IAEA Fusion Energy Conference October 13th - 18th 2025 – Chengdu, People's Republic of China

WEST LONG-PULSE ACHIEVEMENTS IN SUPPORT OF NEXT-STEP FUSION DEVICES

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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.

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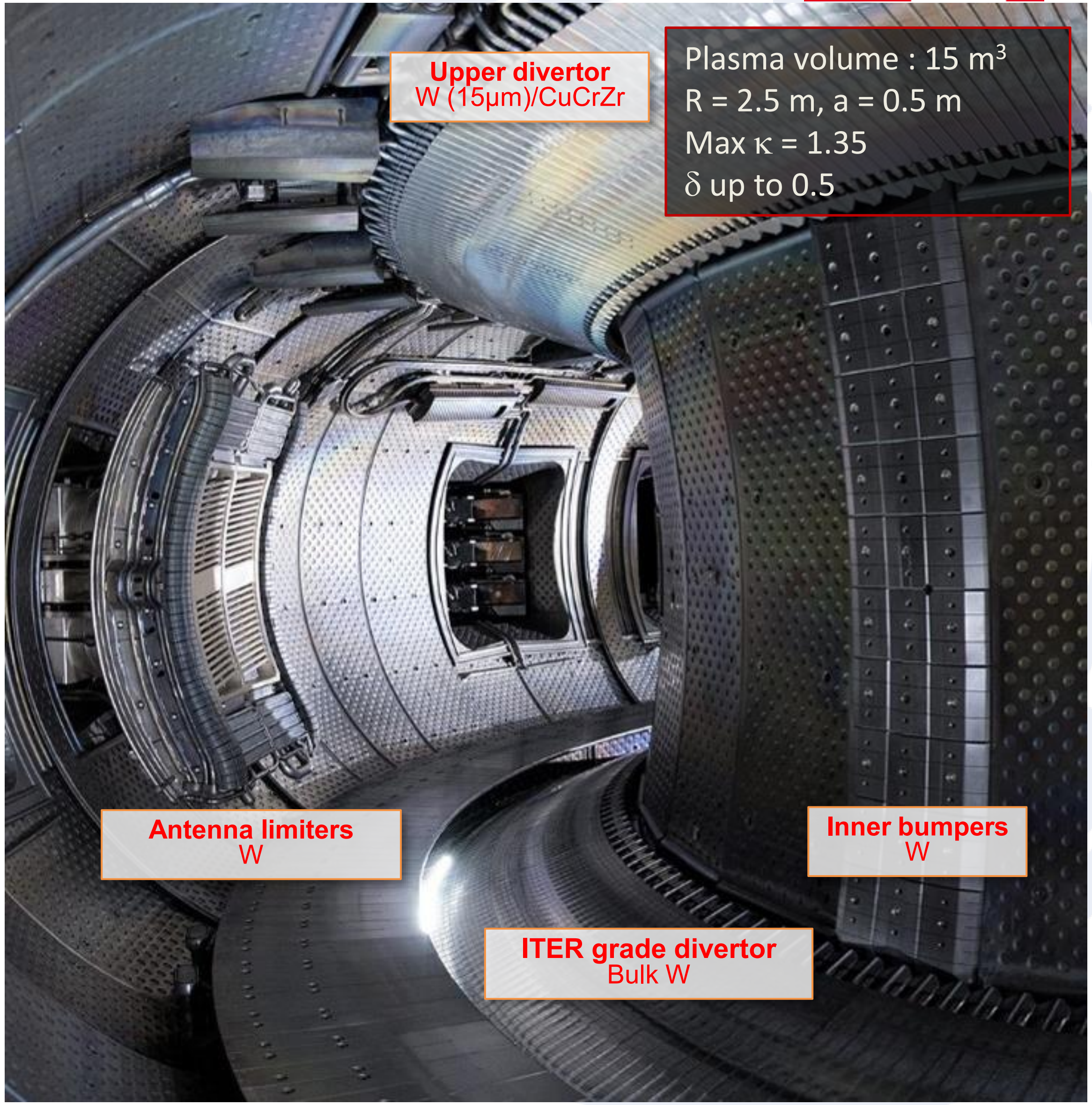
Long pulse operation: a crucial element in the development of fusion-based power plants

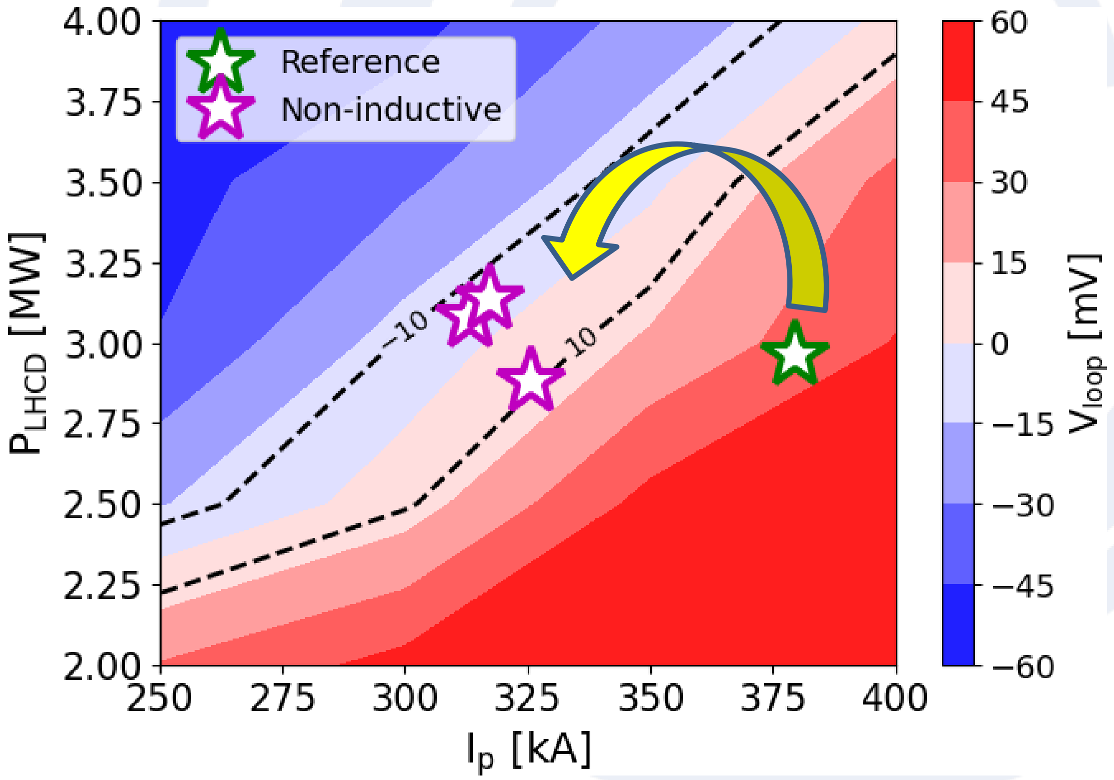
- Long Pulse Operation [Litaudon, 16/10 PM, P4-2770]
  - Discharges with durations well above the characteristic plasma times, approaching plasma-wall interaction timescales
  - Specific topics:
    - First-wall material studies (erosion, surface damage, fuel retention) [Corre, 17/10 16:30, oral]
    - Technical aspects related to long pulses [Lamaison, 16/10 16:30, oral; Mitteau, 18/10 AM, P7-3049]
    - Integrated high-performance long-pulse plasma scenarios (this talk)
- WEST: a testbed to prepare for long pulse operation in ITER [Bucalossi, 14/10 14:50, overview]
  - Superconducting magnets, nominal field B_0~3.7 T
  - Full-tungsten environment, with periodic glow discharge boronizations [Geulin, 18/10 AM, P7-3072]
  - Bespoke radiofrequency (RF) systems
    - ICRH (~55 MHz)
    - LHCD (3.7 GHz)
      2 launchers: 7 MW/CW
    - ECRH/CD (105 GHz)
      1 antenna: 1 MW, started operation in 2025 → 3 MW (2026)

  → dominant electron heating / low torque

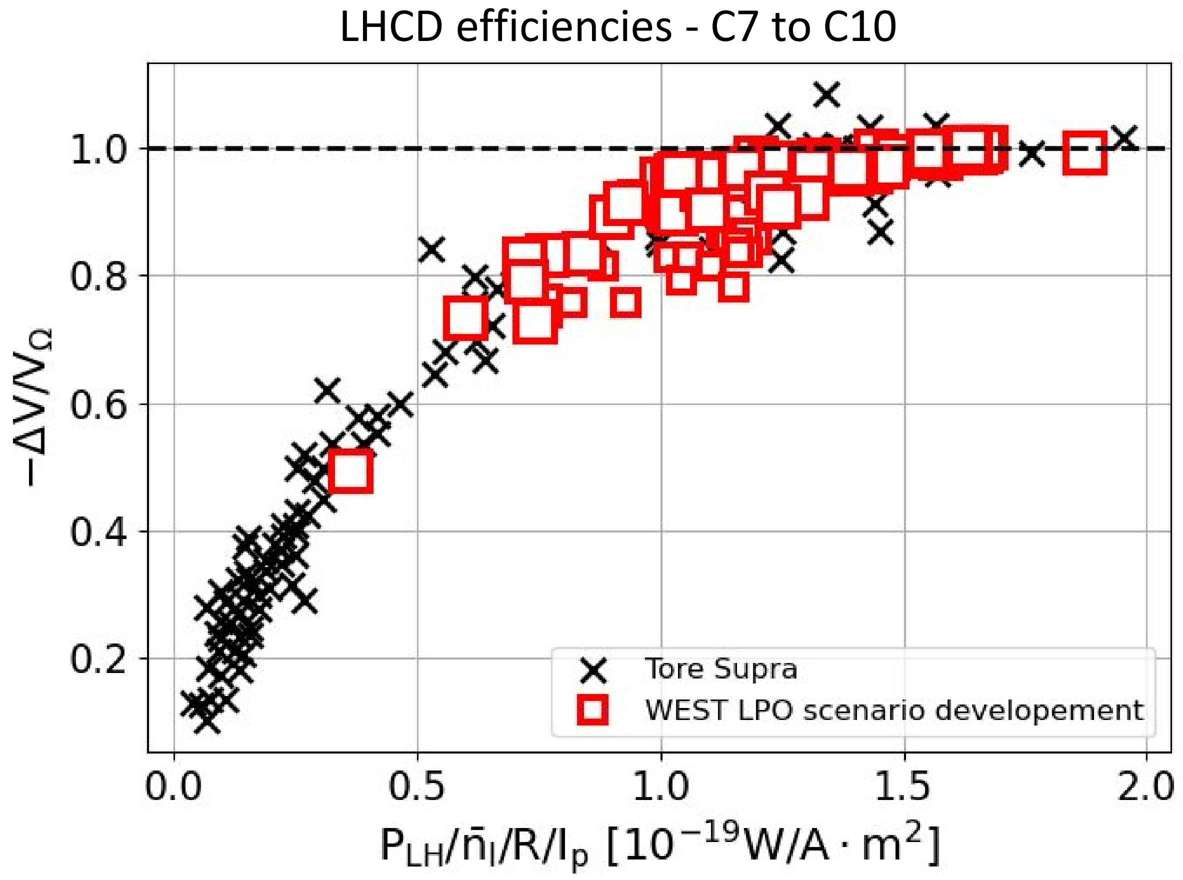


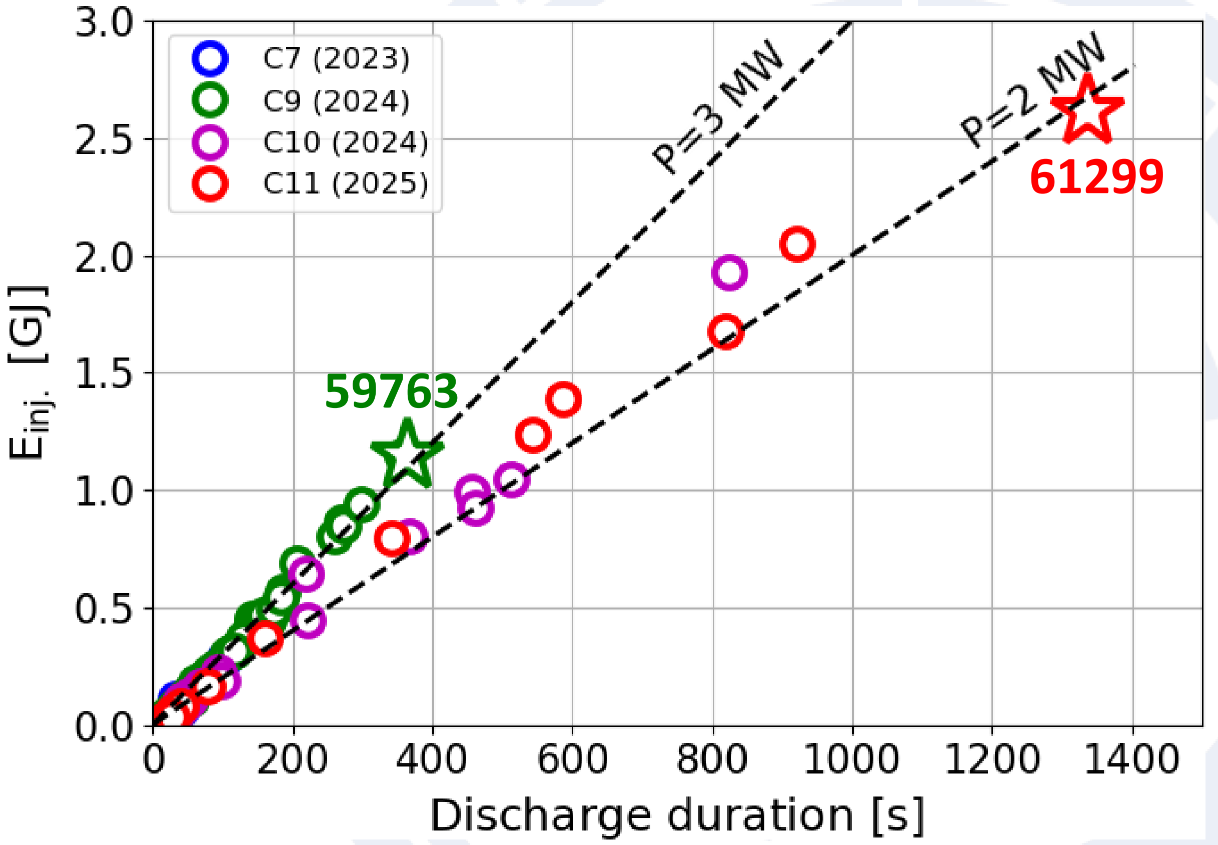
Pulse development in WEST based on predict-first integrated modelling strategy

- 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: $\eta_{LH} \alpha \tau_E^{0.4}$ [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_{loop}=47 mV) for thorough code validation
  - Predictive HFPS simulations to identify parameter domain adequate for non inductive operation [Fonghetti, NF 2025]



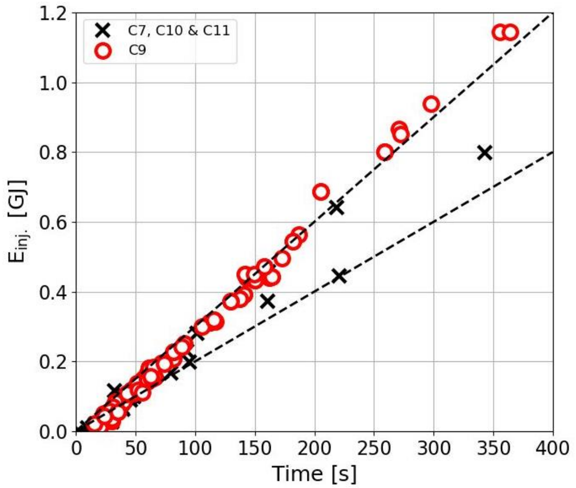
Continuous progress in long pulse development, based on LHCD power during the 2023-2025 period

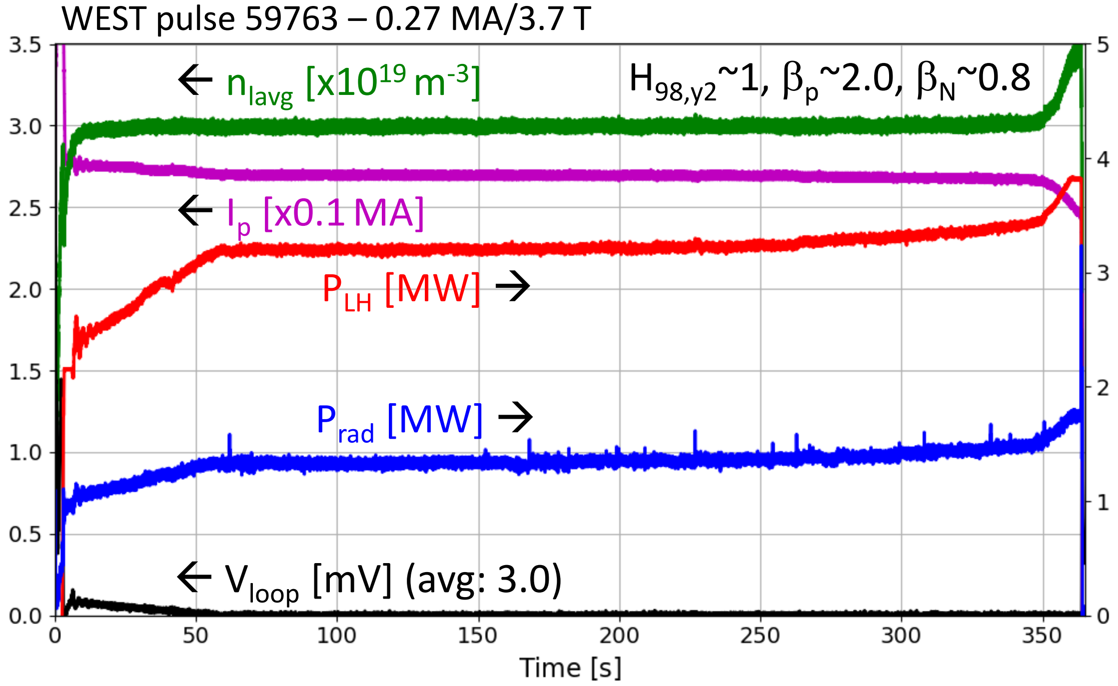




- Tore Supra LHCD efficiencies recovered, consistently with Fokker-Planck calculations (LUKE) predicting no significant influence of W impurities on LHCD [Peysson, 15/10 PM, P2-2743]
- Twenty L-mode discharges exceeding 200 s performed, with LHCD power only

Outgassing from far-off elements limited development of 3 MW-class scenarios



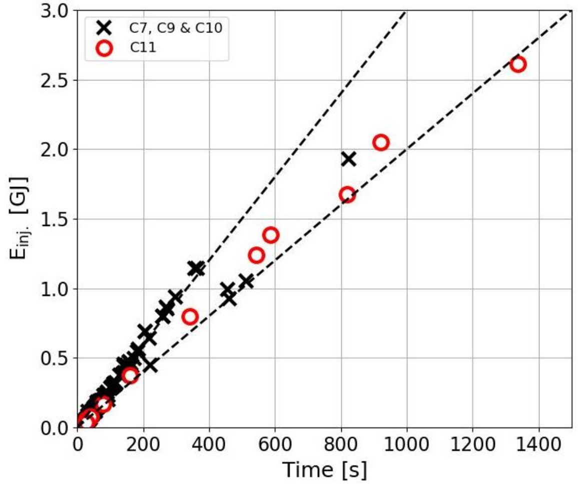


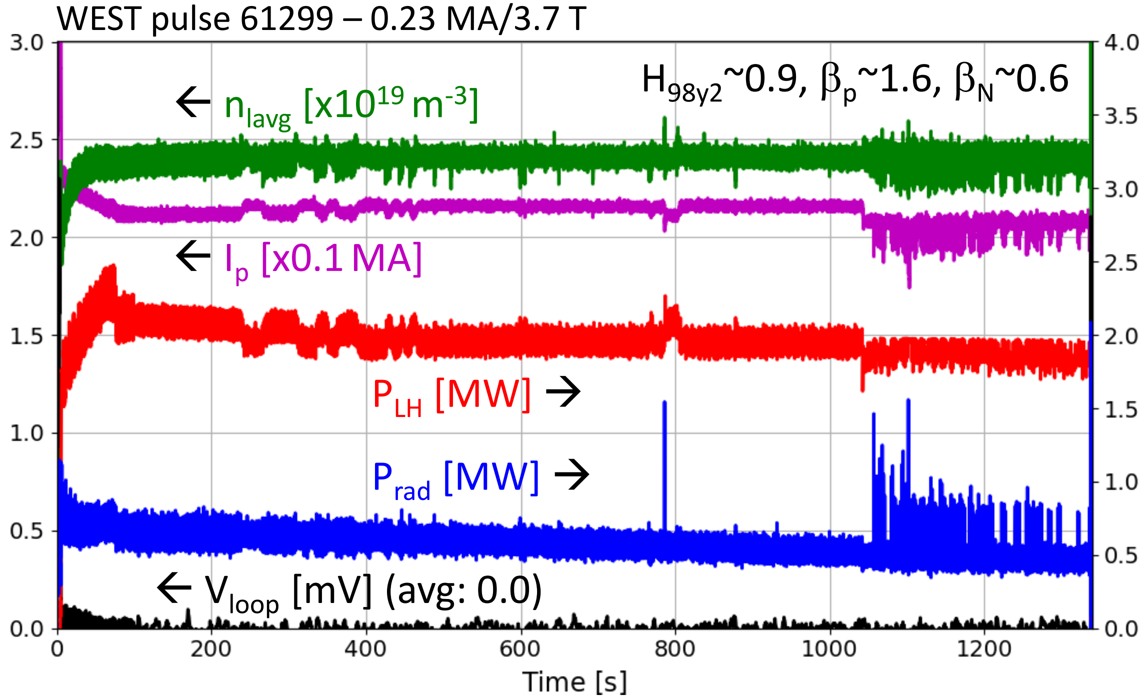
WEST pulse 59763

- Duration: 364 s
- Energy injected/extracted: 1.15 GJ
- Double feedback-control (V_{loop}, V_{CS}), (I_p, P_{LH})
- Plasma current 0.27 MA, LHCD power ~3-3.5 MW
- Loop voltage: 3 mV → could in principle last >1100 s
- Increase of density at ~300 s, caused by outgassing of remote elements in vacuum vessel
  - I_p decrease despite increase of LHCD power by feedback control system → MHD crash
  - Slow conditioning effect observed between pulses
  - However, conditioning time incompatible with experimental time envelope for long pulse developments in 2025

[Dumont, APS 2024]

Lower plasma currents allowed further record pulses to be performed

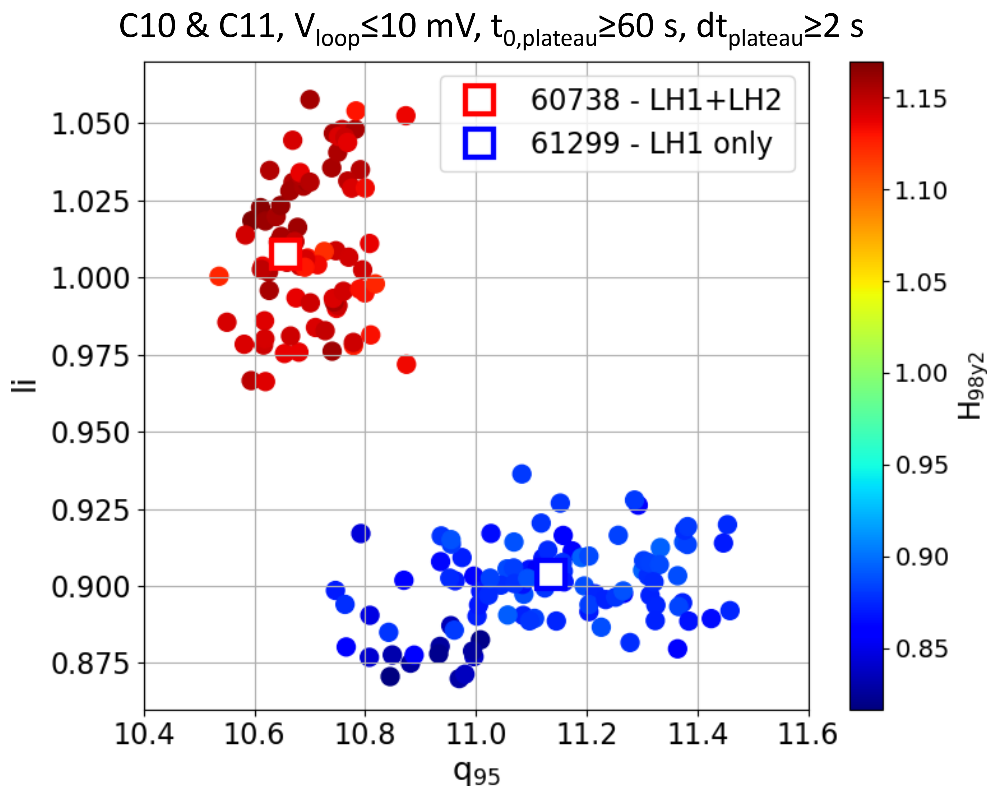




WEST pulse 61299

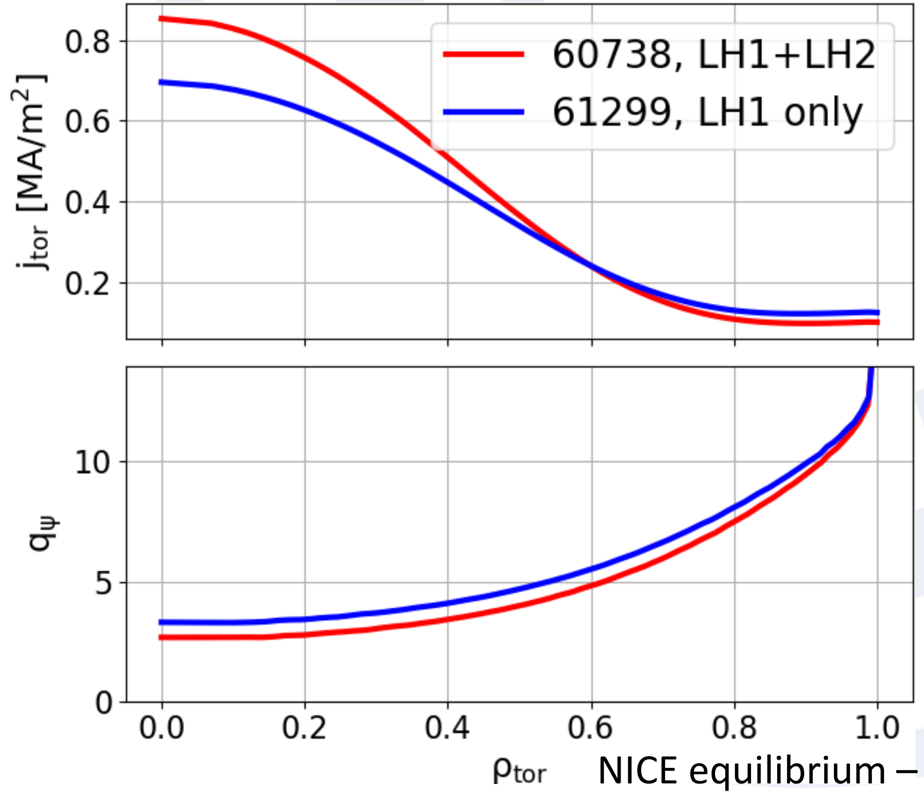
- Duration: 1337 s
- Energy injected/extracted: 2.61 GJ (Current duration/energy record for WEST)
- Plasma current 0.23 MA, LHCD power ~2 MW
- Loop voltage: 0 V (fully non-inductive)
- Quite resilient to external perturbations (failures of RF plant, W ingress [Corre, 17/10 16:30, oral], …)
- Mild MHD activity present during whole duration when using one LH antenna
  - In this particular pulse: non-linear MHD regimes with spontaneous transitions
- This pulse performed in H_2 gas. Similar long pulses performed in D_2:
  - Isotope effect under study
  - Hydrogen concentration slowly increasing during entire D_2 pulse duration → outgassing still present

