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Tungsten wall compatibility in long pulse operation : Overview of WEST achievements and lessons learnt for ITER.

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Tungsten wall compatibility in long pulse operation: Overview of WEST achievements and lessons learnt for ITER.

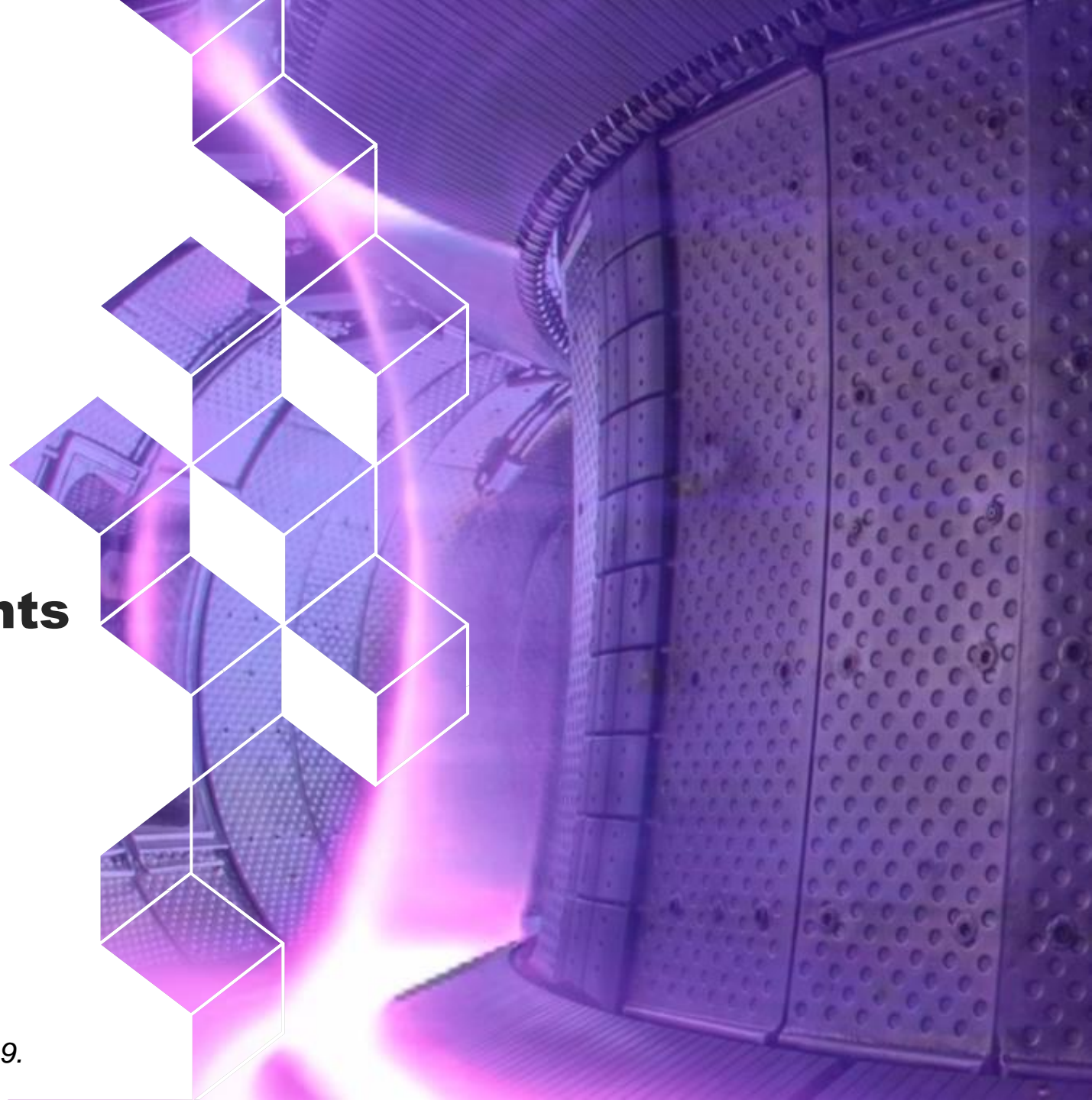
G. Ciraolo and the WEST[#] team and the EUROfusion Tokamak Exploitation Team^{##}

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

Special thanks to R. Dumont, N. Fedorczak and H. Yang

[#]See <http://west.cea.fr/WESTteam>

^{##}See the authorlist of E. Joffrin et al 2024 Nucl. Fusion 64 112019.





irfm

West

<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.”

Outline

- 1. Long pulse operation in WEST: requirements, preparation and achievements**
- 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)**
 - **Experimental results**
 - **Interpretative modeling with SOLEDGE3X-EIRENE**
- 4. Summary & Prospects for WEST**

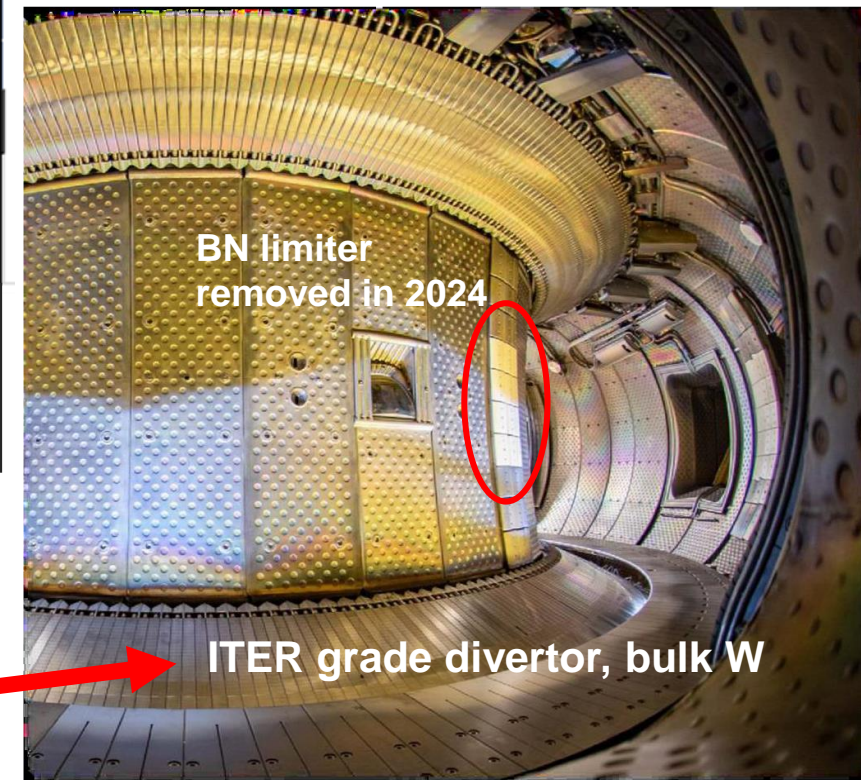


Since 2023, WEST has cumulated just over 18 hours of plasma on ITER grade PFCs

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			
				5h30				5h45				7h00			
Cumulated plasma time															

WEST « phase 2 » configuration

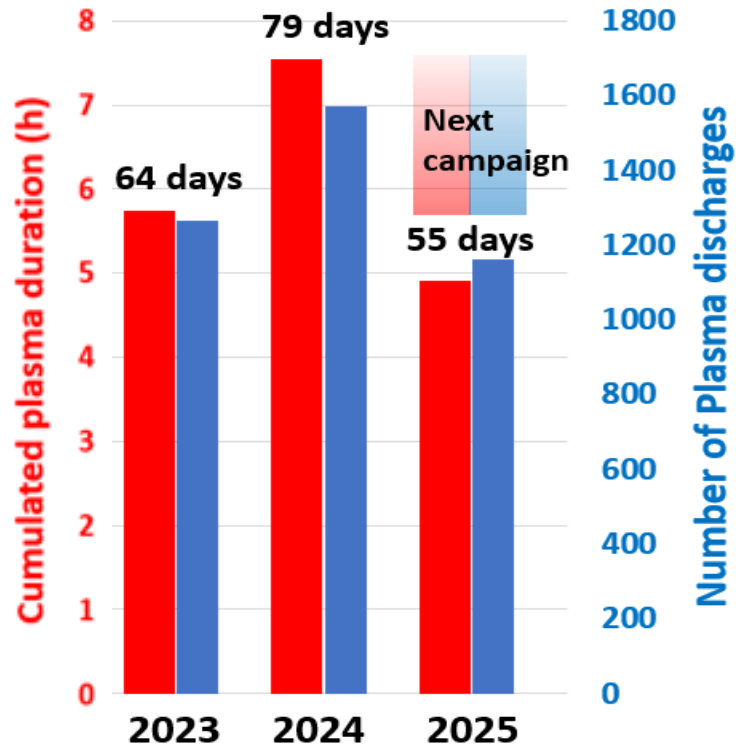


Boron-Nitride limiters removed in 2024 (after C9) to study the **ITER new W First Wall baseline configuration**



M. Missirlian et al., FED, 2023

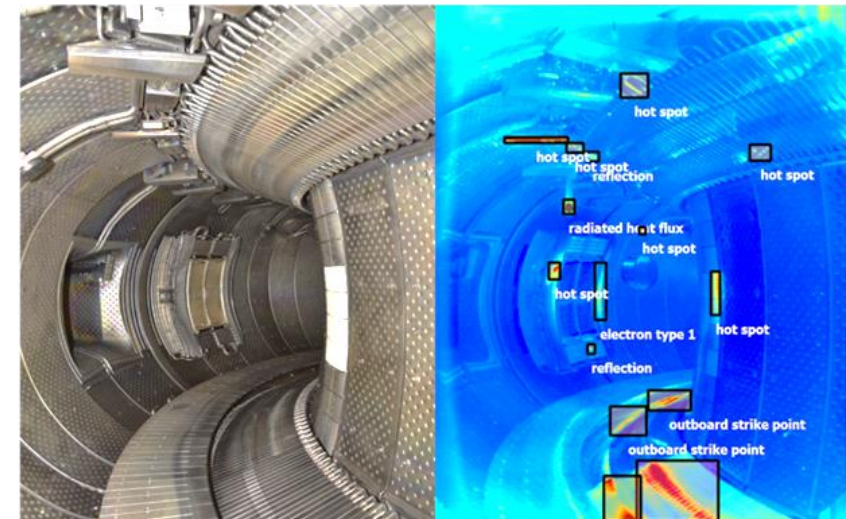
WEST structured and effective for long pulse operation




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

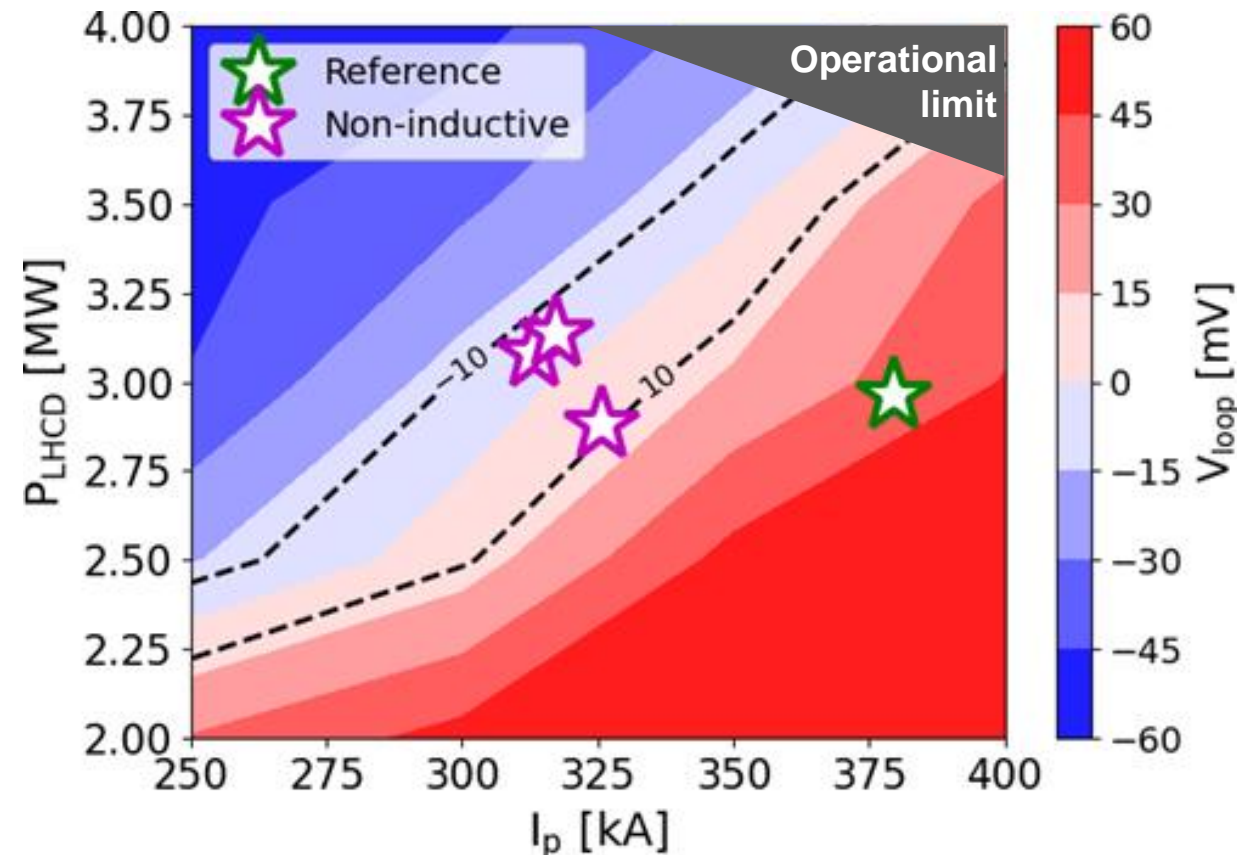
The cumulative plasma duration per year: **7.5 hours in 2024**
Machine availability on experimental days: **75 % in 2023-2025**



