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R Dumont, T Fonghetti, P Maget, P Manas, C Bourdelle, J Morales, K Afonin, T Barbui, G Ciraolo, Y Corre, et al.

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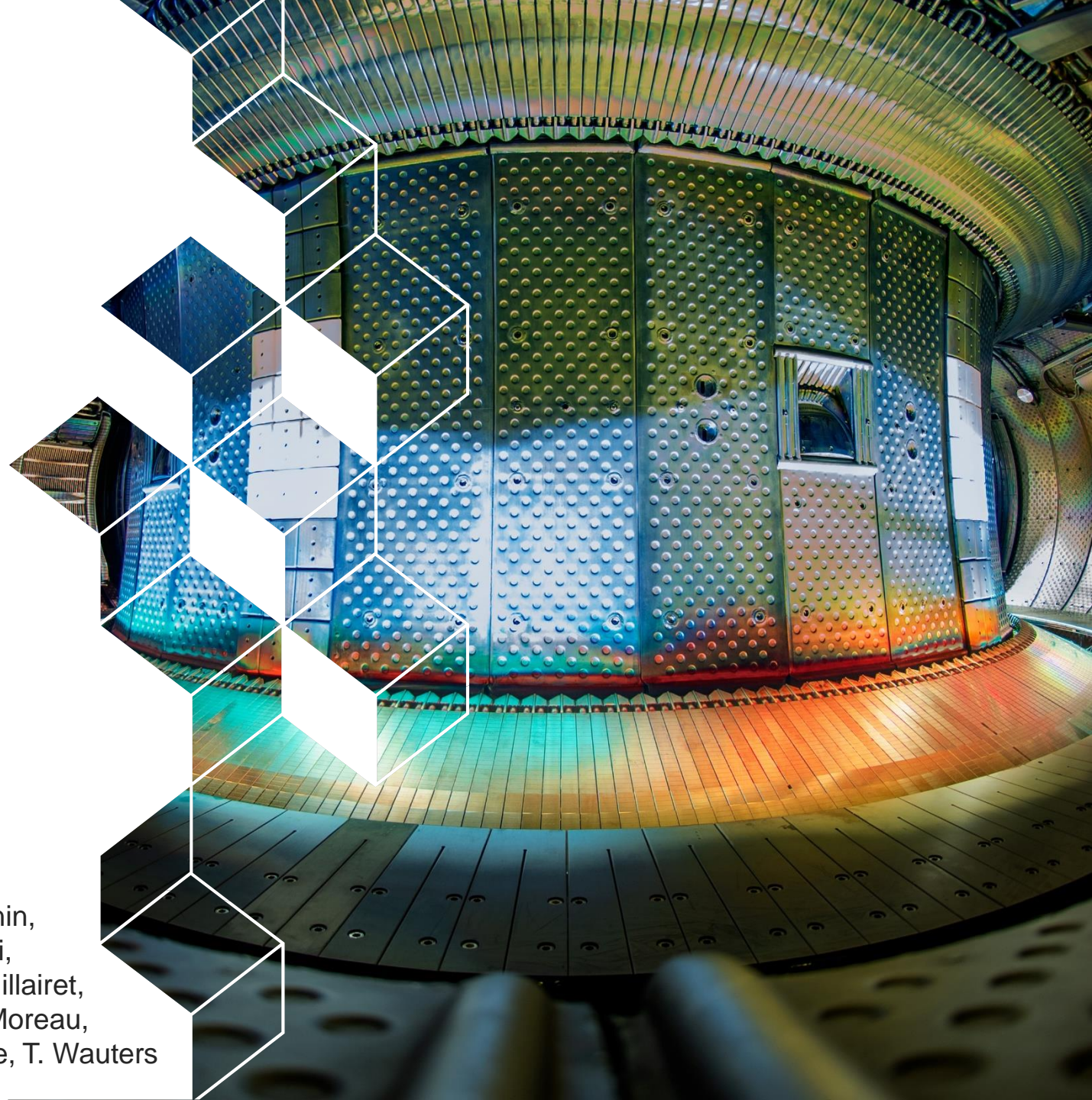
# Long-duration plasma operation in WEST

R. Dumont, on behalf of the WEST team\*  
CEA, IRFM, F-13108 Saint Paul-lez-Durance, France

\* see <http://west.cea.fr/WESTteam>

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T. Fonghetti, P. Maget, P. Manas, C. Bourdelle, J. Morales, K. Afonin,  
T. Barbui, G. Ciralo, Y. Corre, L. F. Delgado-Aparicio, J. Dominski,  
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E. Lerche, X. Litaudon, R. A. Lunsford, D. Mazon, D. Moiraf, Ph. Moreau,  
R. Nouailletas, C. Reux, N. Rivals, Y. Savoye-Peysson, E. Tsitrone, T. Wauters

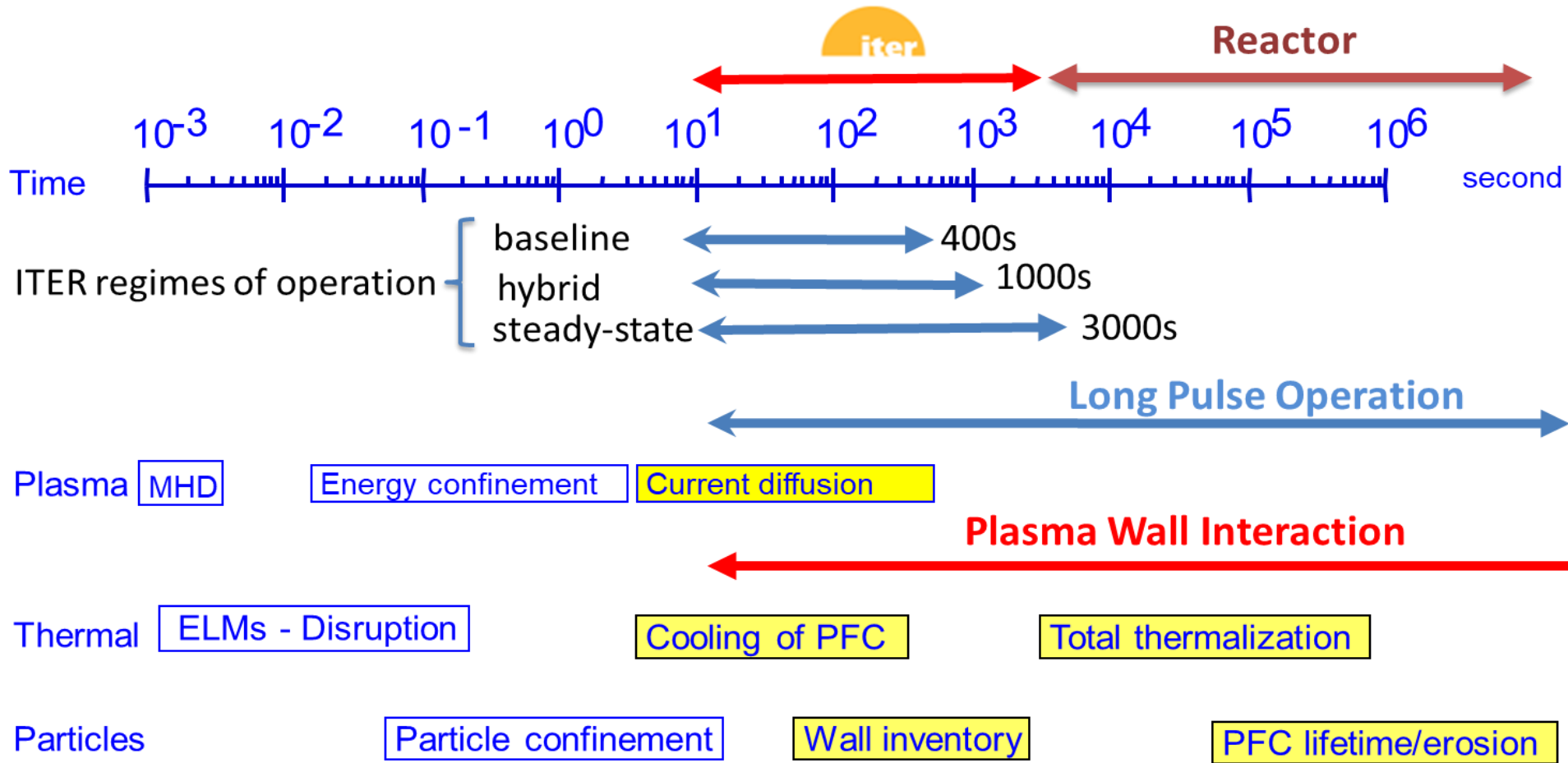


# Long Pulse Operation (LPO): a definition

[CICLOP group, NF 2024]



- Plasma with durations well above the plasma confinement time, approaching plasma-wall integration timescales
  - ITER 100-400s H-mode regime belongs to the LPO category



## Operational limits ?

- Limit in available flux
- PFC Limits (e.g. temperature, flux  $10\text{MW/m}^2$ )
- Flaking/dust





# WEST: a testbed for tungsten-related aspects of ITER preparation

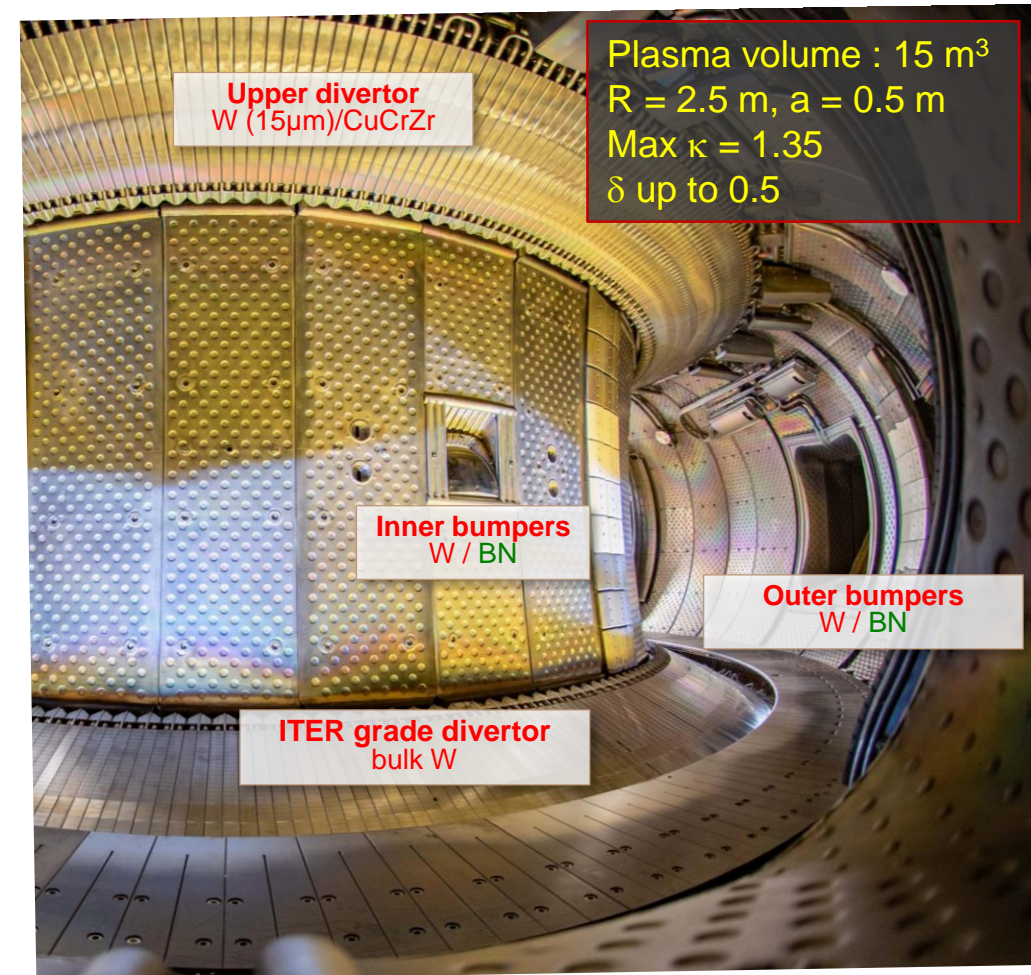
- Long Pulse capability, dominant electron heating, no external momentum source

[Bucalossi, NF 2024]

