Impurity Accumulation and Radiation Dynamics in advanced Scenarios in W7-X

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In the neoclassically optimized stellarator Wendelstein 7-X (W7-X)[1], turbulence-driven transport often limits plasma performance, resulting in energy confinement times below the stellarator scaling law (τ_E/τ_{ISS04} <1) and limitation of ion temperature [3-4]. This has been observed in plasmas heated by both ECRH and NBI. In several advanced scenarios[2], high-performance (HP) plasmas with improved energy confinement ($\tau_E/\tau_{ISS04} \geq 1$) have been achieved, where density gradients play a crucial role. However, all these scenarios exhibit enhanced core impurity radiation (ρ<0.5) - a recent finding from bolometer tomography - which is often accompanied by strong line emission of highly charged ions such as Cu and Fe (from the plasma-facing components) recorded by spectroscopic diagnostics. This is typically associated with impurity accumulation, which is characterized by prolonged transport times for impurities (up to several seconds) compared to the faster times in normal scenarios [5-7]. Neoclassical inward convection, driven by a negative radial electric field (E_r) in the 'ion-root' regime is key to this process[8]. Exploring conditions that allow impurity coexistence in the core while without degrading plasma performance is essential for impurity and plasma control. This work presents three such scenarios: (1) a low-power ECRH plasma, (2) a pellet-fueled ECRH plasma, and (3) a combined NBI and ECRH plasma.

I. low-power ECRH plasma

Impurity enrichment in the plasma core has been observed in ECRH plasmas (without pellet injection) at 0.6 MW (see Fig. 1) and 1.2 MW [9]. This is evidenced by radiated power profiles peaking at ρ=0.3−0.4 and spectroscopic detection of high-Z elements like Fe. The SXR bolometer channel shows a ~5s rise time after plasma stored energy (W_p) stabilizes. Impurity transport analysis reveals:

— For ρ<0.5, a low diffusion coefficient (D~0.02 m²/s), ~10 times lower than typical turbulent transport and consistent with neoclassical predictions.

— A reversal of impurity convection (V) near the radiation peak, where impurity accumulation occurs, coinciding with an E_r transition from "electron-root" to "ion-root."

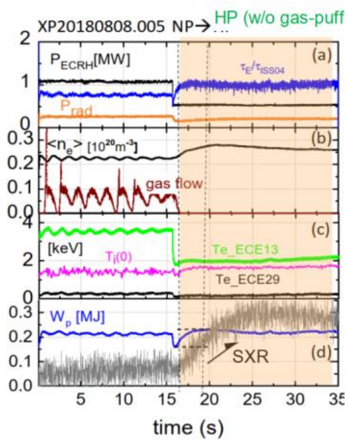

Fig.1 Time traces of relevant diagnostics in XP20180808.005.

Despite the impurity accumulation, the plasma phase exhibits enhanced energy confinement (τ_E = 0.4 s and a ratio of τ_E/τ_{ISS04} ~1). The transition from normal-performance (NP) to HP occurs when gas supply is turned off to create a pure, recycling-neutral fuel supply. The edge plasma density decreases, steepening the profile (see Fig.4 in [9])). The density and temperature gradient lengths become similar ($\eta_i = (a/L_{Ti})/(a/L_{ne}) \approx 1$), aligning with "stability valley" conditions (see Fig.14 in [9]) in which micro-instabilities like ITG turbulence are reduced [10]. These results suggest that edge fueling details impact the density profile and turbulent transport. A similar low power HP plasma phase from the recent experimental campaign (e.g. XP 20241126.031) shows the reduction in density fluctuations, with the density gradient steepening when the gas puff is turned off.

II. Pellet refuelled ECRH discharges

HP plasma phases has been observed in W7-X experiments with hydrogen pellet fueling, highlighting the impact of density profiles [11-12]. In the latest campaign, the HP phase with W_p~0.9MJ and τ_E~0.3s lasts ~1s after pellet injection (see Fig. 2 for key diagnostics). Fig. 3(a) and (b) show the time evolution of radial radiation and E_r-profiles, respectively. Key impurity radiation observations:

- Enhanced core radiation (r_{eff}<25 cm) in the HP phase linked to increased SXR emission and CuXXVI line (11 nm) radiation.
- The emissivity peak is ~10cm away from the plasma center (green, Fig. 4a), differing from that before reaching the HP (blue).