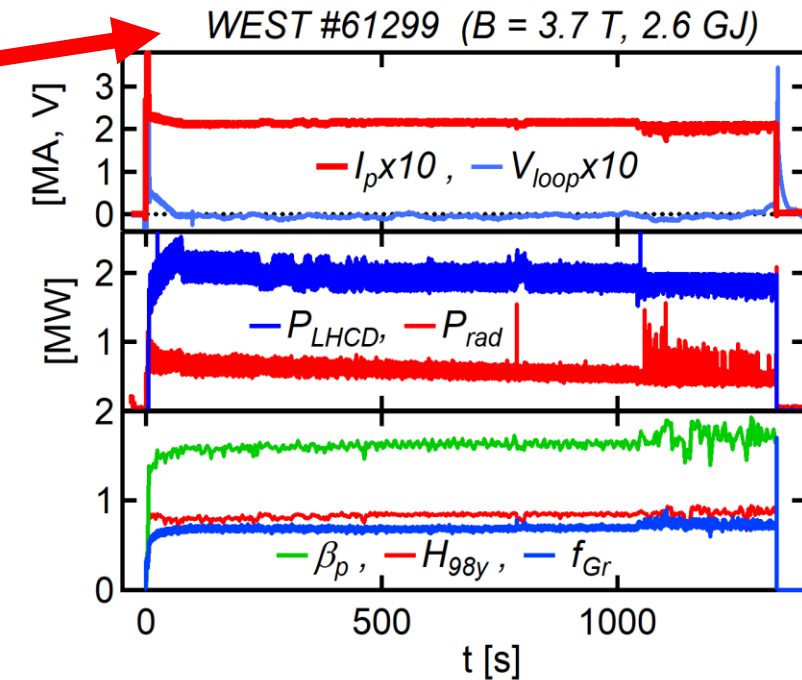
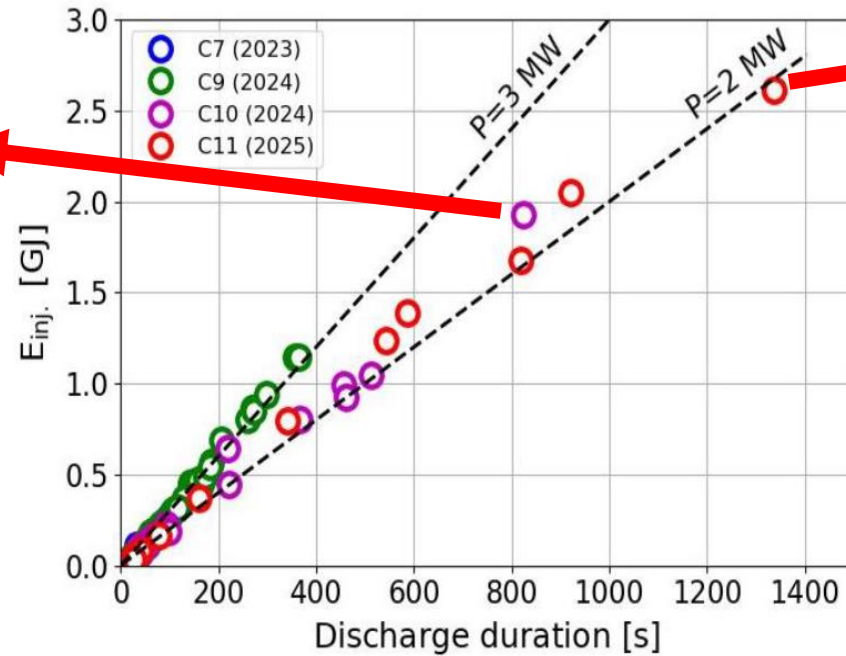
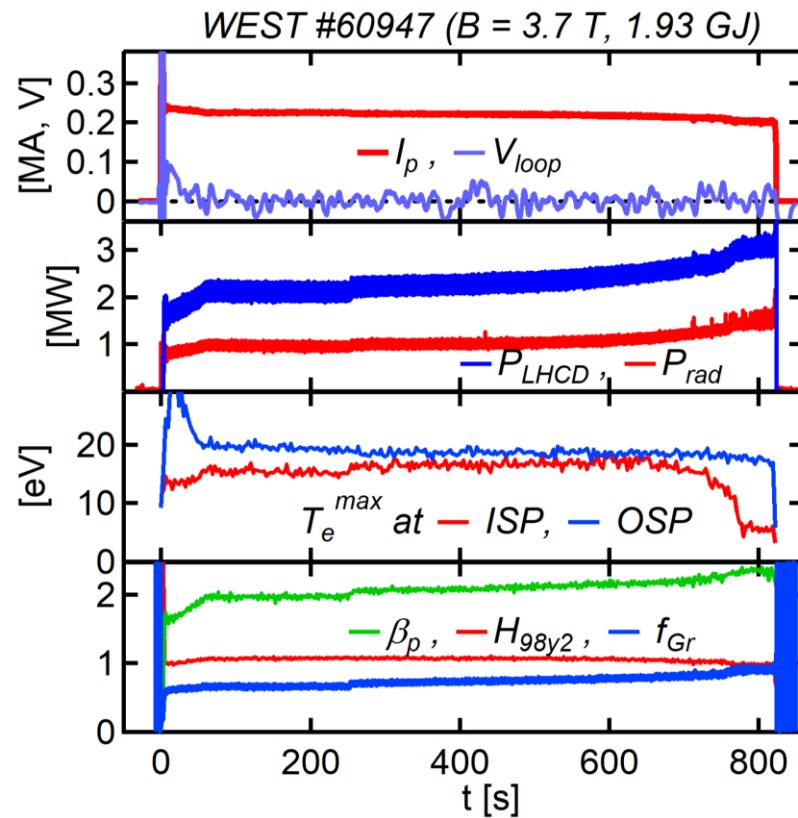
WEST non-inductive domain predicted first by modelling before the experiments

- Fully non-inductive discharges → complex non-linearities, especially in W environments (current profile, power source, heat and particle transport...)
- High Fidelity Pulse Simulator (HFPS) based on JINTRAC/JETTO employed  EUROfusion
 - Simplified model used for LHCD deposition profile [Dumont, PoP 2000], with experimental scaling law for current drive efficiency: $\eta_{\text{LH}} \propto \tau_{\text{E}}^{0.4}$ [Goniche, AIP proc. 2005]
 - TGLF-sat2 model for turbulent transport [Staebler, PPCF 2020; Angioni, NF 2022]
- Additional elements, with strong impact on available parameter space:
 - Superthermal electron losses → heating of cooling pipes
 - Occurrence of q-profile reversal typical of LHCD plasmas
- Predict-first modelling strategy → operational domain
 - Reference pulse from 2023 (57757, 101 s, $V_{\text{loop}}=47$ mV) for thorough code validation
 - Predictive HFPS simulations to identify parameter domain adequate for non inductive operation [Fonghetti, NF 2025]

T. Fonghetti et al., Nuc. Fus. 2025



Long pulses developed in WEST in 2024-25



Record tokamak pulse of 22 min!

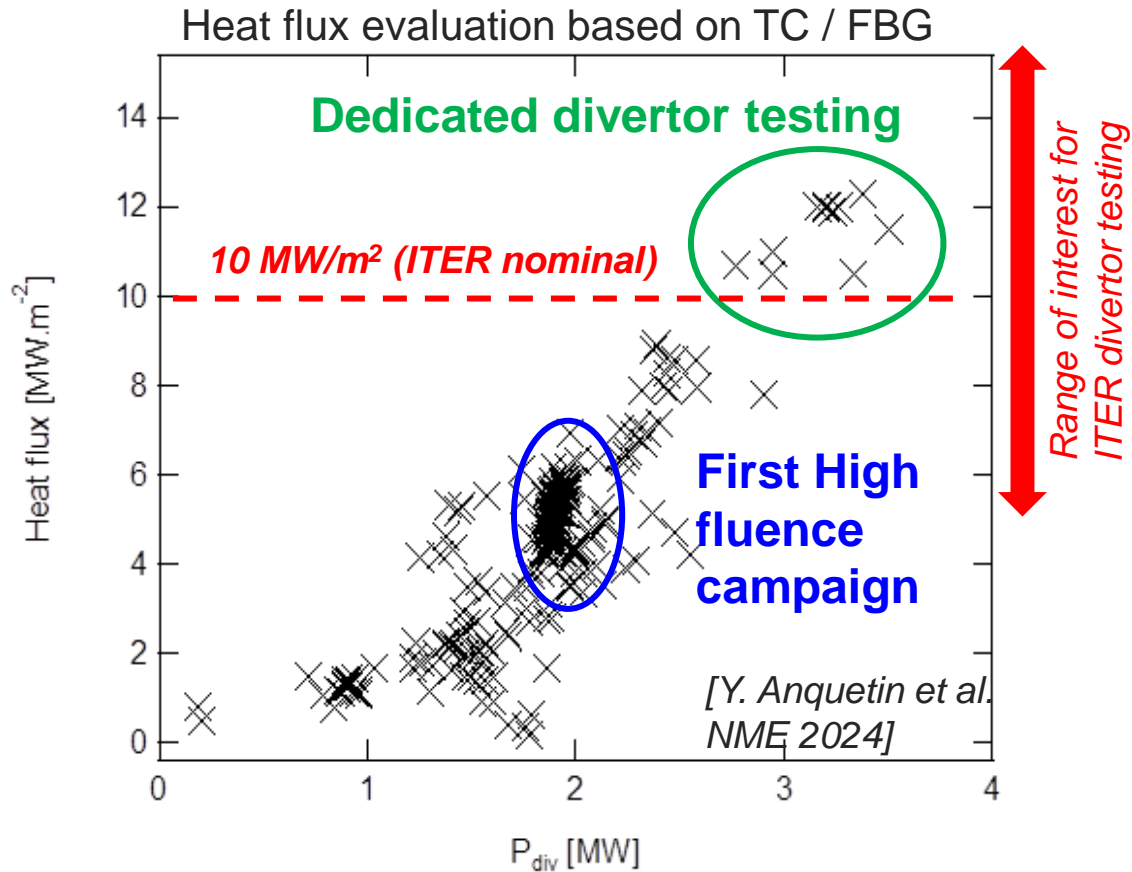
- Operated with double feedback control (V_{loop} , CS voltage) + (I_P , P_{LH})
- Outgassing observed after 700-800s when using more than 2 MW (2 launchers)
- With one LH launcher, discharges could be extended beyond 1000s

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WEST provides ITER relevant heat flux / particle fluence



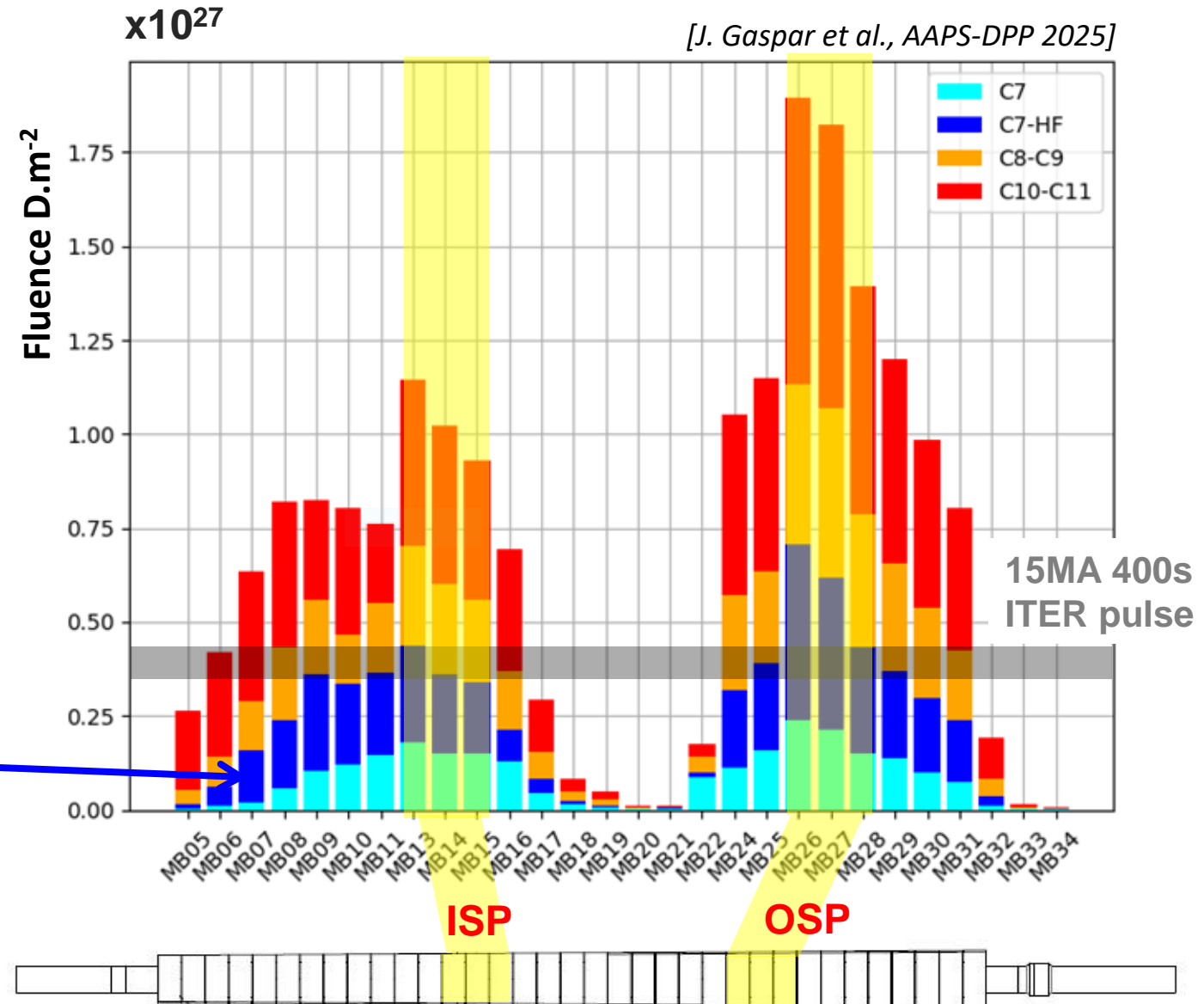
- WEST provides **high peak heat flux** for divertor testing
- Heat flux in the ITER range routinely achieved in WEST in **steady-state up to 12 MW/m²**
- **High fluence campaign:** repetitive long pulses of 60s during one month of operation.
- Large number of transients recorded (> 2400 disruptions)