- Superconducting magnets, nominal magn. field 3.7 T
- LHCD power up to 7 MW – 1000 s
- ICRH power up to 9 MW
- *ECRH 1 MW (2024), 3 MW from 2025*
- Lower/Upper X-point, Double-Null configurations

- Tungsten environment

- Actively cooled ITER-grade tungsten divertor
- Inner / outer bumpers
  - W coated until mid-2020,
  - BN at mid-plane until spring 2024,
  - *Bulk W from autumn 2024*



# Outline

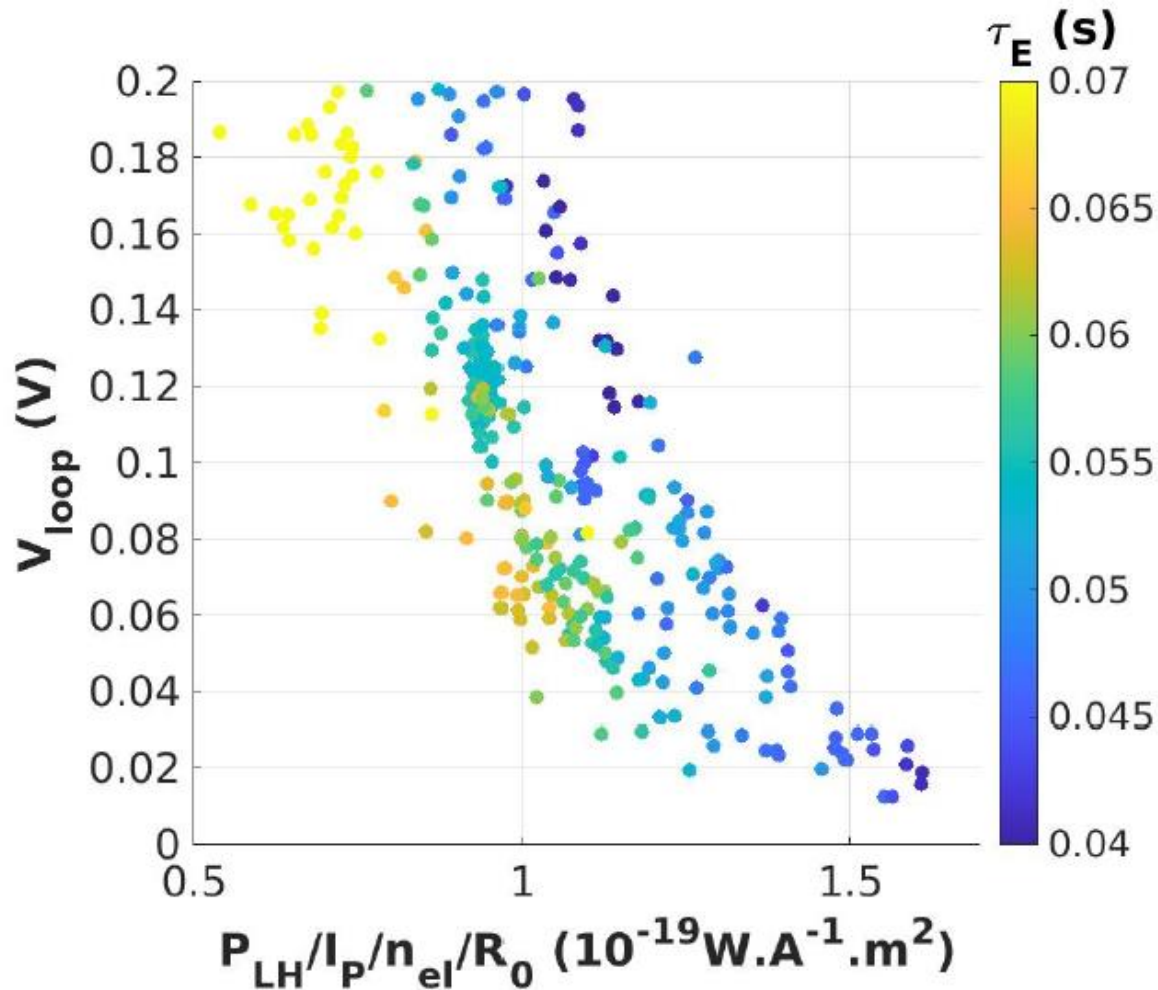
- 1. Long pulse scenario development based on integrated modelling**
- 2. Challenge #1: outgassing**
- 3. Challenge #2: UFOs**
- 4. Outlook: EC power**





# **1 ■ Long pulse scenario development based on integrated modelling**

# LHCD physics determines key parameters for non-inductive current maximization



- Loop voltage drop when LH power is applied

$$-\frac{\Delta V}{V_\Omega} = f_{bs} + \eta_{LH} \frac{P_{LH}}{\bar{n}_e R I_p}$$

- LHCD efficiency (fit)

$$\eta_{LH} = 2.37 \times 10^{19} D^{0.3} Z_{eff}^{-0.12} \tau_E^{0.4}$$

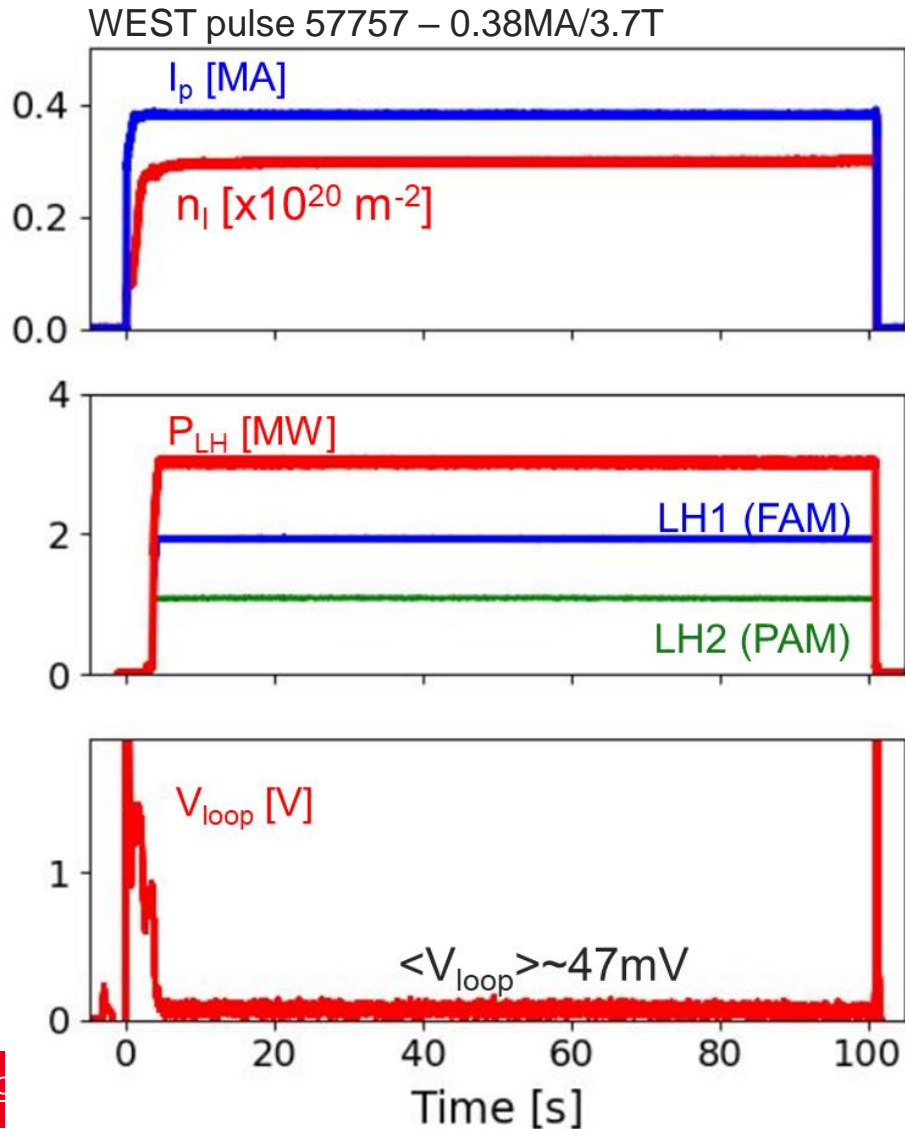
[Goniche, AIP proc. 2005]

[Fonghetti, in preparation]

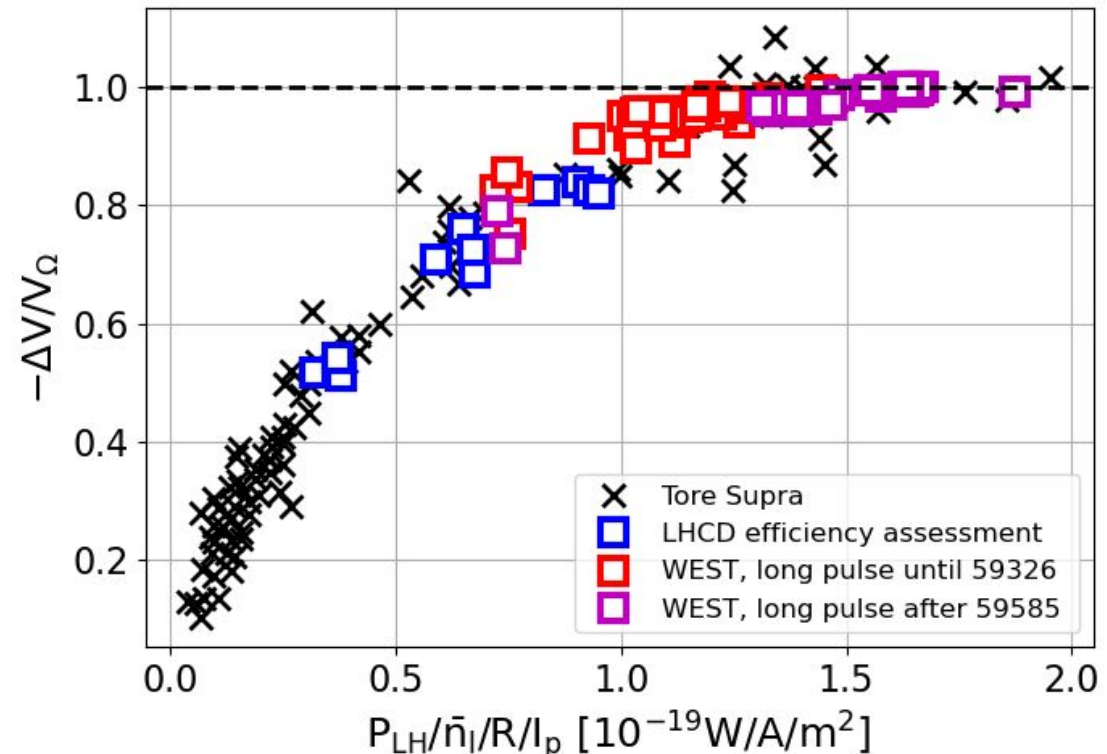
- Fraction of current driven by LH waves

$$\frac{I_{LH}}{I_P} \propto \frac{P_{LH}}{\bar{n}_e R I_p} \tau_E^{0.4}$$

# Steady progress towards long pulses in recent WEST campaigns




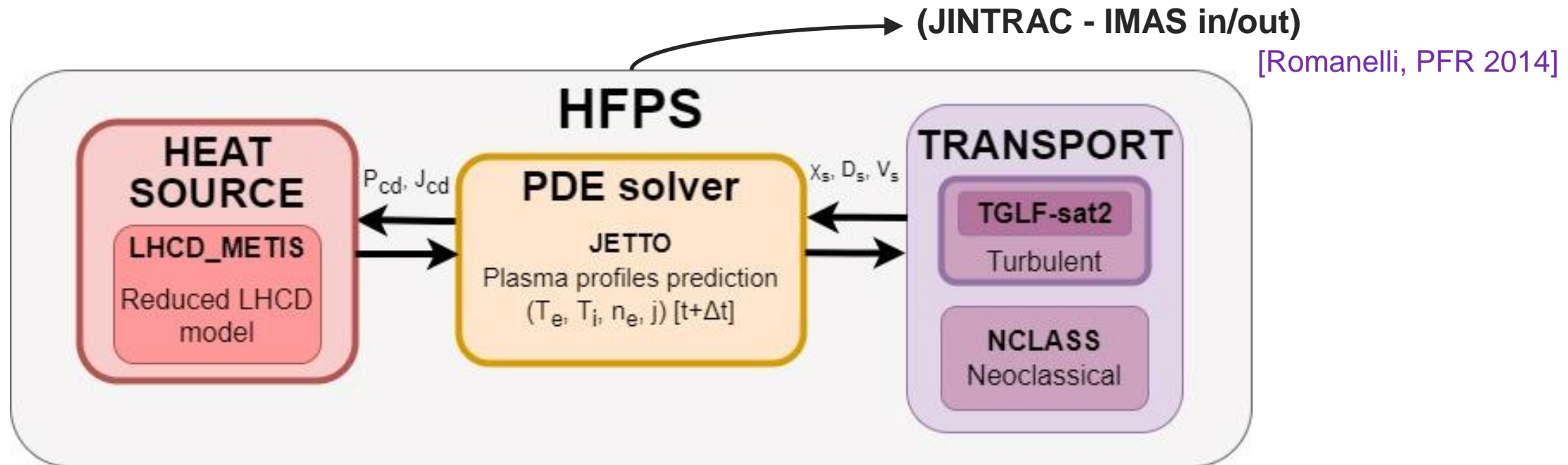
- Tore Supra LHCD efficiencies recovered, consistently with LUKE predicting no significant influence of W impurities on LHCD [Peysson, IAEA 2020]
- 02/2023: WEST pulse 57757 achieved  $V_{loop} \sim 47 \text{ mV}$  during 101s with 3MW LH power (E~290MJ) - Termination related to cooling pipe temperature interlock  
→ used as **reference pulse** for further developments



