

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

R. DUMONT

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



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.



¹R. Dumont, ¹T. Fonghetti, ¹P. Maget, ¹P. Manas, ¹J.-F. Artaud, ²T. Barbui, ¹C. Bourdelle, ¹L. Colas, ¹G. Ciruolo, ¹Y. Corre, ²L.F. Delgado-Aparicio, ¹A. Ekedahl, ¹N. Fedorczak, ¹P. Forestier-Colleoni, ¹A. Gallo, ³J. Gaspar, ¹E. Geulin, ¹B. Guillermin, ⁴A. Grosjean, ¹C. Guillemaut, ¹J.P. Gunn, ¹J. Hillairet, ⁶J. Huang, ¹F. Imbeaux, ¹E. Joffrin, ⁵E. Lerche, ⁶M. Li, ¹X. Litaudon, ¹D. Mazon, ¹S. Mazzi, ¹J. Morales, ¹Ph. Moreau, ¹R. Nouailletas, ¹P. Puglia, ¹C. Reux, ¹N. Rivals, ¹Y. Savoye-Peysson, ¹E. Tsitrone, ¹S. Vartanian, ³E. Vergnaud, and the WEST team[#], and the EUROfusion Tokamak Exploitation team^{##}

¹CEA, IRFM, Saint-Paul-lez-Durance Cedex, France

²Princeton Plasma Physics Laboratory, Princeton, NJ, USA

³Aix Marseille Université, Marseille, France

⁴University of Tennessee, Knoxville, USA

⁵LPP-ERM-KMS, Association EUROFUSION-Belgian State, TEC partner, Brussels, Belgium

⁶Institute of Plasma Physics, Chinese Academy of Sciences

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

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



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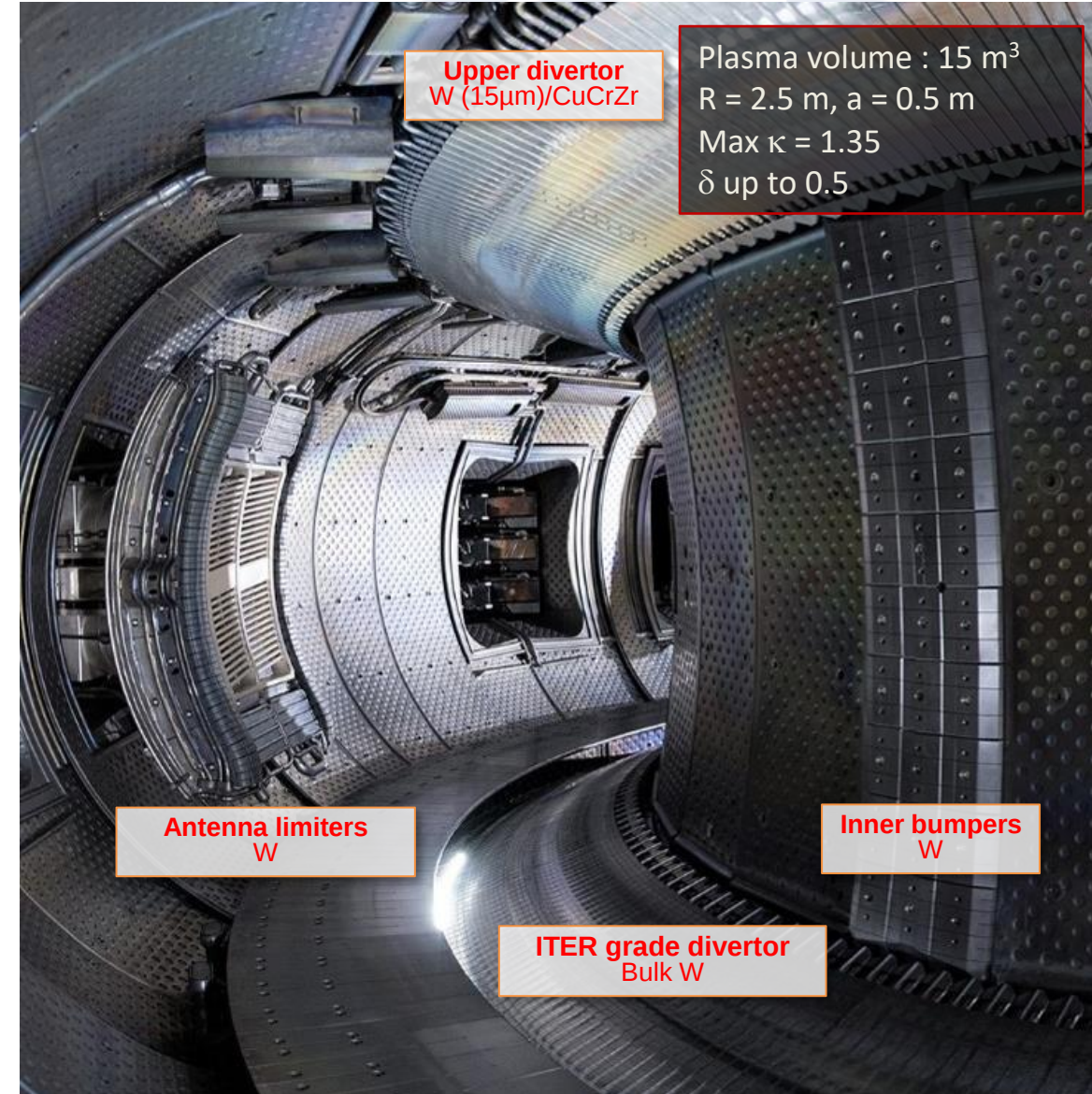




Long pulse operation: a crucial element in the development of fusion-based power plants

- 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 $B_0 \sim 3.7$ 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 $\rightarrow$ 3 MW (2026)