WEST operating with relevant ITER divertor particle fluence

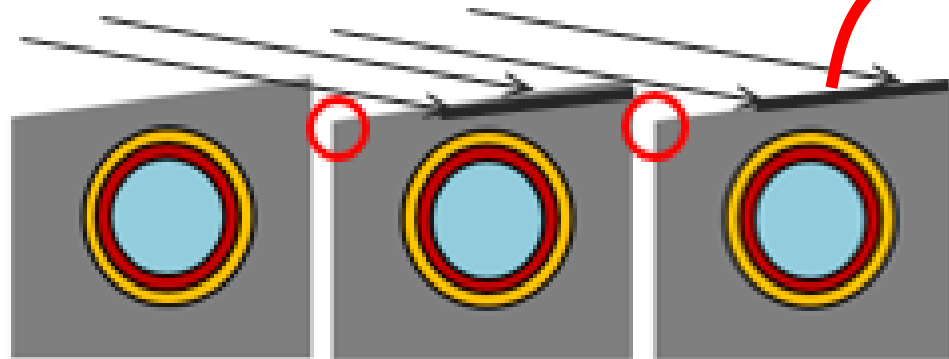
- > 18 hours plasma cumulated time
- Cumulated deuterium fluence on ITER grade divertor : $1.8 \cdot 10^{27} \text{ D/m}^2$ = a few ITER pulses

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

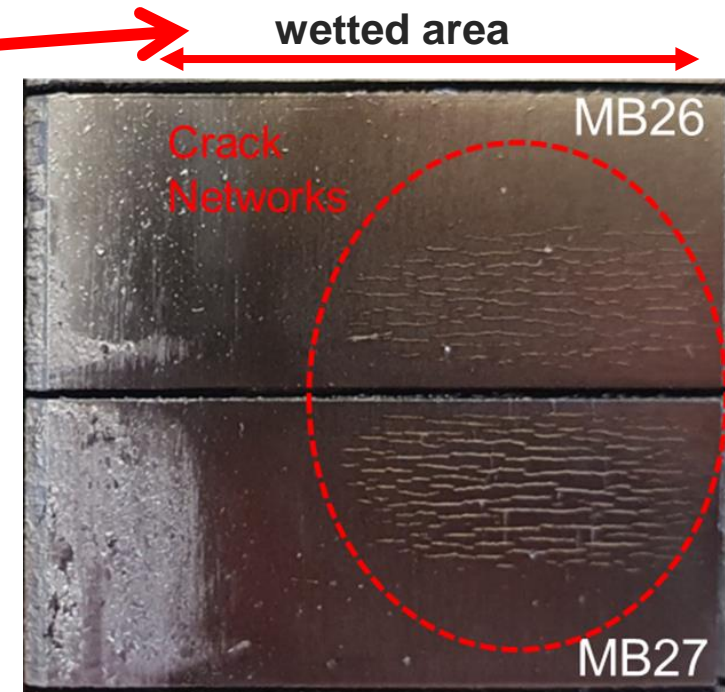
Dedicated High Fluence campaign (C7) (repetitive attached discharges)



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 $\sim 5 \text{ MW/m}^2$)
- Most pronounced on MB27 (not most usual strike point location)

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

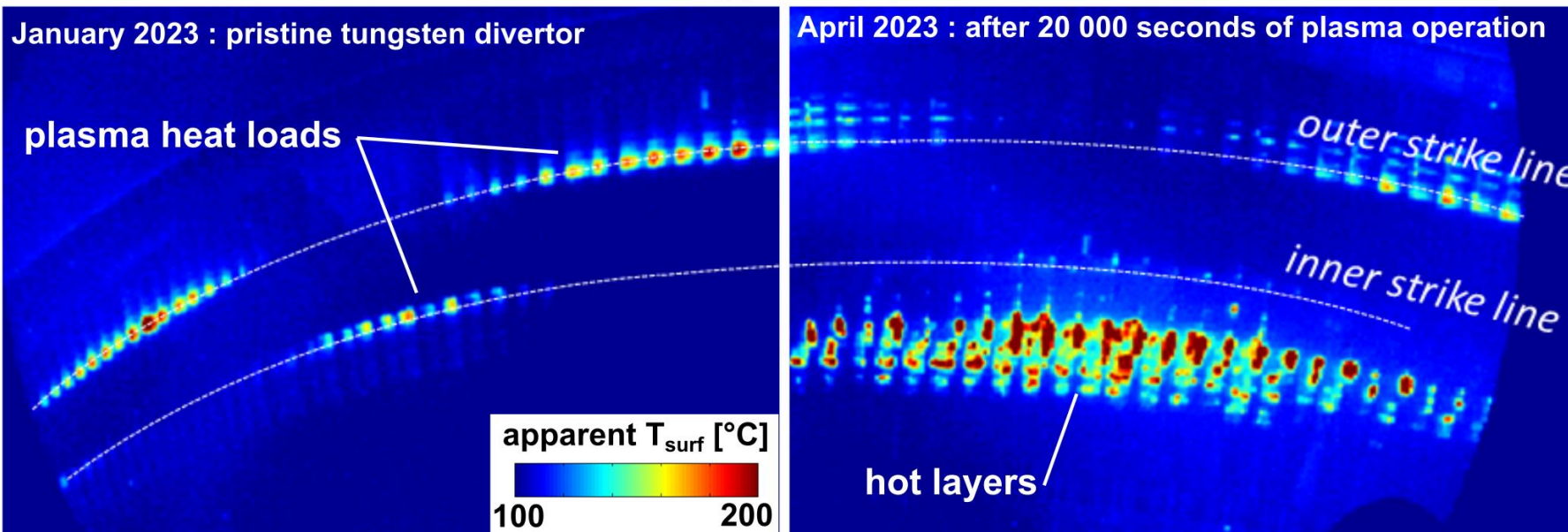
Tungsten rich layers build up on divertor surface, disturbing infra-red monitoring & plasma operation

False surface temperature from hot emissive layers, growing in time [1]

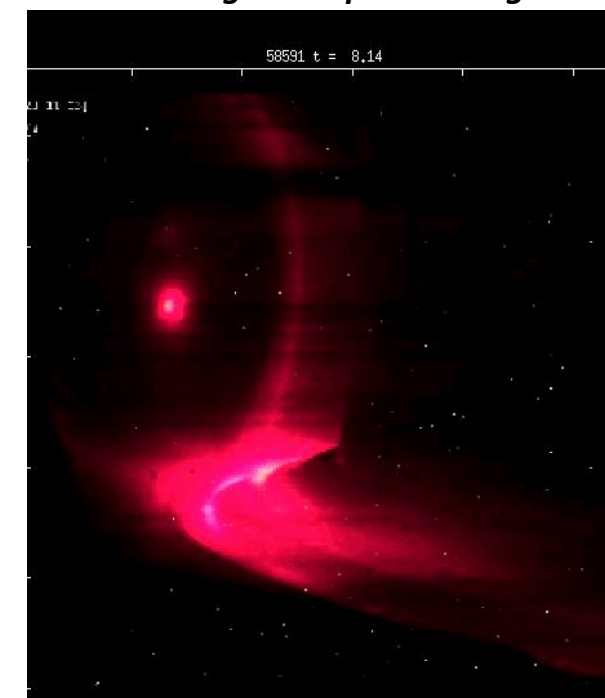
Flakes emitted to the plasma, frequency growing during campaigns [2]

Cumulated operation (~5 hours) representative of **a few** ITER pulses [3]

Infra red view of lower divertor sector during plasma operation

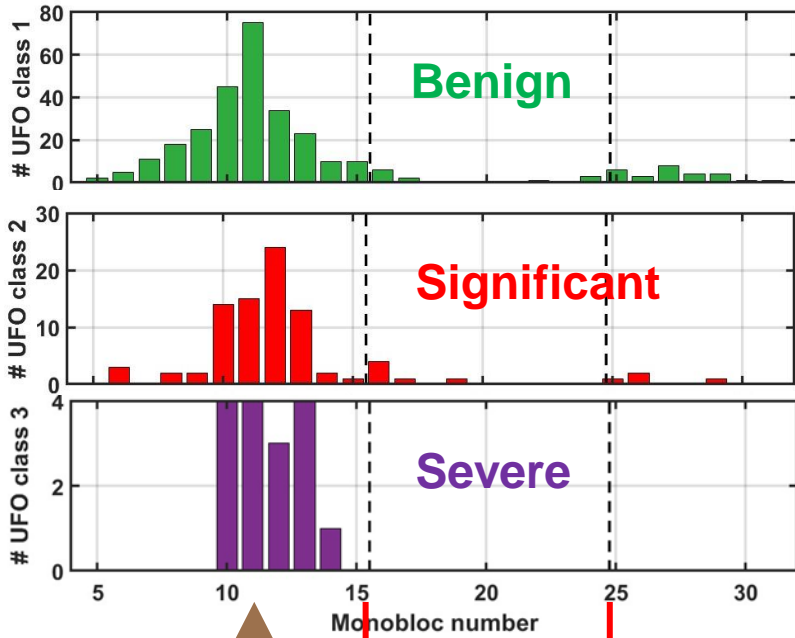


Flake burning in the plasma edge



- [1] J. Gerardin Nuc. Mater. & Energy 41 (2024)
- [2] J. Gaspar Nuc. Mater. & Energy 41 (2024)
- [3] N. Fedorczak Nuc. Mater. & Energy 41 (2024)

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

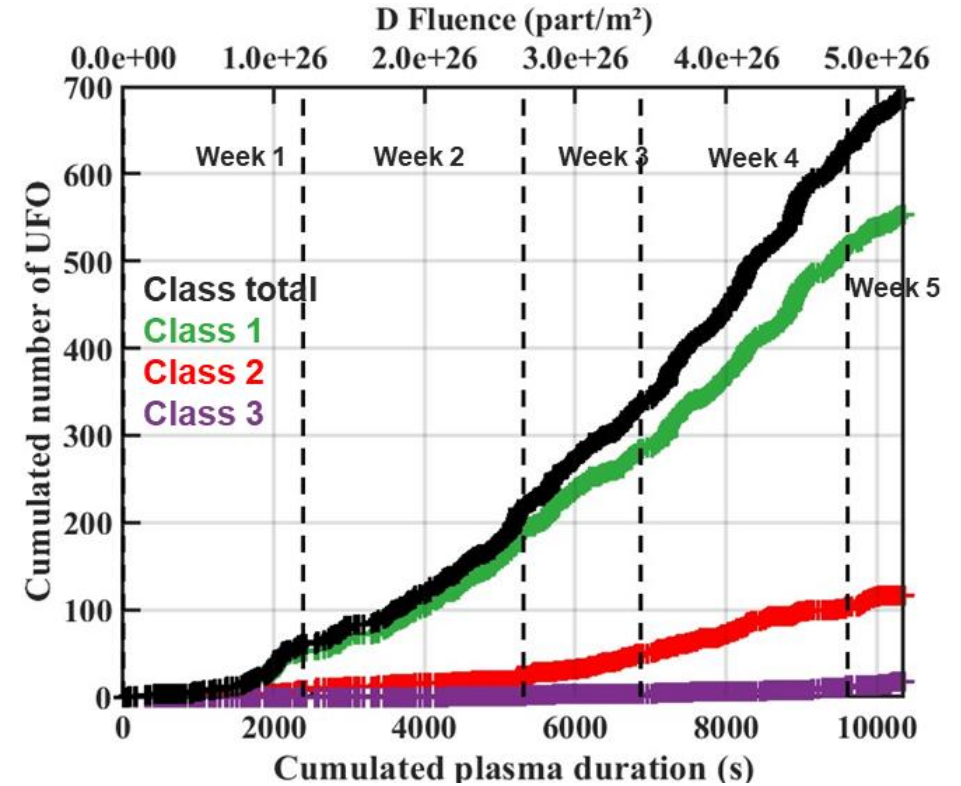


Class 1:
benign impact

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

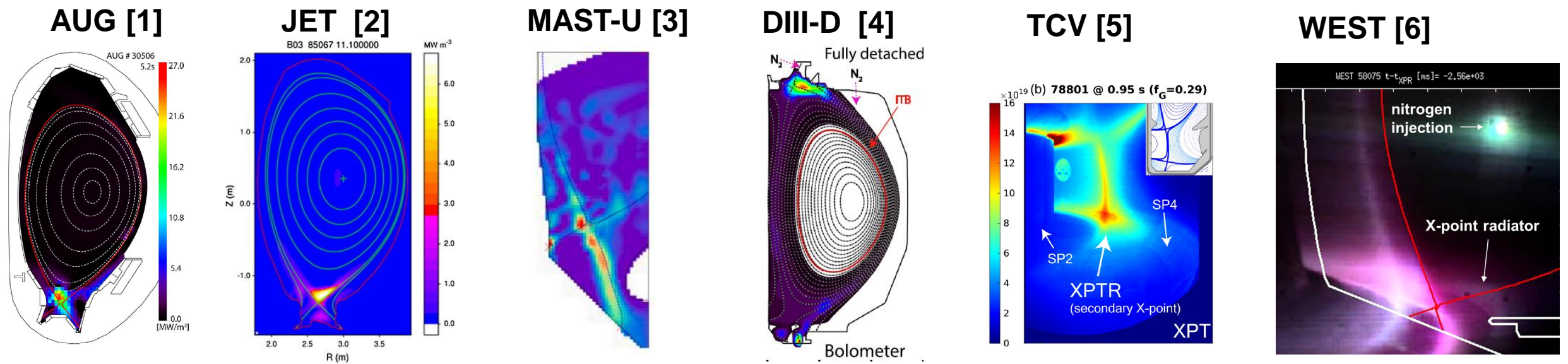
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Dissipative divertor regimes, in particular X-point radiation regime, is the focus of intense research worldwide



