# Overview of WEST contribution to the new ITER baseline and Fusion Power Plants

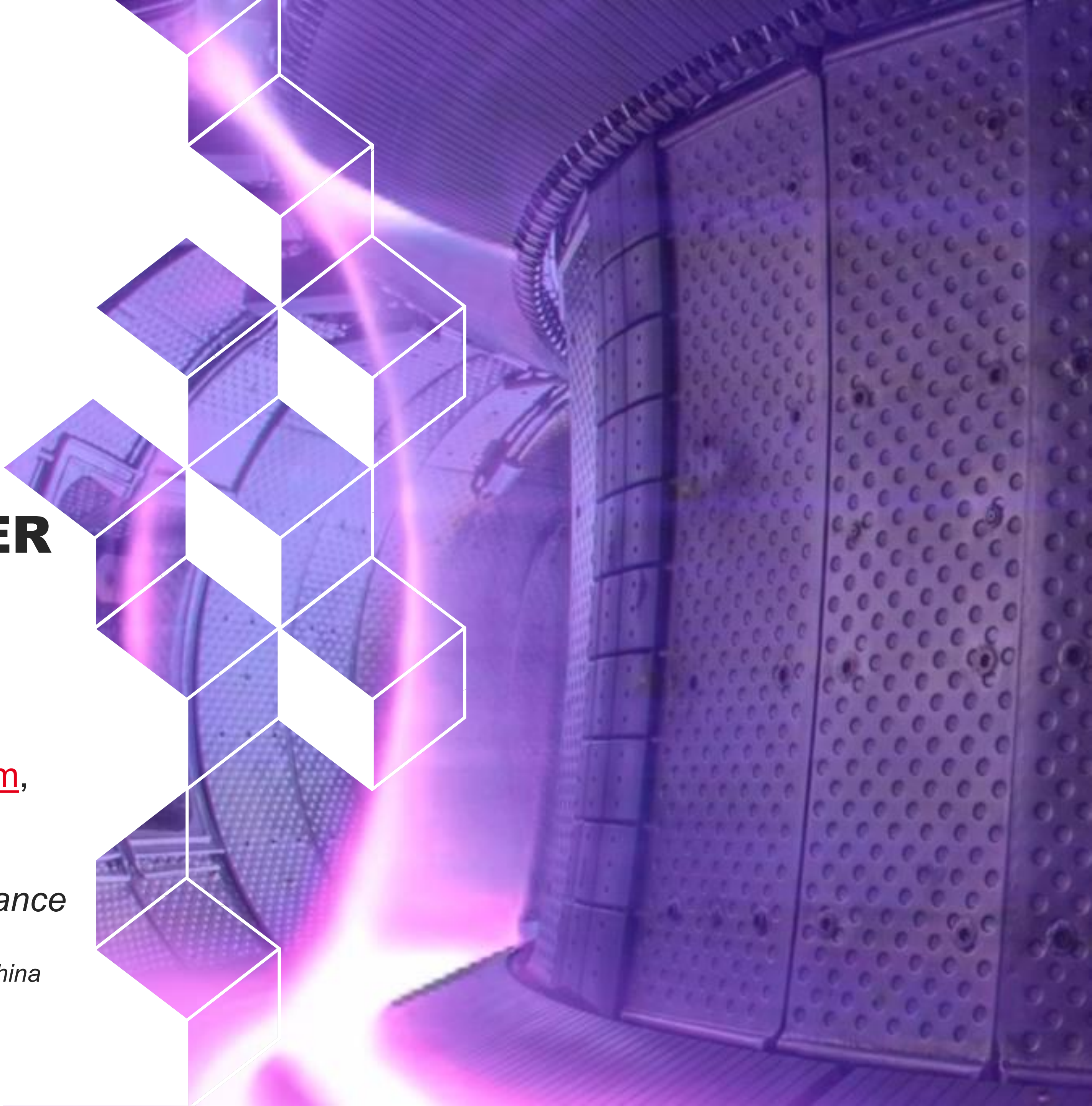
J. Bucalossi,

the WEST team: see http://west.cea.fr/WESTteam,

and the EUROfusion Tokamak Exploitation Team

*CEA, IRFM, F-13108 Saint Paul-lez-Durance, France*

*30th IAEA Fusion Energy Conference (IAEA FEC 2025), Chengdu, China*



https://westusers.partenaires.cea.fr

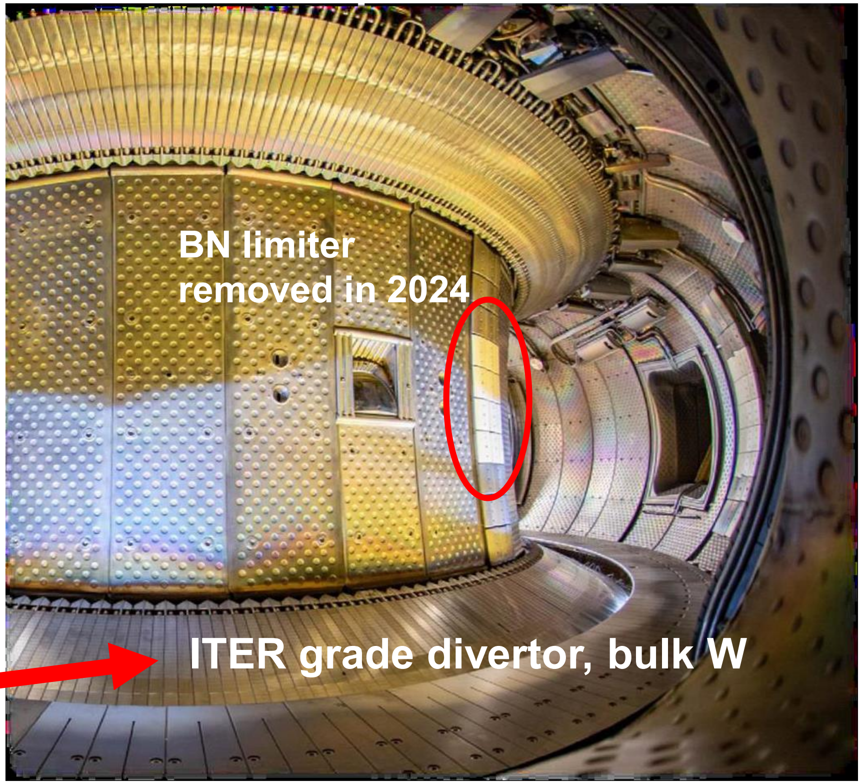
*"This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect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

# Since 2023, WEST has cumulated just over 18 hours of plasma on ITER grade PFCs

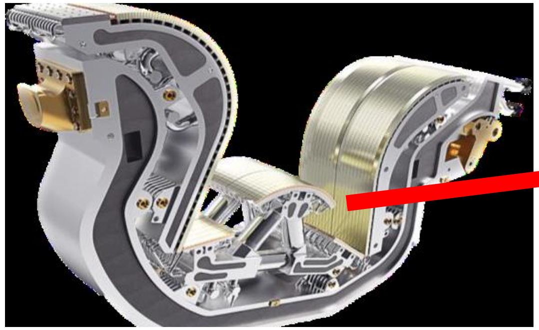
## WEST tokamak: a test bed for plasma exhaust solutions and long pulse design

| | 2022 | | | | 2023 | | | | 2024 | | | | 2025 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T1 | T2 | T3 | T4 | T1 | T2 | T3 | T4 | T1 | T2 | T3 | T4 |
| Full ITER grade divertor | | | | | C6-C7 | | | | C8-C9 | | | | C10-C11 | | | |
| Cumulated plasma time | | | | | 5h30 | | | | 5h45 | | | | 7h00 | | | |

WEST « phase 2 » configuration




Boron-Nitride limiters removed in 2024 (after C9) to study the **ITER new W First Wall baseline configuration**

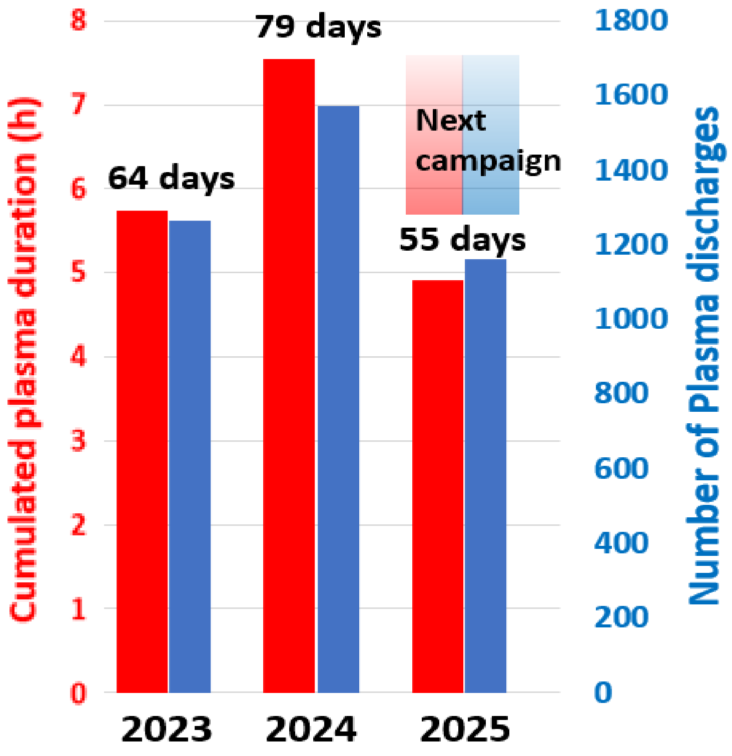


*M. Missirlian et al., FED, 2023*

# Outline – Reports on the key achievements of the past two years

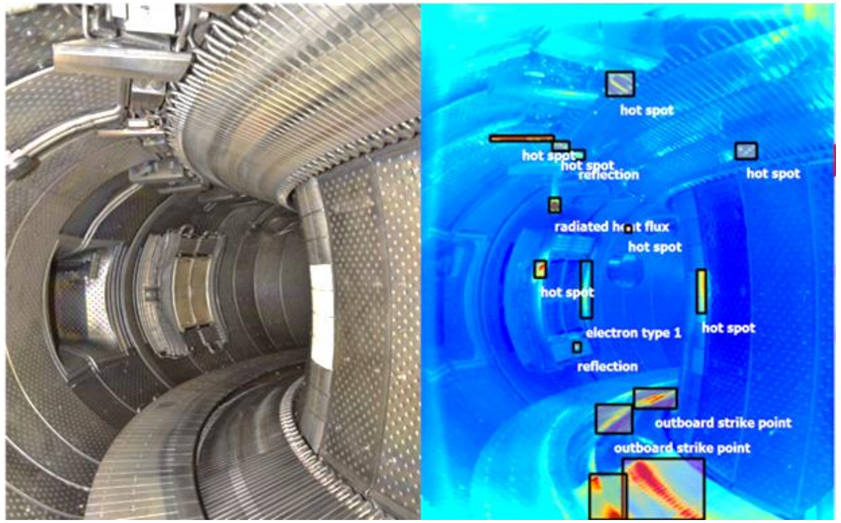
1. **The making of long pulses**
2. **Impact of long pulse on ITER grade W divertor under high power and particle flux**
3. **Plasma Exhaust scenario for limiting erosion: X-point Radiator (XPR)**
4. **Additional contributions to the new ITER baseline (W first wall)**
5. **Summary & Prospects for WEST**

# WEST structured and effective for long pulse operation




## Essential for operating long pulses:

- Permanent toroidal magnetic field (3.7T)
- Actively cooled plasma-facing components
- LHCD system for current drive
- Advanced wall protection by Infrared real time diagnostic:
  IR coverage: 52% of 1st wall 85% of Lower Divertor




The cumulative plasma duration per year: **7.5 hours in 2024**

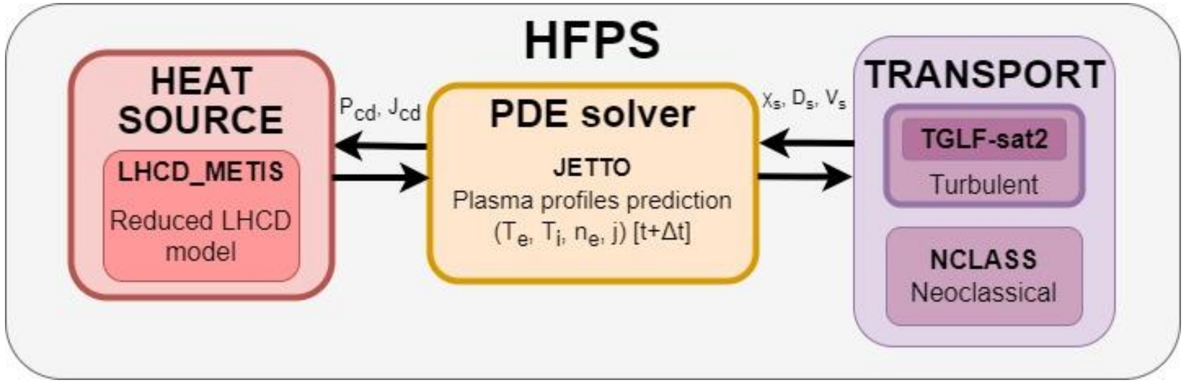
Machine availability on experimental days: **75 % in 2023-2025**

