Forschungszentrum Jülich

in der Helmholtzgemeinschaft
EURATOM-Association

EU development of high heat flux components

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A Development of plasma facing components

B Cyclic thermal loads → thermal fatigue

C Intense transient loads → thermal shock

D Neutron induced material degradation

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A

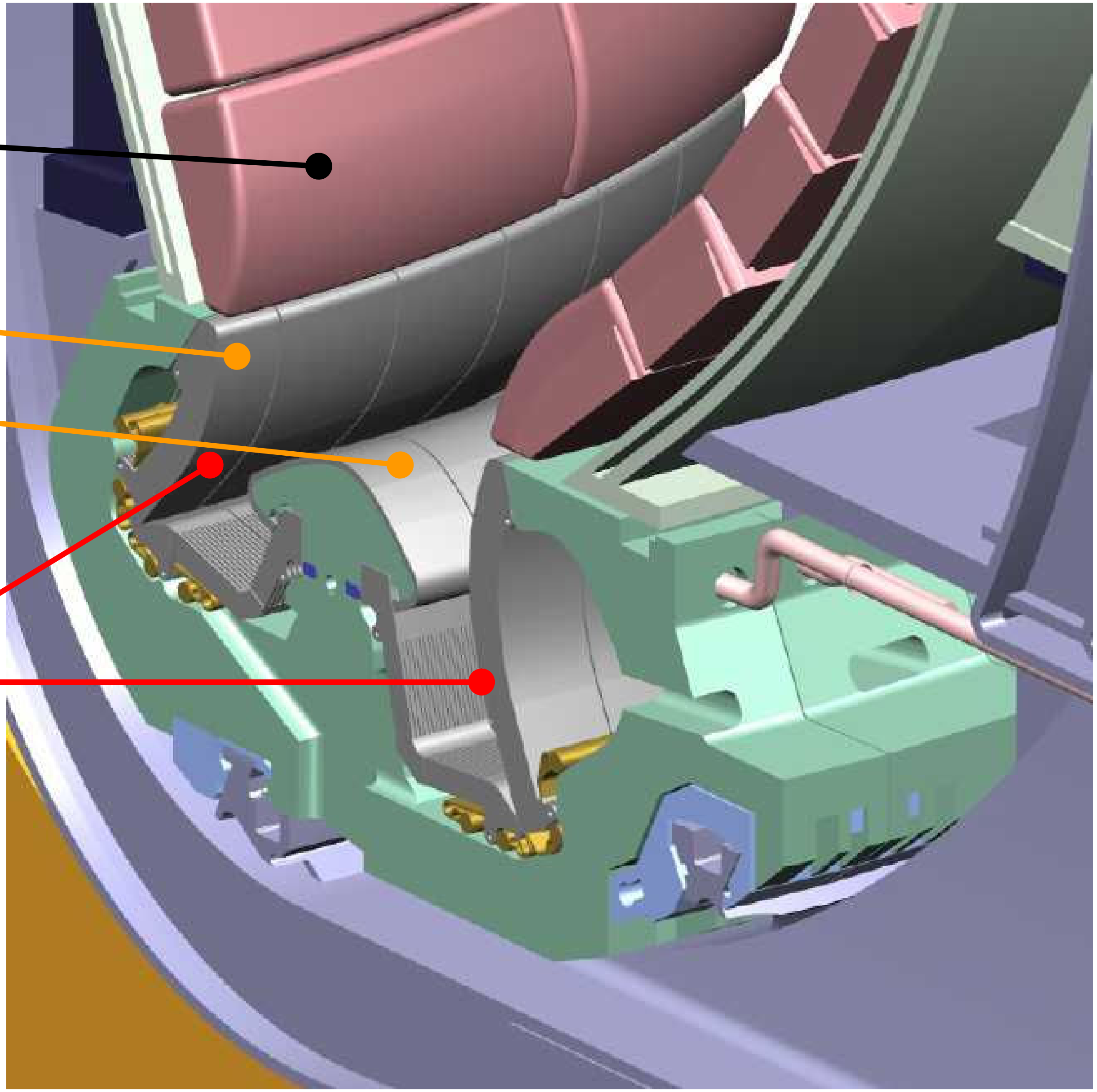
Development of plasma facing components

Plasma Facing Components in ITER

Be: port limiter, primary wall, baffle

W: upper vertical target, dome

CFC: lower vertical target



Wall loads on plasma facing components in ITER

	divertor	first wall
normal operation		
peak surface heat flux / MWm^{-2}	10 (CFC) / 5 (W)	0.5 (Be)
duration / s	≤ 450	≤ 450
number of cycles	3.000	30.000
Slow transients		
peak surface heat flux / MWm^{-2}	20 (on CFC)	---
duration / s	10	---
frequency / %	10	---
disruptions		
peak surface heat load / MJm^{-2}	10 - 30	1
duration / ms	0.1 - 3	0.1 - 3
frequency / %	10	10
vertical displacement events (VDE)		
peak surface heat load / MJm^{-2}	60	---
duration / ms	100 - 300	---
frequency / %	1	---
edge localized modes (ELMs)		
peak surface heat load / MJm^{-2}	1	?
duration / ms	0.1 – 0.5	0.1 – 0.5
frequency / Hz	1	1
Neutron wall load		
displacements per atom / dpa	0.7 (W, CFC) 2 (Cu)	1 (Be) 3 (Cu)
(not considering divertor replacements)		

Development of divertor components for ITER

component design	material qualification	joining techniques	mockups	neutron irradiation	prototype
monoblocks flat tiles (macrobrush)	armour: CFC and W heat sink: DS-Cu CuCrZr	CFC/Cu: laser texturing AMC® e-beam HT-brazing HIPing W/Cu: casting e-beam HT-brazing HIPing	approx. 100 small scale components qualification: ultrasonic thermography HHF-testing: $\geq$ 20 MWm^{-2}, $\geq$ 1000 cycles	materials and components T_{irr}: 200 – 700 °C fluence: 0.1 – 1 dpa (PIE plus in-pile testing)	medium scale VT full scale VT full scale dome

Primary first wall development for ITER

component design	material qualification	joining techniques	mockups	neutron irradiation	prototype
flat tiles (shield block design with poloidal coolant channels)	armour: beryllium heat sink: DS-Cu CuCrZr	Be/DS-Cu: HT-HIPing HT-brazing Be/CuCrZr: LT-HIPing fast brazing DS-Cu/SS, CuCrZr/SS: HAT-HIPing	approx. 50 small scale components qualification: ultrasonic HHF-testing: $\geq$ 2.5 MWm^{-2}, $\geq$ 30.000 cycles	materials and components T_{irr}: up to 700 °C fluence: 0.3 – 1.0 dpa (PIE plus in-pile testing in preparation)	several full scale primary first wall components

B

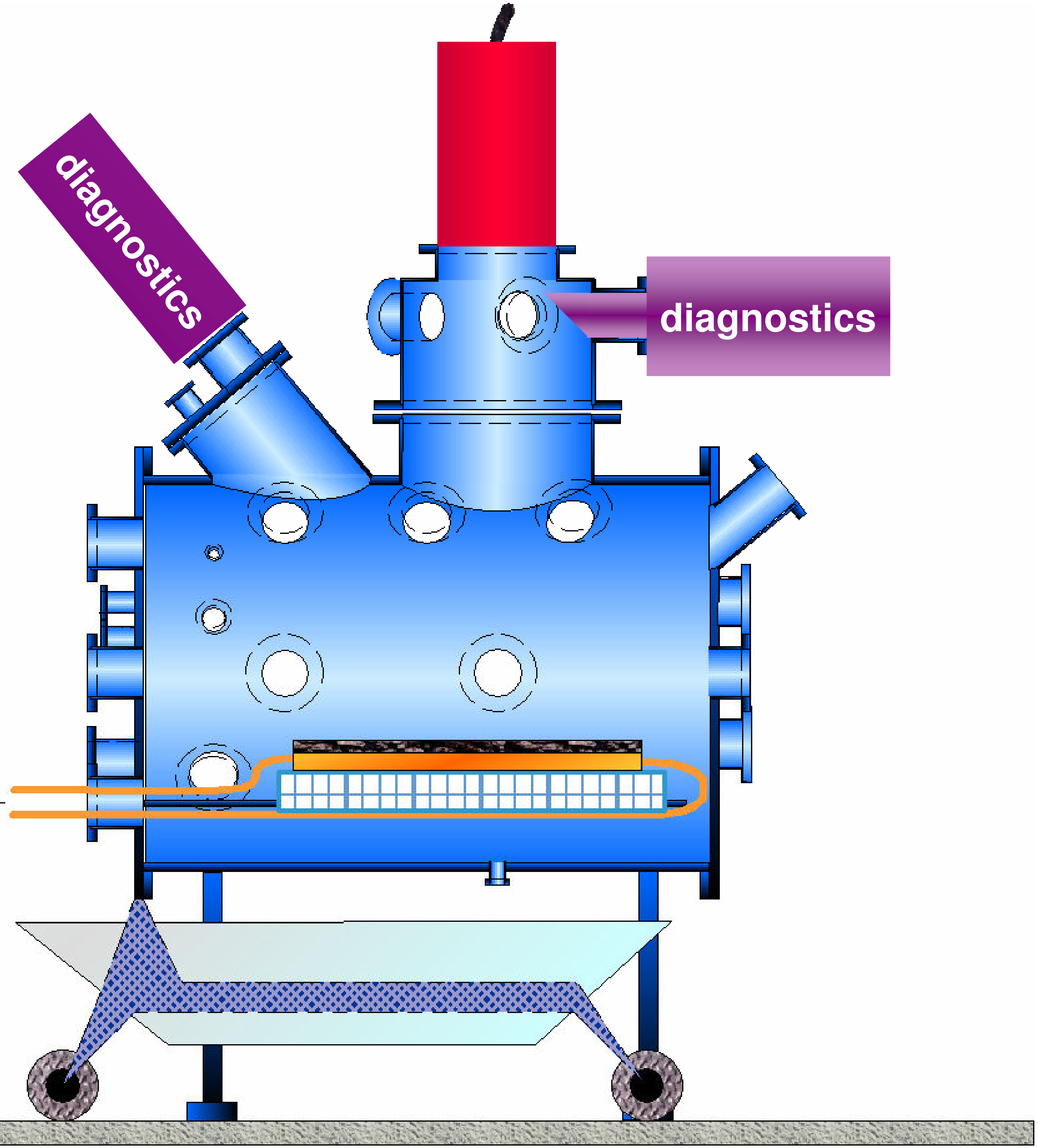
Cyclic thermal loads $\rightarrow$ thermal fatigue