Goal: increase divertor radiation to lower intense plasma loads

How: inject light impurities to emit intense line radiations

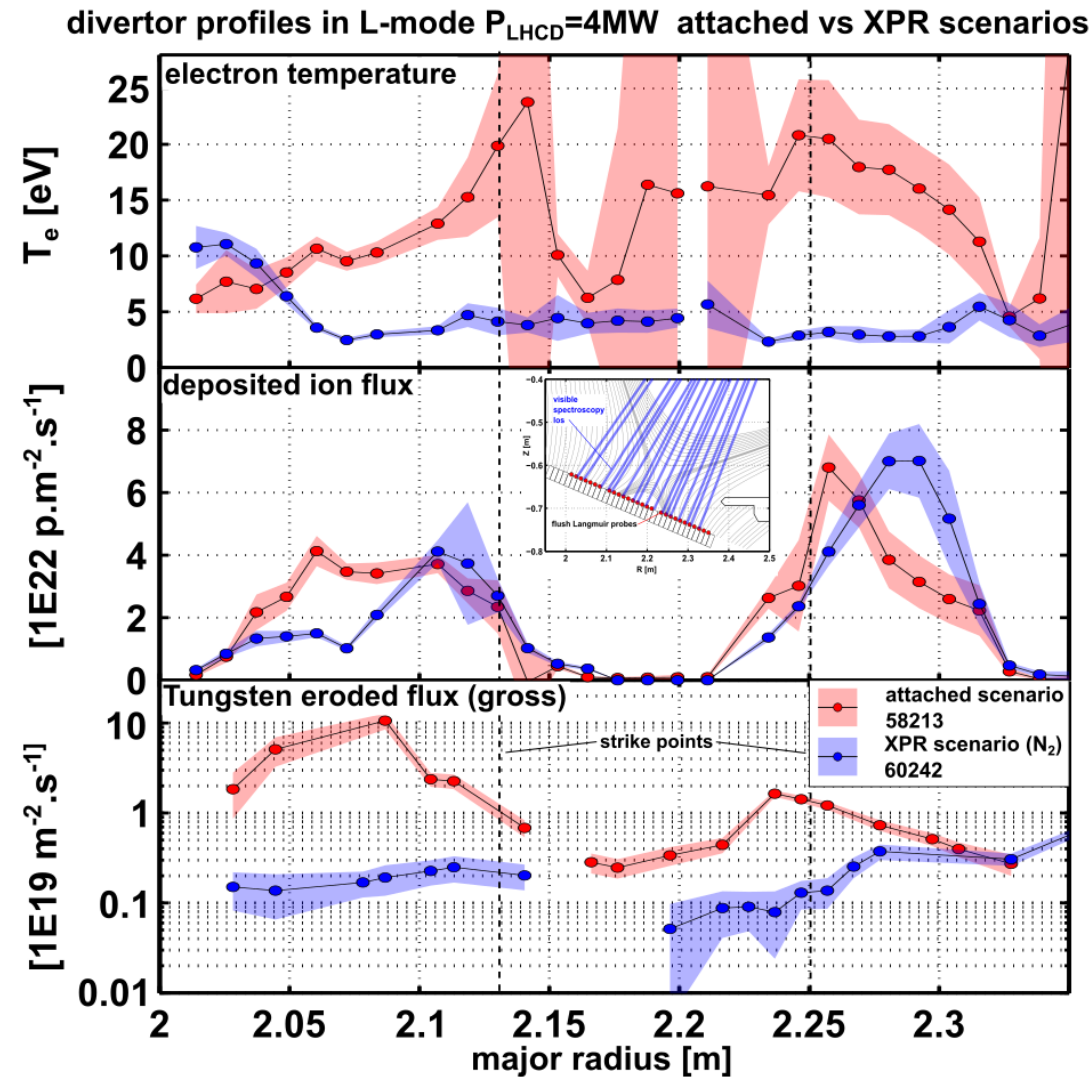
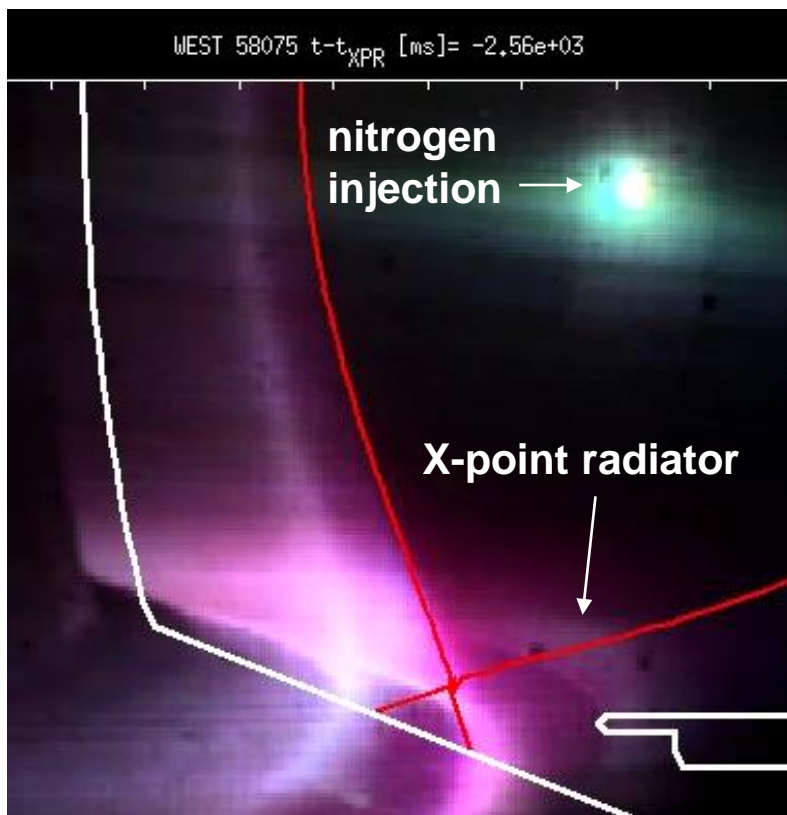
→ Often features an “X-point radiator” (radiation pattern)

→ Obtained both in H-mode and/or in L-mode (see ref. papers)

[1] M. Bernert Nucl. Fusion 61 (2021)
 [2] M. Wischmeier J. Nuc. Matter 463 (2015)
 [3] F. Federici Nuc. Mater. & Energy 43 (2025)
 [4] L. Wang Nature Communication (2021)
 [5] K. Lee PRL 134 (2025)
 [6] N. Fedorczak, EPS 2025 and PPCF in prep. (2025)

Dissipative “X-point radiator” operation demonstrated in WEST with nitrogen seeding

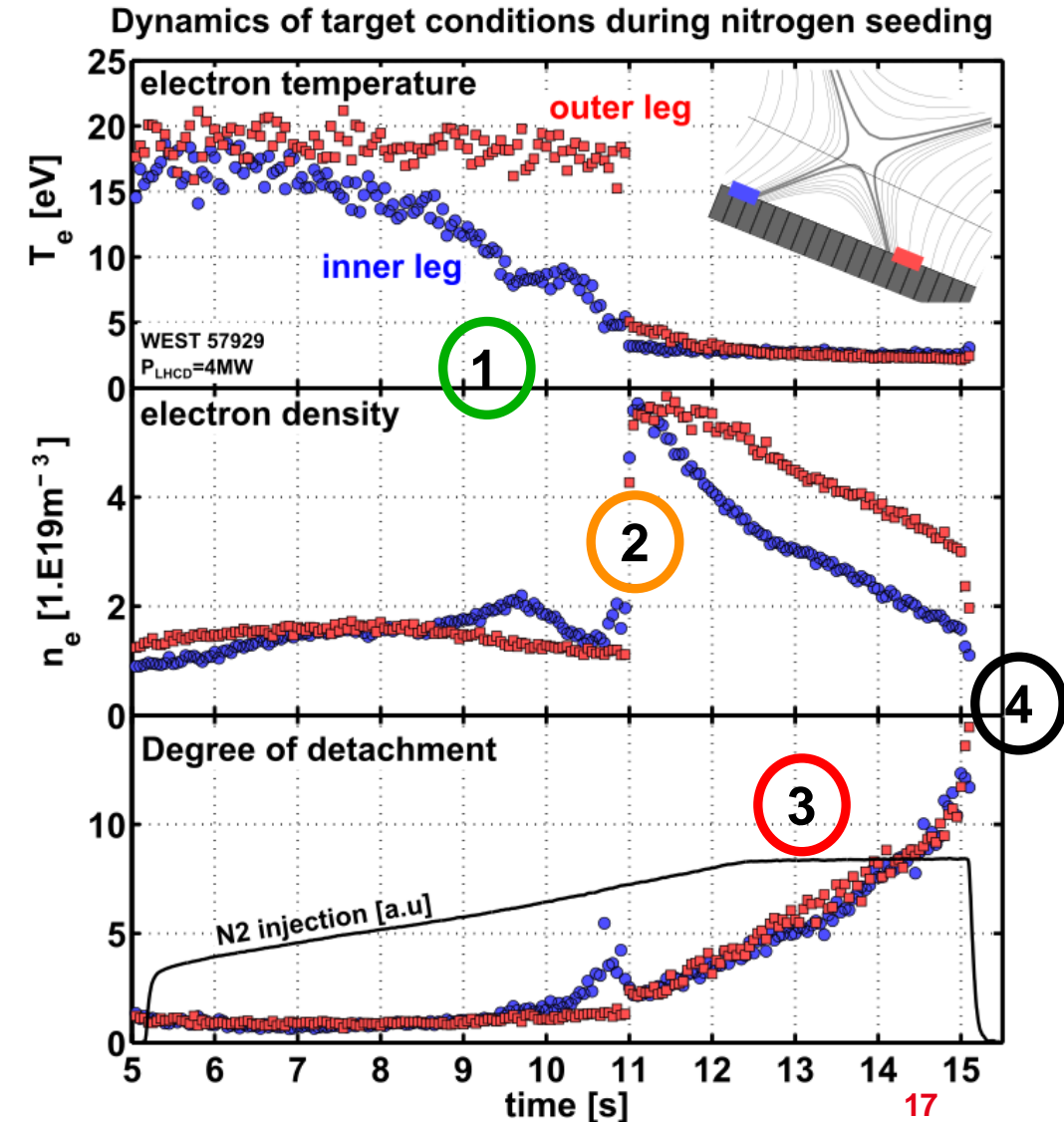
- Triggers X-point radiator in nitrogen injection
- Divertor plasma is cold ($<5\text{eV}$), W erosion is tamed
- Entry, stabilisation and exit demonstrated



Bifurcation into a cold and dense target state, followed by continuous dissipation

Dynamics during constant nitrogen injection:

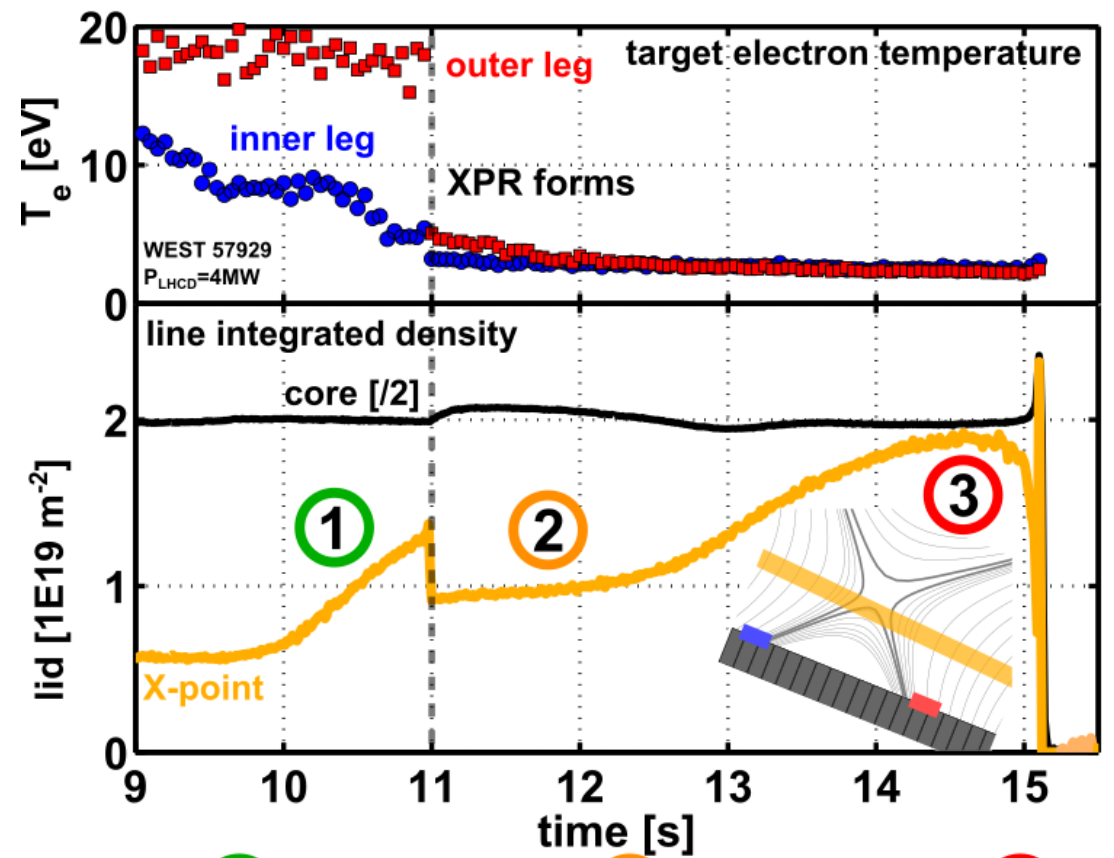
1. continuous cooling of inner target down to 5eV
2. Bifurcation into X-point radiator (<1 ms)
 - abrupt cooling of outer target below 5eV
 - abrupt increase of target plasma density→ global change of the whole divertor plasma
3. Continuous increase of dissipation (heat & particle loads)
4. Eventual trigger of radiative instability & disruption