$\rightarrow$ dominant electron heating / low torque

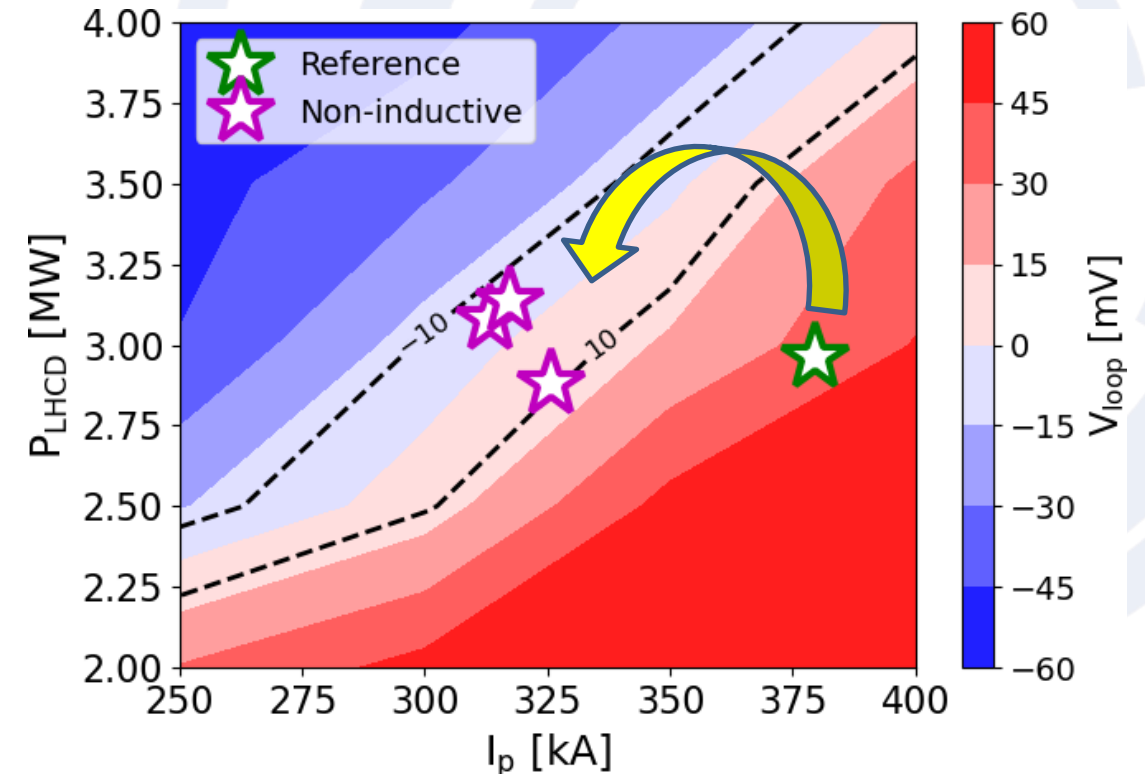




Pulse development in WEST based on predict-first integrated modelling strategy



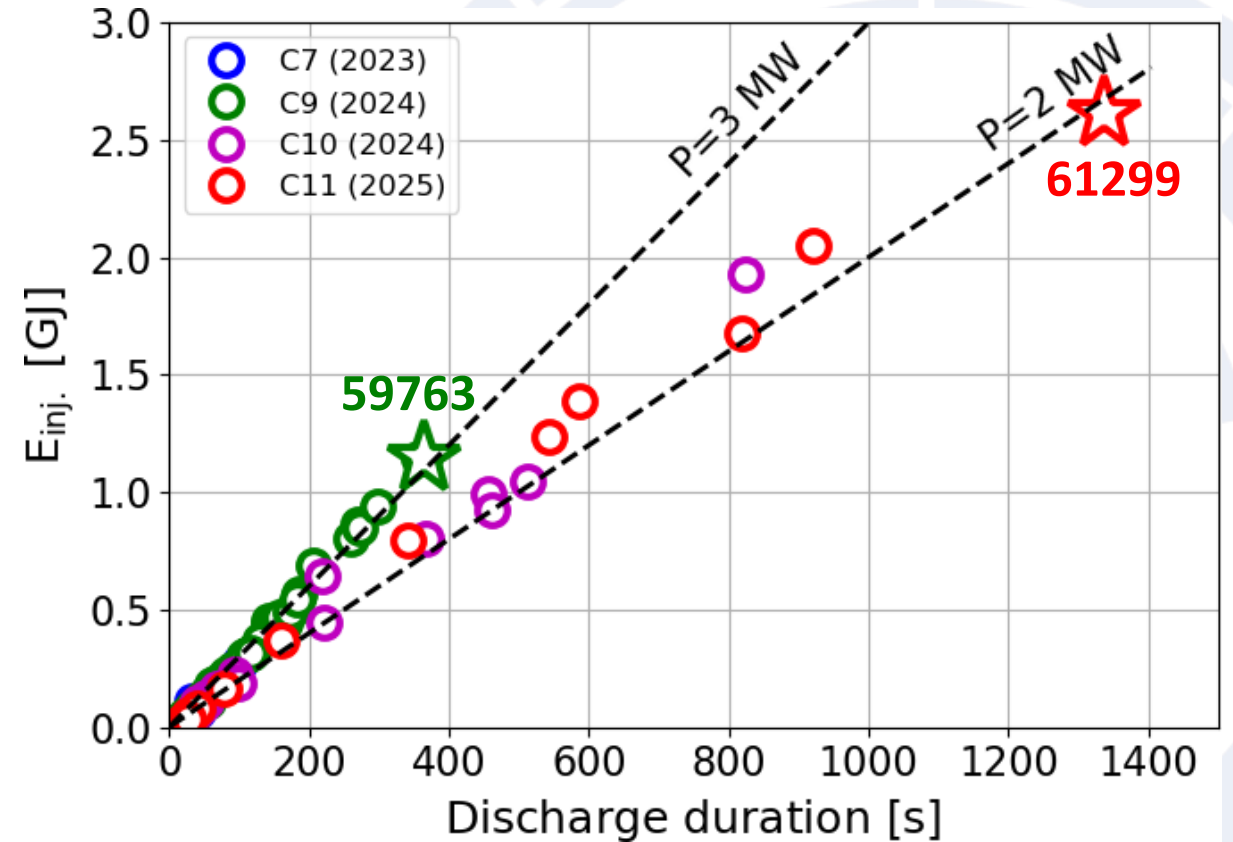
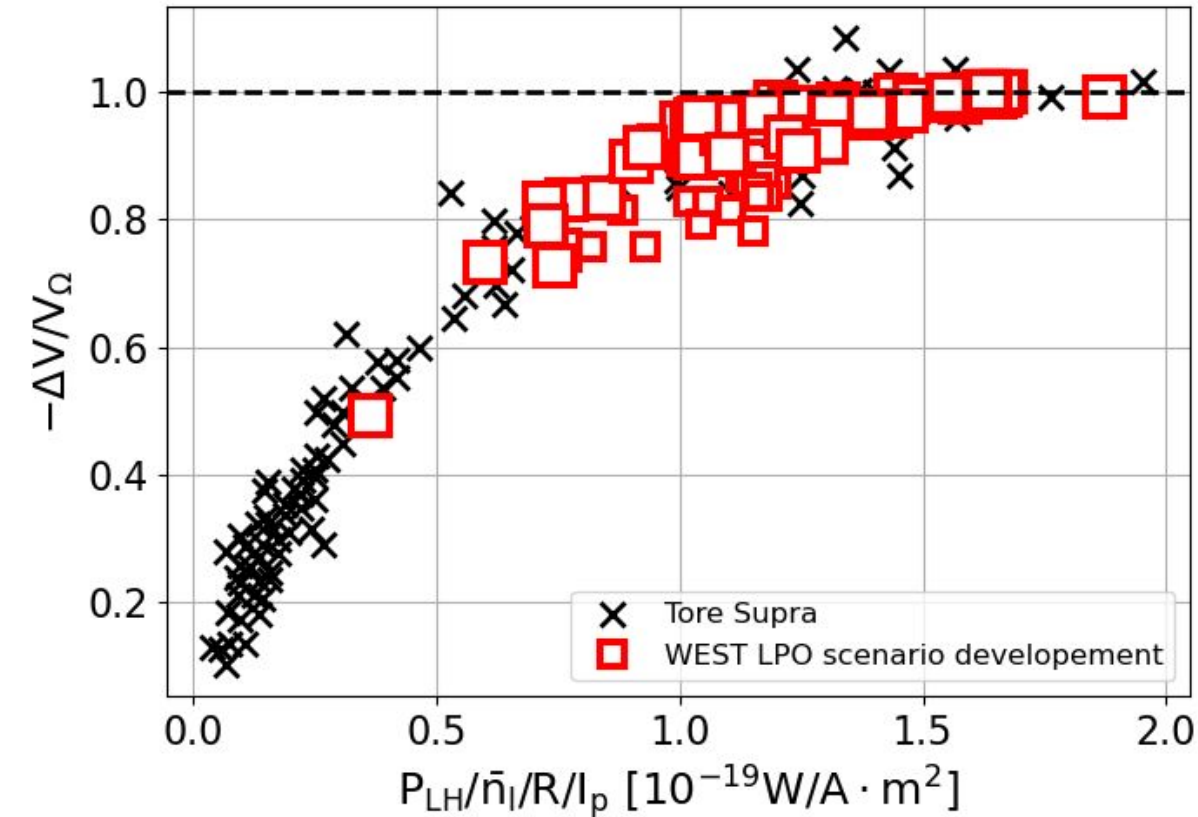
- Fully non-inductive discharges → complex non-linearities, especially in W environments (current profile, power source, heat and particle transport...)