*V. Lamaison et al, this conference TEC-FNT 3448*

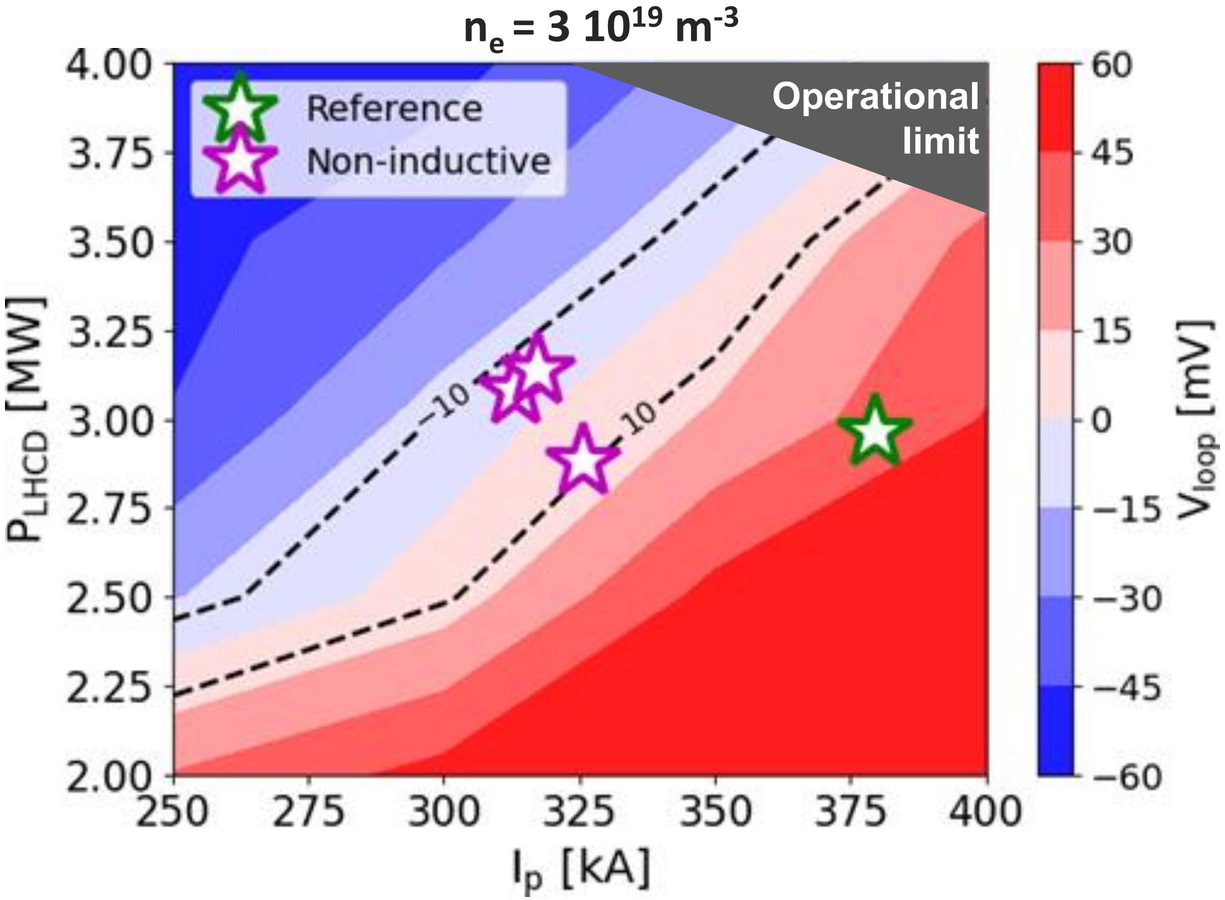
# WEST non-inductive domain predicted first by modelling before the experiments

## Fully non inductive discharges exhibit complex non linearities, especially in a full W environment

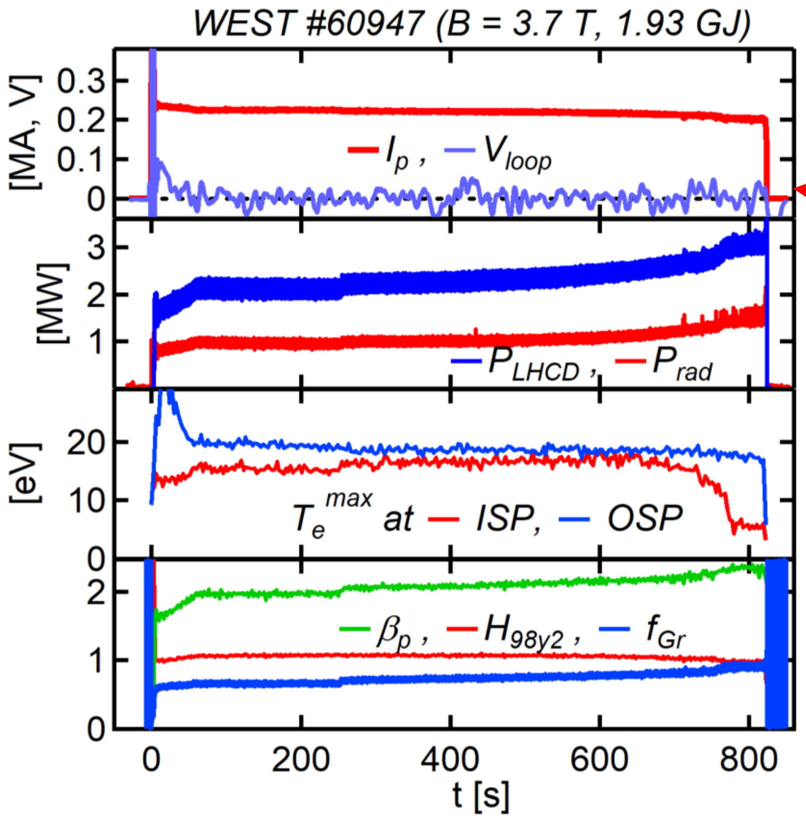
High Fidelity Pulse Simulator (HFPS) based on JINTRAC/JETTO predicts the non-inductive domain within a few mV in WEST starting from a pulse of reference.

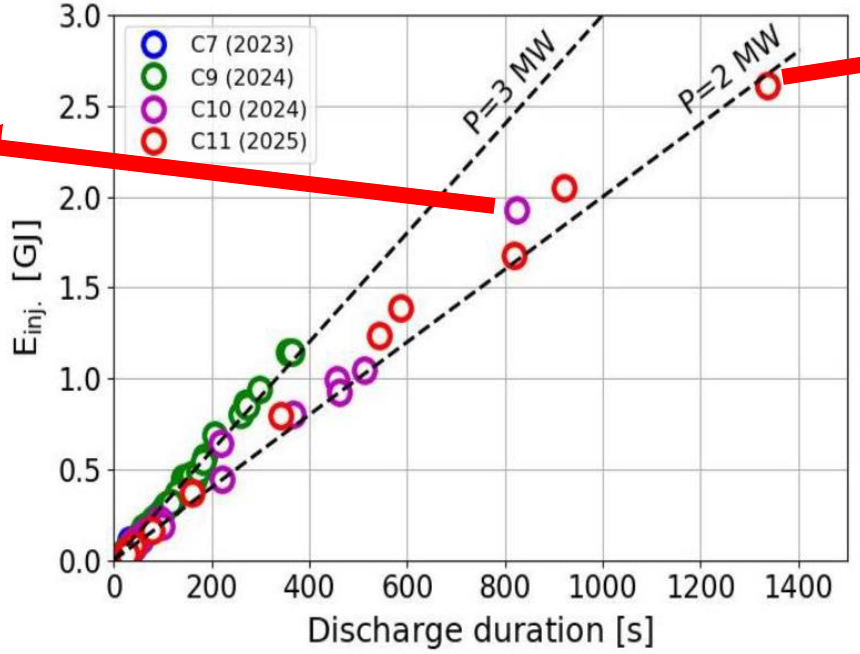


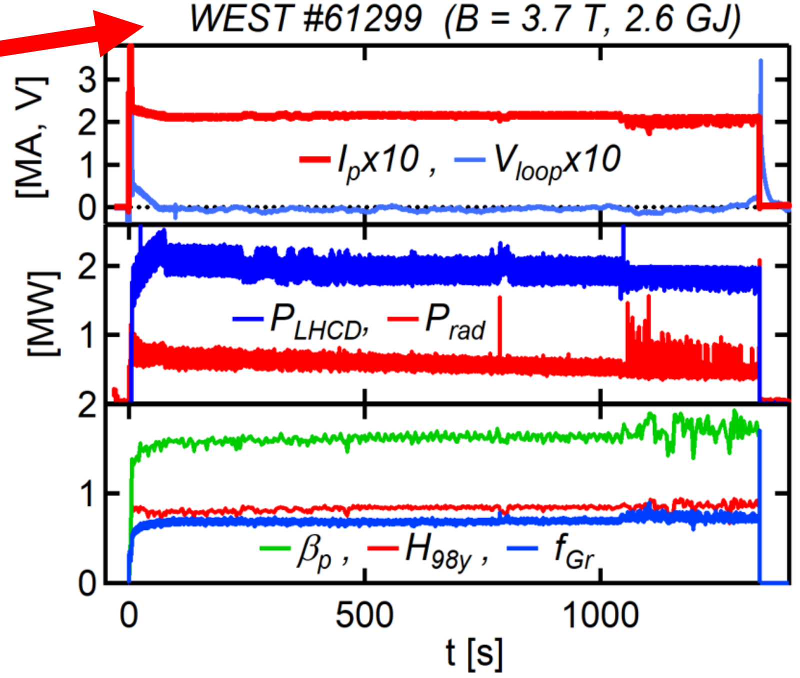

*T. Fonghetti et al., Nuc fus 2025*



# Long pulses developed in WEST in 2024-25




**Record tokamak pulse of 22min!**

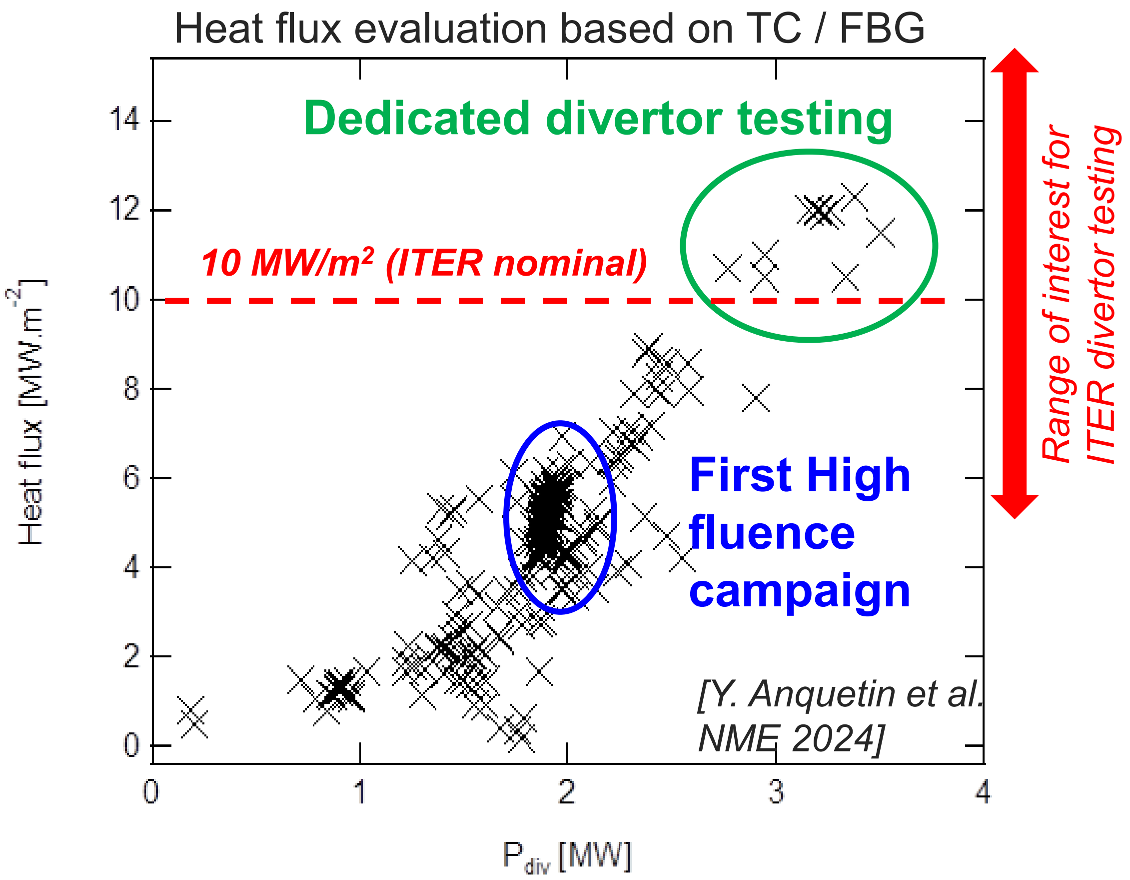
- Operated with double feedback control ( $V_{loop}$ , CS voltage) + ($I_P$ , $P_{LH}$)
- Outgassing observed after 700-800s when using more than 2 MW (2 launchers)
- With one LH launcher, discharges could be extended beyond 1000s

