

Broadening of scrape-off layer width by turbulence spreading in the heavy hydrogen isotope plasmas

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A significant enhancement of turbulence spreading across the last closed flux surface (LCFS) has been observed during the transition from hydrogen (H)- to deuterium (D)-dominated plasmas in the HL-2A tokamak. Experimental results show that boundary turbulence increases in D plasmas compared to H plasmas, while the $E \times B$ shear flow in the vicinity of the LCFS is accordingly reduced. It is found that fluctuations inside the LCFS are dominated by interchange turbulence, which spreads radially outward and penetrates the LCFS into the scrape-off layer (SOL), leading to a broader SOL width and a reduction of parallel heat flux. These findings highlight the significant contribution from turbulence spreading to the broadening SOL width and suggest a promising strategy for controlling exhaust heat load while maintaining good plasma confinement through isotope mass optimization in future fusion reactors.

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I. INTRODUCTION

The mitigation of divertor heat flux while maintaining high plasma performance is one of the great challenges in magnetically confined fusion plasmas [1]. Various schemes have been attempted to reduce the heat load via broadening the scrape-off layer (SOL) width or reducing the heat flux peak, for example, increasing the radiation dissipation via impurity seeding [2,3], extending the divertor legs through optimizing the magnetic geometry [4], and broadening divertor heat flux by the application of resonant magnetic perturbation [5].

The turbulence in near-SOL has been widely recognized as a key player governing SOL width [6,7]. Recently, there has been growing interest in the physical mechanisms of plasma boundary turbulence controlling SOL width. Some theoretical simulations demonstrate that edge turbulence might be one of candidates for the broadening of SOL width [8]. The XGC-1 and BOUT++ simulation codes also address the crucial role of turbulence in setting the SOL width [9,10], which was generally ignored in the heuristic drift model [11]. Substantially, some experimental evidences relating the pedestal turbulence and divertor heat flux width have been observed in several fusion devices, such as DIII-D [12] and EAST [13]. The wider SOL profiles are found to be highly correlated with the strong cross-field transport in JET tritium plasma experiment [14]. A quasiscoherent density fluctuation

detected in SOL is thought to be attributed to the theoretically predicted interchangelike mode, which could significantly enhance SOL particle and heat flux in the high-performance hybrid plasmas [15]. Additionally, the external resonant magnetic perturbation-induced turbulence in large helical device (LHD) stellarator was observed to spread into the stochastic layer, resulting in a remarkable drop of the divertor heat load [16]. In toroidally confined plasmas, however, the instability responsible for production of SOL turbulence as well as the underlying physical mechanism determining SOL width has not been identified yet unambiguously.

In this work, we present experimental evidences demonstrating the significant contribution from turbulence spreading to the broadening of SOL width in HL-2A ohmically heated plasmas. Our finding illustrates that the SOL turbulence increases, whereas the $E \times B$ shear flow near the last closed flux surface (LCFS) correspondingly reduces during the transition from hydrogen (H) to deuterium (D) dominant plasmas. The edge fluctuation, identified as interchange mode, is initially triggered by electron temperature gradient inside the LCFS, and then starts to spread radially across the LCFS into SOL, leading to the broadening of SOL width and reduction of parallel heat flux.

II. EXPERIMENTS

The isotopic experiments were conducted in the ohmically heated deuterium and hydrogen plasmas at the HL-2A tokamak with a limiter configuration [17]. The major and minor radii are $R = 165$ cm and $a = 40$ cm, respectively. The discharge parameters were summarized as follows: The central line-averaged density was $n_{el} \approx 1.3 \times 10^{19} \text{ m}^{-3}$, the plasma current was $I_p \approx 150$ kA, the toroidal magnetic field was $B_t \approx 1.3$ T, and the edge safety factor $q \approx 3$. The diagnostic mainly used in this experiment is double-step Langmuir

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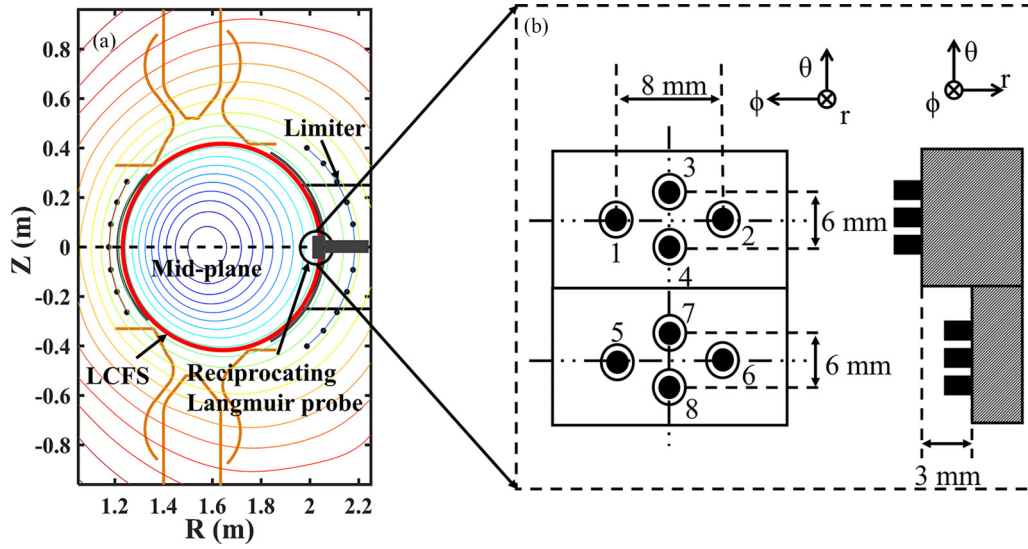


