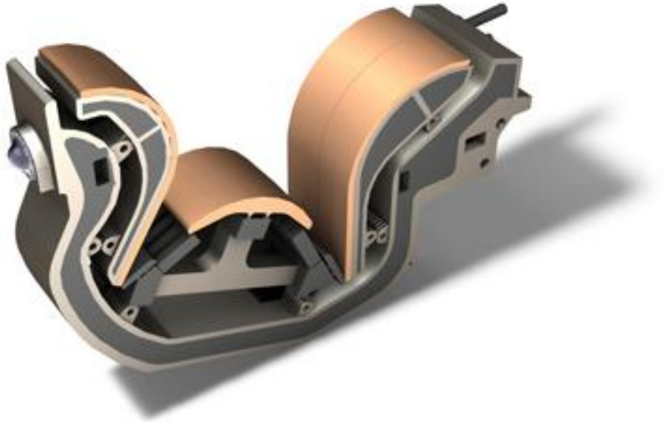
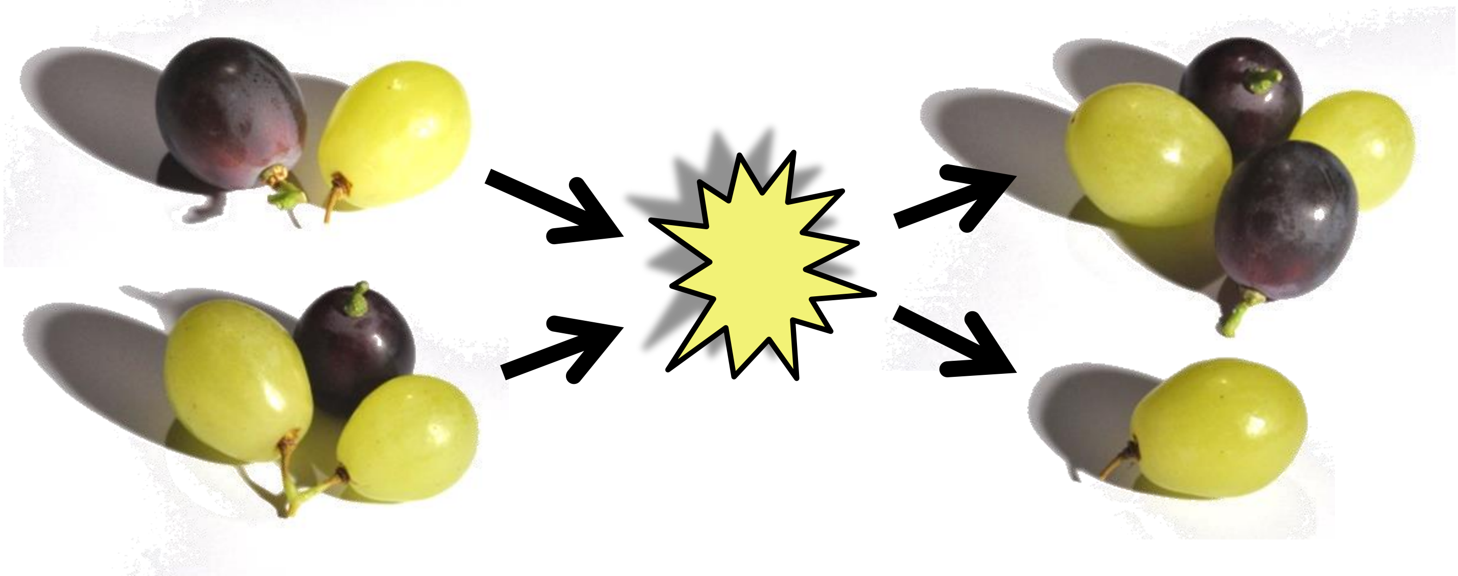


Material issues for plasma facing components in future fusion devices

J. Linke, N. Lemahieu, Th. Loewenhoff, G. Pintsuk, B. Spilker, I. Steudel, M. Wirtz

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

Mysterious fusion



deuterium

tritium

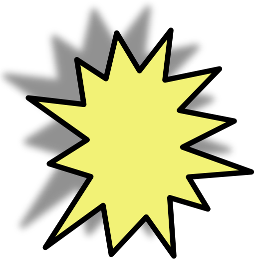
helium
(3.5 MeV)

neutron
(14.1 MeV)

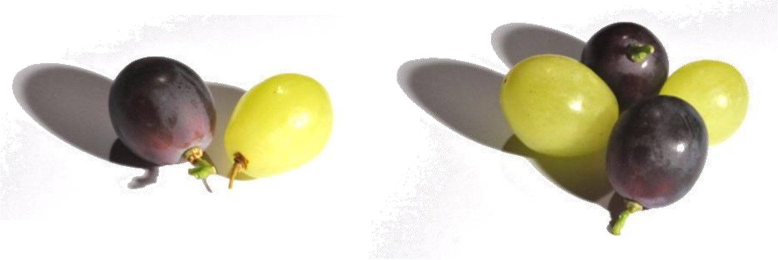
Outline:

A Thermal loads on plasma facing components

B Simulation of intense thermal loads



C Hydrogen and helium effects

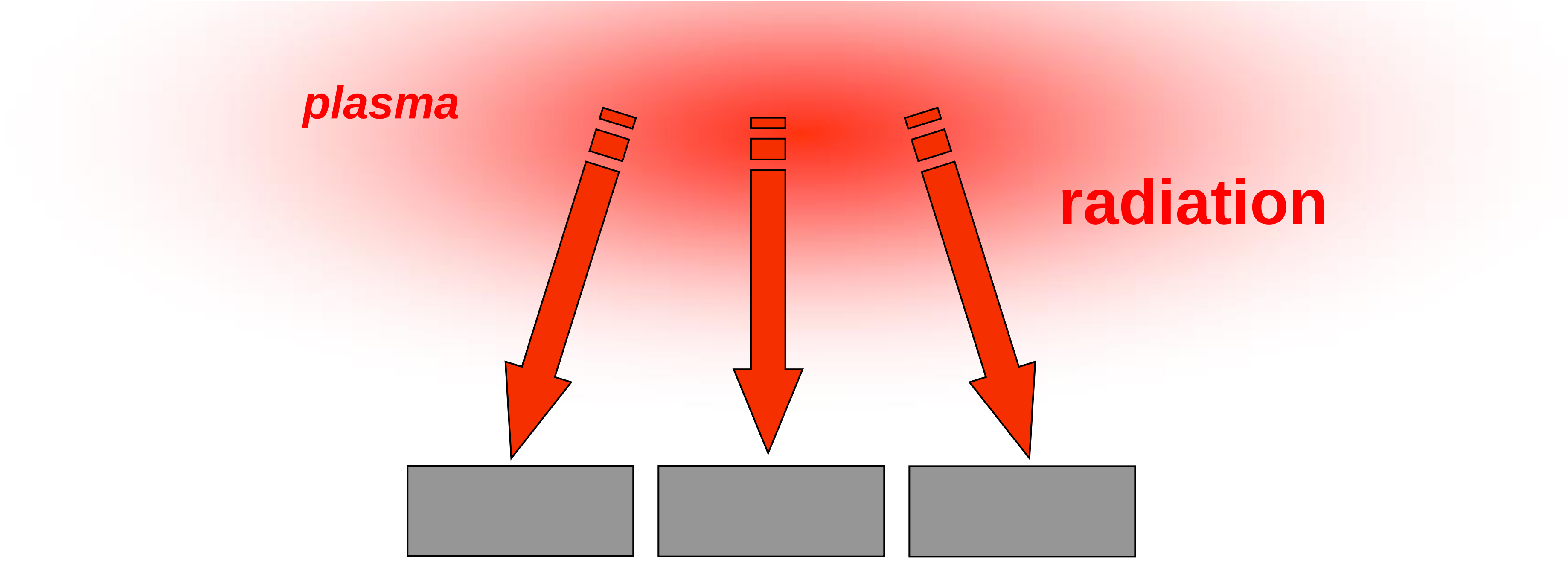


D Material degradation by energetic neutrons

A

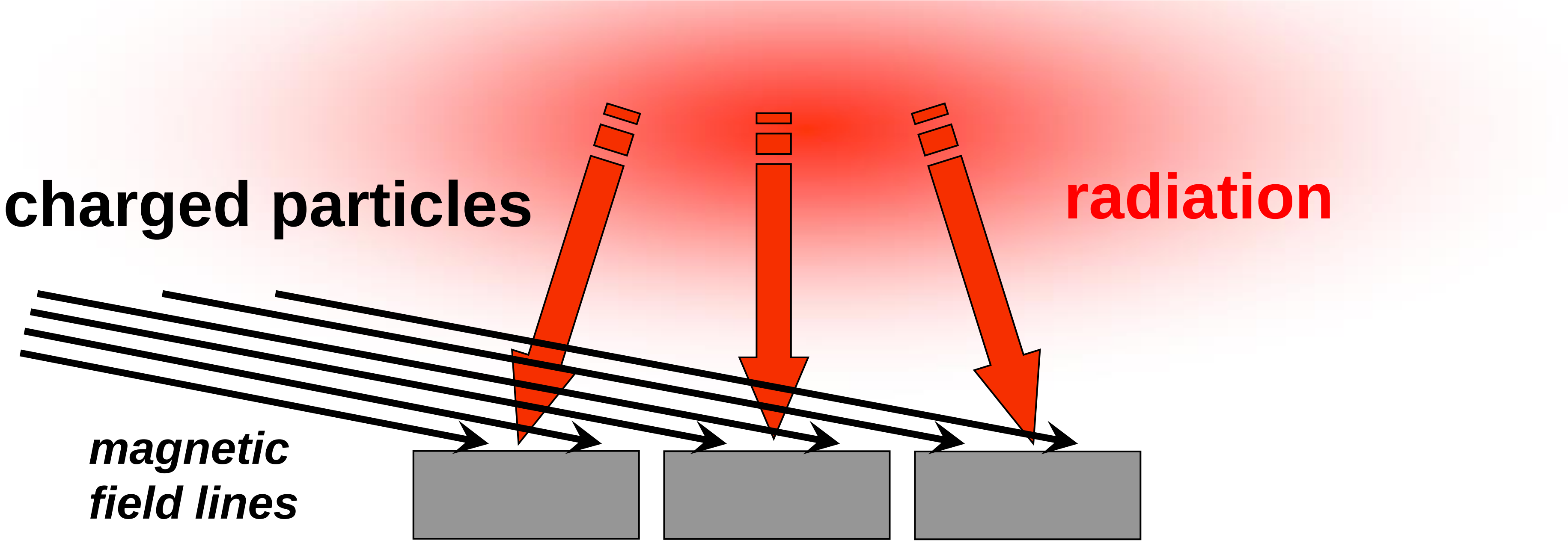
Thermal loads on plasma facing components

Plasma facing components
– plasma exposure –



armour tiles – plasma facing material

Plasma facing components
– plasma exposure –

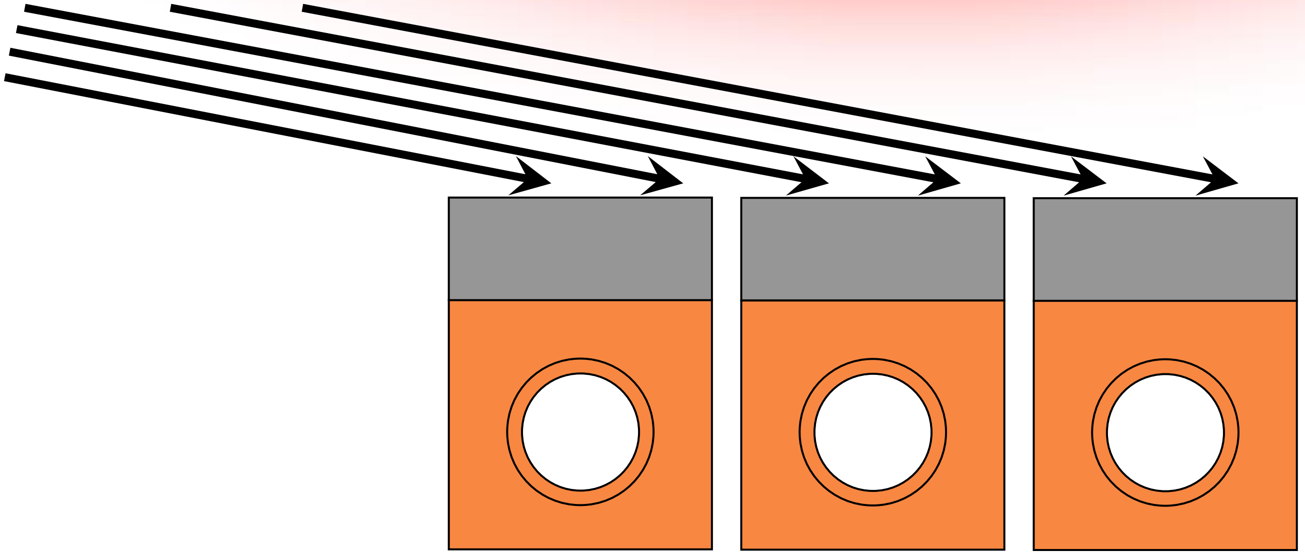


Surface heat flux in ITER:
≈ 1 MWm^{-2} (first wall)
≈ 10 MWm^{-2} (divertor)

→ **effective water cooled heat sink**

Plasma facing components – plasma exposure –

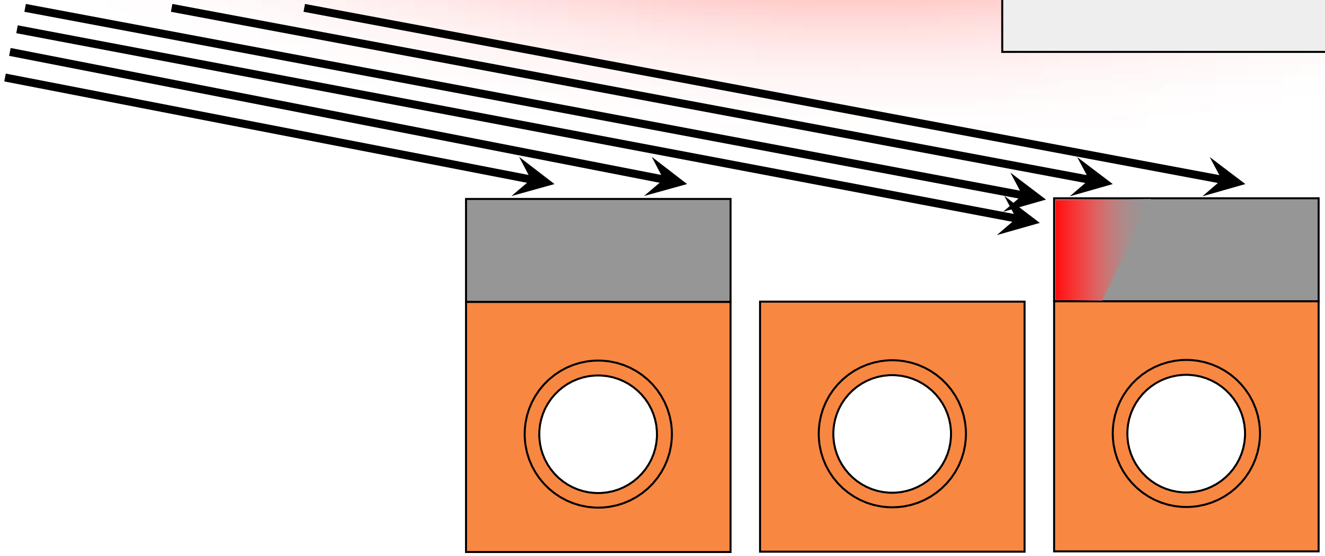
approx. 10^5 joints in the ITER divertor
acceptable failure rate = 0



charged particles

water cooled heat sink (ITER)
helium and/or liquid metal cooled (beyond ITER)

Plasma facing components
– plasma exposure –

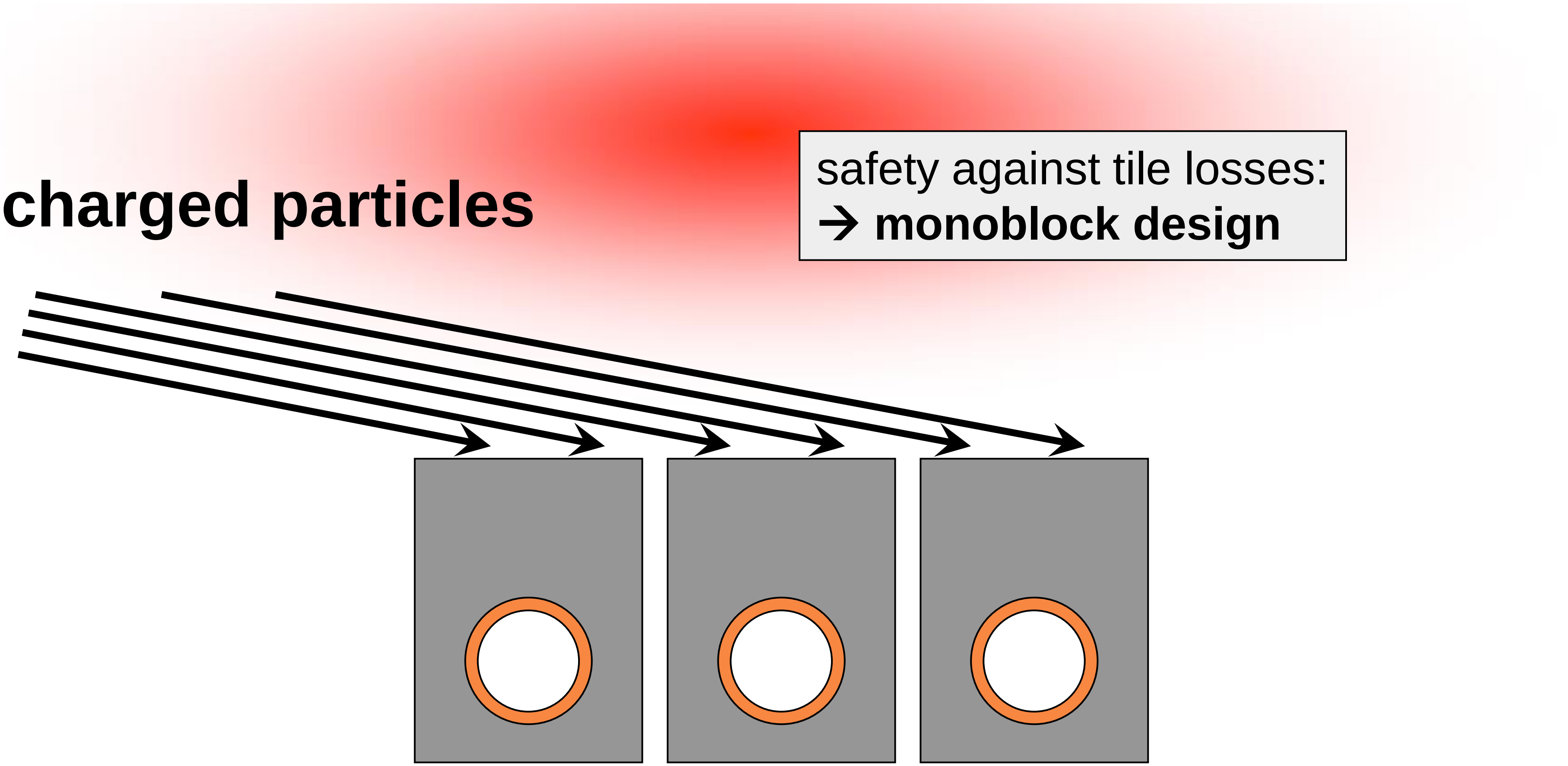


charged particles

local overheating due to
tile detachment or erosion

→ **cascade failure**

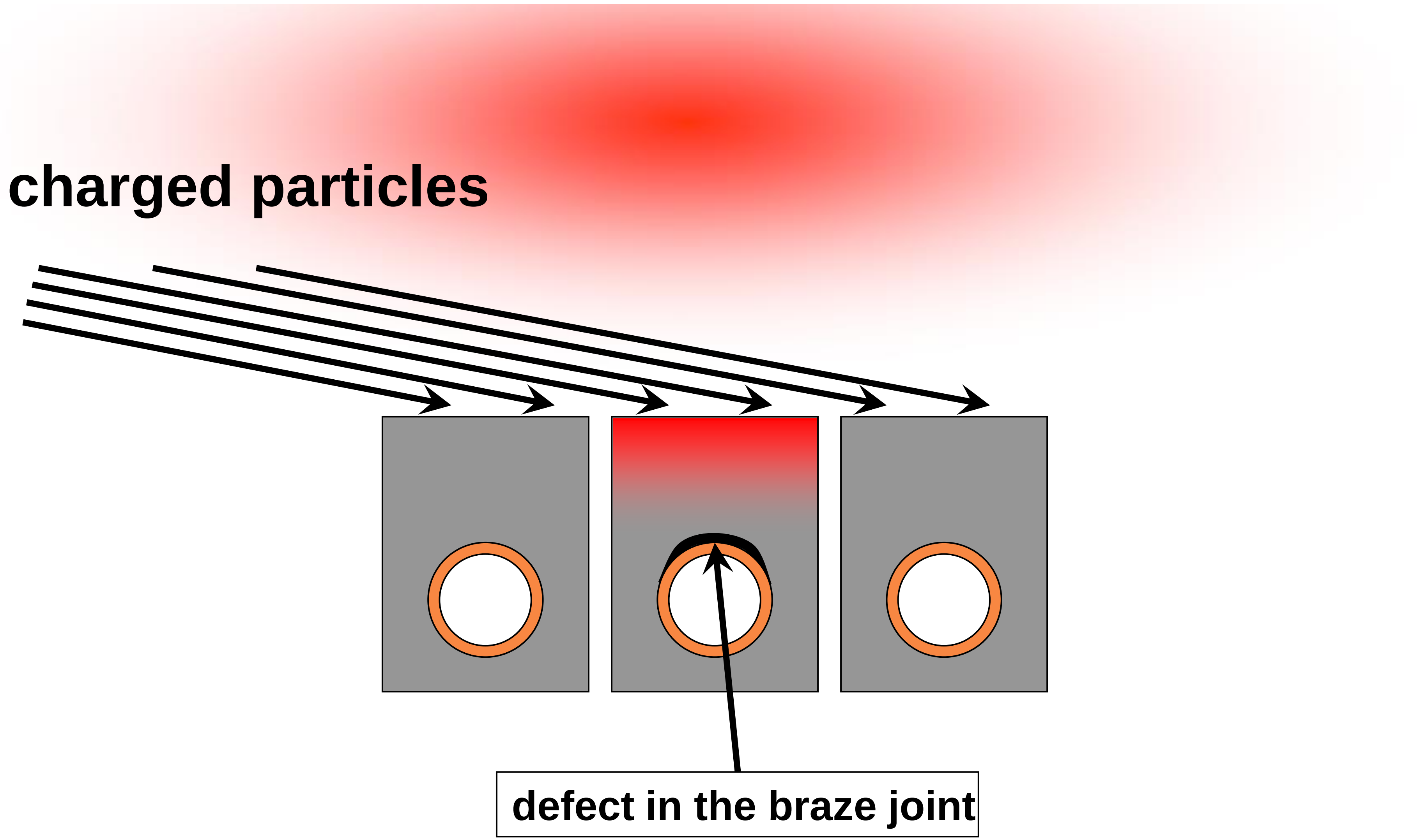
Plasma facing components
– design options –



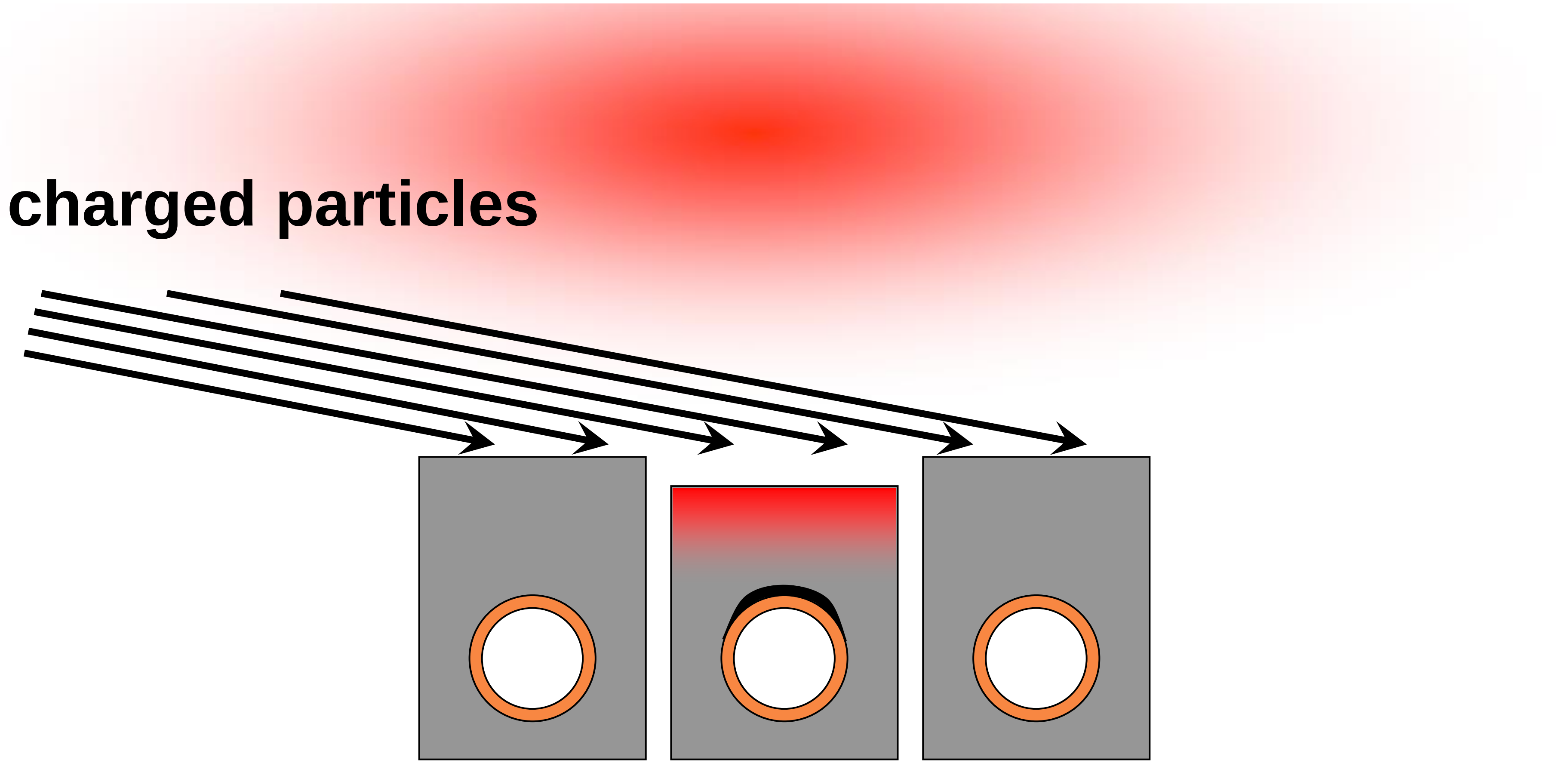
charged particles

safety against tile losses:
→ **monoblock design**

Plasma facing components
– design options –



Plasma facing components
– design options –



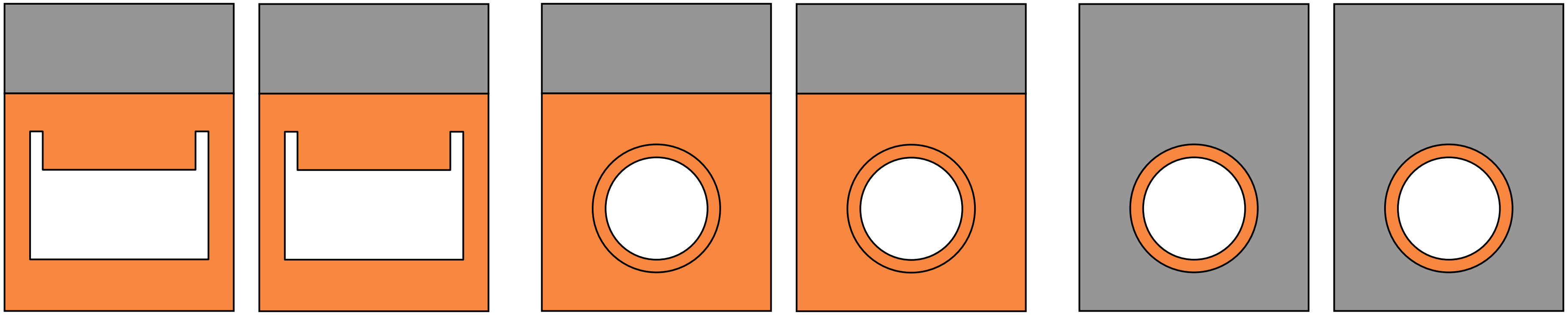
charged particles

Plasma facing components
– design options –

Plasma facing material:
- **beryllium (first wall)**
- **tungsten / carbon (divertor)**