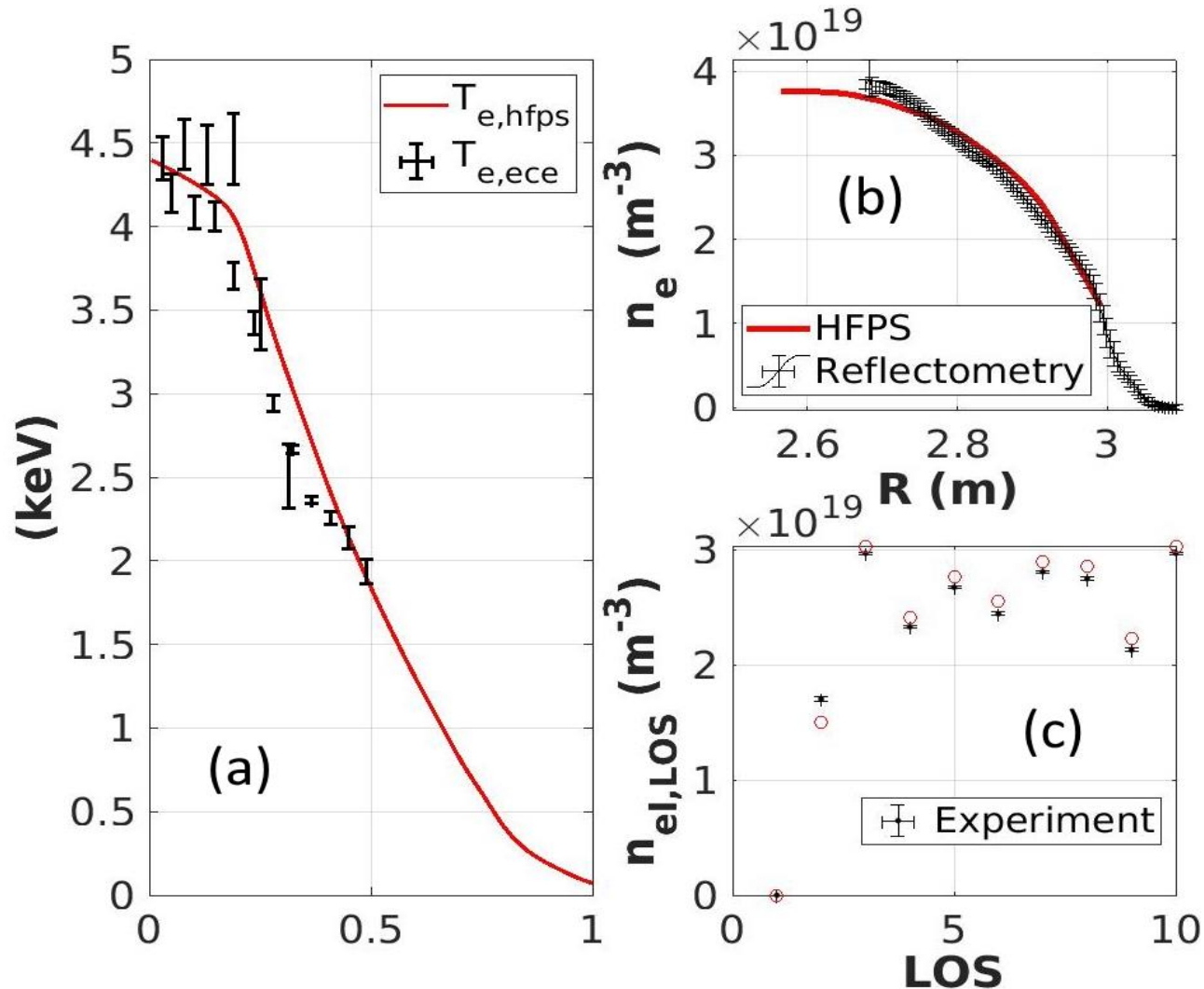


# Reference pulse interpretation requires combined description of heat source and transport

- 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]



# Integrated modelling allows plasma measurements to be recovered



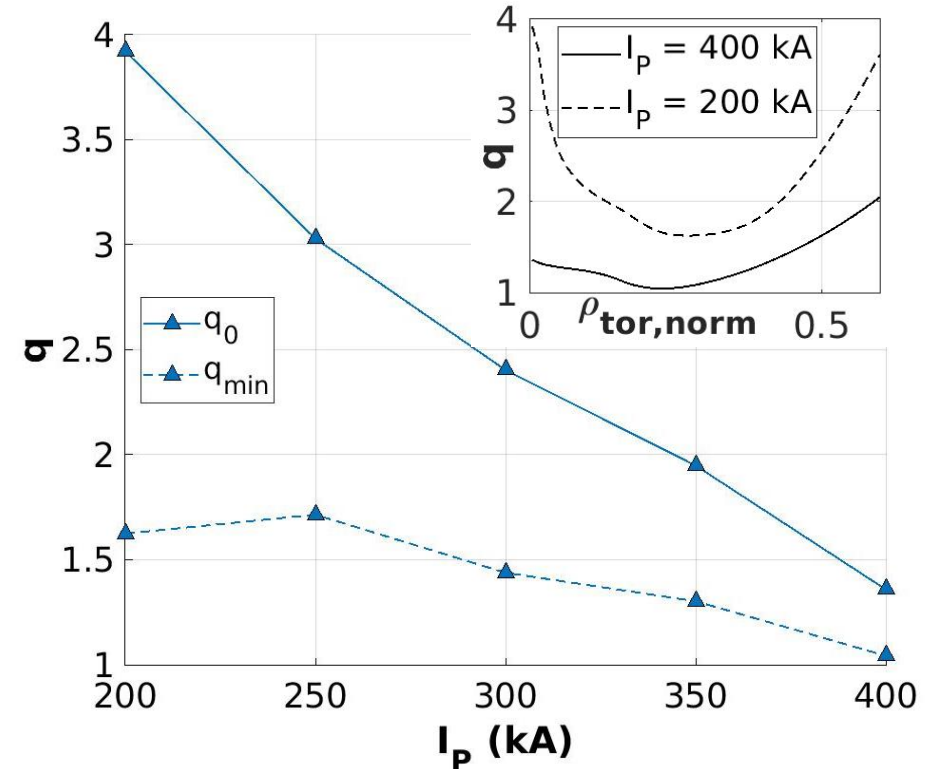
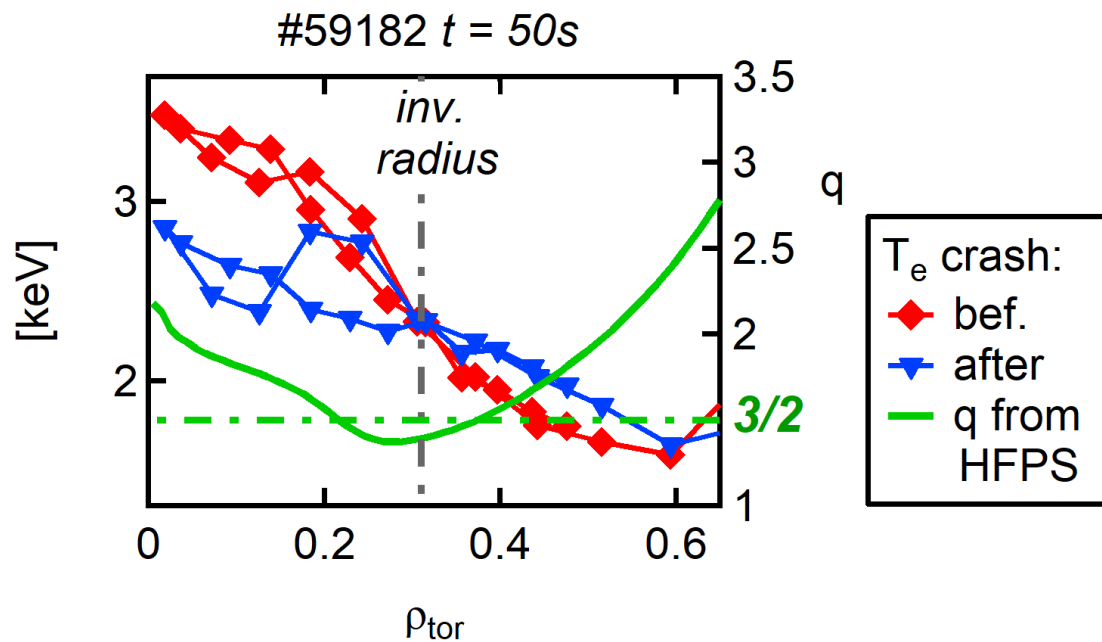
- Electron density and temperature profiles well described  $\rightarrow$  energy content recovered
- Loop voltage recovered within 10mV error range
- Standard energy confinement time dependence with  $I_p$  recovered ( $\tau_E \propto I_p^{0.59}$  found)

$$\frac{I_{LH}}{I_P} \propto \frac{P_{LH}}{\bar{n}_e R I_p} \tau_E^{0.4} \propto \frac{1}{I_p^{0.76}}$$

- HFPS simulations predict fully non-inductive operation in reference pulse conditions (0.38MA) at  $I_p \sim 0.32\text{MA}$
- However, potential difficulties related to MHD stability to be expected as current is lowered

