EUROfusion

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Runaway Electrons impact on JET PFCs in the “ILW” era (2011-2023)

Ionuț Jepu

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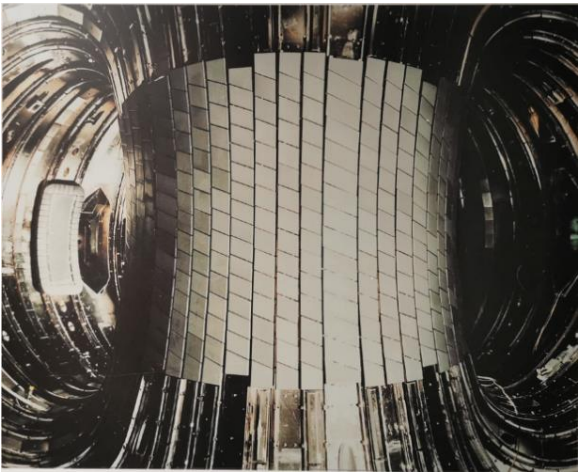
JET cea irfm JÜLICH FORSCHUNGSZENTRUM ENEA KTH

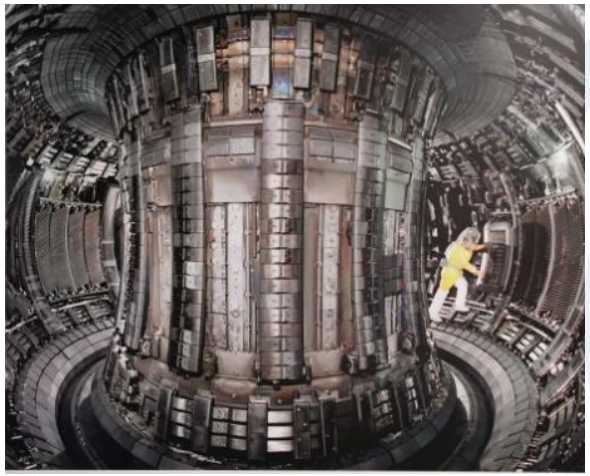
UK Atomic Energy Authority VTT

Background – typical JET materials Evolution

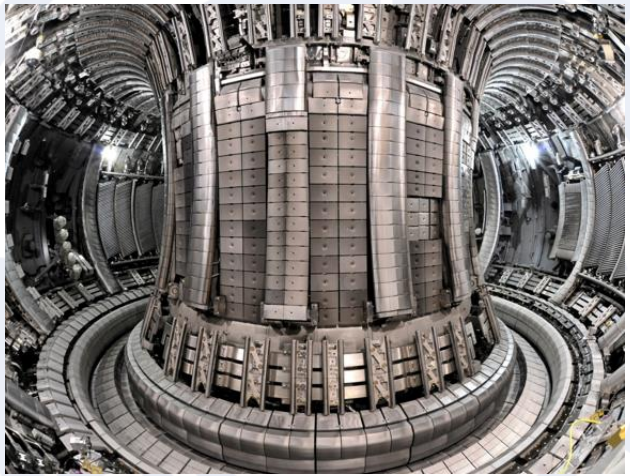
1983



1996



2011 – 2023 (former ILW era)



1983 – 2010:

- **80127 pulses**

2011 - present:

- **25801 pulses**

TOTAL NO OF JET PULSES in 40 years of operation : 105929!

Background – JET plasma disruption

Plasma disruption

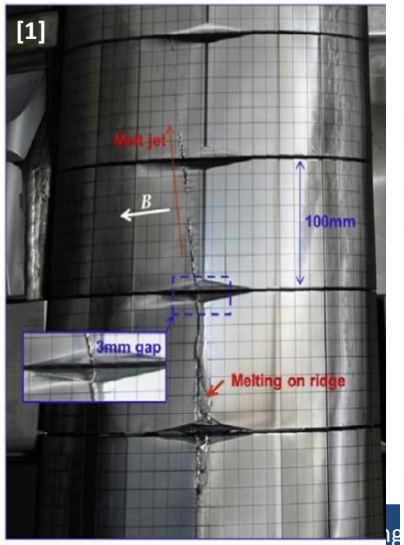
Termination of plasma with rapid loss of thermal and magnetic energy

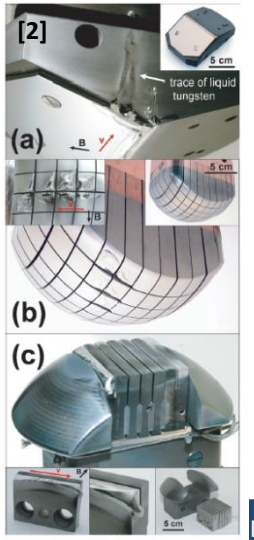
↓

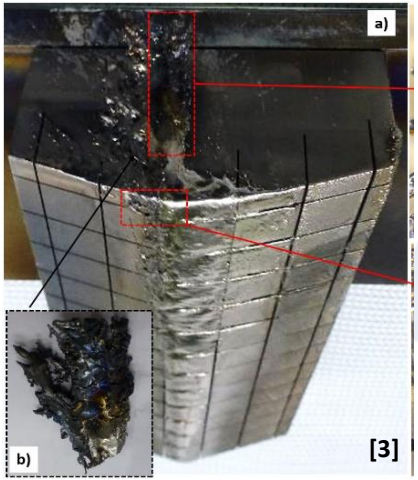
HUGE thermal and mechanical loads on the structure

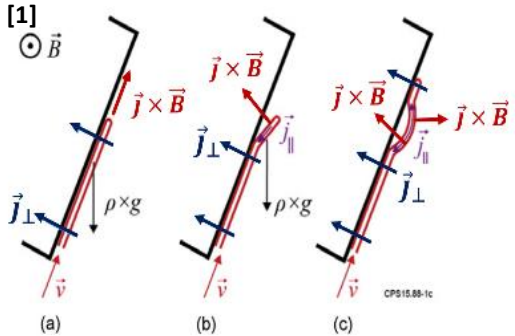
Consequences of the disruptions

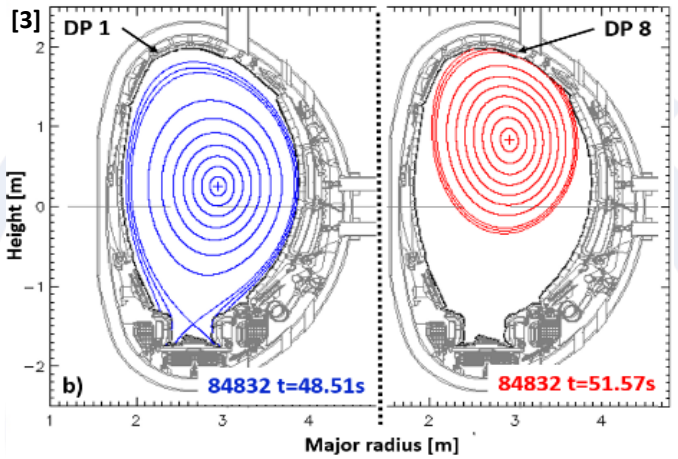
- Thermal loads/Fast melting and electromagnetic forces

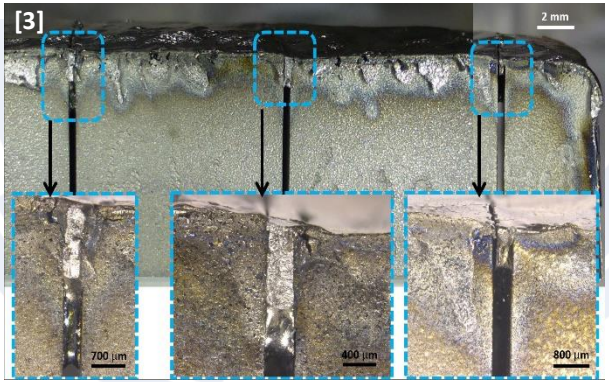












[1] G.F. Matthews, et al., Phys. Scr. T167 (2016) 014070 (7pp)
[2] G. Sergienko et al., Phys. Scr. T128 (2007) 81–86
[3] I. Jepu et al, Nucl. Fusion 59 (2019) 086009

REs damage to JET PFC – Be limiter tile

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

REs damage to JET PFC – Be limiter tile

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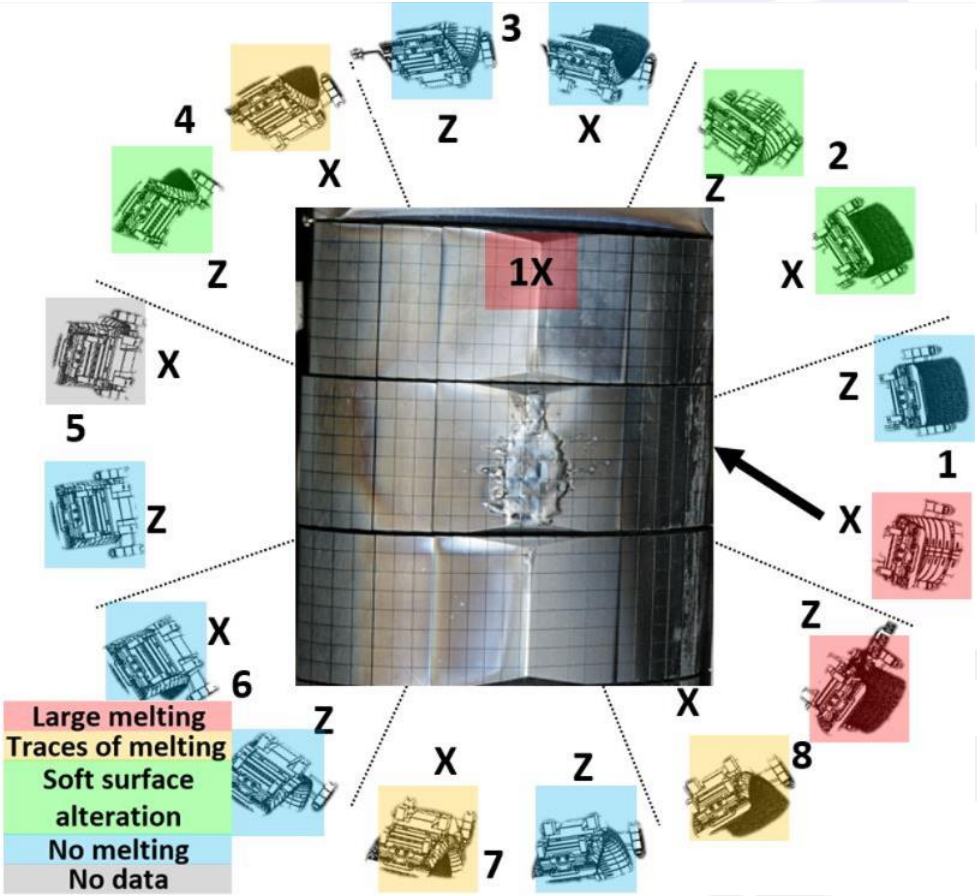
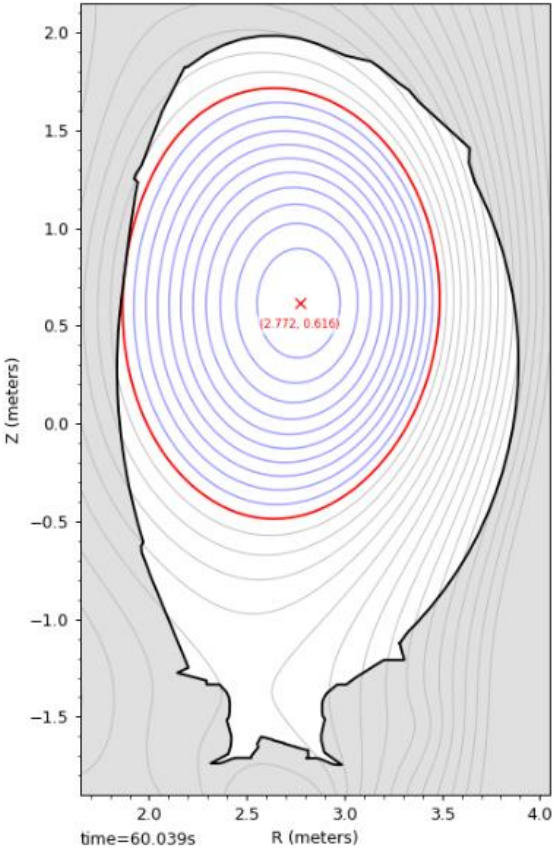


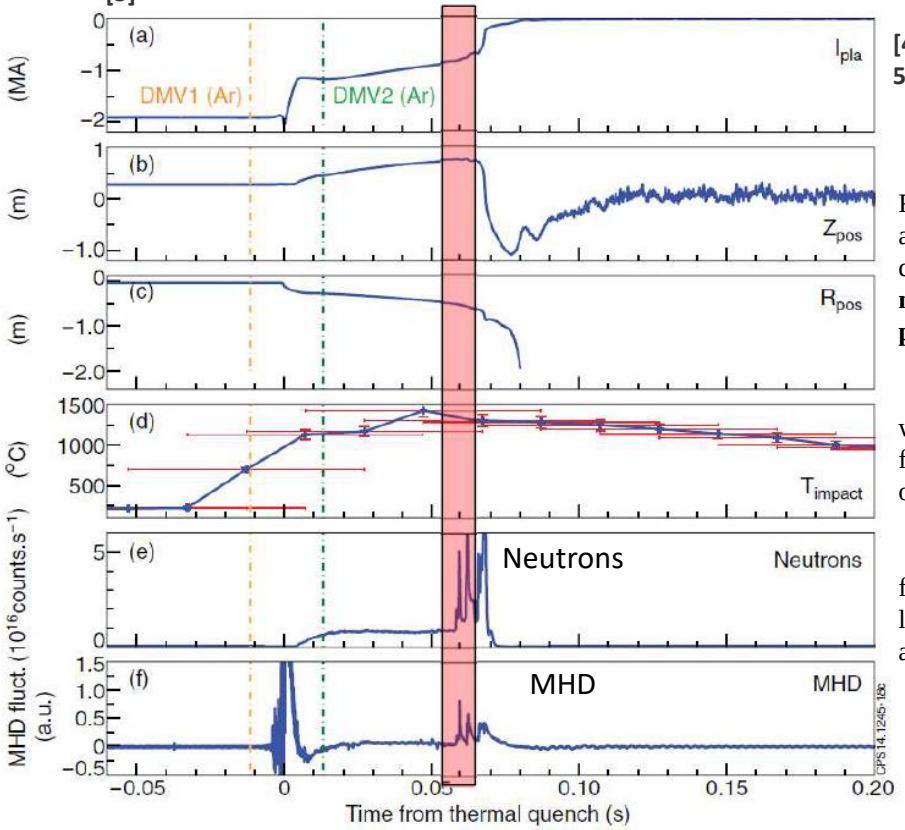
[5] Jepu I. et al 2024 Nucl. Fusion 64 10604

REs damage to JET PFC–pulse identification #86801

Equilibrium profile



[5]



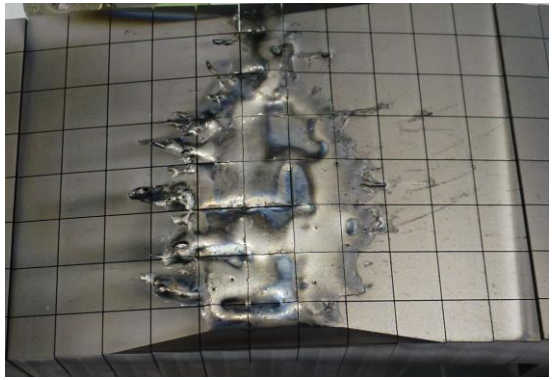
[4] C. Reux et al Nucl. Fusion 55 (2015) 093013

RE up to 20 MeV can be accelerated during the current quench with currents up to **more than half the initial plasma current.**

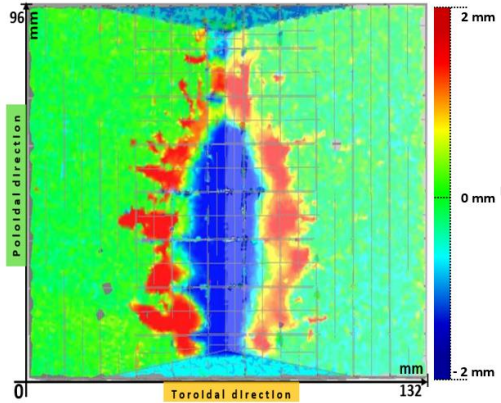
- These electrons form a beam which can be sustained from a few 10 ms to several seconds on present tokamaks.

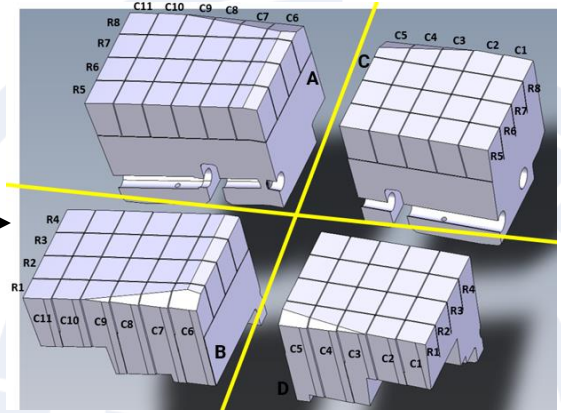
- The beam impact on plasma facing components leads to localized heat loads spread over a few millimetre thickness.[4]

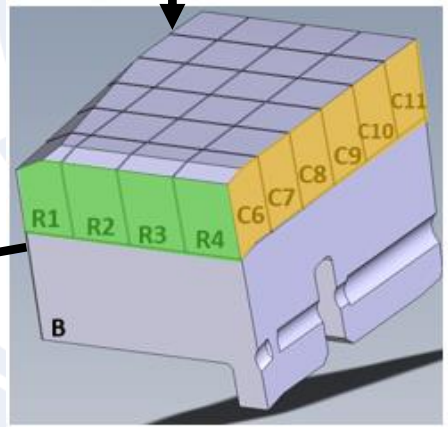
REs damage to JET PFC – Be limiter tile

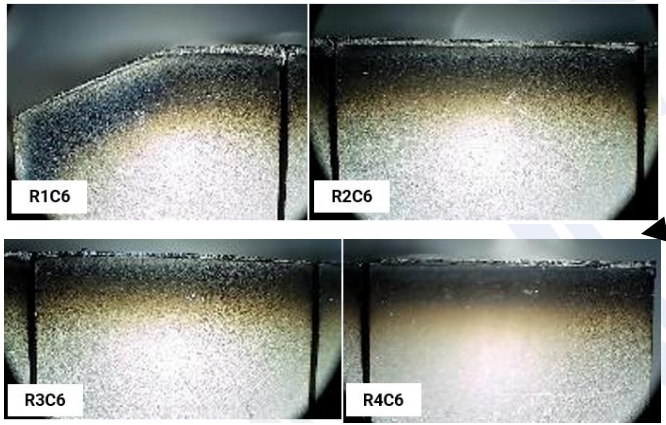


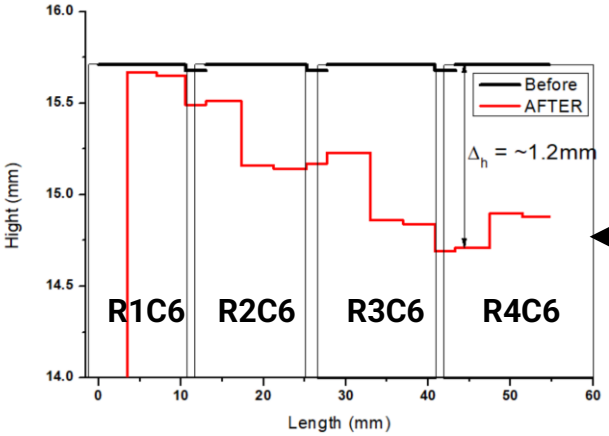
Laser 3D profiling







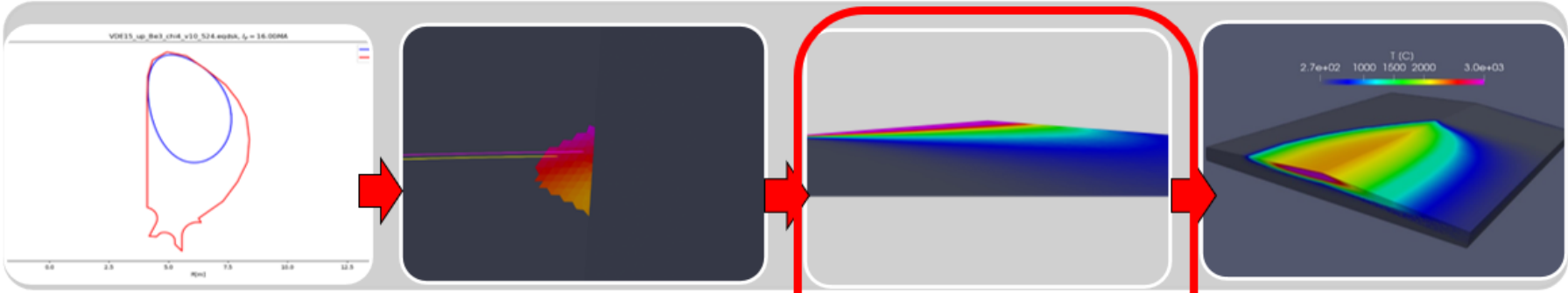




[5] Jepu I. et al 2024 Nucl. Fusion 64 10604

REs damage to JET PFC – Modelling

➢ **Use the DINA-SMITER-GEANT4-MEMOS-U code workflow developed at IO**



DINA
- Time- dependent Plasma Equilibrium
- Various Disruption Scenarios

SMITER
- 3D RE footprint
- Single time-step

MATLAB
- Impact angle
- REs toroidal power density distribution

GEANT4
- Volumetric energy deposition
- Single time-step

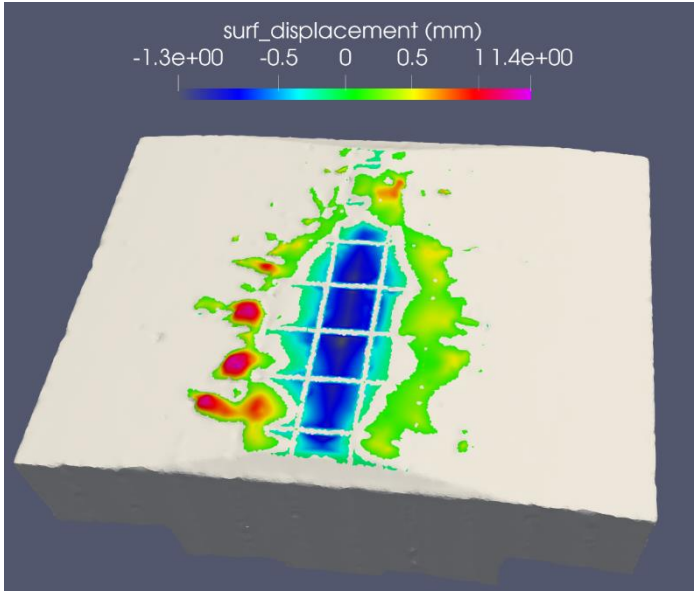
MEMOS-U
- Time-dependent melt formation and motion

[6] CHEN L., et al., in preparation for Nuclear Fusion
[7] L. Chen et al. 5th Asia Pacific Conference on Plasma Physics, 26 Sep-1 Oct 2021
[8] CHEN L. et al. 25th PSI Conference, 14 June 2022

