Disruption consequence on metal wall tokamaks

IAEA TM on Plasma Disruptions and their Mitigation, ITER Headquarters, France, 20 - 23 July 2020

Sergei Gerasimov

With thanks to R.S. Granetz, V. Huber, I. Jepu, P.J. Lomas, S.V. Mirnov, G. Pautasso, L.E. Zakharov and JET contributors

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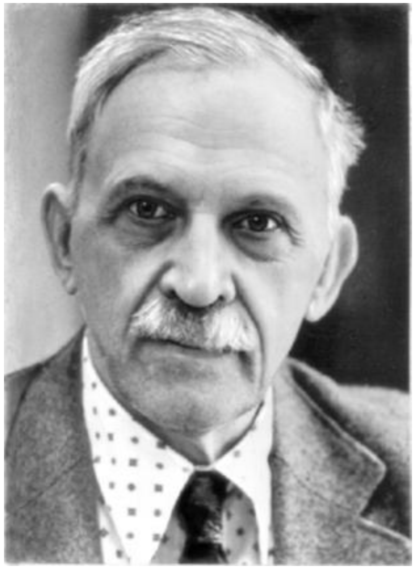
Outline

1. First **high Z-metal wall** tokamak era
2. From high Z-metals to Carbon
3. Second metal wall tokamak era
   - High Z-metal ASDEX Upgrade
   - High Z-metal ALCATOR C-Mod
   - Low+High Z-metal JET-ILW
4. Summary

Historical remarks, 65 years ago…

Igor Golovin's name is associated with the construction of the TMP machine (the first tokamak) in **1955**. Golovin coined the term "**Tokamak**" in **1957**. Later on his interest shifted towards mirror machines.



Nutan Yavlinskii together with Golovin initiated research of the toroidal discharges in magnetic fields along the idea of **Sakharov** and **Tamm**. **Yavlinskii** was a leader on the first tokamaks: TMP, T-1 and T-2. He led the project to construct and launch the **T-3 tokamak**.

He and his family died tragically in an airplane crash in 1962.

Disruptions - historical remarks, 58 years ago…

- **Disruptions were known to exist from the time tokamaks started to behave as tokamaks.**
- Ksenia Razumova (32 years old)

described the disruption instability in 1963 [1,2]:

  - "a strong interaction with the wall" (= wall material effects disruption);
  - "electrons accelerated to large energies … hurl themselves into the … wall" ;
  - - "…current discharges, stabilised by a strong magnetic field".
- The first MHD stable plasma was obtained on the TM-2 tokamak by Razumova (and Gorbunov) in 1962.

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[1] GORBUNOV, E. P. & RAZUMOVA, K. A. 1964 Effect of a strong magnetic field on the magnetohydrodynamic stability of a plasma and the confinement of charged particles in the 'Tokamak' machine. J. Nucl. Energy C 6 (5), 515–525 (translation in At. Energ. 15 (5), 1963, 363–369).

[2] Sergei V. Mirnov. V. D. Shafranov and Tokamaks. J. Plasma Phys. (2016), vol. 82, 515820102

Disruptions - historical remarks, 65 years ago…

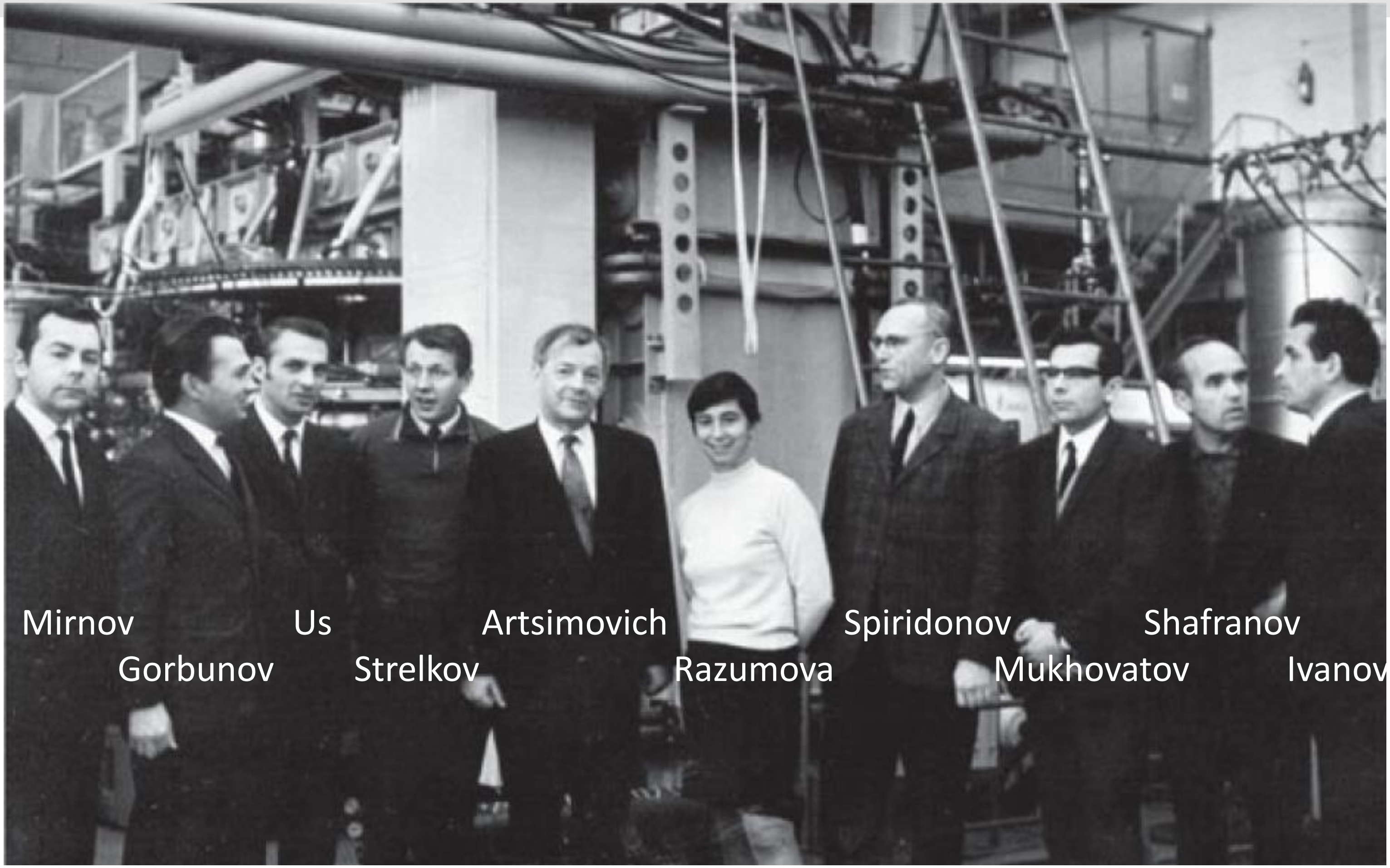
Vitalii SHAFRANOV

q > 1 criteria, the most fundamental theory result in magnetic (tokamak) fusion was obtained by 22 old non-PhD physicist in 1952. He was also confident about the importance of this result to make the title unambiguous: "**The stability of** ……", was published in 1961*.

While the later paper by M. Kruskal and M. Schwarzschild, who derived the same criterion, was cautiously titled "Some instabilities ...".

** courtesy of L.E. Zakharov*

Kurchatov's tokamak team in 1971

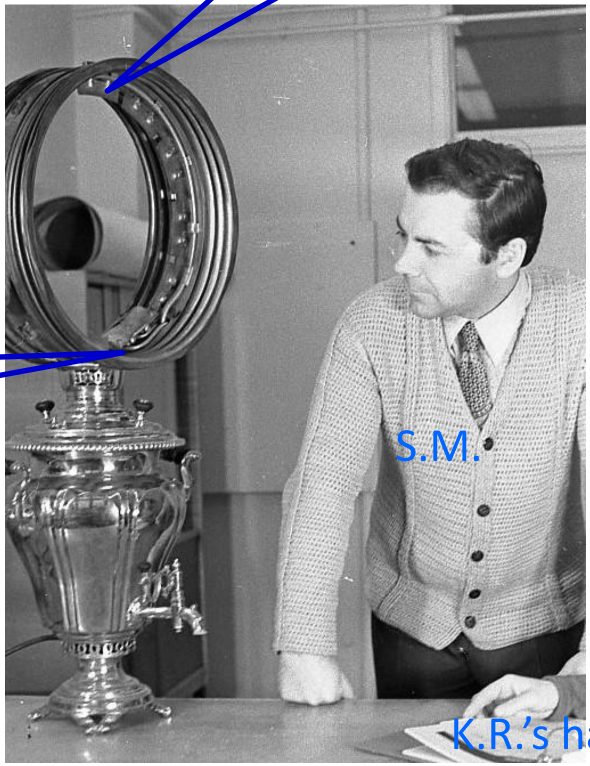


- **Tokamaks were high Z-metal wall machine** (apart from very first TMP porcelain torus)
- **However, high Z-metal wall tokamaks suffered with impurity accumulation**
- **Carbon saved tokamaks for next tens years, but not for ever**

Pioneering high Z metal-wall tokamaks

Stainless steel wall and metal limiter

T1	1957	Unbaked vessel
T2	1959	Bakeable up to 400ºC
TM-2	**1962**	*** First MHD stable plasma ***
T-3	1960	Stainless steel limiter
T-3A	1965	Stainless steel limiter
T-4	1970	**W limiter**



In 1971-73 campaign, runaway electrons (RE) were generated during breakdown and remained in the plasma until disruption(s), **melted and evaporated** large parts of W-limiter. It was thought, that RE hit the W-limiter just before a disruption event*.