FIG. 1. Equilibrium configuration reconstructed by the efrit code together with the location of Langmuir probe measurement [panel (a)] and the sketch of the double-step Langmuir probe [panel (b)]. The innermost position of probe measurement is inside the LCFS about $\Delta r \approx -2$ cm.

probe array as illustrated in Fig. 1(b). The diameter and the exposed length of the probe are 2 and 2.5 mm, respectively. The poloidal separation of adjacent probes is 6 mm and the step height is 3 mm. This probe array installed at the fast-reciprocating system [18] is utilized to measure the equilibrium and fluctuating parameters, such as floating potential (V_f), electron temperature (T_e), and density (n_e). The radial electric field E_r could be derived from $E_r = -\partial V_p / \partial r$, where V_p denotes the plasma potential: $V_p = V_f + \alpha T_e$ ($\alpha \approx 2.5$ and 2.8 for H and D plasmas). Here, it should be noticed that the fluctuation levels for $\frac{\tilde{T}_e}{T_e}$ and $\frac{e\tilde{V}_f}{kT_e}$ are estimated as 3%–8% and 10%–28% in boundary plasma ($-1 \text{ cm} < \Delta r < 2 \text{ cm}$), respectively. It thus can be derived as $\tilde{V}_f^{\text{rms}} / \tilde{V}_p^{\text{rms}} \approx 55\%$ –65%, implying that $\tilde{V}_f$ could be used as a proxy of $\tilde{V}_p$ when temperature fluctuations are less than 10%. The similar analysis has been performed in our previous work [19]. In general discharges, the probe measurement is performed covering the plasma boundary region of $\Delta r \approx -3.0$ to 4.5 cm, where $\Delta r = 0 \text{ cm}$ represents the approximate position of the LCFS calculated by the equilibrium fitting code (efit) with an accuracy of 5 mm, and the negative sign means the measurement inside LCFS. The data acquisition frequency is $f_s = 1 \text{ MHz}$ with an accuracy of 12 bits. The results presented here are well reproducible whenever the Langmuir probe array is inserted into the edge plasmas with the analogous discharge conditions.

Compared in Figs. 2(a)–2(e) are typical discharge waveforms for H and D dominant plasmas, including plasma current (I_p), line-averaged density (n_{el}), plasma stored energy (W_E), radiation power (P_{rad}), and the trajectory of reciprocating Langmuir probe. It was clearly seen that the D plasma has better energy confinement than H plasma when I_p and n_{el} are nearly identical, indicating the presence of isotope effect in ohmically heated plasma [20]. The enhanced zonal flows are expected to explain the confinement improvement during the transition from hydrogen to deuterium dominant plasmas [21]. However, few works have been performed to

study the influence of edge turbulence on the SOL width under different isotopic mass. To this end, we are devoted to explore the characteristics of edge and SOL turbulence (both sides of the LCFS) in the H and D plasma discharges. Compared in Figs. 2(f)–2(k) are the radial variations of plasma parameters in H and D plasmas, where the vertical dashed line denotes the approximate position of the LCFS. One can see that the plasma density has a similar profile in both cases, whereas the electron temperature in H plasmas has a striking different profile in boundary plasma compared to D plasmas. For quantitatively comparing the change of density and electron temperature profiles, we calculate the inverse scale length of density ($L_{n_e}^{-1}$) and electron temperature gradient ($L_{T_e}^{-1}$) and summarized them in Figs. 2(g) and 2(j), respectively. In D plasmas compared to H plasmas, the inverse scale length of electron temperature gradient ($L_{T_e}^{-1}$) increases inside the LCFS and decreases outside, as indicated by the yellow shaded areas; however, the inverse scale length of density gradient ($L_{n_e}^{-1}$) has nearly identical profiles in both cases. On the other hand, one can see that the estimated radial particle flux (Γ_r) and heat flux (Q_r) at near-SOL in D plasmas are larger than those in H plasmas, as compared in Figs. 2(h) and 2(k). According to Fick's law [22], the radial particle and heat flux are expected to have a similar tendency with respect to the radial profiles of density and electron temperature; however, there are some complex physical processes, involving anomalous transport, nonlinear effect, etc., which might lead to a deviation of experimental observation from theoretical prediction [23]. On the other hand, the SOL width (λ_q) is inferred from the first derivative of parallel heat flux for sheath-limited plasmas [24], $\lambda_q^{-1} = (d q_{\parallel} / dr) / q_{\parallel}$, $q_{\parallel} \sim \gamma n_e T_e^{1.5}$, where $\gamma \approx 7.0$ and 7.3 for H and D plasmas, respectively; thus, λ_q^{-1} could be evaluated as λ_q^{-1} . As an example, the estimated λ_q^{-1} at near-SOL region ($0 \text{ cm} < \Delta r < 1 \text{ cm}$) has a smaller value in D plasmas than H plasmas, denoted by a yellow shaded area in Figs. 2(g) and 2(j), suggesting the presence of a wider SOL width in D plasmas.