# Decreasing plasma current / increasing LH power promotes double tearing modes

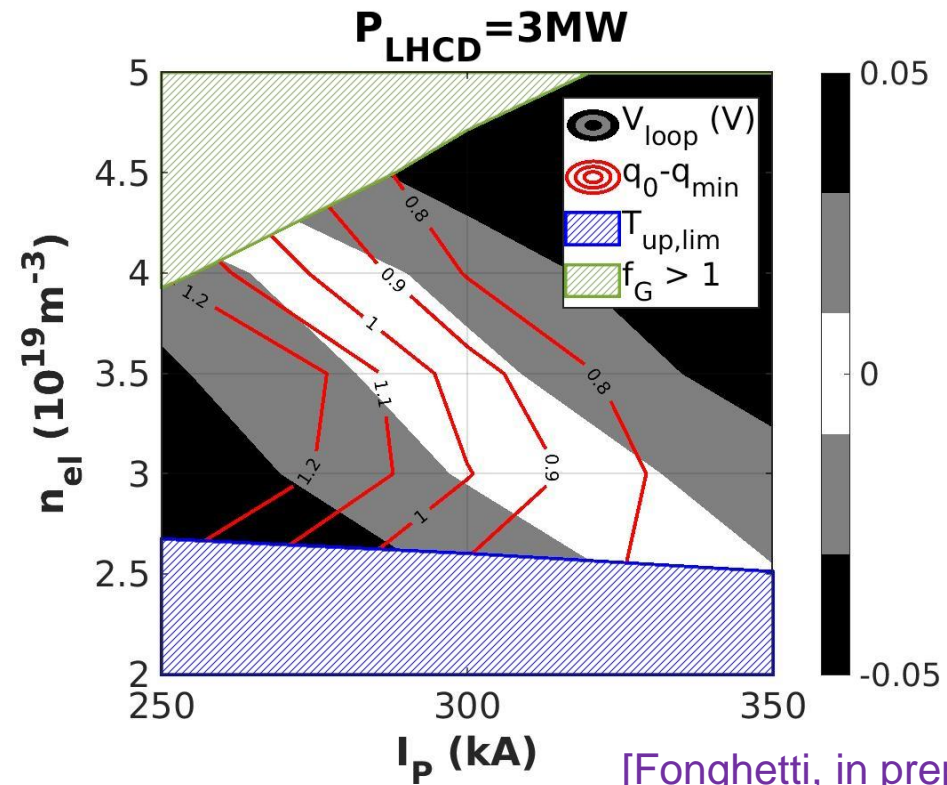
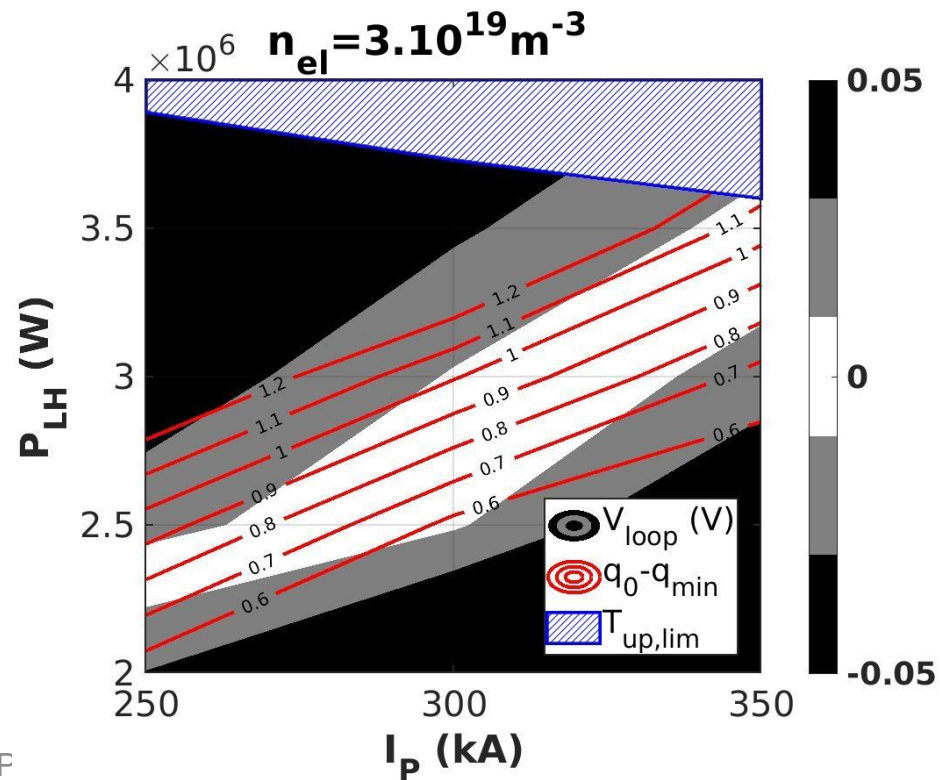
- Experimental location of MHD crashes from ECE consistent with q-profile computed by HFPS - Here (3,2) mode destabilized



- q-profile reversal enhanced at lower current (and/or larger LH power)
- Self-consistent MHD stability module for HFPS currently under test

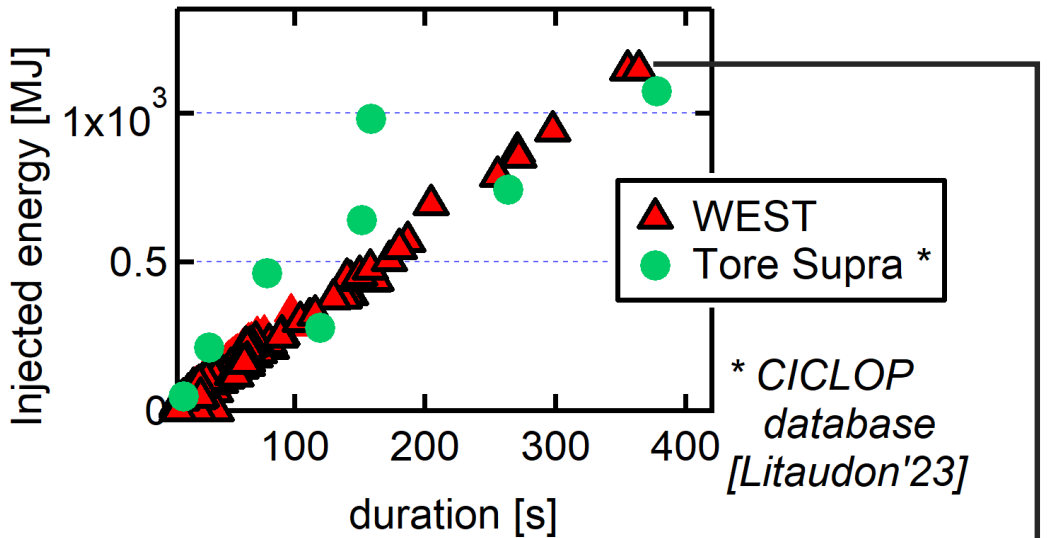
# Further predictive HFPS simulations allow parameter space to be identified

- Operational constraints:
  - Greenwald density limit
  - Upper cooling pipe temperature interlock, consistent with electron ripple loss dependences ( $T_{\max} [^{\circ}\text{C}] \sim 134 + 678 P_{\text{LH}} [\text{MW}]^{1.07} I_p [\text{MA}]^{0.58} n_{13} [10^{19} \text{m}^{-2}]^{-2.24}$ )
  - Occurrence of q-profile reversal minimized at lower  $P_{\text{LH}}$  and/or larger  $I_p$

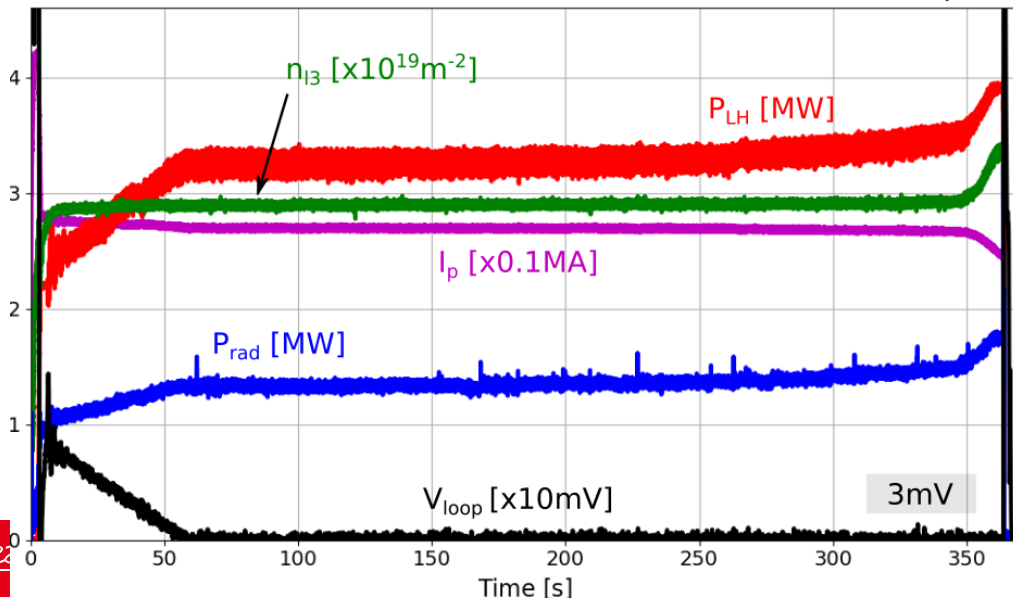




# New records achieved during latest campaign

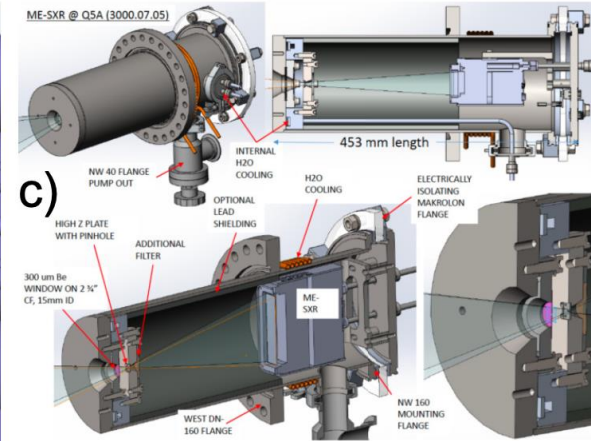
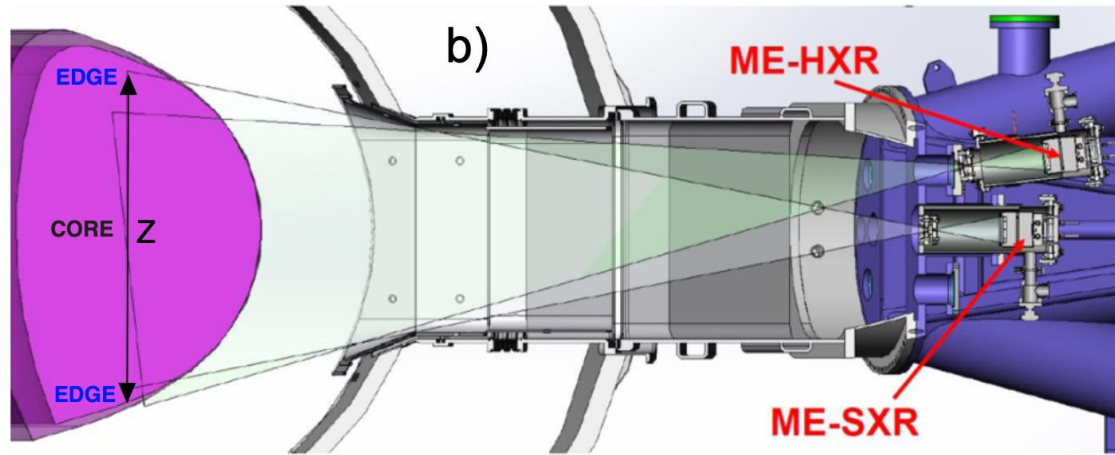
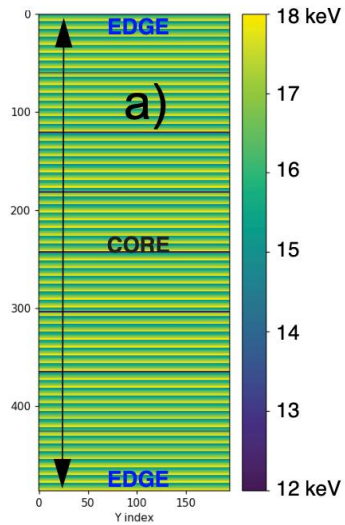