JUDITH II

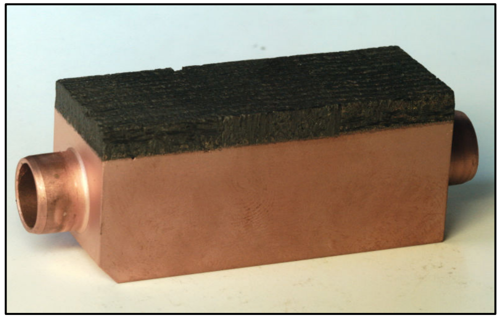
schematic view into the vacuum chamber

Diagnostics:

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



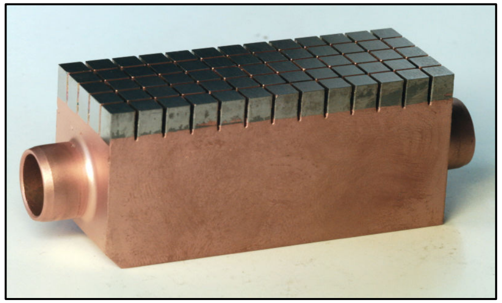
Small scale divertor mock-ups – flat tile design



CFC flat tile mock-up

- active metal casting of CFC tiles (silicon doped SEPcarb NS31)
- e-beam welding to CuCrZr heat sink

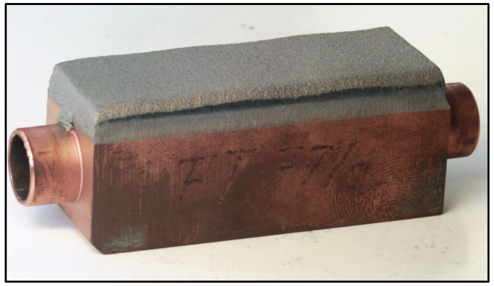
HHF test:
1000 cycles @ 19 MWm^{-2}
without failure
430 cycles @ 23.5 MWm^{-2}
tile detachment



W macrobrush mock-up

- coating of W tiles with OFHC-Cu
- e-beam welding to CuCrZr heat sink

HHF test:
1000 cycles @ 18 MWm^{-2}
without failure



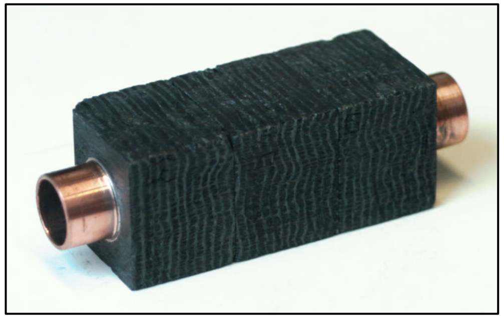
PS-W mock-up

- vacuum plasma spraying of tungsten

HHF test:
1000 cycles @ 5.5 MWm^{-2}
without failure
1000 cycles @ 7.6 MWm^{-2}
increasing T_{surf}

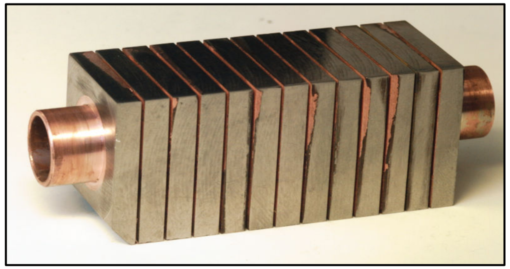
Divertor mock-ups for ITER (second generation), miniaturized for neutron-irradiation
all samples: 22 mm width, 58 mm length

Small scale divertor mock-ups – monoblock design



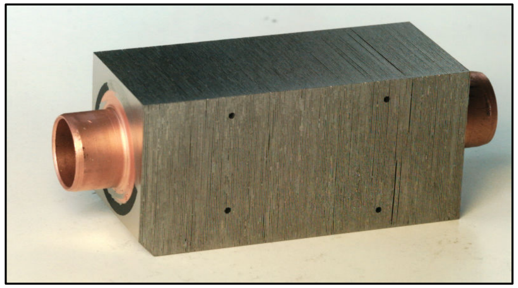
CFC monoblock
- drilling of CFC tiles (SEPcarb NB31)
- active metal casting (AMC)
- low temperature HIPing

HHF test:
1000 cycles @ 19 MWm^{-2}
without failure
683 cycles @ 23 MWm^{-2}
without failure of the braze;
erosion



W monoblock mock-up (monolytic type)
- drilling of W-La_2O_3 monoliths (4 mm thickness)
- casting with OFHC-Cu
- HIPing

HHF test:
1000 cycles @ 18 MWm^{-2}
without failure

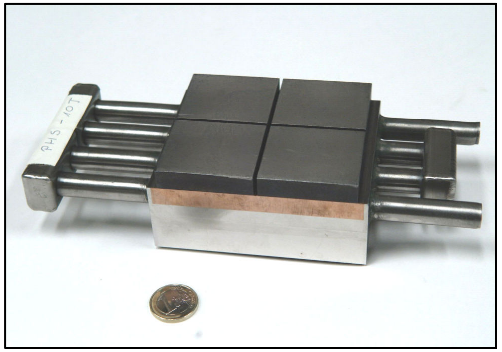


W monoblock mock-up (lamellae technique)
- drilling of W sheets (200 µm thickness)
- casting with OFHC-Cu
- low temperature HIPing

HHF test:
1000 cycles @ 18 MWm^{-2}
without failure

Divertor mock-ups for ITER (second generation), miniaturized for neutron-irradiation
all samples: 22 mm width, 58 mm length

Primary first wall mock-ups / beryllium armour



Primary first wall mock-up

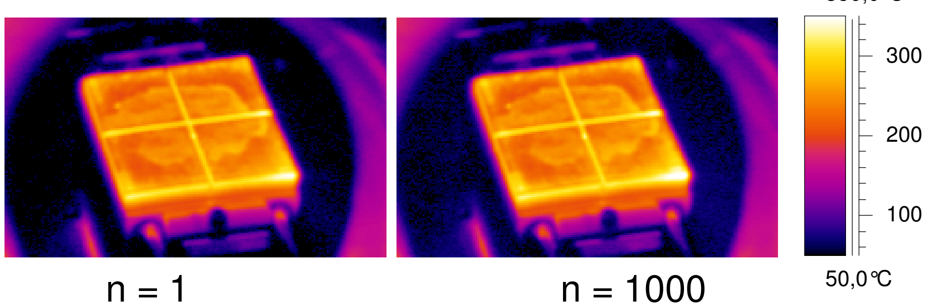
- beryllium tiles (42 x 47 x 10 mm³)
- CuCrZr heat sink (10 mm thickness) with 316L coolant tubes
- 316L backing plate (30 mm thickness)

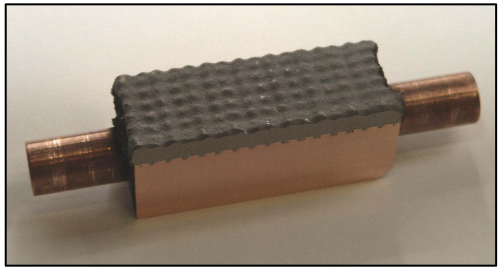
HHF test:
1000 cycles @ 1.5 MWm^{-2} without failure