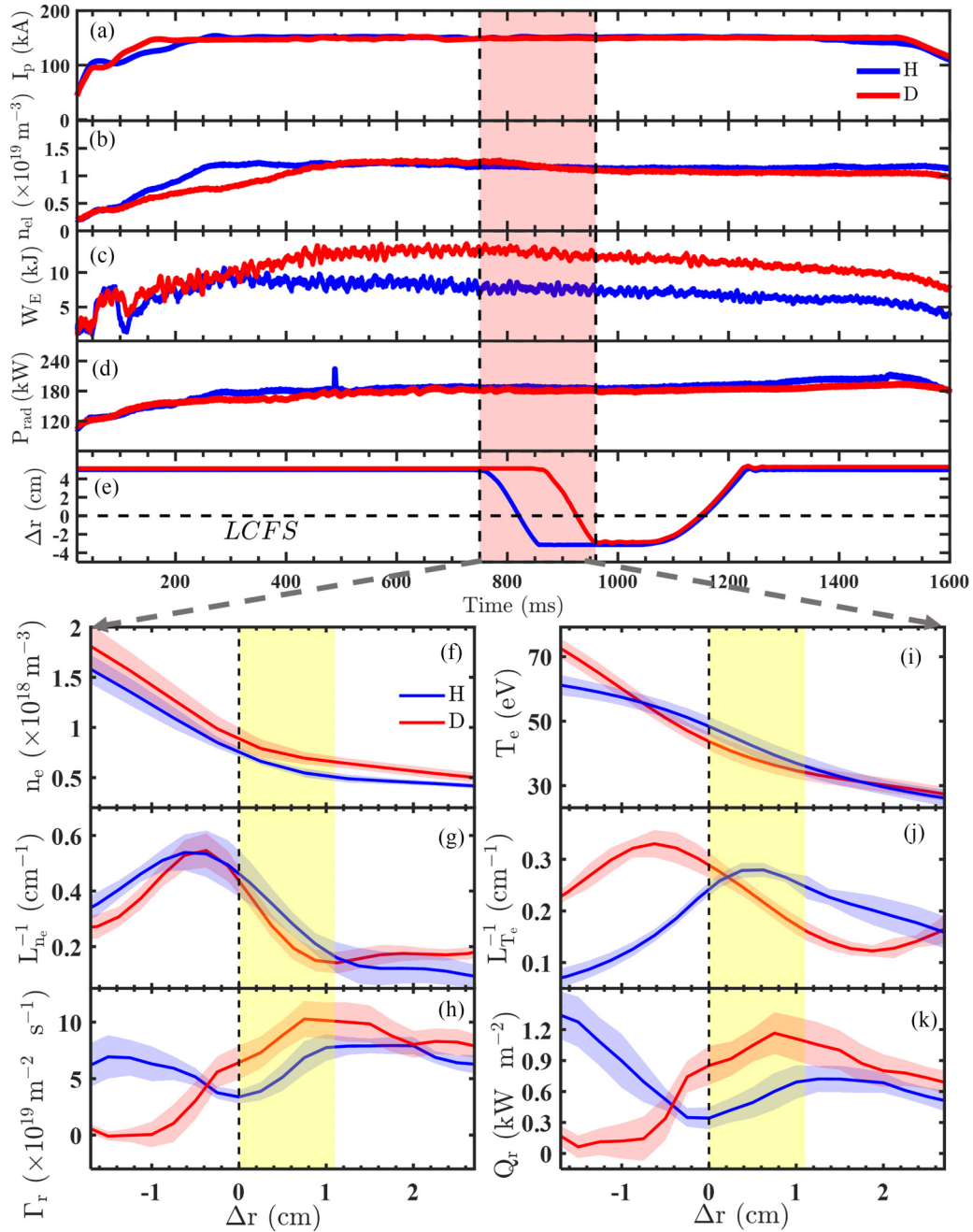


FIG. 2. Time traces of plasma current I_p [panel (a)], line-averaged density n_{el} [panel (b)], plasma stored energy W_E [panel (c)], radiation power P_{rad} [panel (d)], and the trajectory of reciprocating probe [panel (e)]. Comparisons of radial profiles including plasma density n_e [panel (f)], electron temperature T_e [panel (i)], the inverse scale length of density gradient $L_{n_e}^{-1}$ [panel (g)], the electron temperature gradient $L_{T_e}^{-1}$ [panel (j)], particle flux Γ_r [panel (h)], and heat flux Q_r [panel (k)] in H and D plasmas.

