Modelling of brittle destruction of ITER armour under repetitive loads

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Outline

– simulations for ITER divertor erosion with transients in FZK - KIT

– overview of PEGASUS-3D results and verifications

– last results on W cracking simulations

– conclusions and open questions

Simulation of tokamaks armour erosion in KIT

PEGASUS-3D

Simulates:

- physics of brittle destruction
- effective heat conductivity
- dust production
- CPU time consuming code

PHEMOBRID

Simulates erosion :

- using effective heat conductivity and brittle destruction threshold
- fast calculations
- simple and robust

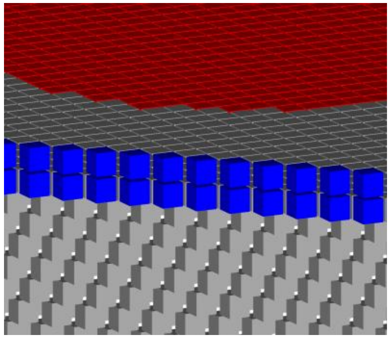
MEMOS

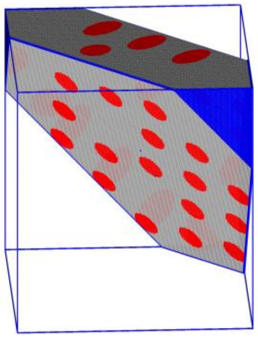
Simulates:

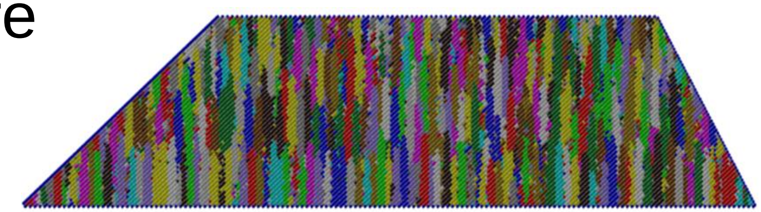
- metal melting and vaporization
- melt splashing

Pegasus-3D code

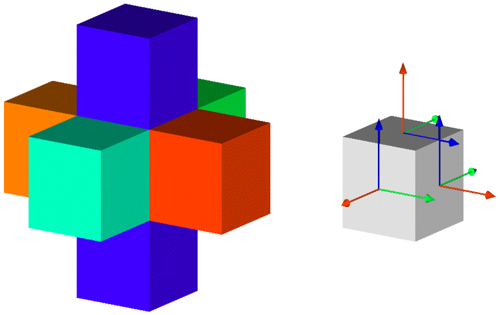
- Simulates cracking of solids under fast heat loads
- Creates numerical sample, which simulates graphite or CFC structure (random grains, fibres, up to 300×300×300 cells)
- Simulates:
  - Heating and heat conductivity in the sample
  - Calculates thermostress
  - Cracks formation and propagation
  - Dust particles splitting
- Calculates the dust particles number and the size statistics