*R. Dumont et al. EX-C 3420*

# Outline – Reports on the key achievements of the past two years

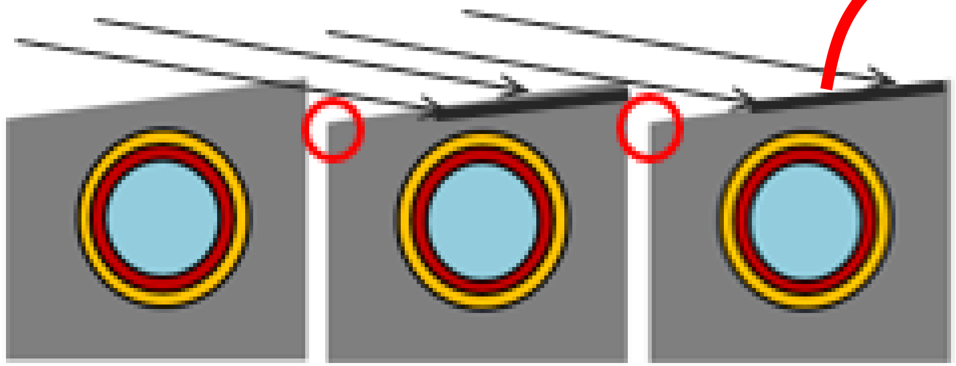
1. **The making of long pulses**
2. **Impact of long pulse on ITER grade W divertor under high power and particle flux**
3. **Plasma Exhaust scenario for limiting erosion: X-point Radiator (XPR)**
4. **Additional contributions to the new ITER baseline (W first wall)**
5. **Summary & Prospects for WEST**

# WEST provides ITER relevant heat flux / particle fluence

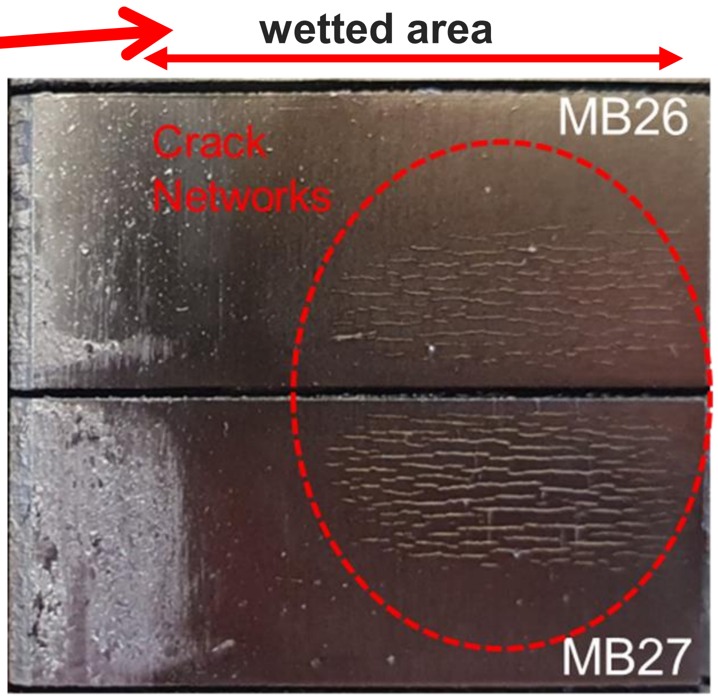



- WEST provides **high peak heat flux** for divertor testing
- Heat flux in the ITER range routinely achieved in WEST in **steady-state up to 12 MW/m²**
- **High fluence campaign:** repetitive long pulses of 60s during one month of operation.
- Large number of transients recorded (> 2400 disruptions)

# Cracks observed on top surface of beveled monoBlocks



**Toroidal bevel (ITER) :**
**no cracks on protected leading edges**



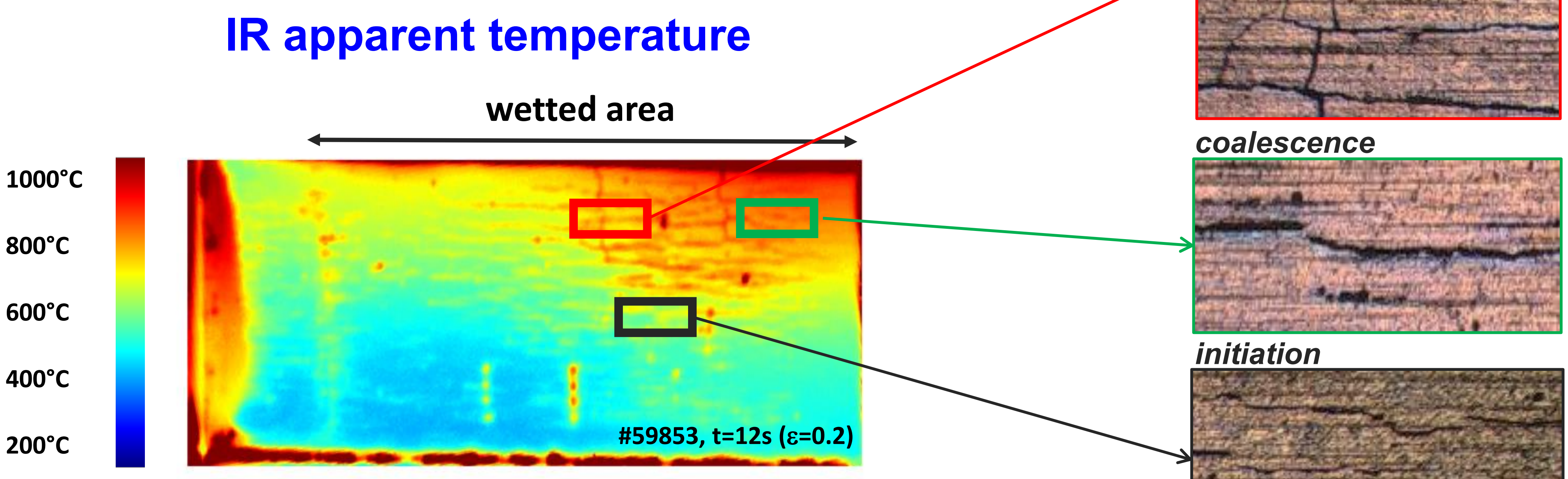

*M. Diez et al, NME 2024*
*A. Ekedahl et al, SOFT 2024*

Crack networks on top surface of the outer strike point MBs (from MB#26 to #29):

- Visible after first phase 2 campaign with beveled mono-blocks although mild heat flux (5h 30min of plasma, heat flux ~5 MW/m$^2$)
- Most pronounced on MB27 (not most usual strike point location)

**➔ No degradation of heat removal capability so far (18 hours of plasma, ~3000 pulses)**

# Top surface crack formation under investigation



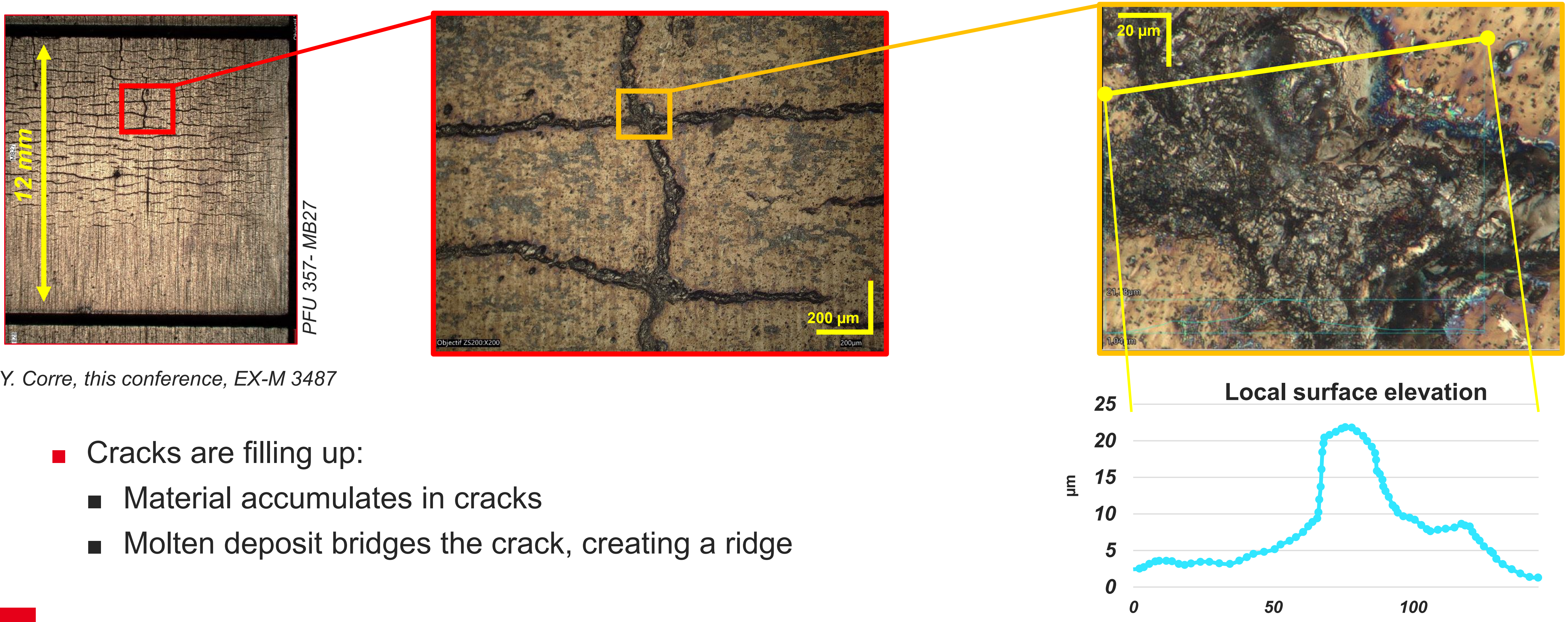

**Cracks visible « in-operando » with VHR IR**

*Y. Corre, this conference, EX-M 3487*

- Cracks unlikely linked to stress release from manufacturing
- **Not reproduced on pristine MB in High Heat Flux facility** in WEST-like conditions for steady state / disruption loads

# New observation: cracks are filled up with molten material

## Observation after the 2025 campaign (C11)




*Y. Corre, this conference, EX-M 3487*

- Cracks are filling up:
  - Material accumulates in cracks
  - Molten deposit bridges the crack, creating a ridge

