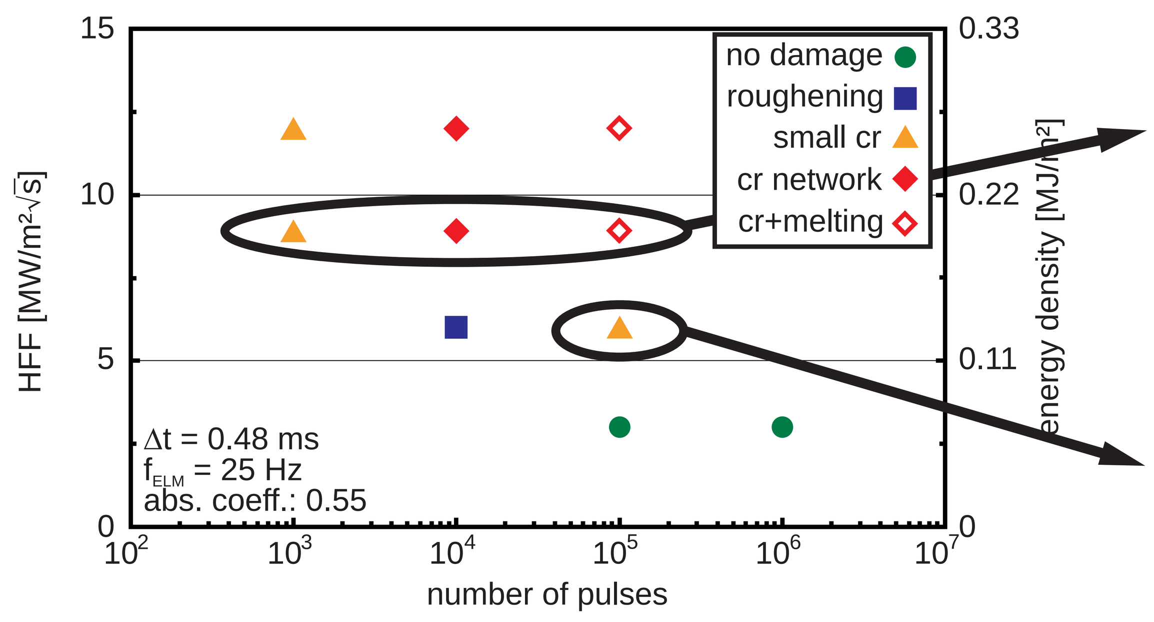
LM picture of undamaged surface



Surface condition after testing pure W at T ≈ 200 °C (0 MW/m² SSHL)

