13th PFMC WORKSHOP and 1st FEMaS CONFERENCE
ROSENHEIM 9-13 MAY 2011

JÜLICH
FORSCHUNGSZENTRUM

Association EURATOM – FZJ

Testing of plasma facing materials and components

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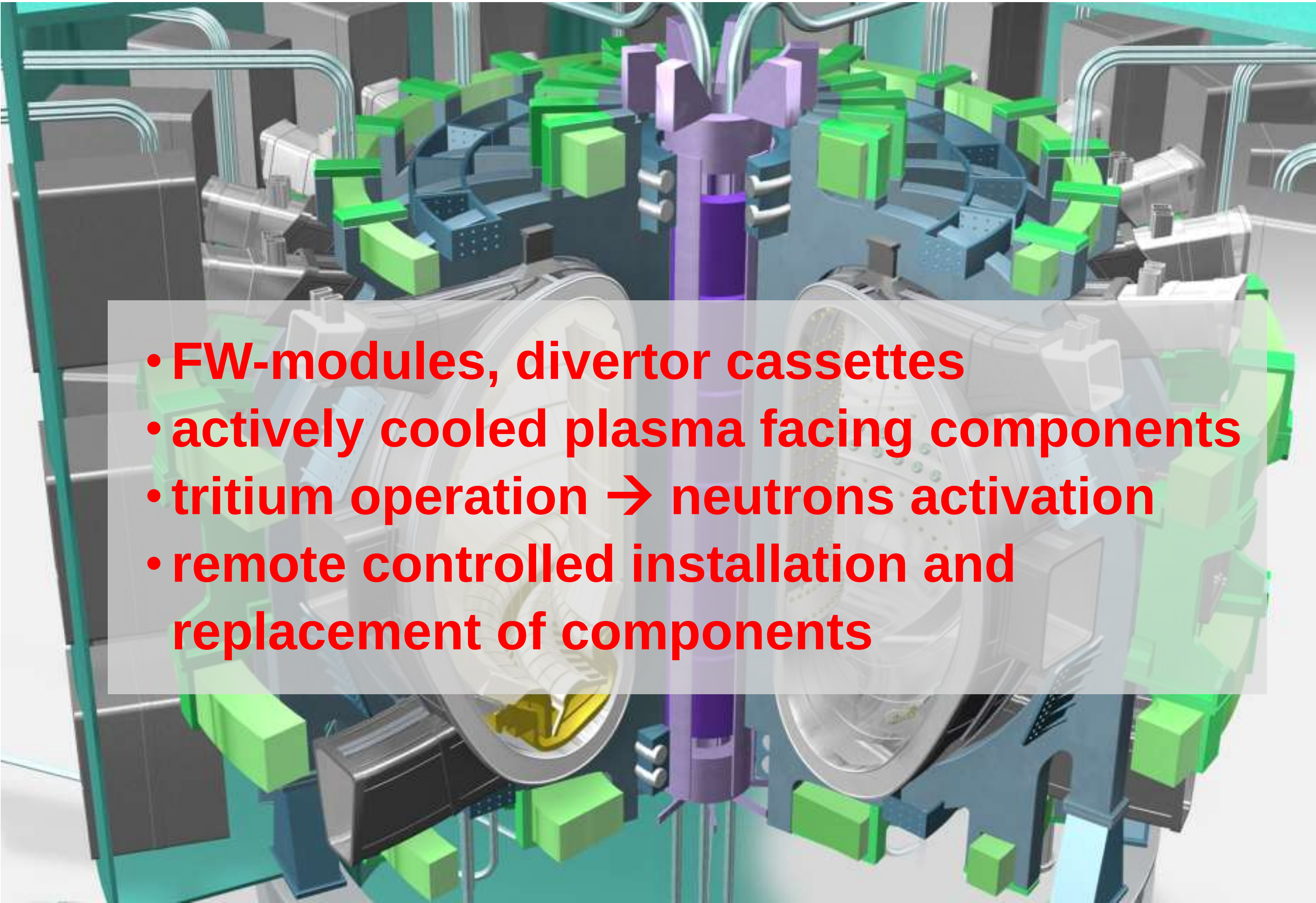
Outline:

- **A** Plasma wall interaction – thermal loads
- **B** High heat flux test facilities
- **C** Cyclic quasi-stationary loads
- **D** Intense transient loads
- **E** Neutron induced material degradation

Plasma facing components in TEXTOR

- FW, limiters or divertor: individual tiles
- no actively cooling of wall components
- no tritium operation → no neutron damage
- no need for remote controlled installation

Plasma facing components in ITER

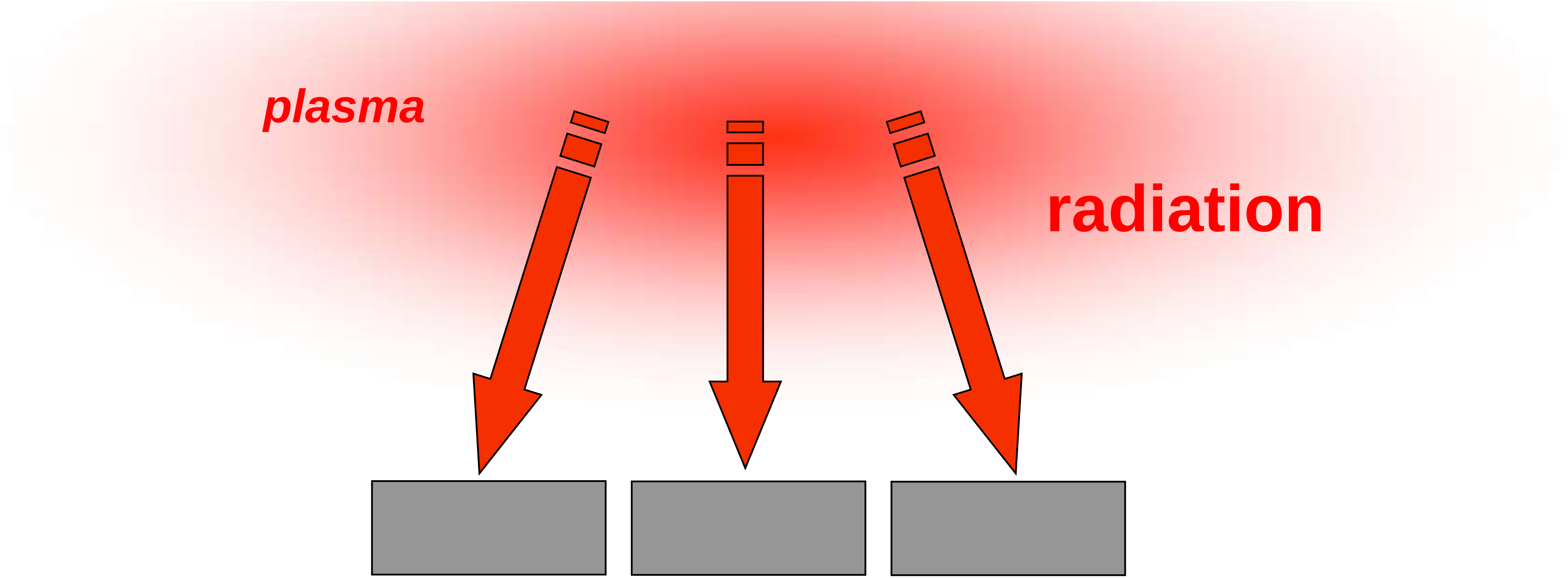


- FW-modules, divertor cassettes
- actively cooled plasma facing components
- tritium operation → neutrons activation
- remote controlled installation and replacement of components

A

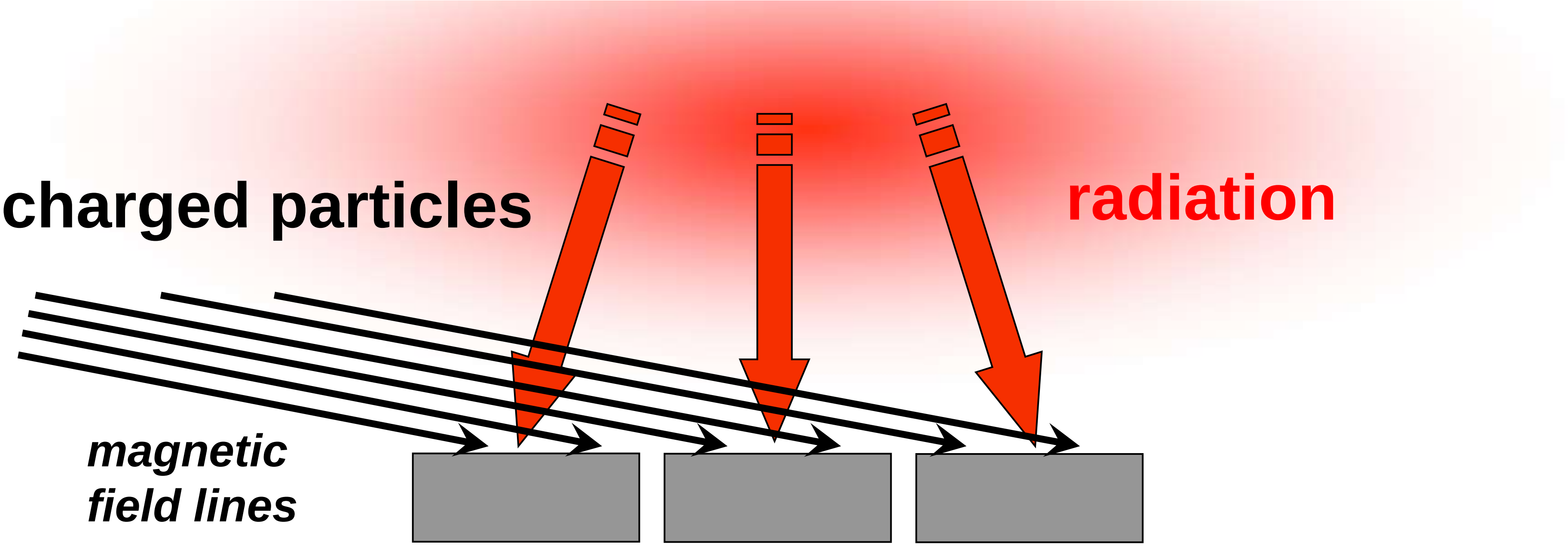
Plasma wall interaction – thermal loads

Plasma facing components
– plasma exposure –



armour tiles – plasma facing material

Plasma facing components
– plasma exposure –



Surface heat flux in ITER:

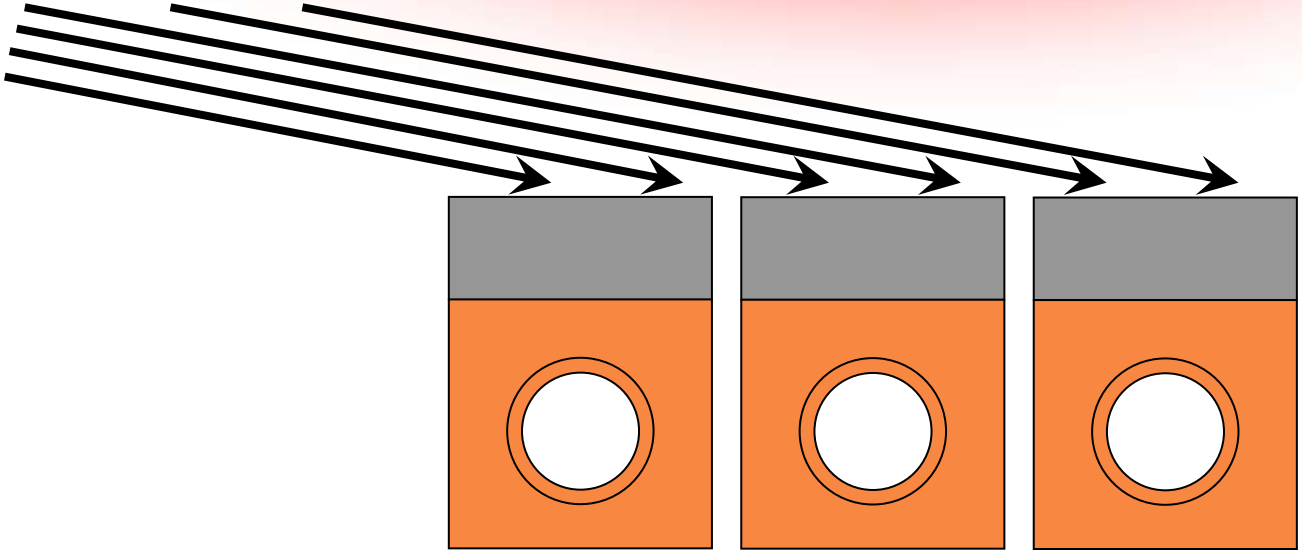
≈ 1 MWm^{-2} (first wall)

≈ 10 MWm^{-2} (divertor)

⇒ **effective water cooled heat sink**

Plasma facing components
– plasma exposure –

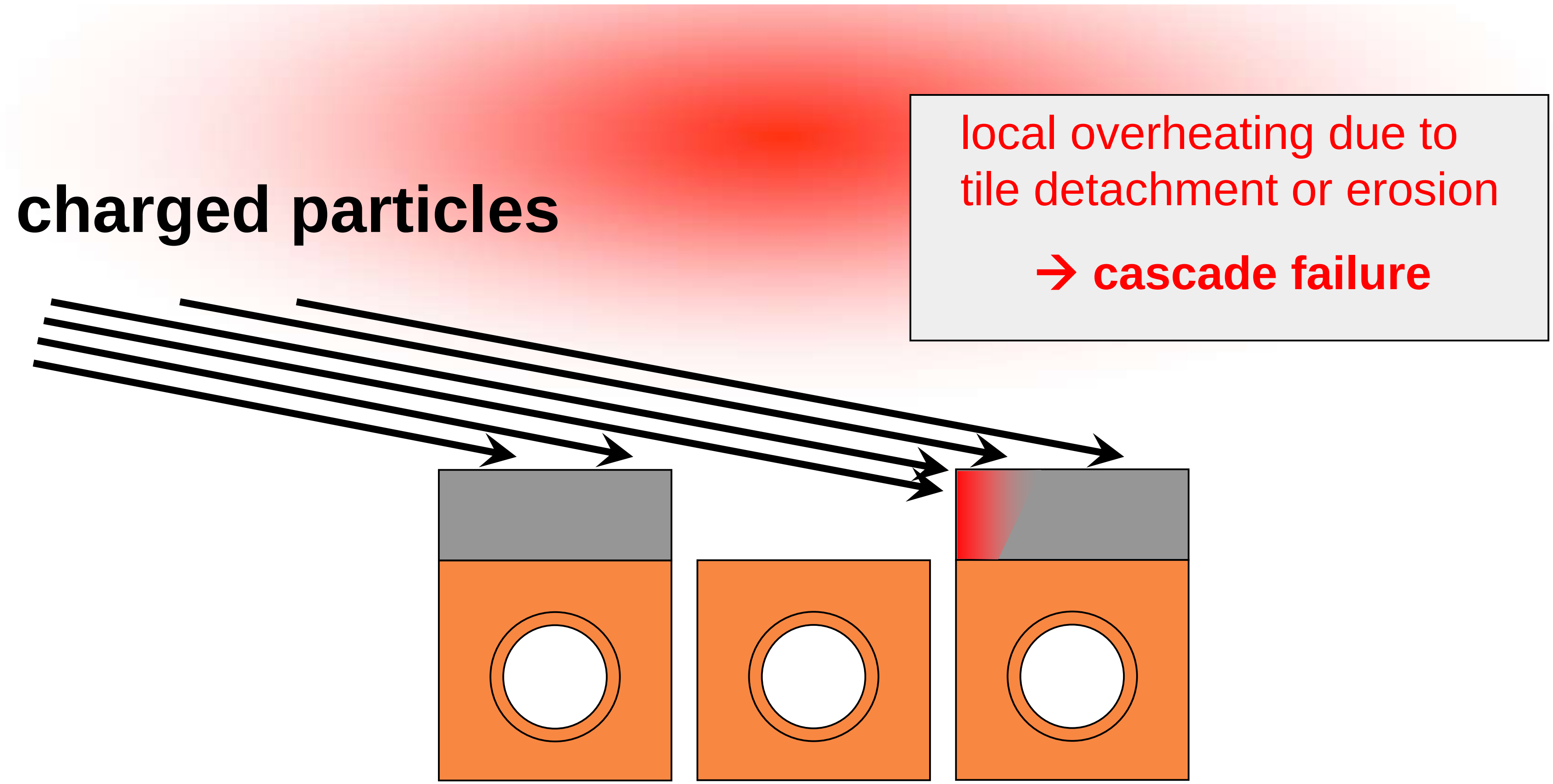
approx. 10^5 joints in the ITER divertor
acceptable failure rate = 0



charged particles

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

Plasma facing components
– plasma exposure –

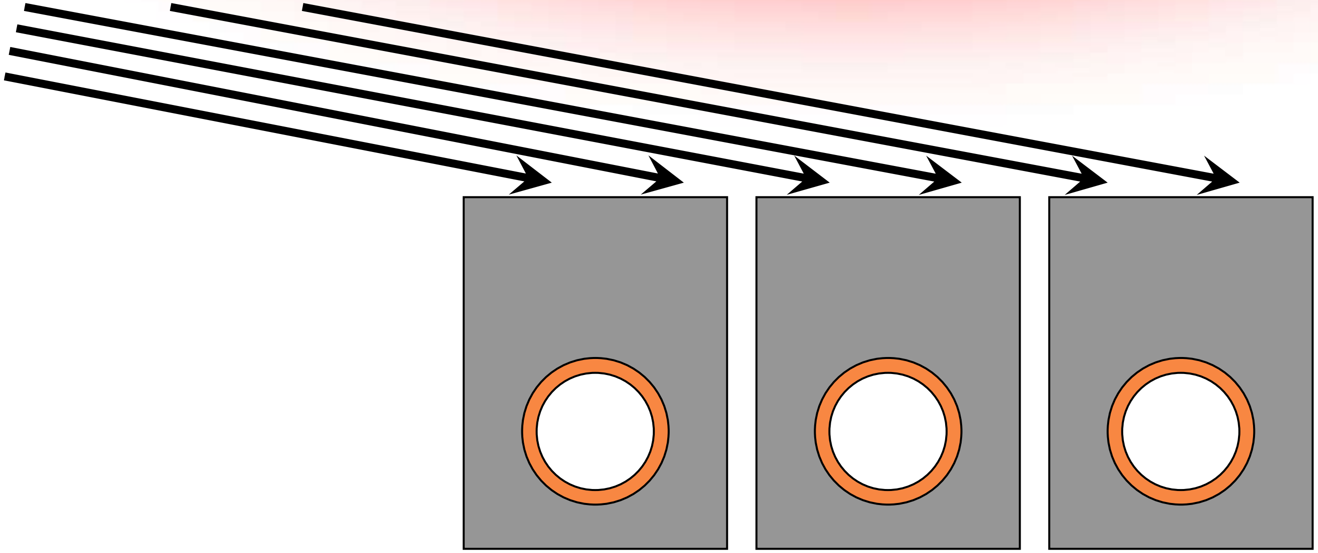


charged particles

local overheating due to tile detachment or erosion

→ **cascade failure**

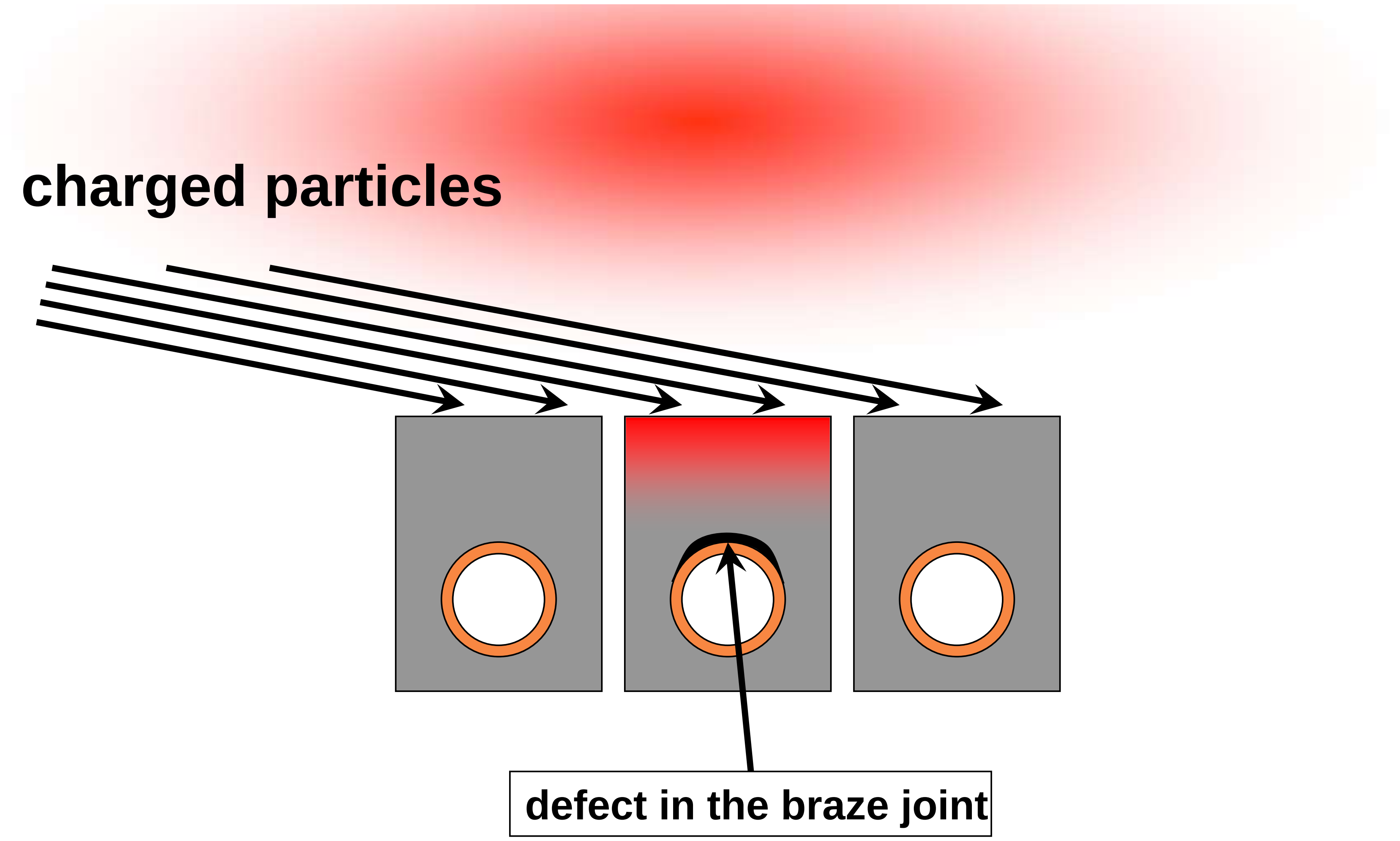
Plasma facing components
– design options –



charged particles

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

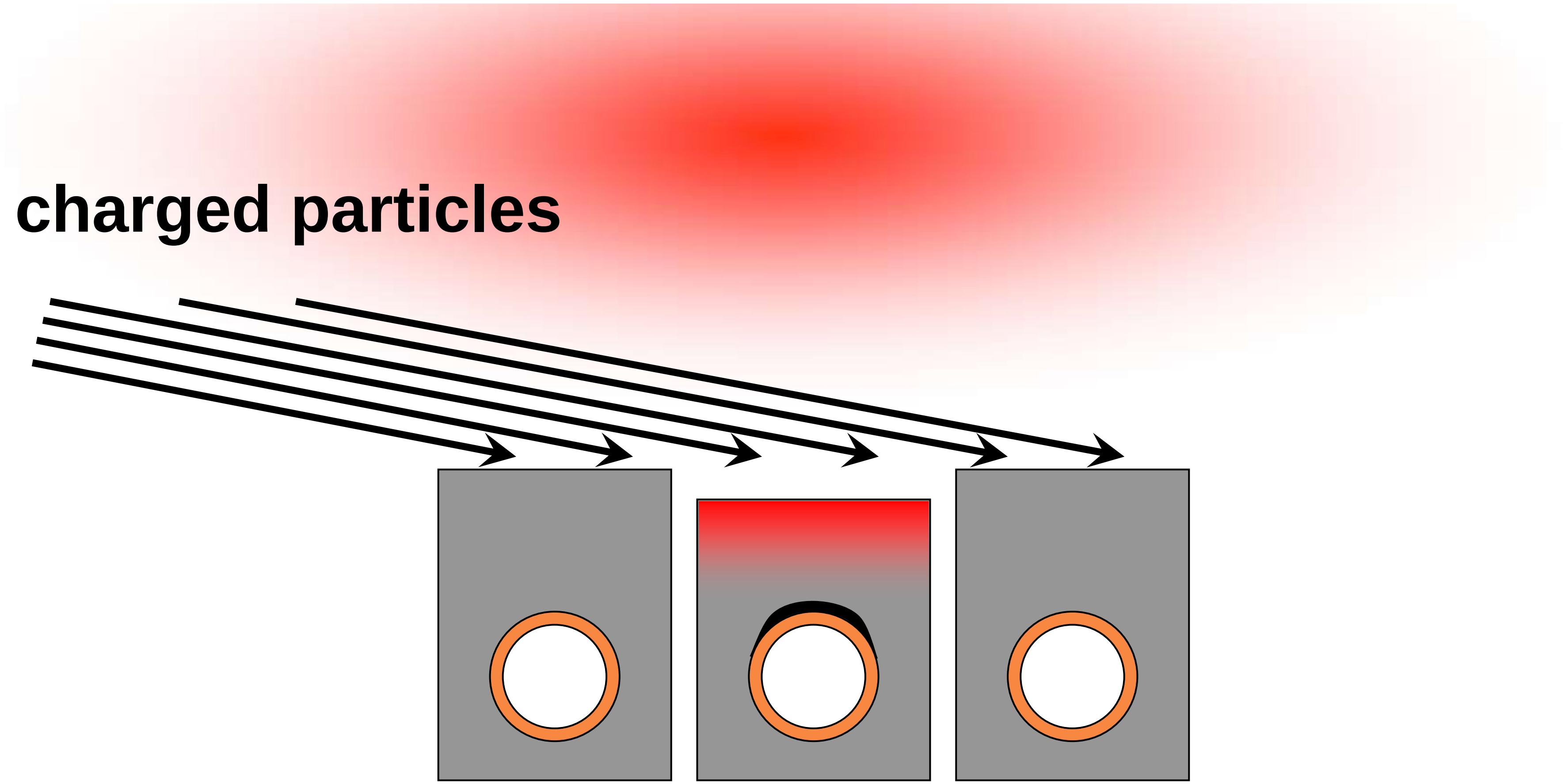
Plasma facing components
– design options –



charged particles

defect in the braze joint

Plasma facing components
– design options –



charged particles

Plasma facing components
– design options –

Plasma facing material:

