Isotope effect and multi-scale physics in fusion plasmas

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1. Introduction

There is clear experimental evidence that at comparable plasma discharge parameters deuterium (D) discharges have improved confinement properties as compared with hydrogen (H) [1, 2] with a degree of confinement improvement depending on plasma regimes. Interestingly the isotope effect seems to be weaker in stellarators than in tokamaks. Considering that the characteristic step size of collisional transport and turbulent structures increase with plasma gyroradius [3], the isotope effect is a counterintuitive phenomenon. Understanding the physics of the isotope effect in plasma confinement remains as a fundamental open question confronting the fusion community for more than thirty years. Recently, the possible influence of the isotope mass on zonal flows has been proposed [4, 5]. In this work, we have investigated the properties of local turbulence and long-range correlation (LRC) in both H and D dominated plasmas in the TEXTOR tokamak and the TJ-II stellarator.

2. Experimental setup

Experiments were performed in ohmic discharges in the TEXTOR tokamak [R=1.75 cm, a≈0.48 m, B_T=(1.6-2.6) T, I_p=(250-400) kA and line-averaged densities $\bar{n}_{e0}$ =(2.0-2.5)×10^{19} m^{-3}] and in ECRH heated plasmas in the TJ-II stellarator [R=1.5 m, a=0.2 m, B_T=1 T, $\bar{n}_{e0}$ = 0.6×10^{19} m^{-3}]. In both devices, the short-range fluctuations (in the order of 1 cm) and long-range fluctuating scales (in the order of 10 m) were measured by two toroidally (and poloidally in TJ-II) spaced Langmuir probe arrays. To quantify the amplitude of long-range similarity of fluctuations, we have computed the cross-correlation between the potential signals x and y measured on the stationary and fast probe, defined as $C_{xy}(\tau)= <[x(t)-\bar{x}][y(t+\tau)-\bar{y}]> / \sqrt{<[x(t)-\bar{x}]^2><[y(t)-\bar{y}]^2>}$, where <…> denotes ensemble averaging and τ is the time lag.

3. Results and discussion

The measurements of the LRC in isotopic plasmas at the TEXTOR tokamak are illustrated in Fig. 1. To study the isotope effect we have changed the H and D content during the experimental campaign by puffing different gas (H or D) species. It has been found that the energy confinement is enhanced from H to D plasmas [1] and the ratio of energy confinement time, τ_D/τ_H, can reach values of ~1.4 at TEXTOR [6]. In figure 1, the top panel shows the evolution of H content from H to D majority plasmas *versus* the shot number. The middle panels depict the time traces of two toroidally distant probe systems used to detect the LRC. The fast probe moves from the scrape-off-layer (SOL) into the plasma edge, whereas the stationary probe stays at a fixed