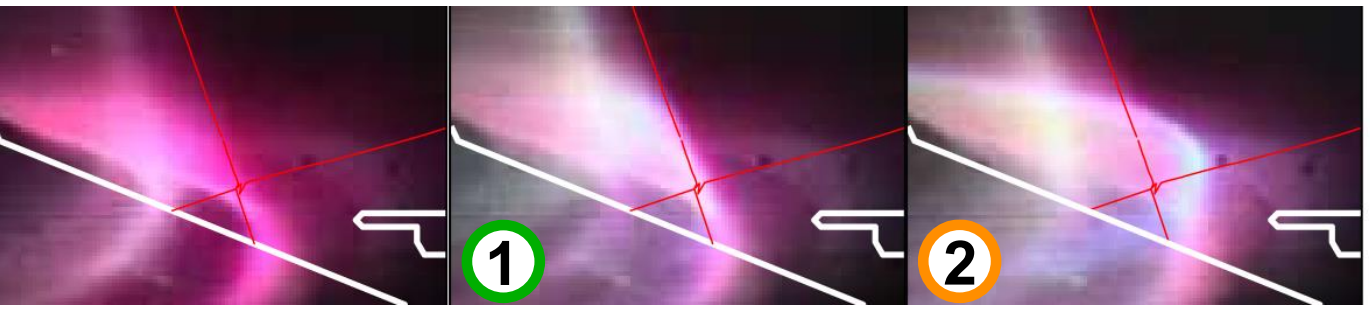


Characterization of the transition into XPR regime in WEST

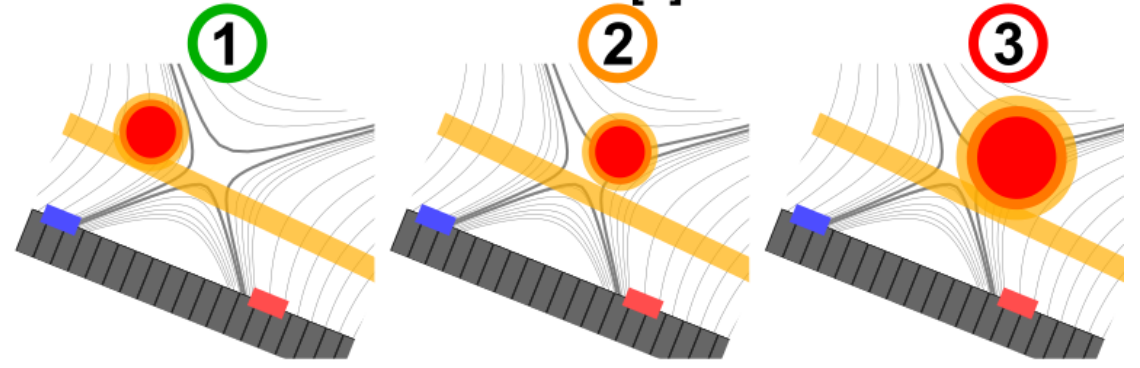
- 1. Inner density ring grows continuously in the vicinity of the X-point, cooling the inner leg
- 2. XPR forms: cold density ring jumps inside the separatrix
- 3. XPR density ring grows continuously, eventually triggers disruption



no seeding Pre-XPR XPR



Visible camera view of the lower divertor





Real time control of XPR regime demonstrated using divertor interferometry

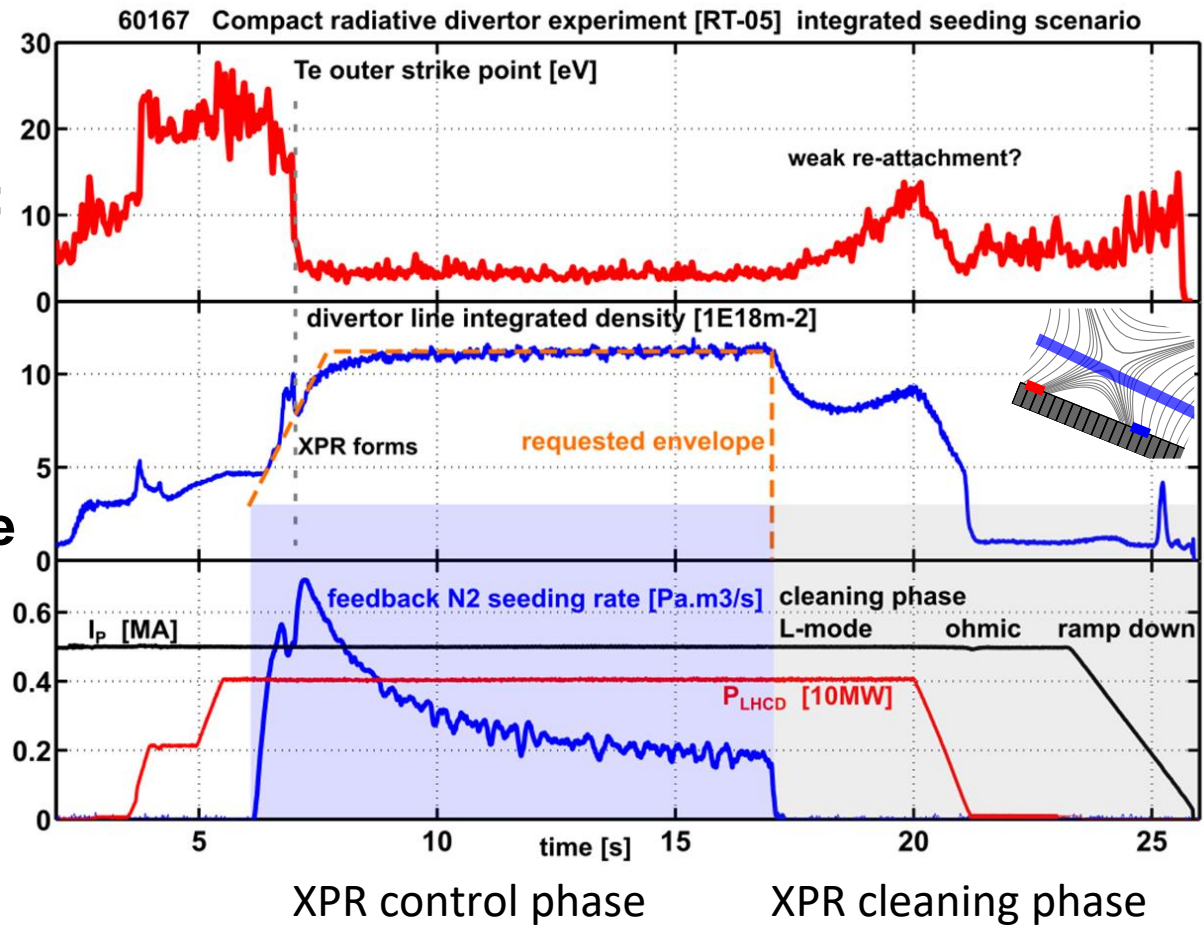
Native real time observable on WEST [1]
Sensitive to XPR formation and disruptive limits
Nitrogen seeding controlled with proportional gain:

$$\Phi_{N_2} = g \times (lid^{request} - lid^{measured})$$

XPR transition occurs during request ramp
Steady-state maintained with decaying seeding rate
→ Slow pumping ($\tau_{pump} \approx 5$ s)

When seeding stops, the XPR state is sustained a few seconds (pumping time & wall desorption)

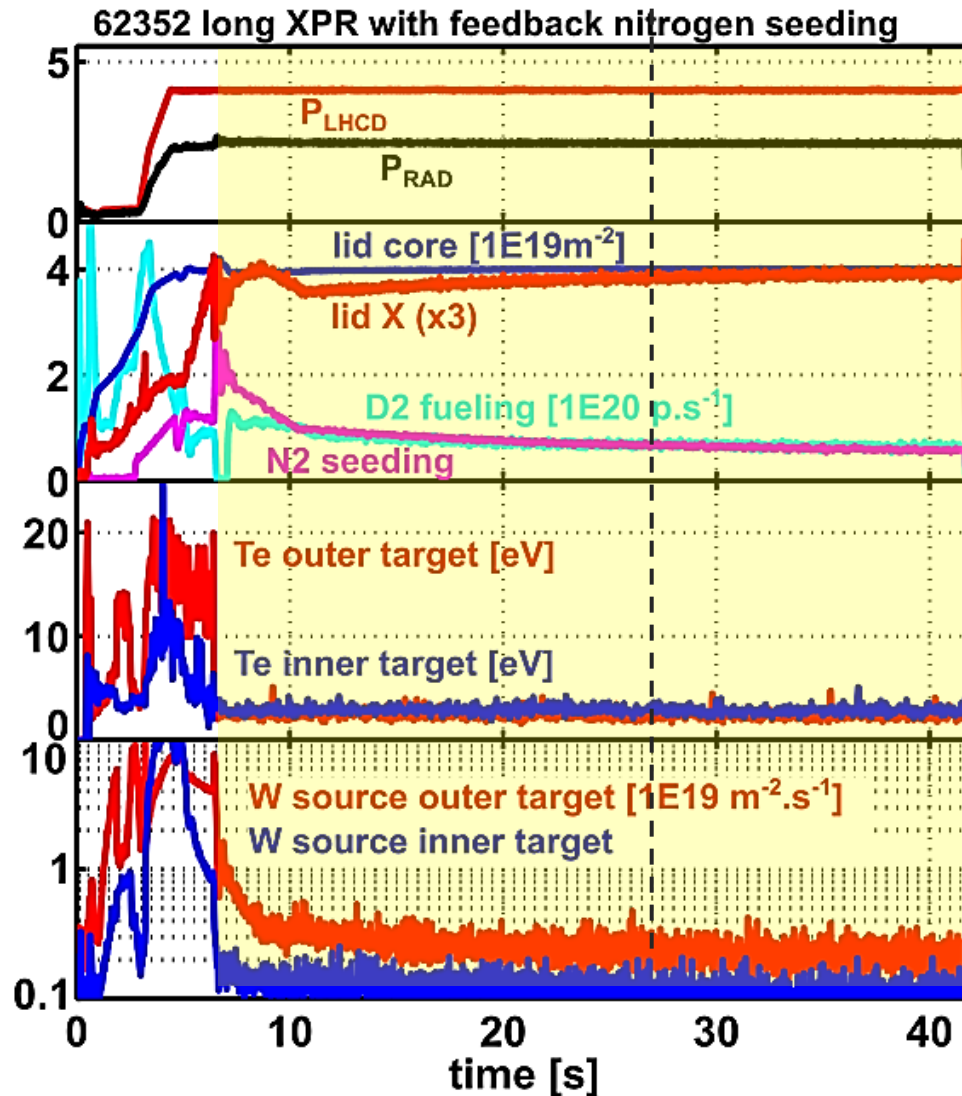
- Live cleaning procedure for the next pulse
- Non disruptive termination



[1] C. Gil et al. Fusion Engineering and Design 140 (2019)



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

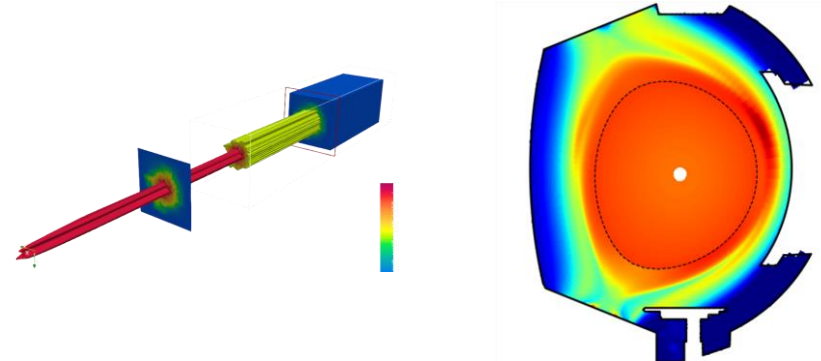
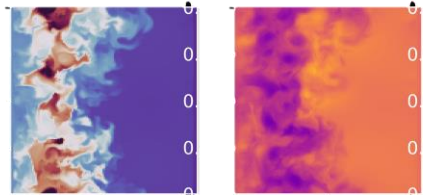
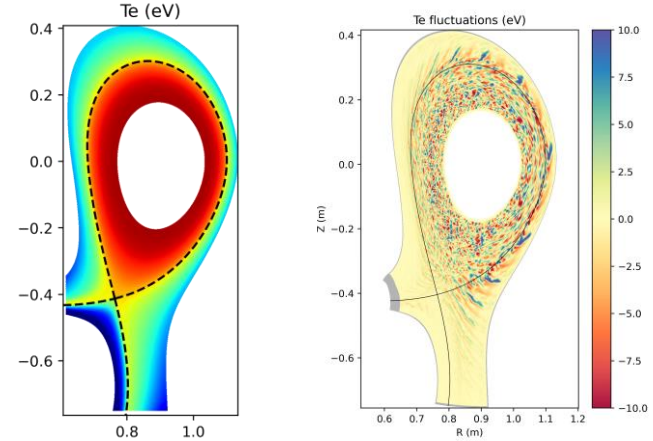
➔ Next high fluence campaign will start in two weeks using the XPR scenario



Numerical modeling studies of XPR with SOLEDGE3X

SOLEDGE3X: a versatile fluid code for edge plasma modelling

- **Drift-fluid code based on Braginskii's equations** with Zhdanov closure terms for multi-component plasma [H. Bufferand et al., NF 2015, NF 2021]
- **Up to the first wall with full geometry** thanks to immersed boundary conditions
- Complete plasma **geometrical flexibility** (arbitrary number of X-points)
- **Kinetic neutrals** via coupling with EIRENE
- Applications:
 - 2D and 3D transport simulations
 - 2D and 3D turbulent simulations
- Recent developments:
 - 3D turbulent studies for **linear devices**
 - **Core-edge integrated version**
- More information and references on www.soledge3x.com





SOLEEDGE3X modelling for interpretative simulations of XPR in WEST

Particle, momentum and energy conservation models [1]

- Fluid electrons & ions (incl. impurities), kinetic neutrals
- Convection and conduction along magnetic field
- Diffusion & $\vec{F} \times \vec{B}$ drifts across magnetic field
- Sheath models (Bohm-like) at wall interface

Objectives:

- Initialize conditions resembling experiments
- Access to X-point radiator regime [2], focus on dynamics
- Identify key physics ingredients in the process