Peaked current profiles favourable for fusion performance



	60738 (LH1+LH2)	61299 (LH1 only)
β_p	2.0	1.6
β_N	0.8	0.6
H_{98y2}	1.1	0.9

- L-mode plasmas
- Similar pulses performed with one LH coupler (LH1, 61299) vs the two couplers (LH1+LH2, 60738)
- LH1 only pulses (including record pulse)
  - Lower performance obtained
  - Current profile broader

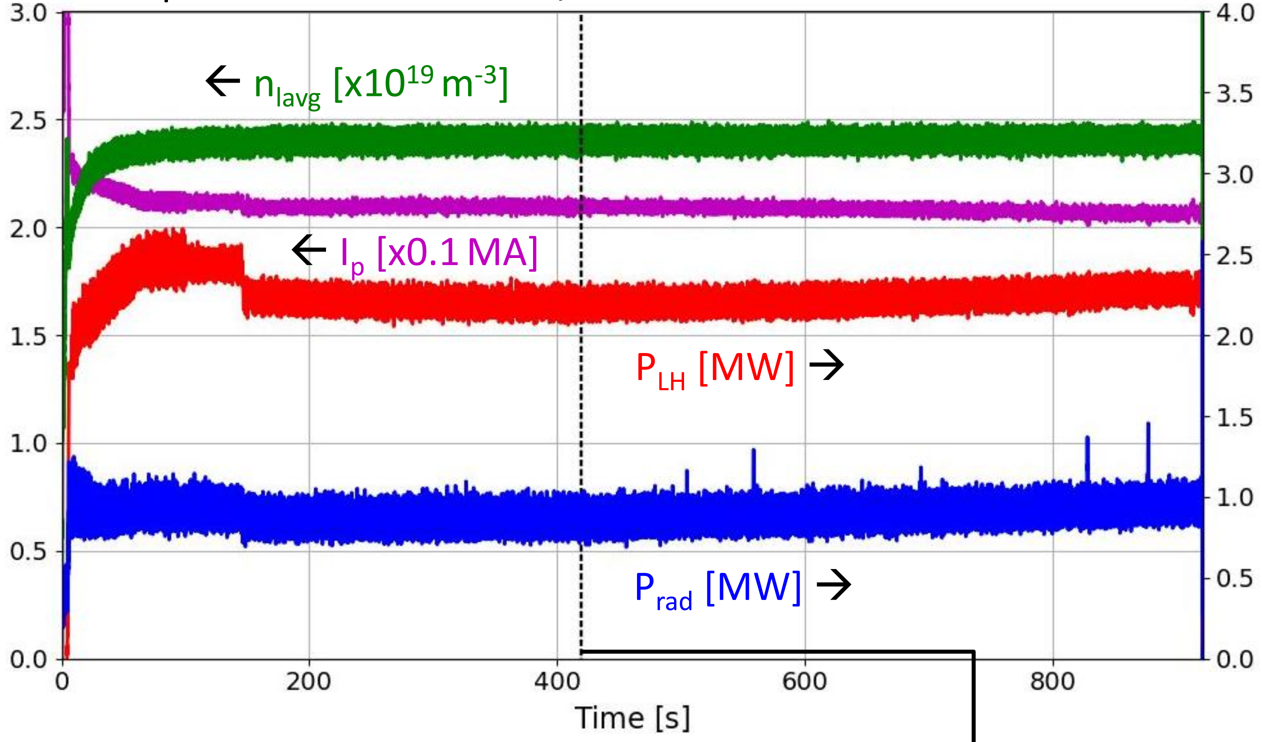


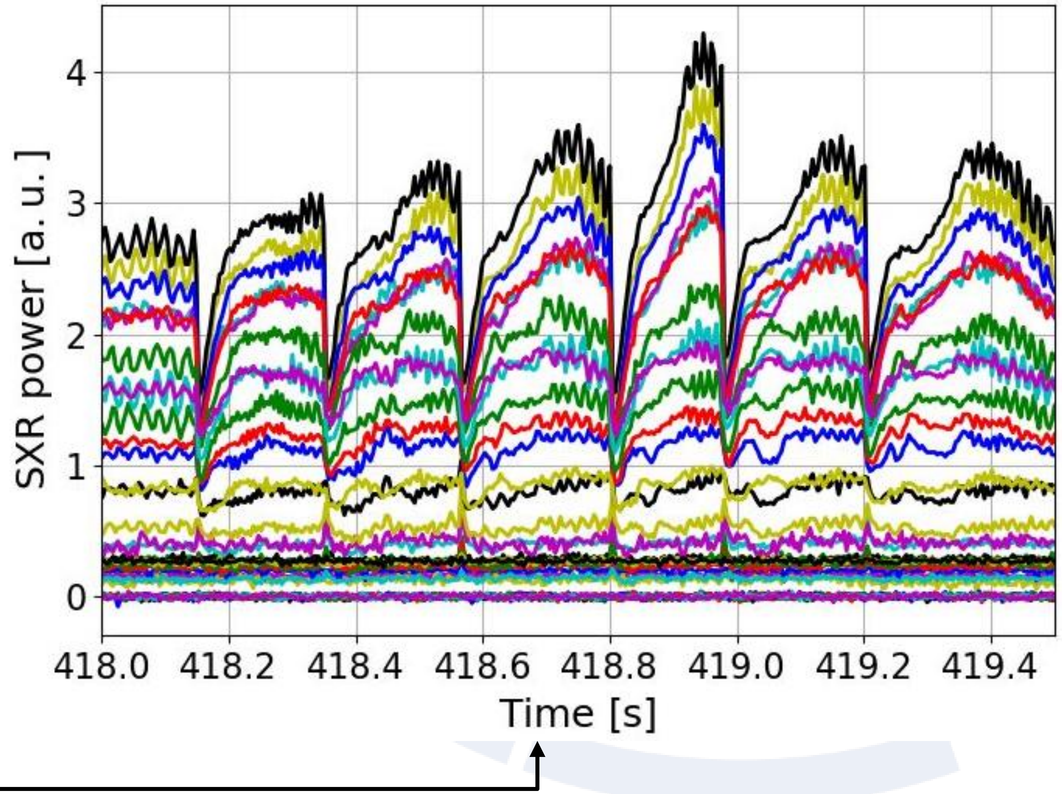
NICE equilibrium – t = [92-292] s

Mild MHD activity likely responsible for confinement degradation

- Presence of MHD activity in 2 MW pulses with LH1 coupler only
  - Steady mode at ~0.8 kHz
  - LHCD efficiency moderately impacted
  - Periodic relaxations of central electron temperature

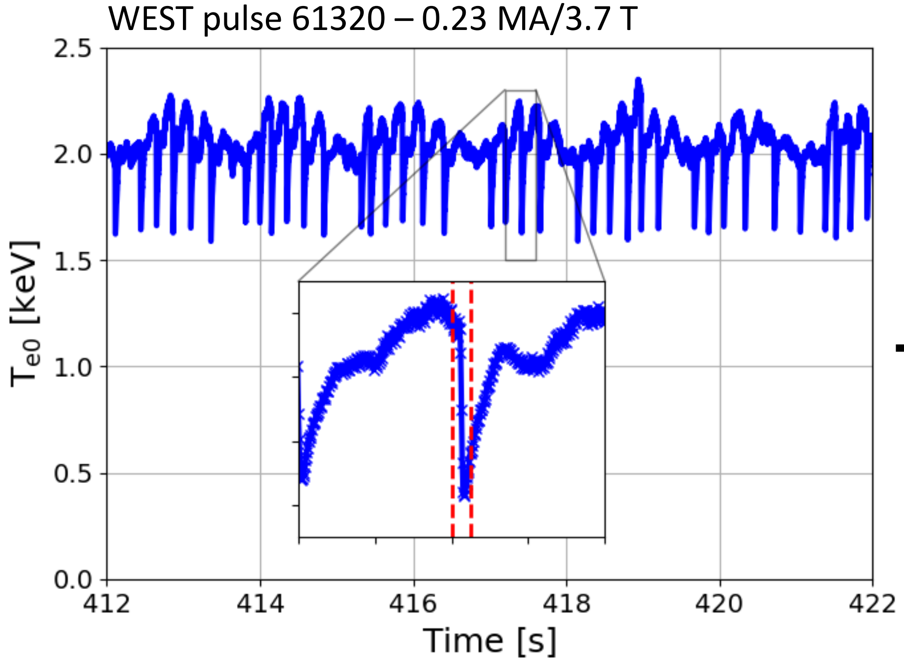
WEST pulse 61320 – 0.23 MA/3.7 T

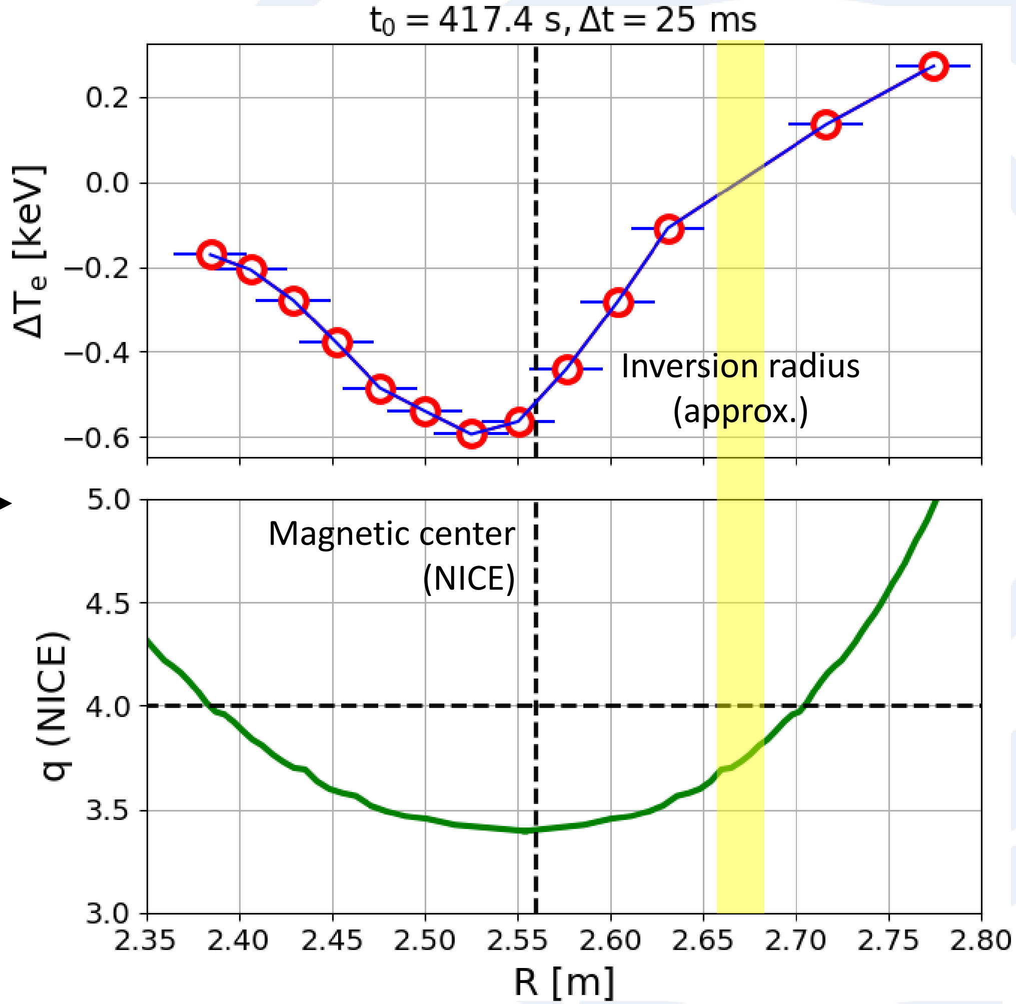




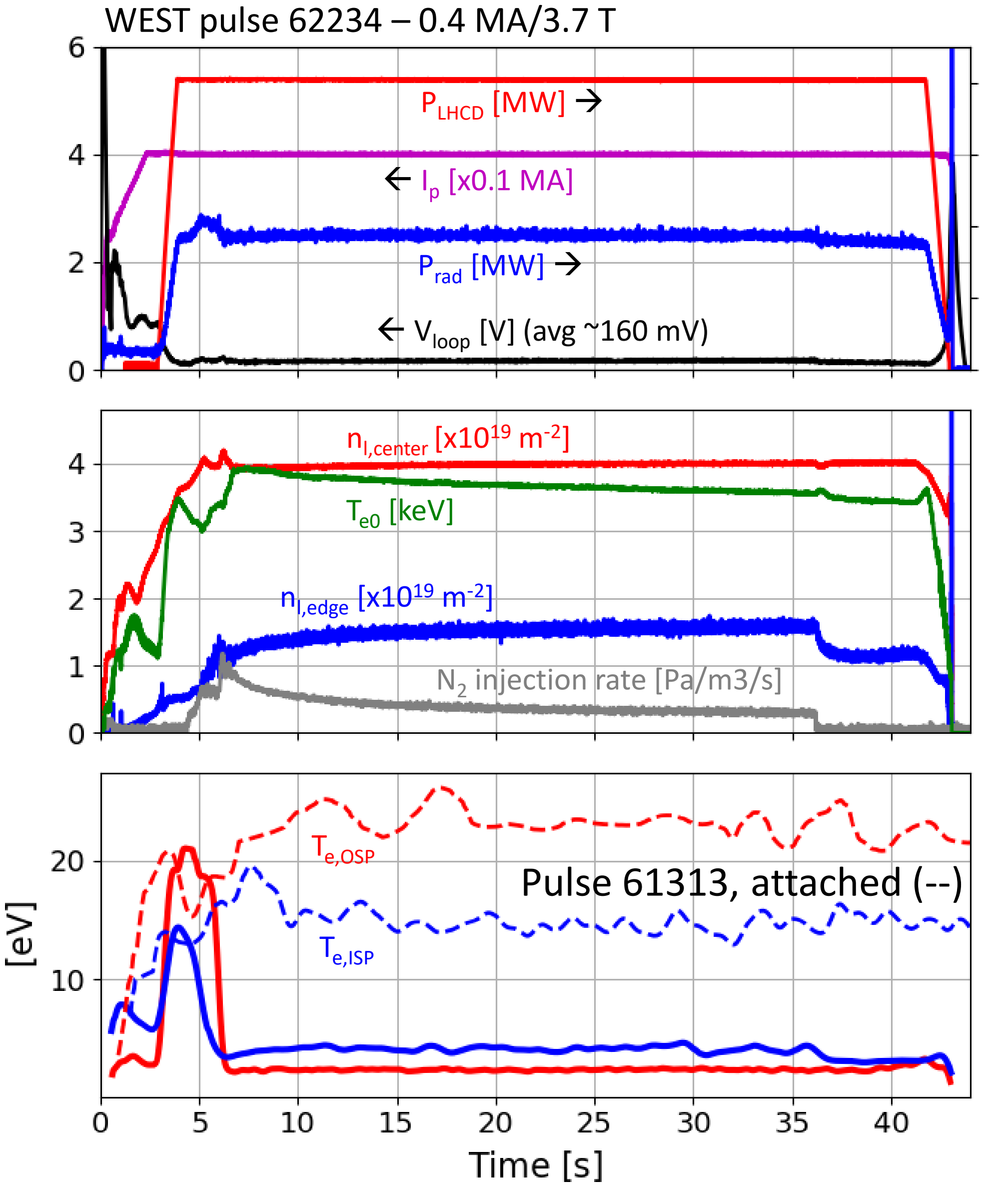
Mild MHD in long pulses attributed to interaction between modes on q=3/1 and 4/1

- Mirnov coil data for ~0.8 kHz mode
  - Toroidal mode number n=1
  - Poloidal mode m=3 and/or m=4
- Fast acquisition ECE radiometer data
  - Islands on q=3/1 and 4/1 surfaces, then crash on q=4





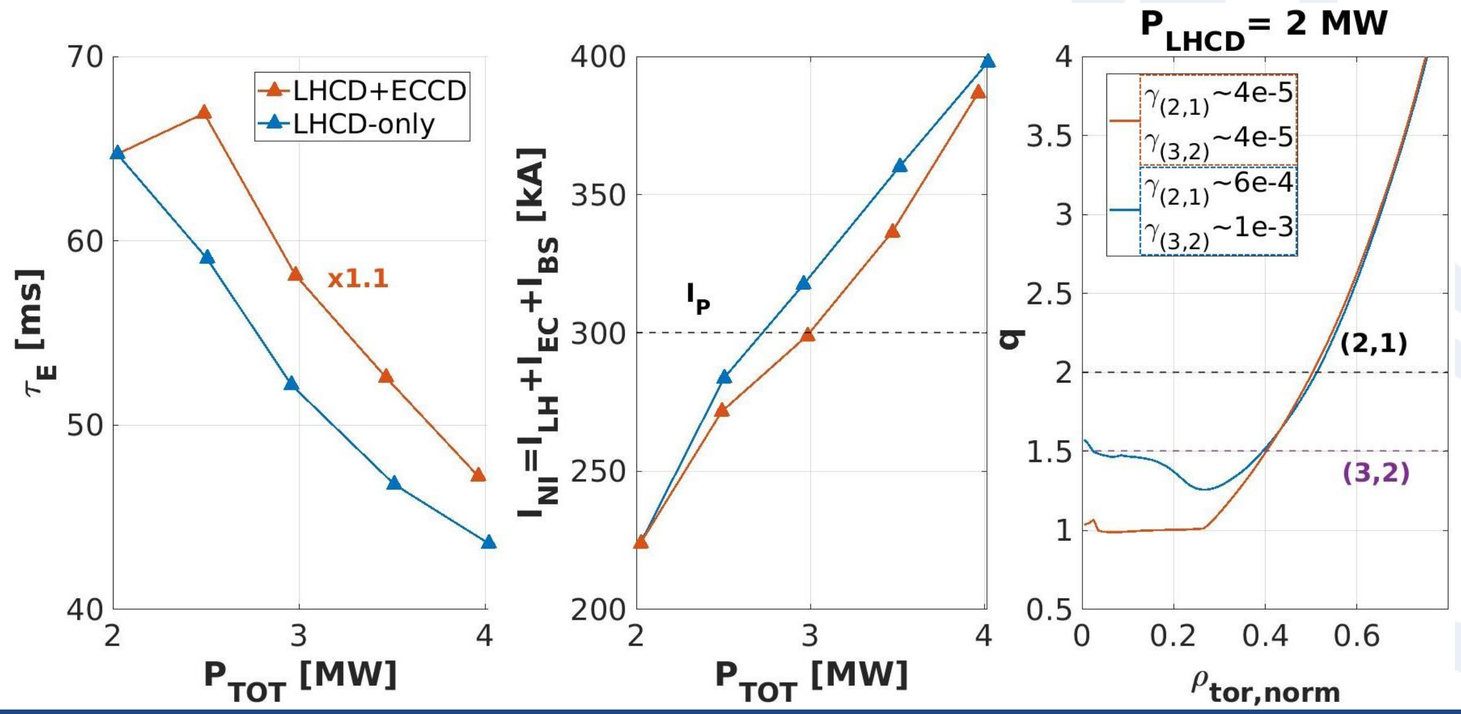
Ongoing effort to extend long pulse operation to XPR regime



- Record duration discharges in attached divertor regime: $T_{e,ISP}$~15 eV, $T_{e,OSP}$~20 eV
- Development of fully non-inductive scenarios in XPR regime (next-step relevant plasma edge conditions) [Rivals, 15/10 PM, P2-3065]
- LHCD efficiencies lower than attached divertor regime efficiencies at comparable levels of power/density
- Frequent MHD activity occurring in these pulses
- Most recent pulses made it to the end in XPR regime
  - 32 s with V_{loop}~160 mV → could be extended to ~45-50 s
  - $T_{e,ISP}$~3.5 eV, $T_{e,OSP}$~2.0 eV

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

- EC power available in WEST: 1MW (2025) → 3MW (2026)
- Applications to long-duration pulses
  - H-mode access
  - Central ECRH against radiative collapses observed as density increased [Ostuni, NF 2022; Morales, NF 2025] or ICRF power applied [Maget, PPCF 2023]
    - Counterbalances central radiation in unstable range of electron temperatures (T_e~1.5-3keV)
    - "Anchors" LH deposition profile to plasma core [e.g., in EAST: Du, NF 2018; Li, NF 2023]
  - Central ECCD to improve overall CD efficiency, control q-profile reversal [Fonghetti, NF 2025]



HFPS simulations

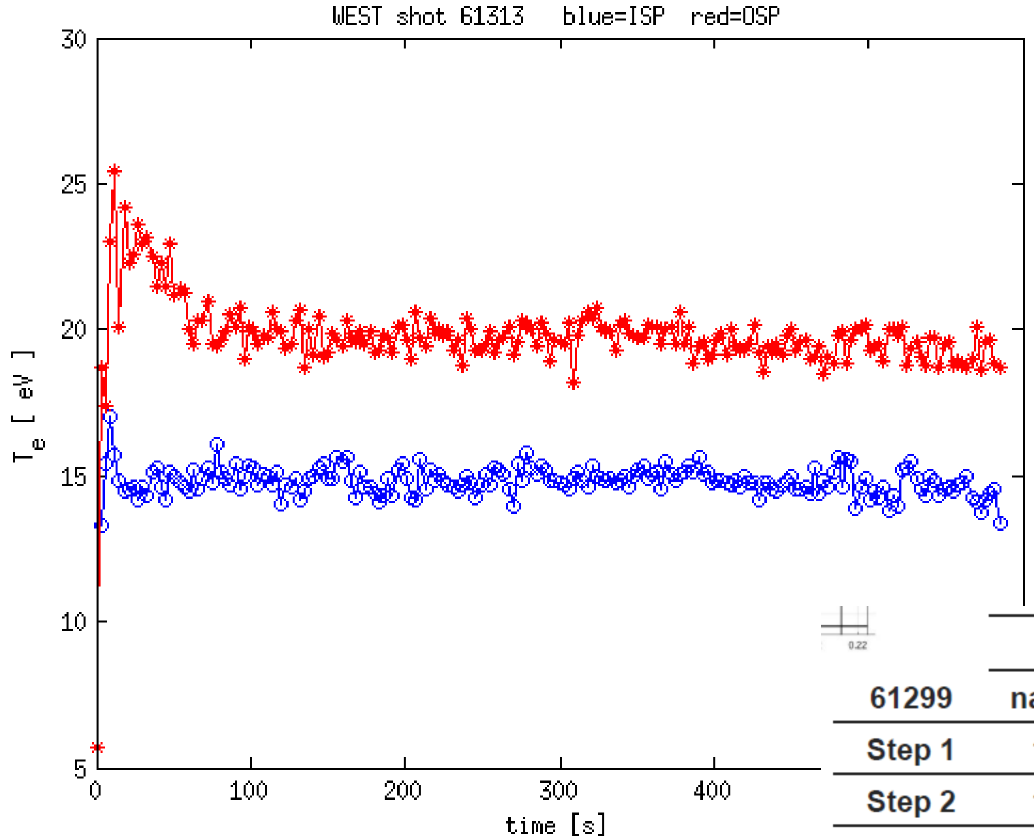
Conclusions and prospects

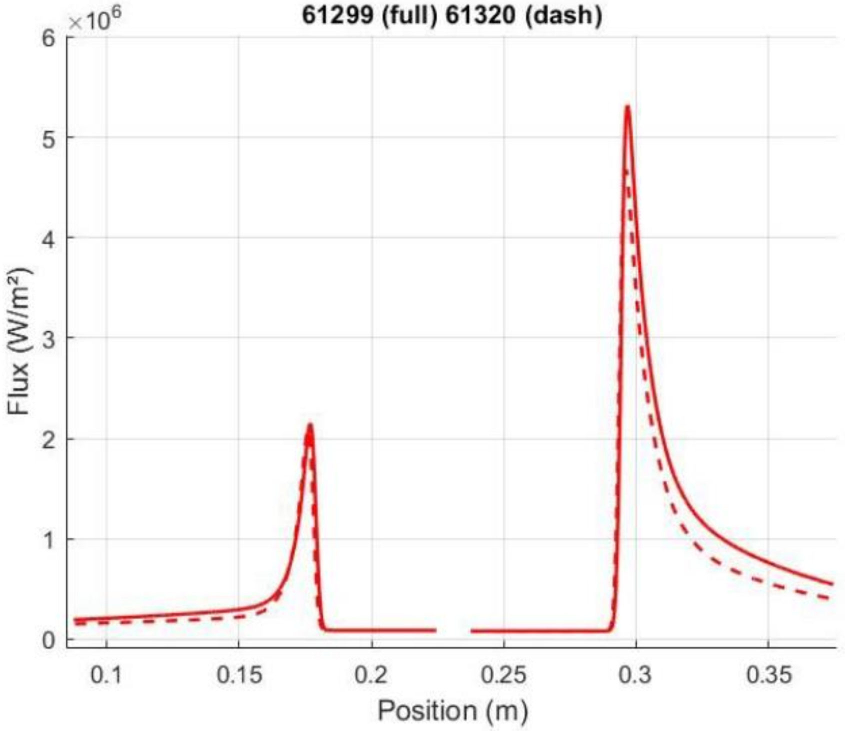
- Various aspects related to Long Pulse Operation of future devices, including ITER, extensively explored in WEST
  - Technical and operational issues, and remedial actions
  - Plasma-wall equilibration (e.g. fuelling & exhaust, outgassing, …)
  - Non-linearities in heat sources / current profile / heat and particle transport / W radiation
- Predict-first integrated modelling strategy → several classes of long pulse L-mode scenarios developed and implemented
  - Operation at 3-3.5 MW up to ~400 s limited by outgassing, with slow conditioning observed
  - New records achieved at P_{LH}~2 MW, up to 22 min, 2.61 GJ
  - Pulses in H_2 and D_2 performed. Isotope studies ongoing
- Towards increasing plasma performance in non-inductive regimes
  - First sessions at larger densities (broader current profile) promising
  - Development of non-inductive pulses in XPR regime ongoing
  - EC power expected to enlarge parameter space, enhance performance