Compared in Figs. 3(a) and 3(b) are the radial profiles of $E \times B$ mean flow shear rate ($\gamma_{E \times B}$) obtained from multiple shot data in H and D plasmas. The $E \times B$ mean flow shear rate ($\gamma_{E \times B}$) is generally inferred from the derivative of radial electric field [25], i.e., $\gamma_{E \times B} = B_r^{-1} \partial E_r / \partial r$, where the radial electric field E_r is calculated from $E_r = -\partial V_p / \partial r$ and V_p represents the plasma potential. One can see that the $E \times B$ mean flow shear rate has a peaking around the LCFS position in H plasmas, whereas its value is reduced by at least 45% within measurement uncertainty in D plasmas. Figures 3(e)–3(g) depict the radial variations of the frequency

spectrum of density fluctuations in H and D discharges, and the logarithm of the ratio of density power in D to H plasmas expressed by $S = \log_{10}(\tilde{n}_{e,D} / \tilde{n}_{e,H})$. It is clearly seen that the fluctuation level below 40 kHz in H plasmas has a notable reduction around the LCFS, which might be correlated with the weak $E \times B$ shear flow as shown in Fig. 3(a). Furthermore, we observed an enhanced turbulence in the frequency range of 5–20 kHz localized at near-SOL region in D plasmas. For elucidating the change in turbulent magnitude, we estimate the logarithm of the ratio of density power in D to H plasmas, i.e., $S = \log_{10}(\tilde{n}_{e,D} / \tilde{n}_{e,H})$ and plot it in Fig. 3(g),

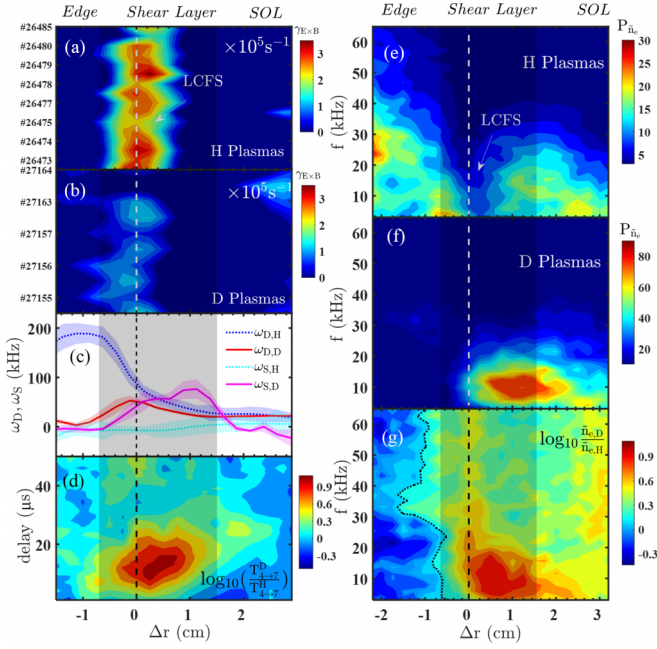


FIG. 3. Radial profiles of $E \times B$ flow shear rate $\gamma_{E \times B}$ obtained from multiple shots in H [panel (a)] and D [panel (b)] plasmas, the comparisons of local turbulence drive ω_D and turbulence spreading ω_S in H and D plasmas [panel (c)], the logarithm of the ratio of transfer entropy in D to H plasmas [panel (d)], the frequency spectrum of $\tilde{n}_e$ in H [panel (e)] and D [panel (f)] plasmas, and the ratio of density fluctuations in D/H plasmas [panel (g)], where the vertical dashed line represents the approximate position of the LCFS.

where the positive and negative signs of S mean the turbulence increase or decrease, respectively. One can see that the positive values of S mainly appear outside the LCFS, indicating that the enhanced turbulence is mainly localized at near-SOL during the transition from H- to D-dominated plasmas.