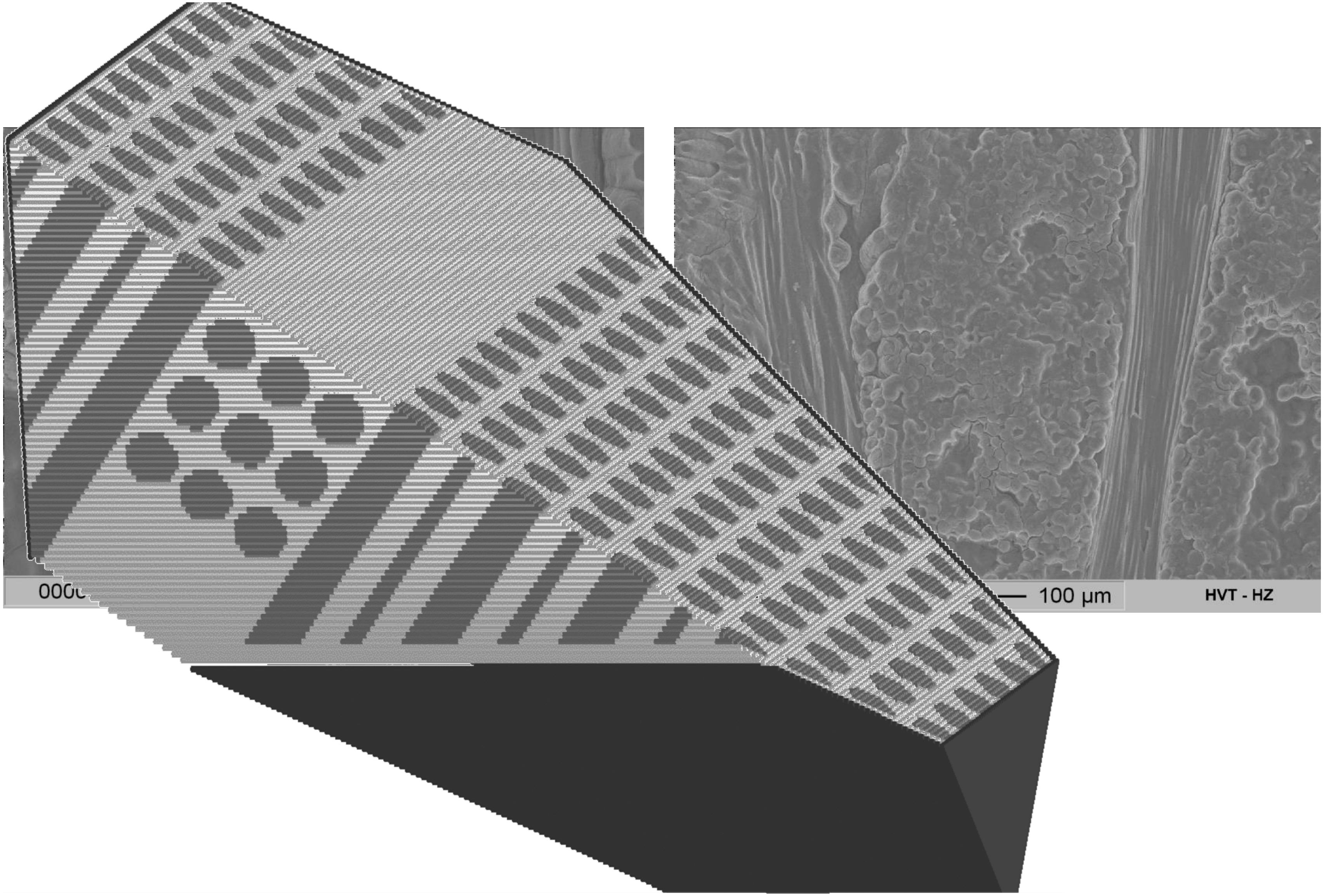




numeric sample and the forces



Simulation of the CFC erosion pattern with PEGASUS-3D code



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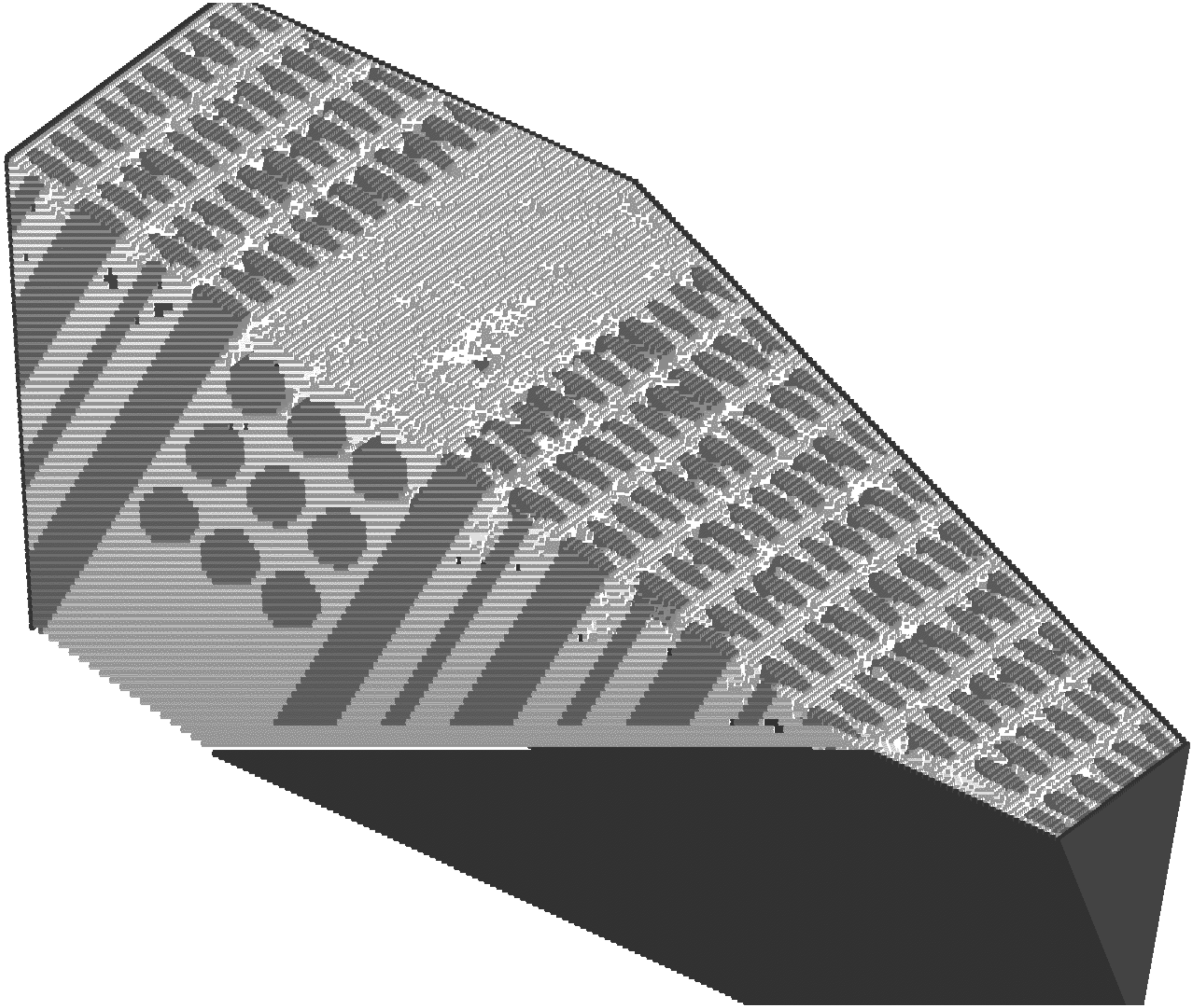

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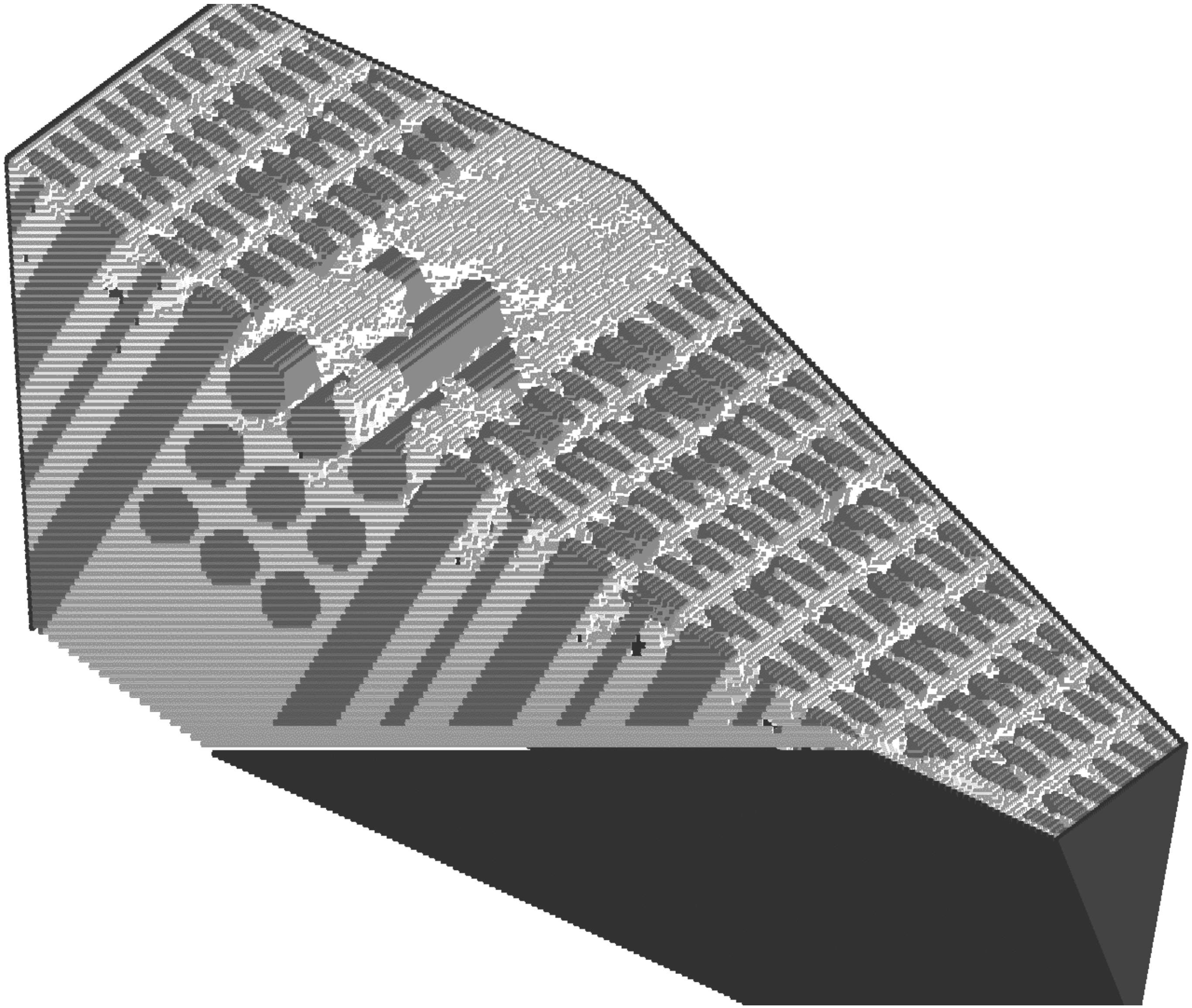