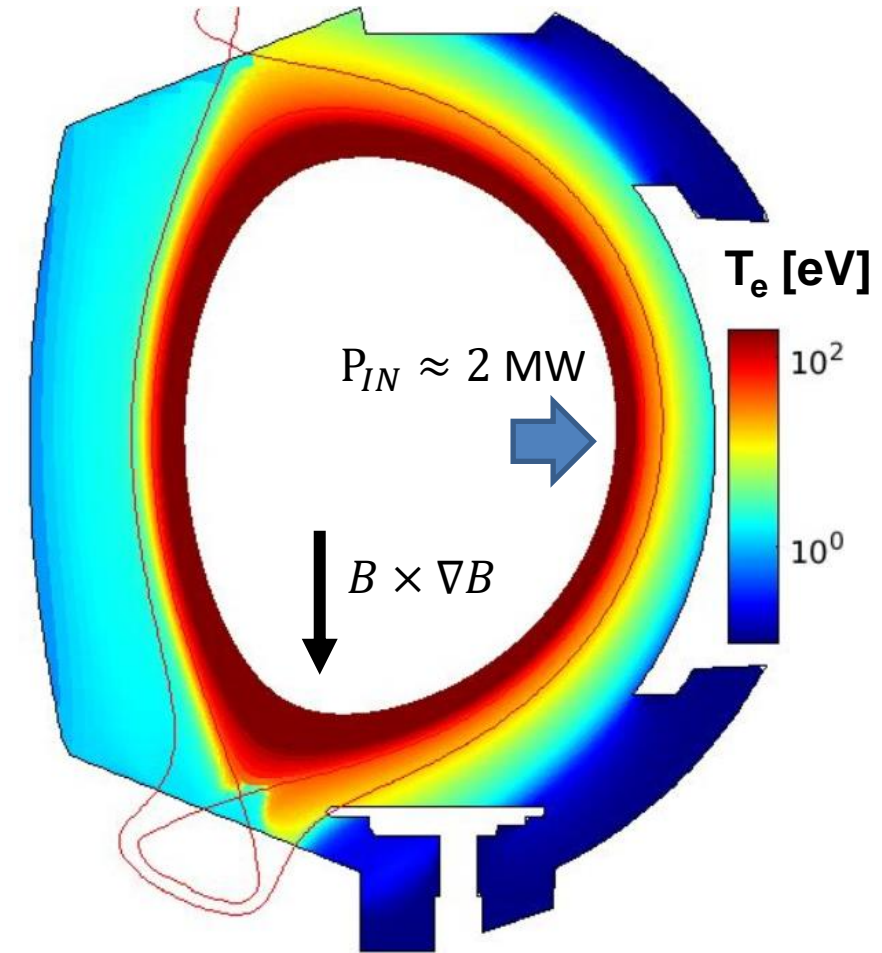
Note: Regimes obtained also with other plasma solvers (SOLPS-ITER, GRILLIX,...) [3,4,...]

[1] H. Bufferand et al., *Plasma Phys. & Contr. Fusion* 64 (2022)

[2] N. Rivals *Nuc. Mater. & Energy* 41 (2024) [3] O. Pan, *Nuclear Fusion* (2022)

[4] K. Eder, *Nuclear Fusion* 2025

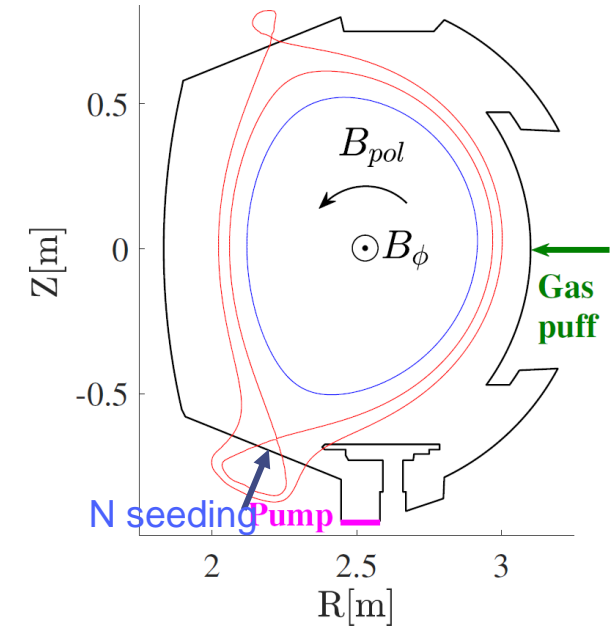
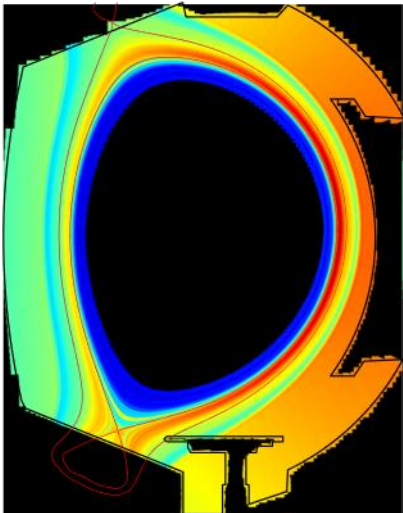
Electron temperature map



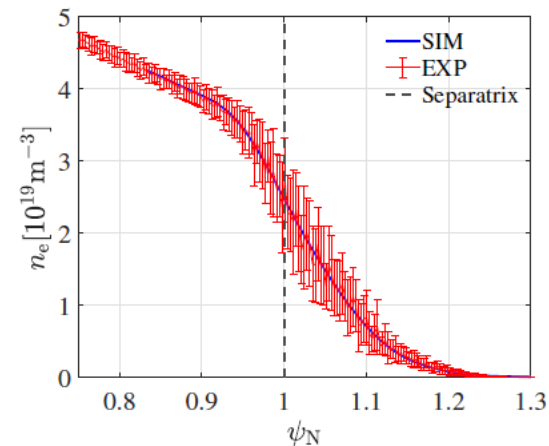
Simulation setup in SOLEDGE3X-EIRENE

- Plasma simulations in time-dependent 2D transport mode with micro second time resolution
- $P_{in,sim} = 2\text{MW}$
- $R_{wall,N} = 0.9$
- $R_{wall,D} = 1$
- Pumping speed = $35\text{ m}^3/\text{s}$
- **With full drifts** (see H. Bufferand et al, NME 2017)
- **With experimental-based diffusion map (including ballooning)**

2D map of cross-field diffusion coefficient



electron density at the
Outer midplane #56420



SOLEEDGE3X modelling of XPR dynamics:

- Time-dependent simulations in SOLEEDGE3X-EIRENE, including magnetic drifts, have reproduced experimentally observed rapid divertor transition from attached to XPR regime.

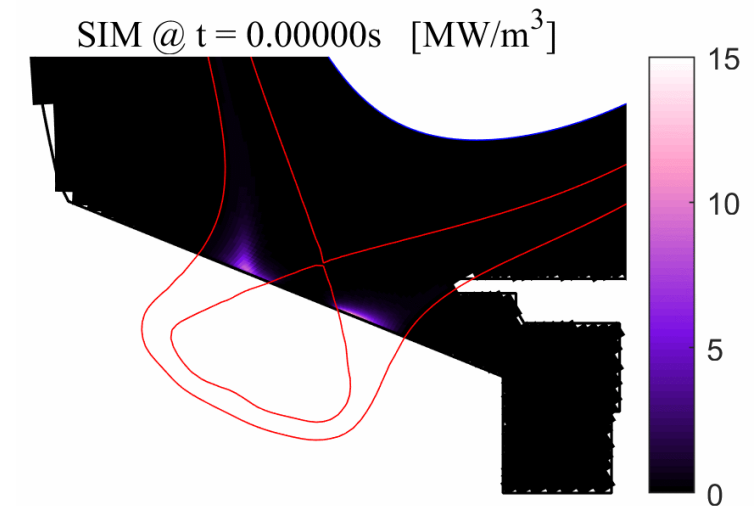
- The simulations reveal an X-point-centered plasma vortex that dynamically evolved and governs the transition from the attached to the XPR regime.

[H. Yang et al, submitted]

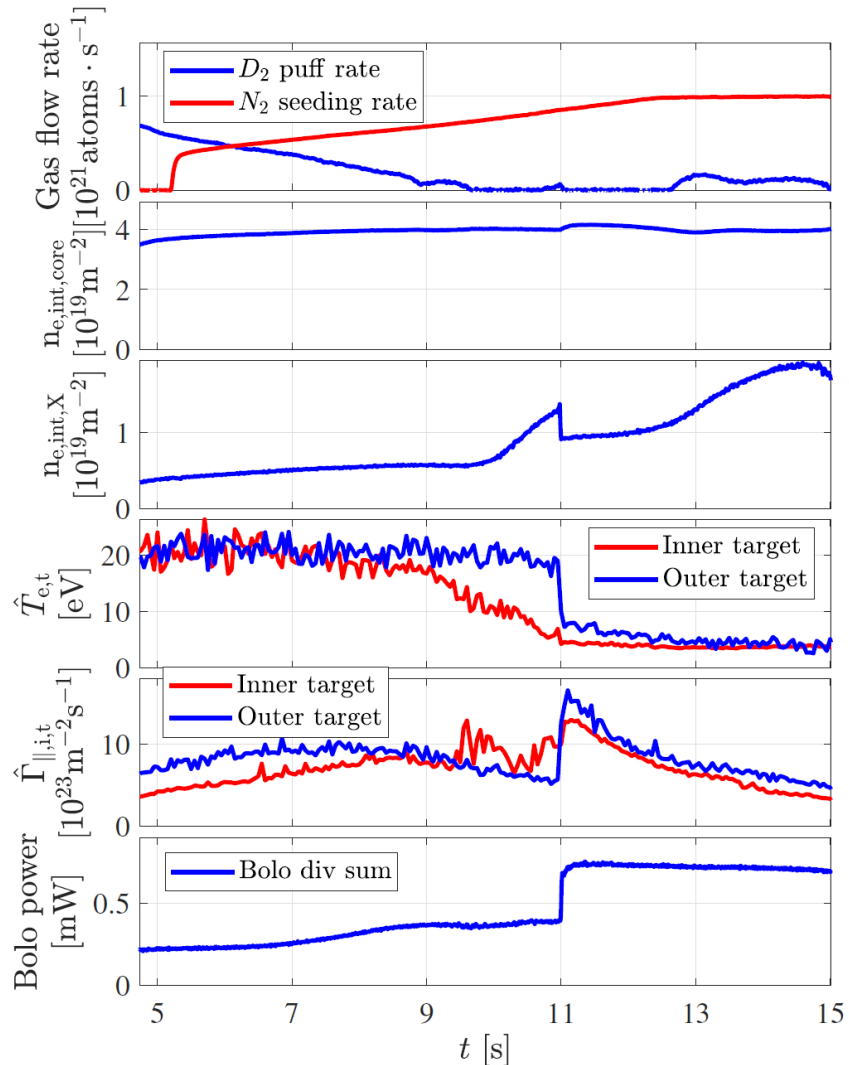
EXP :
#57929



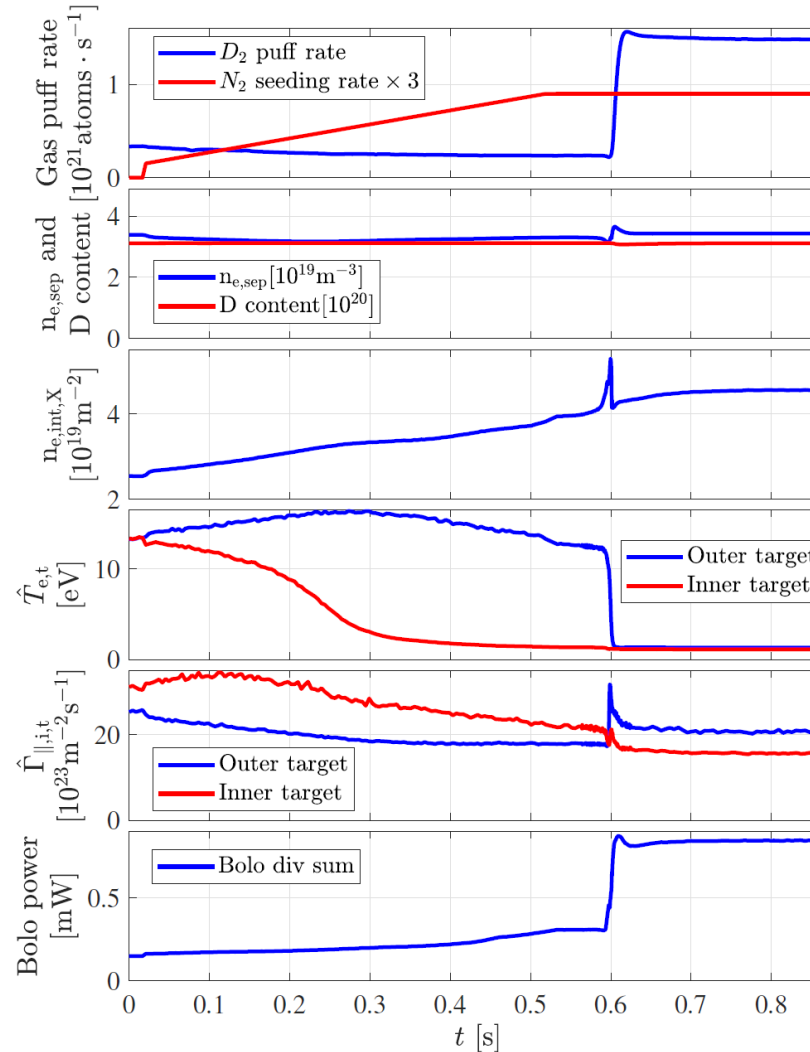
SIM :