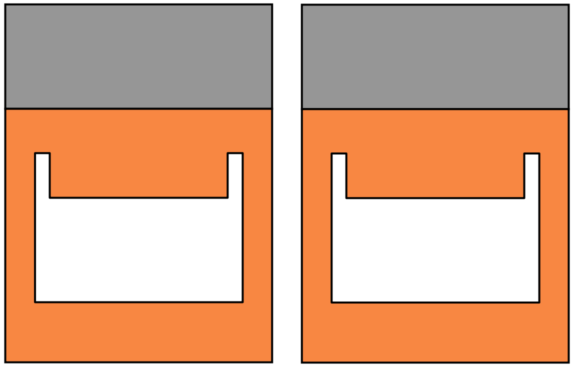
- beryllium (first wall)
- CFC, tungsten (divertor)

Heat sink material:

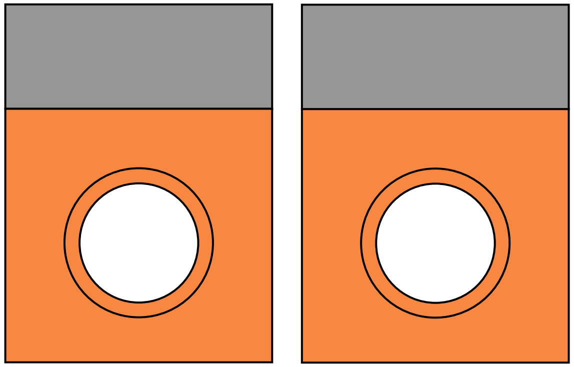
- copper alloys (CuCrZr, DS-Cu)
- stainless steel (first wall)

Joining techniques:

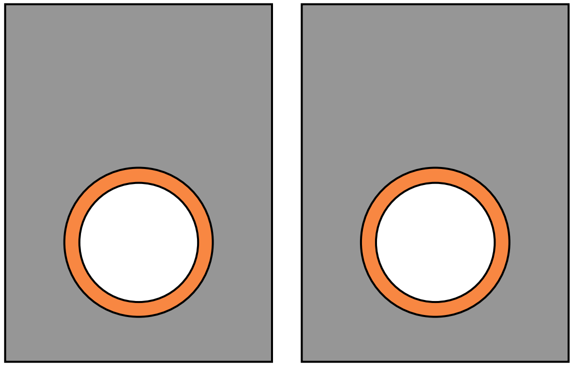
- *brazing*
- *HIPing*
- *e-beam welding*
- *diffusion bonding*



hypervapotron

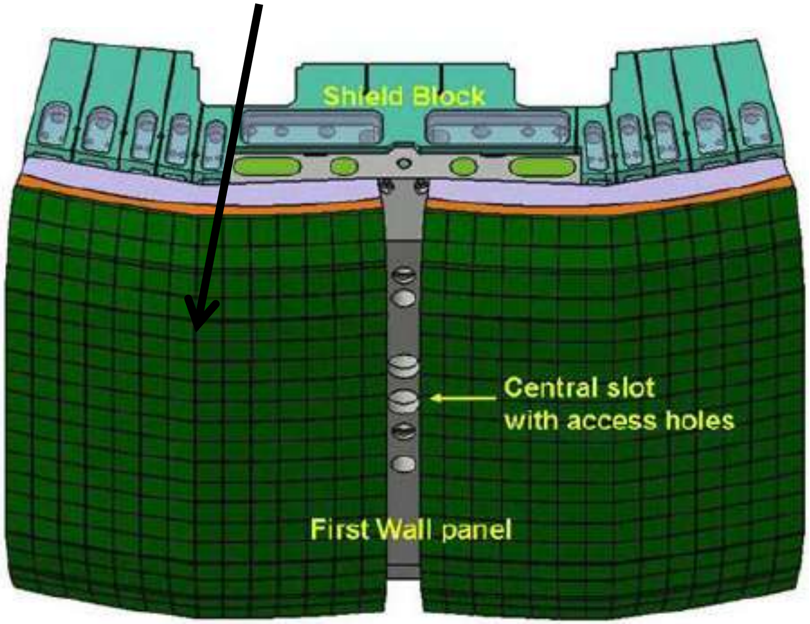


flat tile design



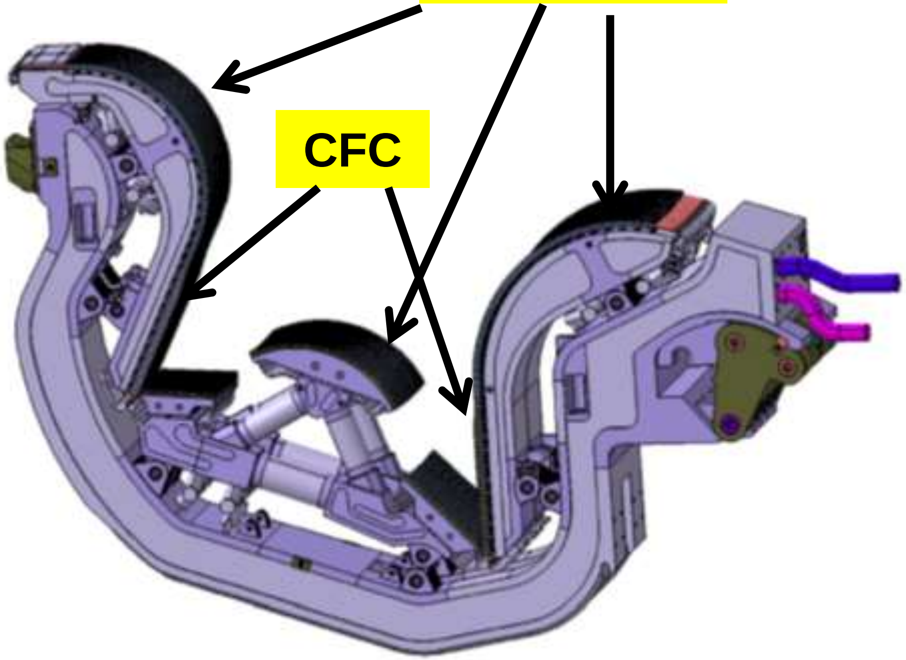
monoblock

Plasma facing components for ITER



beryllium

440 first wall panels (1.5 m)



tungsten

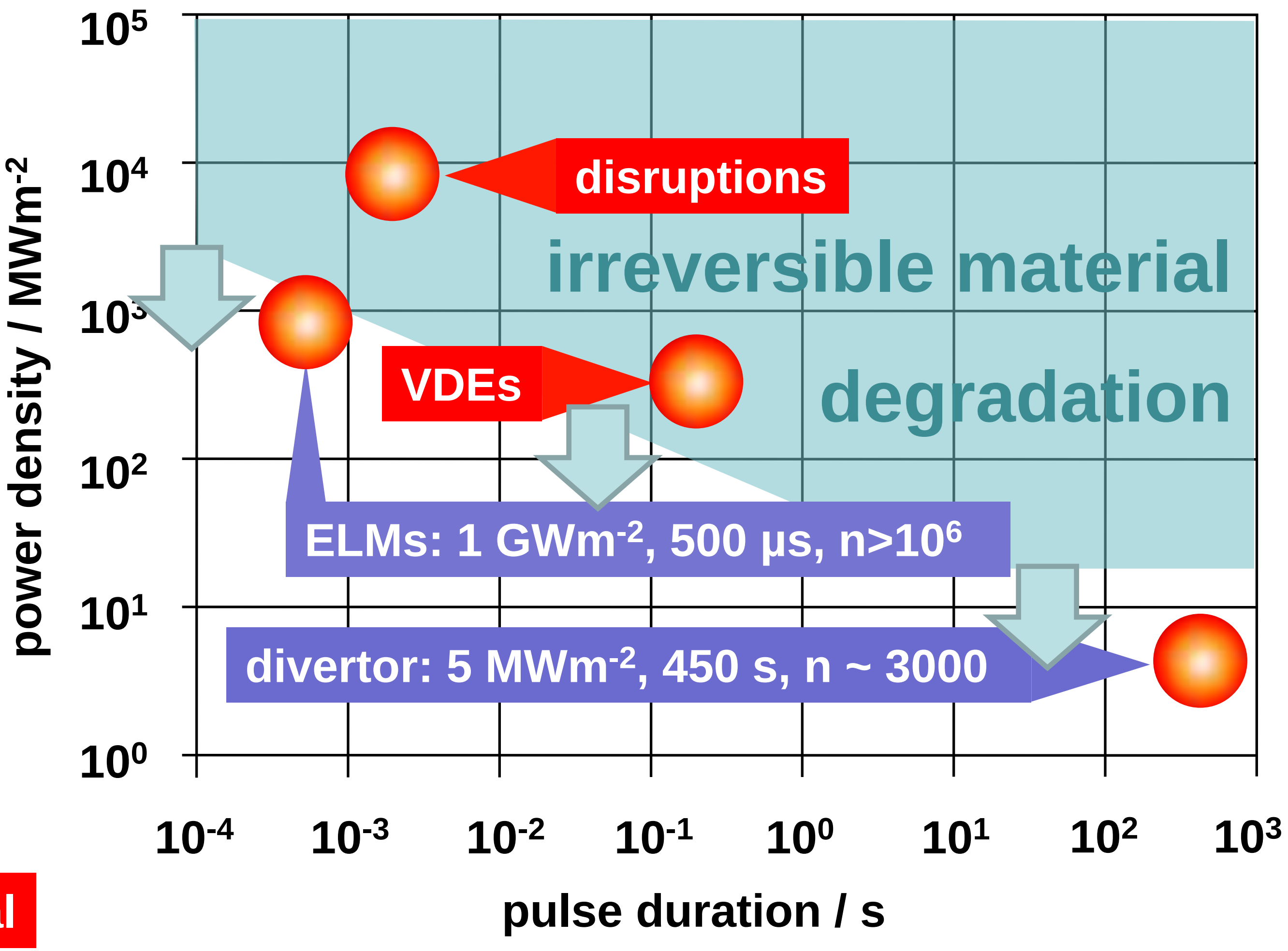
CFC

54 divertor cassettes (3.4 m)

source: M. Merola, ISFNT-9, Dalian, China, 2009 &
http://www.iter.org/doc/www/newsline/Newsline/116/blanket.jpg

Wall loads on plasma facing components in ITER

neutron induced material degredation



🟥 off-normal

🟪 normal

High heat flux components in non-fusion applications

PWR-fuel element

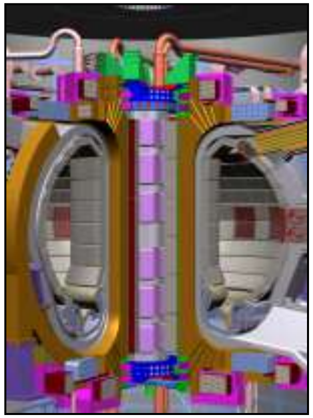
reentry vehicle

Ariane 5 / Vulcain 2

≈ 1 **≤ 20** **85** **2000**

Power density MW/m²

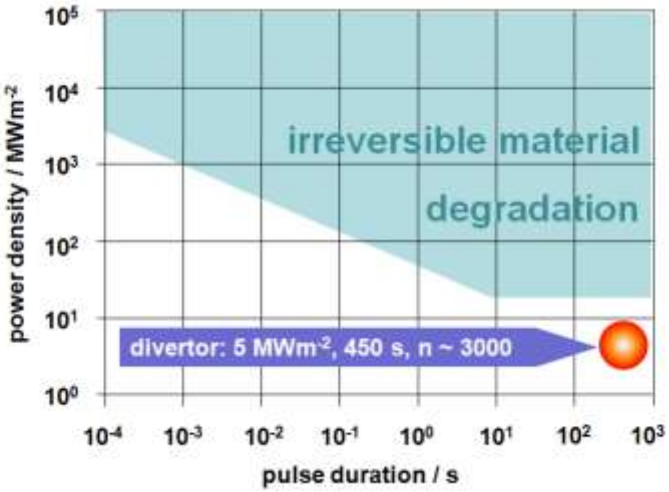
Rolls-Royce Trent 900



ITER Divertor

ELMs in ITER

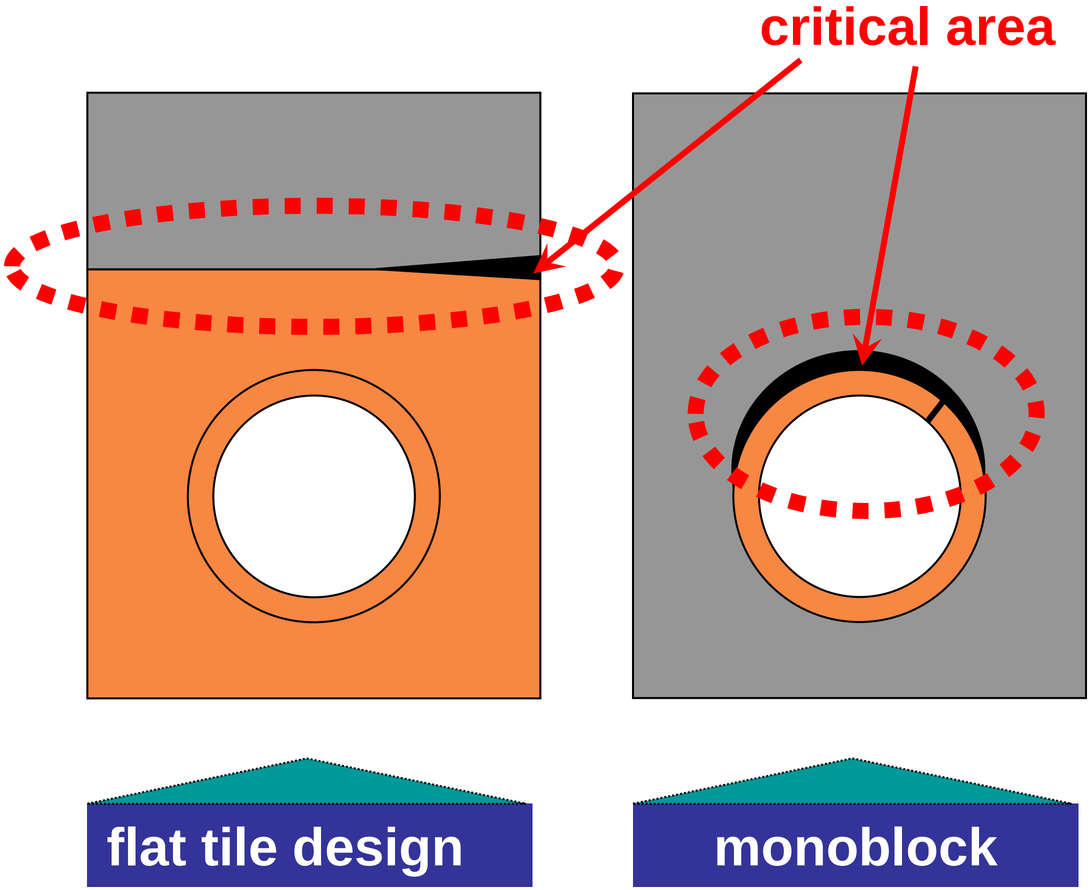
Wall loads on plasma facing components in ITER



Normal operation regime:

5 – 10 MWm^{-2}, Δt = 450 s

→ low cycle thermal fatigue

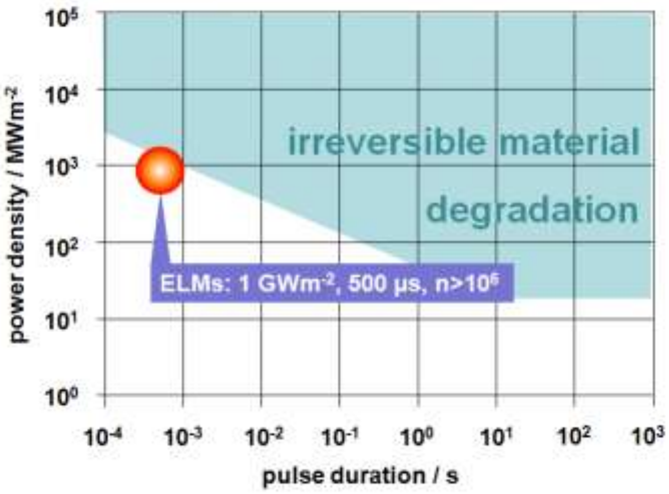


critical area

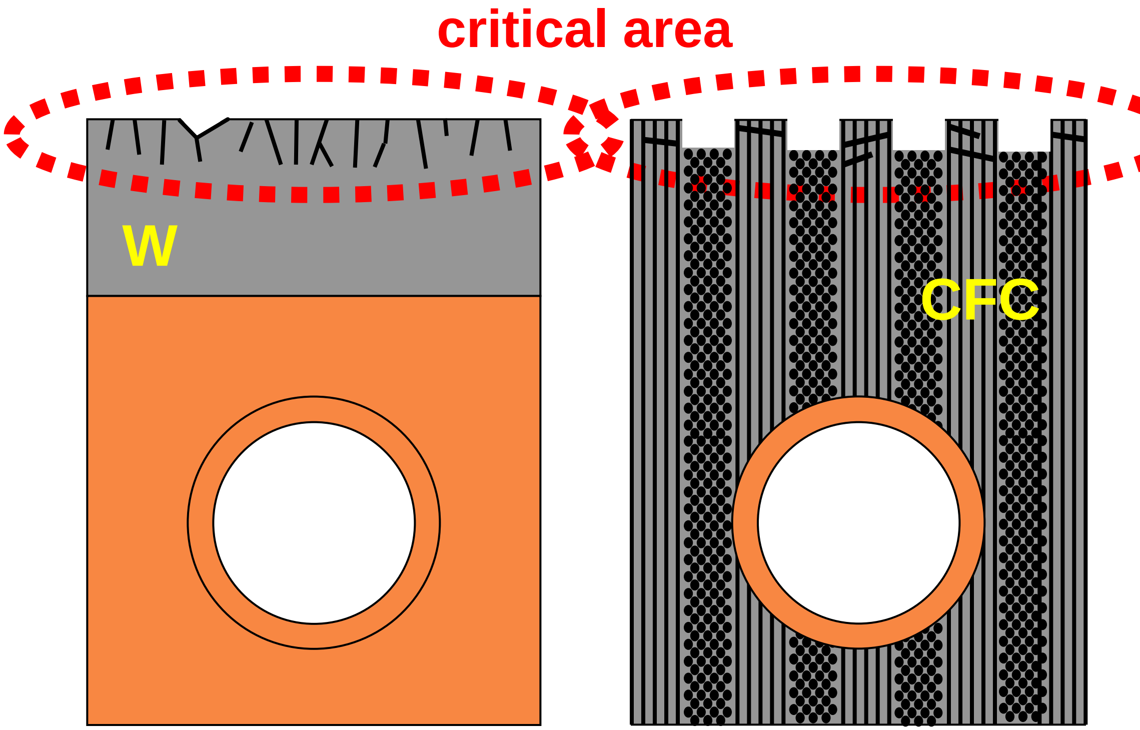
flat tile design

monoblock

Wall loads on plasma facing components in ITER



Thermal load during ELMS:
$\leq$ 1 GWm^{-2}, Δt = 500 µs, 1 Hz
→ high cycle thermal fatigue



flat tile design

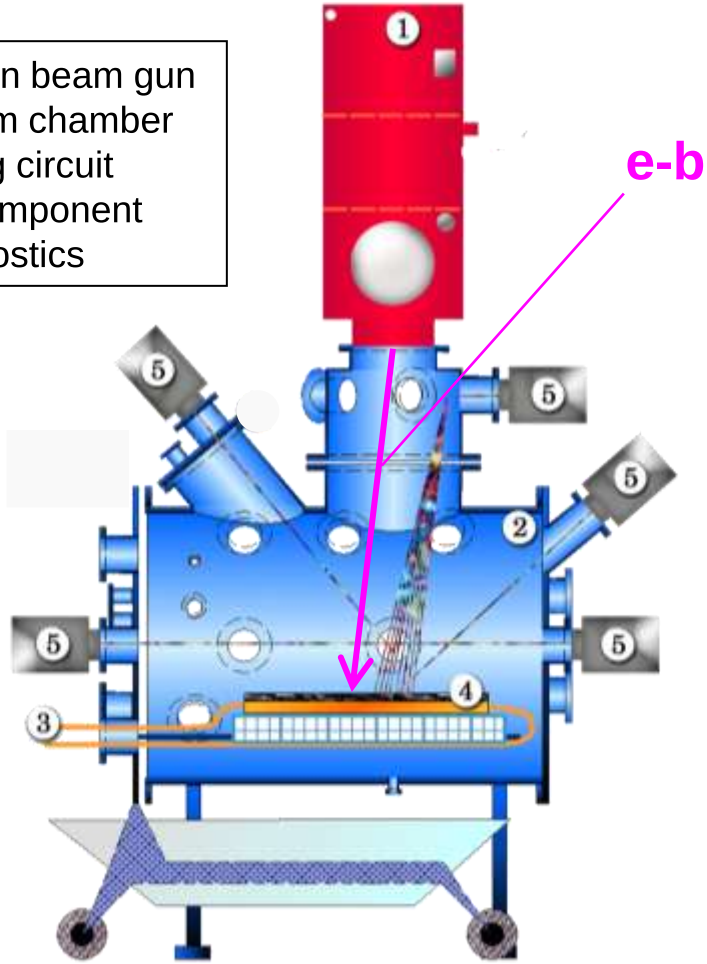
monoblock

B

High Heat Flux test facilities

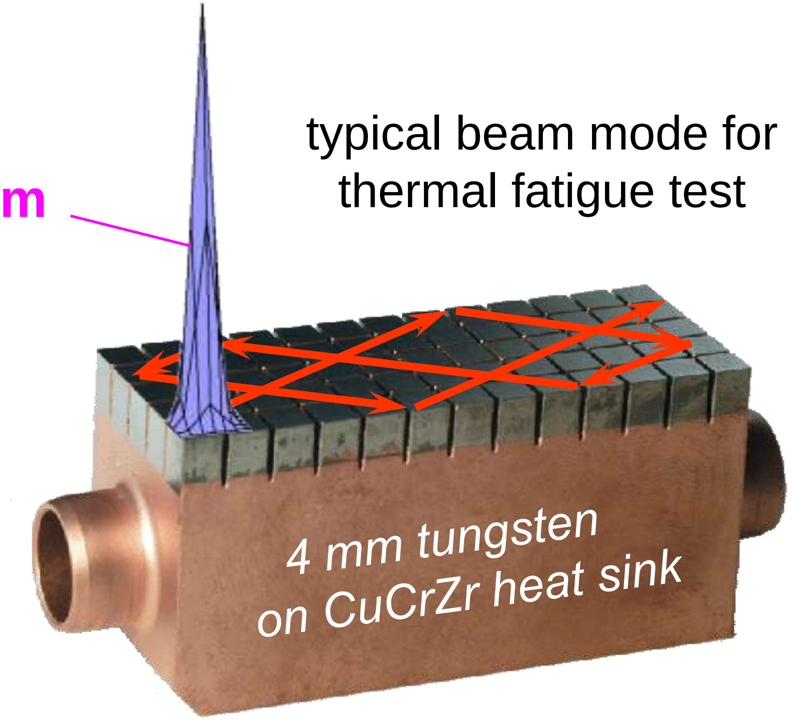
Electron beam simulation of ITER relevant thermal loads

1 electron beam gun
2 vacuum chamber
3 cooling circuit
4 test component
5. diagnostics