200 cycles @ 2.0 MWm^{-2} slight increase of t_{surf}

tile detachment @ 2.5 MWm^{-2}

fatigue testing at 1.5 MWm^{-2}



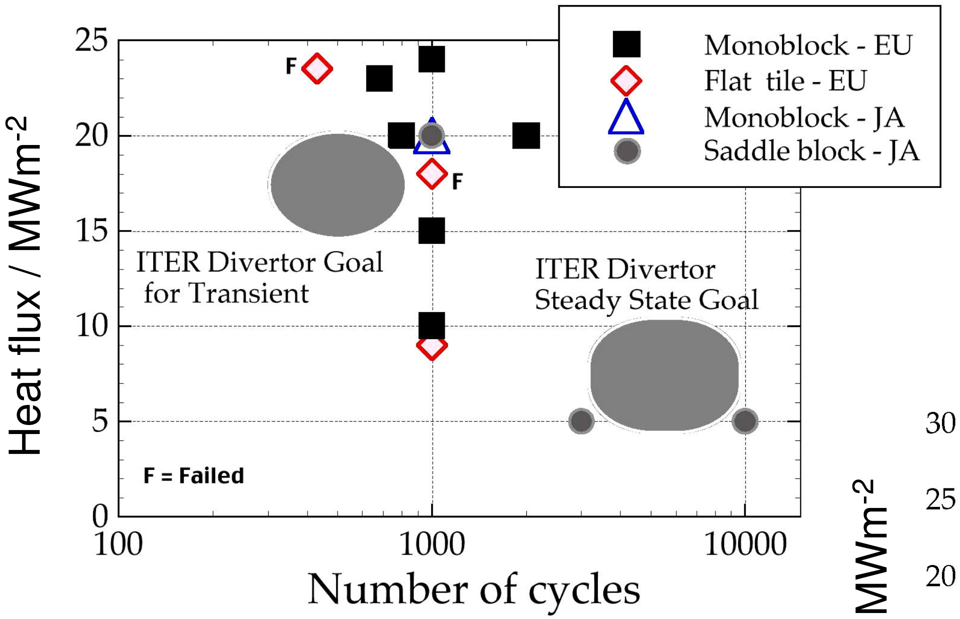


PS-Be mock-up

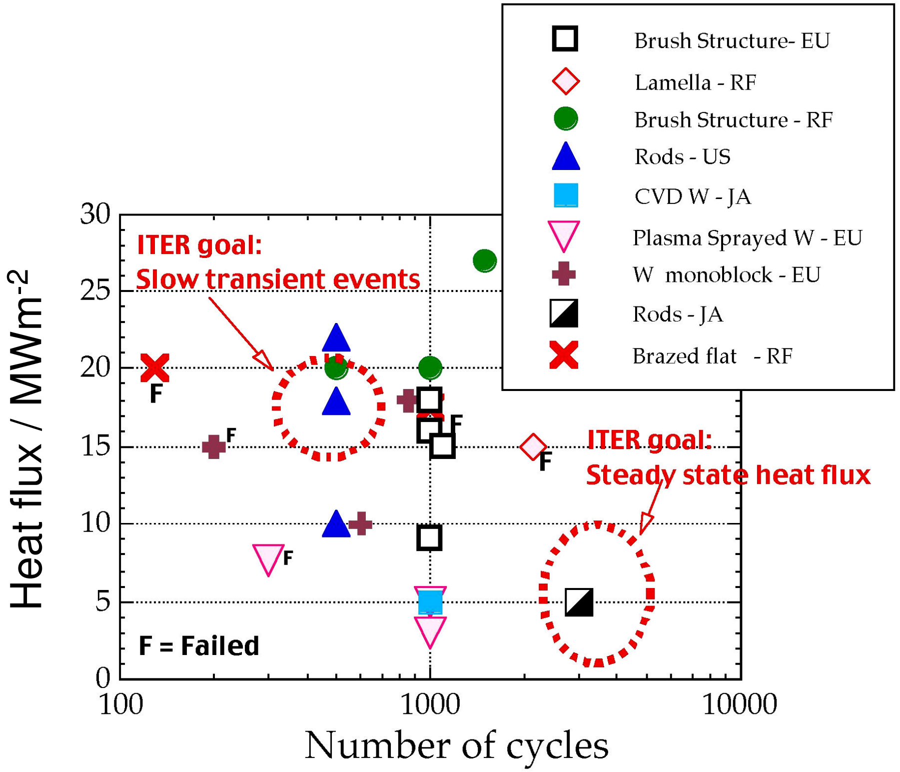
- vacuum plasma spraying of beryllium (5 mm thickness) (R. Castro, Los Alamos Nat. Lab.)

HHF test:
1000 cycles @ 3.0 MWm^{-2} without failure
100 cycles @ 4.0 MWm^{-2} increasing T_{surf}

High heat flux performance of divertor components



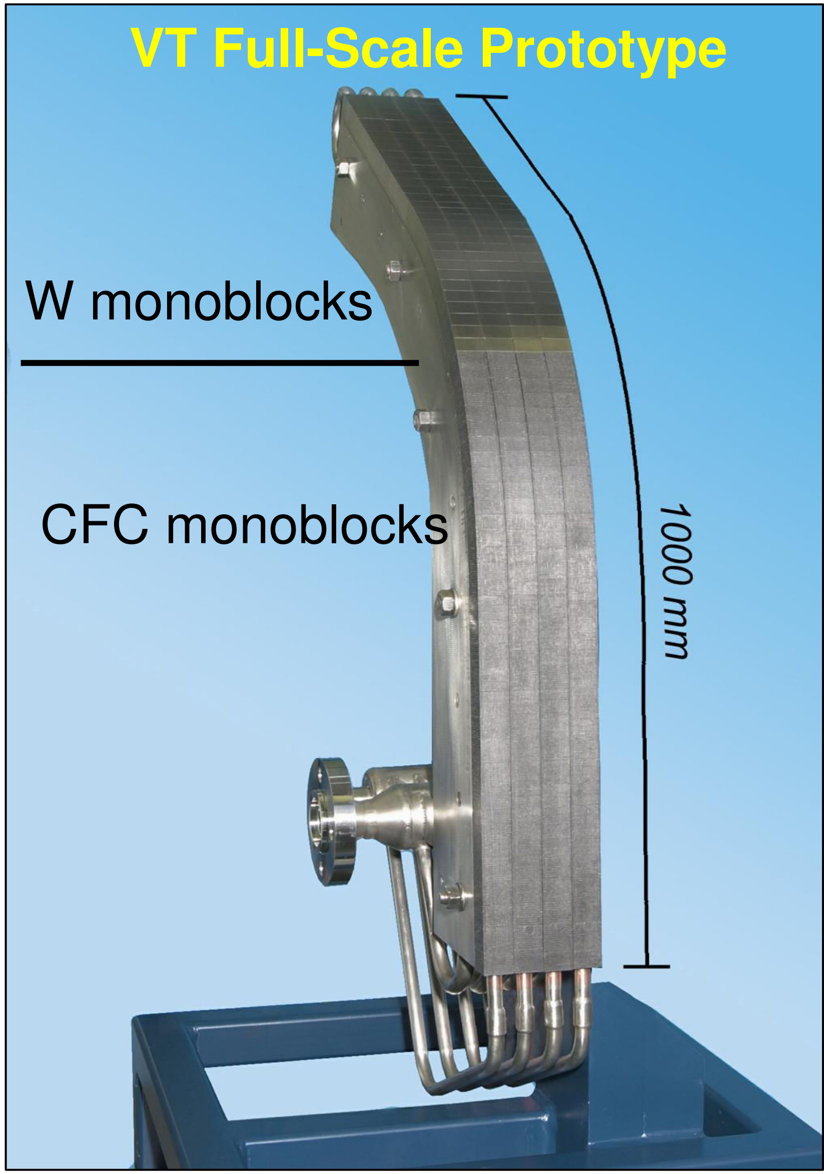
CFC-Cu joints



tungsten-Cu joints

Source: http://www.iter.org/

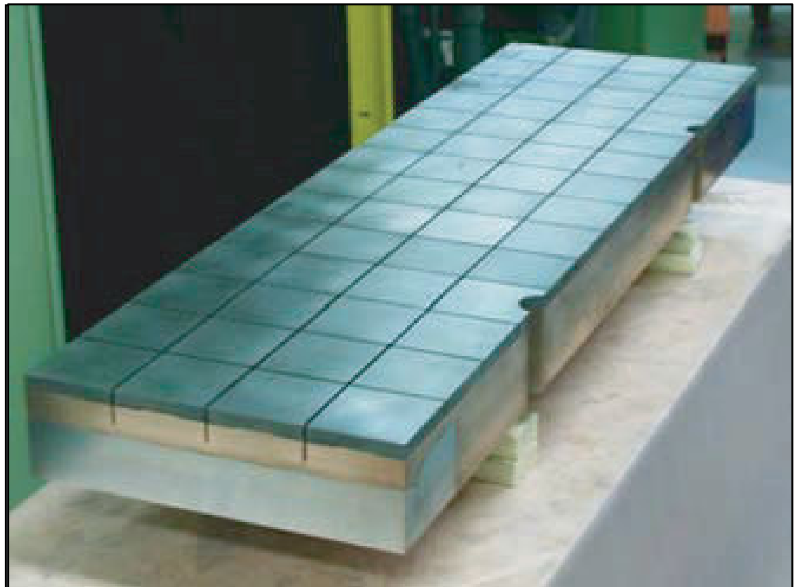
Development of medium / full-scale components



HHF tests in the FE200, Le Creusot (F):

W monoblocks: 10 MW/m^2 x 700 cycles

CFC monoblocks: 23 MW/m^2 x 2000 cycles



Full scale FW panel prototype (Be brazed to DSCu)

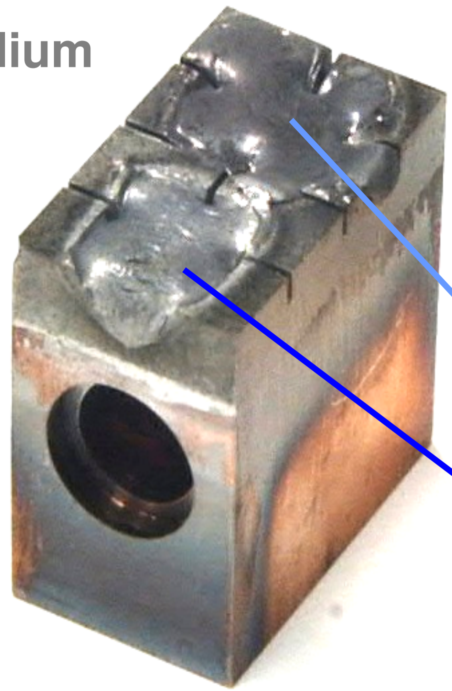
C

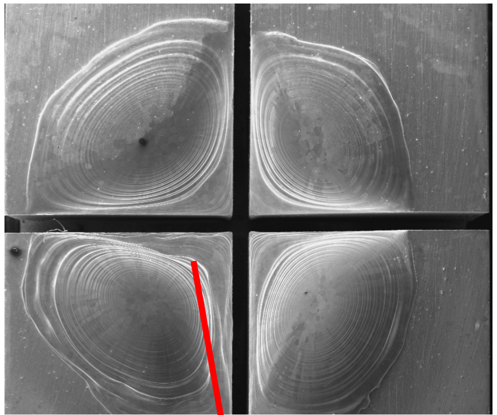
Intense transient loads $\rightarrow$ thermal shock

Vertical displacement events (VDEs)

e-beam experiments: absorbed energy density: 60 MJm^{-2}

beryllium
S65C





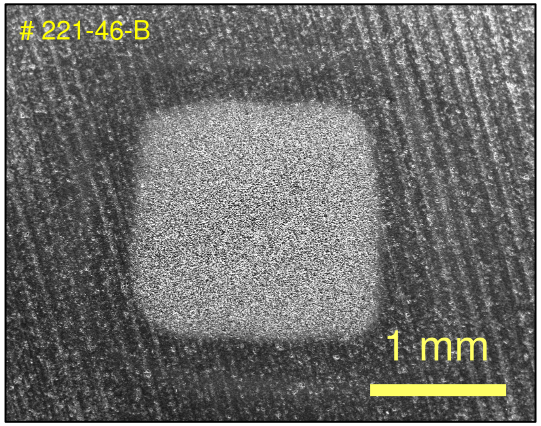
$W1\%La_2O_3$

material	pulse length [ms]	melt depth [mm]
$W1\%La_2O_3$	100	1.3
	300	1.0
beryllium S65C	100	2.3
	300	2.8