* *courtesy of S.V. Mirnov*

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From high Z-Metals to low Z-Carbon tokamaks

Carbon era*

- **PETULA** (France): winter 1975-76, C-limiter, the results of these experiments were not very promising [Bardet 1976 NF 16 579]
- **TFR:** early 1977 C-limiter [TFR Group 1977 EUR-CEA-875 preprint]
- **T-4:** Feb-Mar 1977 (C+B)-limiter drop of Z_{eff} from 5 (W limiter) down to ~2 [Vorobyev 1978 Fiz. Plazmy 4 982]

The graphite era really began with the PLT

- **PLT 1977-1978:** W-limiters were replaced with C-limiters: Central impurity radiation was dramatically reduced [J. Hosea et al 1985 NF 25 1155]

C-limiter/wall tokamaks have sufficiently high fuel retention, so C-limiter/wall machine are not compatible with tritium operation

** S. Mirnov 12-Jun-15 private communication*

** G. McCracken 19-Jun-15 private communication*

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U-turn! Return to high Z-metal - ASDEX Upgrade

1991: AUG first wall tiles are (almost) all graphite covered with tungsten

Arc "spots" were clearly observed in the divertor*

** G. Pautasso 24-Apr-20 private communication*

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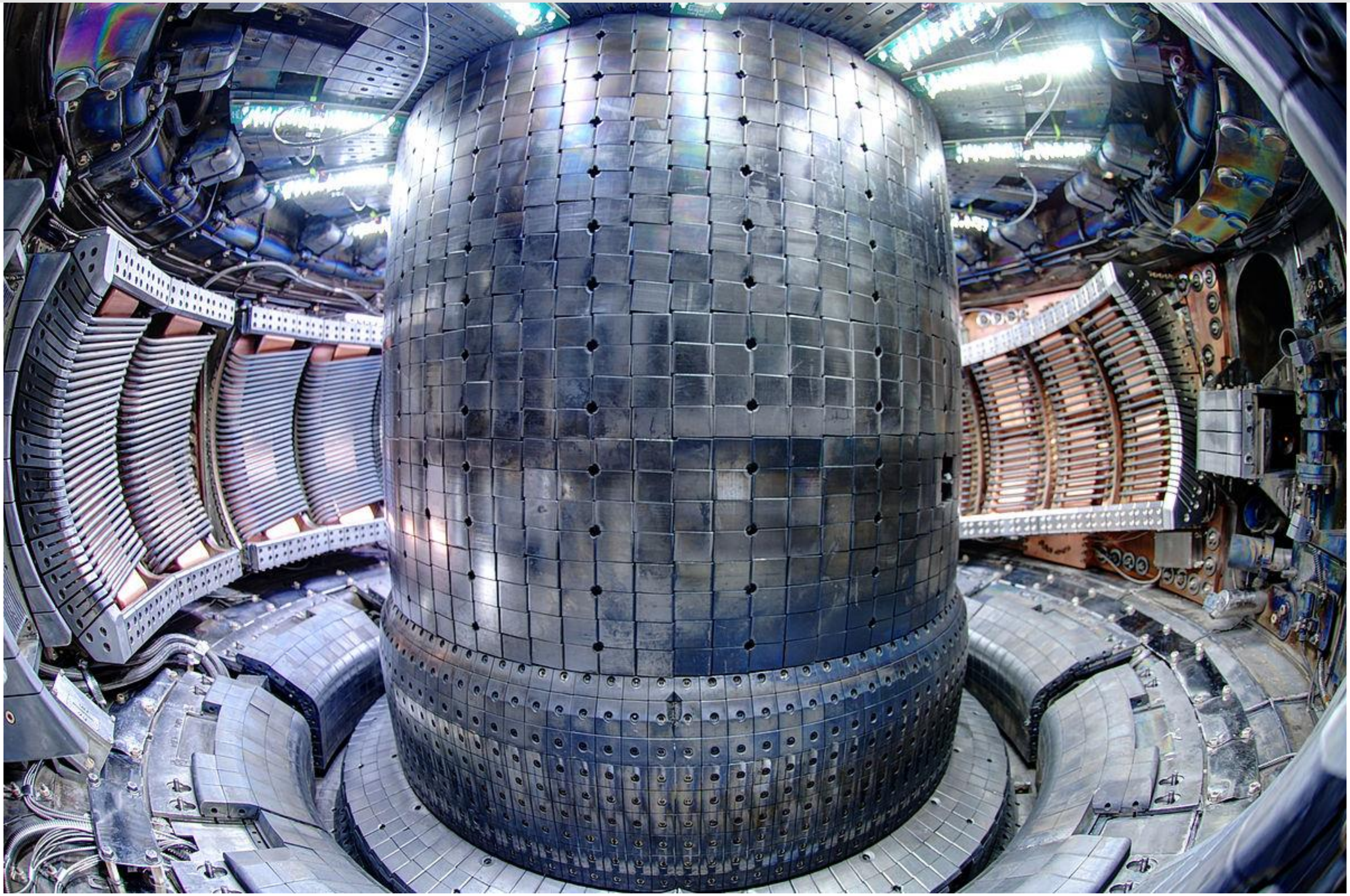
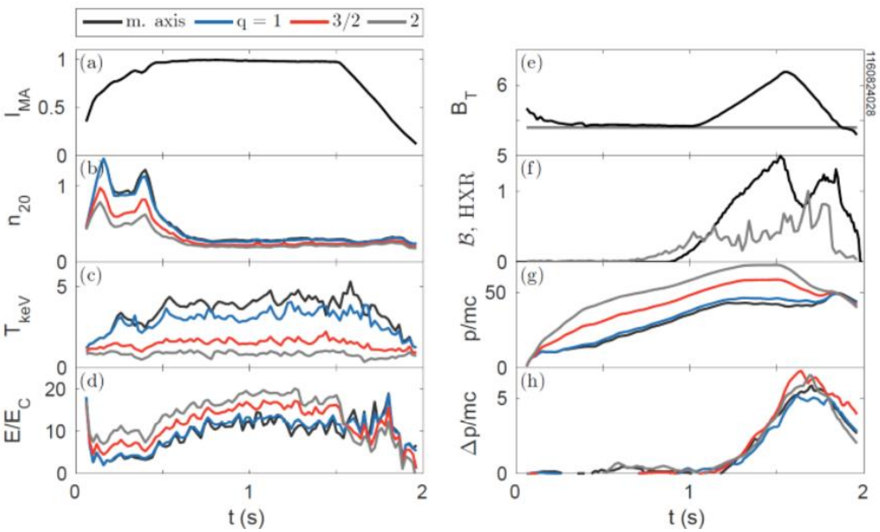
Return to high Z-metal - ALCATOR C-Mod



1993 - 2016 20 mm thick **Molybdenum** tiles covering most of the first wall and all of the divertor

ALCATOR C-Mod, high Z-metal Molybdenum wall

- #1160824028 pulse the **RE** purposefully generated during the flattop (low density) to study synchrotron radiation.
- During the plasma current ramp-down, the REs hit an outer wall molybdenum limiter, producing a spray of molten metal.
- The RE hit the wall at the end of the CQ, so probably around t ~ 1.9s.



** R. Granetz 17-Apr-20 private communication*

A. Tinguely Nucl. Fusion 58 (2018) 076019

ALCATOR C-Mod, high Z-metal Molybdenum wall

- Disruption create **massive thermal loads** on the divertor tiles resulting in sprays of molten molybdenum, shot 1160617021.
- Badly **melted molybdenum tile edges**, and even entire tiles, on the misaligned edges of top divertor modules have been observed.

Disruptions also create **large forces** that deformed divertor structural support hardware (inconel!), from the JxB forces due to halo currents*.

** R. Granetz 17-Apr-20 private communication*

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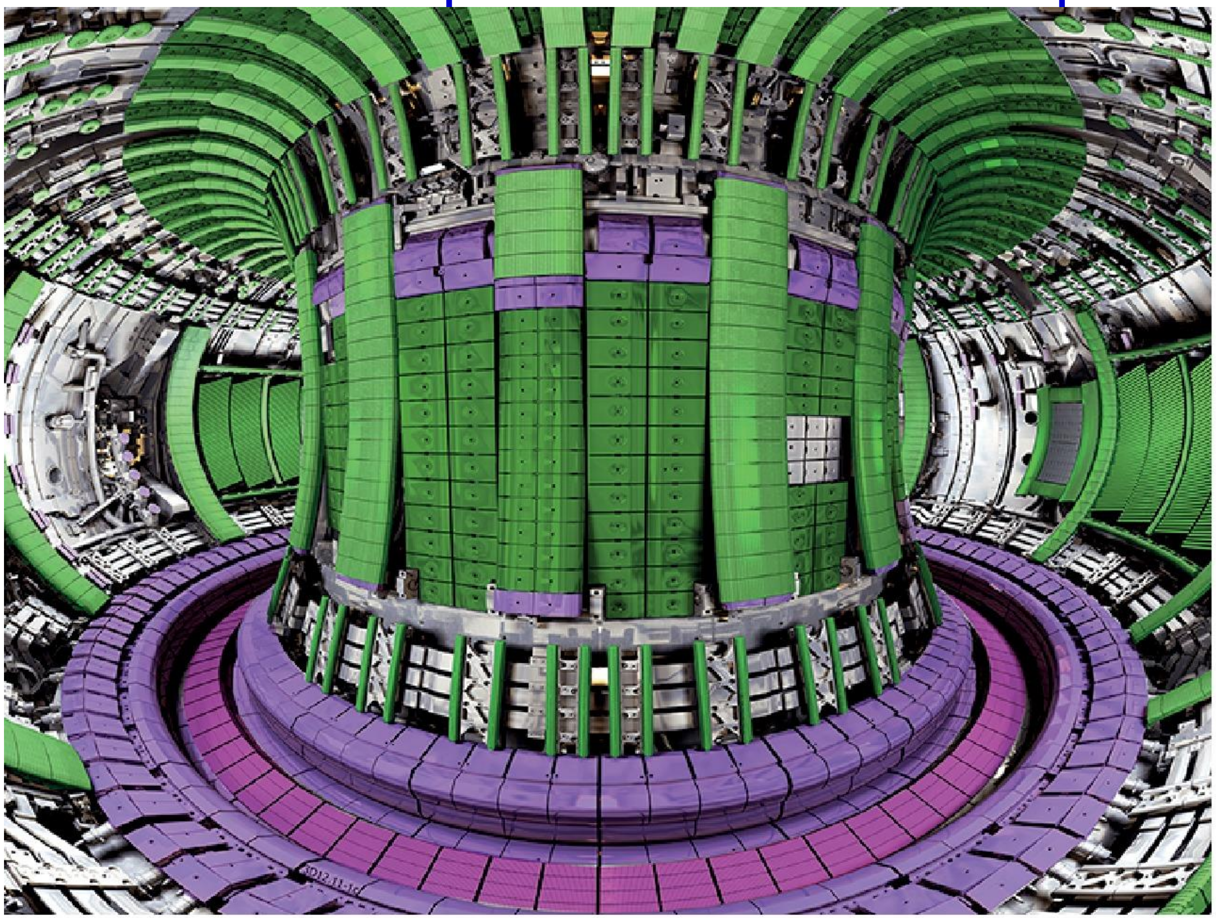
From Carbon to Low+High Metal, JET-ILW

