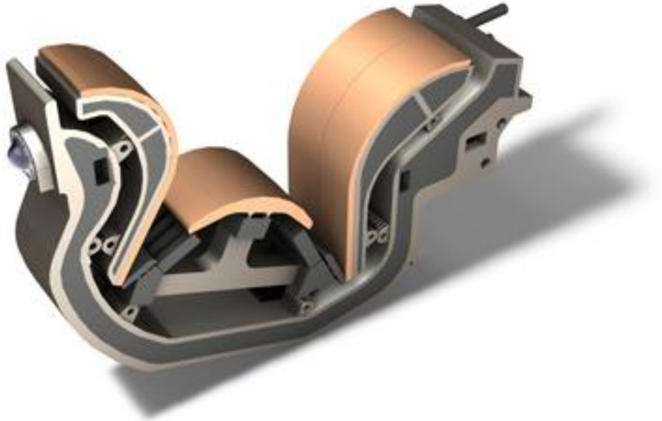


Materials for Future Fusion Reactors under Severe Stationary and Transient Thermal Loads

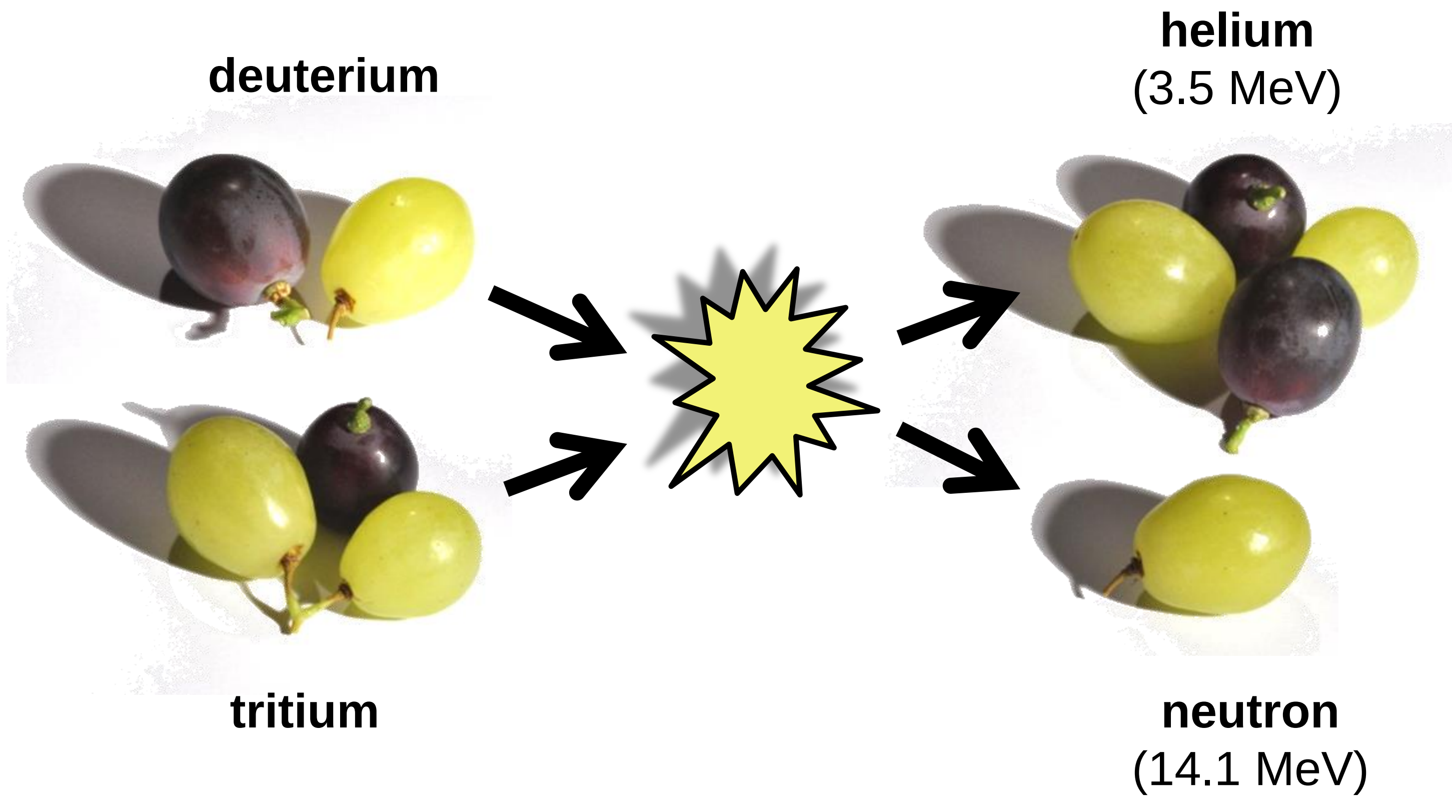
J. Linke, J. Du, N. Lemahieu, Th. Loewenhoff, G. Pintsuk, B. Spilker, T. Weber, M. Wirtz

Forschungszentrum Jülich, Institut für Energie- und Klimaforschung, 52425 Jülich

HELSMAC Symposium - Downing College, Cambridge – 7th-8th April 2016

Mysterious fusion

Mysterious fusion



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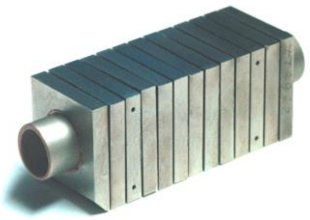
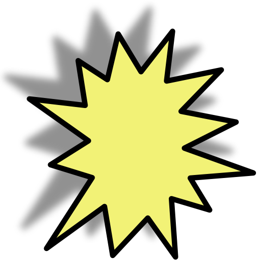
Outline:

A **Thermal loads on plasma facing components**



B **Simulation of intense thermal loads**



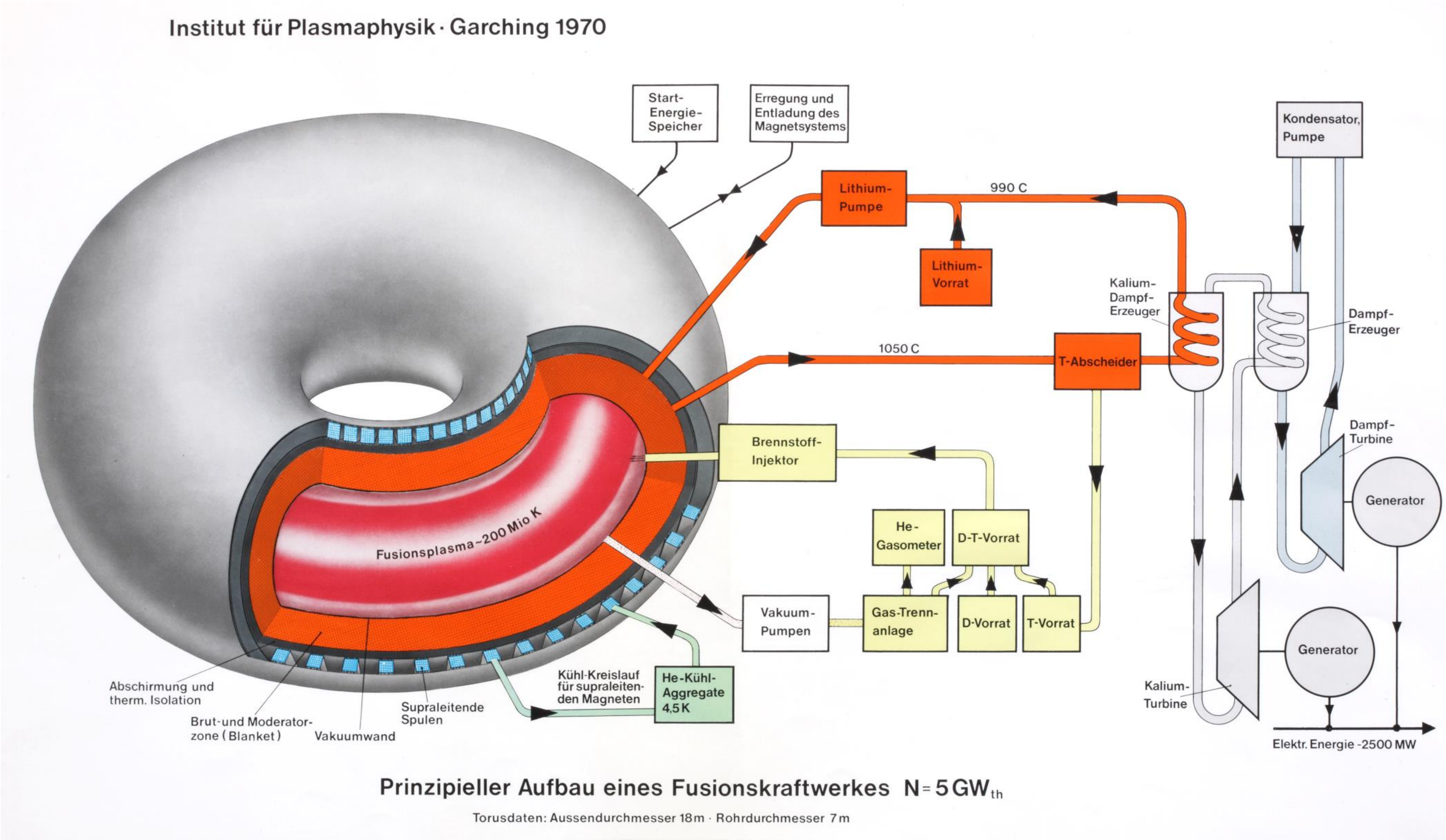
C **Hydrogen and helium effects**

D **Material degradation by energetic neutrons**

A

Thermal loads on plasma facing components

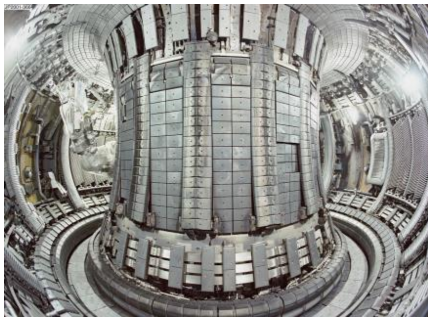
Energy conversion in a thermo-nuclear reactor