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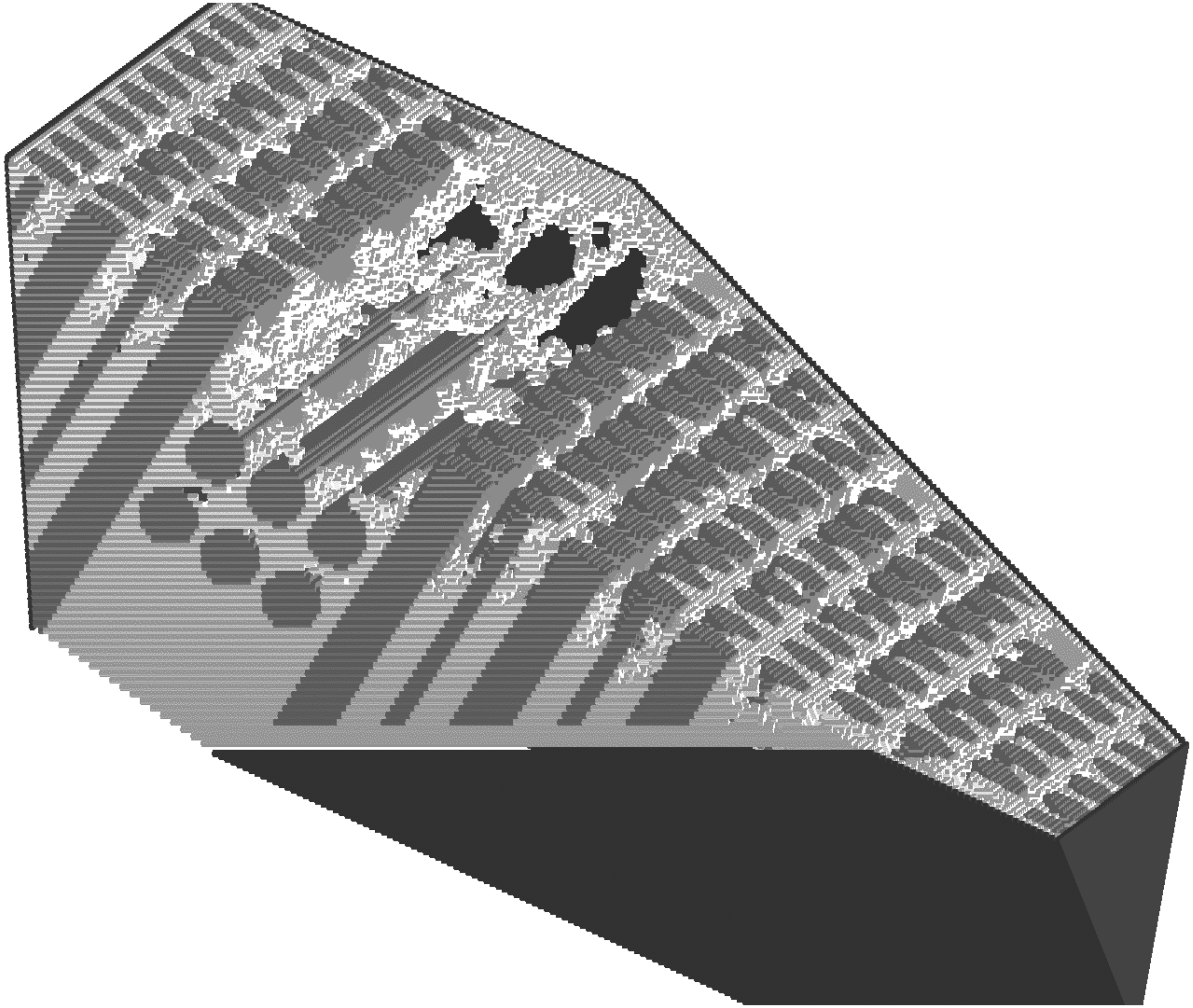
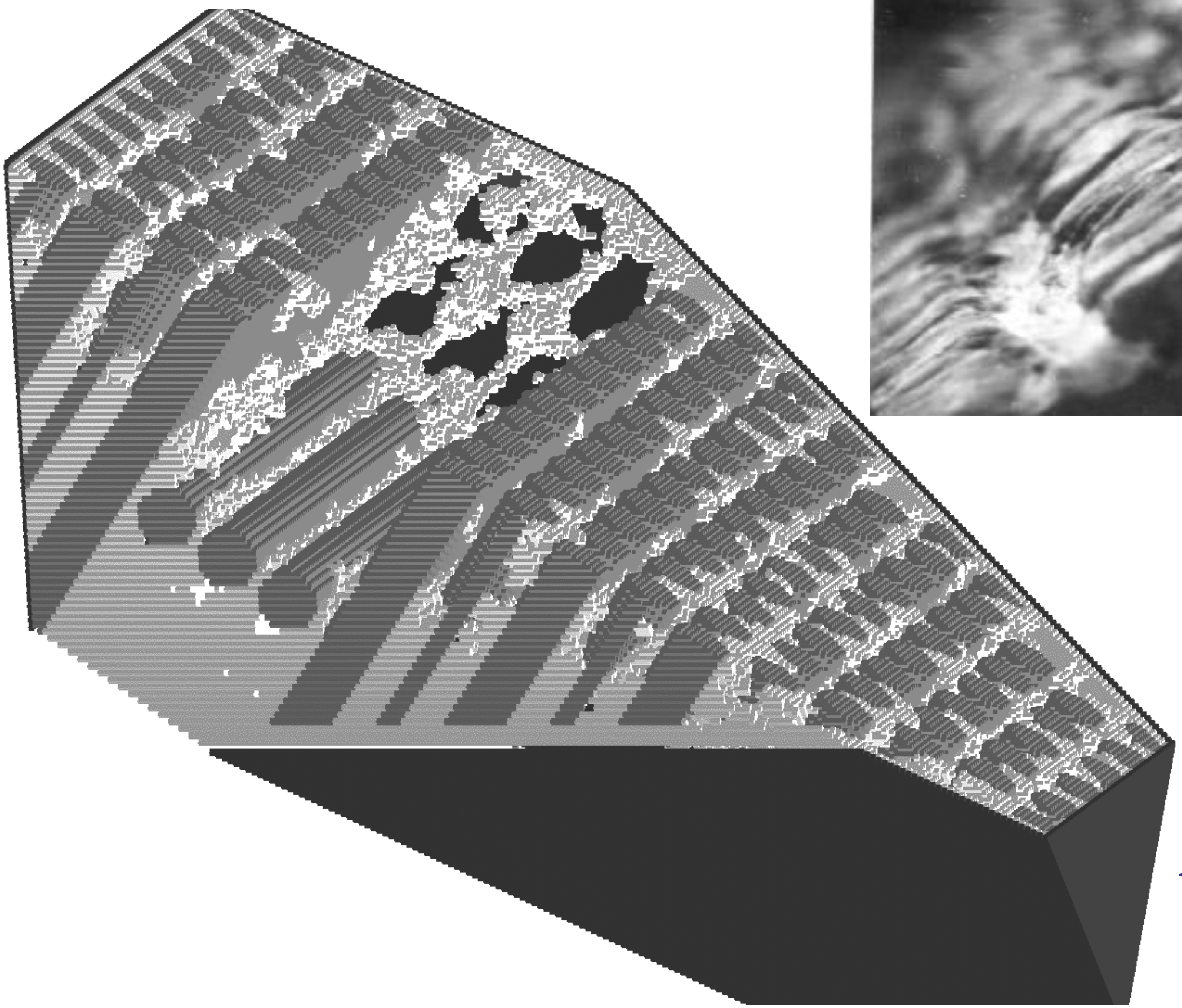