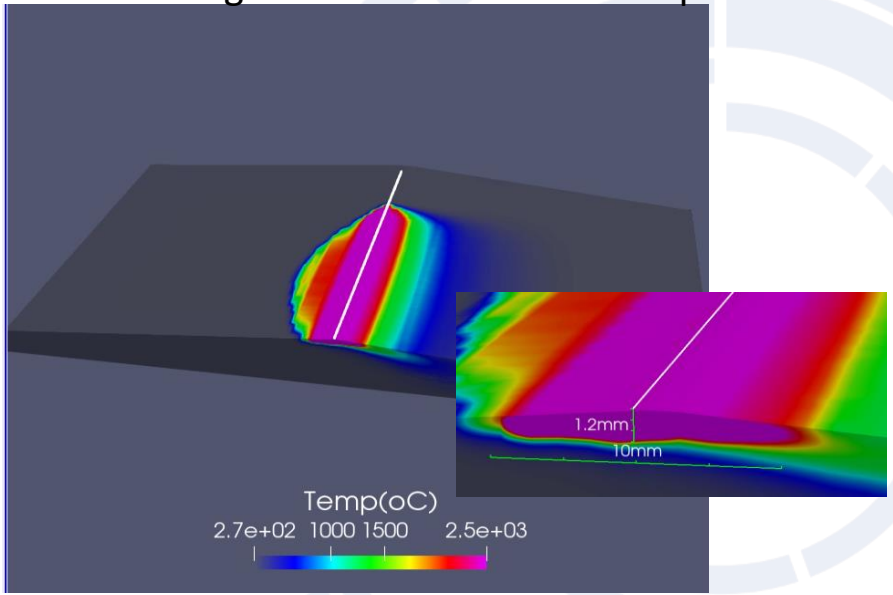
REs damage to JET PFC – Modelling

Simulation vs exp. (v_r=12 km/s, E_{dep}=50 kJ)

Exp. beryllium erosion crater: 484mm^3



MEMOS: Boiling volume at the end of RE pulse 554mm^3

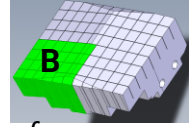


Boiling patterns, volume and depth consistent with experimental findings:

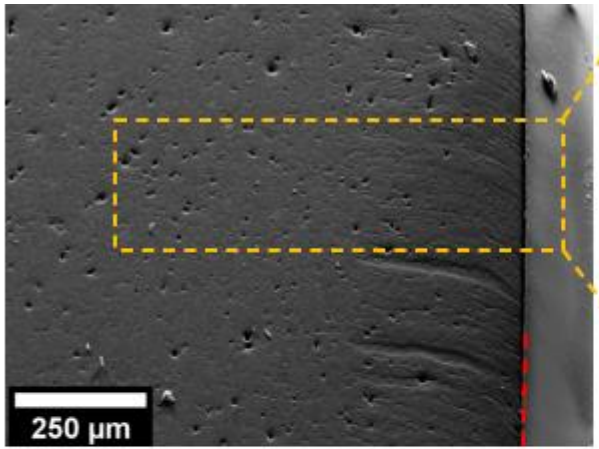
- Symmetric boiling profile from MEMOS-U and symmetric erosion from exp.
- Simulated evaporated mass ~ 0.2 g → experimental mass difference between regions of deposition and erosion ~ 0.1 g (from surface displacement map)
- Boiling depth ~ 1.2 mm, width ~ 10 mm consistent with post-mortem analysis on damaged limiter

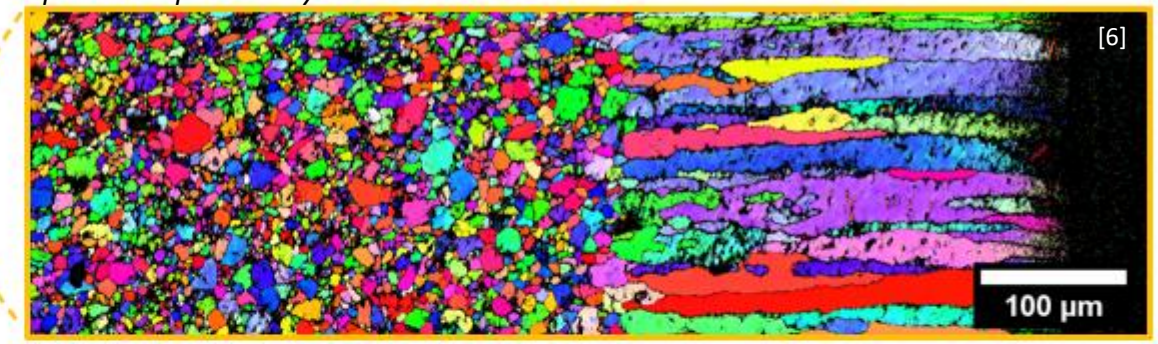
[6] CHEN L., et al., in preparation for Nuclear Fusion
[7] L. Chen et al. 5th Asia Pacific Conference on Plasma Physics, 26 Sep-1 Oct 2021
[8] CHEN L. et al. 25th PSI Conference, 14 June 2022

REs damage to JET PFC – Be limiter tile SEM/EBSD



Surface normal-projected inverse pole figure (IPF) orientation map near surface area of the plasma-exposed beryllium





Melted-resolidified area

beryllium

epoxy

Plasma-exposed surface

- **Beryllium base material has uniaxial grains** – typical for vacuum hot pressed beryllium (**average diameter < 10 µm**)
- **The melted and re-solidified areas consist of elongated grains with large axis perpendicular to the surface** (i.e. perpendicular to the solidification direction)
- Investigated surface grains grain were >300 µm long however they might be longer in other areas with deeper plasma induced melting

[5] Jepu I. et al 2024 Nucl. Fusion 64 10604

End of part 1

New damage to JET PFC (Dec 2023) - IWGL

6 Dec 2023 Late

Session details »

Experiment/aims: RT22-03-T7 Runaway Electrons

Task force: —

EIC: Nick Balshaw **SL:** Scott Silburn **SC:** Cedric Reux **DC:** Marco Zerbini **VSO:** Peter Cooper

Pulse	Time	B_T	I_P	Pre-pulse comment	Post-pulse comment
105649	21:57:18	2.350	1.800	ohm cleaning pulse	—
105648	21:35:44	3.000	1.900	back to program, ref. 102617	good
105647	21:15:25	2.350	1.800	ohm cleaning pulse	disrupts
105646	20:48:30	3.000	1.900	delay SPI 10ms	good
105645	20:07:32	3.000	1.900	ref. 102617	
105644	19:36:33	3.500	2.500	repeat	
105643	19:11:31	3.500	2.500	—	
105642	18:45:49	3.500	2.500	Elongated p	
105641	17:52:18	3.500	2.500	repeat, DMV	
105640	17:22:33	3.500	2.500	ref #103138	
105639	16:57:31	2.300	1.800	ref #104029	
105638	16:09:22	3.400	3.000	—	
105637	15:25:15	3.400	3.000	repeat with	

14 Dec 2023 Late

Session details »

Experiment/aims: RT22-03-T7 Runaways

Task force: —

EIC: Paul Finburg **SL:** Peter Lomas **SC:** Cedric Reux **DC:** Kingsley Collie **VSO:** Ewa Kowalska-Strzeciwilk

Pulse	Time	B_T	I_P	Pre-pulse comment	Post-pulse comment
105802	21:49:12	3.000	1.450	Repeat 105790, increase Ar. SPI A, B, DMV3. DMV2 10bar D2 48.65s	Worked, absolutely benign
105801	21:28:55	2.300	1.750	Cleaning, ref 103655	Good
105800	21:10:05	3.450	2.900	Repeat, higher DMV3, DMV2 16 bar	Surprisingly not benign
105799	—	—	—	Repeat, higher DMV3, DMV2 16 bar	Aborted
105798	20:41:56	3.450	2.900	Repeat 105795, without DMV2	Surprisingly more benign than
105797	20:17:17	3.450	2.450	Repeat 105794, 2 bar argon	Surprisingly more benign than reference
105796	19:40:32	3.000	1.450	Repeat 105791, no SPI	Surprisingly more benign than reference
105795	19:15:41	3.400	2.900	Repeat, higher current, less Ar, DMV2, no SPI	Absolutely not benign
105794	18:44:47	3.400	2.400	Repeat, higher field, 2 bar Ar	Good, absolutely not benign
105793	17:53:05	3.000	1.900	Repeat	Good, not benign
105792	17:21:00	3.000	1.900	Repeat 102618, more Ar	Early stop due to ERFA alarm
105791	16:38:28	3.000	1.45(		
105790	16:09:03	3.000	1.45(		
105789	—	—	—		

18 Dec 2023 Late

Session details »

Experiment/aims: Final plasma shift: RT22-02-NT Negative Triangularity & RT22-03 Unmitigated RE Reference

Task force: —

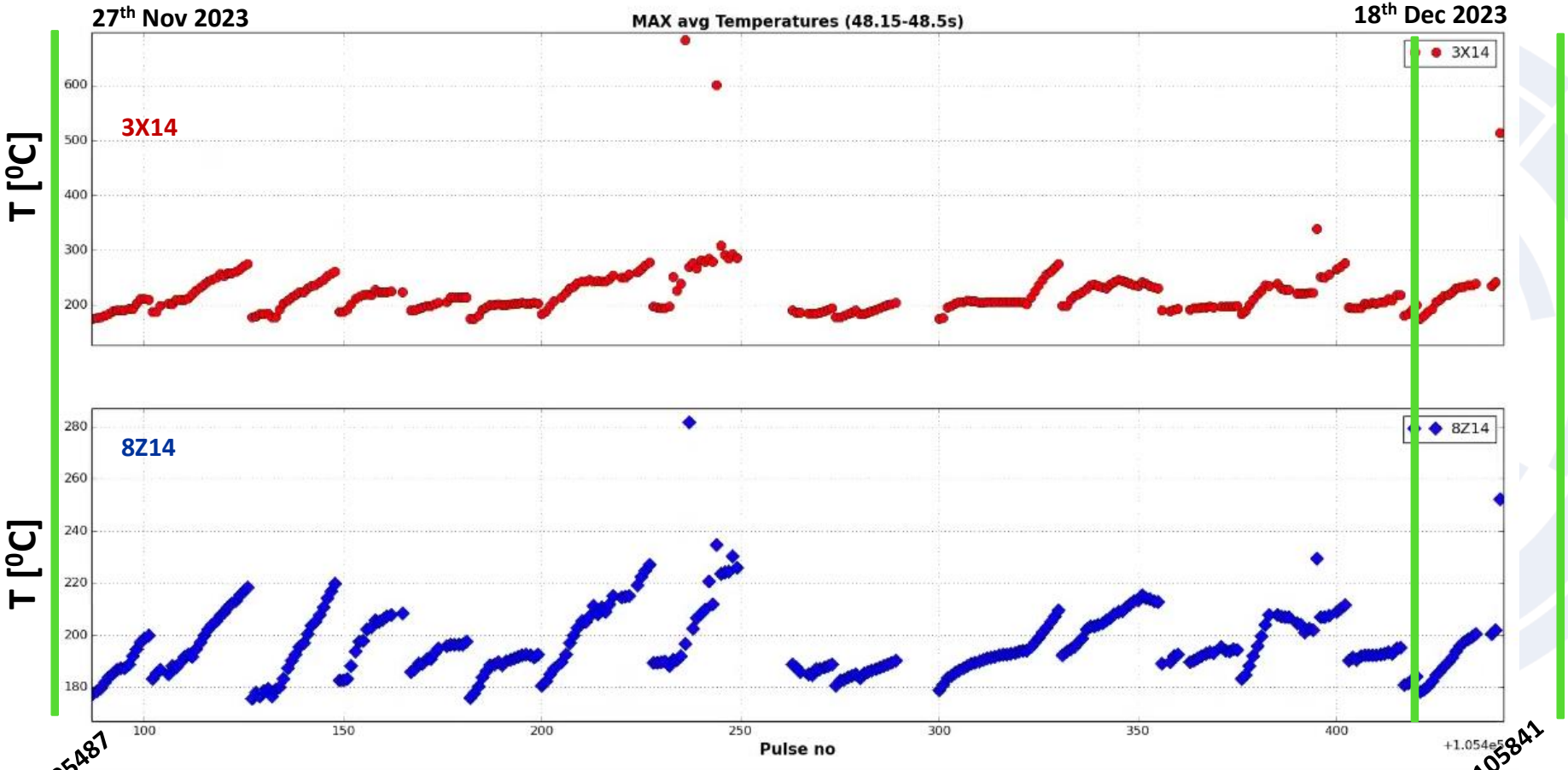
EIC: Nick Balshaw **SL:** Christopher Lowry / Scott Silburn **SC:** Olivier Sauter **DC:** Domagoj Kos **VSO:** Pedro Carvalho

Pulse	Time	B_T	I_P	Pre-pulse comment	Post-pulse comment
105841	21:16:42	3.450	2.900	RE beam with high impact	Great, 127 ms, 1.7MA -> 1.2 MA

Single RE pulse

New damage to JET PFC (Dec 2023) - IWGL

IVIS inspections



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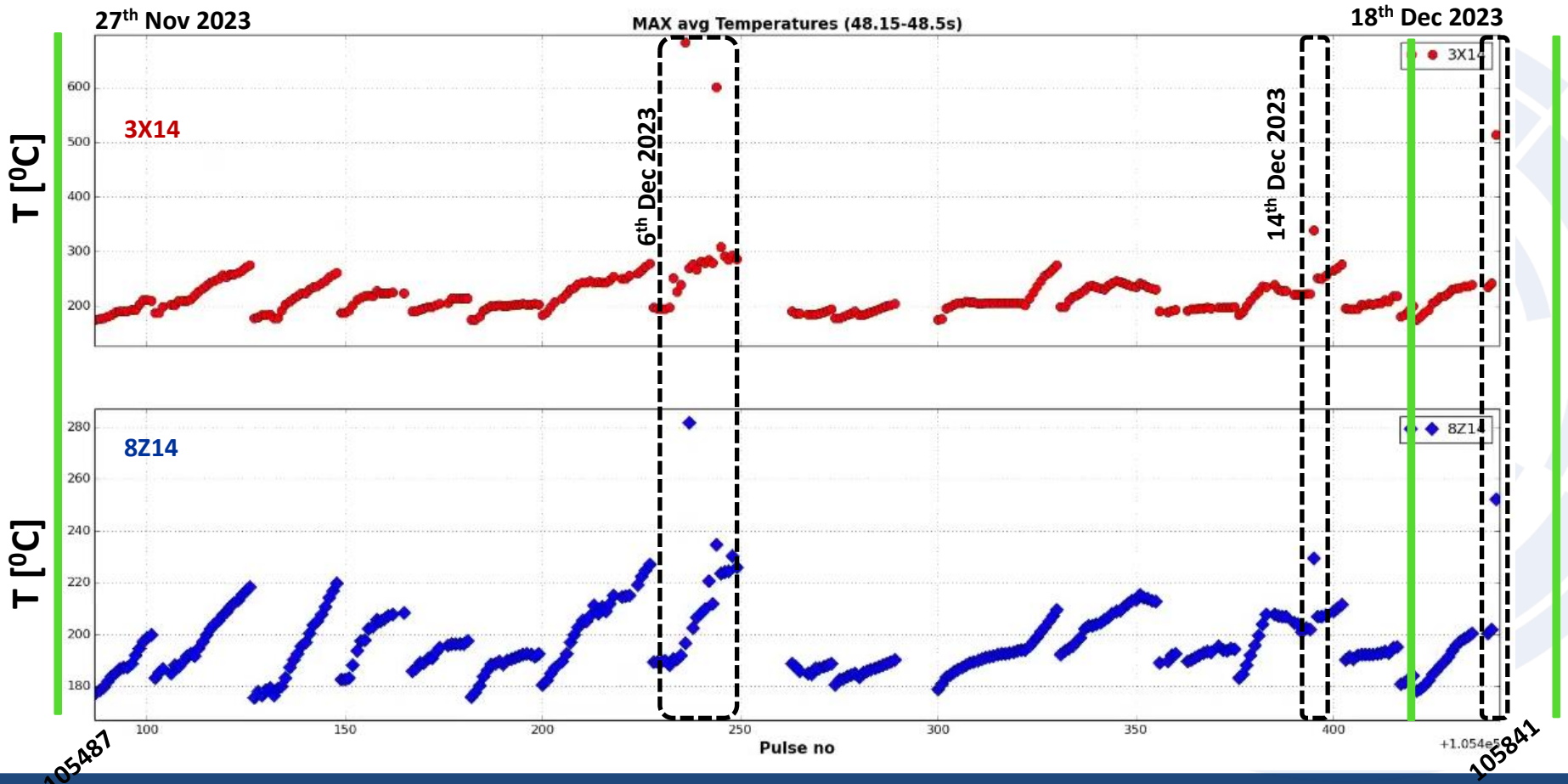
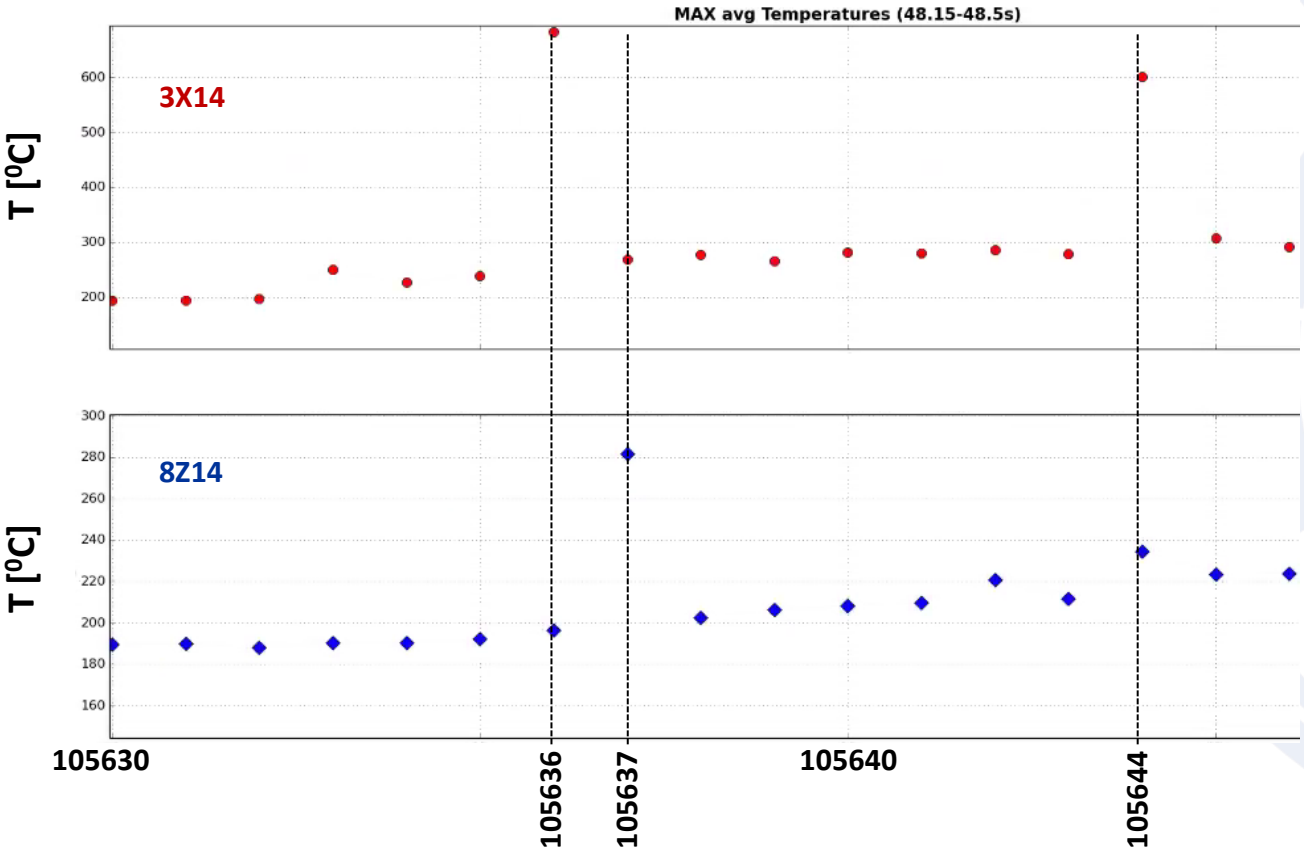
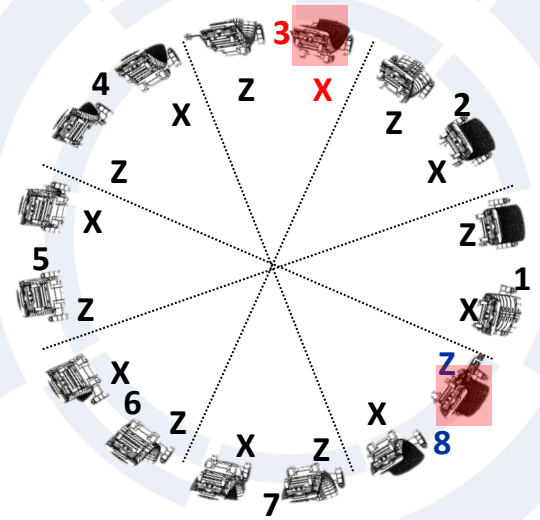