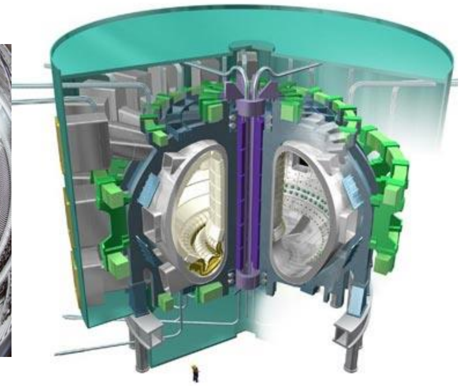


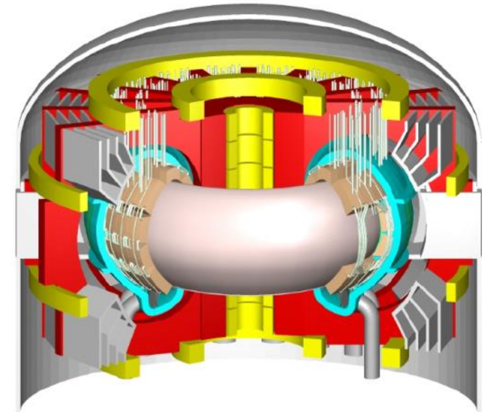
Steps towards the reactor

JÜLICH FORSCHUNGSZENTRUM

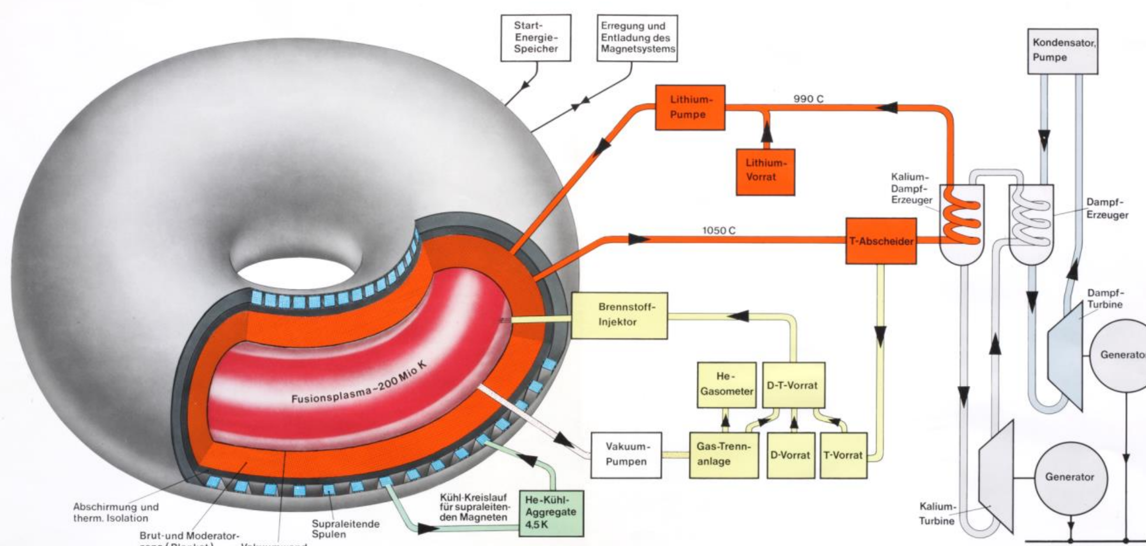
JET	ITER	DEMO



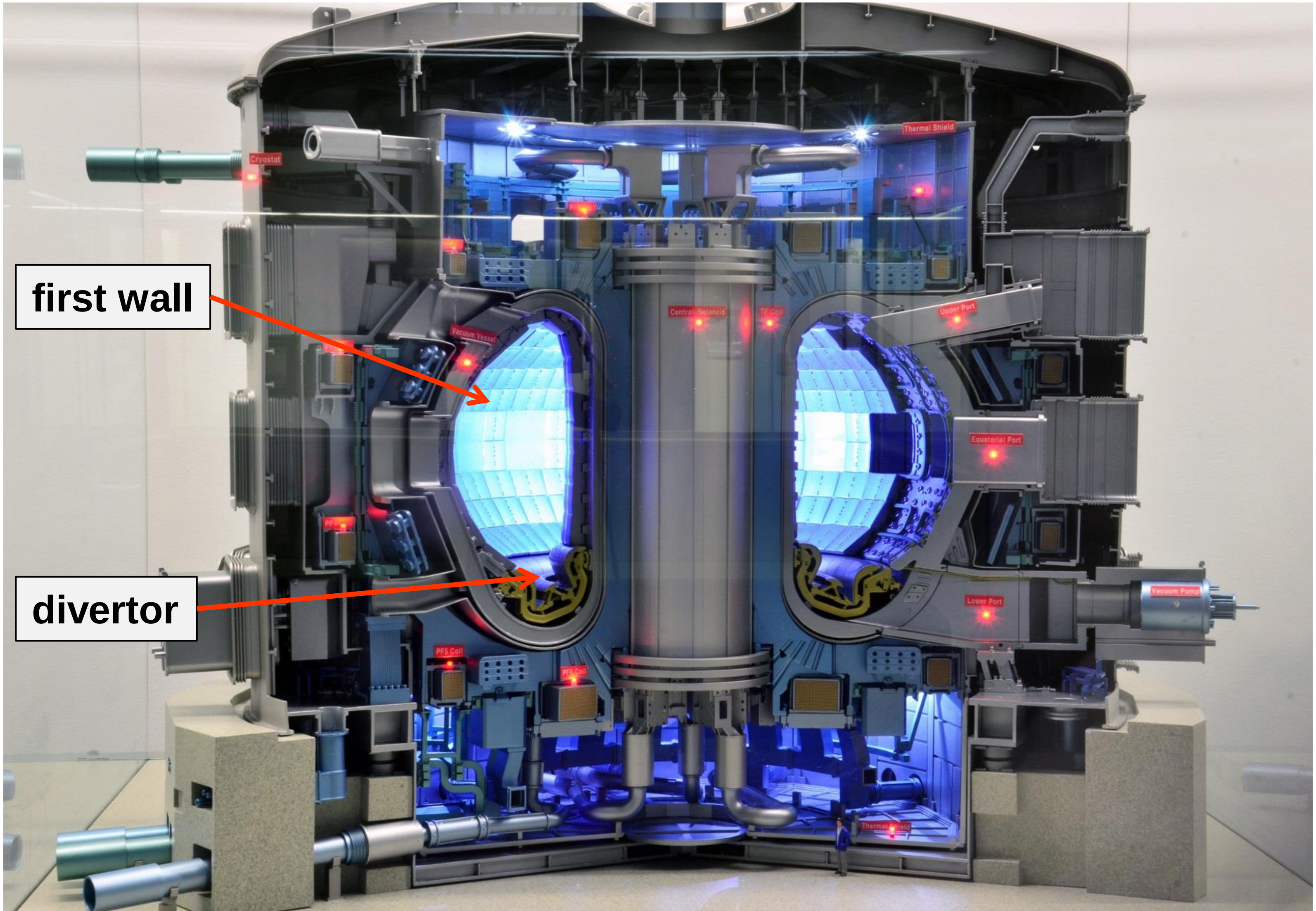




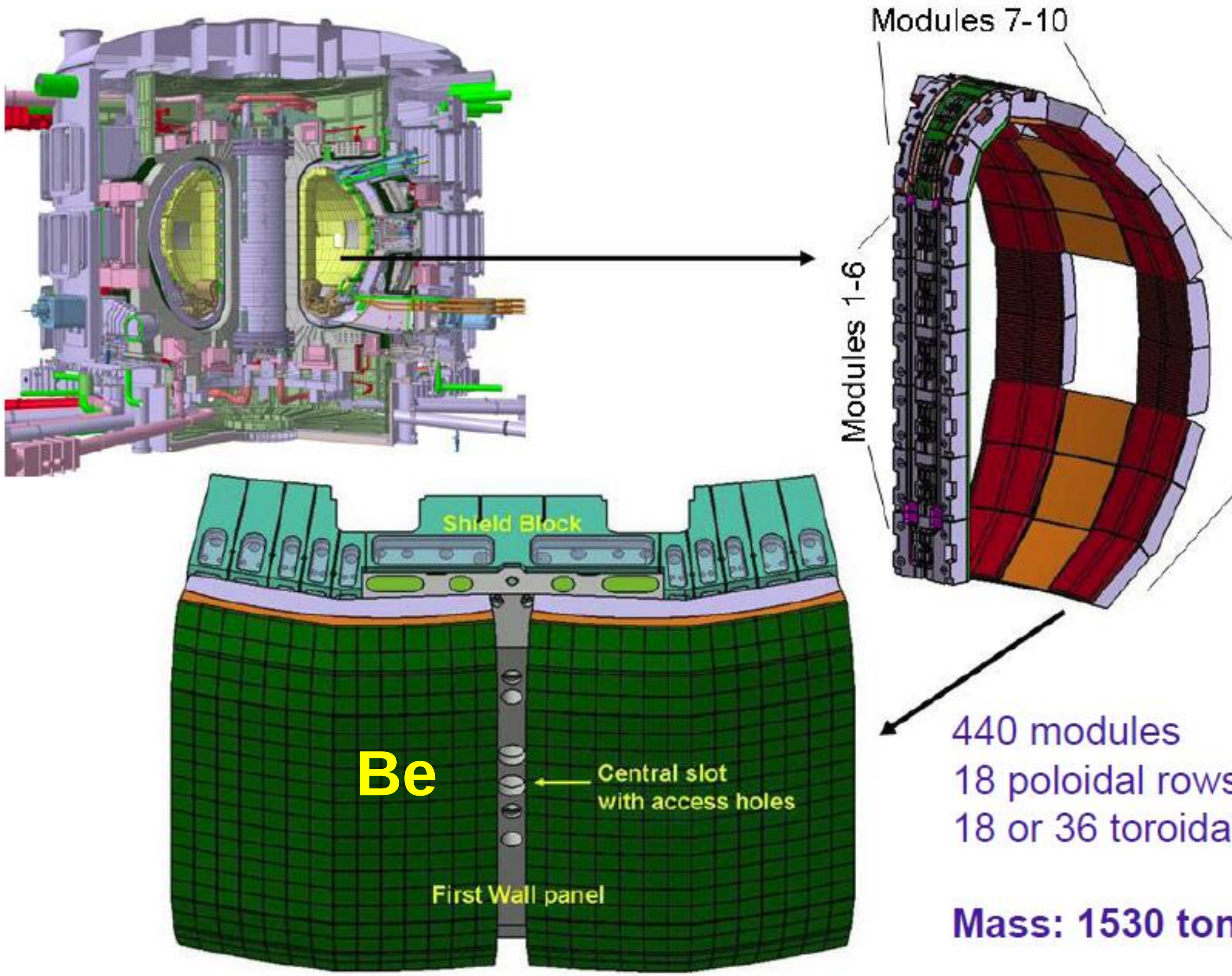
n-dose: 10^{-9} dpa | 1 dpa | 100 dpa



ITER and the plasma facing components



The ITER blanket design



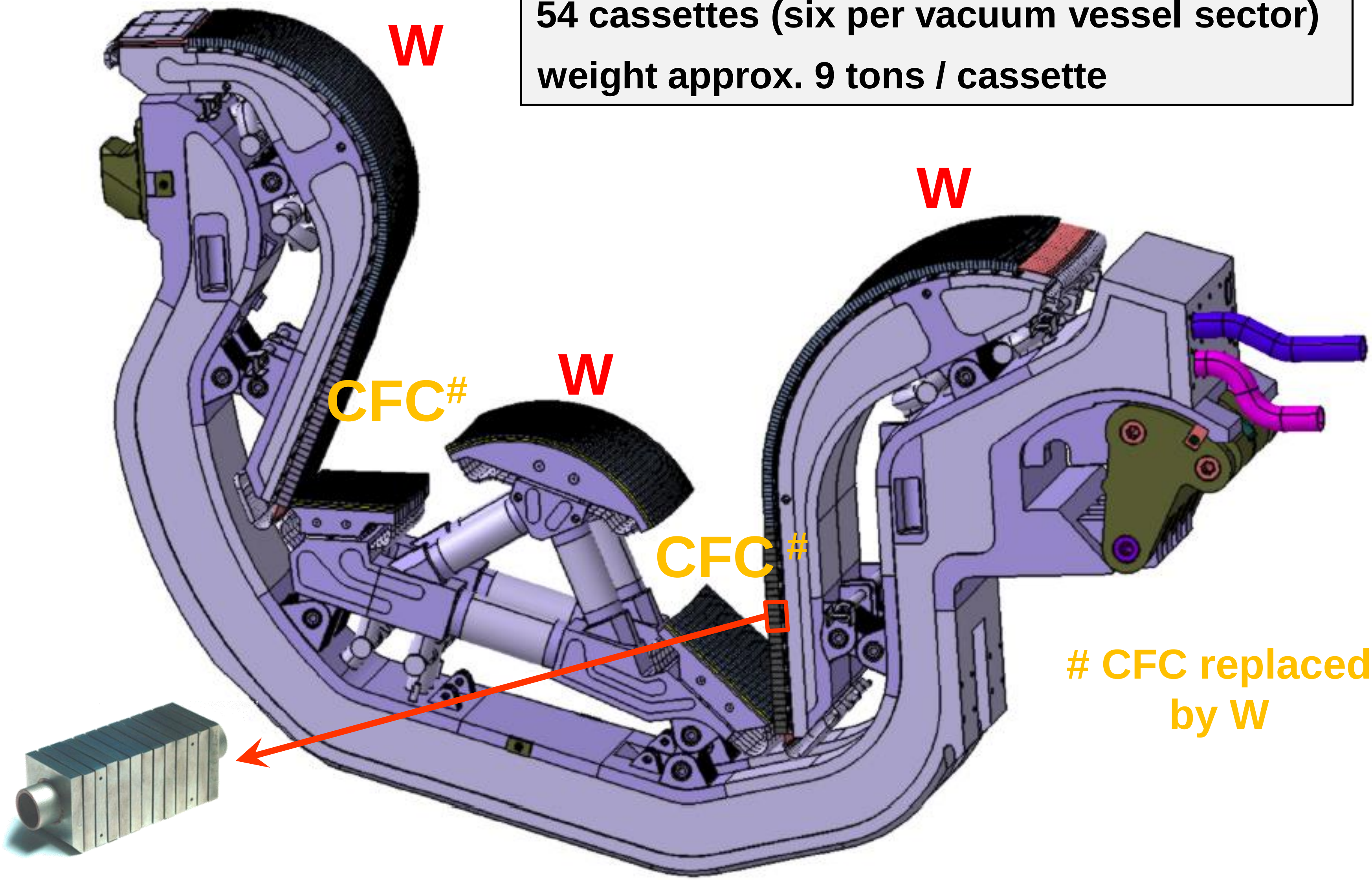
440 modules
18 poloidal rows
18 or 36 toroidal rows

Mass: 1530 tons

The new ITER divertor cassette

54 cassettes (six per vacuum vessel sector)

weight approx. 9 tons / cassette



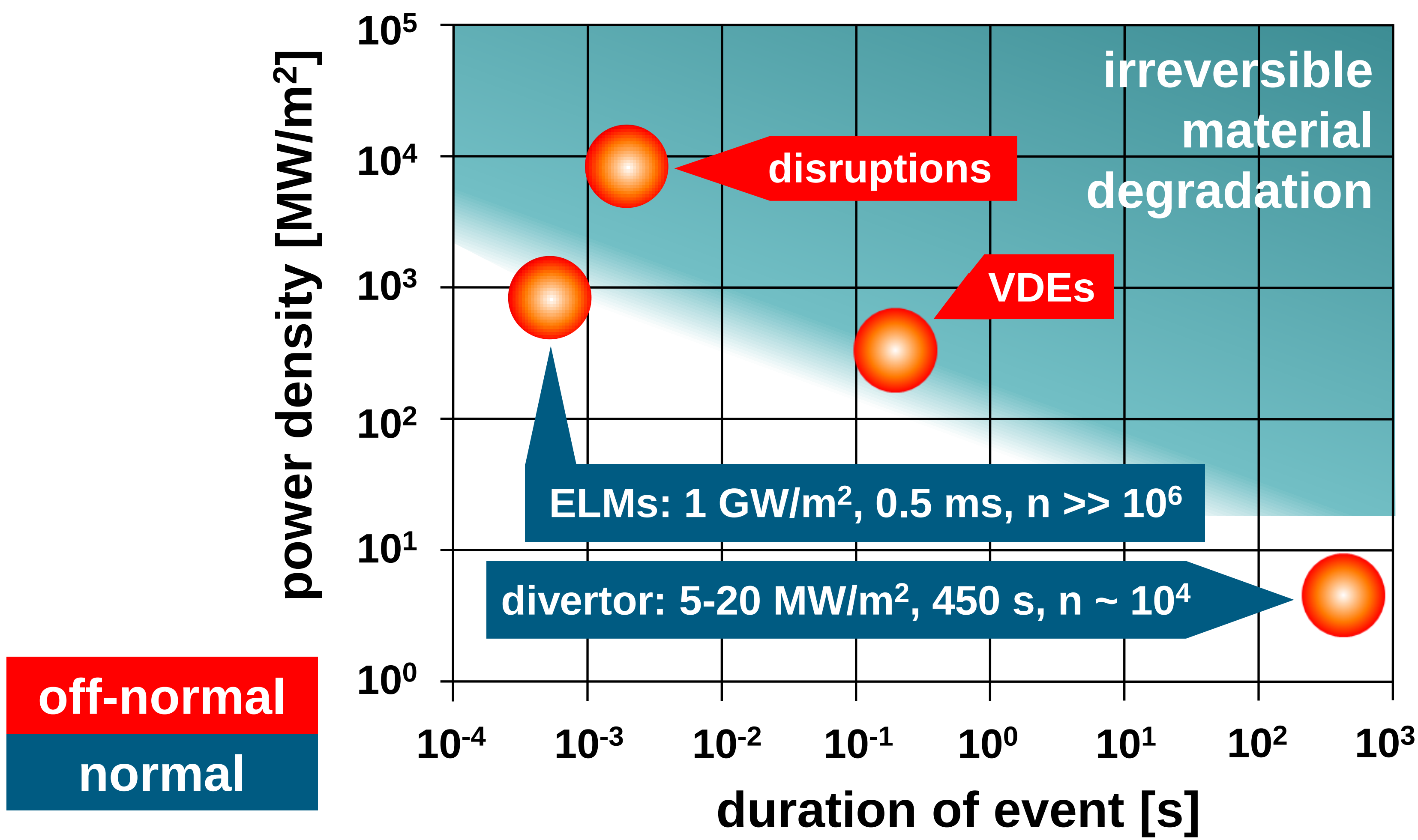
$L_{max} \leq 100$ mm

source: M. Merola, ISFNT-9, Dalian, China, 2009

B

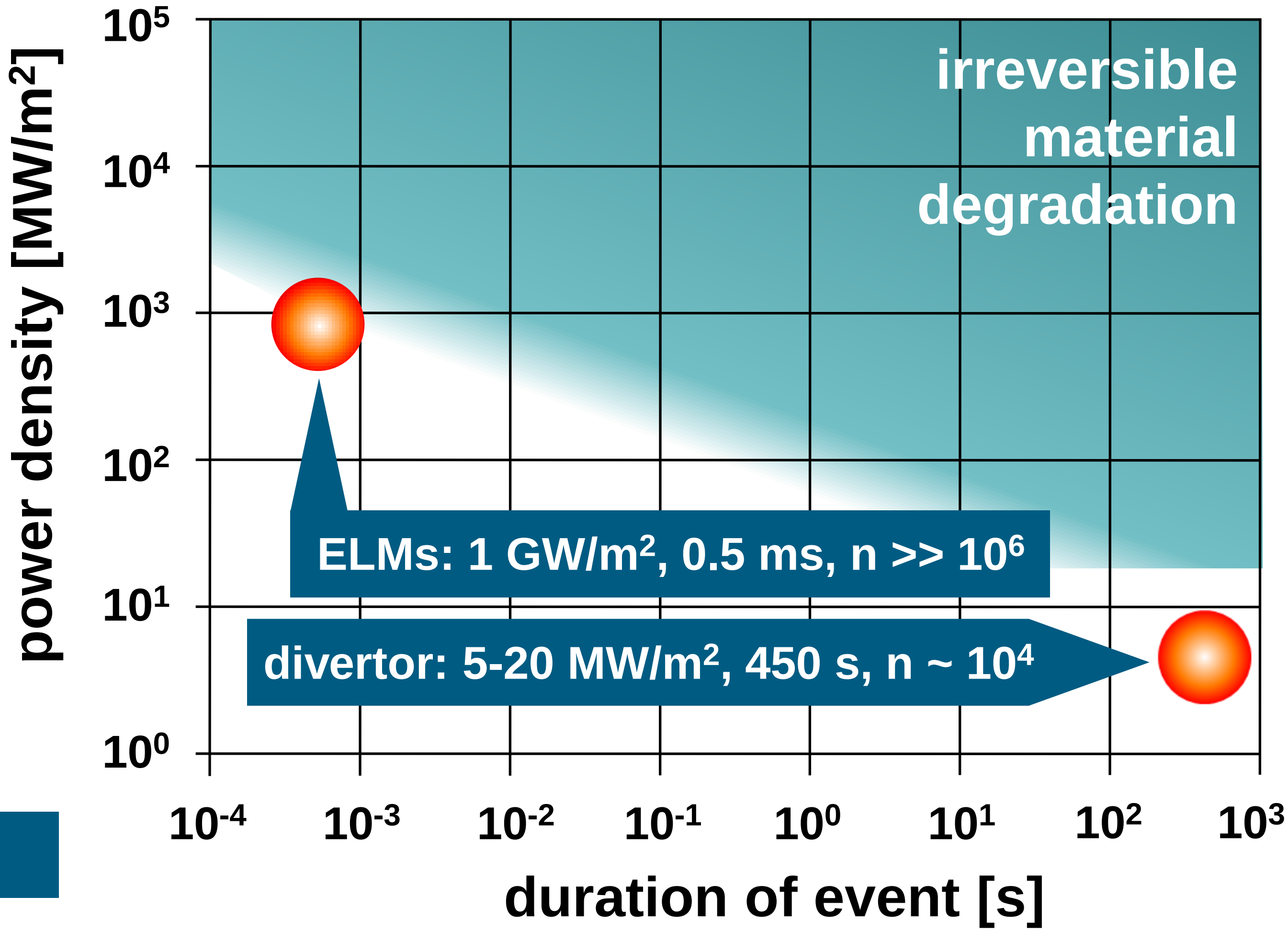
Simulation of intense thermal loads on plasma-facing components

