Overview of Wendelstein 7-X high-performance operation

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The superconducting long-pulse stellarator Wendelstein 7-X (W7-X) has recently completed two experimental campaigns, marking a significant step forward in its mission to demonstrate the feasibility of optimized stellarator concepts for steady-state plasma confinement. These campaigns included extensive system upgrades, notable among which was the enhancement of the electron cyclotron resonance heating (ECRH) system, operation of a new steady-state pellet injector for efficient long-pulse core fueling, and an ion cyclotron resonance heating (ICRH) system. The ECRH heating capabilities were enhanced by the introduction of a new high-power gyrotron, capable of delivering a power up to $P = 1.3MW$ at a frequency of $f = 140GHz$, increasing the total ECR heating power to $P_{ECRH} = 8.5MW$ and allowing to considerably widen the W7-X parameter space. The new steady-state pellet injector is designed to facilitate continuous density profile control and upgrades the previously operated short-pulse pellet fueling system by broadening its operation space in pellet size, speed, and long-time fueling capacity up to 30min plasma operation. The ion cyclotron resonance heating system was fully operational with a two-strap antenna for the first time. A key aspect was to demonstrate minority heating schemes at W7-X for the first time for the generation of fast ion population, necessary to study the fast ion confinement properties of the optimized magnetic field geometry. Studies of wall conditioning strategies with energized magnetic field complemented the methods to control loading of the first wall to provide enhanced plasma density control.

The primary focus of these experimental campaigns was threefold: (1) extending long-pulse operation, with a target of achieving an energy turnover approaching 2 GJ, (2) enhancing confinement performance through density profile shaping strategies, using the pellet injector and neutral beam injection to initiate central density peaking and (3) investigating divertor detachment and turbulent transport across a wide range of magnetic configurations. The long-pulse operation efforts in the previous experimental campaign already yielded a substantial increase in energy turnaround, approaching 1.3 GJ, a significant milestone that underscores the success of the recent upgrades of the fully water-cooled divertor. The next step was to extend the long-pulse operation to 2GJ energy turnaround at increased plasma heating power, an important step before addressing the W7-X project goal of 18GJ. The major challenge was to control the long-time bootstrap current evolution, which significantly alters the spatial location of the resonant edge magnetic islands and consequently the heat load pattern on the divertor targets.

A key aspect of the confinement studies was to extend the high-performance operation by increasing the ion temperature, stored plasma energy and fusion triple product. The approach was two-fold: With the new pellet injector and using the neutral beam injection, previous approaches to generate central density peaking were extended. The use of pellet injection allowed for controlled core fueling and enabled high plasma densities close to the O2 heating cutoff. An alternative confinement enhancement scheme using neutral beam injection with specifically tailored ECRH operation was employed. As shown in Fig. 1, this method effectively triggered central density peaking and resulted in an unprecedented energy storage of 1.8 MJ, setting a new record for the triple product in stellarators. These results indicate that optimized fueling strategies, in conjunction with advanced heating methods, are crucial for achieving high-performance plasma conditions in W7-X. An important success is plasma operation at reduced magnetic field to achieve plasmas at high-β, a pre-requisite for improved fast ion confinement. The scheme, displayed in Fig. 1(b), facilitates ECRH X2 plasma startup with one gyrotron tuned down in frequency, the take over by neutral beam injection to increase plasma density and electron temperature, before prolonging the discharge by ECRH in X3 polarization.

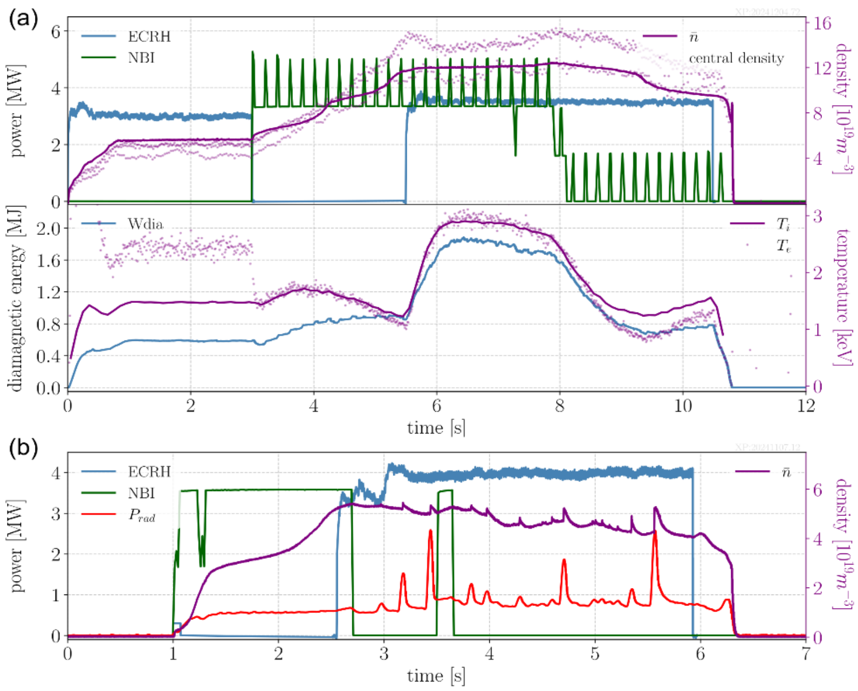

Figure 1: (a) Demonstration of combined ECRH and NBI heating to achieve centrally peaked plasma density profiles with increased stored energy and ion temperature. (b) Plasma generation at reduced magnetic field with a series of ECRH X2 startup, take over by neutral beam injection heating and prolongation of discharge by ECRH in X2 polarization.

By exploring different magnetic configurations in a wide configuration space —varied in terms of magnetic shear, island topology, magnetic mirror ratio, and iota profile — the experimental campaigns provided valuable insights into the evolution of plasma turbulence and the associated transport, MHD stability, scrape-off layer dynamics and flows, and the divertor behavior. Of particular interest was the study of divertor heat loads, which is a crucial limitation on the verge of the planned further increase of plasma heating power. The influence of various actors, as, e.g., tailoring of the edge magnetic field configurations and increased plasma radiation to reduce divertor heat loads, were studied in detail and heat load mitigation strategies were developed. An effective scheme to avoid high divertor heat loads are operation with divertor detachment. The studies aimed to investigate detachment stability in a variety of different magnetic configurations and power and particle exhaust solutions necessary for steady-state operation. The experimental results demonstrated effective detachment control over a range of magnetic configurations, revealing important dependencies between magnetic topology and divertor performance. These findings contribute to the ongoing development of strategies for mitigating heat loads on plasma-facing components, a crucial factor for future reactor-scale stellarators.

In conclusion, the recent experimental campaigns at Wendelstein 7-X have yielded critical advancements in long-pulse plasma operation, heating and fueling techniques, divertor detachment control, and turbulence suppression. The integration of upgraded heating and fueling systems has significantly enhanced plasma confinement and stability, bringing W7-X closer to its goal of demonstrating the viability of stellarators for continuous and high performance plasma operation.

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