Simulation of the CFC erosion pattern with PEGASUS-3D code

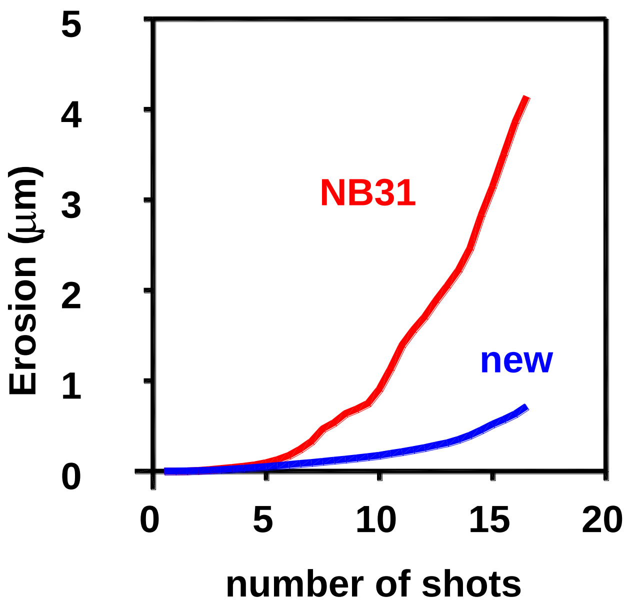


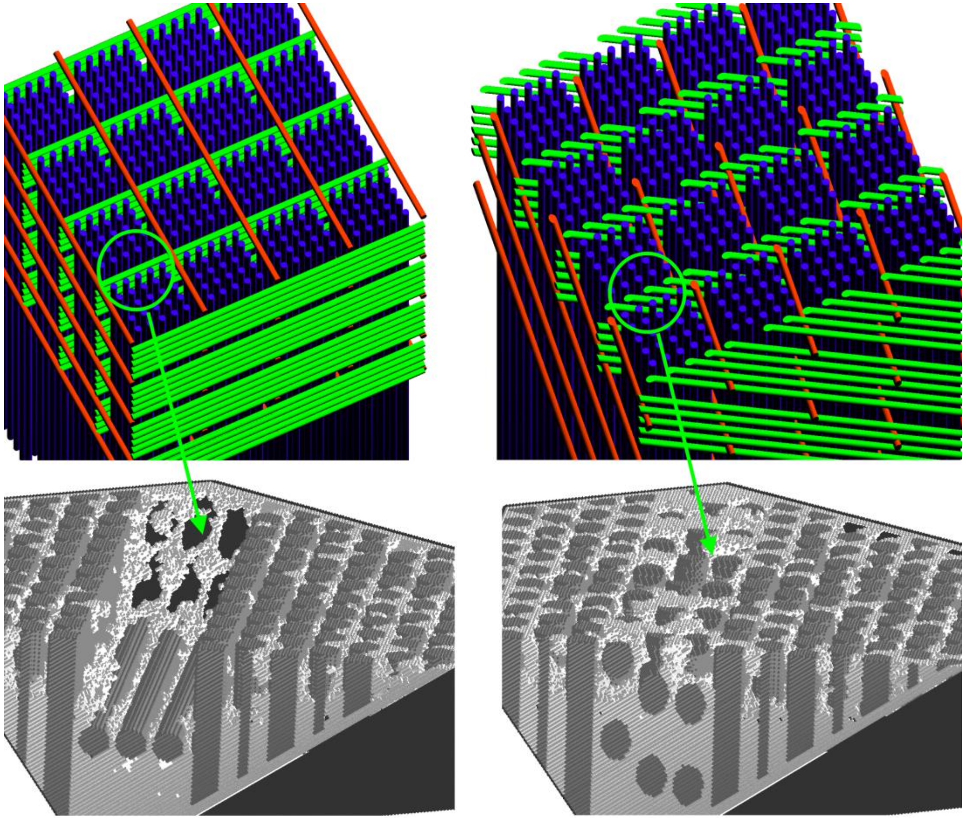
QSPA-T:
The erosion
pattern
(PAN)

PEGASUS:
Simulation of
the erosion
mechanism

CFC erosion optimisation

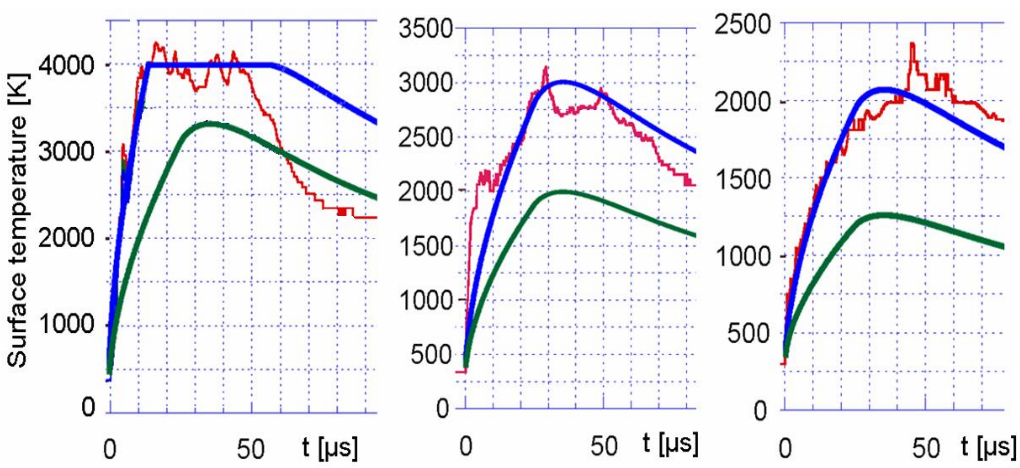
- New fiber structure for CFC has been proposed, (Fus. Eng. Des. 81 (2006) 275–279)
  - Experimental verification for theoretical predictions (MK-200UG experiment)
- The patent has been issued