Expected heat loads on the ITER divertor



R. A. Pitts, et al., Journal of Nuclear Materials 438 (2013) S48-S56
J. Linke, Transactions of fusion science and technology 49 (2006) 455-464
A. Loarte et al., Plasma Physics and Controlled Fusion 45 (2003) 1549-1569

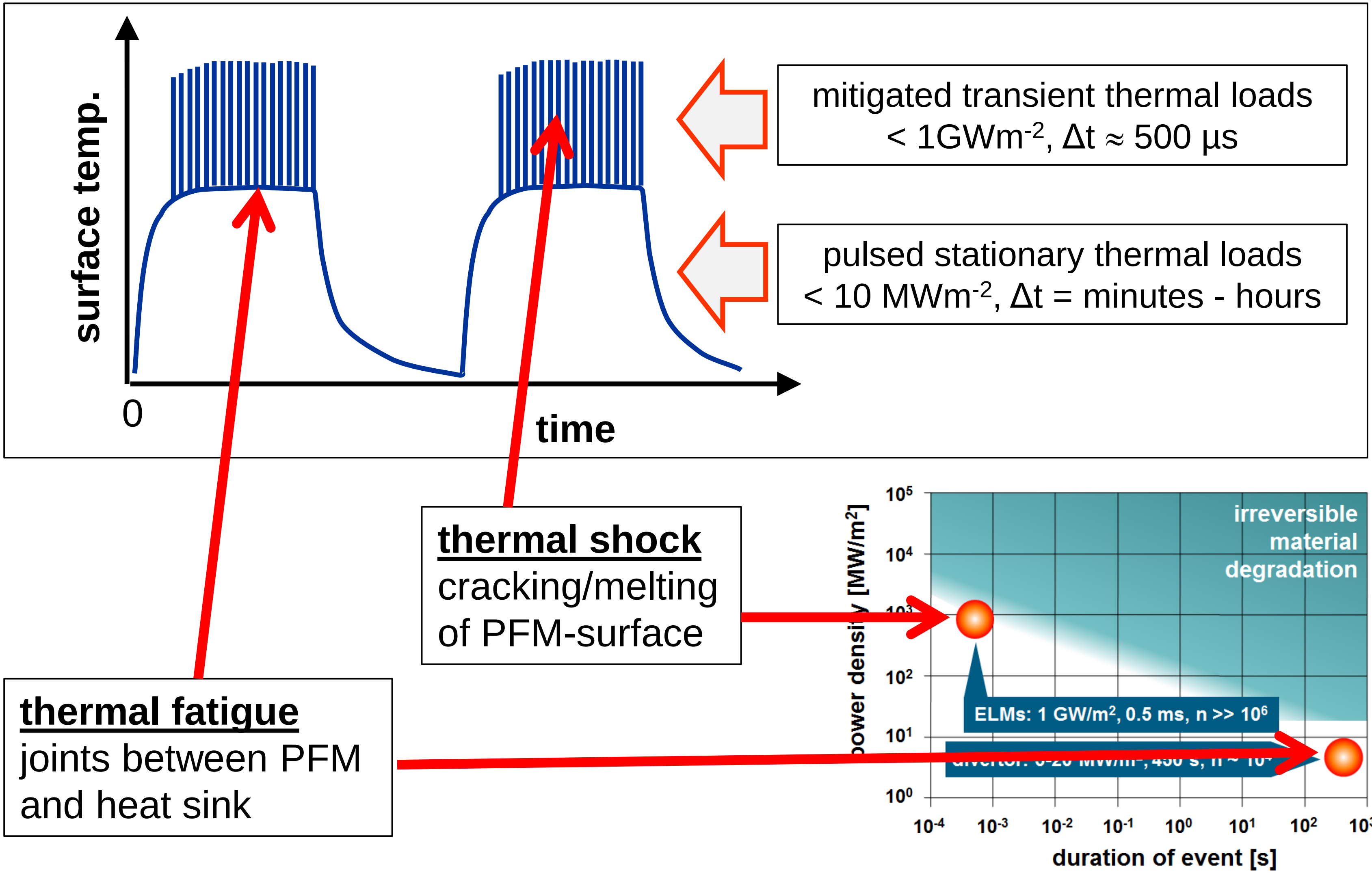
Expected heat loads on the ITER divertor



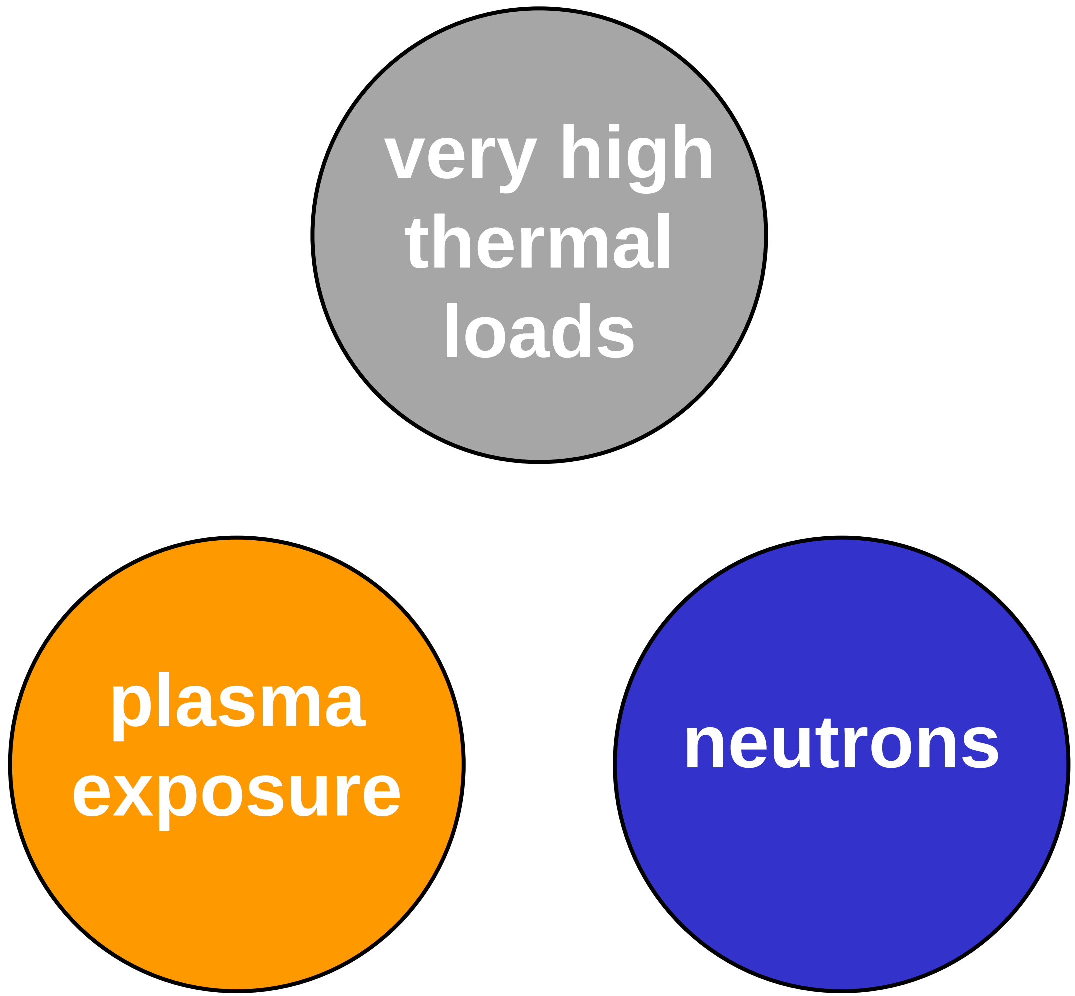
normal

R. A. Pitts, et al., Journal of Nuclear Materials 438 (2013) S48-S56
J. Linke, Transactions of fusion science and technology 49 (2006) 455-464
A. Loarte et al., Plasma Physics and Controlled Fusion 45 (2003) 1549-1569

Wall loading in a toroidally confined plasma (Tokamak)



Loads on plasma facing components



Loads on plasma facing components

Steady state heat loads:

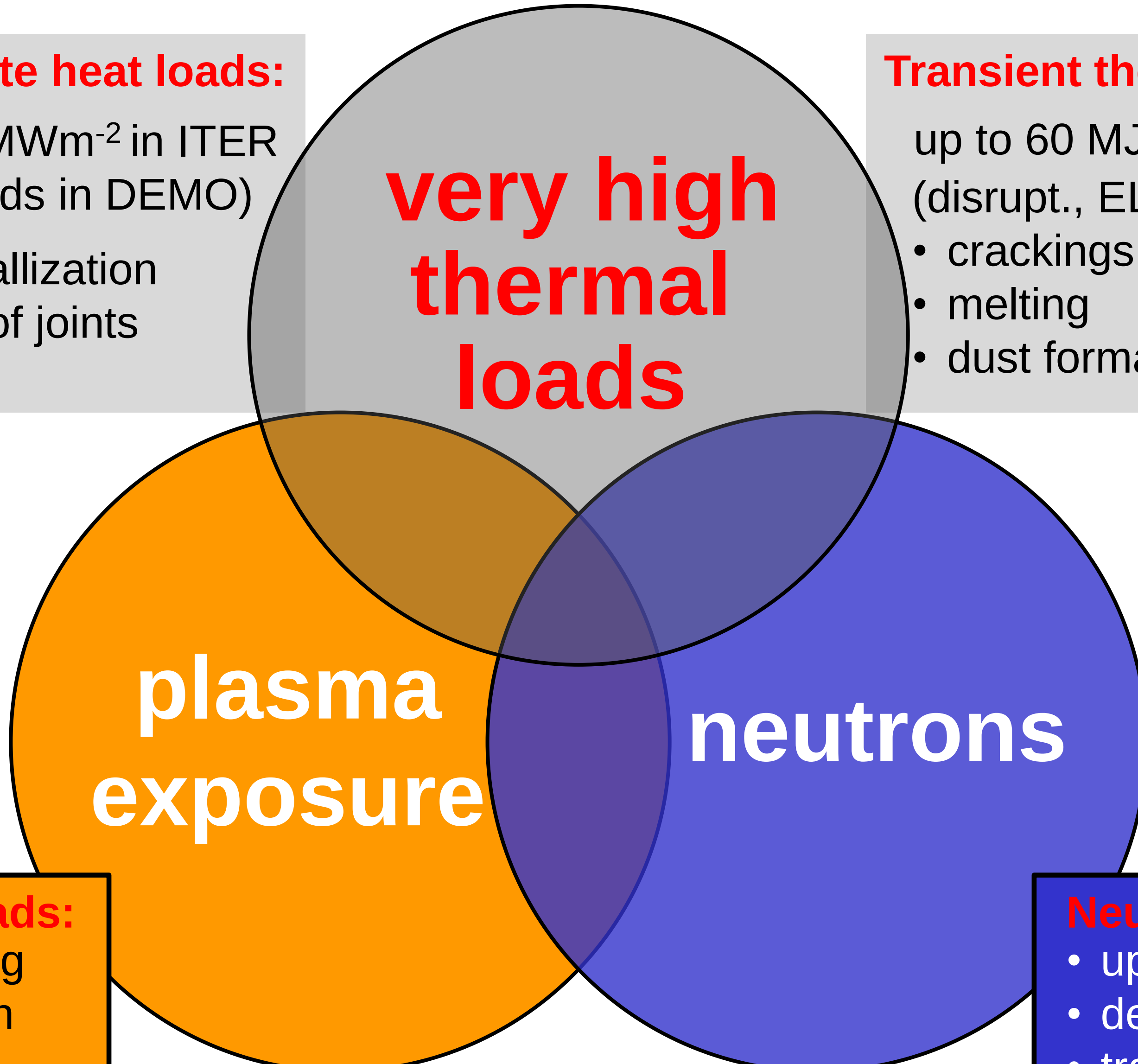
up to 20 MWm^{-2} in ITER
(lower loads in DEMO)

- recrystallization
- failure of joints

Transient thermal loads:

up to 60 MJm^{-2}
(disrupt., ELMs, VDEs)

- crackings
- melting
- dust formation



Plasma loads:

- sputtering
- hydrogen
- helium

Neutrons:

- up to 14 MeV
- defects
- transmutation

High heat flux test facilities

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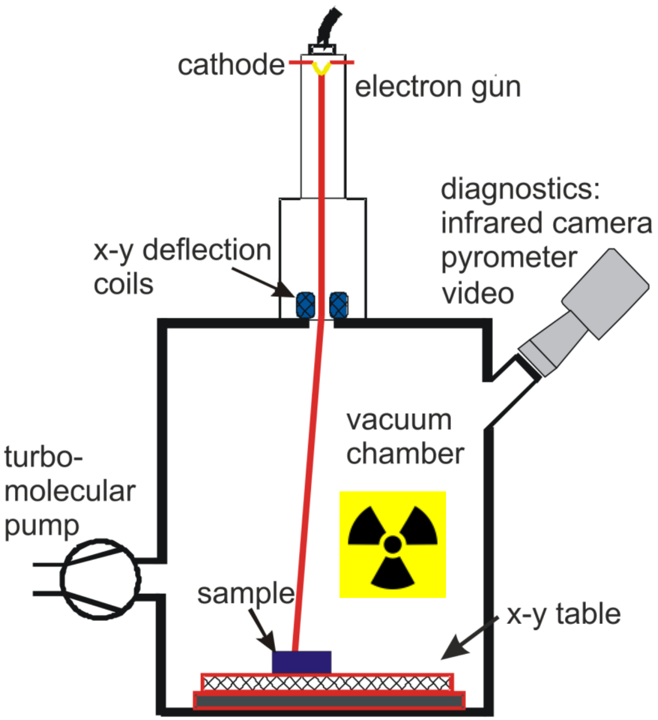
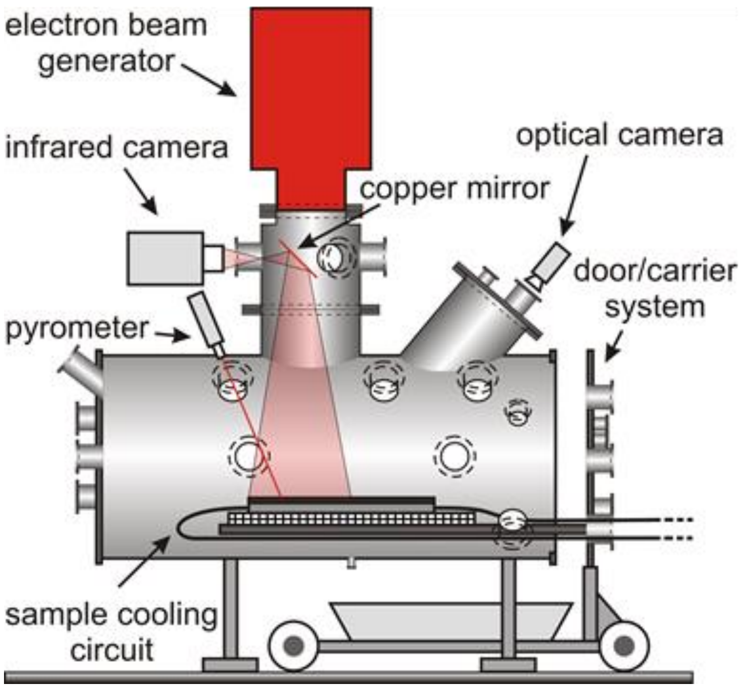
Electron beam facility JUDITH 1



- max. power 60 kW
- acceleration voltage < 150 kV
- EB diameter ~1 mm FWHM
- loaded area 10 x 10 cm^2

Electron beam facility JUDITH 2



- max. power 200 kW
- acceleration voltage 30 – 60 kV
- EB diameter ≤ 5 mm FWHM
- loaded area 40 x 40 cm^2

