

Long pulse achievements in the WEST tokamak

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Introduction: WEST is a superconducting tokamak with a full tungsten environment and an actively cooled ITER-grade divertor [1]. It is a unique European facility, offering crucial insights for the operation of future magnetic fusion devices in metallic environment in steady-state conditions. The heating and current drive in WEST [2] is provided exclusively by radiofrequency (RF) systems, thus featuring dominant electron heating with negligible torque input. Since the installation of the ITER-grade tungsten divertor in 2022, a large effort has been placed on long duration plasma scenarios (well beyond 100 s), relevant for plasma-wall interaction phenomena and far above the plasma current diffusion timescale ($\sim 1-2$ s). Such long discharges are made possible by the use of Lower Hybrid Current Drive (LHCD), supplemented by bootstrap current with a fraction reaching $\sim 20\%$. The long pulse scenario development, supported by integrated modelling [3], has now resulted in a new record plasma discharge of 1337 s (~ 22 minutes), with injected/extracted energy of 2.6 GJ. The progress made over the experimental campaigns between 2023 and 2025 is shown in Figures 1 and 2.

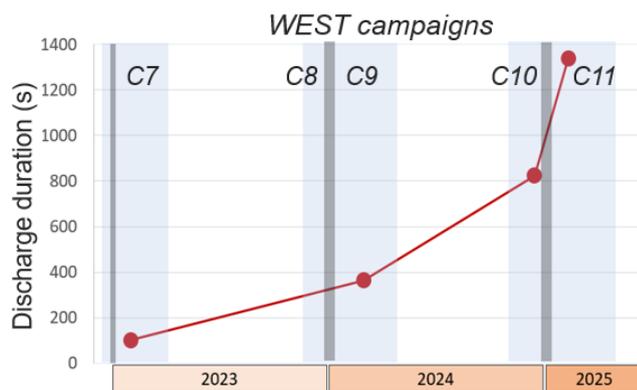


Figure 1: Progress in WEST discharge length in the campaigns since the installation of the full ITER-grade divertor.

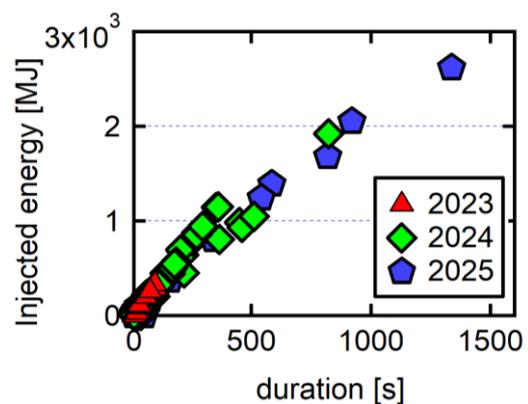


Figure 2: Injected energy in WEST versus duration. 2.6 GJ and 1337 s was achieved in February 2025.

Long pulse scenario development: The available operational space in terms of global parameters (plasma current, electron density, LHCD power) in which long pulses can be performed in WEST are delimited by several boundaries related to physics aspects and/or technology limitations. To account for these constraints, a systematic predict-first simulation approach was adopted [3]. The scenario development was fully supported by integrated modeling using the High Fidelity Plasma Simulator (HFPS), the European IMAS-coupled version of JETTO/JINTRAC [4], which integrates physics-driven modules into a unified framework, and allows the current diffusion, electron density, electron and ion temperature to be computed up to the plasma separatrix together with the LHCD efficiency. This workflow was employed to interpret measurements performed in discharges from earlier WEST campaigns, and then applied to determine the operational domain that would allow the pulse duration to be extended up to 1000 s or more. For example, one of the boundaries that had to be taken into account was the potential overheating of water cooled in-vessel components due to electron ripple losses. These components are surveyed in real-time by infrared cameras and a security system limits the LHCD power if the temperature threshold is reached. This constrains the electron density domain for a given plasma current and LHCD power.

Experimental results: In the long pulse experiments carried out in 2023 and early 2024, a scenario based on plasma current of 270 kA and ~3.3 MW LHCD power was adopted. An example of a 6 minutes long discharge (364 s) is shown in Figure 3. A double feedback control scheme was employed in the experiments [5]. The plasma current (270 kA) was feedback controlled by acting on the LHCD power, whereas the loop voltage (3 mV) was feedback controlled by the voltage in the central solenoid [5]. The discharge #59763 (Figure 3) featured good confinement in L-mode regime ($H_{98y,2} \sim 1$, $\beta_p \sim 2$, $\beta_N \sim 0.8$) and central electron temperature of ~4 keV was sustained throughout the discharge [6]. One can note that the LHCD power increased slowly from 250 s and then more strongly from 350 s. This was related to an increase in density, attributed to outgassing from remote areas in the vacuum vessel. Several long discharges were needed to gradually condition the vessel to increase the duration.