A question that arises is which physical process controls the turbulent transport? To this end, we adopt the dynamics equation of turbulence energy ($\tilde{n}_e^2$) derived from the continuity equation by neglecting cross-field coupling and damping, which is expressed as follows [26]:

$$\frac{1}{2} \frac{\partial}{\partial t} \langle \tilde{n}_e^2 \rangle = - \left\langle \frac{\partial n_e}{\partial r} \right\rangle \langle \tilde{v}_r \tilde{n}_e \rangle - \frac{1}{2} \frac{\partial}{\partial r} \langle \tilde{v}_r \tilde{n}_e^2 \rangle, \quad (1)$$

where the angular brackets $\langle \dots \rangle$ denote the time average over an interval much larger than the turbulence correlation time. The first and second terms represent the local product of turbulence and the diffusion of turbulent energy, respectively. By the normalization of the local turbulence amplitude ($\tilde{n}_e^2$), we obtain two rates of turbulence. One is the rate of turbulence drive (ω_D) due to the local density gradient and another is the rate of turbulence spreading (ω_S) due to turbulence energy gradient, which are defined as follows:

$$\omega_D = -2 \left\langle \frac{\partial n_e}{\partial r} \right\rangle \langle \tilde{v}_r \tilde{n}_e \rangle / \langle \tilde{n}_e^2 \rangle, \quad (2)$$

$$\omega_S = - \frac{\partial \langle \tilde{v}_r \tilde{n}_e^2 \rangle}{\partial r} / \langle \tilde{n}_e^2 \rangle. \quad (3)$$

In fact, it is very difficult to separate turbulence origin, i.e., locally driven turbulence and spreading turbulence, in usual turbulence measurements. Compared in Fig. 3(c) are the radial variations of the rates of turbulence drive (ω_D) and turbulence spreading (ω_S) in H and D plasmas denoted by dotted and solid lines, respectively. One can see that the D plasmas have a smaller ω_D than H plasmas inside the LCFS, which might be correlated with the low particle loss due to zonal flows [27]. It is discovered that the rate of turbulence spreading ω_S in D plasmas significantly increases in the region of $-0.5 \text{ cm} \leq \Delta r \leq 1.5 \text{ cm}$ in comparison to H plasmas, which is the signature of the enhancement of turbulence spreading. Meanwhile, the LCFS $E \times B$ shear rate has a corresponding reduction as shown in Figs. 3(a) and 3(b), which is favorable to the turbulence penetrating across LCFS into SOL. Similar experimental observation was also reported in TJ-II [28]. This comparison clearly demonstrates that locally driven turbulence is dominant in H-plasma and a significant contribution of spreading turbulence in D plasma. It is therefore concluded that the LCFS $E \times B$ shear blocks the spreading of turbulence rather than suppressing locally driven turbulence.

Additional experimental evidence for the existence of enhanced turbulence spreading into SOL is shown in Fig. 3(d). We performed the transfer entropy analysis on the basis of the Langmuir probe data [29]. This technique is widely used to study the directional flow of information between two signals $x(t)$, $y(t)$, which is defined as

$$T_{yx} = \sum P(x_{n+1}, x_{n-k}, y_{n-k}) \log_2 \frac{P(x_{n+1} | x_{n-k}, y_{n-k})}{P(x_{n+1} | x_{n-k})}, \quad (4)$$

where P is the probability distribution function (PDF) and $P(a|b) = P(a, b)/P(b)$ denotes the conditional PDF. The transfer entropy is estimated with the two floating potentials radially separated by 3 mm (4# and 7# tips) as sketched in Fig. 1(b). The analysis was carried out with a slipping time-averaged window of 2.5 ms and the bin number of $m = 3$, assuming plasma state is stable during the Langmuir probe measurement. The transfer entropy calculation shows that $T_{4 \rightarrow 7}$ (outward) largely dominates $T_{7 \rightarrow 4}$ (inward) at the edge region in H and D plasmas, suggesting that the presence of predominant radial outward propagation over inward one. For the sake of comparison, we calculate the logarithm of the ratio of transfer entropy $T_{4 \rightarrow 7}$ in D plasmas to that in H plasmas, i.e., $S' = \log_{10}(T_{4 \rightarrow 7}^D / T_{4 \rightarrow 7}^H)$ and present it in Fig. 3(d). The $S' > 0$ means increase of transfer entropy in D plasmas compared to that in H plasmas. Here, an interesting observation is that the enhanced transfer entropy mainly occurs at near-SOL ($0 \text{ cm} < \Delta r < 1.5 \text{ cm}$), which is also consistent with the result obtained by cross-correlation calculation from two floating potentials radially separated by 3 mm. These results indicate that turbulence spreading across LCFS might be the main cause for the increased SOL turbulence in D plasmas.