High heat flux test facilities

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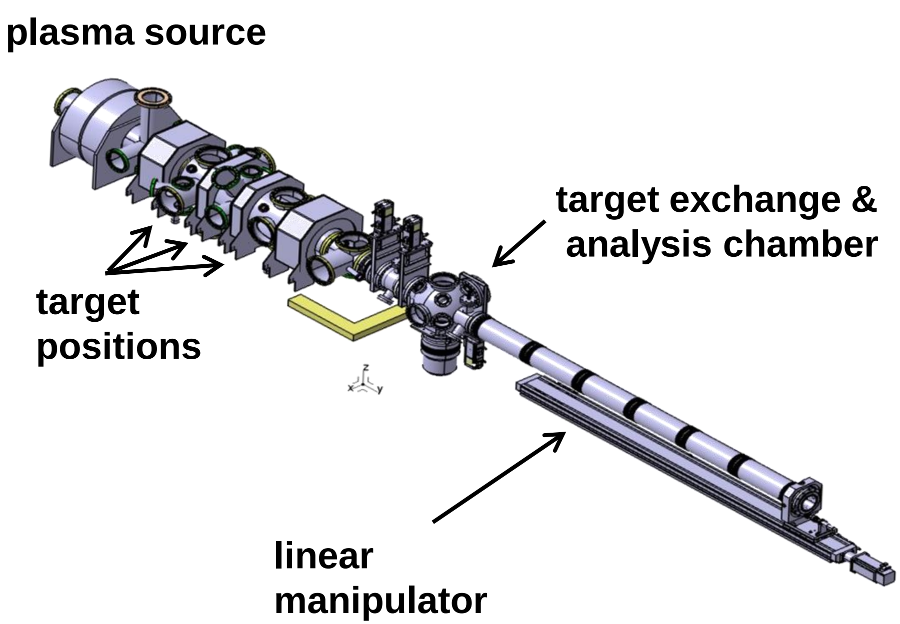
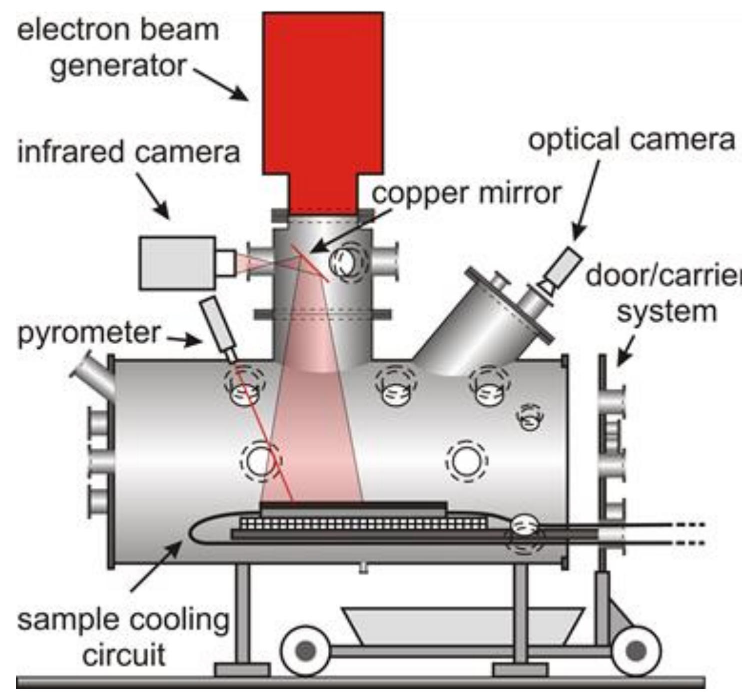
Linear Plasma Device PSI-2



- plasma diameter 60 mm
- particle flux ≤ 10^{23} $m^{-2}s^{-1}$
- incident ion energy (bias) 10 – 300 eV
- Nd:YAG laser 1064 nm
- laser energy 32 J

Electron beam facility JUDITH 2



- max. power 200 kW
- acceleration voltage 30 – 60 kV
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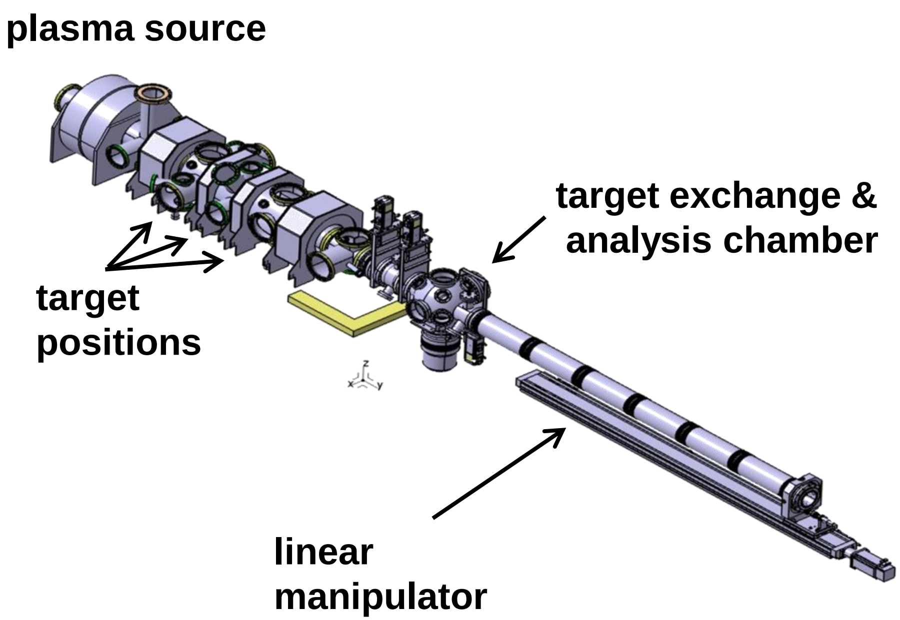
- loaded area 40 x 40 cm^2

High heat flux test facilities

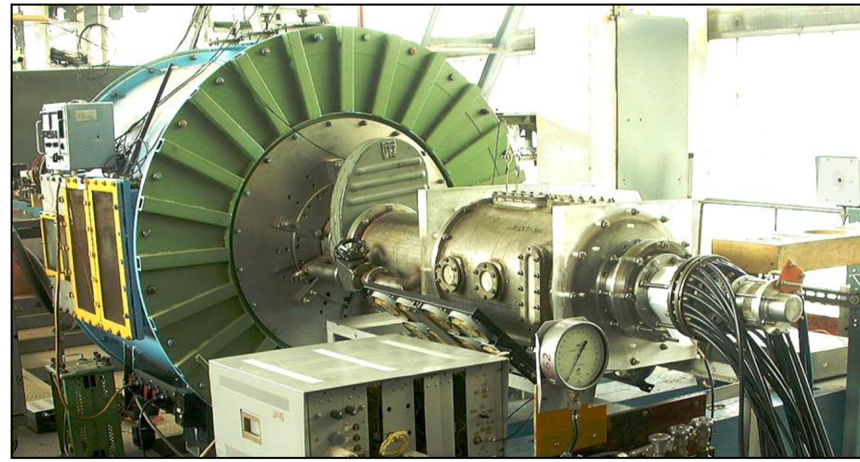
JÜLICH FORSCHUNGSZENTRUM

Linear Plasma Device PSI-2



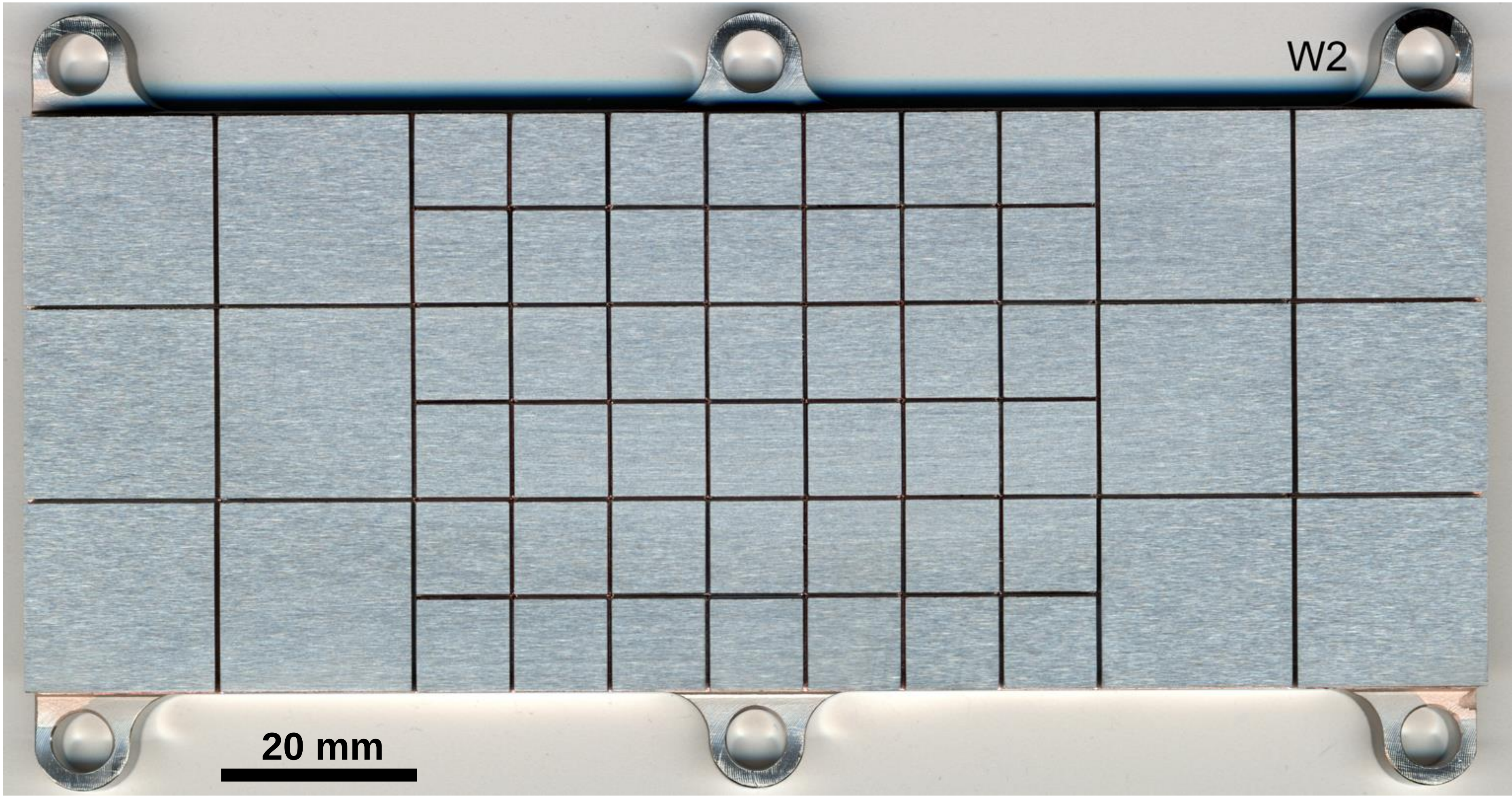
- plasma diameter 60 mm
- particle flux ≤ 1023 m-2s-1
- incident ion energy (bias) 10 – 300 eV
- Nd:YAG laser 1064 nm
- laser energy 32 J

Quasi Stationary Plasma Accelerator (QSPA)



• heat load	0.5 – 2 MJ/m^2
• pulse duration	0.1 – 0.6 ms
• plasma diameter	5 cm
• magnetic field	0 T
• ion impact energy	≤ 0.1 keV
• electron temp.	< 10 eV
• plasma density	≤ 10^{22} m^{-3}