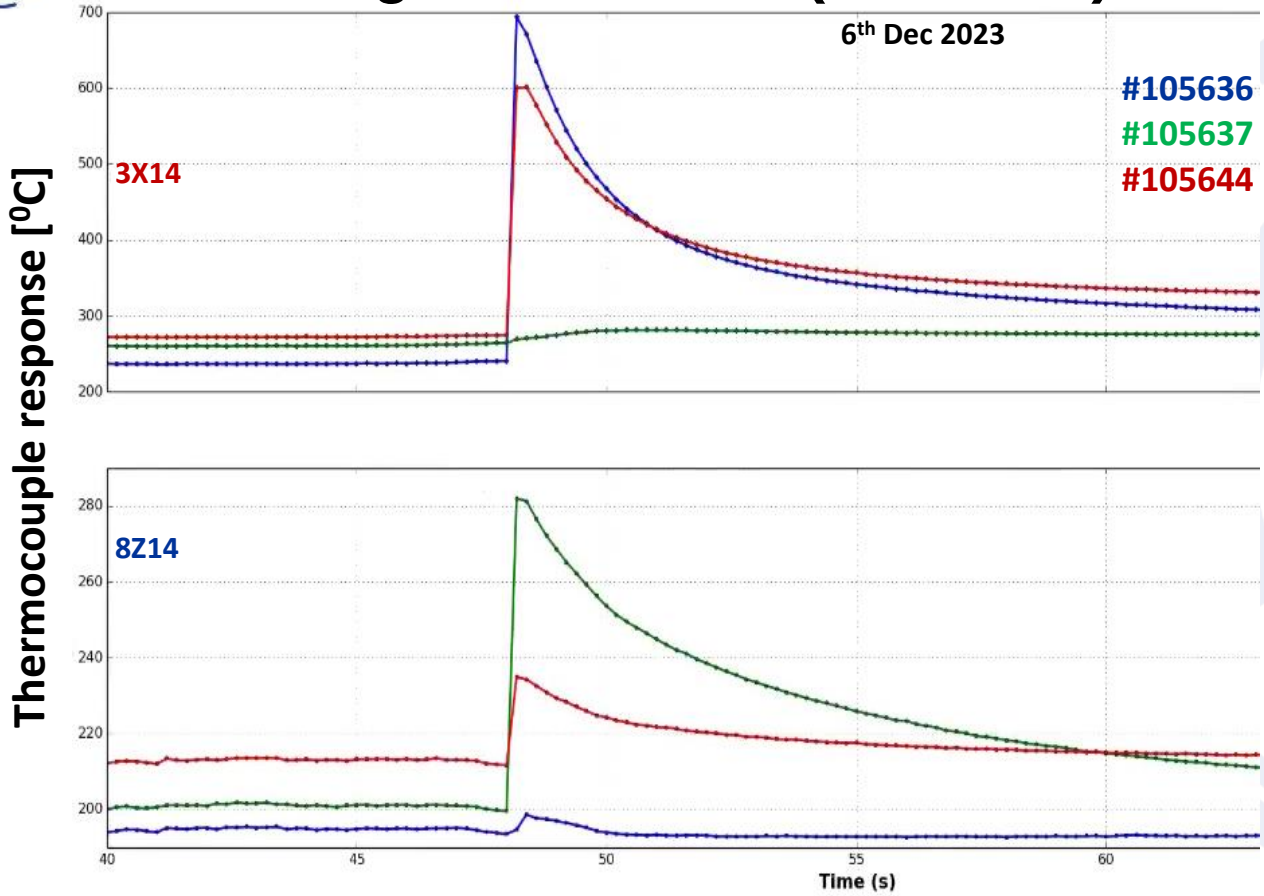
New damage to JET PFC (Dec 2023) - IWGL

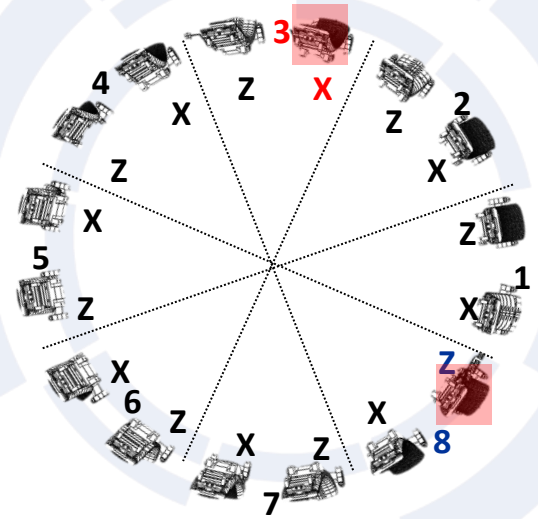
6th Dec 2023





New damage to JET PFC (Dec 2023) - IWGL





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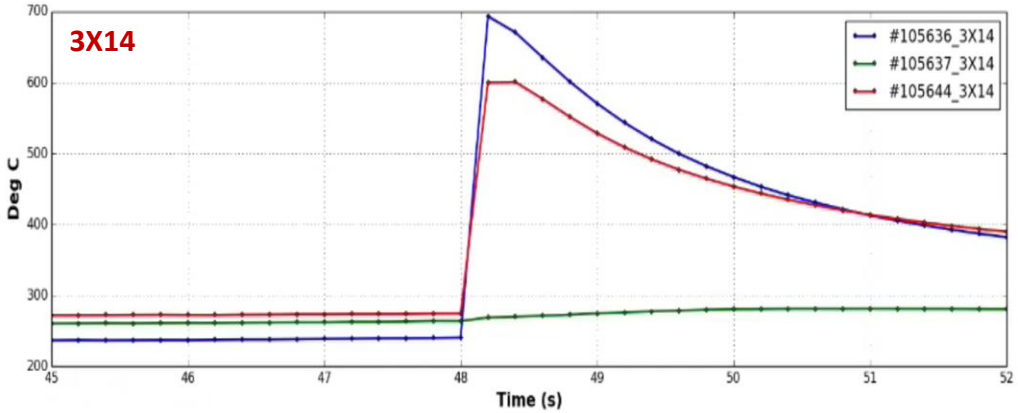

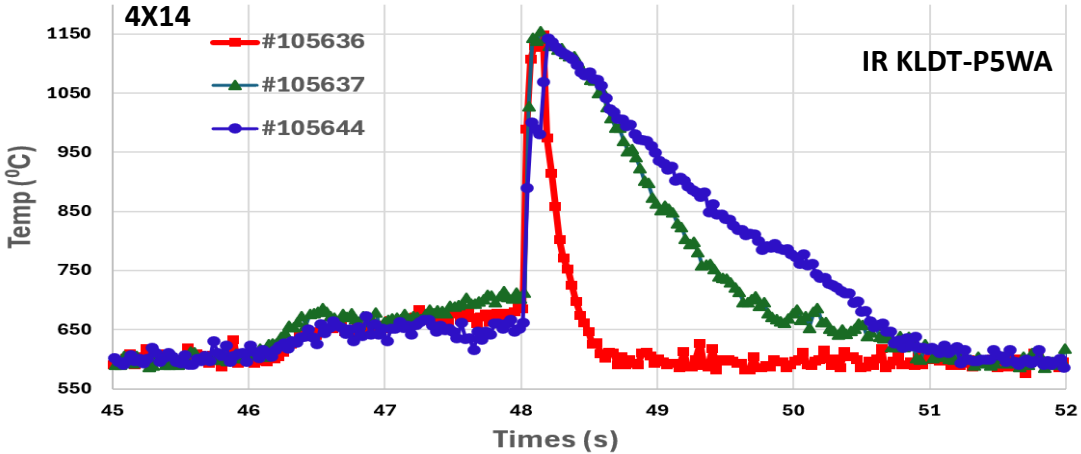

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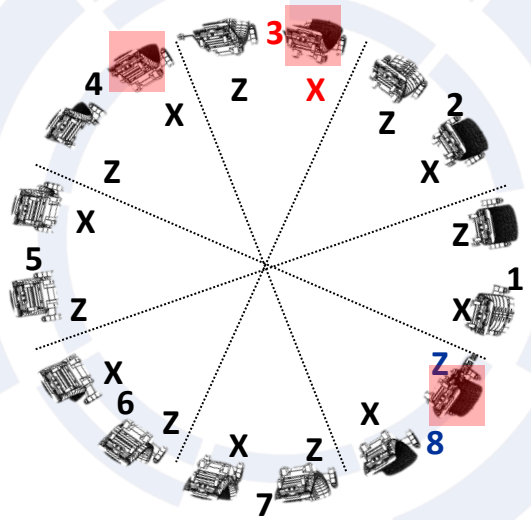

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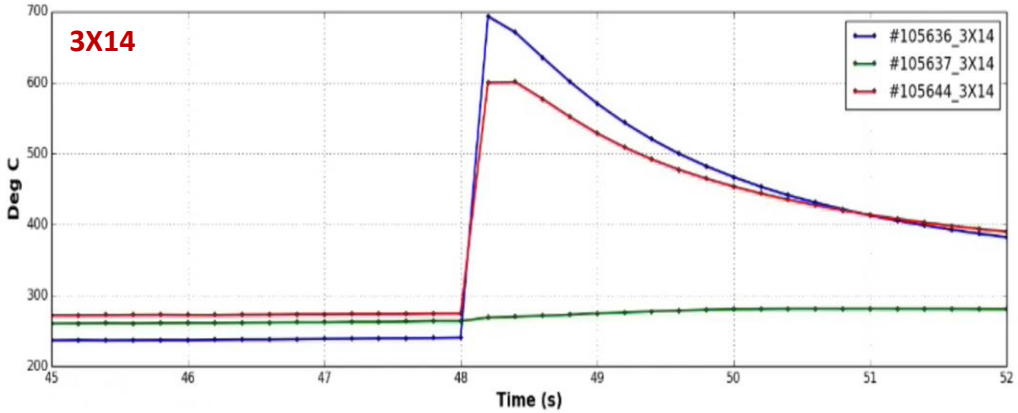

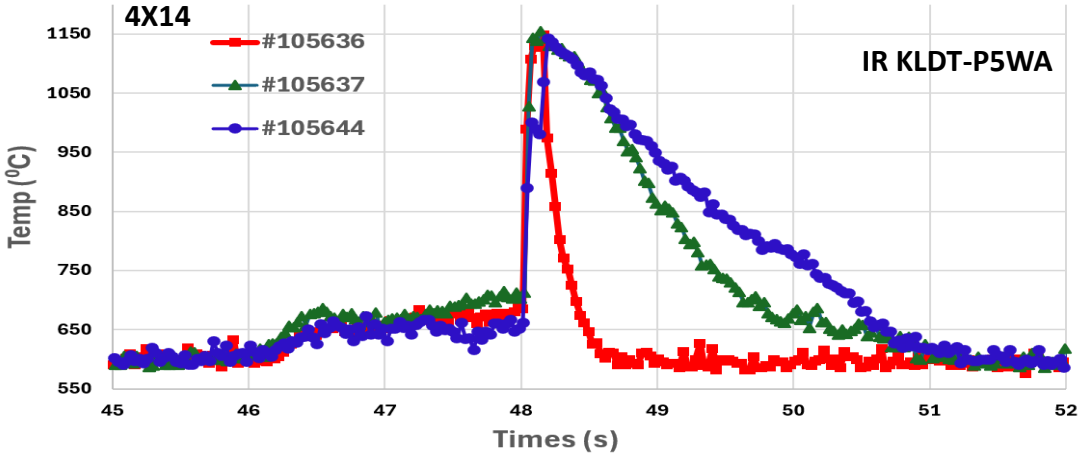

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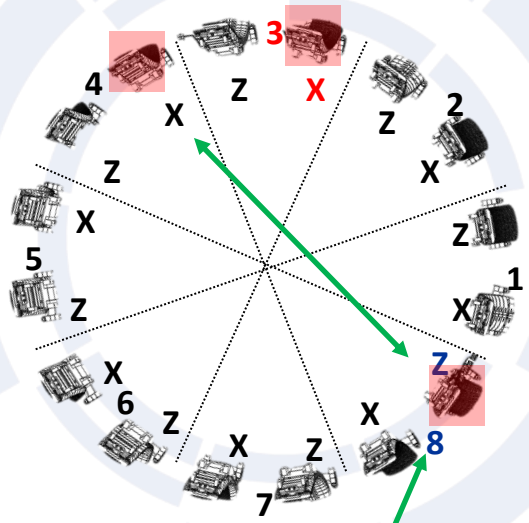

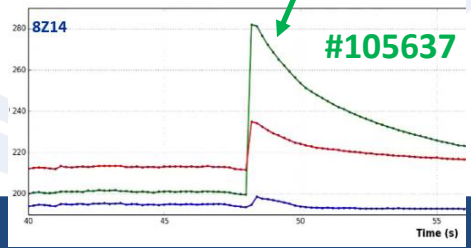

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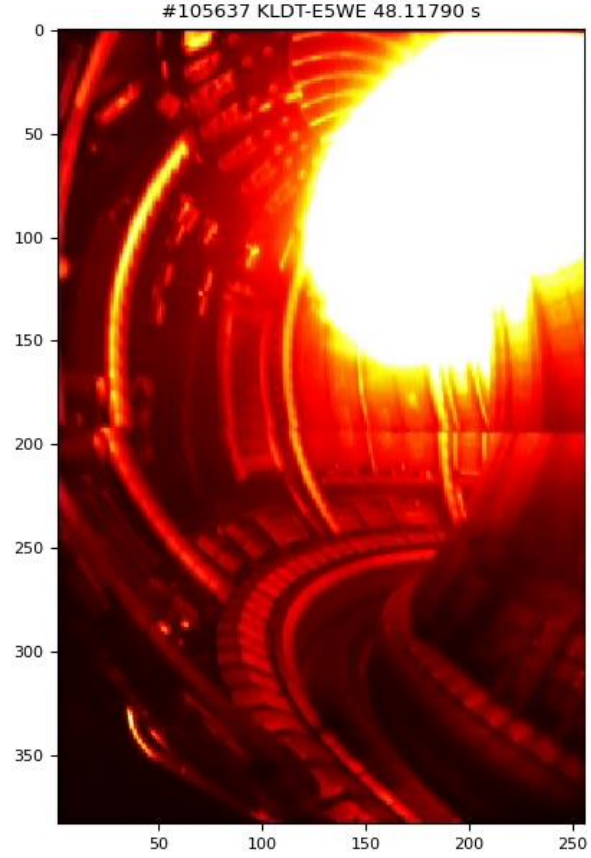
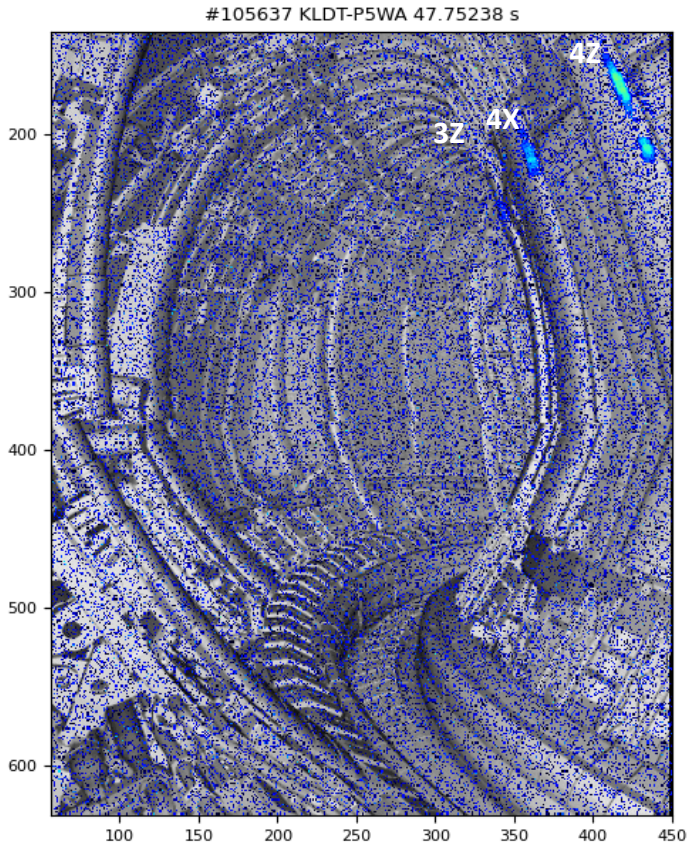
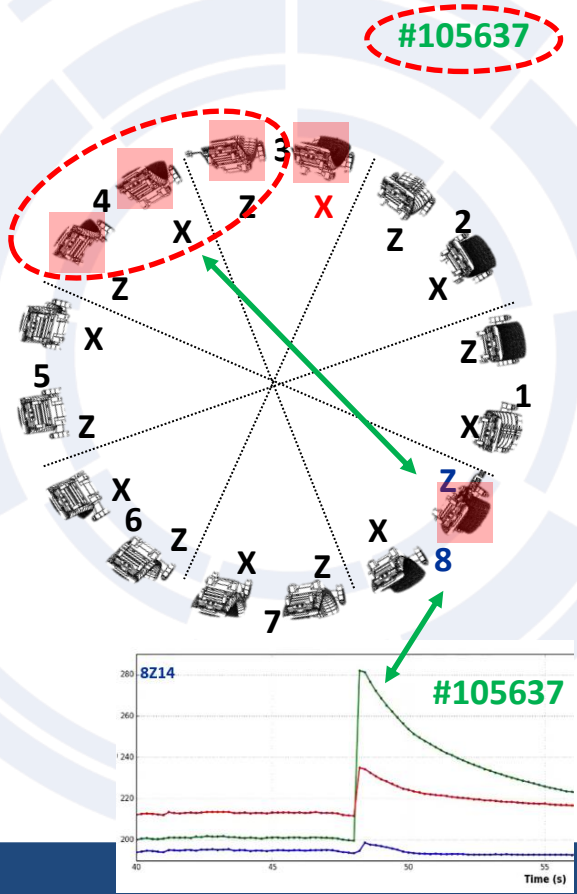
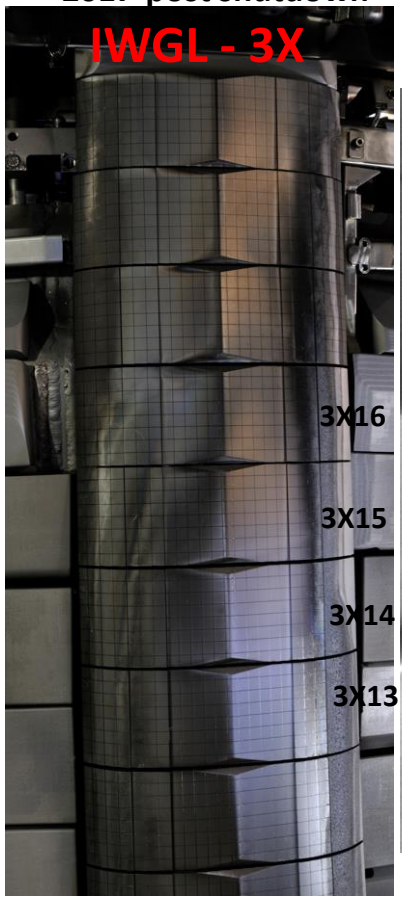




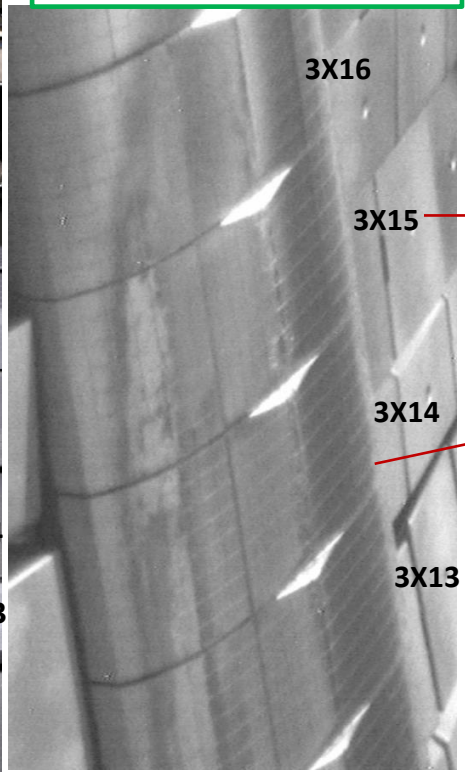


New damage to JET PFC (Dec 2023) - IWGL

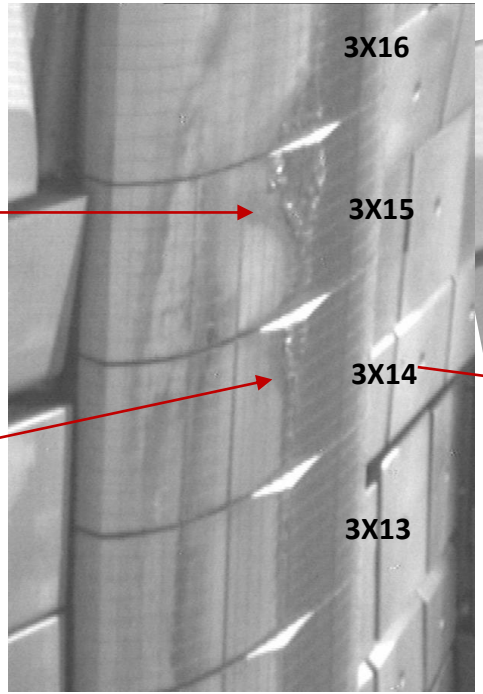
2017-post shutdown



26.11.23 IVIS – **no damage**



17.12.23 IVIS



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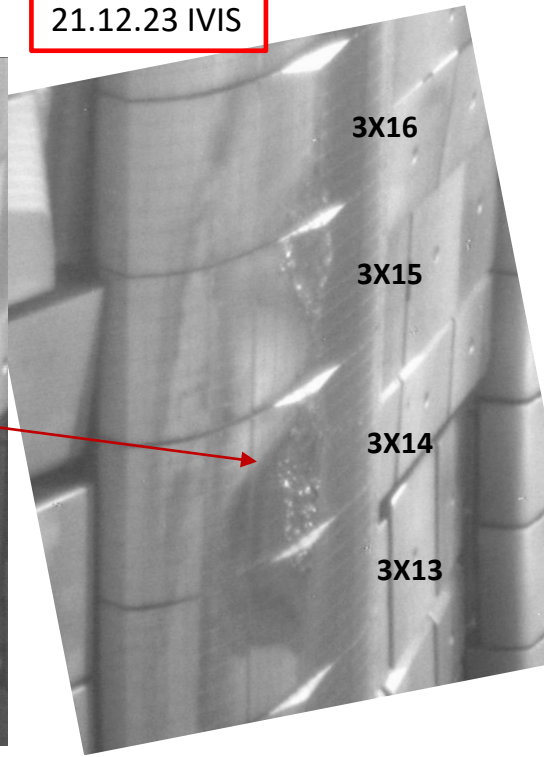


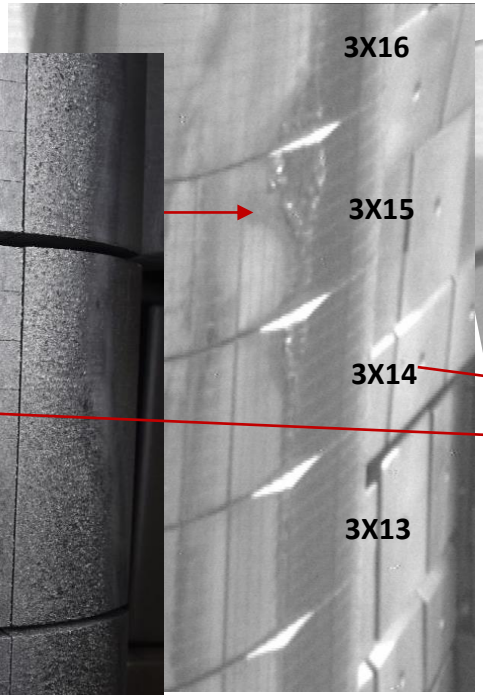
3X14 damage part of single day of ops (18th Dec 23)
To be removed in the 1st phase intervention

