



Runaway Electrons damage on plasma facing components in JET fusion device

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L. Chen, R.A. Pits, S. Ratynskaia and JET Contributors



This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.



Background

**Lawson criterion:
Fusion “triple product”**

$$n \times T \times \tau_E > 5 \times 10^{21} \text{ keV m}^{-3} \text{ s}$$

n = Plasma ion density;
 T = Ion temperature;
 τ_E = Energy confinement time.



**Fusion Power is proportional
with the reactor’s size**



Fusion Efficiency Factor

$$Q_{DT} = P_{\text{output}} / P_{\text{input}} \geq 10$$

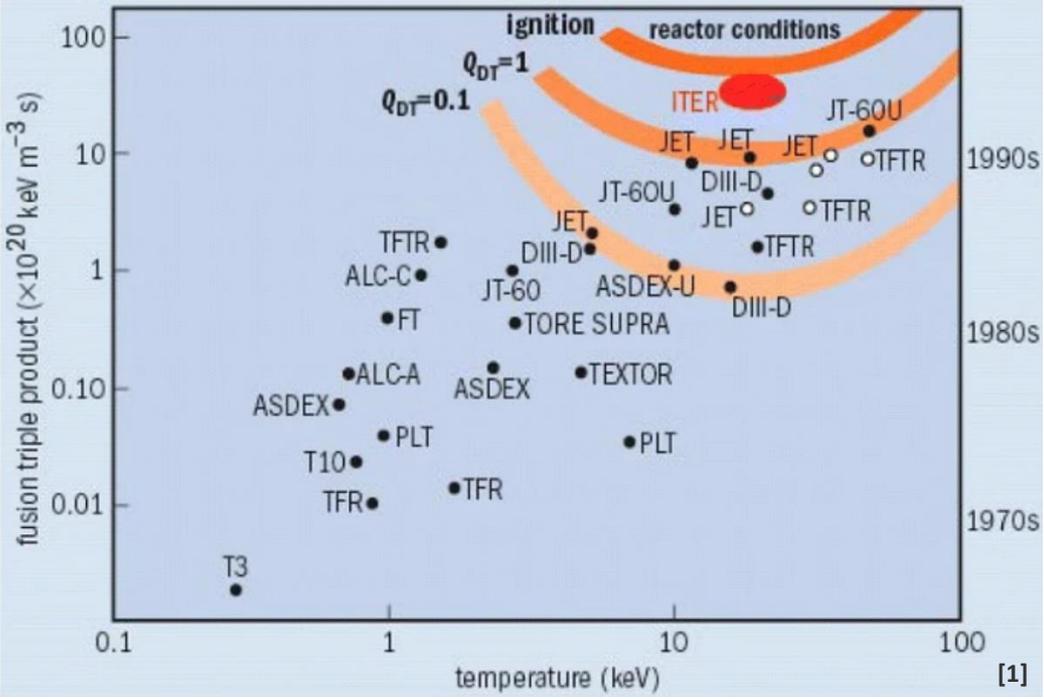


Better confinement = Higher plasma current



Higher plasma current = POTENTIAL HIGHER DAMAGE to the reactors due to the plasma disruptions

Fusion tokamak performance



[1] Pitts, R., R. Buttery, and S. Pinches. 2006. Fusion: The way ahead. *Physics World* 19: 20–26

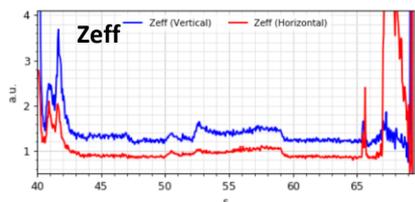
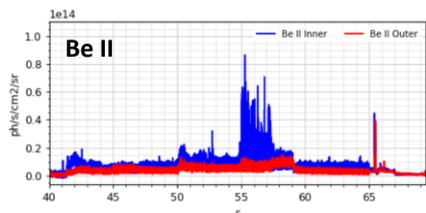
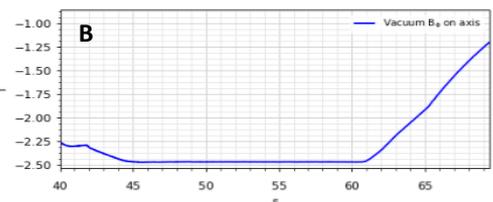
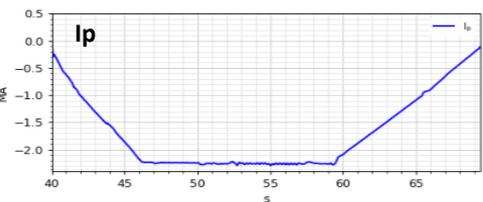
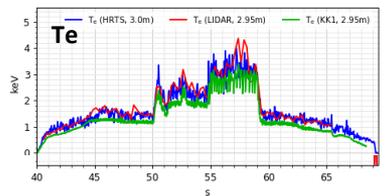
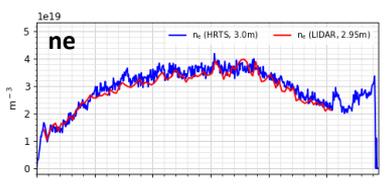
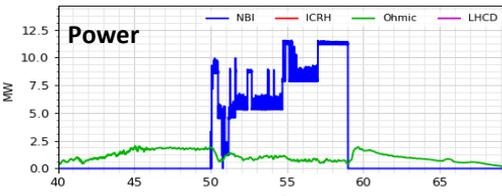
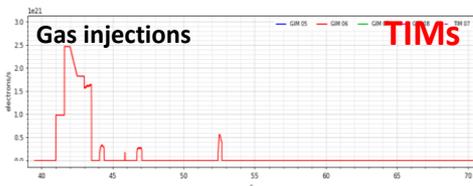
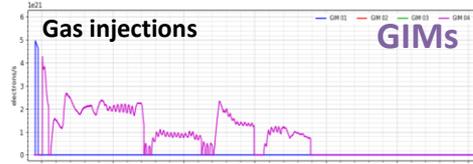
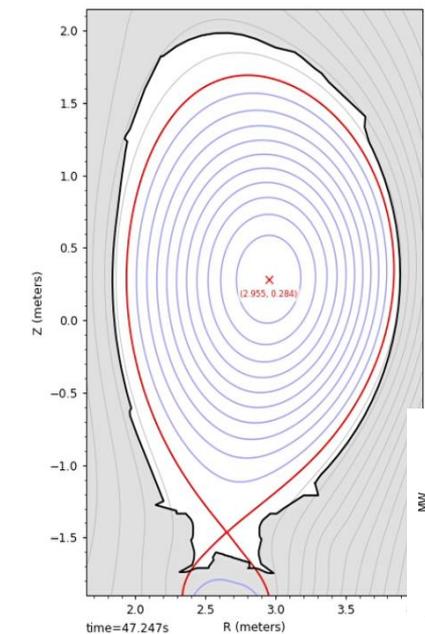
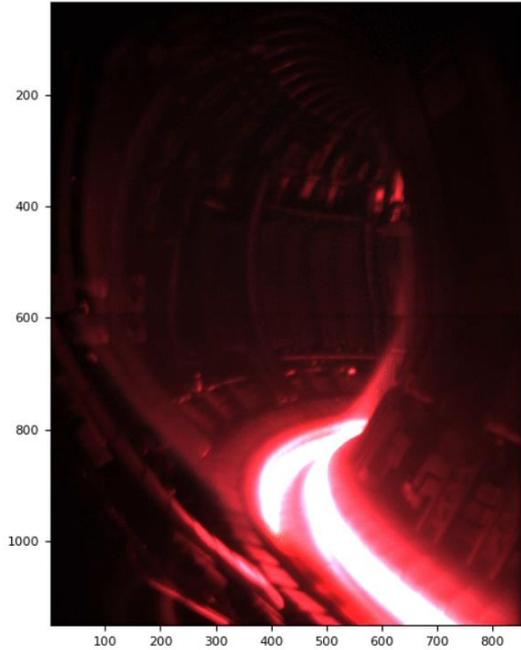


Background – typical JET operation

Example of a JET pulse (#98855)

#98855 KLDT-05WB 51.59086 s

Equilibrium profile



Background – JET plasma disruption



Plasma disruption

Termination of plasma with rapid loss of thermal and magnetic energy

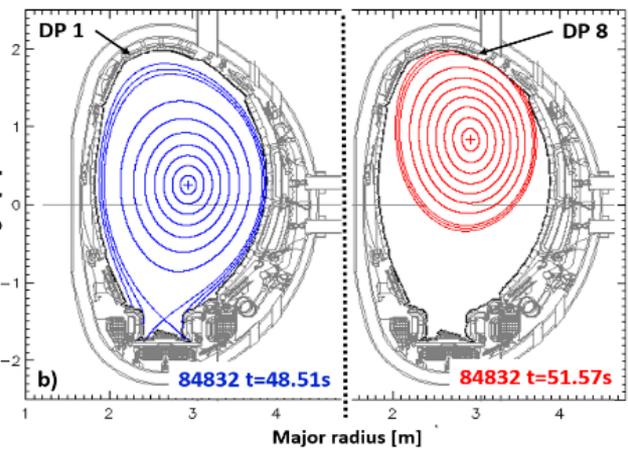
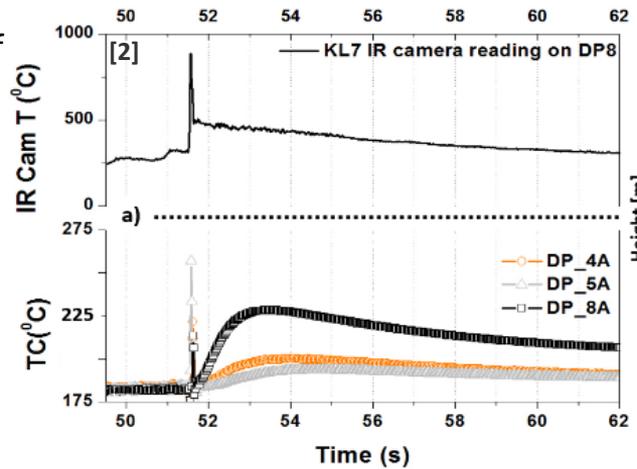


HUGE thermal and mechanical loads on the structure

Background – JET plasma disruption



Plasma disruption
Termination of plasma with rapid loss of thermal and magnetic energy
↓
HUGE thermal and mechanical loads on the structure