Figures 4(a) and 4(b) compare the radial profiles of maximum cross-correlation [$\max(\gamma_{\tilde{n}_e \tilde{v}_f}^C)$] and the phase shift ($\theta_{\tilde{n}_e \tilde{v}_f}$) between density ($\tilde{n}_e$) and floating potential ($\tilde{v}_f$) fluctuations in H and D plasmas, which are generally estimated as follows [30]:

$$\gamma_c(\tau) = \sum \tilde{n}_e(t + \tau) \tilde{v}_f(t) / \sqrt{\sum \tilde{n}_e^2(t + \tau) \sum \tilde{v}_f^2(t)}, \quad (5)$$

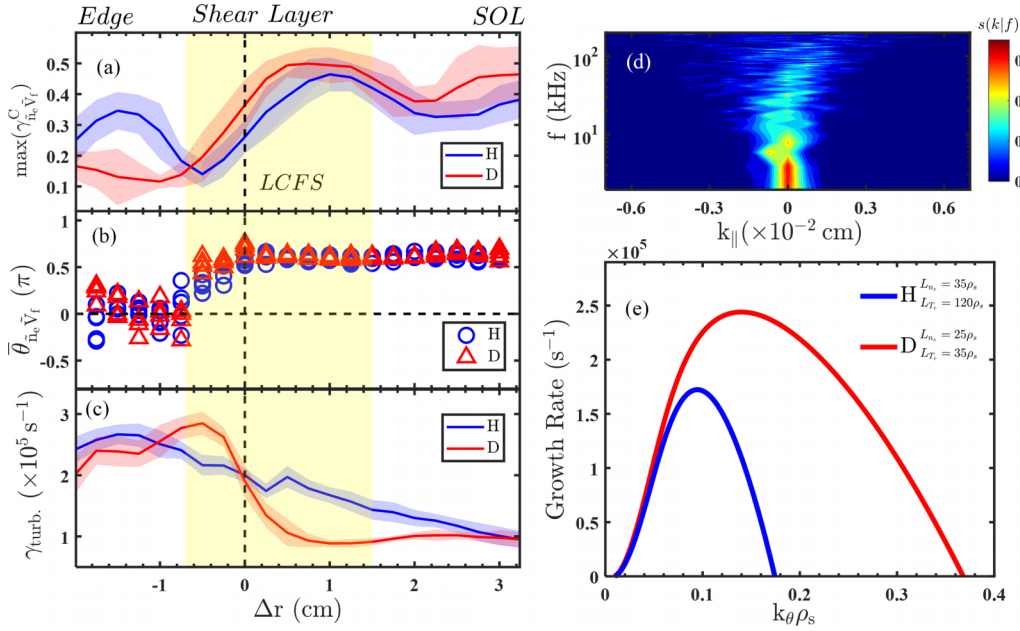


FIG. 4. Radial profiles of maximum cross-correlation [panel (a)], phase shift [panel (b)] between density and floating potential fluctuations, and the estimated turbulent growth rate $\gamma_{\text{turb.}}$ [panel (c)] in H and D plasmas. The frequency-wave number spectrum $s(k_{\parallel}, f)$ estimated with two floating potentials toroidally separated by 210 cm measured inside the LCFS about 0.6 cm ($\Delta r \approx -0.6$ cm) [panel (d)], and comparison of the linear growth rate of interchange mode as a function of $k_{\theta} \rho_s$ in H and D plasmas represented by blue and red lines, respectively [panel (e)].

$$\bar{\theta}_{\tilde{n}_e \tilde{v}_f} = \left[\int_{f_1}^{f_2} |P_{\tilde{n}_e \tilde{v}_f}(f)| |\theta_{\tilde{n}_e \tilde{v}_f}(f)| df \right] / \left[\int_{f_1}^{f_2} |P_{\tilde{n}_e \tilde{v}_f}(f)| df \right], \quad (6)$$

where $P_{\tilde{n}_e \tilde{v}_f}(f)$ and $\theta_{\tilde{n}_e \tilde{v}_f}(f)$ denote the cross power and the phase shift between density ($\tilde{n}_e$) and floating potential ($\tilde{v}_f$) fluctuations, and $[f_1, f_2]$ means the integration frequencies in fluctuations of interest. Here, note that the electron temperature fluctuation is less than 10%, which has a minor influence on the plasma potential; thus, the $\tilde{v}_f$ could be used a proxy of $\tilde{V}_p$. The similar results have been reported in recent work [31]. It is seen that the phase shift ($\bar{\theta}_{\tilde{n}_e \tilde{v}_f}$) distributes around nearly zero with slight scattering points inside the LCFS about 0.8 cm, which is a signature of drift-wave turbulence together with interchange mode [32]. From this position toward the LCFS, the phase shift is transited to around nearly $\pi/2$, implying the predominance of interchange mode. In fact, the competition between drift wave and interchange mode might be determined by the parallel electron dynamics [33], involving the magnetic geometry, collisionality, kinetic effects, etc. Gyrofluid simulation work indicates that the varying collisionality has an impact on the phase shift between density and floating potentials in edge plasmas [34]. To further confirm the presence of interchange mode, we present another experimental evidence as shown in Fig. 4(d), where $S(k_{\parallel}, f)$ is calculated by the two floating potentials toroidally separated by 210 cm based on two-point correlation technique [35]. The main power of parallel wave number spectrum is localized at nearly zero wave number with a finite width of $\sigma_{k_{\parallel}} \approx 1 \times 10^{-3} \text{ cm}^{-1}$ by integrating the frequencies of interest (< 40 kHz), which clearly indicates that this low-frequency fluctuation exhibits a long-range correlation structure. The similar result has been reported in our previous work [36]. Ac-

