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Turbulent Properties Against Hydrogen Isotope Ratio and Zonal Flow Activities in Heliotron J

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Turbulence properties against the variation of isotope ratio and zonal flow activity are elucidated in Heliotron J. The turbulence amplitudes for density and potential fluctuations reduce as the hydrogen/deuterium(H/D) gas ratio is varied from H to D dominant plasmas and zonal flow activity is enhanced. Two-point correlation analysis reveals that the correlation of the fluctuations decreases in D plasmas, although the turbulence scale size increases as D gas fraction increases. A statistical analysis using a joint probability density function technique also indicates that the density and potential fluctuations are decoupled in D plasmas, which should contribute to the suppression of turbulence-driven transport and the confinement improvement in D plasma. These observations suggest that the isotope effect can emerge through the reduction and decoupling of density/potential fluctuations, which is attributed to the enhanced zonal flow activity in D plasmas observed in the experiment.

Confinement improvement in deuterium plasmas, called "isotope effect", has been a long-standing issue in the study of magnetic confinement fusion. The isotope effect contradicts a fundamental model of transport, because an increase of characteristic scale (ion Larmor radius or turbulence scale size here) simply gives the increase of transport, in other words, D plasmas should have a degraded performance compared with the H plasmas, incompatible with the experimental observations. A hypothesis is proposed to explain the isotope effect recently, which is attributed to isotope dependence of turbulence system including a zonal flow activity. A couple of experimental works, including our past work, also report the dependence of zonal flow activity exists on the H/D isotope ratio. However, turbulence responses behind the isotope dependence of zonal flow have not yet been studied in detail so far.

In this study, the isotope dependence of local turbulence properties is characterized in a helical device, Heliotron J. The machine has major/minor radii of $R/a = 1.2/0.17\mathrm{m}$ with the magnetic field strength $\mathrm{B} = 1.25\mathrm{T}$ on axis. In this experiment, the plasma was sustained with electron cyclotron heating with the power of $< 0.3\mathrm{MW}$, and the H/D ratio was carefully controlled to keep line-averaged density constant ($0.2\times10^{19}\mathrm{m}^{-3}$) and to reproduce the same plasma conditions. Two Langmuir probes, located at different toroidal sections, were used by fixing them at the same flux surface of $\rho \sim 0.8$ to measure the local turbulence and zonal flow.

The frequency spectra of floating potential and ion saturation current indicate that the turbulence level gradually increases against H/D ratio, as hydrogen is more dominated and zonal activity is enhanced as shown in Fig. 1(a) and (b). Interestingly, the small difference in the spectra can be seen; higher frequency components of $> 100\mathrm{kHz}$ emerge in the case of floating potential, and fluctuation level in all the frequency range increases in ion saturation current, as hydrogen becomes dominant. This observation suggests that turbulence-induced transport increases in H plasmas.

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Dependence of turbulence correlation length on the H/D ratio was also evaluated with a two-point cross-correlations technique, by using a pair of adjacent probe tips with a distance of $\sim n_H/(n_D + n_H$. The cross-correlations for density and potential are plotted against the H/D ratio in Fig. 1(c) and (d), respectively. In this analysis, the correlation is evaluated with the dominant fluctuation in the frequency range from $\sim 5\mathrm{mm}$ to 10. This is because the fluctuation component less than $40\mathrm{kHz}$ is dominant in edge plasmas, and noises such as cross-talk in the frequency range $> 50\mathrm{kHz}$ are not large but non-negligible for the correlation analysis. Fig.1(c) shows that no clear dependence against HD ratio exists for potential fluctuation, and however significant dependence is found for density fluctuation (ion saturation current). The correlation for density fluctuation decreases as hydrogen gas becomes dominant, which implies that the scale size of density fluctuation is smaller in H but larger in D plasmas. This observation is qualitatively consistent with the past experimental results, however, it is unfavourable for transport. The correlation between density and potential fluctuations, which is essentially important to determine turbulence-induced transport, is then characterized, as shown in Fig. 1(e). The correlation decreases as the D gas is dominated in Fig. 1(e). This decrement suggests that the potential and density fluctuation are more decoupled in D plasmas, and the decoupling contributes to the reduction of turbulence-induced transport, even if the turbulence scale size increases in D plasma as mentioned in the previous paragraph.

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Furthermore, the decorrelation of density and potential is also demonstrated from a statistical viewpoint using a joint probability density function(joint-PDF) technique, as shown in Fig. 2(a-c). The joint-PDF is an extension of one-dimensional PDF, and the distribution shows each PDF of each quantity and indicates a degree of correlation between two different quantities. If two quantities are strongly correlated with a linear relation, the distribution has a distorted, linear shape. A more randomized, rounded distribution shape indicates a weaker coupling, and the distribution should be symmetric in X-Y axes in the case of completely random variables. The joint-PDF for potential and density fluctuations can be seen to be a more elliptic shape in the H plasma, compared with the case in D plasmas, which shows that the fluctuations are correlated more in H plasmas while are decoupled in D plasmas. The difference between the two cases is also shown in Fig. 2(c), representing that the correlated components with an asymmetric shape reduce at the higher fluctuation level （$>$ 50kHz the standard deviations σ_{Vf} and σ_{is}), while the uncorrelated components increase at the lower fluctuation level ($< >$ and σ_{is}) in D plasmas. The reduction of the correlated component corresponds to the decoupling between density and potential fluctuations and the distortion of the fluctuation PDF, which could reduce particle/heat fluxes in D plasmas.

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