- High Fidelity Pulse Simulator (HFPS) based on JINTRAC/JETTO employed  EUROfusion
 - Simplified model used for LHCD deposition profile [Dumont, PoP 2000], with experimental scaling law for current drive efficiency: $\eta_{\text{LH}} \propto \tau_{\text{E}}^{0.4}$ [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]





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

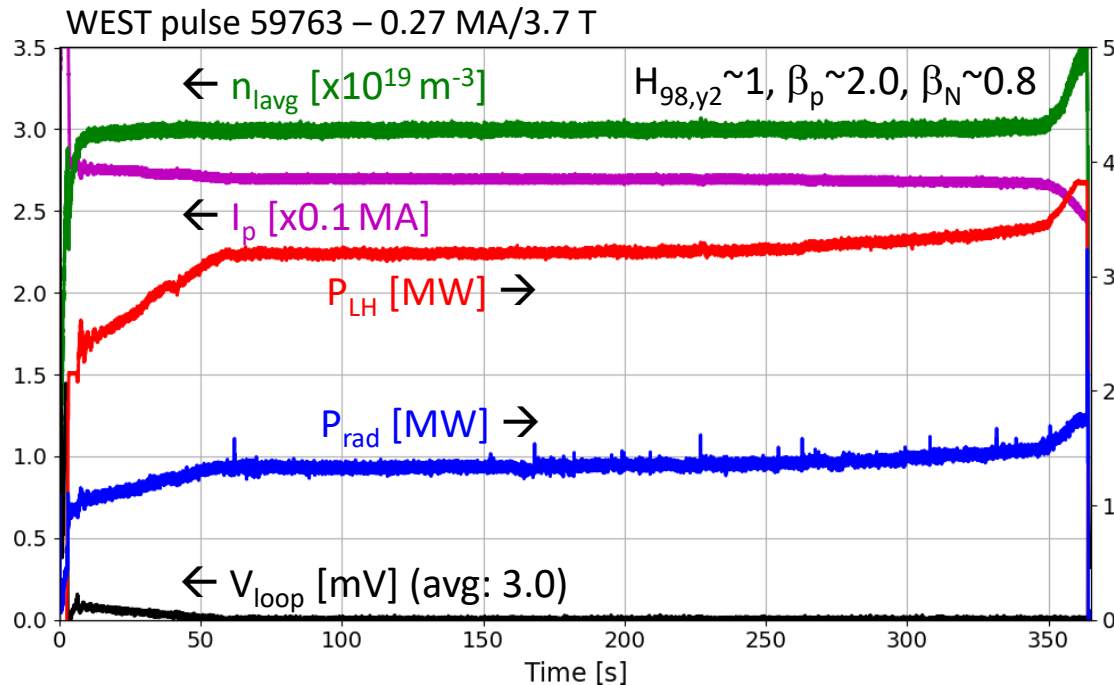
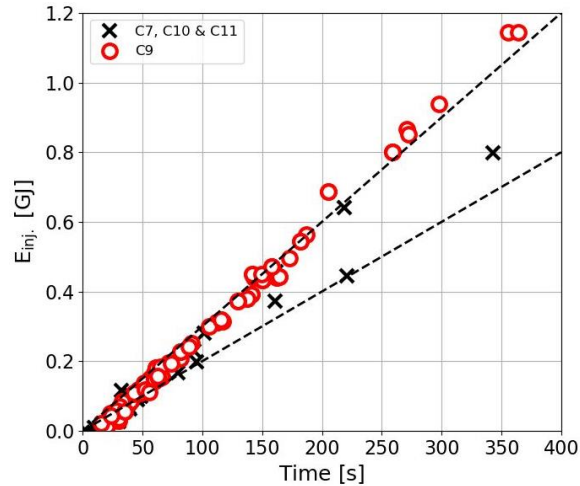
LHCD efficiencies - C7 to C10