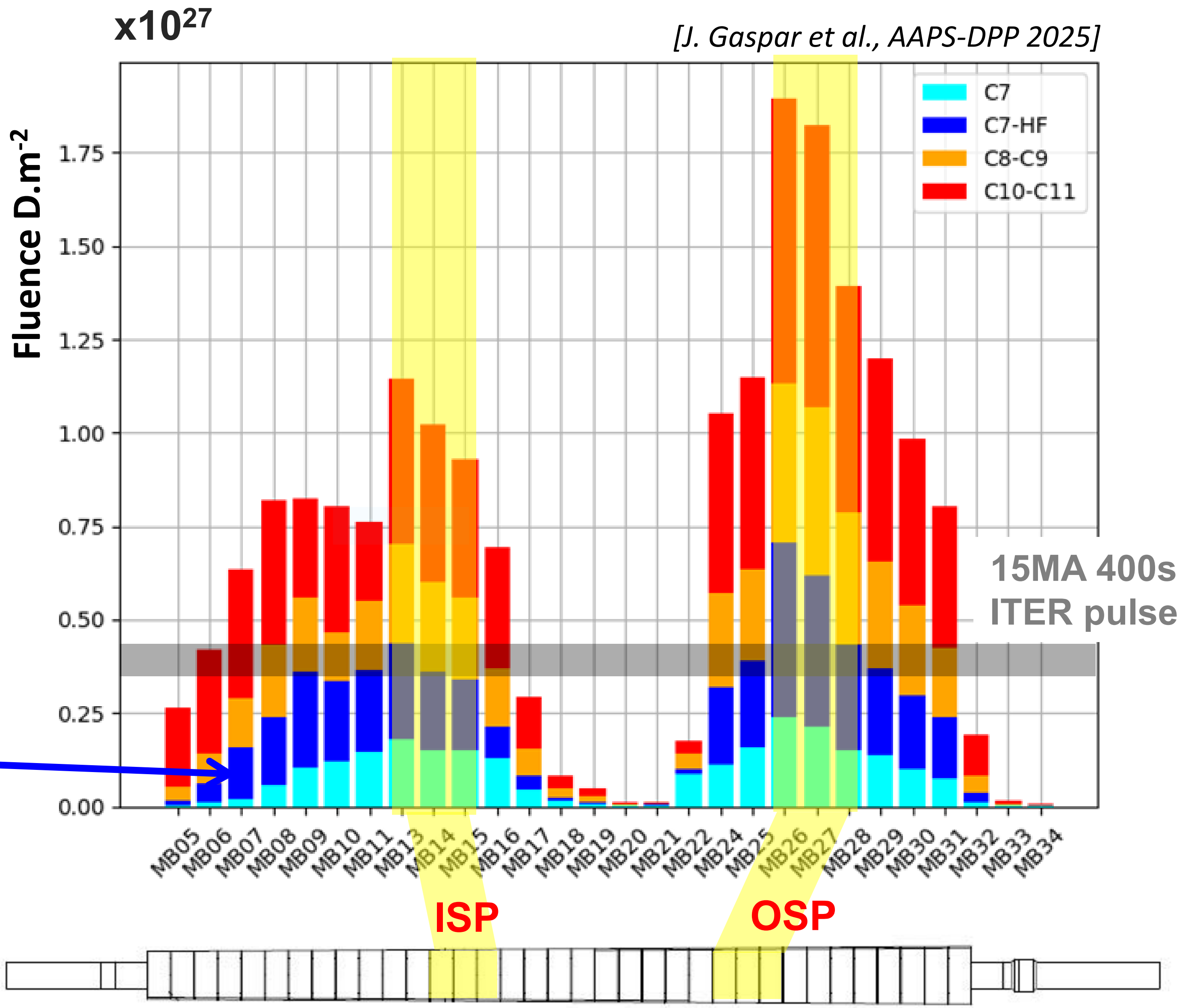
# WEST operating with relevant ITER divertor particle fluence

- > **18 hours plasma** cumulated time
- Cumulated deuterium fluence on ITER grade divertor : **1.8 $10^{27}$ D/m$^{-2}$** = a few ITER pulses

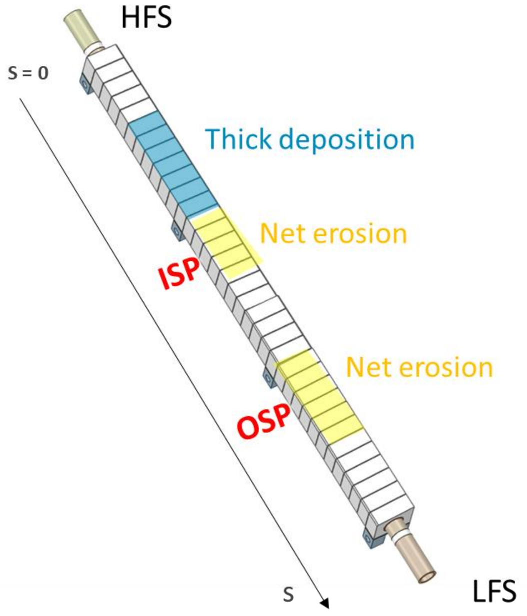
EUROfusion

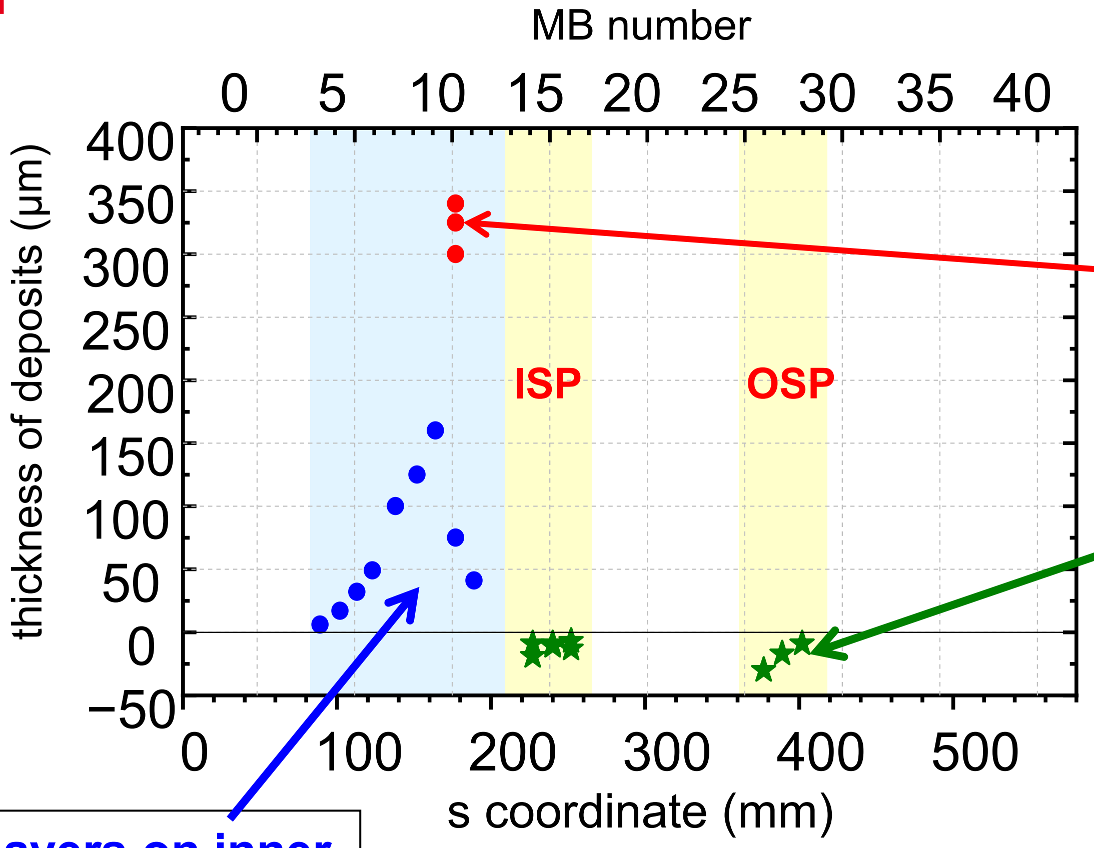
| C7 | 5h30 |
| --- | --- |
| C8-C9 | 5h45 |
| C10-C11 | 7h00 |

**Dedicated High Fluence campaign (C7) (repetitive attached discharges)**



# Significant divertor erosion / deposition after high fluence exposure




Confocal microscopy after last campaign

**Never cleaned (18h of plasma)**

**Net erosion in strike points area : up to ~25 microns**

➔ campaign integrated net erosion rate ~ 0.1-0.5 nm/s (similar to AUG)

*[M. Diez et al., PFMC 2025]*

*[M. Balden et al., , PFMC 2025]*

*[A. Hakola et al., this FEC conference]*

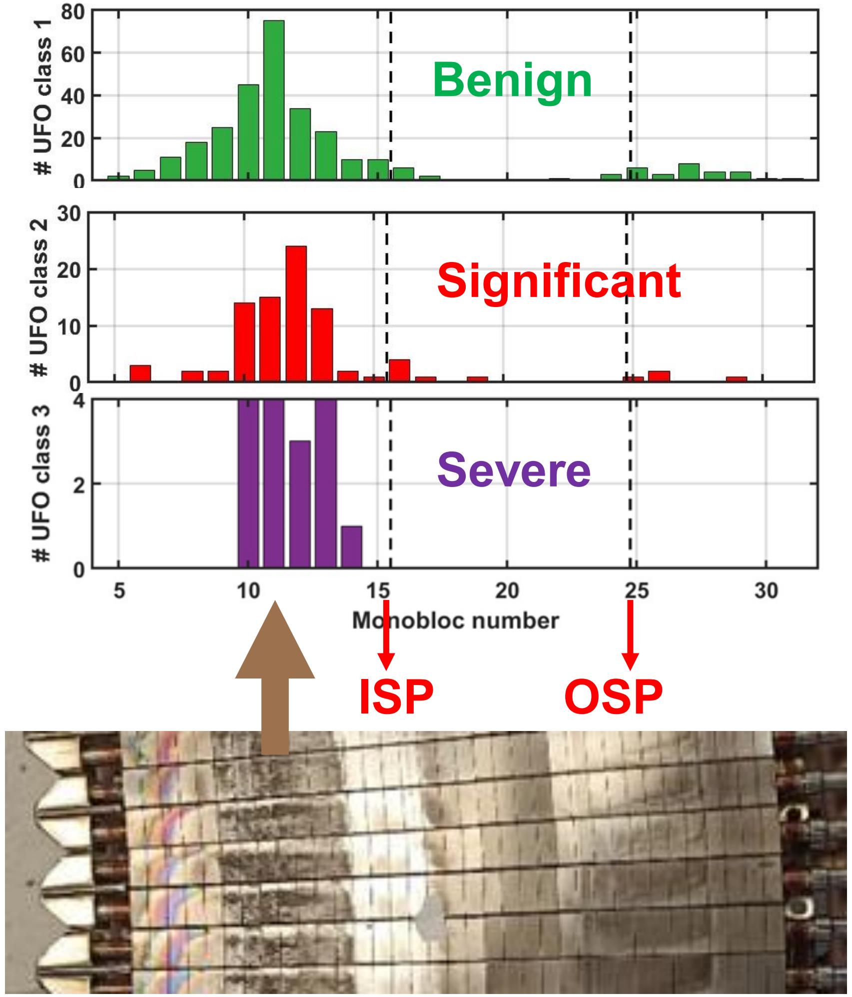
**Build up of deposited layers on inner divertor HFS : up to ~ 300 microns**