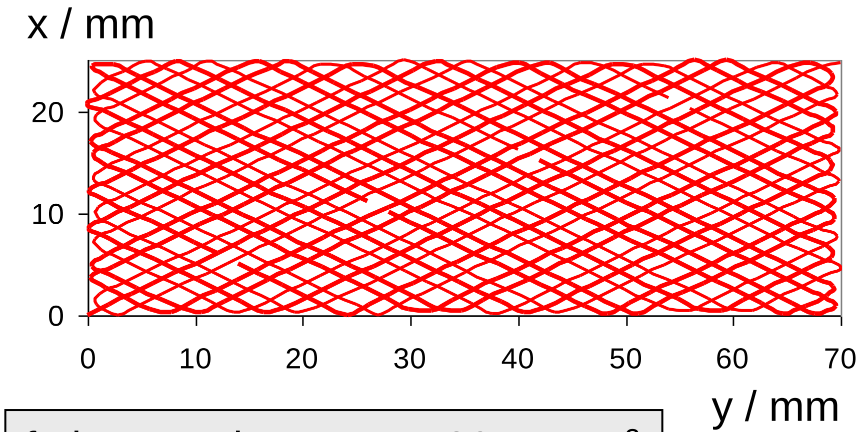


Electron beam test facility JUDITH 2

P = 200 kW (30...60 keV)
P/a $\leq$ 10 GWm^{-2}



typical beam mode for thermal fatigue test



fatigue testing: up to ~20 MWm^{-2}
10 s on / 10 s off

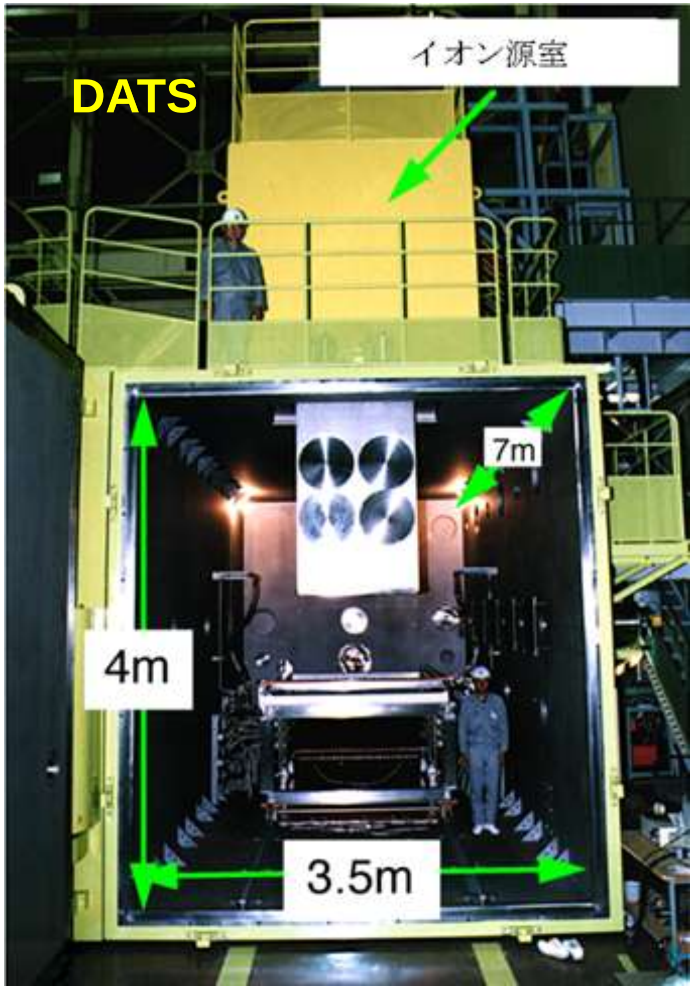
High heat flux test facilities
(simulation of quasi-stationary heat loads – thermal fatigue)

	facility	particle type	particle energy [keV]	beam power [kW]	max. loaded area [m^2]	power density [GWm^{-2}]	remarks	institute *ITER-partner*
A	TSEFEY	e^-	30	60	0.25	0.2	scanned beam, ϕ = 20 mm beryllium compatible	Efremov *RF*
	Tsefey-M Since 2008)	e^-	40	200	1.0	1.0	scanned beam, ϕ = 8÷20 mm beryllium compatible hot water- & hot He cooling loop	Efremov *RF*
	IDTF (ITER Divertor Test Facility)	e^-	60	800	2.25	1.0	scanned beam, ϕ = 15÷50 mm hot (ITER-like) water cooling loop	Efremov *RF*
B	**JUDITH1** **JUDITH2**	**e^-**	**120** **30 - 60**	**60** **200**	**0.01** **0.25**	**10**	**irradiated samples** **beryllium**	**FZJ** ***EU***
C	FE 200	e^-	200	200	1.0	60	scanned beam, ϕ ≈ 2 - 3 mm hot coolant loop	CEA *EU*
D	JEBIS	e^-	100	400	0.18	2	beam sweeping ϕ ≈ 1 - 2 mm	JAEA *JA*
E	EB 1200	e^-	40	1200	0.27	10	scanned beam, ϕ ≈ 2 - 12 mm hot coolant loop	SNLA *US*
F	DATS	H^+, He^+	50	1500	0.1	0.06	2 ion sources à 0.75 MW ϕ ≈ 150 mm	JAEA *JA*
G	GLADIS	H^+	50	2200	0.3	0.05	2 ion sources à 1.1 MW ϕ ≈ 70 mm	IPP *EU*
H	MARION	H^+, He^+	60	5000	0.01	0.12	1 ion source à 5 MW ϕ ≈ 200 mm	FZJ *EU*

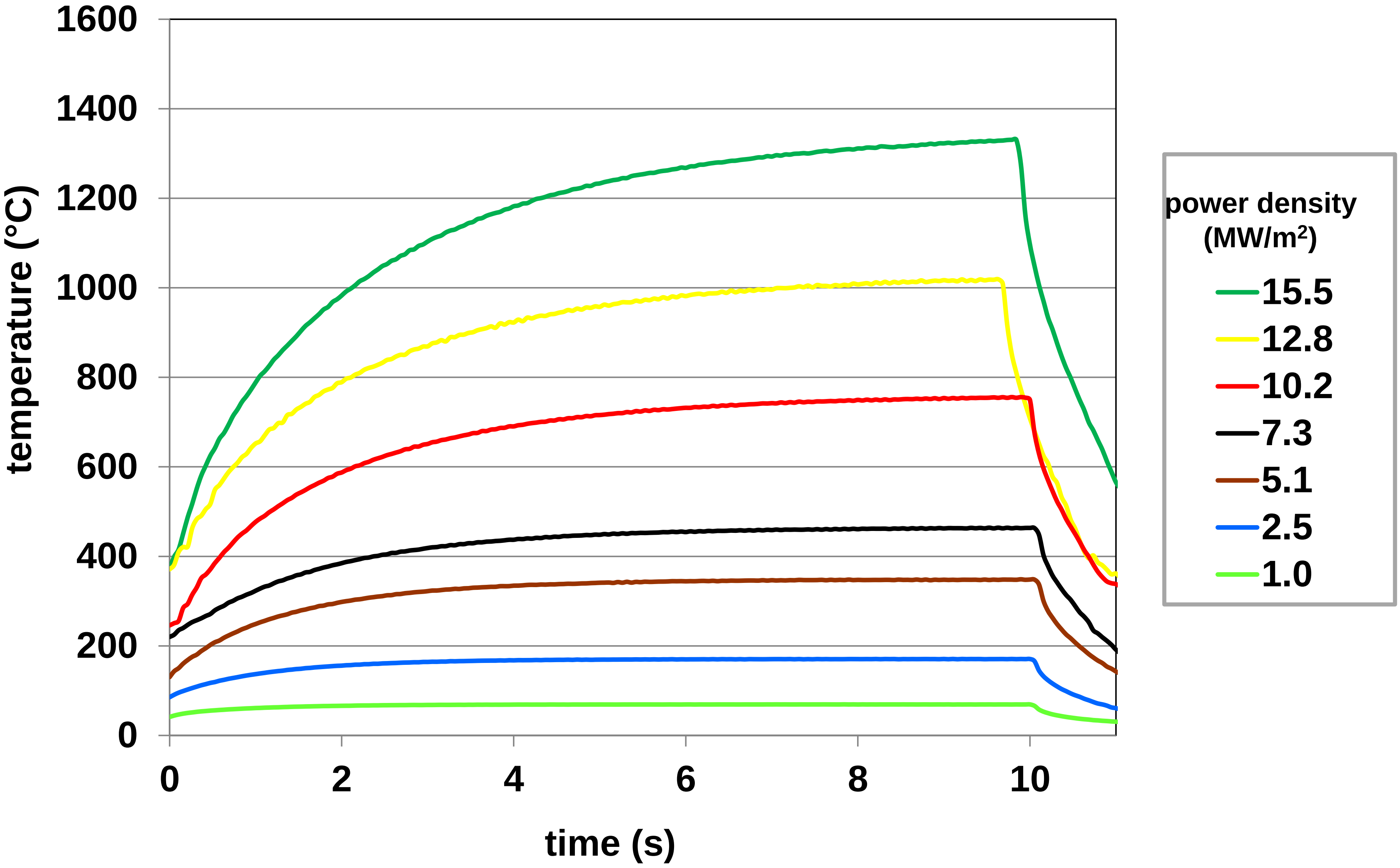
Other HHF test facilities: IR test stands (≤ 1MW/m2), solar furnaces
plasma wind tunnel (reenty vehicles), burner rigs (TBCs)

High heat flux test facilities

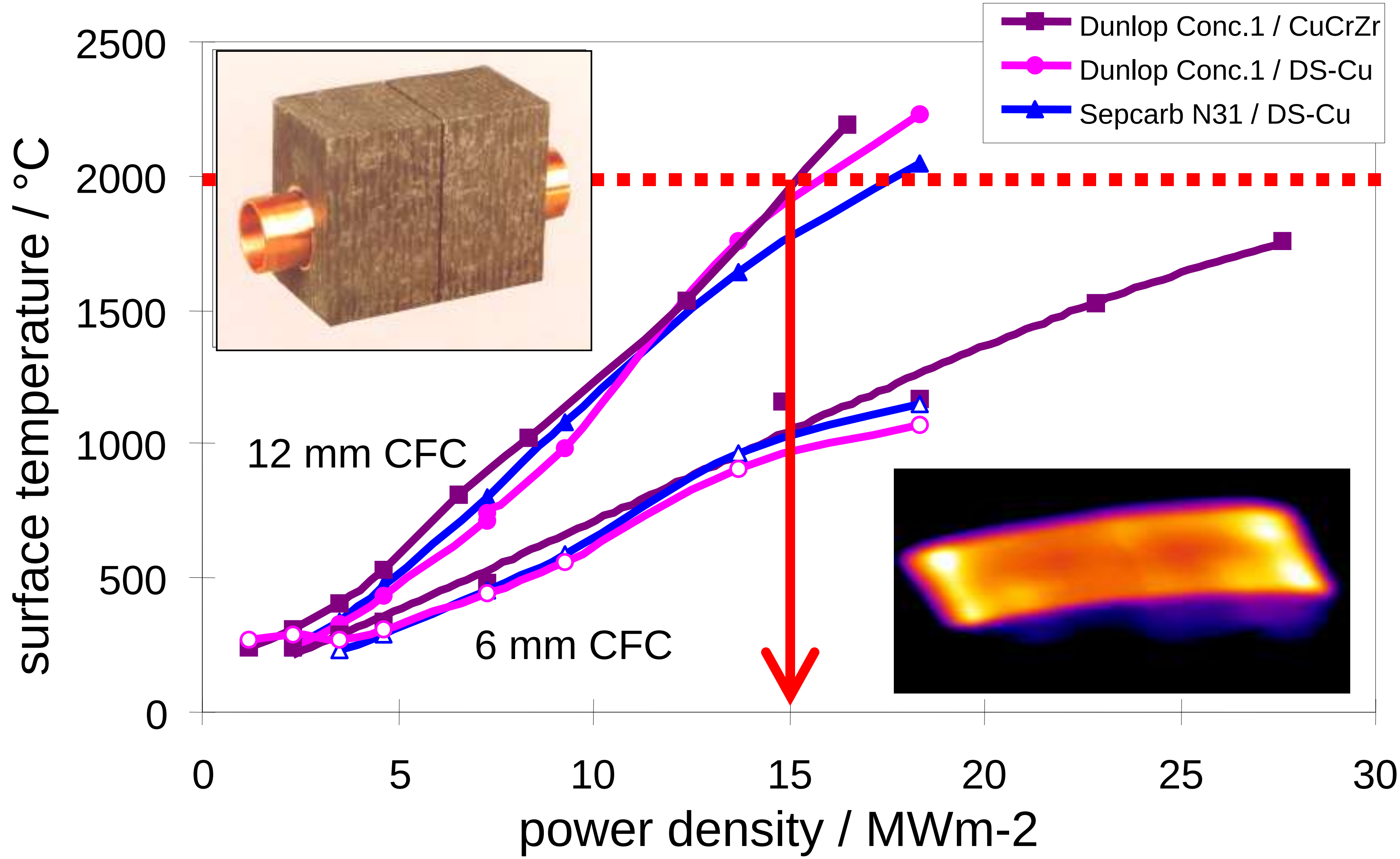
ion beam facilities for the simulation of quasi-stationary heat loads



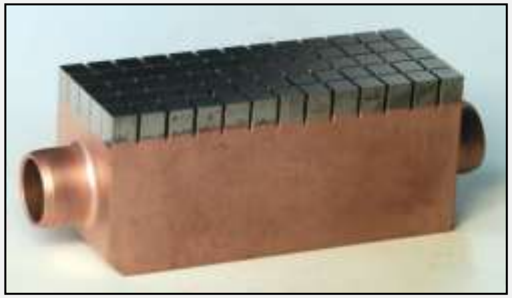
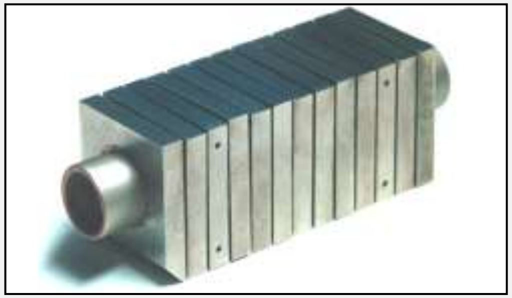
High heat flux experiment
– screening test –



Thermal response of different CFC-modules



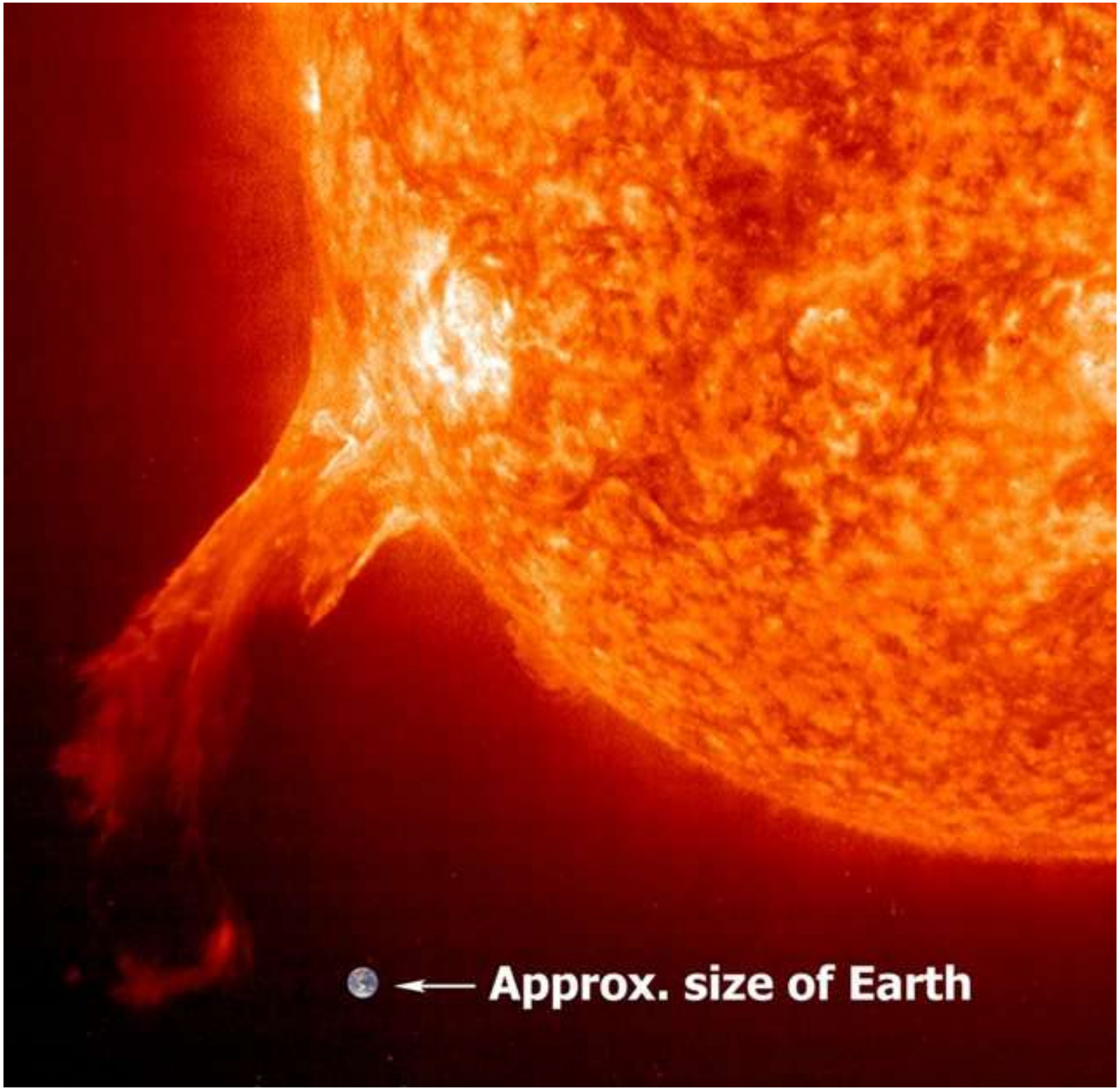
Fatigue testing on PFCs for ITER

	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}**

D

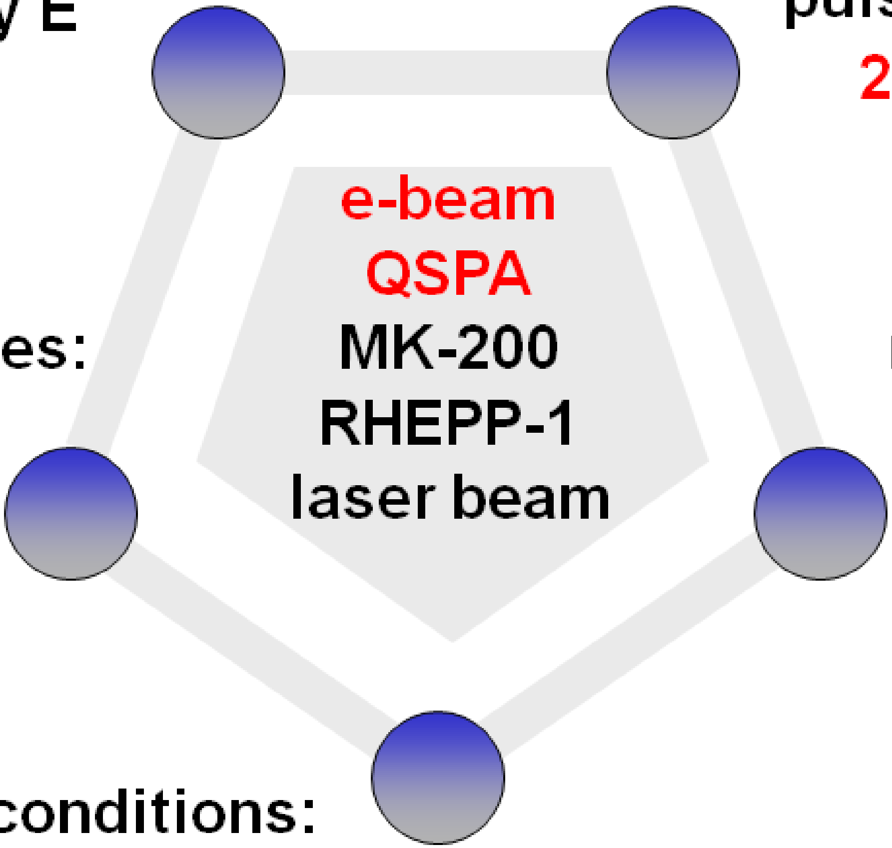
transient thermal loads:
plasma disruptions, VDEs & ELMs

Solar flares, a stellar equivalent to ELMs



Wayne Houlberg, http://www.iter.org/newsline/166/628

ELM simulation
– main influencing parameters –



energy density E
0.5 MJm^{-2}

pulse duration Δt
200 – 500 µs

e-beam
QSPA
MK-200
RHEPP-1
laser beam

incident particles:
electrons
ions
photons

repetition rate:
≥ 1 Hz

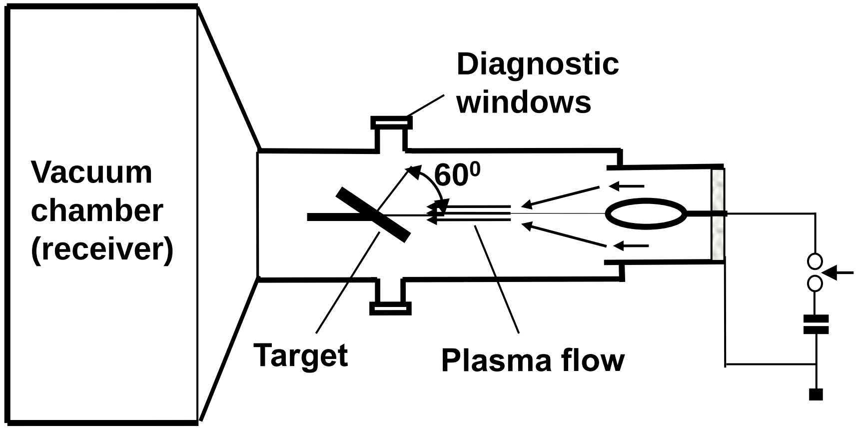
ITER divertor:
≥ 10^6 events

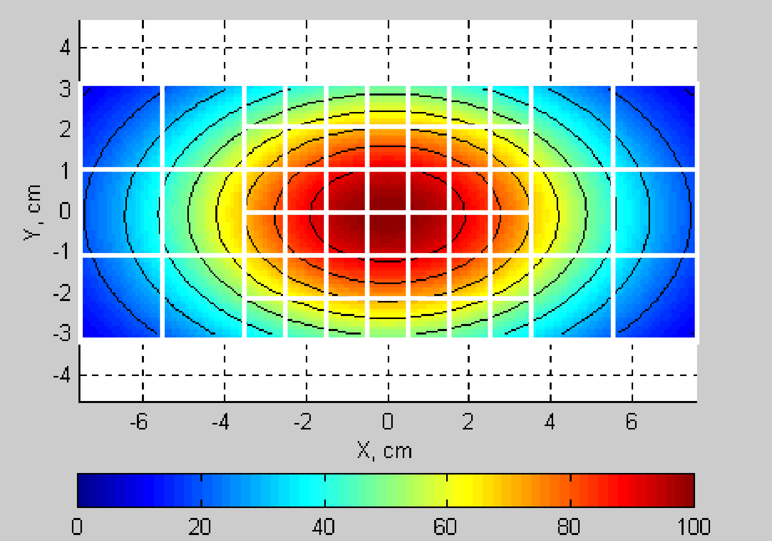
boundary conditions:
- magnetic field
- plasma pressure
- preheated targets
- n-irradiated materials

ITER ELM conditions are shown in red

Simulation of short transient heat pulses

Quasi Stationary Plasma Accelerator (QSPA)





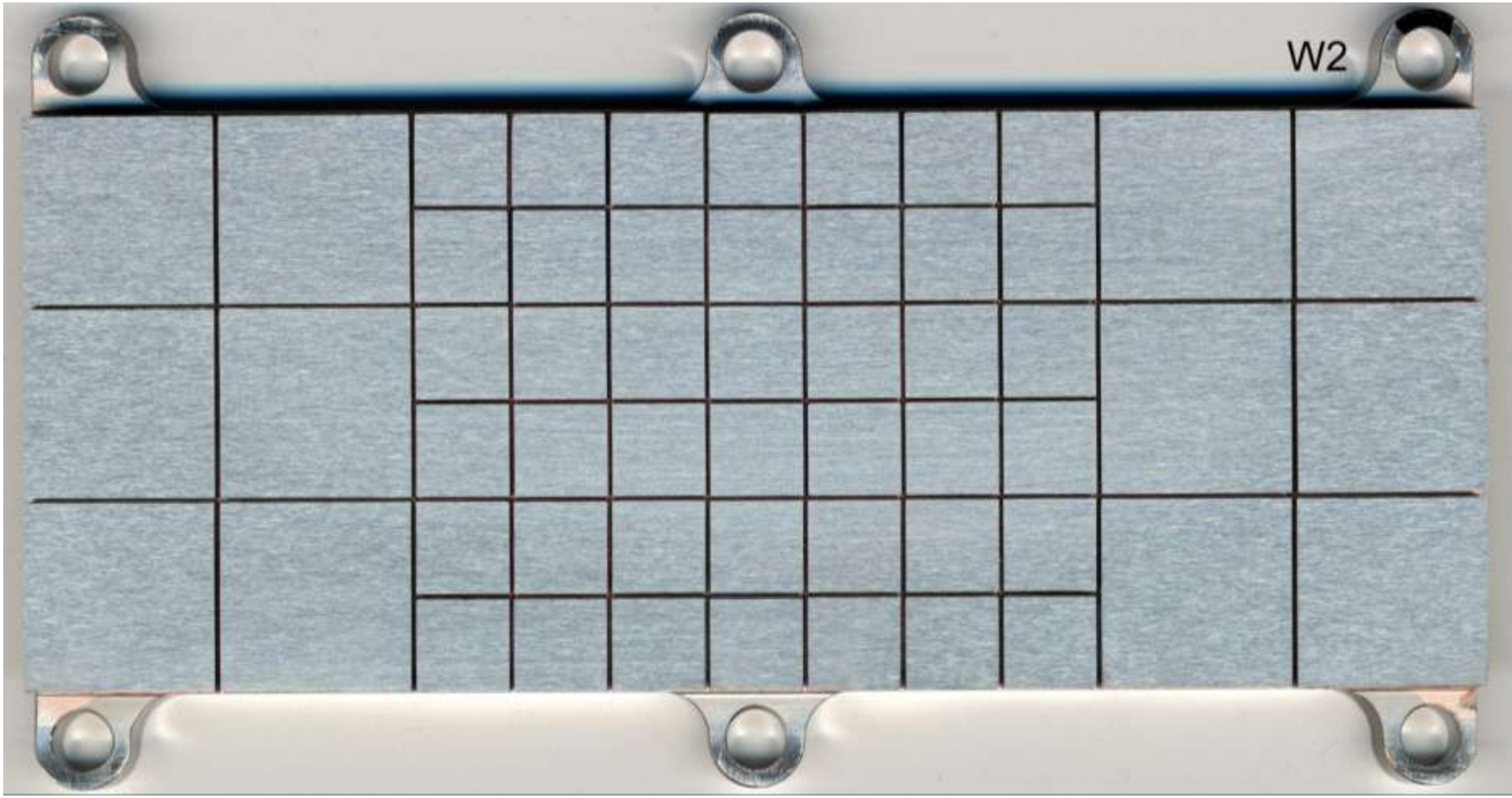
The energy density distribution on W surface,%