cording to the above-discussed characteristics, i.e., the nearly $\pi/2$ phase shift between density and floating potential fluctuation and the nearly zero parallel wave number, we therefore conclude that this turbulence is essentially attributed to the theoretically predicated interchange mode [32]. A possible explanation for the phase shift transition inside the LCFS is the existence of an electron temperature threshold, which is closely associated with the local collisionality (control parameter for turbulence [37]). Above this threshold, drift-wave turbulence dominates, whereas below this value, interchange turbulence (resistive ballooning mode) prevails, which has been verified in the similar discharges on HL-2A [38]. This interchange turbulence might have a highly localized mode with high growth rate due to their small yet finite parallel wave number, consistent with theoretical predictions [39]. Given in Fig. 4(c) are the radial profiles of turbulent growth rate ($\gamma_{\text{turb.}}$) in H and D plasmas, which is roughly estimated by balancing turbulent an eddy turnover time [40], i.e., $\gamma_{\text{turb.}} \sim \tau_c^{-1}$, where τ_c denotes the correlation time derived from the e-folding time of autocorrelation function. An interesting finding here is that the experimentally estimated turbulent growth rate ($\gamma_{\text{turb.}}$) in the SOL region decreases by 50% in D plasmas in comparison to H plasmas, suggesting that the increased turbulence as observed in the SOL region is not due to the locally driven, but the turbulence spreading from another position. What is the nature of the turbulence observed at plasma edge? For this purpose, we carry out a linear stability analysis based on the electron continuity, the vortices, and electron energy evolution equations [41]. The linearized equations are shown as follows:

$$(-i\omega + a_1)\tilde{n}_e + b_1\tilde{\phi} + c_1\tilde{T}_e = 0, \quad (7)$$

$$a_2\tilde{n}_e + (b_2 + ik_y^2\omega)\tilde{\phi} + c_2\tilde{T}_e = 0, \quad (8)$$

$$a_3\tilde{n}_e + b_3\tilde{\phi} + (-i\omega + c_3)\tilde{T}_e = 0, \quad (9)$$

where $a_1 = Dk_y^2 + \sigma - (\Lambda/L_T)ik_y + igk_y$, $a_2 = igk_y$, $a_3 = 2igk_y/3$, $b_1 = (ik_y/L_{n_e}) - \sigma - gik_y$, $b_2 = (-vk_y^2 + i\Lambda k_y/L_T)k_y^2 - \sigma + i\Lambda k_y/L_T^3$, $b_3 = ik_y/L_T - 4\sigma - 2igk_y/3$, $c_1 = \sigma(\Lambda + 1/2) + igk_y$, $c_2 = \Lambda\sigma + igk_y$, and $c_3 = -i\Lambda k_y/L_T + k_e k_y^2 + 7igk_y/3 + 4\sigma(\Lambda + 3/2)$. Here, $\sigma \equiv \rho_s/L_c$ denotes the normalized sheath conductivity (ρ_s and L_c are the ion Larmor radius and the connect length). The curvature is represented by $g = \rho_s/R$. The perpendicular diffusion coefficient D and viscosity coefficient ν are normalized by $T_e/(eB_t)$ and Λ denotes the normalized floating potential, $\phi = \Lambda T_e$. L_{n_e} and L_T are normalized by ρ_s , i.e., $L_{n_e}/\rho_s \rightarrow L_{n_e}$, $L_T/\rho_s \rightarrow L_T$. From Eqs. (3)–(5), the dispersion relation could be expressed as follows:

$$\begin{vmatrix} -i\omega + a_1 & b_1 & c_1 \\ a_2 & b_2 + ik_y^2\omega & c_2 \\ a_3 & b_3 & -i\omega + c_3 \end{vmatrix} = 0. \quad (10)$$

The dispersion relation was solved numerically and the γ_L is obtained from Eq. (6) as a function of the normalized poloidal wave number $k_y\rho_s$ for H and D plasmas. We use input parameters from the HL-2A H/D plasmas, e.g., $L_n \sim 2 \text{ cm}/2 \text{ cm}$, $L_T \sim 6.7 \text{ cm}/2.7 \text{ cm}$, $\rho_s \sim 0.6 \text{ mm}/0.8 \text{ mm}$, $\sigma \sim 2.6 \times 10^{-5}/3.6 \times 10^{-5}$, $g \sim 3.7 \times 10^{-4}/4.8 \times 10^{-4}$, and $D = \nu = k_e = 9 \times 10^{-2}/4 \times 10^{-2}$. Here, note that the great difference for the input parameters used is the electron temperature gradients, which are normalized by the ion Larmor radius, i.e., $L_T = 120\rho_s$ for H plasmas and $L_T = 35\rho_s$ for D plasmas, respectively, measured at the radial position of $\Delta r \approx -0.6 \text{ cm}$. The linear growth rate (γ_L) against the normalized poloidal wave number is plotted in Fig. 4(e). It is found that the maximum linear growth rate (γ_L) of interchange mode is two times larger in D plasmas than H plasmas because of a steeper temperature gradient used here, suggesting that edge electron temperature gradient might be the main source for driving this fluctuation, which contributes to the SOL turbulence in D plasmas via turbulence spreading.