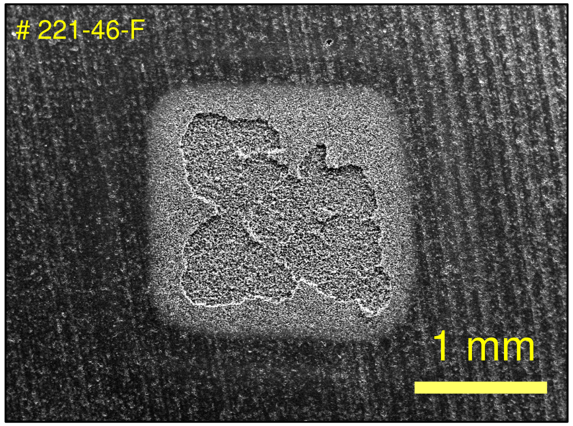
Brittle destruction analysis (graphite R6650)

simulation of plasma disruptions
with a scanned electron beam

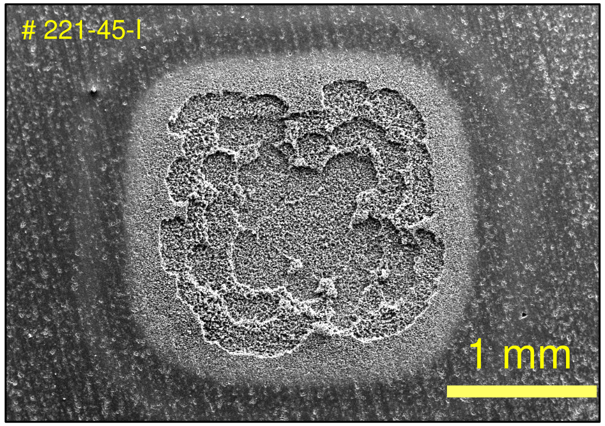
Increasing power density



P_{abs} = 3.1 GW m^{-2}



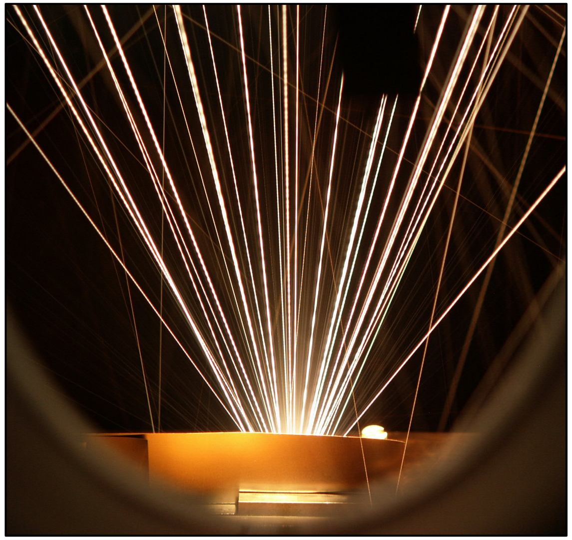
P_{abs} = 3.3 GW m^{-2}

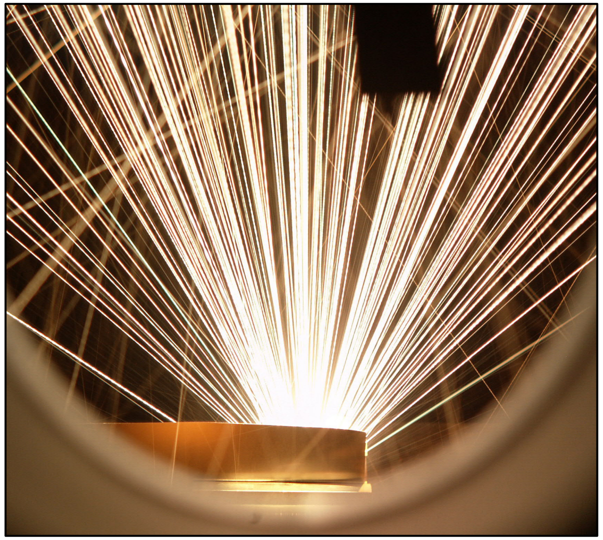


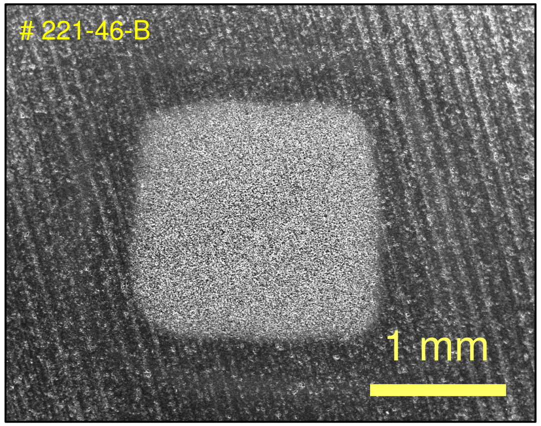
P_{abs} = 4.3 GW m^{-2}

U_{acc} = 120 kV, Δt = 2 ms

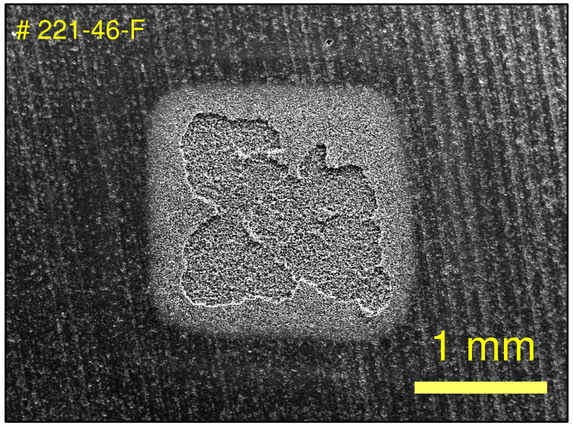
Brittle destruction analysis (graphite R6650)