59763 - 0.27MA/3.7T

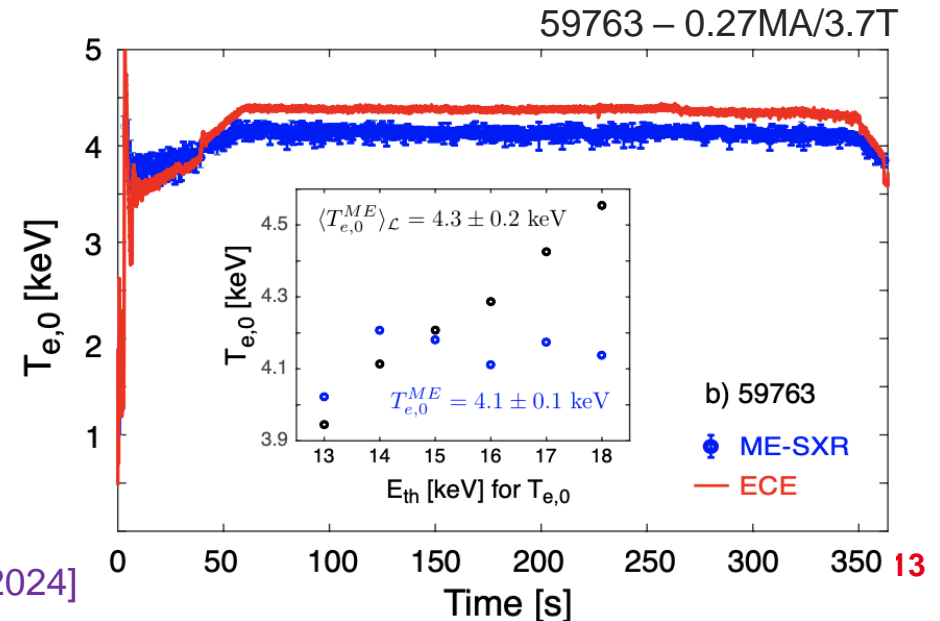


- **Pulse 59763**: new WEST duration & energy record
- **Duration: 364s**
- **Energy injected/extracted: 1.15GJ**  
(Overall energy record of WEST **and** Tore Supra!)
- Double feedback-control ( $V_{loop}$ ,  $V_{G0}$ ), ( $I_p$ ,  $P_{LH}$ )
- Plasma current 0.27MA
- LH power  $\sim 3\text{-}3.5\text{MW}$ , no ICRH
- Loop voltage: 3mV  $\rightarrow$  could in principle last  $>1100\text{s}$
- $H_{98,y2} \sim 1$ ,  $\beta_p \sim 1.6$ ,  $\beta_N \sim 0.7$
- No particular issue related to tungsten contamination
- **Several UFOs seen**, with no lasting consequences
- **Increase of density** at  $\sim 300\text{s}$ , caused by **outgassing** of remote elements in vacuum vessel  
 $\rightarrow I_p$  could not be maintained despite increase of LH power by feedback control system

# New multi-energy (ME) x-ray cameras operated @ WEST as part of US (DOE) & French (CEA) collaboration



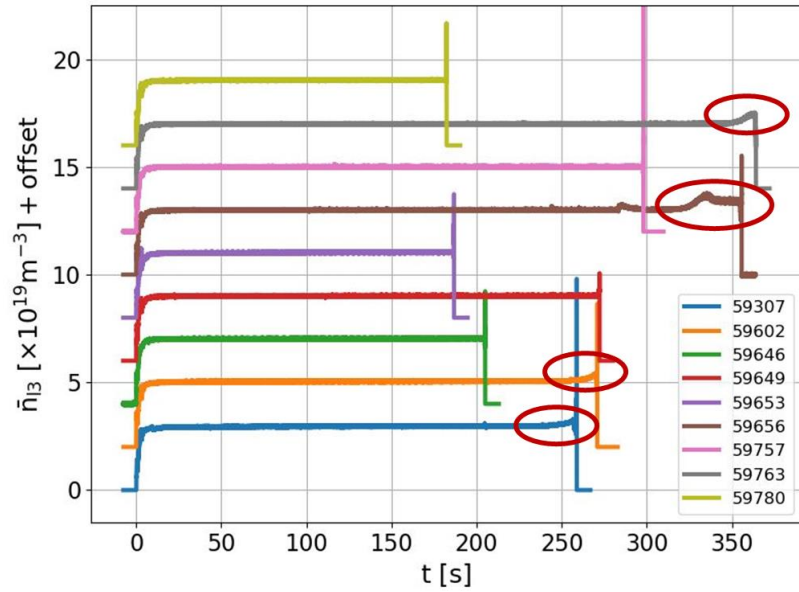
Multi-energy systems use *smart pixel technology* to disentangle  $n_W$  and  $T_e$ -effects in spatially recorded spectra



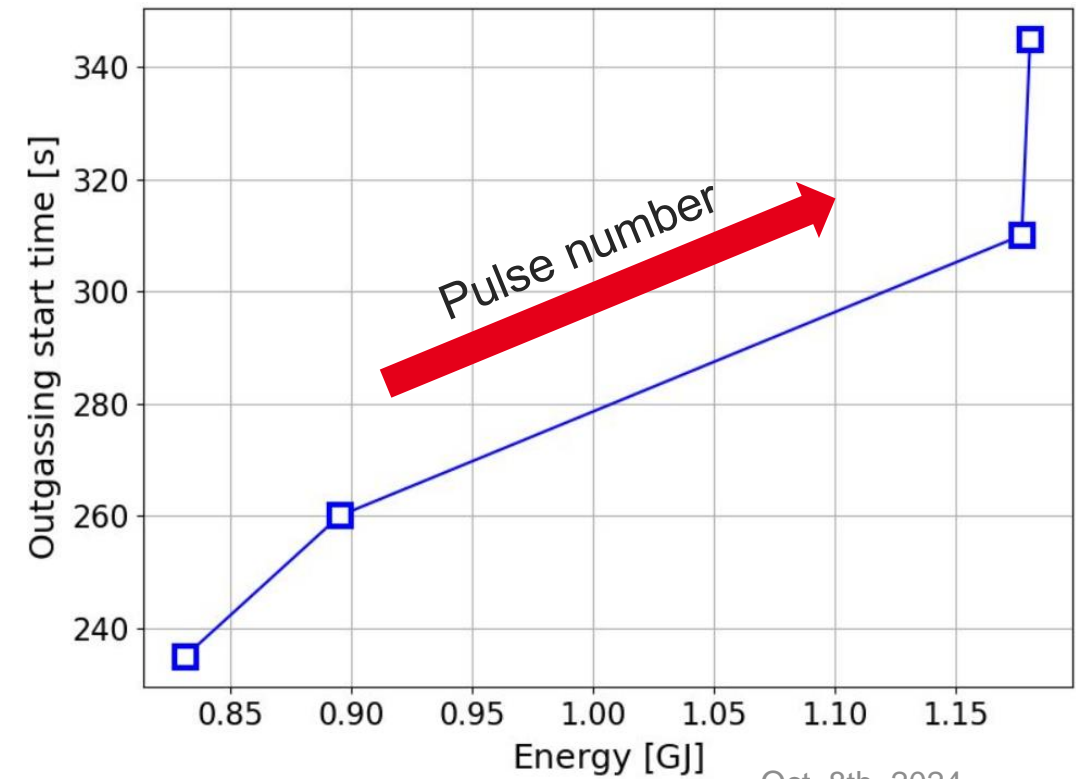
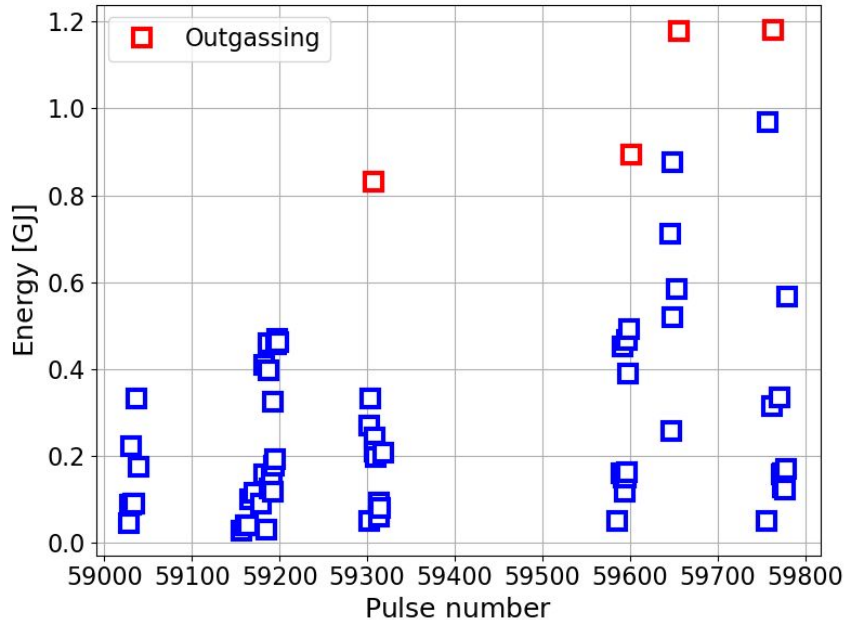


# 2 ■ Challenge #1: outgassing

# Longest duration pulses display outgassing



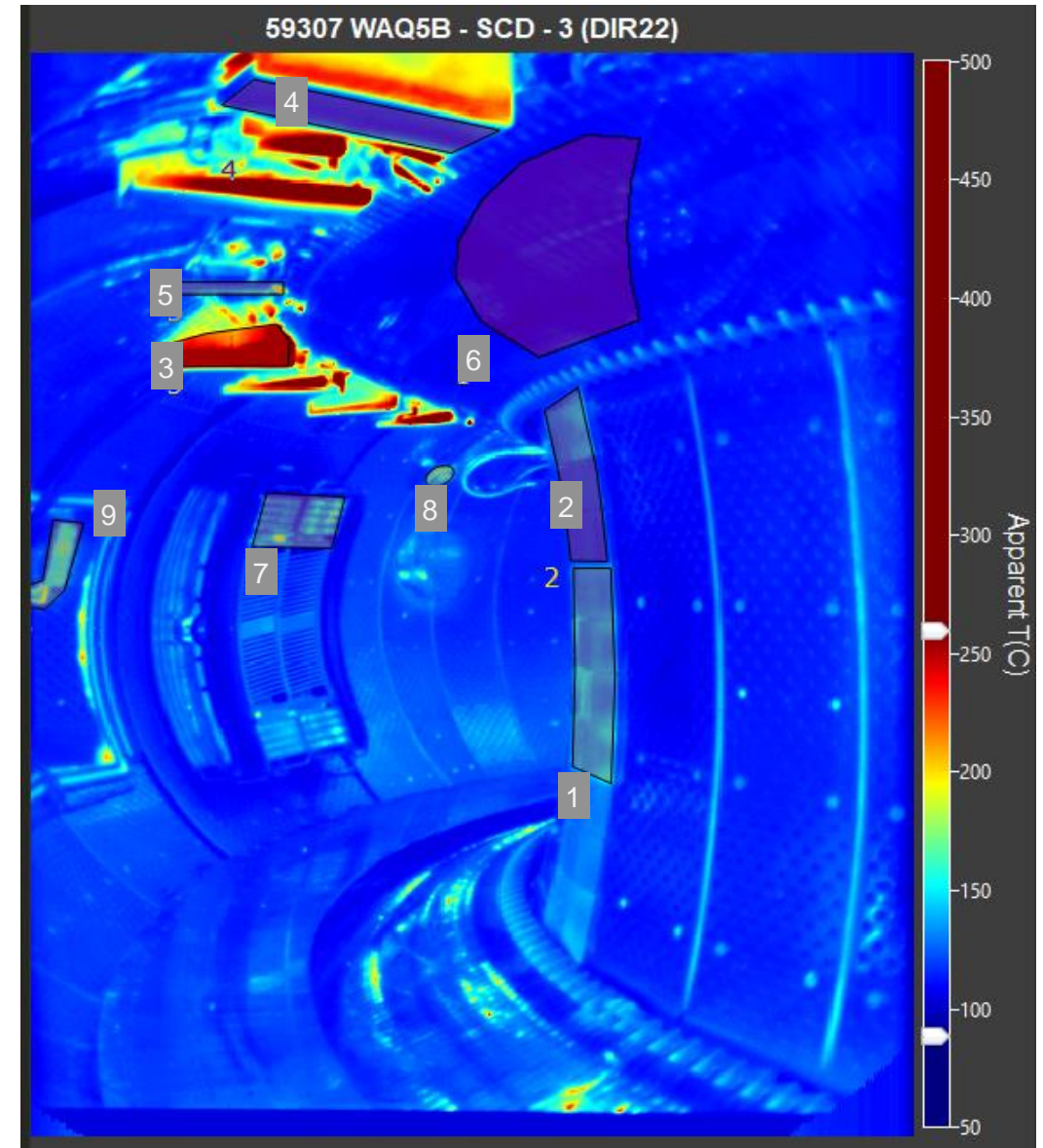
- Outgassing observed, probably related to remote elements in vacuum vessel
- Occurs at energies reaching  $\sim 1$ -1.2GJ
- Slow conditioning effect observed





# A possible suspect: BN tiles on inner/outer bumpers

- Mass spectrometer displays
  - Dominant contribution of  $D_2$  mass
  - Gradual increase of  $H_2$  and HD masses, related to wall heating and subsequent outgassing
- **BN limiter tiles** (Region Of Interest #1 in IR analysis picture)
  - Known to outgas  $H_2$  at beginning of campaigns, when poorly conditioned
  - Reach higher max. temperatures during long pulses, consistent with slow conditioning observed
  - However contribution difficult to establish firmly (e.g. no temperature threshold observed for  $H_2$  release)
- BN tiles have been removed during shutdown, replaced by W tiles → **Impact on long pulses in forthcoming campaign to be assessed**