2011 - all metal Be/W composition wall which is planned for ITER



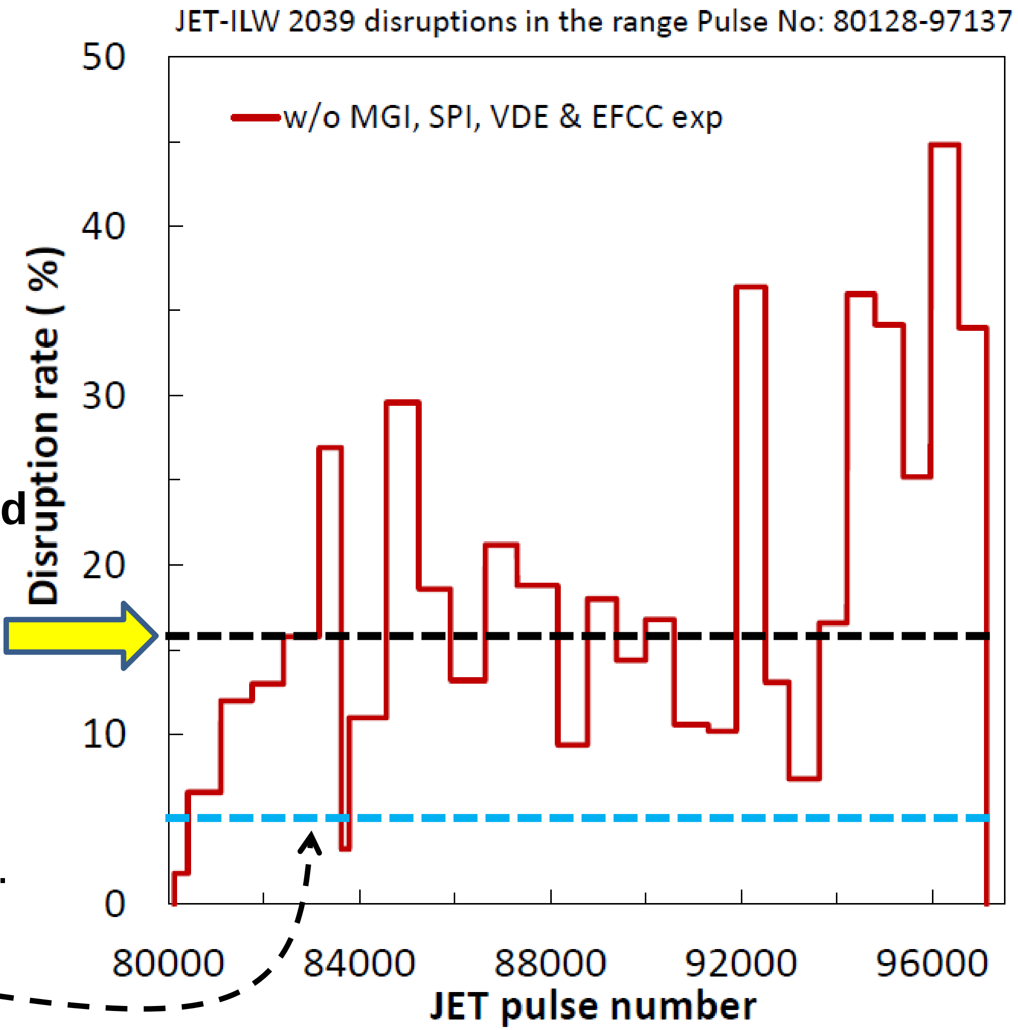
Bulk Be PFCs
Be–coated inconel PFCs
Bulk W
W–coated CFC PFCs

See Riccardo et al Fusion Eng. Des. 88 (2013) 585– 589

CCFE CULHAM CENTRE FOR FUSION ENERGY

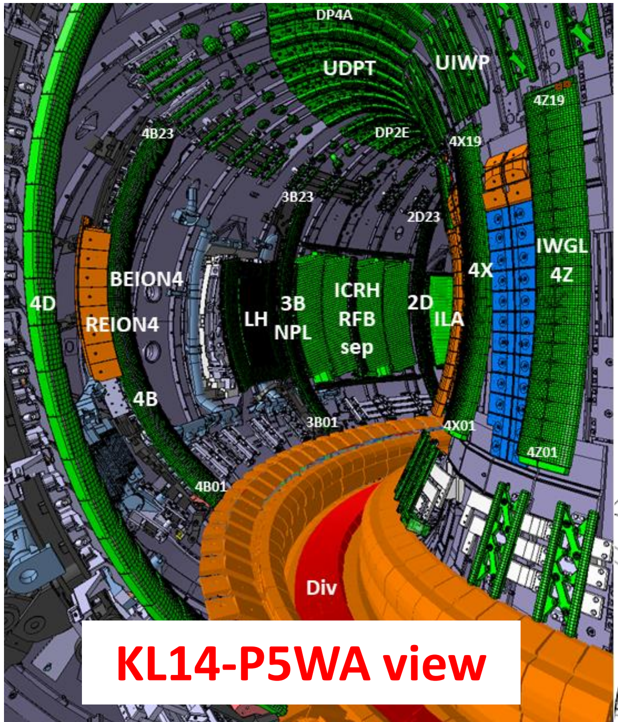
JET-ILW disruption rate: 24/08/2011 (first ILW plasma pulse) - 23/03/2020

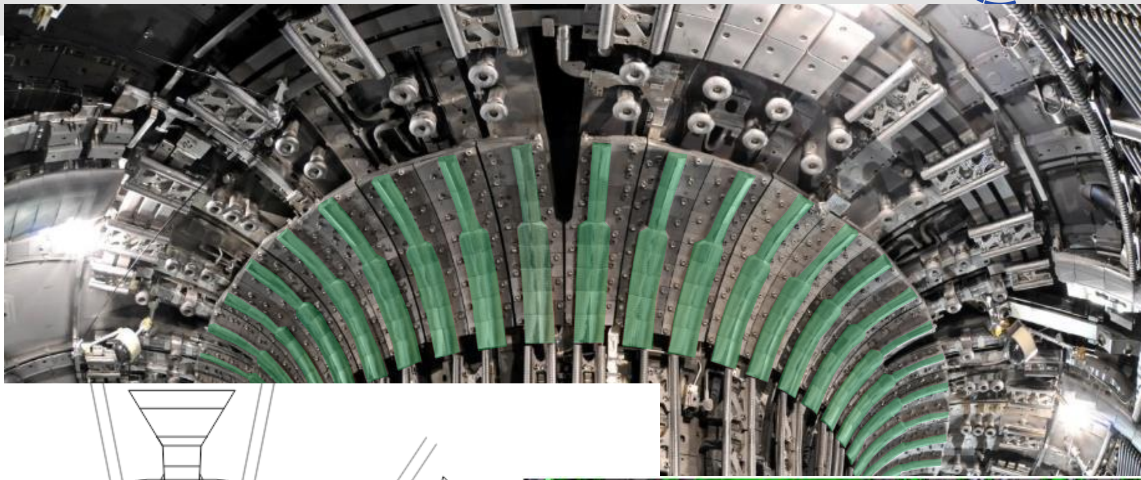
- **Total number of Plasma shots: 13467**
- **2039 "unintended" disruptions with $|I_p^{dis}| > 0.8$ MA**
- **High disruption rate (up to ~ 50%)** attributed to exploration of operational space for high performance plasmas
- **Average disruption rate of unintended disruption is ~ 16%**
- **16% disruption rate** is considerably above the ITER target (~ 5%) at 15 MA.

