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

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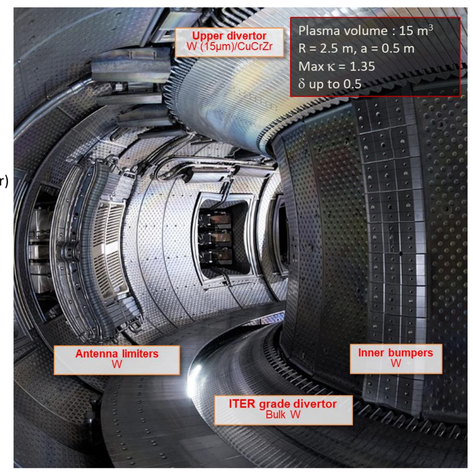
Long pulse operation in WEST

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

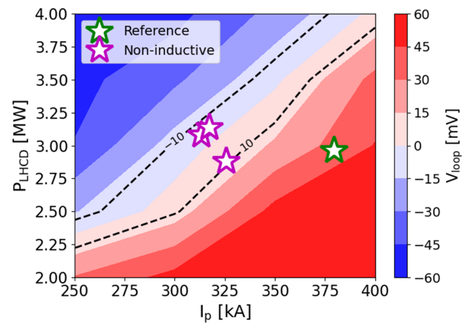
- Long Pulse Operation [Litaudon, this conference]
  - Discharges with durations well above the characteristic plasma times, approaching plasma-wall interaction timescales
  - Specific topics:
    - First-wall material studies (erosion, surface damage, fuel retention) [Corre, this conference]
    - Technical aspects related to long pulses [Lamaison, this conference]
    - Integrated high-performance long-pulse plasma scenarios (this poster)
- WEST: a testbed to prepare for long pulse operation in ITER [Bucalossi, this conference]
  - Superconducting magnets, nominal field B_0~3.7 T
  - Full-tungsten environment, with periodic glow discharge boronizations [Geulin, this conference]
  - Bespoke radiofrequency (RF) systems [Bernard, this conference]
    - ICRH (~55 MHz)
      3 load-resilient antennas: 9 MW/30 s - 3 MW/1000 s
    - 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



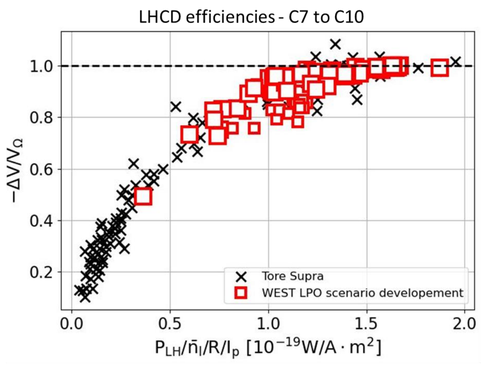
Pulse development in WEST based on predict-first integrated modelling

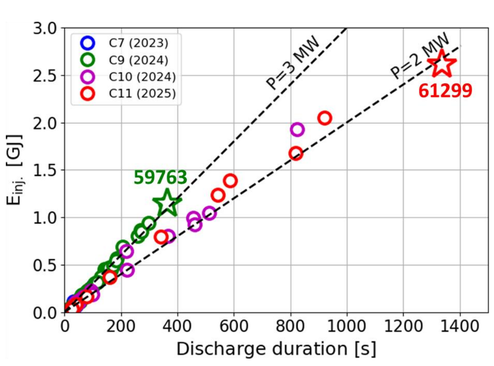
- Fully non-inductive discharges → complex non-linearities, especially in W environments (current profile, power source, heat and particle transport…)
- High Fidelity Pulse Simulator (HFPS) based on JINTRAC/JETTO employed EUROfusion
  - Simplified model used for LHCD deposition profile [Dumont, PoP 2000],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



Long pulse achievements in WEST

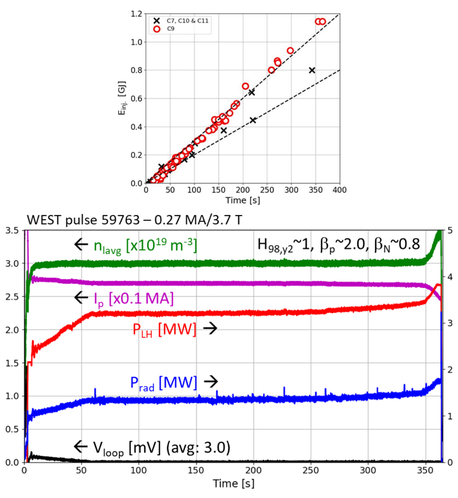
Continuous progress in long pulse development, based on LHCD power





- Tore Supra LHCD efficiencies recovered, consistently with Fokker-Planck calculations (LUKE) predicting no significant influence of W impurities on LHCD [Peysson, IAEA 2020]
- Twenty L-mode discharges exceeding 200 s performed, with LHCD power only

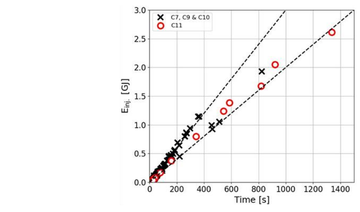
Outgassing from far-off elements limited development of 3 MW-class scenarios

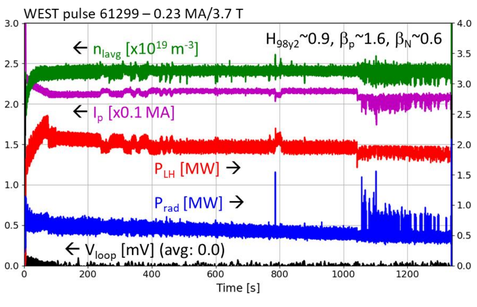


WEST pulse 59763

- Duration: 364 s
- Energy injected/extracted: 1.15 GJ
- Double feedback-control (V_{loop}, V_{G0}), (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
- No particular issue related to tungsten accumulation
- 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
  - 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