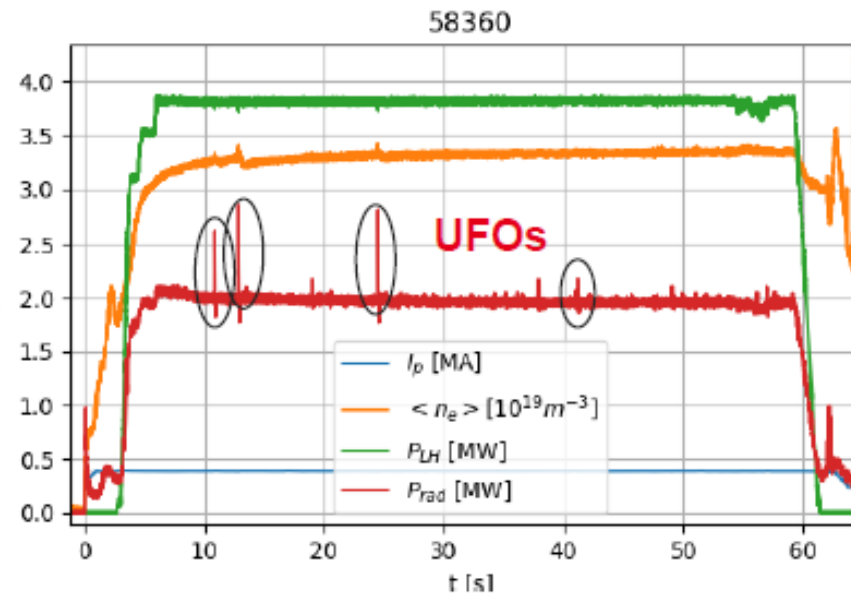
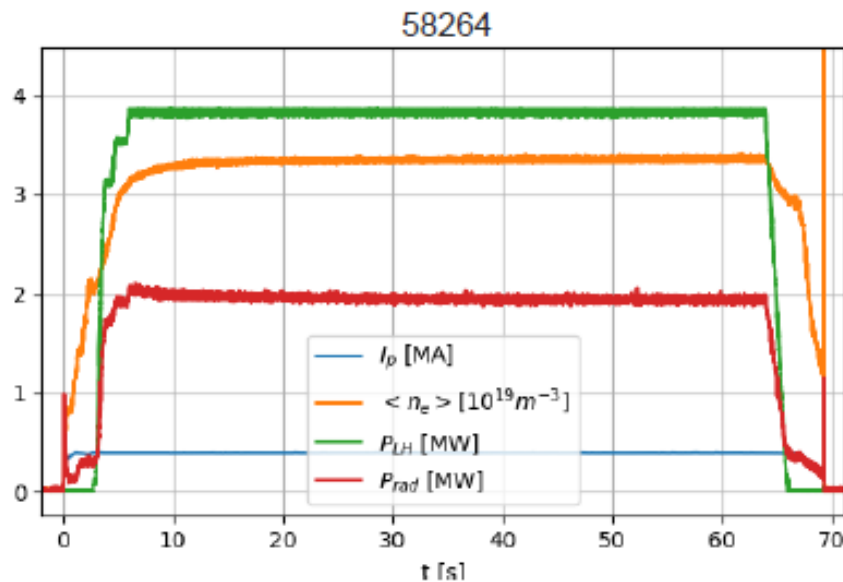




# 3 ■ Challenge #2: UFOs

# UFOs have significantly impacted high fluence operation in attached divertor conditions

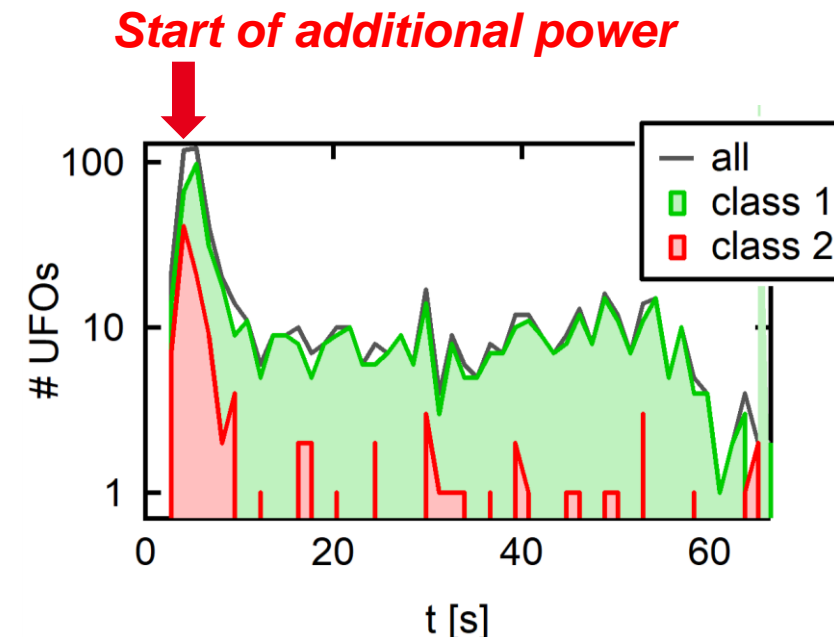
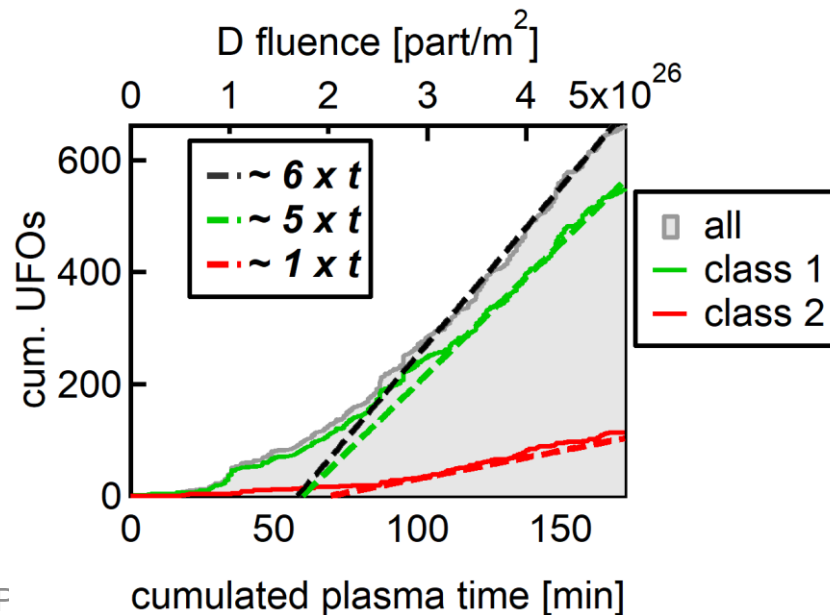
- High Fluence campaign performed in 2023 in L-mode attached divertor regime
  - Cumulated plasma time of about 3h in attached regime ( $T_e$  divertor  $\sim 20$  eV), without boronisation
  - Cumulated fluence at lower divertor reached  $5 \times 10^{26}$  D/m<sup>2</sup> (more than an ITER PFPO pulse)
- Divertor erosion generates deposits, flakes and UFOs
  - Short peaks of radiated power, becoming more and more frequent  $\rightarrow$  impact on plasma operation
  - Extensive identification and analysis of UFOs performed [Gaspar, NME 2024]



# Formation & ejection of flakes on divertor elements



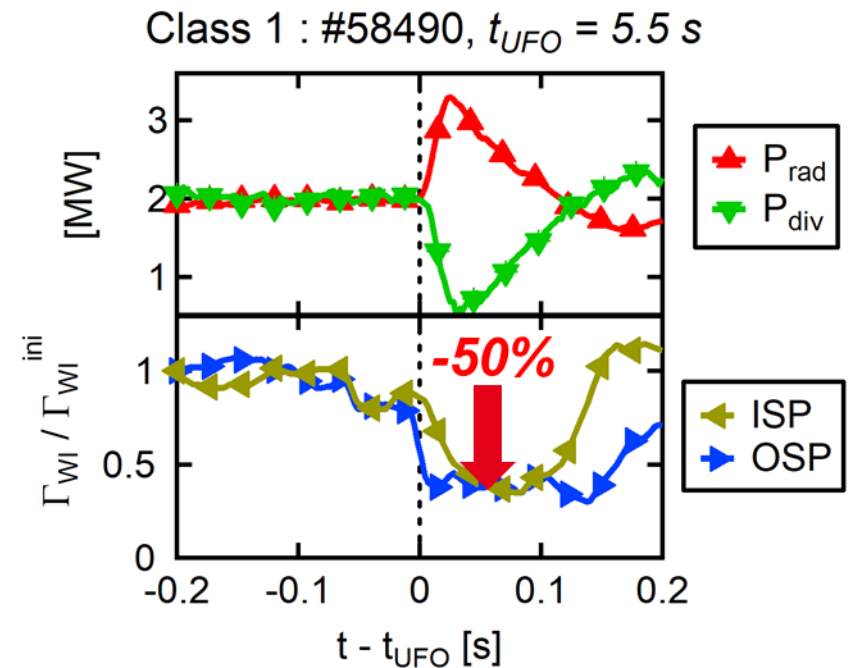
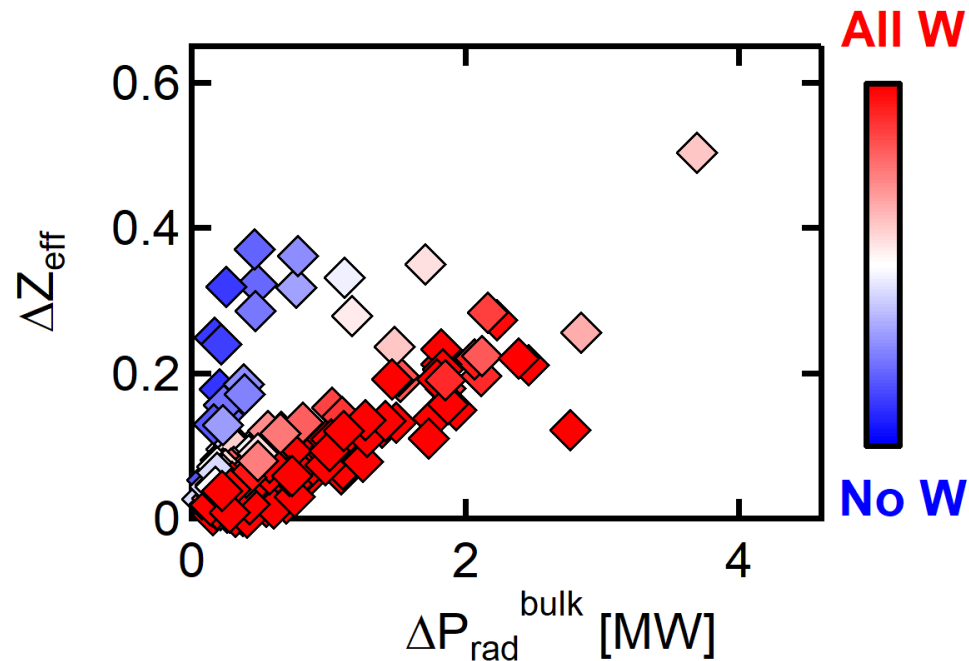
- UFO classified in three categories
  - 1) Minor impact (~80%) / 2) Disruption after more than 0.2s (~17%) / 3) Disruption after less than 0.2s (~3%)
  - Stationary regime after ~ 100 min of plasma for classes 1 and 2, but class 3 still growing
- Similarities between WEST UFOs and W dust size evaluated on JET-ILW (~Ø140-180µm) [Sertoli, JNM 2014]
  - However, no UFO issues reported in JET high fluence experiments [Brezinsek, NF 2019]  
→ difference in divertor geometry, temperature, inner wall material?
- Origin of the UFOs
  - Temporal: mostly at the start of the additional power → thermal stress as the main trigger
  - Spatial: mostly coming from the High Field Side (HFS) region [Gaspar, NME 2024]
  - Historical: most UFOs originate directly from the thick deposits