➔ Delamination of thick layers

➔ UFO hampering plasma operation

**➔ Need to mitigate W erosion but also deposition when running long pulses**

# Events (UFOs) observed with progressive higher frequency & impact during high fluence campaign

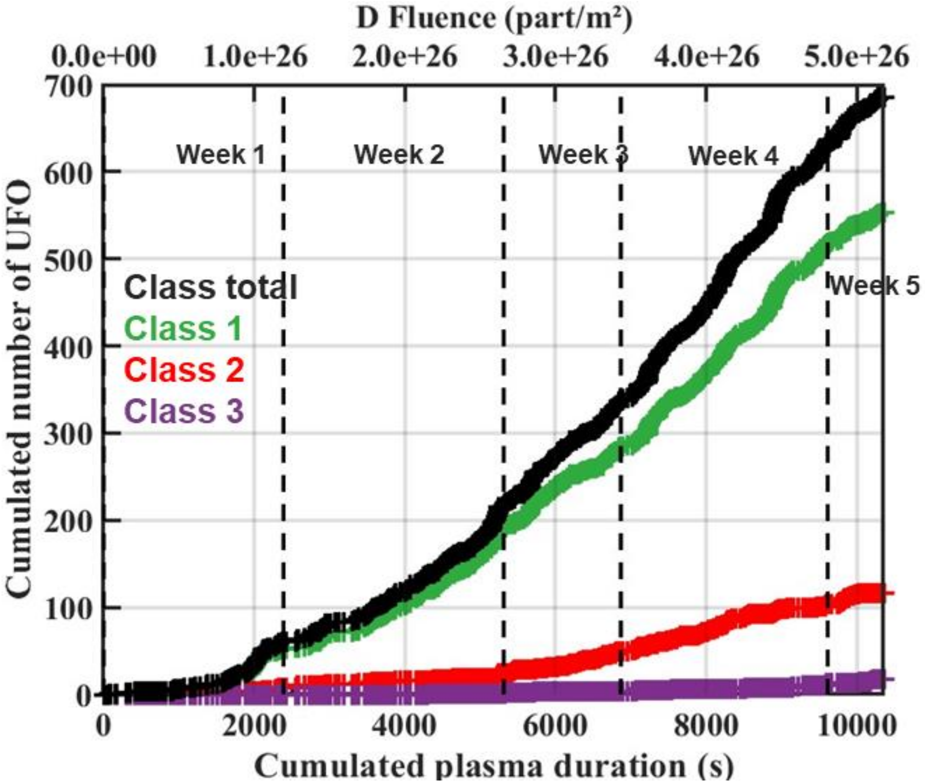



**Class 1: benign impact**

**Class 2: high radiation leading to disruption**

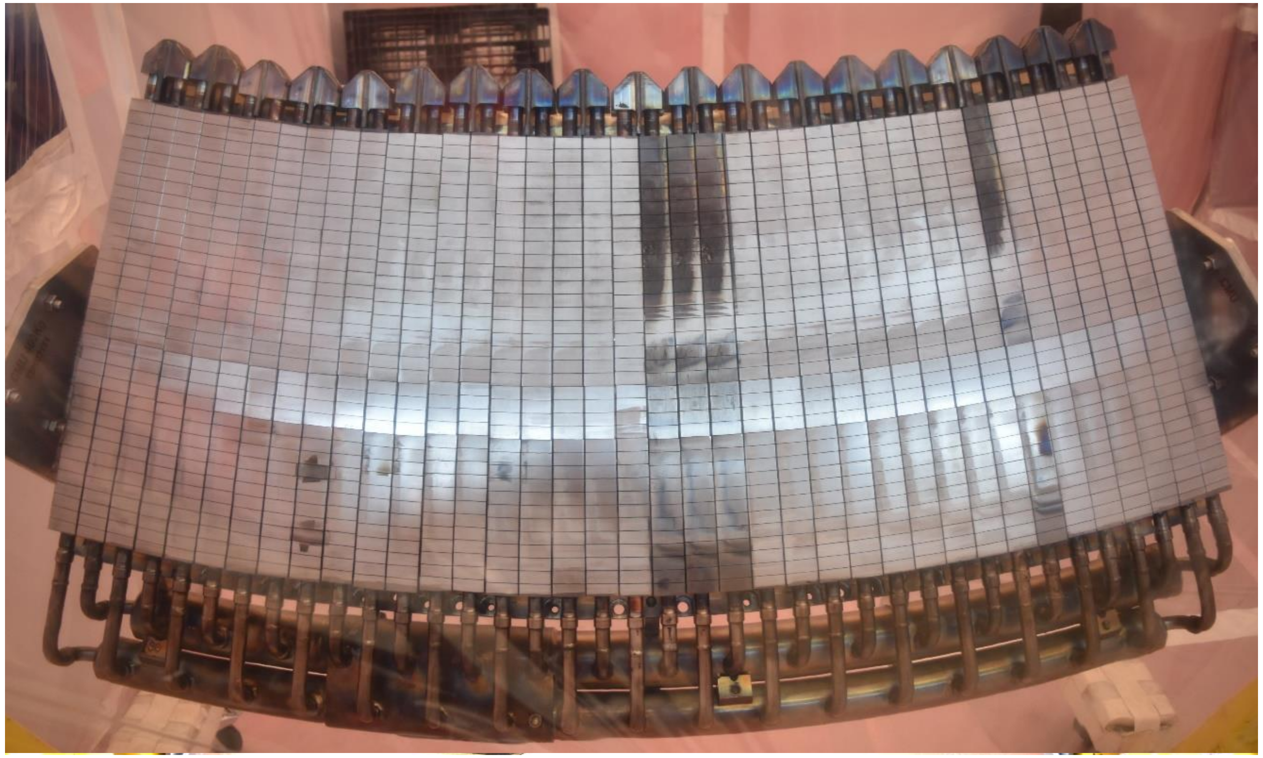
**Class 3: immediate disruption**

*J. Gaspar et al., NME 2024*
*P. Maget et al., EPS 2025*




- **UFOs** Frequency / impact **growing with time**
- Flakes originating mostly from deposited layers on HFS
- Observed cumulated mass entering the plasma reaches **15mg of W after a fluence of $5.10^{26}$ part/m$^2$**

# Laser cleaning technique developed to remove deposited layers in situ



*M. Firdaouss (in preparation) & J. Gerardin et al, NME 2024*

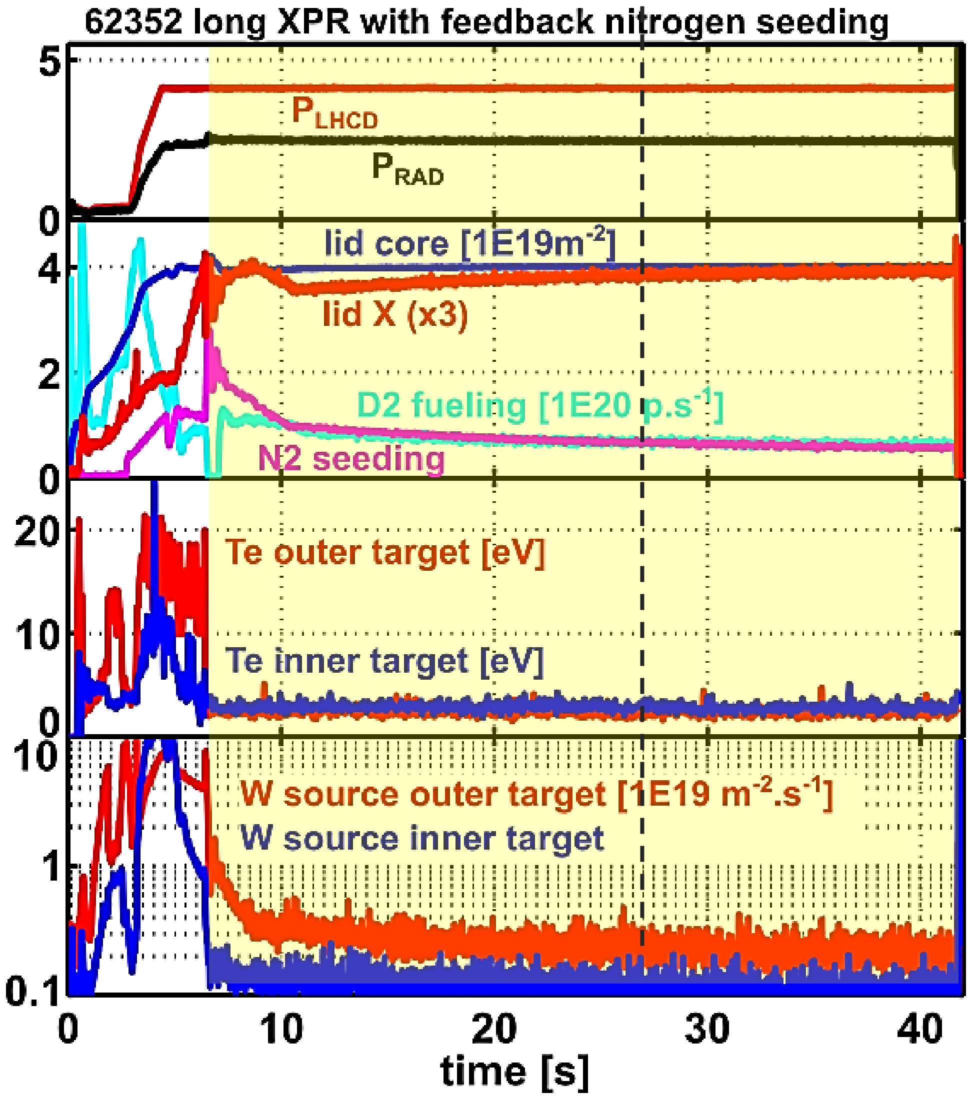
Plasma generated by laser interaction with the deposit – vapour and dust generated are pumped out

**➔ 190g of dust were collected by laser cleaning: consistent with 25µm of eroded W**

# Outline – Reports on the key achievements of the past two years

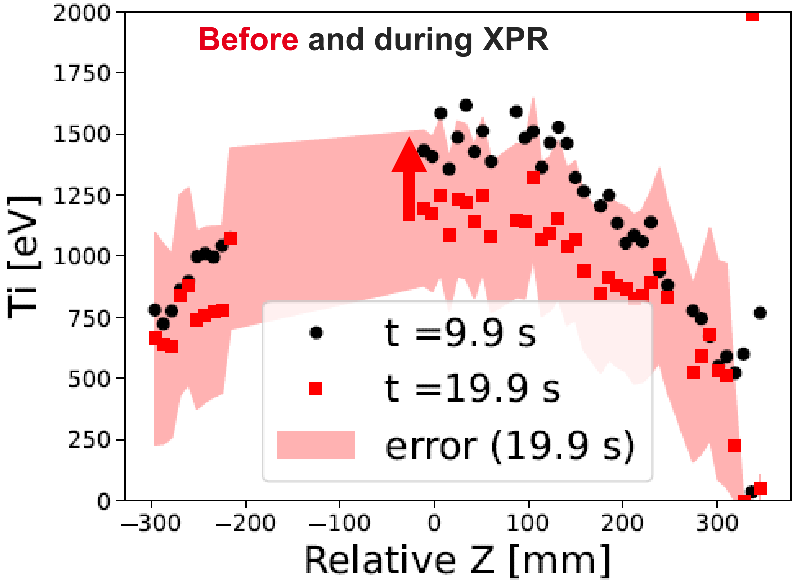
1. **The making of long pulses**
2. **Impact of long pulse on ITER grade W divertor under high power and particle flux**
3. **Plasma Exhaust scenario for limiting erosion: X-point Radiator (XPR)**
4. **Additional contributions to the new ITER baseline (W first wall)**
5. **Summary & Prospects for WEST**

# XPR regime extended to 35s in WEST




- **4MW of Lower Hybrid coupled** successfully
- **Line density through the divertor** used for controlling **$N_2$ seeding** in real time
- $T_e$ from Langmuir probes below 5 eV in both **inner** and **outer** targets
- W sources reduced by two order of magnitudes on both **inner** and **outer** targets