- 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



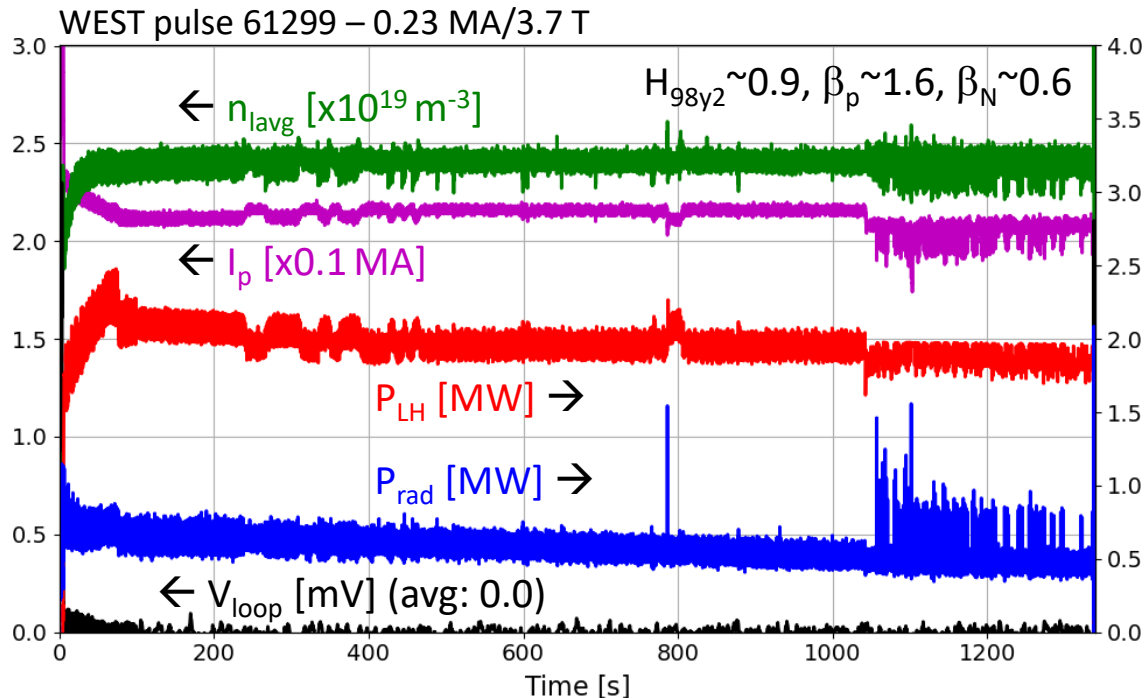
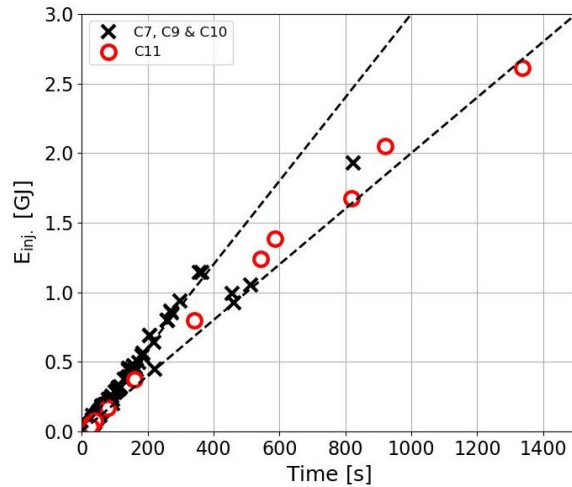
WEST pulse 59763

- 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 $\rightarrow$ 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 $\rightarrow$ 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