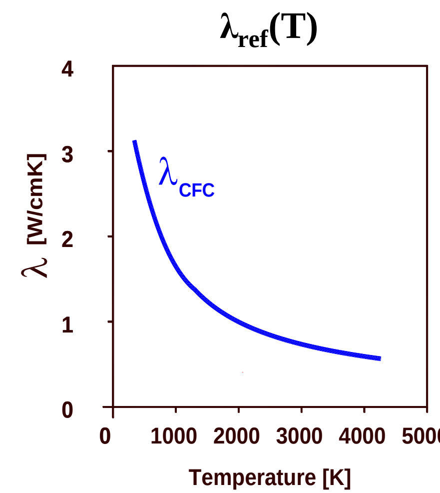




Thermal conductivity of NB31 CFC

Safronov, MK-200UG: 0.24 MJ/m^2, 0.145 MJ/m^2 and 0.09 MJ/m^2 shots and PEGSAUS-3D simulations with $\lambda(T) = \lambda_{ref}(T)$ (green) and $\lambda(T) = 0.35\,\lambda_{ref}(T)$ (blue)





Bulk CFC:

$\lambda = \lambda_{ref}(T)$

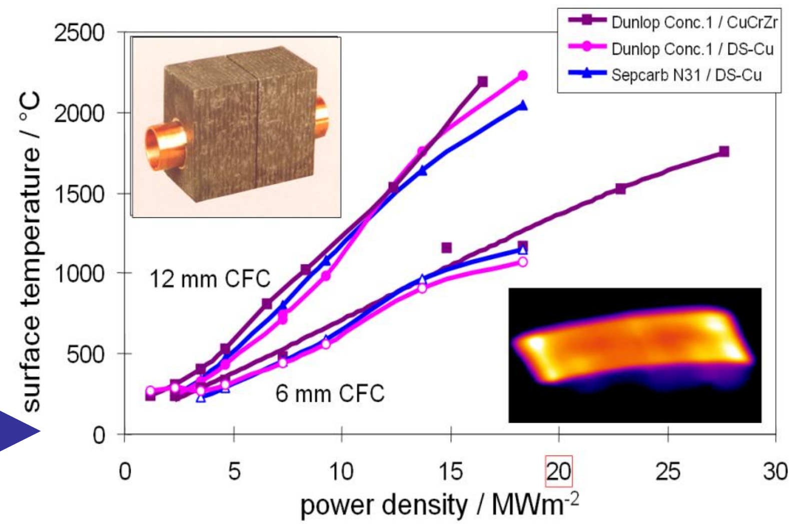
Thin surface layer:

$\lambda(T) = 0.35\,\lambda_{ref}(T)$

due to the cracks

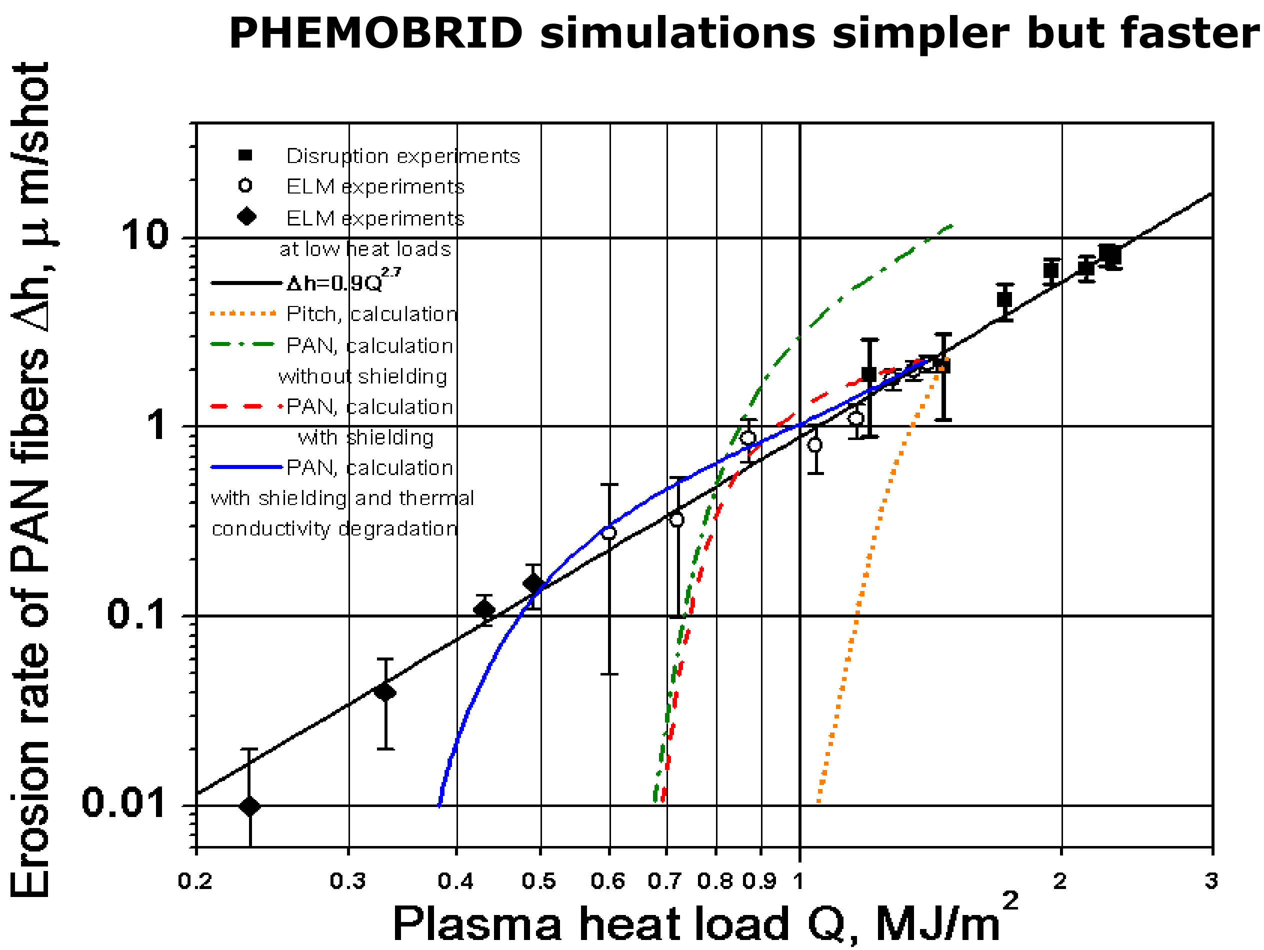
Physica Scripta. Vol. T111, 218–220, 2004