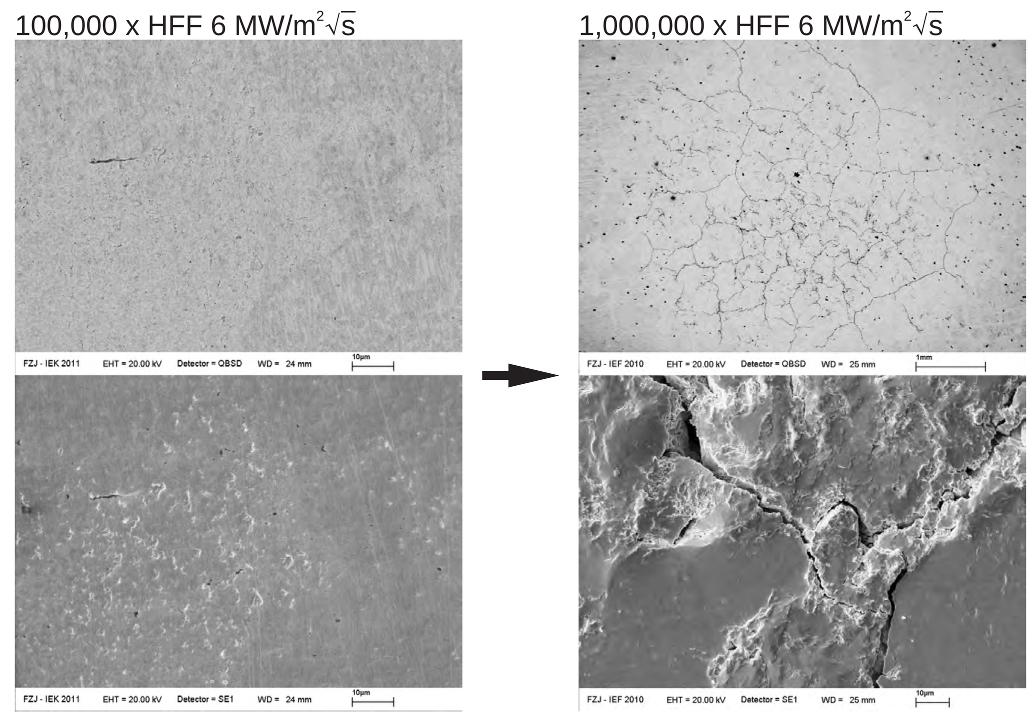


Surface condition after testing pure W at T ≈ 700 °C (10 MW/m² SSHL)