A well-defined 'ion-root' region in the HP phase with E_r~−40 kV/m is observed (Fig. 3(b)). The correlation between the position of the peak emissivity and the transition from the "electron root" to the "ion root" are to be determined.

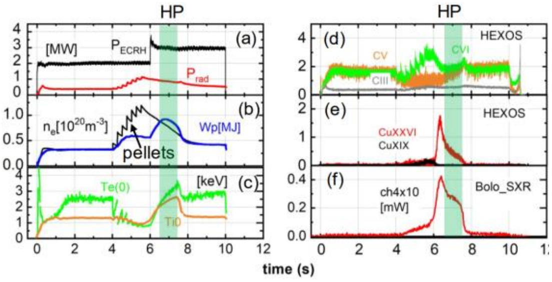

Fig. 2 Time traces of diagnostics in XP20241121.038.

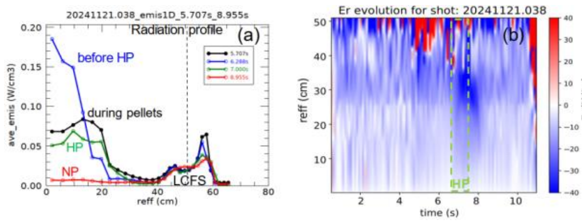

Fig. 3 Time evolution of the radiation profile (a) and the E_r-profiles (b) in XP20241121.038 with pellet injections.

III. Combined NBI and ECRH discharges

NBI particle fueling in W7-X modifies the core density profile, affecting particle transport and often leading to impurity accumulation [13], strong core radiation, and reduced temperatures. Additional ECRH power might mitigate these effects, but its precise impact on the density profile remains uncertain [4]. A balanced increase of NBI and ECRH power to optimize the density profile is being explored. A well-optimized case from the latest campaign is shown in Fig. 4, where the HP phase (W_p~1.8 MJ) lasts ~1.5s. The enhanced 'ion-root' regime in the HP phase is shown as marked in Fig. 5(b). Detailed heat and particle transport analysis is ongoing. Key impurity behavior findings:

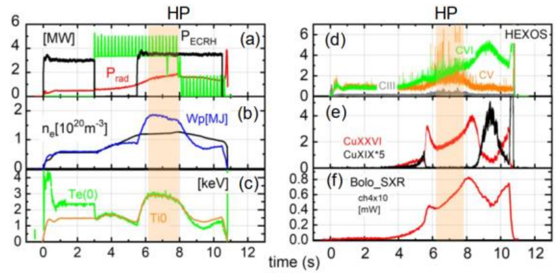

Fig. 4 Time traces of diagnostics in XP 20241204.072.

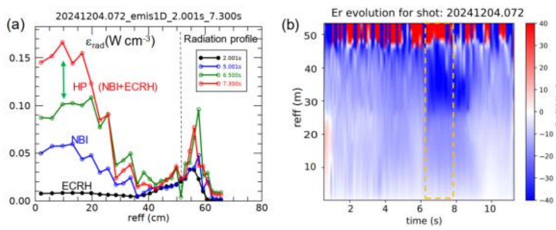

Fig. 5 Evolution of radiation (a) and E_r (b) profiles in discharge XP 20241204.072.

i. In the NBI scenario, significant core radiation (r_{eff}<25 cm) is observed, unlike the hollow radiation profile in the ECRH scenario (see Fig. 5(a)).
ii. Shortly after adding ECRH, both total SXR emission and CuXXVI line emission decrease. At t~6.2s, W_p reaches its maximum (~1.8 MJ).
iii. During the HP phase, core impurity radiation gradually becomes pronounced (red in Fig. 5(a)) while W_p gradually declines. This decline in *Wp* could be due to the increased core radiation. A detailed investigation is underway.

In this study, we also observed that all HP phases exhibit a core radiation fraction of ~20–30%, with emissivity peaking 10–20 cm from the plasma center. Higher radiation fractions with centrally peaked profiles negatively impact core performance. Sustaining HP phases requires effective control of density gradients and impurity transport, making it a key research focus for W7-X.

References:

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