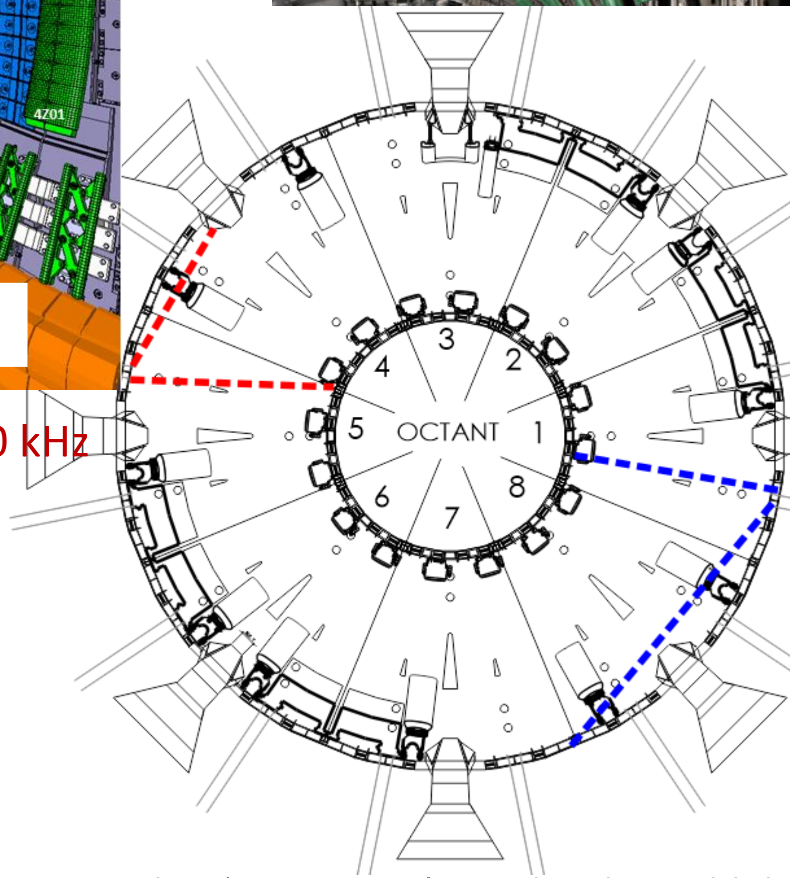


***2554** disruption shots = **2039** "unintended" + 515(480 disruption experiments (MGI, SPI, VDE and EFCC) + 35 human errors, hardware/software tests/faults)*

JET Infrared Cameras and Be Upper Damp Plate



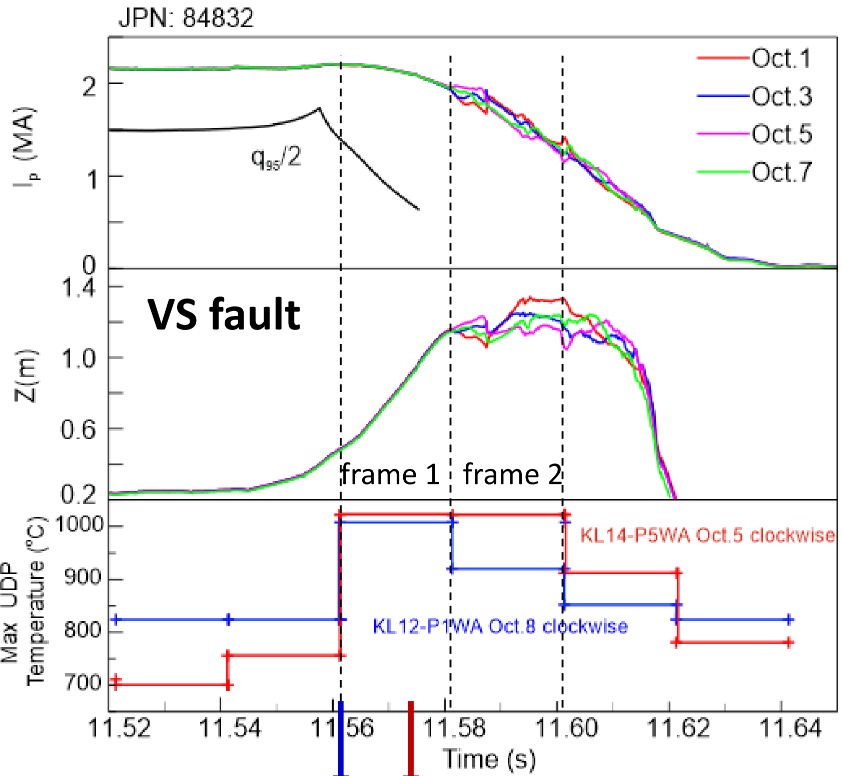


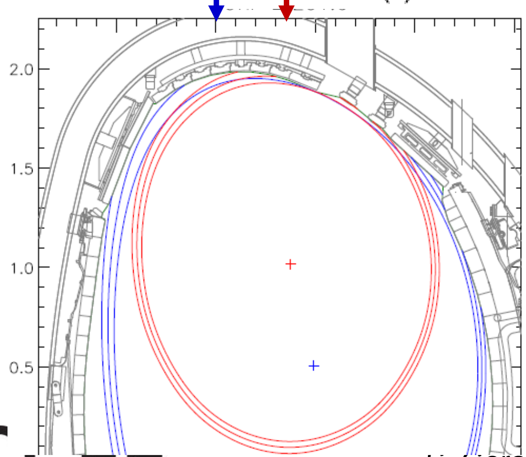


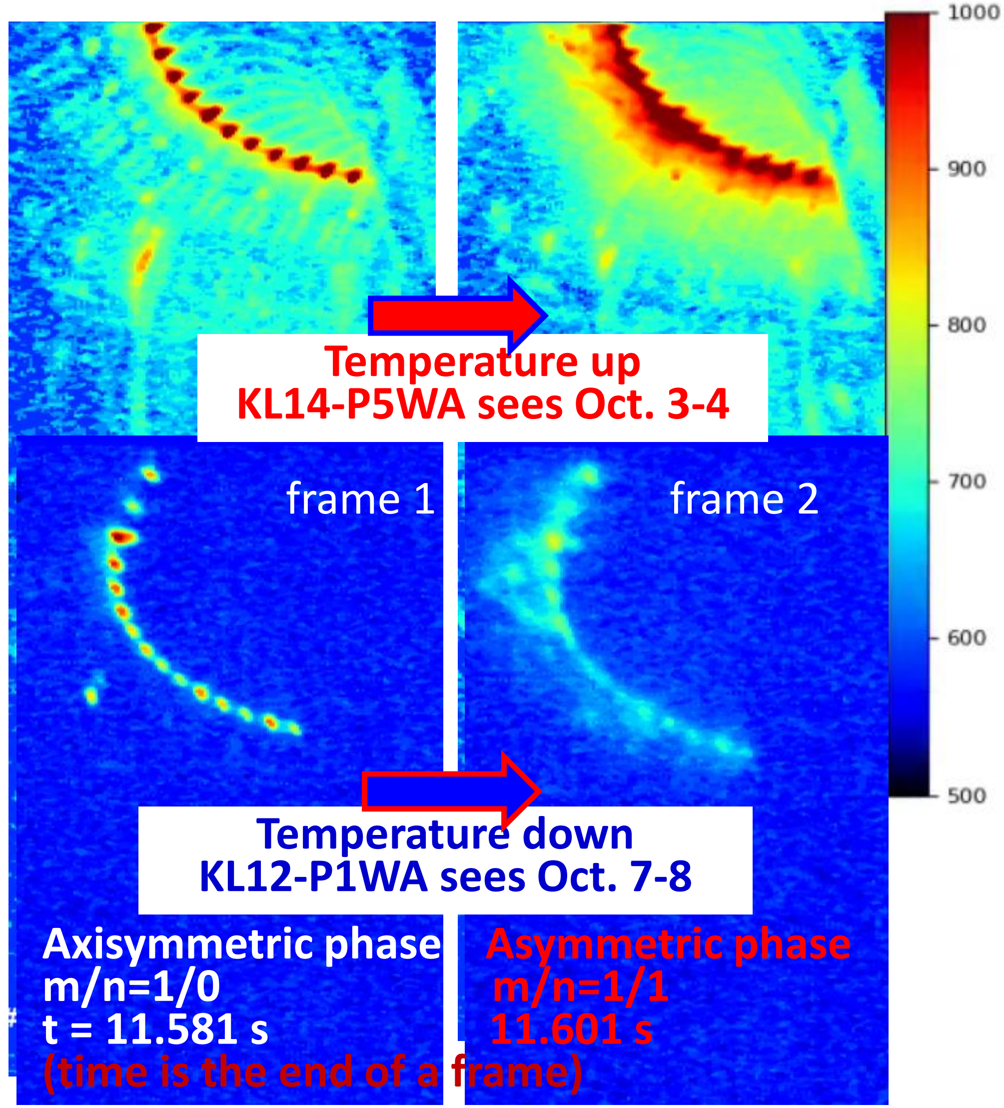
Exposure time 20 ms, 50 kHz

courtesy of V. Huber, S. Silburn, I. Jepu

AVDE* (#84832**) melted Upper Dump Plates (UDP)