[2] I. Jezu et al, Nucl. Fusion 59 (2019) 086009



Background – JET plasma disruption

Plasma disruption

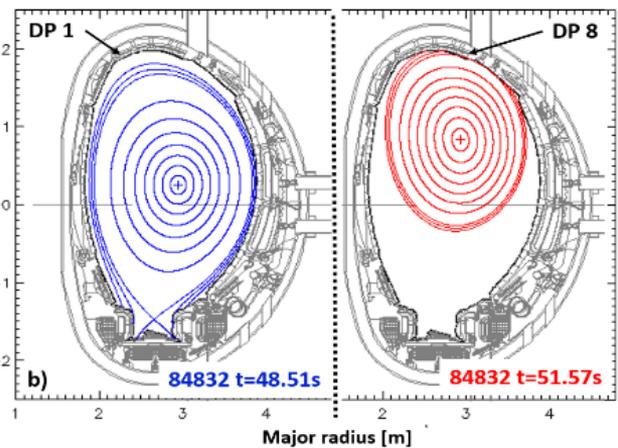
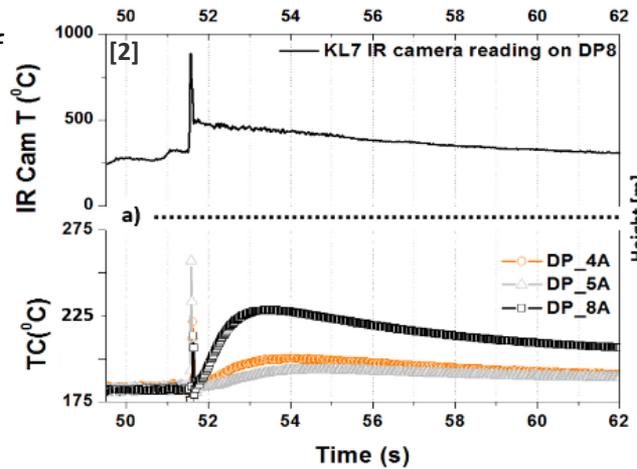
Termination of plasma with rapid loss of thermal and magnetic energy



HUGE thermal and mechanical loads on the structure

Consequences of the disruptions

- Thermal loads/Fast melting and electromagnetic forces



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Background – JET plasma disruption

Plasma disruption

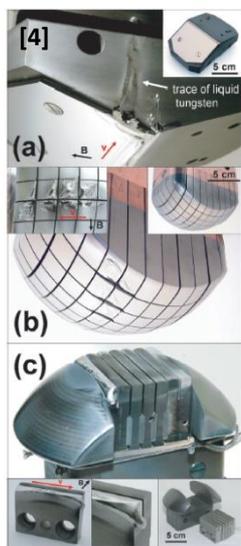
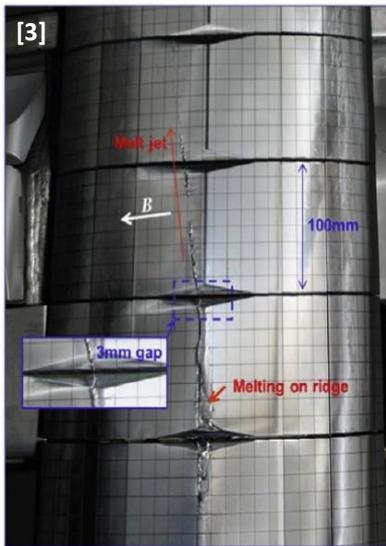
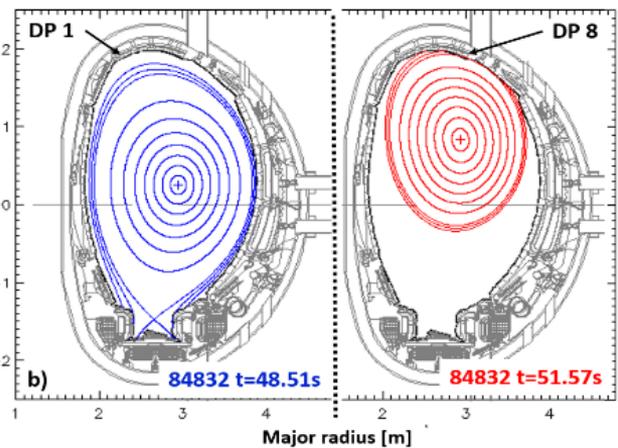
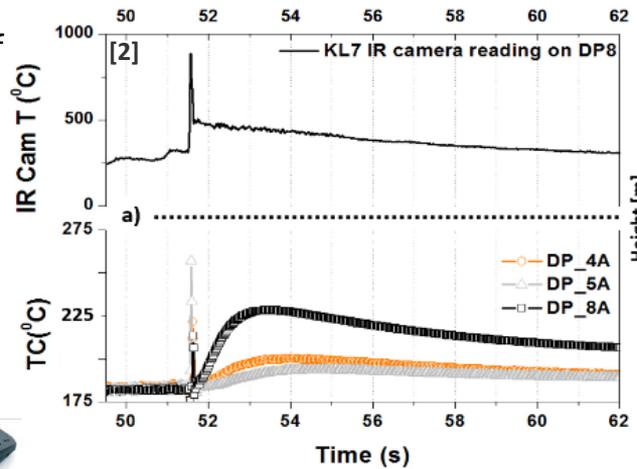
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[2] I. Jecu et al, Nucl. Fusion 59 (2019) 086009
 [3] G.F. Matthews, et al., Phys. Scr. T167 (2016) 014070 (7pp)
 [4] G. Sergienko et al., Phys. Scr. T128 (2007) 81–86



Background – JET plasma disruption

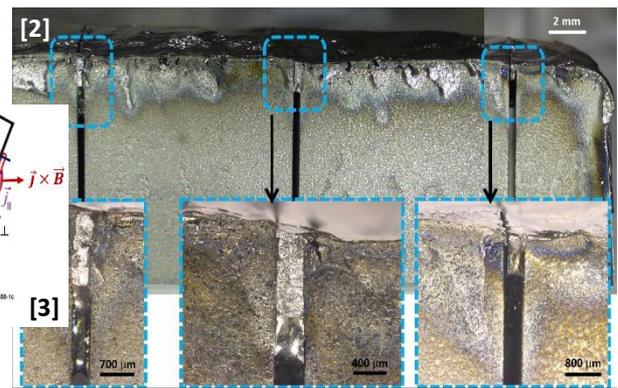
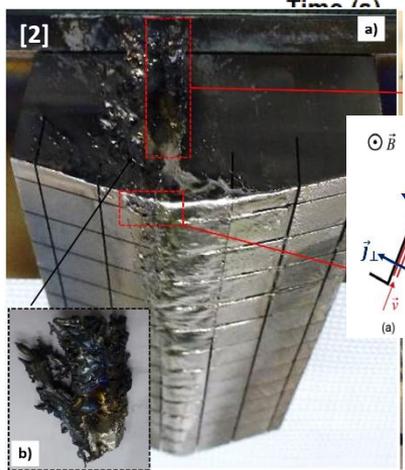
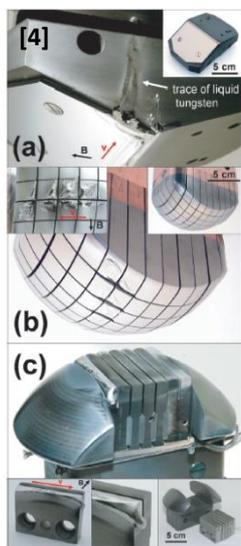
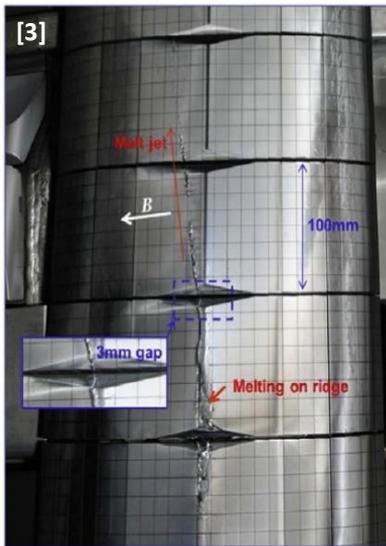
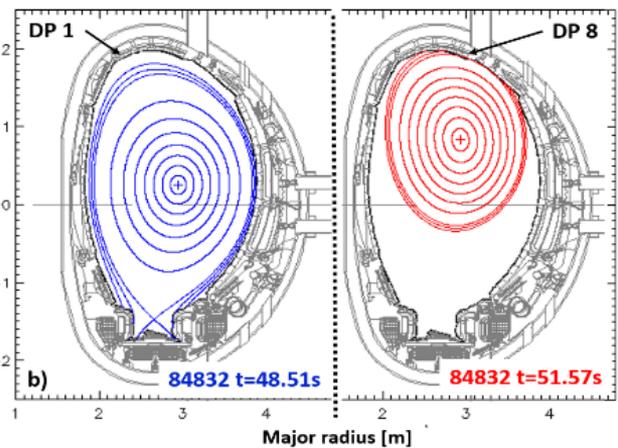
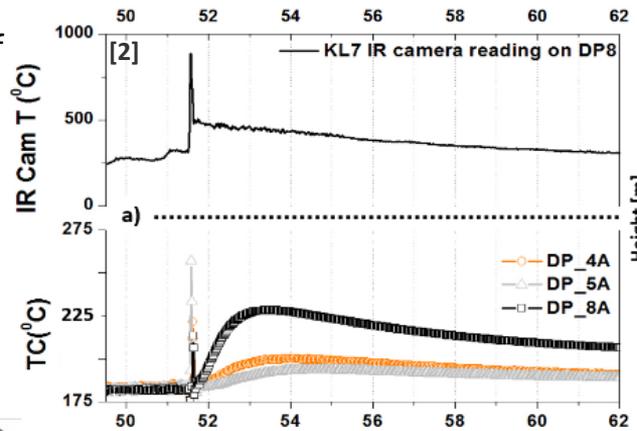
Plasma disruption
Termination of plasma with rapid loss of thermal and magnetic energy



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Background – JET plasma disruption



Plasma disruption

Termination of plasma with rapid loss of thermal and magnetic energy



HUGE thermal and mechanical loads on the structure

Consequences of the disruptions

- Thermal loads/Fast melting and electromagnetic forces

- **High energy**

Runaway Electrons (RE)