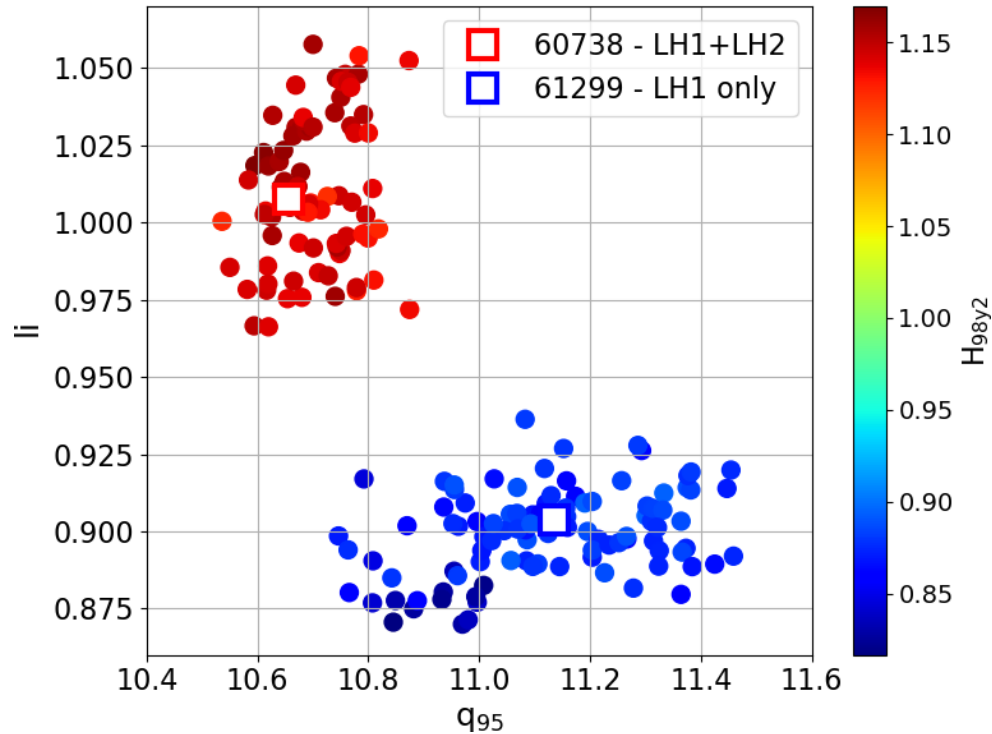
WEST pulse 61299

- 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 H₂ gas. Similar long pulses performed in D₂:
 - Isotope effect under study
 - Hydrogen concentration slowly increasing during entire D₂ pulse duration $\rightarrow$ outgassing still present



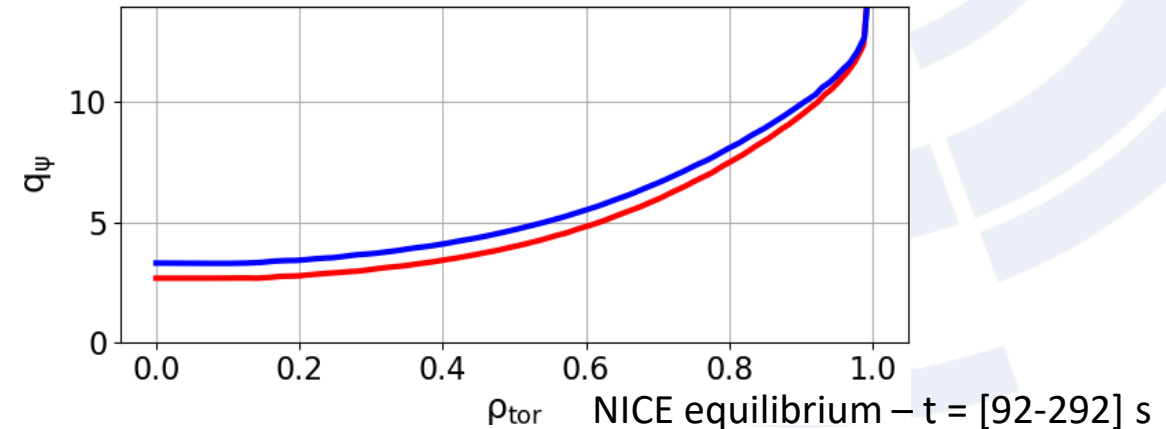
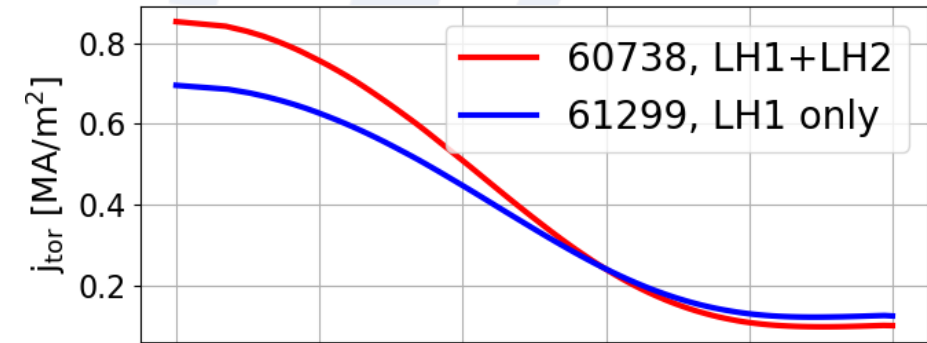
Peaked current profiles favourable for fusion performance

C10 & C11, $V_{\text{loop}} \leq 10$ mV, $t_{0,\text{plateau}} \geq 60$ s, $dt_{\text{plateau}} \geq 2$ s