QSPA plasma parameters (ELMs):

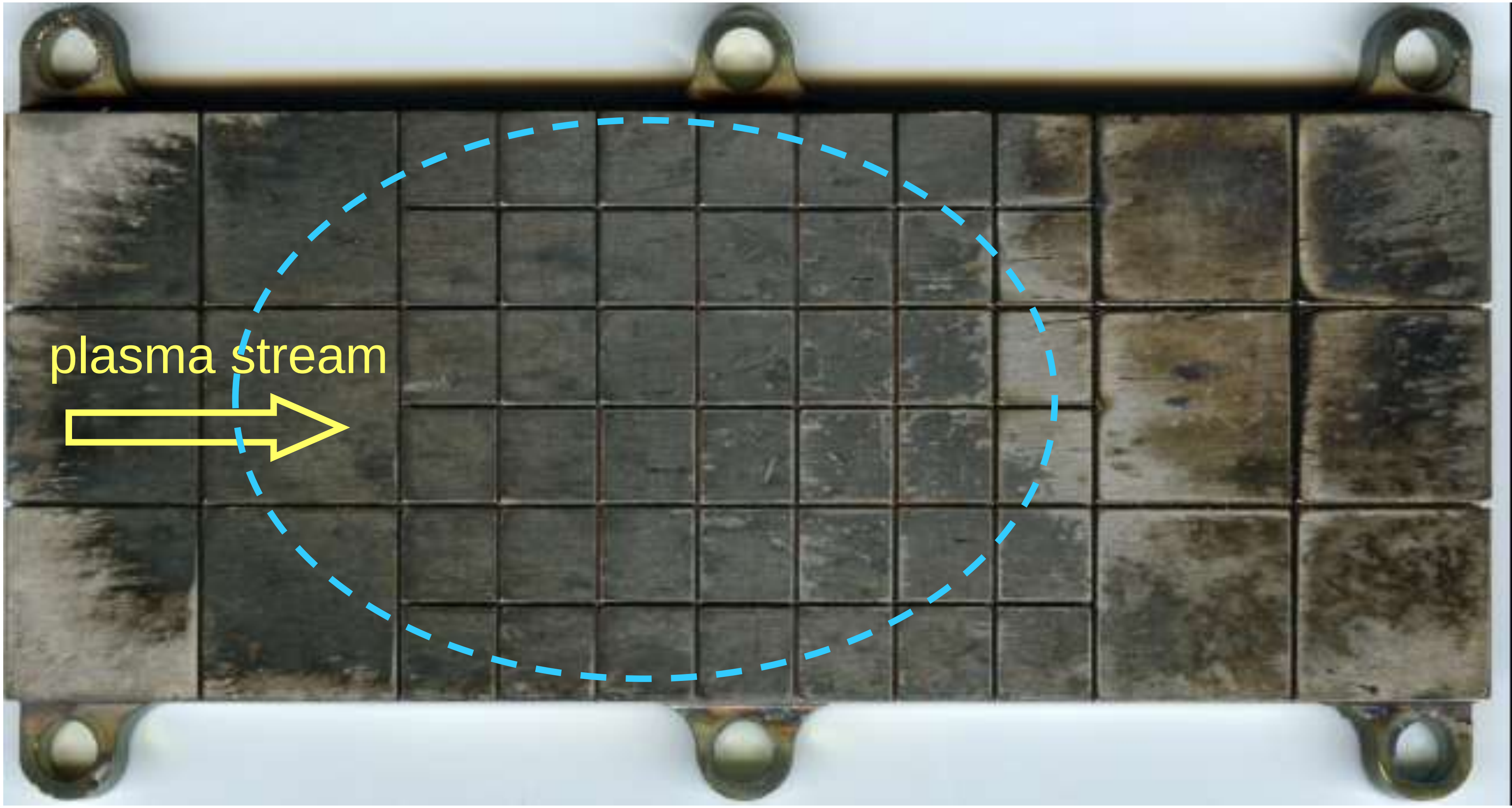
Heat load	0.5 – 2 MJ/m^2
Pulse duration	0.1 – 0.6 ms
Plasma diameter	5 cm
Magnetic field	0 T
Ion impact energy	≤ 0.1 keV
Electron temperature	< 10 eV
Plasma density	≤ 10^{22} m^{-3}

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

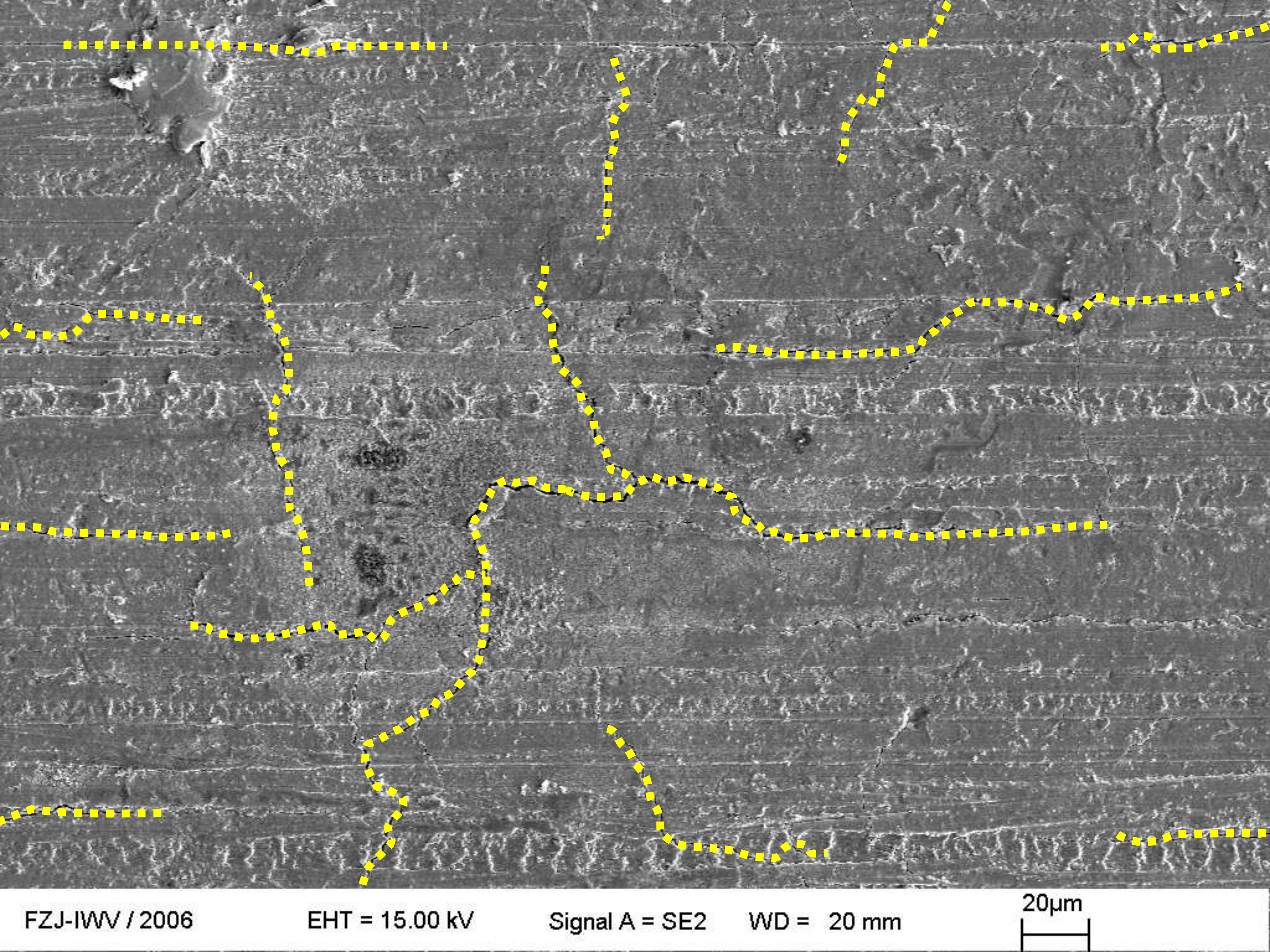
Simulation of ELMs in QSPA



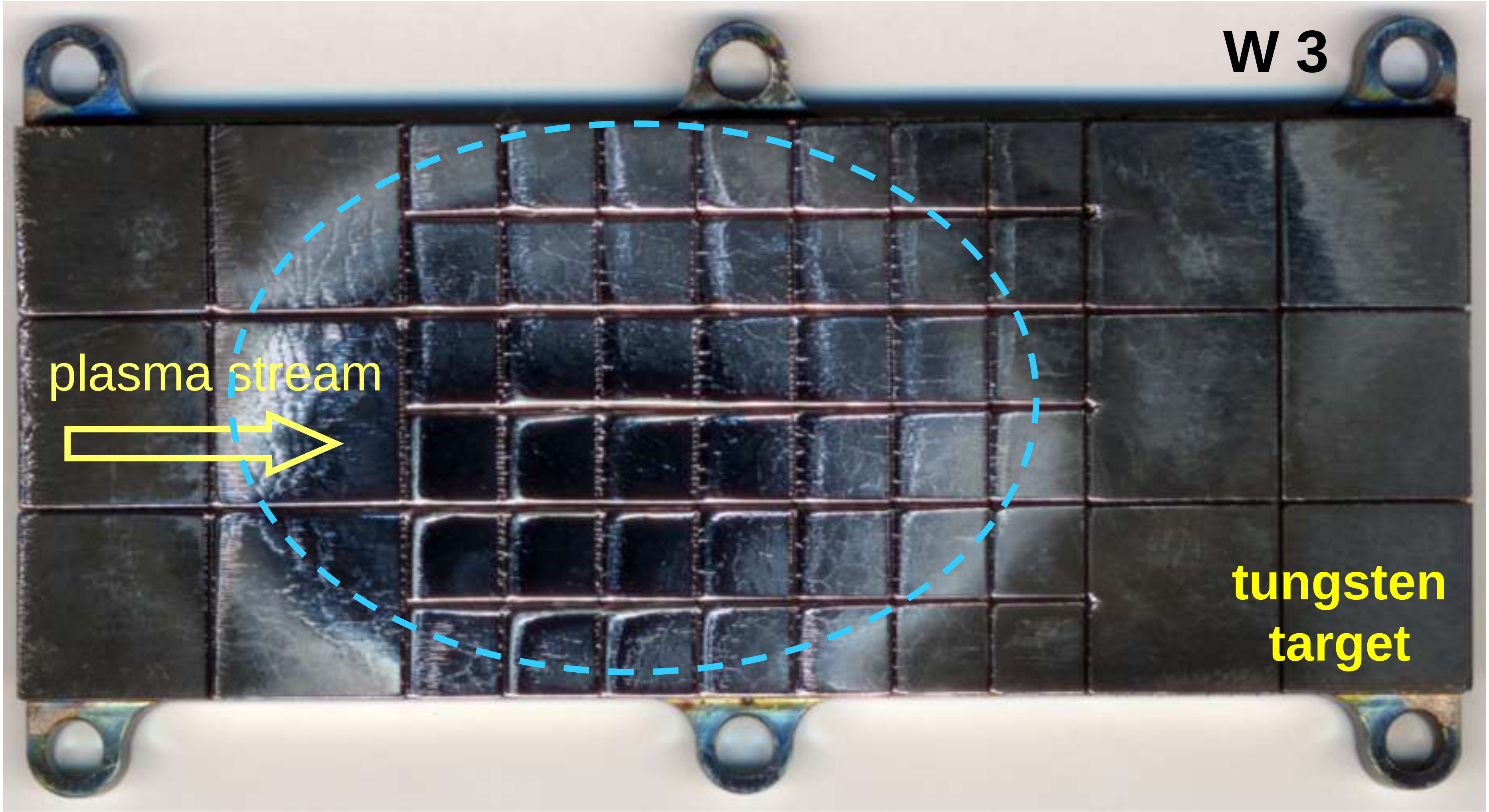
Simulation of ELMs in QSPA



E = 0.5 MJm^{-2} Δt = 500 µs 100 pulses T_0 = 500°C

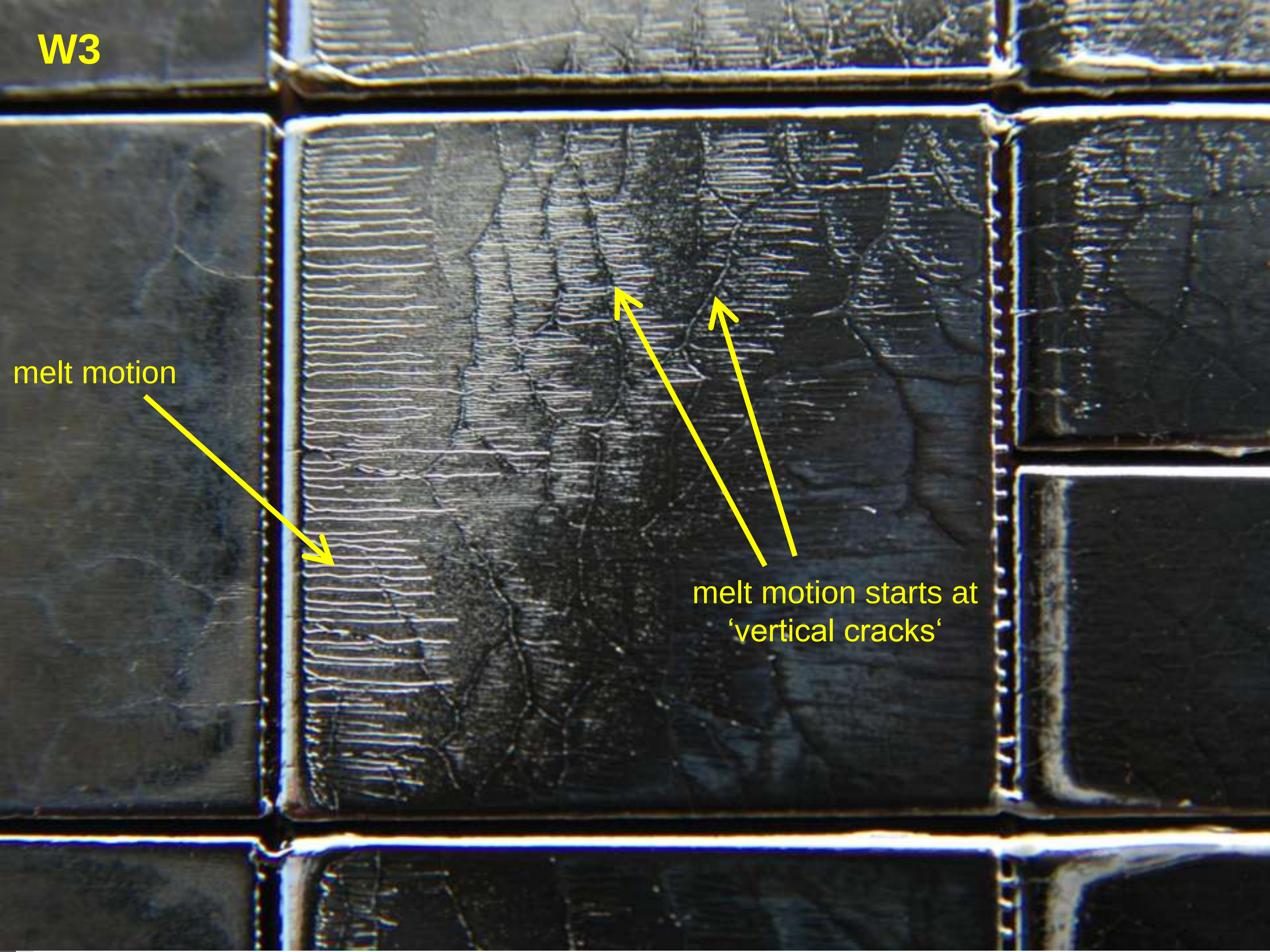

FZJ-IWV / 2006
EHT = 15.00 kV
Signal A = SE2
WD = 20 mm
20µm

Simulation of ELMs in QSPA



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

W3

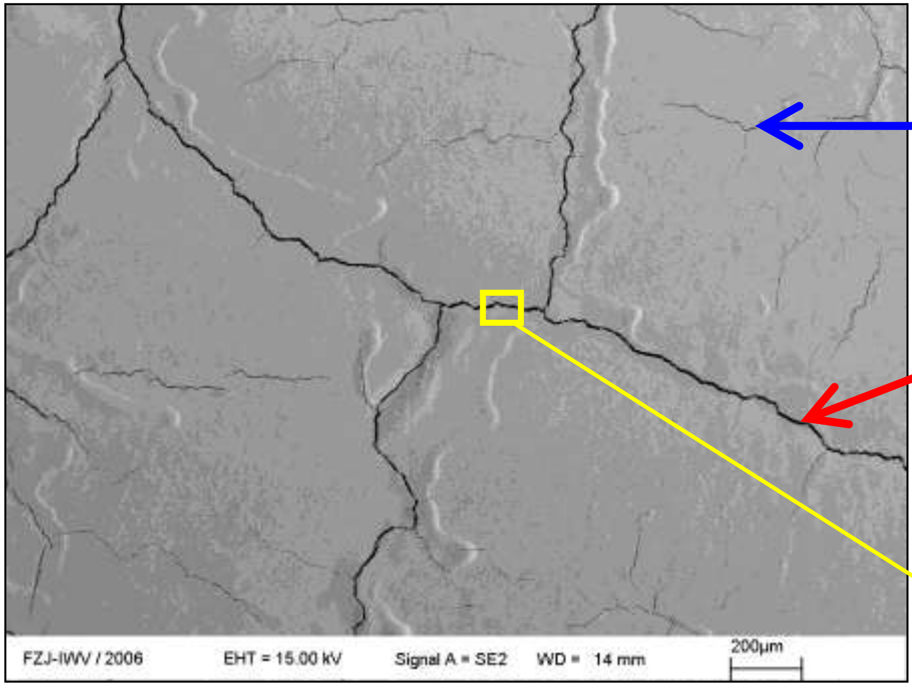


melt motion

melt motion starts at
‘vertical cracks‘

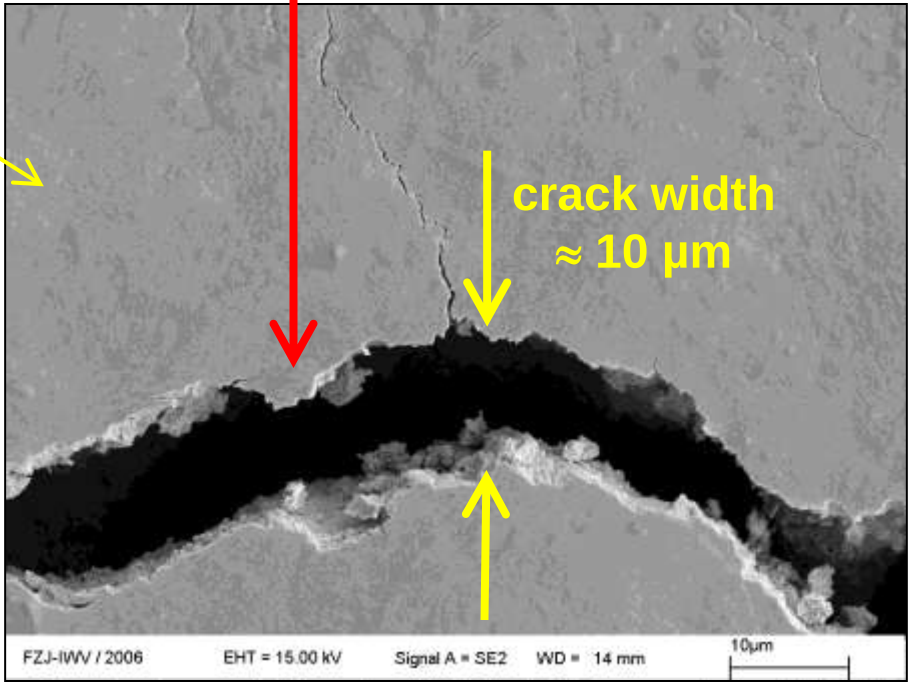
Crack formation on tungsten in QSPA

(energy density E = 0.9 MJ/m^2 @ 500 µs)