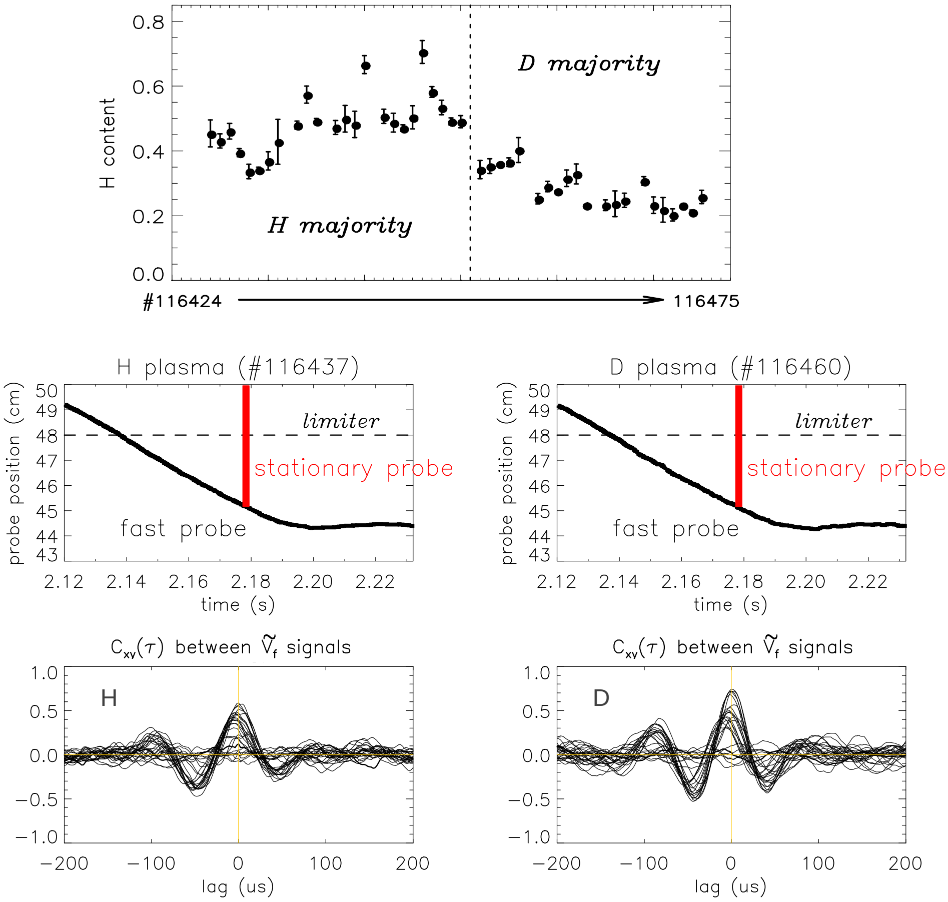

FIG. 1 Top panel: evolution of H content from H to D majority plasmas *versus* shot number at TEXTOR. Middle panels: time traces of two toroidally distant probe systems (toroidal angle ≈180°) to detect the LRC in plasma fluctuations. Bottom panels: cross-correlation function of potential fluctuations between fast and stationary probes as a function of time lag in H (left side) and D (right side) dominated plasmas, respectively.

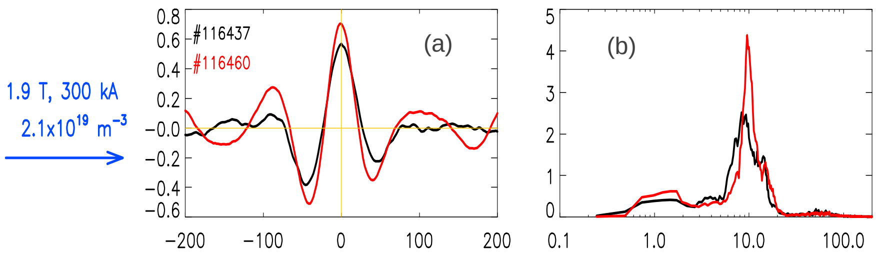

FIG. 2 Comparison of (a) maximum LRC and (b) frequency spectra of floating potentials between H (black curves) and D (red curves) dominated plasmas under the same discharge conditions at the maximum LRC location of r ≈ 45.2 cm.

radial location. The results of the LRC are plotted in bottom panels. For a comparison of the isotope effect on the LRC magnitude, the $C_{xy}(\tau)$ are shown for H (left side) and D (right side) dominated plasmas under the same discharge parameters (B_T=1.9 T,

I_p=300 kA and $\bar{n}_{e0}$ = 2.1×10^{19} m^{-3}). One can see that (i) the maximal value of the LRC appears (at τ=0) when the two distant probes are located at the same radial position; (ii) the amplitude of the maximum LRC is higher in D majority than H majority plasmas under the same discharge condition. Figure 2 further plots the $C_{xy}(\tau)$ and frequency spectra of potential fluctuations at the maximal LRC location (r≈45.2 cm) for those two shots. The results show that the LRC is dominated by low frequency fluctuations around 10 kHz. It has been found that the observed long-range correlation is attributed to large-scale GAM zonal flows oscillating at f ≈10kHz with axisymmetric n=0 mode structures in potential fluctuations [7]. Figure 3(a) plots the amplitude of the maximum LRC as a function of H concentration for the whole shot series (scanned by four different B_T) displayed in Fig. 1. It shows clearly a systematic tendency with the LRC amplitude decreasing with increasing H content, regardless of plasma parameters. Similar increase in the LRC amplitude of GAM zonal flows has

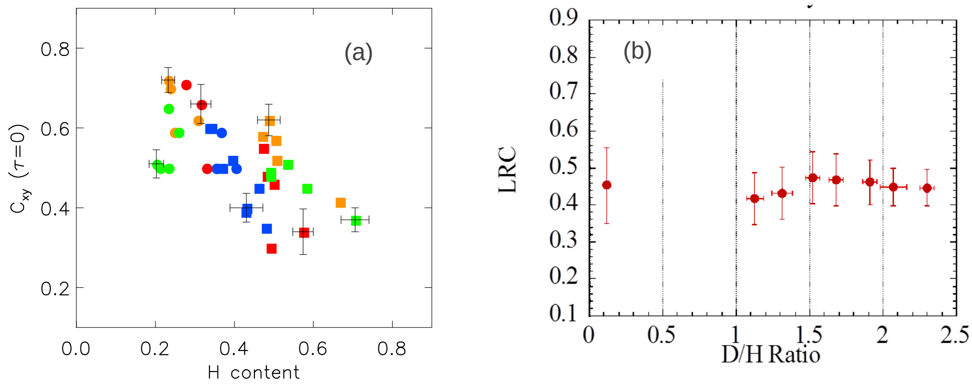

FIG. 3 Comparison of the LRC between tokamak and stellarator. (a) Amplitude of the LRC in floating potential signals as a function of H concentration at the TEXTOR tokamak under four different B_T discharges (blue – 2.25 T, red – 1.9 T, yellow – 1.6 T, green – 2.6 T); (b) Amplitude of the LRC as a function of D/H ratio in the TJ-II stellarator.

also been observed by the correlation reflectometer and Li-beam emission spectroscopy in density and velocity fluctuations from H to D majority plasmas [8].