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

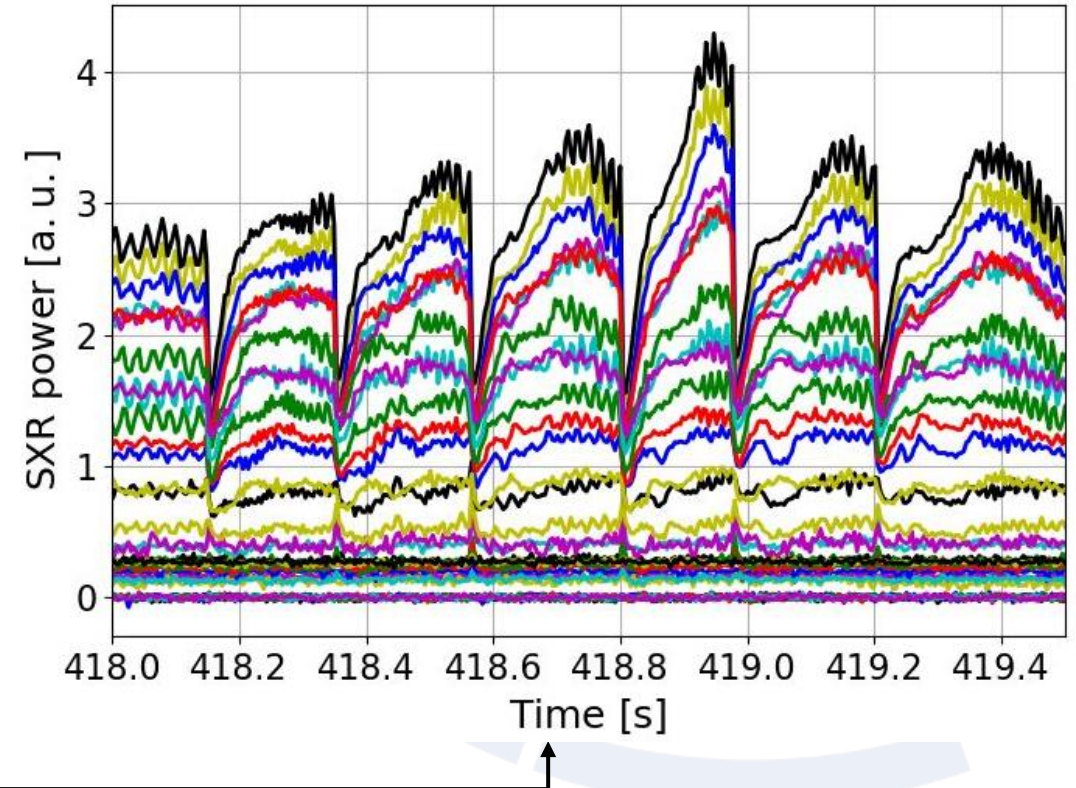
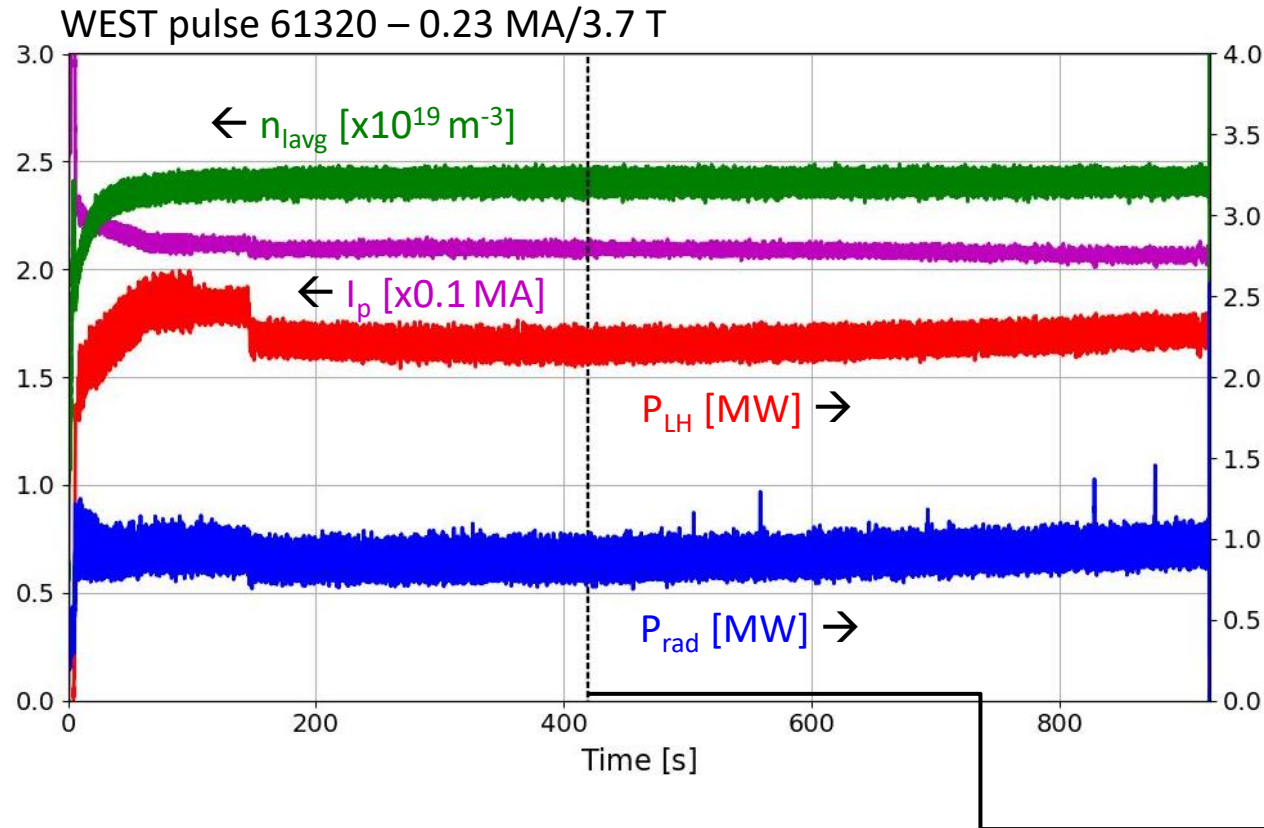
- L-mode plasmas
- Similar pulses performed with one LH coupler (LH1, 61299) vs the two couplers (LH1+LH2, 60738)
- LH1 only pulses (including record pulse)
 - Lower performance obtained
 - Current profile broader





