VALIDATION OF PLASMA -WALL SELF-ORGANIZATION THEORY BY HIGH DENSITY LIMITS ACHIEVED ON EAST

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Achieving high electron density is essential for tokamaks to reach energy breakeven and sustain a burning plasma. However, tokamak operation is often constrained by an upper density limit, beyond which disruptions occur. Understanding and overcoming this density limit remains a key challenge. Here, we present experimental results from the EAST tokamak, achieving a line-averaged electron density in the range (1.3-1.65) Greenwald density limit n_G, while the usual range in EAST is (0.8-1.0) n_G. This was achieved through ECRH-assisted Ohmic start-up combined with a sufficiently high initial neutral density. This technique is motivated by and consistent with predictions of a recent plasma-wall self-organization (PWSO) theory, that increasing ECRH power or pre-filled gas pressure leads to lower plasma temperatures around divertor target and higher density limits by mimicking a stellarator start-up [1]. Furthermore, the experiments are confirmed operating within the density-free regime predicted by the PWSO model. These results suggest a promising scheme for substantially increasing the density limit in tokamaks, a critical advancement toward achieving the burning plasma.

Two experimental series were systematically conducted: (1) varying the pre-filled neutral gas pressure with a fixed ECRH power of 600kW, and (2) varying ECRH power while maintaining a constant pre-filled gas pressure. Both approaches resulted in an enhancement of the density limit (Fig. 1). The achieved high-density regime exhibits three distinct characteristics. First, the density limit n_c exhibits a monotonic increase with decreasing target region plasma temperature T_t (Fig. 1a), highlighting the role of plasma-wall interaction in setting the density limit. Second, an inverse correlation between density limit n_c and total radiation was observed (Fig. 1b), where the density limit increased by ~17% as total radiation decreased by ~21%, indicating improved plasma cleanliness, and this improvement may be due to fewer plasma-wall interactions. Finally, the successive effective discharges shown in Fig. 2 demonstrate the striking fact that the target region plasma temperature T_t decreases with discharge number, which indicate an improvement in wall conditions.

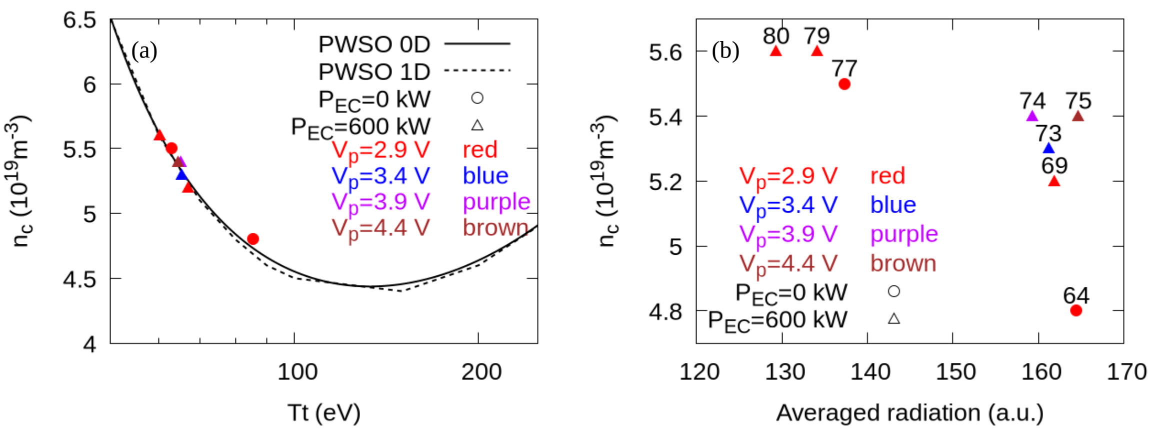

Fig. 1: Density limit as functions of (a) target region plasma temperature T_t and (b) averaged total radiation, where the number labels xx denote the last 2 digits of the shot numbers #1430xx.

In summary, these experiments demonstrate that the above technique improves the DL and highlight that the density limit can be strongly influenced by plasma-wall interactions.

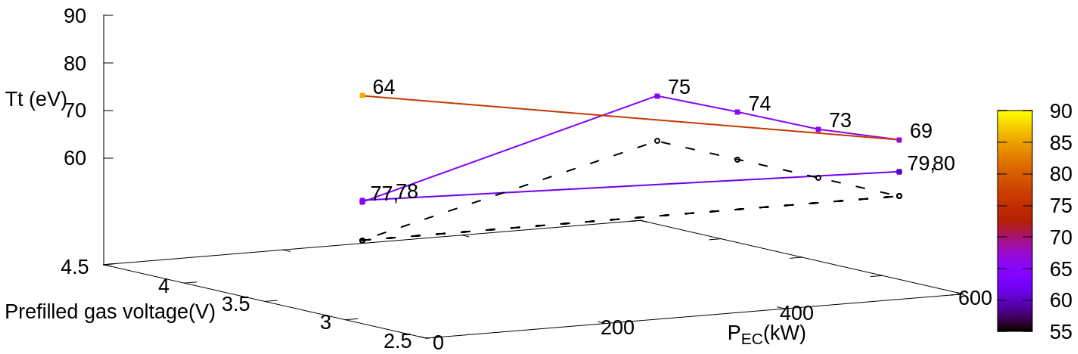

Figure. 2: 3D diagrams displaying target region plasma temperature T_t as a function of both ECRH power and pre-filled gas voltage.

The PWSO theory describes the plasma-wall interaction through the relationship between sputtered impurities' radiation and heating power [1]. The basic idea of the PWSO theory is the existence of a time delay in the feedback loop relating impurity radiation and impurity production on divertor/limiter plates. Both zero-dimensional (0D) and one-dimensional (1D) PWSO models have been validated against EAST experimental data. As shown in Fig. 1b, the experimental results exhibit quantitative agreement with the PWSO 0D model assuming an impurity radiation rate of $10^{-30}Wm^{-3}$ and a perpendicular impurity diffusion coefficient of 120 m^2s^{-1}. Further agreement with the PWSO 1D model is achieved by assuming a thermal diffusion coefficient of 0.5 m^2s^{-1}. The EAST experimental results are found to locate in the density-free regime of PWSO theory with much higher density limits than the Greenwald density limit.

Moreover, the decreasing target region plasma temperature T_t with discharge number (Fig. 2) further confirms that EAST is working in the virtuous process of the density freedom basin indicated by the PWSO theory [1]. This trend reflects the beneficial feedback loop of decreasing plasma temperature and increasing density limits described by the theory. These results extend the experiments and validation on J-TEXT [2]. By demonstrating stable operation in the density-free regime, these findings suggest a promising approach for next-generation devices like ITER, where exceeding n_G is critical for achieving burning plasmas.

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