Spare material

Realisations C10 / C11 LPO : divertor regime

– **Plasma is attached at divertor**
  - Temperature : 15 eV (ISP) / 20 eV (OSP) [J. Gunn]
  - Heat flux 2 MW/m2 (ISP) / 5 MW/m2 (OSP) [J. Gaspar]



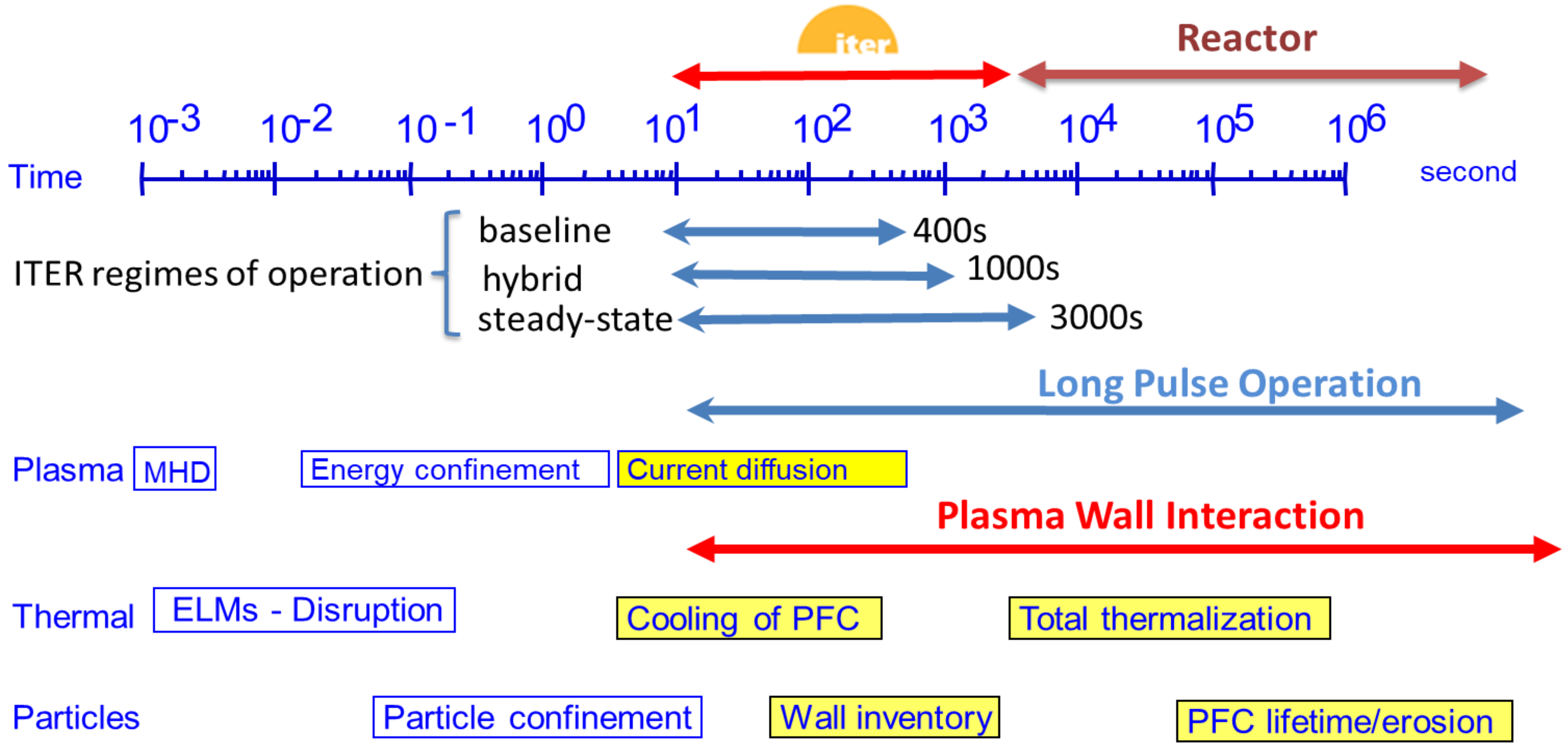


61299	ϕ_m (MW/m²) narrow	ϕ_m (MW/m²) far	λ_q^t (mm) narrow	λ_q^t (mm) far	x_0 (mm)	S (mm)	ϕ_{BG} (kW/m²)	Ptot (MW)	Prad (MW)	Pdiv (MW)
Step 1	1.82	0.26	4.6	97.2	178.7	2	88	2.08	0.63	1.45
Step 2	1.62	0.23	4.6	97.2	179.2	2	88	1.95	0.57	1.39
Step 3	1.52	0.21	4.6	97.2	178.6	2	88	1.95	0.51	1.44
Step 4	1.52	0.17	4.7	97.2	176.9	2	88	1.88	0.47	1.41

Long Pulse Operation (LPO): a definition

[CICLOP group, NF 2024]

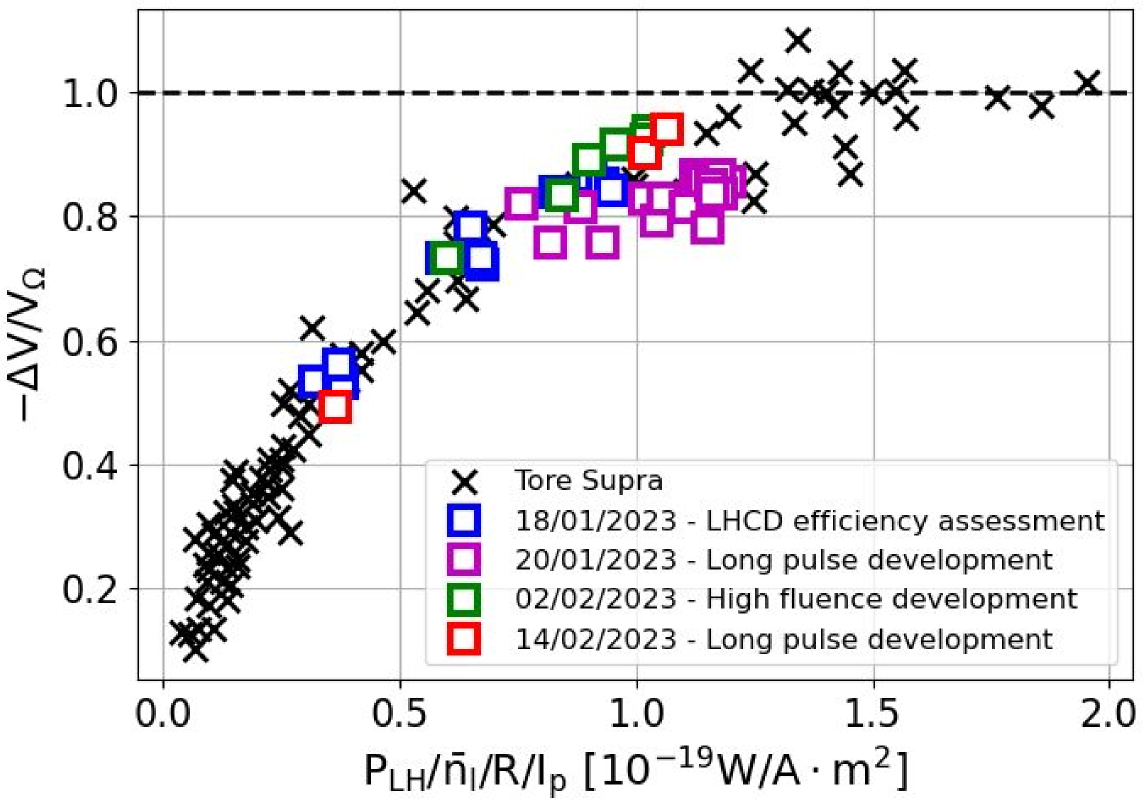
- Plasma with durations well above the plasma confinement time, approaching plasma-wall integration timescales
  - ITER 100-400s H-mode regime belongs to the LPO category



Operational limits ?

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

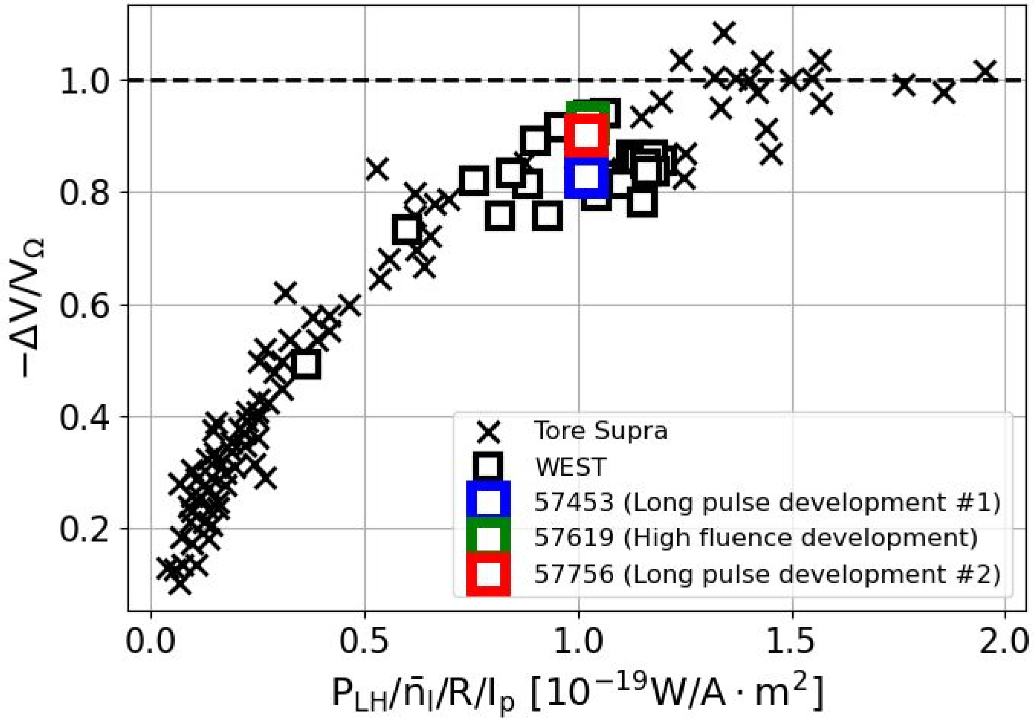
Early developments”: 2023 campaign

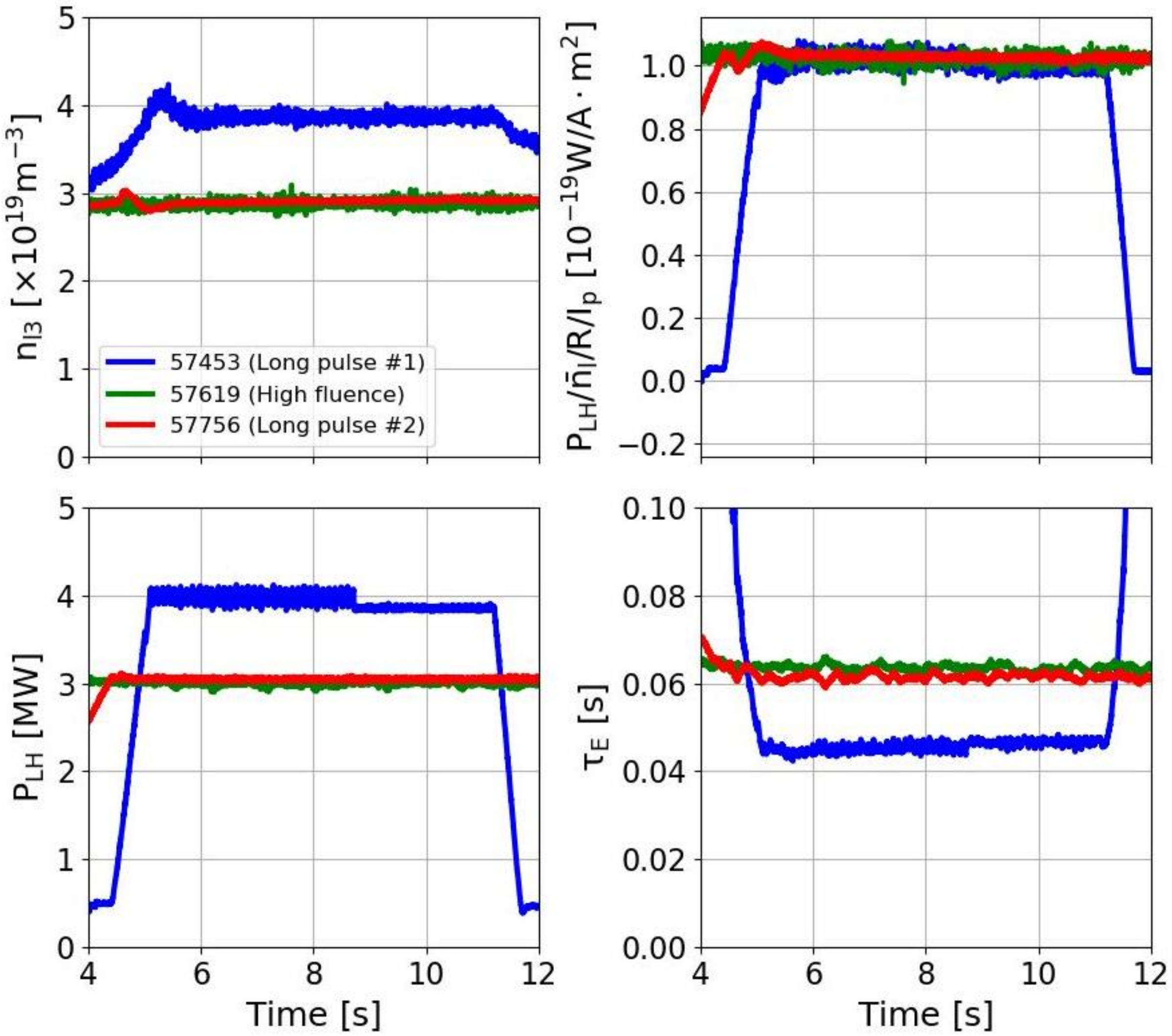


- LHCD efficiency assessment experiment - ■
  - Tore Supra LHCD efficiencies recovered, consistently with LUKE predicting no significant influence of W impurities on LHCD [Peysson, IAEA 2020]
- Early LPO sessions (e.g. 20/01/2023) - ■
  - 400kA / 3.7T
  - Simultaneous increase of P_{LH} and n_l
  - V_{loop} levels off as normalized P_{LH} increases
- In parallel, good progress of high fluence development effort (e.g. 02/02/2023) - ■
  - 400kA / 3.7T
  - Progressive decrease of n_l at constant P_{LH}~3MW
  - Better efficiencies obtained

→ LPO scenario development strategy updated

Increasing density adversely impacts confinement in WEST, favoring lower Ip route





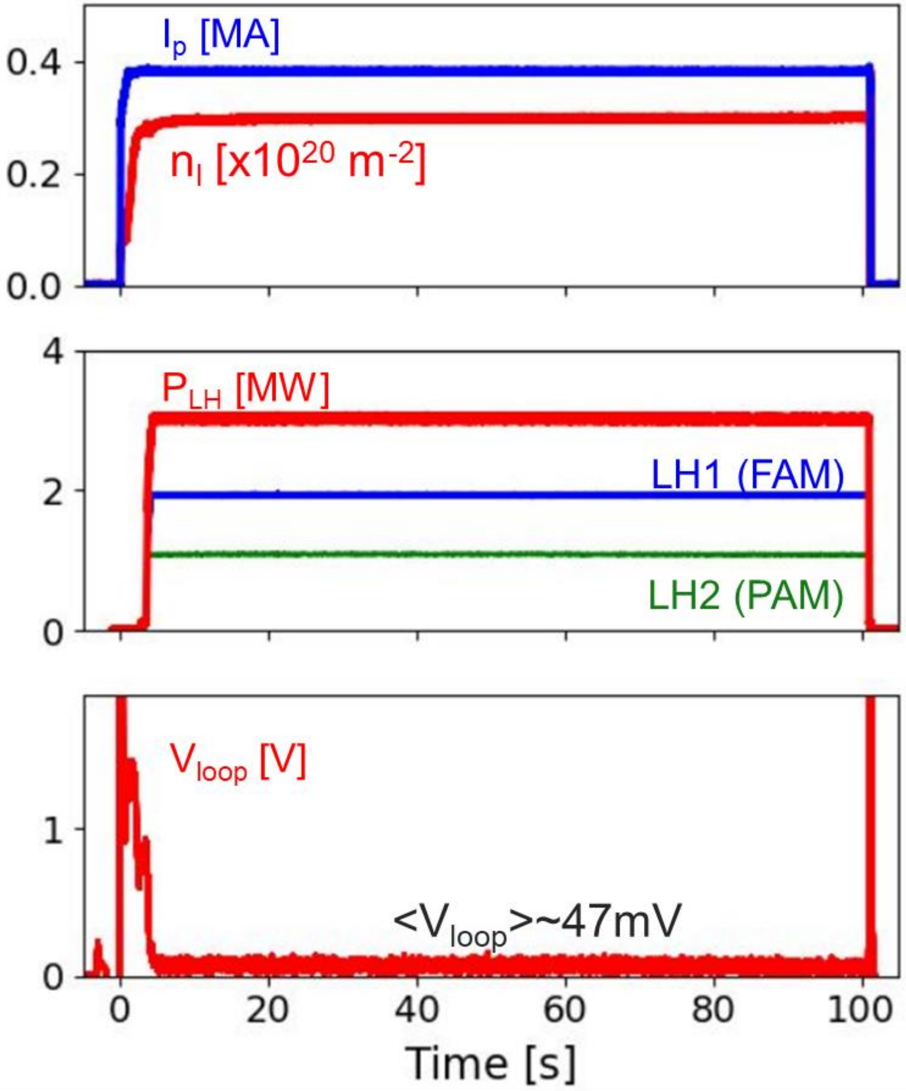
- Increasing density in WEST
  → negative impact on confinement [Ostuni, NF 2022]
  → degraded LH efficiency [Goniche, AIP proc. 2005]

Table 1. Regression coefficients for ITER96-L and WEST databases.

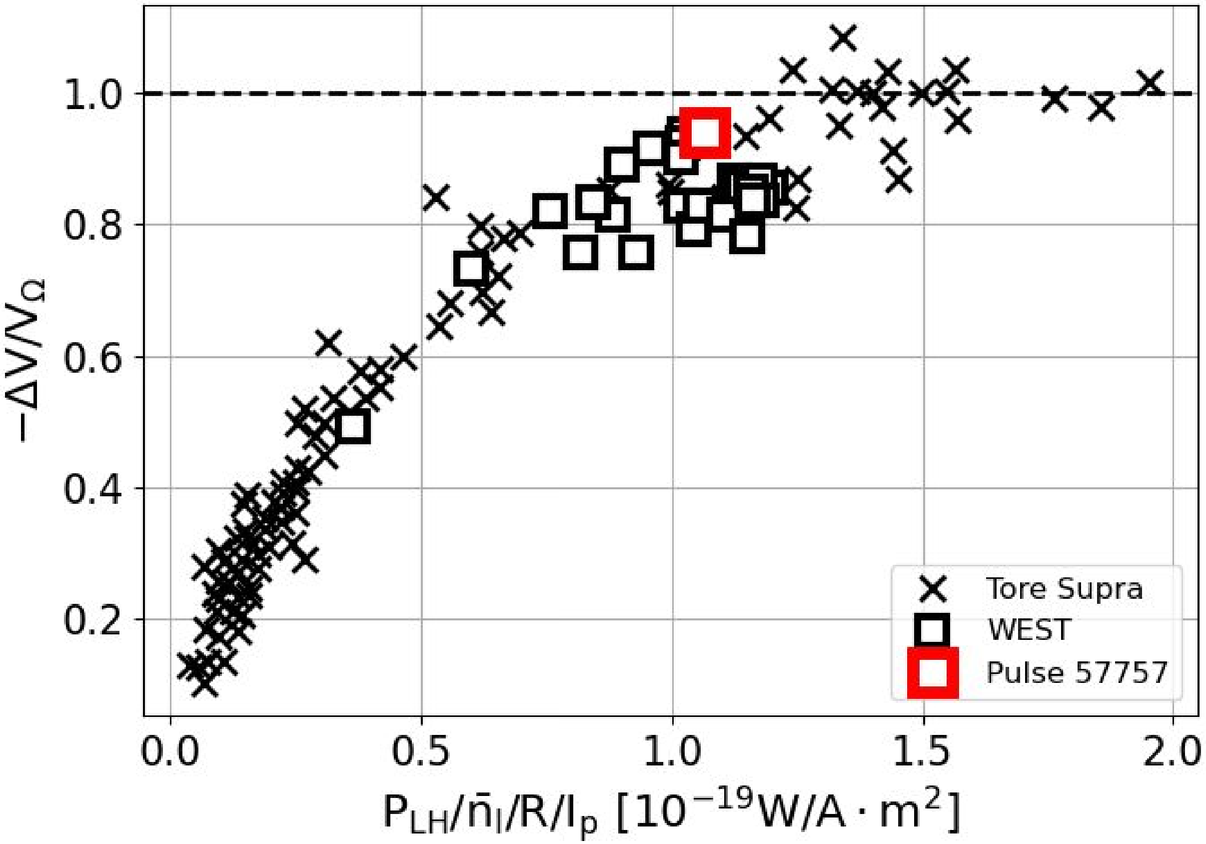
	α_{I_p}	$\alpha_{\overline{n_e}}$	$\alpha_{P_{tot}}$	RMSE
ITER96-L	0.96	0.40	−0.73	18.9
WEST	1.35	−0.16	−0.75	13

Reference pulse for further development obtained during C7 campaign (2023)

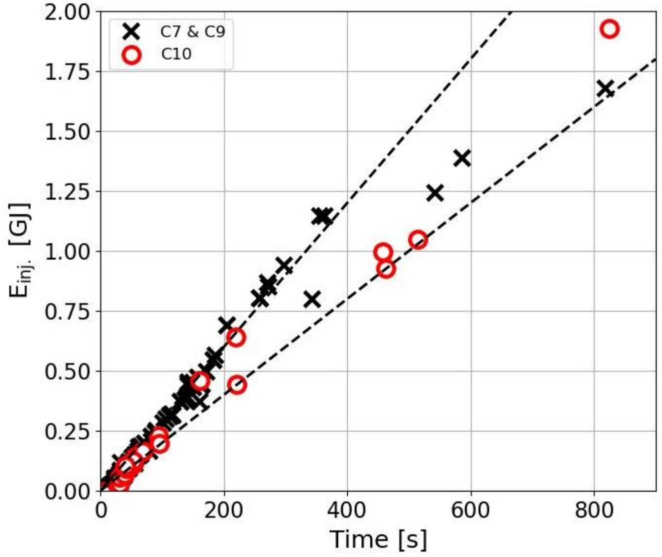
WEST pulse 57757 – 0.38MA/3.7T

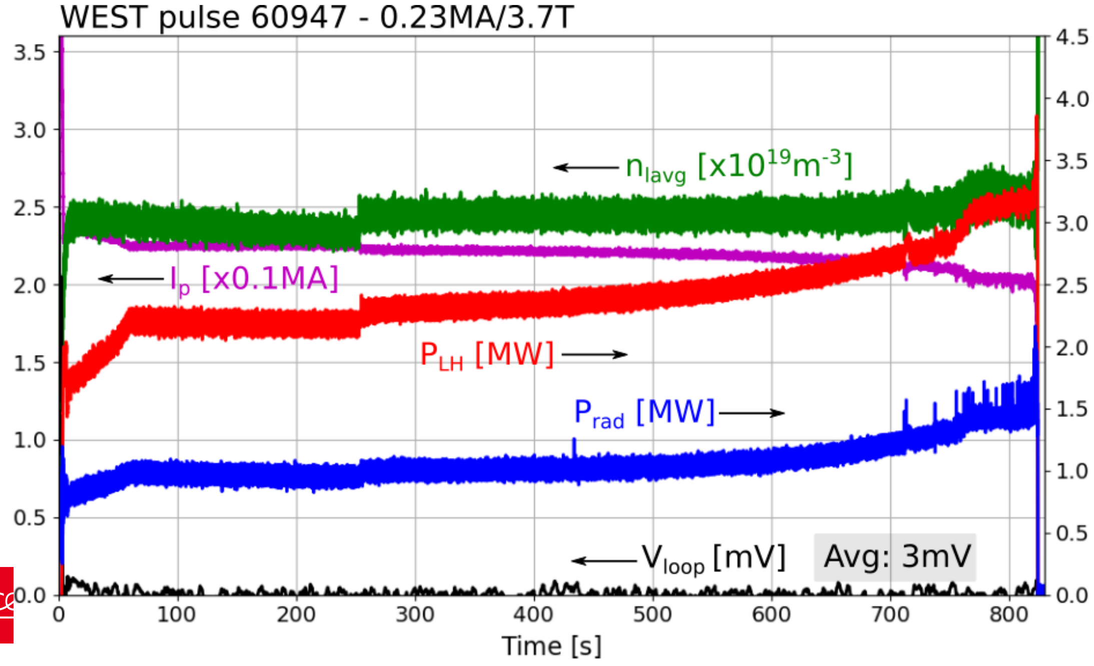


- 02/2023: WEST pulse 57757 achieved V_{loop}~47mV during 101s with 3MW LH power (E~290MJ) - Termination related to cooling pipe temperature interlock
  → used as reference pulse for further developments