Linke, JUDITH: using $\lambda_{ref}(T)$ fits with good accuracy



CFC erosion

Comparison of experimental and modeling results

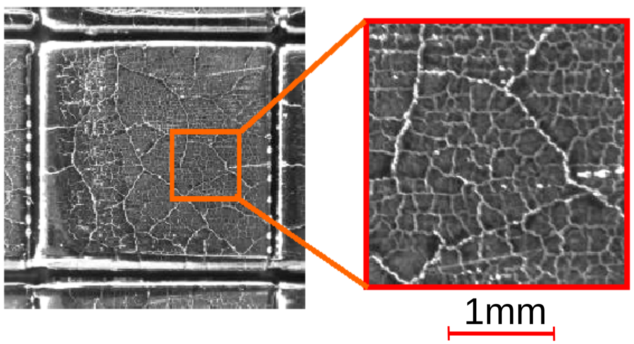


PAN-fiber erosion increase from 0.01 μm/pulse to 10 μm/pulse in the heat load range of 0.2-2.4MJ/m^2

Simulation of W cracking with PEGASUS-3D code

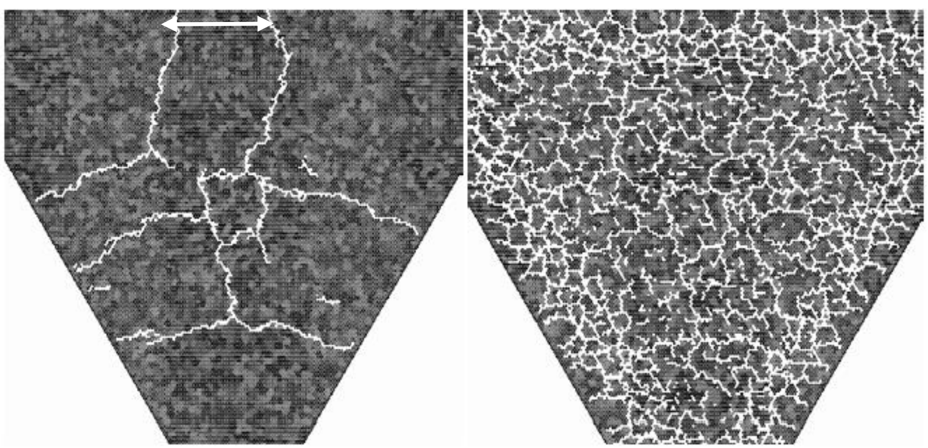
PEGASUS modelling for W cracks due to large ELMs (surface melting)

Fus. Eng. Des. 82 (2007) 1657–1663



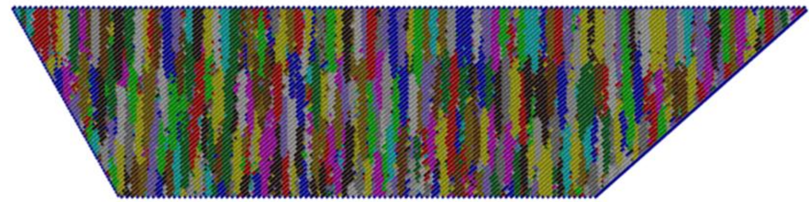
On the depth of 200 µm

surface cracks

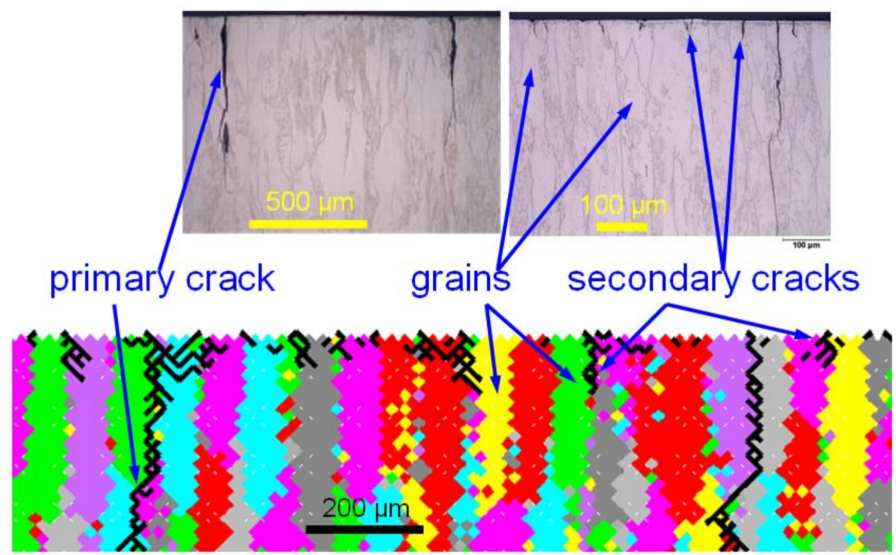


PEGASUS simulation of fractal cracks on W surface

Tungsten sample with elongated grains



W cross-section with the cracks:
QSPA results versus PEGASUS simulation.
Q = 0.9 MJ/m^2, τ = 0.5 ms



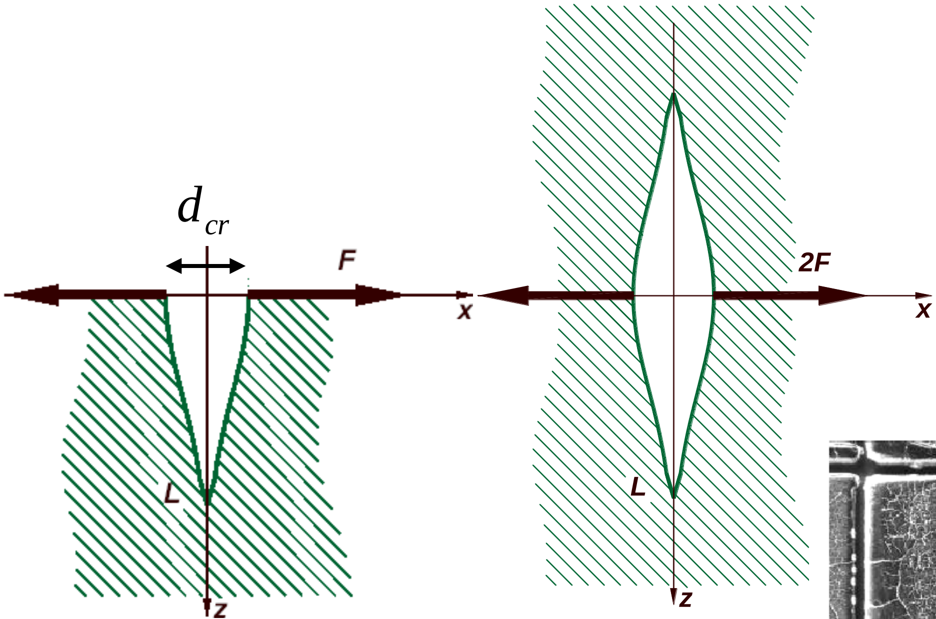
Fractal crack pattern due to the stress relaxation