Heat sink material:
- **copper alloys (CuCrZr, DS-Cu)**
- **stainless steel (first wall)**

Joining techniques:
- ***brazing***
- ***HIPing***
- ***e-beam welding***
- ***diffusion bonding***



hypervapotron *flat tile design* *monoblock*

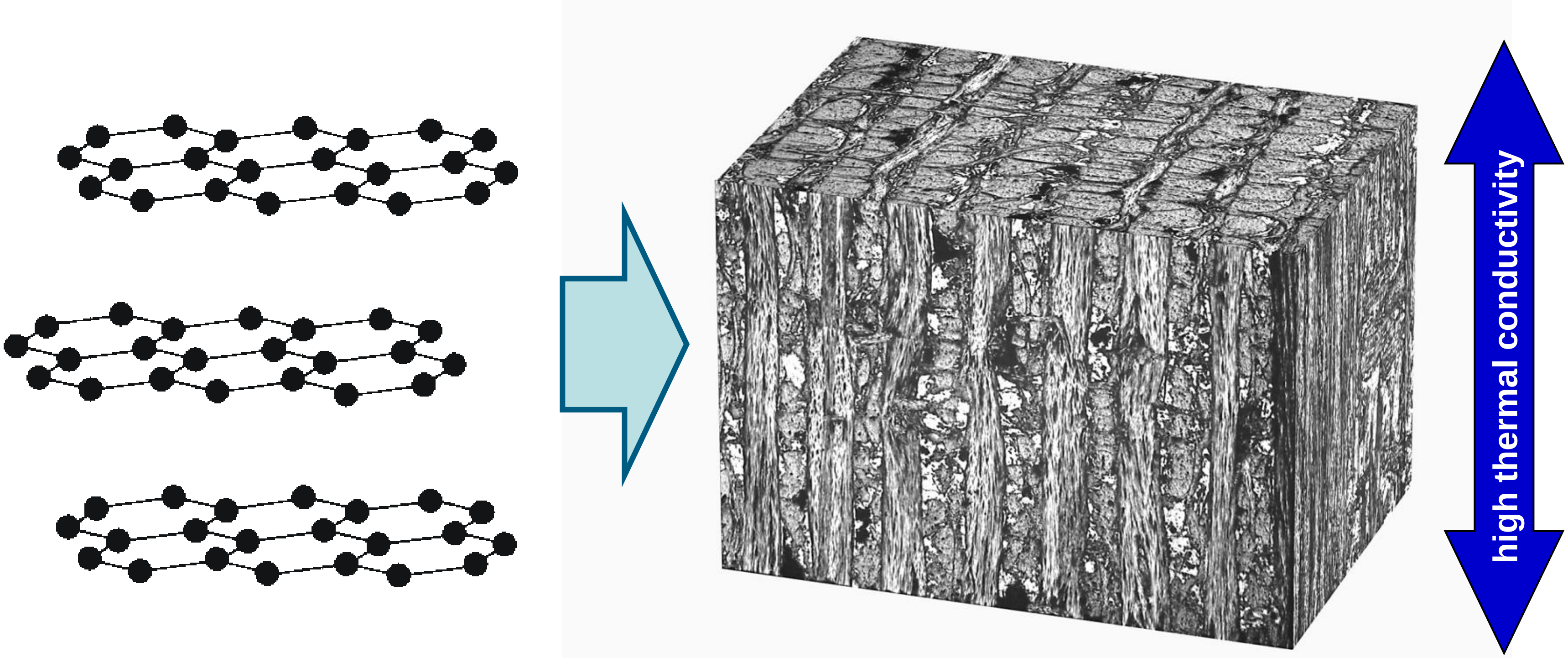
C-based materials - pros and cons

+ low-Z
+ no liquid phase
+ high thermal conductivity λ
+ low CTE
+ low activation
+ wide spectrum of commercially available grades

-- n-induced degradation of λ

-- chemical erosion

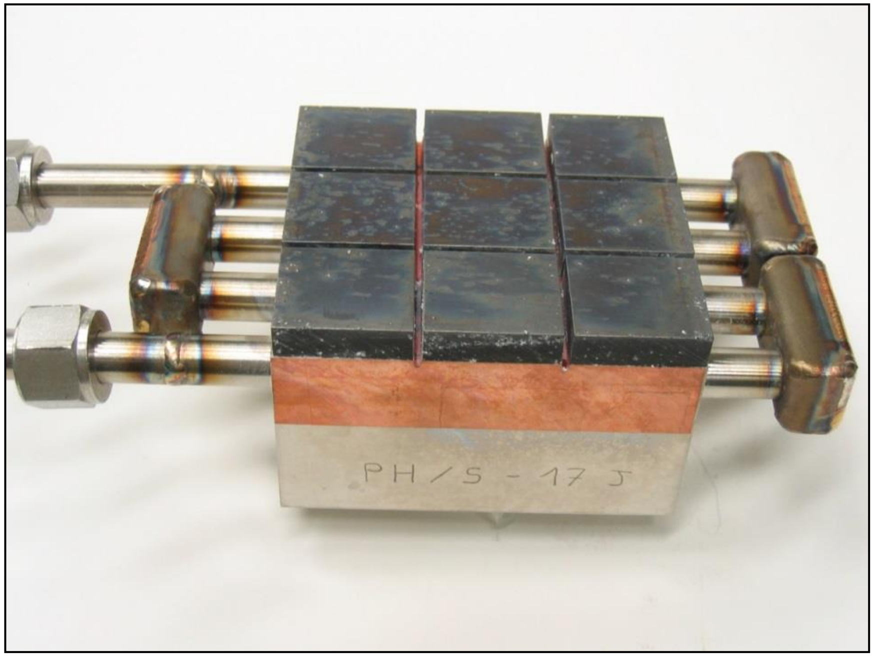
-- tritium inventory



Beryllium (first wall) pros and cons:

- \+ low-Z
- \+ affinity to oxygen
- \+ high thermal conductivity λ
- \+ low activation

- -- toxicity
- -- relatively low melting point
- -- T-generation
- -- limited thermal shock resistance

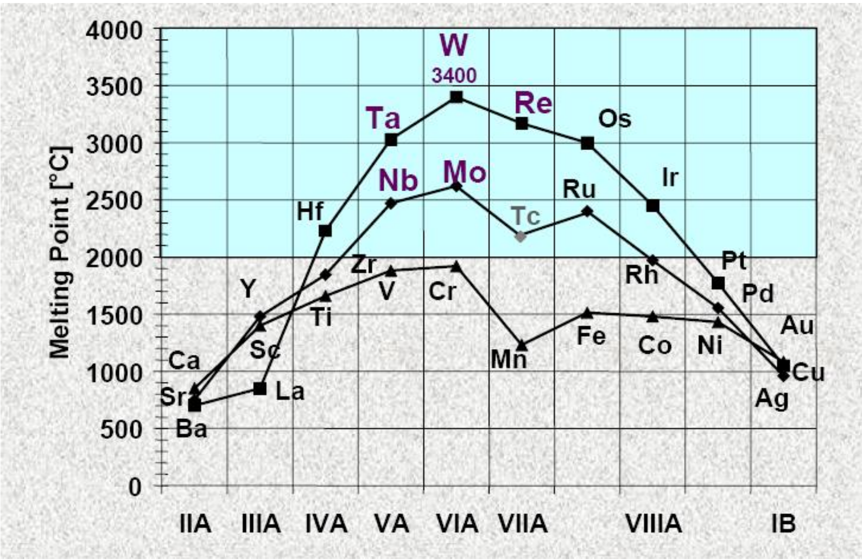


FW-module for ITER
Joining between beryllium and copper alloy by hot isostatic pressing (HIP); stainless steel tubes and back-plate

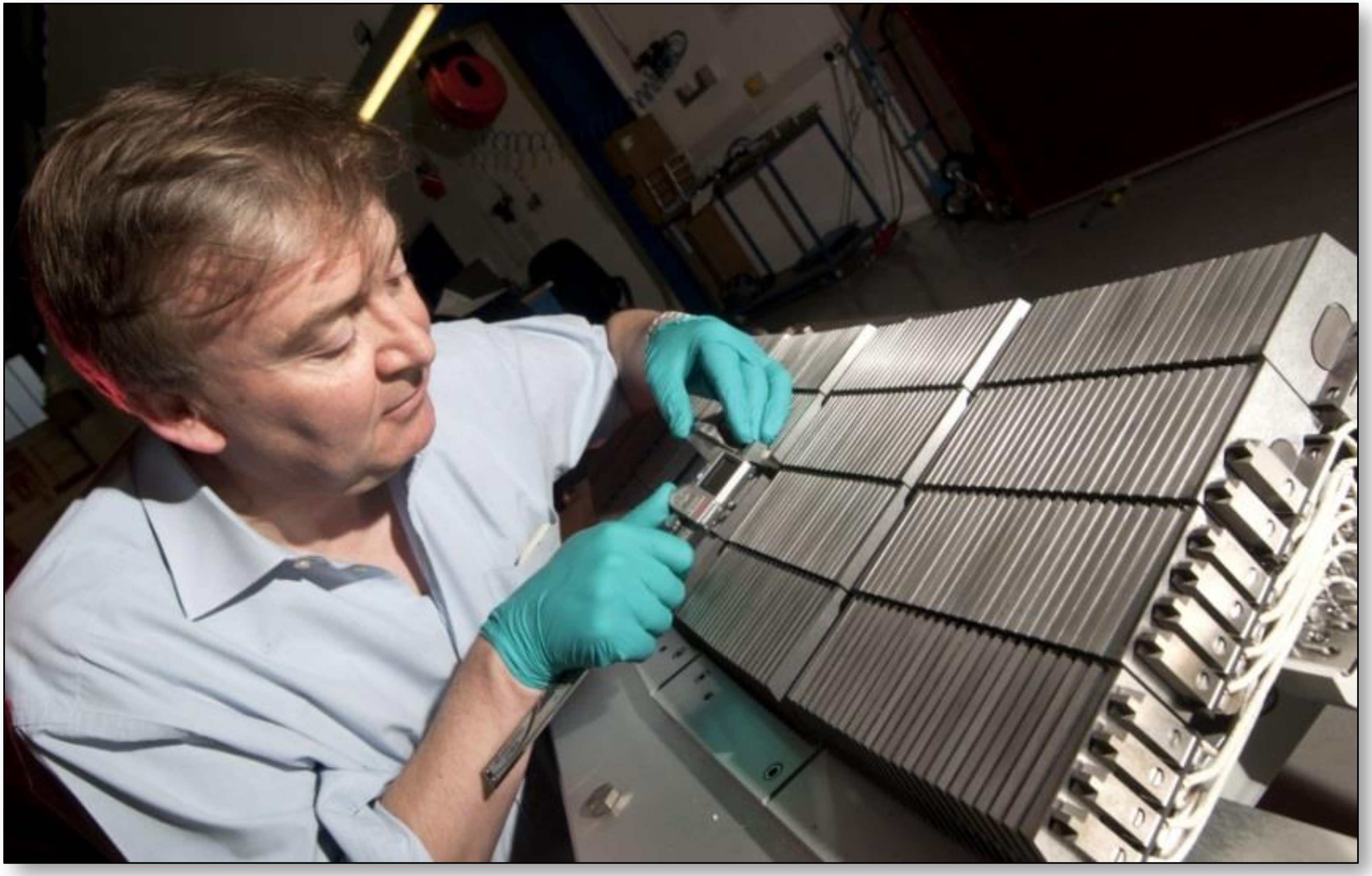
Tungsten / tungsten alloys pros and cons:

- \+ high threshold for sputtering; low sputtering yields
- \+ highest melting point
- \+ high thermal conductivity λ
- \+ low CTE
- \+ moderate activation

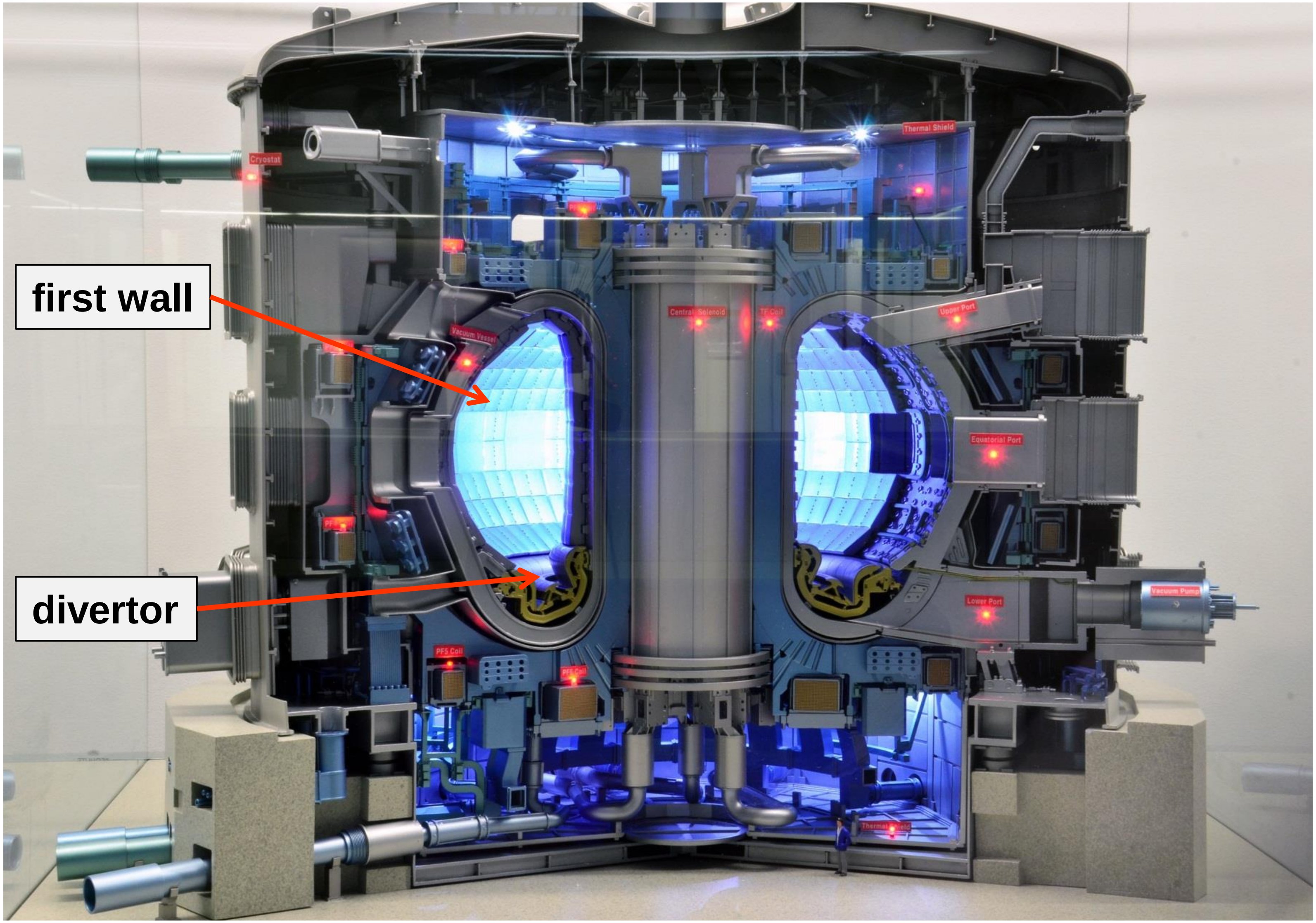
- -- high Z (large radiation losses from plasma core)
- -- irradiation induced activation and transmutation (→Re →Os)
- -- high hardness
- -- high DBTT (difficult machining, sensitive to thermal shocks)
- -- n-induced embrittlement
- -- oxidation of W during accidents



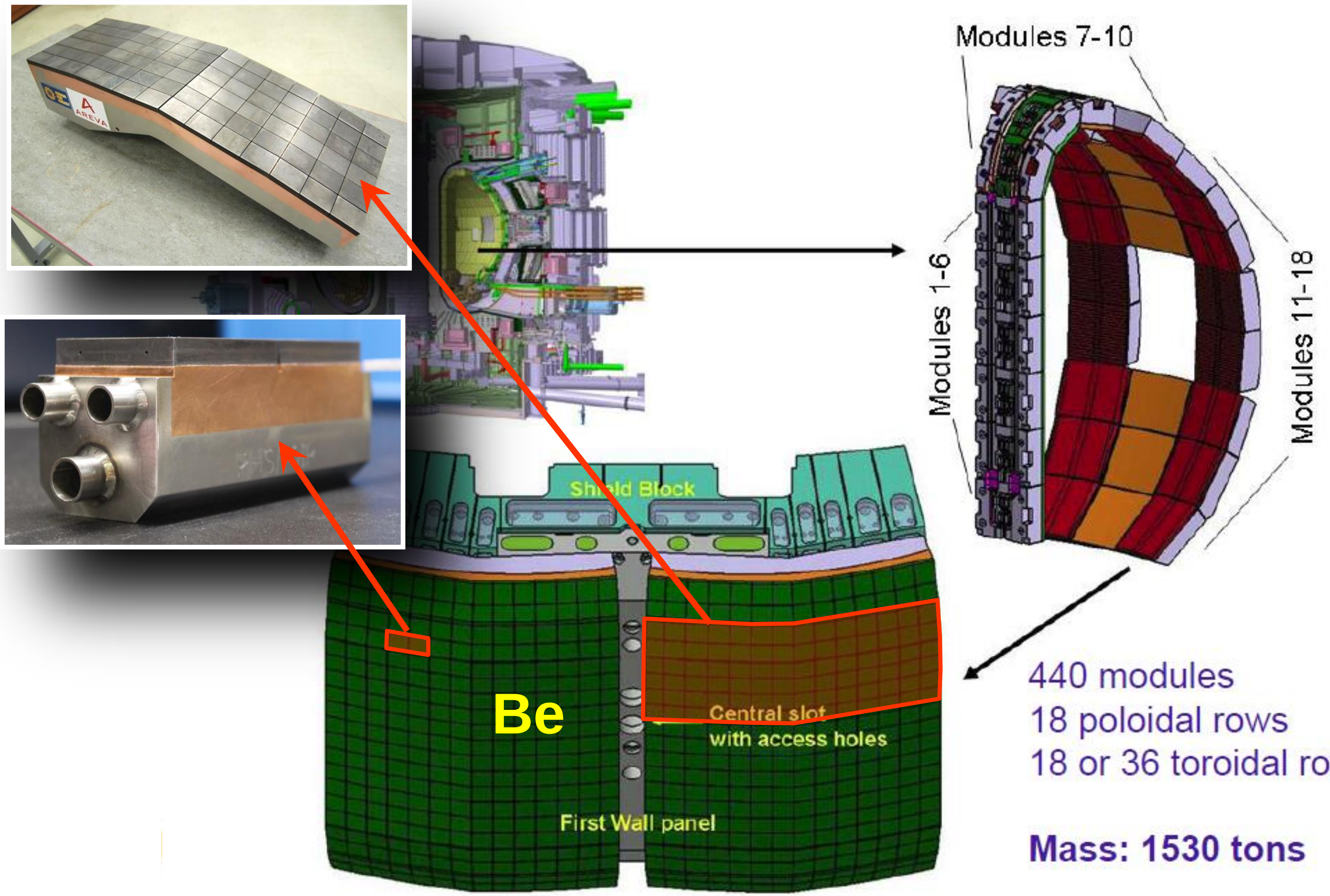
A full tungsten divertor for the ITER like Wall in JET



ITER and the plasma facing components



The ITER blanket design



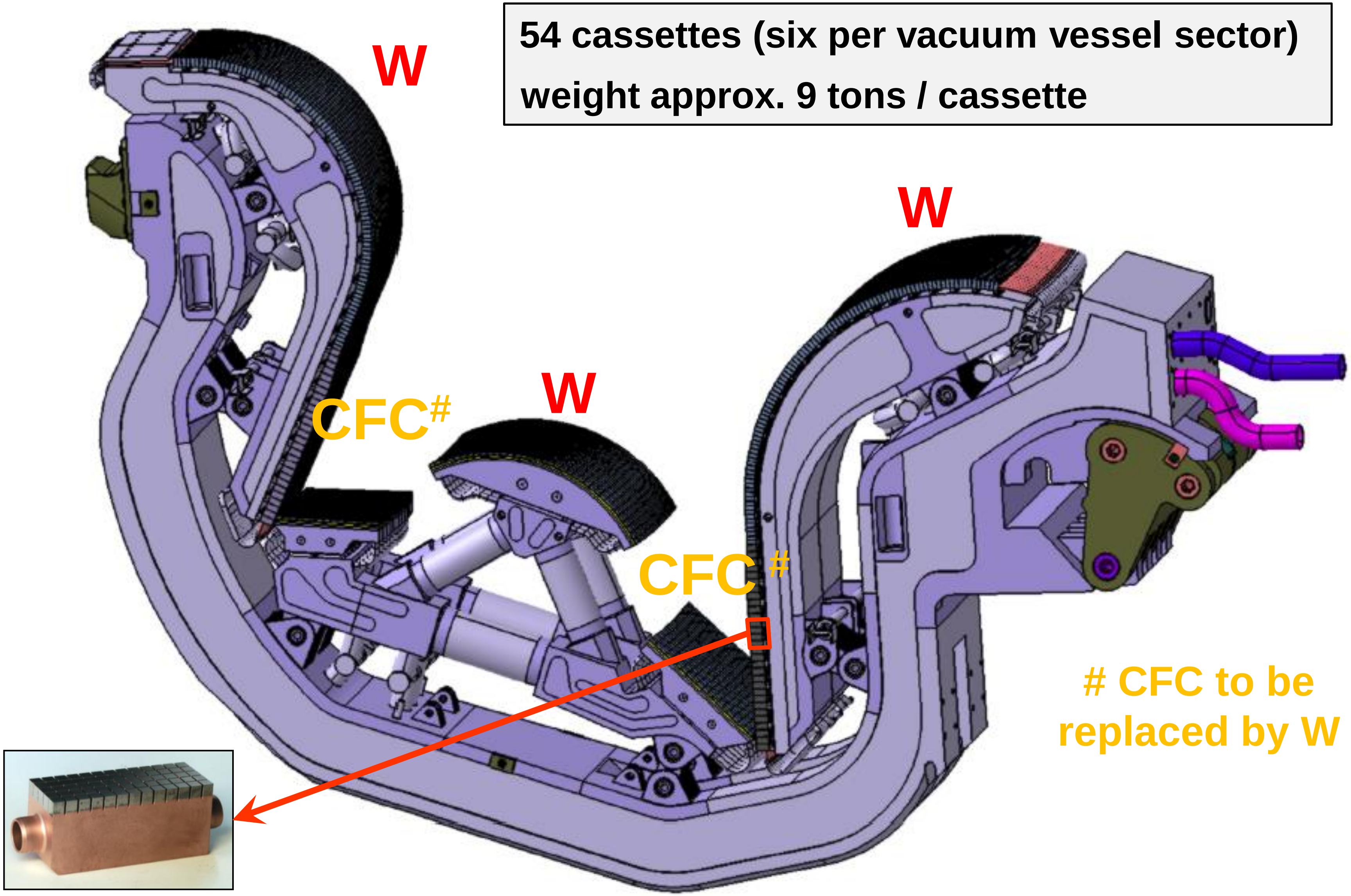
440 modules
18 poloidal rows
18 or 36 toroidal rows

Mass: 1530 tons

The new ITER divertor cassette

54 cassettes (six per vacuum vessel sector)

weight approx. 9 tons / cassette



 # CFC to be replaced by W

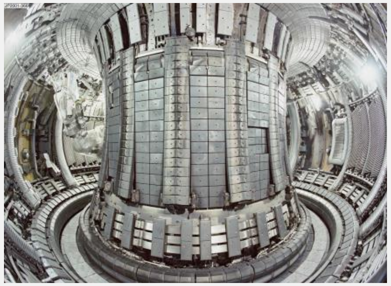
$L_{max} \leq 100$ mm

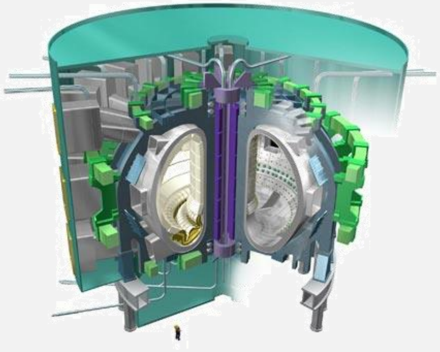
source: M. Merola, ISFNT-9, Dalian, China, 2009

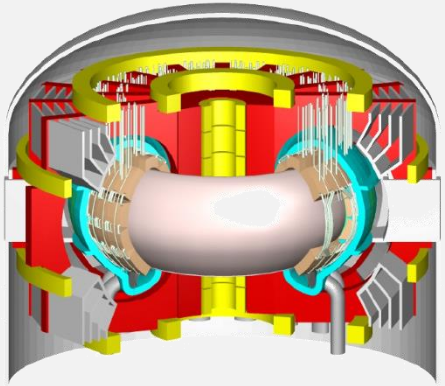
Plasma facing components

fusion devices:


COMPASS


JET


ITER


DEMO

heat removal:

passively cooled PFCs

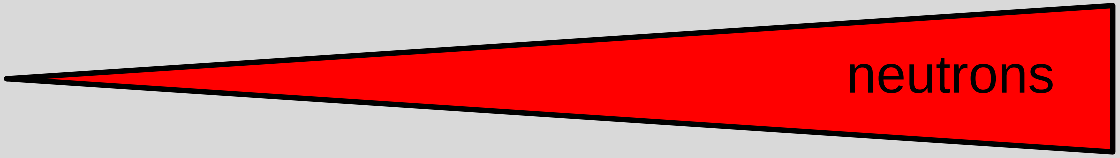
actively cooled PFCs

water

He, liquid metal

tritium fuel:

- increased T inventory
- n-induced material degradation



life time fluence:

0 dpa

10^{-9} dpa

1 dpa

10^{2} dpa

High heat flux components in non-fusion applications

reentry vehicle

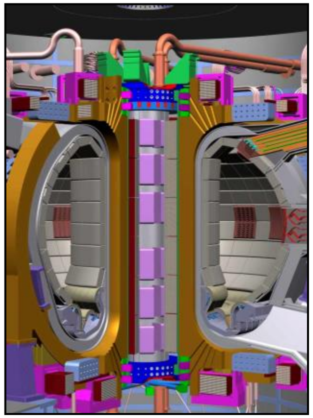
Ariane 5 / Vulcain 2

PWR-fuel element

≈ 1 ≤ 20 85 2000

Power density MW/m²

Rolls-Royce Trent 900



ITER Divertor

ELMs in ITER

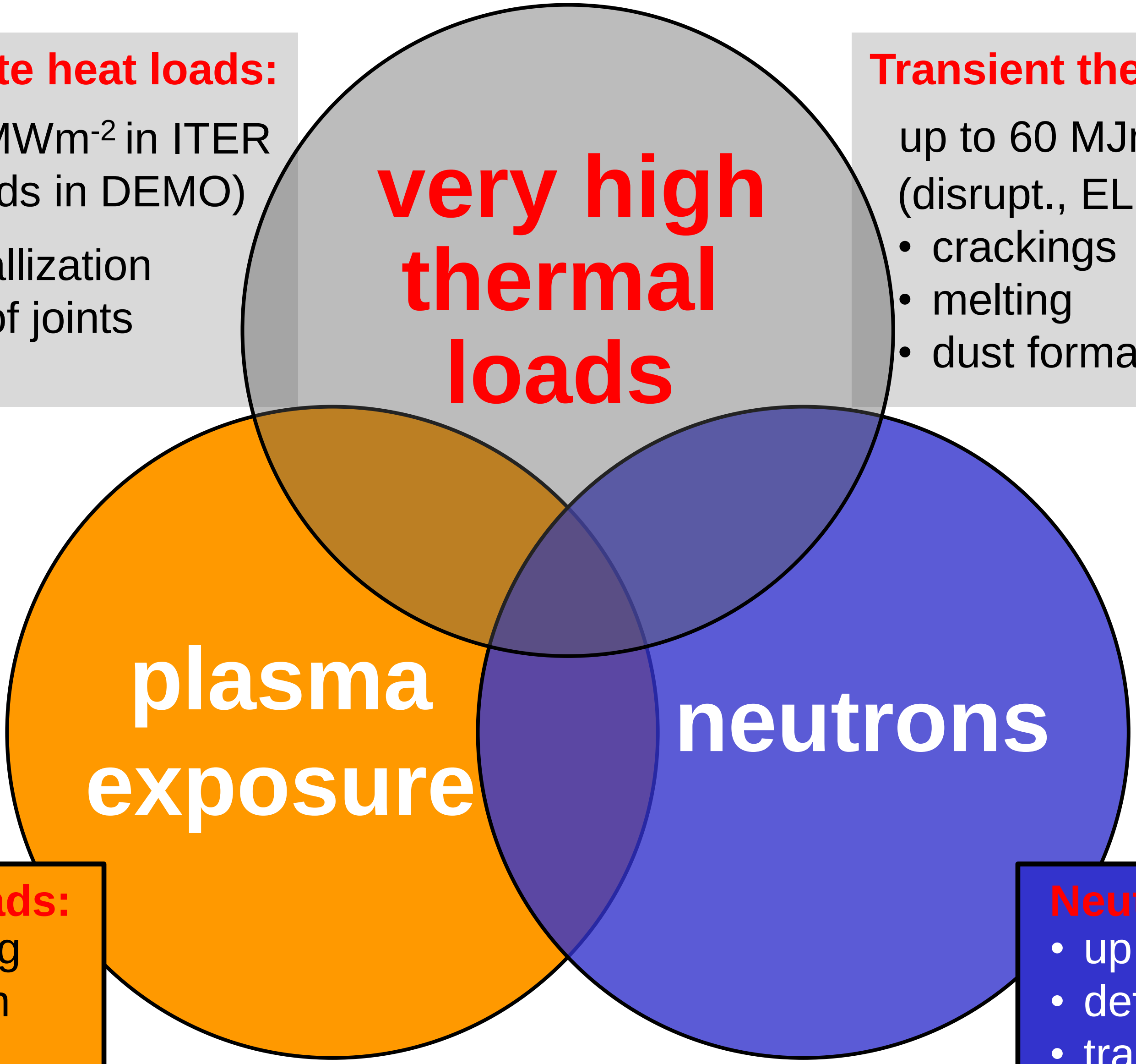
Loads on plasma facing components

very high thermal loads

plasma exposure

neutrons

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

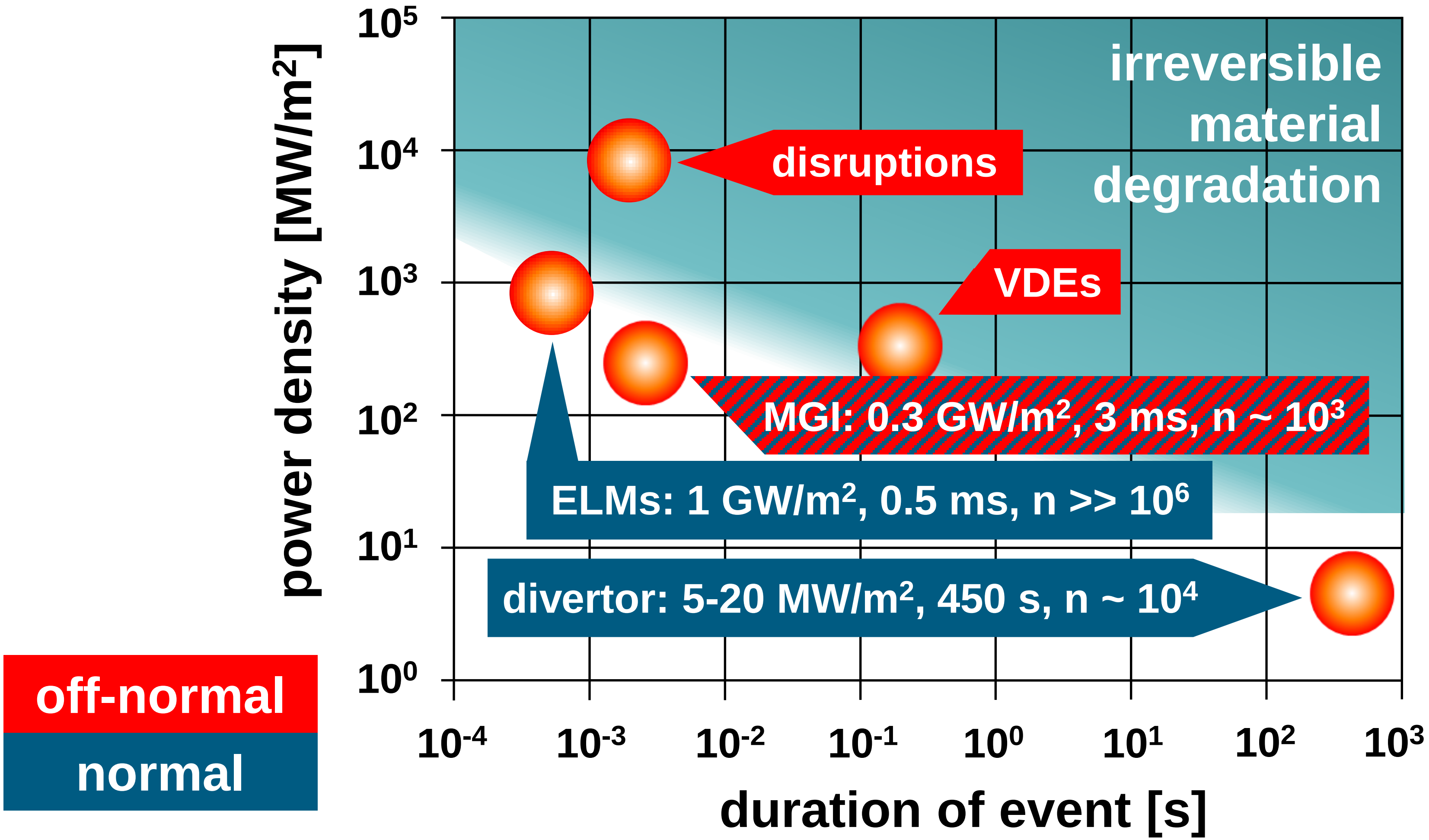
Neutrons:

- up to 14 MeV
- defects
- transmutation

B

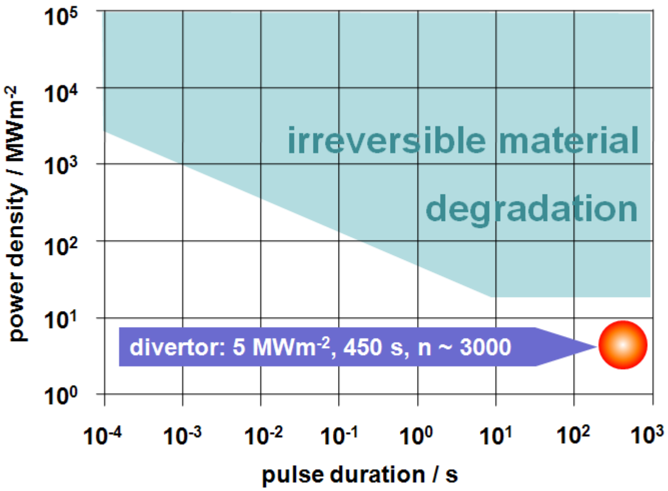
Simulation of intense thermal loads on plasma-facing components

Wall loads on plasma facing components in ITER



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

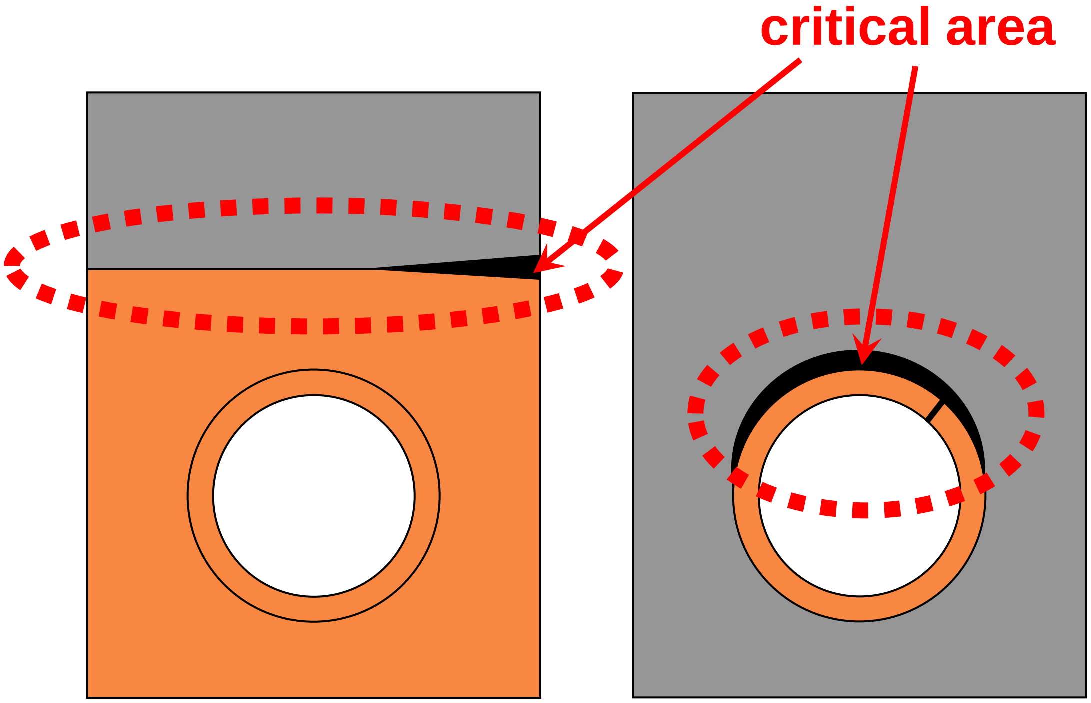
Wall loads on plasma facing components in ITER



steady state loads:

5 – 10 MWm^{-2}, $\Delta t = 450$ s

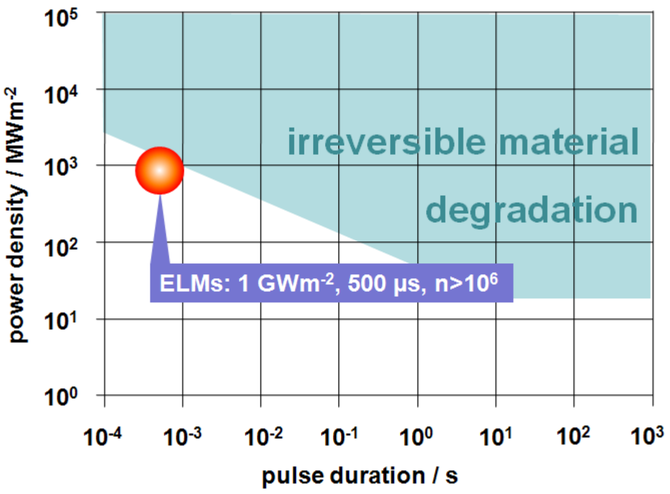
→ low cycle thermal fatigue



flat tile design

monoblock

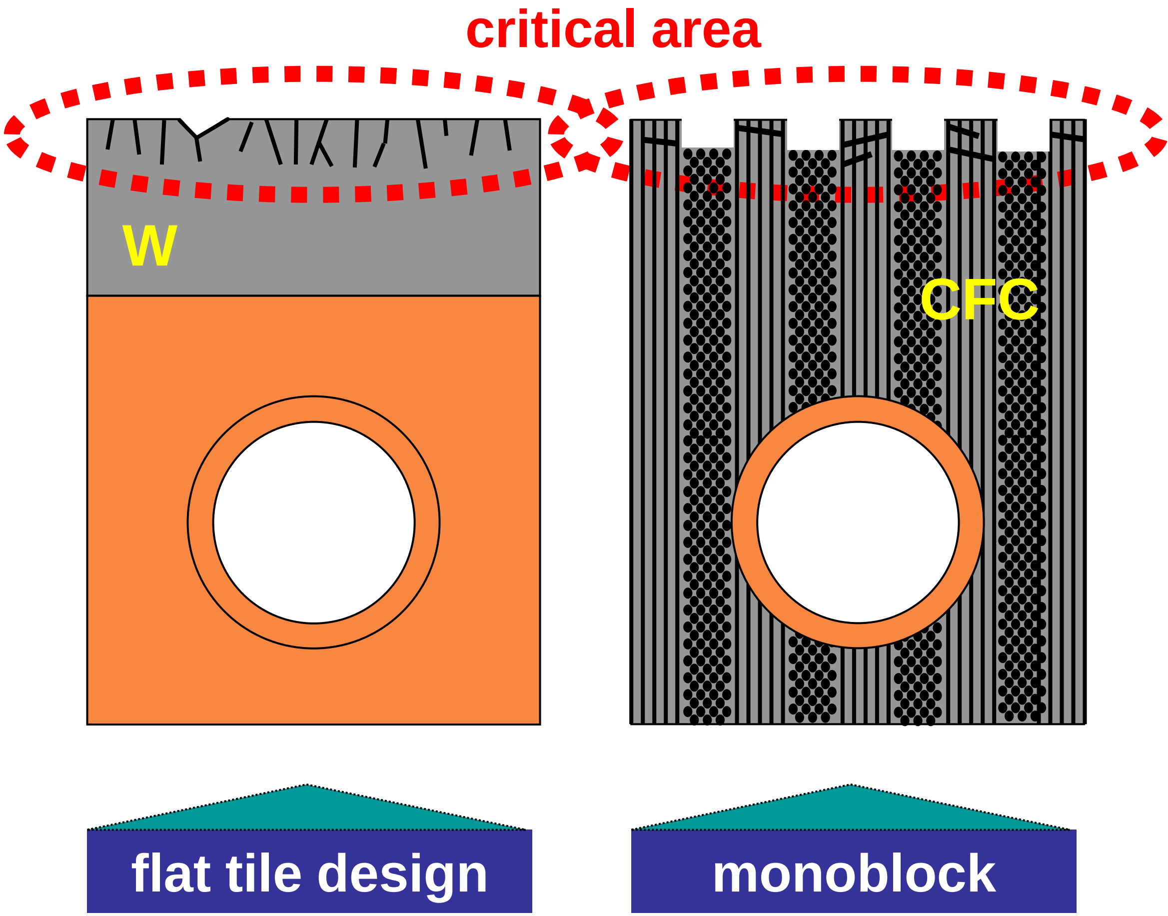
Wall loads on plasma facing components in ITER



transients (e.g. ELMs):

$\leq$ 1 GWm^{-2}, Δt = 500 µs, 1…20 Hz

→ high cycle thermal fatigue

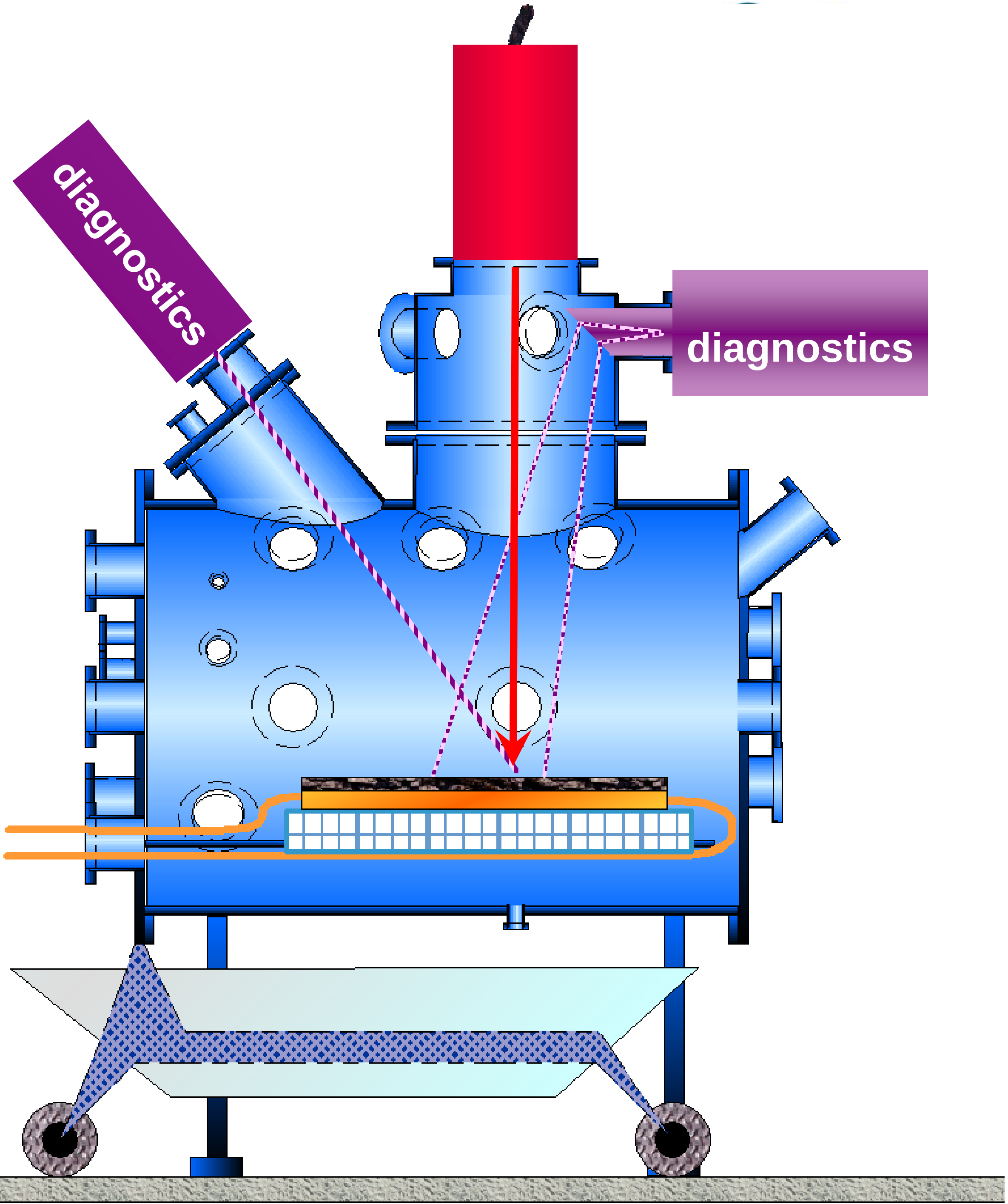


JUDITH 2

schematic view into the vacuum chamber

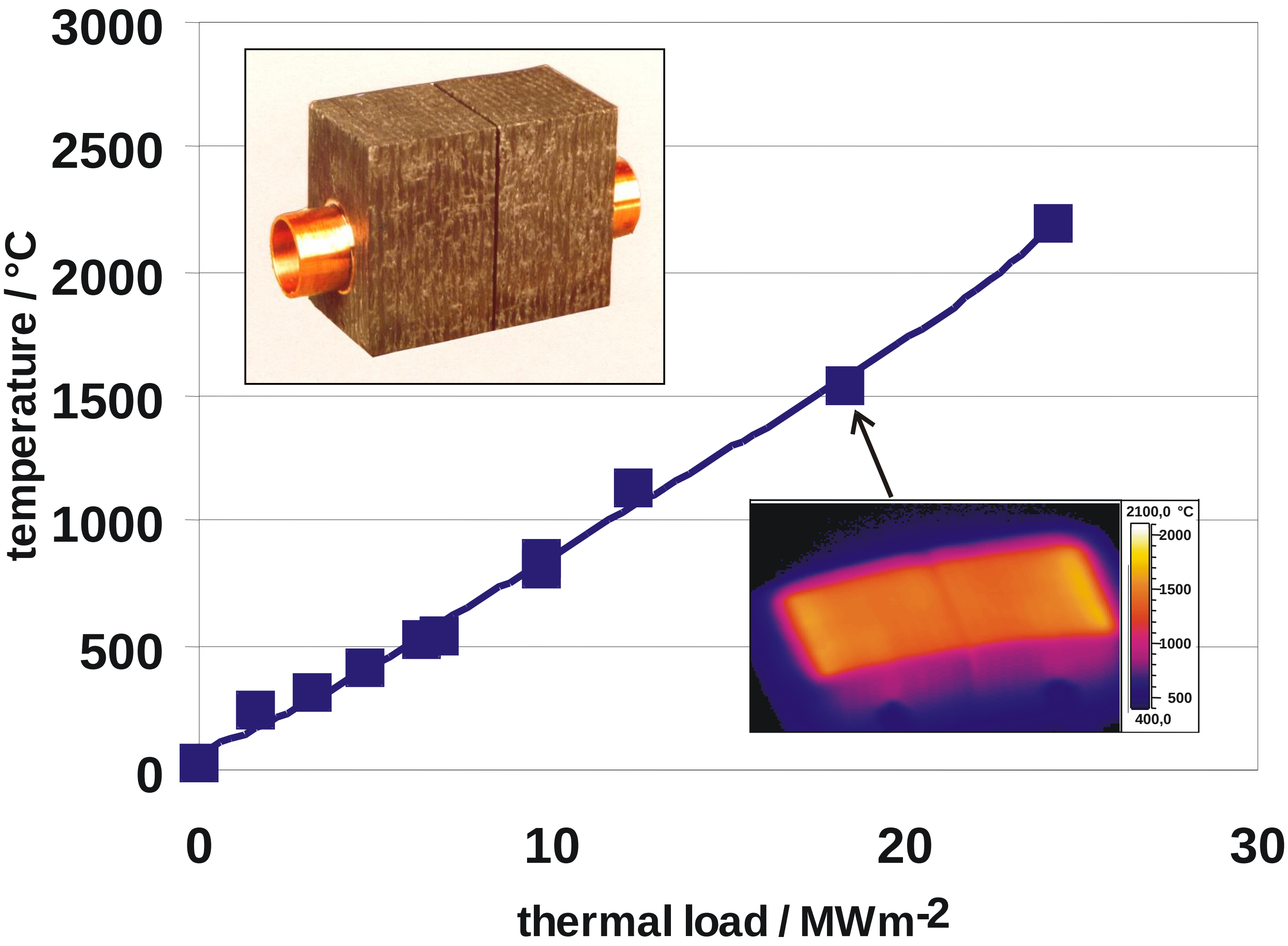
Diagnostics:

- IR-camera
- Optical camera
- Pyrometers
- Spectroscopy
- Thermocouples
- Photo diodes
- Acoustic emission



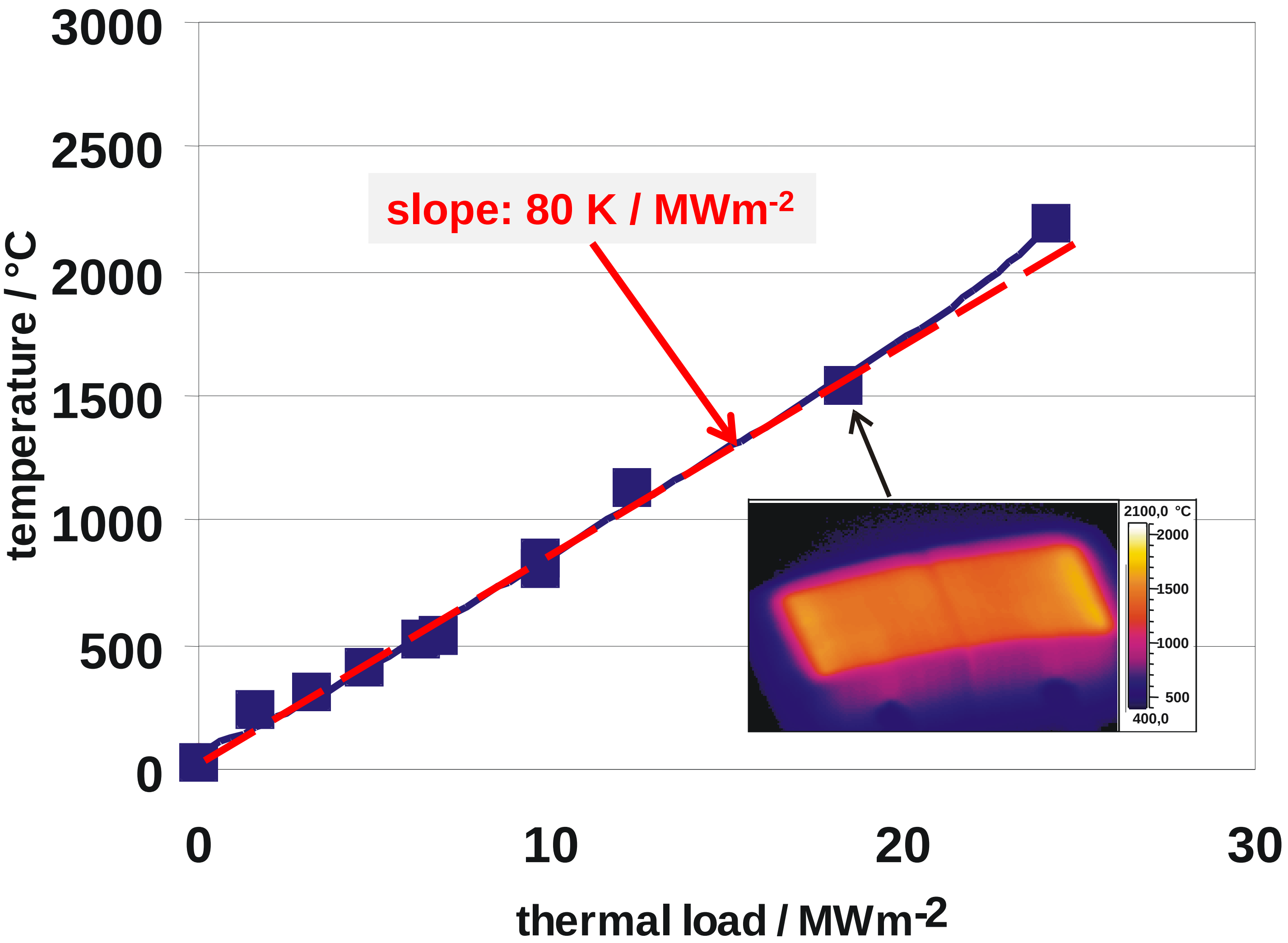
Thermal response of divertor modules

Dunlop Concept 1 (12 mm) / CuCrZr



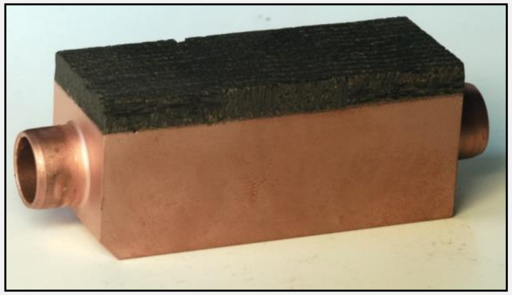
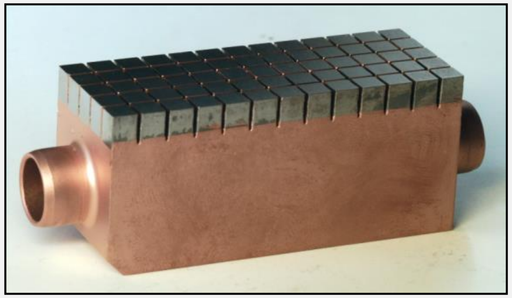
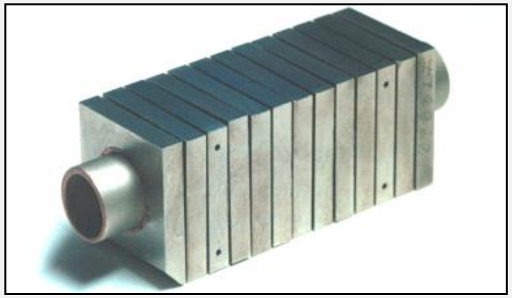
Thermal response of divertor modules