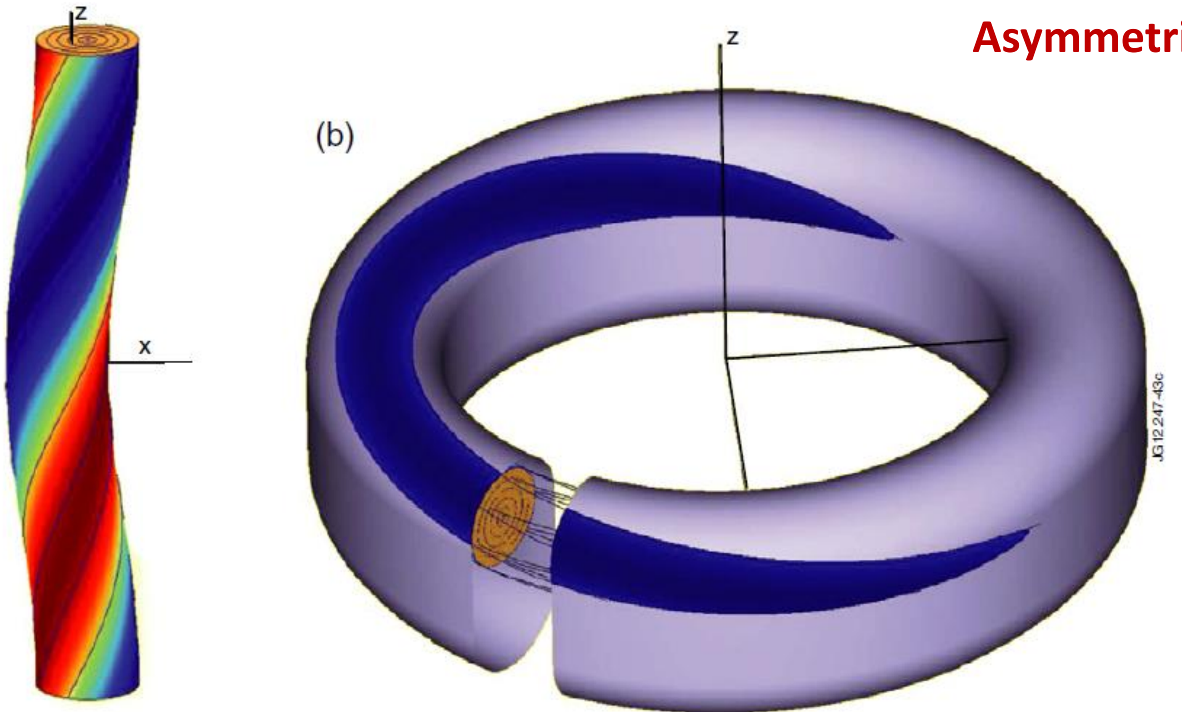


*Gerasimov NF 54 073009; Gerasimov NF 55 113006

**Jepu NF 59 086009

AVDE* melted Be Upper Dump Plates

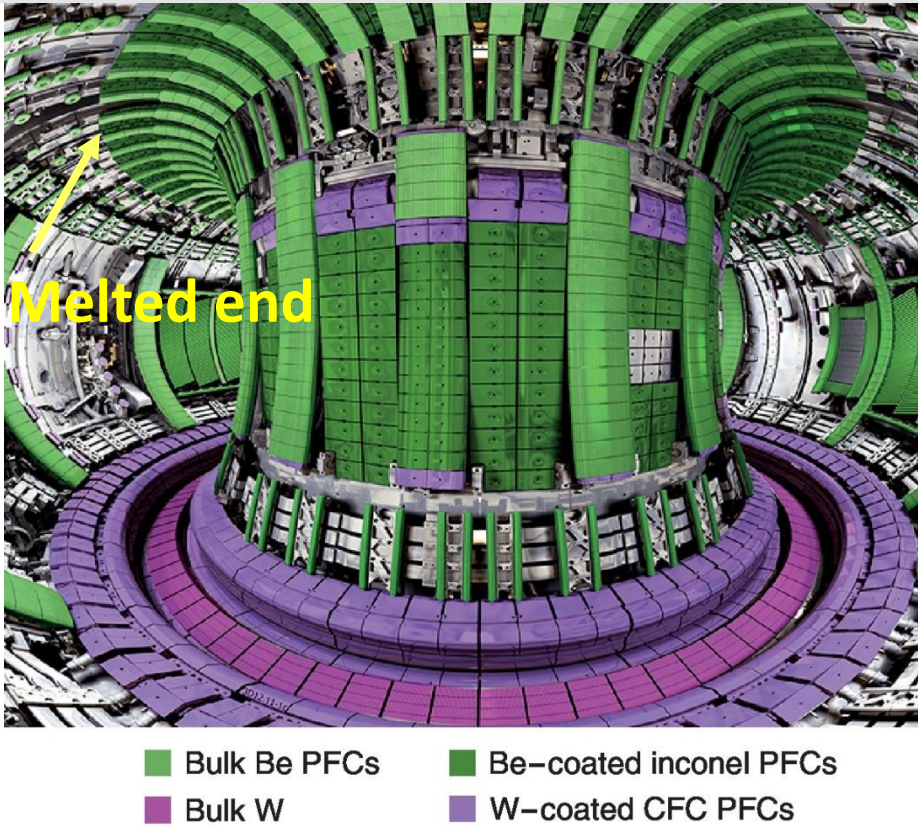
Asymmetric phase of VDE, m/n=1/1



- **The bulged-out surface always carries the negative (blue) current, opposite to *Ip***
- **Dark blue colour represents negative surfaces plasma current shared between plasma and the wall in AVDE due to *m/n* = 1/1 kink mode**
- **This current (which is generated by plasma to maintain the equilibrium) melted the Be upper dump plates in JET**

**Gerasimov NF 54 073009; Gerasimov NF 55 113006*

JET-ILW Melted Be UDP (1)



Melted end of UDP 8

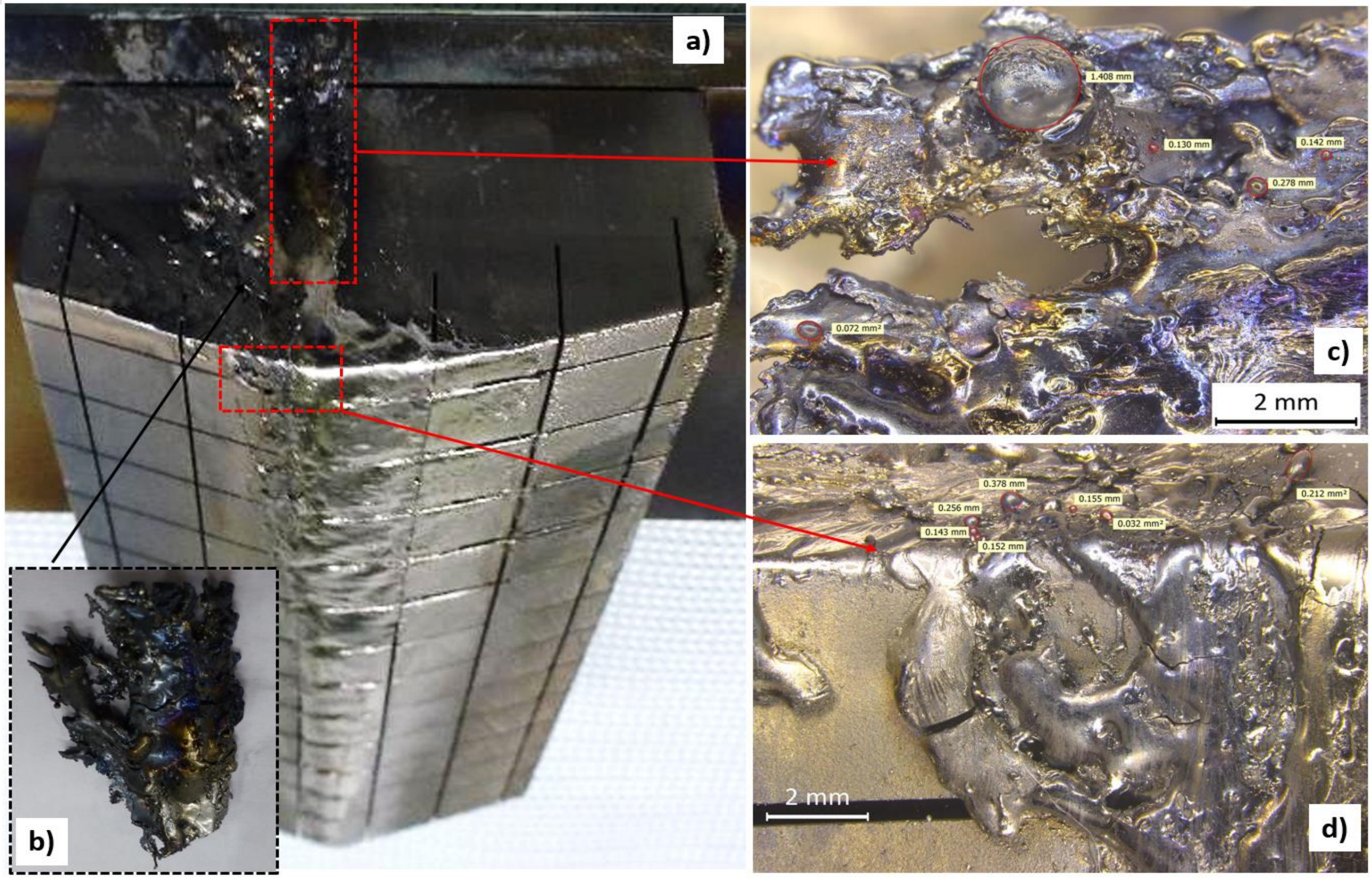
courtesy of I. Jepu

JET-ILW Melted Be UDP (2)

a) **Melted UDP 8**

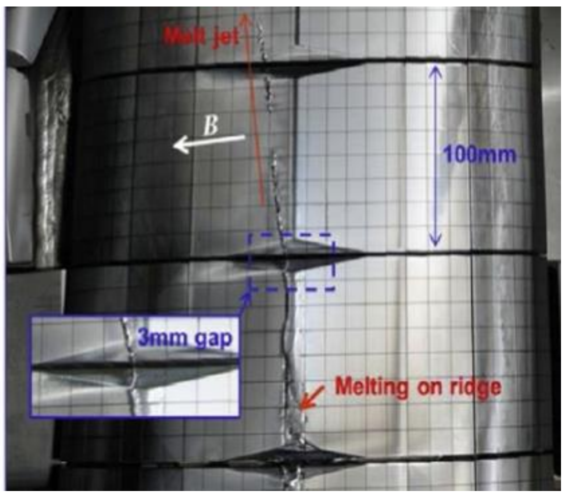
b) **Flake closeup**

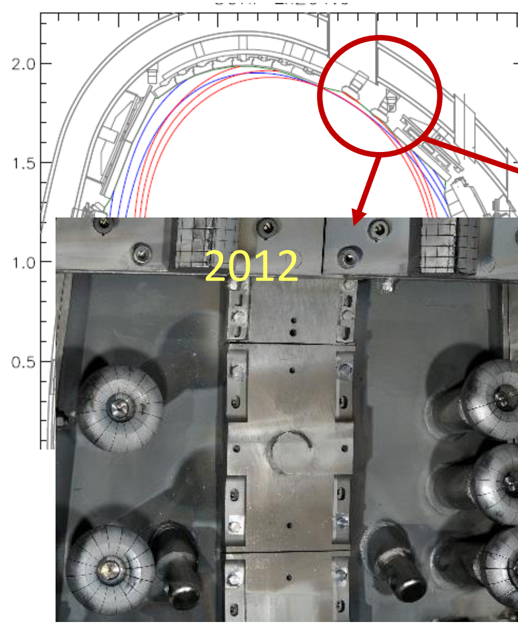
c) & d) **Complex features of the melted areas**