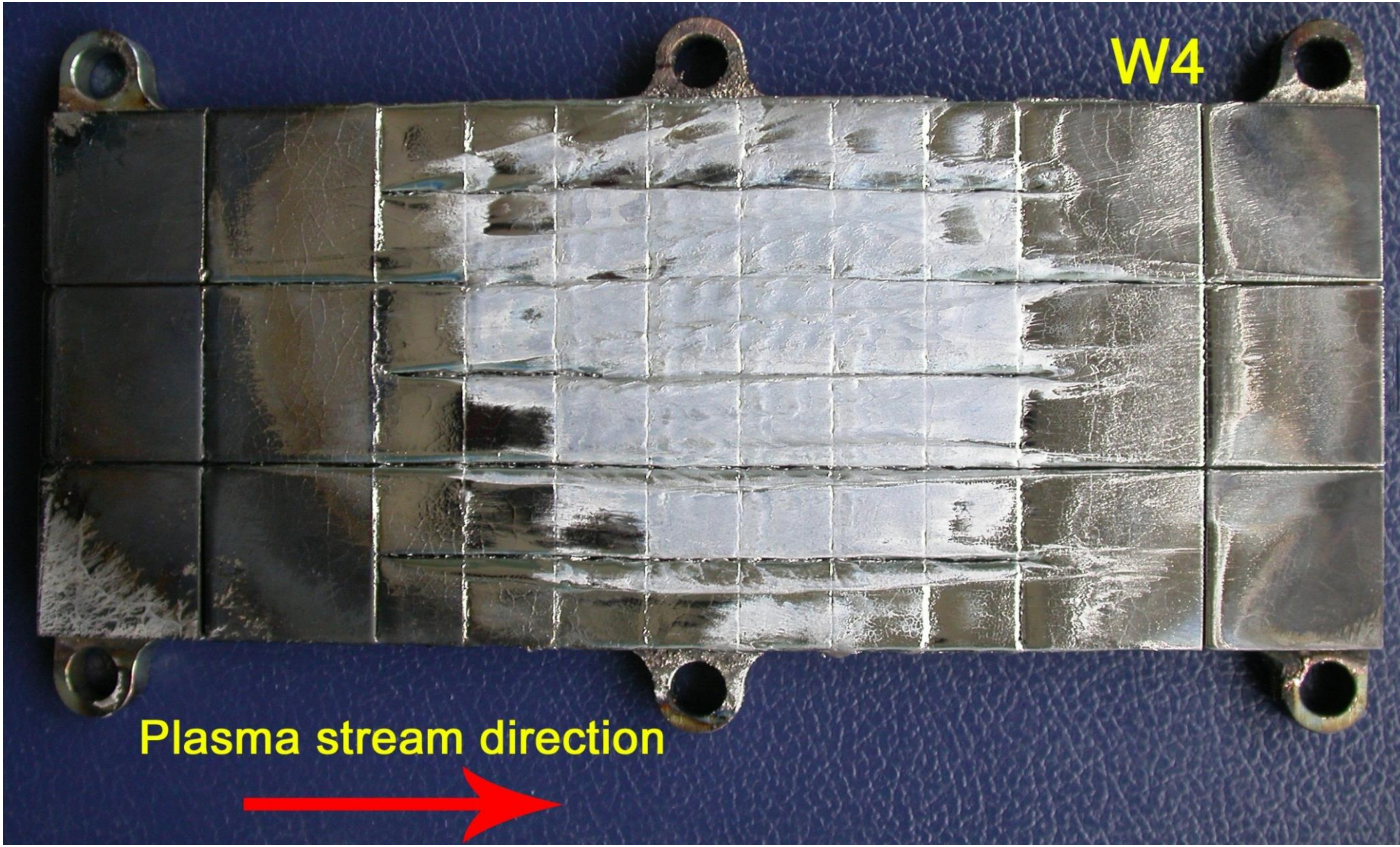
Simulation of ELMs in QSPA



Bridging of gaps due to melt motion

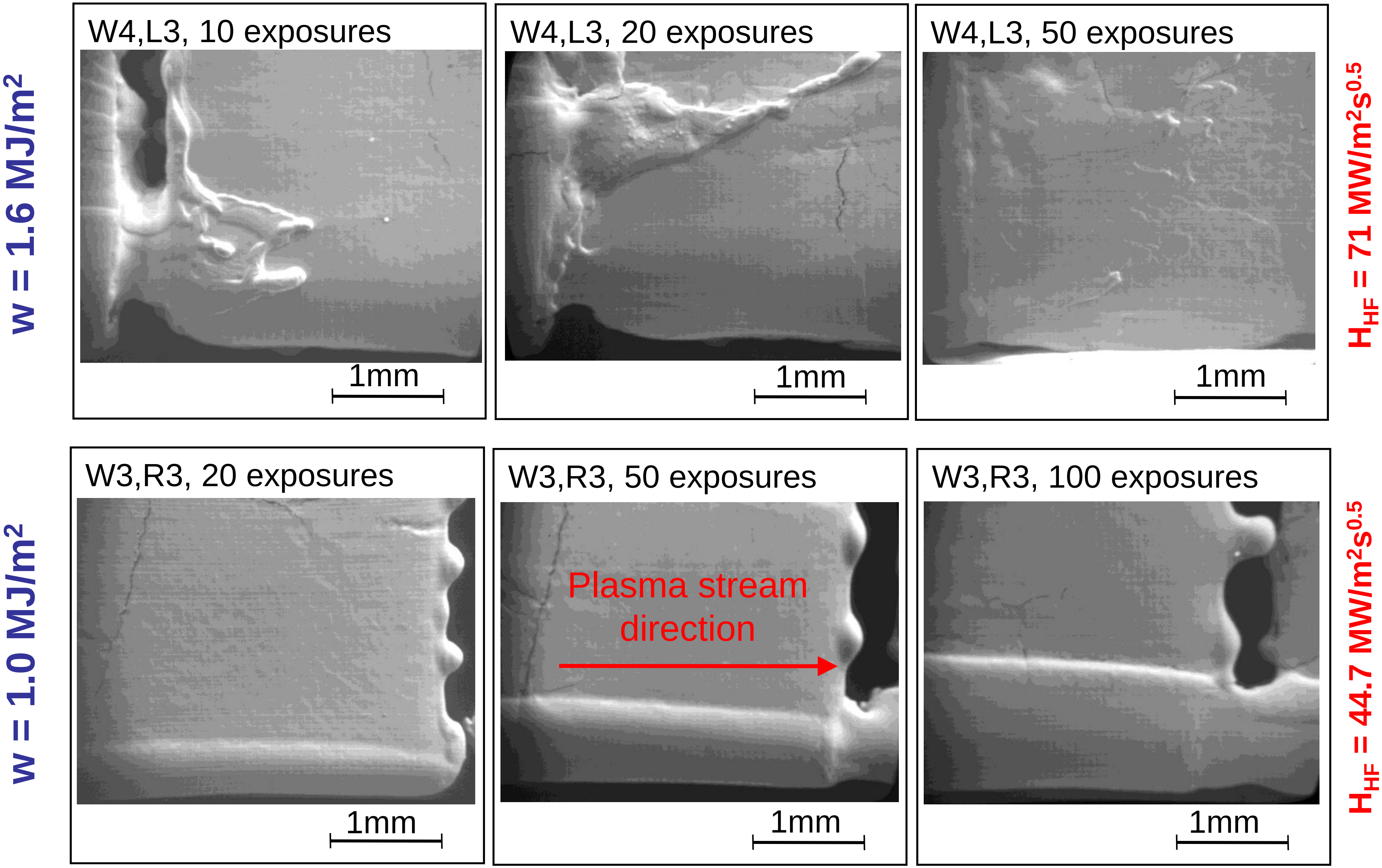
100 pulses @ E = 1.6 MJ/m², Δ= 500 µs

H_{HF} = 71 $MW/m^2s^{0.5}$



Source: A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

Bridge formation between tungsten tiles

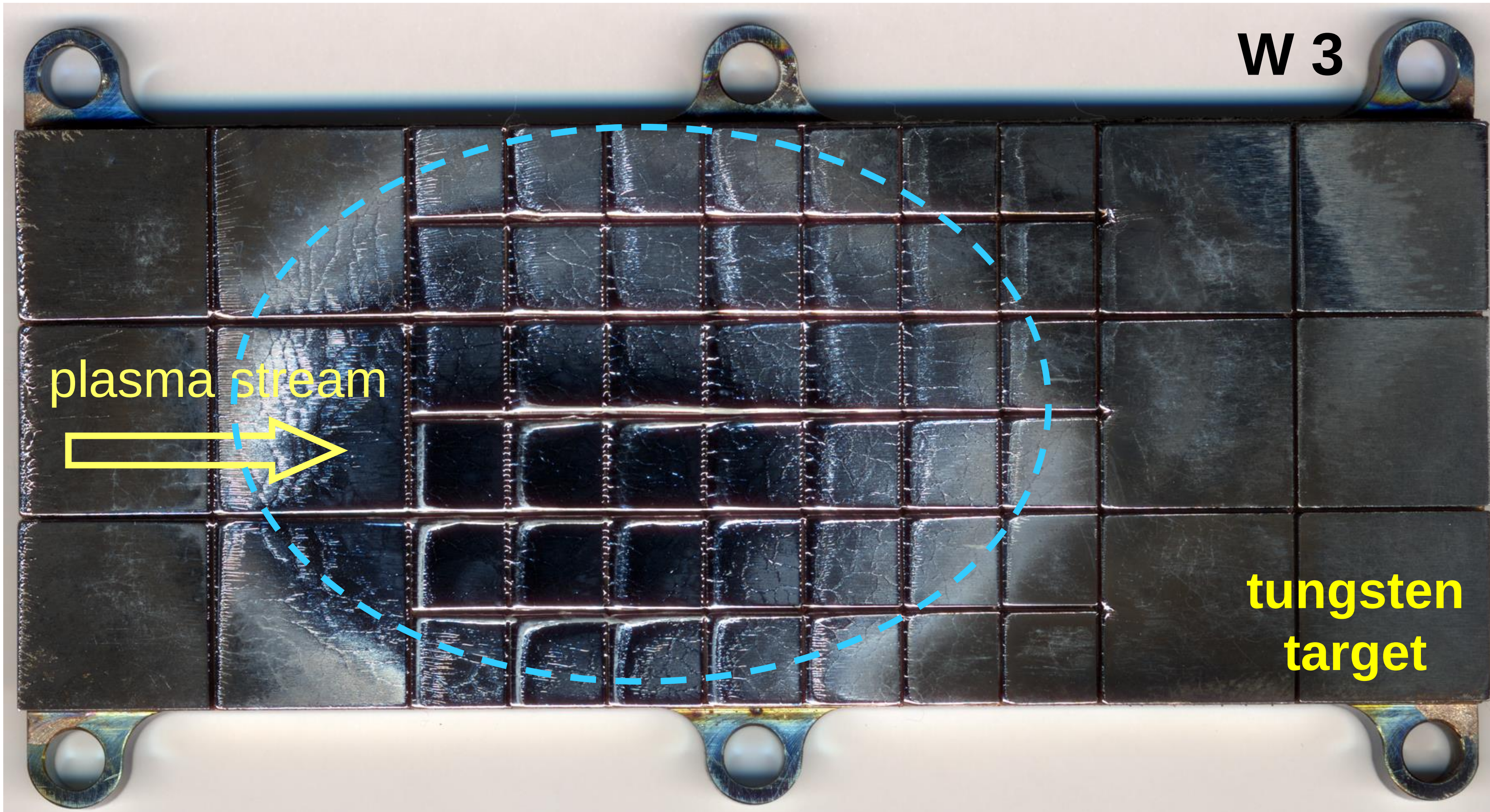


Δt = 500 µs

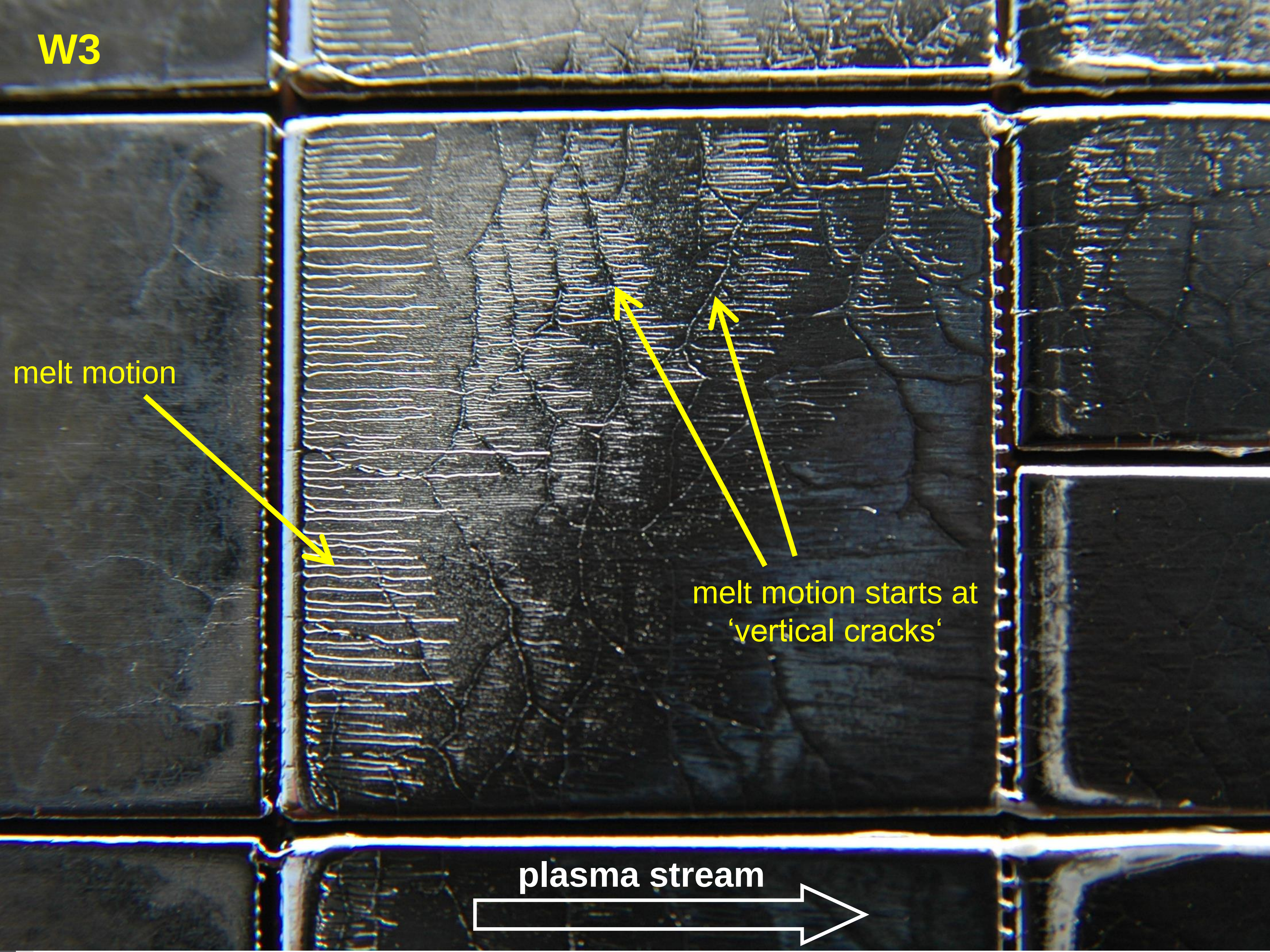
Source: A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

Simulation of ELMs in QSPA

H_{HF} = 44.7 MW/m^{2}s$^{0.5}$



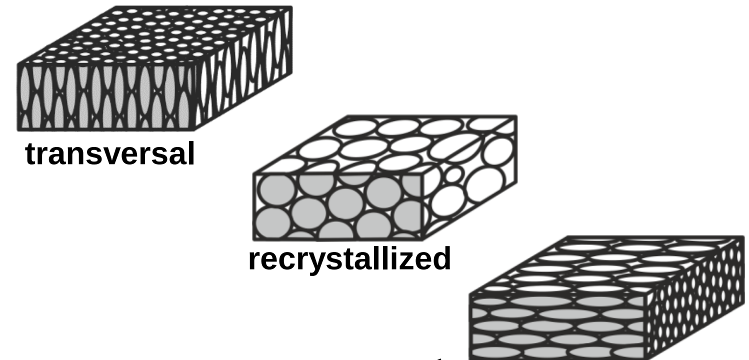
E = 1.0 MJm^{-2} Δt = 500 µs 100 pulses T_0 = 500°C

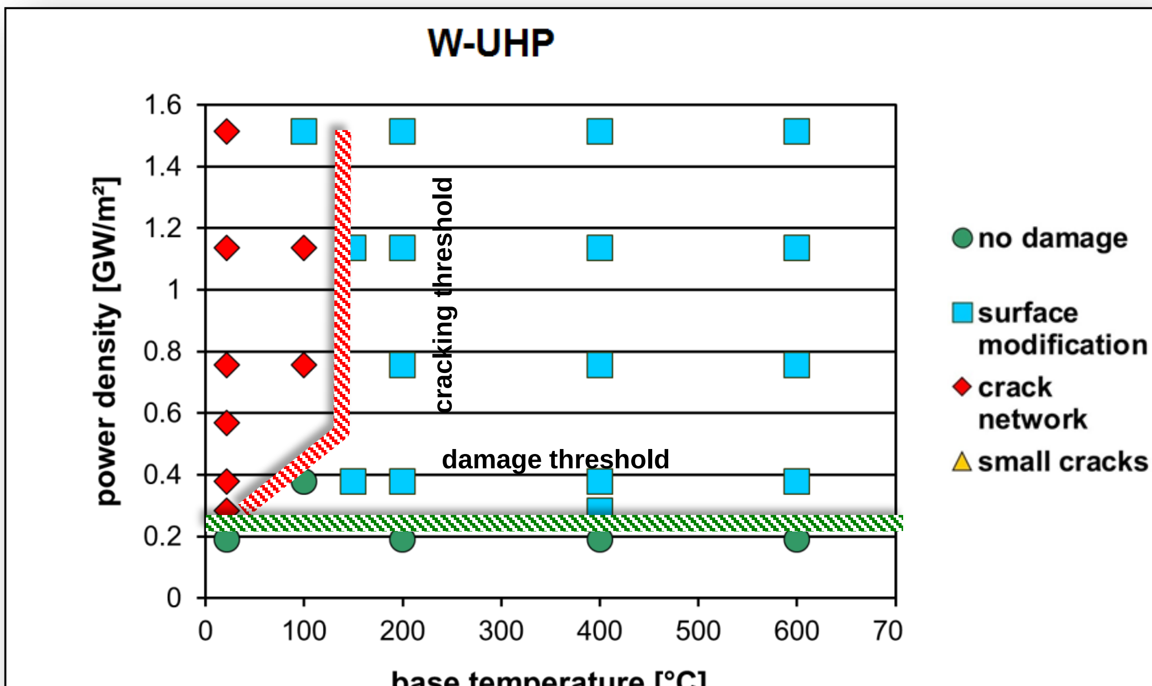

W3
melt motion
melt motion starts at
'vertical cracks'
plasma stream

Thermal shock tests on tungsten

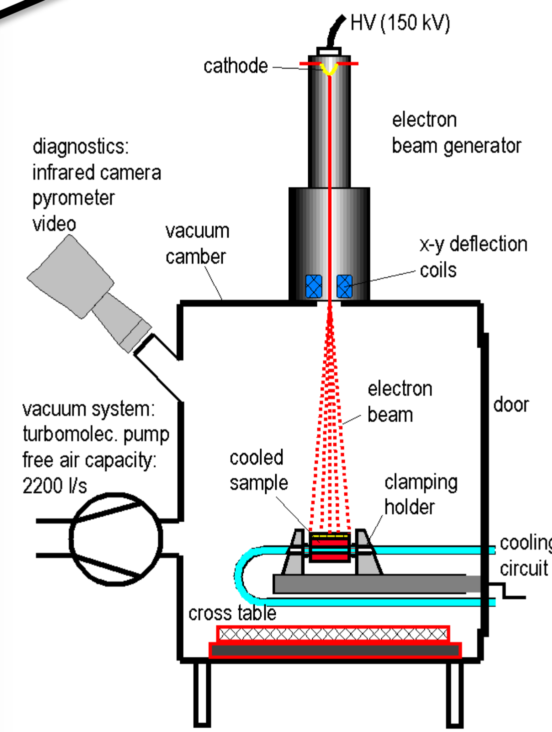
Experimental setting

- Sample size 12 × 12 × 5 mm³
- Loaded area 4 × 4 mm²
- Base temperature: RT up to 1000 °C
- Power densities: 0.19 to 1.51 GW/m²