Dunlop Concept 1 (12 mm) / CuCrZr



slope: 80 K / MWm^{-2}

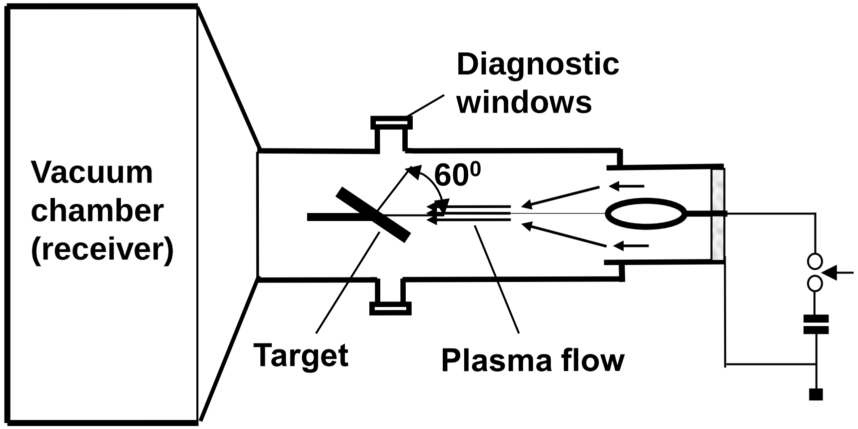
Fatigue testing on PFCs for ITER

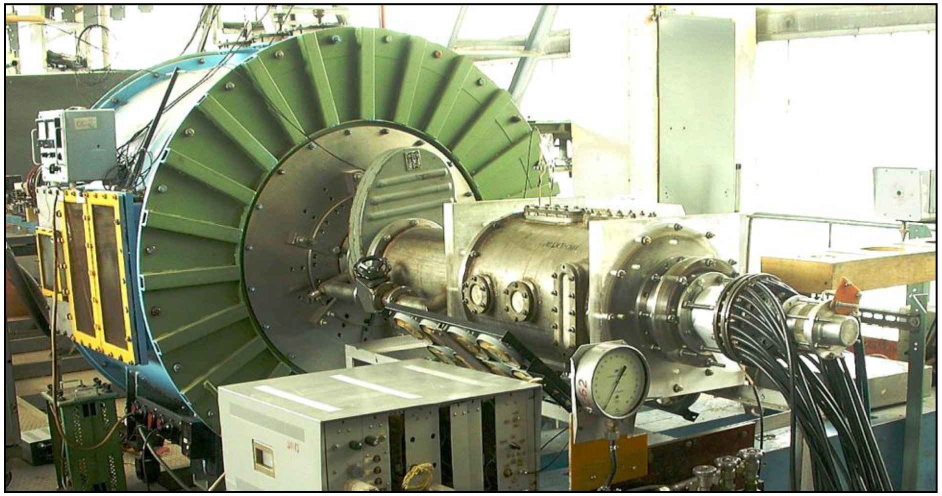
	CFC armour	tungsten armour
flat tile design	 **CFC flat tile** Silicon doped CFC NS31, active metal casting, e-beam welding to CuCrZr heat sink **1000 cycles @ 19 MWm^{-2}**	 **W macrobrush** coating of WLa_2O_3 tiles with OFHC-Cu, e-beam welding to CuCrZr heat sink **1000 cycles @ 18 MWm^{-2}**
monoblock design	 **CFC monoblock** drilling of CFC tiles (NB31), active metal casting (AMC®) low temperature HIPing **1000 cycles @ 25 MWm^{-2}**	 **W monoblock** lamellae technique, drilling of WLa_2O_3 blocks, casting with OFHC-Cu, HIPing **1000 cycles @ 20 MWm^{-2}**

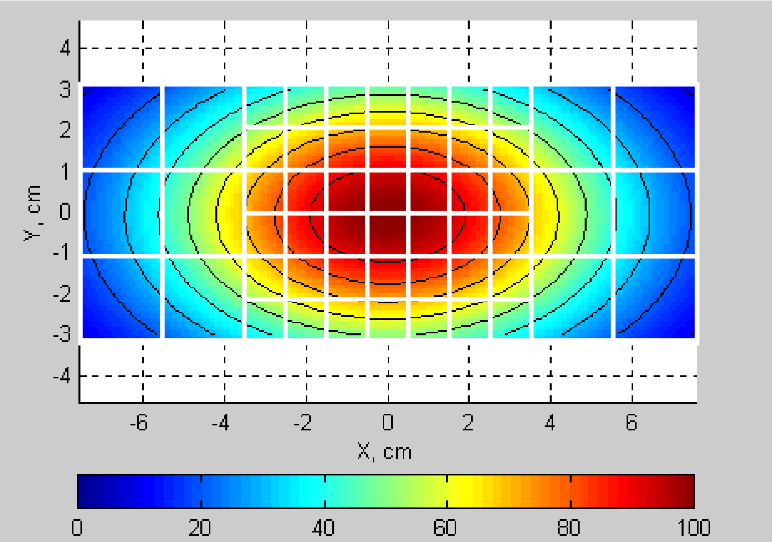
Simulation of short transient heat pulses

JÜLICH
FORSCHUNGSZENTRUM

Quasi Stationary Plasma Accelerator (QSPA)







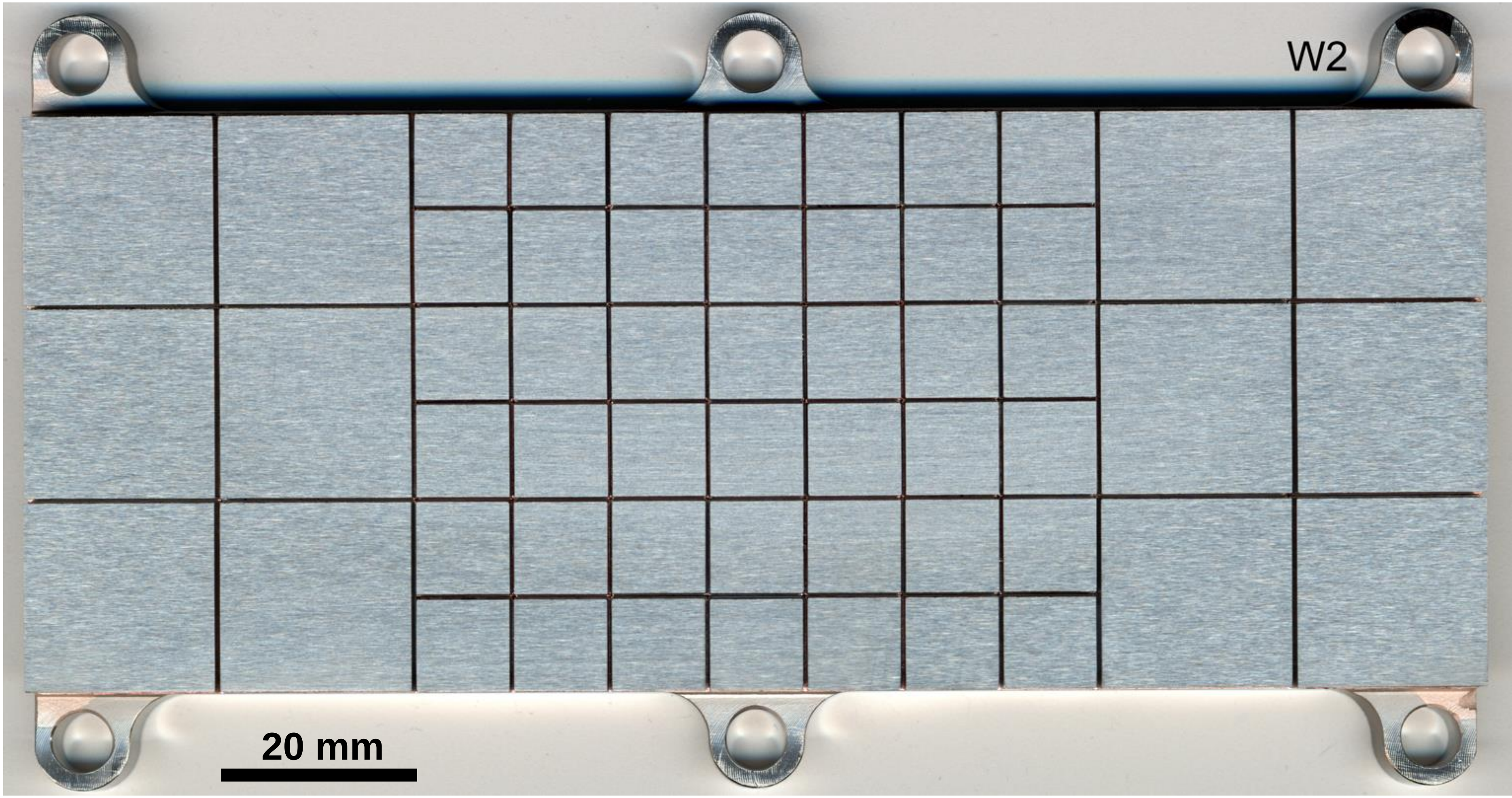
The energy density distribution on W surface,%

QSPA plasma parameters (ELMs):

• 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 temperature	< 10 eV
• Plasma density	≤ 10^{22} m^{-3}

Source: A. Zhitlukhin, 17th PSI, Hefei, 2006

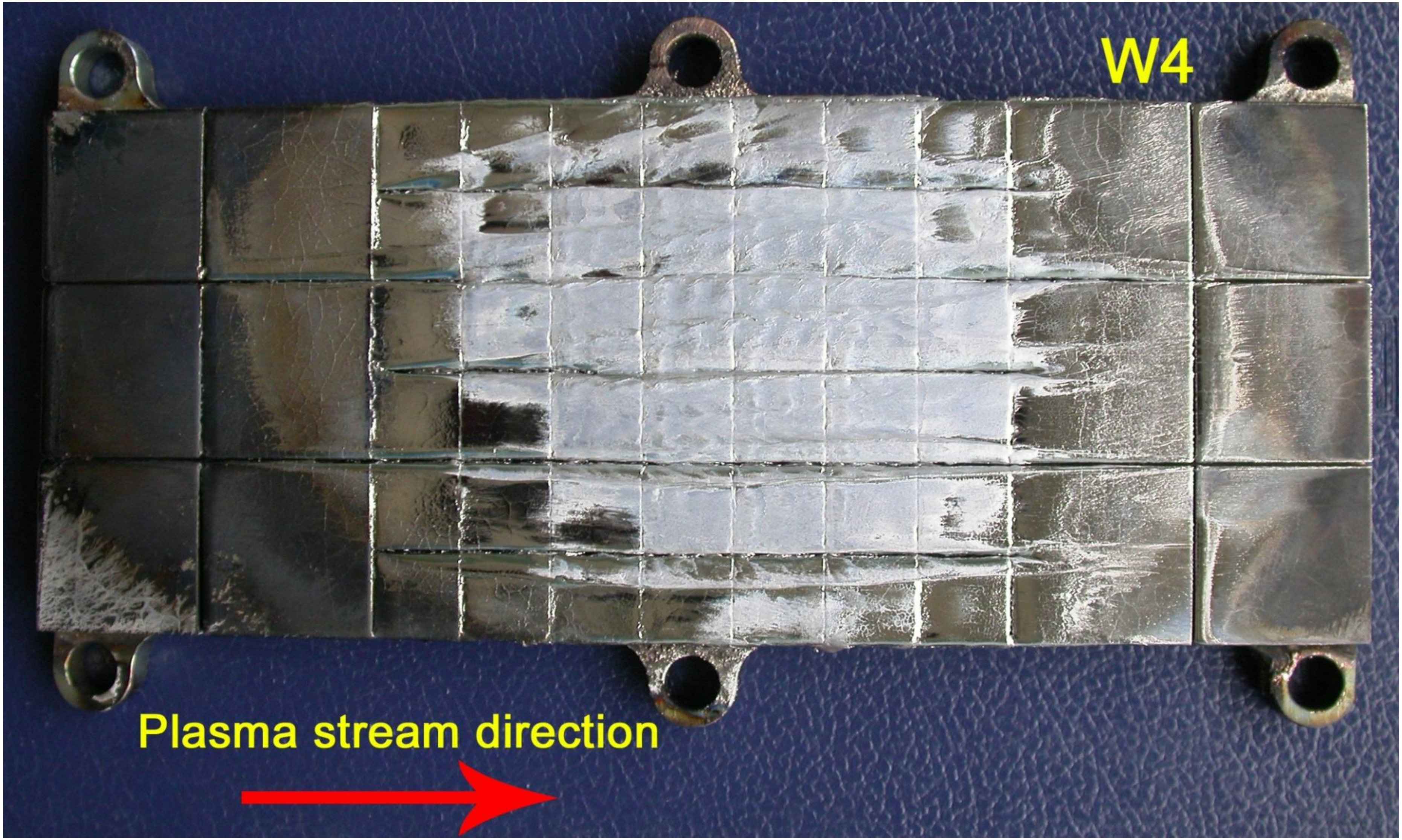
Simulation of ELMs in QSPA



Bridging of gaps due to melt motion

100 pulses @ E = 1.6 MJ/m², Δ= 500 µs

H_{HF} = 71 MW/m²s$^{0.5}$

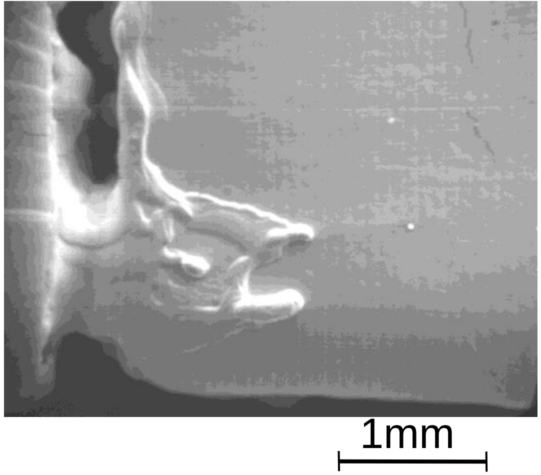


Source: A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

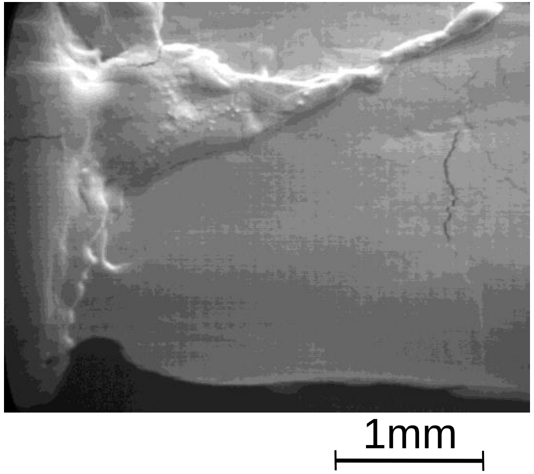
Bridge formation between tungsten tiles

$w = 1.6\ \mathrm{MJ/m^2}$

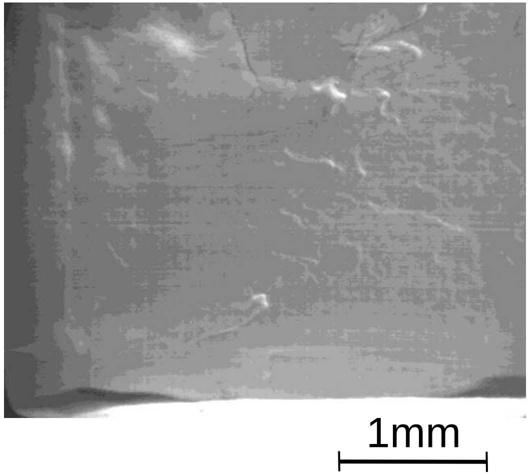
W4,L3, 10 exposures



W4,L3, 20 exposures



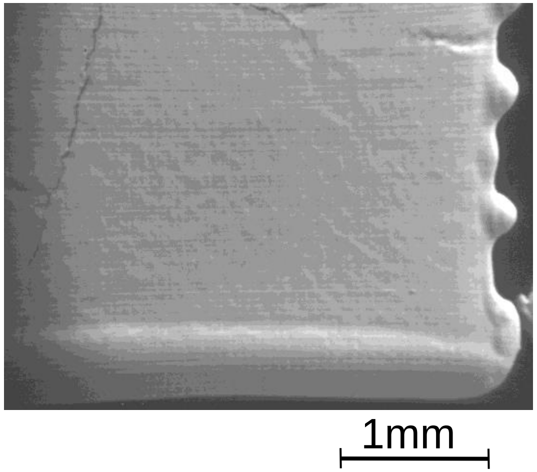
W4,L3, 50 exposures



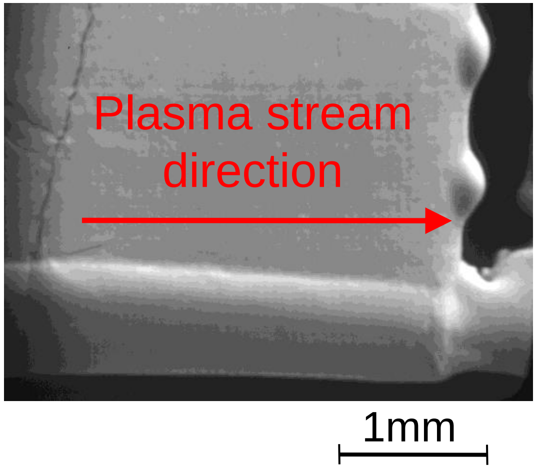
$H_{HF} = 71\ \mathrm{MW/m^2s^{0.5}}$

$w = 1.0\ \mathrm{MJ/m^2}$

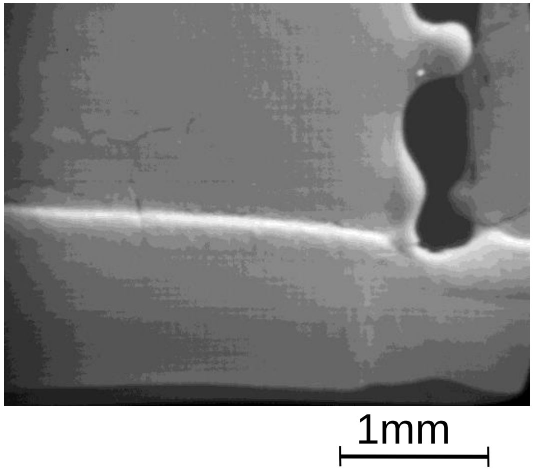
W3,R3, 20 exposures



W3,R3, 50 exposures



W3,R3, 100 exposures



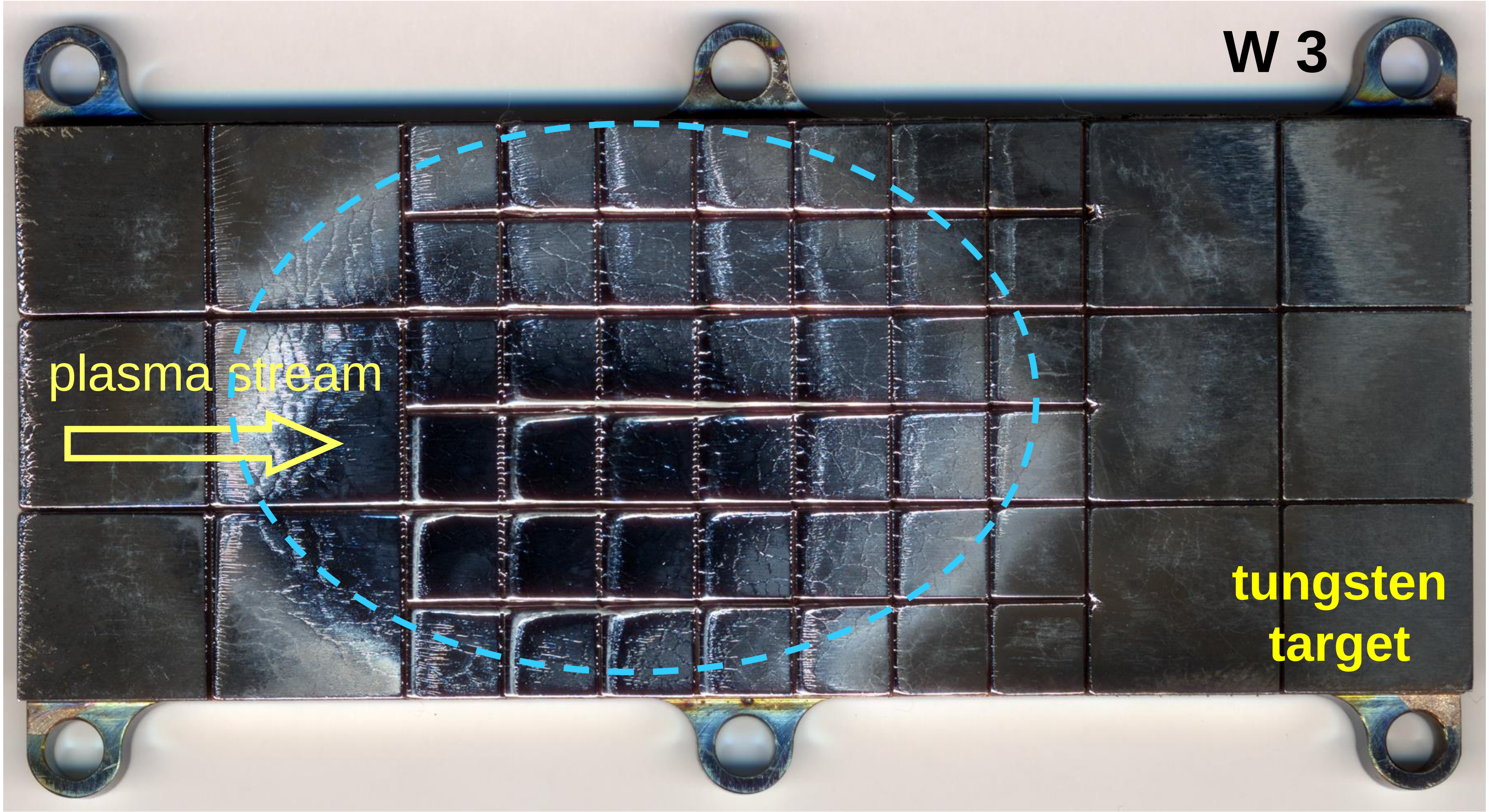
$H_{HF} = 44.7\ \mathrm{MW/m^2s^{0.5}}$

$\Delta t = 500\ \mu s$

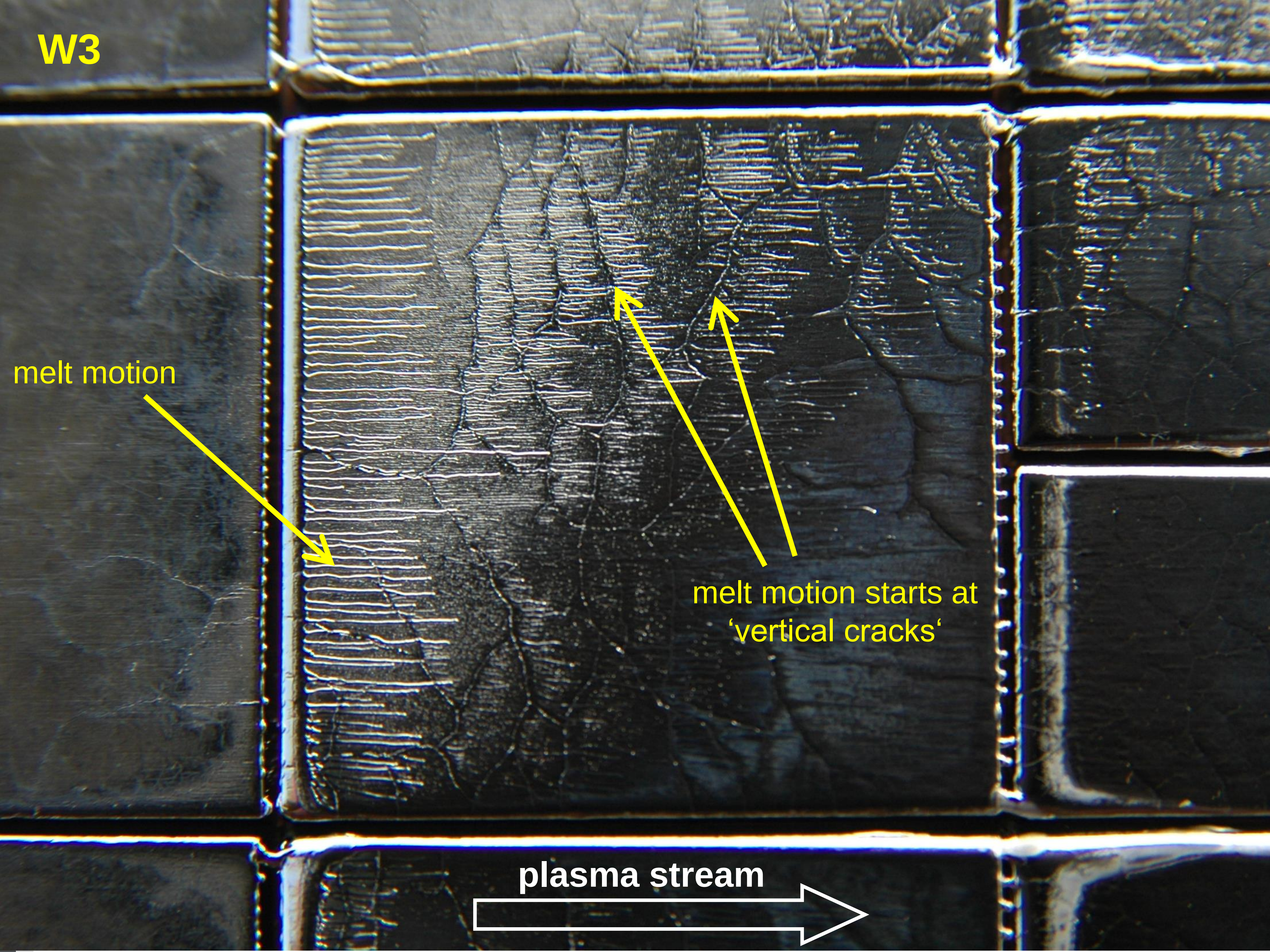
Source: A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