**XPR: increase of confinement and ion temperature**



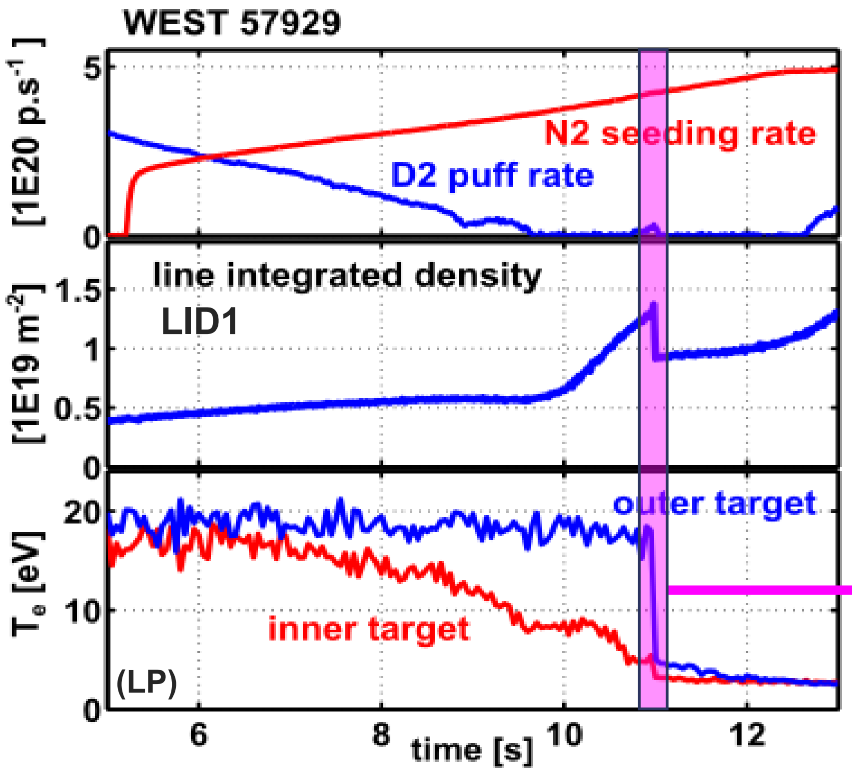

*P. Forestier-Colleoni et al. in preparation, 2025*

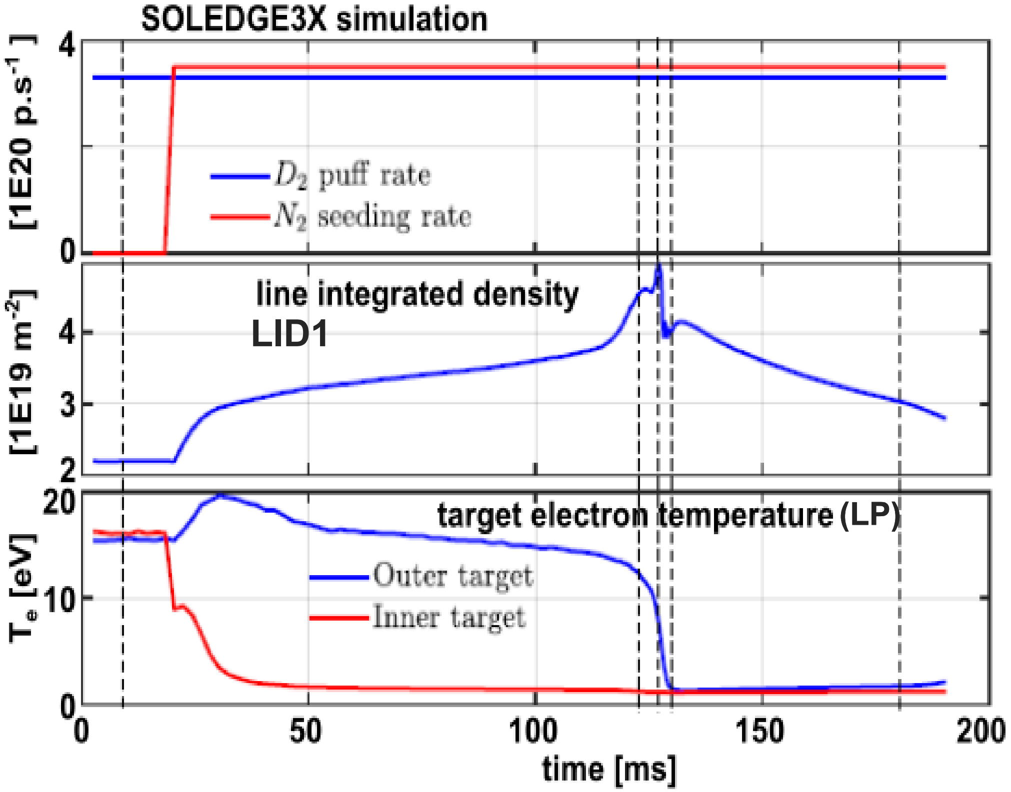
*N. Fedorczak et la., EPS 2025*

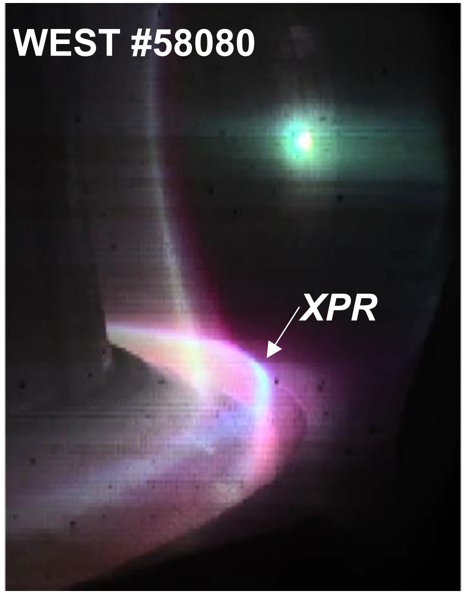
*N. Rivals et al., NME 2024*

**➔ Next high fluence campaign planned in fall 2025 using the XPR scenario**

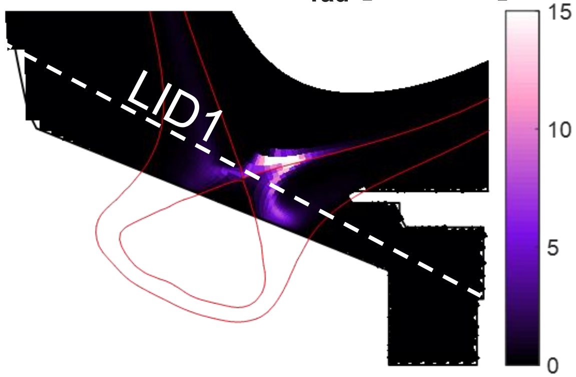
# SOLEDGE recovers $T_e$ cliff and high radiation region above the X-point




SOLEDGE3X $P_{rad}$ [MW/m$^3$]

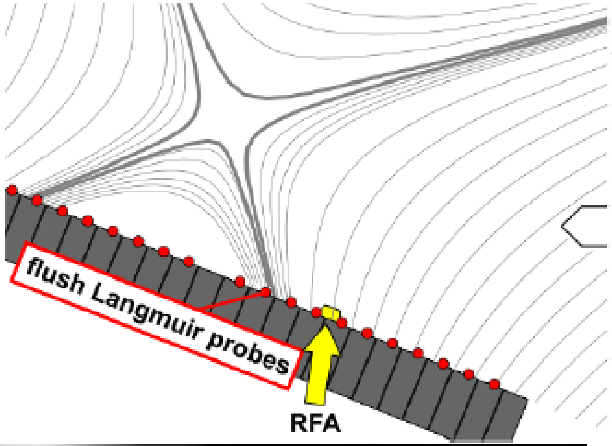


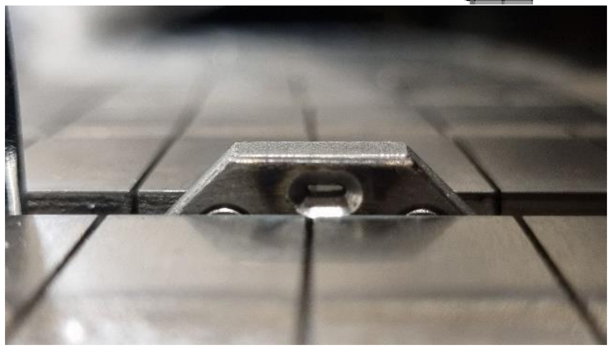

- Transition to XPR modelled with SOLEDGE with drifts included (required)
- Sharp cooling at outer target ($T_e$ cliff) reproduced
- Langmuir Probe ($T_e$) measurements qualitatively reproduced.

*N. Rivals et al, this conference EX-D 3067*

# Divertor ion temperature, a key player for erosion / heat flux in scenario

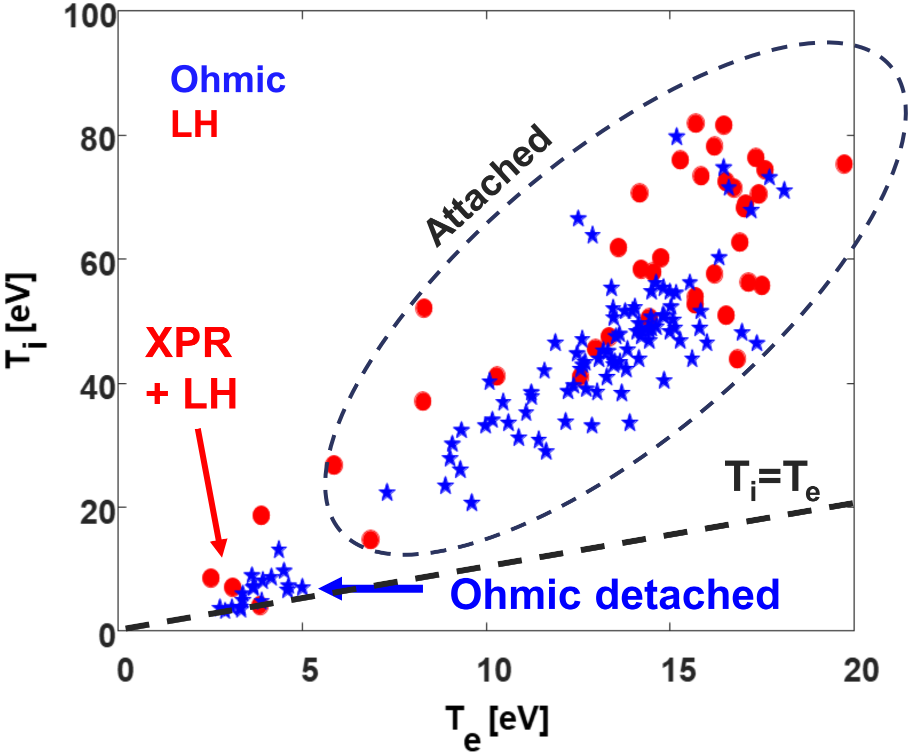
**Ion temperature from the new retarding field analyser (RFA)**

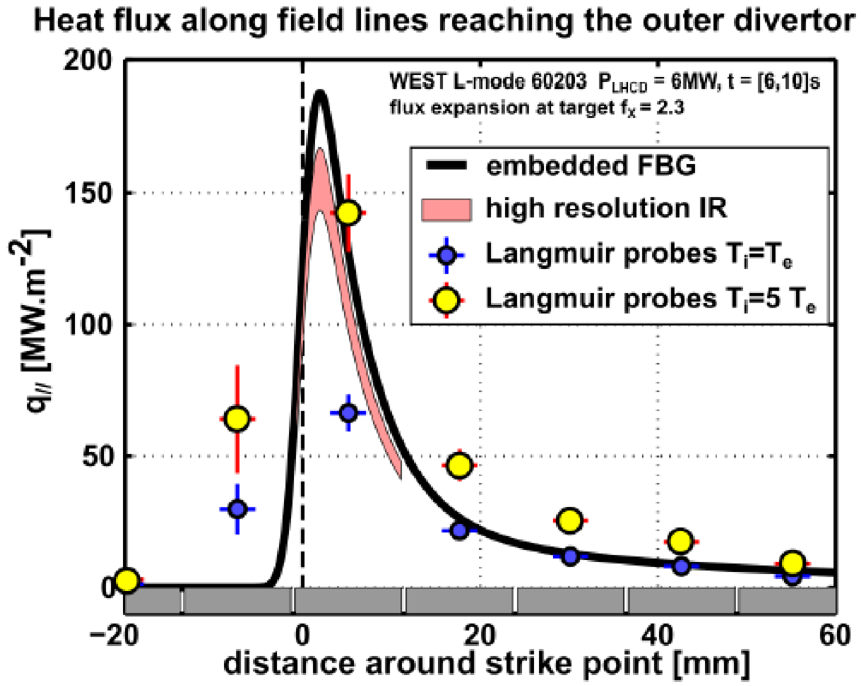


**Retarding Field Analyser divertor**

*[J. Gaspar et al., AAPS-DPP 2025]*




*[P. Ivanova, J. P. Gunn]*

| | $T_i$ | $T_e$ | $T_i/T_e$ |
|---|---|---|---|
| Conventional scenario | 100eV | 20eV | 3-6 |
| Dissipative scenario | 10eV | 5eV | 1-2 |

**➔ High $T_i$ consistent with high resolution IR camera measurements**

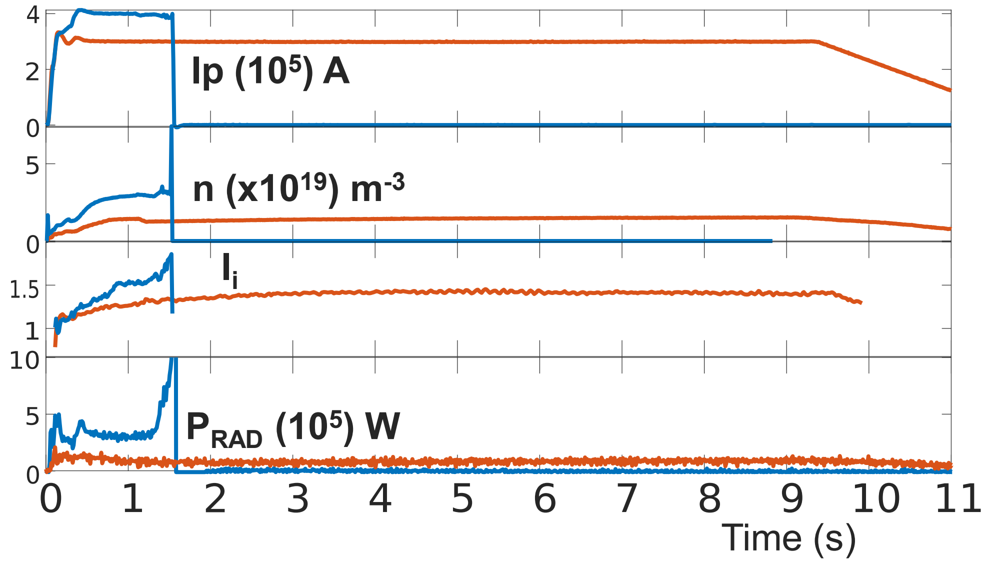
# Outline – Reports on the key achievements of the past two years

1. **The making of long pulses**
2. **Impact of long pulse on ITER grade W divertor under high power and particle flux**
3. **Plasma Exhaust scenario for limiting erosion: X-point Radiator (XPR)**
4. **Additional contributions to the new ITER baseline (W first wall)**
5. **Summary & Prospects for WEST**