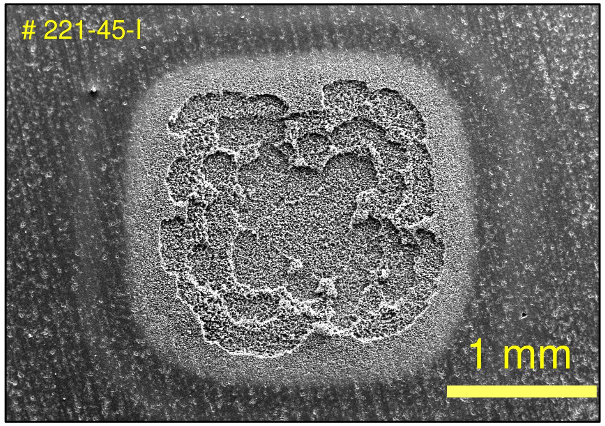




P_{abs} = 3.1 GW m^{-2}



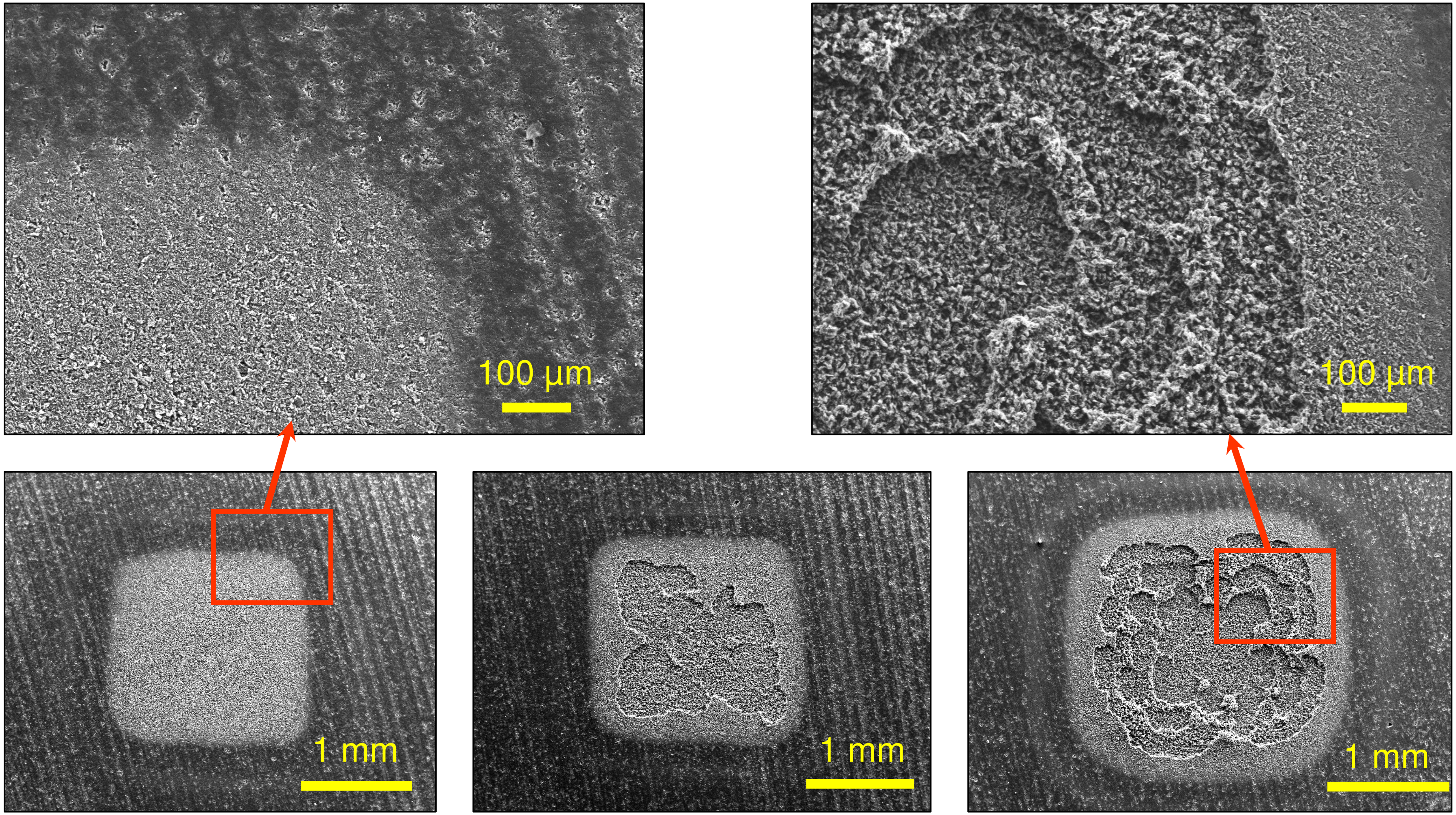
P_{abs} = 3.3 GW m^{-2}



P_{abs} = 4.3 GW m^{-2}

U_{acc} = 120 kV, Δt = 2 ms

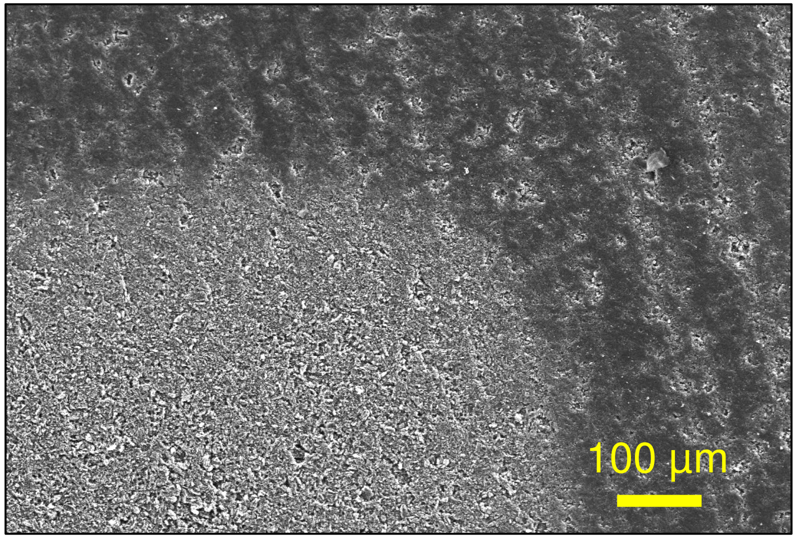
Brittle destruction analysis (graphite R6650)

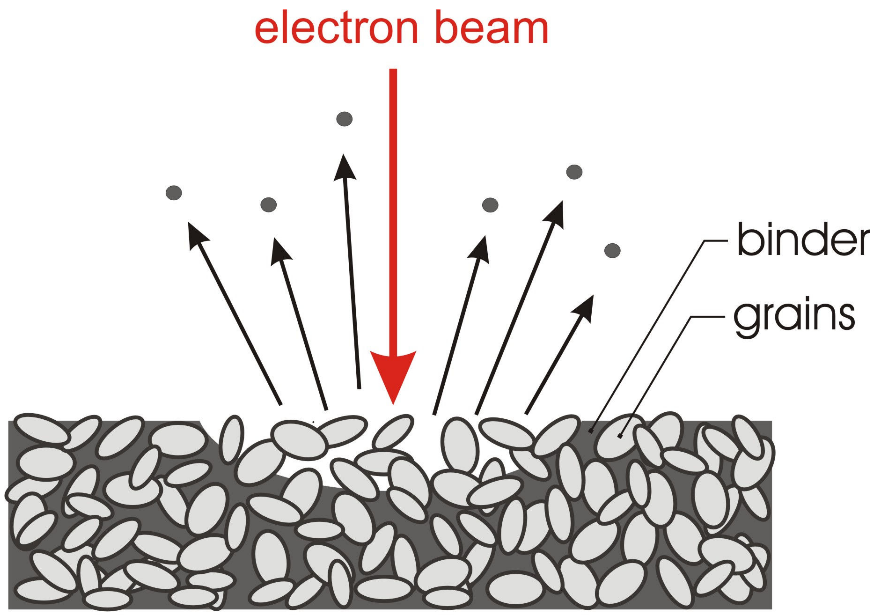


P_{abs} = 3.1 GW m^{-2} P_{abs} = 3.3 GW m^{-2} P_{abs} = 4.3 GW m^{-2}

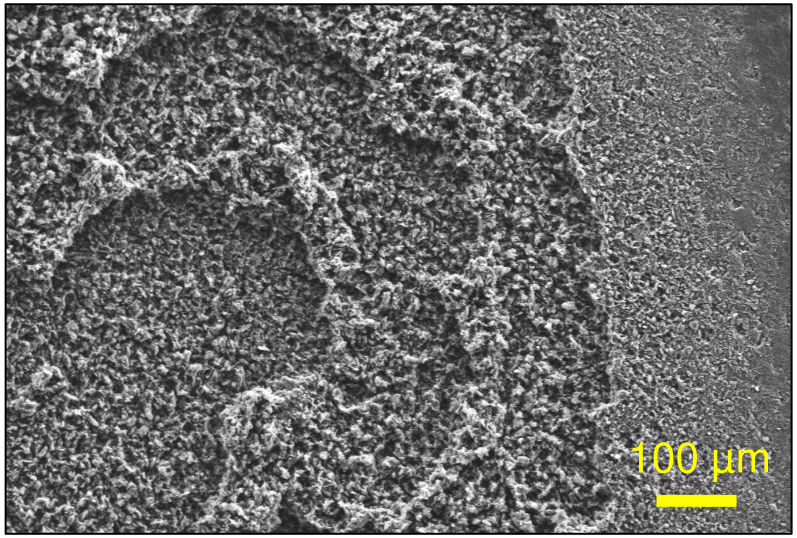
U_{acc} = 120 kV, Δt = 2 ms

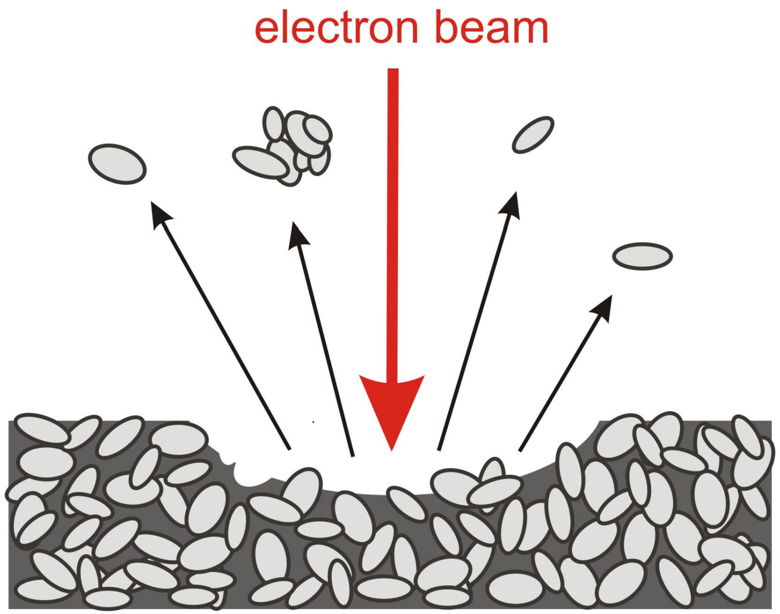
Brittle destruction analysis (graphite R6650)