New damage to JET PFC (Dec 2023) - IWGL

2017-post shutdown

26.11.23 IVIS – **no damage**

17.12.23 IVIS



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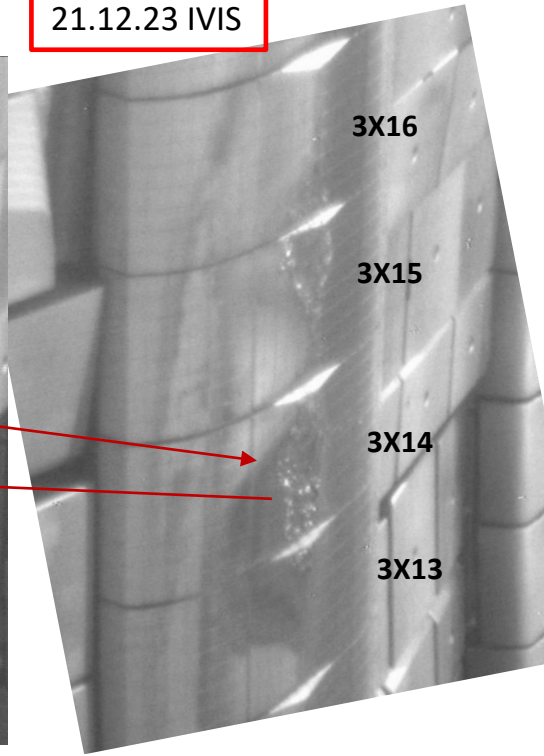
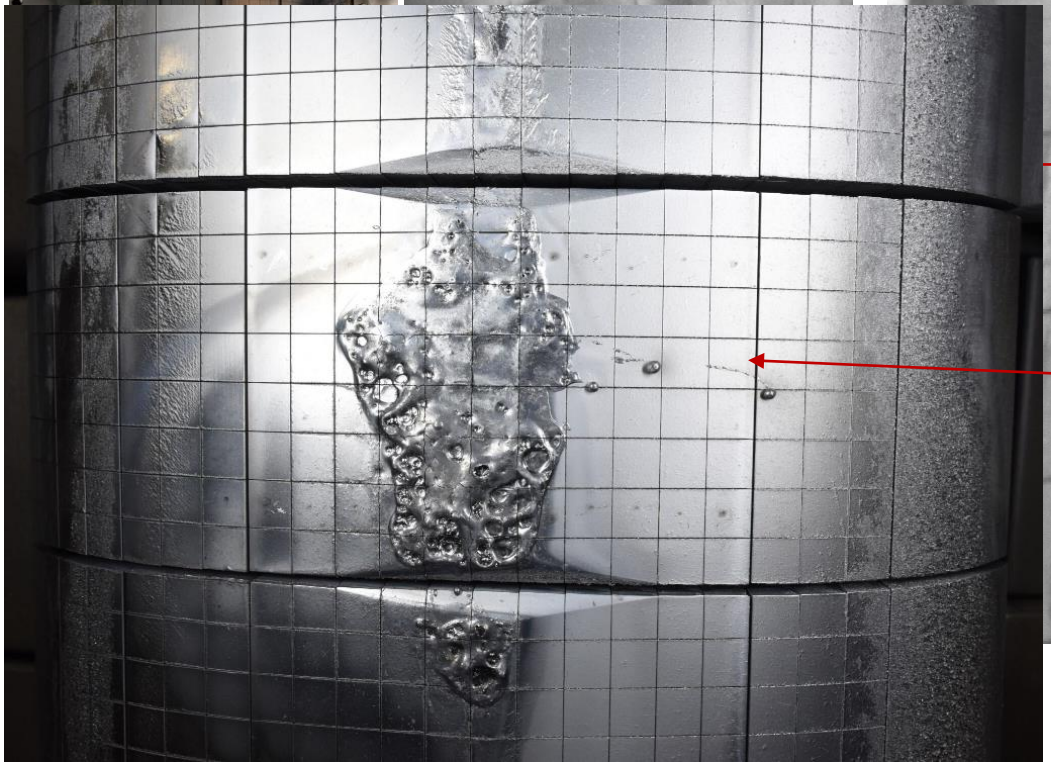


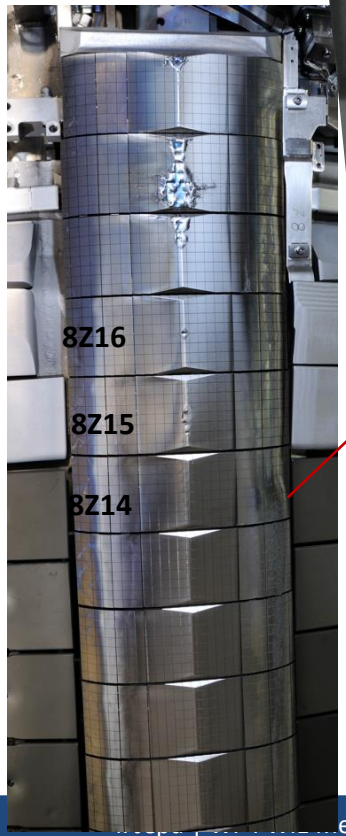


3X14 damage part of single day of ops (18th Dec 23)
To be removed in the 1st phase intervention

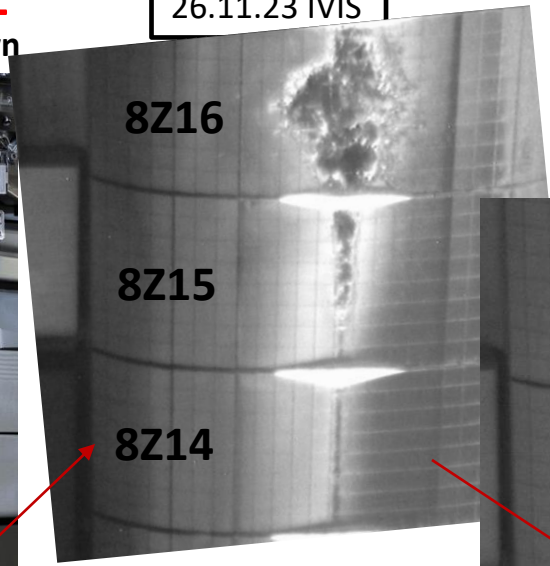
New damage to JET PFC (Dec 2023) - IWGL

IWGL – 8Z

2017-post shutdown



26.11.23 IVIS



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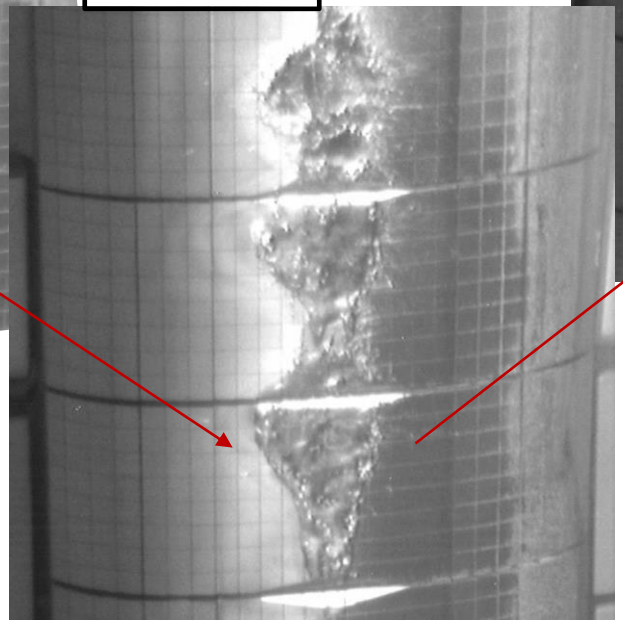
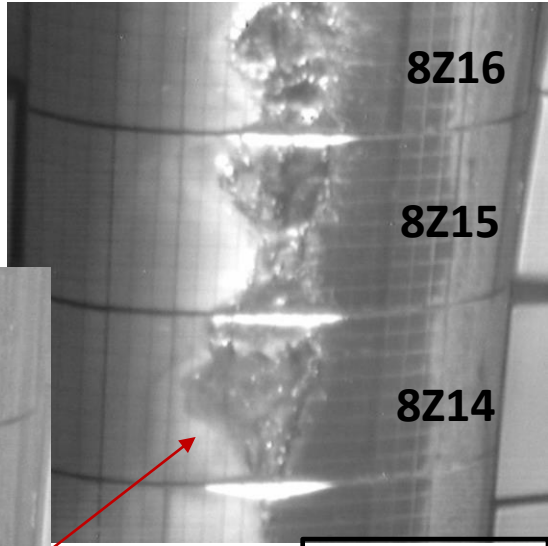




21.12.23 IVIS

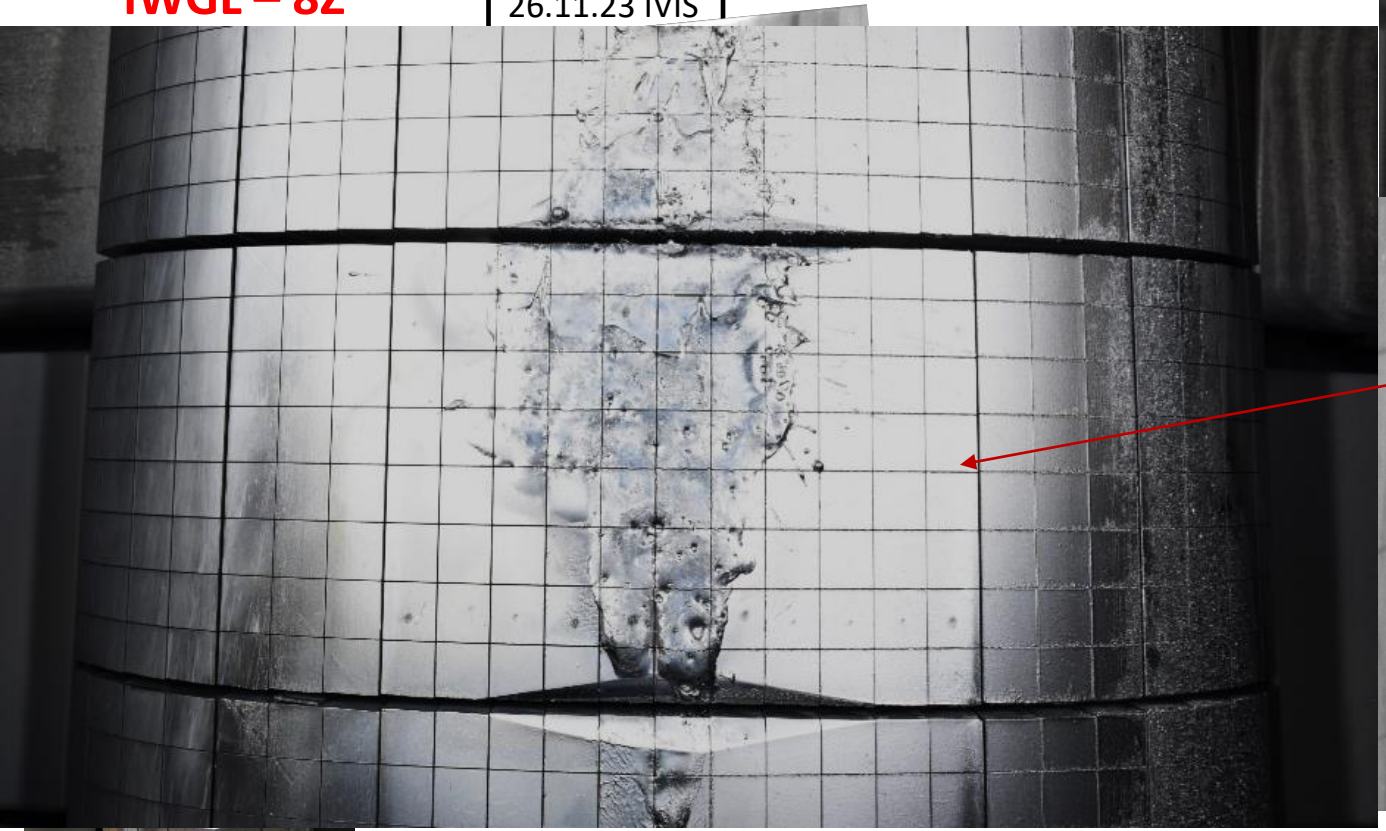
8Z14 damage part of multiple RE damages (6th , 14th & 18th single RE shot Dec 2023)

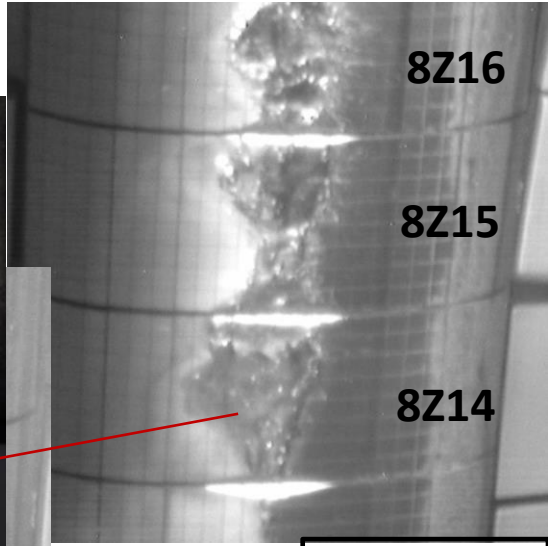
To be removed in the 1st phase intervention

New damage to JET PFC (Dec 2023) - IWGL

IWGL – 8Z

26.11.23 IVIS



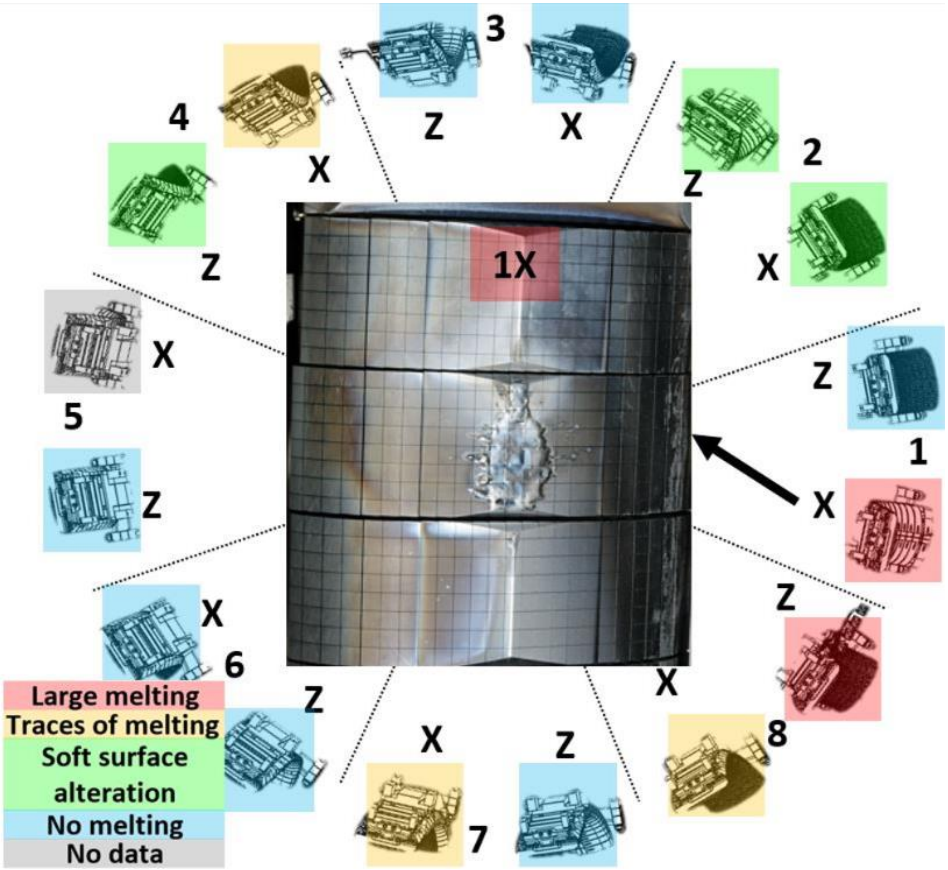


21.12.23 IVIS

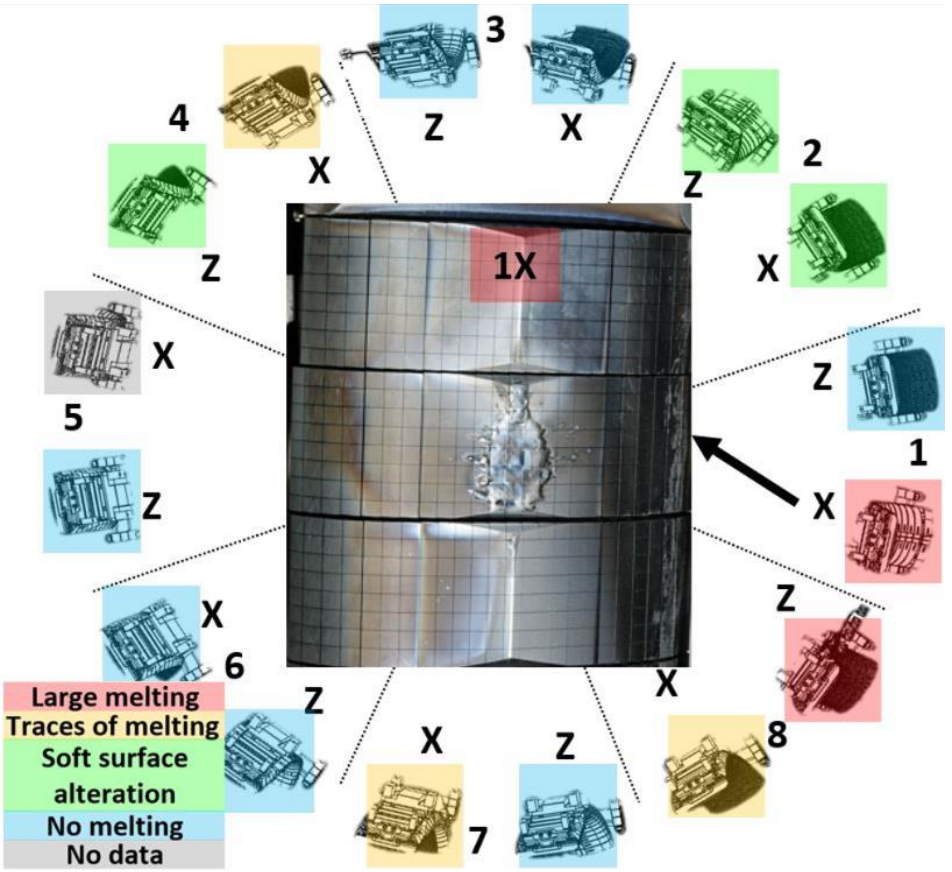
8Z14 damage part of multiple RE damages (6th , 14th & 18th single RE shot Dec 2023)

To be removed in the 1st phase intervention

RE damage 2014 – Inner wall

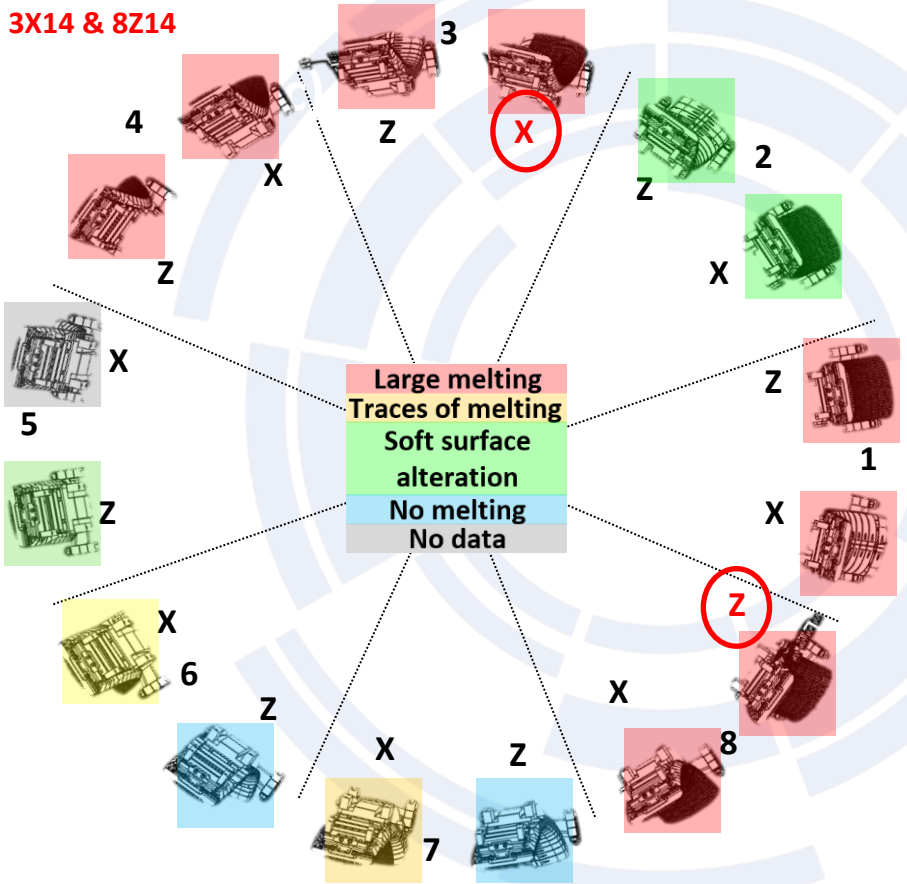


RE damage 2014 – Inner wall



RE damage Nov-Dec 2023 – Inner wall

*to be removed in 2024 intervention
3X14 & 8Z14



New damage to JET PFC (Dec 2023) - Divertor

– 14 Dec 2023 Late

Session details »

Experiment/aims: RT22-03-T7 Runaways

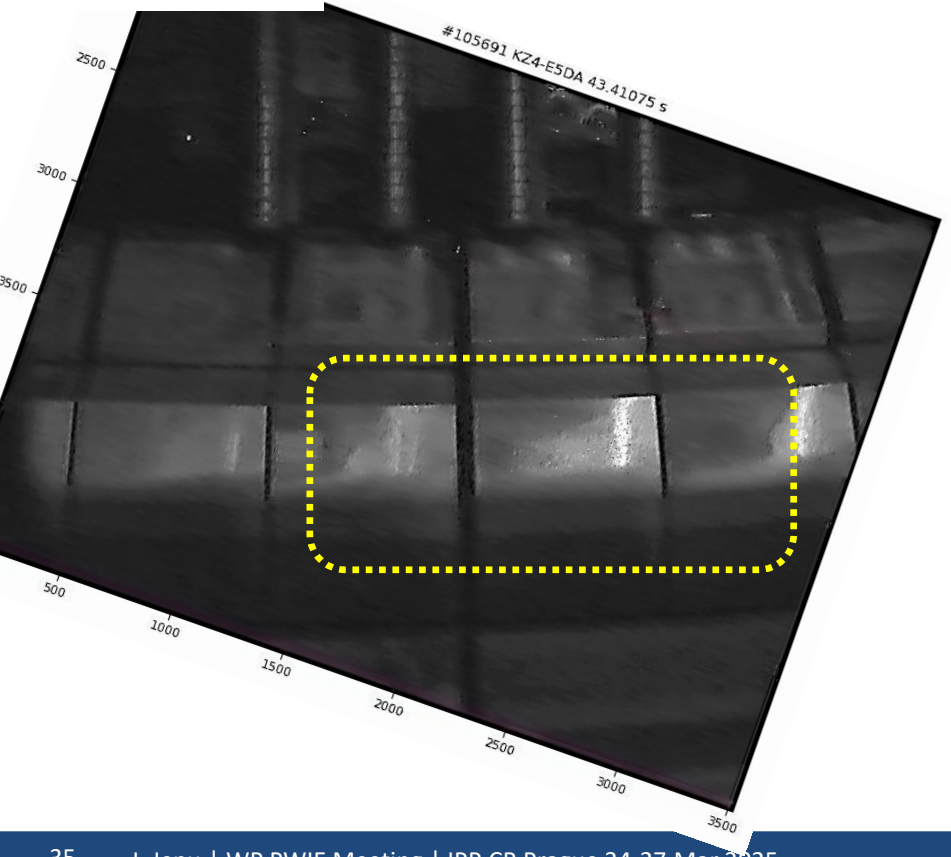
Task force: —

EIC: Paul Finburg **SL:** Peter Lomas **SC:** Cedric Reux **DC:** Kingsley Collie **VSO:** Ewa Kowalska-Strzeciwilk