Simulation of ELMs in QSPA

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



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

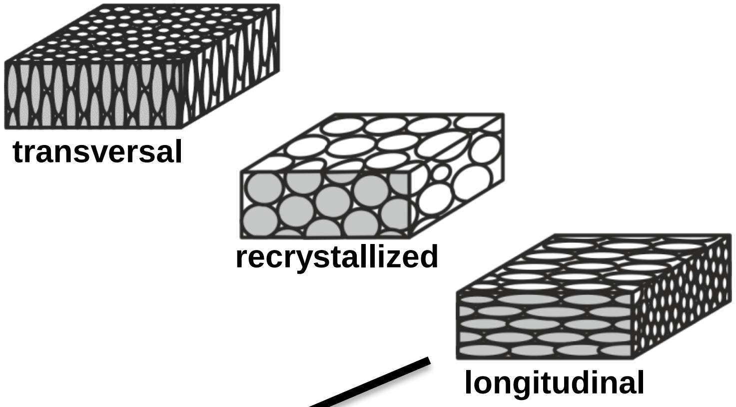


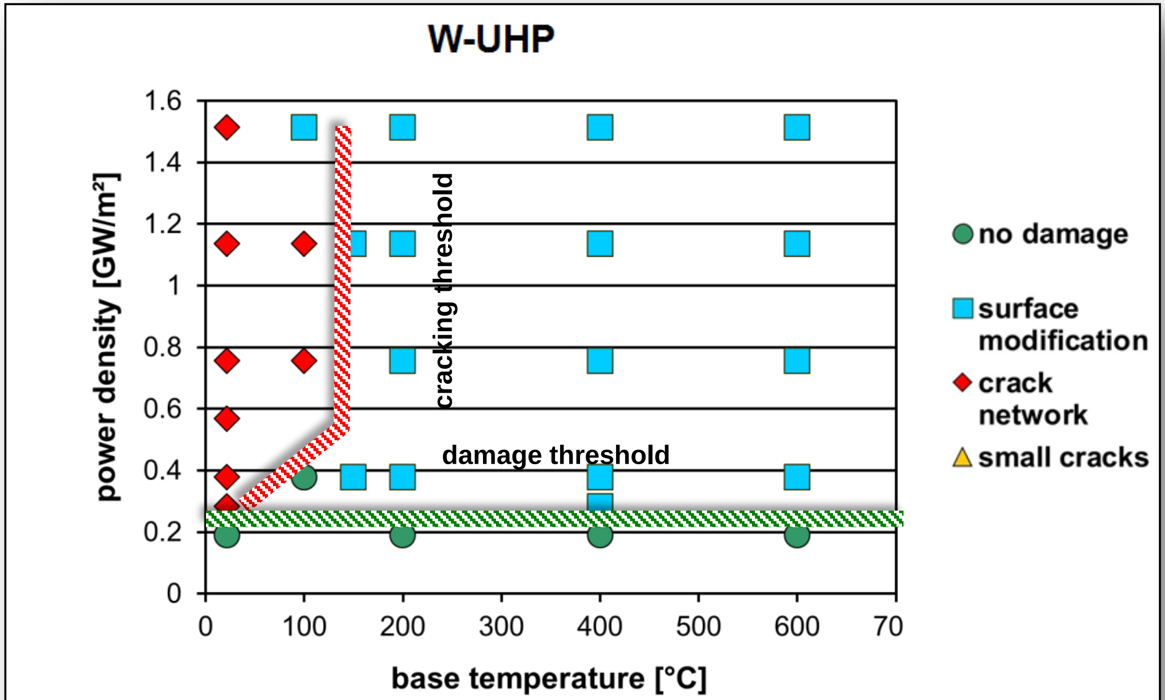
W3
melt motion
melt motion starts at 'vertical cracks'
plasma stream

Thermal Shock Tests

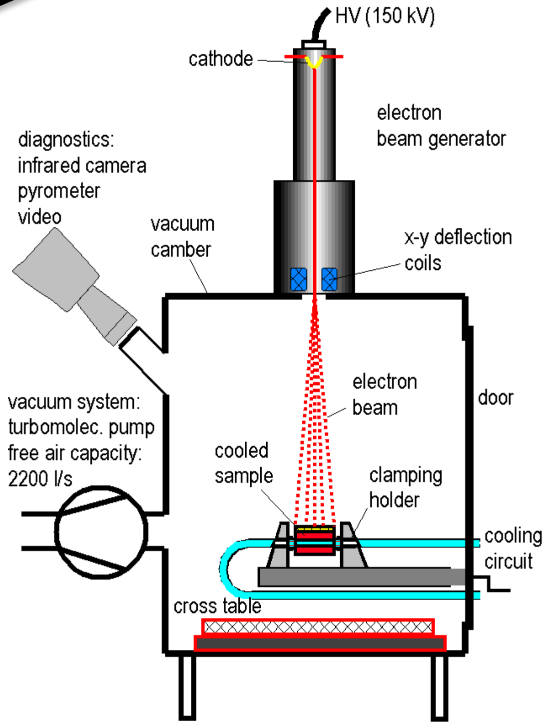
Experimental setting

- 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



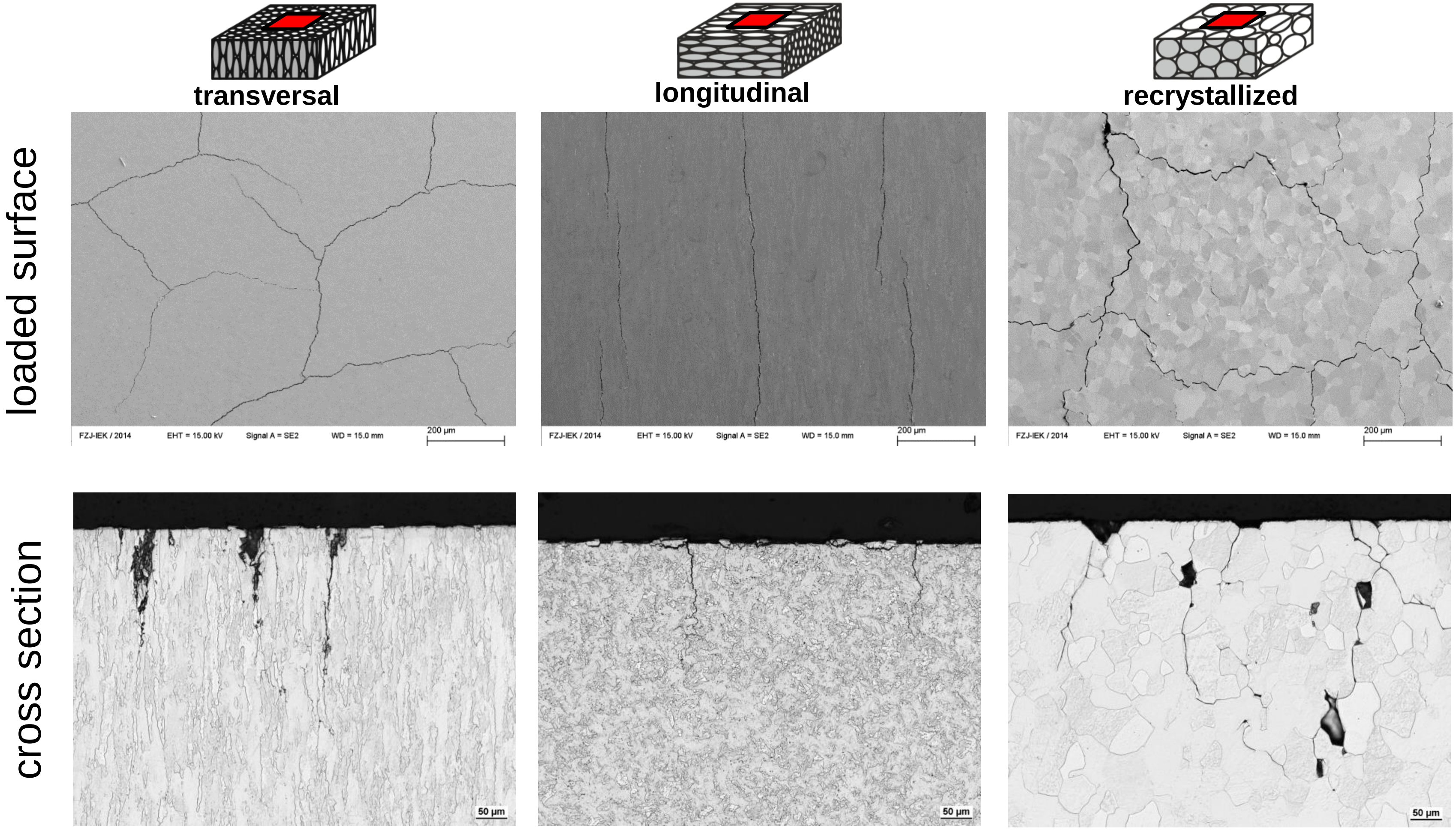


100 pulses with a duration of 1 ms; absorption coefficient 0.55



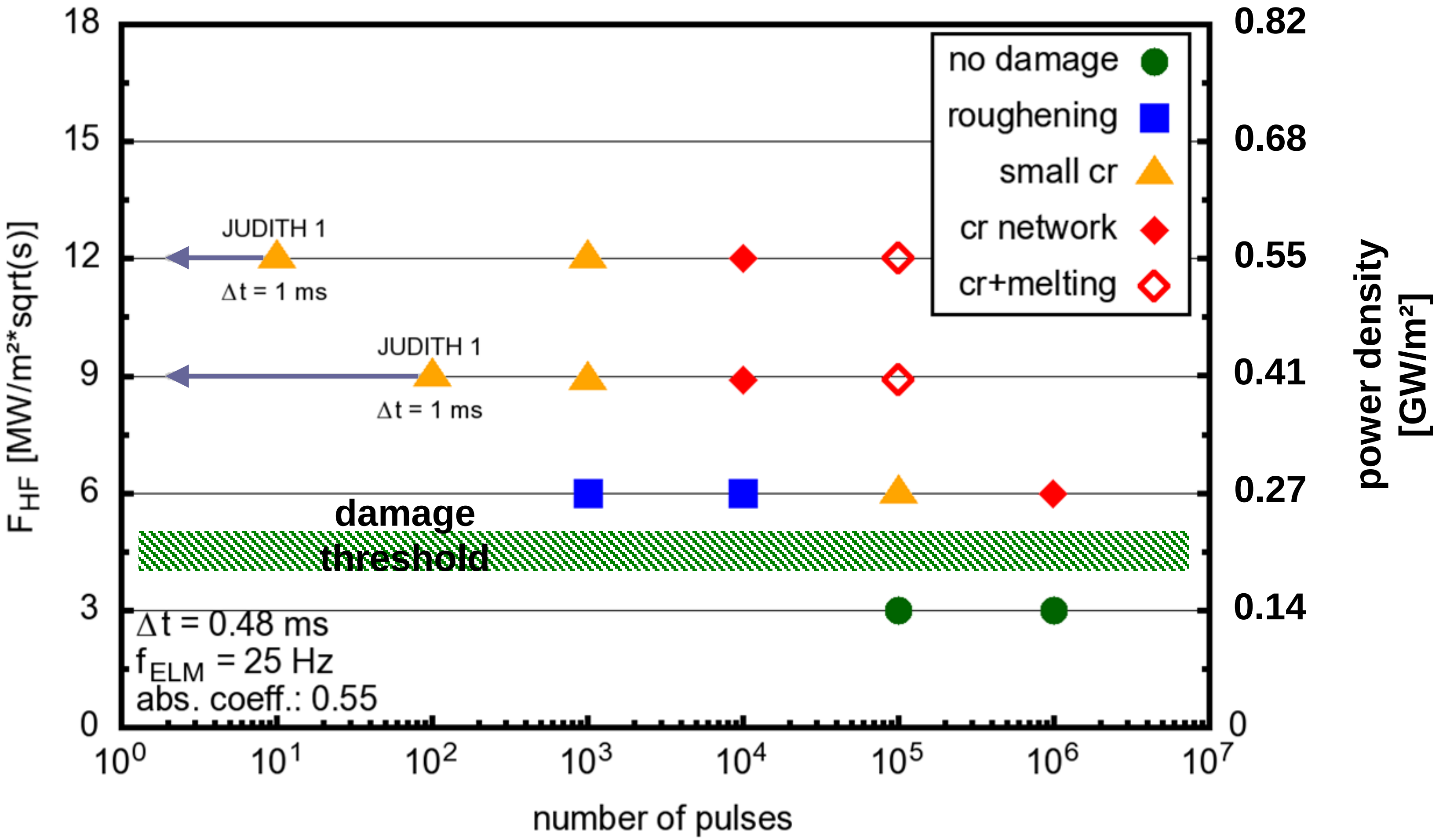
Crack Formation

- 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

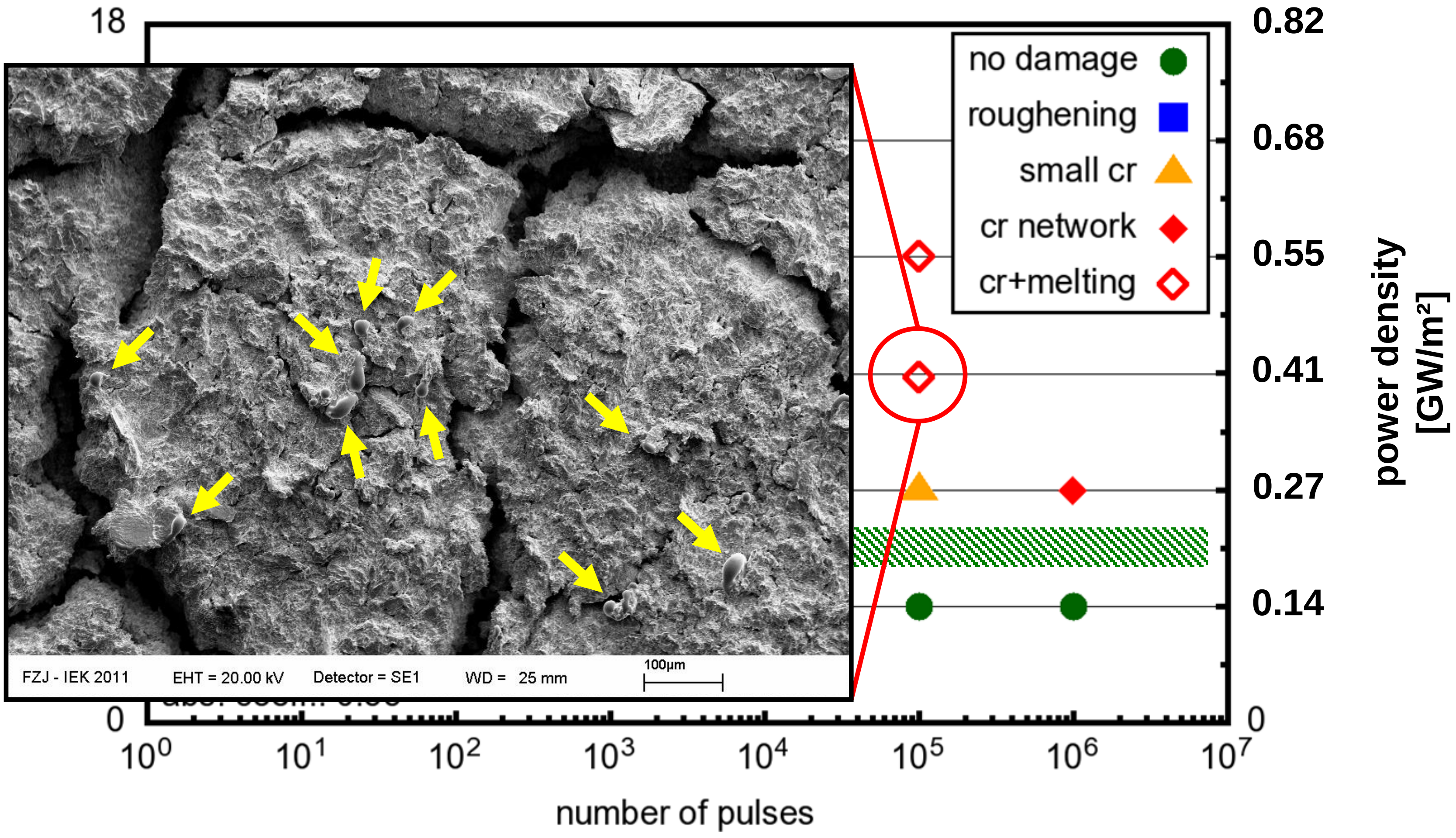
Surface condition after testing pure W at $T_{surf} \approx 700$ °C (10 MW/m^2 SSHL)



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

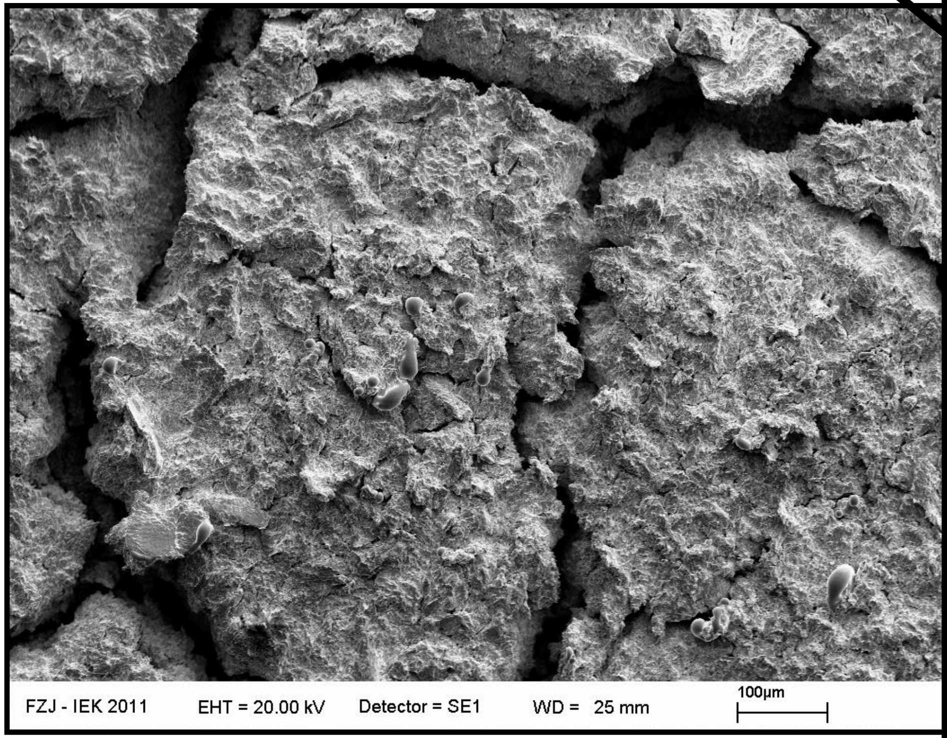
ELM simulation using e-beams with high repetition rates in JUDITH 2

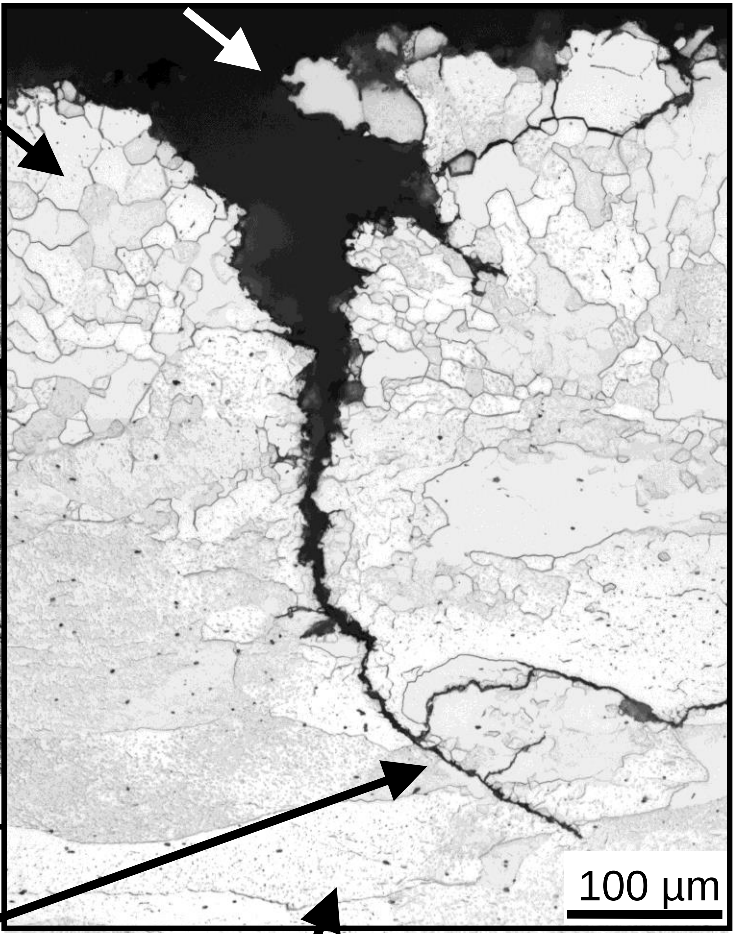
Surface condition after testing pure W at $T_{surf} \approx 700$ °C (10 MW/m^2 SSHL)