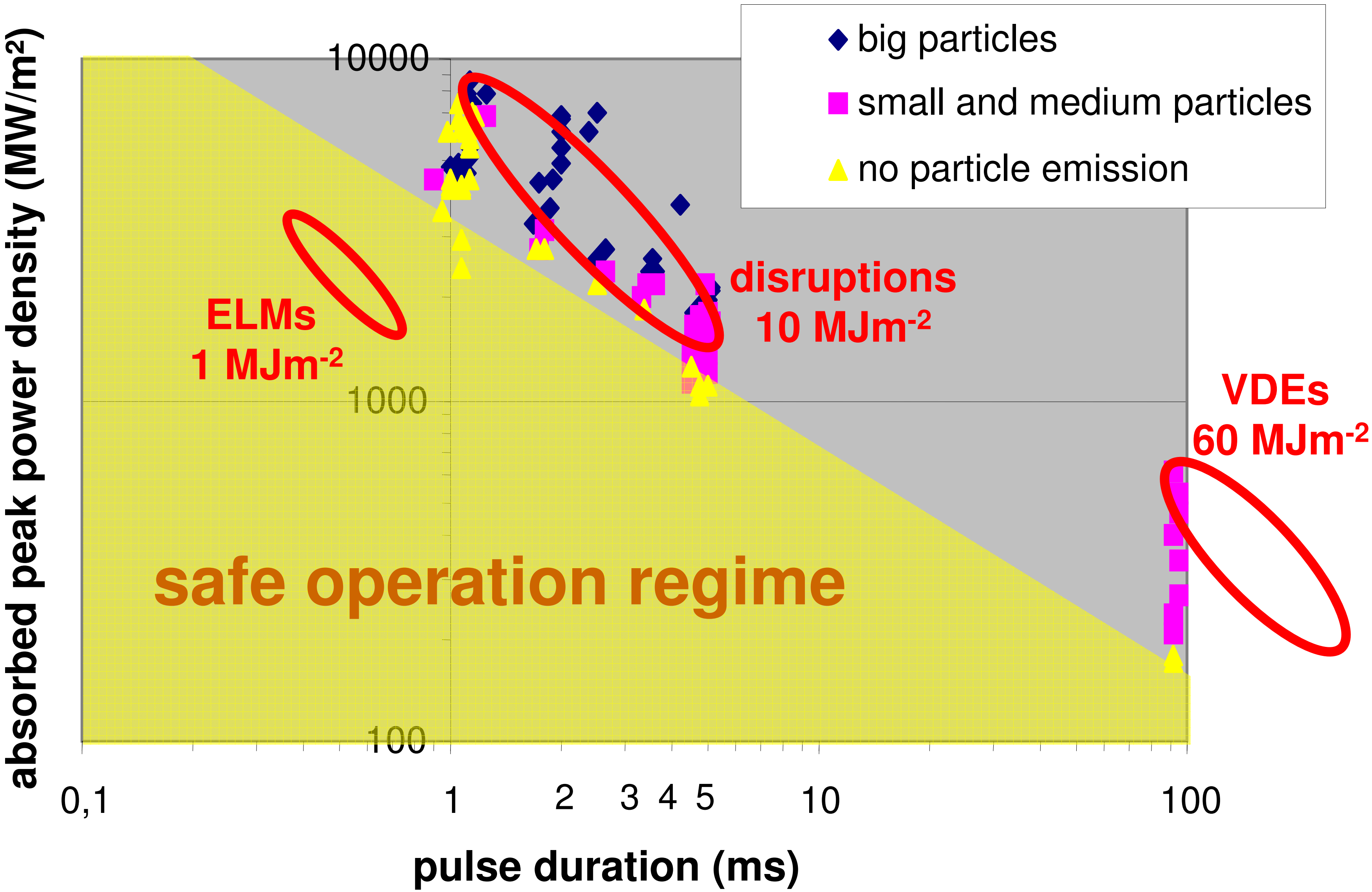
isotropic fine grain graphite



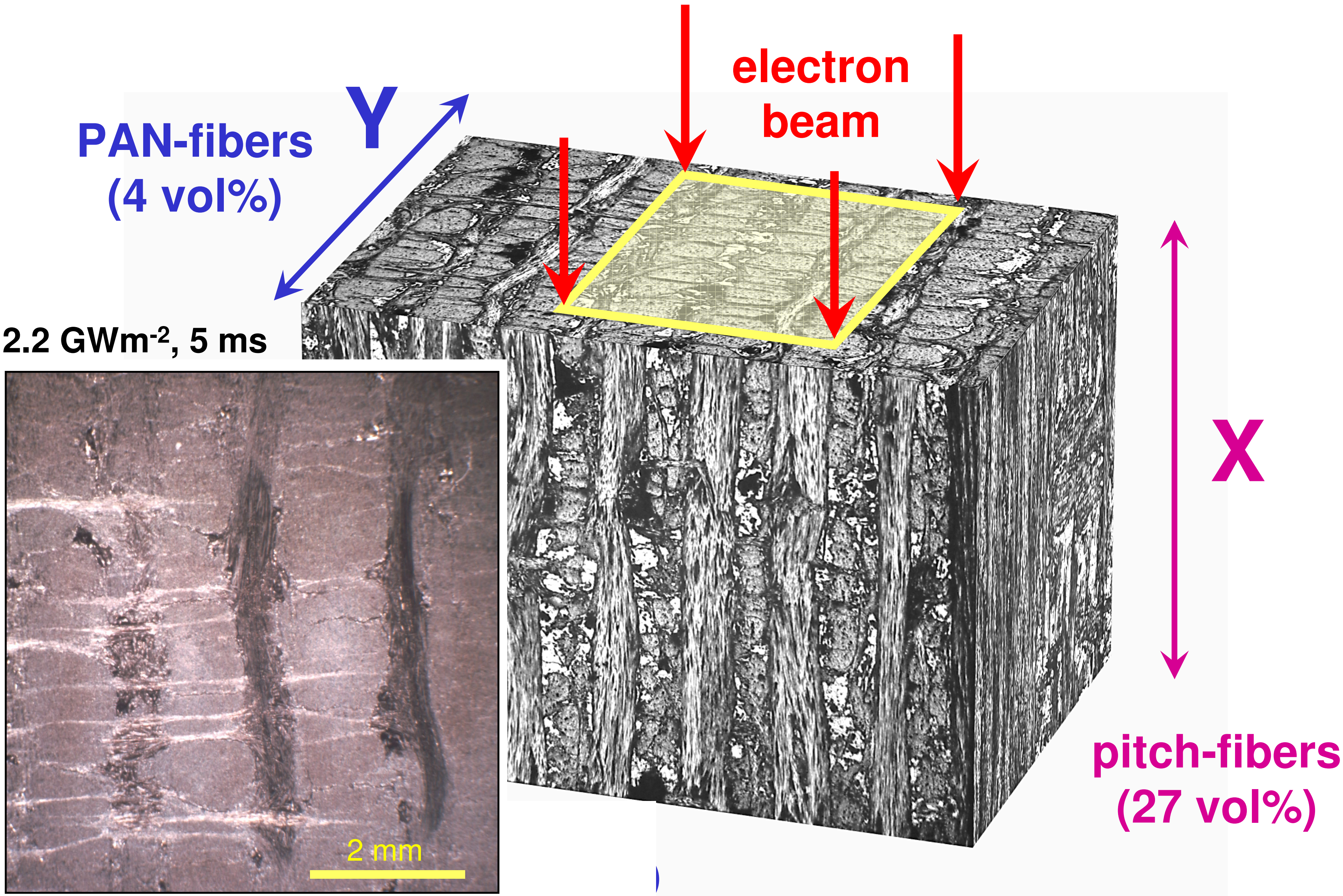


isotropic fine grain graphite

Brittle destruction analysis (graphite R6650)

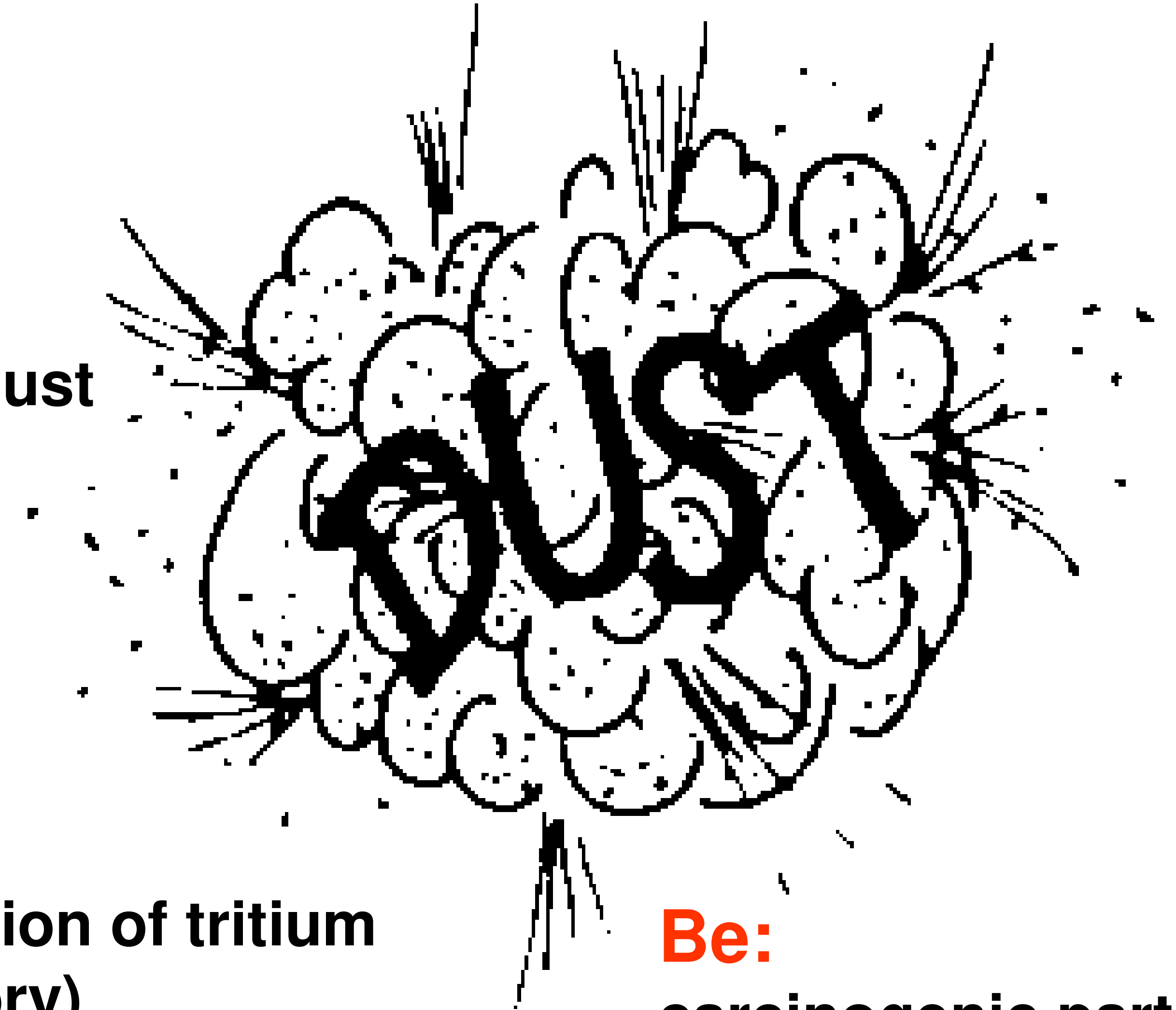


Carbon fiber composite NS31



Transient thermal loads on graphitic or metallic wall materials

W:
activated dust



CFC:
codeposition of tritium
(T inventory)