Pulse	Time	B_T	I_P	Pre-pulse comment	Post-pulse comment
105802	21:49:12	3.000	1.450	Repeat 105790, increase Ar. SPI A, B, DMV3. DMV2 10bar D2 48.65s	Worked, absolutely benign
105801	21:28:55	2.300	1.750	Cleaning, ref 103655	Good
105800	21:10:05	3.450	2.900	Repeat, higher DMV3, DMV2 16 bar	Surprisingly not benign
105799	—	—	—	Repeat, higher DMV3, DMV2 16 bar	Aborted
105798	20:41:56	3.450	2.900	Repeat 105795, without DMV2	Surprisingly more benign than
105797	20:17:17	3.450	2.450	Repeat 105794, 2 bar argon	Surprisingly more benign than reference
105796	19:40:32	3.000	1.450	Repeat 105791, no SPI	Surprisingly more benign than reference
105795	19:15:41	3.400	2.900	Repeat, higher current, less Ar, DMV2, no SPI	Absolutely not benign
105794	18:44:47	3.400	2.400	Repeat, higher field, 2 bar Ar	Good, absolutely not benign
105793	17:53:05	3.000	1.900	Repeat	Good, not benign
105792	17:21:00	3.000	1.900	Repeat 102618, more Ar	Early stop due to ERFA alarm
105791	16:38:28	3.000	1.450	Ref 98150, runaway disruption at 48s	Good, not benign
105790	16:09:03	3.000	1.450	Ref 103645, runaway disruption at 48s	No long runaway beam
105789	—	—	—	—	Aborted

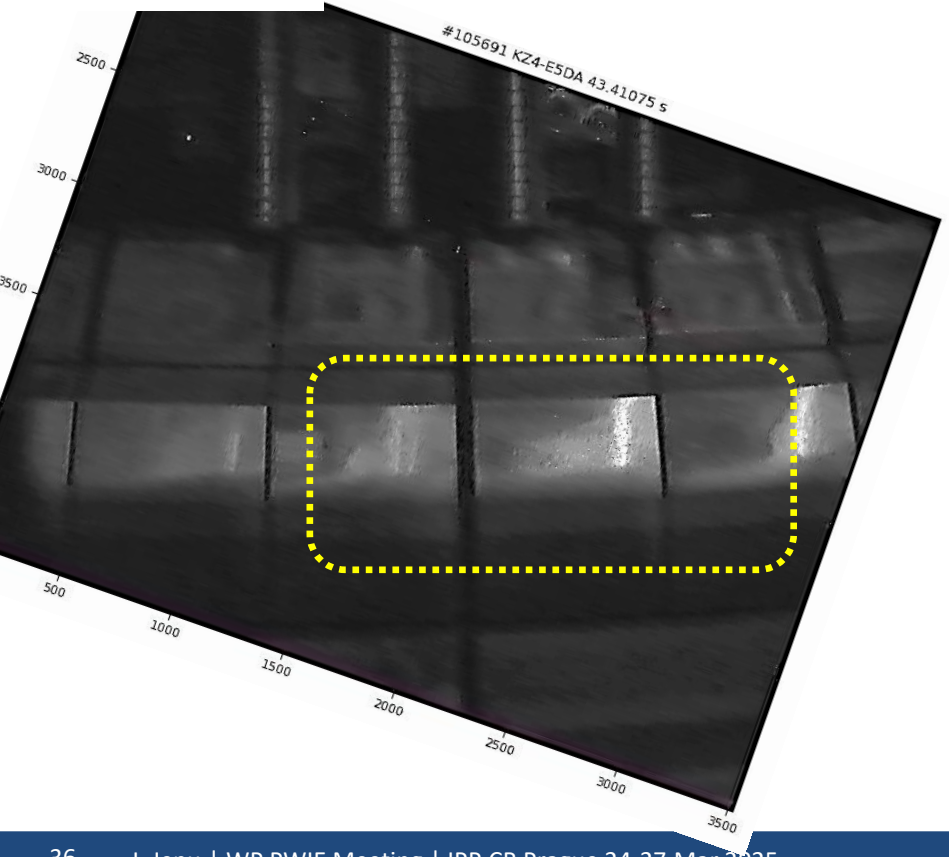
New damage to JET PFC (Dec 2023) - Divertor

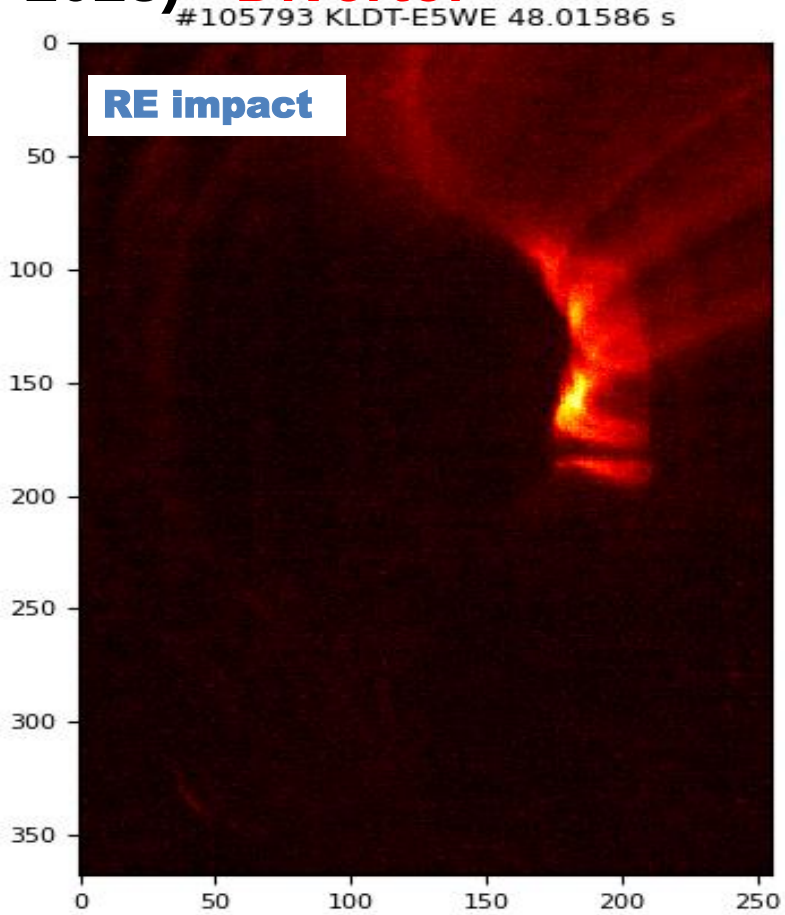
Before RE impact



New damage to JET PFC (Dec 2023) - Divertor

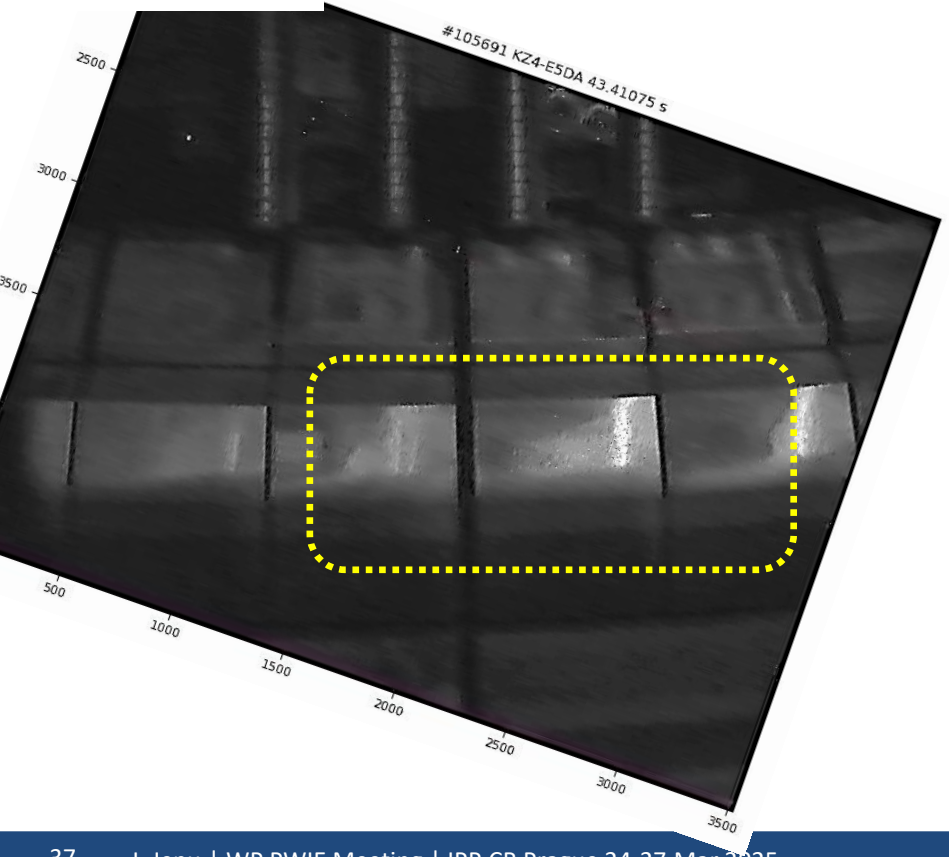
Before RE impact

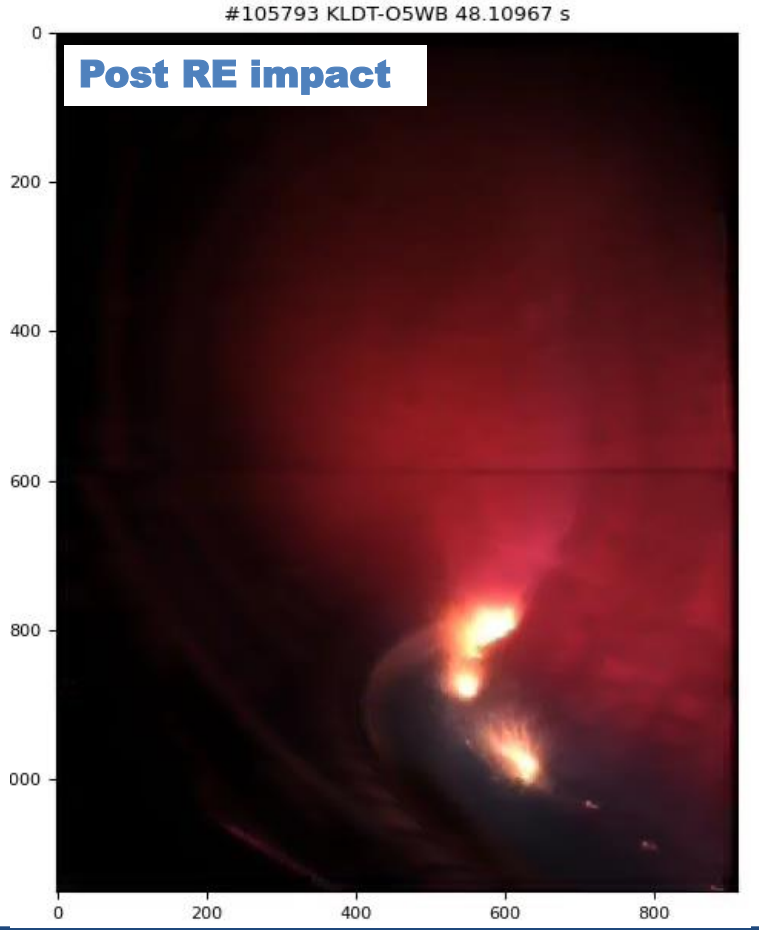




New damage to JET PFC (Dec 2023) - Divertor

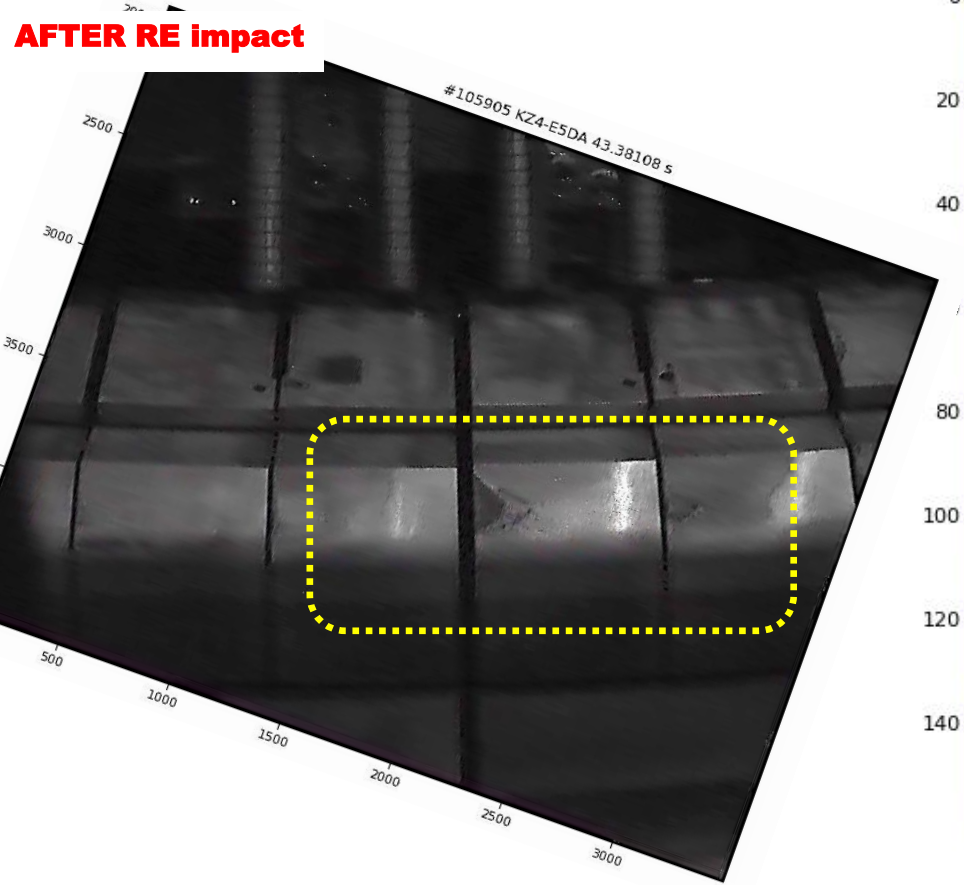
Before RE impact

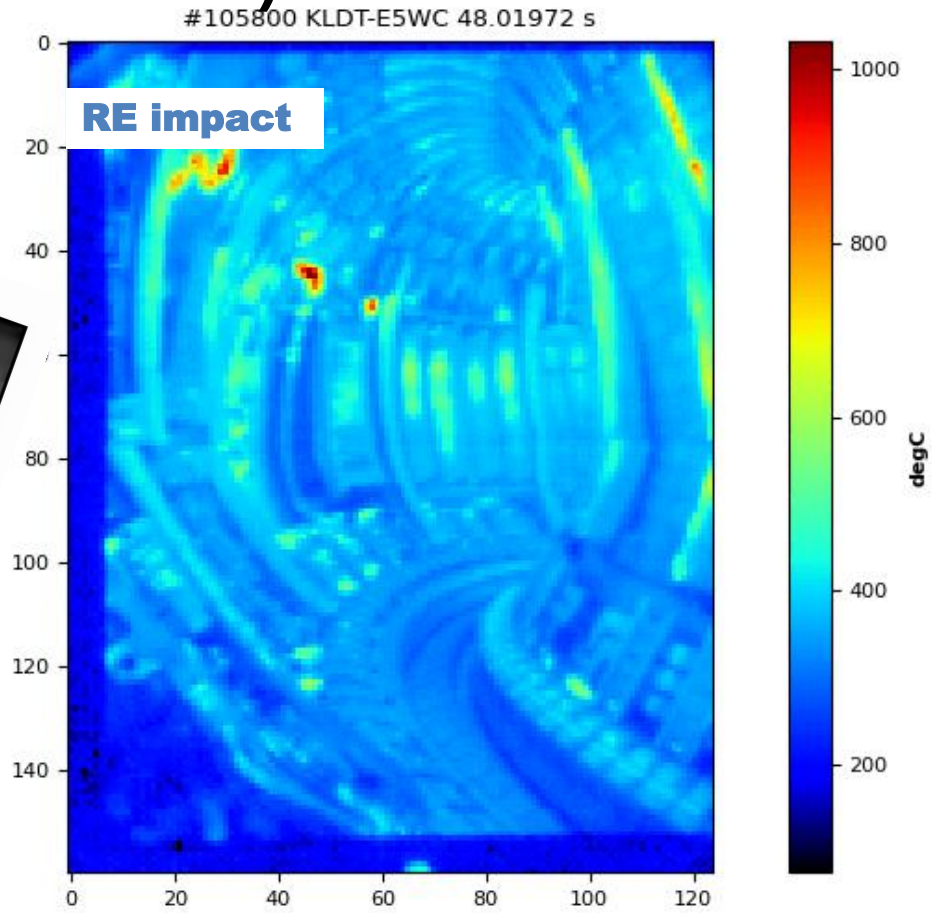




New damage to JET PFC (Dec 2023) - Divertor

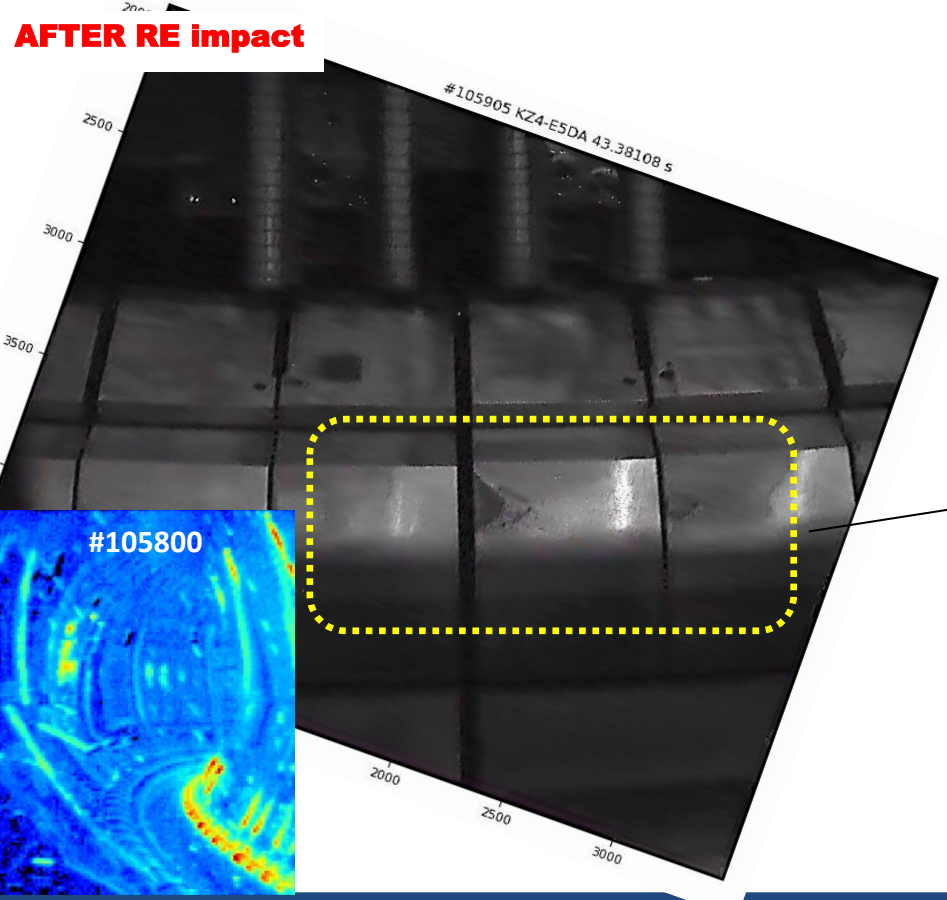
AFTER RE impact

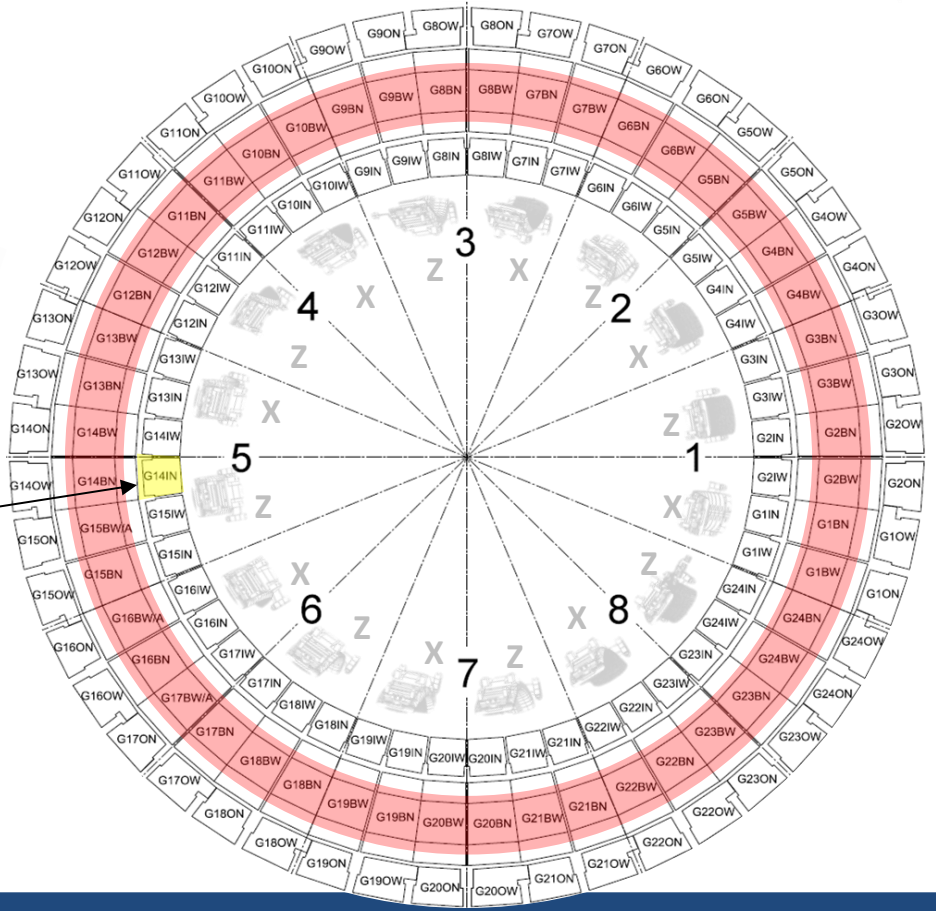




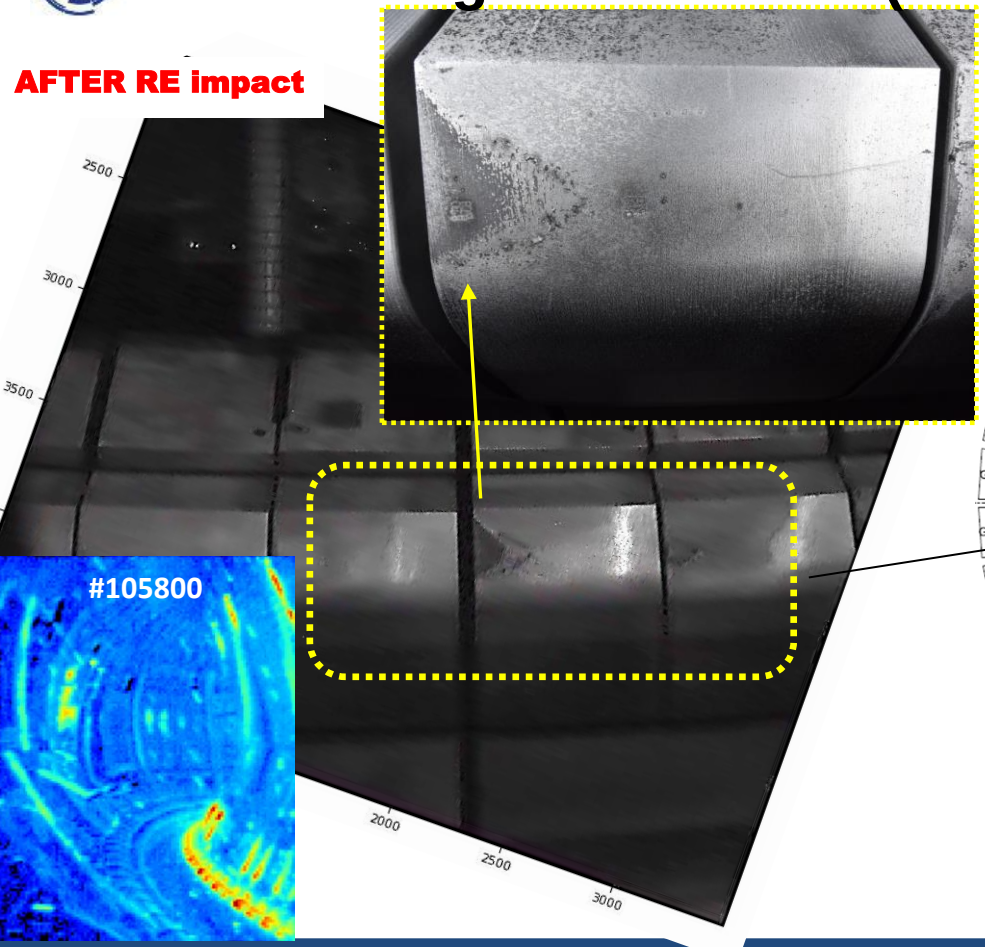
New damage to JET PFC (Dec 2023) - Divertor