Serious threats to future tokamaks



Background – JET REs

Plasma disruption

Termination of plasma with rapid loss of thermal and magnetic energy



HUGE thermal and mechanical loads on the structure

Consequences of the disruptions

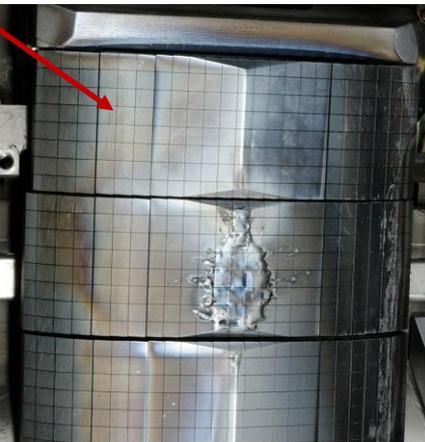
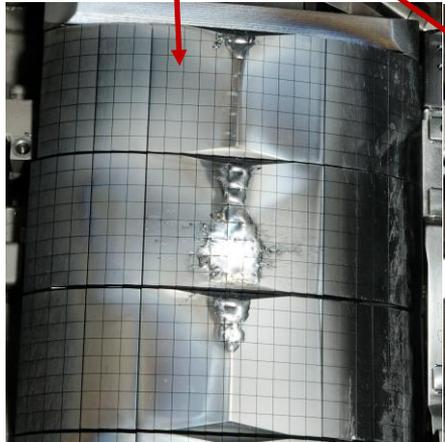
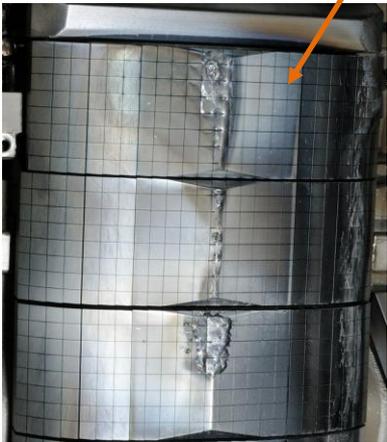
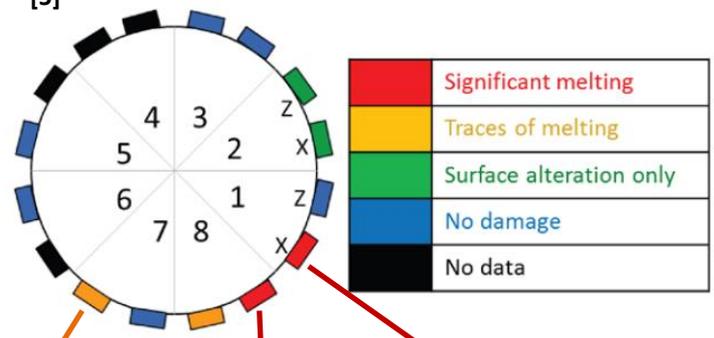
- Thermal loads/Fast melting and electromagnetic forces

- **High energy Runaway Electrons (RE)**



Serious threats to future tokamaks

[5]



[5] C. Reux et al Nucl. Fusion 55 (2015) 093013



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Termination of plasma with rapid loss of thermal and magnetic energy



HUGE thermal and mechanical loads on the structure

Consequences of the disruptions

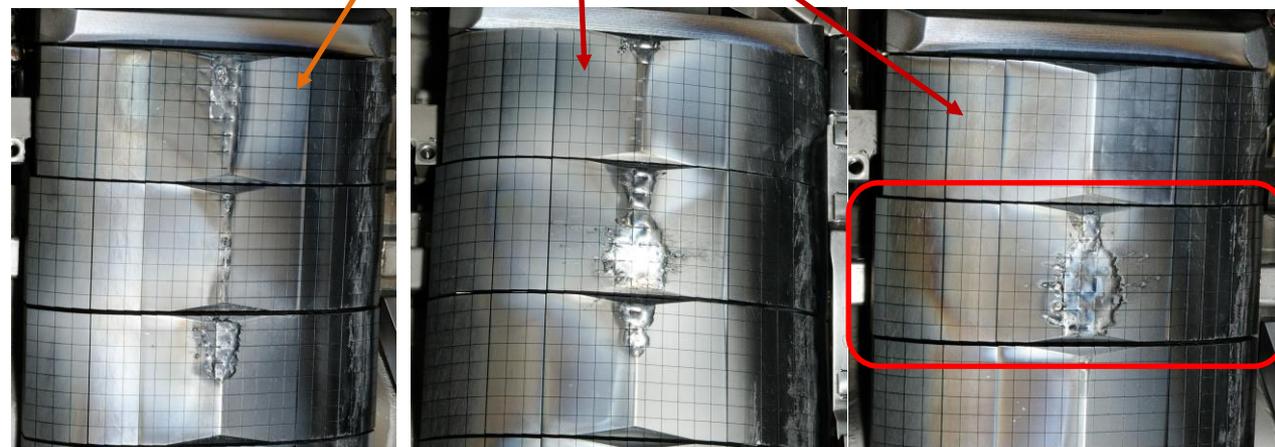
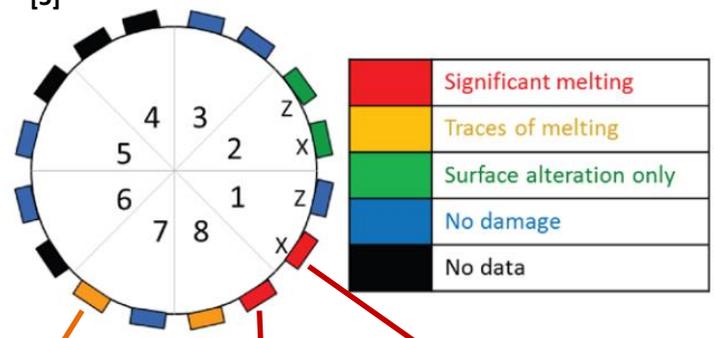
- Thermal loads/Fast melting and electromagnetic forces

- **High energy Runaway Electrons (RE)**



Serious threats to future tokamaks

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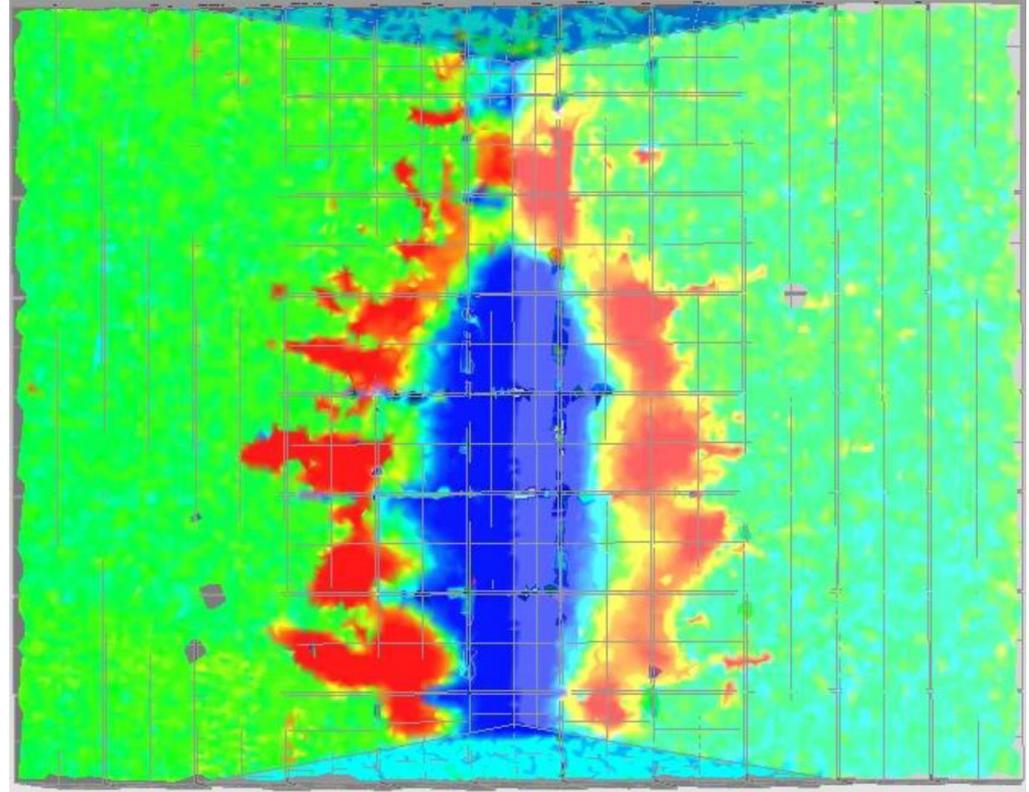
REs damage to JET PFC – Be limiter tile



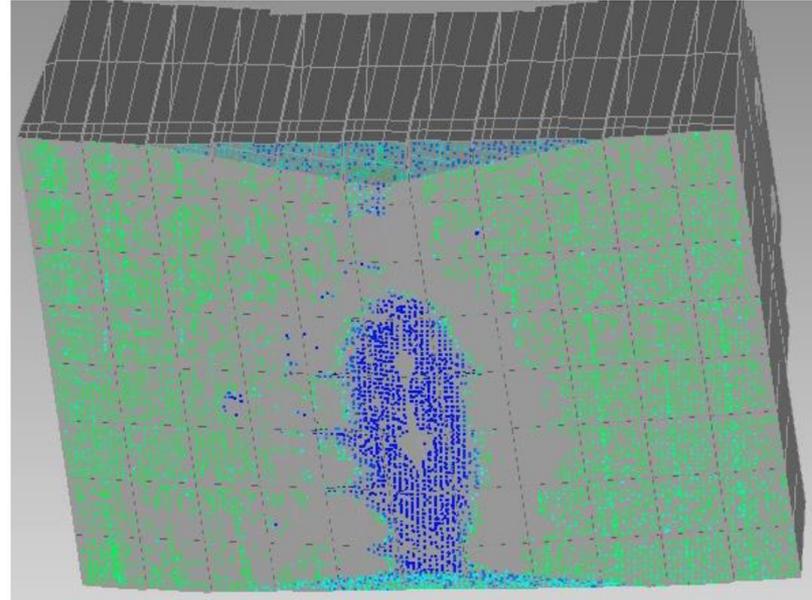
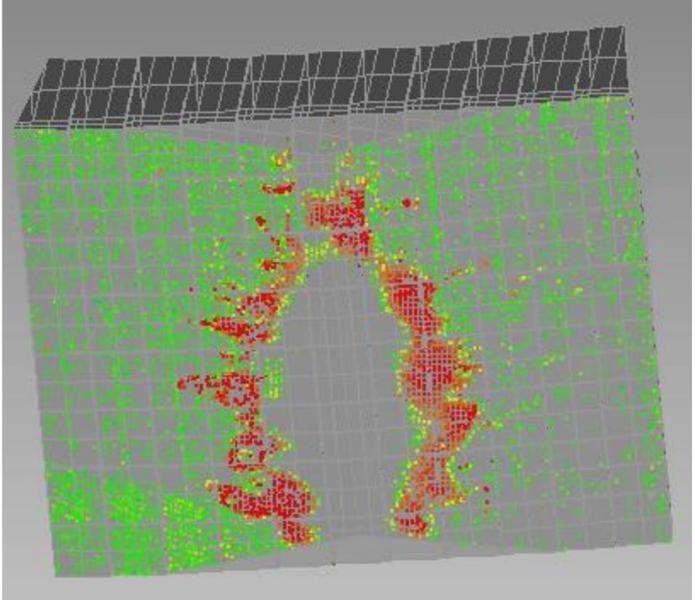
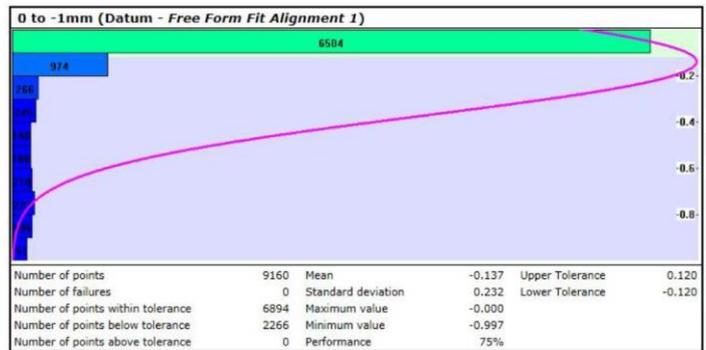
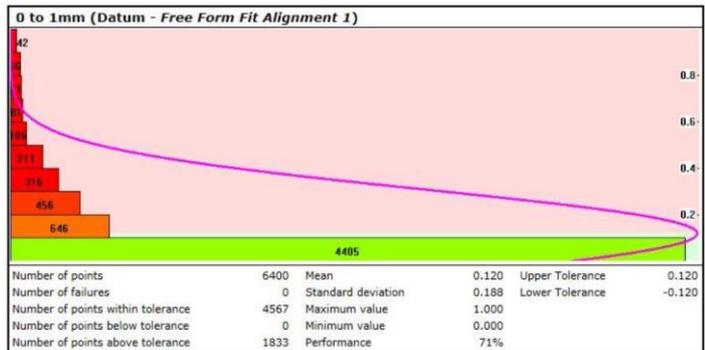
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Laser 3D profiling

