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

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The WEST superconducting tokamak, featuring a full tungsten environment and equipped with an actively cooled ITER-grade tungsten divertor, provides valuable inputs for the operation of future magnetic fusion devices [1]. As a tokamak with plasma heating exclusively supplied by radiofrequency systems, it features dominant electron heating with negligible torque input. With these design choices, essential physics and technology items can be addressed in support of next-step metallic wall machines. In recent campaigns, a special emphasis has been placed on the development of plasma scenarios aimed at performing long discharges, i.e. with durations relevant for plasma wall interaction phenomena (~100s and beyond), i.e. well above plasma current diffusion timescales (~1-2s). This endeavour is part of a wider effort addressing the growing importance of this topic for magnetically confined fusion research [2]. Achieving long-pulse discharges requires operating at values of loop voltage approaching zero, which is made possible by relying on Lower Hybrid Current Drive (LHCD) capabilities to drive most of the plasma current non-inductively, supplemented by a contribution of bootstrap current typically reaching 20% in these L-mode, attached divertor regime, plasmas. In terms of global plasma parameters (I_p, n_e, P_{LH}), the available space in which long pulses can be performed is delimited by several boundaries, related to physics aspects and/or device-specific technology limitations. To take these operating conditions into account consistently, a systematic predict-first simulation approach has been adopted in preparation of these experiments. Scenario development was fully supported by integrated modeling using the High Fidelity Plasma Simulator (HFPS), the European IMAS-coupled version of JETTO/JINTRAC [3], which integrates physics-driven modules into a unified framework, and allows the current diffusion, electron density, electron and ion temperatures to be computed up to the plasma separatrix together with the LHCD efficiency. This workflow was employed to interpret measurements performed in discharges from previous campaigns, and good agreement was obtained with core density measurements, tungsten concentrations and electron temperature measurements using ECE and ME-SXR [4]. The HFPS was then applied to determine the operational domain that would allow the pulse duration to be extended up to 1000s or more. As a result of this numerical exploration, long duration discharges lasting up to 1337s have been achieved, with an energy injected/extracted reaching 2.61GJ. The global effort that was conducted in WEST during the 2023-2025 period is summarized in Figure 1. The main time-traces corresponding to the rightmost point on this figure, representing the current record pulse (#61299) performed at I_p~210kA with ~2MW of LH power, are shown in Figure 2.

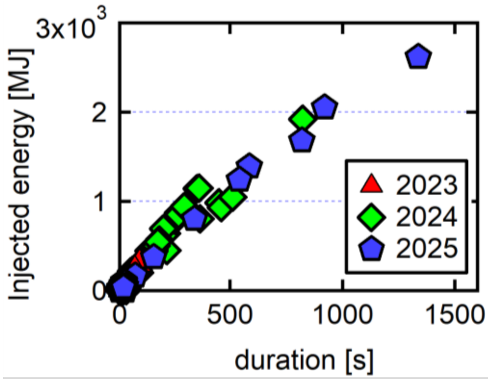

Figure 1 : progress in long-pulse achievements in WEST during the 2023-2025 period.

In the course of these developments, new challenges related to the operation in full metallic environments, and directly relevant to the operation of next-step fusion devices, have been identified. The first challenge is linked to the plasma current ramp-up phase, which is found to depend (at least during the period during which the plasma is limited), on whether the discharge is initiated on boron-nitride (BN) or full-tungsten tiles. Early nitrogen injection has been employed as a method to increase the central electron temperature, and has shown to improve MHD stability [5]. Achieving a reliable scenario requires careful optimizations of density, as well as LH power waveform in order to avoid MHD instabilities typical of non-inductive regimes [6]. Another challenge relates to the increasing likelihood of W-rich flake detachment from deposit layers formed on the divertor plates during the campaign, and can have operational consequences on the discharge [7]. Whereas scenarios with plasma currents I_p~210kA such as shown in Figure 2 have allowed durations exceeding 1000s to be attained, scenarios at larger currents (~280kA), which require ~3MW of LH power, have displayed limitations in terms of injected energy and duration caused by outgassing, likely from far-off inertial elements, with evidence of progressive conditioning. In terms of tungsten contamination, a resilient radiative fraction is observed in WEST. SOLEDGE modelling has allowed this effect to be attributed to a strong connection between radiative losses and erosion of the plasma facing components [8]. Mitigation strategies for tungsten contamination-related effects include wall conditioning using boron [9]. In complement, developing X-point radiator regimes is a promising approach under active development at this time in WEST [10]. Finally, integrated modelling allows predictions for long pulses in upcoming campaigns to be performed, based on the analysis of existing discharges. In particular, in 2025, WEST is equipped with a new Electron Cyclotron (EC) Resonance Heating system. This radiofrequency system will eventually supply up to 3MW of RF power at frequency 105GHz [11]. Integrated modelling confirms that this additional power source will be instrumental in enlarging the operational space of WEST: central electron heating to balance the core power radiation, localized current drive to control safety factor profile reversal and improve MHD stability. As an illustration, Figure 3Figure shows the safety factor profile computed with the HPFS in the reference, LHCD-only, case versus the situation when P_{EC}=500kW of central EC power is applied in the same discharge, driving an on-axis current I_{ECCD}=15kA. This additional power is also key for exploring improved confinement regimes.

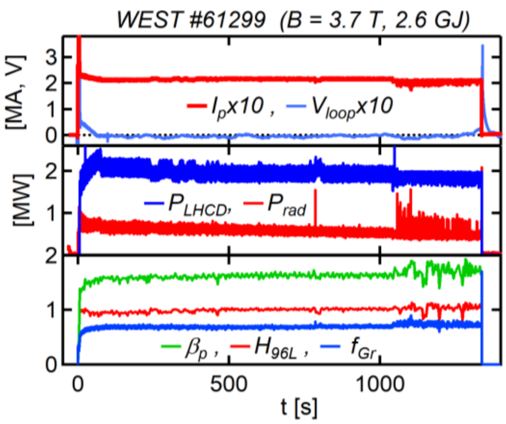

Figure 2: Overview of record WEST pulse #61299 (1337s, 2.61GJ), from top to bottom: plasma current and loop voltage; LH and bulk radiated power; poloidal beta, confinement scaling factor H_{96L} and Greenwald fraction.

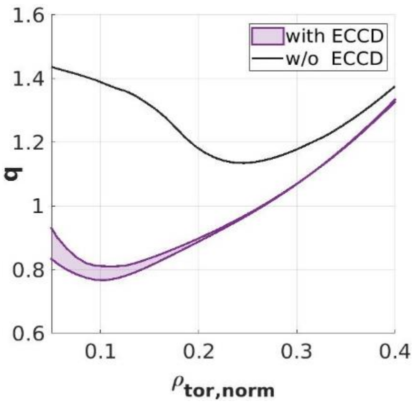

Figure 3: Safety factor modification induced by central ECCD (P_{EC}=500kW).

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