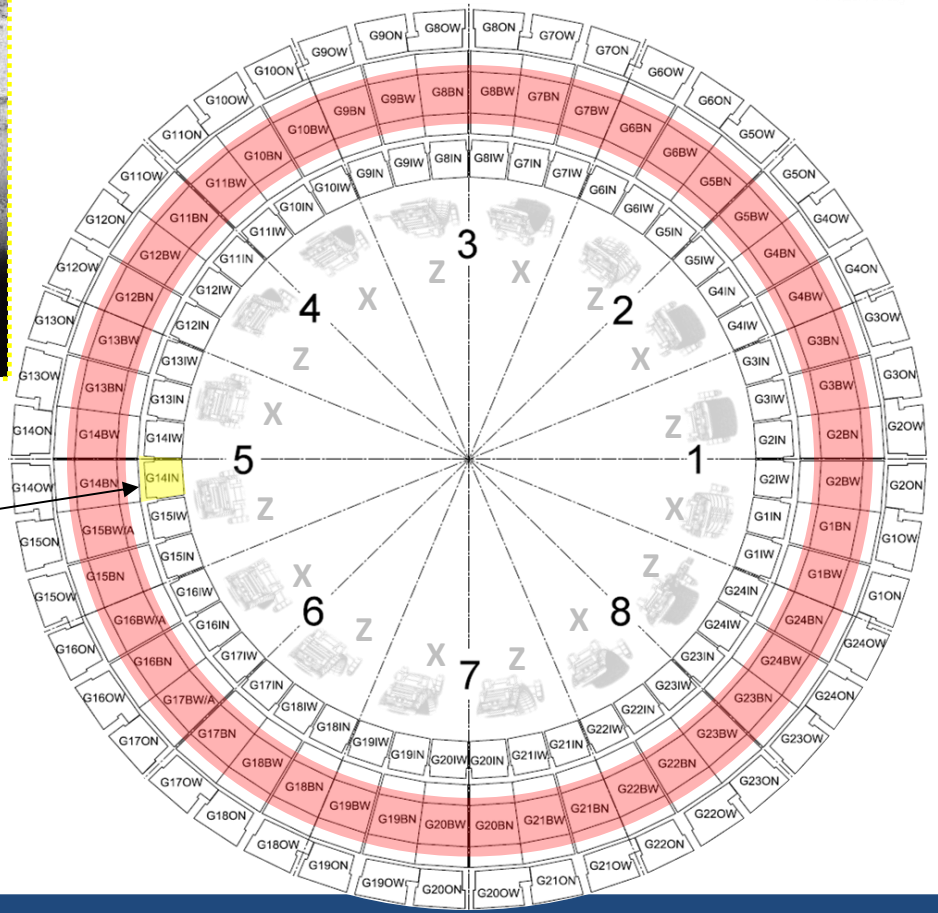
AFTER RE impact



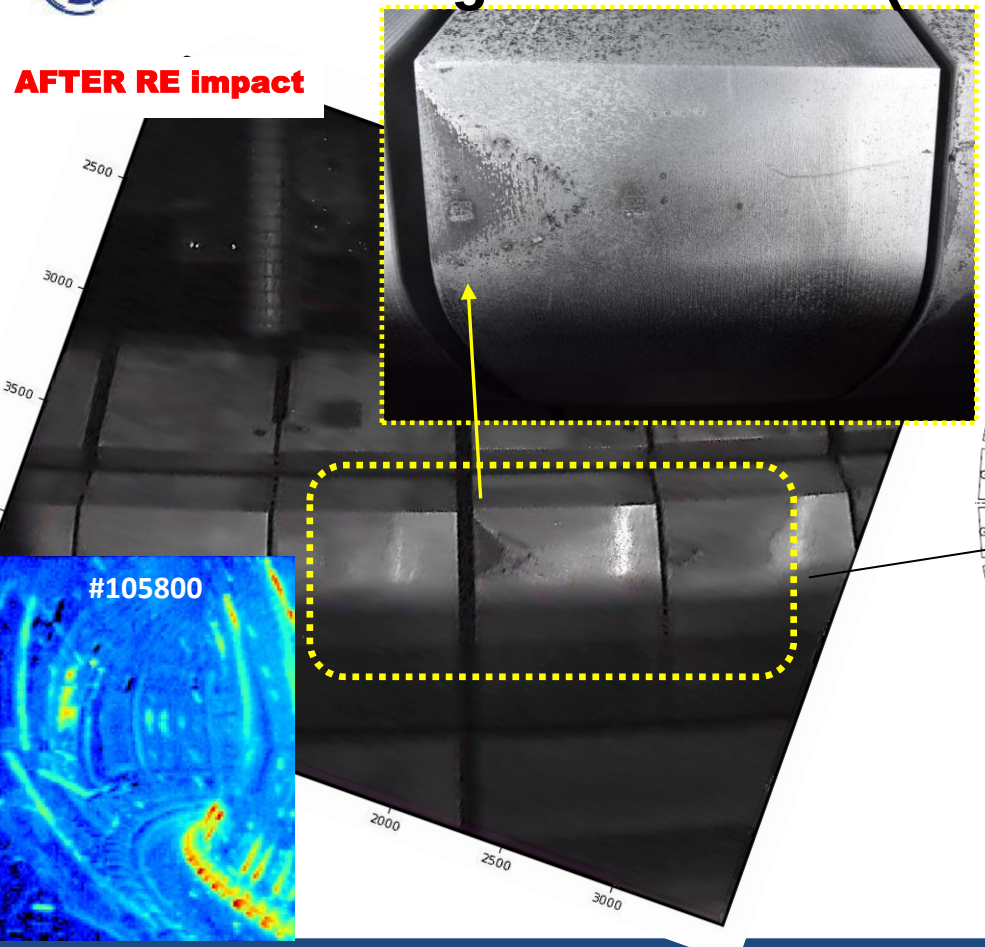


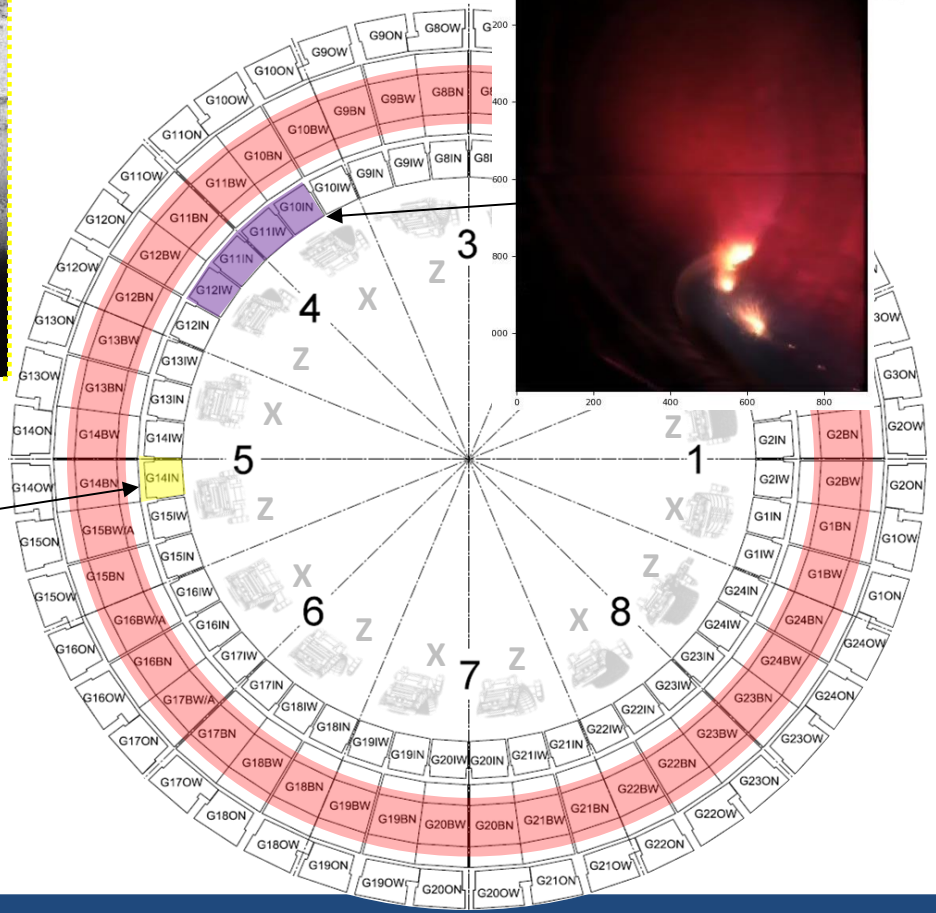
New damage to JET PFC (Dec 2023) - Divertor



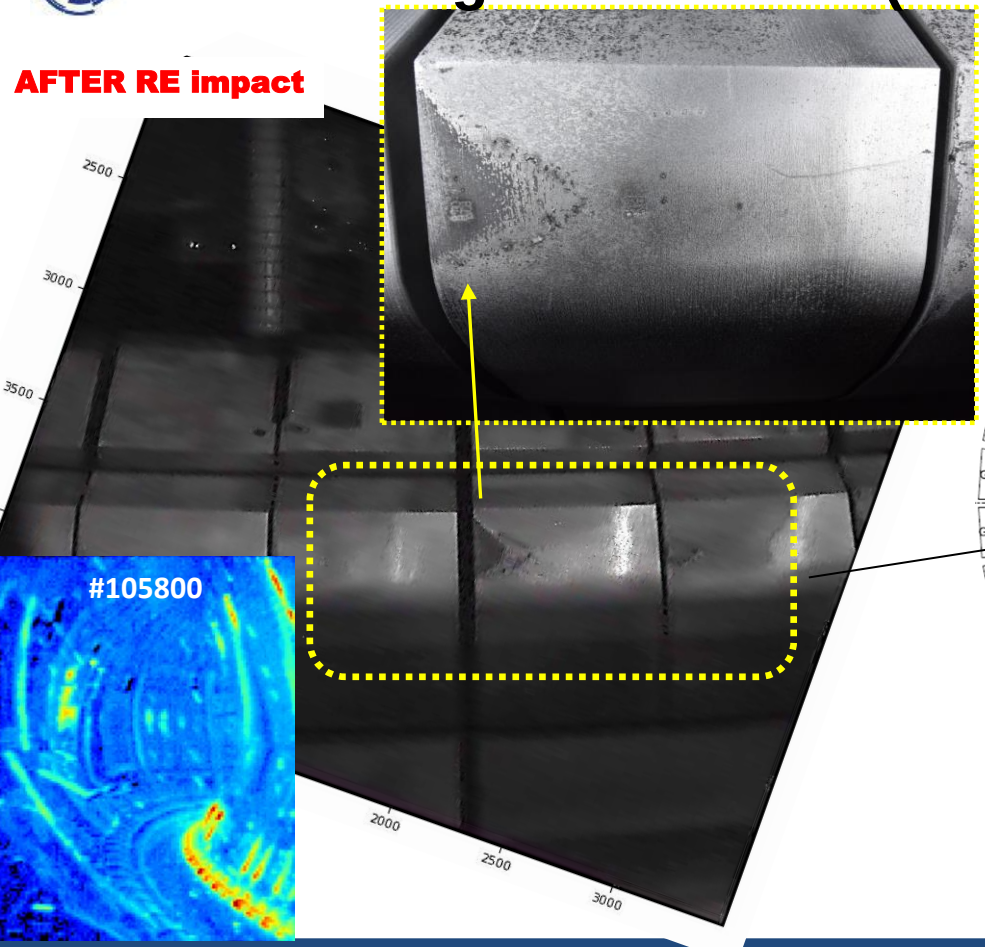


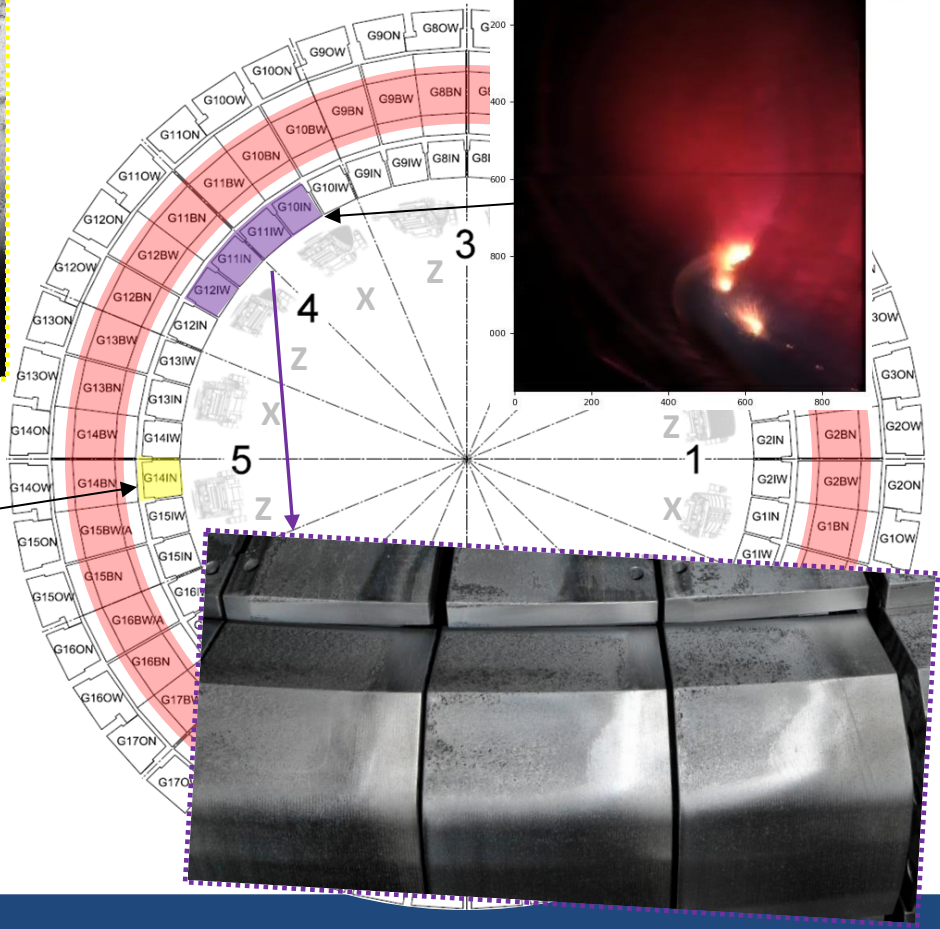
New damage to JET PFC (Dec 2023) - Divertor





New damage to JET PFC (Dec 2023) - Divertor

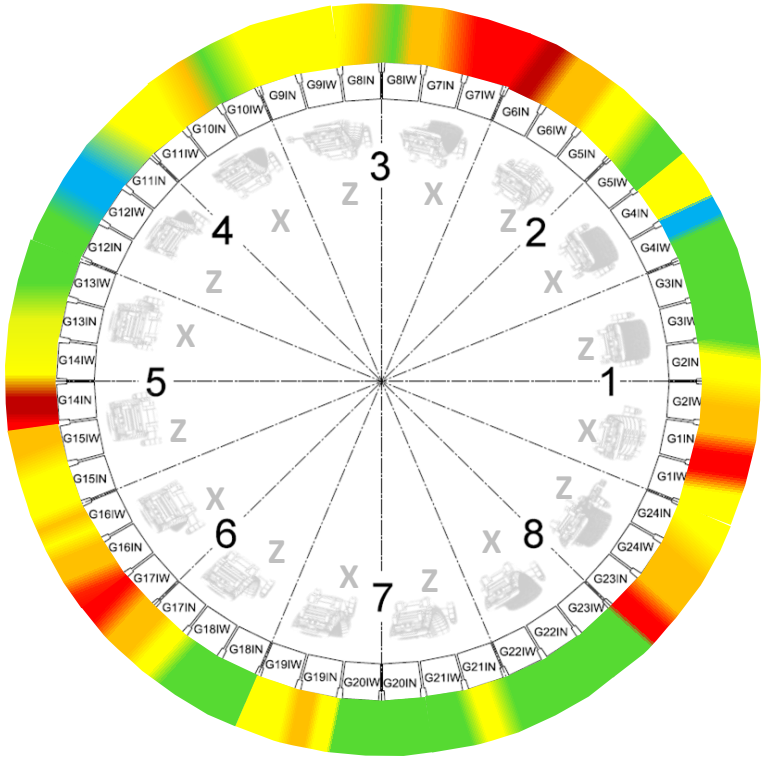




New damage to JET PFC (Dec 2023) - Divertor

AFTER RE impact

Massive layer removal (CFC visible)
Same pattern, smaller area (CFC visible)
Same pattern, deposit removal (no CFC)
Signs of damage
Soft damage
No damage



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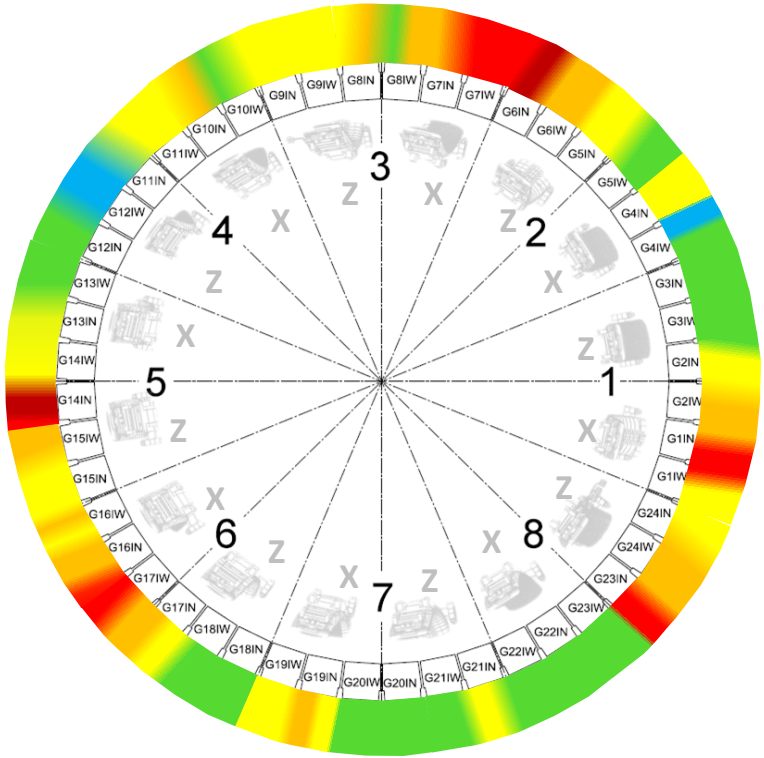
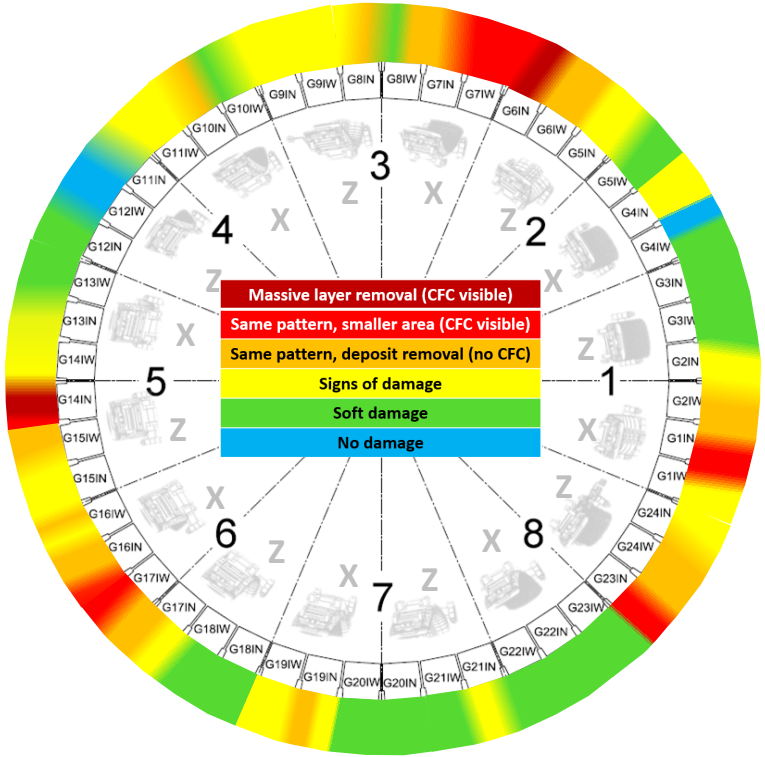