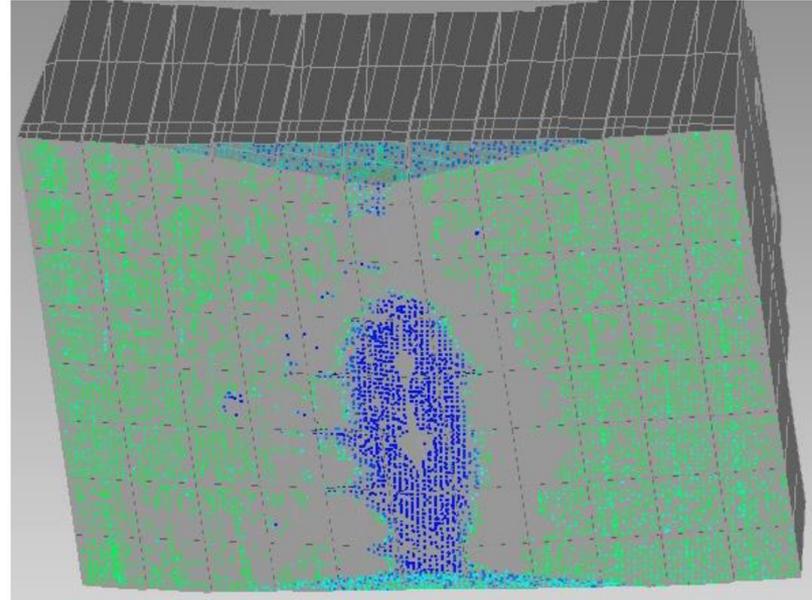
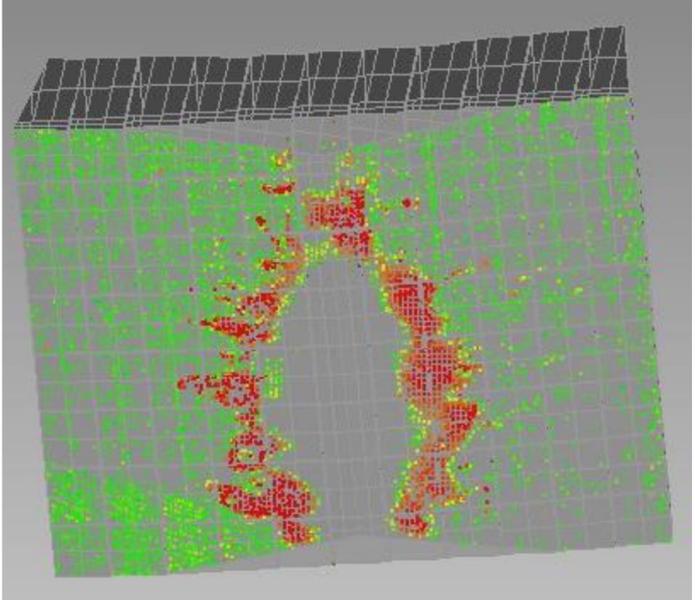
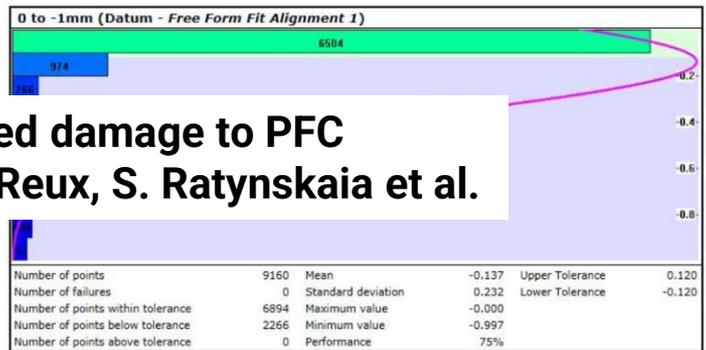
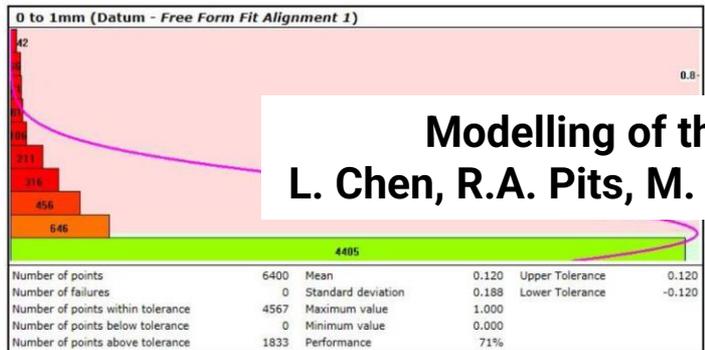


REs damage to JET PFC – Be limiter tile Laser 3D profiling



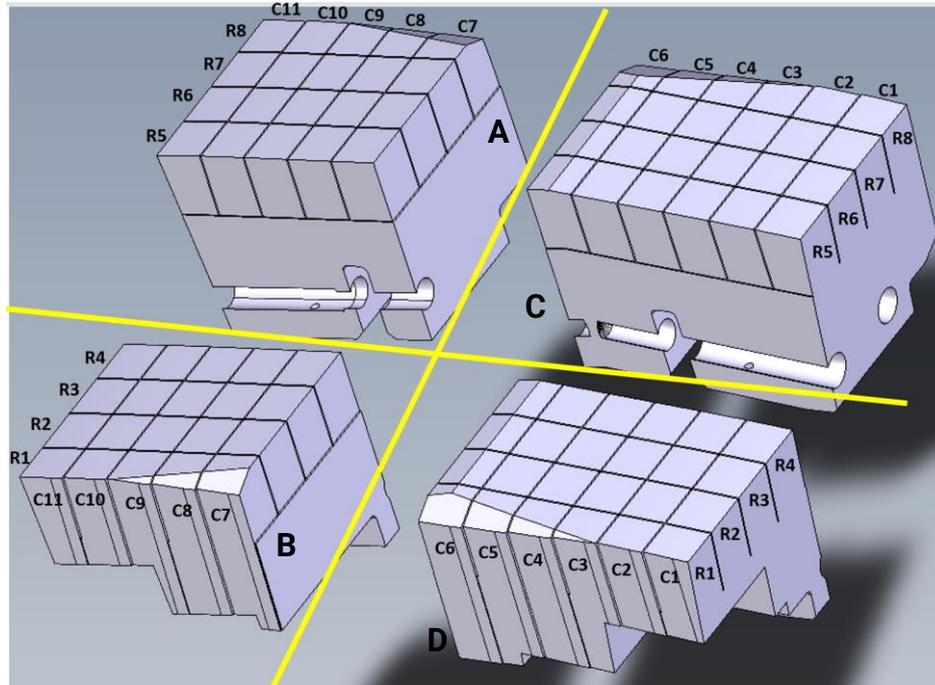


Modelling of the RE induced damage to PFC L. Chen, R.A. Pits, M. Lehnen, C. Reux, S. Ratynskaia et al.



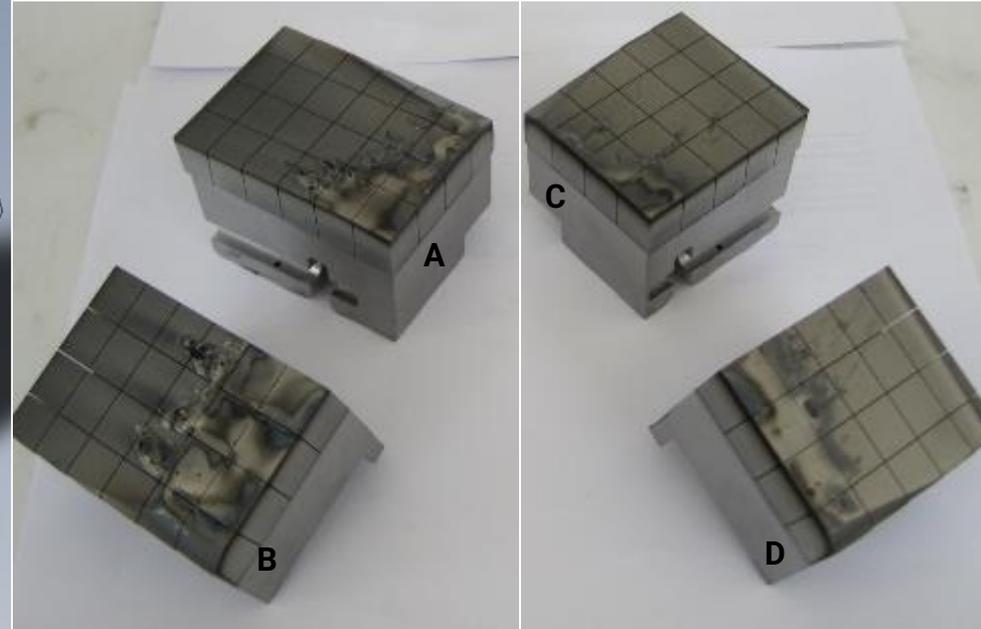
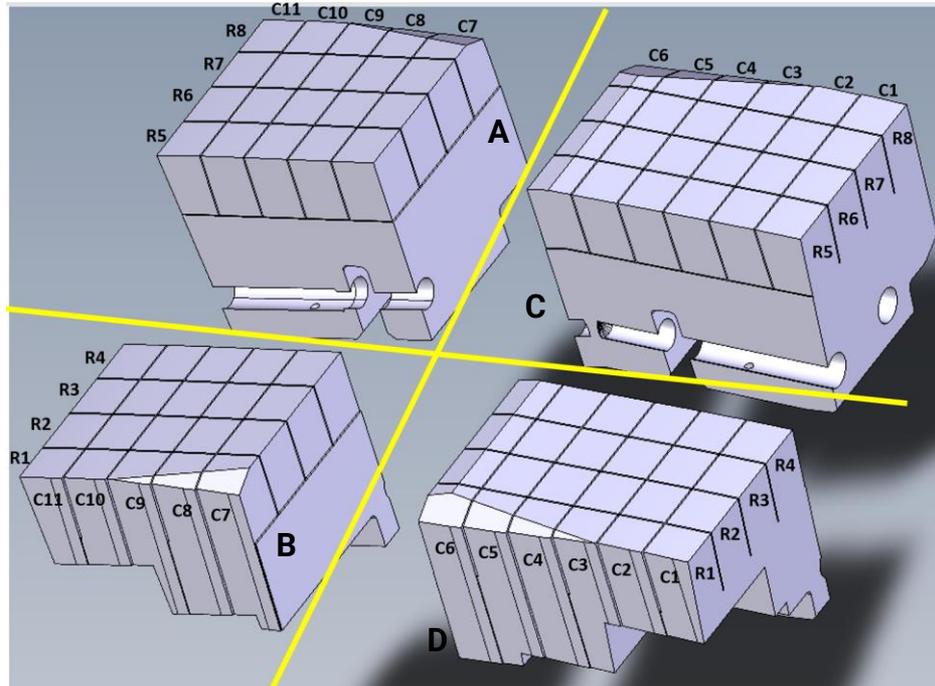
REs damage to JET PFC – Be limiter tile