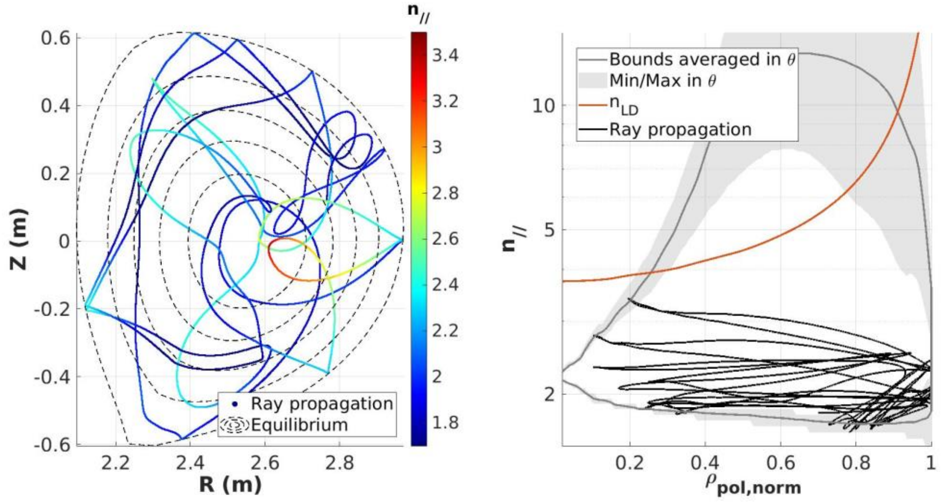
Duration records achieved during C10

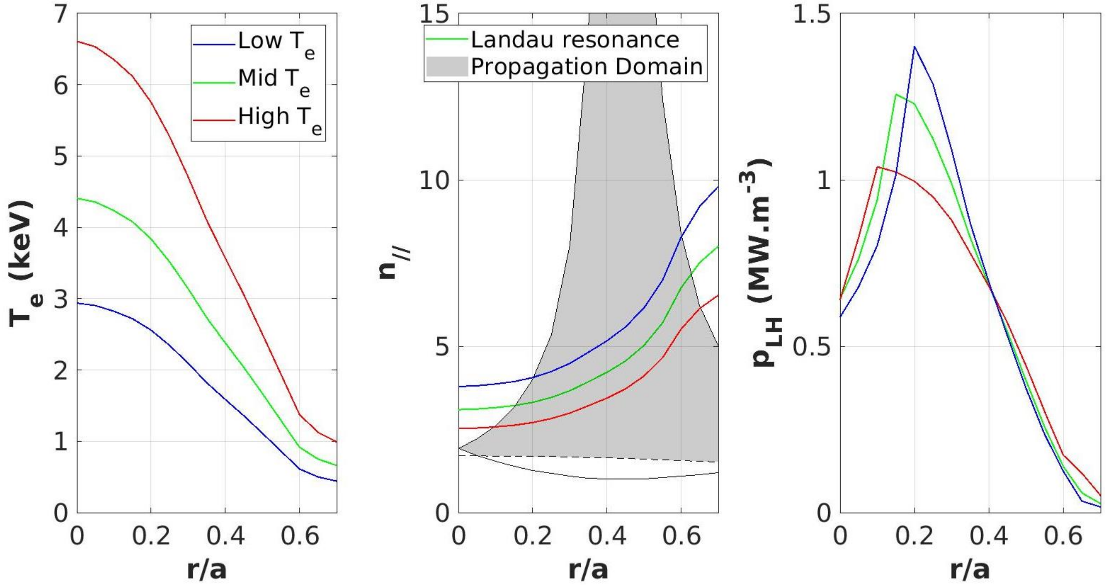




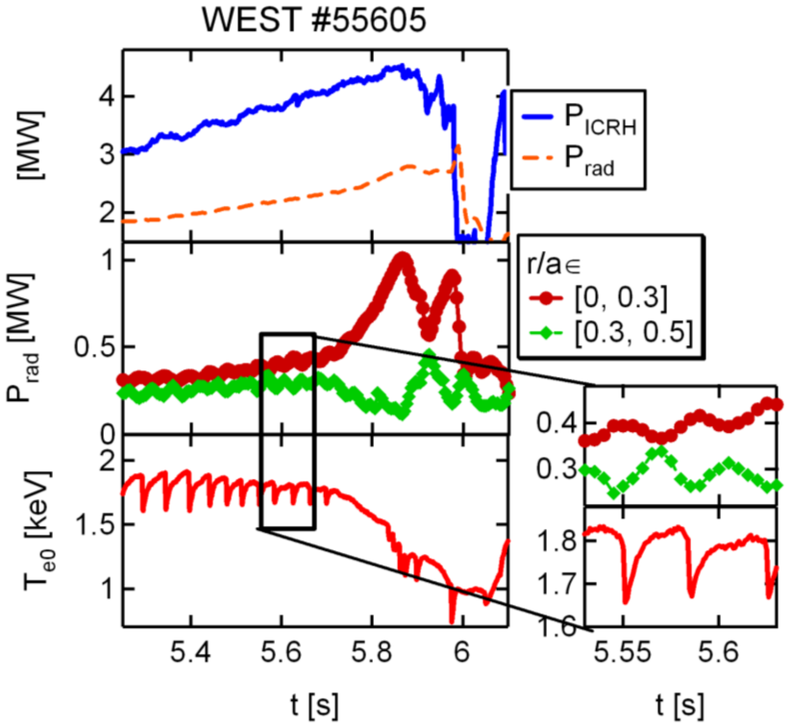
- New duration & energy record **(WEST pulse 60947)**
  - **Duration: 824s, energy injected/extracted: 1.93GJ** (Overall records for WEST **and** Tore Supra!)
  - Double feedback-control (V_{loop}, V_{G0}), (I_p, P_{LH})
  - Plasma current ~230kA, LH power ~2MW
  - Loop voltage: 3mV → could in principle last >1100s
  - Plasma current 0.23MA, with small-amplitude forced oscillation at 0.66Hz to make system more robust w/r to perturbations (jump to feedback control mode, UFOs,…) → positive impact still to be confirmed
  - Fault on H2O laser at ~250s induces uncertainty in density measurement, and possibly change of LH deposition
- Limitation in B60 cooling loop capability would have limited this pulse to ~860s
  - → will be remedied during next shutdown
  - → until then, optimization of klystron cooling parameters (in liaison with THALES) + operation with LH1 only

Reduced LHCD model captures outward displacement of LH-driven current when central Te decreases





Observation of radiative collapses during ICRH operation

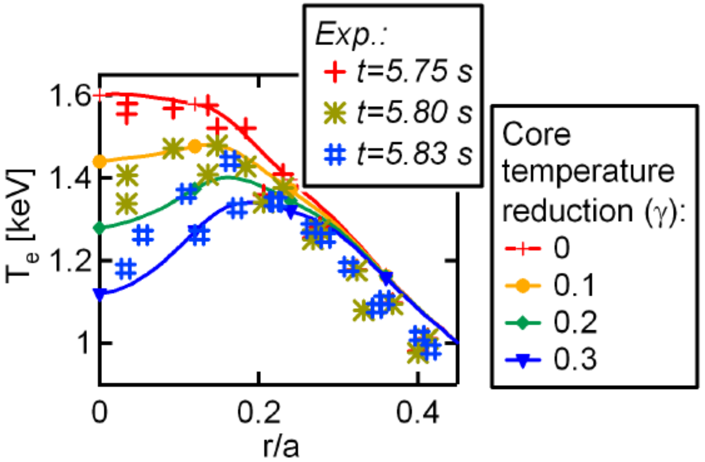


Pulse series at 500 kA shows radiative collapse above a given level of ICRH power

- Threshold in ICRH power increases with plasma density
- Electron temperature saturates above 1 MW of ICRH, while ion temperature increases ~linearly with P_{IC}
- No collapse at 700 kA and larger density

Radiative collapse events are key to evaluate sources / sinks

- Core electron temperature profile becomes hollow at *t>5.75s*
- Signature of radiative losses exceeding electron heat source [Maget, PPCF, submitted 2023]



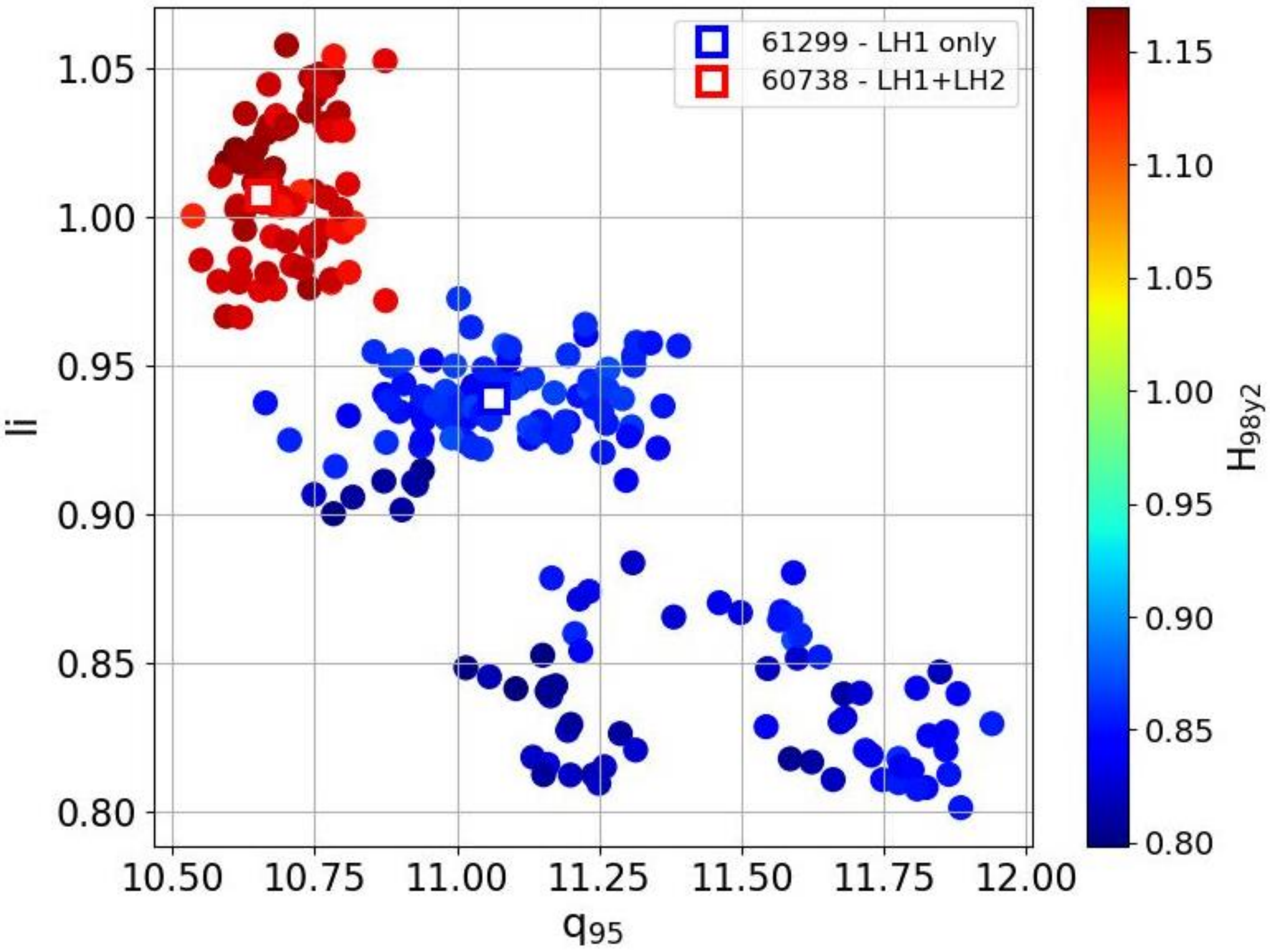
ICRF-driven energetic ions expected to impact W accumulation

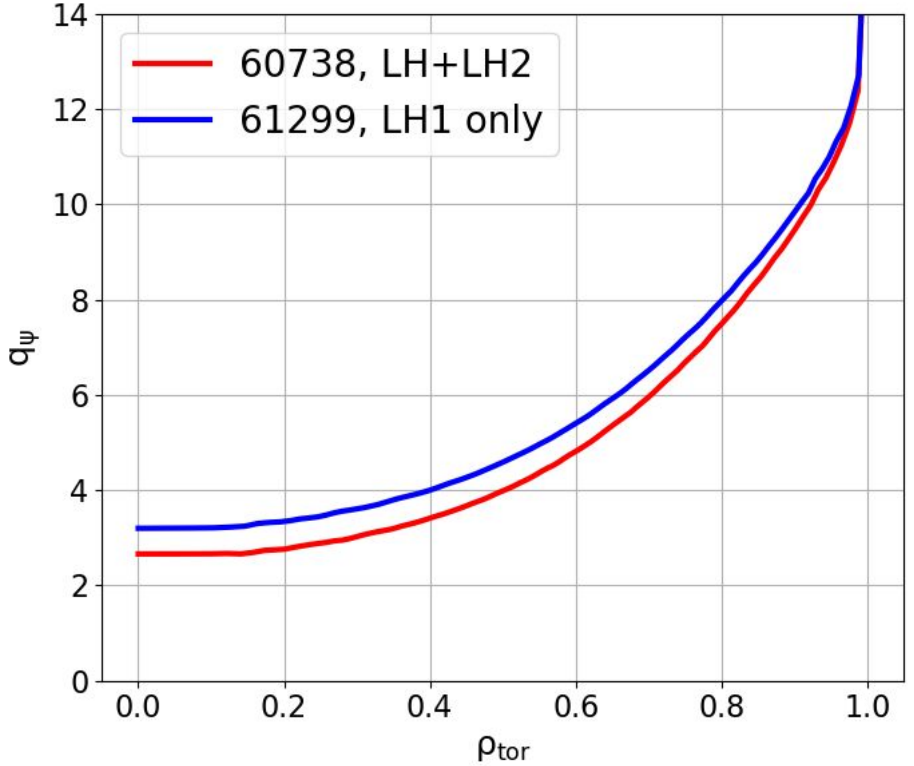
- Core electron heating to balance radiated power
- Minority population anisotropy → poloidal asymmetry

Objective: RF simulations → sources for integrated modeling

Peaked current profiles key to achieve high confinement

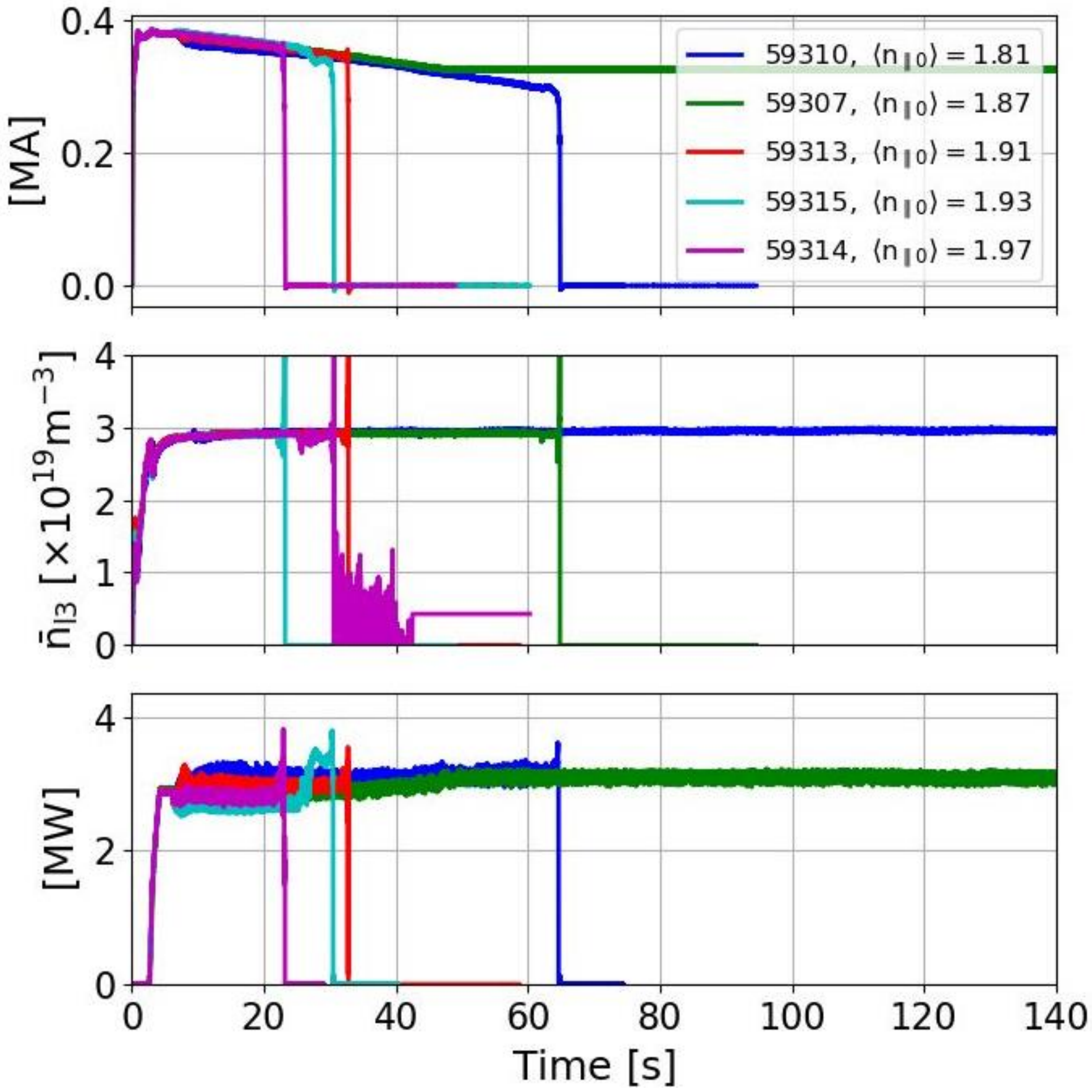
C10 & C11, V_{loop}≤10mV, $t_{0,plateau}$≥60s, $dt_{plateau}$≥2s

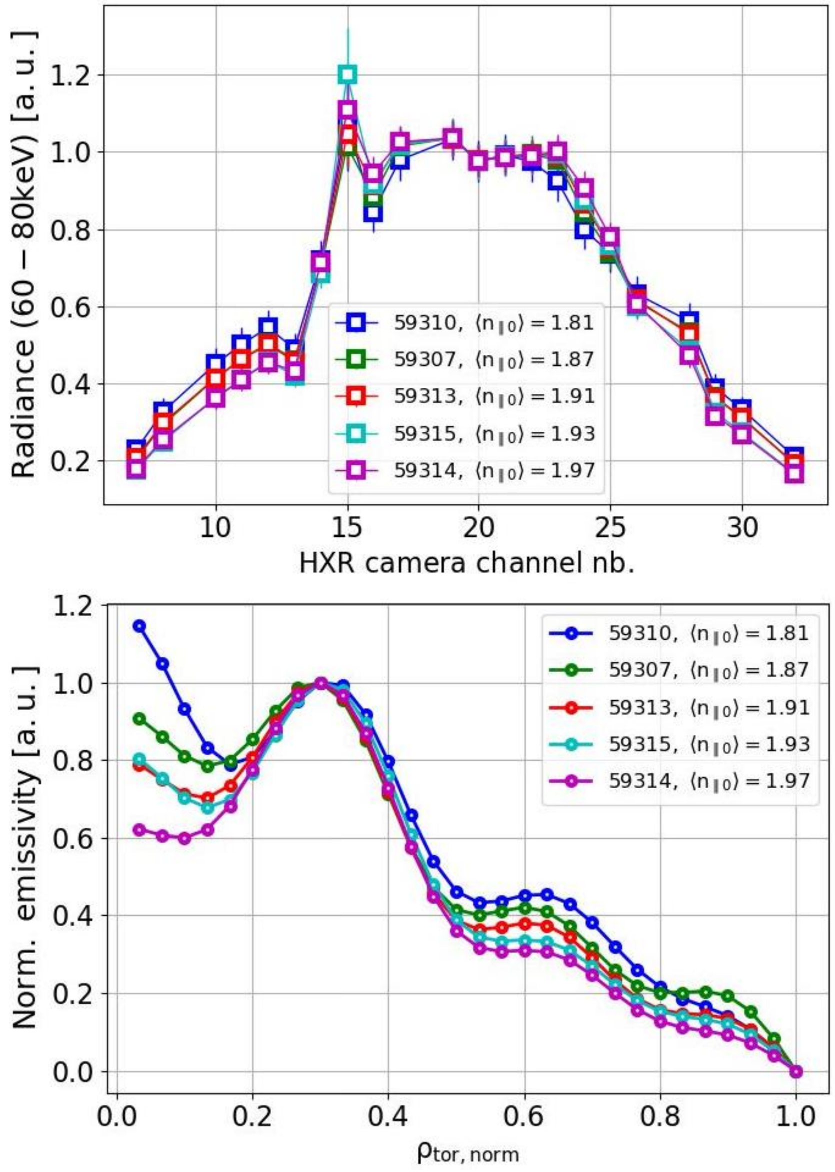




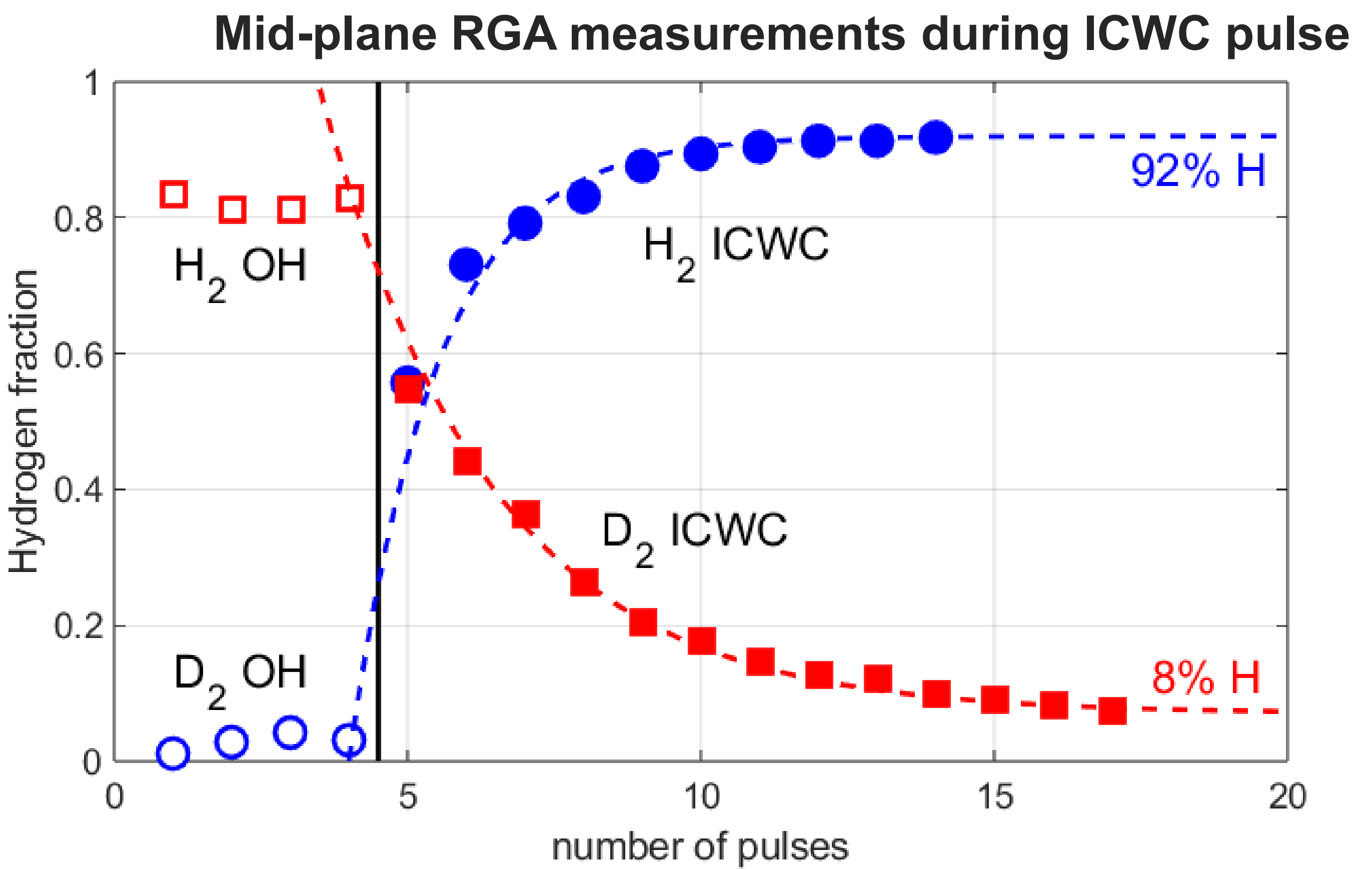
q-profile from NICE (constrained by polarimetry), averaged 60-260s

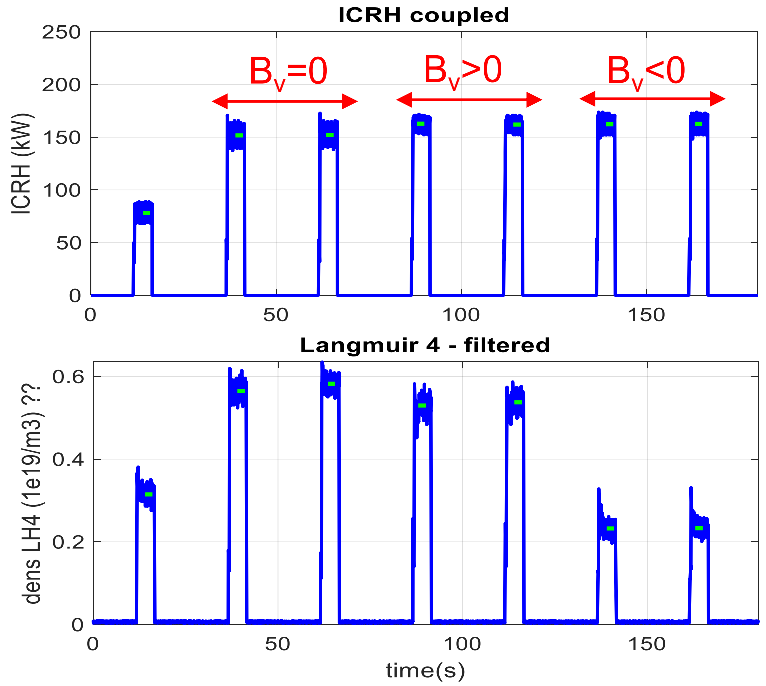
Toroidal spectrum has limited impact on LHCD profile shape, still strongly influences scenario