AFTER RE impact



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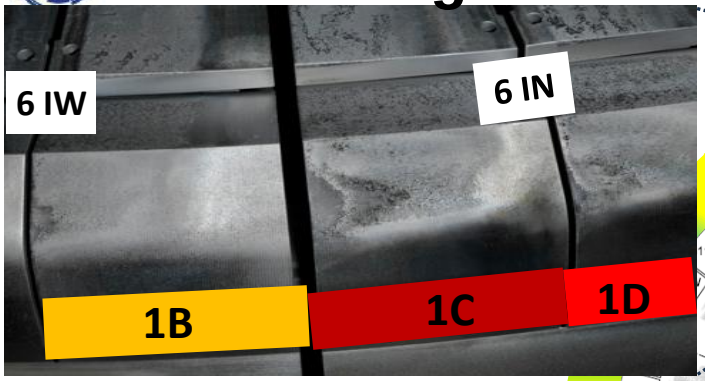
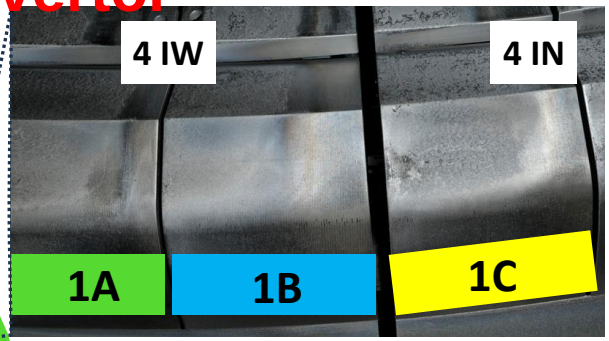
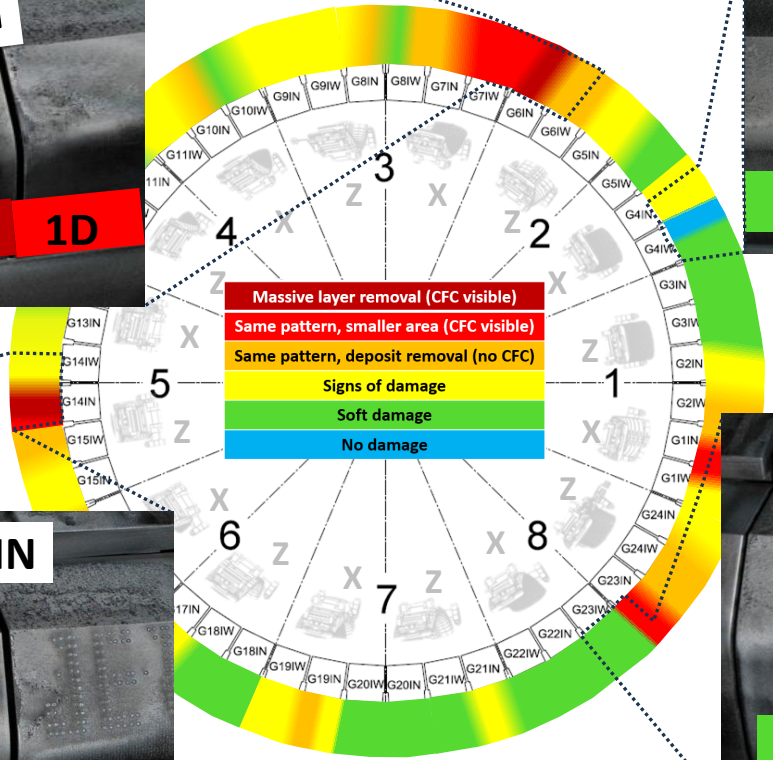
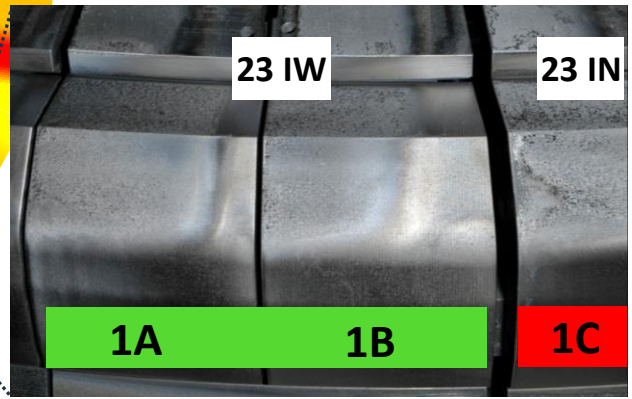
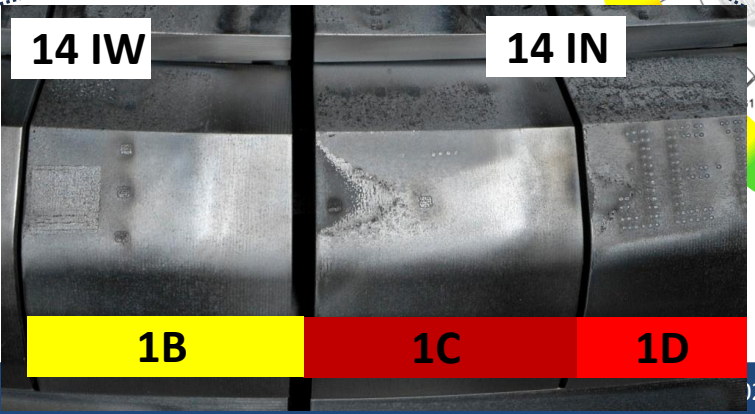




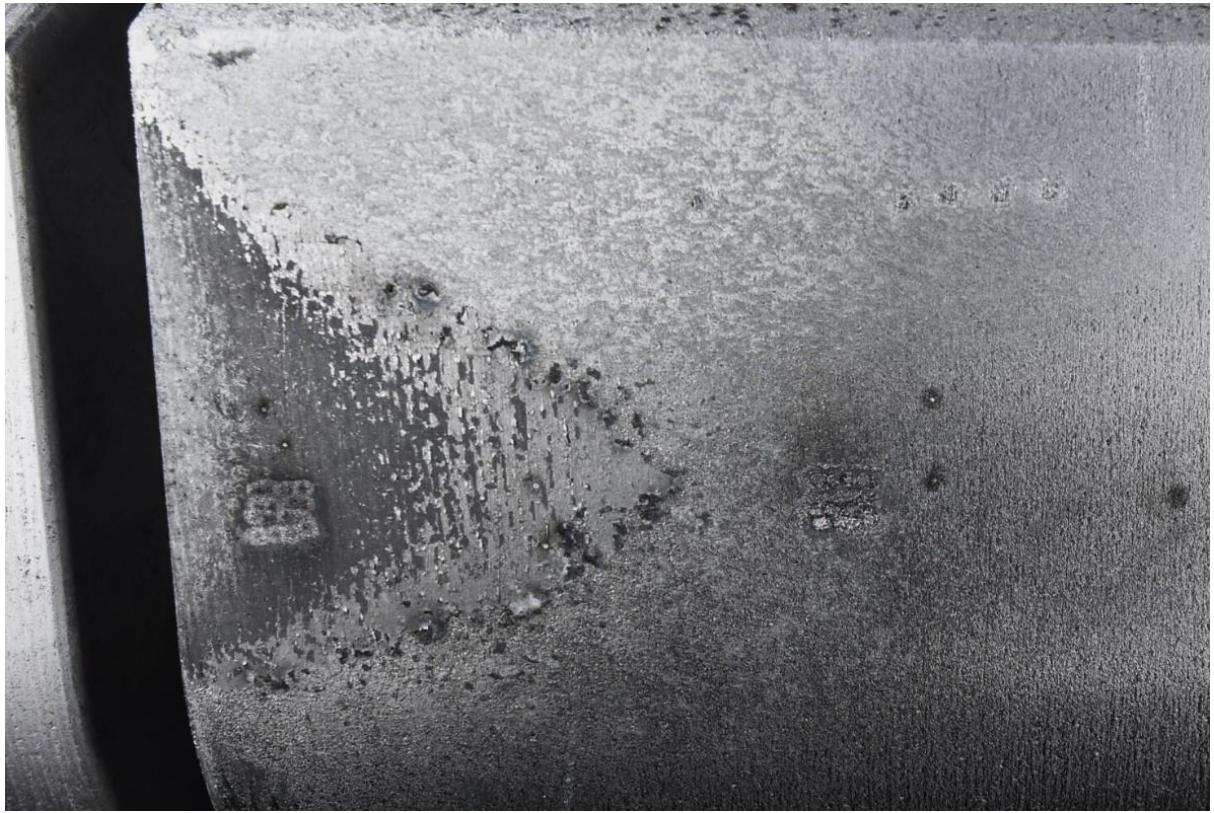






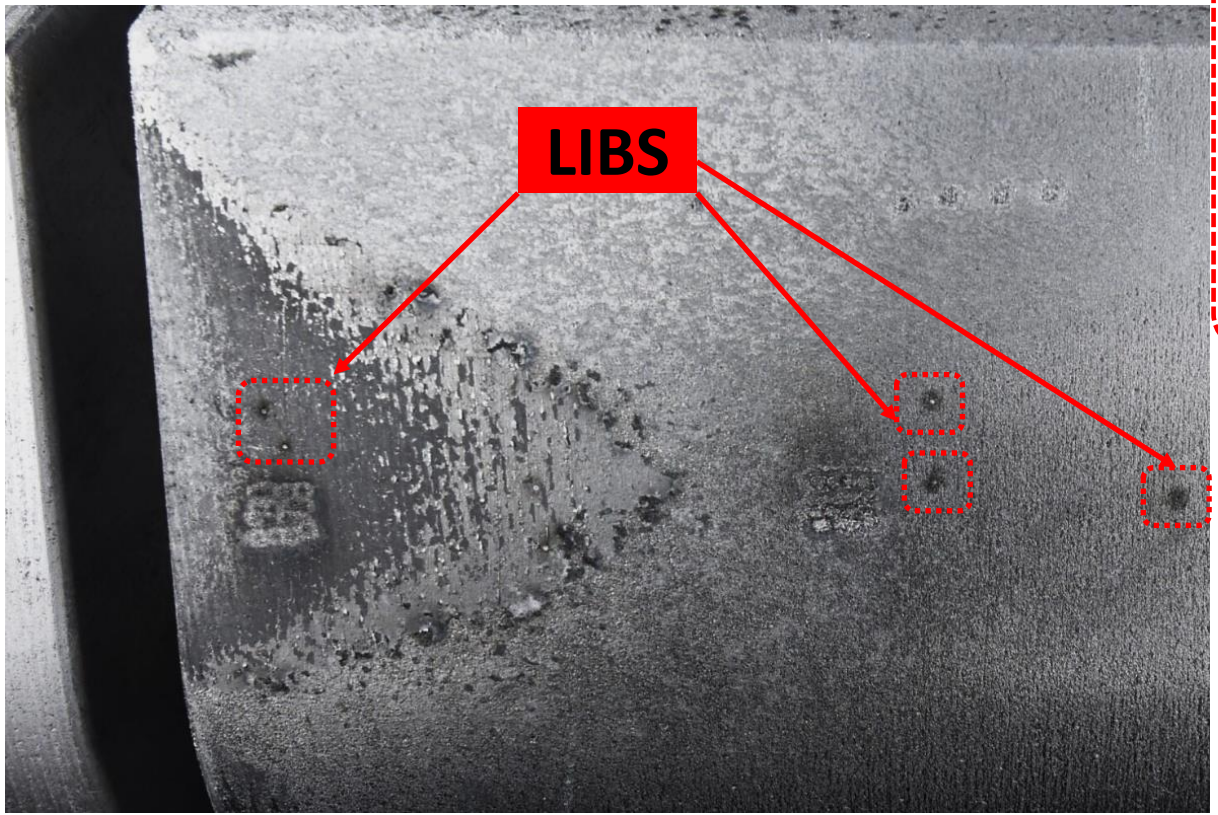
New damage to JET PFC (Dec 2023) - Divertor

Preliminary in-situ analysis

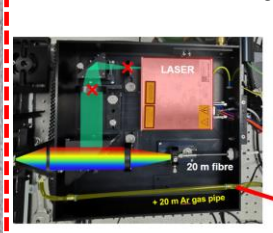


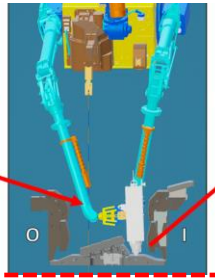
New damage to JET PFC (Dec 2023) - Divertor

Preliminary in-situ analysis



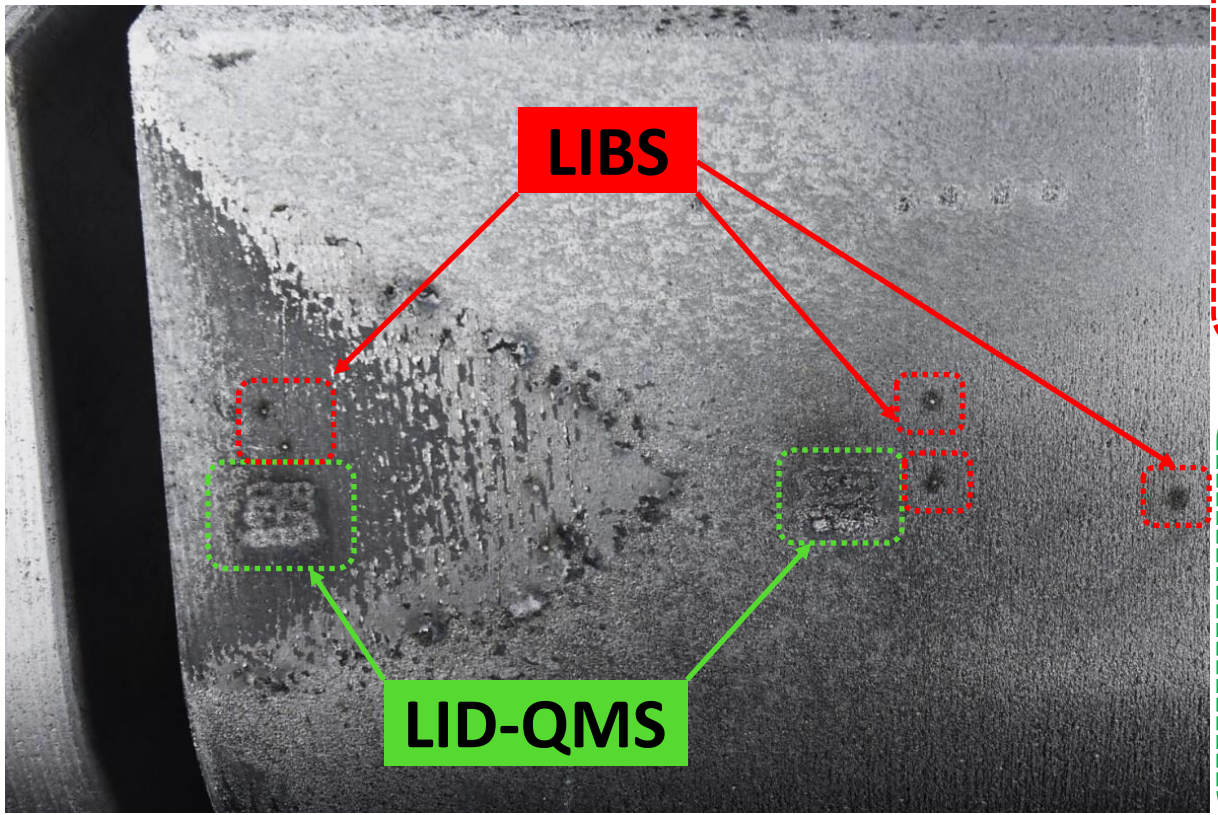
Laser Induced Breakdown Spectroscopy
- Material composition
- Fuel retention



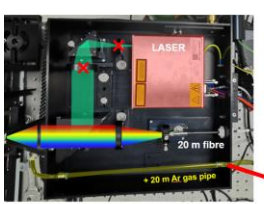


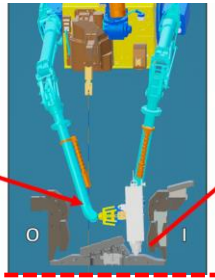
New damage to JET PFC (Dec 2023) - Divertor

Preliminary in-situ analysis

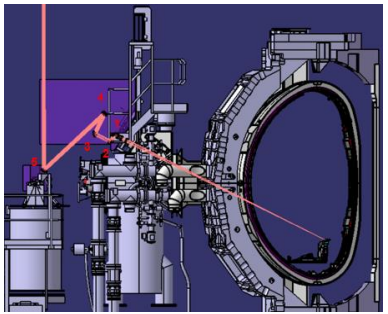


Laser Induced Breakdown Spectroscopy
- Material composition
- Fuel retention

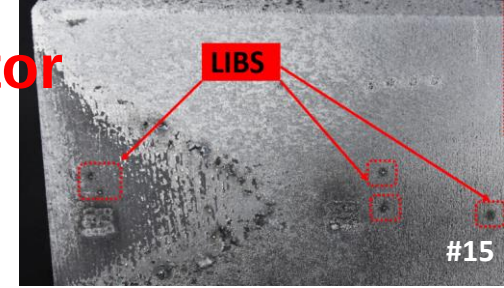




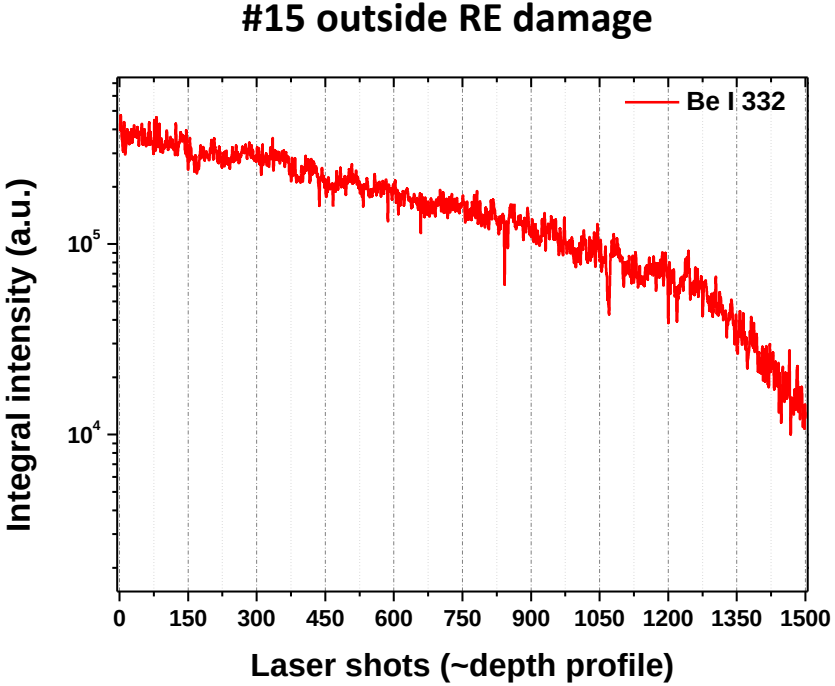
Laser Induced Desorption via QMS
- Fuel retention



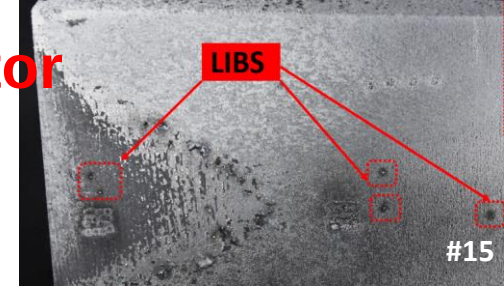
New damage to JET PFC (Dec 2023) - Divertor



Preliminary in-situ analysis – LIBS (material composition)



New damage to JET PFC (Dec 2023) - Divertor



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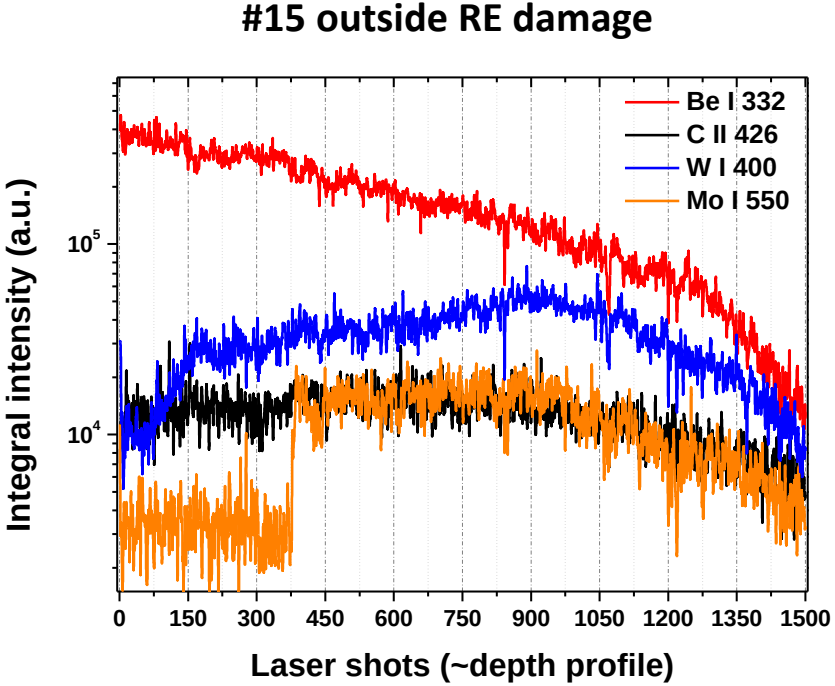
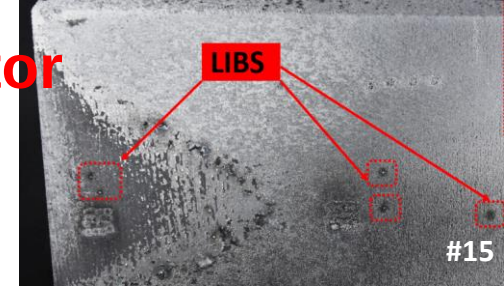
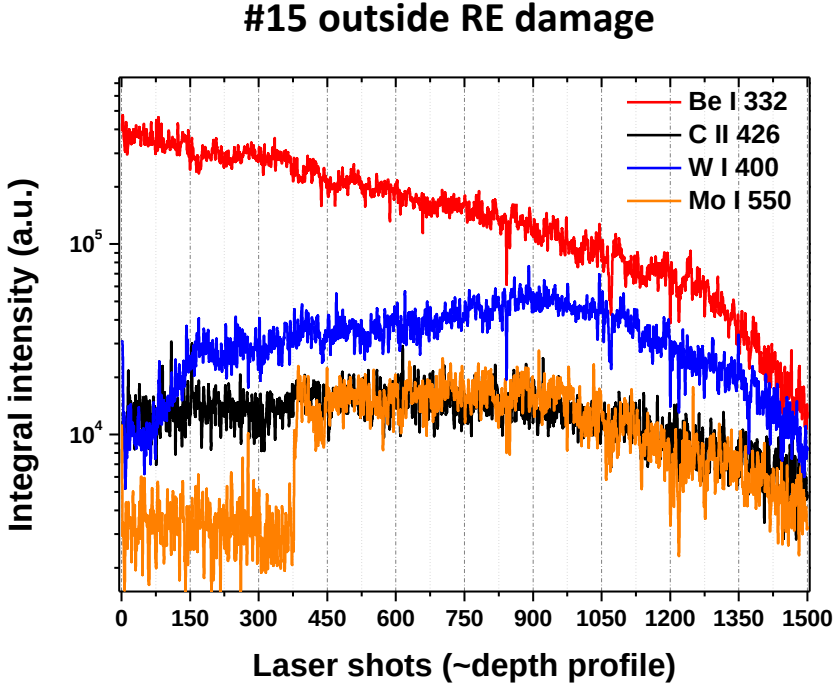
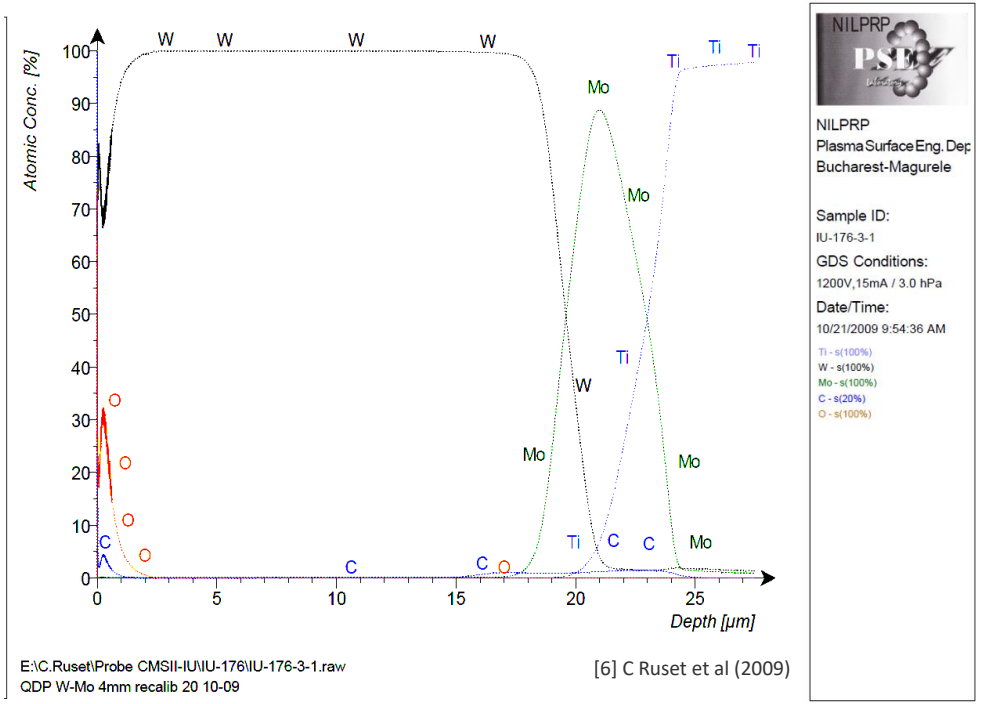