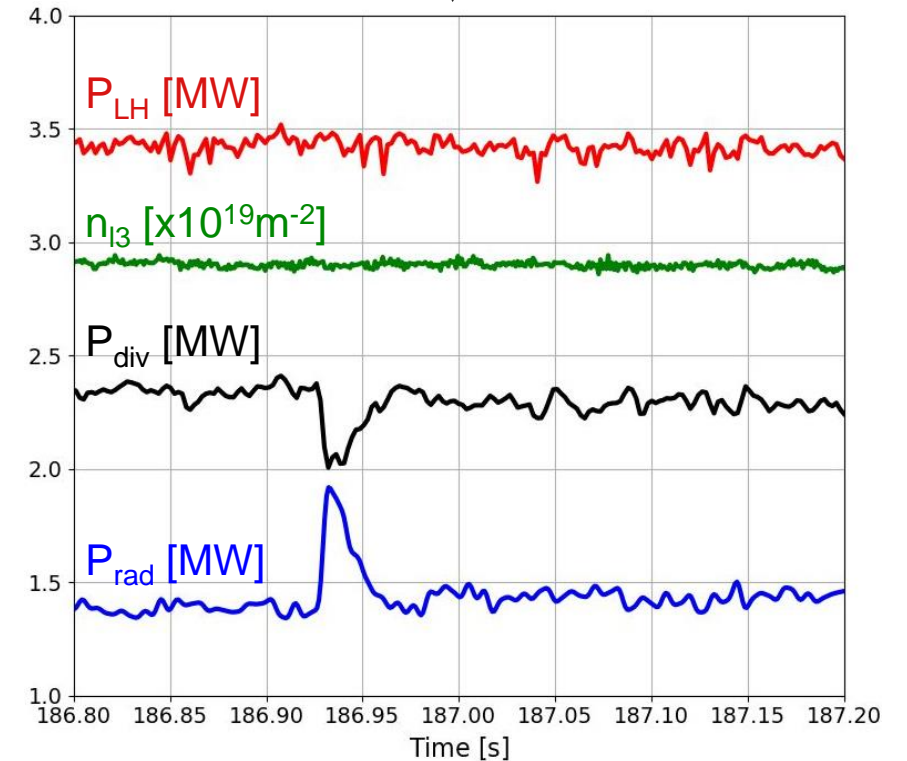
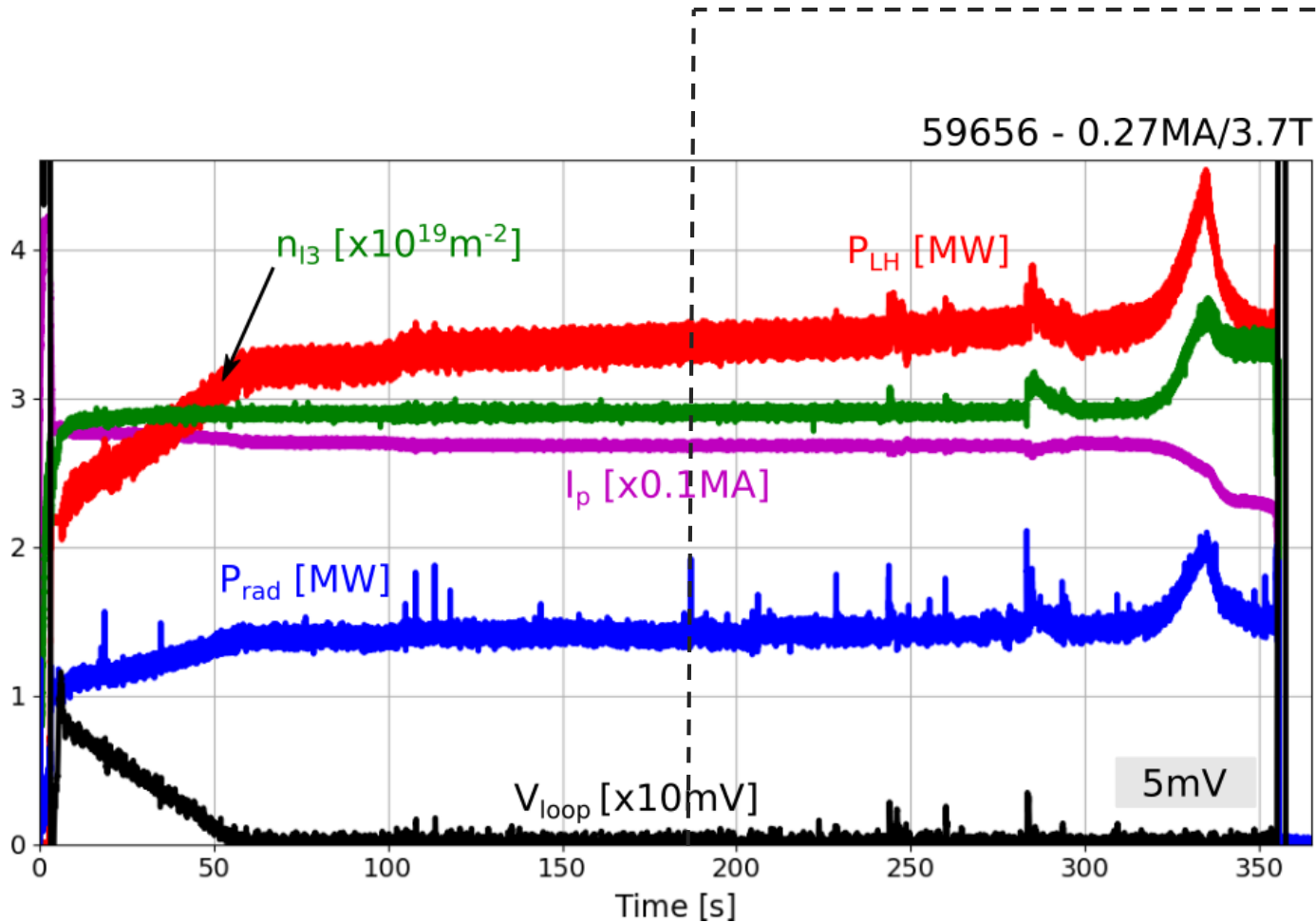


# UFO composition and radiation resilience

- UFO composition
  - From Zeff / bolometry measurements: mostly tungsten, but light impurities sometimes present
  - In line with previous post-mortem results on deposit composition [Hakola, NF 2021; Balden, PS 2021]
- Consequences for plasma operation:
  - **Class 1**: reduction of incoming W flux after UFO → fixed operation point in frad (resilience)
  - **Classes 2 & 3**: radiation peak impacts safety factor profile → MHD stability degraded

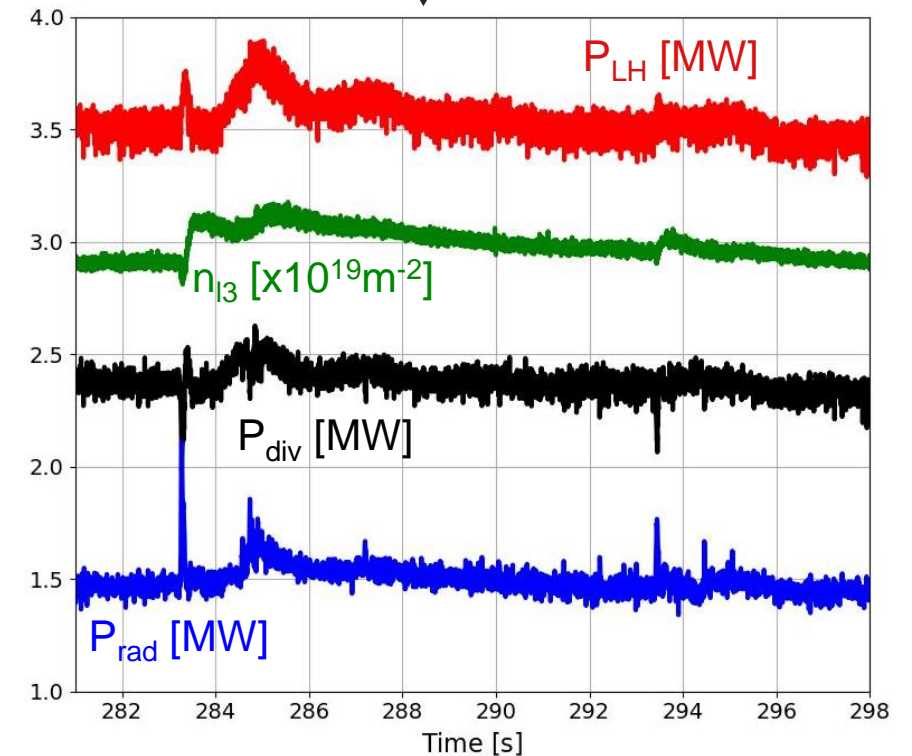
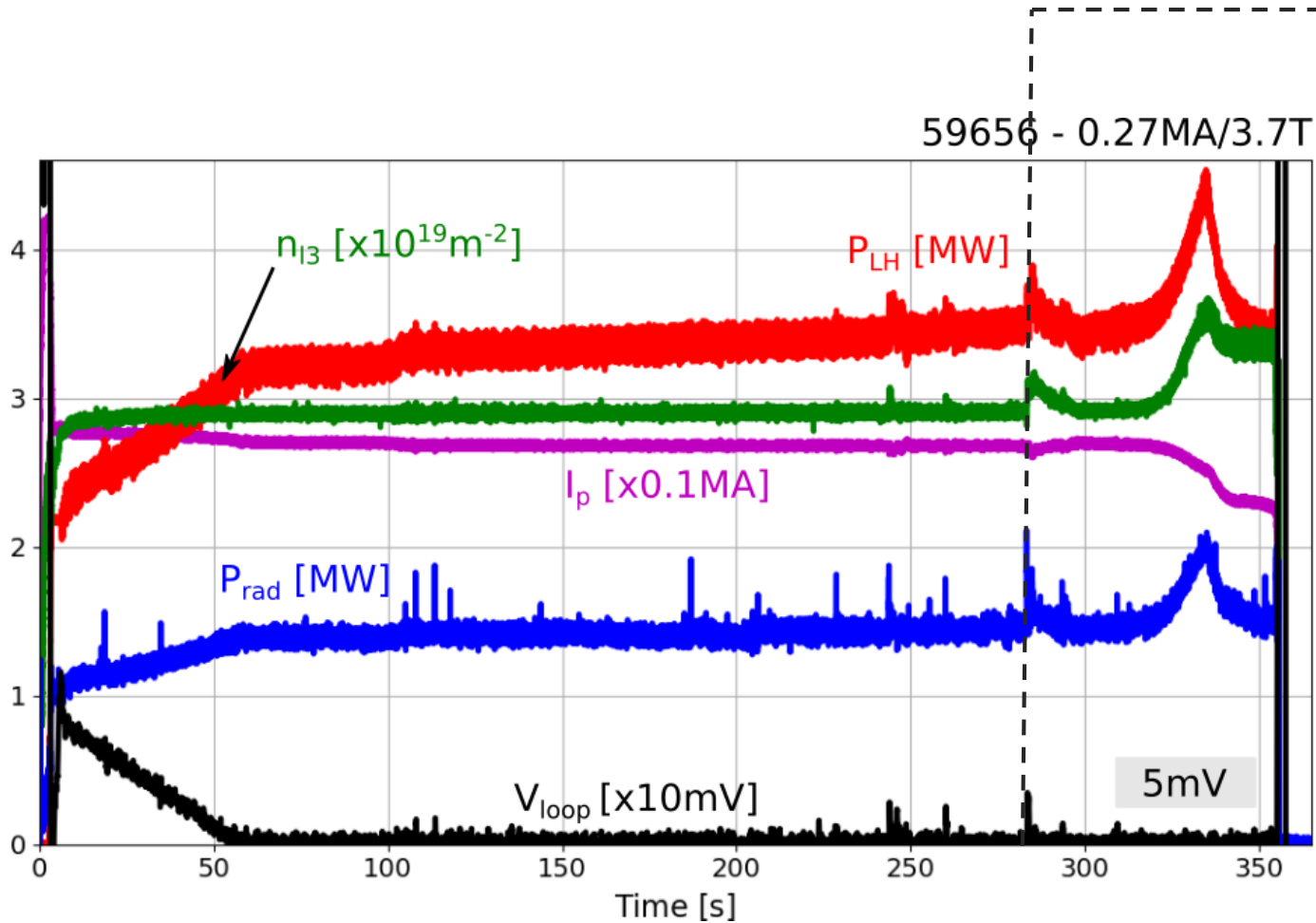


