DIRECT CONTROL OF TURBULENCE FOR IMPROVED PLASMA CONFINEMENT

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Turbulence and anomalous transport are minimized during a turbulence transition between ion temperature gradient turbulence and resistive interchange mode in the Large Helical Device. In this study, an exhaustive search with Support Vector Machine was applied to explore the turbulence transition conditions. The classification result suggests that electron density and electron temperature are key parameters governing the turbulence transition. Experimental verification demonstrated that real-time plasma control under the turbulence transition conditions, achieved through electron temperature control using electron cyclotron resonance heating and electron density control using gas puffing, successfully suppressed turbulence and improved confinement performance around 20%. These results underscore the promise of direct turbulence control as a viable strategy for improving plasma confinement performance in magnetic confinement devices.

A reduction of turbulence-driven anomalous transport is one of the foremost physics challenges in the early realization of fusion reactors. The most straightforward approach is to target and directly control the turbulence itself. Recently, the turbulence transition (TT) between ion temperature gradient turbulence (ITG) and resistive interchange mode (RI) was found in the Large Helical Device (LHD) [1], with turbulence and anomalous transport observed to be minimized simultaneously during the TT. In other words, plasma operations that satisfy the TT condition (TTC) are those that minimize anomalous transport. In this study, we first explore the TTC at the LHD inward shift configuration ($R_{ax} = 3.6\text{m}$, $B_t = 2.75\text{T}$) and then establish control methods to satisfy the TTC, validating their effectiveness through real-time plasma control.

An exhaustive search with Support Vector Machine (ES-SVM) was applied to explore the TTC. SVM is a supervised machine-learning algorithm applicable to both classification and regression tasks, but is more popularly used in classification tasks. Meanwhile, the exhaustive search method investigates all parameter combinations. That is, ES-SVM is a method in which SVM is applied to all possible parameter combinations to find the best classification parameters. The parameters explored in this study include electron density (n_e), electron temperature (T_e), ion temperature (T_i) and electron-ion temperature ratio (T_e/T_i) and electron density gradient (dn_e/dr), electron temperature gradient (dT_e/dr) and ion temperature gradient (dT_i/dr) averaged at $\rho = 0.5 - 0.7$. Here, ρ is a normalized minor radius and $\rho = 0.5 - 0.7$ is the radial position where the TT study was conducted[1]. These parameters are important for stabilizing and destabilizing ITG and RI. The estimation accuracy was improved using k-fold cross-validation, and the classification model was evaluated based on the F1-score. Ion-scale turbulence was measured by two-dimensional phase contrast imaging (2D-PCI)[2], and ITG and RI were distinguished by the turbulence propagation direction in the laboratory coordinate system (ion-diamagnetic direction ~ ITG, electron diamagnetic direction ~ RI). As a result, the best classification performance was achieved when the number of parameters (N) was 3, using the combination of n_e, T_e, and dn_e/dr. The classification formula, that is, the TTC is $n_e = 2.47T_e + 0.28\,dn_e/dr - 2.62$. However, it is impractical to selectively control the electron density gradient by gas-puffing. Fortunately, excellent classification performance was also achieved when N was 2, using the combination of n_e and T_e. Figure 1 shows the SVM classification plot by using n_e and T_e. The green line indicates the boundary that distinguishes ITG (blue symbol) and RI (red symbol) based on the SVM, and it is the TTC, expressed by the

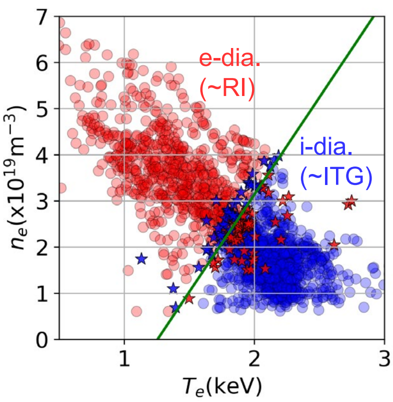

Fig. 1 SVM classification plot by n_e and T_e. The colors indicate the turbulence propagation direction; the blue and red symbols are the ion-diamagnetic and electron-diamagnetic directions, which roughly correspond to ITG and RI, respectively.

formula $n_e = 4.20T_e - 5.28$. Several misjudgments (star symbol) appear, but are distributed near the green line and are expected to be weak turbulence.