Similar measurements of the LRC have also been carried out in the TJ-II stellarator in different D/H ratio plasmas [9]. The results are shown in Fig. 3(b). In different from those in the TEXTOR tokamak, the LRC values keep nearly constant in the TJ-II stellarator with the increase of D/H ratio from 0.15 to 2.3. Considering that the isotopic effect on the confinement time is weaker in stellarators than in tokamaks [2], these results suggest that the enhanced LRC (or zonal-flow-like structures) by the isotope mass in tokamaks plays a crucial role in improving plasma confinement. The results therefore point to the importance of the multi-scale physics, i. e., how large-scale structures can be affected by small-scale events.

In order to investigate the small-scale properties of plasma fluctuations at TEXTOR, we have computed the poloidal wave-number spectra $S(k_\theta)$ using the standard two-point correlation technique [10]. The two floating potential signals were measured by two poloidally separated pins (≈ 5 mm) of the fast probe. The results indicate that under the same discharge conditions, the width of the poloidal spectrum is generally reduced from H to D majority plasmas [11]. Plotted in Fig. 4 is the evolution of the averaged poloidal correlation length ($L_{c\theta,}$ estimated as the inverse of the k_θ spectrum broadening) versus H content in the whole plasma shots shown in Fig. 1. One can see that the $L_{c\theta}$ decreases with increasing H content, i. e., the poloidal correlation length increases during the smooth transition from H to D dominant plasmas, in agreement with previous experimental findings [3].

The impact of the isotope effect on zonal-flow-like structures might be explained as follows: The development of zonal flows by reversed energy cascades via E×B symmetry breaking mechanisms [12, 13] is expected to be *k* dependent (in the order 5-10 cm^{-1}) and the maximum energy transfer should be strongly sensitive to the size of turbulent structures. Thus minor increasing of the turbulence size from light to heavy ion isotope may result in an increasing in the amplitude of zonal flows with beneficial effects on transport. In the framework of this interpretation, differences in the level of isotope effect in tokamaks and stellarators could be understood as a consequence of the stronger damping of zonal flows in non-optimized stellarators than in tokamaks.

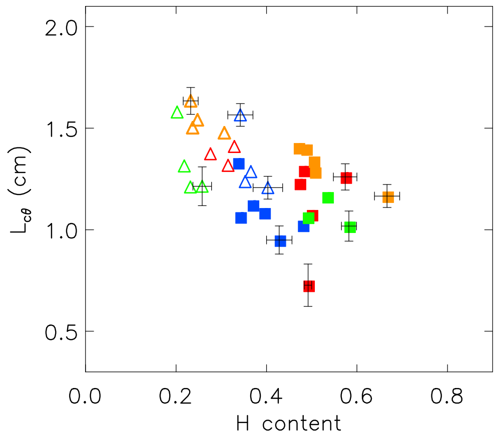

FIG. 4 Evolution of $L_{c\theta}$ versus H concent. The four different colors denote the four different B_T discharges shown in Fig. 3(a). The squares and triangles represent the H and D dominated plasmas, respectively.

4. Conclusion

We have investigated the properties of local turbulence and large-scale flows in the TEXTOR tokamak and the large-scale flows in the TJ-II stellarator in the isotope H and D dominated plasmas. Results show a systematic increasing of zonal flows during the transition from H to D plasmas at TEXTOR, but not in TJ-II. These results suggest the role of the ion mass on the amplitude of zonal flows with beneficial effects on transport at tokamaks.

Reference:

[1] M. Bessenrodt-Weberpals et al., Nucl. Fusion 33, 1205 (1993).
[2] U. Stroth et al., Plasma Phys. Control. Fusion 40, 9 (1998).
[3] M. Ramisch et al., Phys. Plasmas 12, 032504 (2005).
[4] T. H. Watanabe et al., Nucl. Fusion 51, 123003 (2011).
[5] T. S. Hahm et al., Nucl. Fusion 53, 072002 (2013).
[6] U. Samm et al., Proc. 16th EPS Conf. on Plasma Physics (Venice, 1989) Vol. 13B, Part~III, p.995.
[7] Y. Xu et al., Plasma Phys. Control. Fusion 53, 095015 (2011).
[8] A. Krämer-Flecken and S. Zoletnik, private communication.
[9] M. A. Pedrosa et al., P2.180, this conference.
[10] S. J. Levinson et al., Nucl. Fusion 24, 527 (1984).
[11] Y. Xu et al., Phys. Rev. Lett. 110, 265005 (2013).
[12] A. Alonso et al., Plasma Phys. Control. Fusion 48, B465 (2006).
[13] Y. Xu et al., Nucl. Fusion 53, 072001 (2013).