# Class 1 UFOs observed in non-inductive discharges, transiently impact performance



- **Smallest** UFOs does not impact density, loop voltage  $\rightarrow$  no LH power response

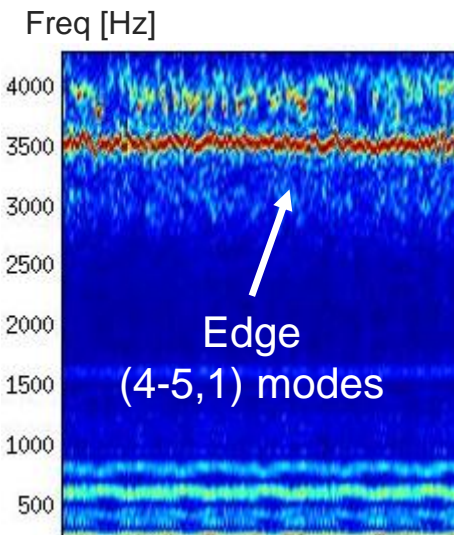
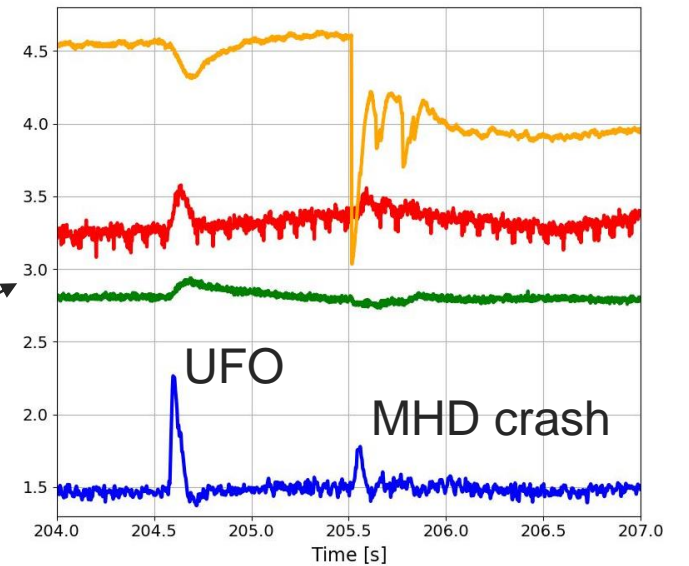
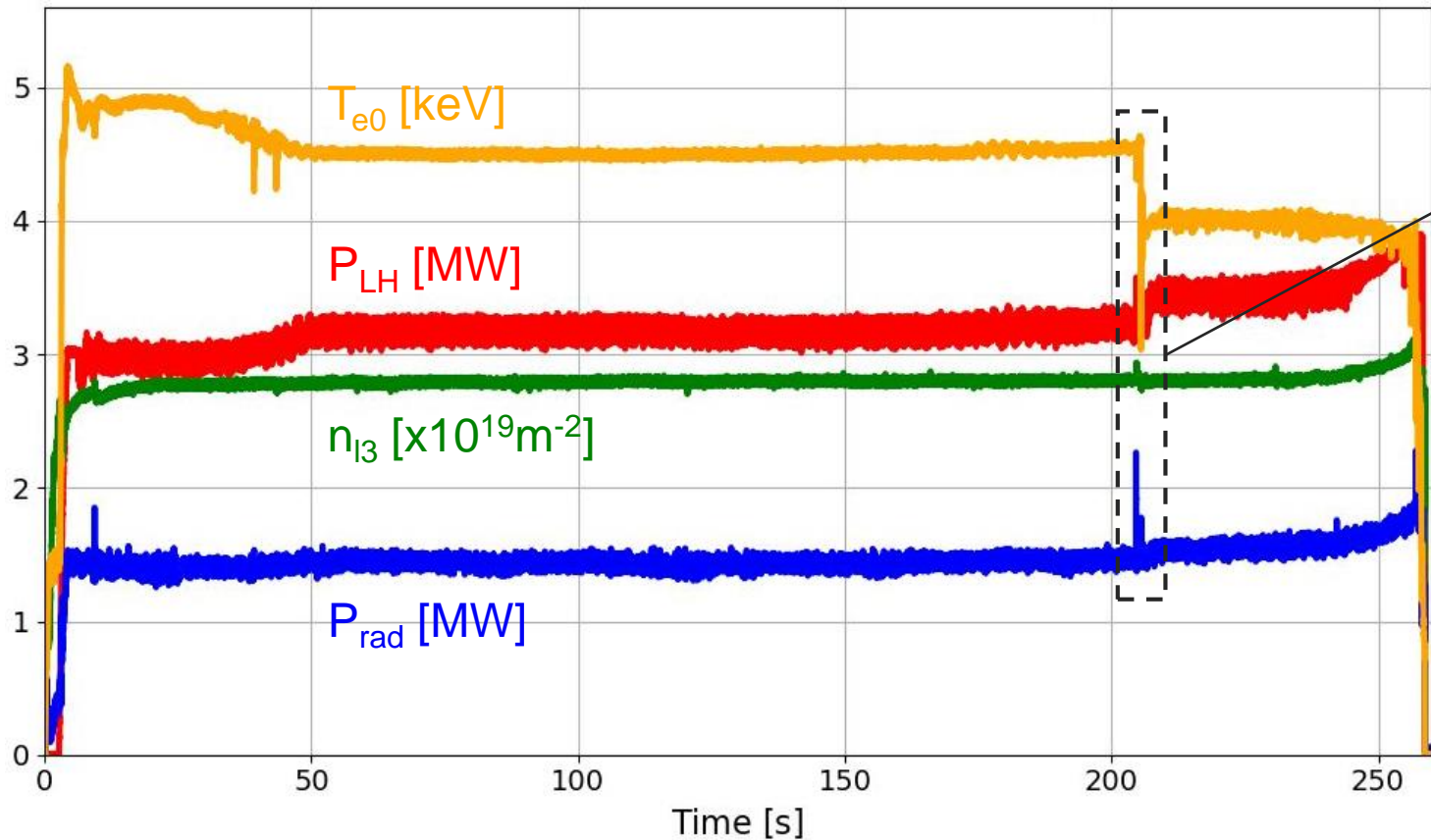
# Class 1 UFOs observed in non-inductive discharges, transiently impact performance



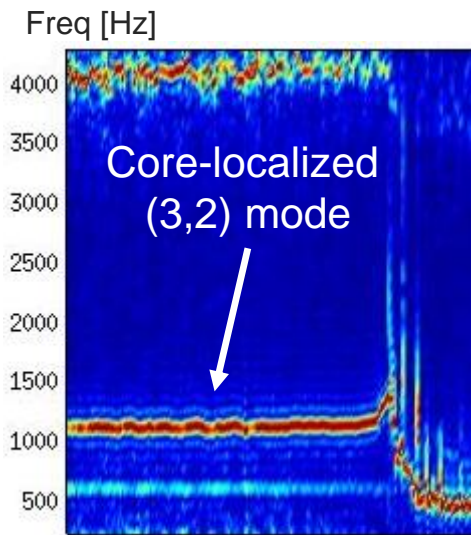
- Larger UFOs can increase significantly density, loop voltage, plasma current  $\rightarrow$  transient LH power response ( $\sim$ few seconds)

# Class 2 UFOs can alter current profile, leading to MHD crash and poor confinement

59307 – 0.32MA/3.7T



t~24s



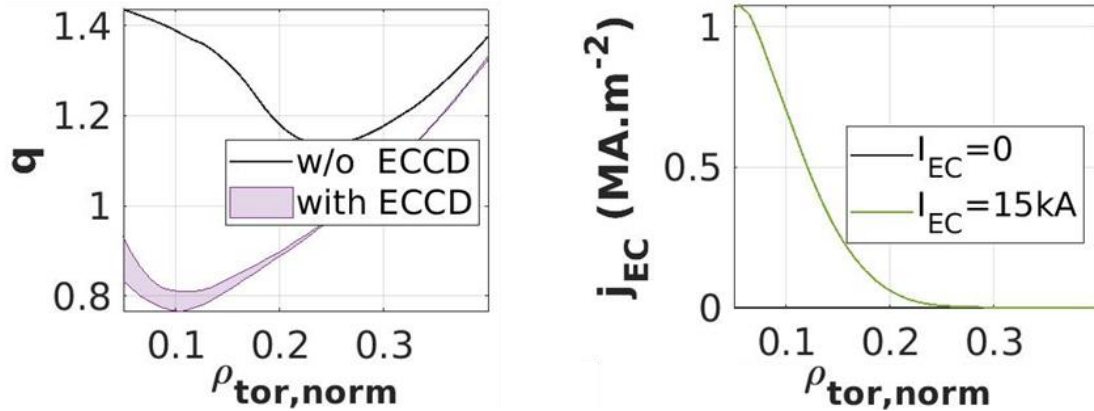
t~256s 23



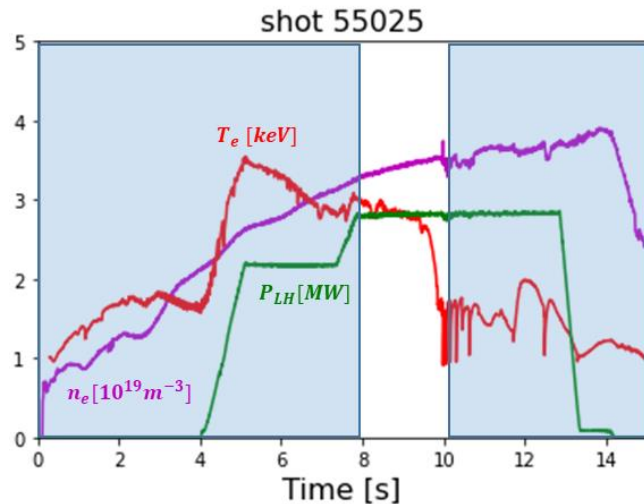


# 4 ■ Outlook: EC power

# EC power to enlarge parameter space, help increase performance in non-inductive regimes



HFPS simulation of central ECCD to control q-profile reversal [Fonghetti, in preparation]



Radiative collapse in a LHCD-only pulse, caused by combination of W radiation and off-axis LH power deposition [Ostuni, NF 2022]

- EC power available in next WEST campaigns: 1MW in 2024 → 3MW in 2025
- Applications to long-duration pulses
  - Central ECCD to control q-profile reversal [Fonghetti, in preparation], improve overall CD efficiency → possibility to control current profile, operate at larger densities
  - Central ECRH against radiative collapses observed as density increased [Ostuni, NF 2022] or ICRF power applied [Maget, PPCF 2023]
    - Counterbalances central radiation in unstable range of electron temperatures ( $T_e \sim 1.5-3\text{keV}$ )
    - “Anchors” LH deposition profile to plasma core
    - Opens the possibility to use ICRF power, beneficial for MHD stability when  $V_{loop} \sim 0$  [Dumont, PPCF 2014]
- H-mode access
- MHD control
- ...

# Summary and prospects

- **Many adaptations to WEST hardware and software systems to prepare for long durations**
  - Opens the possibility to explore various aspects related to Long Pulse Operation relevant to future devices, including ITER:
    - Boronization and long-term influence of conditioning [Gallo, this conference; Afonin, this conference]
    - Deposits and flakes on divertor elements (e.g. UFOs)
    - Plasma-wall equilibration aspects impacting plasma scenarios (e.g. fuelling & exhaust, outgassing, ...)
- **Discharges with  $V_{loop}$  down to ~3mV achieved, could in principle be extended to >1000s durations**
  - Double feedback-control ( $V_{loop}$ ,  $V_{G0}$ ), ( $I_p$ ,  $P_{LH}$ ) successfully implemented
  - Outgassing appears when E reaches ~1-1.2GJ, possibly linked to BN tiles. Slow conditioning effect observed
  - UFOs can adversely impact performance
- **New record pulse: 364s (59763), over Tore Supra energy records**
  - Developed using “predict-first” integrated modelling based on reference discharges from previous campaign
- **Outlook**
  - Long-duration scenarios in low-temperature divertor regimes currently under development
  - EC power will enlarge parameter space, help increase performance in non-inductive regimes