Be:
carcinogenic particles

D

Neutron induced material degradation

Neutron irradiation experiment PARIDE

thermal shock specimens

4-point bending test

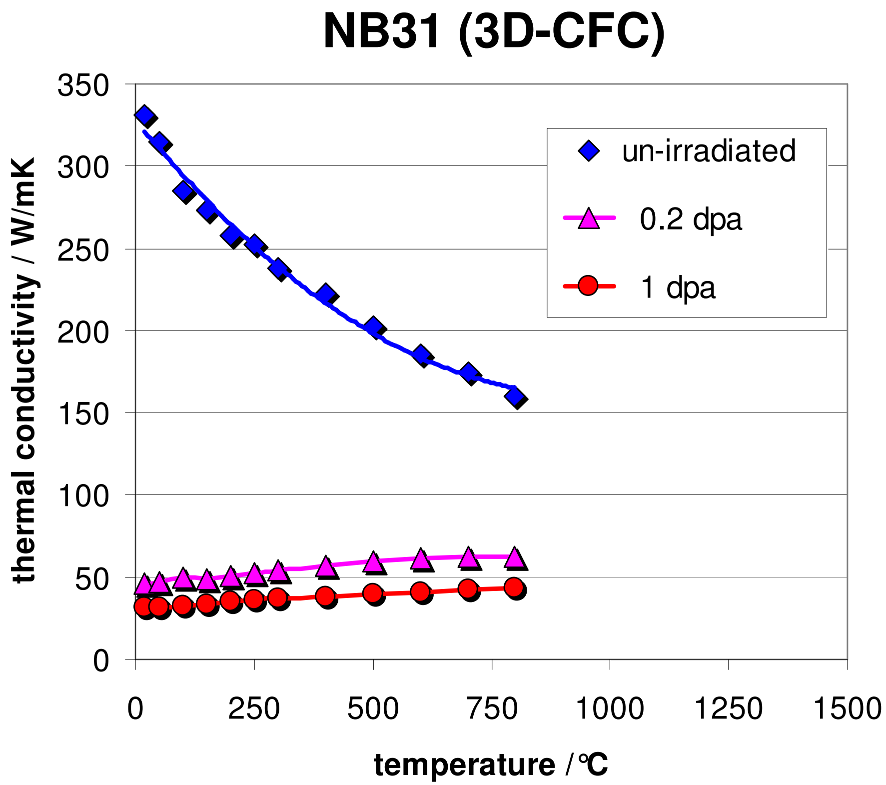
mechanical testing of joints

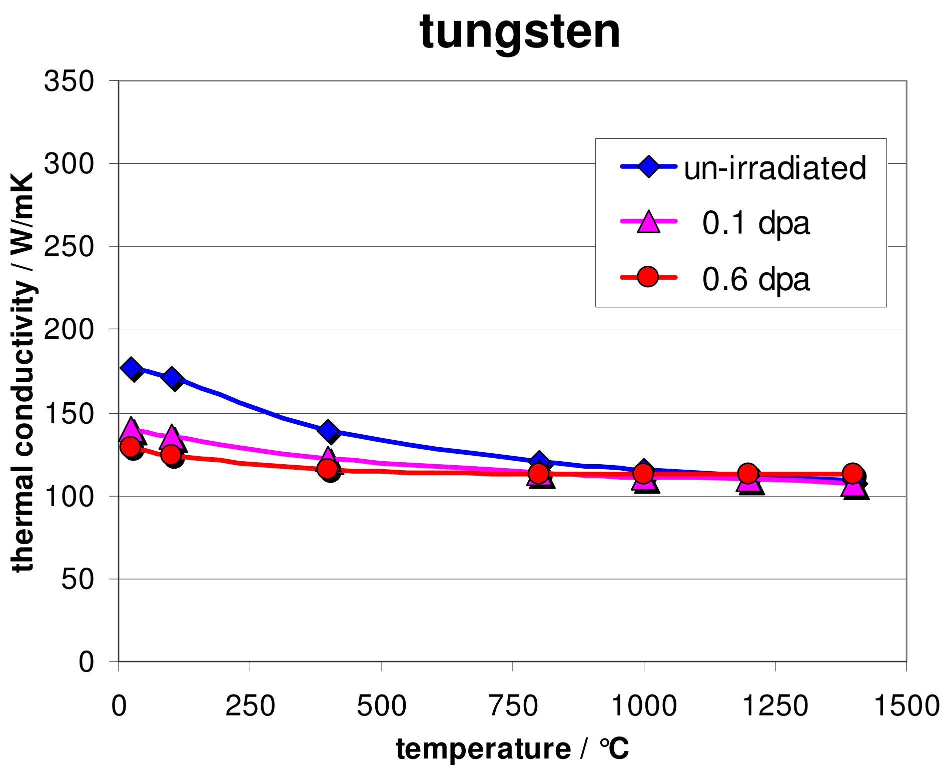
thermal conductivity

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	

Neutron irradiation effect on thermal conductivity





Testing of irradiated CFC mooblock mock-ups

width 22 mm , length 58 mm

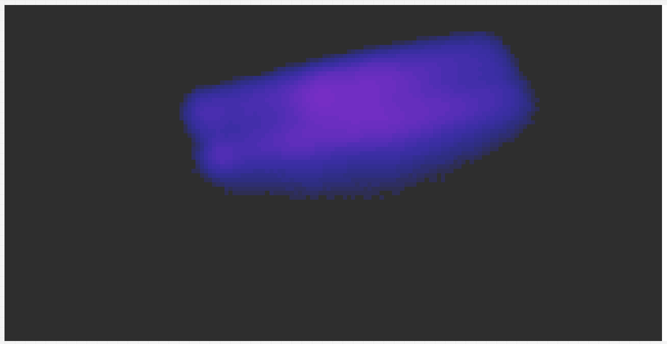
armour material: CFC SEPcarb NB31

heat sink material: CuCrZr tube

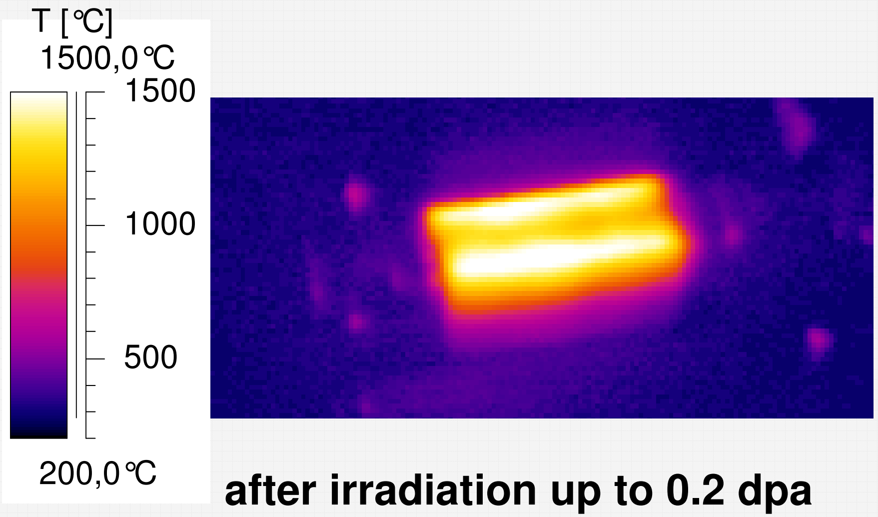
production process:
- **drilling of CFC tiles**
- **laser structuring of CFC**
- **active metal casting (AMC) of CFC tiles**
- **low temperature HIPing to CuCrZr tube**

producer: Plansee AG

screening test at 5 MW/m²



unirradiated
max. surface temp.: 401 °C



after irradiation up to 0.2 dpa
max. surface temp.: 1580 °C

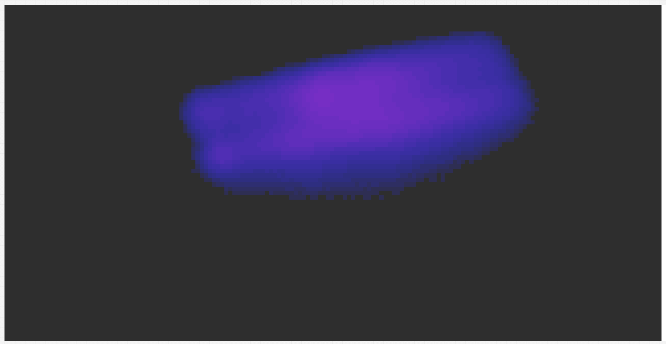
Testing of irradiated CFC monoblock mock-ups

width 22 mm , length 58 mm

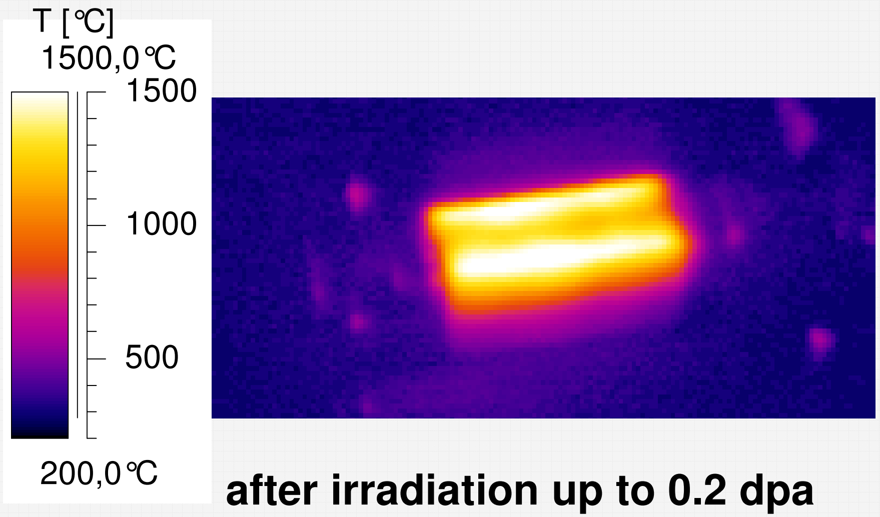
unirradiated
- 1000 cycles @ 19 MW/m2- no failure
- 700 cycles @ 23 MW/m2 – no failure,
  (test stopped due to surface erosion)

PARIDE 3: 200°C, 0.2 dpa (in carbon)
- 1000 cycles @ 10 MW/m² – no failure
- 1000 cycles @ 12 MW/m² – no failure
- screening @ 14 MW/m² - surface erosion

