Development of long-pulse detached plasmas in the Wendelstein 7-X stellarator

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Wendelstein 7-X (W7-X) is the world's largest stellarator-type fusion experiment. A central goal of W7-X is to demonstrate safe, steady-state plasma operation for up to 30 minutes, while maintaining efficient energy and particle exhaust. To achieve this, W7-X employs a stellarator-specific island divertor concept, featuring a modular array of water-cooled carbon-fiber composite (CFC) target elements positioned within intrinsic edge magnetic islands. These targets are designed to sustain continuous heat loads of up to 10 MW/m^2.

For the operation of a fusion reactor, radiative detachment is paramount to protect the divertor from heat loads above the mentioned limit. W7-X could already demonstrate that the island divertor concept is a promising approach for a stellarator reactor [1, 2]. In the most recent plasma campaign, OP2.3, feedback-controlled injection of impurities using a proxy for the total plasma radiation (P_{rad}) was successfully implemented. This allowed reliable detached plasma operation in different plasma heating scenarios and magnetic configurations. A key outcome of the new feedback control system was the successful extension of seeded detachment schemes to a broader range of plasma conditions—including continuous pellet injection and low to medium line-averaged densities ($4–10 \times 10^{19}$ m^{-2}). This enabled stable, long-duration detachment with controlled plasma radiation levels, supporting sustained divertor heat load mitigation across varying operational regimes.

Building on this approach, W7-X achieved a stable, long-pulse detached plasma scenario at a relatively high heating power of 5 MW sustained for 360 seconds – marking a new record in injected heating energy (1.8 GJ). It represents the longest detached plasma operation at W7-X to date. Feedback-controlled Neon seeding was used to successfully establish high radiation (frad~85%), translating into safe wall and divertor loads for the entire plasma duration. With the selected (also feedback-controlled) plasma density of ne~5e19/m^2 and by actively water-cooling the first wall, a stable hydrogen fuelling scheme could be applied. No significant wall inventory outgassing or plasma-wall interaction events were observed. This is a major technical achievement, as many non-divertor wall components experienced temperature increases due to continuous radiation exposure, thus indicating a well-conditioned machine throughout the long pulse. The plasma core performance was not impacted via impurity accumulation, and the diamagnetic energy stayed constant throughout the long pulse at ~500 kJ. This is a key milestone for the stellarator concept and associated reactor designs that adopt the island divertor concept.

References

[1] M. Jakubowski et al (2021) Nucl. Fusion **61** 106003
[2] Y. Feng et al (2021) Nucl. Fusion **61** 086012