Cutting



REs damage to JET PFC – Be limiter tile

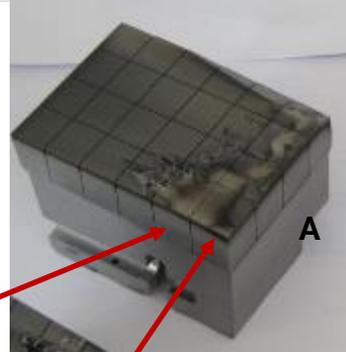
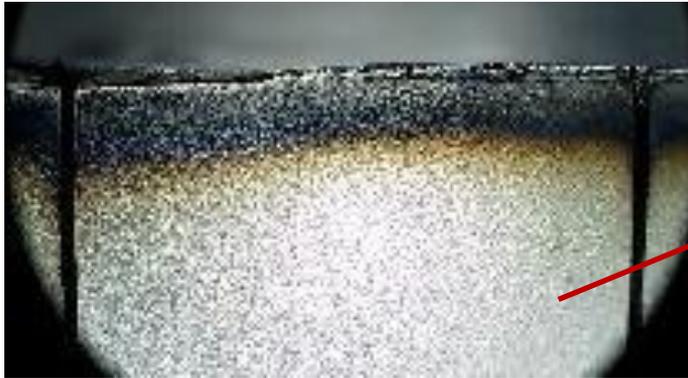
*Cutting



*Details on cutting performed at IAP to follow

REs damage to JET PFC – Be limiter tile

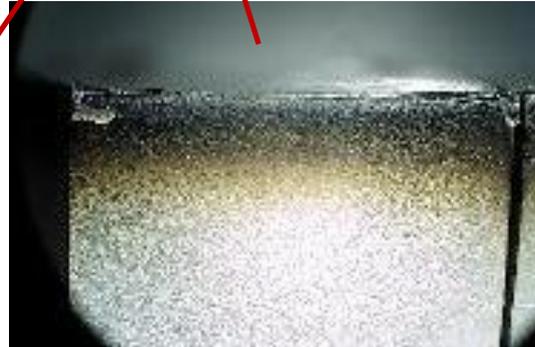
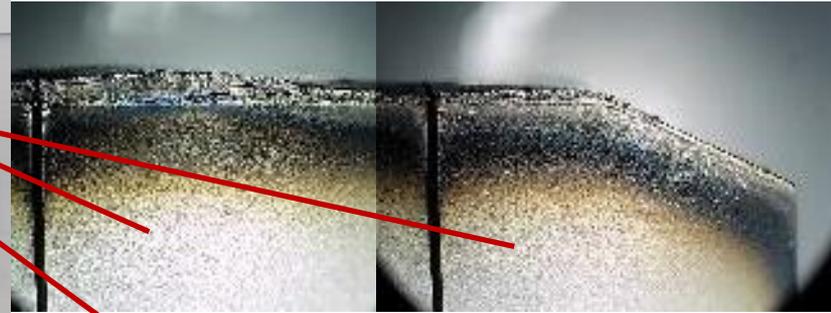
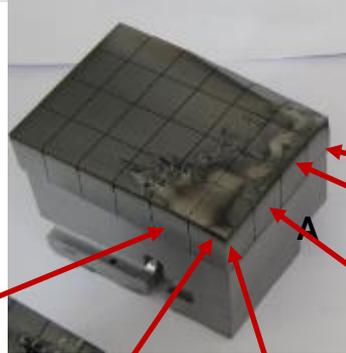
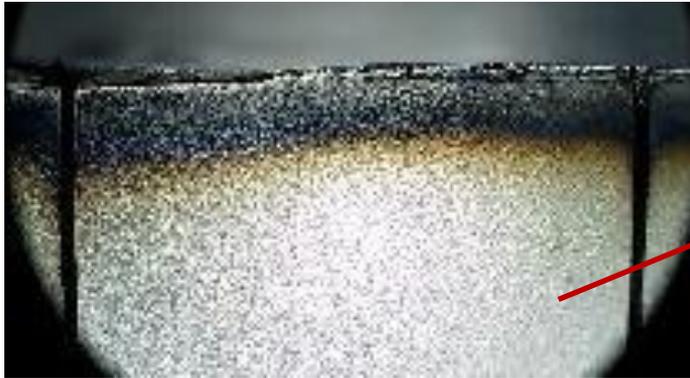
*Imaging and
Microscopy



*performed at IAP

REs damage to JET PFC – Be limiter tile

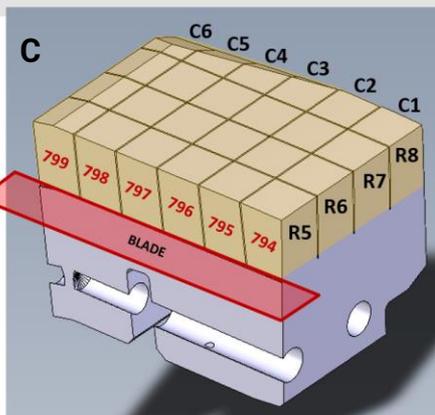
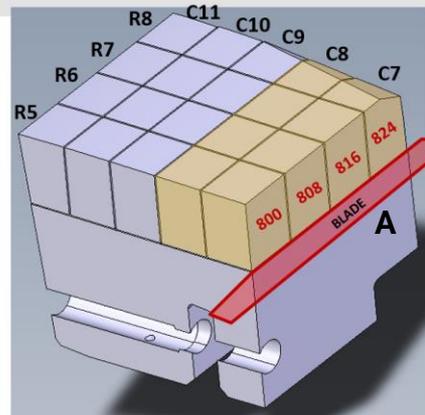
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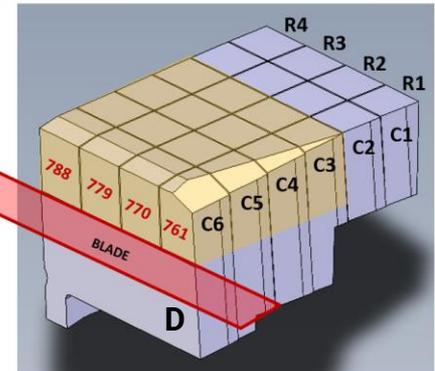
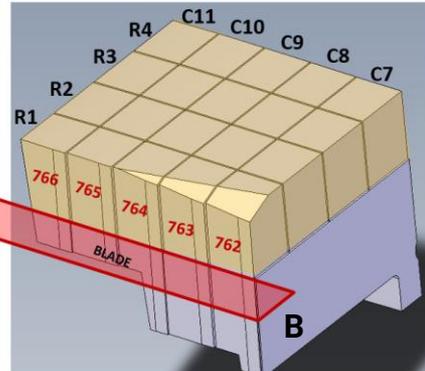
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REs damage to JET PFC – Be limiter tile

To DO

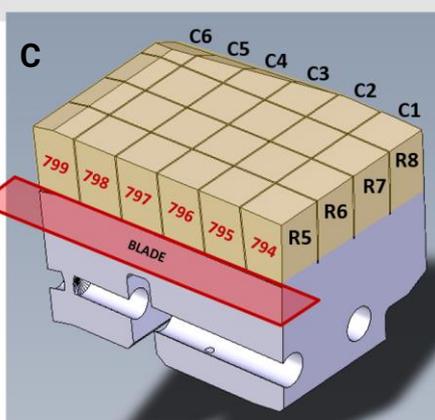
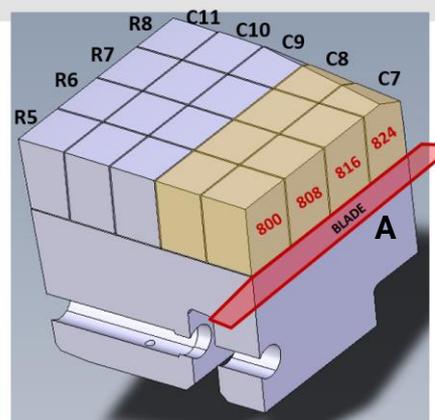


Position of the engraved ID will show sample orientation

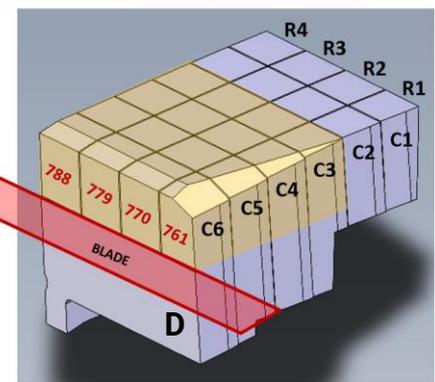
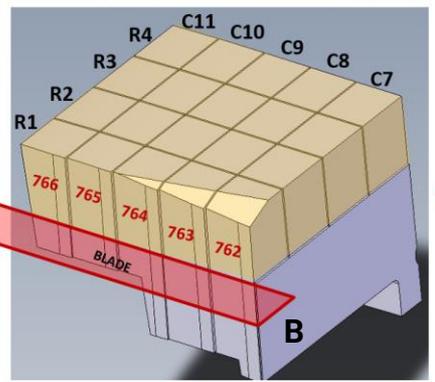




