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Advances in Turbulence-Driven Transport Control for improved Plasma Confinement

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The reduction of turbulence-driven anomalous transport is one of the foremost challenges in the early realization of fusion reactors. The most straightforward approach is to target and directly control the turbulence itself. Recently, a turbulence transition (TT) between ion temperature gradient (ITG) turbulence and resistive interchange (RI) mode was observed in the Large Helical Device (LHD) [1]. Turbulence suppression is maximized in the LHD when this turbulence transition occurs. This transition has been observed across various magnetic configurations and heating conditions in LHD. Therefore, plasma operations that satisfy the turbulence transition condition (TTC) are expected to minimize anomalous transport.

In this study, we report on the implementation of real-time plasma control designed to satisfy the TTC, and its effects on turbulence suppression and transport improvement. Prior to applying control, the TTC was determined using an exhaustive search with a Support Vector Machine (ES-SVM). For the inward-shifted LHD configuration (R_{ax} = 3.6 m, B_t = 2.75 T), the TTC can be expressed simply as $n_e = 4.20T_e - 5.28$.

Then, we attempted to operate the plasma under low-turbulence conditions by controlling it in real time to follow the relation $n_e = 4.20T_e - 5.28$. In this study, we demonstrated two different approaches: electron temperature control and electron density control. Here, the result of temperature control is presented in detail. In the temperature control, density is kept constant by gas-puff feedback control. To meet the target T_e based on TTC, the electron cyclotron resonance heating (ECRH) power is varied every 200ms.

Figure 1 compares plasma experiments with and without temperature control, indicated in red and blue, respectively. In both cases, neutral beam injection (NBI) is used as the main heating to sustain the plasma, while ECRH is applied for temperature control. As shown in panel (a), the electron density remains constant during the time intervals highlighted in orange and green. By adjusting the ECRH power, as shown in panel (b), the electron temperature reaches the target value in the case with control, whereas it does not in the case without control. As a result, the normalized global energy confinement time ($\tau_{E\,W_{pei}}/\tau_E^{ISS04}$) improved by up to 20%. Figure 2 presents the comparison of turbulence amplitude profiles with and without control. A clear suppression of turbulence is observed in the $\rho = 0.5 - 0.7$ in both cases. A similar level of confinement improvement and turbulence suppression was also achieved using the density control approach via gas puffing.

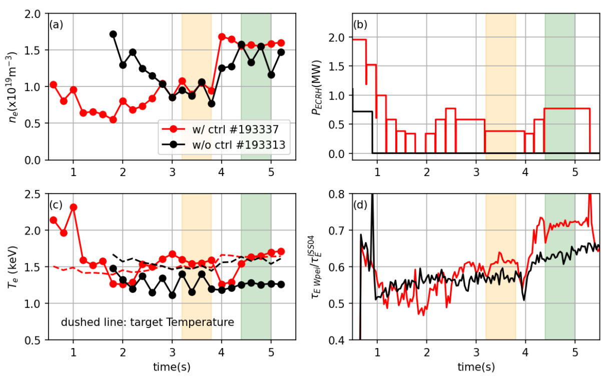

Figure 1 Time evolutions of (a) electron density, (b) ECRH power for temperature control, (c) electron temperature, and (d) $\tau_{E\,W_{pei}}/\tau_E^{ISS04}$. Here are shown with control (#193337) and without control (#193331), with both densities coinciding in the highlighted areas.

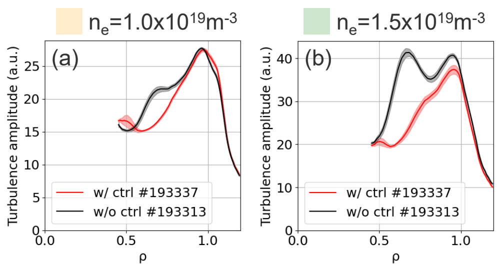

Figure 2 Comparison of time-averaged turbulence profiles during two different phases. (a) Time window t = 3.2–3.8 s (corresponding to the orange highlighted region in Figure 1). (b) Time window t = 4.4–5.0 s (corresponding to the green highlighted region in Figure 1).

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