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

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





melting

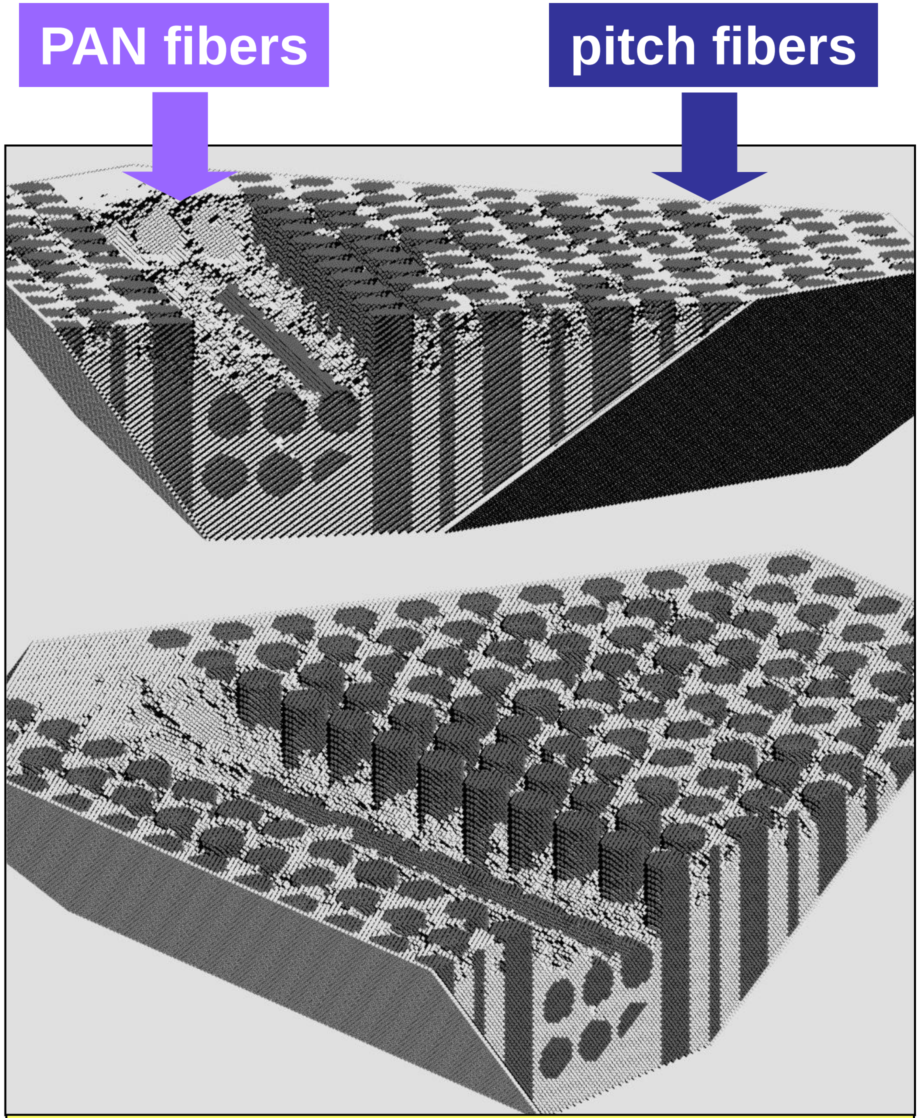
recrystallization

recrystallization around crack edges

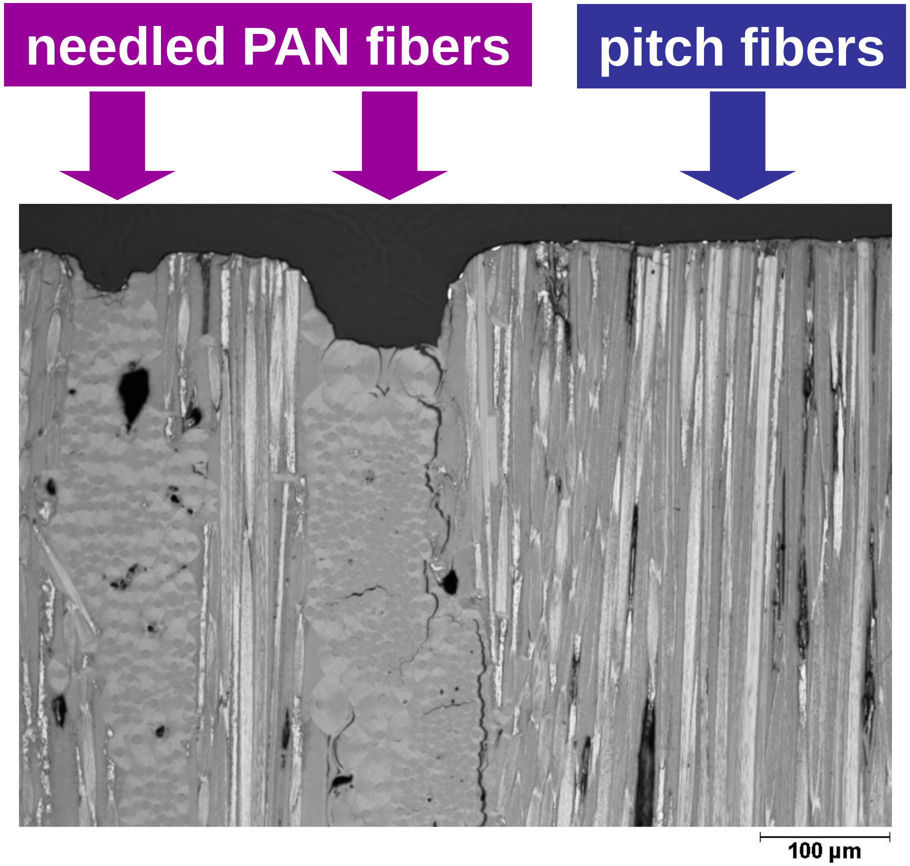
original grain structure

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

Thermally induced erosion of NB31



modeling: S. Pestchanyi et al., KIT

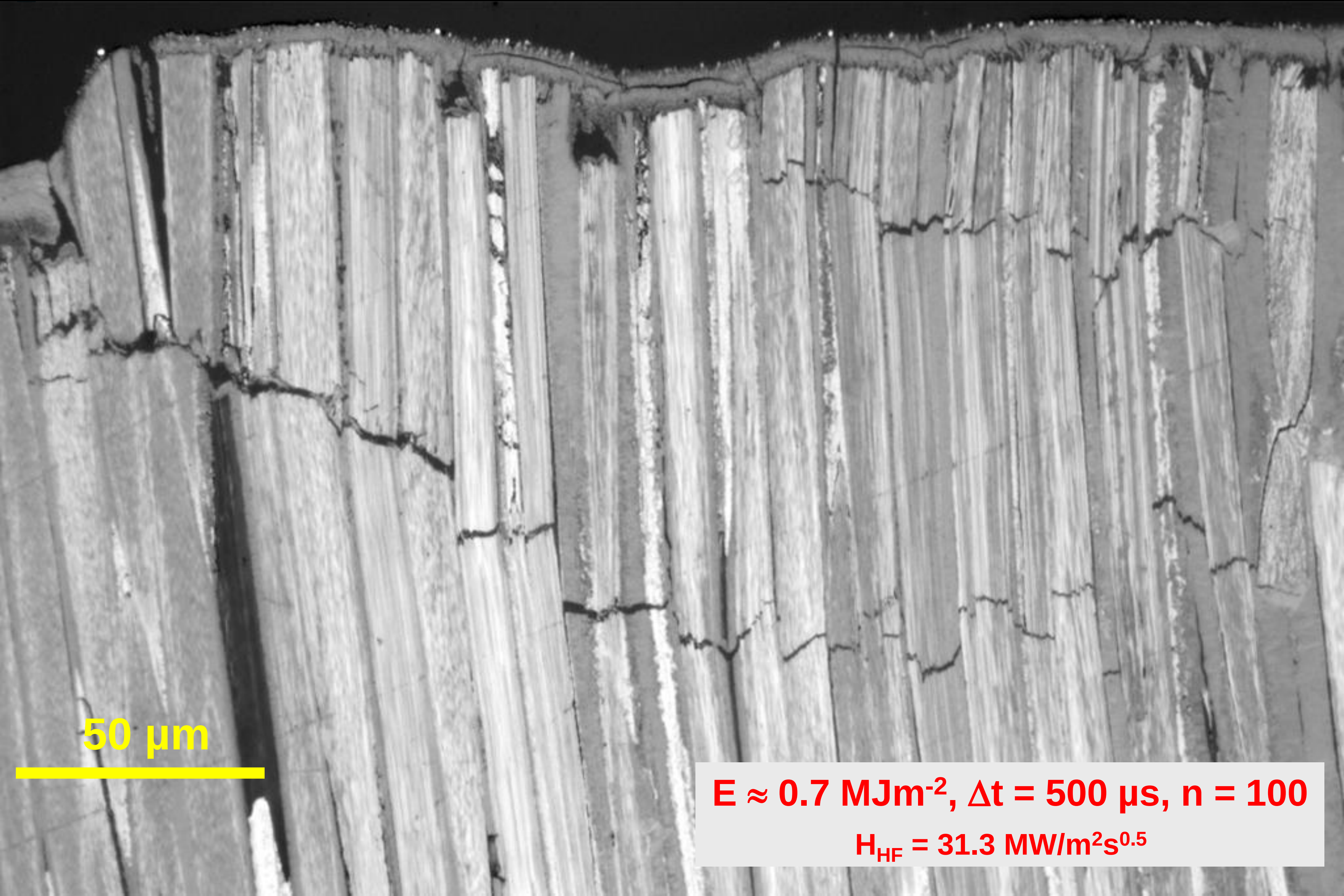


$E \approx 1.0\ \mathrm{MJm^{-2}}$, $\Delta t = 500\ \mu s$, $n = 100$

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

→ **erosion depth: ~ 1 µm / shot**

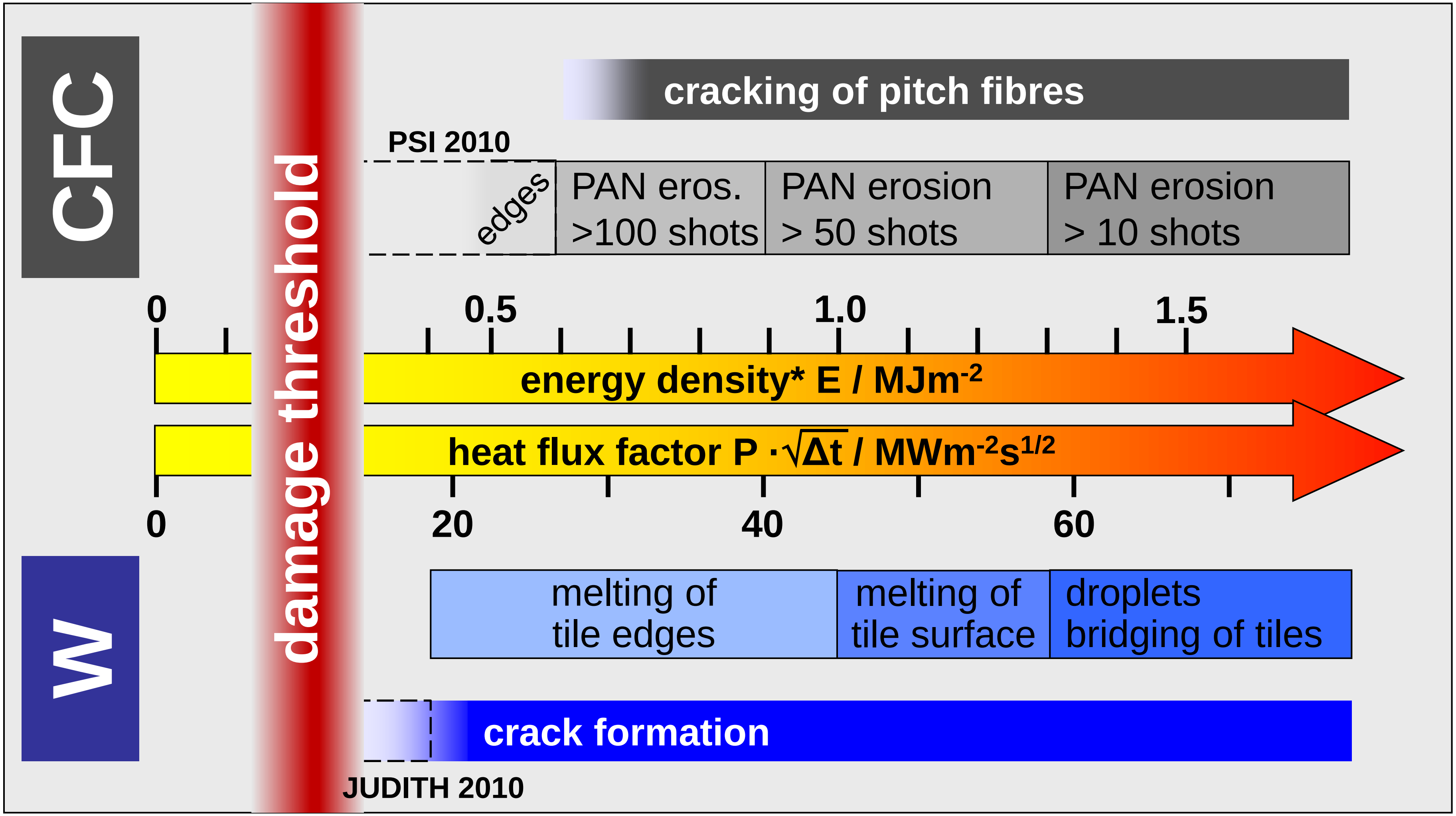
Crack formation in pitch fibers of NB31



$E \approx 0.7\ \mathrm{MJm^{-2}}$, $\Delta t = 500\ \mu s$, $n = 100$

$H_{HF} = 31.3\ \mathrm{MW/m^2 s^{0.5}}$

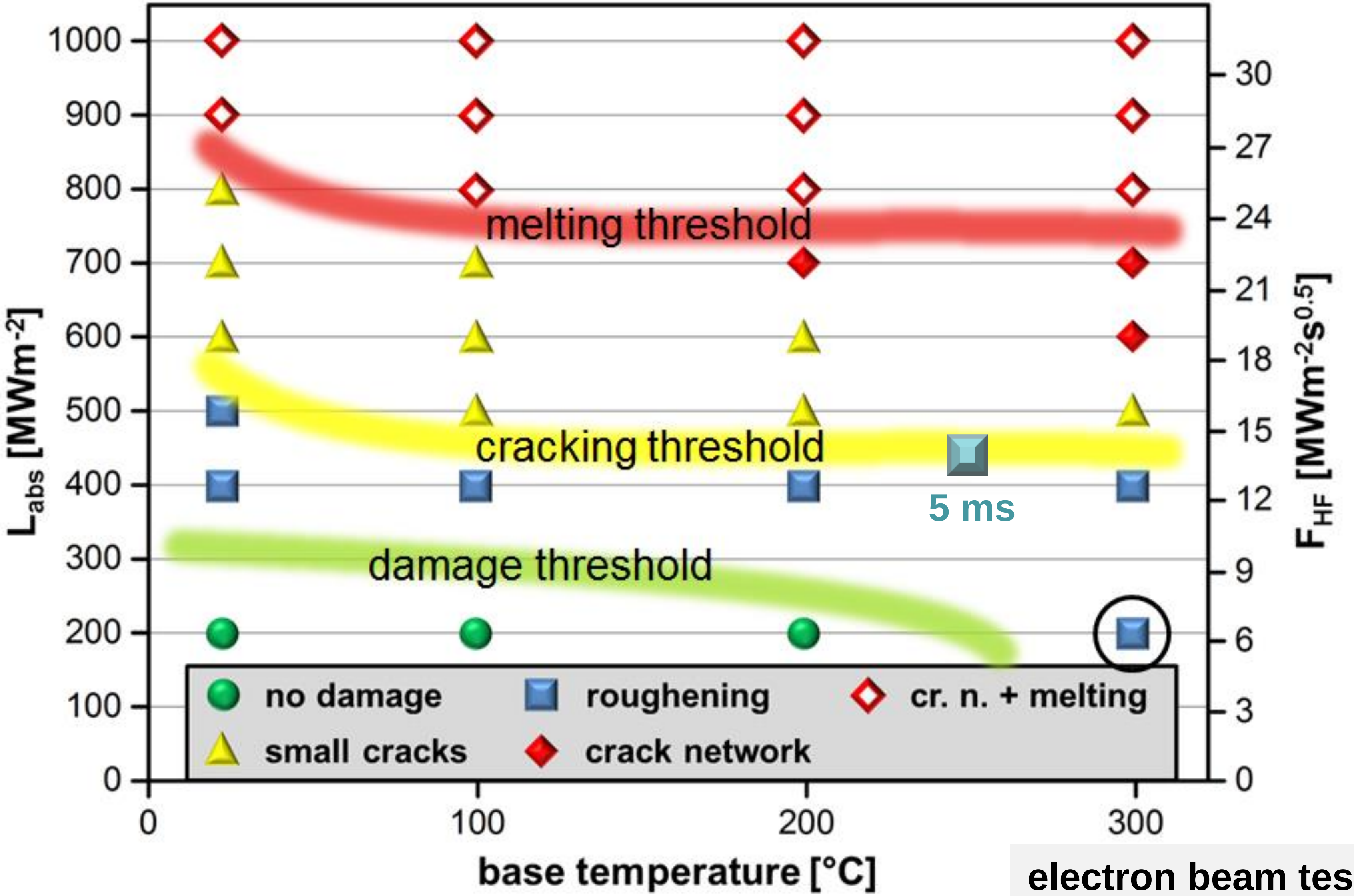
Threshold values for ELM loads



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

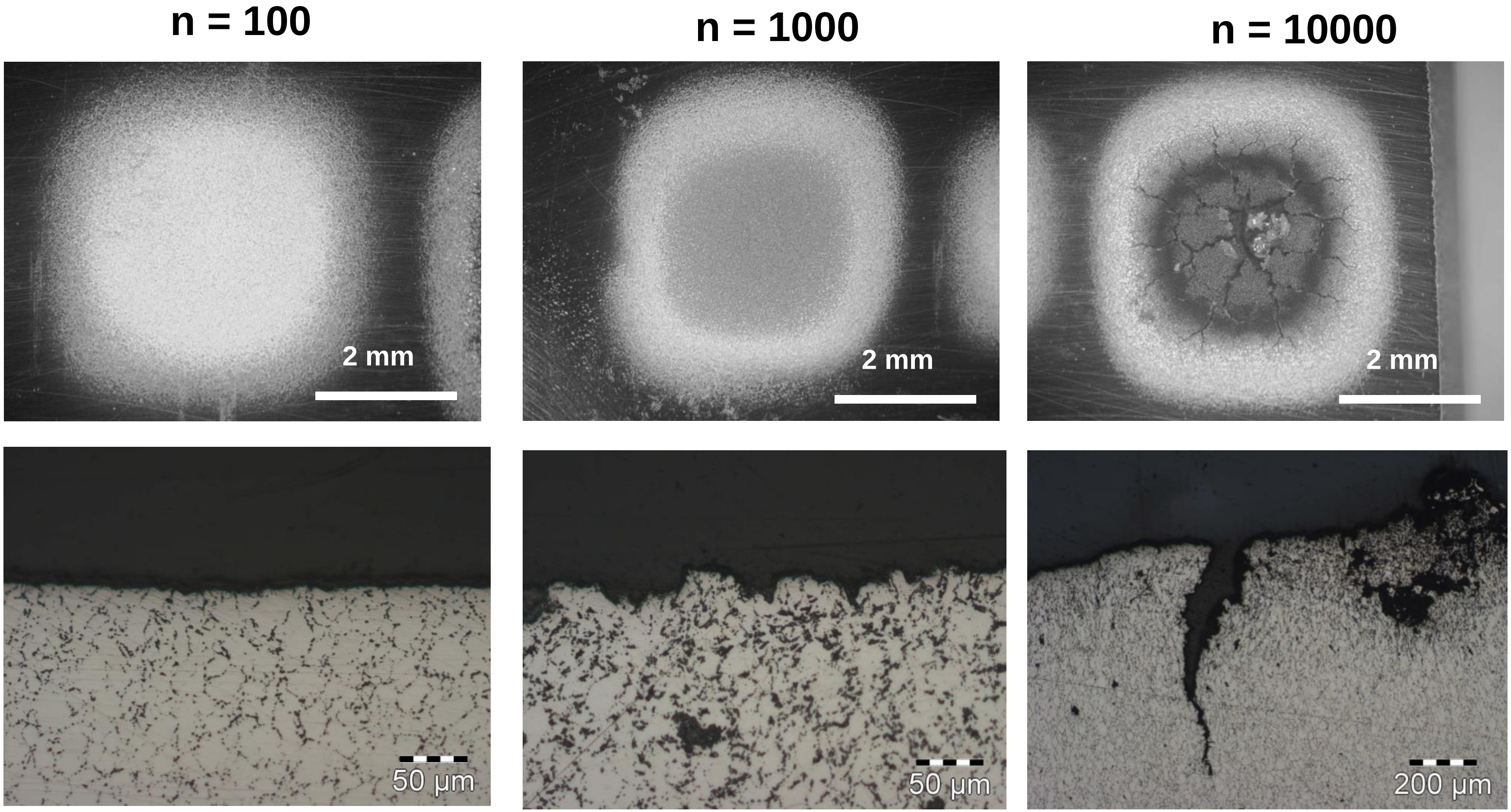
source: PSI 2006 / 2010

Thermal shock testing of beryllium



electron beam tests with 100 cycles

Repeated thermal shock testing of Be



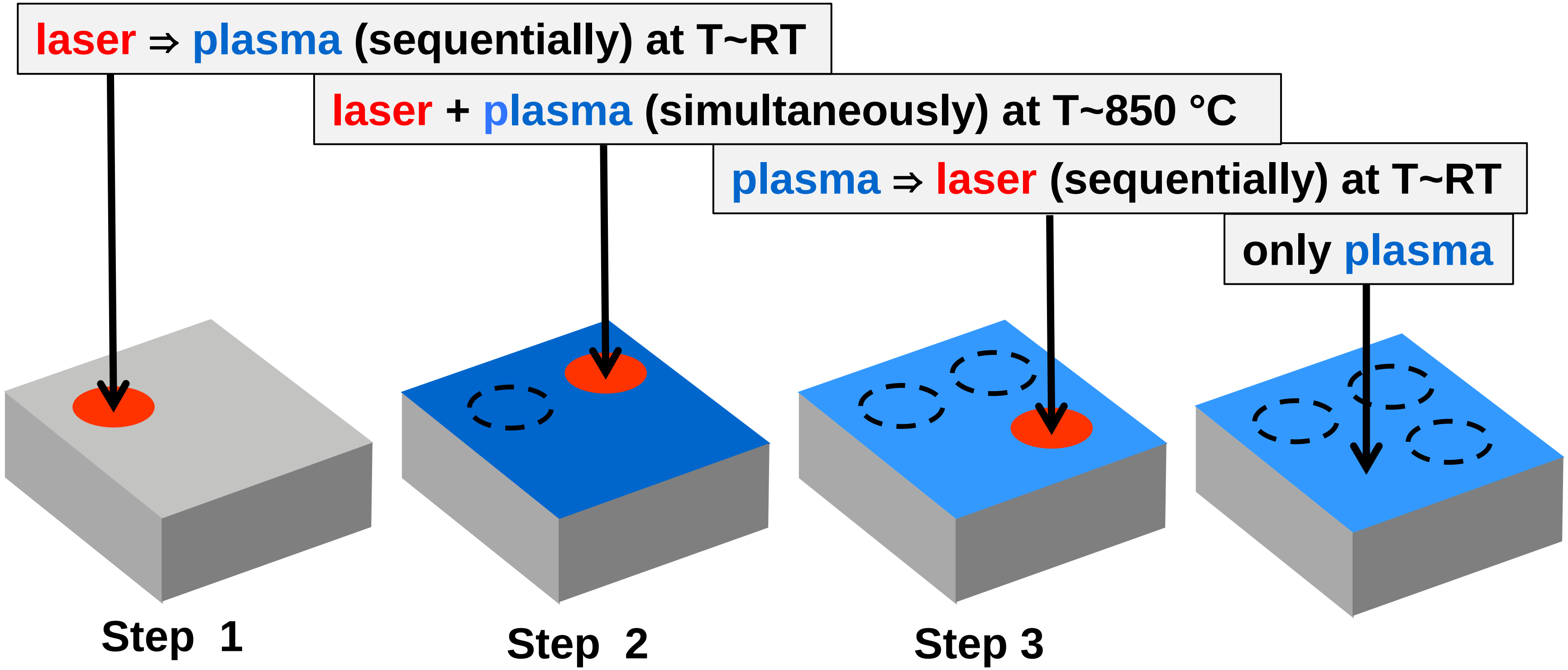
power density P =1.0 MJ/m^2
P · √(Δt) = 14 MW/m^{2}s$^{1/2}$

pulse duration Δt = 5 ms
base temperature T_0 = 250°C

C

Hydrogen and helium effects

Combined tests in PSI-2



laser ⇒ plasma (sequentially) at T~RT

laser + plasma (simultaneously) at T~850 °C

plasma ⇒ laser (sequentially) at T~RT

only plasma

- 1000 ELM-like heat pulses
- absorb. power density 0.19 – 0.76 GW/m²
- pulse duration 1 ms
- frequency 0.5 Hz

- Hydrogen (deuterium) plasma
- Helium plasma
- T_{base} = RT - 850 °C

Thermal shock and H-loading in PSI-2

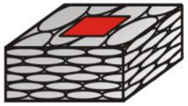
Laser beam

1000 ELM-like events at RT

absorbed power density: 0.3 GW/m^2

pulse duration: 1 ms (f = 0.5 Hz)

H-Plasma

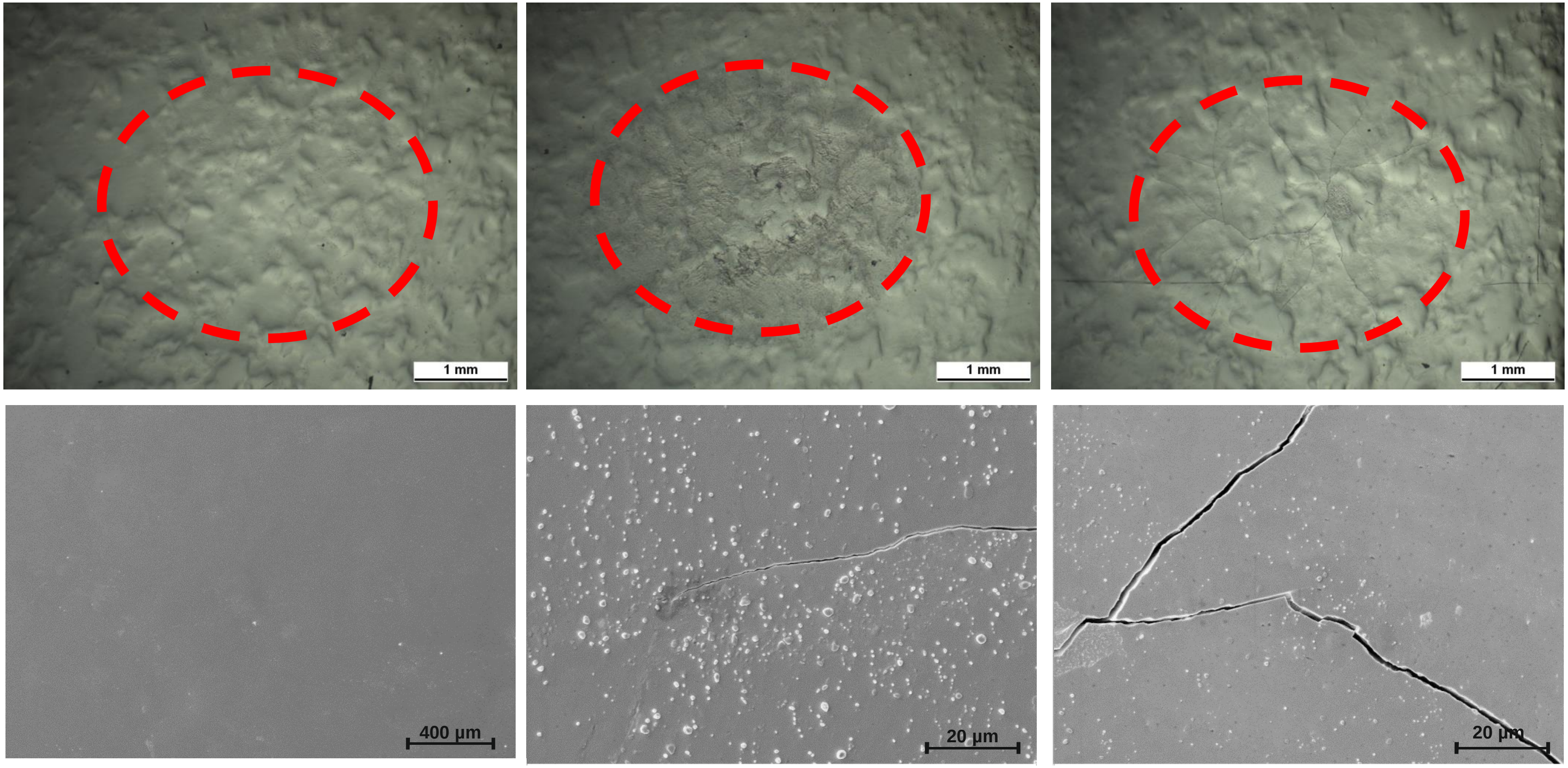


biasing voltage: - 60 V

source current: 150 A

plasma flux: 2.5 – 4.0 × 10^{21} $m^{-2}s^{-1}$

Laser ⇒ H-Plasma **Simultaneous (ΔT ≈ 100 °C)** **H-Plasma ⇒ Laser**



Thermal shock and H-loading in PSI-2

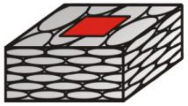
Laser beam

1000 ELM-like events at 400 °C

absorbed power density: 0.38 GW/m^2

pulse duration: 1 ms (f = 0.5 Hz)