REs damage to JET PFC – Be limiter tile



Position of the engraved ID will show sample orientation



To DO

- Cutting of selected castellations;
- IBA analysis in poloidal, toroidal and “depth” direction;
- SIMS analysis;
- SEM/EDX analysis



Sectioning and preparation of samples from metallic JET components at IAP. Microscopy investigations and sample distributions to other laboratories

I. Jepu, A. Widdowson, Y. Zayachuk, P. Coad
UKAEA

C. Porosnicu, C.P. Lungu, B. Butoi, O. G. Pompilian, C. Staicu, V. Zoroschi
IAP (Institute of Atomic Physics, Bucharest, Romania)



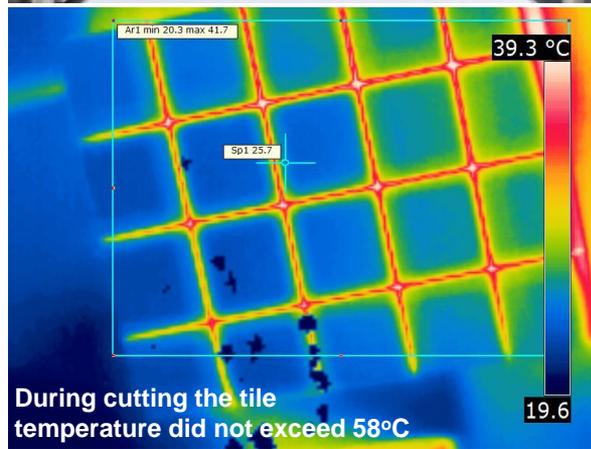
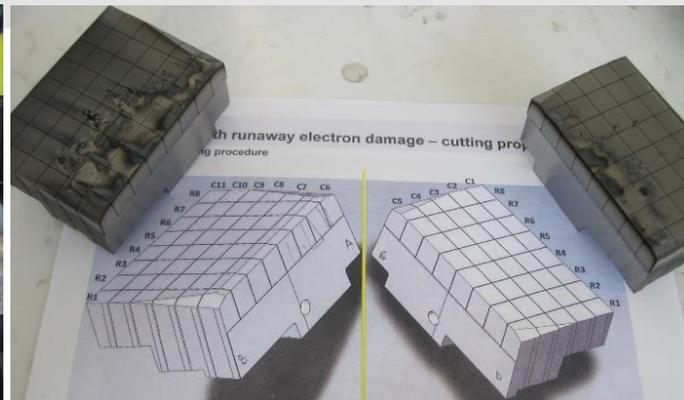
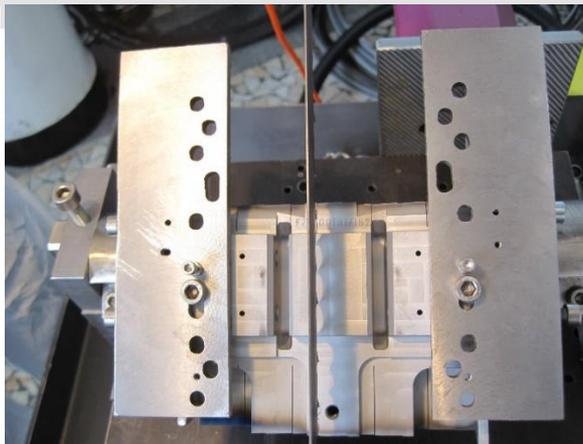
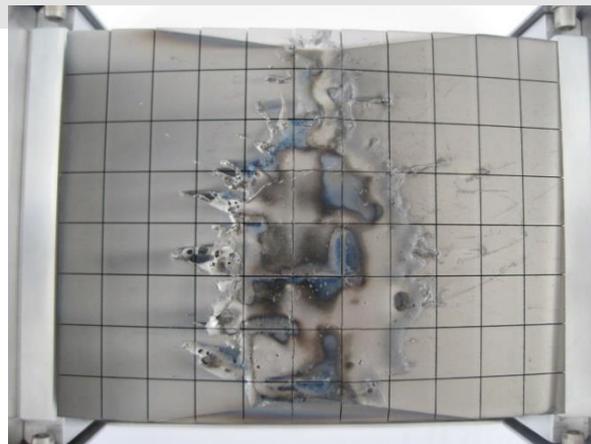
 UK Atomic Energy Authority



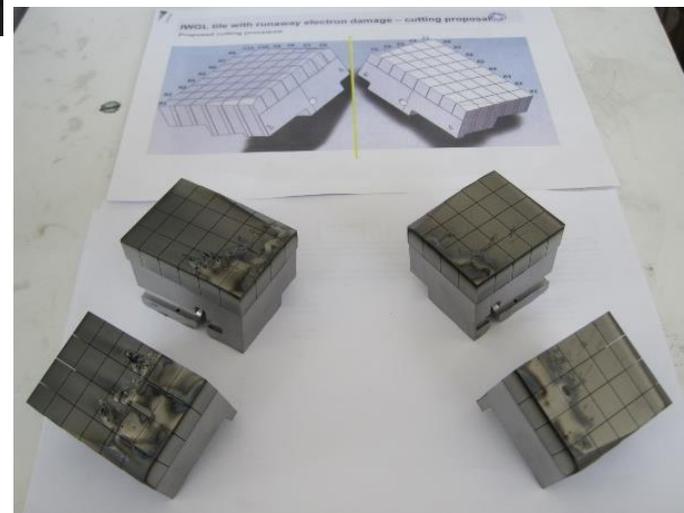
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.



2022 Sample preparation and cutting – Be tile ✓ Cutting



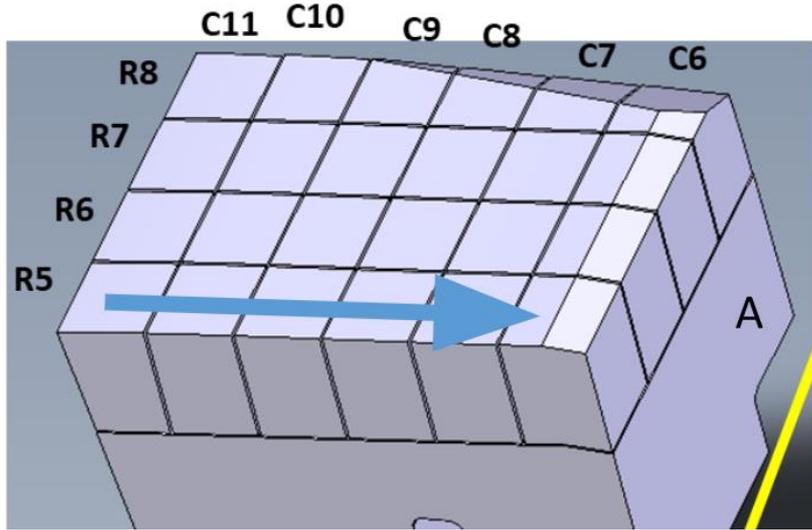
- ✓ Using the beryllium processing facility, cutting was performed on the Be RE damaged tile
- ✓ Typical sample sizes: 10 mm x 10 mm x 10-12 mm or 10 mm x 10 mm x 2.5 mm
- ✓ Any other size is possible with some constraints



For temperature monitoring in real time a FLIR® E-Series Advanced Thermal Imaging Camera, (+/- 1 °C ; 20-900 °C) was used

2022 Sample preparation and cutting – Be tile

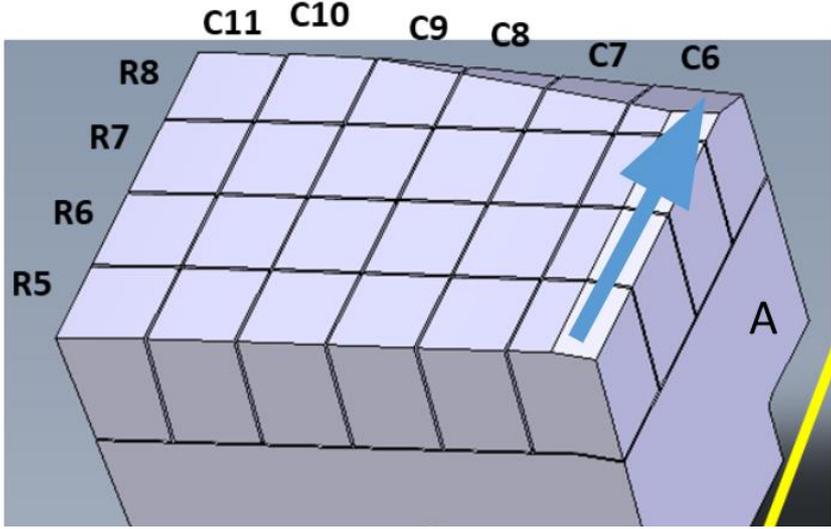
✓ Optical Microscopy

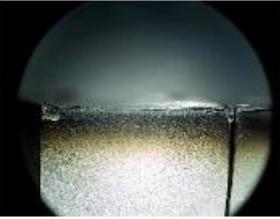
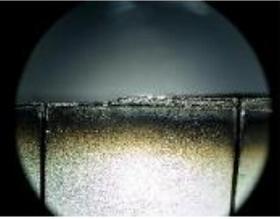
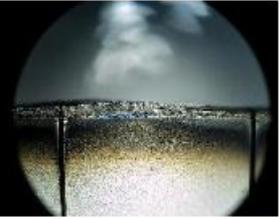
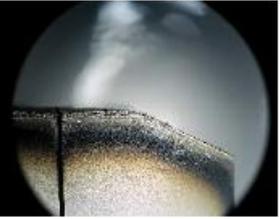