Mild MHD activity likely responsible for confinement degradation

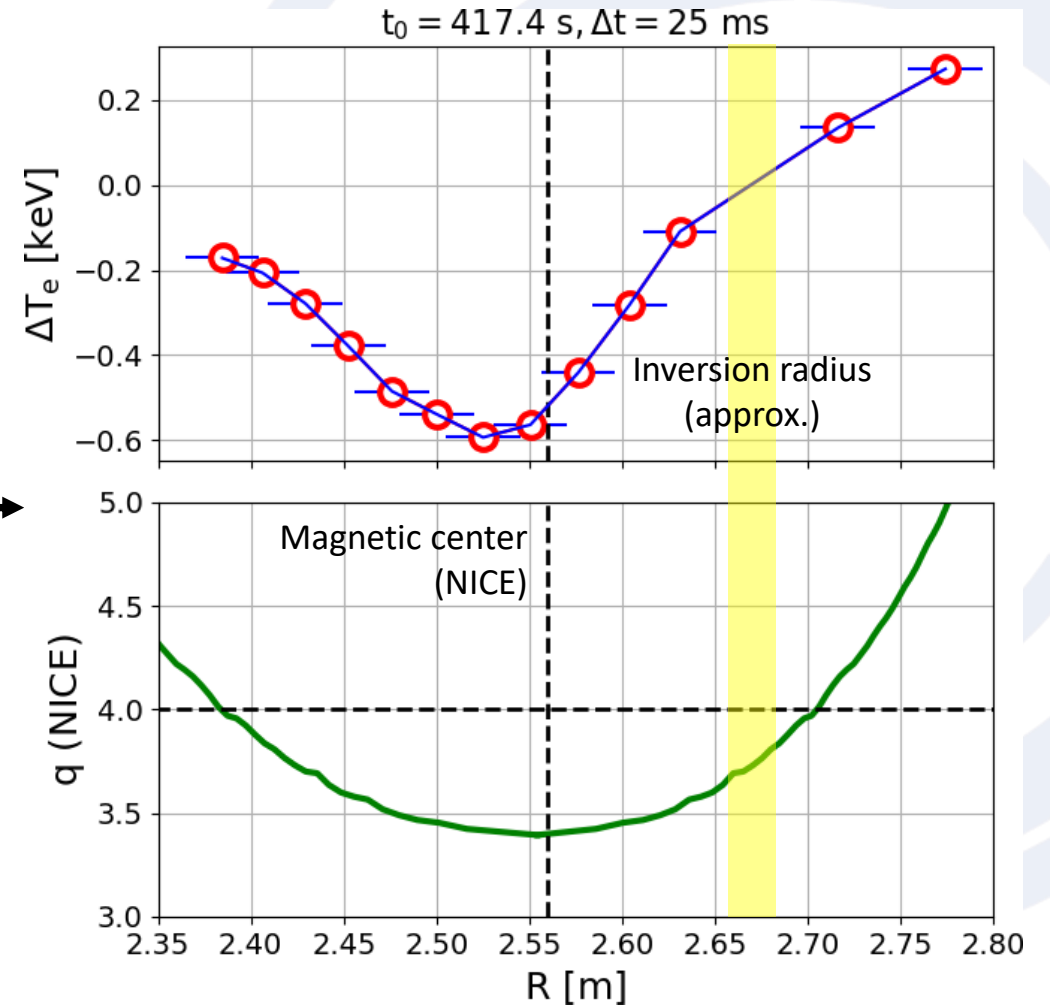
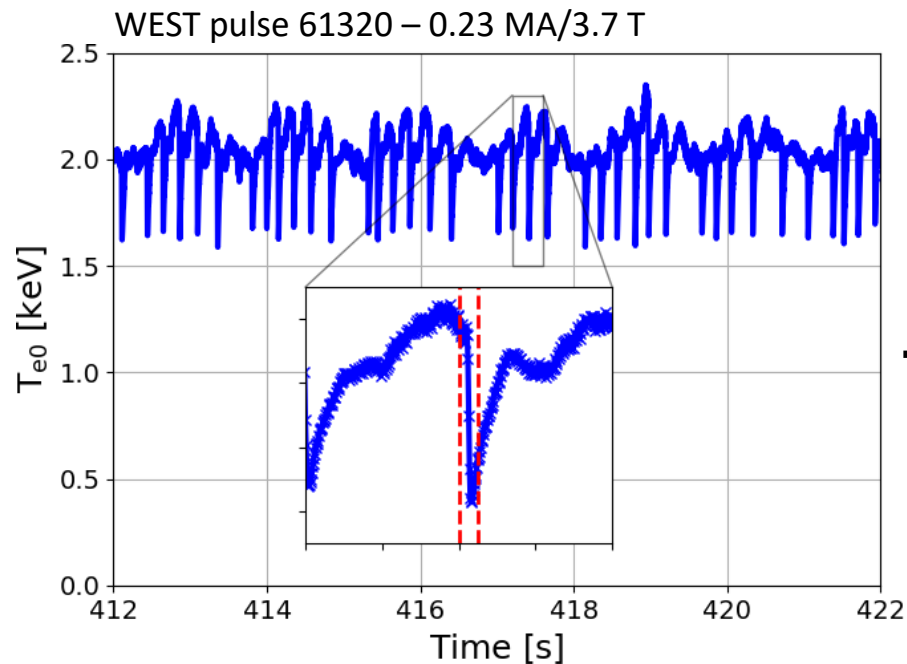
- Presence of MHD activity in 2 MW pulses with LH1 coupler only
 - Steady mode at ~ 0.8 kHz
 - LHCD efficiency moderately impacted
 - Periodic relaxations of central electron temperature





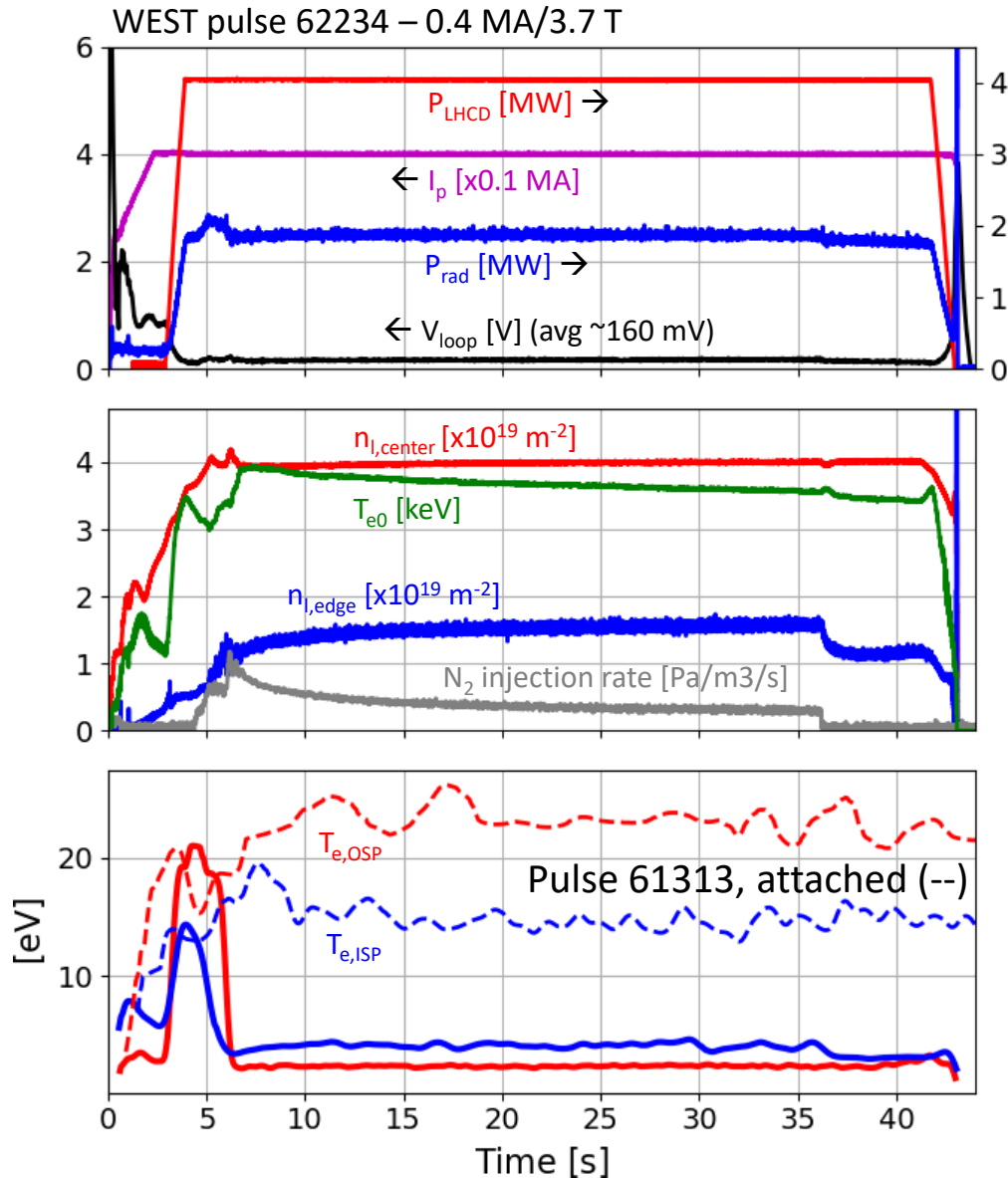
Mild MHD in long pulses attributed to interaction between modes on $q=3/1$ and $4/1$