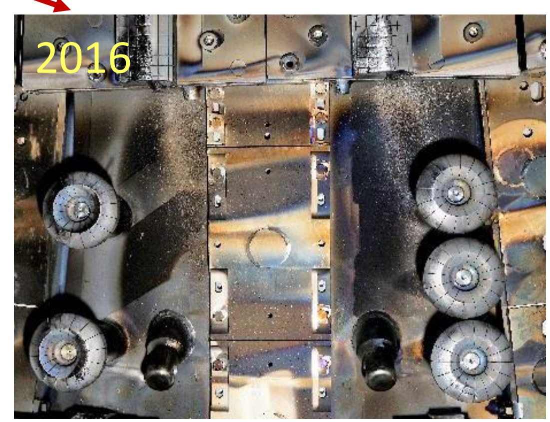


courtesy of I. Jepu

JET-ILW Melted Be UDP (3)







courtesy of I. Jepu;

G.F. Matthews Phys. Scr. T167 (2016) 014070

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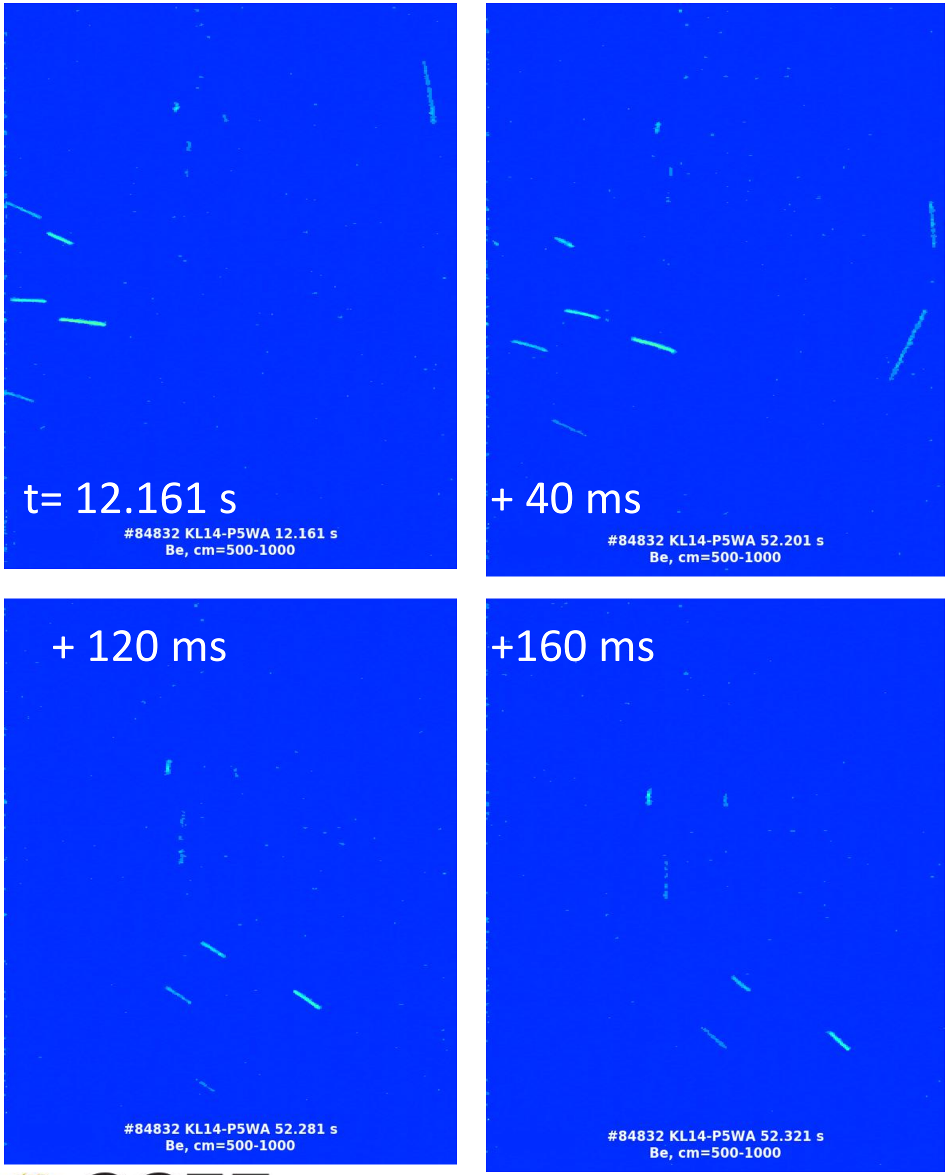
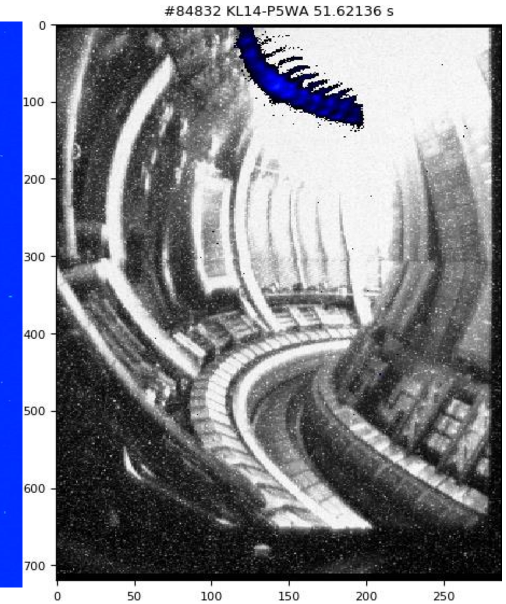
Be rain* after #84832 CQ



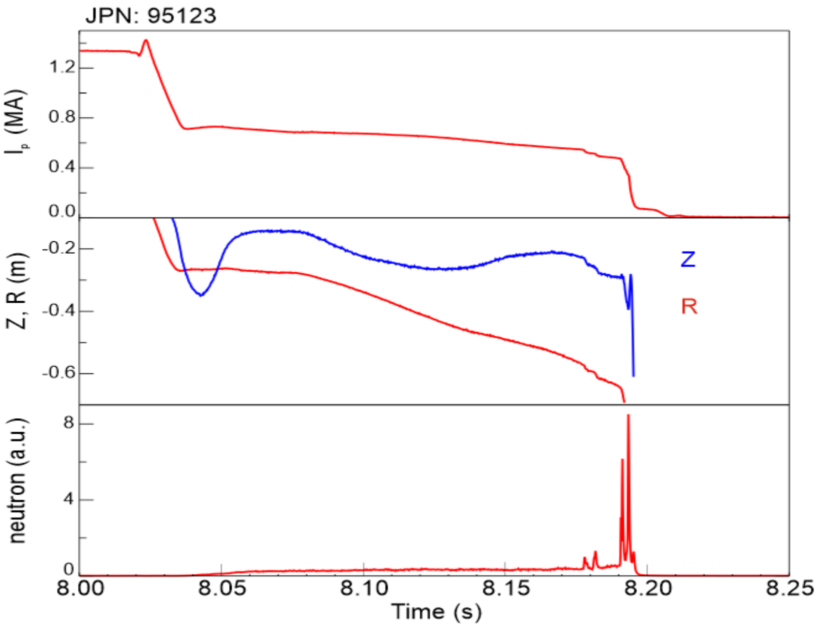


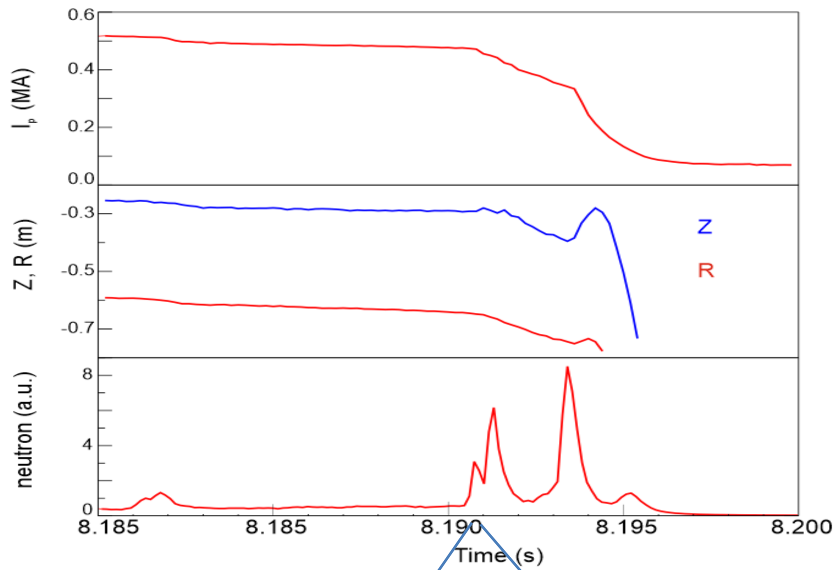
- **Melted Be drops to W divertor**
- **Be droplets on W affect next pulse performance**