# Robust plasma start-up enabled with non uniform boronization

ITER SRO plans non-uniform boronization ➔ tested in WEST and AUG after vent

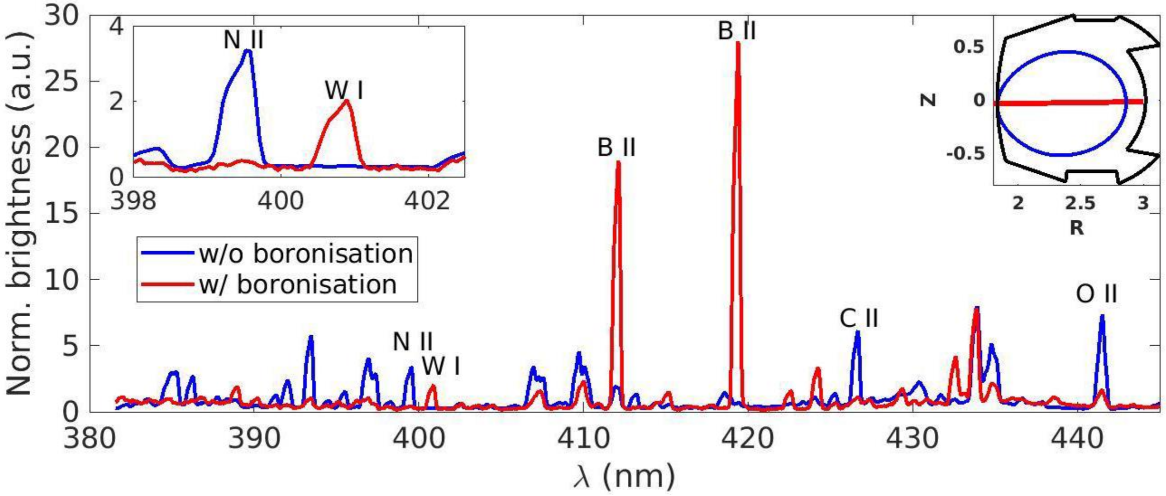
60496 / 60527: before / after boronization

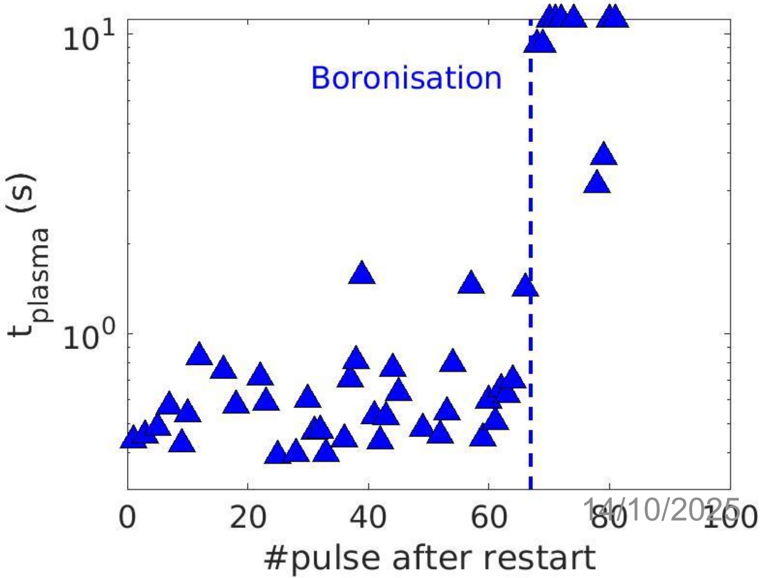



*(consistent with ASDEX upgrade observations)*

*P. Manas et al, EPS 2025.*
*J. Hobirk, this conference EX-C-3308*

Visible spectrum



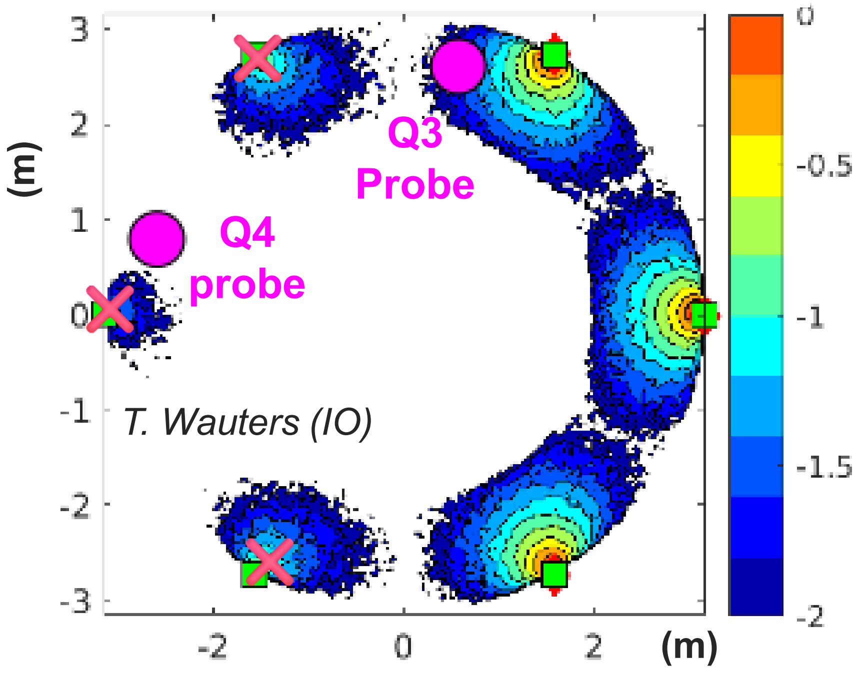



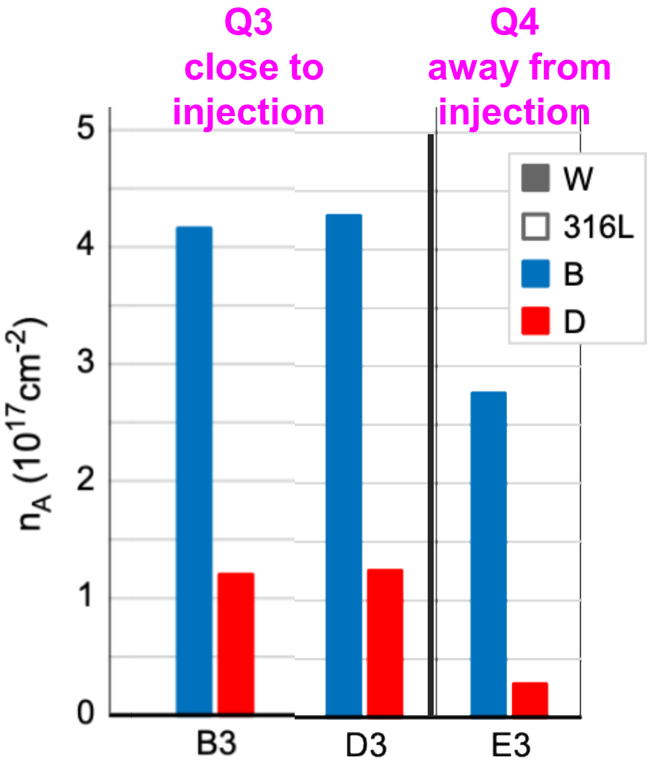

**➔ Start-up dramatically improved after non-uniform boronization in WEST**

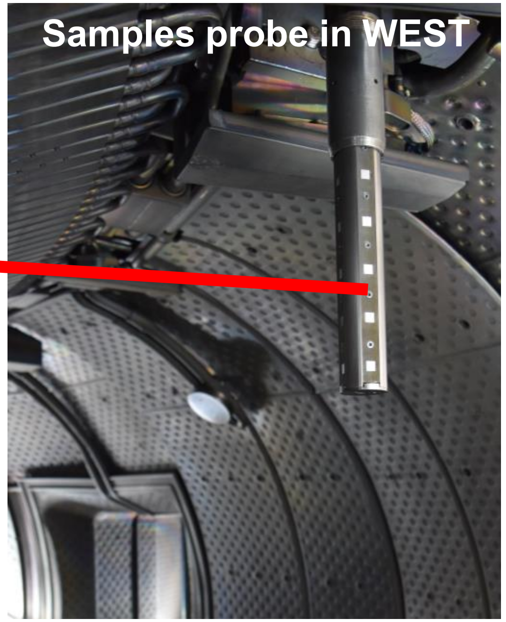
# Impact of non uniform boronization on B deposition

- Non-uniform boronization tested in WEST with half of diborane injection points active (3 out of 6)
- Probe with samples (W, 316 L steel) exposed to GDB in 2 locations : close and away from injection points
- Preliminary modelling predicts strong asymmetry in Boron deposition for non uniform GDB

**Diborane dissociation / ionisation map for non uniform GDB**




*K. Krieger et al., AAPPS-DPP 2025*

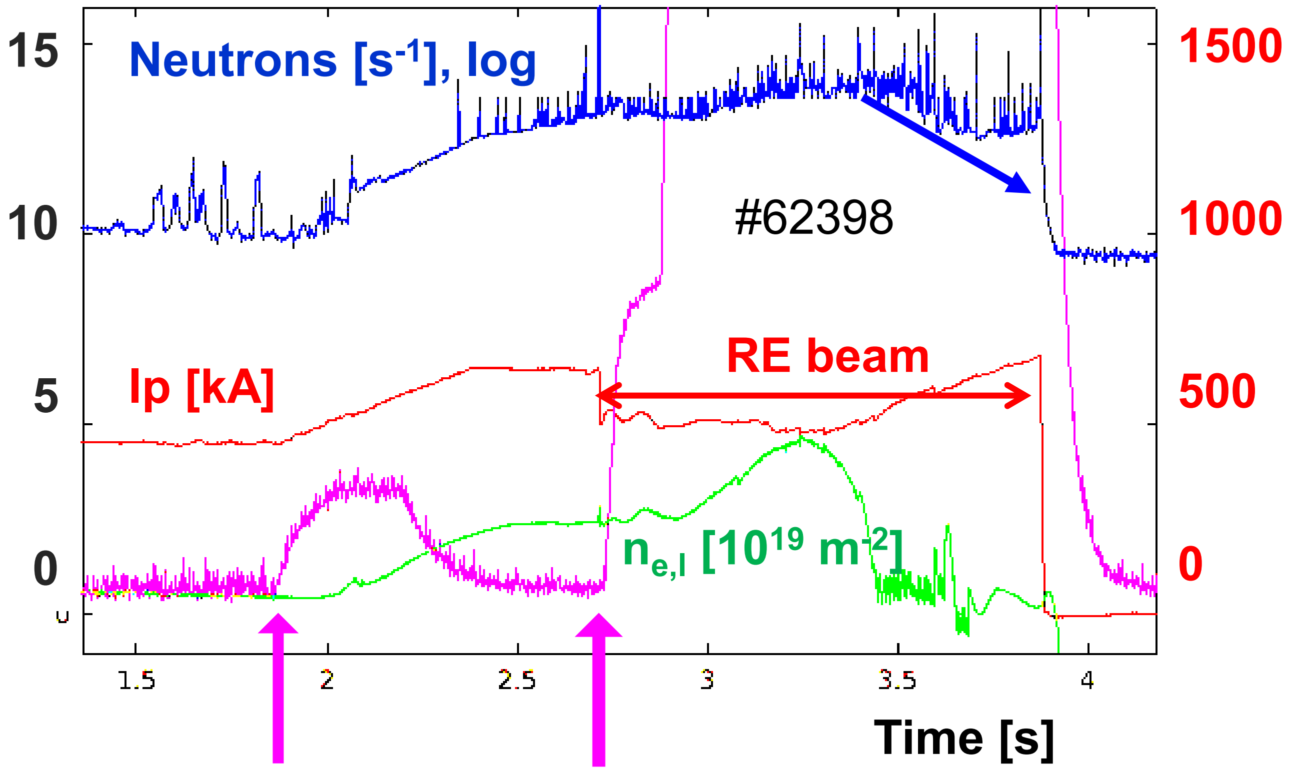
*E. Geulin, et al this conference EX-M 3072*

- B deposition lower away from injection points, but 40% asymmetry only in contrast to modelling

