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Isotope effects in internal transport barrier strength on Large Helical Device

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Strength of the internal transport barrier (ITB) is quantified in deuterium (D) and hydrogen (H) plasmas using a unique criterion based on the transport nonlinearity on the temperature. Two distinct isotope effects are found: (i) Stronger ITBs in D plasmas and (ii) edge confinement degradation accompanied by the ITB formation emerging in H plasmas. Principal component analysis reveals the important role of the density peaking for the strong ITB formation.

The isotope effect in magnetically confined plasma physics has been a long-standing mystery unsolved. In general, there are a number of experimental case studies on the isotope effect in tokamaks, but less in stellarators/heliotrons. The isotope effect is particularly prominent in transport barrier formation in tokamaks. For systematic understanding of the background physics, the isotope effect in the transport barrier property in stellarators/heliotrons need be assessed. Here, we report a recent progress on isotope effect studies for the ITB in Large Helical Device (LHD).

Unlike the case of tokamak plasmas, there is no generally accepted criterion for the ITB strength in stellarators/heliotrons. Here, a new criterion for the ITB strength is proposed by defining a unique scalar coefficient. The typical L-mode plasmas in LHD are characterized by the dome-shaped temperature profile with the diffusion coefficient being proportional to the temperature to the power of a factor α, i.e., $\chi \propto T^{\alpha}$, where $\alpha = 1$ is widely applicable. The reference L-mode profile $T_{\mathrm{L}}^{\mathrm{ref}}(r)$ is defined by extrapolating the edge temperature profile to the core according to the solution of the thermal diffusion equation with $\chi \propto T^{\alpha}$. By comparing $T_{\mathrm{L}}^{\mathrm{ref}}(r)$ with the entire temperature profile, the profile gain factor as the ITB strength is defined as $G_{1.0} = \int n(r)T(r)dV / \int n(r)T_{\mathrm{L}}^{\mathrm{ref}}(r)dV$, where the subscript 1.0 represents the α value used [A].

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The proposed method is applied to both D and H discharges with the line averaged density $\bar{n}_{\mathrm{e}}$ scan in the shot-to-shot basis. In LHD, the ITB in the ion temperature profile is typically formed when an intense neutral beam heating is applied to low $G_{1.0}$ plasmas. Figures 1 (a) and (b) compare the high and low $G_{1.0}$ discharges for corresponding pairs of D and H plasmas, where the neoclassical transport is optimized by shifting the magnetic axis inward. Symbols and curves correspond to the measured data and $\bar{n}_{\mathrm{e}}$, respectively. Inserts present the electron density $\bar{n}_{\mathrm{e}}$ profiles in the low $\bar{n}_{\mathrm{e}}$ discharges, showing that $T_{\mathrm{L}}^{\mathrm{ref}}(r)$ tends to peak in D plasmas. However, the peaking of n_{e} is very weak and no ITB in $\bar{n}_{\mathrm{e}}$ profile is present. Stronger ion temperature ITB is formed in the low n_{e} D plasma with n_{e} compared to the H plasma with n_{e}. The ITB foot-points in D and H plasmas are similar. Unlike the L-H transition, it is hard to define the threshold power for the ITB in LHD. In stead, we discuss $\bar{n}_{\mathrm{e}}$ dependence of the ITB strength $G_{1.0} \sim 1.5$ in Fig. 1 (c), where the systematic comparison between D and H plasmas is performed. When $G_{1.0} \sim 1.3$ is high, $\bar{n}_{\mathrm{e}}$ that corresponds to the L-mode, and decreasing $G_{1.0}$ leads to a non-monotonic increase in $\bar{n}_{\mathrm{e}}$. Larger $G_{1.0} \sim 1$ is routinely observed in D plasmas in $\bar{n}_{\mathrm{e}}$. In addition, the edge temperature decreases when the ITB is formed in the H case as shown in Fig. 1 (b). The insert in Fig. 1 (c) shows the $G_{1.0}$ dependence of the edge ion temperature $G_{1.0}$ averaged in $\bar{n}_{\mathrm{e}} < 2 \times 10^{19}\mathrm{m}^{-3}$. As $G_{1.0}$ increases, $T_{\mathrm{i,edge}}$ clearly decays in H plasmas. This limits the core temperature increment even in the presence of the ITB in H plasmas [B].

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It is essential to identify parameters that play a role for determining the ITB strength. To resolve the relation among parameters that change with $0.68 < r_{\mathrm{eff}}/a_{99} < 0.83$, the principal component analysis (PCA) is performed. As appeared in literature, the inverse electron density gradient length $G_{1.0}$, the carbon density $T_{\mathrm{i,edge}}$ and its inverse gradient length $\bar{n}_{\mathrm{e}}$ are predicted to impact on the ITB formation. The PCA is applied for the database in the five-dimensional parameter space ($L_{n_e}^{-1}$), where data with different magnetic configurations and the isotope mass are taken all at once. Here, the local parameters are obtained at the ITB foot-point of n_c. Note that the density profiles apparently having no ITBs are treated as the background elements that possibly affect the ITB property. It is found that the primary and secondary principal components are almost equivalent to $L_{n_c}^{-1}$ and $\bar{n}_e, G_{1.0}, L_{n_e}^{-1}, n_c, L_{n_c}^{-1}$, respectively, and $r_{\rm eff}/a_{99} = 0.6$ and $\bar{n}_e$ have high correlations with $L_{n_e}^{-1}$. According to the PCA, $\bar{n}_e$ is plotted as a function of $L_{n_e}^{-1}$ and $G_{1.0}$ for D and H plasmas in Fig. 2. Stronger ITBs are formed when $G_{1.0}$ is large and $\bar{n}_e$ is small. A working hypothesis is drawn from the observation: In D plasmas $L_{n_e}^{-1}$ profile tends to peak due to the particle transport or the beam fueling. The peaked $L_{n_e}^{-1}$ profile enhances the ITB formation, possibly due to the ion temperature gradient mode stabilization [C]. The radial electric field shear remains approximately unchanged with $\bar{n}_e$, showing less impact on the ITB formation.

The isotope effect in the transport barrier formation property is stronger than that in the L-mode plasma confinement in LHD [D-F]. This is qualitatively similar to the tokamak case, where the isotope effect in the transport barrier threshold power is much clearer with respect to that in the confinement scaling exponent. A detailed comparison between LHD and tokamaks stimulates the phenomenological understanding of the isotope effect.

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