screening test at 5 MW/m²

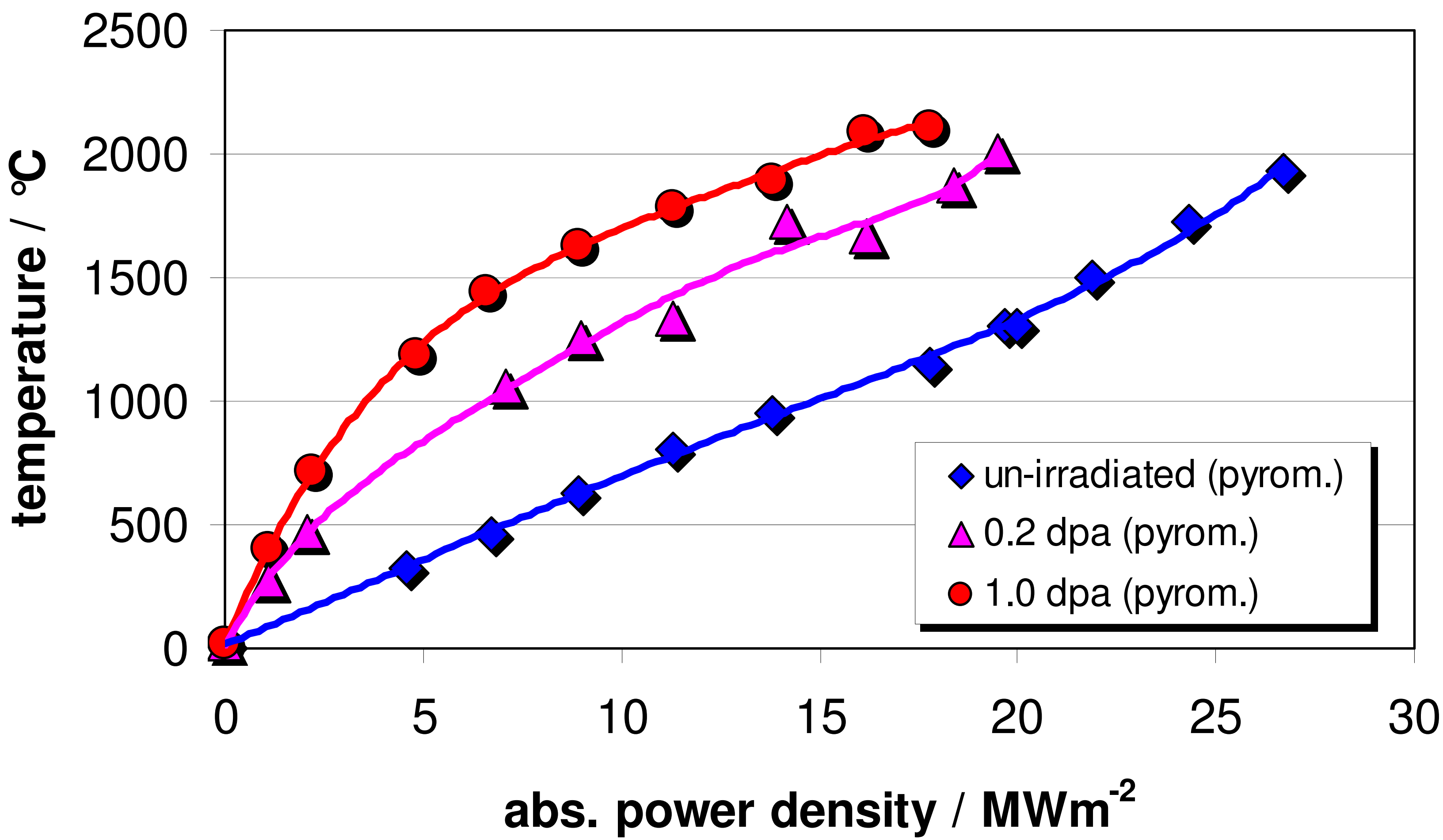


unirradiated
max. surface temp.: 401°C

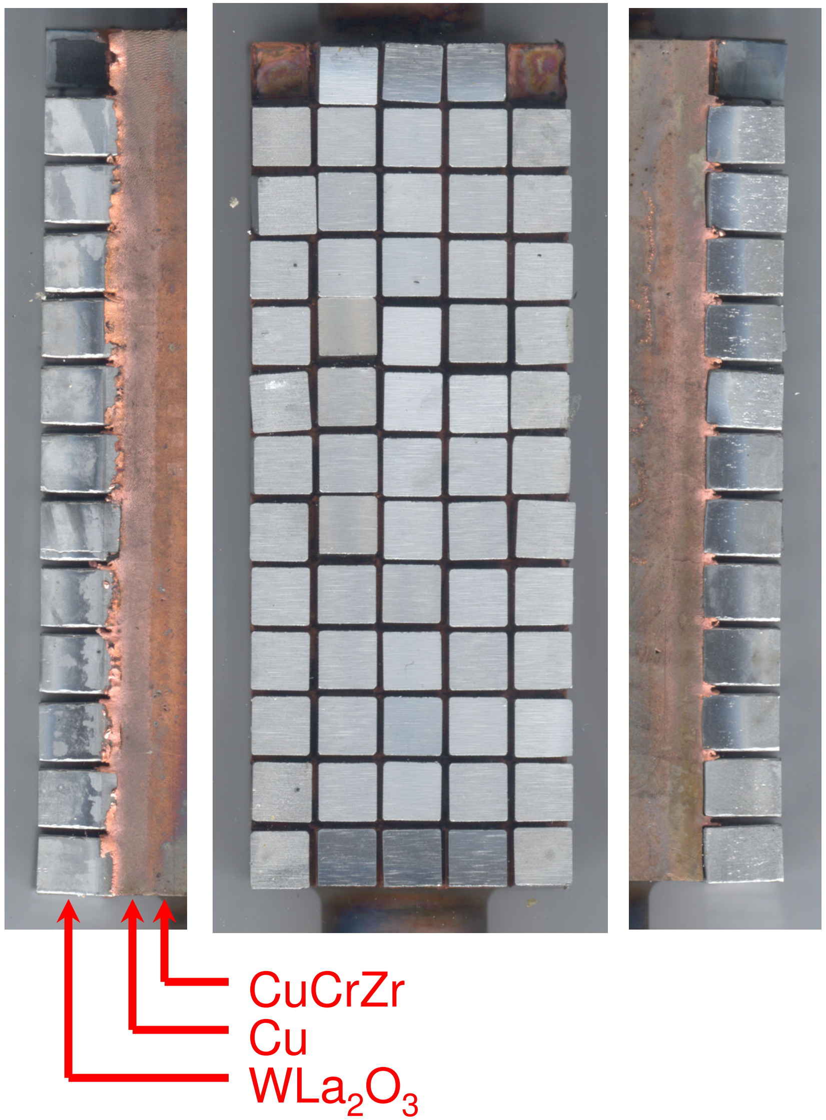


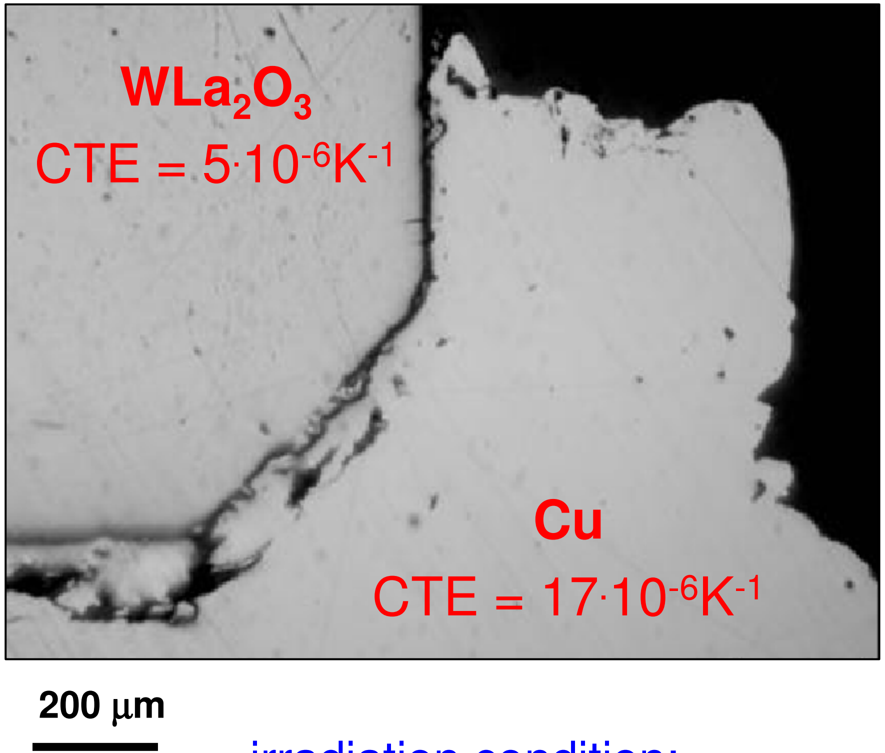
after irradiation up to 0.2 dpa
max. surface temp.: 1580°C

Thermal response of irradiated CFC flat tile modules
(NS31 on CuCrZr)



Thermal fatigue testing of a tungsten macrobrush module irradiated in the HFR-Petten

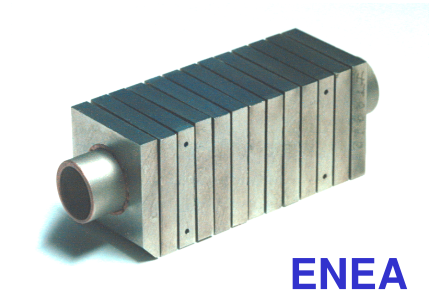
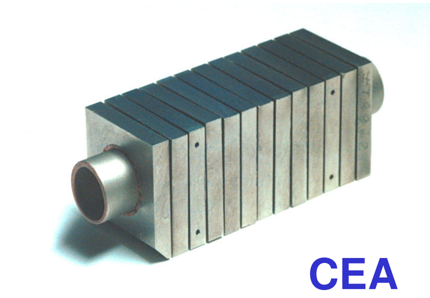
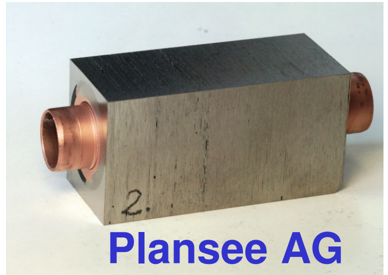




irradiation condition:
200°C – 0.1 dpa (in W)

loading condition:
1000 cycles at 10 MW/m^2

Thermal Fatigue Testing of Tungsten Monoblock Mock-Ups
- Results -

	W-monoblock 	W-monoblock 	W-lamellae design 
unirradiated	1000 x 14.5 MW/m^2	1000 x 9.6 MW/m^2 1000 x 18.0 MW/m^2	1000 x 7.5 MW/m^2 1000 x 14.4 MW/m^2
0.1 dpa **T_{irr} = 200ºC**	1000 x 10.0 MW/m^2 100 x 13.7 MW/m^2 1000 x 17.9 MW/m^2		1000 x 10.0 MW/m^2 1000 x 13.7 MW/m^2 1000 x 18.1 MW/m^2
0.6 dpa **T_{irr} = 200ºC**		1000 x 10.0 MW/m^2 1000 x 13.7 MW/m^2 1000 x 18.0 MW/m^2	1000 x 14.0 MW/m^2 1000 x 17.1 MW/m^2

no failure observed !

Summary

Plasma facing materials / components

- materials for high heat flux components in ITER (CFCs, tungsten and beryllium, copper alloys) have been qualified
- ≈ 100 small and full scale components have been manufactured using different joining techniques (casting, e-beam welding, HIPing, brazing)

Thermal fatigue and thermal shock

- technical solutions for cyclic thermal loads up to ~20 MWm^{-2} are available (CFC- or W-monoblocks represent a more robust design solution)
- off-normal events such as VDEs or disruptions result in irreversible damage (melting, crack formation, ...)
- 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 drastically decreased (especially for CFCs)
- the surface temperature of high heat flux components is significantly increased after neutron irradiation