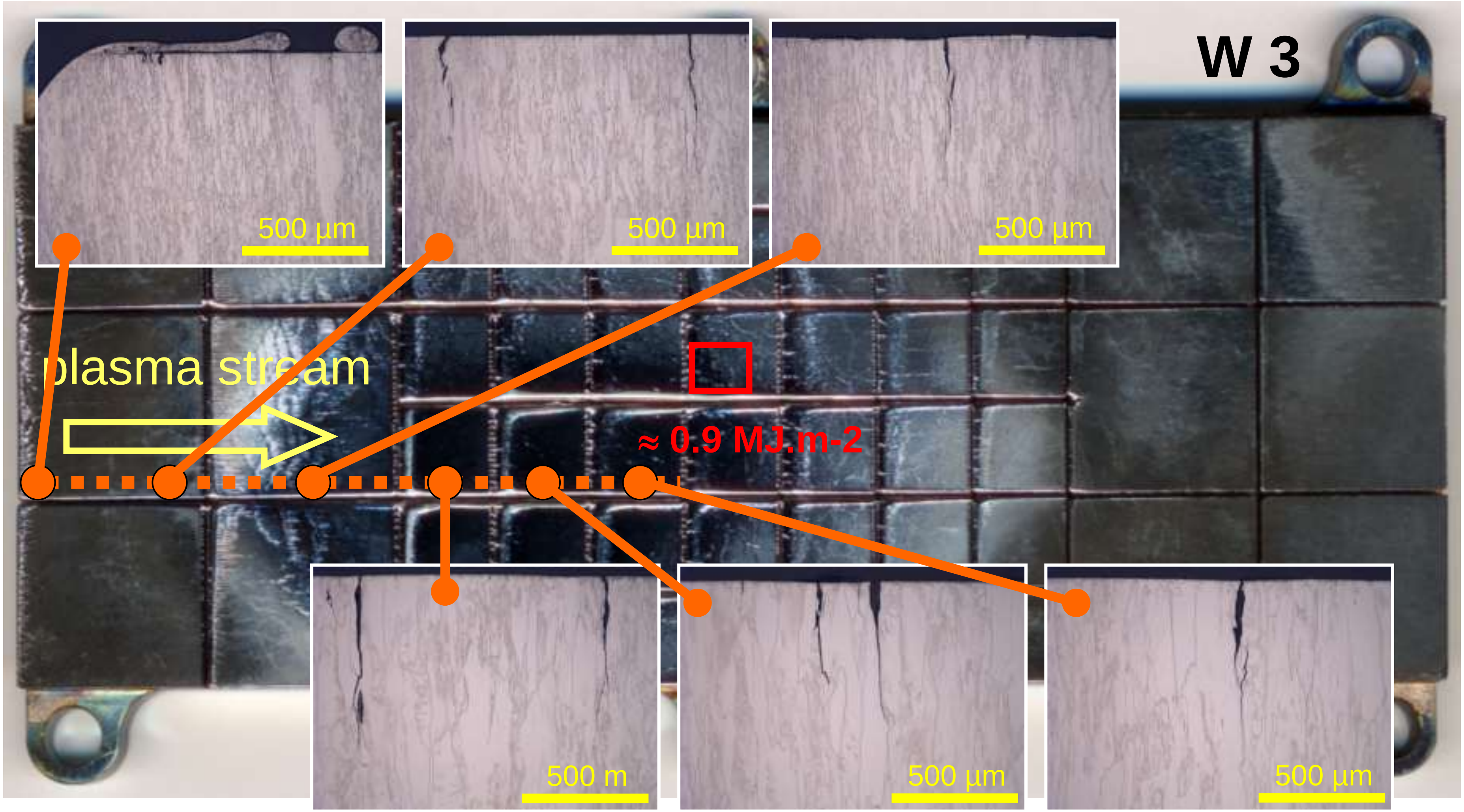
secondary cracks

primary cracks

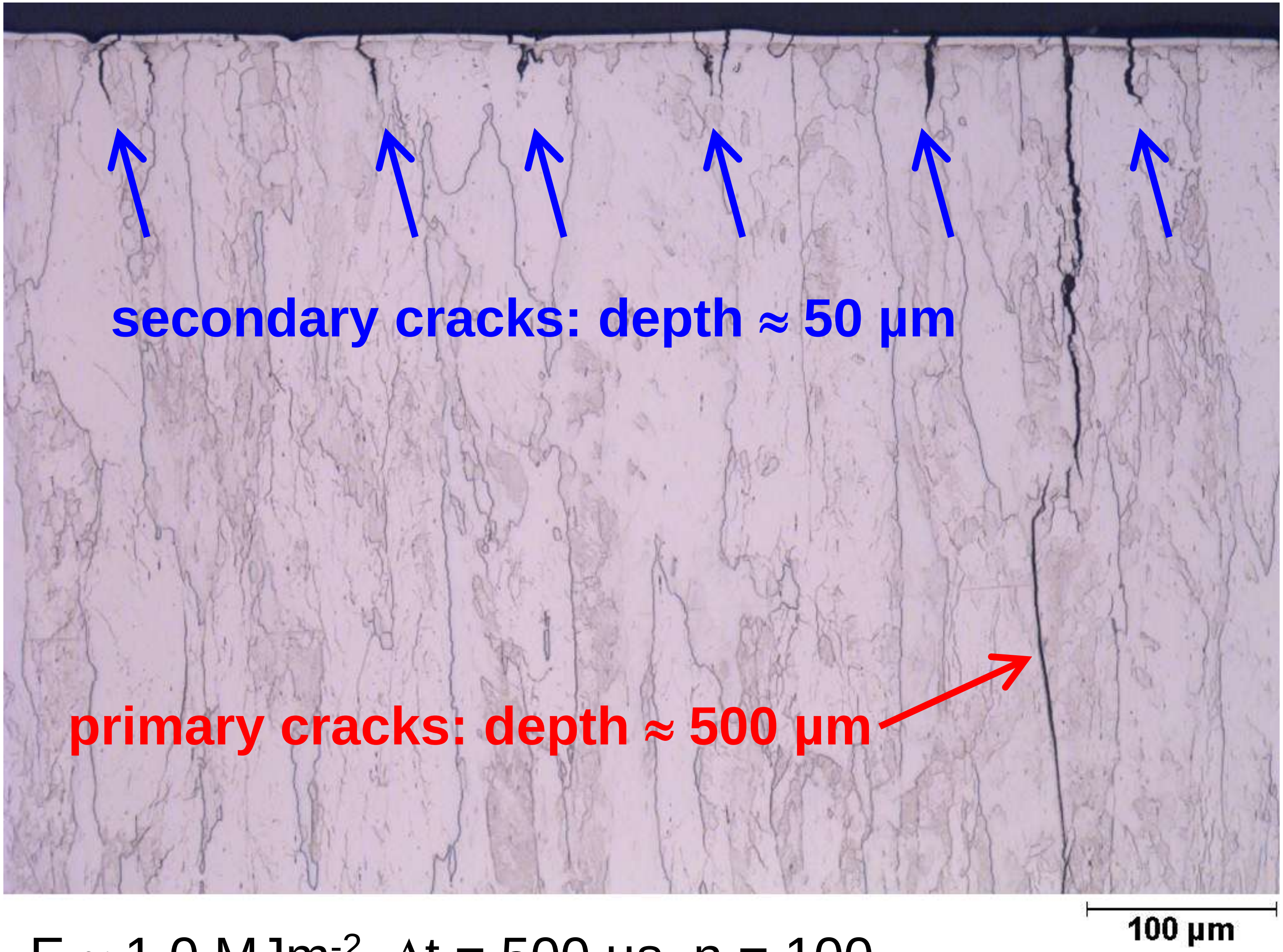


plasma stream

Crack formation on tungsten in QSPA



Crack formation at the melting threshold



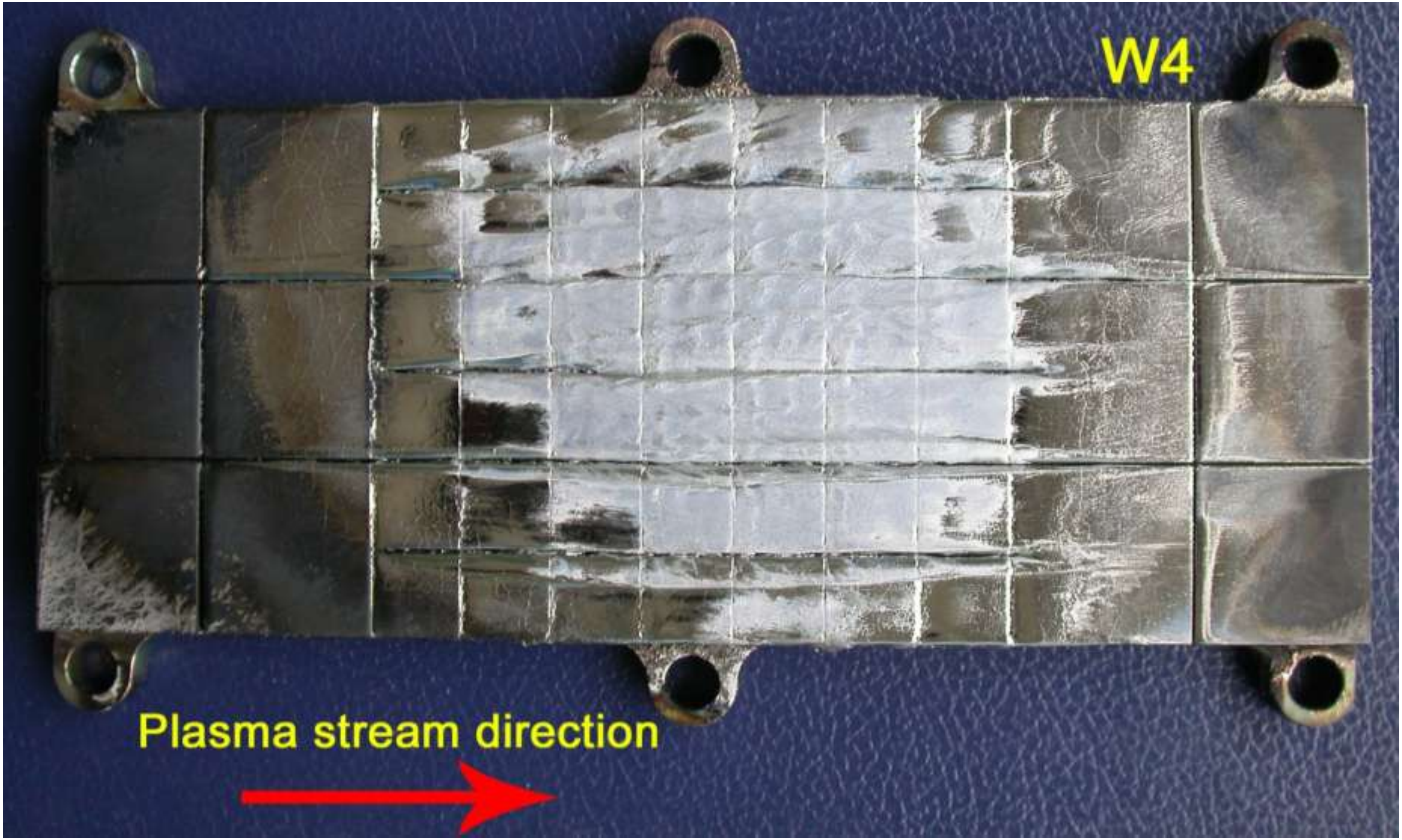
secondary cracks: depth ≈ 50 µm

primary cracks: depth ≈ 500 µm

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

Bridging of gaps due to melt motion

100 shots @ E = 1.6 MJ/m^2

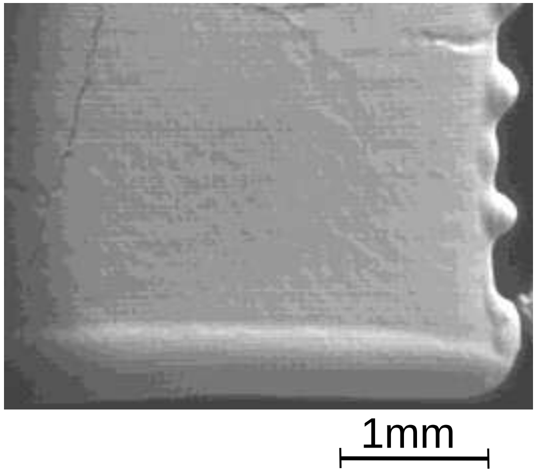


Source: A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

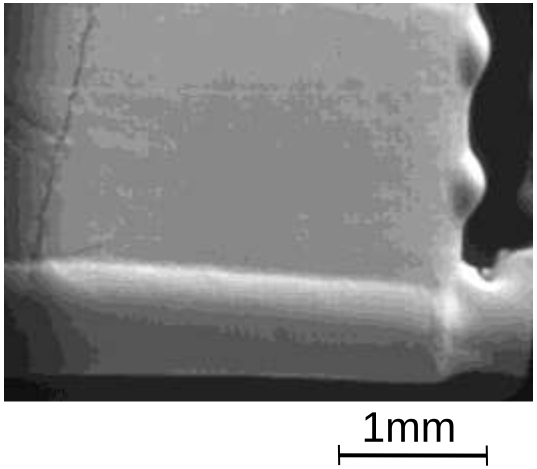
Bridge formation between tungsten tiles

w = 1.0 MJ/m²

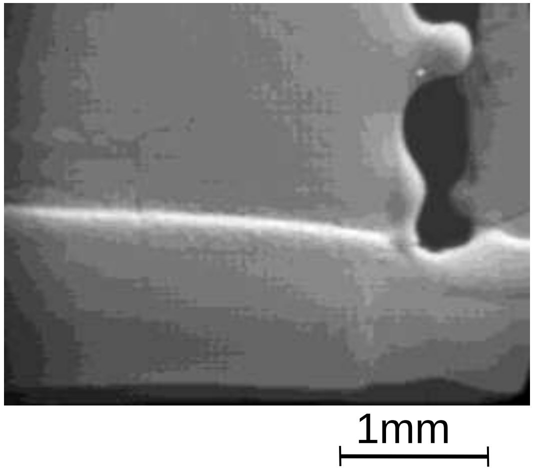
W3,R3, 20 exposures



W3,R3, 50 exposures

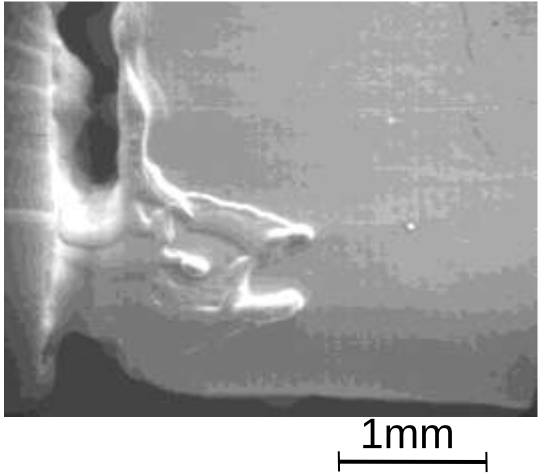


W3,R3, 100 exposures

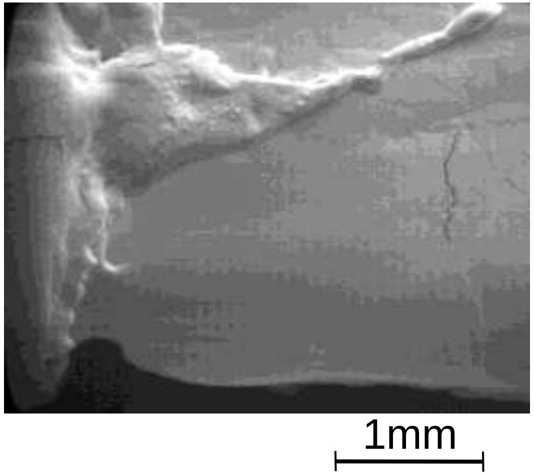


w = 1.6 MJ/m²

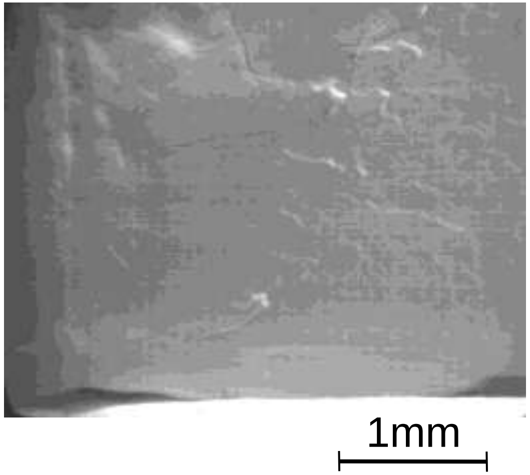
W4,L3, 10 exposures



W4,L3, 20 exposures



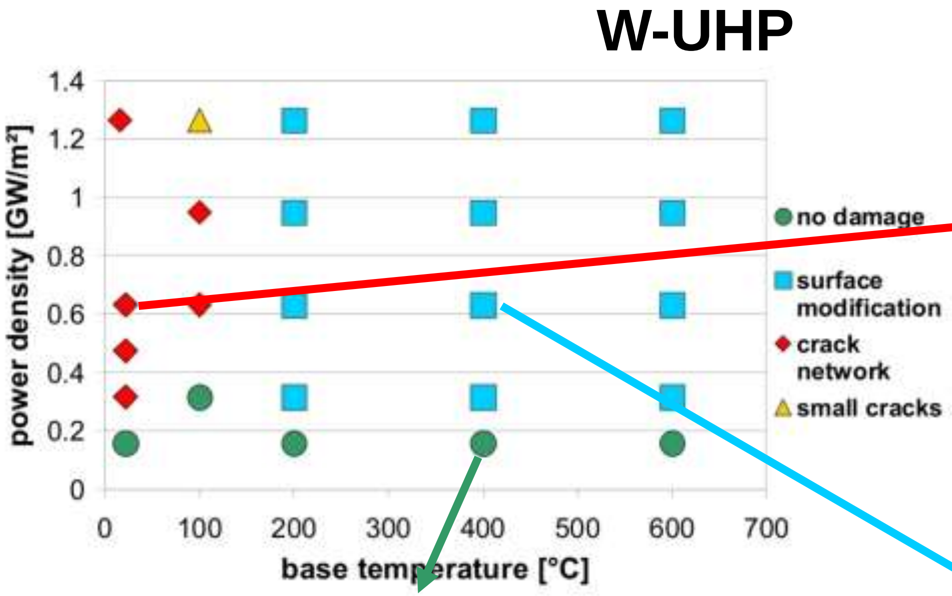
W4,L3, 50 exposures

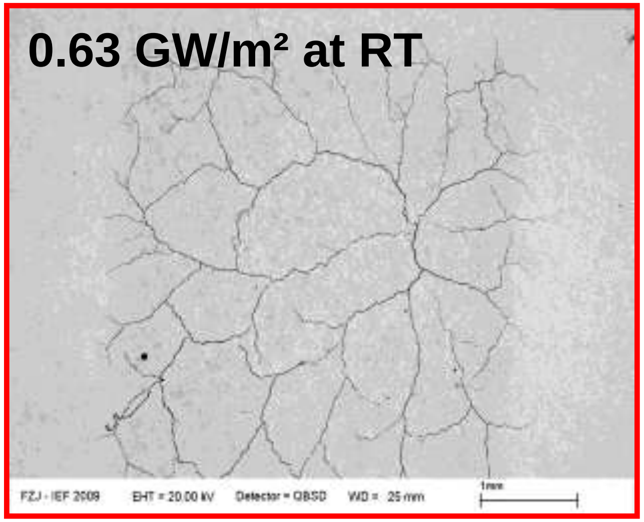


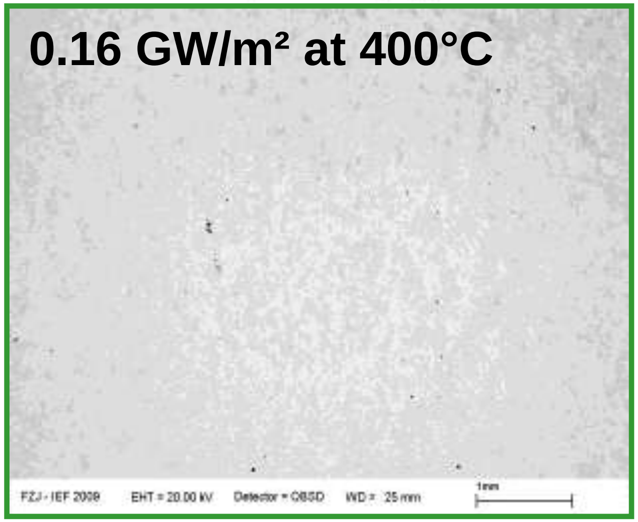
Source: A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

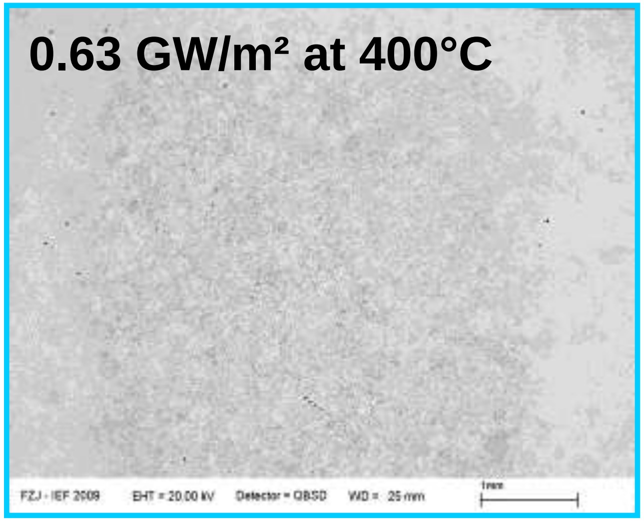
Transient heat load tests on tungsten

Electron beam simulation of ELM-specific thermal loads (n = 100)



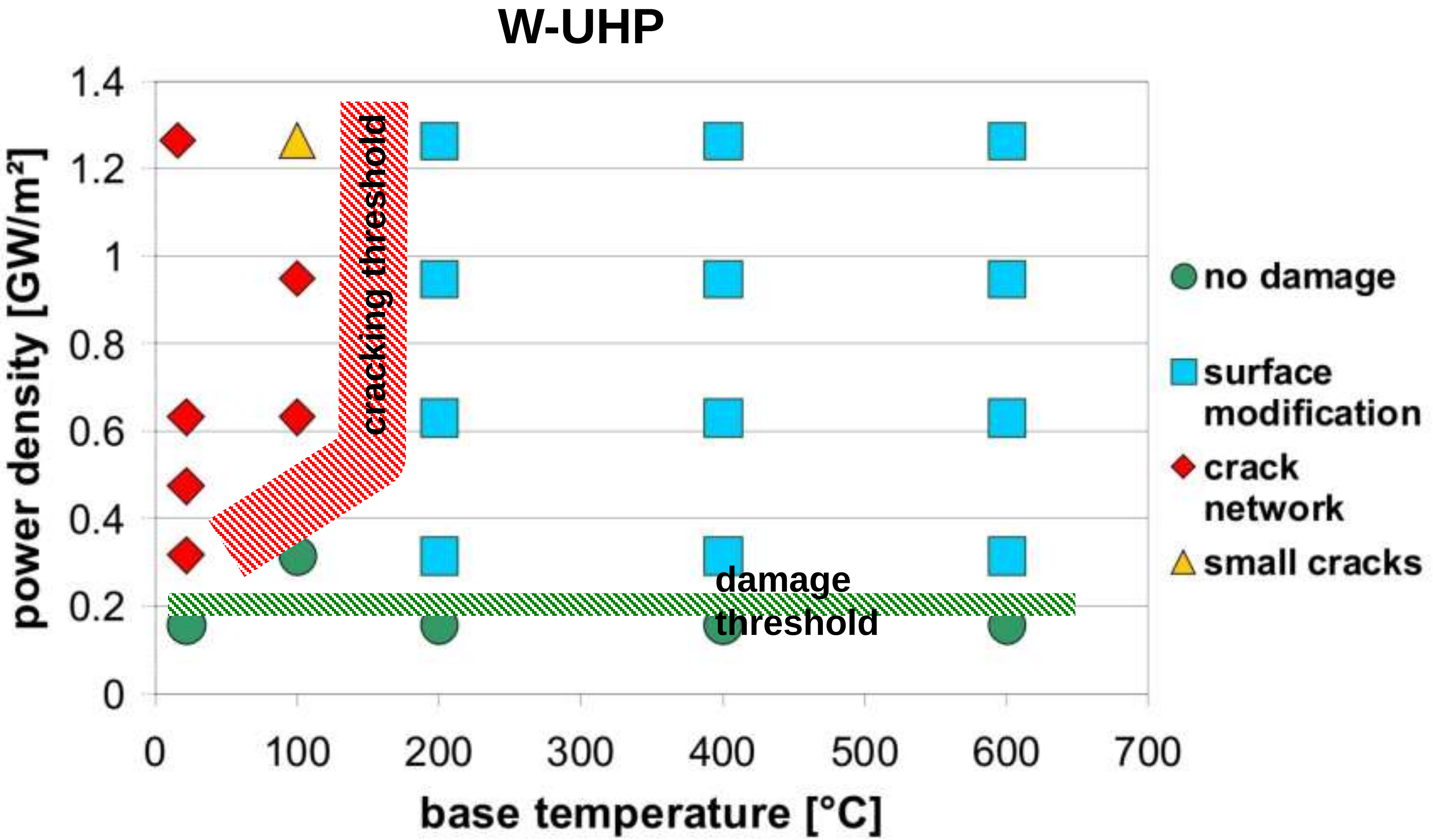

0.63 GW/m^2 at RT


0.16 GW/m^2 at 400°C


0.63 GW/m^2 at 400°C

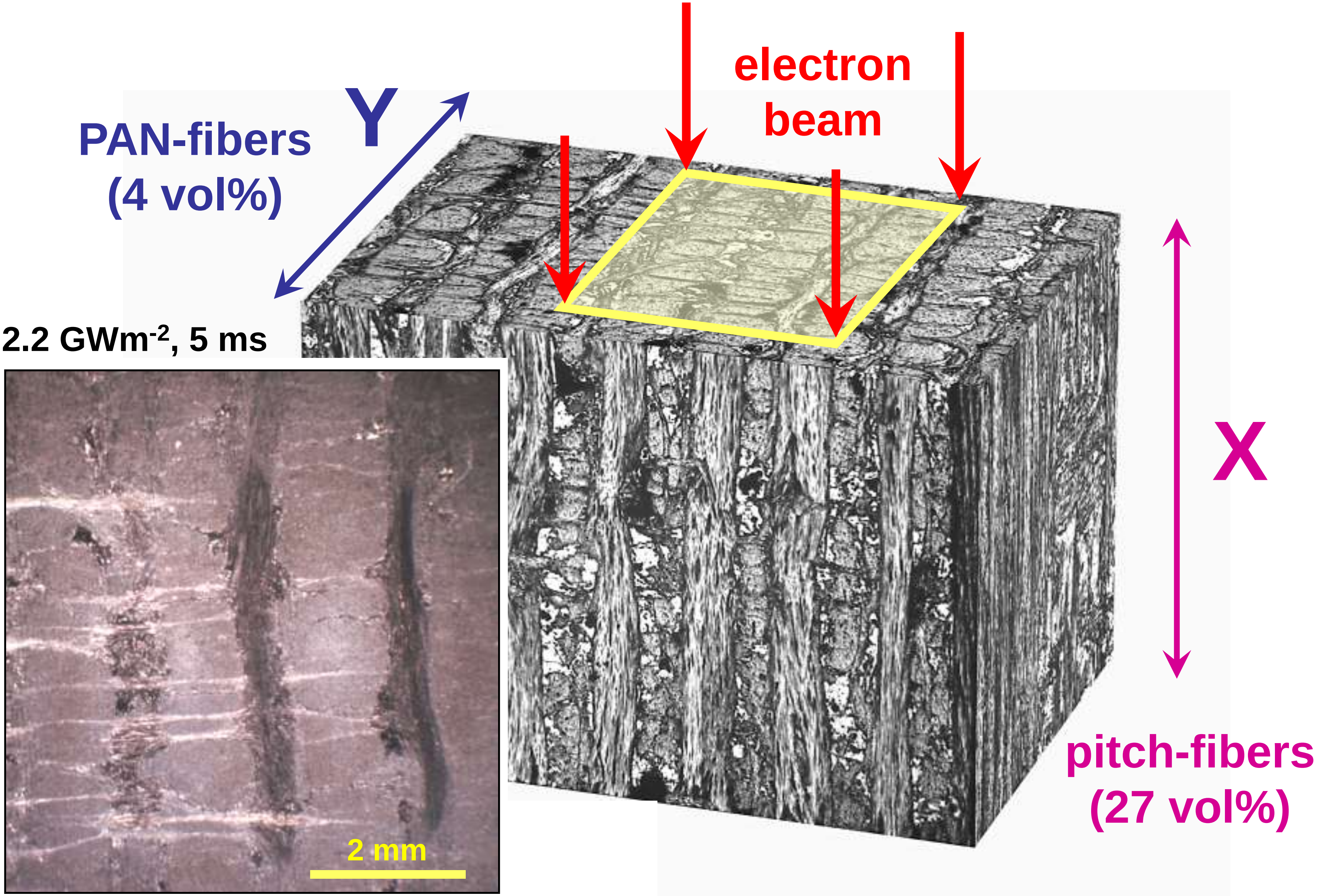
Transient heat load tests on tungsten

Electron beam simulation of ELM-specific thermal loads (n = 100)



100 cycles with a duration of 1 ms; absorption coefficient: 0.46

Fiber arrangement in 3-D CFCs



electron beam

PAN-fibers **(4 vol%)**

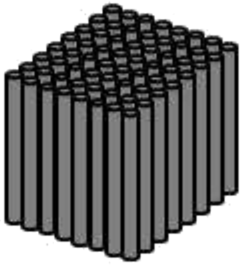
Y

X

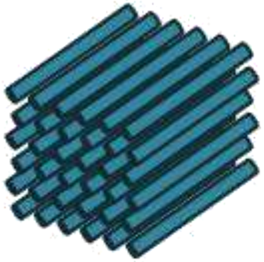
pitch-fibers **(27 vol%)**

2.2 GWm^{-2}, 5 ms

Fibre assembly in a 3D-CFC (NB31)