Experiment vs simulation: sharp transition into XPR captured

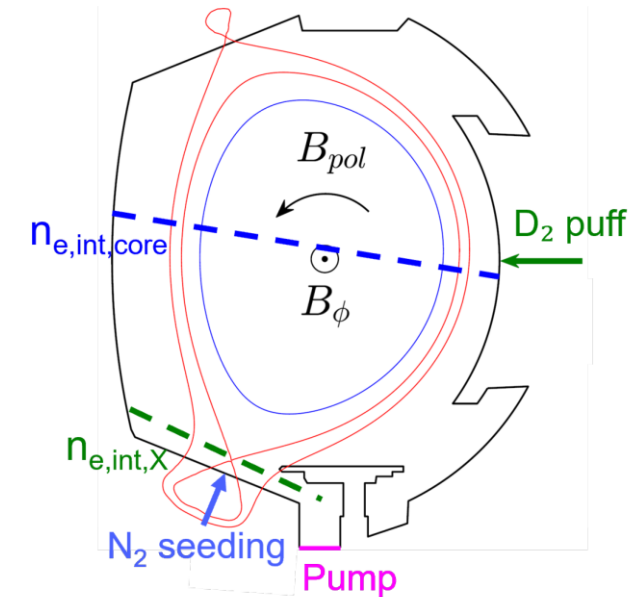


(a) Experiment #57929



(b) Simulation

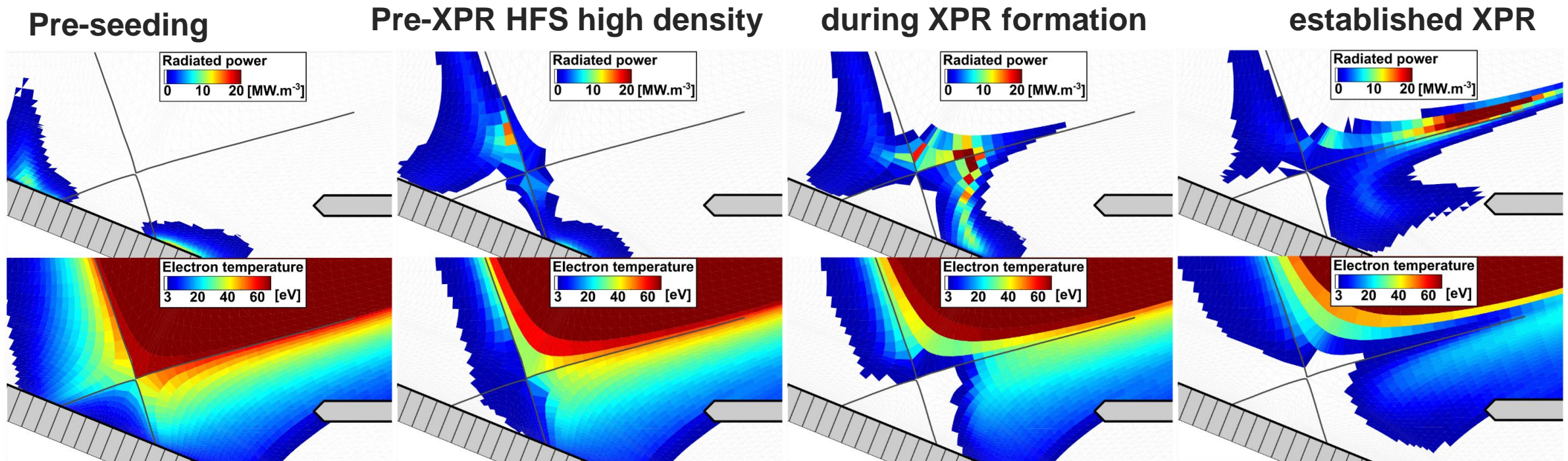
- This rise in gas puff rate follows the transition rather than driving it.
- Time scale difference due to faster N ramp up in the SIM and less delay of recycling from wall.





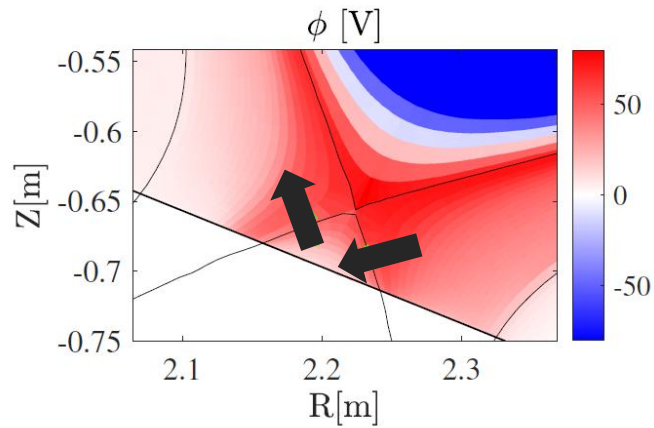
SOLEEDGE3X modelling of XPR dynamics: Transition into XPR initiated from the inner density front, jumping through the separatrix

Radiation & temperature maps from SOLEEDGE3X simulations across the XPR transition

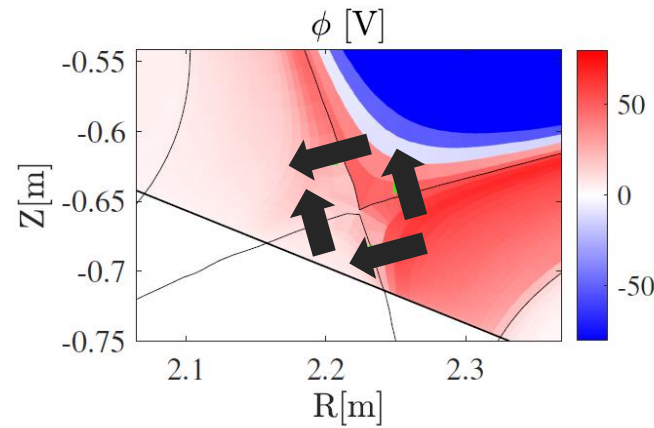


The X-point radiator stabilizes inside separatrix, but displaced from X-point region
→ effect of drift flow entrainment

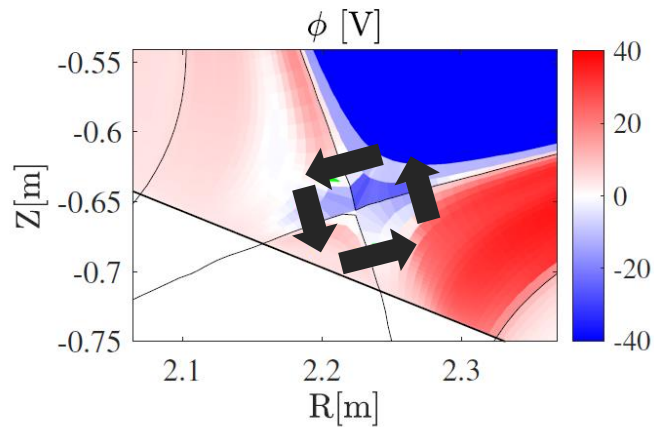
Potential well formation and X-point vortex



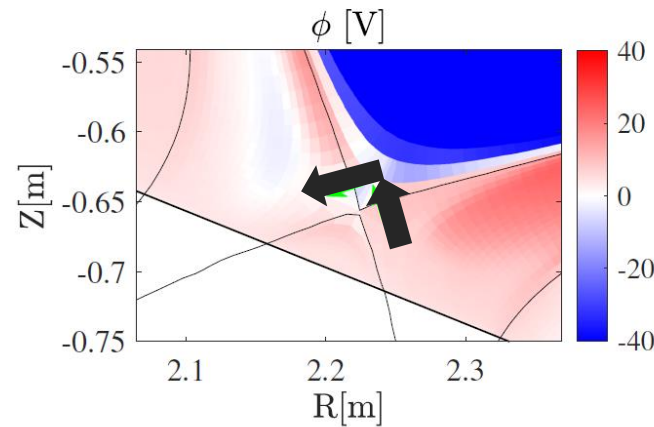
(a) $t = 0.019$ s, Attached



(b) $t = 0.551$ s, inner divertor detached



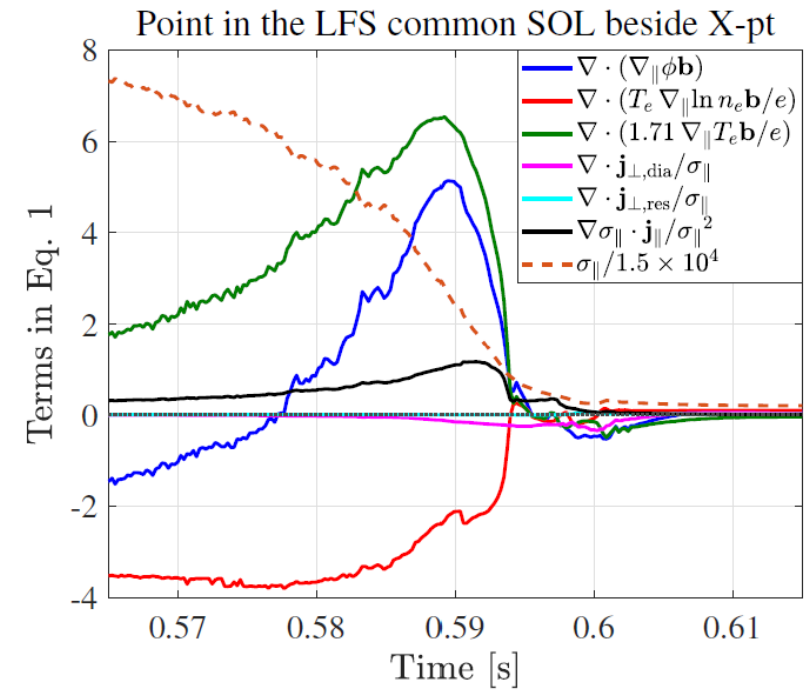
(c) $t = 0.599$ s, post-onset of XPR



(d) $t = 0.869$ s, deep XPR

➔ Radial particle flux direction

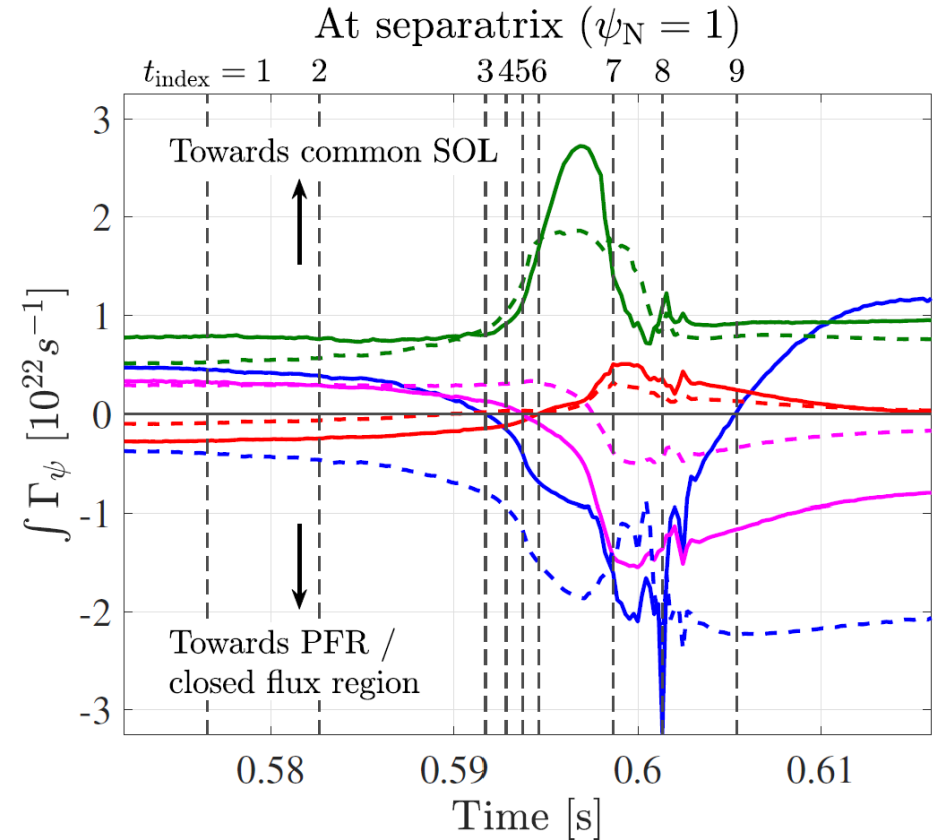
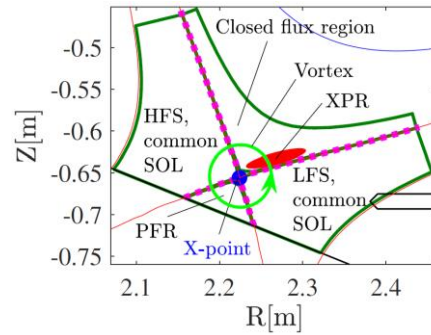
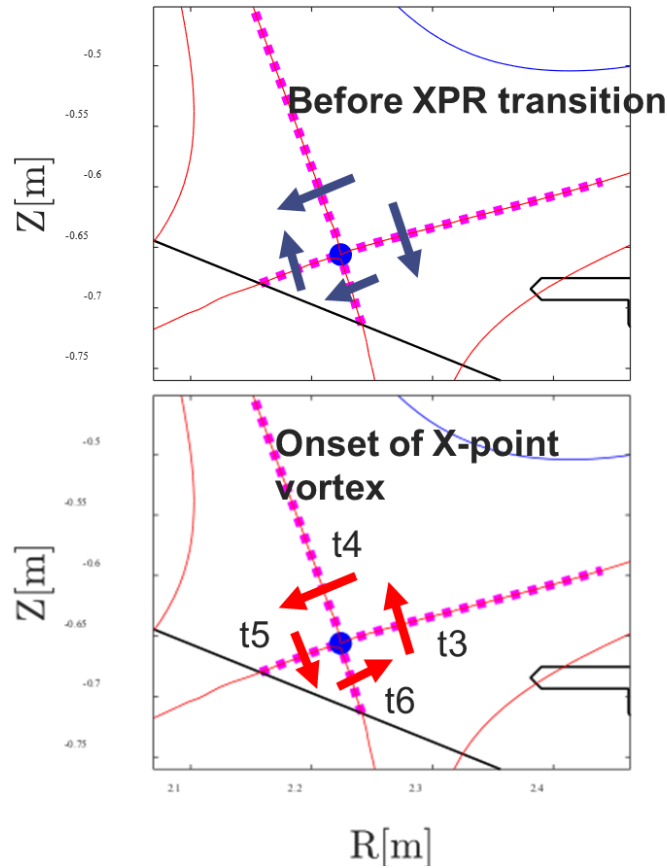
$$\nabla \cdot (\nabla_{\parallel} \phi \mathbf{b}) = \nabla \cdot \left(\frac{T_e \nabla_{\parallel} \ln n_e \mathbf{b}}{e} + \frac{1.71 \nabla_{\parallel} T_e \mathbf{b}}{e} \right) + \frac{\nabla \cdot \mathbf{j}_{\perp, \text{dia}}}{\sigma_{\parallel}} + \frac{\nabla \cdot \mathbf{j}_{\perp, \text{res}}}{\sigma_{\parallel}} + \frac{\nabla \sigma_{\parallel} \cdot \mathbf{j}_{\parallel}}{\sigma_{\parallel}^2}$$