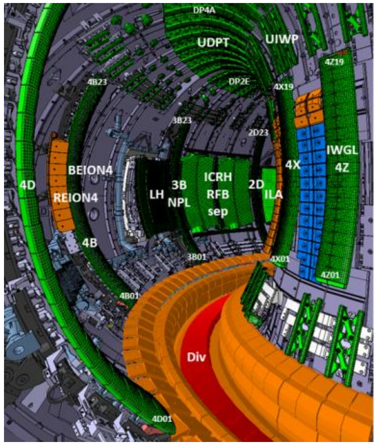
**Jepu NF 59 086009*

Run Away Electrons (RE) hit the wall

#95123* M18-36 Runaway electron suppression with the SPI 10/09/2019

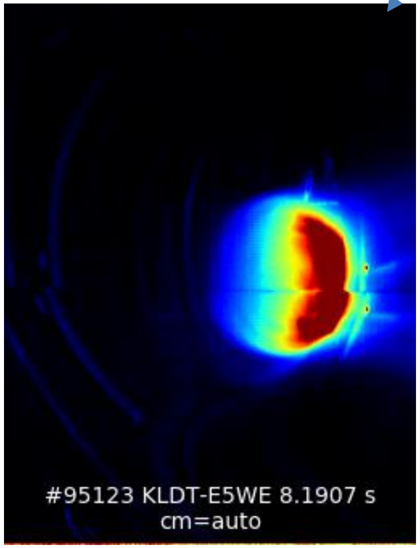


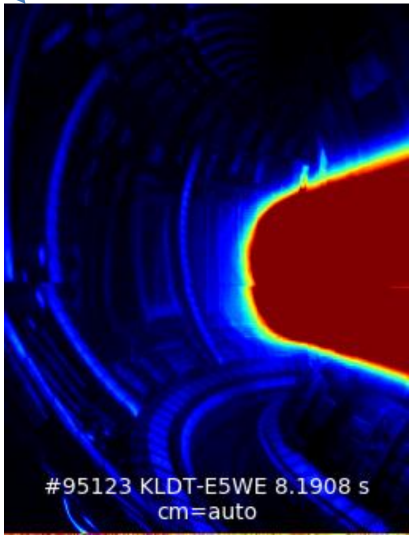




KLDT-E5WE
Fast visible camera
Frame =6.7 µs

RE limiter (inboard) impact.



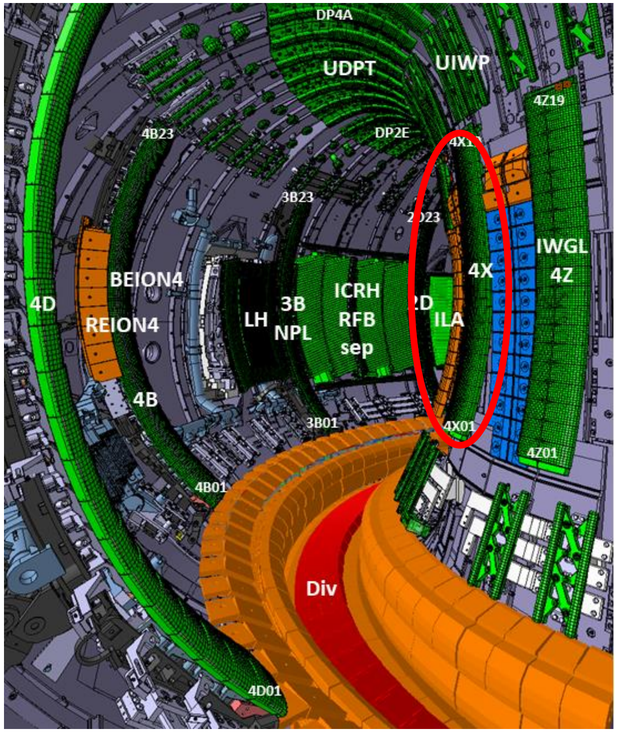


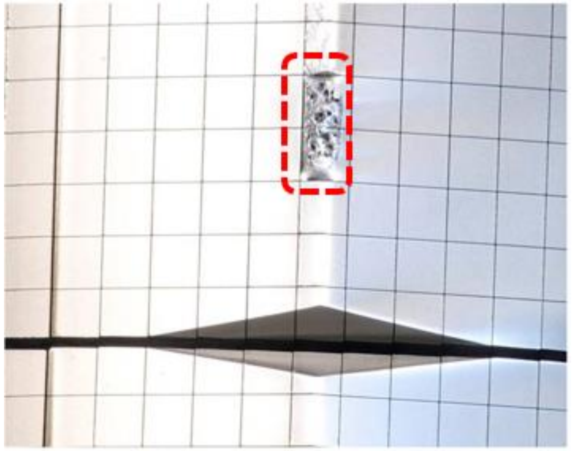
** Cedric Reux was a SC*

Run Away Electrons (RE) hit and melted the wall

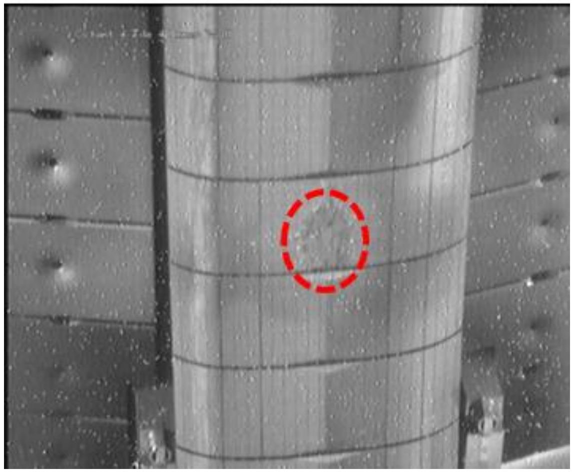
#95123 M18-36 Runaway electron suppression with the SPI 10/09/2019

RE (#95123) melted of the Tile 4 of the inner wall limiter 4X





Shutdown 2017
Severe but localised damage



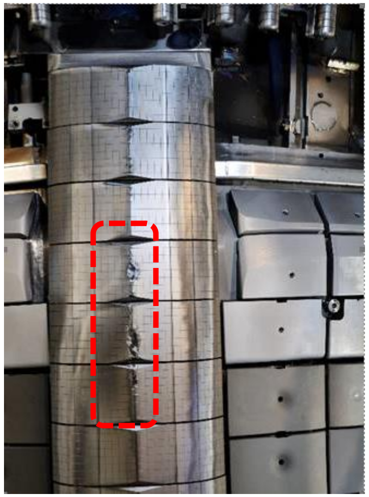
Inspection
10/09/2019
Severe damage over large area

