INVESTIGATING LONG-DURATION PLASMA OPERATION WITH THE INTERNATIONAL MULTI-MACHINE DATABASE

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Achieving both high fusion performance and long-pulse operation is a key integration challenge in the development of magnetic fusion energy. Addressing these challenges requires a comprehensive approach that integrates physics, operational strategies, and engineering considerations to simultaneously extend plasma duration and increase fusion power reliably. The revised ITER baseline and the need to test tritium breeding blanket technology in dedicated long-pulse facilities introduce additional challenges that require further R&D, supported by current long-pulse experiments.

Significant progress has been made in both tokamaks and stellarators with recent advancements in plasma duration and performance. These developments are reviewed by analyzing the latest experimental data from ten tokamaks (ASDEX Upgrade, DIII-D, EAST, JET, JT-60U, KSTAR, TCV, TFTR, Tore Supra, and WEST) and two stellarators (LHD and W7-X), expanding on the pioneering work of M. Kikuchi [1]. Data collection and coordination have been facilitated by the recently established IEA-IAEA CICLOP group (**C**oordination on **I**nternational **C**hallenges on **L**ong duration **OP**eration).

The published database [2], which initially included data up to January 2022, has been expanded with a total of 146 pulses and approximately 5400 entries, incorporating data up to December 2024. This updated dataset reflects recent advancements in long-pulse operation across several key research areas (Fig. 1).

Long-Pulse Operation in Attached Divertor. EAST has achieved repeatable long-pulse operation with an L or H mode edge (up 1066 s) in fully non-inductive conditions with dominant electron heating and enhanced power exhaust, utilizing a new water-cooled tungsten lower divertor [3-4]; WEST has demonstrated long-pulse operation (up to 1337 s) with a full ITER-grade tungsten divertor, achieving up to 2.6 GJ of injected energy in non-inductive conditions [5-6]; the vessel conditioning in WEST is performed using ITER-relevant boronization techniques; WEST has also produced reproducible 100 s-long plasmas, simulating ITER divertor particle fluence (up to 10^{27} D/m^2 over eleven hours of cumulative attached plasma operation); KSTAR has achieved a 102 s high-performance long-pulse discharge using its newly installed W-shaped tungsten divertor [7]; W7-X has sustained a 480 s attached plasma discharge with an energy turnover of 1.3 GJ using its actively water-cooled C-divertor [8]; JET has set in 2023 its own record for injected energy in ELMy H-mode (up to 450MJ, up to 60s in deuterium plasmas) with the inertially cooled tungsten divertor [9].

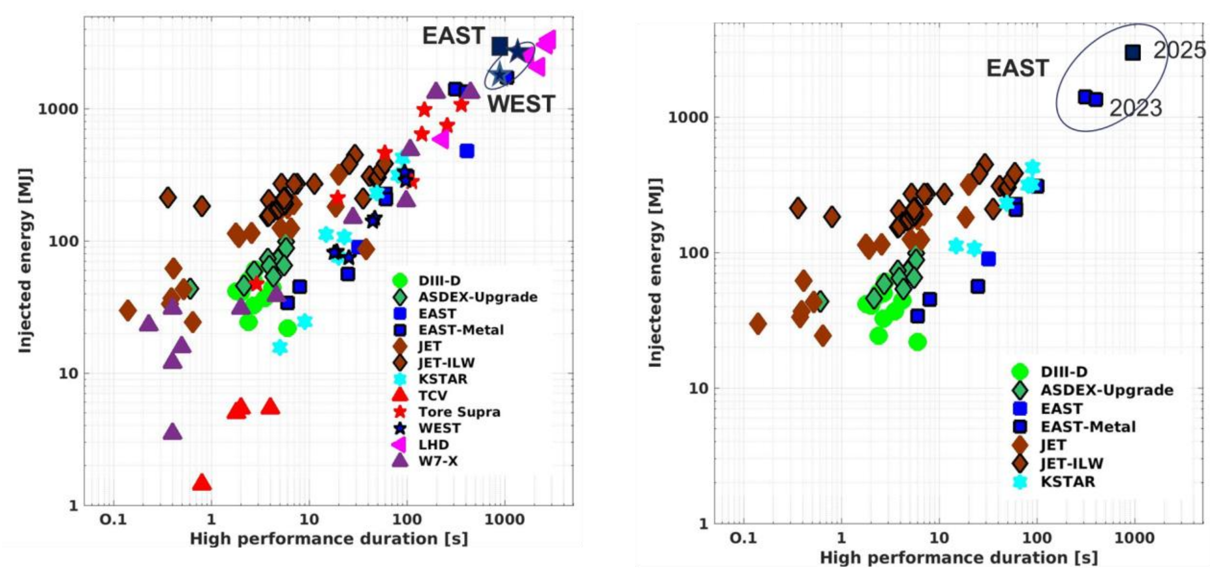

Fig. 1: (left) Injected energy versus high performance duration for the whole database; (right) for tokamaks H-mode data only. Experiments performed with a metallic wall have symbols with a black contour line.

Long-Pulse Radiative Divertor Operation. High-radiation regimes have been sustained using noble gas injection on ASDEX Upgrade, JET, WEST (up to 18 s), and EAST (up to 70 s) [10]. W7-X has achieved high-density, 112 s-long detached plasmas with neon seeding [8]. JET has demonstrated sustained fusion energy production in deuterium-tritium plasmas with an edge radiative mantle (neon seeding), achieving 4 MW of fusion power for up to 6.5 s [11].

Long-Pulse High-Normalized Pressure Operation. Development of long-pulse high-normalized pressure regimes is critical for compact or reduced-plasma-current steady-state fusion pilot plants. ASDEX Upgrade and, more recently, DIII-D have extended operational scenarios at high poloidal beta (β_p), achieving improved energy confinement at plasma densities exceeding the Greenwald limit [12-13]. EAST has sustained fully non-inductive high-β_p scenarios with zero torque injection and high density for up to 100 s [4]. KSTAR has demonstrated steady-state high-β_N operation ($\beta_N \sim 2.7$) with a carbon wall and achieved a 25 s-long stationary scenario featuring an internal transport barrier and high ion temperatures (~10 keV).

Multi-Machine Database Analysis and Projection. The latest advances in injected energy, duration, injected power, and sustained performance are reviewed and compared using the multi-machine international database. Progress have been made to sustain long-pulse operation in tokamaks and stellarators with superconducting coils, actively cooled components, and/or, with different kind of metallic walls. The fusion triple product exhibits a reduction of at least two orders of magnitude when increasing plasma duration from under one second to 100 s. Indeed, long-pulse operation is usually reached in dominant electron-heating modes with RF heating at reduced density to optimize the external non-inductive current drive but with low ion temperatures ranging from 1 to 3 keV for discharges above 100 s.

Challenges in extending plasma duration arise from the difficulty of coupling high heating powers over long timescales and the evolving plasma-wall interactions, which may lead to unstable operational conditions. For instance, it was reported on WEST that the performance could be hampered by increase occurrence of tungsten events originating from the deposited W-layers on the divertor. Gaps in physics and technology for long-pulse operation have been identified, and the limiting factors for plasma duration and fusion performance in present experiments have been assessed. Critical issues to be addressed before ITER operation and DEMO design are also analyzed. Different metrics for comparing the fusion performance of present-day scenarios using a unified approach will be presented, along with extrapolations for future devices such as ITER [13, 14]. In particular, long-pulse performance projections for ITER will be estimated using a dimensionless analysis based on ρ^* scaling of the CICLOP database, as proposed in [14].

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