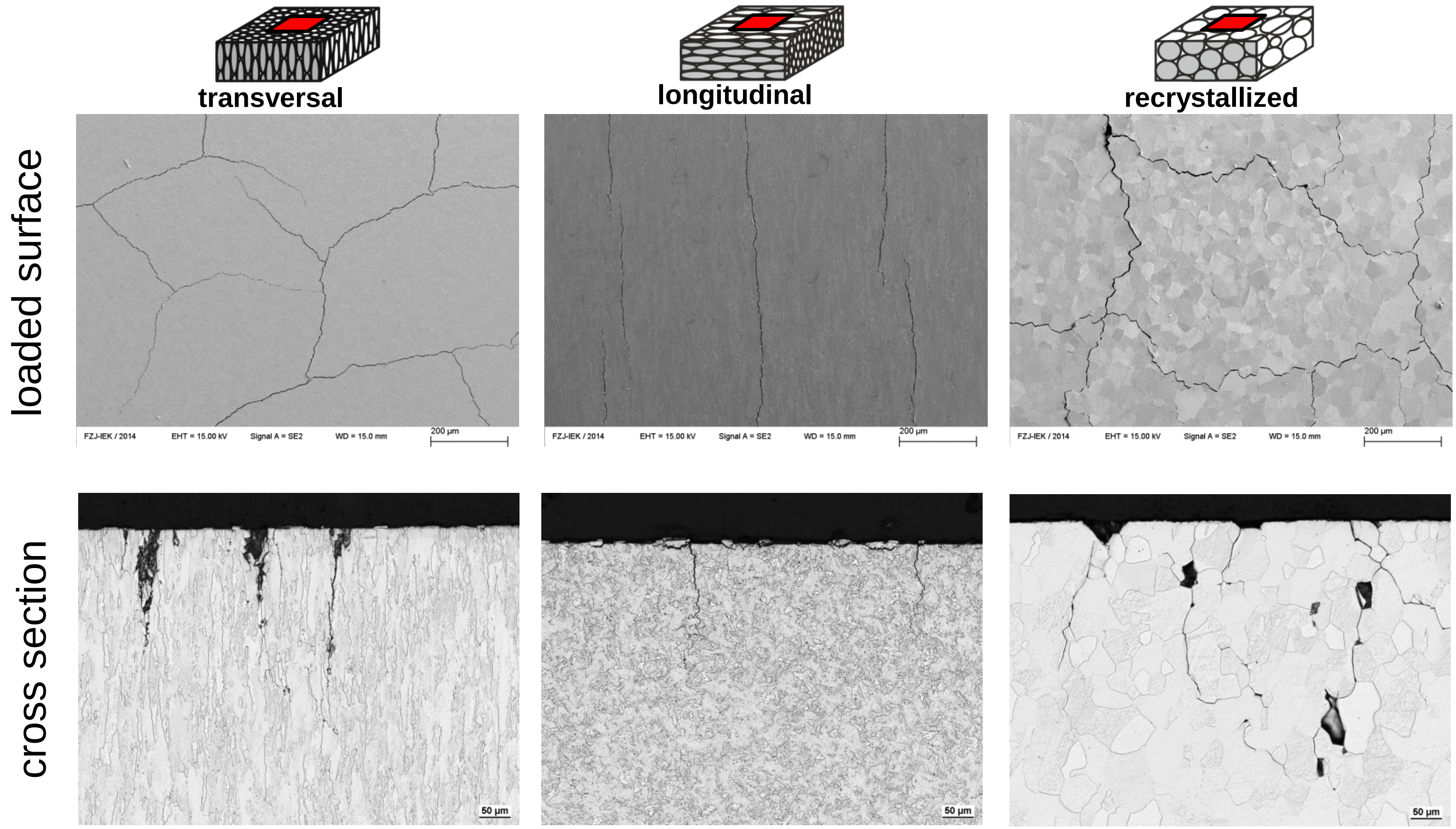


100 pulses with a duration of 1 ms; absorption coefficient 0.55

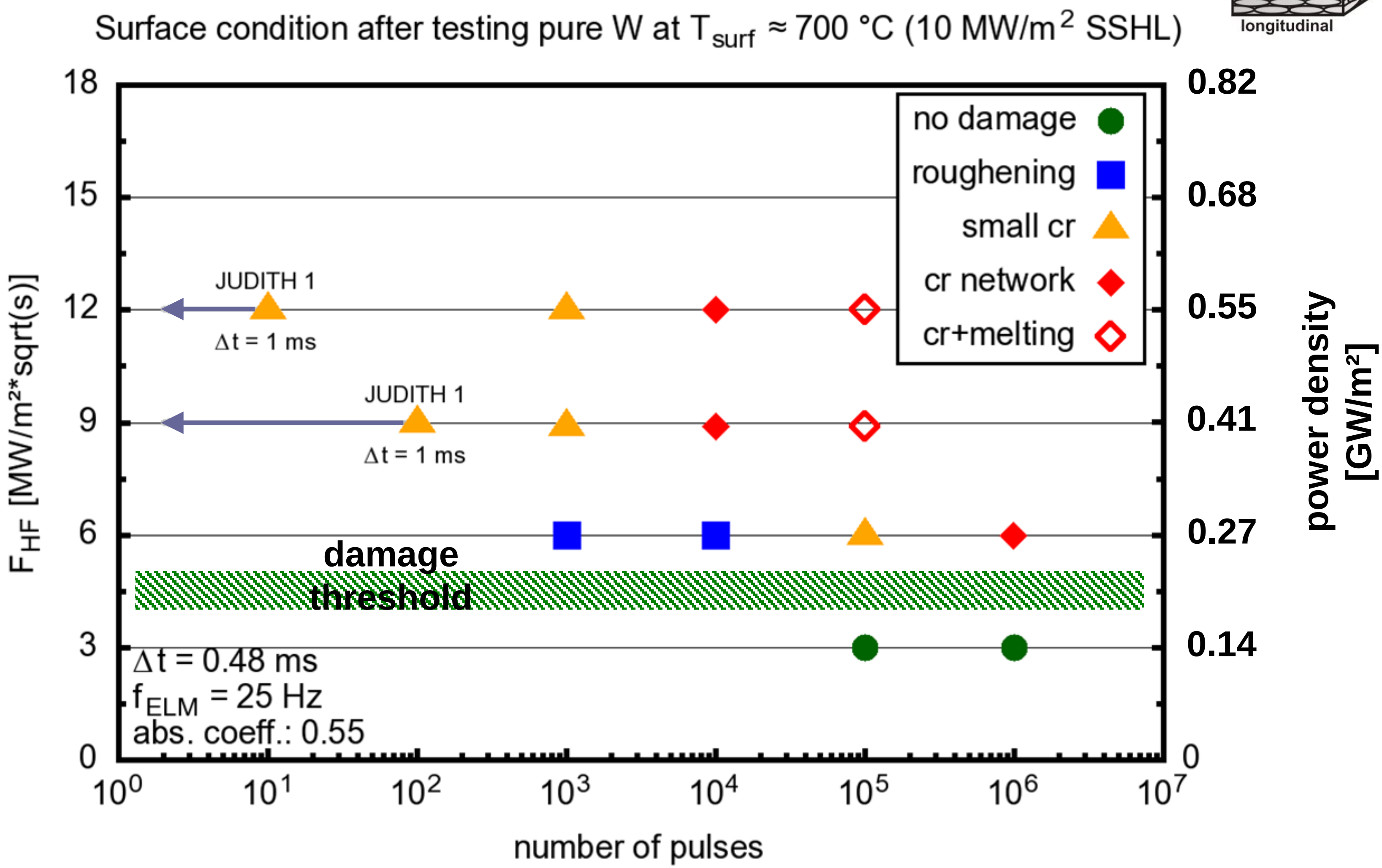


Crack Formation

- Plansee pure tungsten according to ITER specifications ("IGP")
- L_{abs} = 0.38 GW/m^2 (F_{HF} = 12 MW/m^{2}s$^{1/2}$), T_{base} = RT



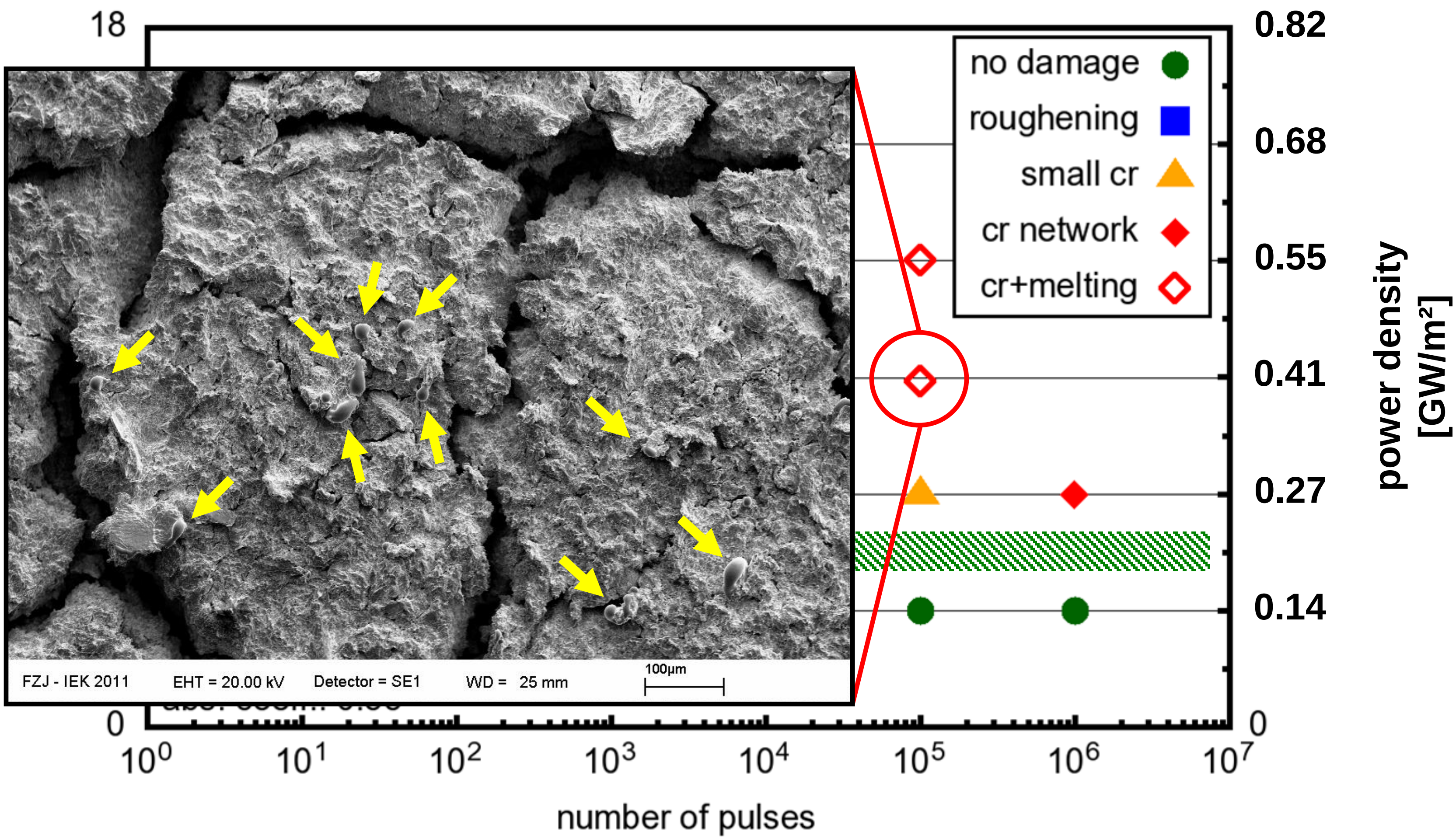
ELM simulation using e-beams with high repetition rates in JUDITH 2



Th. Loewenhoff et al., Physica Scripta T145 (2011) 014057

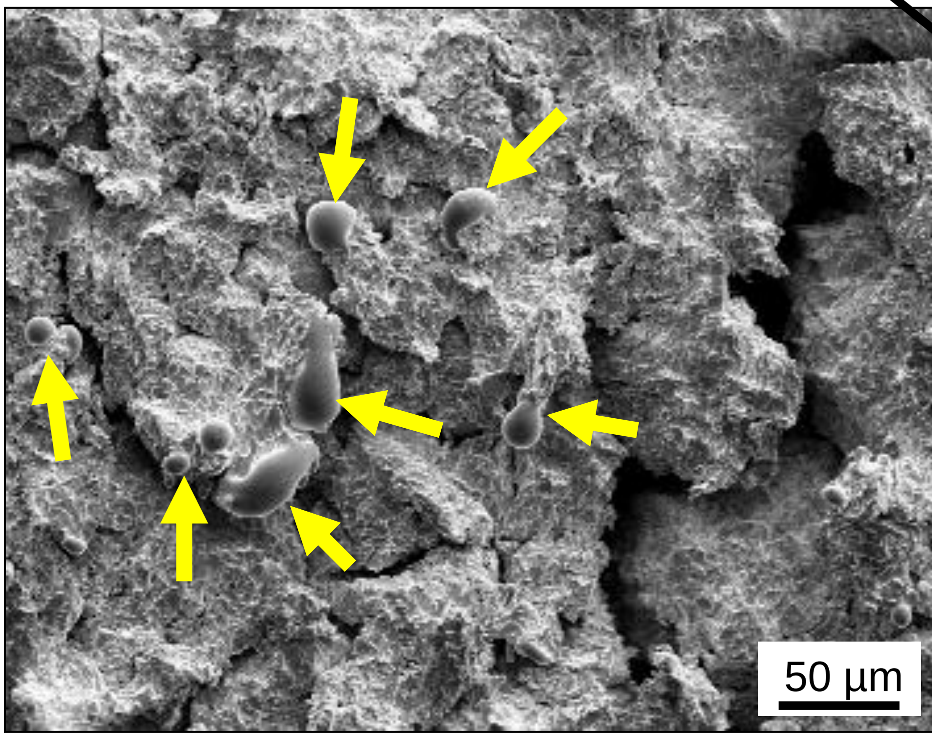
ELM simulation using e-beams with high repetition rates in JUDITH 2

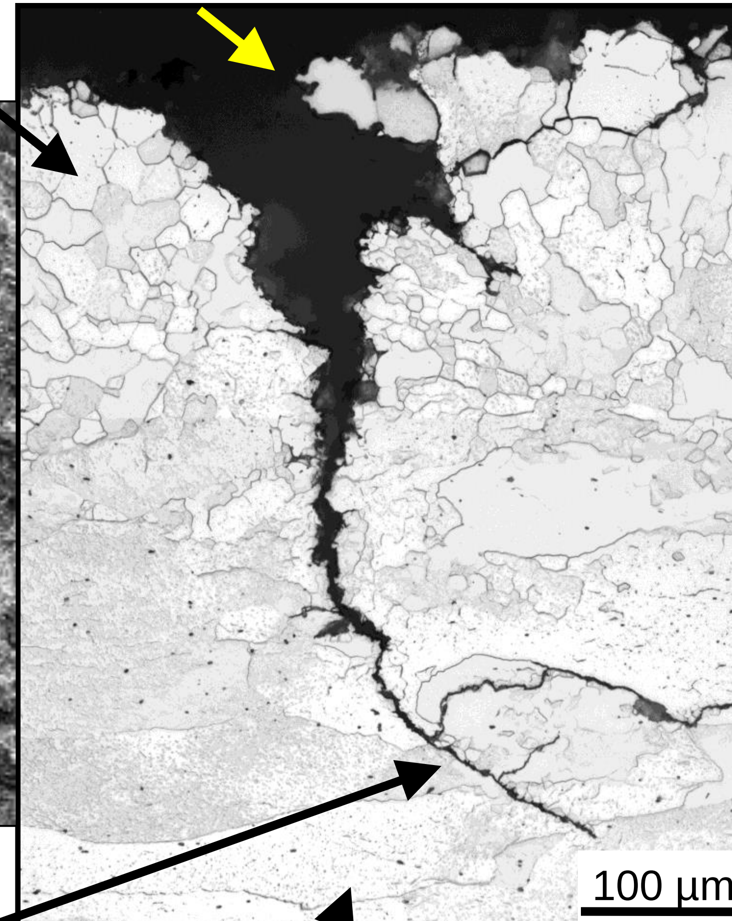
Surface condition after testing pure W at $T_{surf} \approx 700$ °C (10 MW/m^2 SSHL)