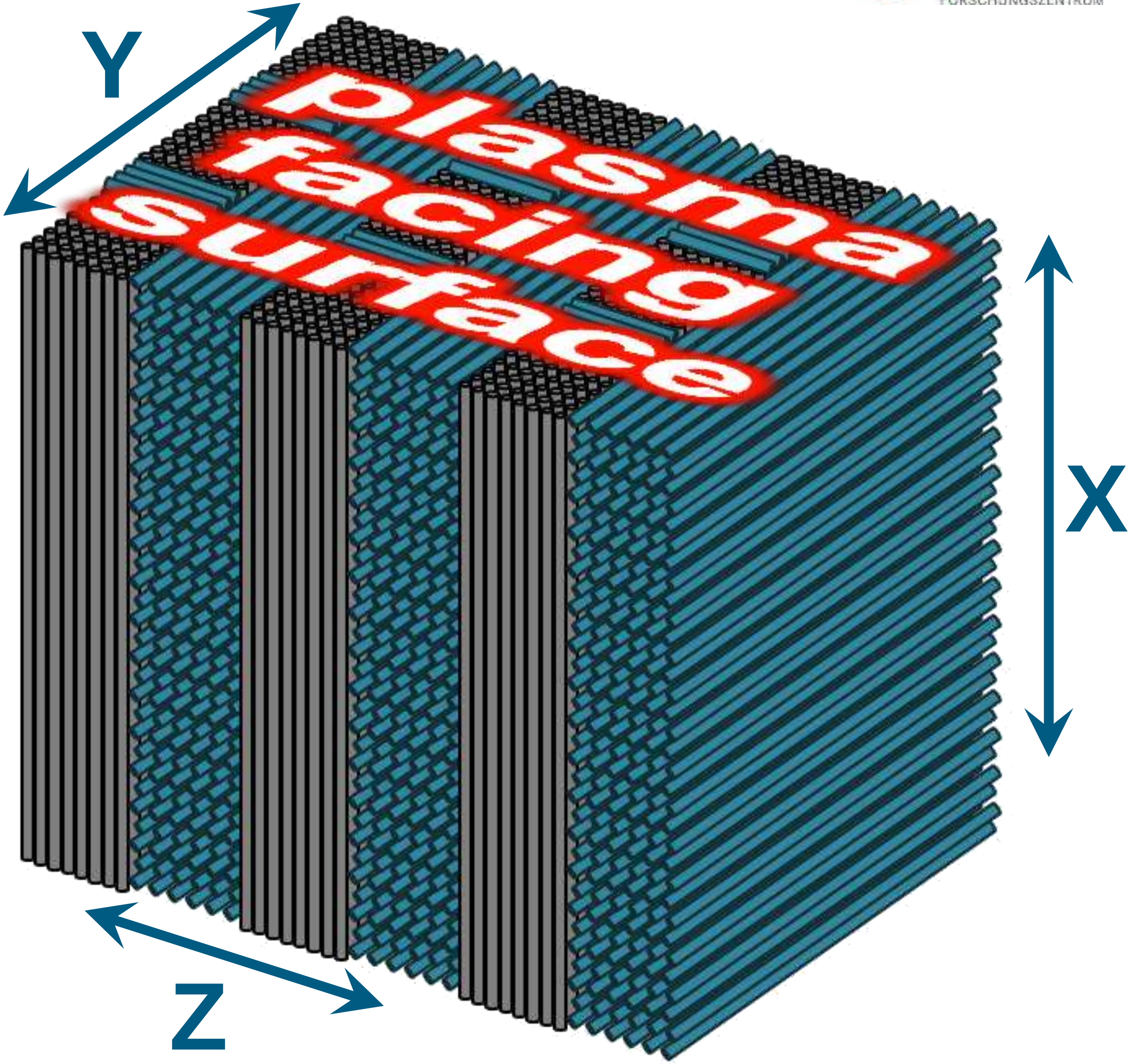


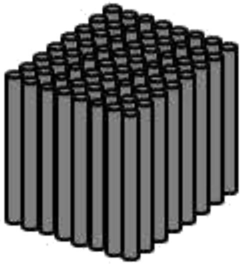
X: pitch fibres



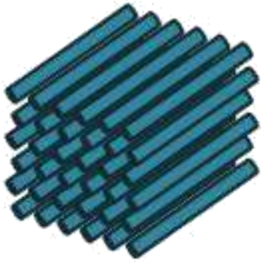
Y: PAN fibres

Z: needled
PAN fibres



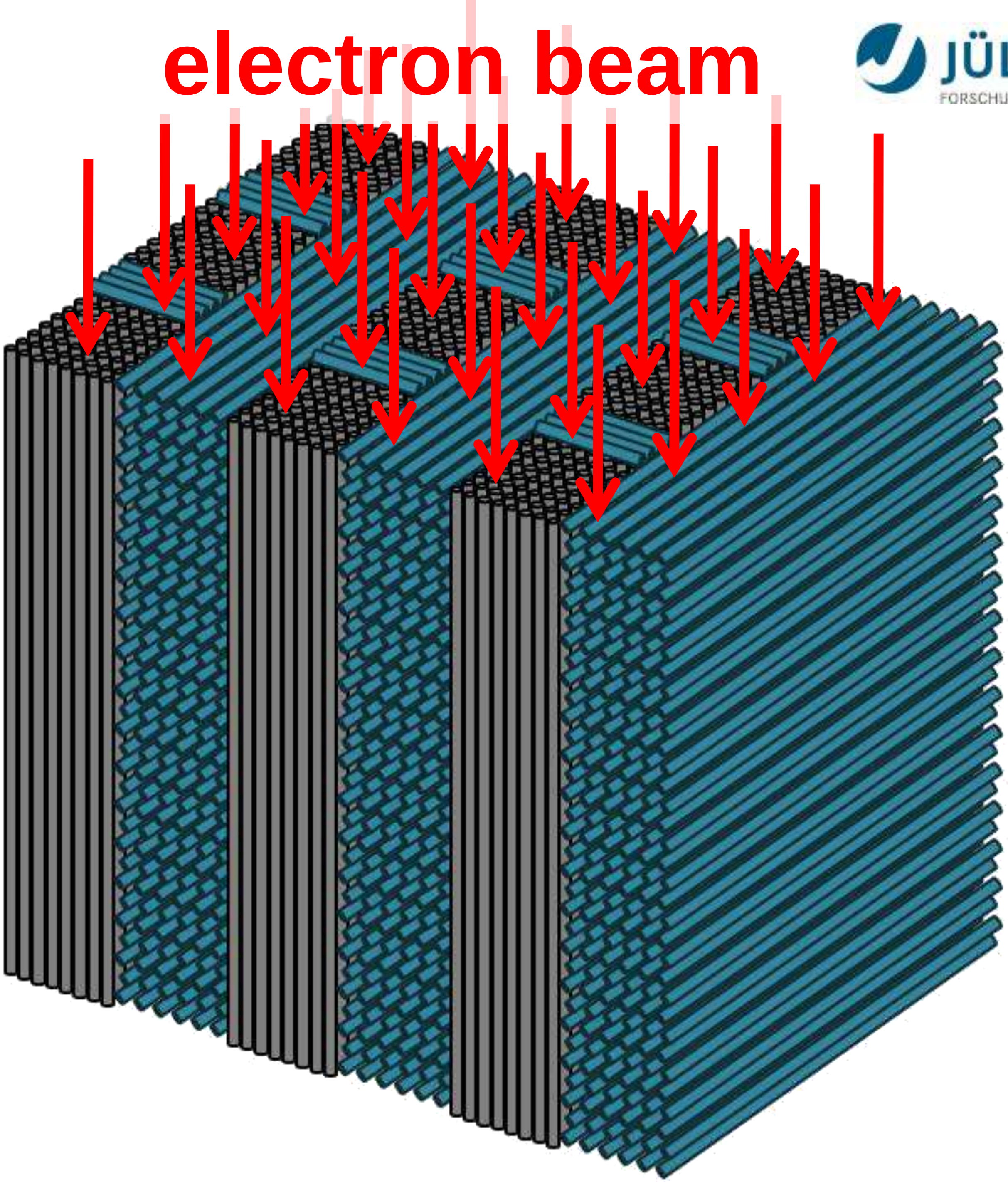


pitch fibres

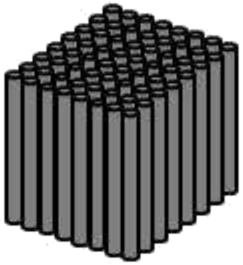


PAN fibres

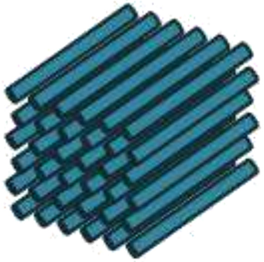
needled
PAN fibres



Fibre assembly in a 3D-CFC (NB31)

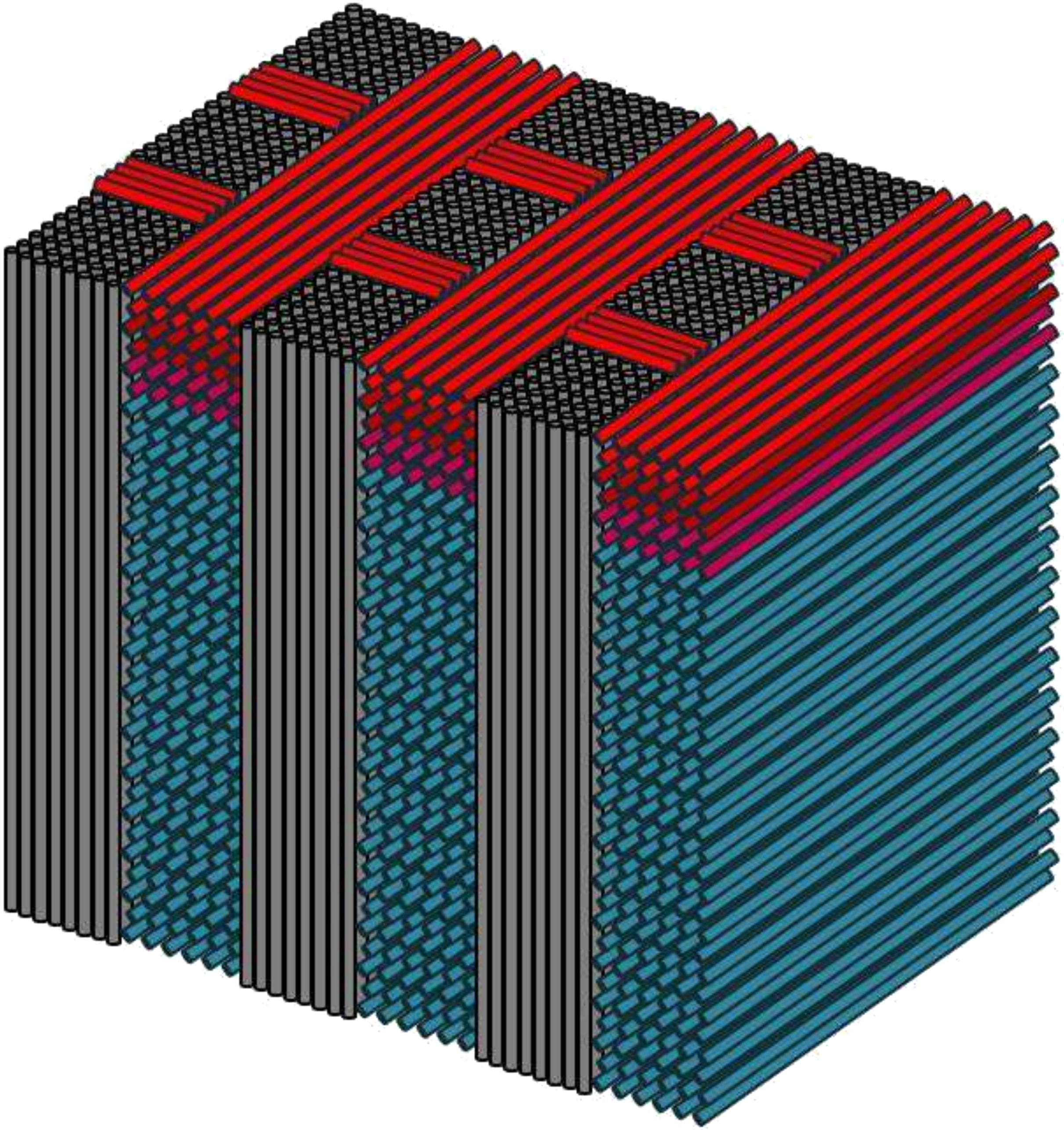


pitch fibres

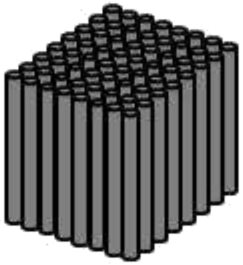


PAN fibres

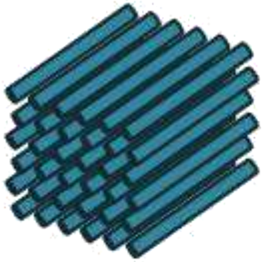
needled PAN fibres



Fibre assembly in a 3D-CFC (NB31)

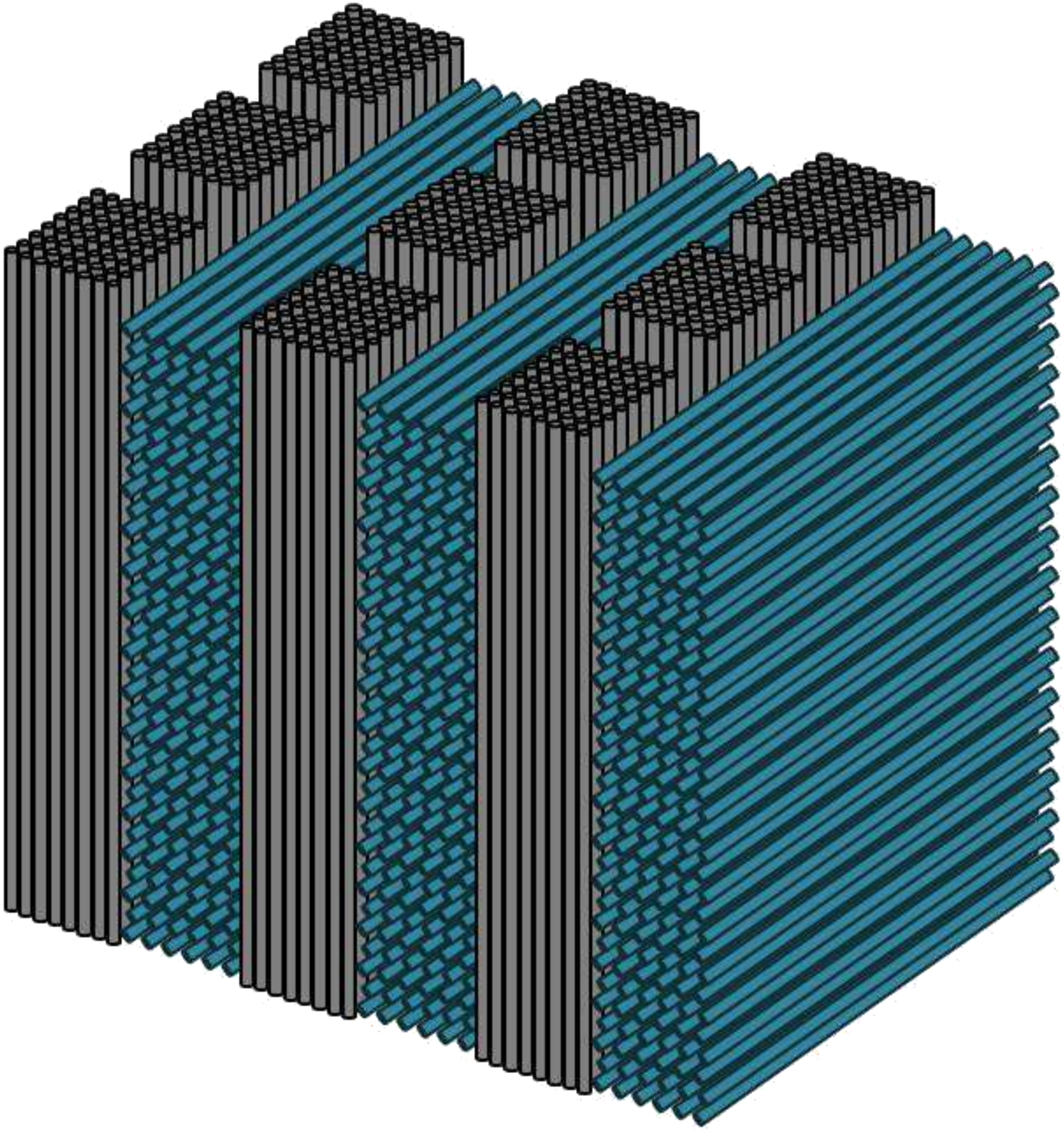


pitch fibres

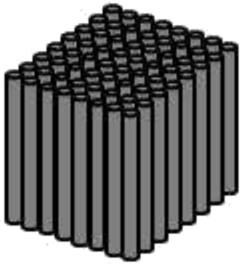


PAN fibres

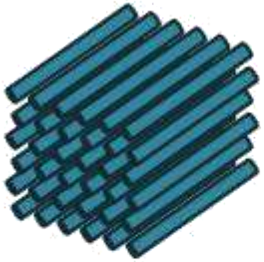
needled
PAN fibres



Fibre assembly in a 3D-CFC (NB31)