- 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

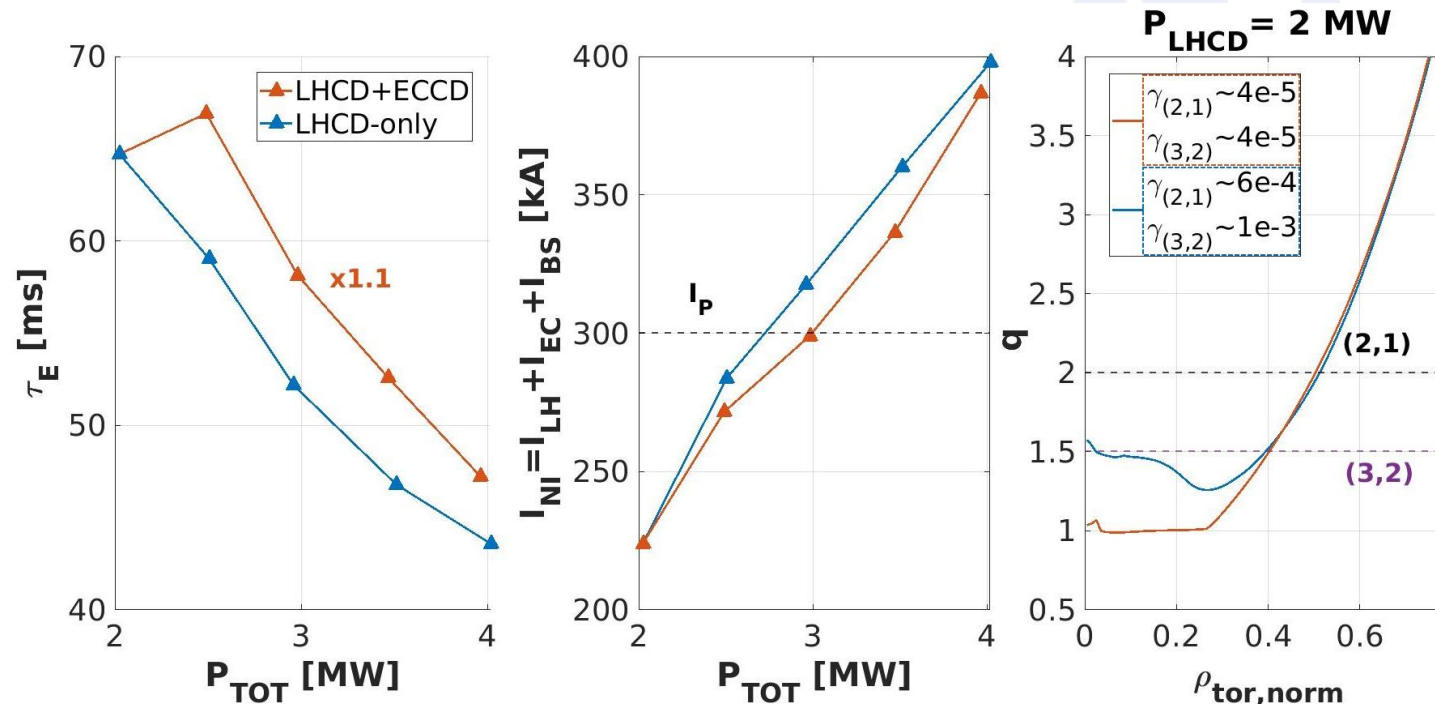


- Record duration discharges in attached divertor regime: $T_{e,\text{ISP}} \sim 15$ eV, $T_{e,\text{OSP}} \sim 20$ eV
- Development of fully non-inductive scenarios in XPR regime (next-step relevant plasma edge conditions) [Rivals, 15/10 PM, P2-3065]
- LHCD efficiencies lower than attached divertor 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 $V_{\text{loop}} \sim 160$ mV $\rightarrow$ could be extended to ~ 45 -50 s
 - $T_{e,\text{ISP}} \sim 3.5$ eV, $T_{e,\text{OSP}} \sim 2.0$ eV



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

- EC power available in WEST: 1MW (2025) $\rightarrow$ 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 ($T_e \sim 1.5\text{-}3\text{keV}$)
 - “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]





- 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 $P_{LH} \sim 2$ 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