Th. Loewenhoff et al., Physica Scripta T145 (2011) 014057

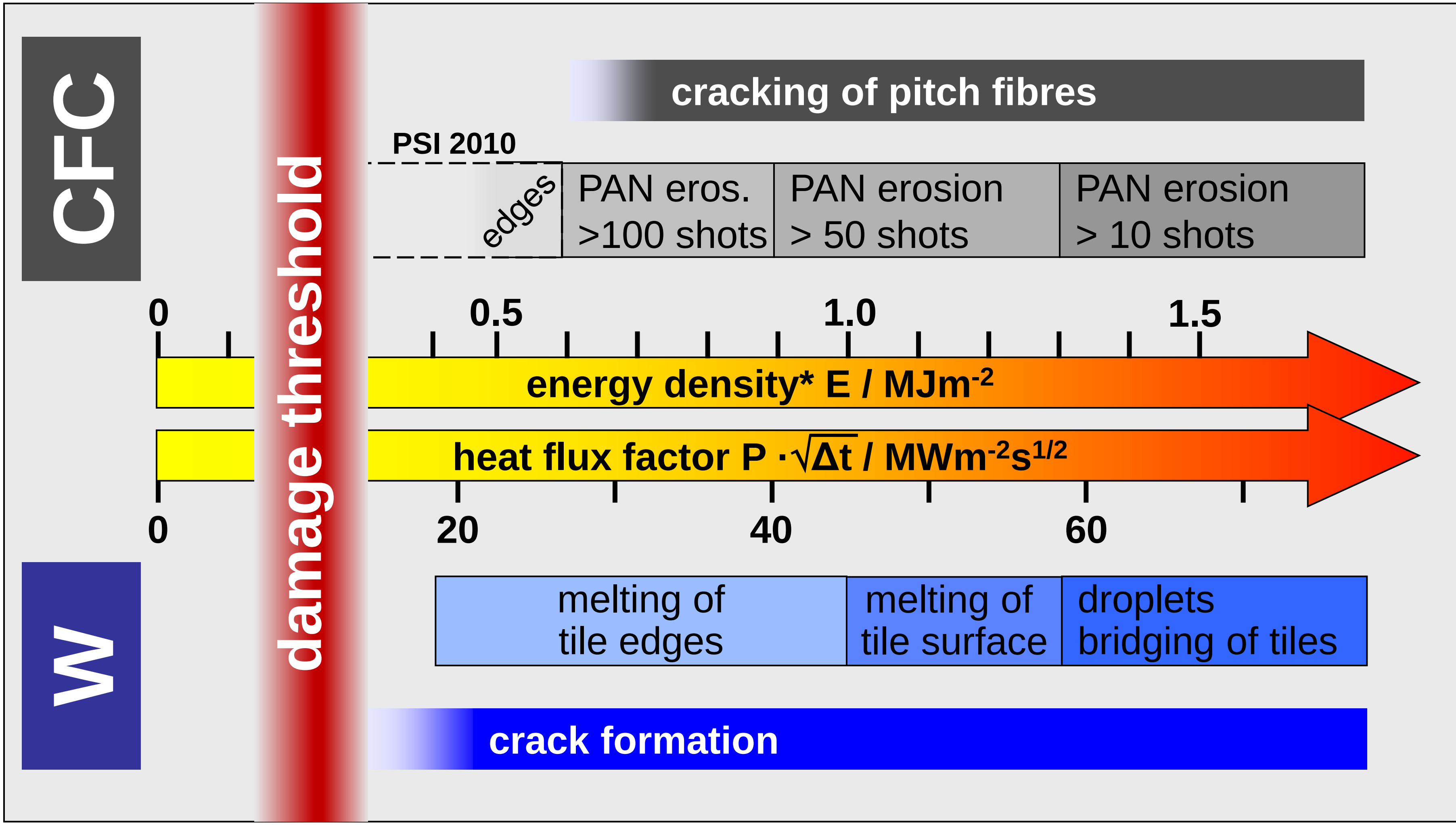
ELM simulation using e-beams with high repetition rates in JUDITH 2





Th. Loewenhoff, et al., Fusion Engineering and Design 87 (2012) 1201-1205

Threshold values for ELM loads



* Δt = 500 µs
T_0 = 500°C
CFC: NB31
W: forged rod material

source: PSI 2006 / 2010

Thermal shock testing of beryllium

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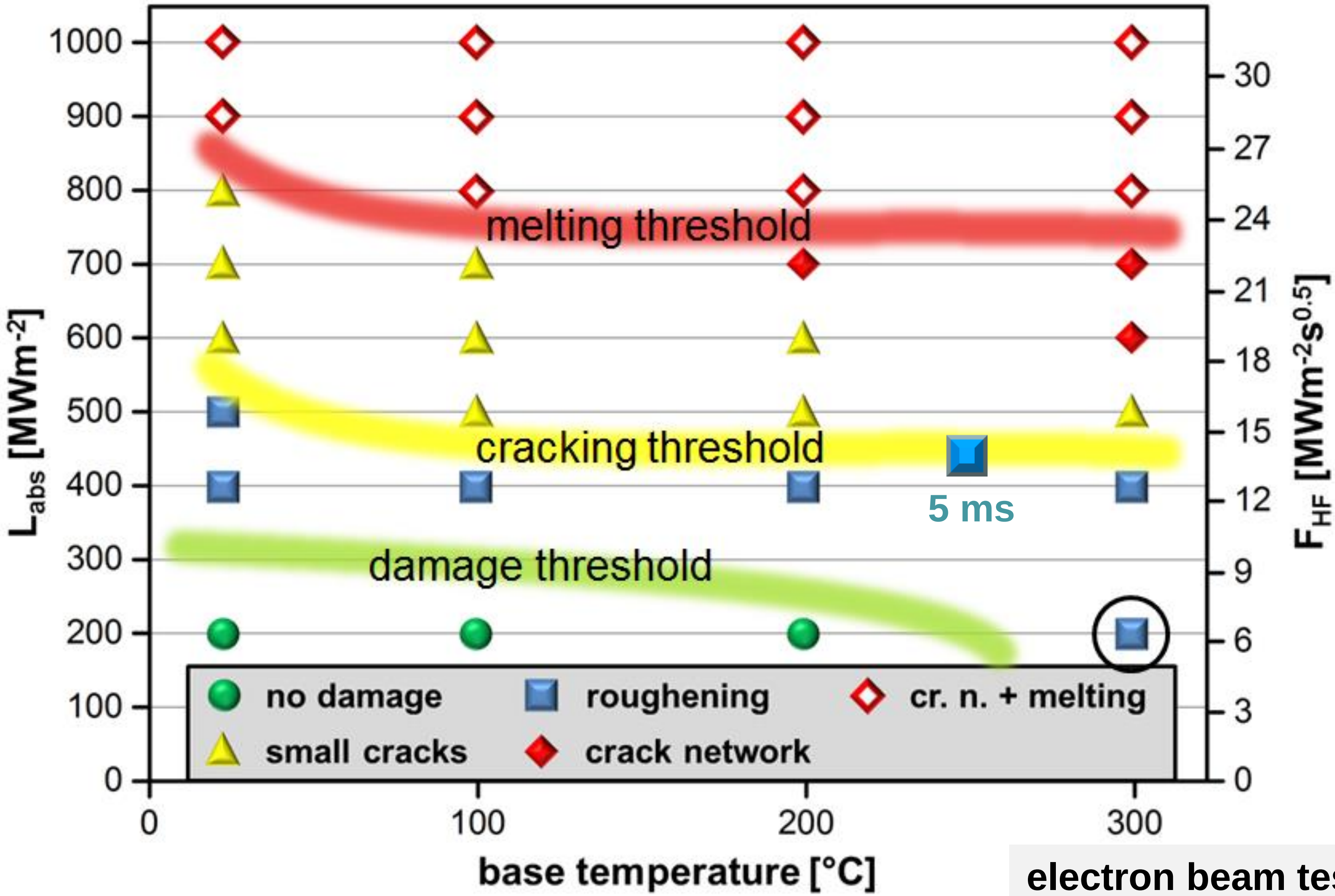
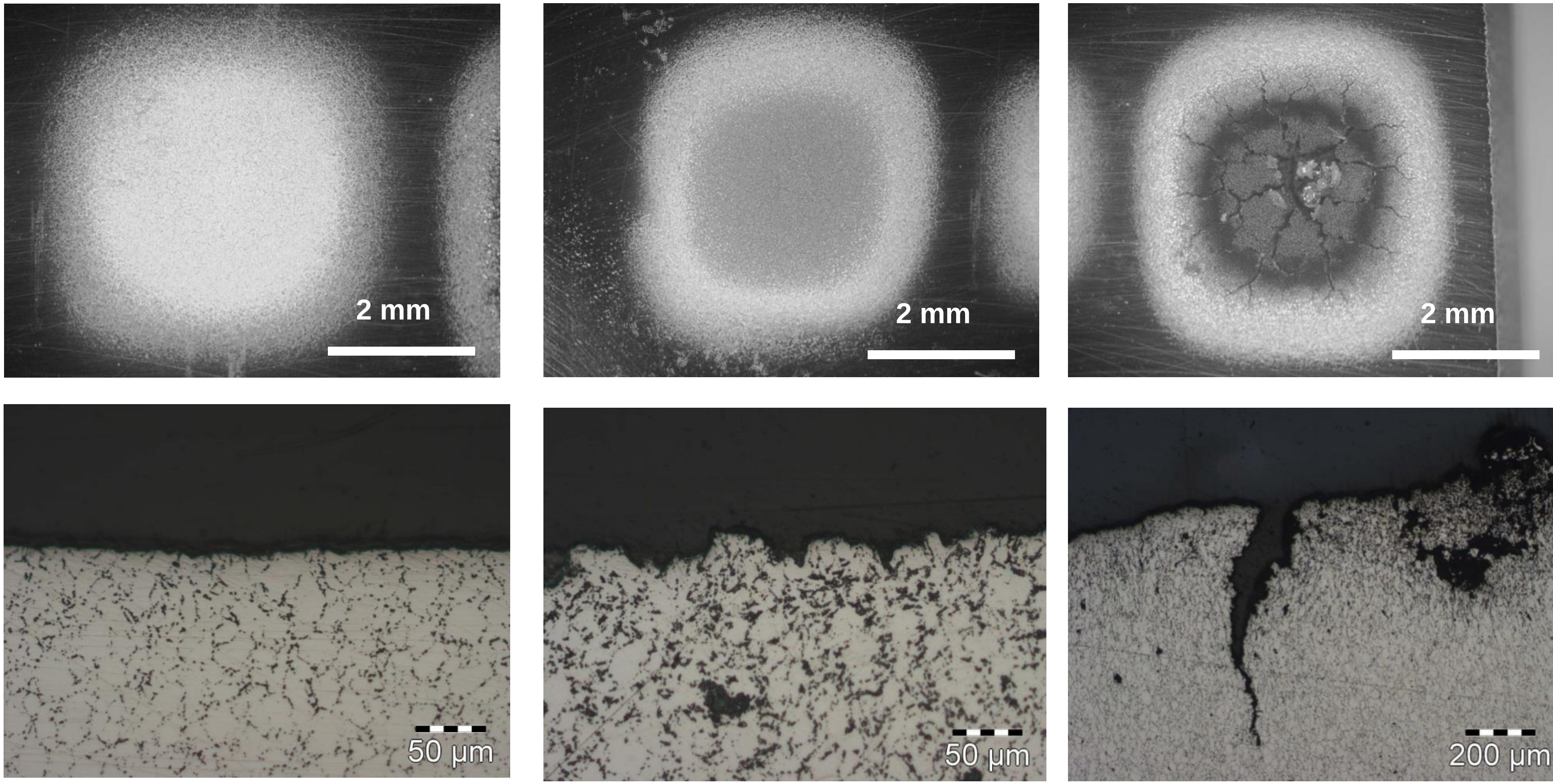


electron beam tests with 100 cycles

Repeated thermal shock testing of Be

n = 100 | **n = 1000** | **n = 10000**



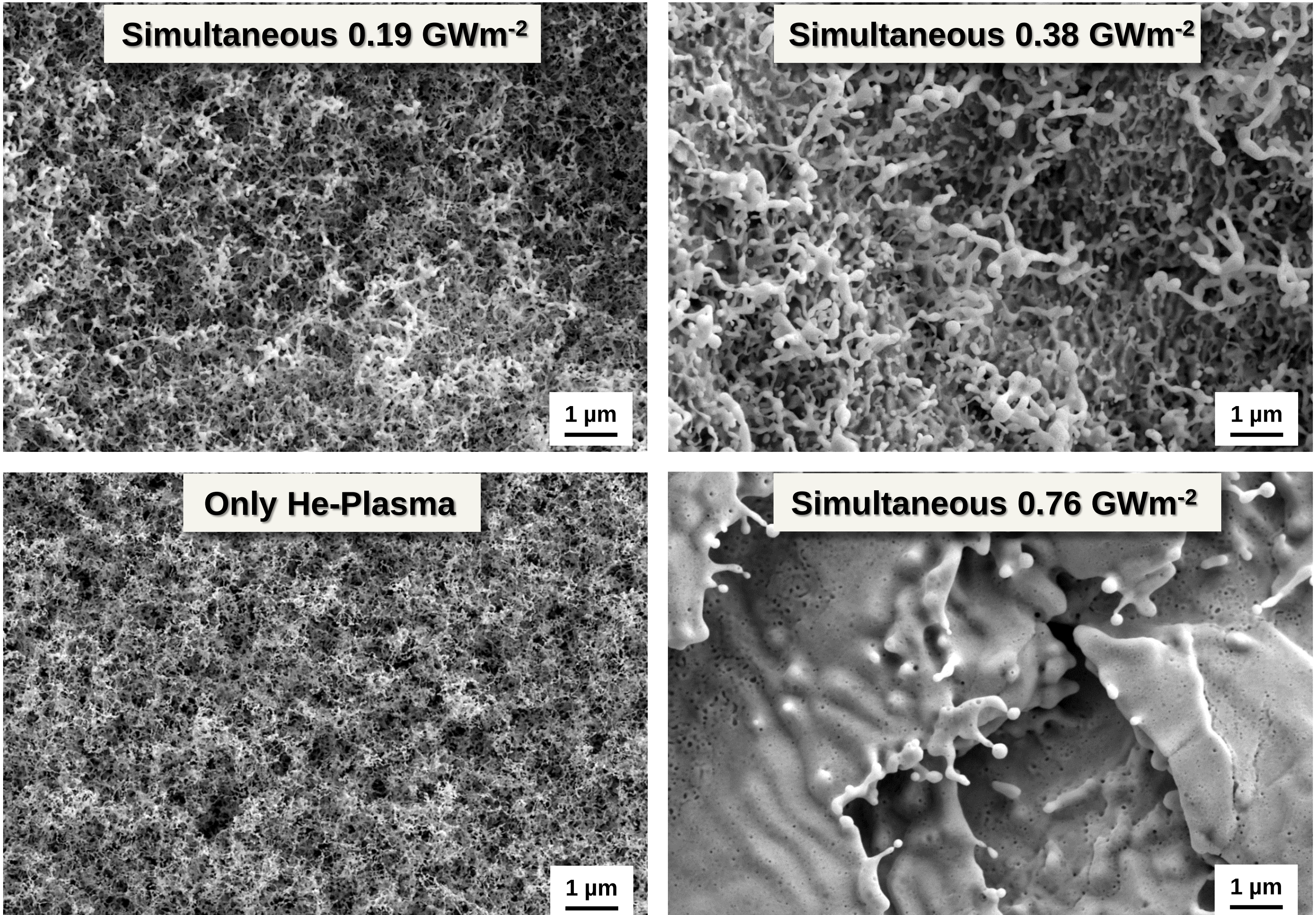
power density $P = 1.0\ MJ/m^2$
$P \cdot \sqrt{(\Delta t)} = 14\ MW/m^2 s^{1/2}$