ICWC wall changeover in WEST



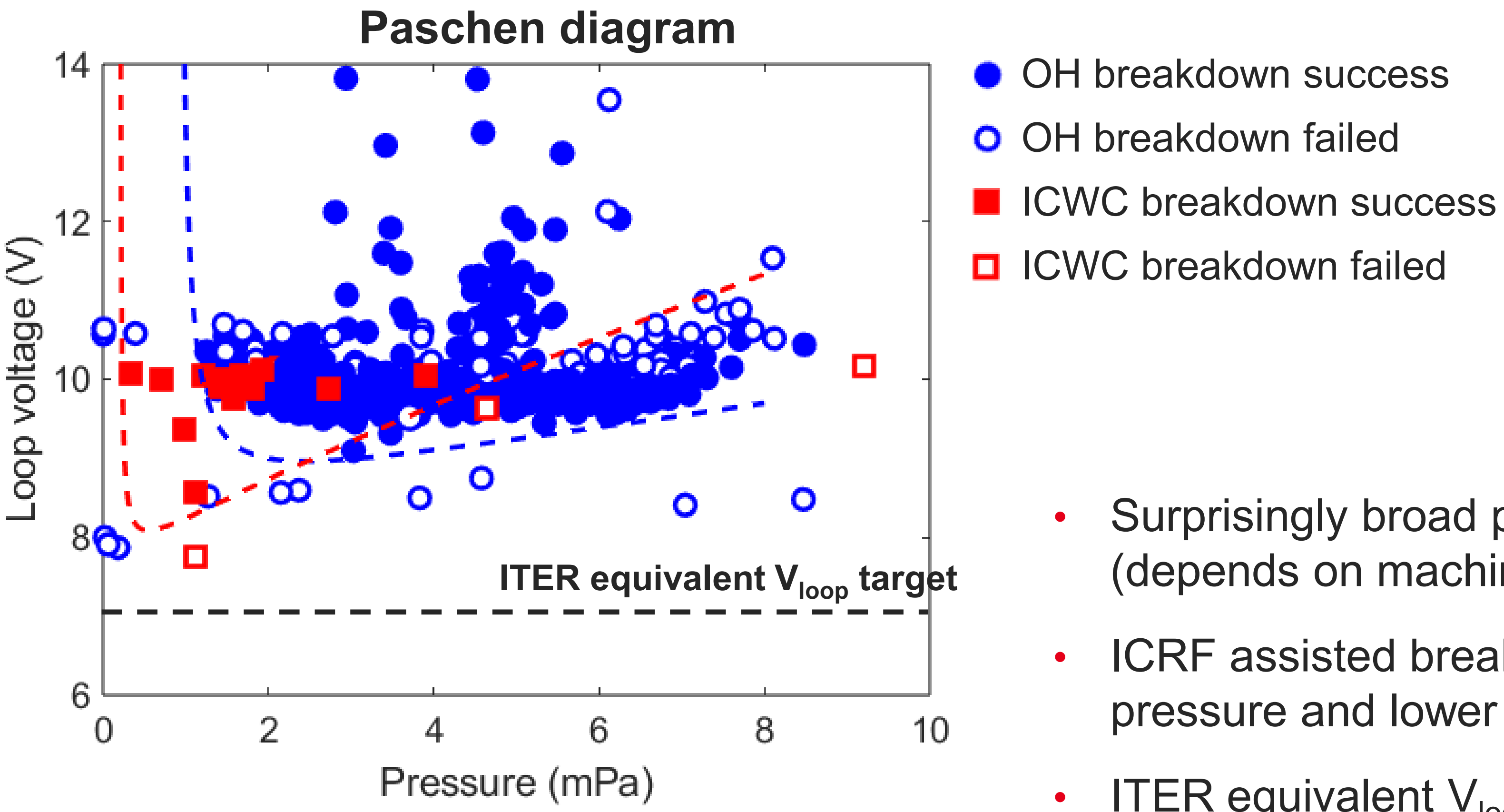


→ 5s ICWC 'slugs' with different vertical fields: "effect torchon"

- Efficient D_2 → H_2 → D_2 wall changeover with ICWC achieved in WEST (160kW, 2 antennas)
- It takes longer for H_2 → D_2 changeover than for D_2 → H_2 (H_2 is implanted deeper in the wall?)
- Detailed analysis & modelling ongoing (contributors are welcome)

[E. Lerche, private communication]

ICRF-assisted breakdown in WEST

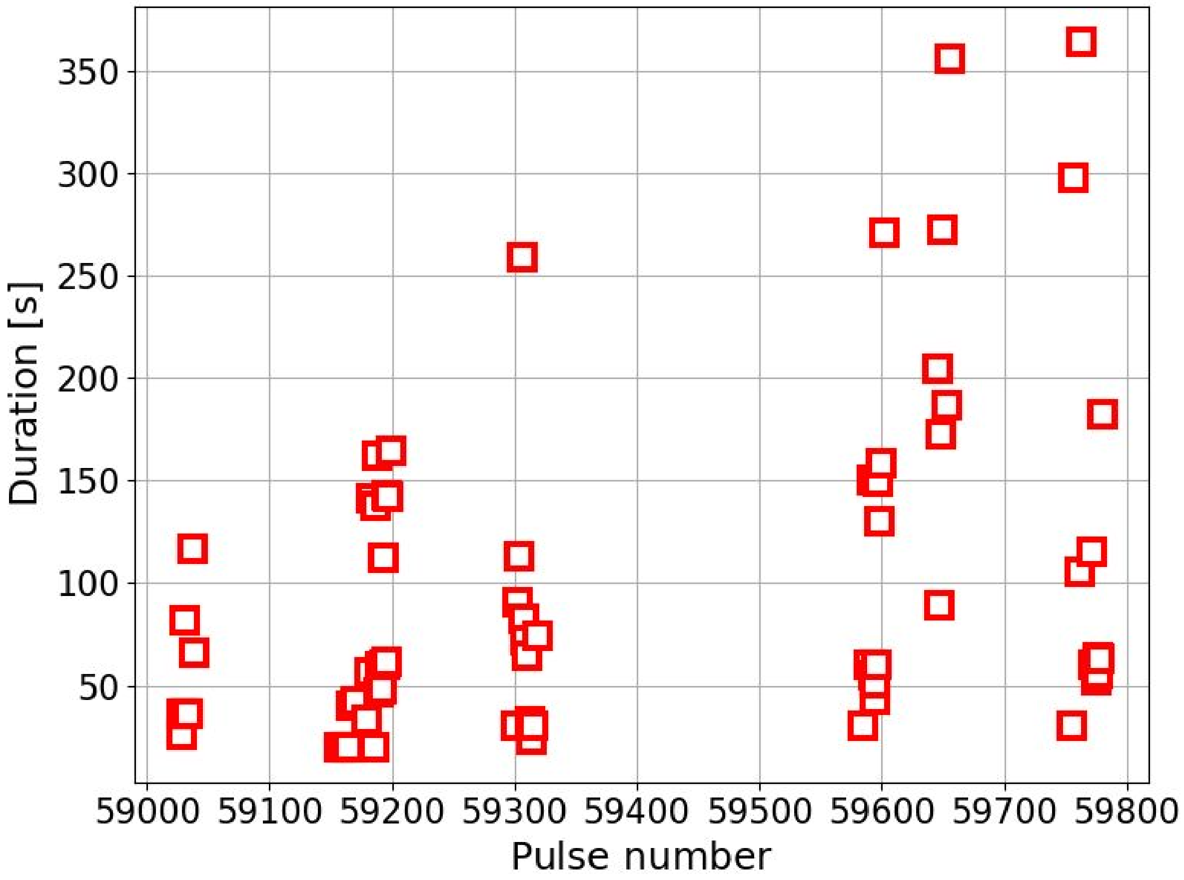


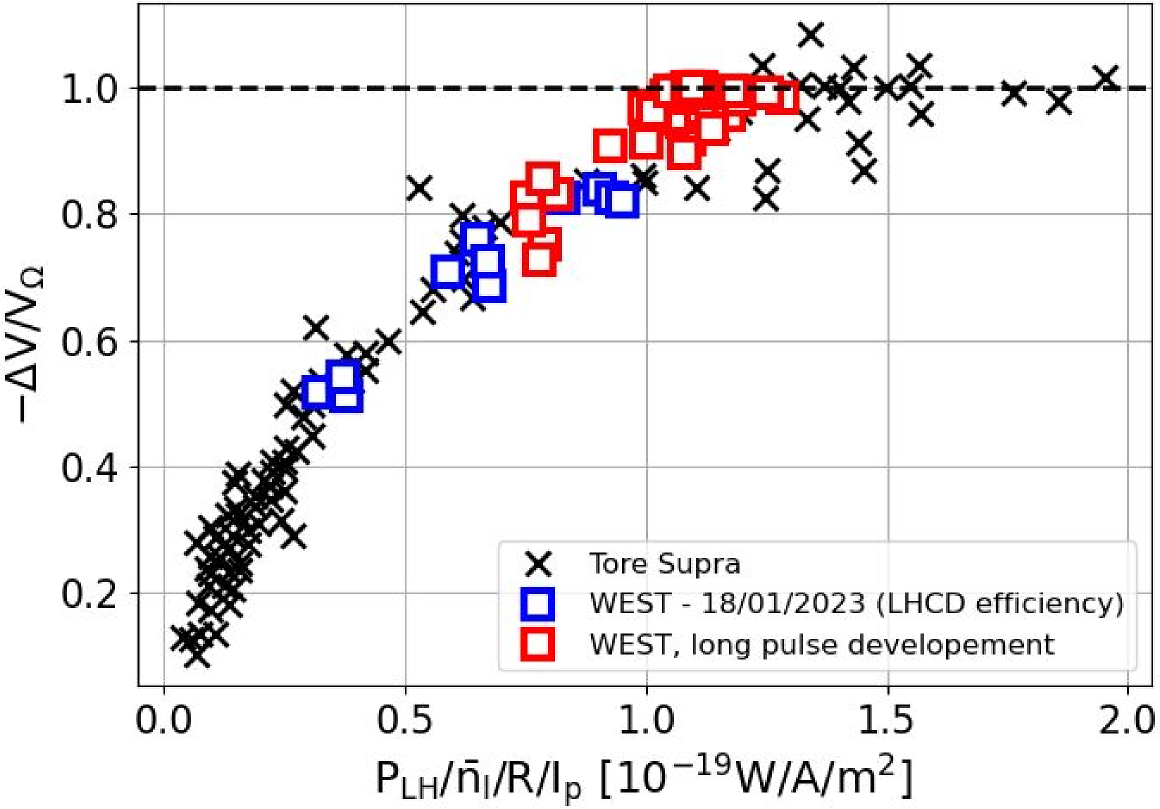
- Exp. data points: pressure @ t=0, V_{loop} @ t=0.05s
- Paschen curves are only indicative

- Surprisingly broad pressure range for OH breakdown (depends on machine conditions)
- ICRF assisted breakdown expands operation to lower pressure and lower V_{loop} ranges
- ITER equivalent V_{loop} target not yet achieved in WEST (but magnetic config. and target pressure not optimized)
- Analysis & modelling barely started (contributors are welcome)

[E. Lerche, private communication]

Steady progress in non-inductive regime developement effort



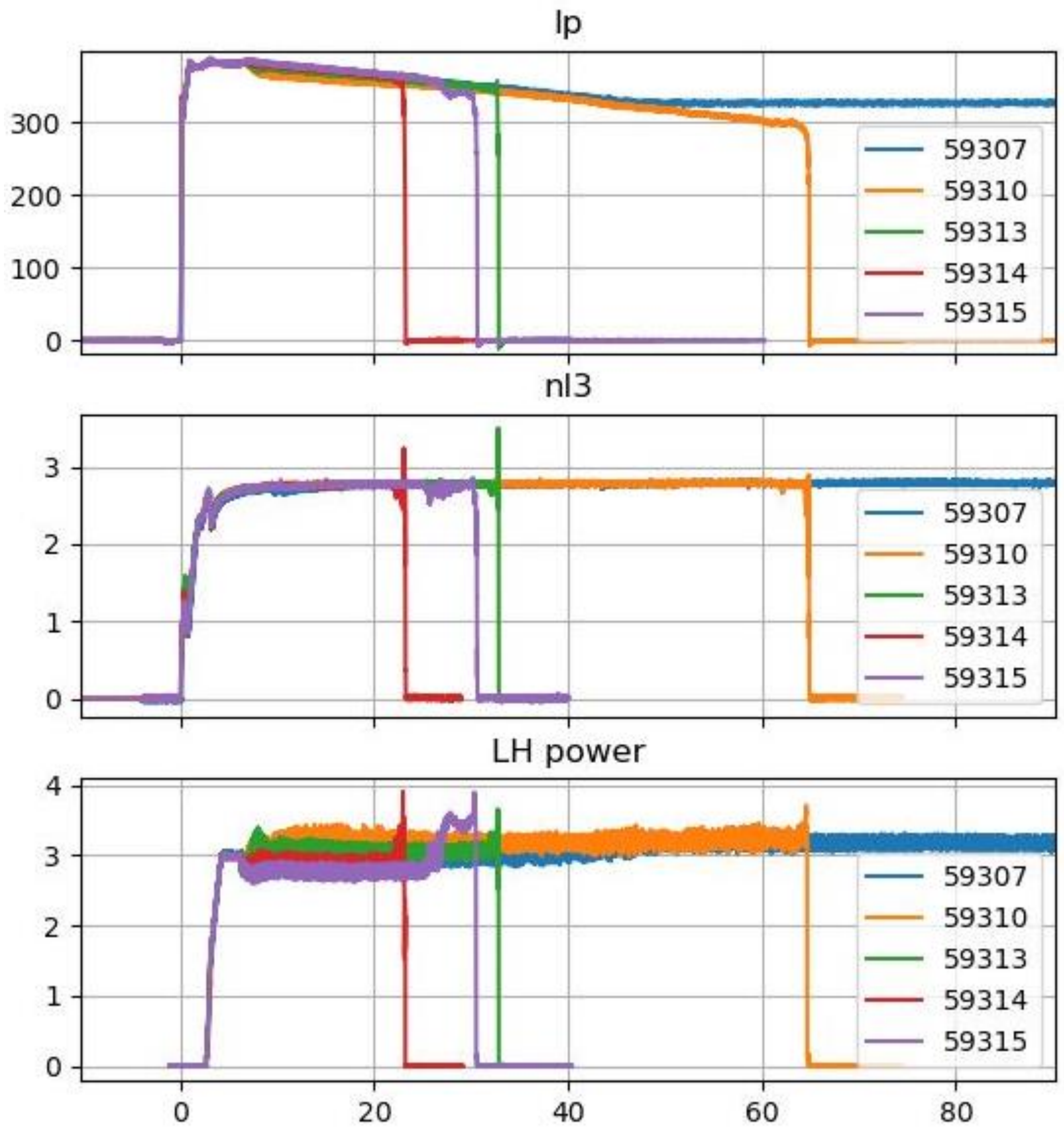


5 sessions so far

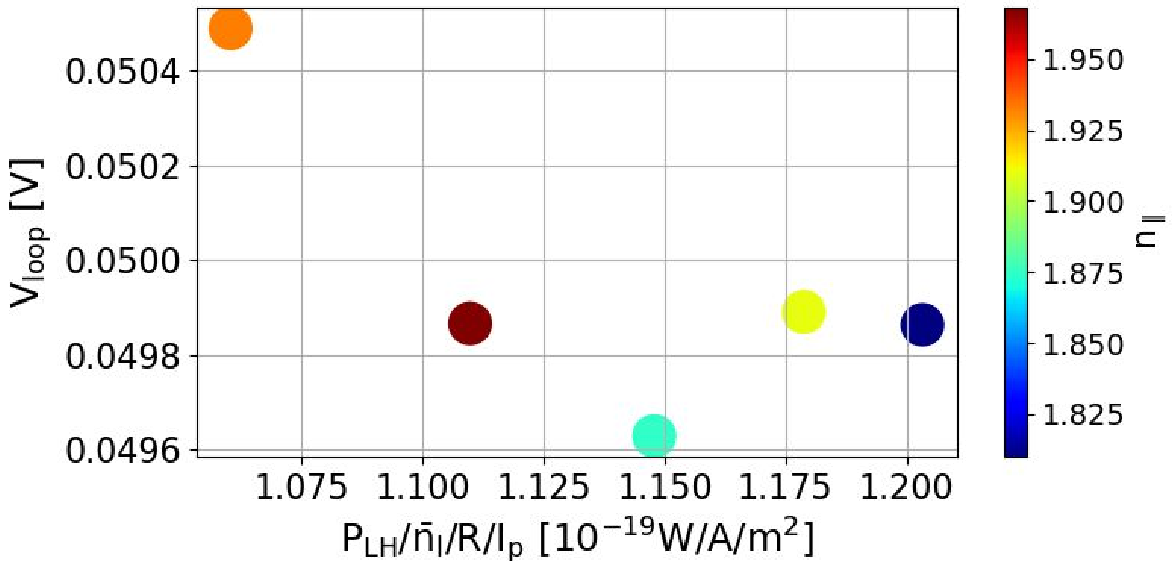
- Attached divertor regime
- Stable discharges down to 3mV achieved
- Tore Supra LHCD efficiencies recovered

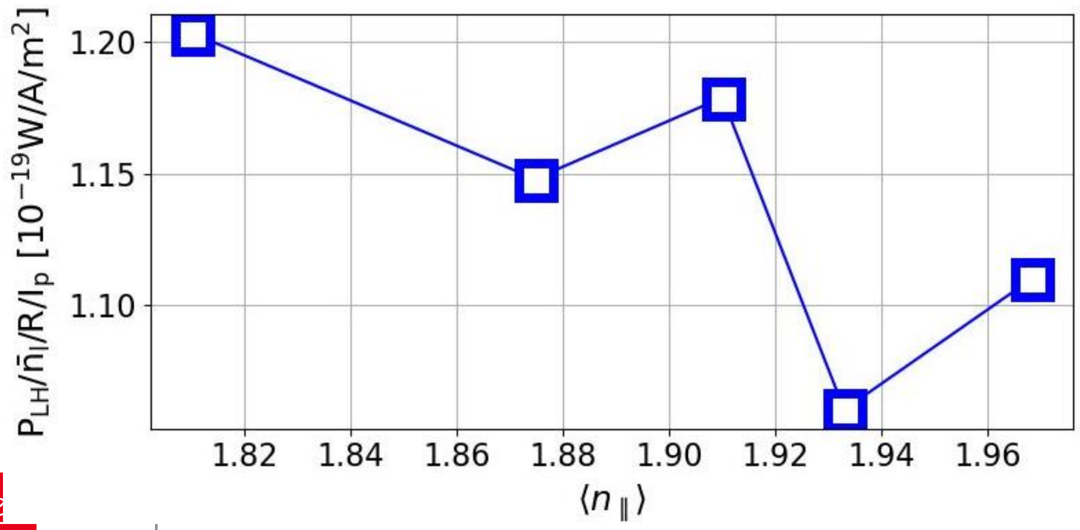
Various $n_{//}$ tested, provide limited flexibility

		LH1			
		-90° (2.0)	-120° (1.9)	-150° (1.8)	-180° (1.7)
LH2	-120° (1.9)	**59314 MHD**	**59313 MHD**	x	x
	-150° (1.8)	**59315 MHD**	**59307 Good**	**59310 Pipe T°**	x
	-180° (1.7)	x	x	x	x

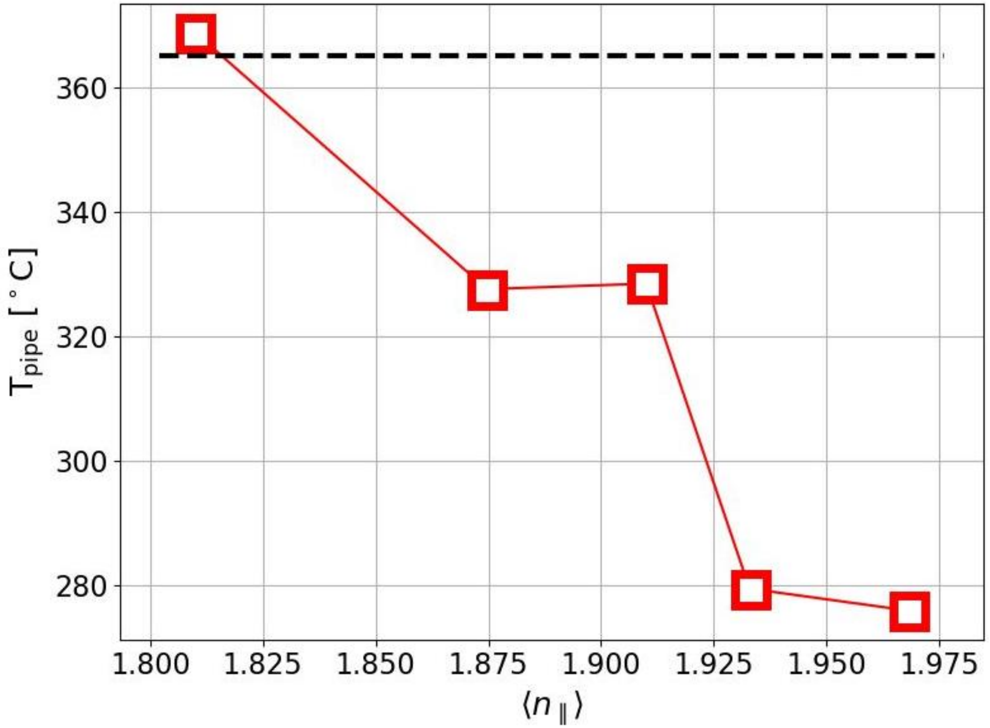


Various $n_{//}$ tested, provide limited flexibility

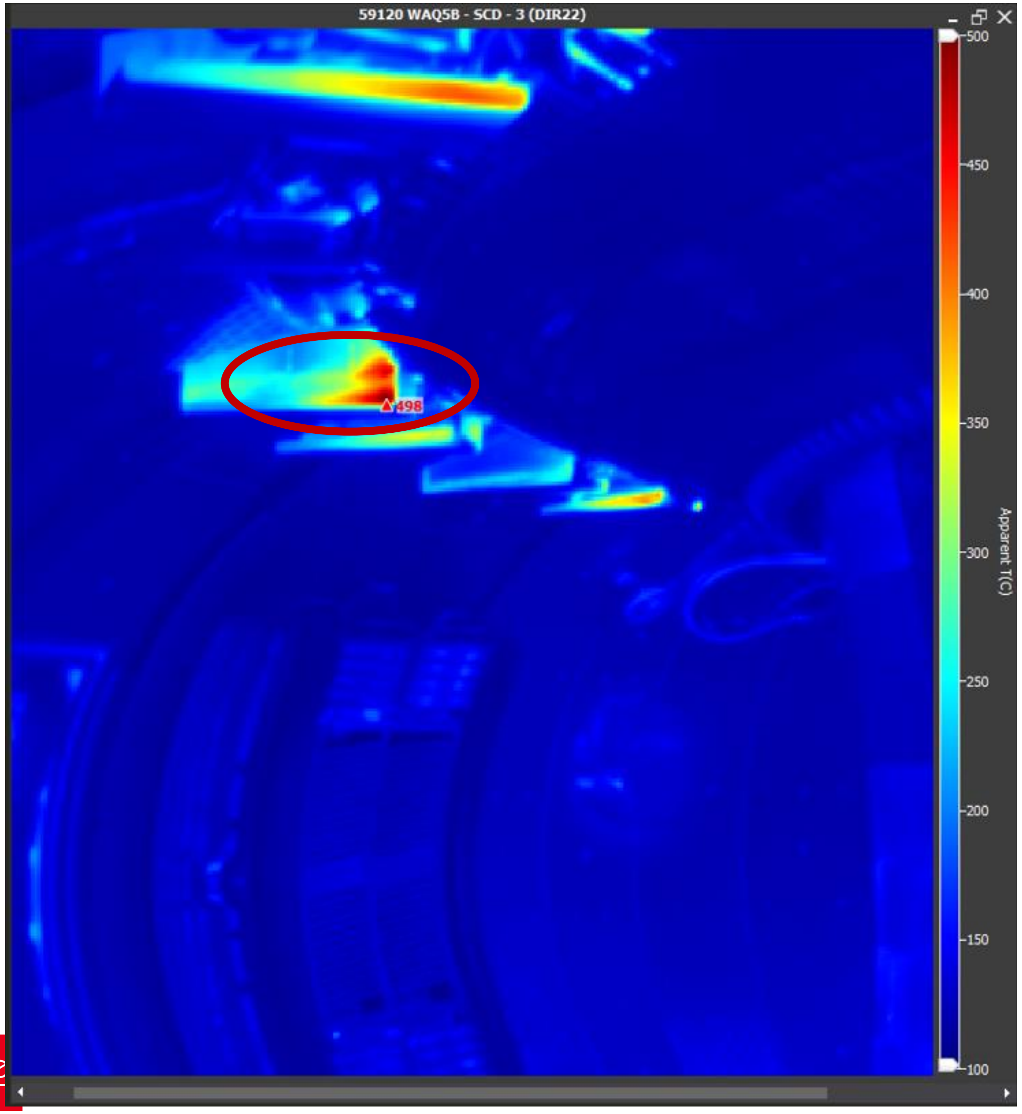




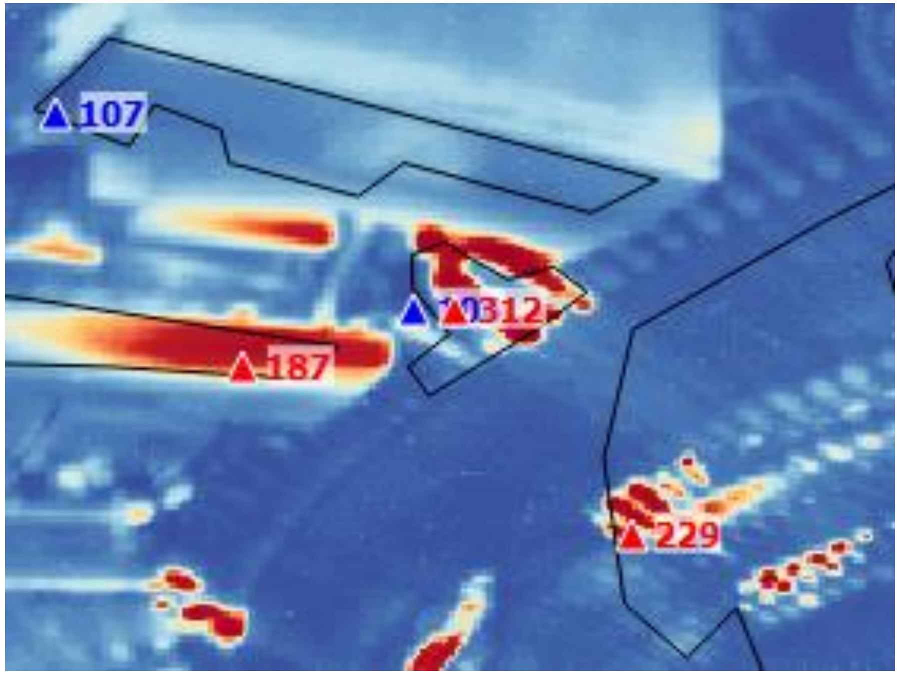
- Impact on performance difficult to assess
  - Often transient because of MHD
  - Not only related to LHCD physics
- Clear effect on pipe temperature, consistent with LH-driven electron physics