**➔ New insight for improving GDB modelling for ITER**

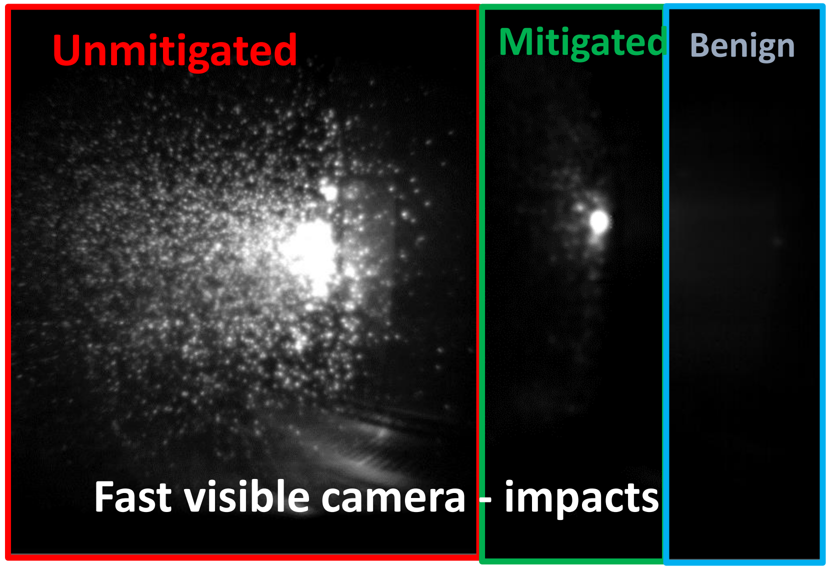
# RE benign termination confirmed on WEST

Reproducible controlled run-away beam achieved up to 1.2s




Argon injection to generate the RE beam

D2 injection to mitigate the RE beam




*C. Reux, in preparation*

**$D_2$ mitigation behaves as on other tokamaks:**

- Companion plasma recombination
- Current increases due to lower resistivity
- Neutron flux decreases
- Lower heat loads at impact

**➔ Diagnosed by REIS, fast IR camera, HXR, fast visible & IR camera + impact damage**

# Outline – Reports on the key achievements of the past two years

1. **The making of long pulses**
2. **Impact of long pulse on ITER grade W divertor under high power and particle flux**
3. **Plasma Exhaust scenario for limiting erosion: X-point Radiator (XPR)**
4. **Additional contributions to the new ITER baseline (W first wall)**
5. **Summary & Prospects for WEST**

# Summary

- In the past 2 years WEST has developed **long pulses operation on a routine basis** and tested ITER grade components with particle fluence and heat load approaching those of ITER

- ITER grade **components have been tested up to 12MW/$m^2$** and cracks have been observed and are currently being studied. Cracks do not seem to cause any operation consequences so far.

- Analyses show an **erosion of 0.1 to 0.5nm/s** at the strike point, but a **redeposition area** on the high field side which generates UFOs hampering plasma operation.

- The **XPR regime of operation has been extended to 34s** using real time control and physics understanding has been gained using SOLEDGE including drifts. Next programme will develop even longer pulses for high fluence experiments in XPR regime conditions.

- In support of the new ITER baseline, **non-uniform boronisation has been tested** and is efficient for plasma start-up. In contrast to preliminary modelling, non uniform boronization has an impact away from the diborane injection points.

- **New run-away experiments** (up to 0.5s of RE beam) confirms RE mitigation by $D_2$ injection and is now addressing component damage in support of ITER.

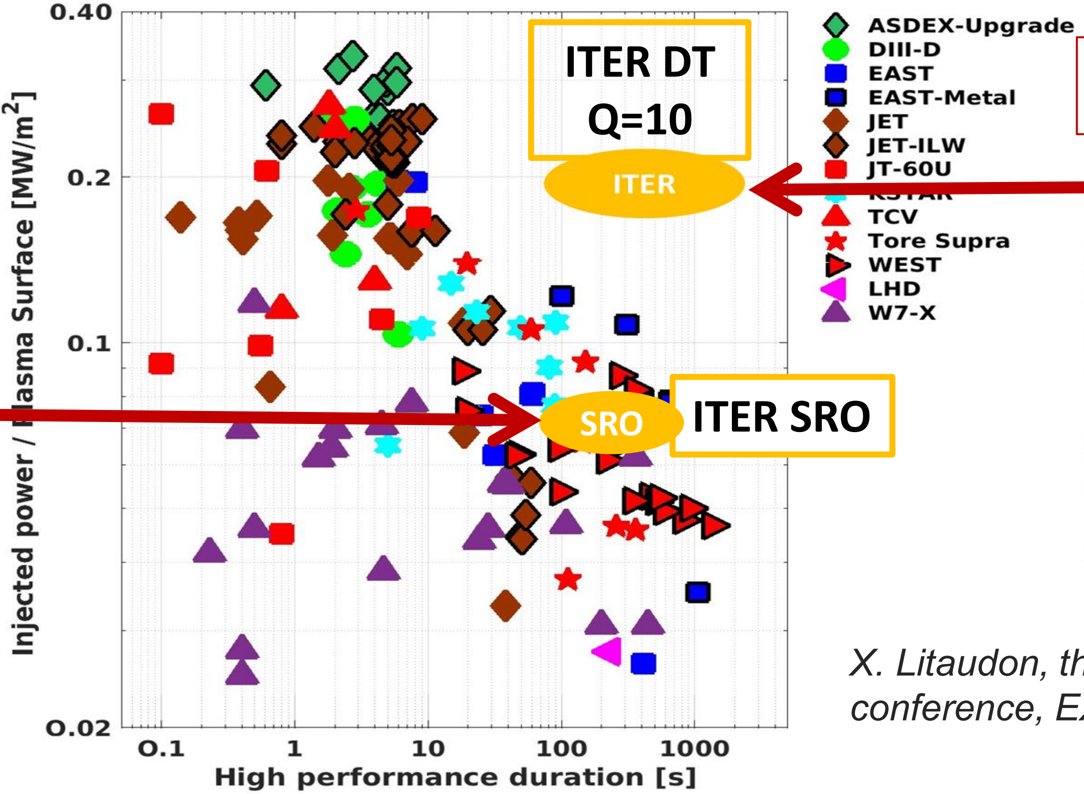
# Next WEST phase: high power exhaust over ITER relevant pulse duration

**Power & heat exaust increase:**

- ECRH system (3MW in 2026)
- New TWA ICRH antenna (2027)
- New ITER-like W First Wall (2028)

- Better core W control
- Control of kinetic and current profiles
- Long pulse operation in H-mode regime
- Higher heat loads & particle fluences

WEST Phase 2 (now)


WEST Phase 3 (2028+)


*X. Litaudon, this conference, EX-H 2770*

# WEST contributions

## ORAL contributions

### Wednesday 15th:

- **H. Bufferand** et al, HIERARCHY OF TURBULENT TRANSPORT MODELS WITH THE SOLEDGE3X CODE, TH-P 3411

### Thursday 16th:

- **V. Lamaison** et al, WEST OPERATION – RELIABILITY AND AVAILABILITY OF A LONG PULSE FUSION TOKAMAK, TEC-FNT 3448
- **M. Richou** et al. ACTIVELY COOLED PLASMA FACING COMPONENTS DESIGN FOR W7-X AND JT-60SA IN SUPPORT OF THE ITER DIVERTOR, TEC-IVC 3450
- **R. Dumont** et al, WEST LONG-PULSE ACHIEVEMENTS IN SUPPORT OF NEXT-STEP FUSION DEVICES, EX-C 3420

### Friday 17th:

- **E. Bernard** et al, ANTICIPATING TRITIUM IMPACT AND TRANSFER IN FISSION AND FUSION POWERPLANTS, TEC-T 2934
- **Y. Corre** et al, TESTING TUNGSTEN PLASMA FACING COMPONENTS IN WEST AND AUG TOKAMAKS : LESSONS FOR ITER

## POSTER contributions

### Wednesday 15th:

- **N. Rivals** et al, The X-Point Radiator regime in the WEST tokamak for divertor operation in next step fusion devices, P2-3067
- R. Guirlet et al., (presented by P. Manas), Determination of tungsten characteristics in WEST by means of UV emission and articficial intelligence, P1-2746
- **Y. Peysson** et al, On the selfconsistency between ray-tracing/Fokker-Planck and the toroidal MHD equilibrium for the Lower Hybrid current drive, P2-2743

### Thursday 16th:

- **S. Mazzi** et al, How MeV-range ions and high $\beta$ will shape the core plasma dynamics of fusion power plants, P3-2747
- **P. Manas** et al, Breaking of the ion temperature clamping in electron heated plasmas with turbulence stabilization P3-2929
- **X. Litaudon** et al, Investigating long duration plasma operation with the international multi-machine database P4-2770

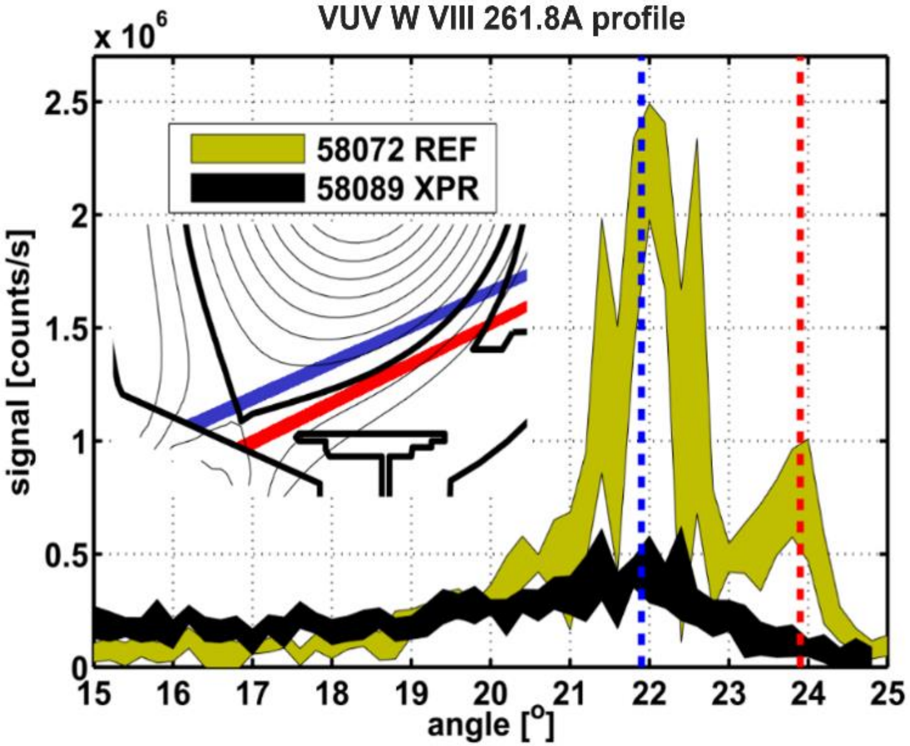
### Saturday 18th:

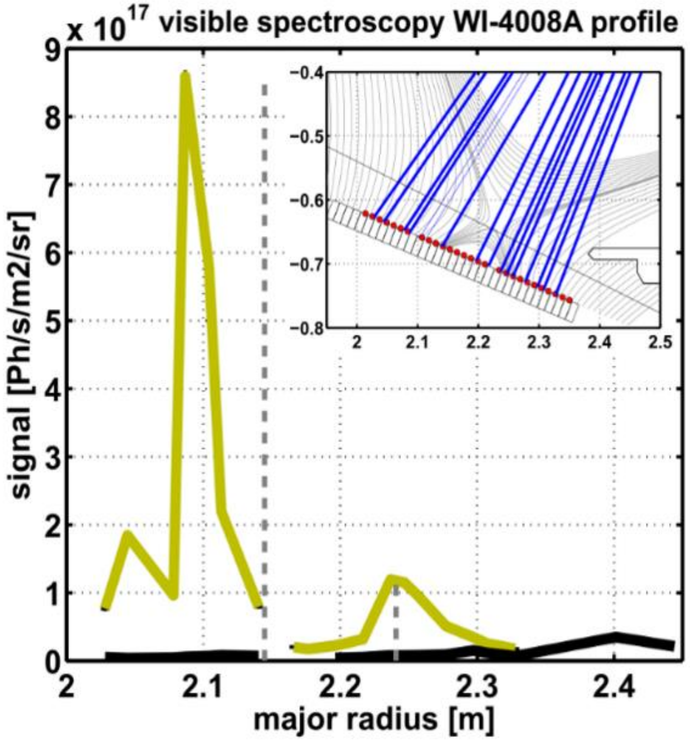
- **E. Geulin** et al, WEST wall conditioning with boron: lessons for ITER and fusion power plants, P7-3072
- **R. Mitteau** et al. WEST advanced wall protection achievements toward long pulse operation P7-3049
- **A. Hakola** et al, Material migration and erosion of plasma-facing components in the full-tungsten WEST tokamak during its Phase 1 and Phase 2 operations, P7-2788
- **C. Wan et al.,** Estimation of plasma parameters based on discharge settings on WEST, P6-2841
- **D. Mazon et al.,** Overview of the WEST-ITER diagnostic instrumentation (WDIA) collaboration activities, P6-3525

# Thank you for your attention

# XPR regime helps in minimizing erosion

**VUV and visible spectroscopy (W7+ and W0) of tungsten in the divertor shows strong reduction of signal in the XPR phase.**




- Divertor particle flux similar to standard scenarios
- But cold & non eroding divertor conditions