The increase of $\nabla \cdot (\nabla_{\parallel} \phi \mathbf{b})$ is dominated by $\nabla \cdot (1.71 \nabla_{\parallel} T_e \mathbf{b} / e)$

[H. Yang et al, submitted]

X-point vortex: competition between ExB and diffusive particle fluxes



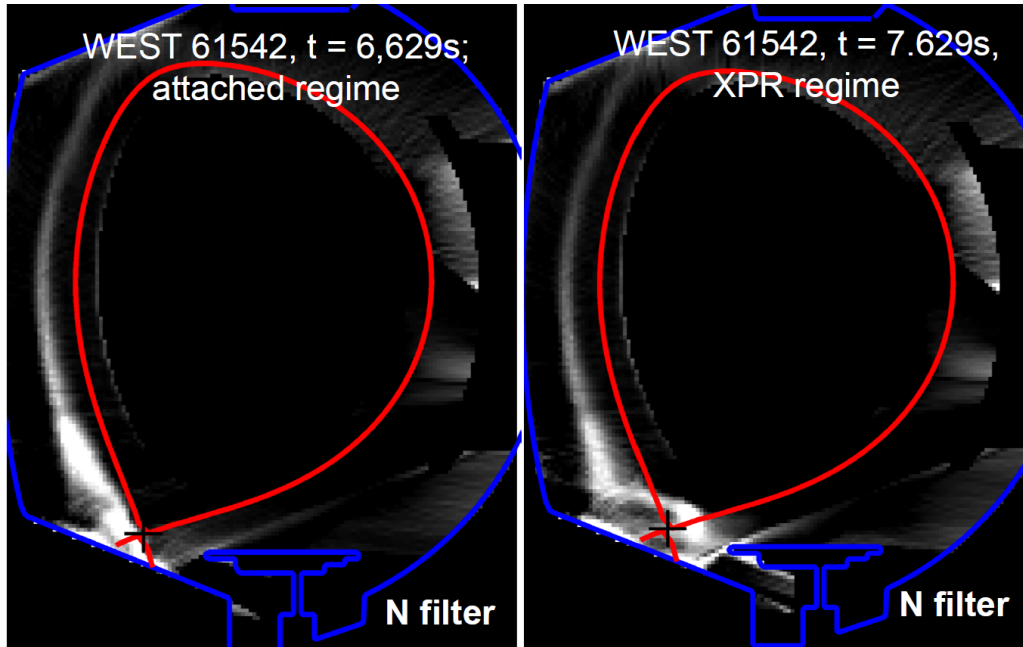
- $\int \Gamma_\psi, \text{total}$, LFS above X-pt - - - $\int \Gamma_\psi, \text{ExB}$, LFS above X-pt
- $\int \Gamma_\psi, \text{total}$, LFS below X-pt - - - $\int \Gamma_\psi, \text{ExB}$, LFS below X-pt
- $\int \Gamma_\psi, \text{total}$, HFS above X-pt - - - $\int \Gamma_\psi, \text{ExB}$, HFS above X-pt
- $\int \Gamma_\psi, \text{total}$, HFS below X-pt - - - $\int \Gamma_\psi, \text{ExB}$, HFS below X-pt

- The total flux evolution mainly follows the ExB flux

[H. Yang et al, submitted]

NITROGEN II RADIATION PATTERN

Radiation map from fast visible camera with interference filters

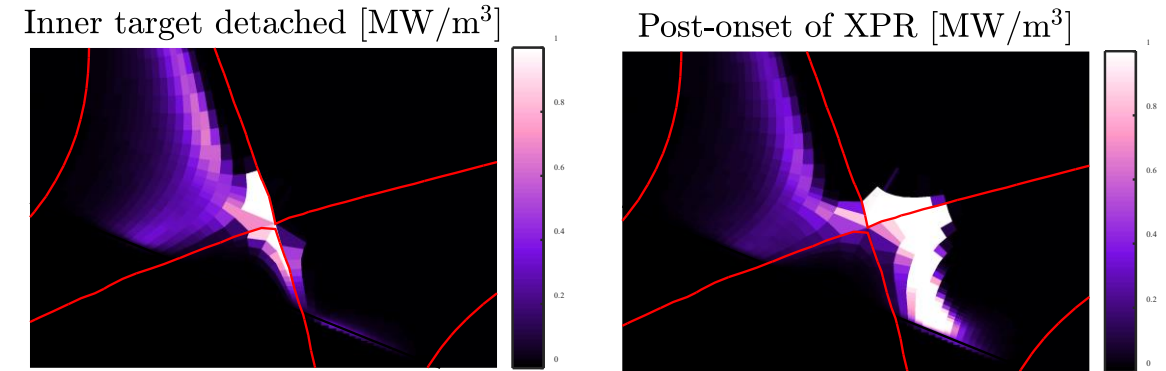


Before XPR

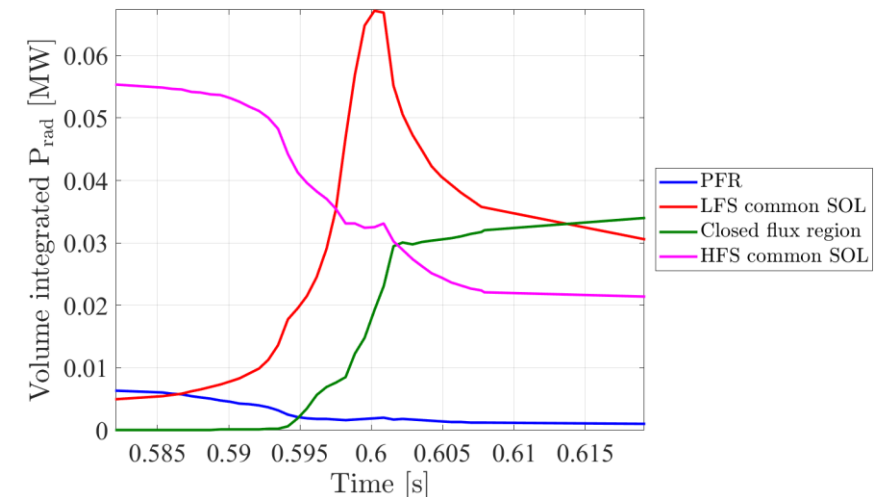
XPR established

- Reduced Prad at HFS and PFR after XPR formation
- Increased Prad at LFS and closed flux region

Radiation map from SOLEDGE3X simulations



Time evolution of Prad from N+



SOLEDGE3X-EIRENE simulation

Role of $\vec{F} \times \vec{B}$ drifts evidenced in experiment: Same phenomenology in SOLEDGE3X simulations

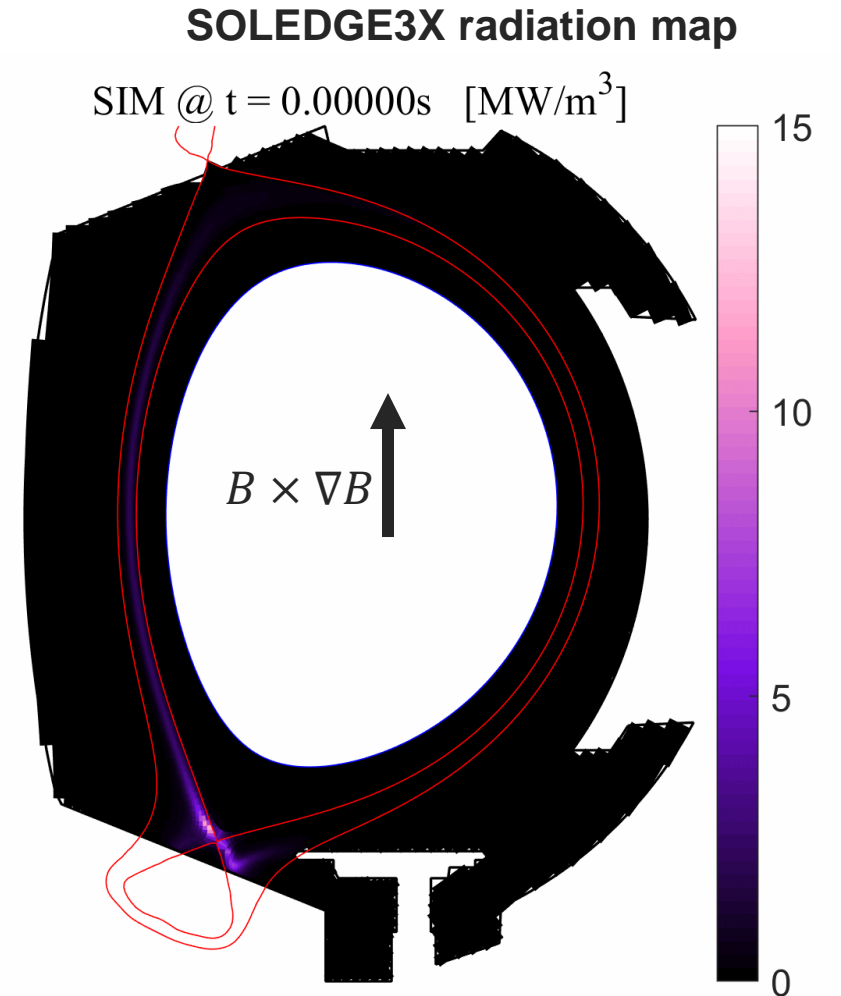
WEST Upper single null scenario (ref. 4MW)

Midplane nitrogen injection leads to inner target cooling

Bifurcation to XPR occurs, but:

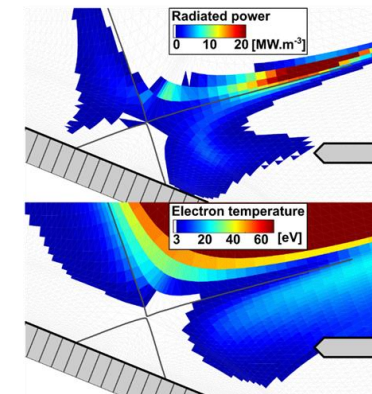
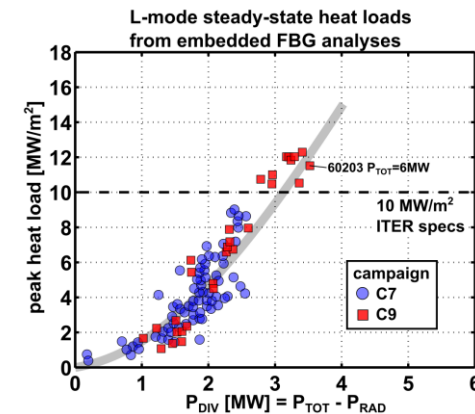
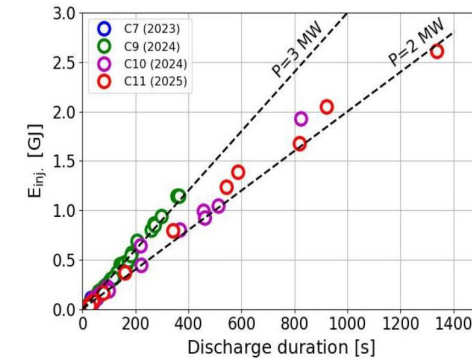
- Radiation falls along inner separatrix toward lower divertor
- Radiative disruption follows immediately
- SOLEDGE3X ran in Lower single null, reversed B

→ Same phenomenology as in experiment



Summary and perspectives

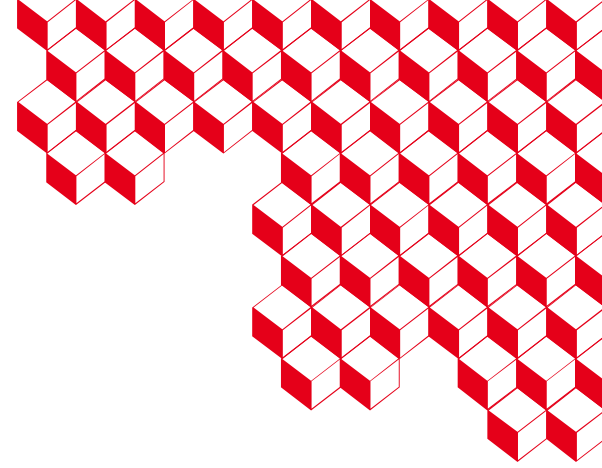
- In the past 2 years **WEST** has developed long pulses operation on a routine basis and tested ITER grade components with particle fluence and heat load approaching those of ITER
- **ITER grade components have been tested up to 12MW/m²** and cracks have been observed and are currently being studied. Cracks do not seem to cause any operation consequences so far.
- The **XPR regime of operation has been extended to 35s** using real time control and physics understanding has been gained using **SOLEEDGE3X-EIRENE** including drifts. We will develop even longer pulses for **high fluence experiments in XPR regime conditions (scheduled for the ongoing WEST campaign).**



WEST-related contributions at this conference



- Boron injection rate as actuator for wall conditioning and enhancement of core performance in WEST - [D. Sgrelli](#)
- Impact of wall conditions on impurity sourcing and core pollution during high fluence experiment and standard ohmic pulses in WEST – [A. Grosjean](#)
- Interpretation of boron deposition patterns in the main chamber of WEST – [S Kosslow](#)
- Evaluation of upper divertor impurity sourcing and transport across different plasma shapes in the WEST tokamak – [B Putra](#)
- Modeling the Radial Profile of Tungsten Ions in the WEST tokamak with Local Transport Models and Atomic Interactions Between Charge States – [J. Dominski](#)
- First DIII-D/WEST Hybrid Scenario Similarity Experiments for ITER-Relevant Long-Pulse Operation – [X. Litaudon](#)
- Impact of the plasma current on access conditions and stabilization of XPR in the WEST tokamak – [V. Quadri](#)



Thank you for your attention