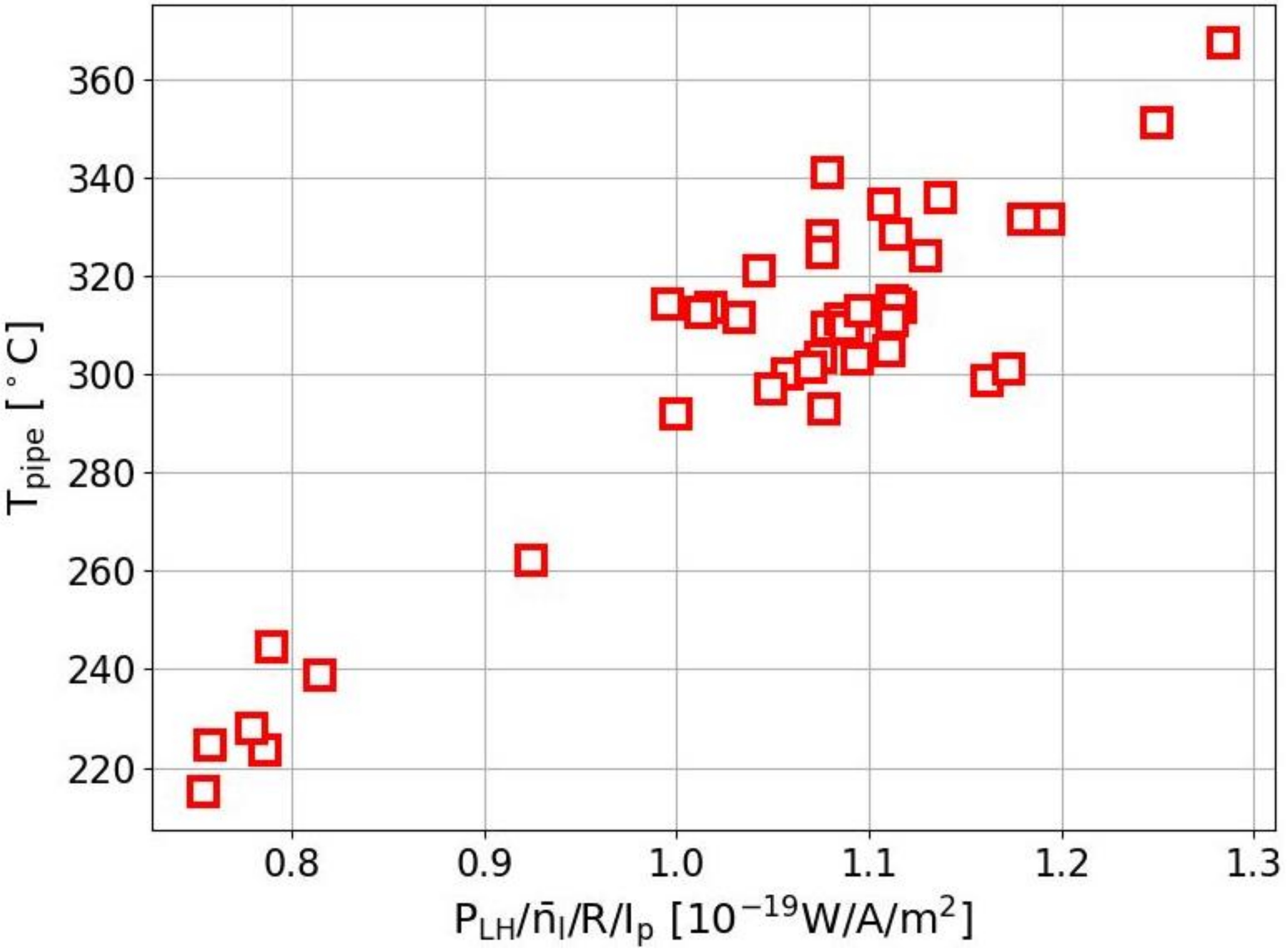
Overheating of upper ripple protection pipes restricts operational domain



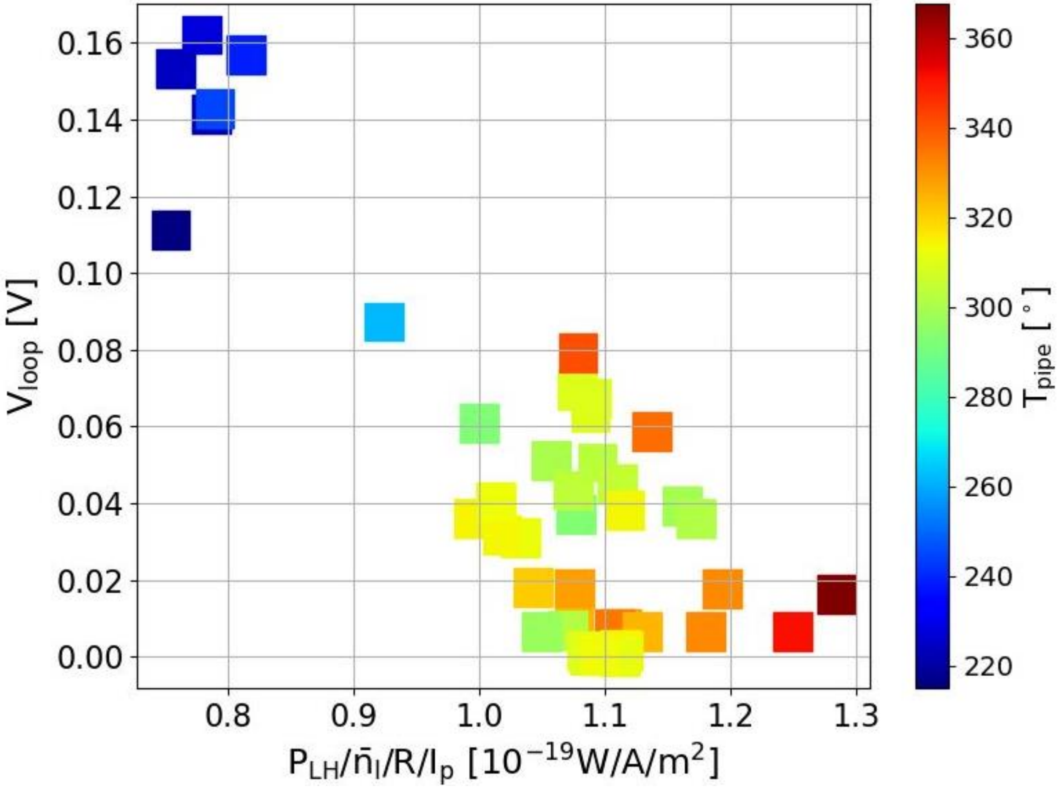
- (Updated) WEST operating instructions
  - Feedback on P_{LH} if T_{IR}>365°
  - Soft stop if T_{IR}>375°



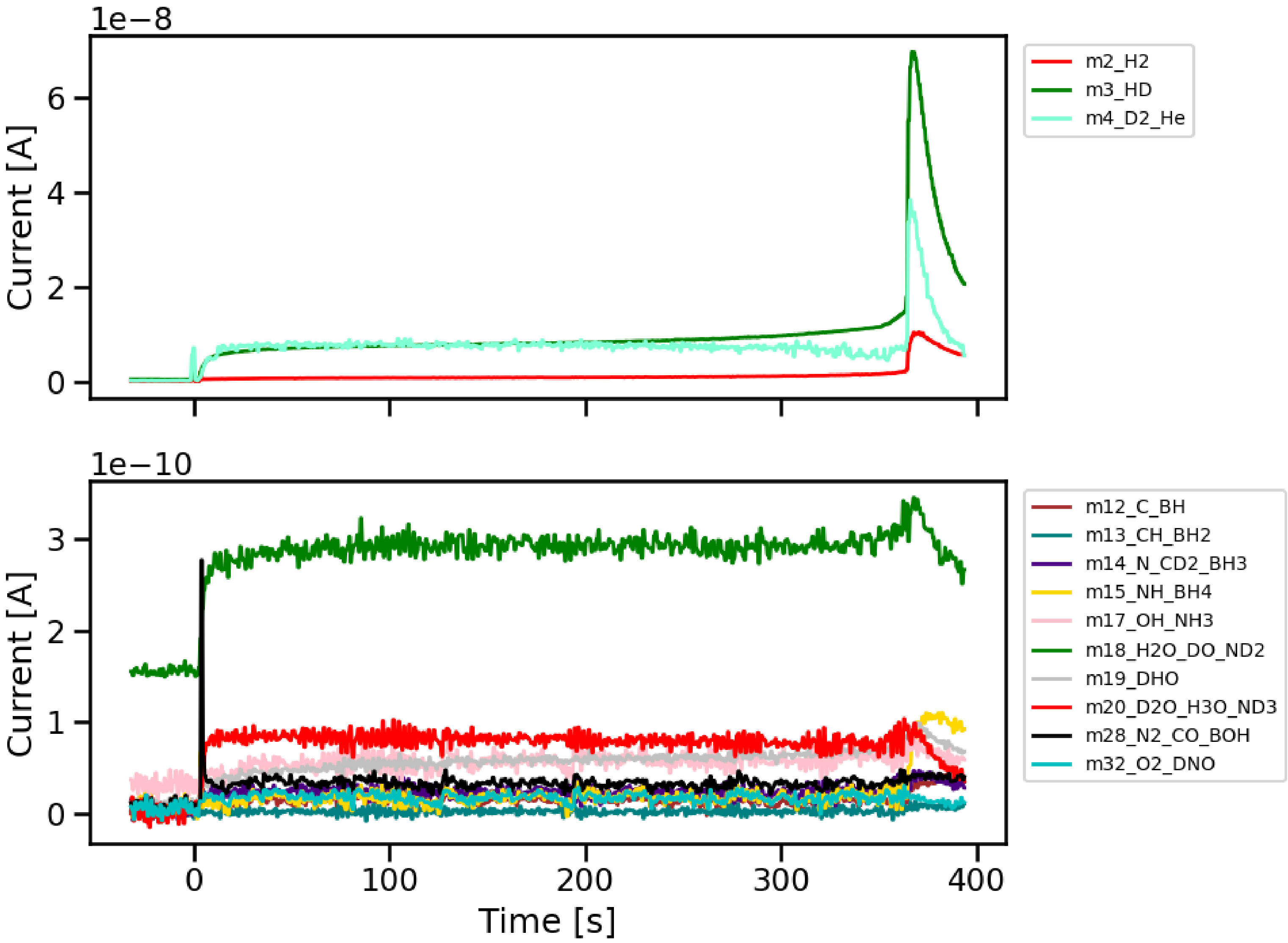
Overheating of upper ripple protection pipes restricts operational domain, favors lower Ip operation



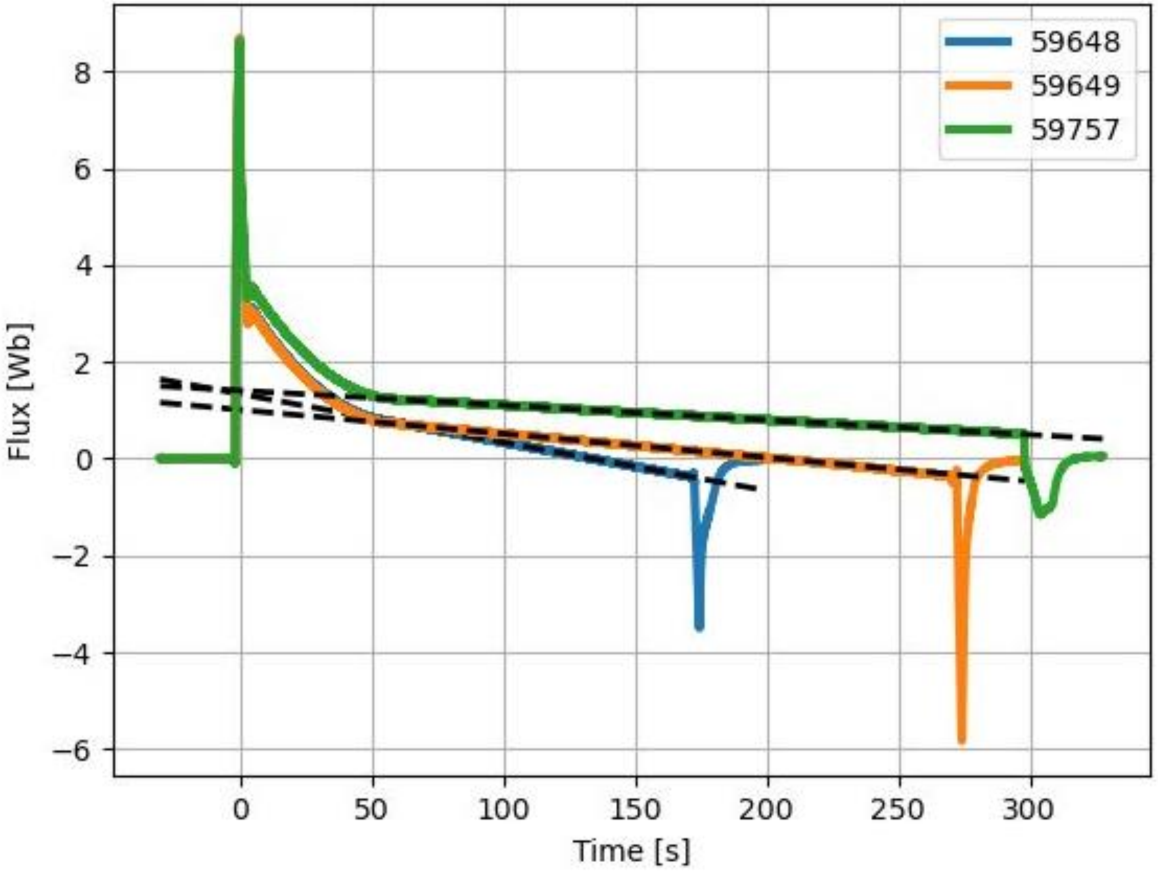
- Apparent IR temperature on upper pipes follows known electron ripple loss dependences
  $T_{max\ [°C]}=134+678\ P_{LH[MW]}^{1.07}\ I_{p[MA]}^{0.58}\ n_{l3[10^{19}m^{-2}]}^{-2.24}$



RGA analysis ni Q6B sudivertor spectrometer confirms slow increase of H2



Double RT control scheme developed

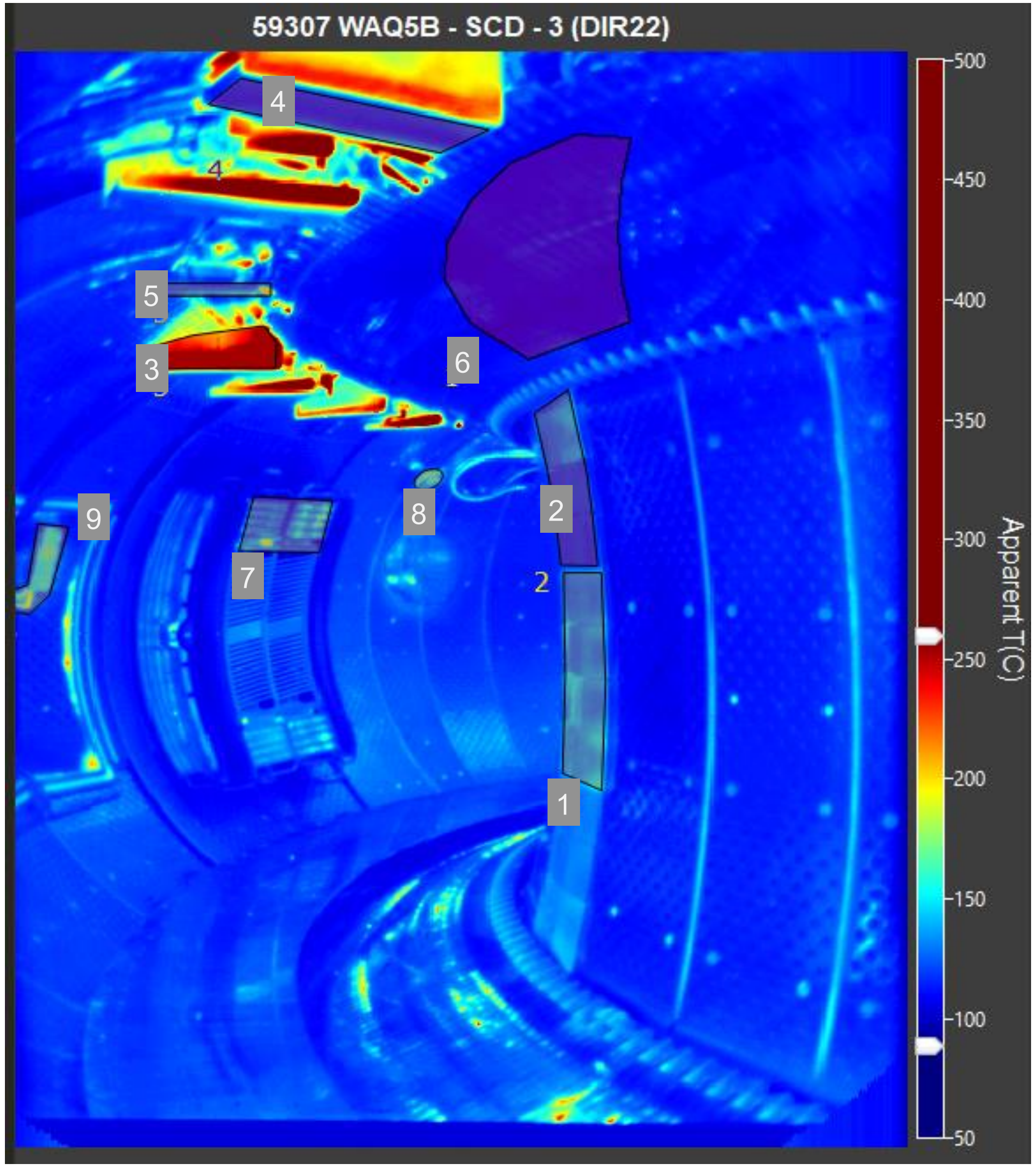


- Double feedback-control scheme implemented
  - V_{loop} set by V_{G0}
  - I_p set by P_{LH}
- Although sufficient flux potentially available for Δt>1000s, thermal I^2t effect on central solenoid coils disqualifies $V_{loop} \geq 5$mV discharges

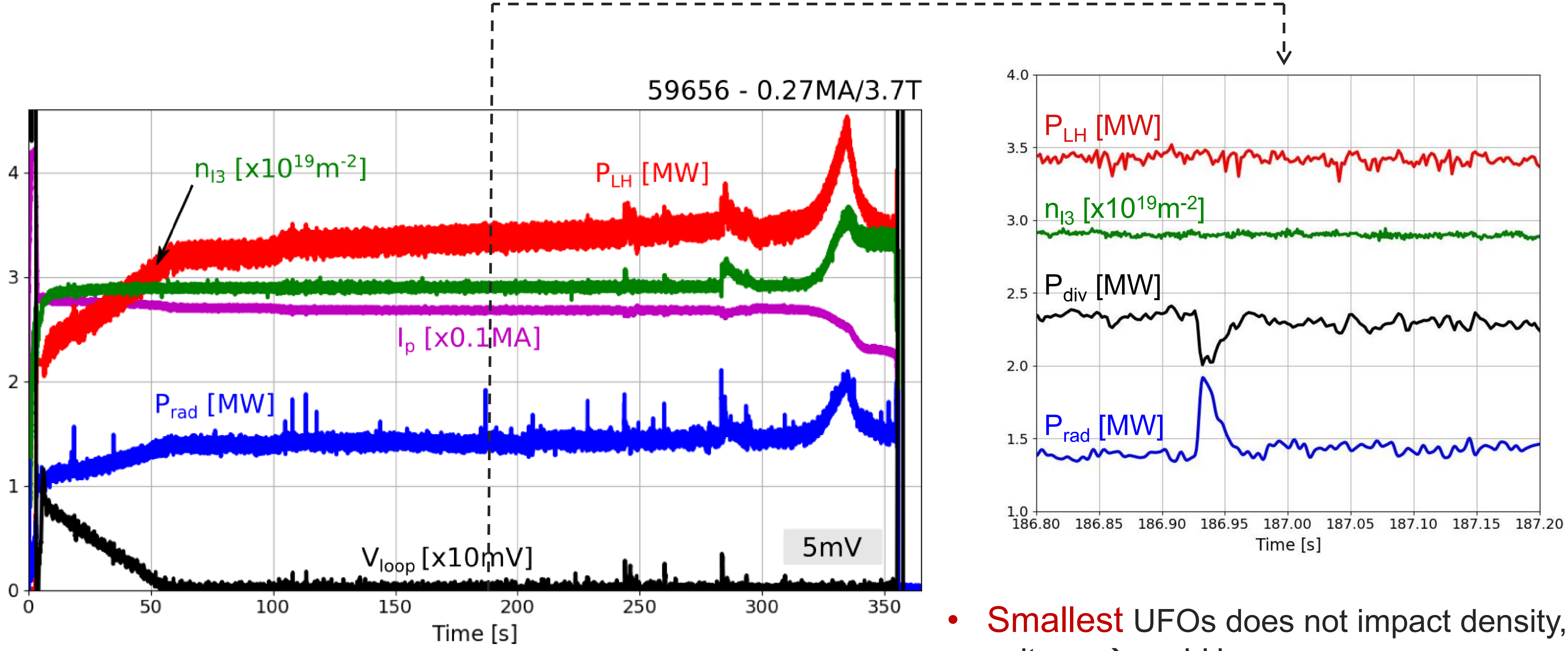
Pulse	Vloop (from flux)	Max duration (ϕ_{min} = -6Wb)	Vloop (magnetics)
59648	10.0mV	734s	12.8mV
59649	5.0mV	1422s	8.1mV
59757	3.0mV	2435s	4.3mV

No definite conclusion on outgassing element(s) from IR analyses at this stage

		Temperature PFC °C					
		t = -2s		t = 60s		t = degas	
ROI	PFC	Mean	Max	mean	Max	mean	Max
1	IGL BN tile	97	99	127	141	148	177
2	IGL W/graphite tile up	96	99	117	128	136	159
3	Protec VDE W bulk	98	100	177	308	377	565
4	Protec VDE W/Cu	98	100	111	136	133	163
5	Ripple pin	97	99	122	215	153	237
6	Upper divertor	97	101	105	118	117	133
7	ICQ4 pipes	96	99	122	162	149	232
8	Glow electrode	100	104	124	138	173	211
9	Inner Q4B port	100	105	120	140	168	235
1	Baffle (DIVQ6A)	78	80	97	97	122	131
2	Q6 Sample holder	85	86	174	226	331	390

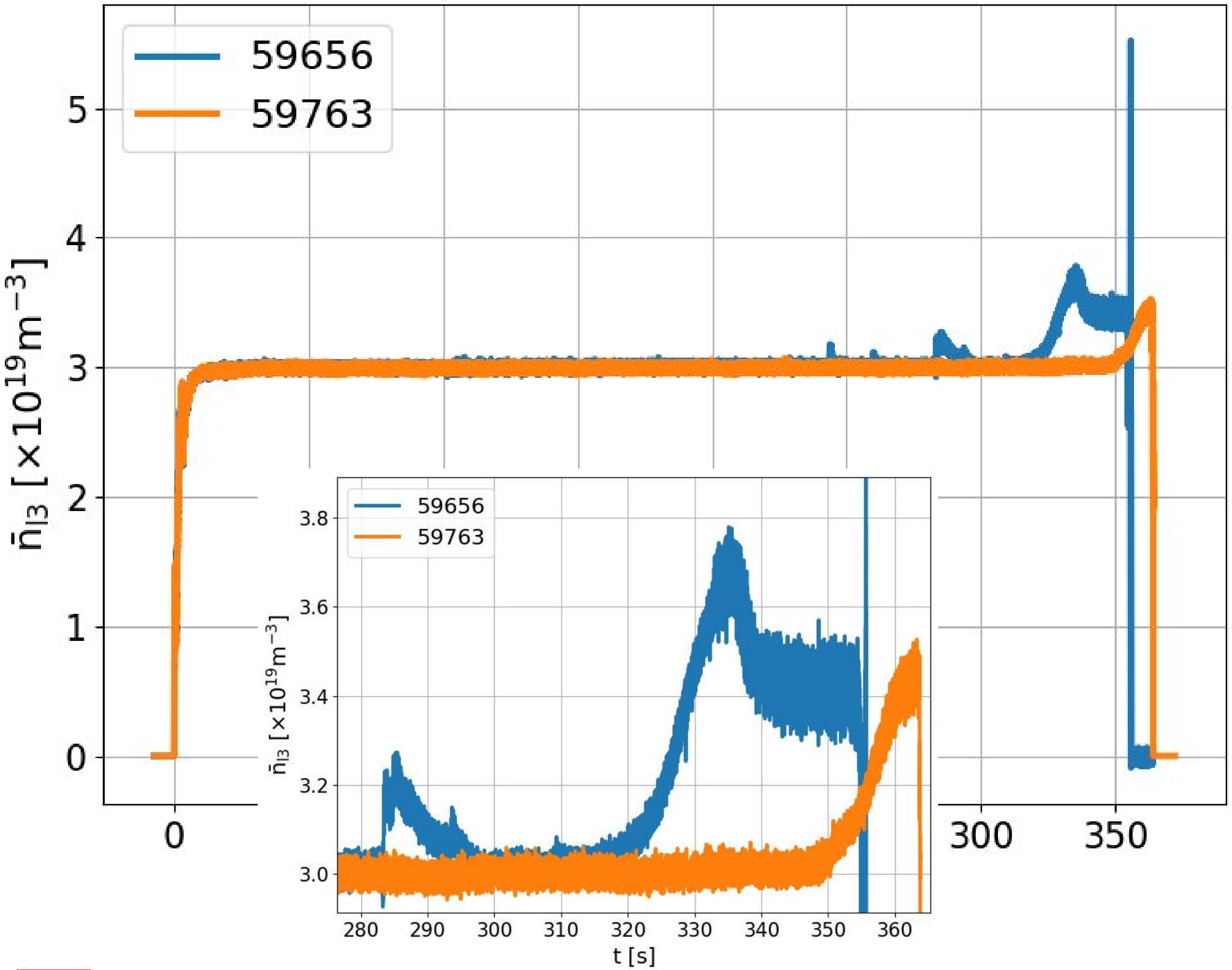


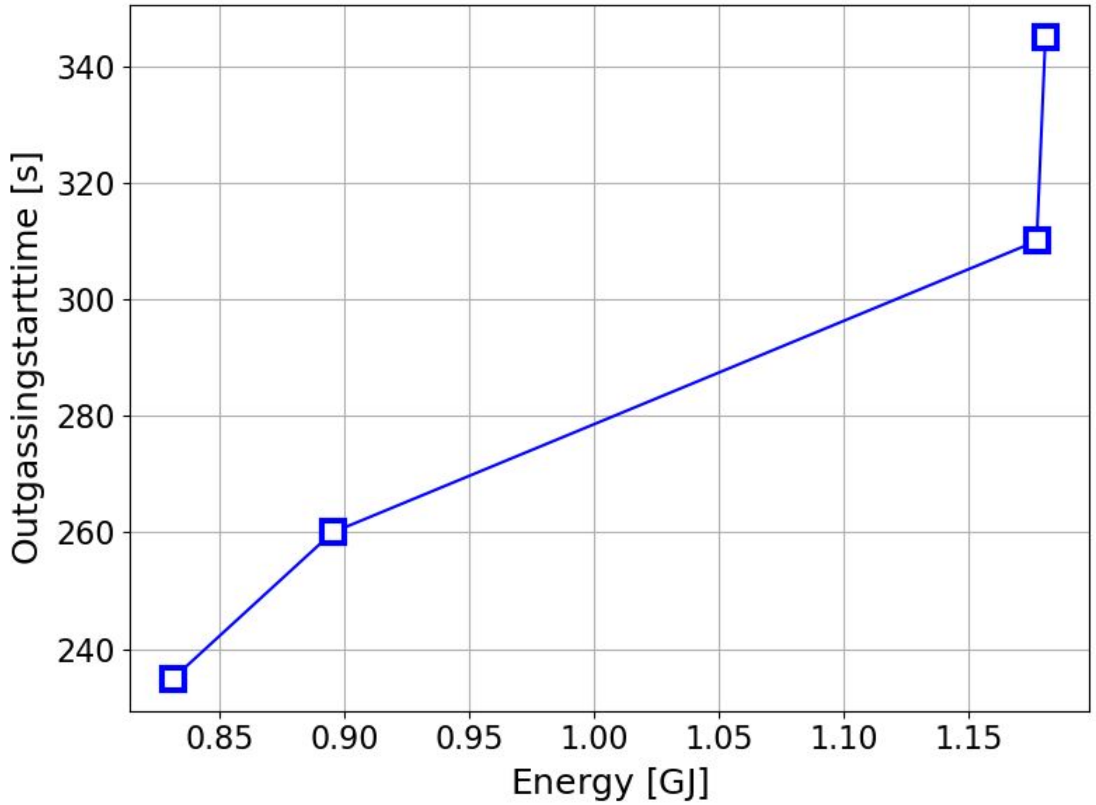
Class 1 UFOs observed in long discharges, transiently impact performance