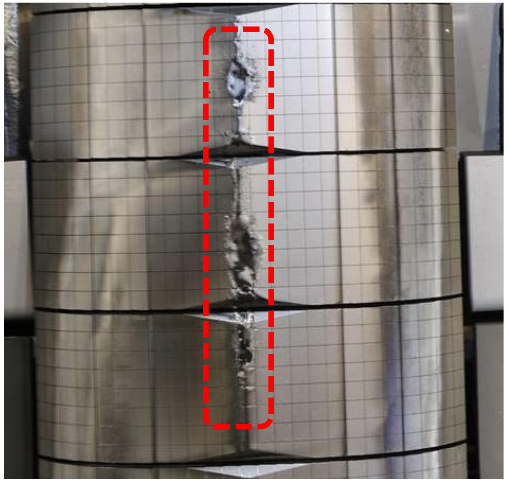
** courtesy of V. Huber*

Upper part of IWGL 4X: Tiles 13-16

Shutdown 2017

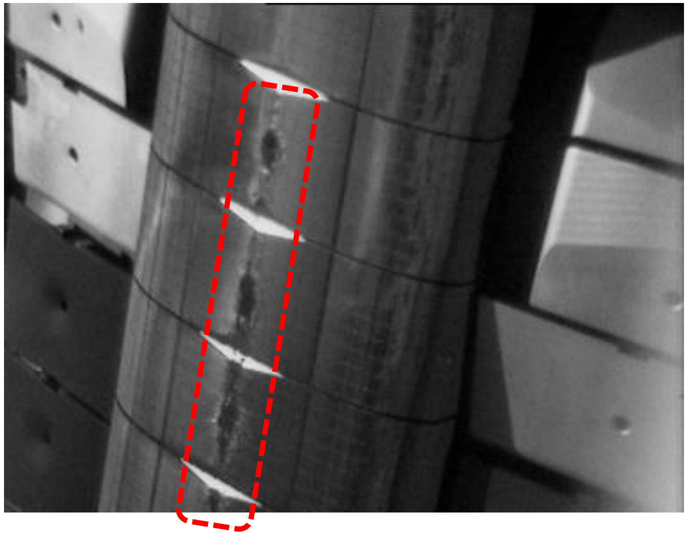
Severe damage

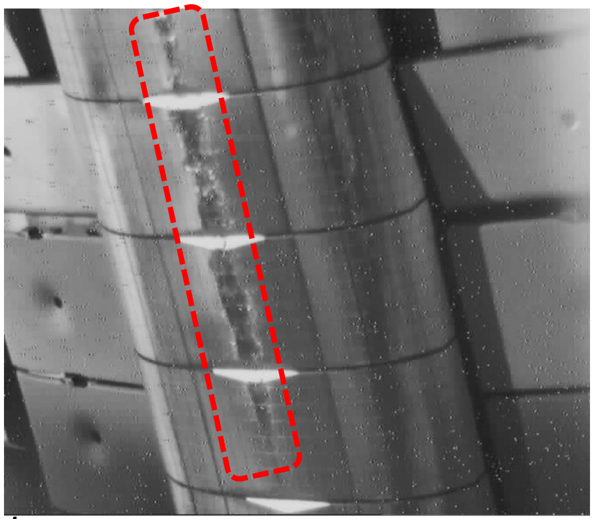




IVIS inspection on September 2nd

Severe damage





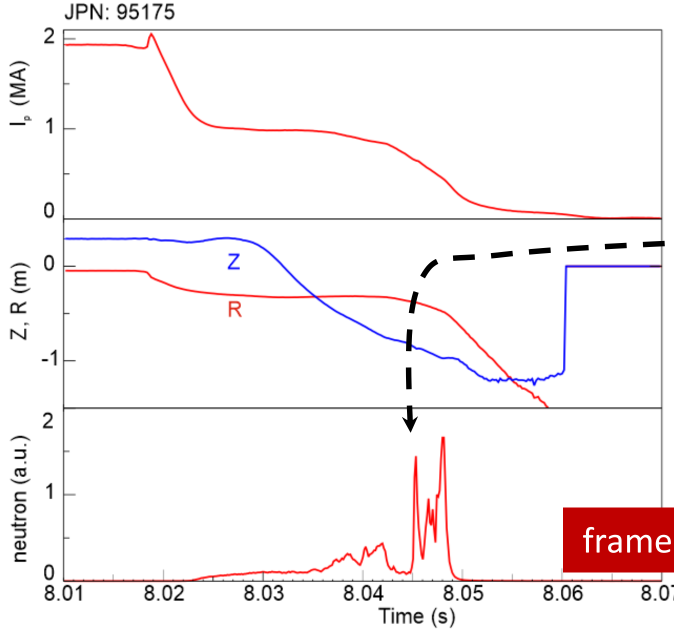
IVIS inspection on September 15th

Further degradation after #95123 of Tiles 13-16

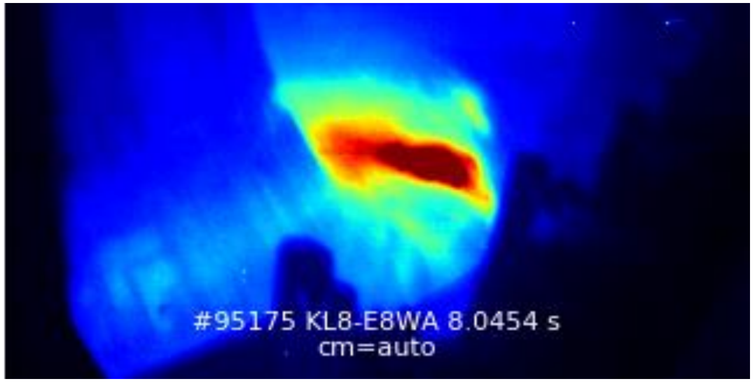
** courtesy of V. Huber*

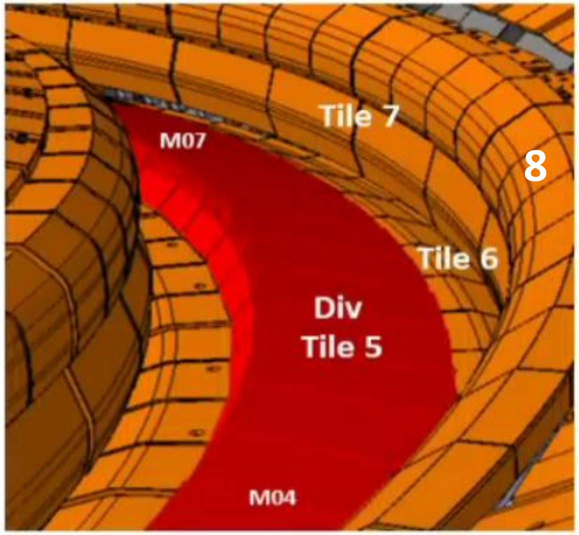
Run Away Electrons (RE) hit divertor tile 8, down VDE

#95175* M18-37 Runaway avoidance and formation conditions 12/09/2019



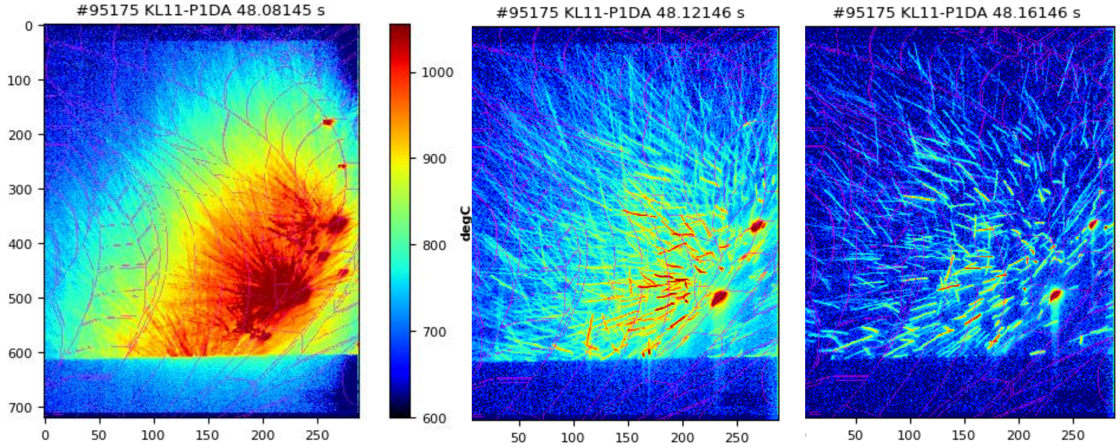
- **RE hits divertor tile 8**





- **Dust shower from W-coated CFC, Tile 8****

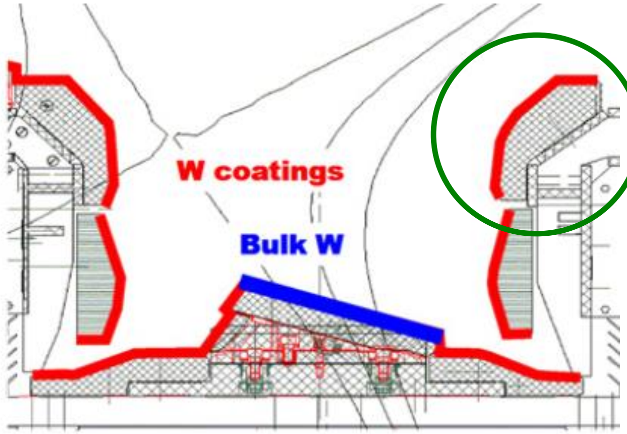
frame1 | 2 | 3



** Cedric Reux was a SC*

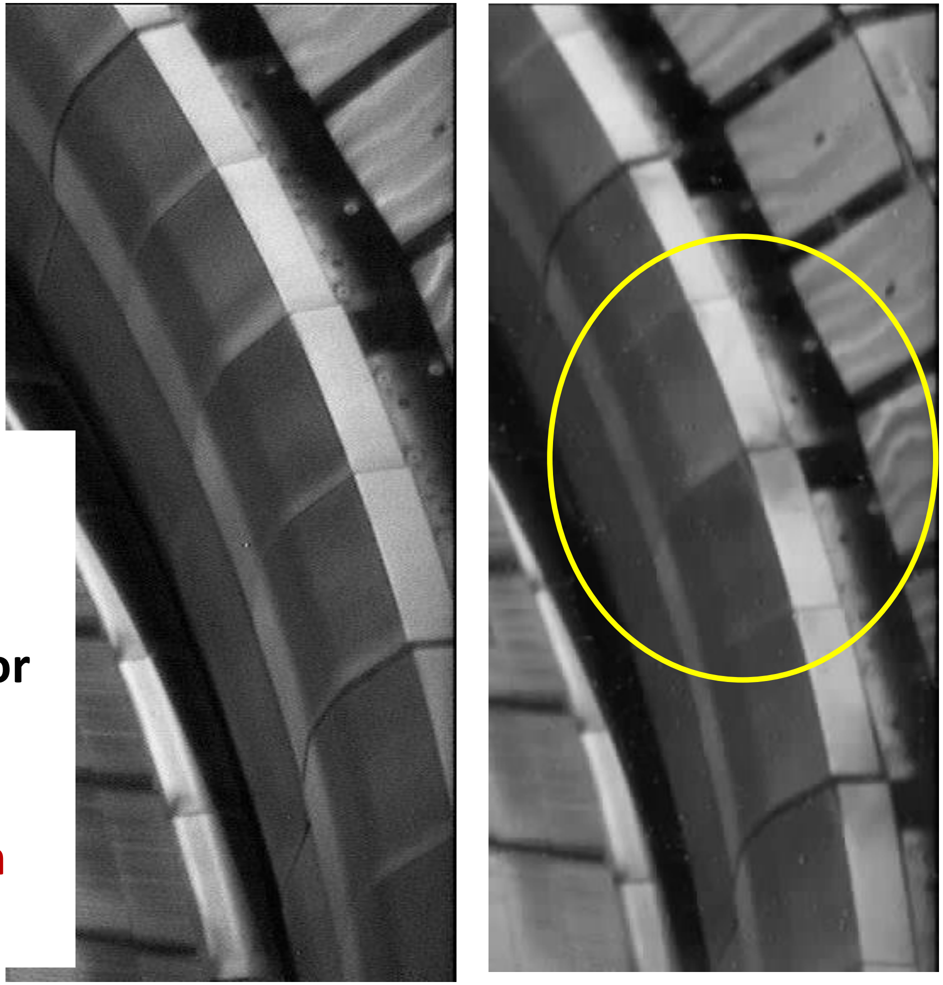
*** courtesy of V. Huber*

W coatings*: Thickness 10-15μm



Octant 8 IVIS inspection

September 2nd September 15th



- **Tolerable damage by RE;**
- **The horizontal surface of tile 8 are not power handling surfaces;**
- **Dust showers are quite common for disruptions that go downwards;**
- **However we should not risk repeating scenarios (RE) which can lead to such events.**

**Maier_2007_Nucl._Fusion_47_009*

** courtesy of V. Huber and P.J. Lomas*

Summary

- Tokamaks began as high Z-metal wall machine, suffered from high Z impurity accumulation;
- From middle 70 Carbon saved tokamaks for next tens years, but not for ever;
- U-turn was done! Tokamaks return to high Z-metal wall in 1991 (ASDEX);
- Following the ITER approach JET was converted from Carbon to Low+High Metal wall machine in 2011, JET-ILW;
- JET-ILW (2011-20) average disruption rate is ~ 16%;
- The disruption rate goes up to 50% for high performance plasmas;
- RE are a well known threat to tokamaks, which can cause a large amount of damage to the wall;
- AVDE plasmas share current with wall, this current causes sideways vessel displacement but also melts the wall;
- However, JET-ILW demonstrated that the disruptions (including AVDE) can successfully mitigated by MGI (and SPI)!