H-Plasma

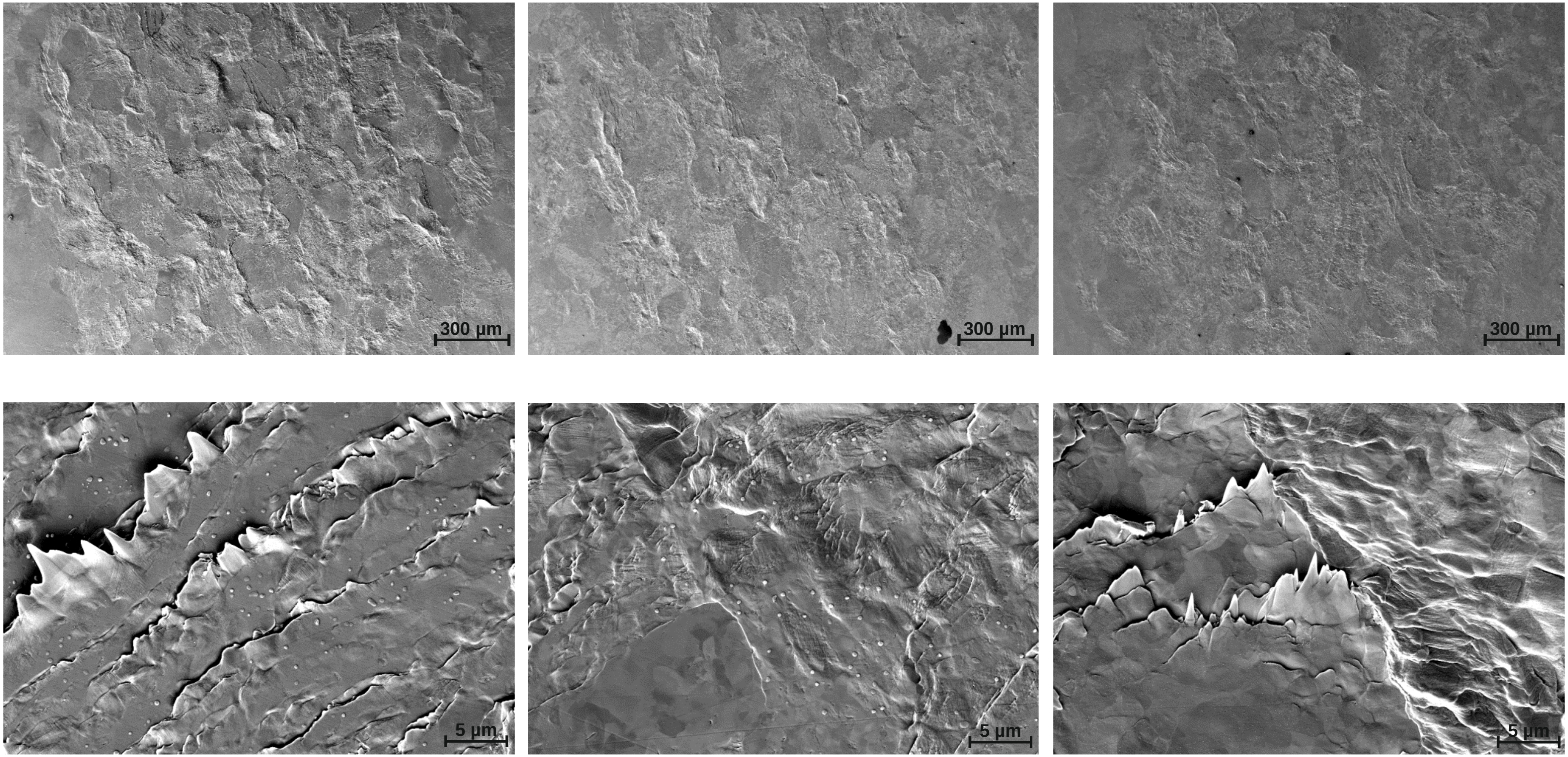


biasing voltage: - 60 V

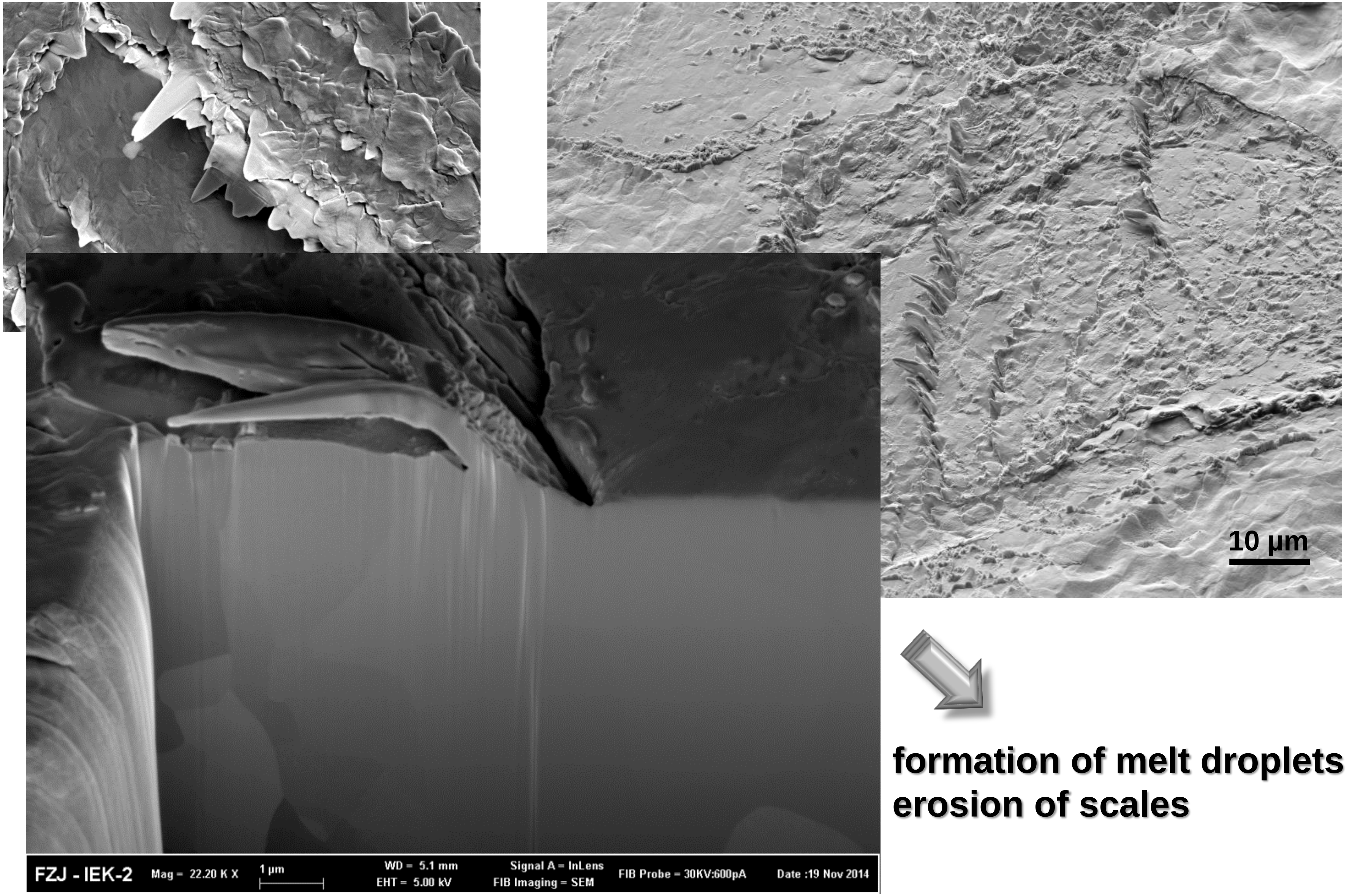
source current: 150 A

plasma flux: 2.5 – 4.0 × 10^{21} $m^{-2}s^{-1}$

Laser ⇒ H-Plasma **Simultaneous** **H-Plasma ⇒ Laser**

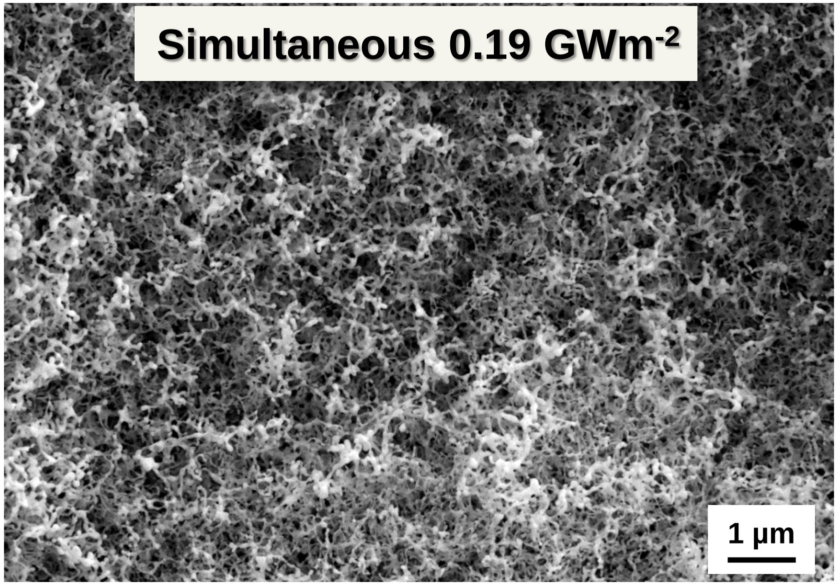


Surface structure analysis via FIB

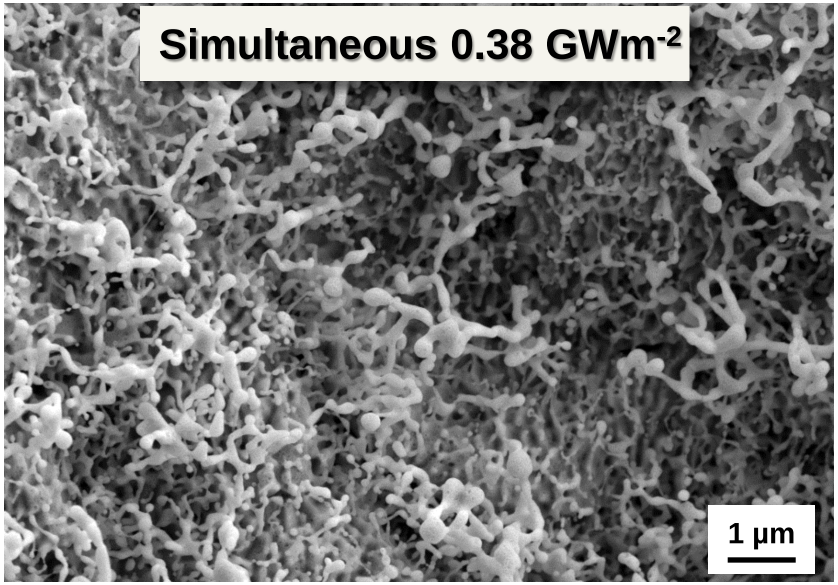


formation of melt droplets
erosion of scales

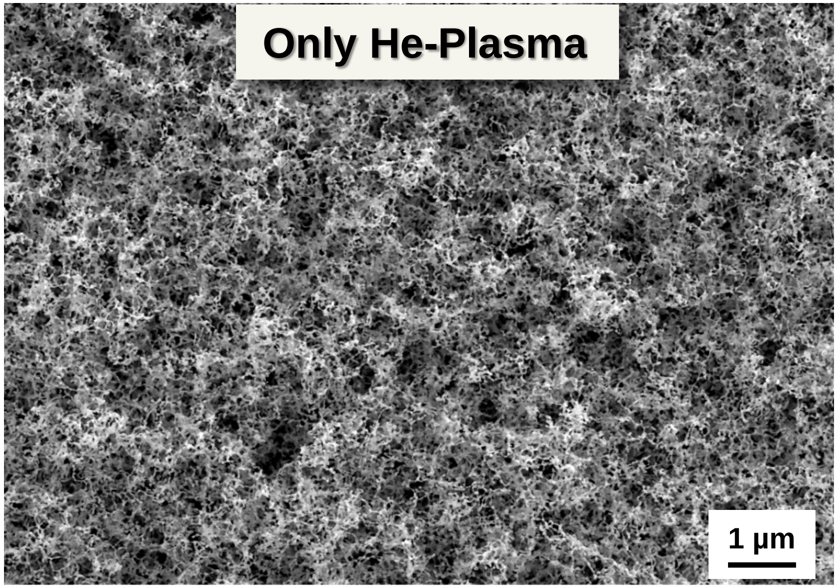
Thermal shock and He-loading



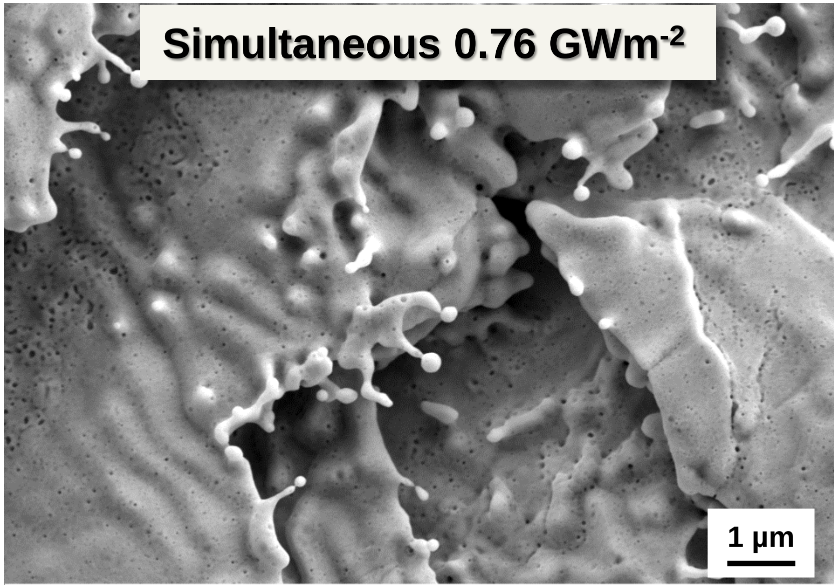
Simultaneous 0.19 GWm^{-2}



Simultaneous 0.38 GWm^{-2}

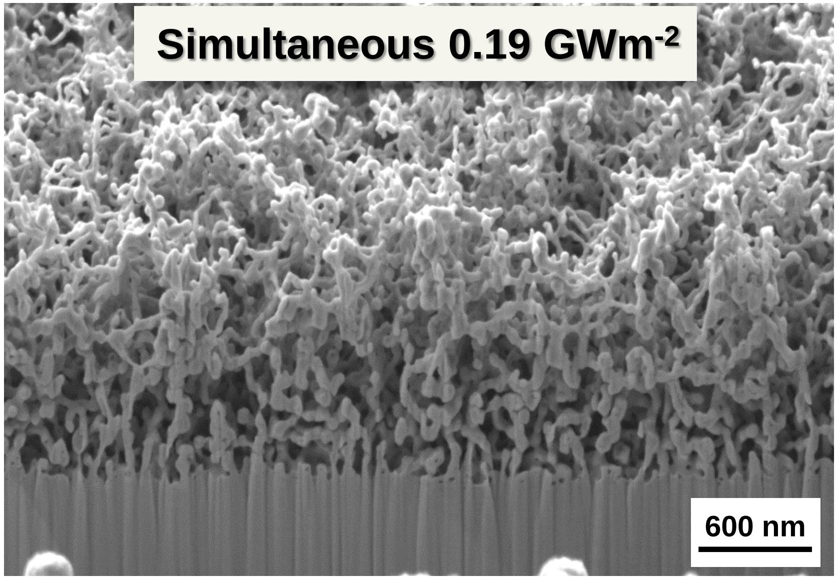


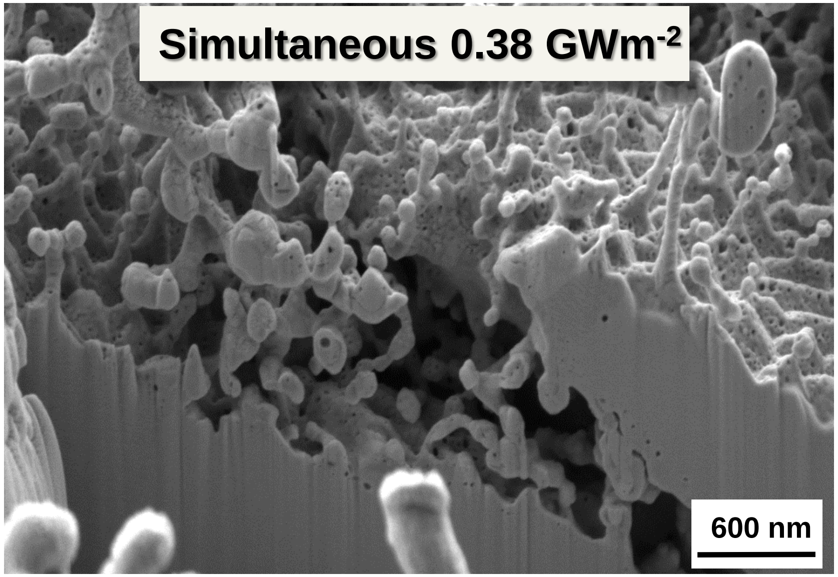
Only He-Plasma

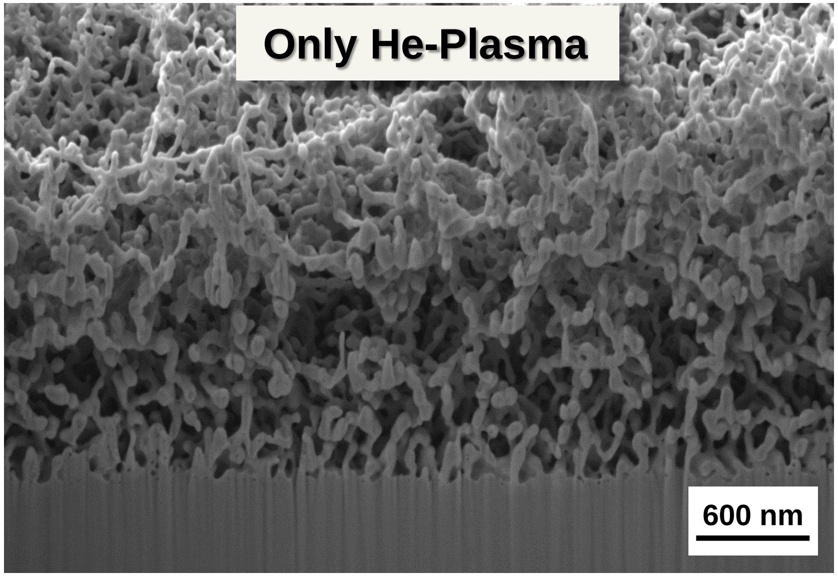


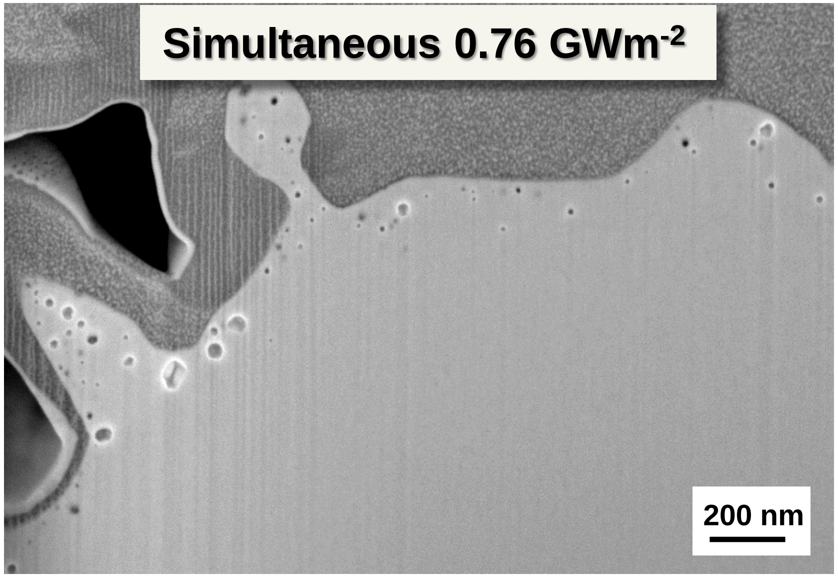
Simultaneous 0.76 GWm^{-2}

Thermal shock and He-loading

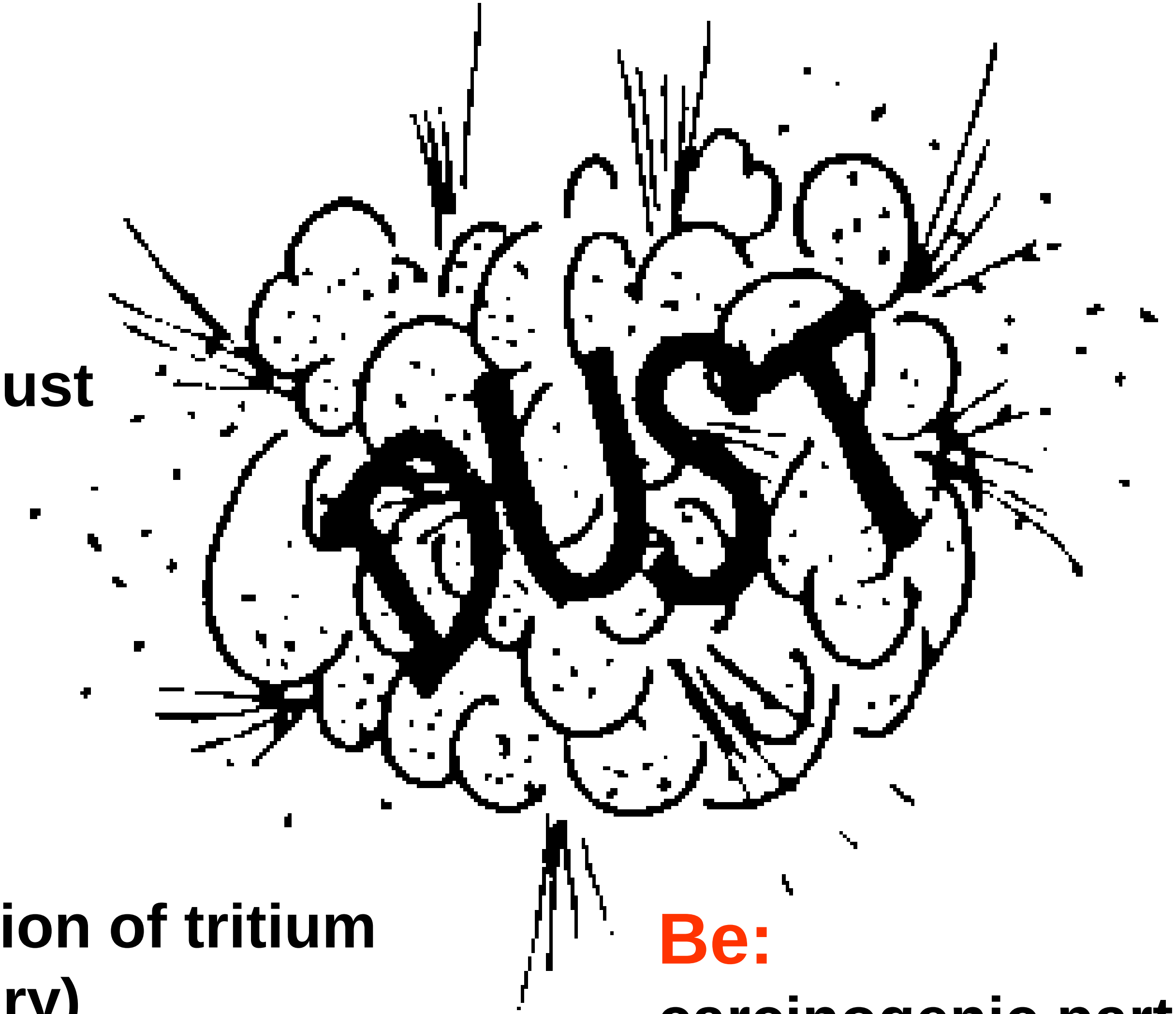

Simultaneous 0.19 GWm^{-2}


Simultaneous 0.38 GWm^{-2}


Only He-Plasma


Simultaneous 0.76 GWm^{-2}

Transient thermal loads on graphitic or metallic wall materials



W:

activated dust

CFC:

codeposition of tritium
(T inventory)

Be:

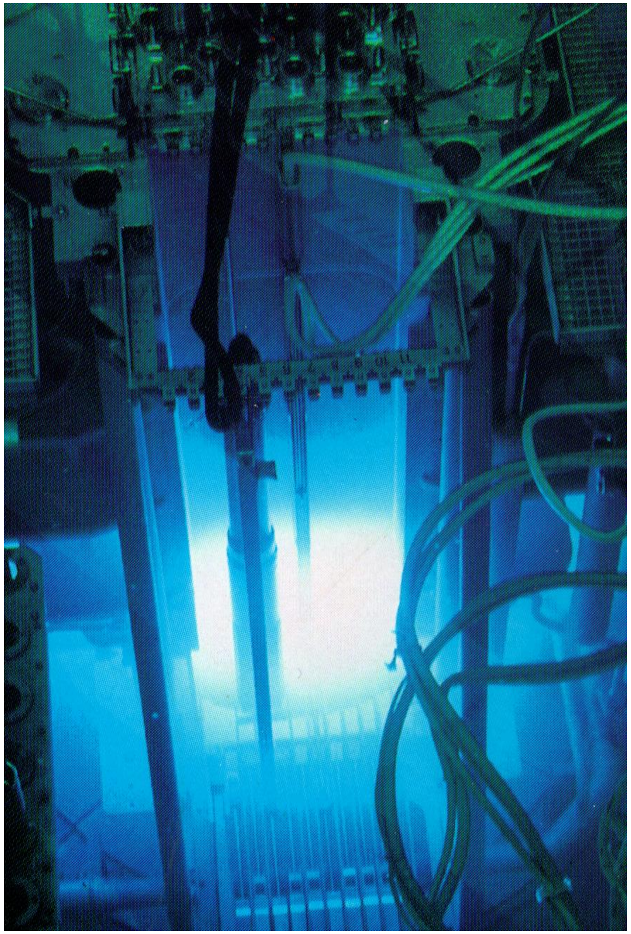
carcinogenic particles

The JET torus

D

Materials degradation by energetic neutrons

Neutron-induced material degradation

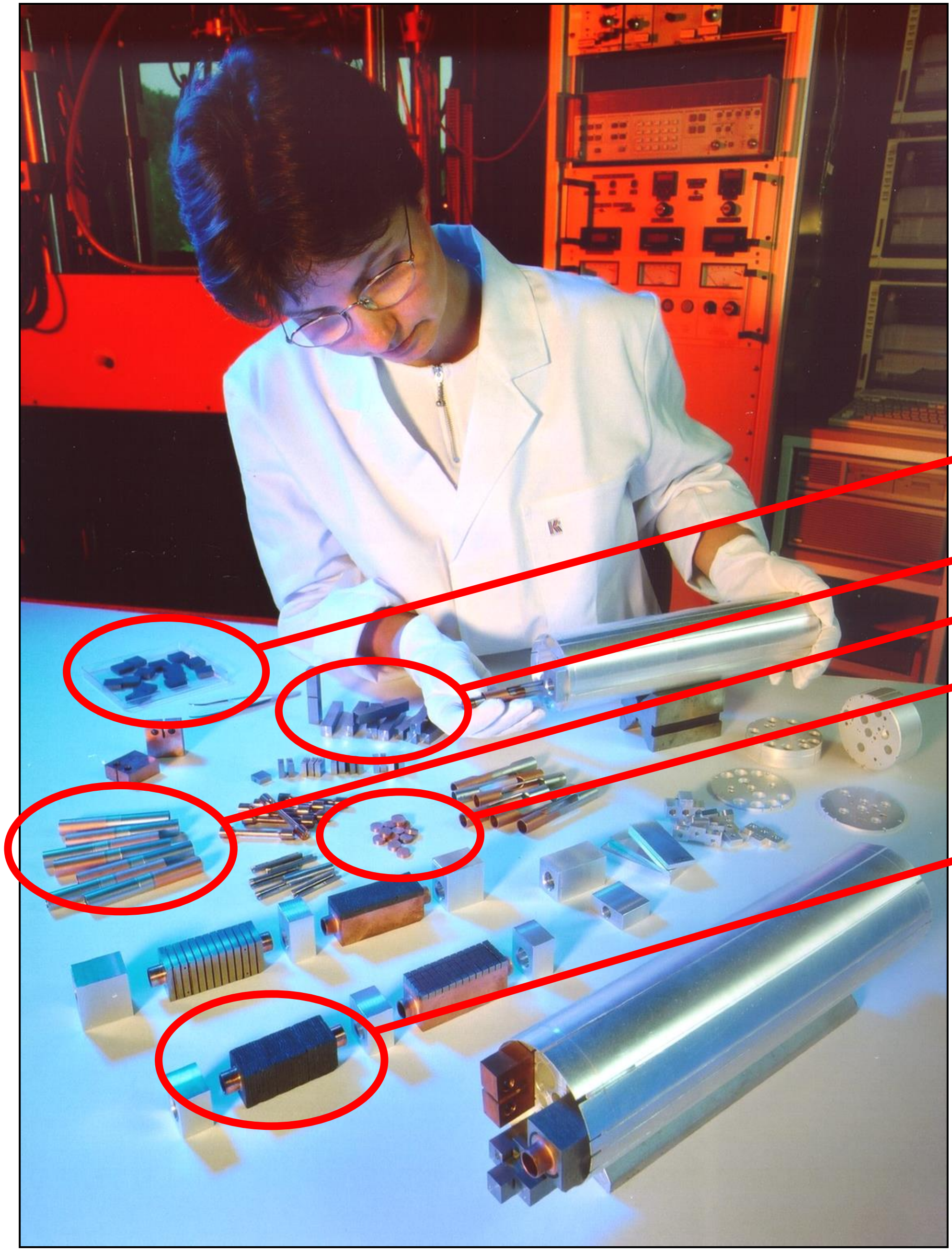


High Flux Reactor (HFR)
Petten, The Netherlands

Neutron induced effects:

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

Neutron irradiation in materials test reactors



thermal shock specimens

4-point bending test

mechanical testing of joints

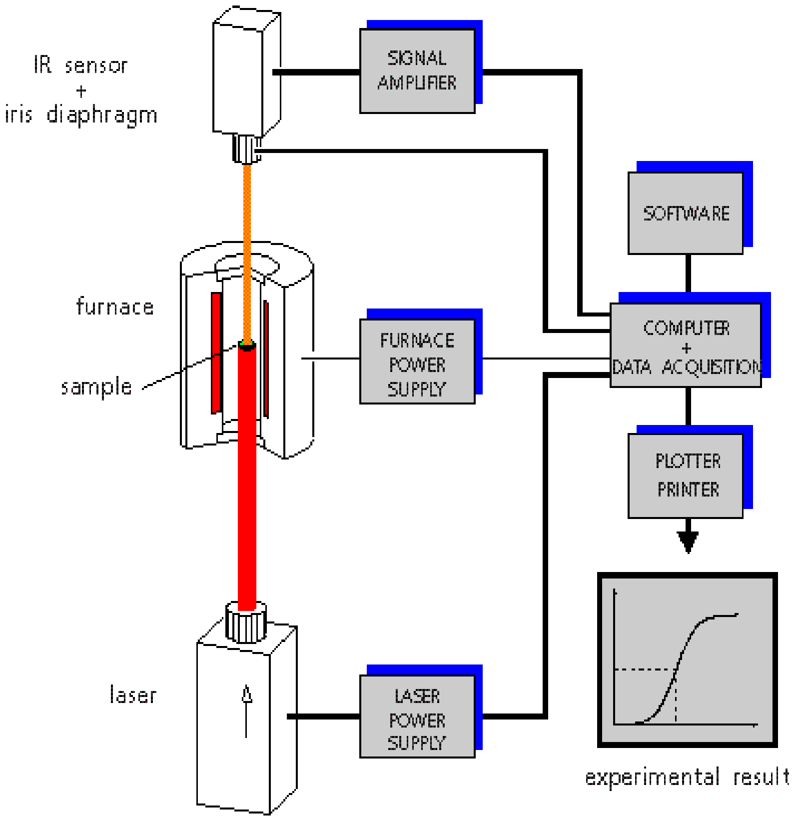
thermal conductivity

actively cooled divertor modules

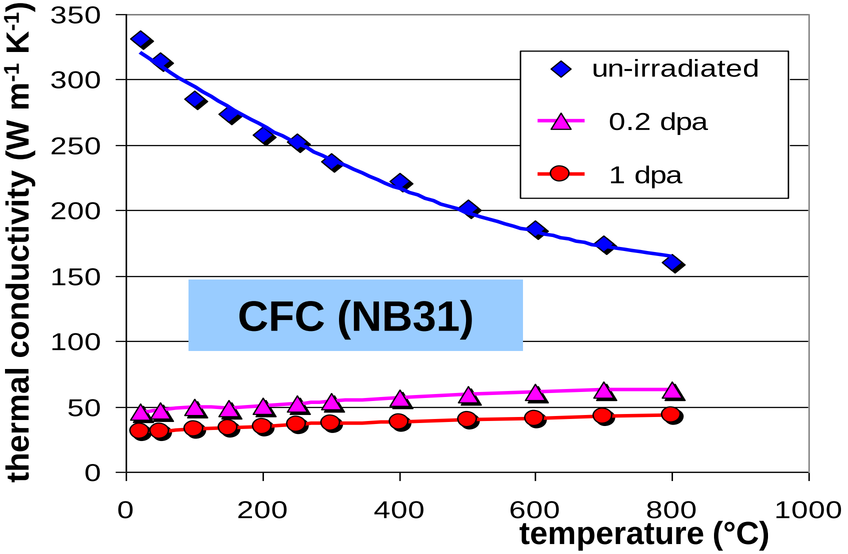
	T_{irr} [°C]	fluence [dpa]	irradiated materials
#1	350	0.35	Be, CFCs, W-alloys SiC
#2	700	0.35	
#3	200	0.2	CFCs, W-alloys, Cu-alloys, joints
#4	200	1.0	