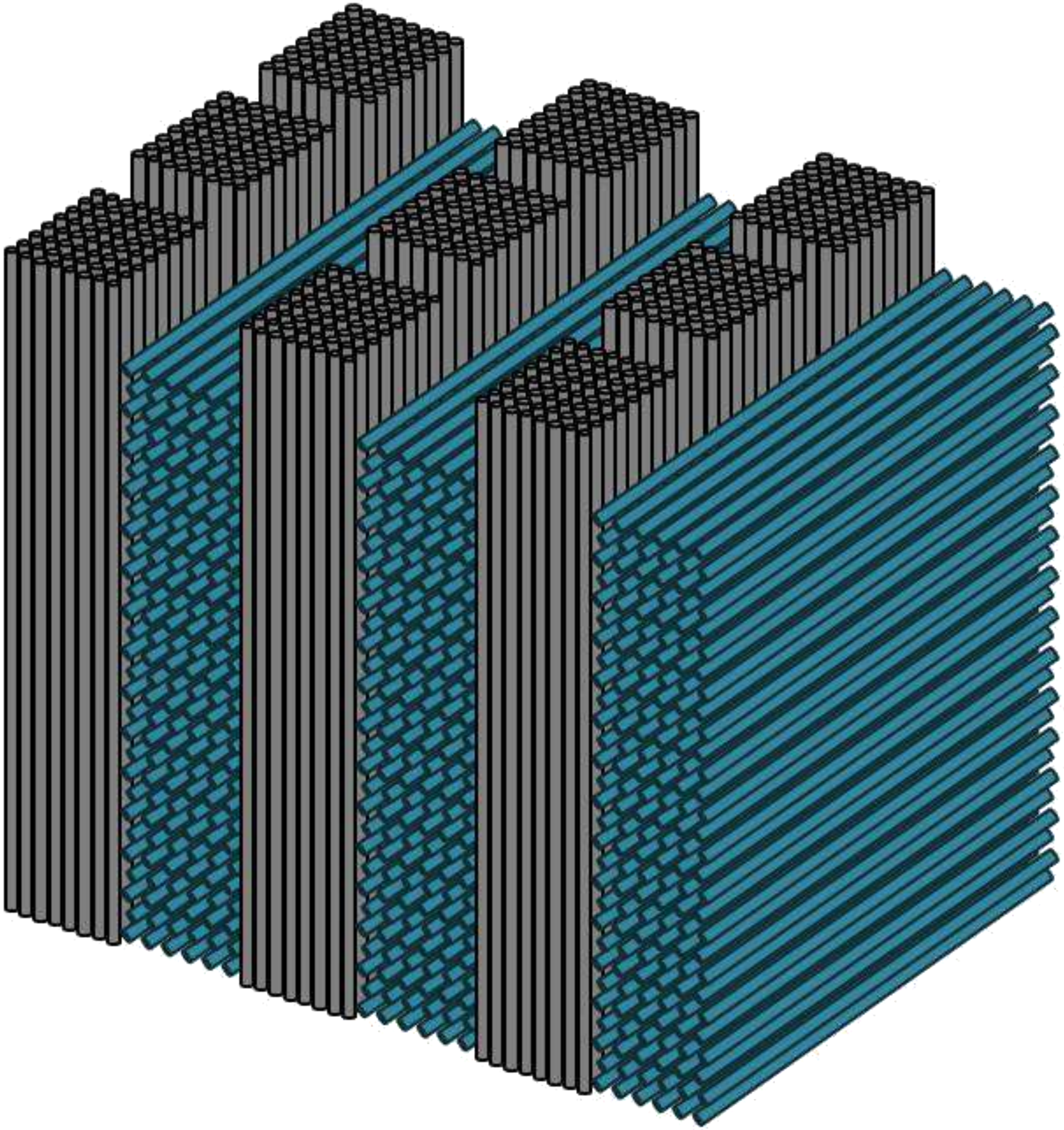


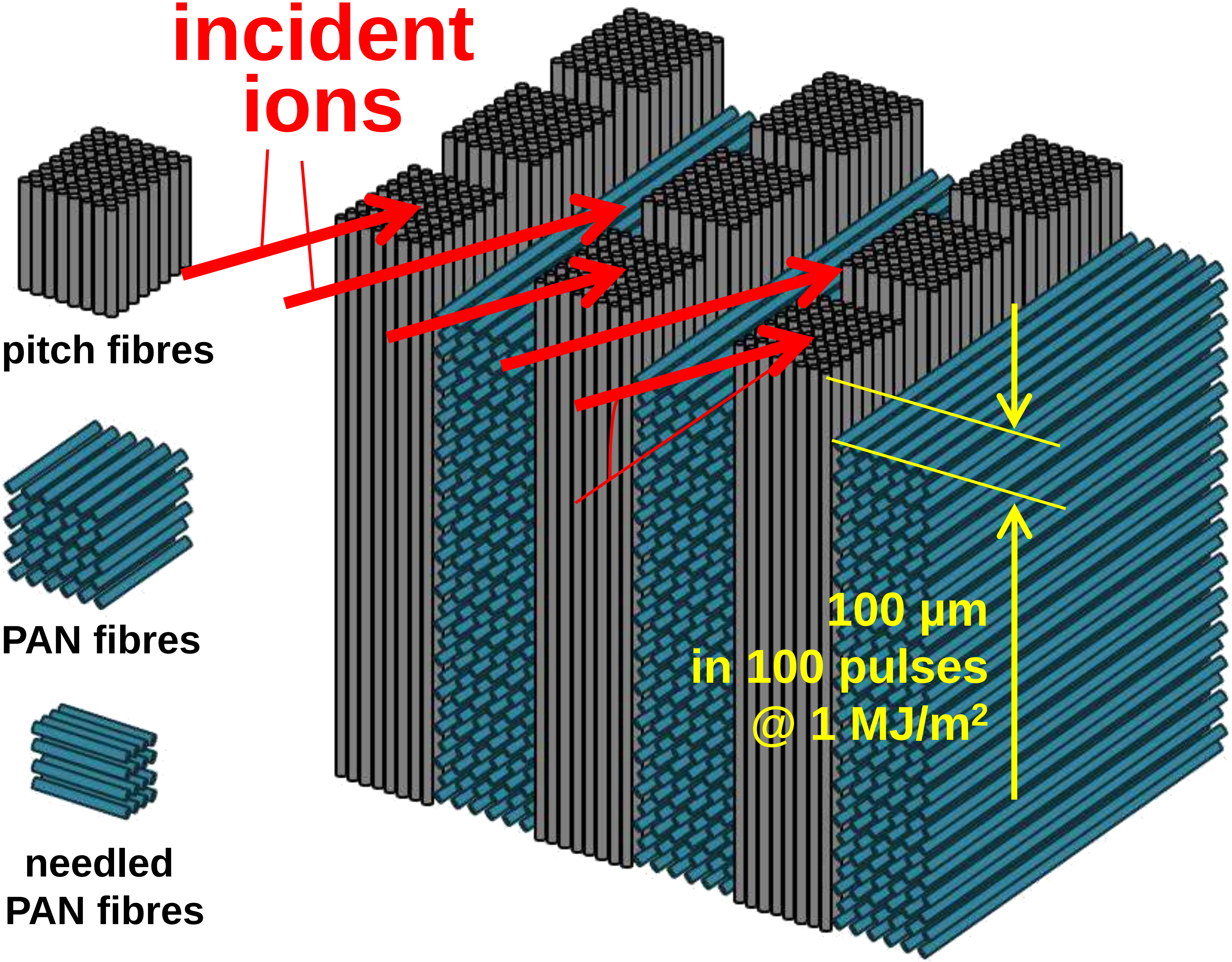
pitch fibres



PAN fibres

needled
PAN fibres





incident ions

pitch fibres

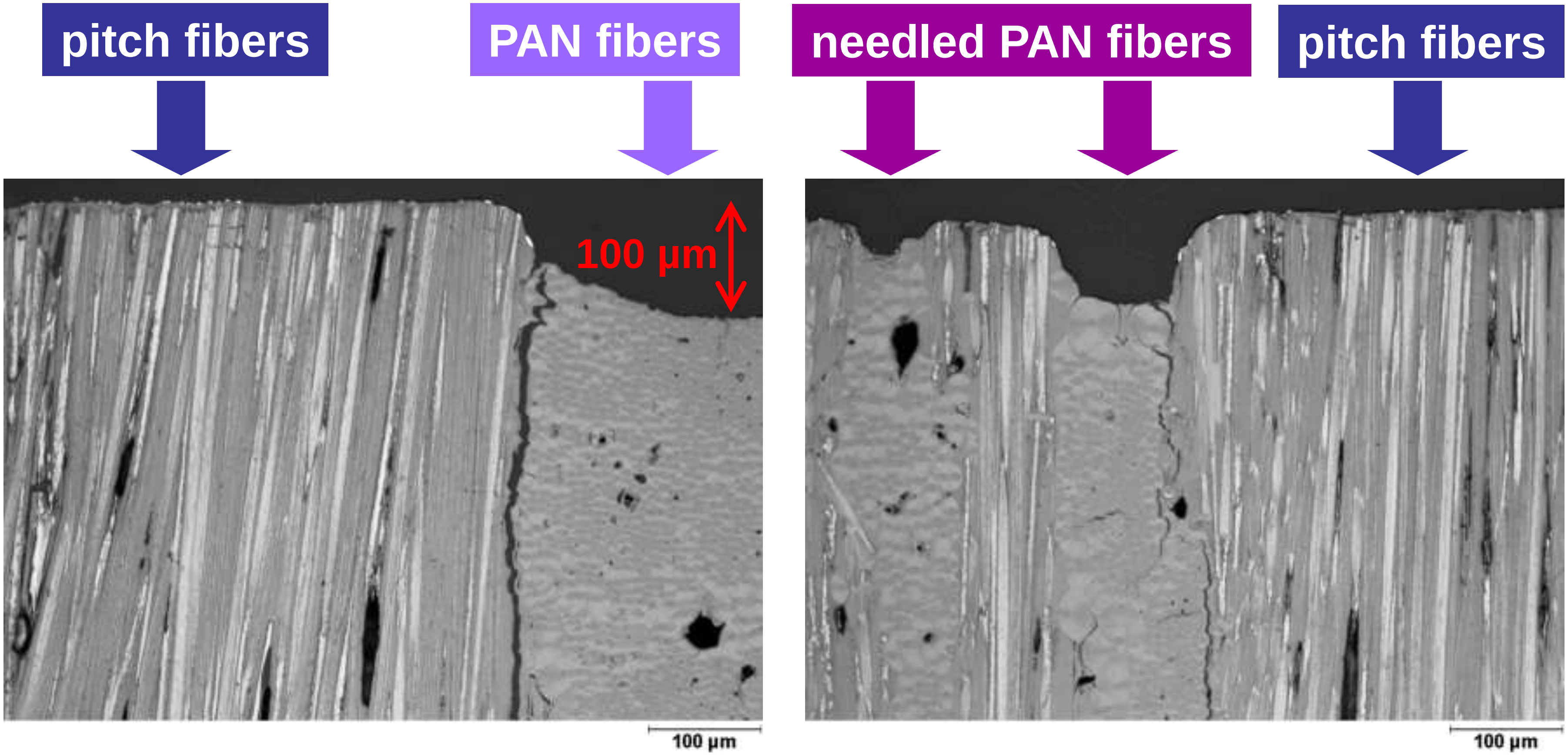
PAN fibres

needled PAN fibres

100 µm in 100 pulses @ 1 MJ/m^2

Thermally induced erosion of NB31

ELM simulation experiments in QSPA, TRINITI, RF



pitch fibers

PAN fibers

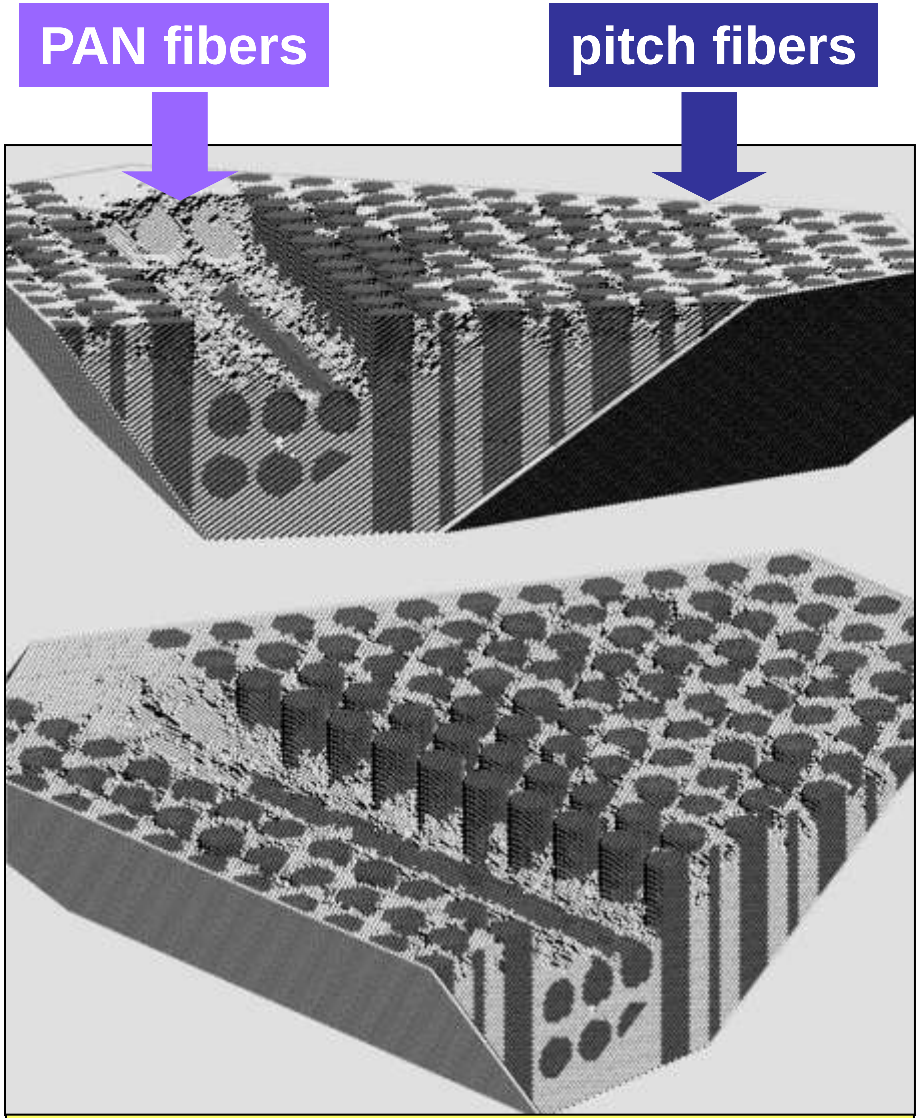
needled PAN fibers

pitch fibers

E ≈ 1.0 MJm^{-2}, Δt = 500 µs, n = 100

→ erosion depth: ~ 1 µm / shot

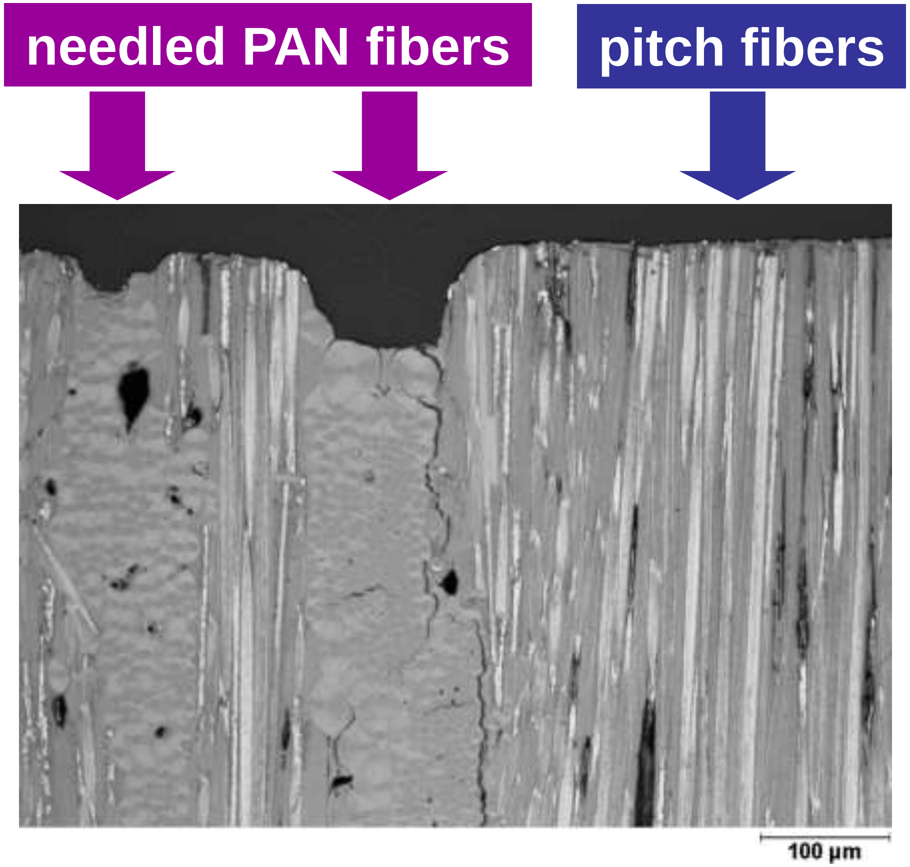
Thermally induced erosion of NB31



PAN fibers

pitch fibers

modeling: S. Pestchanyi et al., KIT



needled PAN fibers

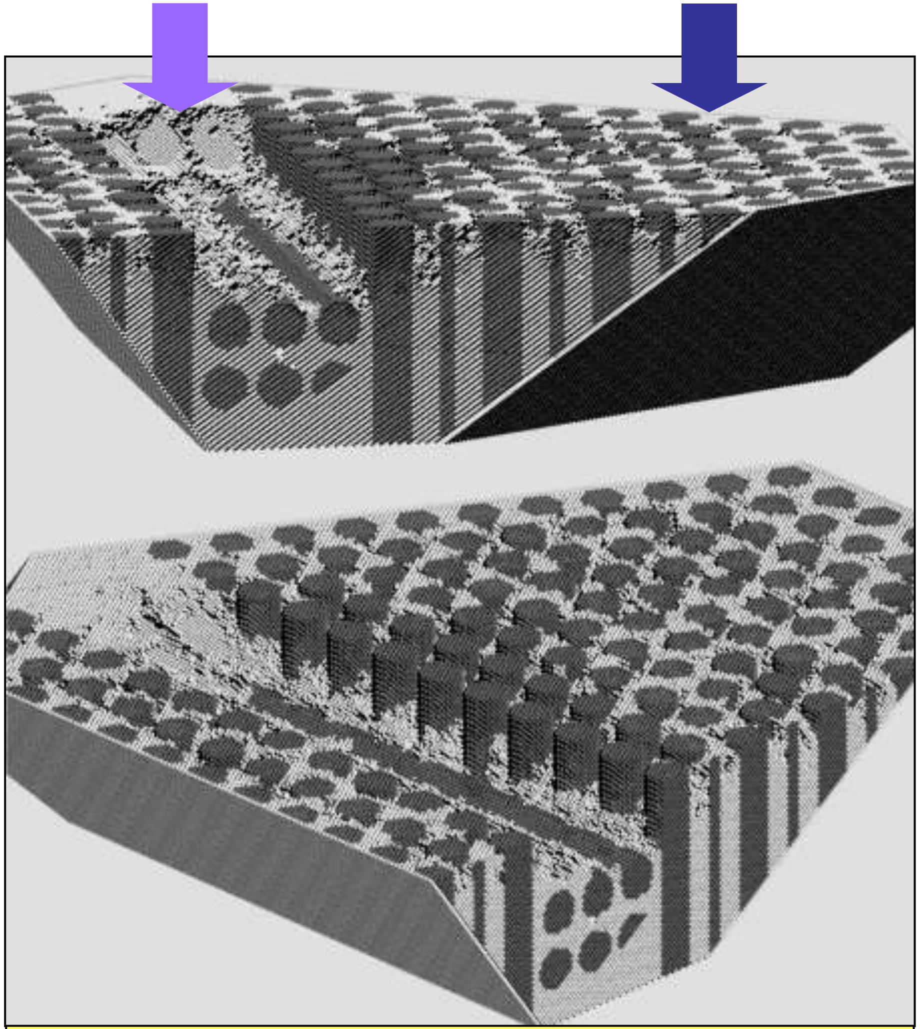
pitch fibers

→ **erosion depth: ~ 1 µm / shot**

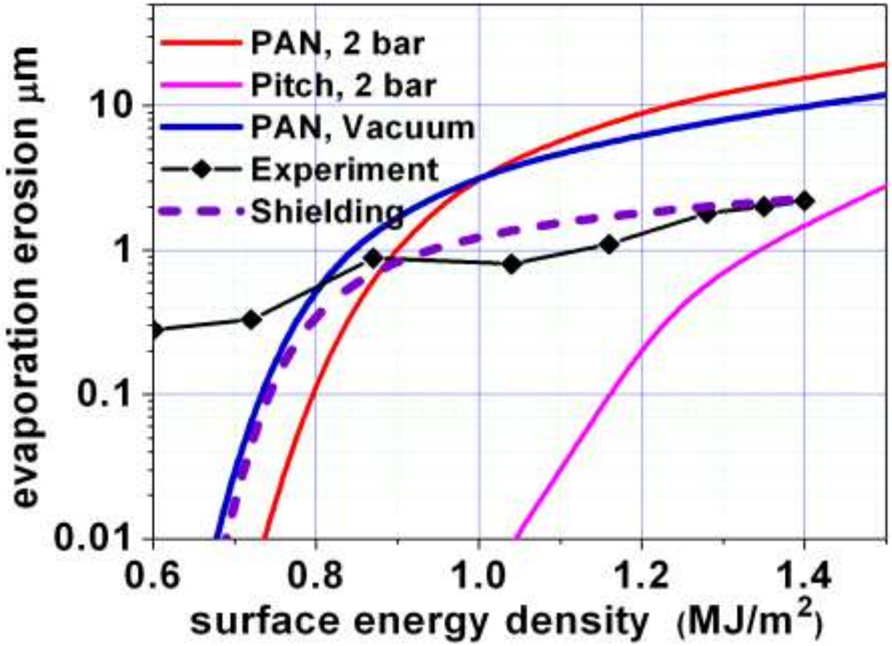
Thermally induced erosion of NB31

PAN fibers

pitch fibers

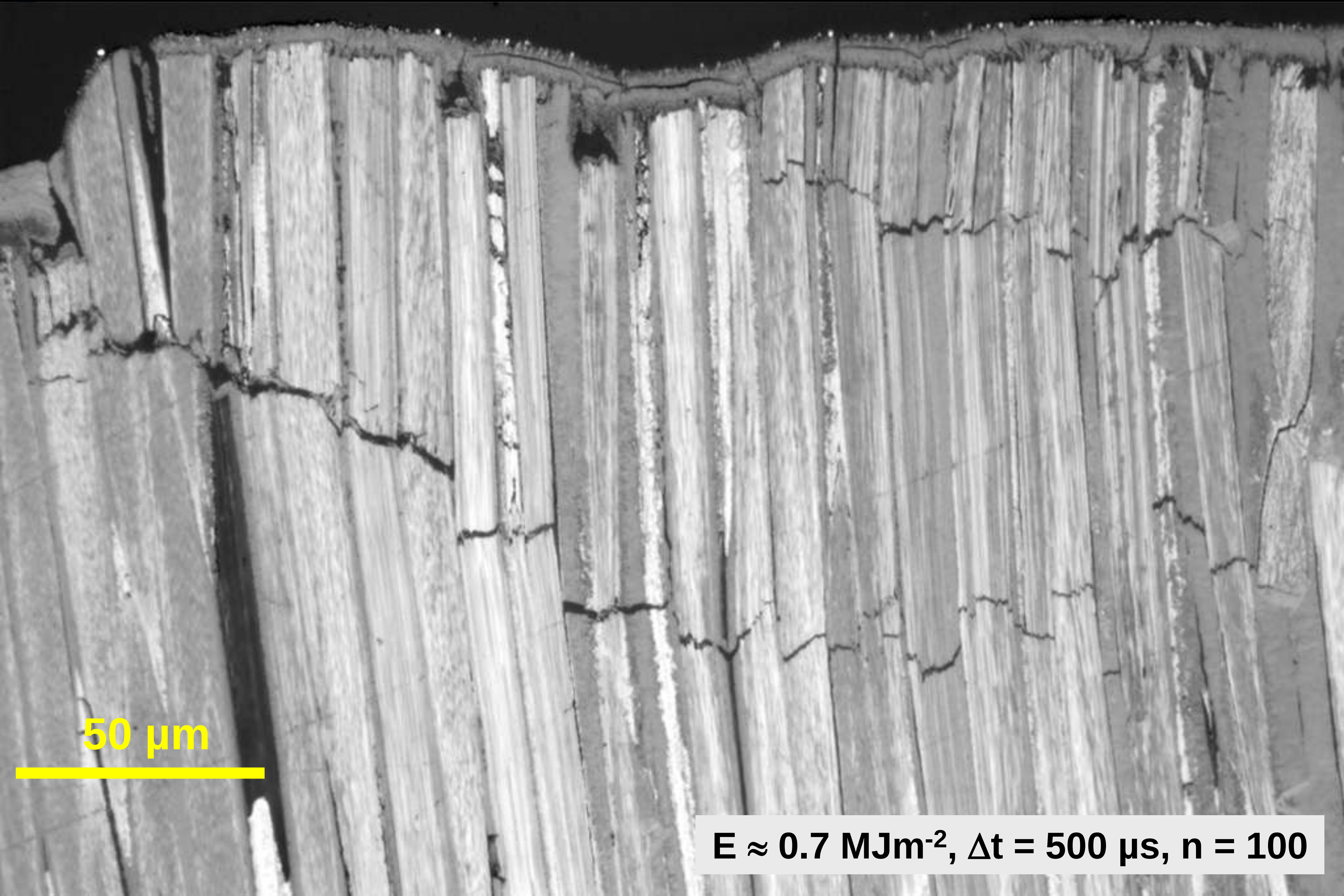


modeling: S. Pestchanyi et al., KIT



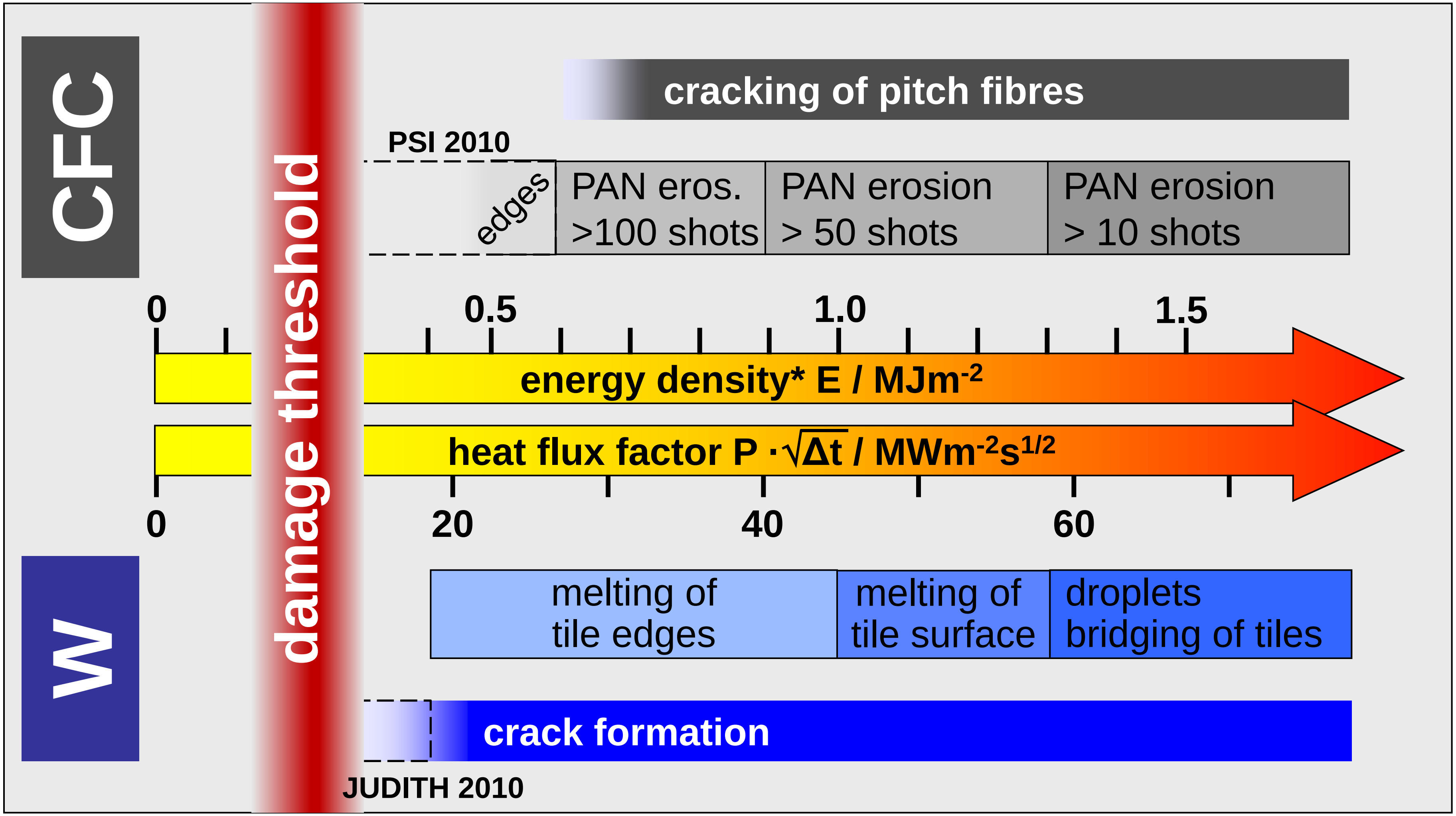
modeling: B. Bazylev et al., KIT

Crack formation in pitch fibers of NB31



E ≈ 0.7 MJm^{-2}, Δt = 500 µs, n = 100

Threshold values for ELM loads



CFC

cracking of pitch fibres

PSI 2010

edges

PAN eros. >100 shots

PAN erosion > 50 shots

PAN erosion > 10 shots

damage threshold

energy density* E / MJm^{-2}

heat flux factor $P \cdot \sqrt{\Delta t}$ / $MWm^{-2}s^{1/2}$

W

melting of tile edges

melting of tile surface

droplets bridging of tiles

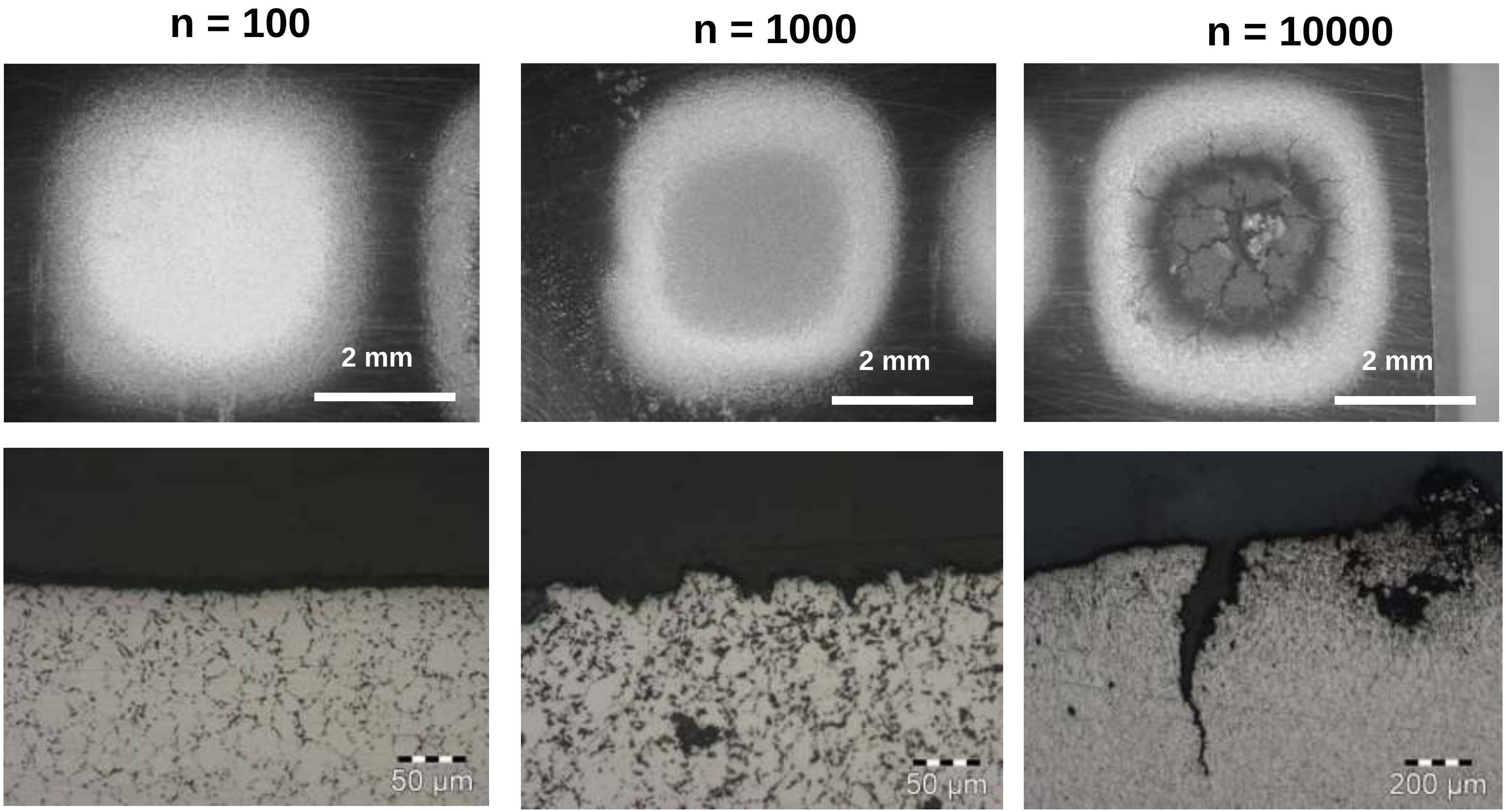
crack formation

JUDITH 2010

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

source: PSI 2006

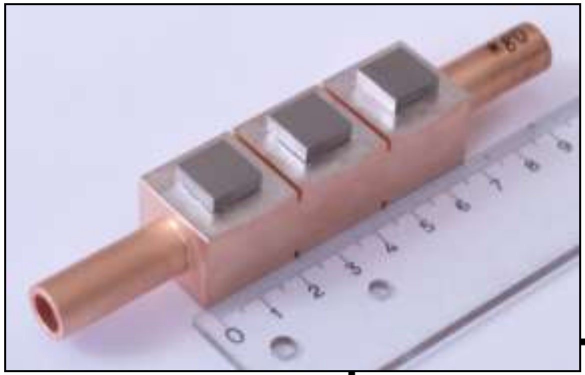
Repeated thermal shock testing of Be



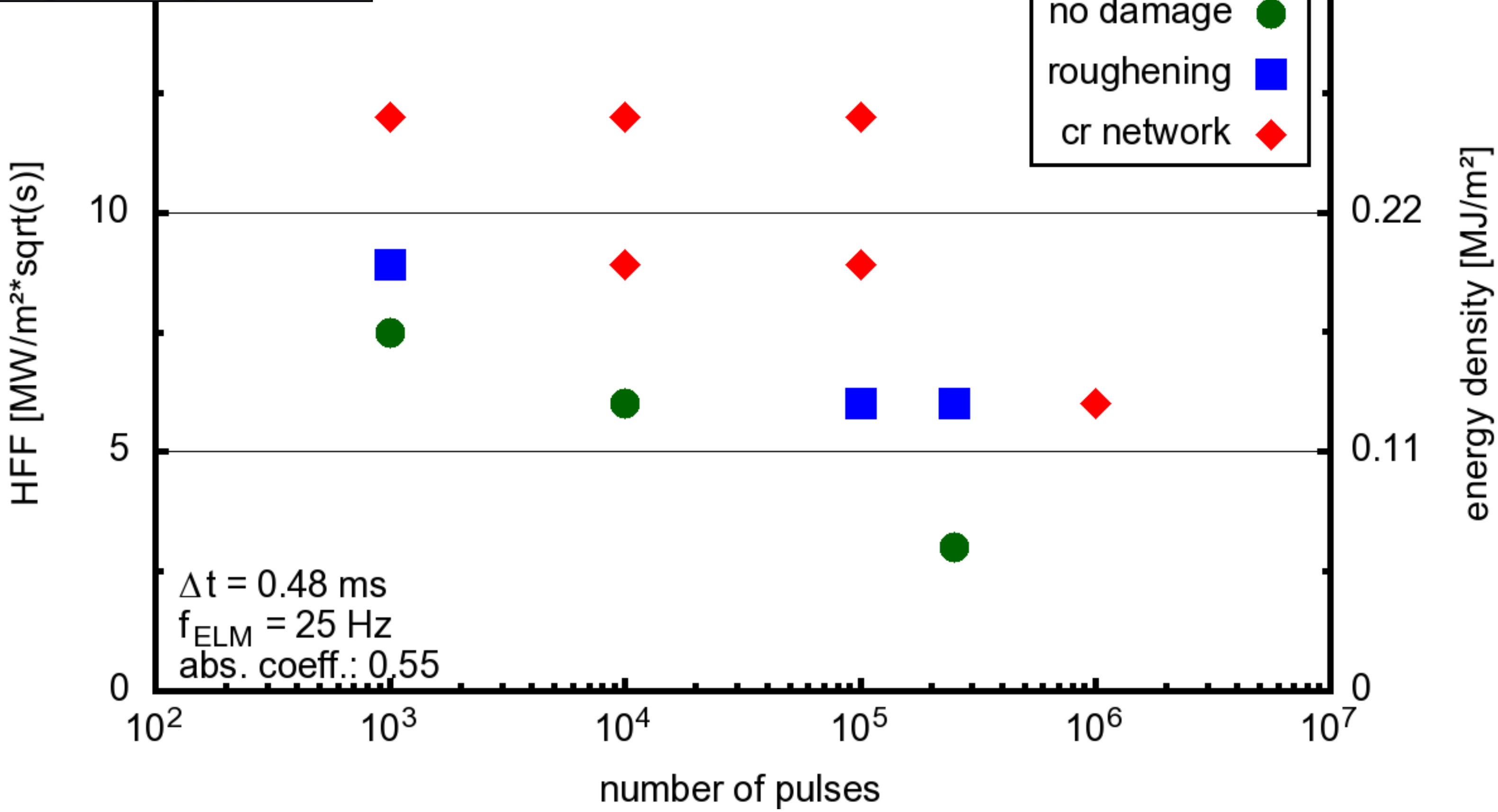
power density P =1.0 MJ/m^2
$P \cdot \sqrt{(\Delta t)} = 14$ MW/m^{2}s$^{1/2}$

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

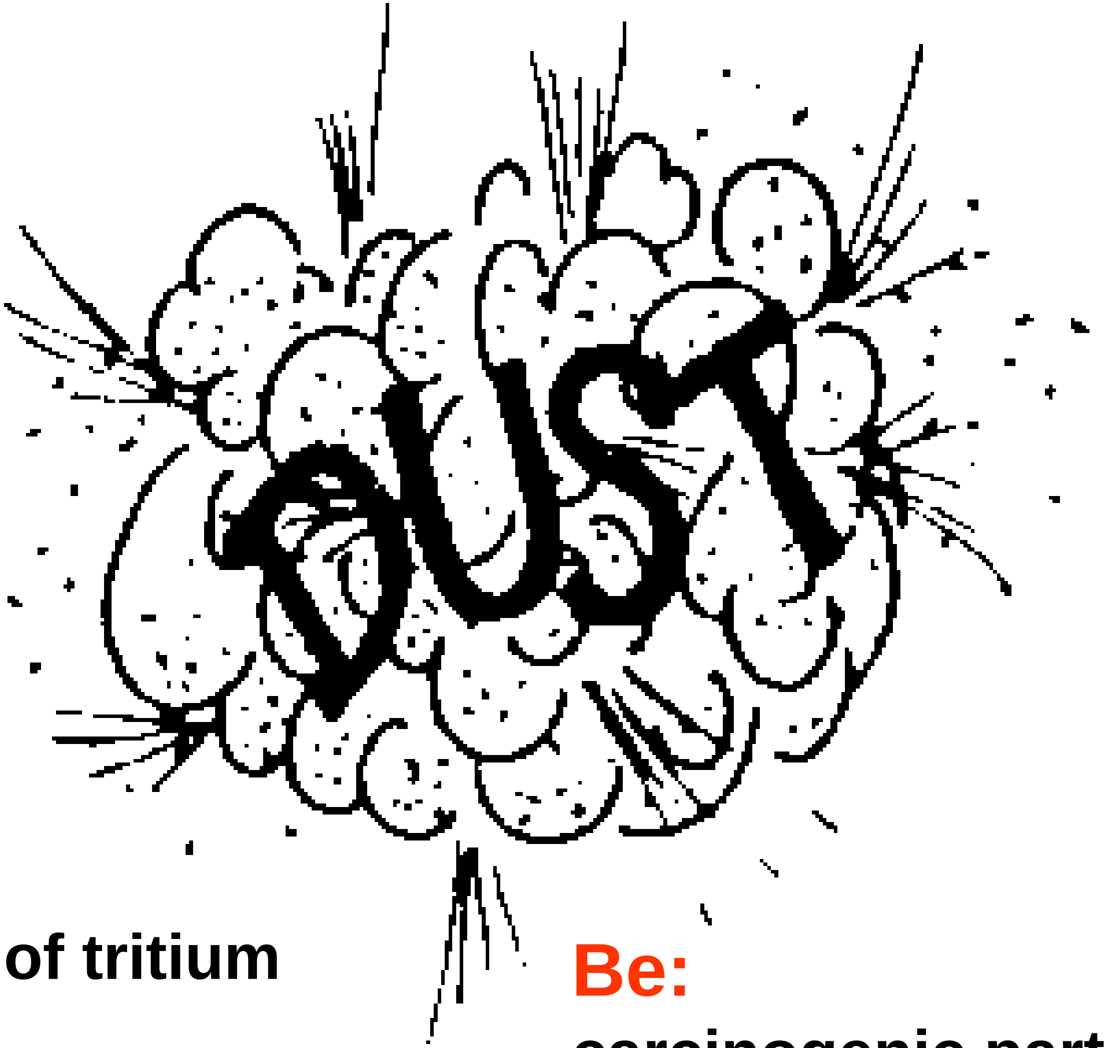
ELM simulation tests on tungsten



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



Transient thermal loads on graphitic or metallic wall materials



W:
activated dust

CFC:
codeposition of tritium (T inventory)

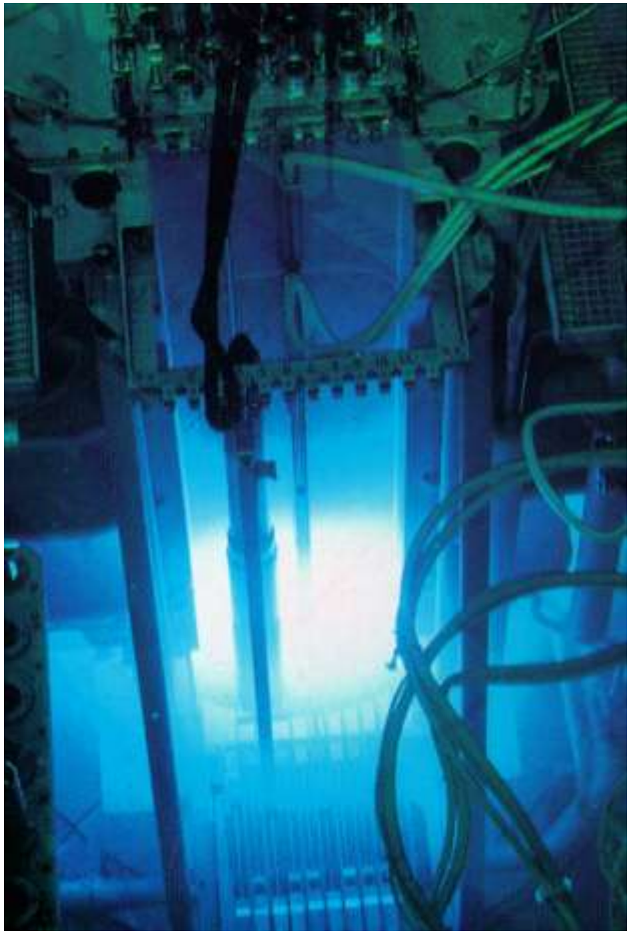
Be:
carcinogenic particles

E

neutron induced material degradation

(f_n = 10^{25} n/m^2 → 1 dpa for ITER)

Neutron-induced material degradation



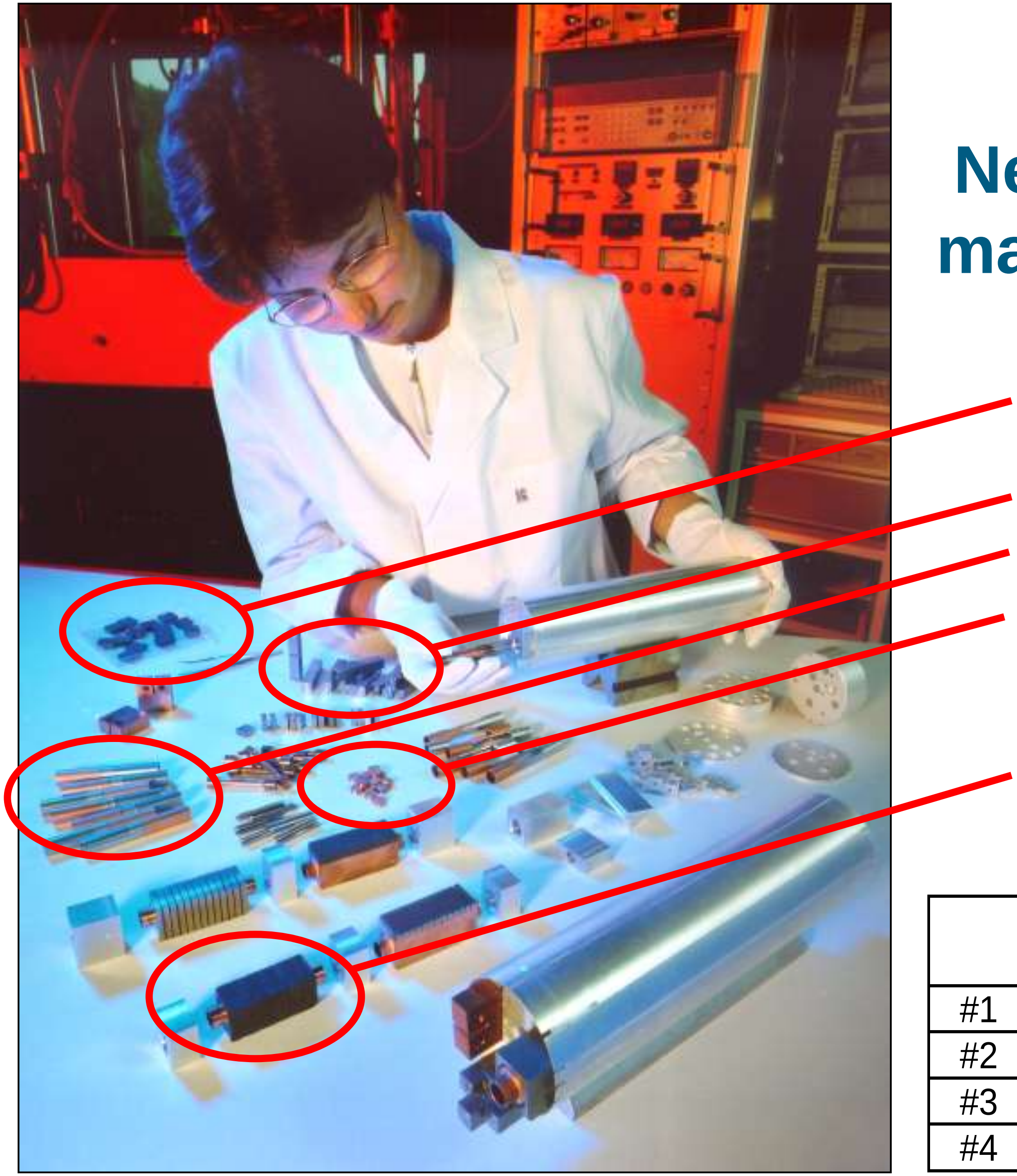
High Flux Reactor (HFR)
Petten, The Netherlands

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

JÜLICH
FORSCHUNGSZENTRUM