pulse duration $\Delta t = 5$ ms
base temperature $T_0 = 250°C$

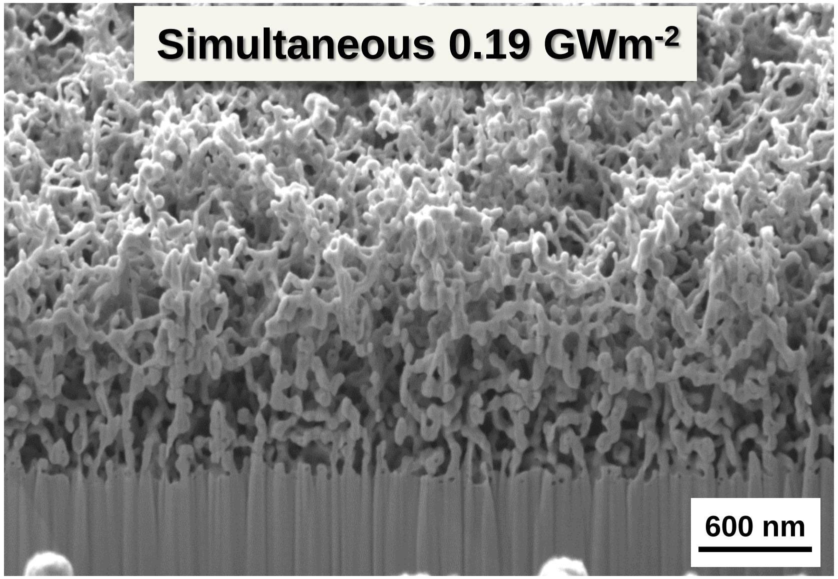
C

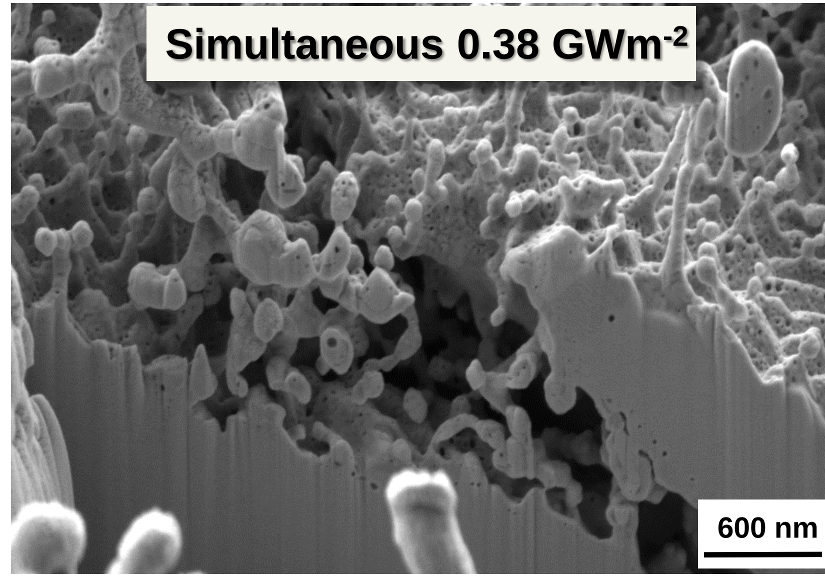
Hydrogen and helium effects

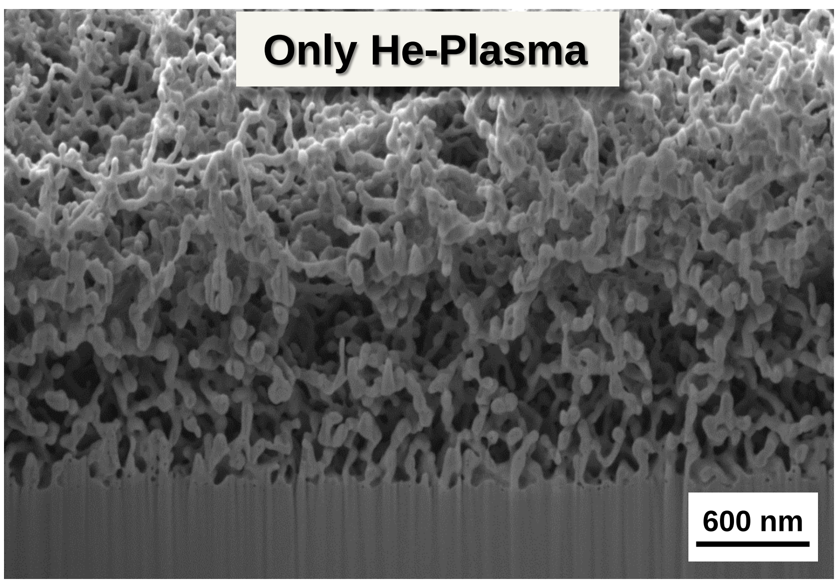
Thermal shock and He-loading

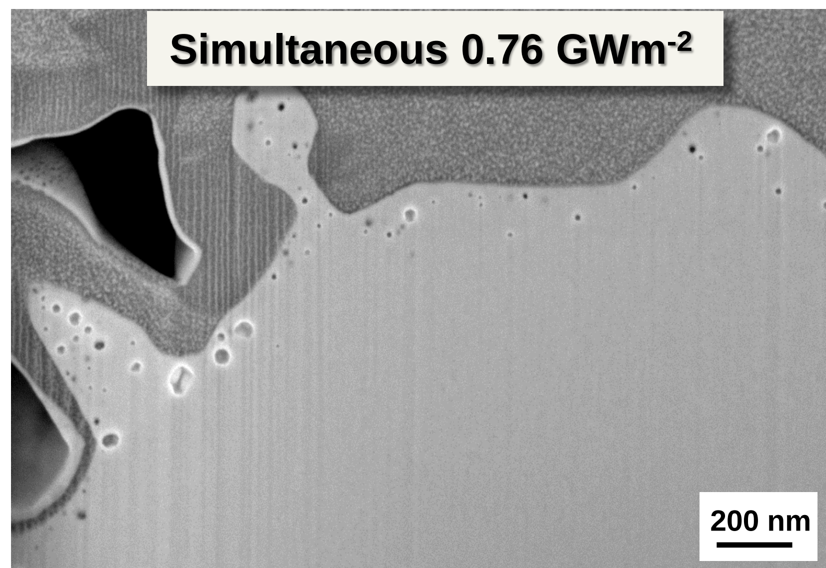


Thermal shock and He-loading





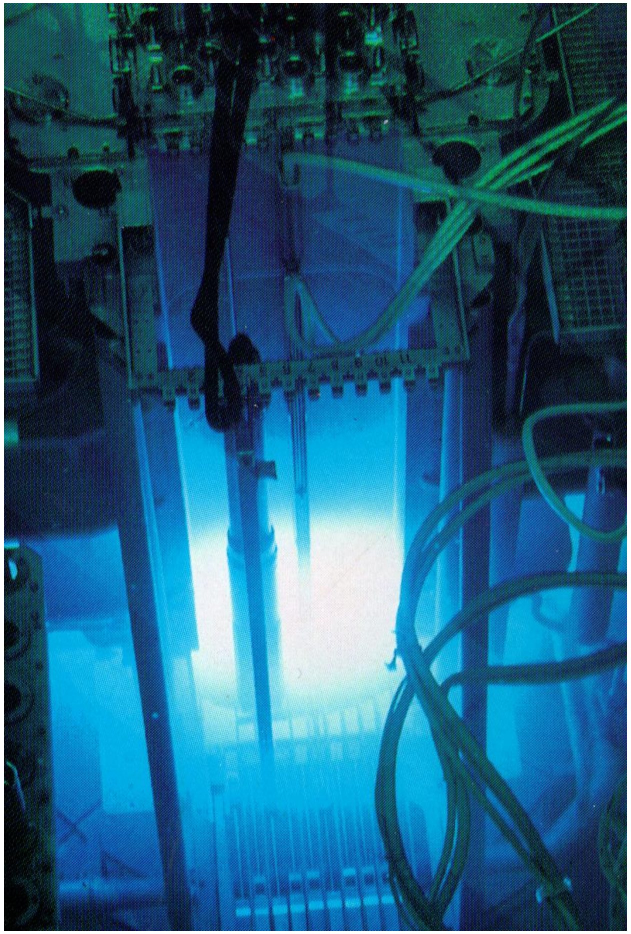




D

Materials degradation by energetic neutrons

Neutron-induced material degradation

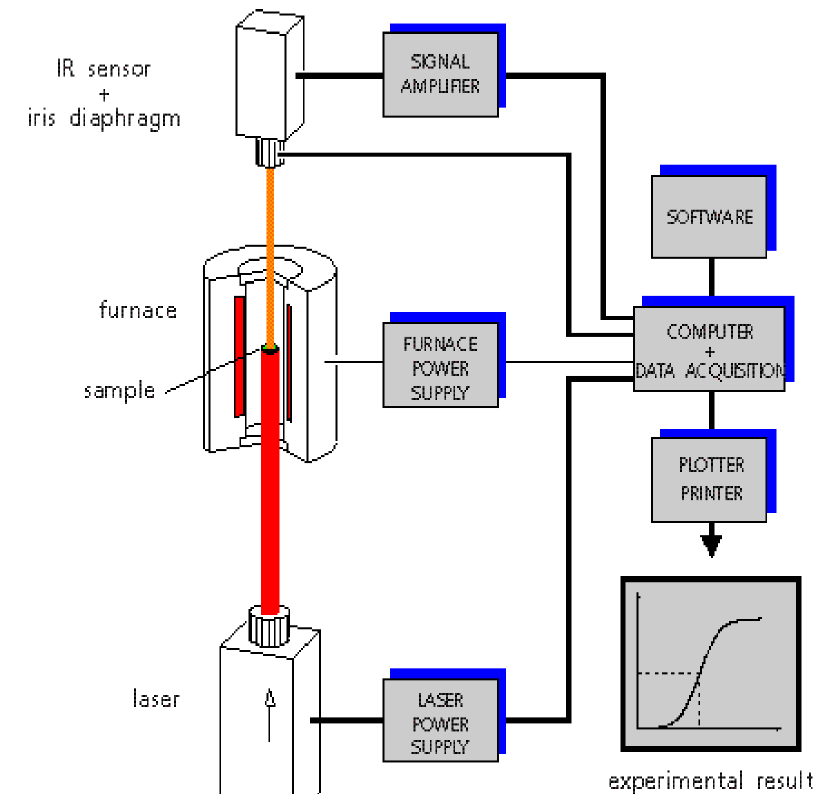


High Flux Reactor (HFR)
Petten, The Netherlands

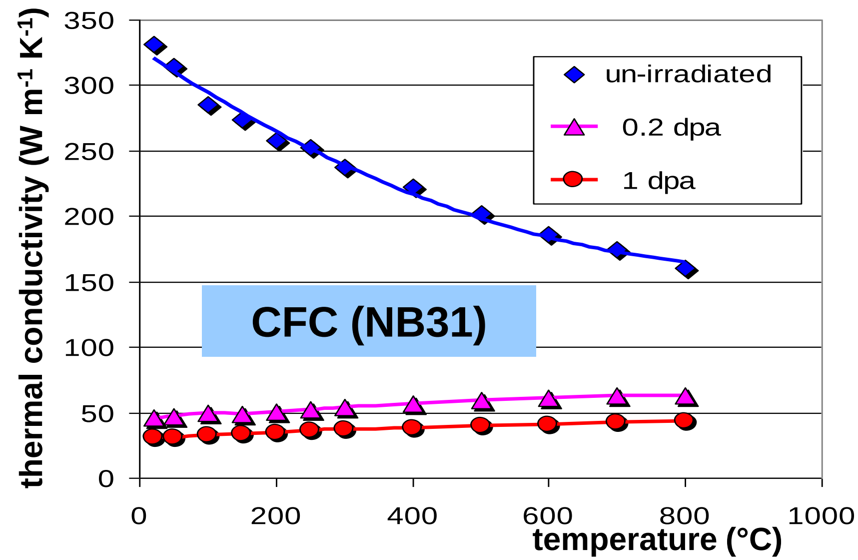
Neutron induced effects:

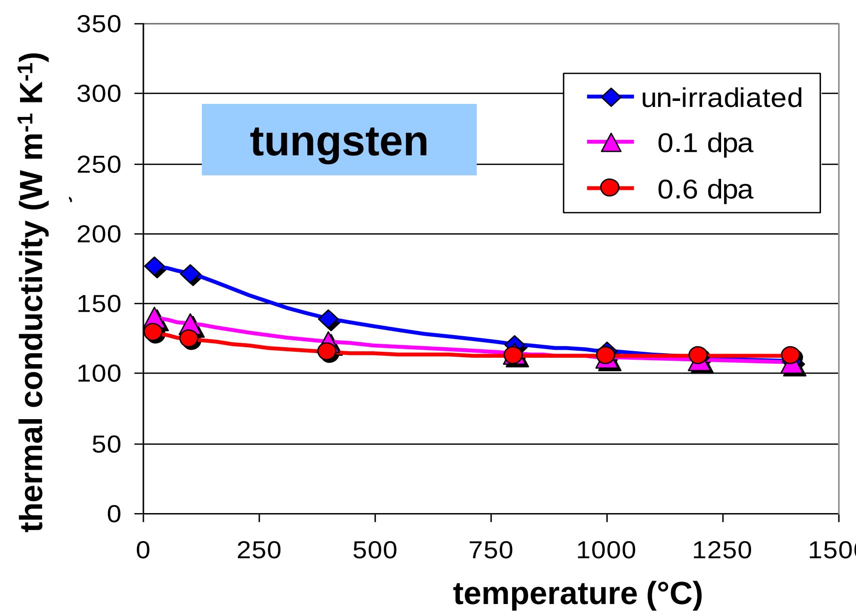
- **activation** of plasma facing and structural materials
  e.g. Co, Ag
- **transmutation** due to 14 MeV neutrons
  $W \rightarrow Re \rightarrow Os$
  $Be \rightarrow He, T$
- **degradation** of thermal and mechanical properties
  thermal conductivity,
  hardening,
  embrittlement

n-irradiation effect on thermal conductivity



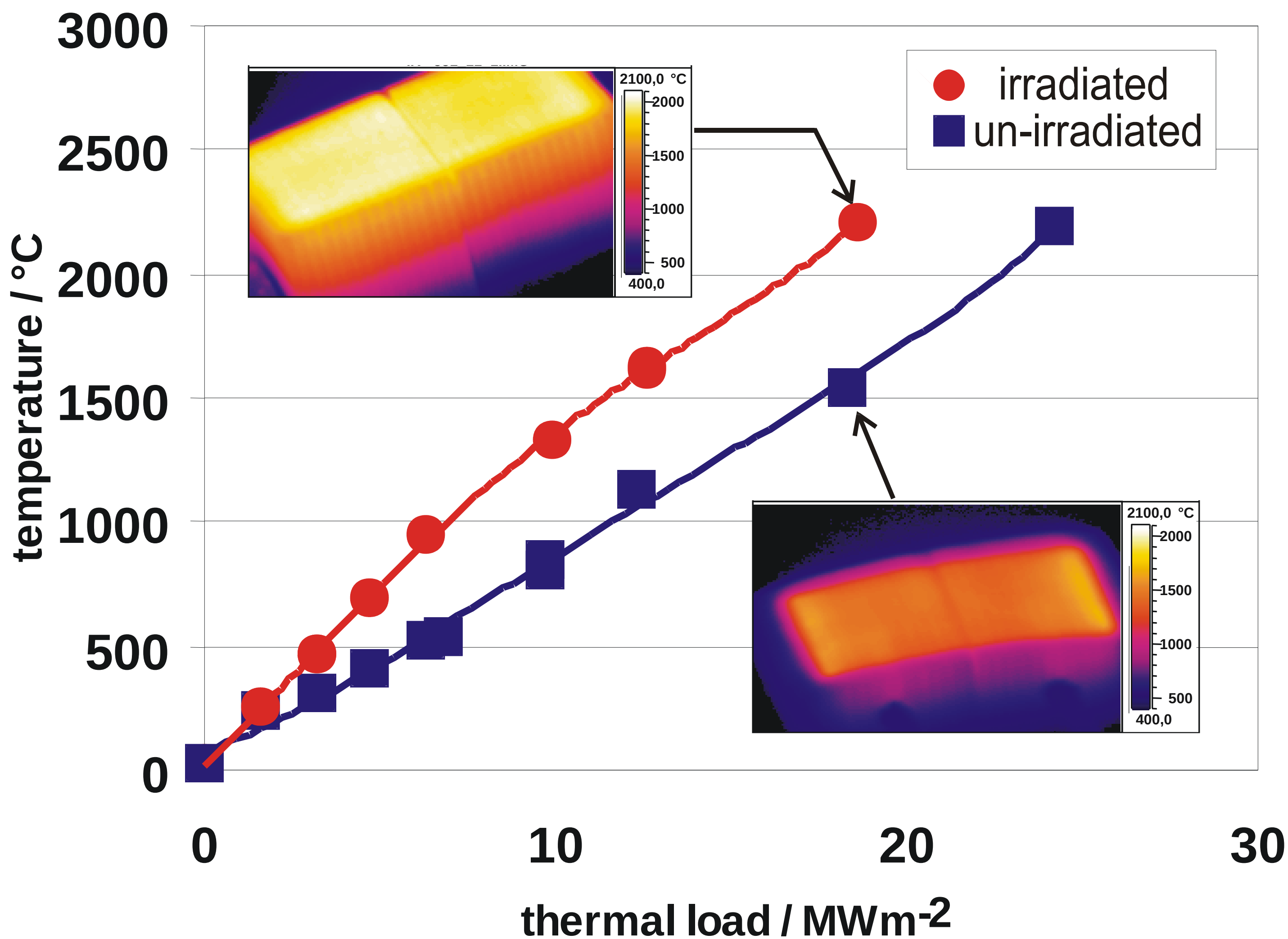
Laser-flash-apparatus (schematic)





HHF performance of neutron irradiated divertor modules

Dunlop Concept 1 (12 mm) / CuCrZr T_{irr} = 350°C / 0.3 dpa



Future fusion materials research in JÜLICH FORSCHUNGSZENTRUM