New damage to JET PFC (Dec 2023) - Divertor

Preliminary in-situ analysis – LIBS (material composition)



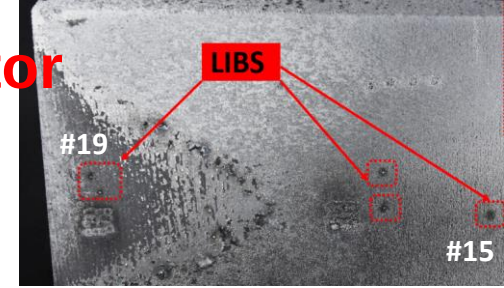




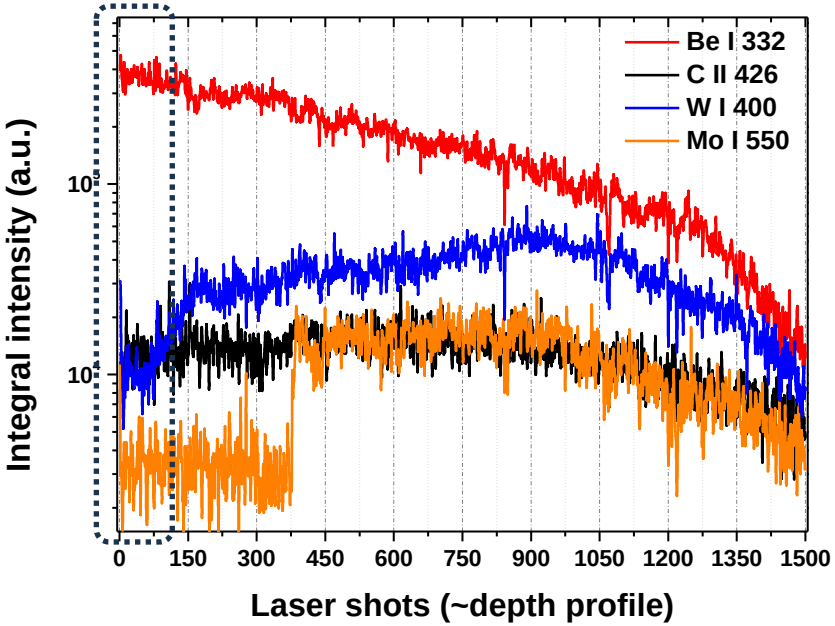
[6] C Ruset et al (2009)

New damage to JET PFC (Dec 2023) - Divertor

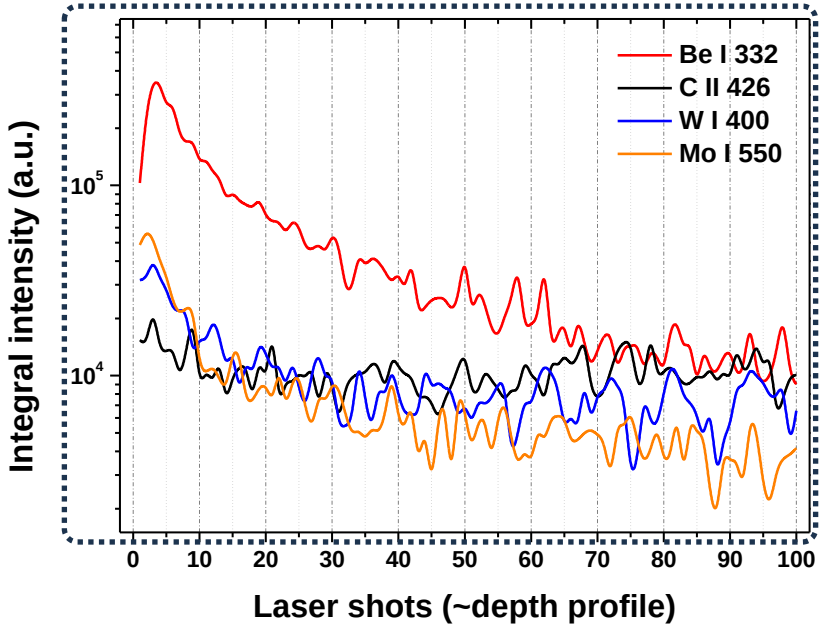
Preliminary in-situ analysis – LIBS (material composition)



#15 outside RE damage

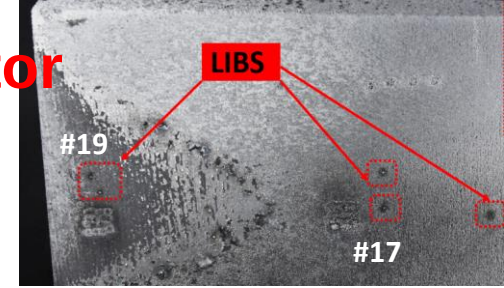


#19 Inside RE damage

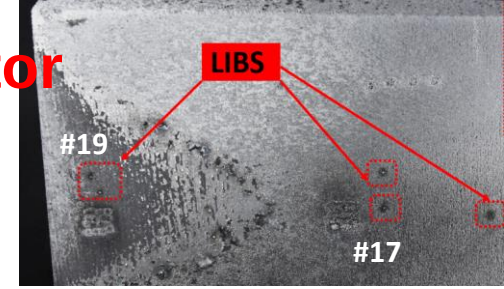


New damage to JET PFC (Dec 2023) - Divertor

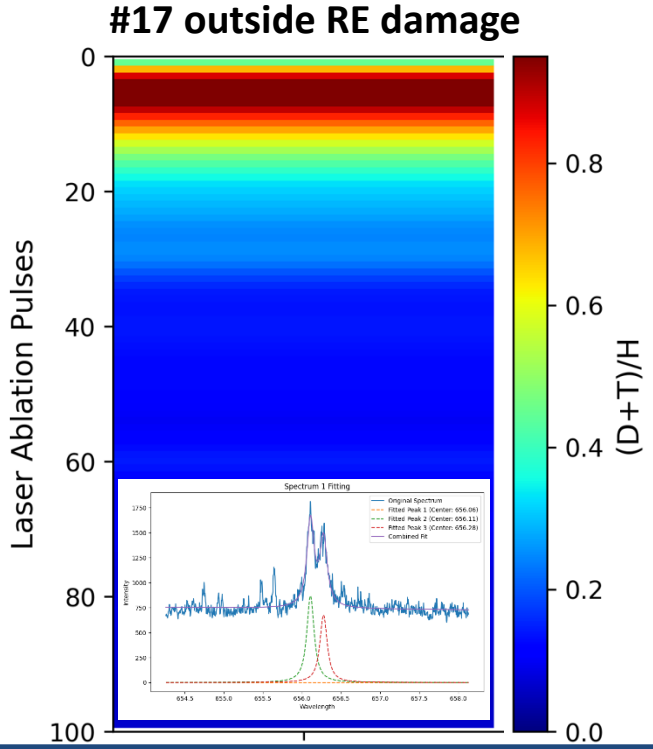
<u>Preliminary</u> in-situ analysis – LIBS (Fuel retention)



New damage to JET PFC (Dec 2023) - Divertor



Preliminary in-situ analysis – LIBS (Fuel retention)



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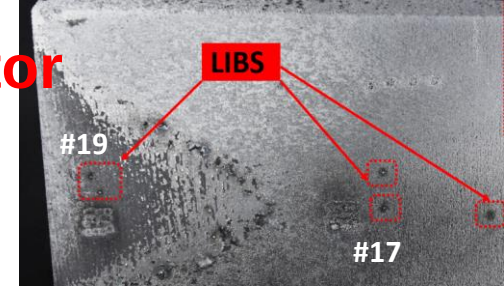
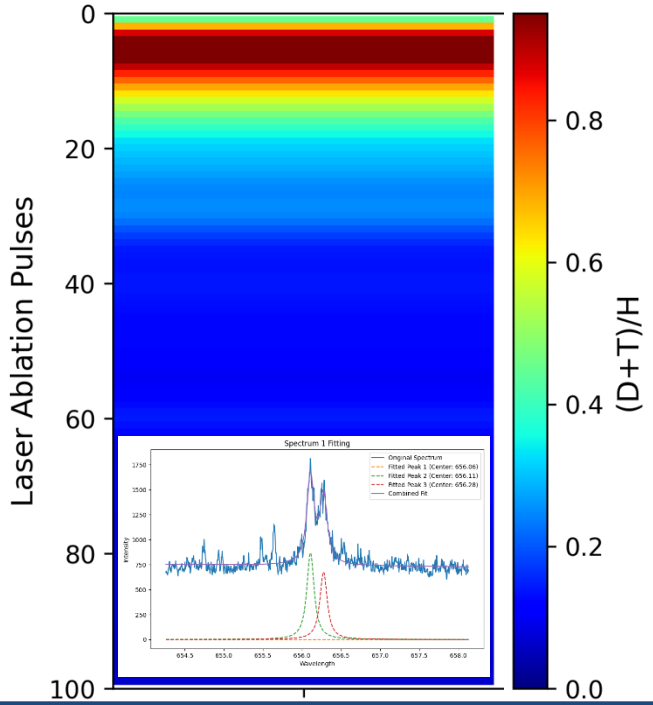
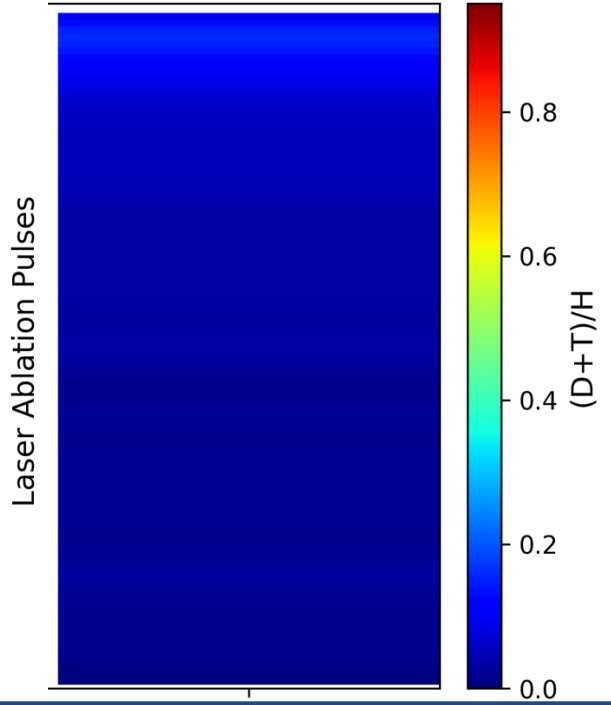


Preliminary in-situ analysis – LIBS (Fuel retention)

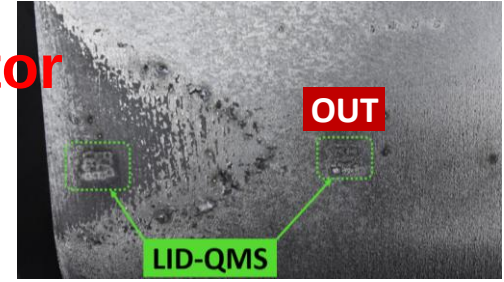
#17 outside RE damage



#19 inside RE damage

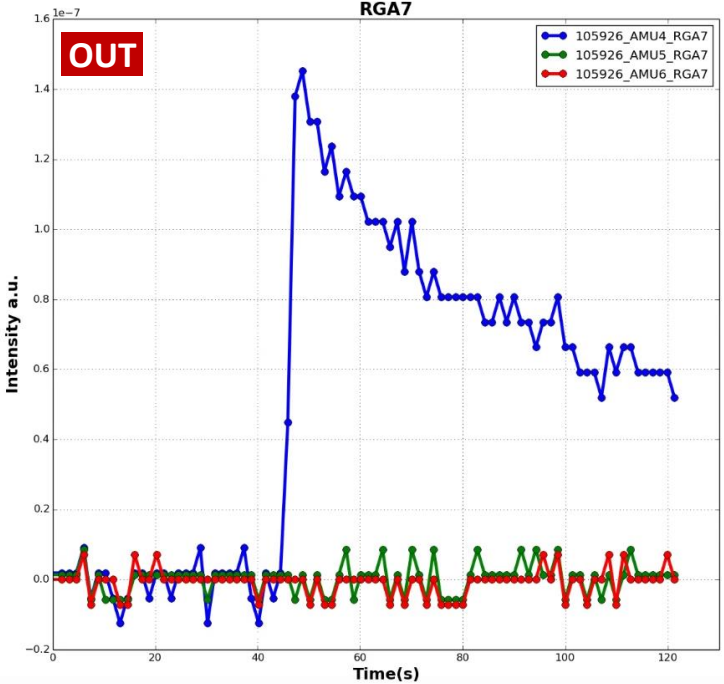


New damage to JET PFC (Dec 2023) - Divertor



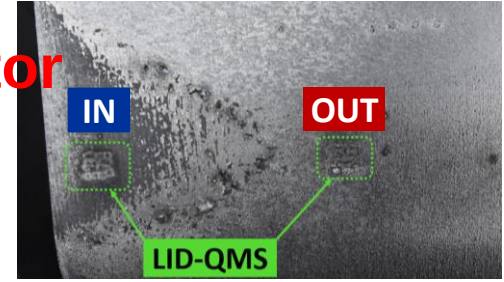
Preliminary in-situ analysis – LID-QMS (Fuel retention)

Outside RE damage

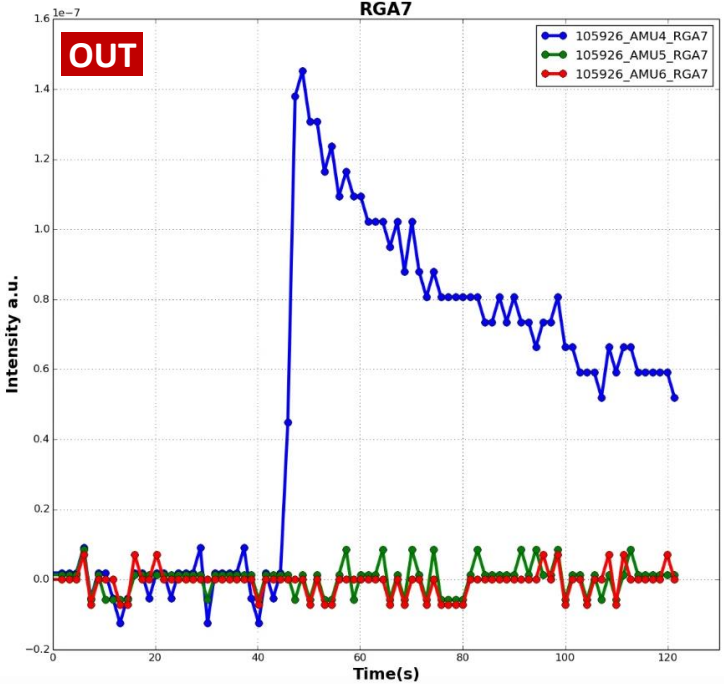


New damage to JET PFC (Dec 2023) - Divertor

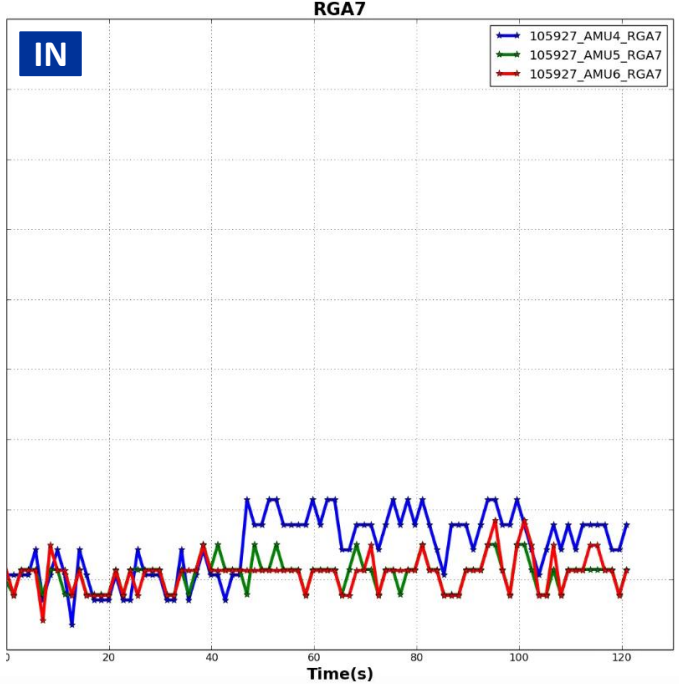
Preliminary in-situ analysis – LID-QMS (Fuel retention)



Outside RE damage



Inside RE damage



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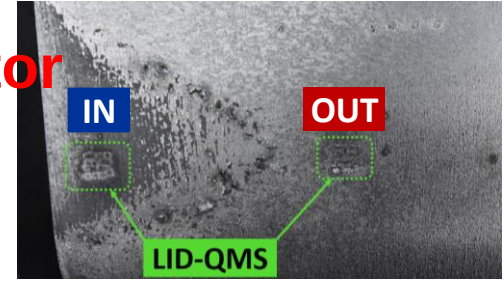
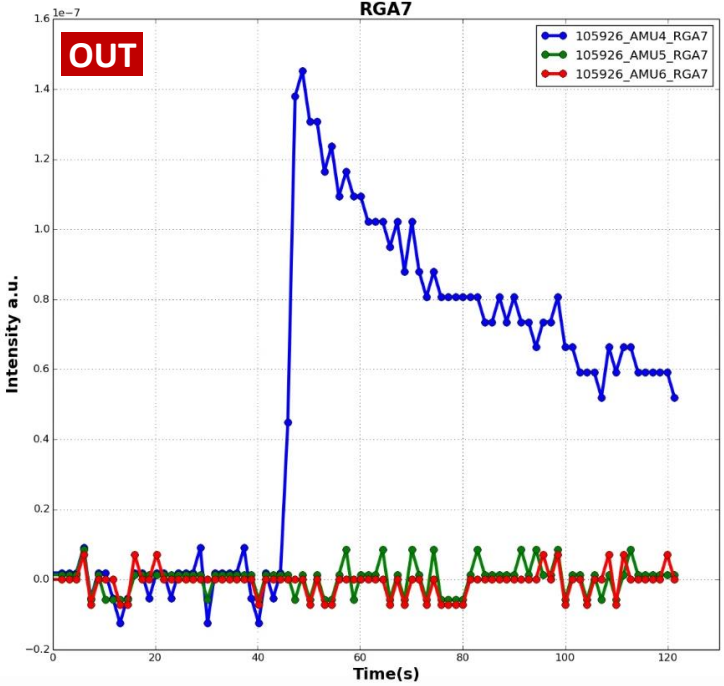
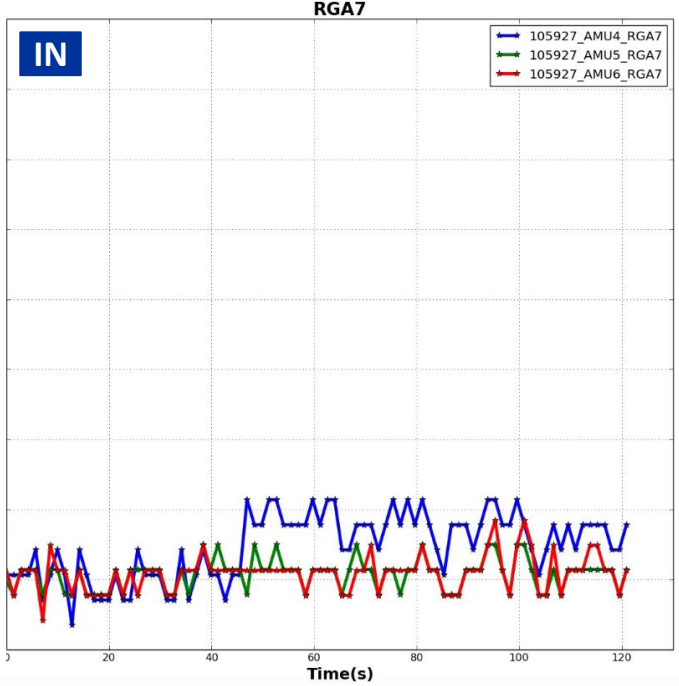


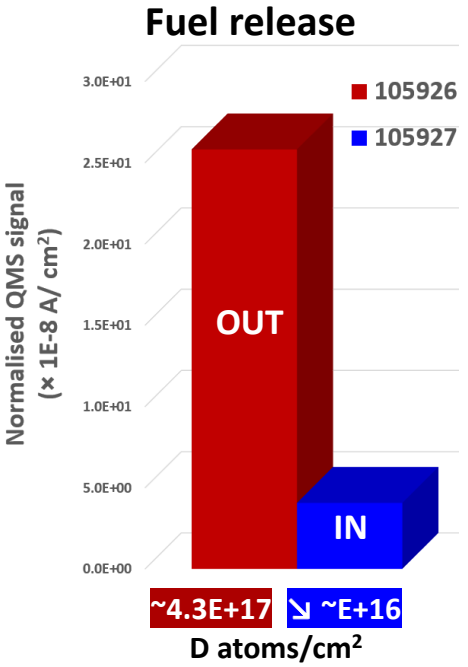
Outside RE damage



Inside RE damage



Fuel release



Conclusions: RE damage to JET's PFCs

- **High Energy REs** represent a real threat to current and in future tokamak devices;
- **The RE experiments in JET were unique, providing information and data on RE generation physics mechanisms and consequently damage to PFCs**
- The damaging effect is **substantial,** and magnitude can vary with the size of the reactor **regardless of the PFCs**
- The post mortem analysis of the Be damaged PFC can serve as an input for modelling **(very good agreement with the physical observations, in terms of depth, area and direction of the melt damage seen on the Be limiter)**
- Melt damage observations for REs impact with PFC are different as compared with the disruption case;
- Damage is localized (?), no signs of layer movement

Conclusions – next steps for JET

- In vessel photography - completed;
- Additional dedicated high-resolution photography on RE damage tiles - completed;
- In situ LIBS on 3X14 and 8Z14 - completed;
- Removal of 3X14 and 8Z14 Be limiters for post-mortem analysis - ongoing
- Removal of divertor RE damaged tile in the 2nd tile removal phase (to be decided)
- Feeding all physical findings to benchmark models to be applied on future fusion devices

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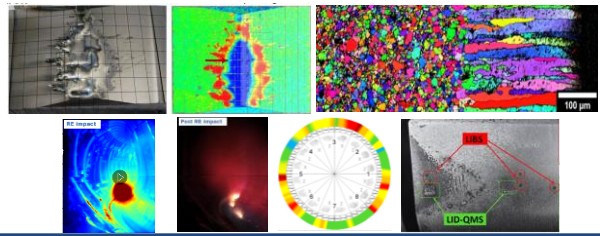
Thank you for your attention!



Overall RE damage to the JET PFC