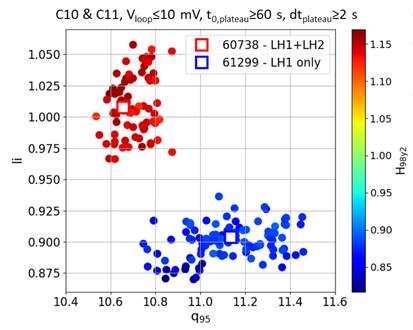


WEST pulse 61299

- 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)
- Performed in H_2 gas. Similar long pulses performed in D_2 → isotope effect under study
- Quite resilient to external perturbations (failures of RF plant, W ingress [Corre, this conference], …)
- Mild MHD activity present during whole duration when using one LH antenna
- In this particular pulse: non-linear MHD regimes with spontaneous transitions

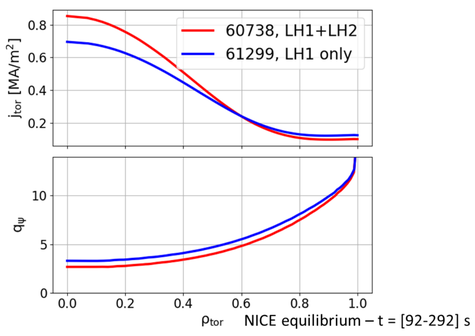
Physics analysis of WEST long-duration pulses

Peaked current profiles favourable for fusion performance



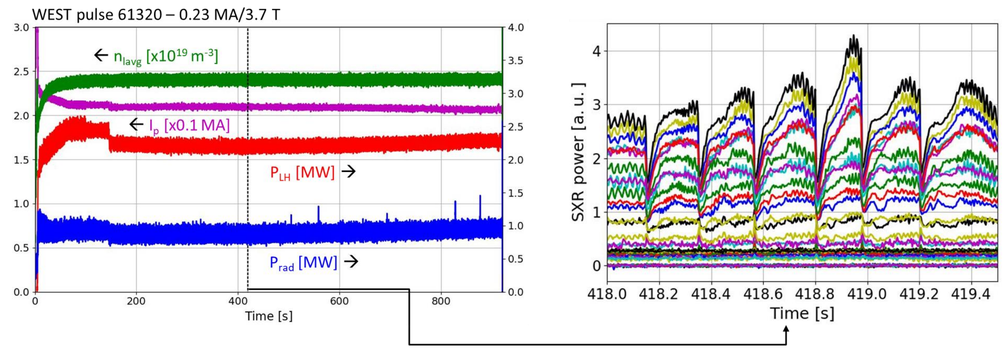
	60738 (LH1+LH2)	61299 (LH1 only)
β_p	2.0	1.6
β_N	0.8	0.6
H_{98y2}	1.1	0.9

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

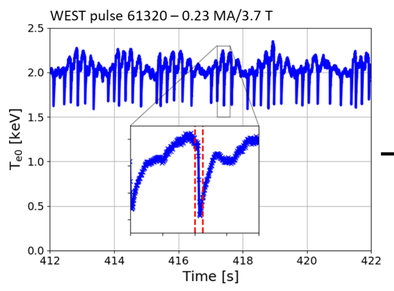


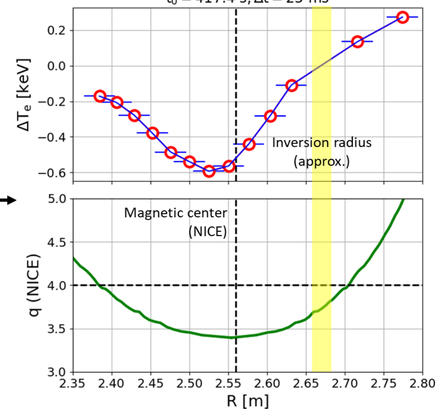
Mild MHD activity likely responsible for confinement degradation

- 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



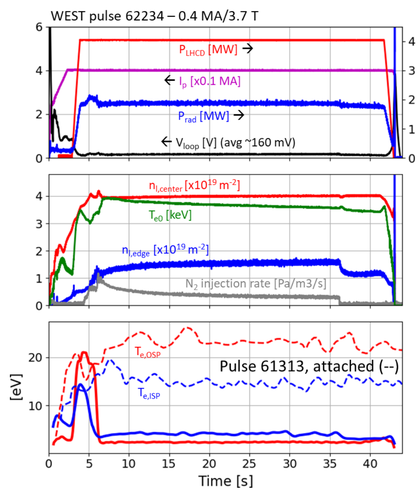
- Mirnov coil data for ~0.8 kHz mode
  - Toroidal mode number n=1
  - Poloidal mode m=3 and/or m=4
- Fast acquisition ECE radiometer data
  - Islands on q=4/1 and 3/1 surfaces, then crash on q=4





Prospects for long pulse development in WEST

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, this conference]
- LHCD efficiencies lower than attached divertor regime efficiencies at comparable levels of power/density
- Frequent MHD activity
- 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

- 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]

Summary and outlook

- **Many adaptations to WEST aimed at exploring various aspects of Long Pulse Operation in future devices**
  - Technical and operational issues and remedial actions
  - Plasma-wall equilibration (e.g. fuelling & exhaust, outgassing, …)
  - Non-linearities in heat source / 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**, in attached divertor regime
- **Development of non-inductive pulses in XPR regime**
  - Pulses up to ~1 min so far, with divertor electron temperatures typical of detached regimes
- **EC power expected to enlarge parameter space, increase plasma performance in non-inductive regimes**

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