C11R5	C10R5	C9R5	C8R5	C7R5	C6R5

2022 Sample preparation and cutting – Be tile

✓ Optical Microscopy

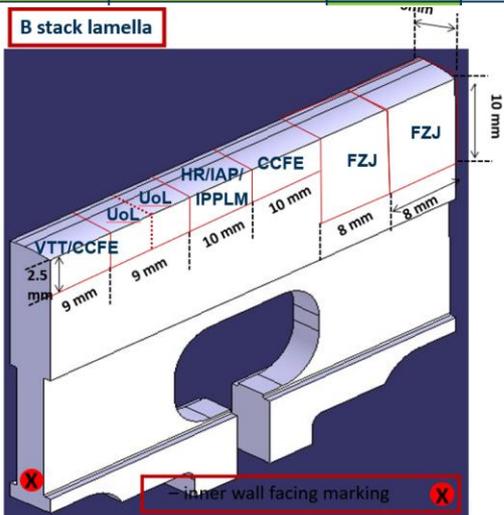


C6R5	C6R6	C6R7	C6R8
			



2022 Sample preparation and cutting – W lamellae

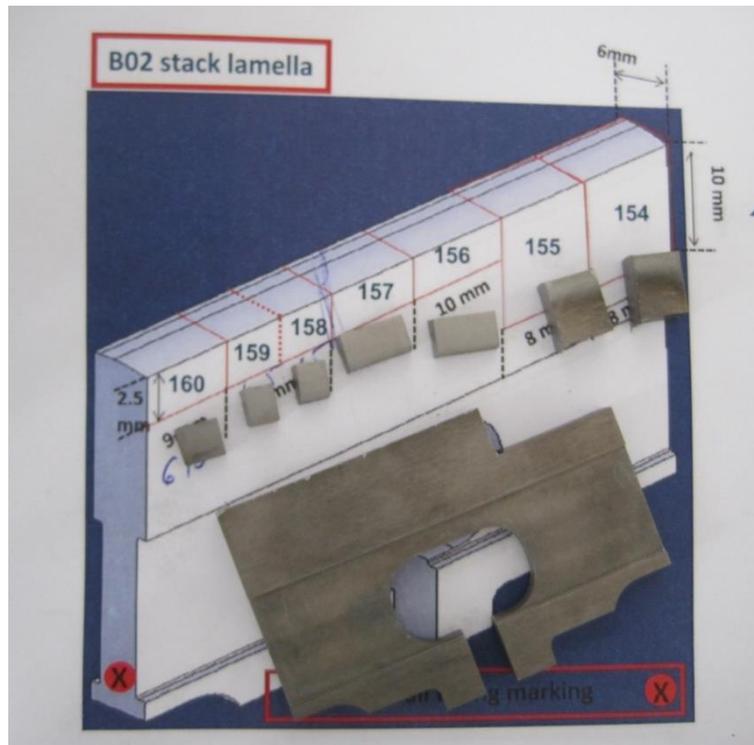
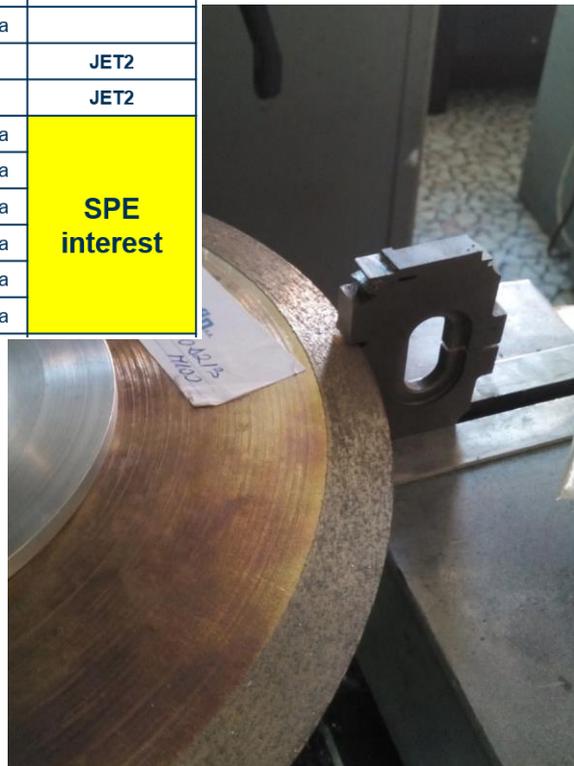
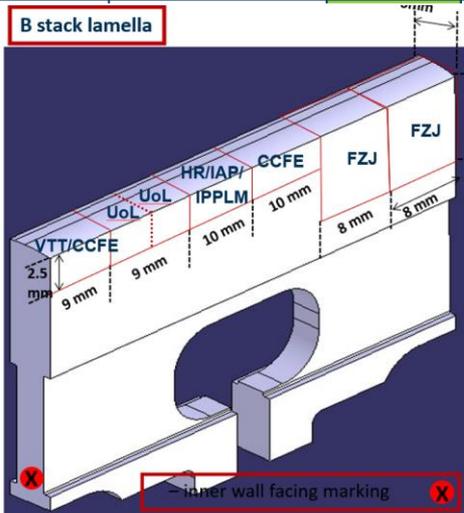
Stack	Lamellae position	Exposure	Status	Comment
A	A02	ILW3	Full lamella	
	A12	ILW1+3	Full lamella	
	A14-MELT	ILW3	Full lamella	
	A23	ILW3	CUT	JET2
	A24	ILW1+3	CUT	JET2
B	B02	ILW3	Full lamella	SPE interest
	B12	ILW1+3	Full lamella	
	B13	ILW3	Full lamella	
	B17	ILW1+3	Full lamella	
	B23	ILW3	Full lamella	
	B24	ILW1+3	Full lamella	





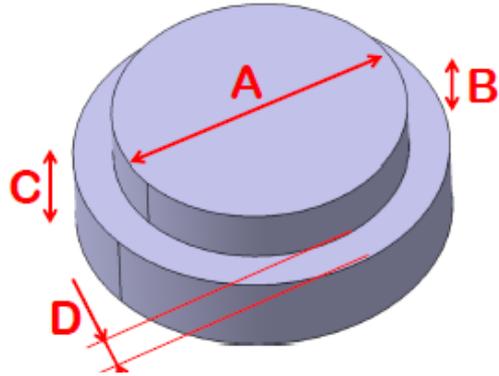
2022 Sample preparation and cutting – W lamellae

Stack	Lamellae position	Exposure	Status	Comment
A	A02	ILW3	Full lamella	
	A12	ILW1+3	Full lamella	
	A14-MELT	ILW3	Full lamella	
	A23	ILW3	CUT	JET2
	A24	ILW1+3	CUT	JET2
B	B02	ILW3	Full lamella	SPE interest
	B12	ILW1+3	Full lamella	
	B13	ILW3	Full lamella	
	B17	ILW1+3	Full lamella	
	B23	ILW3	Full lamella	
	B24	ILW1+3	Full lamella	



2022 Sample preparation and cutting

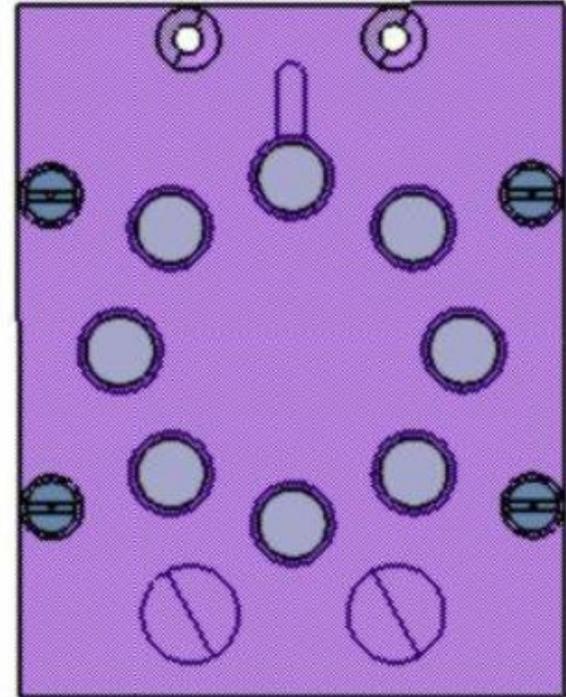
– W coated CFC → exposure to He plasma in the PSI2 plasma linear device



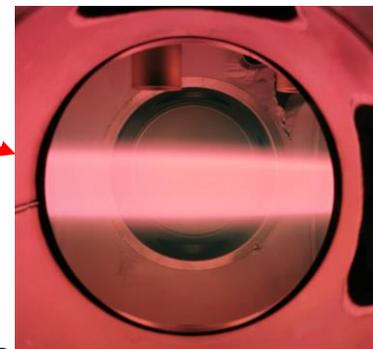
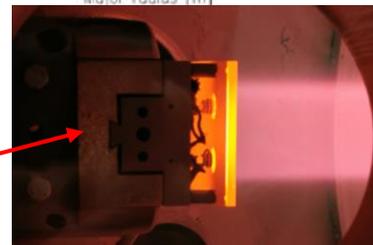
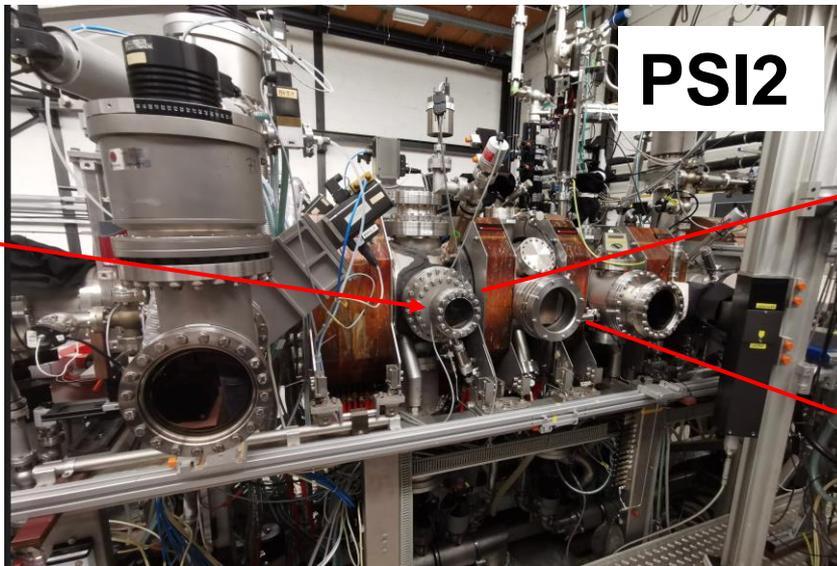
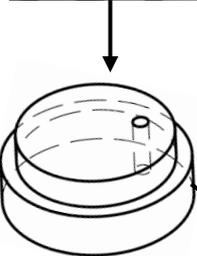
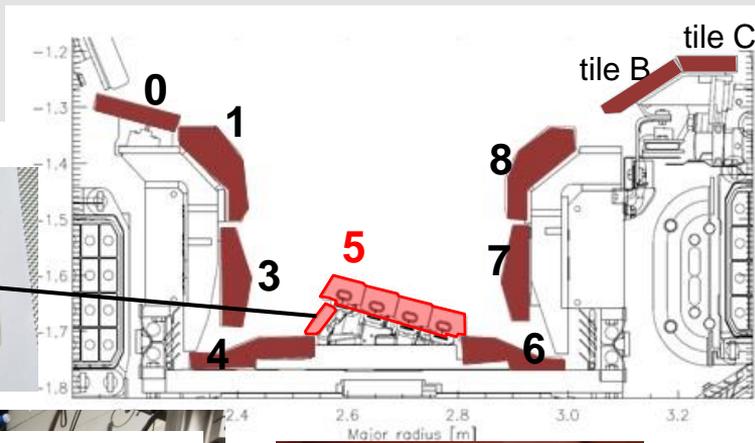
3. Choose your probe size and related maximum amount²:

(2) Probes are equally spread on Plasma maximum intensity circle.