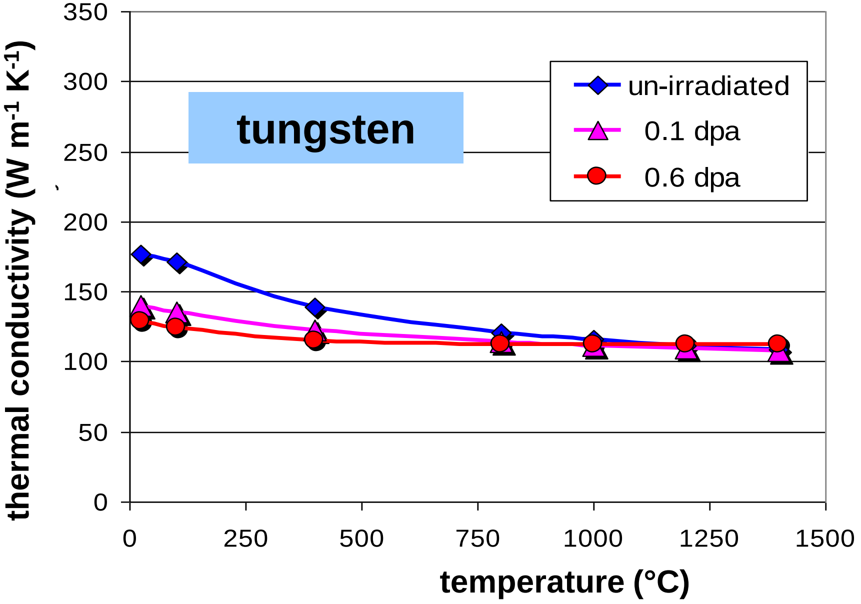
(all dpa‘s in carbon)

n-irradiation effect on thermal conductivity

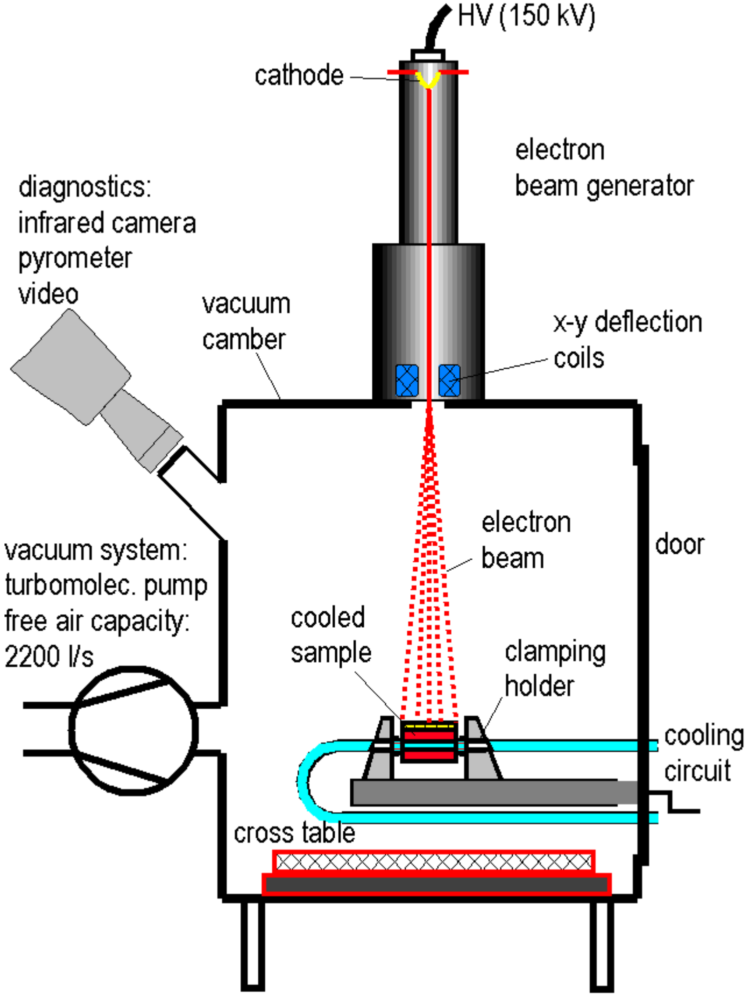


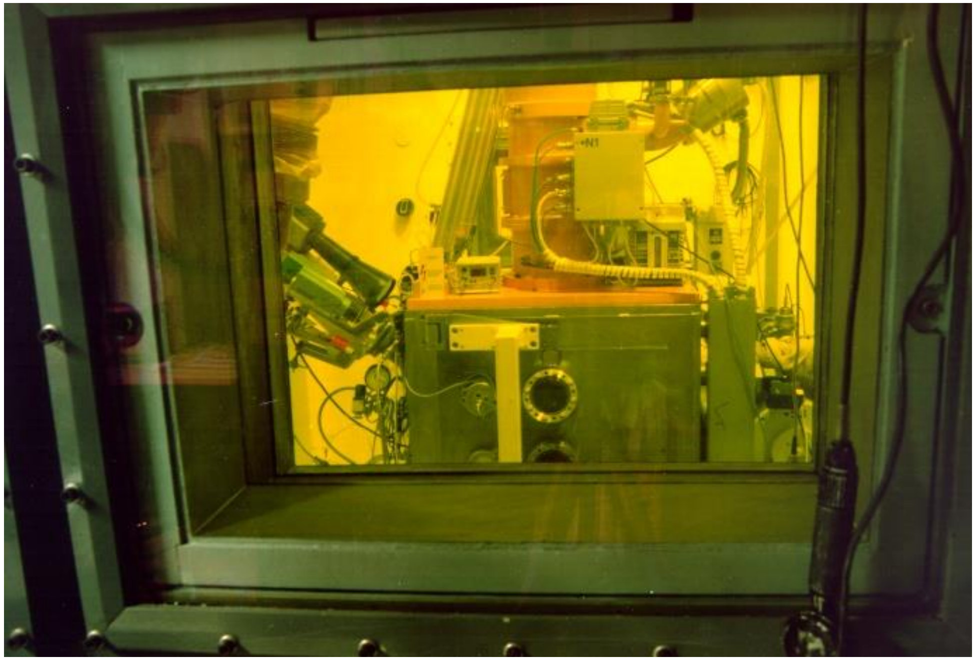
Laser-flash-apparatus (schematic)





Juelich Divertor Test Facility Hot Cells (JUDITH 1)

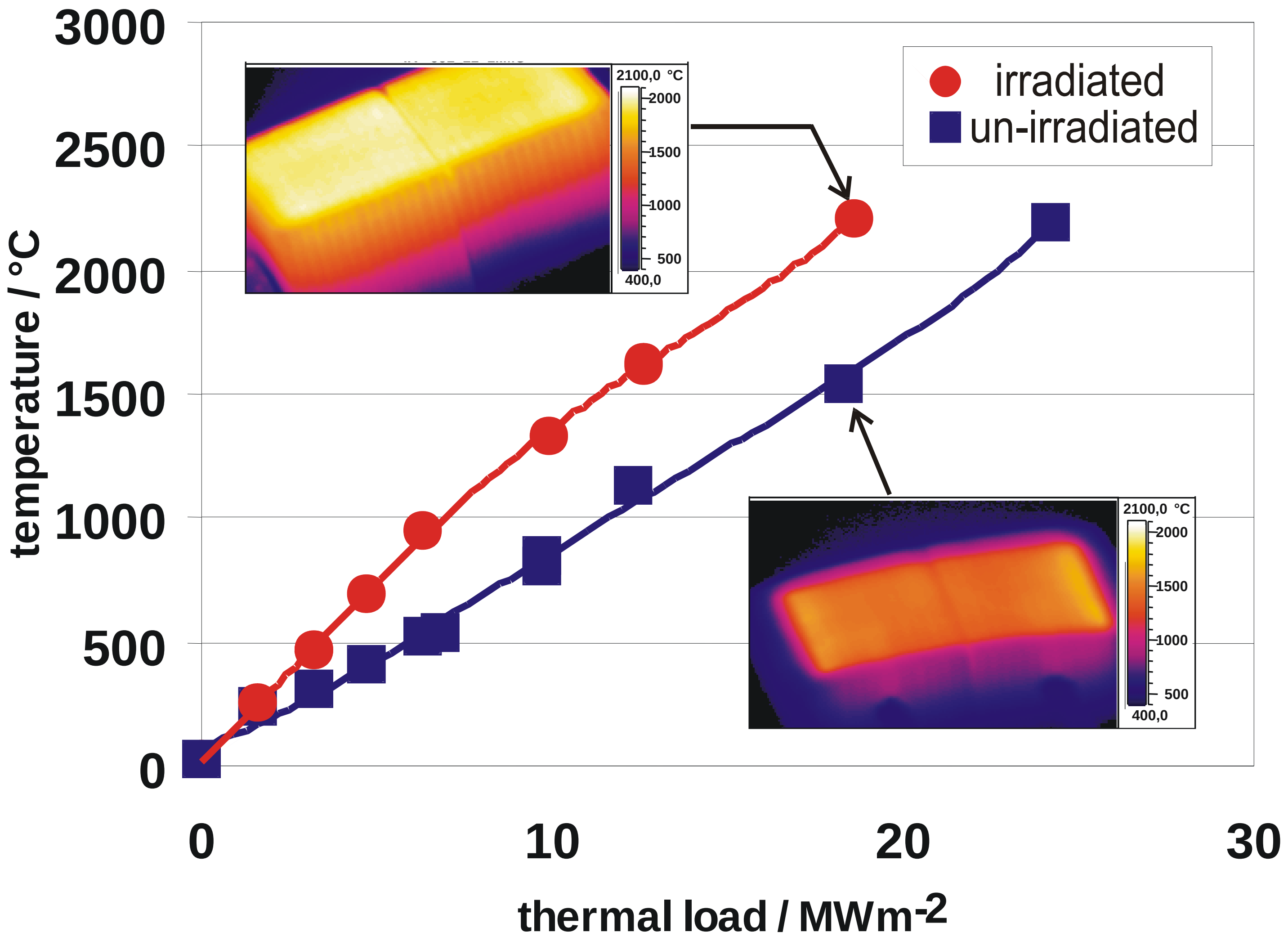




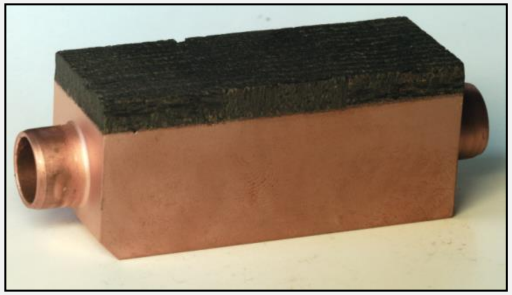
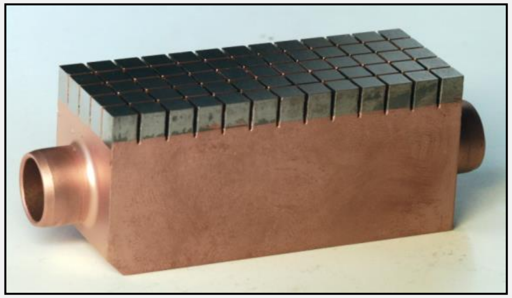
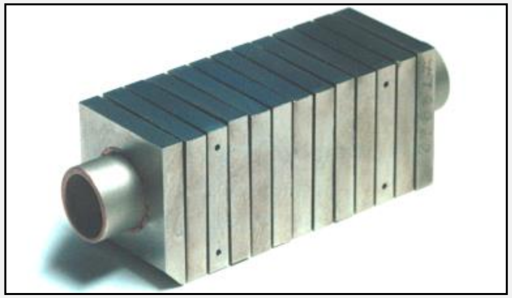
total power:	60 kW
acceleration voltage:	≤ 150 kV
power density:	≤ 15 $\mathrm{GWm^{-2}}$
loaded area:	4 $\mathrm{mm^2}$ … 100 $\mathrm{cm^2}$
pulse duration:	1 ms to continuous

HHF performance of neutron irradiated divertor modules

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



Fatigue testing on PFCs for ITER

	CFC armour	tungsten armour
flat tile design	 **CFC flat tile** 0 dpa: 1000 cycles @ 19 MWm^{-2} **1 dpa: 1000 cycles @ 15 MWm^{-2}** (no degradation)	 **W macrobrush** 0 dpa: 1000 cycles @ 18 MWm^{-2} **0.6 dpa: 1000 cycles @ 10 MWm^{-2}** (increasing of T_{surf})
monoblock design	 **CFC monoblock** 0 dpa: 1000 cycles @ 25 MWm^{-2} **1 dpa: 1000 cycles @ 12 MWm-2** (substancial evaporation @ 14 MWm^{-2})	 **W monoblock** 0 dpa: 1000 cycles @ 20 MWm^{-2} **0.6 dpa: 1000 cycles @ 18 MWm^{-2}** (no degradation)

Blanket module for ITER after neutron irradiation in the LVR-15 reactor at Rez

Vzorek první stěny reaktoru ITER v horké komoře po vyjmutí z jaderného reaktoru.

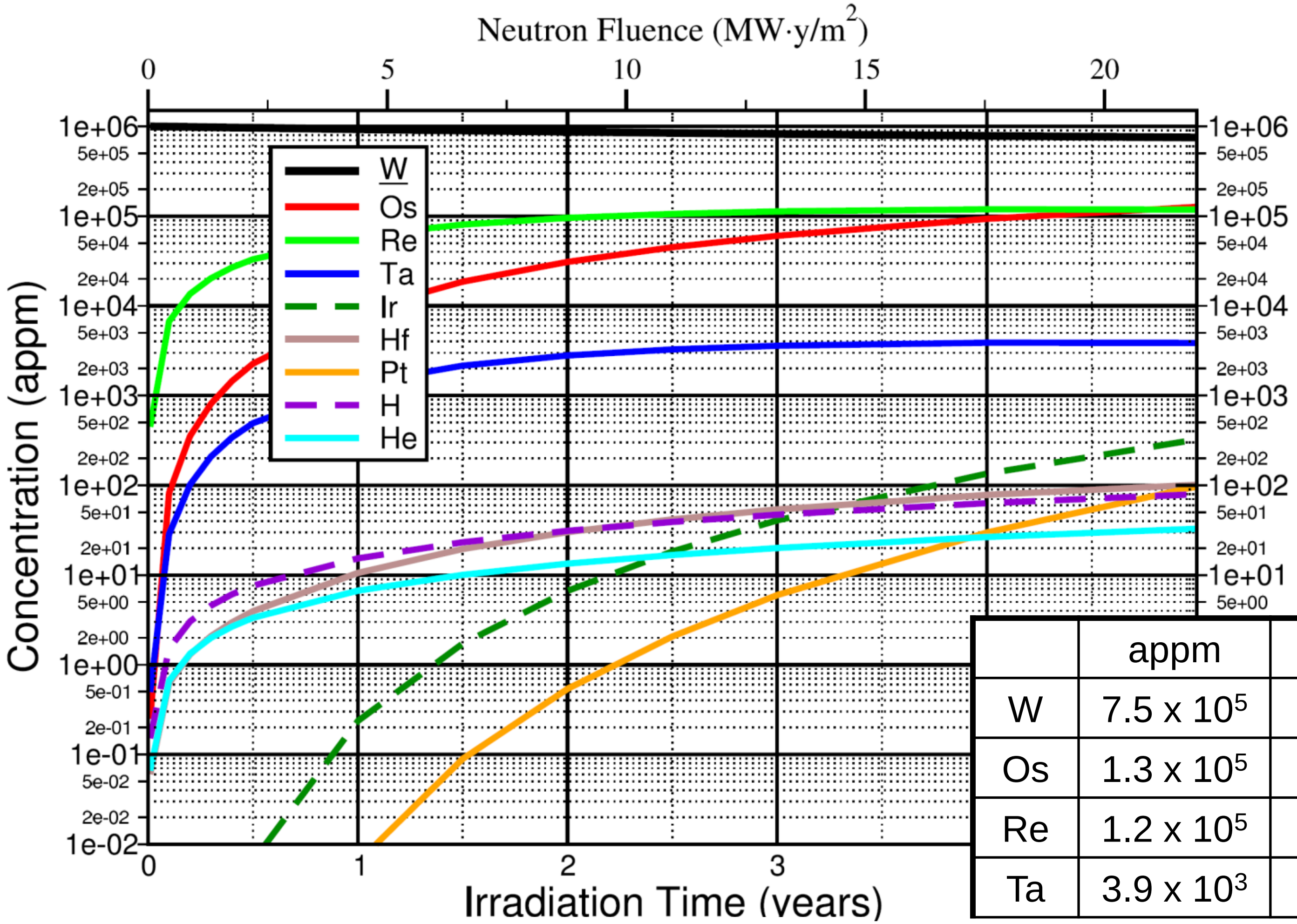
CV Řež

Transmutation of tungsten

JÜLICH
FORSCHUNGSZENTRUM

DEMO first wall – 5 years full power operation

W

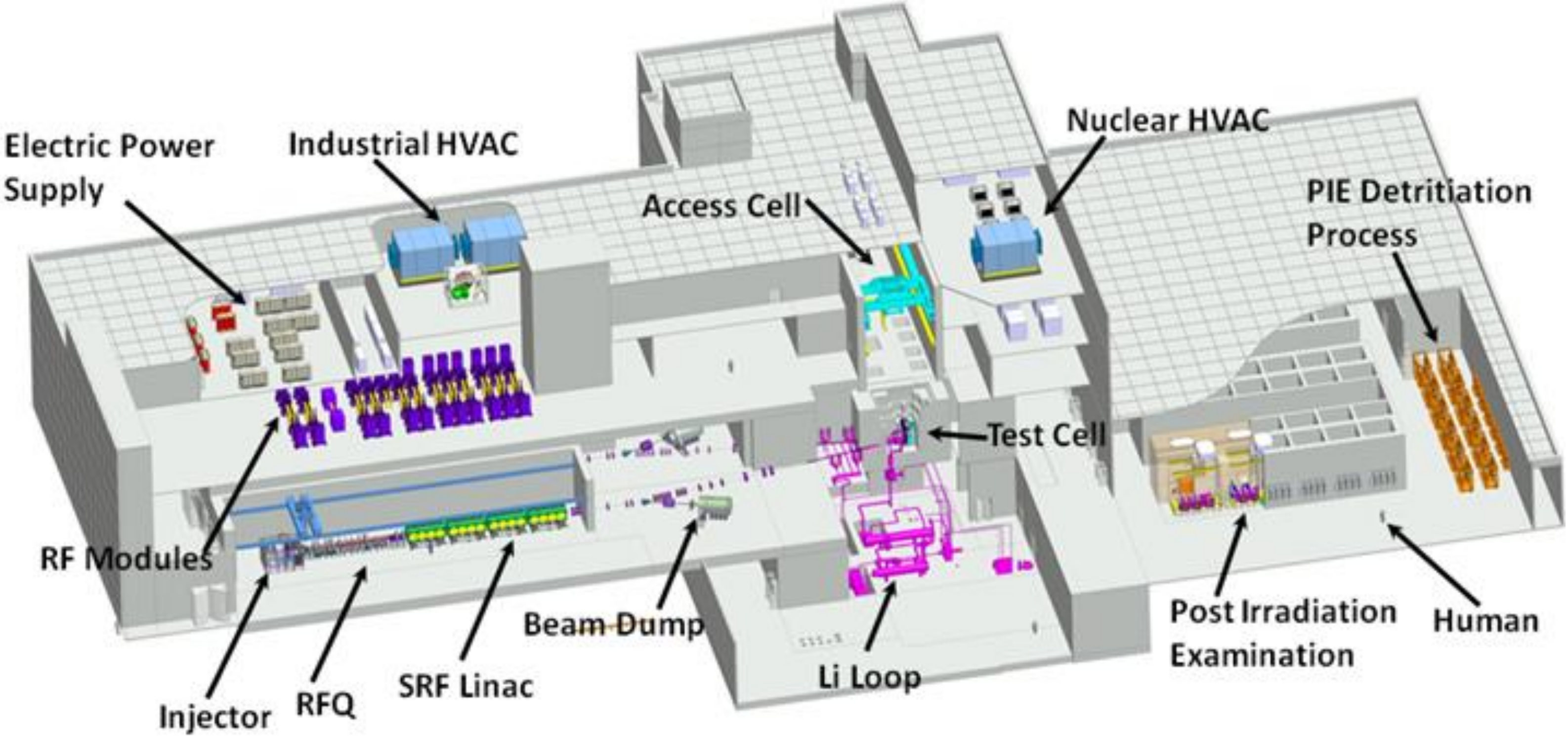


	appm	%
W	7.5×10^5	75.1
Os	1.3×10^5	12.6
Re	1.2×10^5	11.8
Ta	3.9×10^3	0.4

CCFE
CULHAM CENTRE FOR
FUSION ENERGY

source: Mark Gilbert, CCFE Fusion association

International Fusion Materials Irradiation Facility (IFMIF)



High Flux (> 20 dpa/fpy*)	0.5 liter
Medium Flux (1.0 to 20 dpa/fpy)	6 liter
Low Flux (0.1 to 1.0 dpa/fpy)	7.5 liter
Very Low Flux (0.01 to 0.1 dpa/fpy)	>100 liter

Conclusions (1)

Steady state heat loads:

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

- recrystallization
- failure of joints

very high thermal loads

Transient thermal loads:

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

- crackings
- melting
- dust formation

- maximum tolerable heat loads for the DEMO divertor
  < 5 MWm^{-2} (or higher?)
- load limits for ITER W-monoblocks with CuCrZr heat sink
  < 18 MWm^{-2} for quasi stationary (cyclic) loads @ 0.6 dpa
  < 0.2 MJ/m^{-2} for ELMs (500 µs)
- ELM-mitigation is indispensible

Conclusions (2)

- severe hydrogen embrittlement (concern for ELM loads)
- Uncertainties in respect of W-fuzz behavior under ELM-like transient loads (possible source for dust formation)

plasma exposure

Plasma loads:
- sputtering
- hydrogen
- helium

Conclusions (3)

- neutron induced embrittlement
- swelling (> 1% @ 600 – 900°C for 10 dpa)
- degradation of thermal conductivity (< 800°C) at low fluences
- transmutation effects remarkable for high neutron doses (additional effects from alloying elements)
- decay heat required active cooling of PFCs after shut down

less relevant for ITER, but serious concern for DEMO

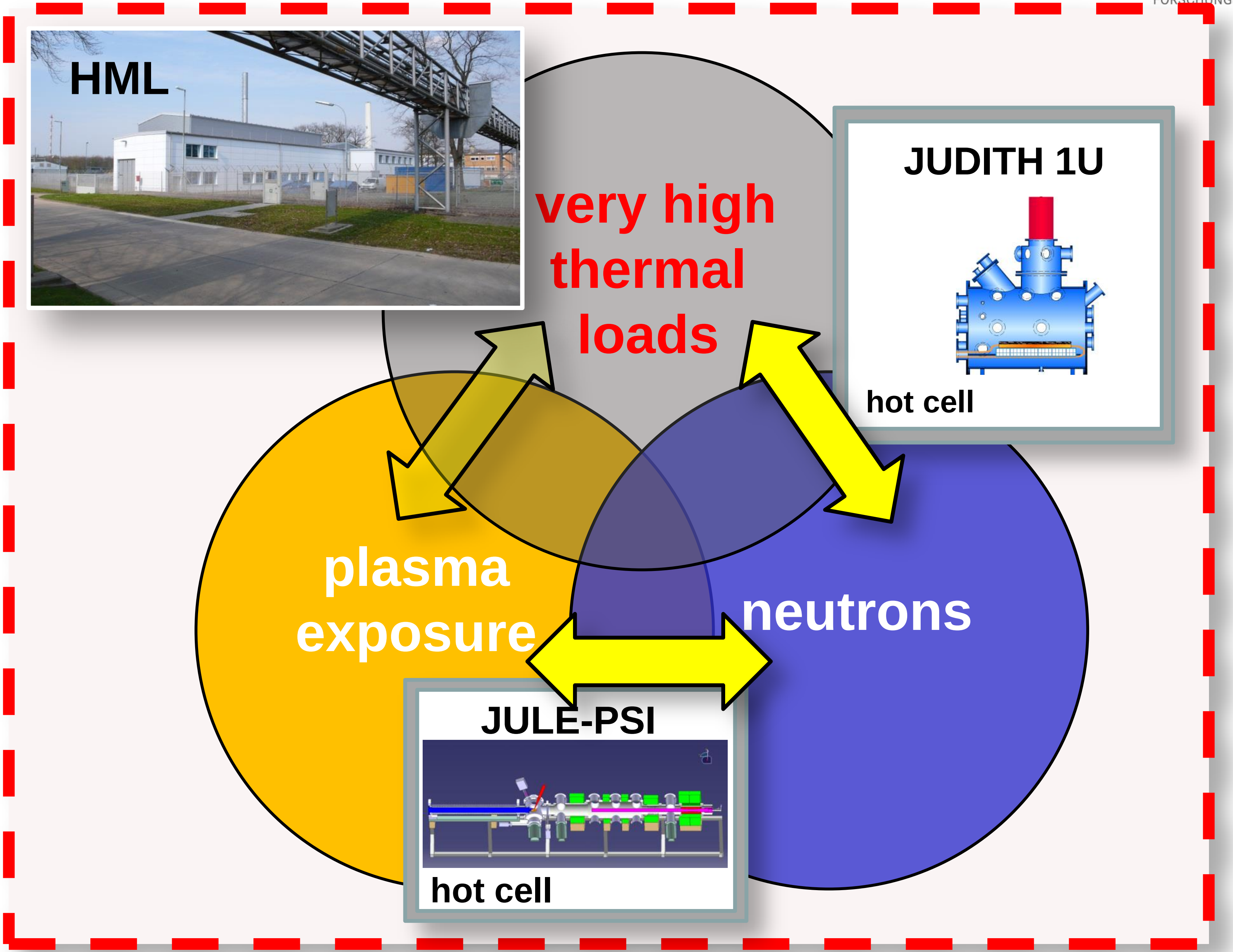
neutrons

Neutrons:

- up to 14 MeV
- defects
- transmutation

Future fusion materials research in

JÜLICH
FORSCHUNGSZENTRUM



HML

very high thermal loads

JUDITH 1U

hot cell

plasma exposure

neutrons

JULE-PSI

hot cell