Finally, we examine the influence of the turbulence spreading on the SOL power width (λ_q) and the parallel heat flux ($q_{\parallel}$). The parallel heat transport in the sheath-limited plasmas is routinely estimated as $q_{\parallel} = \gamma J_s T_e = \gamma n_e C_s T_e \sim \gamma n_e T_e^{1.5}$ [24], where $\gamma \approx 7.0$ and 7.3 for H and D plasmas, respectively, and J_s and T_e are the saturated ion current density and local electron temperature. λ_q is obtained from the first derivative of the parallel heat flux, i.e., $\lambda_q^{-1} = L_{n_e}^{-1} + \frac{3}{2}L_{T_e}^{-1}$, where $L_{n_e}^{-1}$ and $L_{T_e}^{-1}$ represent the inverse scale length of density and electron temperature gradient, respectively. Figures 5(a) and 5(b) plot the statistical relations of the SOL width (λ_q) and the parallel heat flux ($q_{\parallel}$) against the turbulence intensity from multiple shot data. The turbulence intensity is roughly calculated with the density fluctuations filtered within 1–40 kHz of interest as shown in Figs. 3(d) and 3(e) and normalized by $\tilde{n}_e^{\text{rms}}/\langle n_e \rangle$. The probe measurement position is approximately localized at $\Delta r \approx 0.8 \text{ cm}$. It is seen that the SOL width increases from 1.5 to 3 cm as the normalized SOL turbulent level increases from 0.25 to 0.5, whereas the parallel heat flux has a corresponding reduction. These results clearly indicate that the increased SOL turbulence is correlated with the broadening of SOL width and the reduction of parallel heat flux during the transition from hydrogen to deuterium dominant

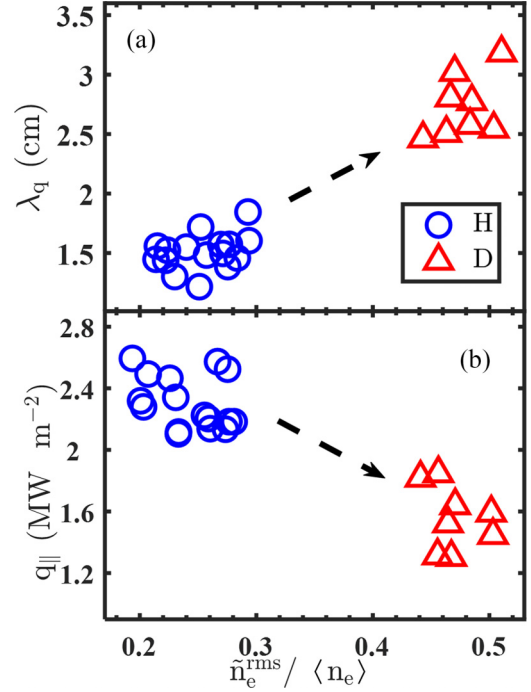


FIG. 5. The statistical relations of SOL width λ_q [panel (a)] and parallel heat flux $q_{\parallel}$ [panel (b)] vs the normalized turbulence intensity ($\tilde{n}_e^{\text{rms}}/\langle n_e \rangle$) measured at near-SOL ($\Delta r \approx 0.8 \text{ cm}$) in H and D plasmas.

plasmas. This is direct experimental evidence demonstrating the significant contribution from turbulence spreading to the broadening of SOL width while maintaining a good plasma confinement performance. This result provides an insight into understanding the enhancement of SOL turbulence in D plasmas with respect to H plasmas.

III. CONCLUSIONS

In summary, we provide experimental evidence demonstrating that turbulence spreading significantly contributes to the broadening of the SOL width during the transition from hydrogen- to deuterium-dominated plasmas in the HL-2A tokamak. The turbulence localized inside the LCFS is identified as interchange turbulence, driven primarily by the steep electron temperature gradients. This turbulence can spread radially outward and penetrate the LCFS into SOL, experiencing weak damping from $E \times B$ flow. It thereby contributes substantially to the enhancement of SOL turbulence, leading to a broader SOL width and a reduction in parallel heat flux. These findings offer a promising strategy for the mitigation of exhaust heat load while maintaining good plasma confinement by optimization of the isotope mass operation in future fusion plasmas.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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