Next, we attempted to operate the plasma in low-turbulence conditions by controlling the plasma in real-time along $n_e = 4.20T_e - 5.28$. We demonstrated two different approaches: electron temperature control using electron cyclotron resonance heating (ECRH) and electron density control using gas-puffing. Here, the result of temperature control will be presented in detail. In addition to ECRH for temperature control, neutral beam injection was used for plasma sustainment, and electron density was kept constant by gas-puff feedback control using far infrared (FIR) laser interferometer. In this control system, the electron density and temperature, averaged over the radial positions $R = 3.1 - 3.3$m and $4.0 - 4.2$ m, where approximately correspond to $\rho = 0.5 - 0.7$, are obtained in real-time using Thomson scattering every 200ms. Then, the target temperature ($T_{e\,tgt}$) is calculated from $n_e = 4.20T_{e\,tgt} - 5.28$, and the ECRH power is changed by changing the ECRH combination based on the difference between T_e and $T_{e\,tgt}$. As shown in Figure 2 (a), the electron density was maintained at $n_e = 1.0 \times 10^{19}\mathrm{m}^{-3}$ and $1.5 \times 10^{19}\mathrm{m}^{-3}$ in the regions highlighted in orange and green, respectively. Note, the solid lines and symbols indicate normal acquisition with 30Hz and real-time acquisition every 200ms at the same radial position, respectively. The red and blue correspond to with and without control. Figure 2(b) shows the time variation of ECRH power, in the without control case, ECRH is not applied. From Fig. 2(c), the electron temperature was controlled to $T_{e\,tgt}$ within the error bar at the hatched timing. To discuss the improvement in confinement due to the control, (d) shows the time evolution of $\tau_{E\,W_{pei}}/\tau_E^{ISS04}$ ($\tau_{E\,W_{pei}}$: kinetic energy confinement time calculated by dividing the electron and ion stored energy by the deposition power, τ^{ISS04}: International stellarator scaling law[3]) and is an indicator of confinement performance considering the heating power. For $n_e = 1.0 \times 10^{19}\mathrm{m}^{-3}$, the improvement in confinement is 8%, while for $n_e = 1.5 \times 10^{19}\mathrm{m}^{-3}$the improvement is nearly 20% by temperature control.

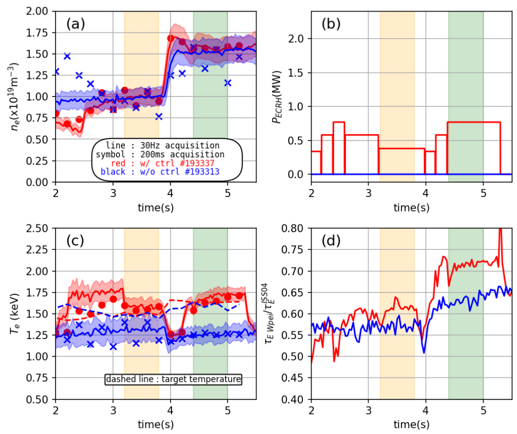

Fig. 2 Time evolutions of (a) electron density, (b) ECRH power for temperature control, (c) electron temperature, and (d) $\tau_{E\,W_{pei}}/\tau_E^{ISS04}$. Here are shown with control (#193313) and without control (#193337), with both densities coinciding in the highlighted timing.

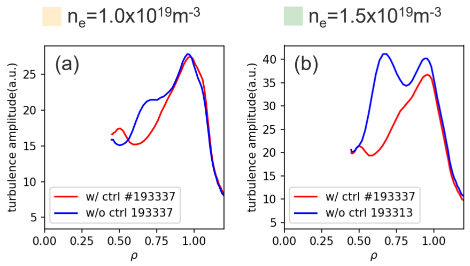

Fig. 3 Comparison of turbulence profile between w/ control and w/o control. The turbulence profile is measured by 2D-PCI.

Figure 3 compares the turbulence profiles with and without control. The turbulence observed at $\rho = 0.5 - 0.7$ in the w/o control is RI and increases with increasing density. Therefore, the turbulence suppression by temperature control is significantly effective at $n_e = 1.5 \times 10^{19}\mathrm{m}^{-3}$, which is qualitatively consistent with the degree of confinement improvement.

An alternative control approach, density control by gas-puffing, also achieved comparable confinement performance and turbulence suppression.

In summary, the dominant turbulence differs depending on the operating region in LHD, and the condition under which the dominant turbulence switches is the condition of minimum turbulence, which can be approximately explained by $n_e = 4.20T_e - 5.28$. In this study, the plasma was controlled to satisfy this condition by two different approaches, and the confinement performance was successfully improved. It was also found that turbulence was clearly suppressed during the confinement improvement. Although the plasma control in this study was based on the LHD-specific ITG-RI turbulence transition, it is applicable not only to the stability-valley in the W7-X and LOC/SOC transitions in tokamak etc., where two types of turbulence exist, but also to the case where turbulence is minimized under specific conditions even with one type of turbulence.

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