In the recent campaigns (late 2024 and early 2025), a new scenario was developed with lower plasma current and LHCD power, in order to overcome the outgassing described above. This resulted in a discharge of 824 s in December 2024, with 1.92 GJ injected/extracted energy and then to the WEST record discharge of 1337 s in February 2025, with 2.6 GJ injected/extracted energy (Figure 4). In #61299, the plasma current was set to 220 kA and the loop voltage to 0 mV, i.e. full non-inductive current drive. The main peak of the launched LHCD wave spectrum

(n_{i0}) was set to 1.7, yielding good current drive efficiency at low density ($n_e = 2.3 \times 10^{19} \text{ m}^{-3}$). Around 2 MW of LHCD power was needed to sustain the discharge, which was found quite resilient to perturbations, e.g. sudden increase in radiated power at $\sim 800 \text{ s}$ (Figure 4). Mild MHD activity was present during whole duration, with a mode related to $q = 4/1$. Spontaneous transitions between different MHD regimes were observed, which resulted in a variation in the requested LHCD power as the current drive efficiency increased or decreased. It can be noted that at $\sim 1100 \text{ s}$, the LHCD power is reduced due the loss of one klystron, but a new regime is established that continued another 200 s. Finally, the discharge ended when the power request to the LHCD system suddenly dropped to zero, for a reason which is unknown. The plasma scenario was stable and could have continued.

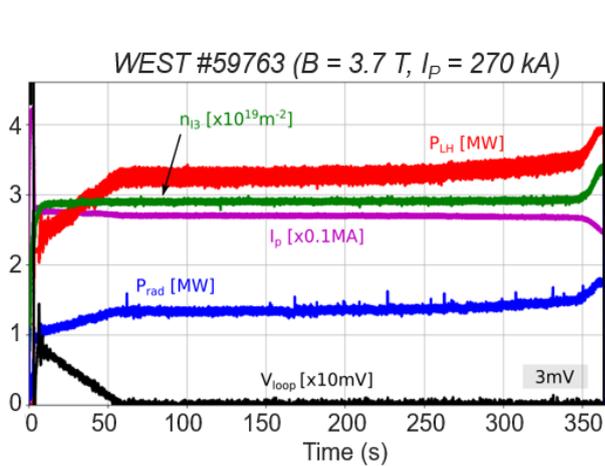


Figure 3: Time evolution of plasma parameters in discharge #59763.

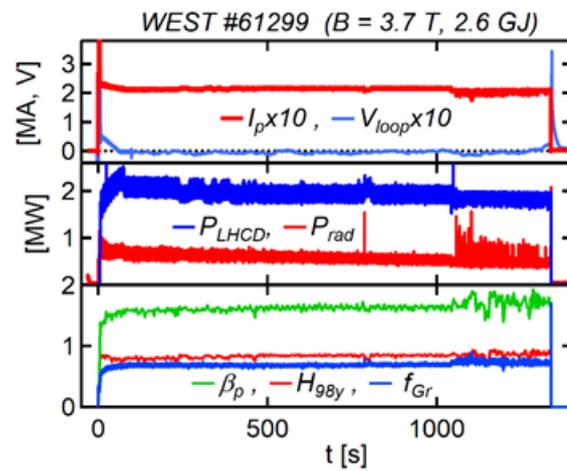


Figure 4: Time evolution of plasma parameters in the record discharge #61299, which lasted 1337 s (~ 22 minutes).

Challenges related to long pulse operation in metallic environment: In the course of the long pulse developments, challenges directly relevant to next-step fusion devices appeared. Firstly, the ohmic plasma current ramp-up phase in full W environment [7] has high radiative fraction ($>60\%$) and is prone to the triggering of resistive MHD modes. This required optimization of the plasma current waveform and early nitrogen injection [8]. Secondly, unforeseen radiative events due to the detachment of W-rich flakes from redeposited layers on the divertor, but also the spontaneous triggering of internal transport barriers, can cause MHD limits. These flakes have been created by erosion and redeposition when running repetitive discharges in the same plasma scenario. Thirdly, outgassing of remote areas in the vessel were encountered as the pulse duration increased and, lastly, the real-time infrared monitoring could trigger LHCD power limitation in case of overheating of water-cooled in-vessel components.

Summary and outlook: WEST has demonstrated reproducible and safe long pulse operation, so far up to 1337 s, thanks to scenario preparation using integrated modelling and by using several control schemes for plasma control and for the safety of the actively cooled in-vessel components. This double control aspect is a critical issue that needs to be developed for safe operation in ITER. In addition, the long pulse developments in WEST allow to improve the technology of plasma facing components (PFCs) and of all the tokamak sub-systems on durations within those foreseen in ITER (400 s to 3000 s). The long pulse discharges constitute a workhorse scenario for the studies of ITER-grade PFCs on retention, erosion and heat load monitoring, so far in attached plasma regime.

Ongoing developments in WEST are now targeted at reaching long pulse scenarios in the X-point radiator (XPR) regime [9, 10]. In the last WEST campaign, a record duration of 35 s controlled XPR was achieved. Future developments will aim at reducing the loop voltage in these discharges in order to extend their duration. The results obtained show good prospects for extending this divertor-preserving regime, crucial for fusion power plant operation, towards long durations with core performance comparable or better than that obtained in attached divertor regime.

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References

- [1] J. Bucalossi et al., Nucl. Fusion **64**, 112022 (2024)
- [2] A. Ekedahl et al., AIP Conference Proceedings **1689**, 030013 (2015)
- [3] T. Fonghetti et al., Nucl. Fusion **65**, 056018 (2025)
- [4] M. Romanelli et al., Plasma and Fusion Research **9**, 3403023 (2014)
- [5] R. Nouailletas et al., Fusion Eng. Des. **192**, 113582 (2023)
- [6] T. Barbui et al., this conference, 4 P 283
- [7] P. Manas et al., this conference, 4 P 257
- [8] P. Maget et al., Plasma Phys. Control. Fusion **64**, 045016 (2022)
- [9] N. Rivals et al, Nucl. Mater. Energy **40**, 101723 (2024)
- [10] N. Fedorczak et al., this conference, O 146