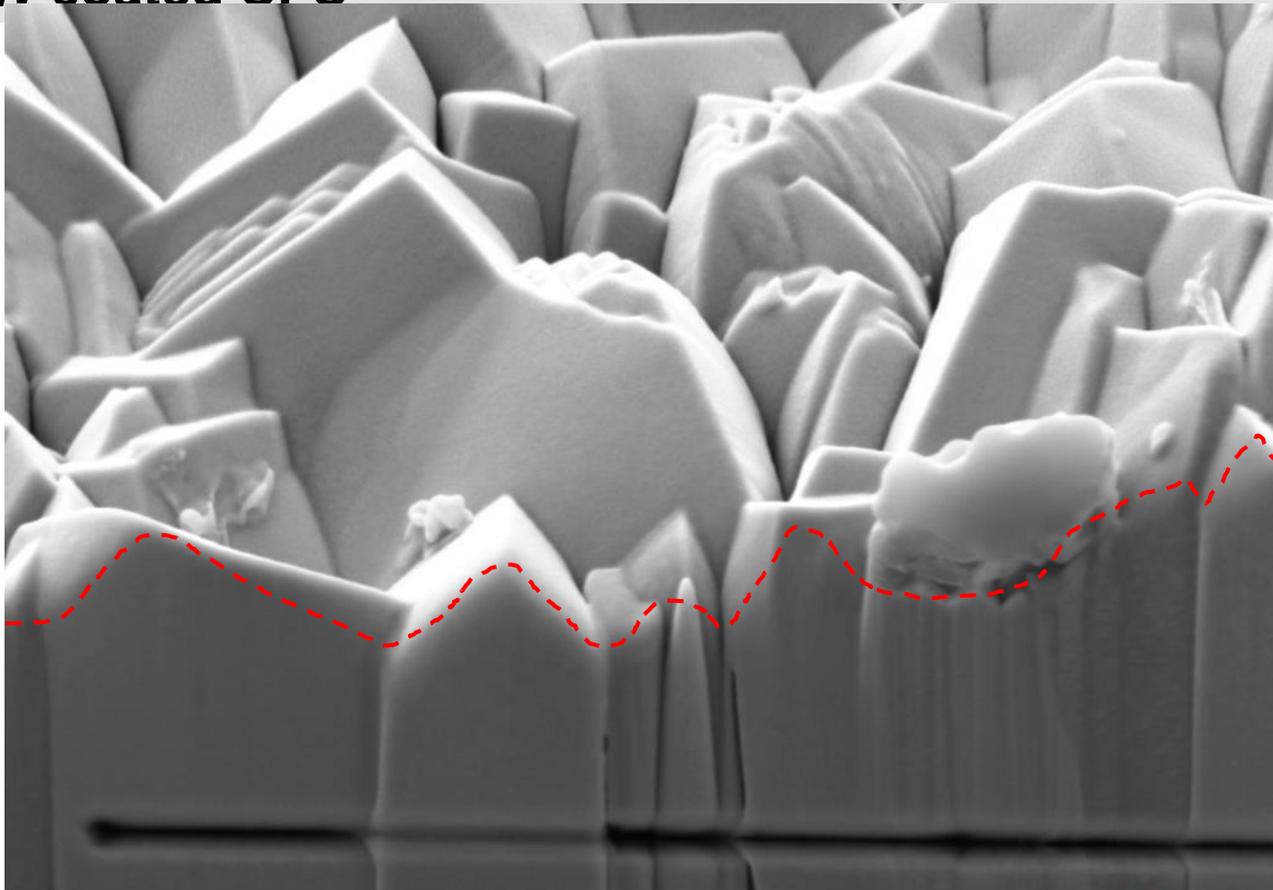
Probe Main dimensions (typical & range)	A (mm)	B (mm)	C ⁽³⁾ (mm)	D, D' (mm)	Maximum amount per mounting
5mm Probe	5	2	3	1	12
10mm Probe	10	2	3	1	8
15mm Probe	15	2	3	1	4
20mm Probe	20	2	3	2	2



2022 Sample preparation and cutting – W coated CFC



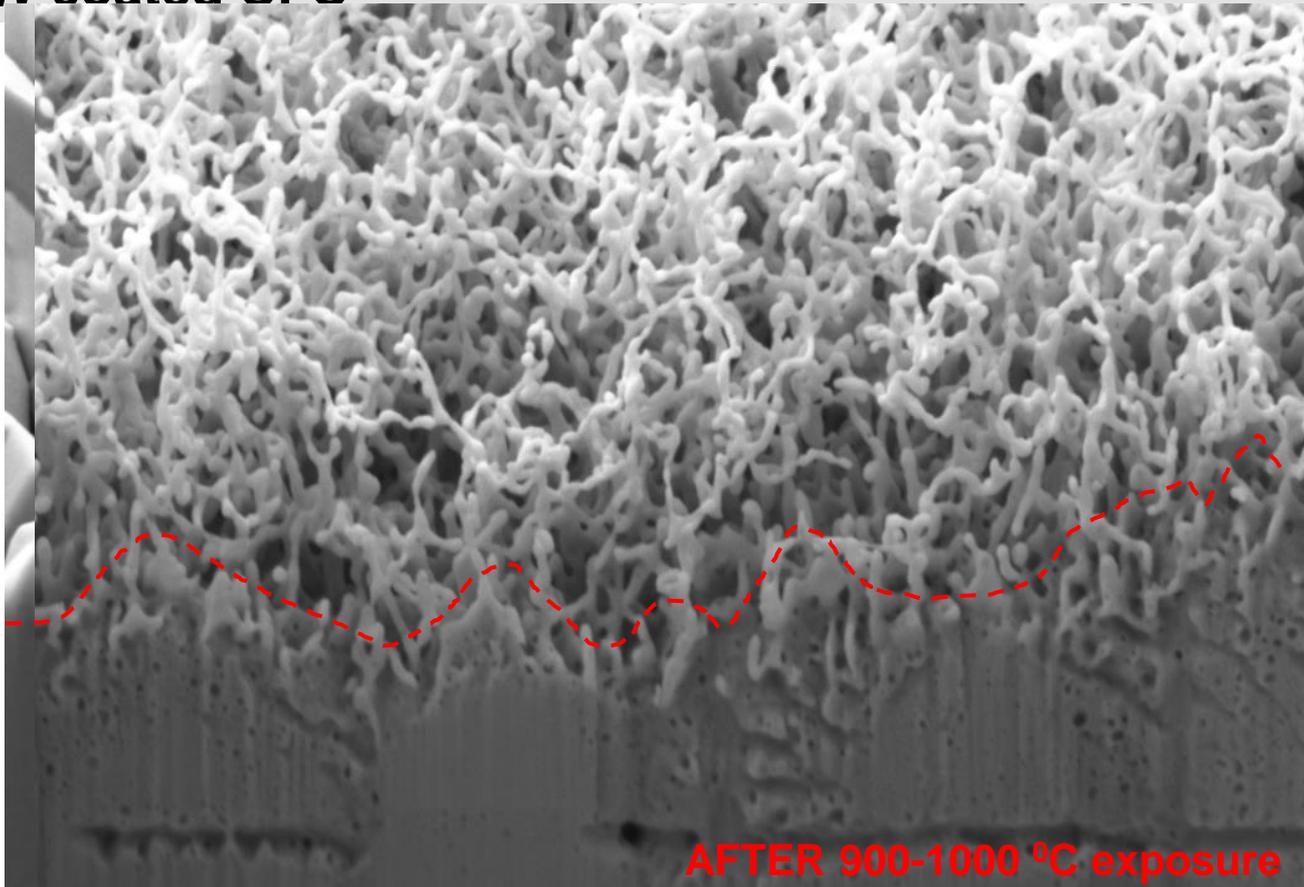
2022 Sample preparation and cutting – W coated CFC



300 nm 5.00 kV I Probe = 800 pA SE2 54.0° On WCh 1 IEK 4 JÜLICH
25.00 K X Width = 4.573 µm WD = 5.1 mm 9 Jun 2022 Rasinski FORSCHUNGSZENTRUM

Detailed results presented
by M. Rasinski et al.
WP PWIE: SP B
Tuesday 18th of Oct 2022

2022 Sample preparation and cutting – W coated CFC



Detailed results presented
by M. Rasinski et al.
WP PWIE: SP B
Tuesday 18th of Oct 2022

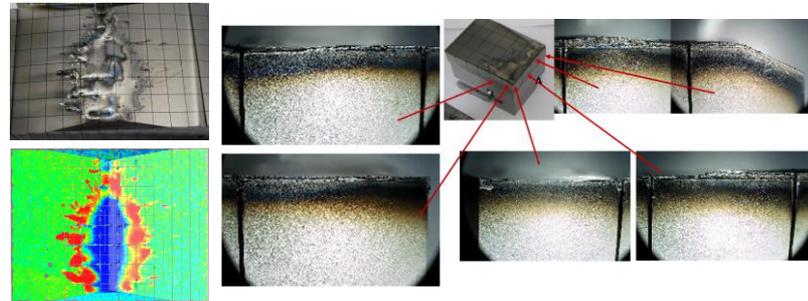
300 nm 5.00 kV I Probe = 800 pA SE2 54.0° On Wch1 IEK 4
25.00 K X Width = 4.573 μm WD = 5.2 mm 28 Jun 2022 PSI-2 exp1 Rasinski

Conclusions



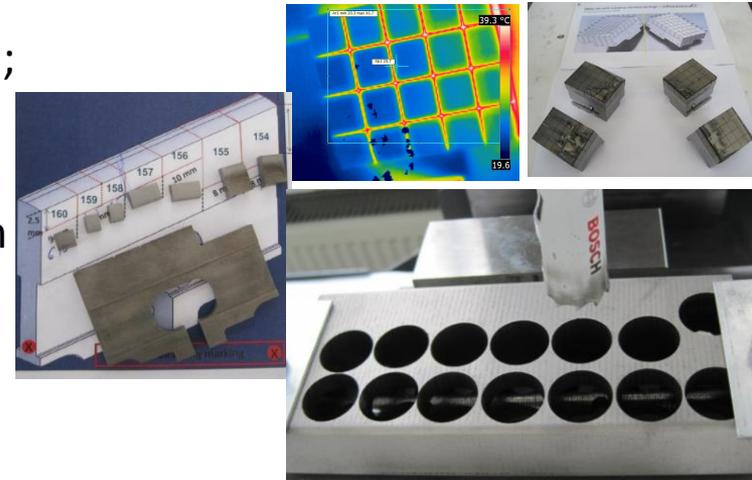
➤ REs damage of the JET's Be limiter started with:

- ✓ Tile profiling;
- ✓ Modelling based on tile profiling results;
- ✓ Cutting;
- ✓ Imaging and optical microscopy.



➤ IAP cutting activities and sample distribution:

- ✓ Cutting of REs damaged Be tile partially completed;
- ✓ Imaging and optical microscopy completed;
- ✓ W-CFC cutting and sample distribution completed;
- ✓ W – lamellae cutting ongoing – sample distribution to EUROfusion to follow



Thank you for your attention!