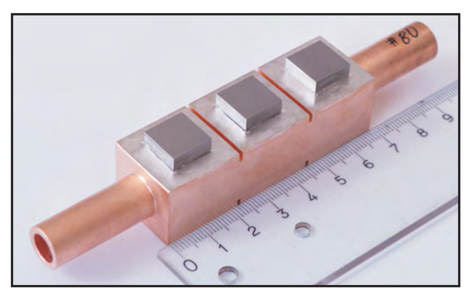


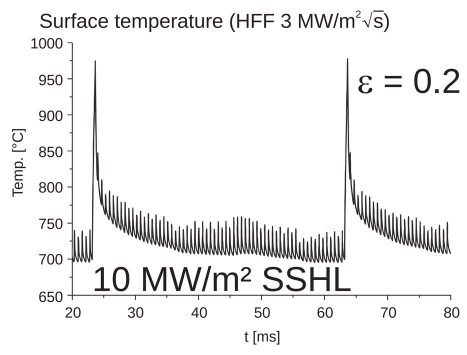
100,000 x HFF 6 MW/m²√s

1,000,000 x HFF 6 MW/m²√s



Test module



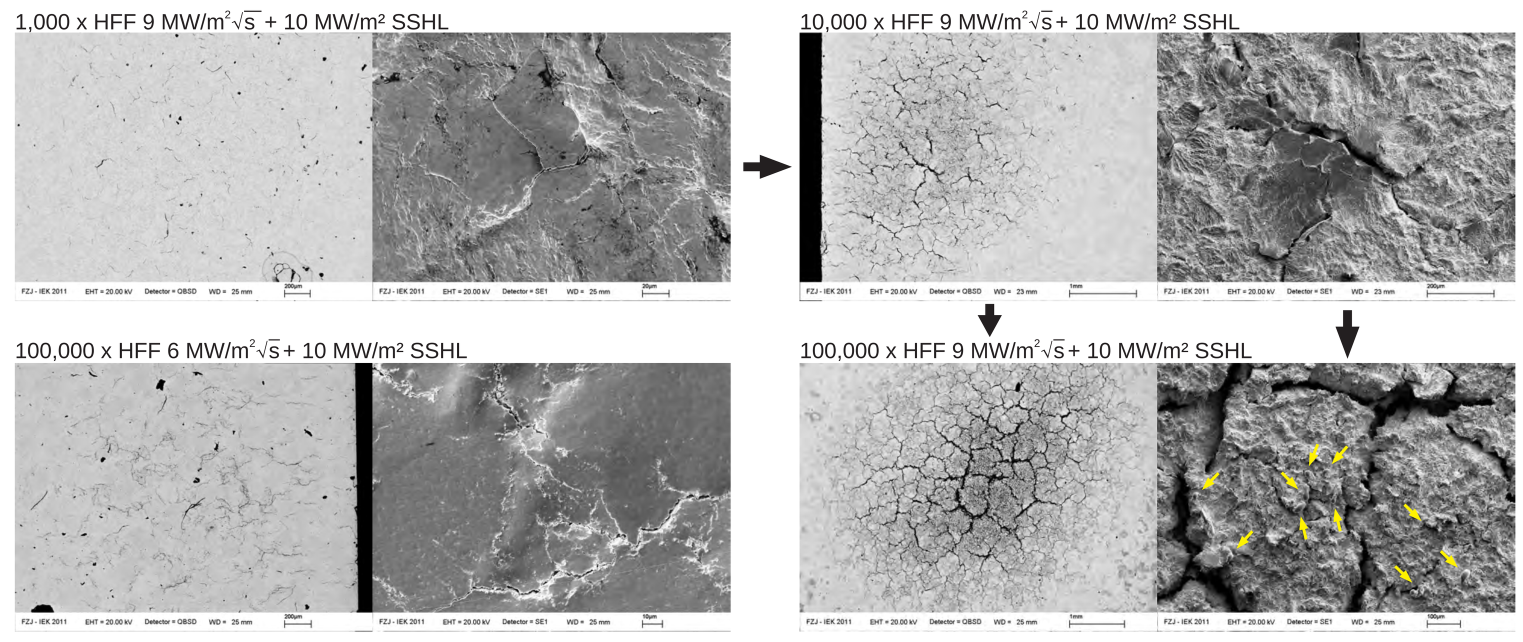


1,000 x HFF 9 MW/m²√s + 10 MW/m² SSHL

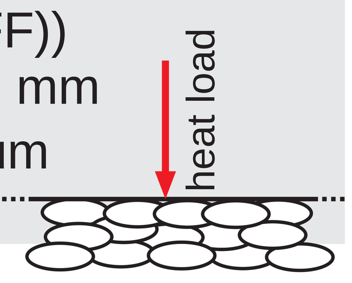
10,000 x HFF 9 MW/m²√s + 10 MW/m² SSHL

100,000 x HFF 6 MW/m²√s + 10 MW/m² SSHL

100,000 x HFF 9 MW/m²√s + 10 MW/m² SSHL



- material: sintered & double forged W → elongated grains, oriented parallel to the loaded surface (aspect ratio ~0.4)
- sample size: W tiles of 12 x 12 x 5 mm³, loaded area: 3.5 – 12 mm² (depending on heat flux factor (HFF))
- active cooling: water with T = 100 °C (module starting/equilibrium temperature) at p = 3 MPa, tube Ø 8 mm
- test mode: 400 s load (f_{ELM} = 25 Hz, pulse Δt = 0.48 ms) → 10,000 pulses, 20 s break (back to equilibrium temperature), tests done with and without additional steady state heat load (SSHL) of 10 MW/m²



Conclusions

- tests showed the feasibility of ELM-like loading in JUDITH 2 for up to 10^6 pulses and additional steady state heat load up to 10 MW/m²
  → simulation of heat loading conditions and temperatures as expected for the ITER divertor
- results show a dependency of material degradation on the number of pulses, the power density and the steady state heat load (surface temperature)
- for higher temp. (700 °C, SSHL 10 MW/m²) the degradation appears earlier (in terms of number of pulses) and is more severe (e. g. additional melting)
- the overall damage threshold is located between HFF 3 – 6 MW/m²√s (→ energy density 0.07 – 0.13 MJ/m²)
- roughening as precursor: roughening is always followed by cracking at higher number of pulses
- erosion of crack edges and/or melting takes place after cracking, depending on surface temperature

This work, supported by the European Communities under the contract of Association between EURATOM/Forschungszentrum Jülich, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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