Neutron irradiation in materials test reactors



thermal shock specimens

4-point bending test

mechanical testing of joints

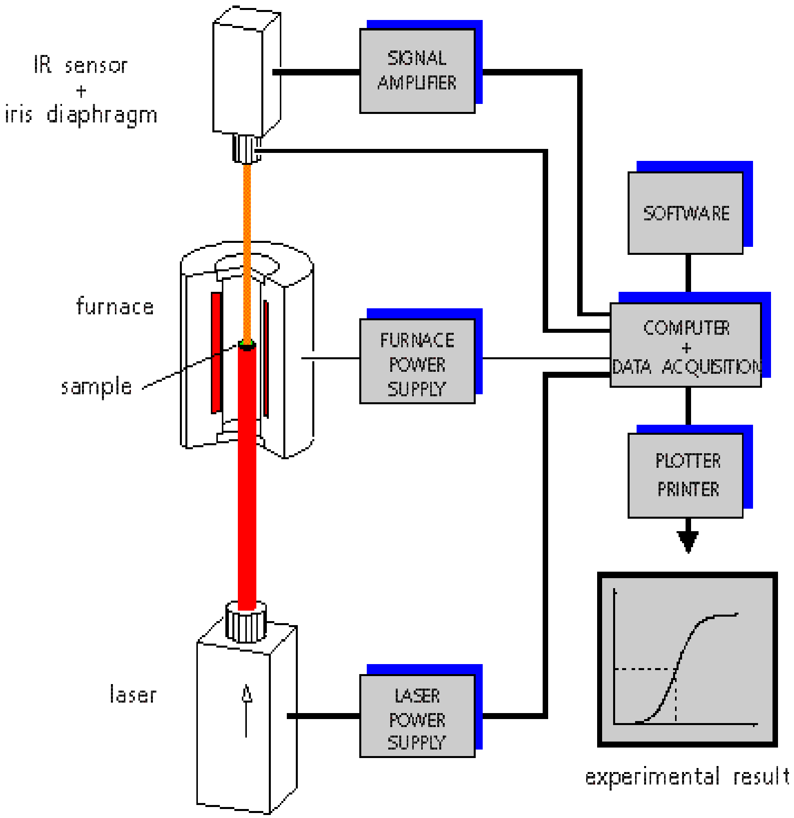
thermal conductivity

actively cooled divertor modules

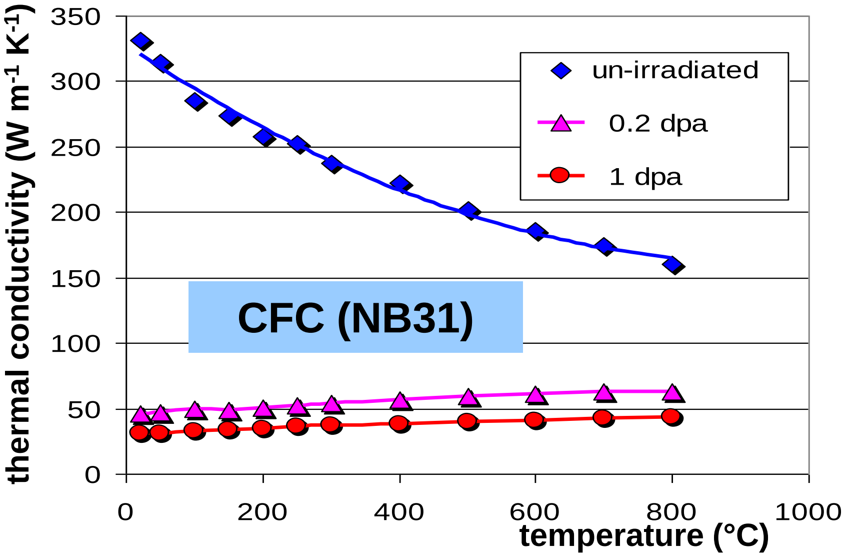
	T_{irr} [°C]	fluence [dpa]	irradiated materials
#1	350	0.35	Be, CFCs, W-alloys SiC
#2	700	0.35	
#3	200	0.2	CFCs, W-alloys, Cu-alloys, joints
#4	200	1.0	

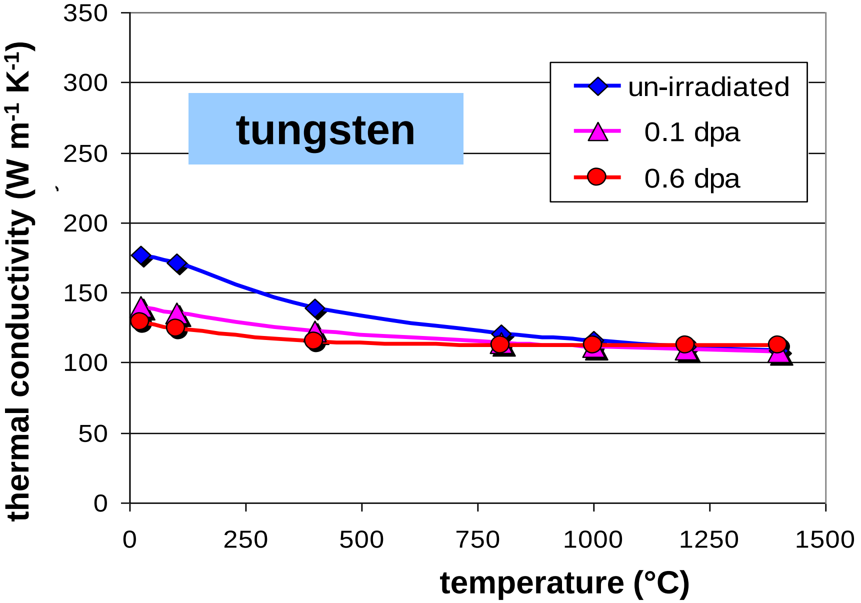
(all dpa‘s in carbon)

n-irradiation effect on thermal conductivity



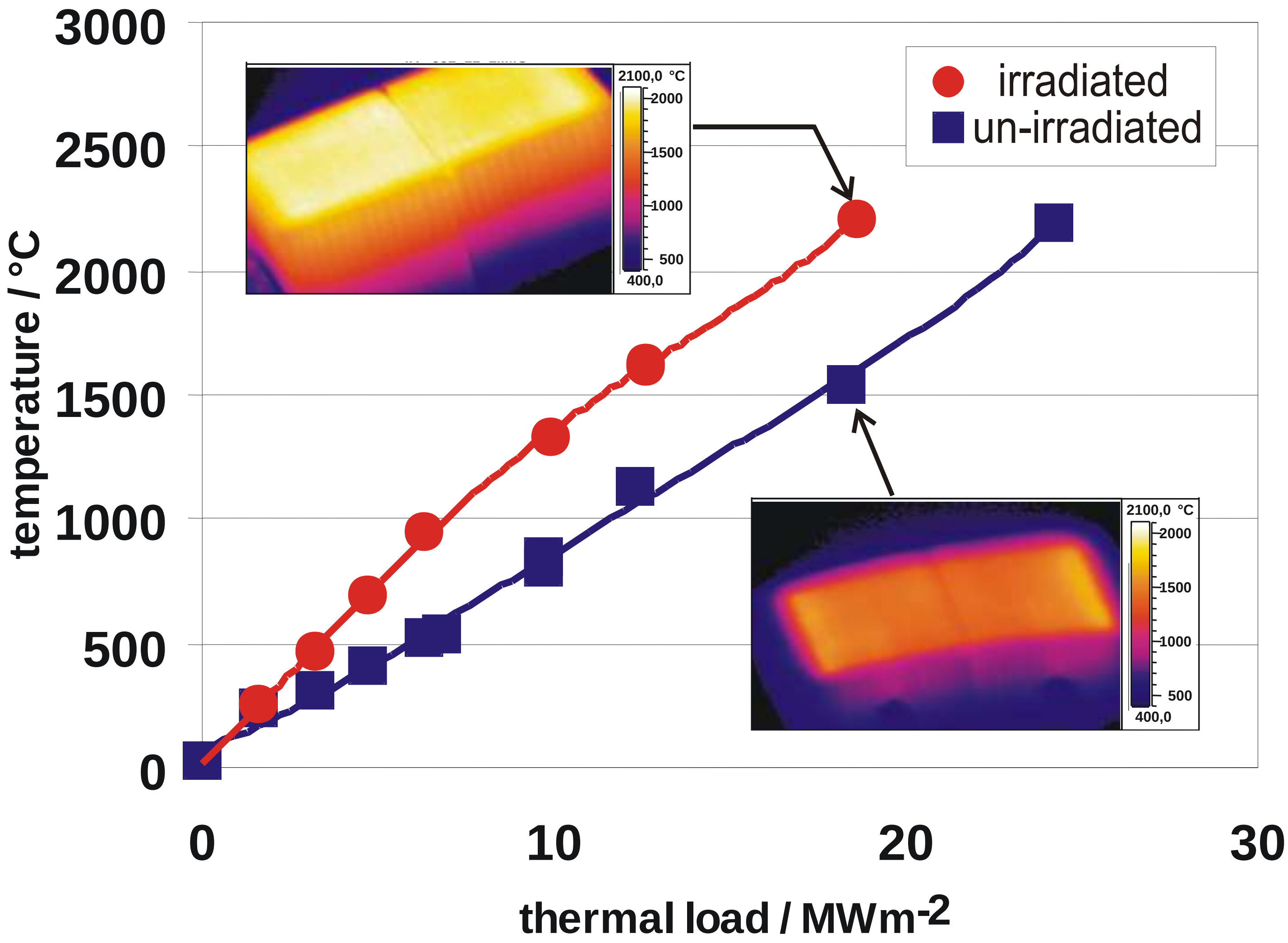
Laser-flash-apparatus (schematic)



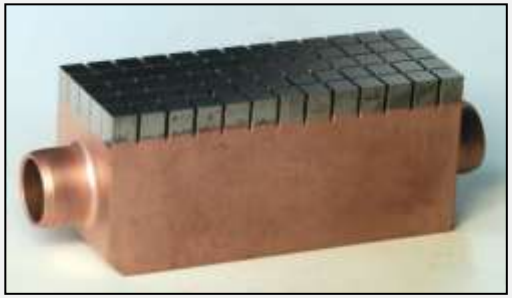
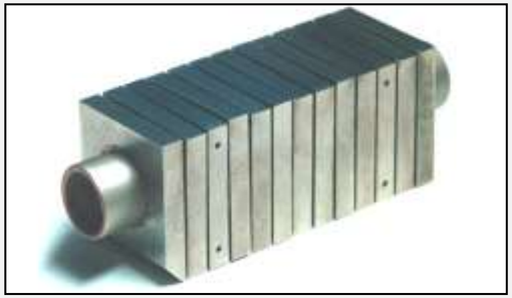


HHF performance of n-irradiated divertor modules

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)

Characterization of plasma facing materials

Microstructure / composition

- metallography / ceramography
- optical microscopy
- electron microscopy (SEM, TEM ….)
- analytical tools (EDX, Auger, SIMS, RBS …)

Mechanical properties

- strength (tensile, compressive)
- Young‘s modulus
- fracture toughness

Thermal properties

- thermal diffussivity (conductivity)
- thermal expansion coefficient (CTE)
- specific heat
- emissivity

Thermal shock resistance under transient loads

Electrical and optical properties

Corrosion / erosion behaviour

Neutron irradiation performance

ITER Materials Documents

Materials Properties Handbook

Materials Assessment Report

and many other data bases

Summary

Materials characterization

- an extensive data base is required including microstructure and all physical properties (mechanical, thermal, electrical, optical etc.)
- these parameters are required for monolithic materials, coatings and interlayers for a wide temperature range & different material treatment

Thermal fatigue and thermal shock

- technical solutions for cyclic thermal loads up to ~20 MWm^{-2} are available (CFC- or W-monoblocks represent a very robust design solution)
- off-normal events such as VDEs or disruptions result cause damage (melting, crack formation, ...) – effect of ELMs needs further analyses
- dust formation is a serious safety issue
  (codeposition of tritium, toxic Be dust, activated tungsten particles)

Material degradation by energetic neutrons

- the thermal conductivity is decreased significantly (e.g. graphite / CFC)
- the surface temperature of carbon based high heat flux components is significantly increased after neutron irradiation