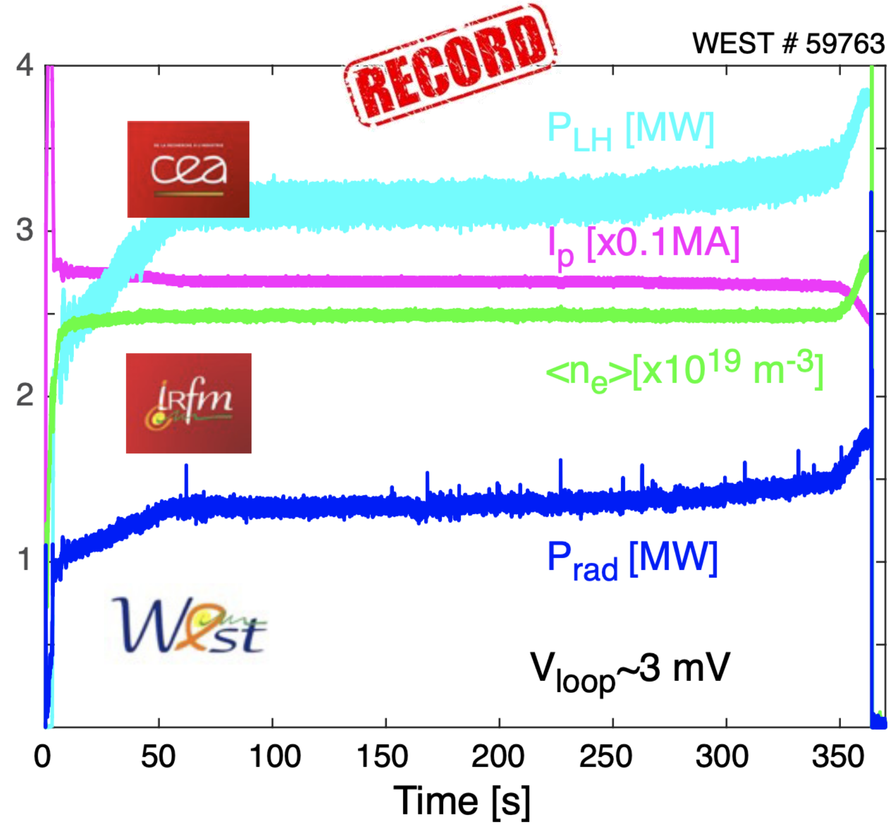
- Smallest UFOs does not impact density, loop voltage → no LH power response

Evidence of progressive conditioning

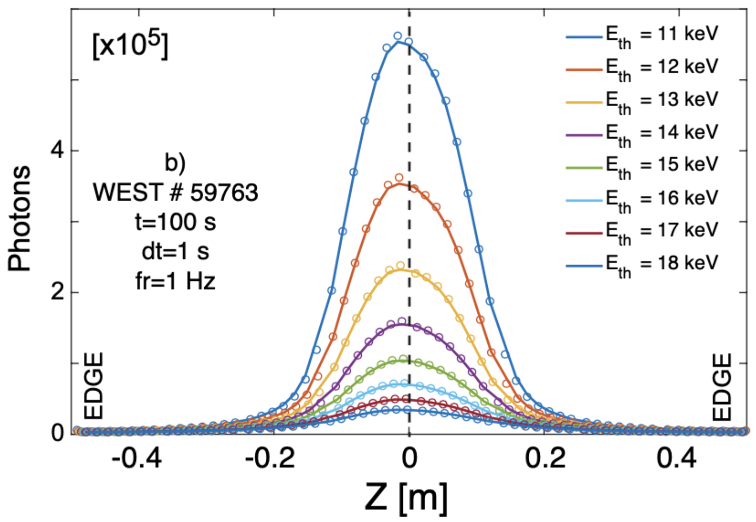




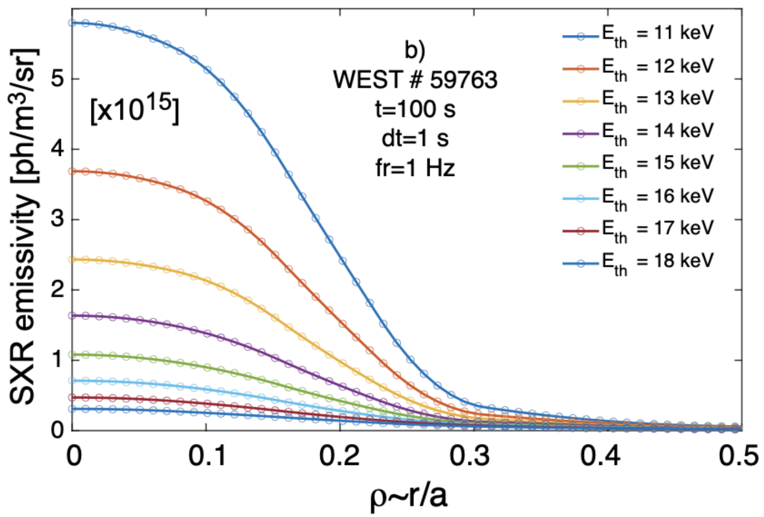
Core multi-energy (ME) fits capture Maxwellian contribution & provide novel 6-point $T_{e,0}$ measurement

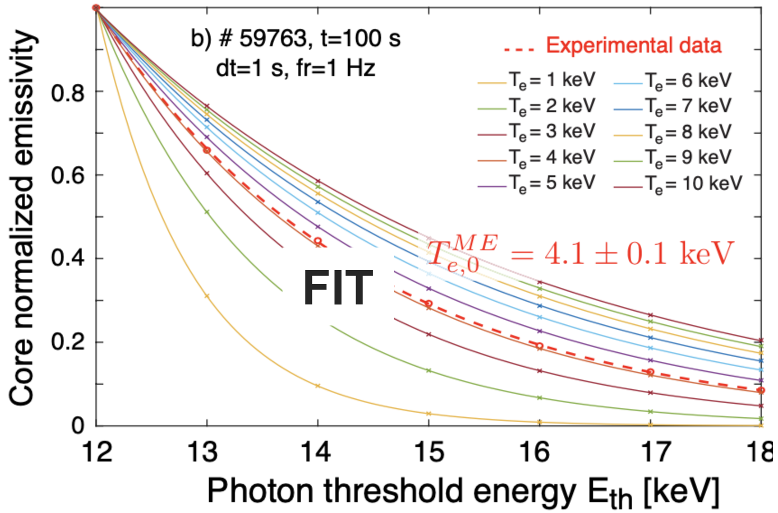


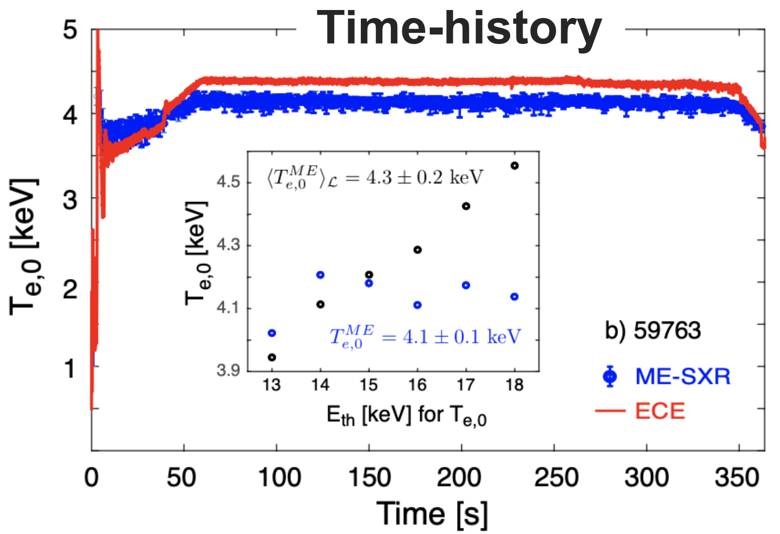
Line-integrated



Reconstructed

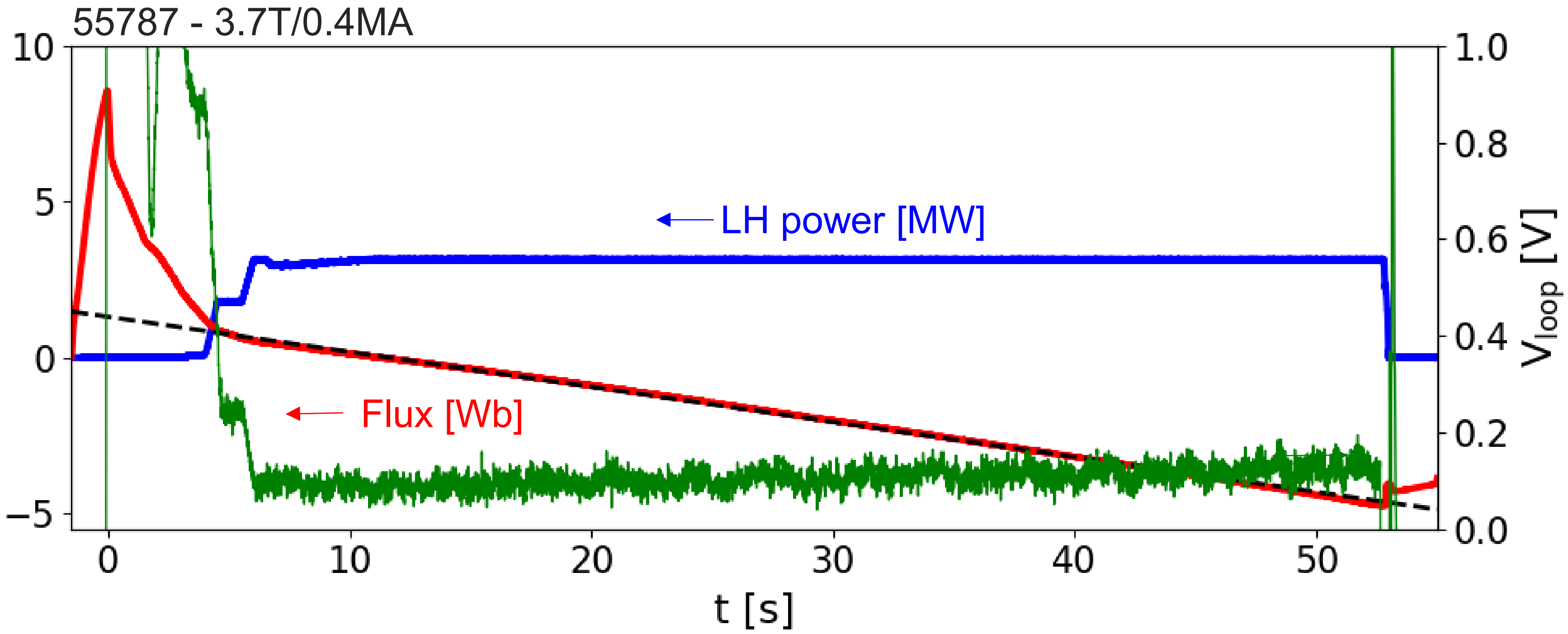






New technology will be used for real-time T_e and n_W measurements at WEST

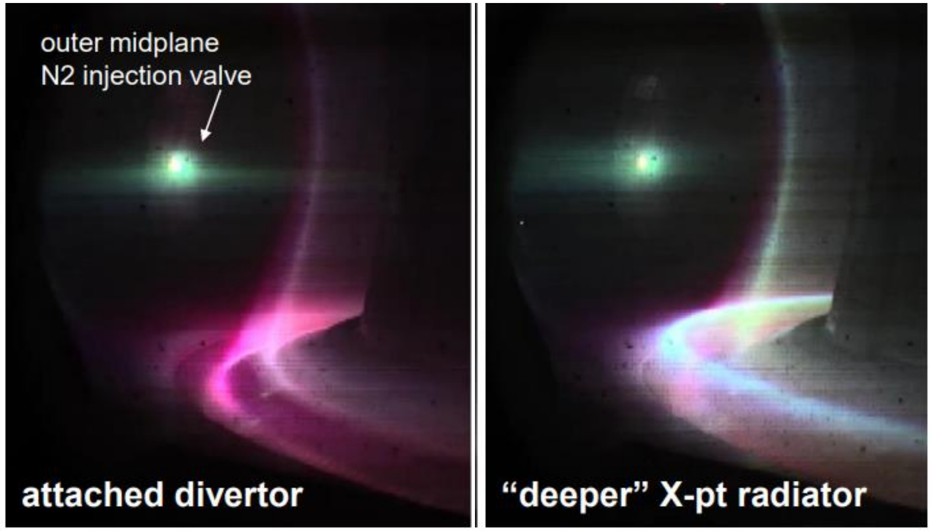
Non-inductive scenario developement requires Vloop minimization, careful tayloring of frontend

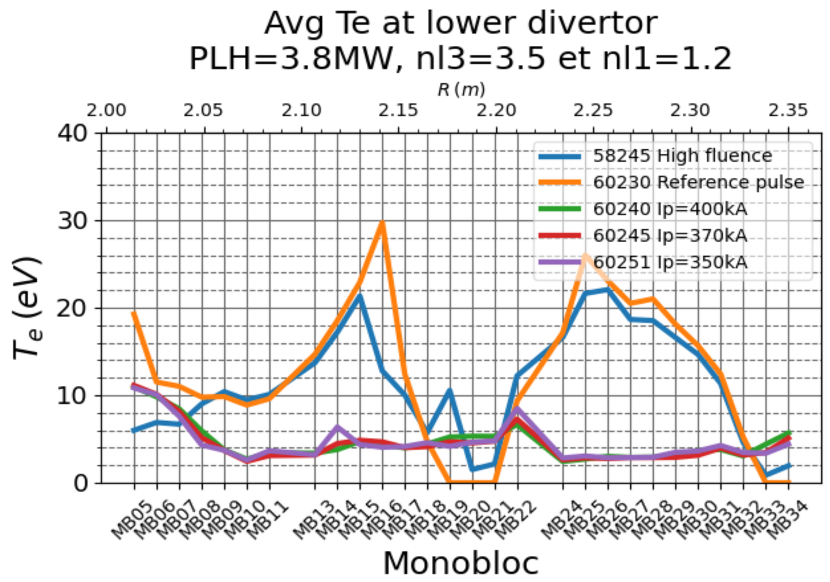


- Maximum flux swing available in WEST: ~14Wb
- LH power required to drive non-inductive current
- In this pulse:
  - Flux consumption fit between 5s and 50s
    $\phi(t)$~0.744-0.112Δt [Wb], agrees well with <V_{loop}>~105mV from magnetic coil measurement
    → target **V_{loop} below 5mV** to reach **1000s** in the same conditions
  - Maximum flux swing ~14Wb not reached because of thermal (I^2t) limit
    → pulse frontend needs to be fine-tuned to switch-on LH power when I_{coil} is sufficiently low

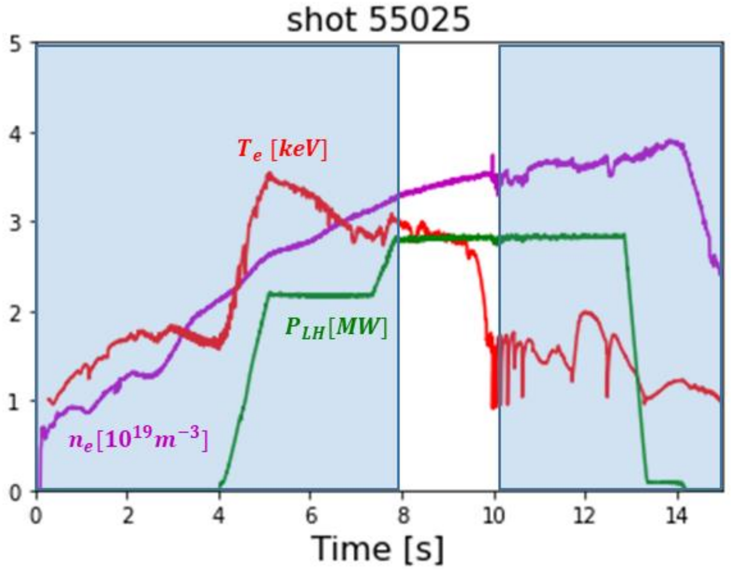
X-Point Radiator scenario developed to operate at low divertor temperatures

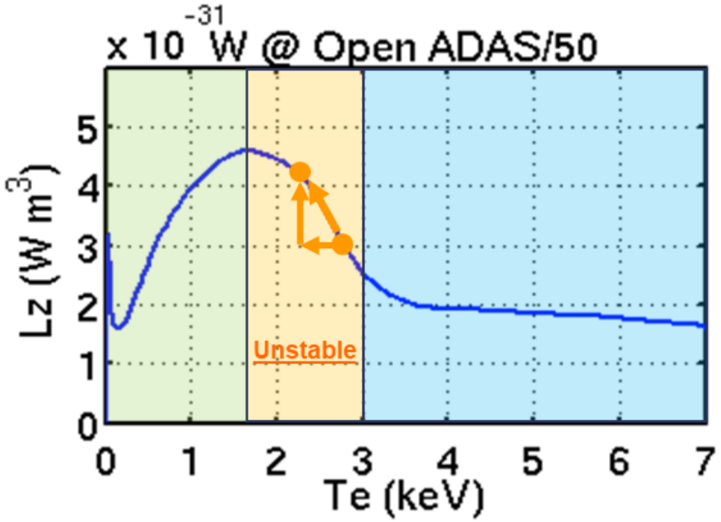
- Low temperature at strike points required to reduce W sources from divertor, flakes
  - Spontaneous transition to low divertor temperature (<10 eV) obtained with light impurity seeding [Fedorczak, PSI 2024]
  - Radiative ring formation above the divertor, transition time scale ~ μs
  - Control scheme on WEST based on interferometry line crossing the X-point region
  - Transition and stability consistent with modelling [Rivals, EPS 2024]
- Demonstrated to be adequate for high-fluence studies (~60s pulses)
- Demonstrated in alternative configurations (double-null and “compact”)
- Long pulse scenario in XPR regimes under development EUROfusion





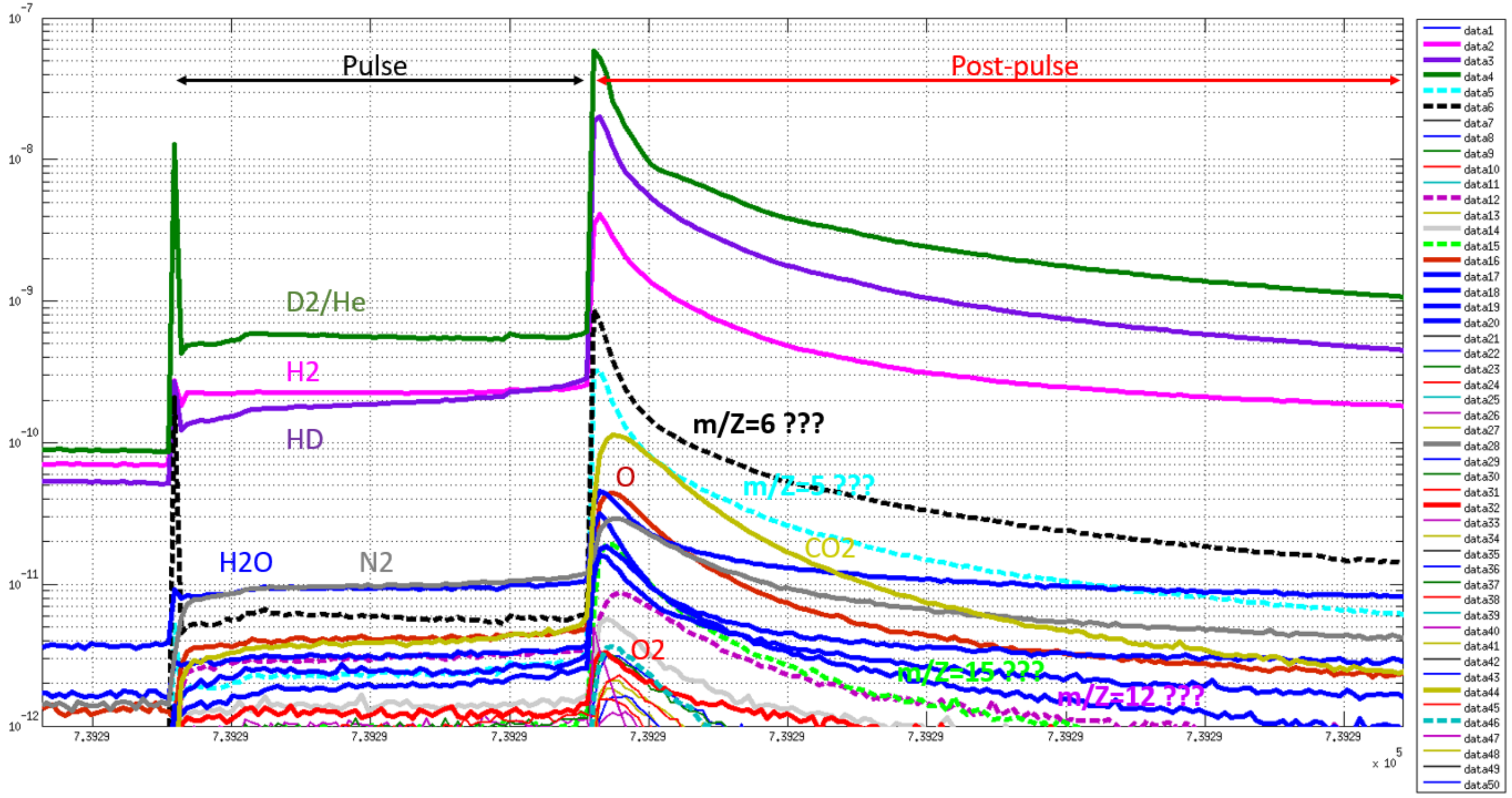
EC power will enlarge parameter space, help increase performance in non-inductive regimes





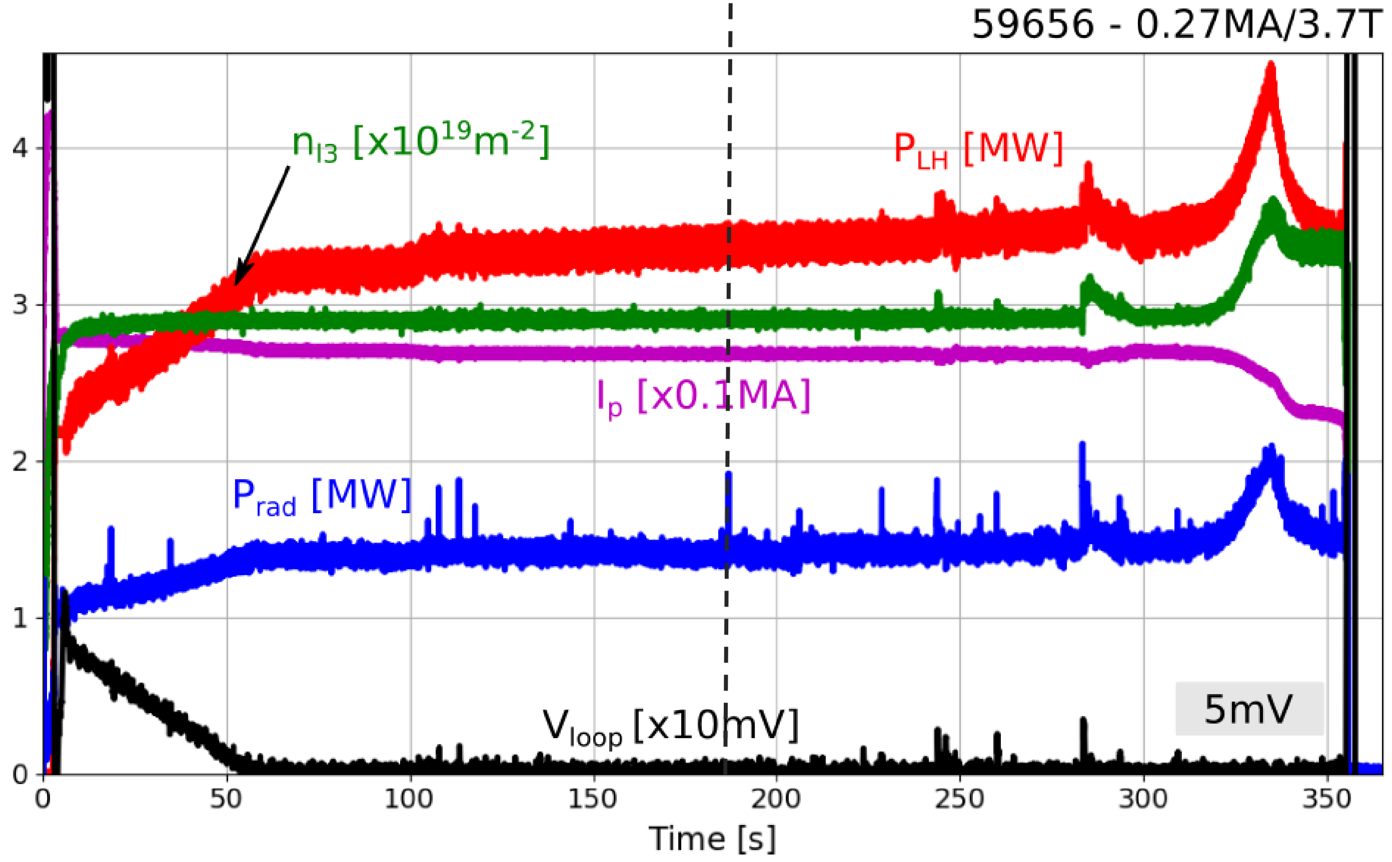
- Radiative collapses observed in some situations [Ostuni, NF 2022]
  - density increases, making Te(0) decrease
    - LH deposition become more off-axis
    - If Te~1.5-3keV, cooling factor increases sharply, increasing W radiation
  - transient events induce $P_{rad}(0)>P_e(0)$
- Central ECRH can
  - Couterbalance central radiation in unstable region of electron temperature
  - “Anchors” LH deposition profile to plasma core
  - Opens the possibility to resort to ICRF power, beneficial for MHD stability in non-inductive pulses [Dumont, PPCF 2014]