$$2L = \frac{F^2(1-\sigma^2)}{\pi\mu E}$$

$$F_1 = E\alpha\Delta T$$

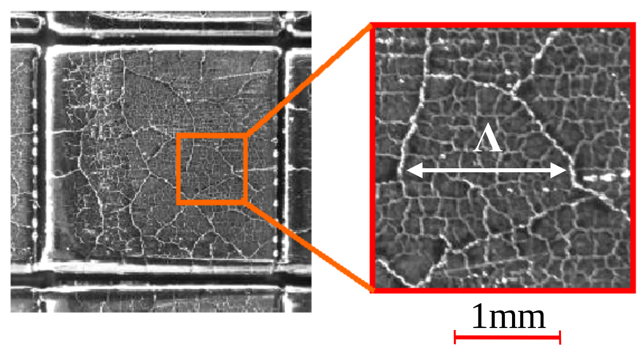
$$F_2 = E\left[\alpha\Delta T - d_{cr}^1/\Lambda_1\right]$$

$$F_3 = E\left[\alpha\Delta T - d_{cr}^1/\Lambda_1 - d_{cr}^2/\Lambda_2\right]$$

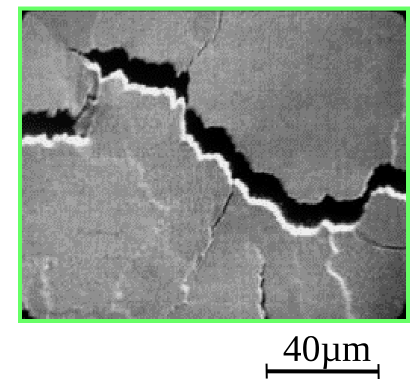


Tensile thermostress F in the resolidified layer is applied to the crack on W surface ($d_{cr} << L$)

The thermostress relieves due to the crack



W surface (QSPA, 100 shots of 0.9 MJ/m^2,
Primary cracks:
L_1~500 µm, Λ_1~1-2 mm
Secondary cracks:
L_2~50 µm, Λ_2~200-300 µm

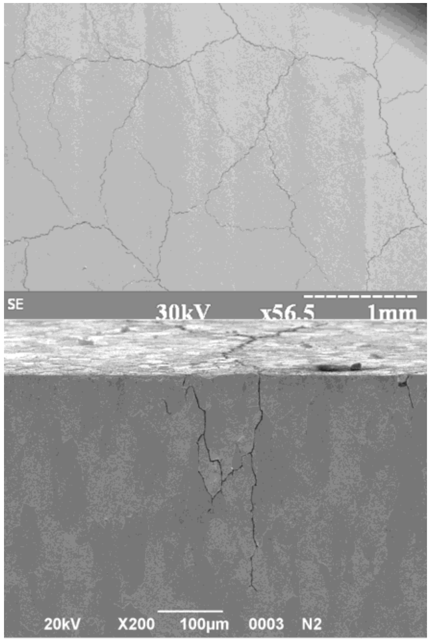


W surface, QSPA,
100 shots of 1.6 MJ/m^2,
Tertiary cracks:
Λ_3<40 µm

Crack depth to mesh size ratio

Analytic solution for the stress:

- External tensile force F is applied to the W surface of a half-space $z>0$ in the interval $-L \le x \le L$
- The stress tensor σ_{ik}, $i,k \in x,z$ depends on x/L and z/L only
- The ratio of the mean crack size at the surface to the crack depth is constant

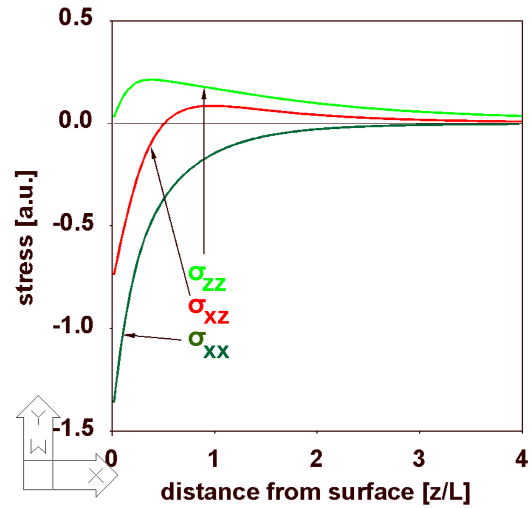


$$\sigma_{xx}(x,z) = -\frac{2\sigma_0 L}{\pi} \times \left[u + \frac{z^2(u+x)}{2(u^2+z^2)} - \frac{3z}{2} arctg\left(\frac{u}{z}\right) + \frac{x}{2}\ln\left|u^2+z^2\right| \right]_{-1-x}^{1-x}$$

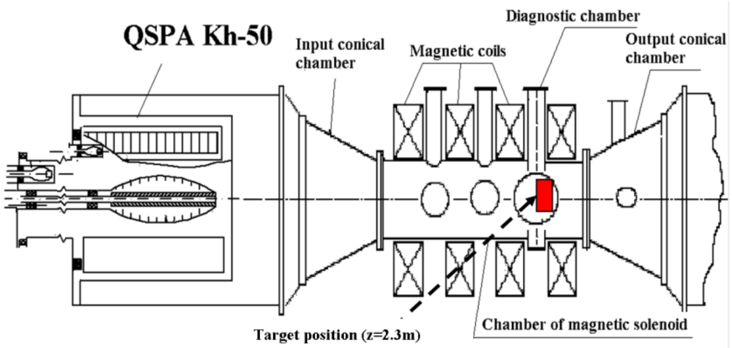
$$\sigma_{xz}(x,z) = \frac{2\sigma_0 L z}{\pi} \times \left[\frac{z^2 - xu}{2(u^2+z^2)} + \frac{1}{2}\ln\left|u^2+z^2\right| + \frac{x}{2z} arctg\left(\frac{u}{z}\right) \right]_{-1-x}^{1-x}$$

$$\sigma_{zz}(x,z) = -\frac{2\sigma_0 L z^2}{\pi} \left[\frac{u+x}{2(u^2+z^2)} - \frac{1}{2z} arctg\left(\frac{u}{z}\right) \right]_{-1-x}^{1-x}$$

$$F(x) = -\sigma_0 x$$



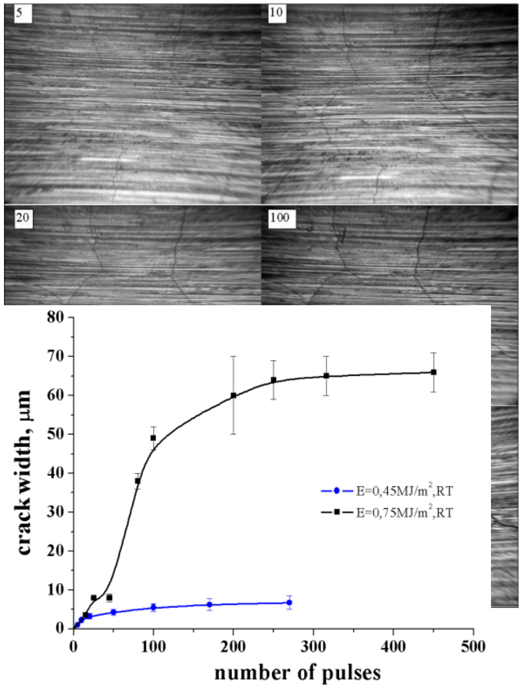
Simulation of stress on W surface in QSPA Kh-50 plasma gun