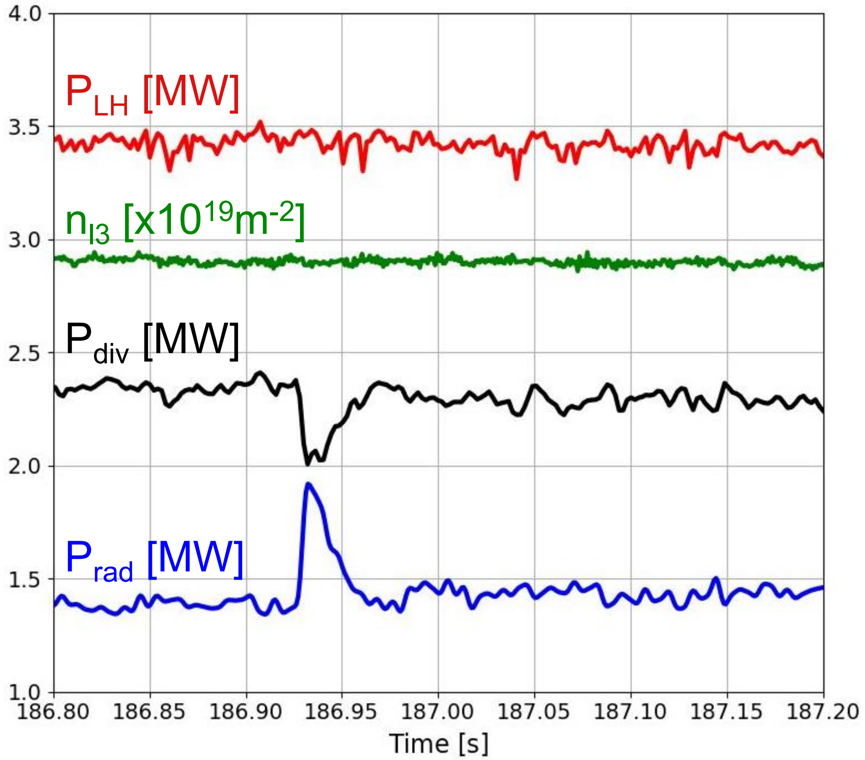
Mass spectrometer analyses of long pulses displays increase of H_2 and DH masses



- During pulse
  - D_2 dominates (fuelling/recycling)
  - H_2 outgassed by the wall
  - HD increases constantly (because of wall heating)
- Potential link to BN limiter tiles temperature increase difficult to establish
  - No temperature threshold observed for H_2 release
  - **But** cannot be ruled out

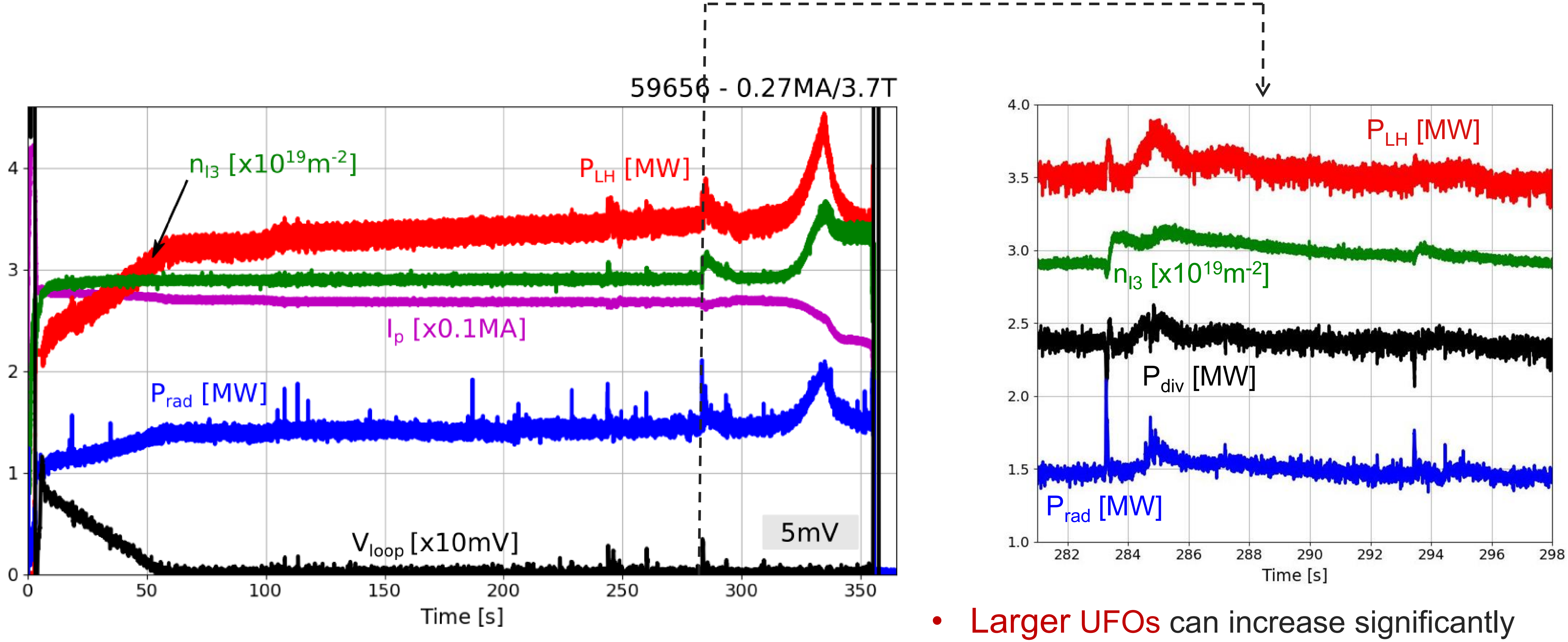
Class 1 UFOs observed in non-inductive discharges, transiently impact performance





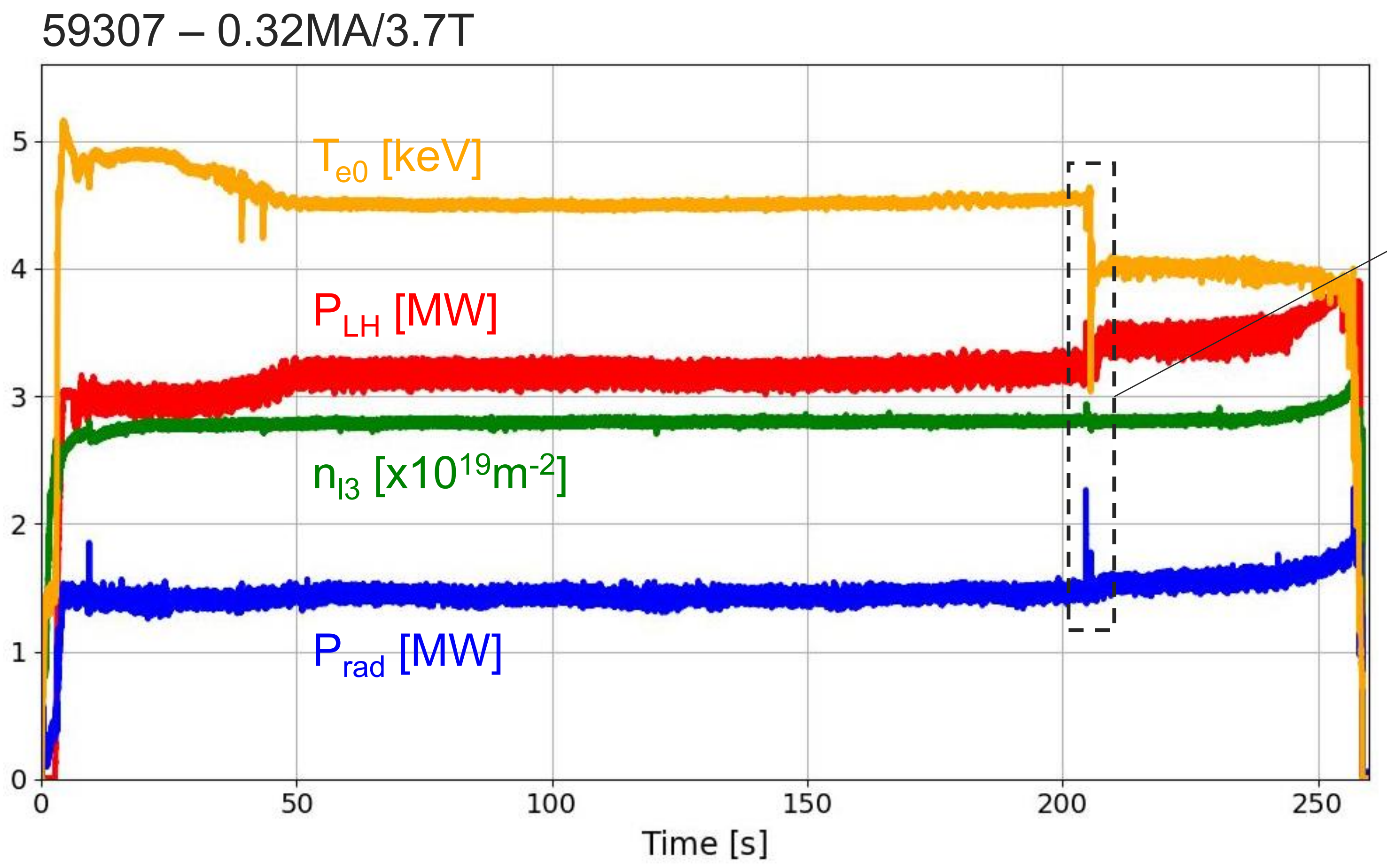
- Smallest UFOs does not impact density, loop voltage → no LH power response

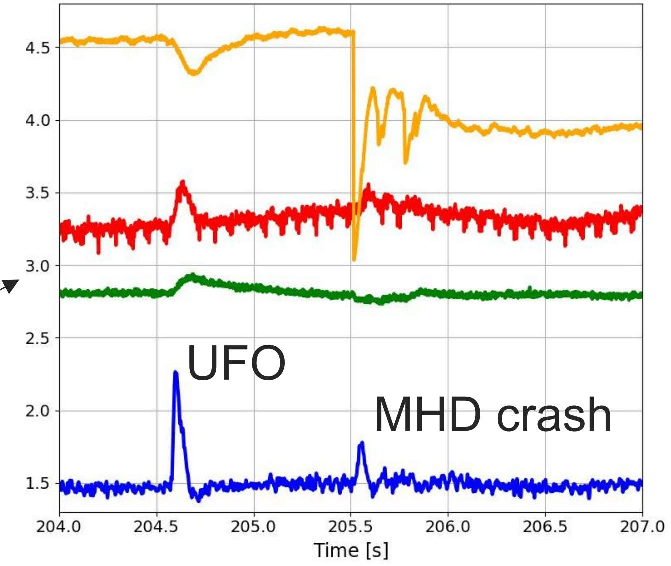
Class 1 UFOs observed in non-inductive discharges, transiently impact performance

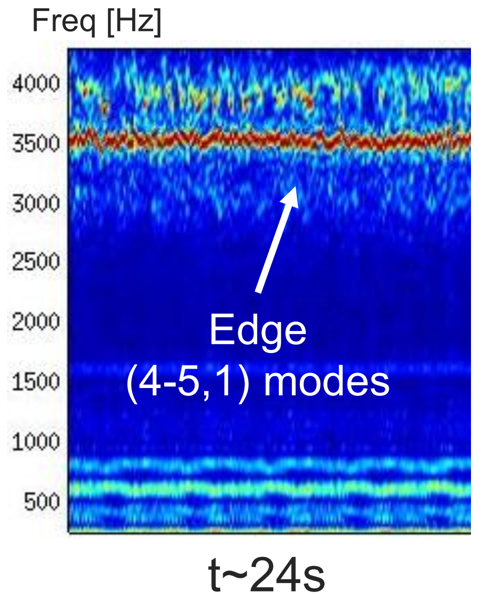


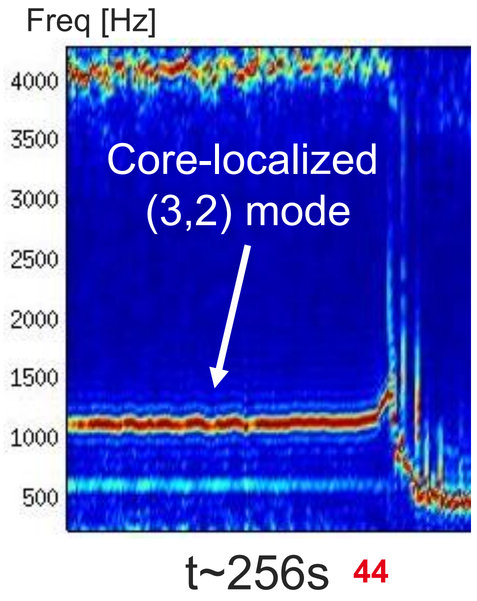
- Larger UFOs can increase significantly density, loop voltage, plasma current → transient LH power response (~few seconds)

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

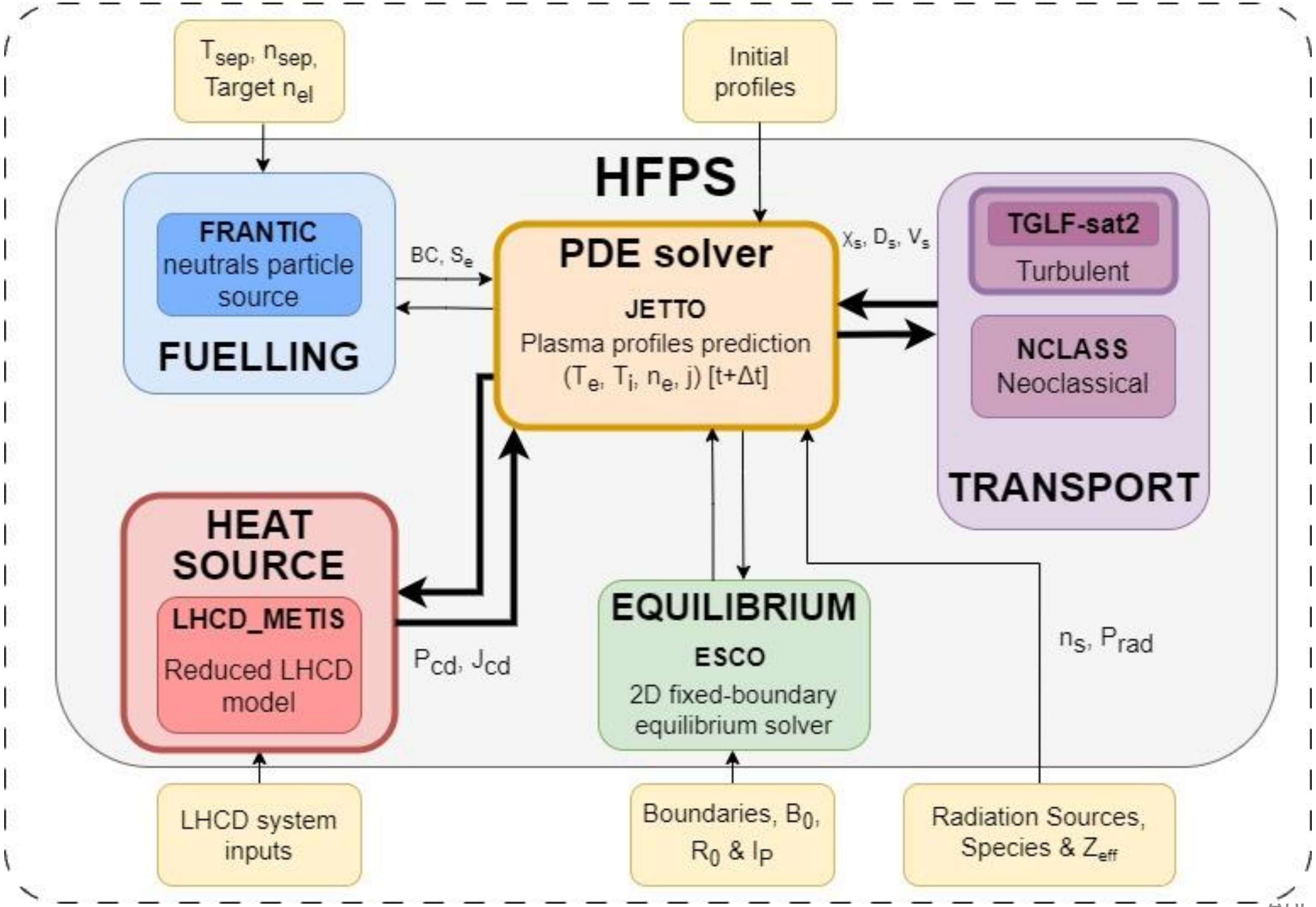






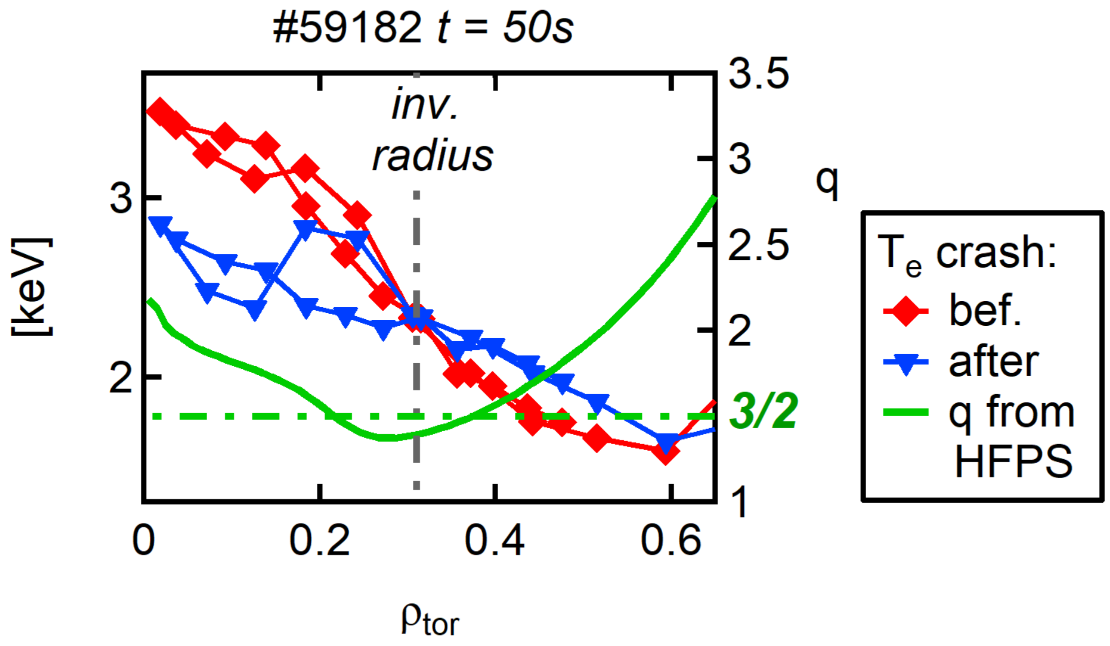


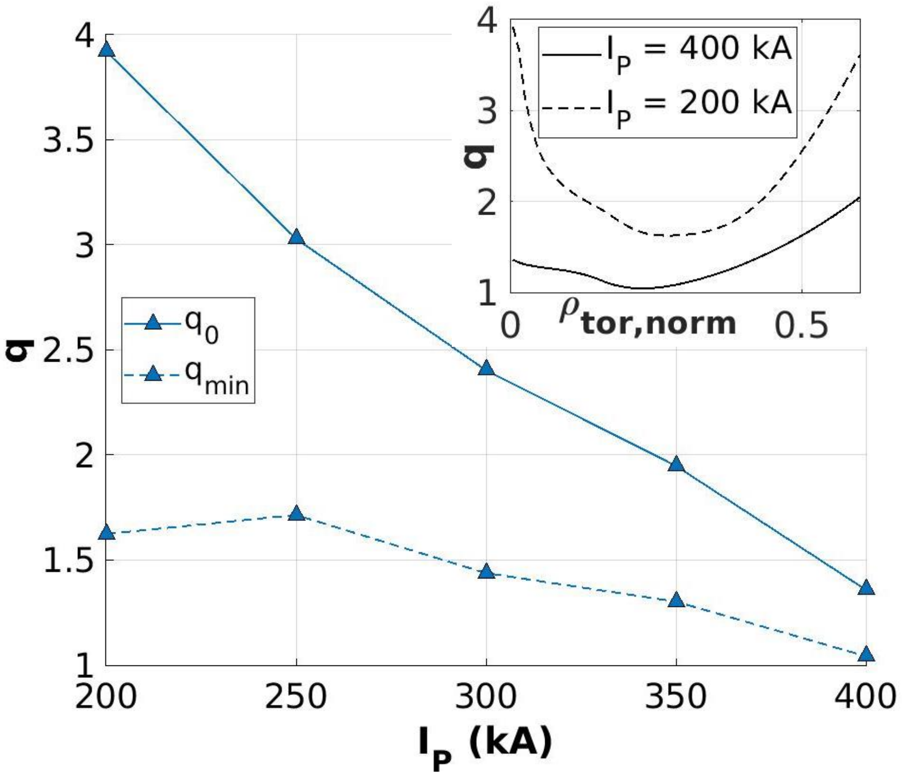
HFPS provides a comprehensive framework for the prediction of long pulses



Decreasing plasma current / increasing LH power promotes double tearing modes

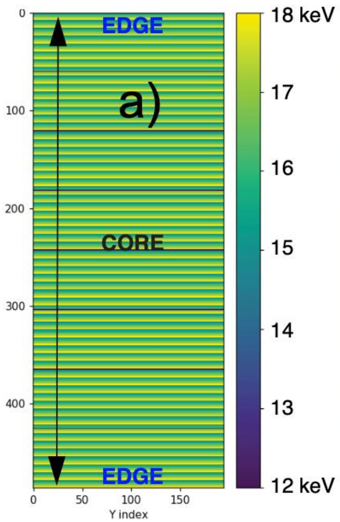
- Experimental location of MHD crashes from ECE consistent with q-profile computed by HFPS - Here (3,2) mode destabilized

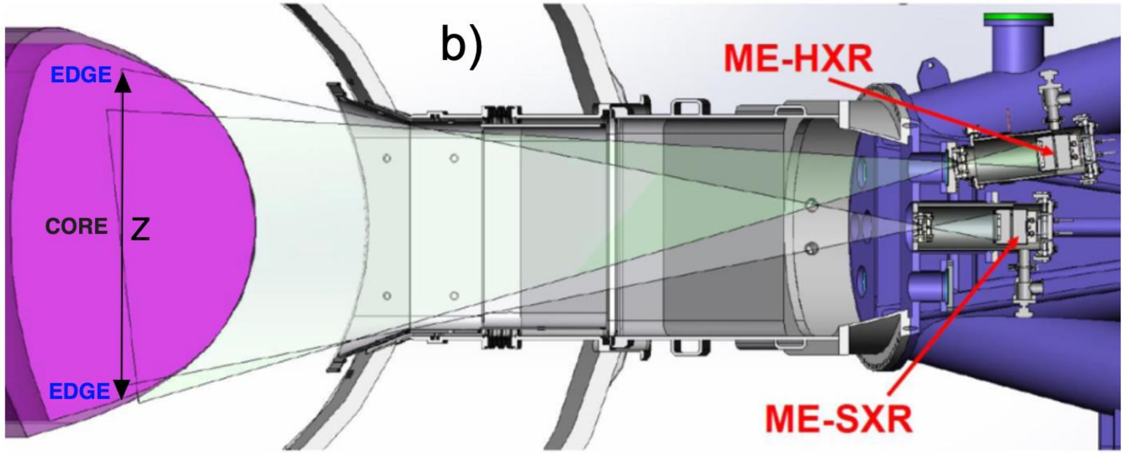


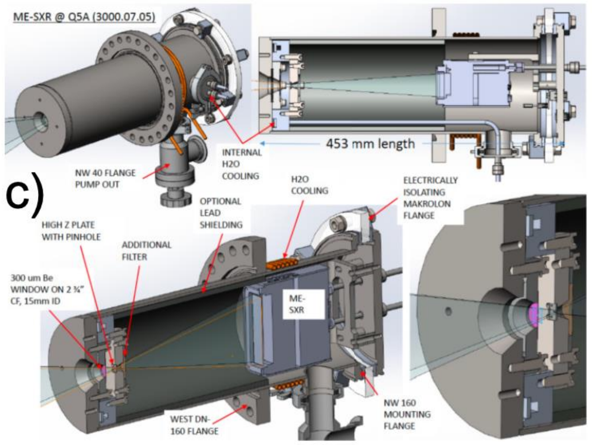


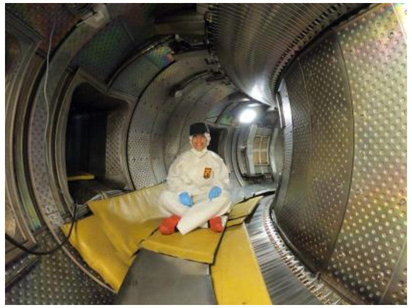
- q-profile reversal enhanced at lower current (and/or larger LH power)
- Self-consistent MHD stability module for HFPS currently under test

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



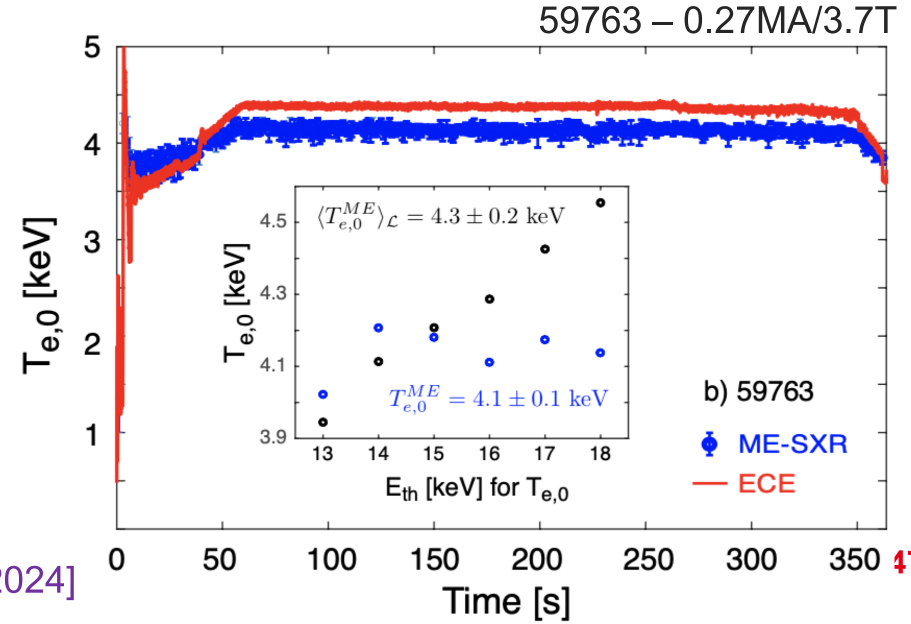






Multi-energy systems use *smart pixel technology* to disentangle n_W and T_e-effects in spatially recorded spectra

PPPL



[Barbui, RSI 2022; Barbui, NF 2024]