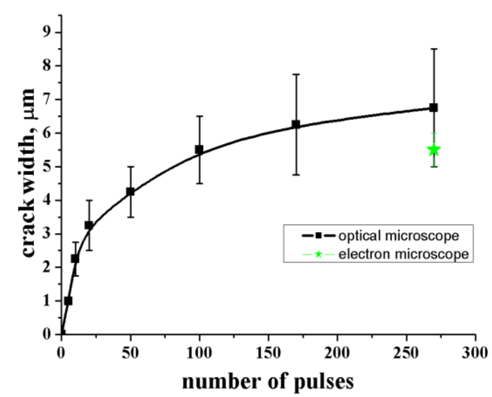


E_i ~ 0.4 keV,
P_{max}= 3.2 bar; $P_{average}$~1.6 bar
n = (2-7) 10^{15} cm^{-3}
Plasma stream diameter 18 cm.
Pulse duration 0.25 ms
Q_1=0.45 MJ/m^2; Q_2=0.75 MJ/m^2;

Simulation of cracks on W target due to small ELMs

- Tungsten cracking under action of the small ELMs is due to plastic deformations
- A cellular crack network with the characteristic size Λ formed at the surface after first ELMs and the crack network does not change further.
- The average crack width Δ saturates value Δ_m
- $\Delta_m/\Lambda \le 2.2\%$ is equal to the tungsten linear expansion at the maximum surface temperature.
- The crack width tends to Δ_m exponentially with the ELMs number
- The accurate tensile strength and yield stress values are of no matter for the average cracks width and for the average mesh size





doi:10.1016/j.fusengdes.2010.05.005

Measurement of the threshold power load for W cracking

Residual stress in MPa measured at the sample surface after 1, 5 and 10 shots in QSPA-Kh50

T, ºC Q, MJ/m²	200			400		600	
	1	5	10	1	5	1	5
0.75	386	362	183	294	268	303	195
0.45	314	240	200	230	240	230	240
0.2	160	120		180	160	149	160

Mean crack width in µm for large cracks of ~200-300µm mean crack depth and ~1 mm mean crack mesh size.

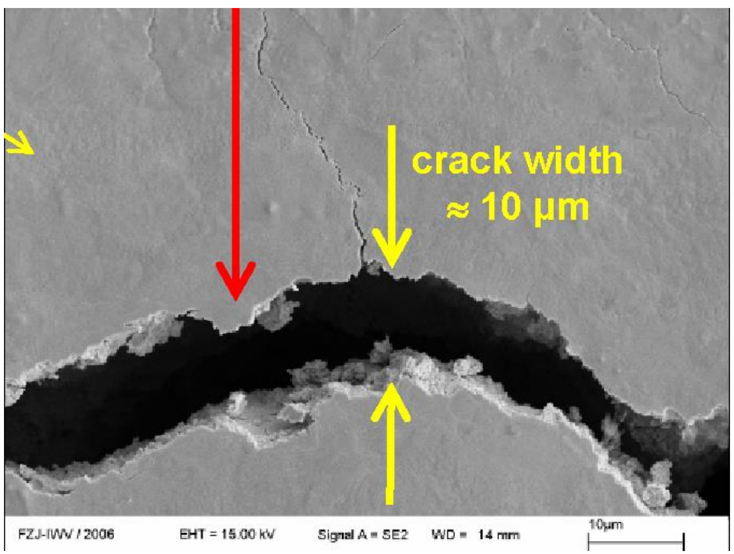
T, ºC	200			400		600	
No of pulses	1	5	10	1	5	1	5
0.75 MJ/m²	X	2-4	4-8	X	X	X	X
0.45 MJ/m²	X	0,5-1,5	1-3	X	X	X	X
0.2 MJ/m²	X	X	X	X	X	X	X

Mean crack width in µm for shallow cracks of ~5-10µm mean crack depth and ~30-50 µm mean crack mesh size at the target surface.

T, ºC	200			400		600	
No of pulses	1	5	10	1	5	1	5
0.75 MJ/m²	X	0.2-0.4	0.3-0.5		0.3-0.5	0.4-0.6	~1
0.45 MJ/m²	X	X	X	X	X	X	X
0.2 MJ/m²	X	X	X	X	X	X	X

Estimations for the threshold power load

- Energy density threshold for tungsten cracking with ELMs of 0.25 ms is measured as 0.3 MJ/m^2
- Small ELMs produce compressive stress ⇒ plastic deformations
- Tensile stress developed in the plastically compressed surface during cooling down after ELM
- Analytical considerations predicts the threshold of ≥0.1 MJ/m^2 when the number of ELMs increases
- Dust produced during cracking



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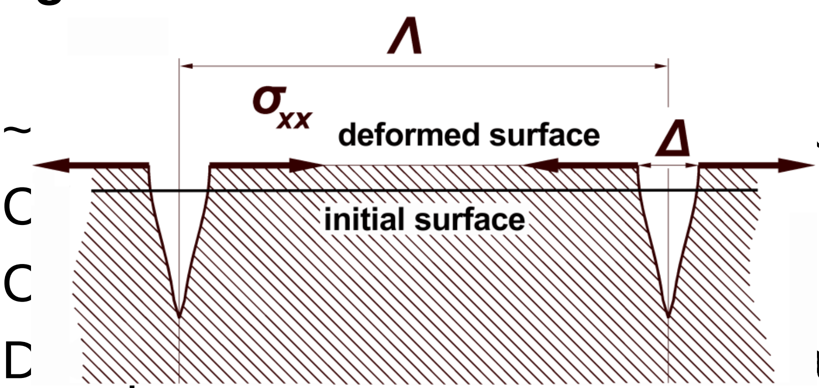
Rough estimation:



- ~ … μm
- C
- C
- D … t/m^2

Conclusions for ITER divertor erosion

- Divertor armour erosion with disruption is negligible for both CFC (48 µm) and W (≤1 µm) even for 100% energy deposition (shielding)
- W melt splashing is tolerable (melt depth 60-80 µm x 200-300 disruptions, crater 5 µm)
  - Disruption mitigation needed only because of the first wall damage with RE and direct plasma heating
  - Direction of disruptive flux to divertor is better than the first wall damage (!)
- For large type I ELMs and CFC armour the divertor erosion is intolerable
  - Erosion ~1 µm/ELM ⇒ armour lifetime is few hundred ITER shots
  - ELMs should be mitigated, but the efficiency is still unknown
  - CFC armour survives 10^6 ELMs if $Q<0.2$ MJ/m^2 (for 0.5 ms ELMs)
- For W armour
  - Erosion (vaporization+splashing) with ELMs is tolerable
  - Growth of the cracks saturates
  - ELMs produce W dust (main danger) ⇒ contamination source ~10^{20} at/m^2
  - Even very small ELMs of ~0.1 MJ/m^2 can cause cracking and produce dust

Thank you for your attention