Interaction between magnetic island, plasma perpendicular flow and turbulence in HL-2A ohmic plasmas

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1. Introduction

The tearing instability associated with magnetic reconnection process was commonly found in astrophysical and laboratory plasmas, e.g., solar flares, coronal mass injection, Earth's magnetosphere and magnetically confined fusion plasmas [1]. The formation of magnetic island associated with tearing mode can change the local plasma profiles and transport [2-4], and if large enough, lead to disruption [5]. However, the observations of internal transport barriers at or near rational surfaces in tokamak plasmas suggest the important role of the magnetic island in the local plasma confinement, via the formation of sheared flows [6-7]. The multi-scale physics such as the interaction between macro-scale MHD modes and micro-scale turbulence was found to play an essential role in the regulation of transport in the core plasma region [8-10], and the interaction between sheared flow and turbulence was considered to be key ingredient in the low-to-high confinement mode transition [11,12]. Therefore, improved understanding of tearing mode physics and the interaction with plasma flow and turbulence is important as it can lead to the improvement of plasma performance and therefore has potential implications for future fusion devices such as the International Thermonuclear Experimental Reactor (ITER).

2. Experimental setup

The experiments were conducted in the HL-2A tokamak with a major/minor radius (R_0/a) of 165/40 cm [13]. The main plasma discharge parameters are: plasma current I_p= 120 kA, magnetic field B_t = 1.3 T, line-averaged electron density $\bar{n}_e = 1.1 \times 10^{19}$ m^{-3}, electron temperature T$_{e0} \approx$ 1 keV. Main diagnostics used in this work: T_e profile was measured by a 60-channel electron cyclotron emission (ECE) radiometer [14]; two-dimensional mode

structure of the magnetic island was identified by two 24×8 electron cyclotron emission imaging (ECEI) arrays [15]; a novel U-band microwave Doppler backscattering (DBS) reflectometer system, with working frequency hopping between 44 GHz and 60 GHz (uniformly spaced by 15 steps, with each step staying 5 ms), operated in the X-mode polarization was used to characterize the perpendicular flow velocity ($V_\perp$) and density fluctuations ($\tilde{n}_e$) simultaneously [16].

3. Experimental results and discussions

3.1 Profile of perpendicular flow and density fluctuations across 2/1 island

The experimental results shown here are from HL-2A 30124 shot, which is an ohmic discharge. An m/n=2/1 tearing mode was identified by ECE and ECEI diagnostics. It rotated in the electron diamagnetic drift direction with a frequency about 2 kHz. The T_e profile was flattened near O-point and steepened at X-point, as shown in figure 1. The island width is about 7 cm, roughly estimated from the relatively flattened area of the T_e profile.

Considering that the rotation frequency and width of the magnetic island was constant during the time period concerned (1250-1350 ms), the radial profiles of $V_\perp$ and $\tilde{n}_e$ across the O-/X-point were obtained through phase-lock averaged method, as shown in Fig. 2. The island region was shaded in the figure and the vertical dashed line indicated the island center. It was observed that across the O-point cut (blue curve), the magnitude of flow and flow shear are about zero near the island center, and strongly enhanced
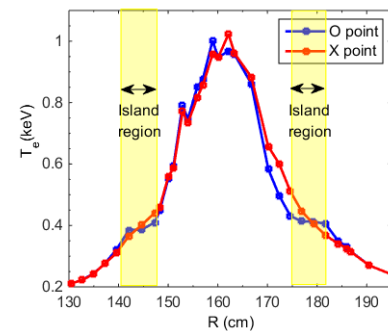

Figure 1. Typical T_e profiles across O-point and X-point of 2/1 magnetic island.

around the outer boundary (R $\approx$ 182.5 cm), resulting in a large increase of the flow shear in the outer half island. This feature is similar to that measured at LHD [17]. However, across the X-point cut, $V_\perp$ is almost flat in the whole island region (R < 182.5 cm), while both flow and flow shear increase in the outer region of R > 184.4 cm. There is almost no difference of $V_\perp$ between across the O- and X-point cut when R > 184.4 cm, suggesting that the island will not modify the profile of flow and flow shear in this area. The ratio of density fluctuations between across O-point and across X-point was used to characterize the response of turbulence level to the island structure, because the DBS system was not

absolutely calibrated with different working frequencies. The figure 2(b) shows $\tilde{n}_e$ dropped inside the island and elevated at the boundary, in agreement with the gradient-driven turbulence.
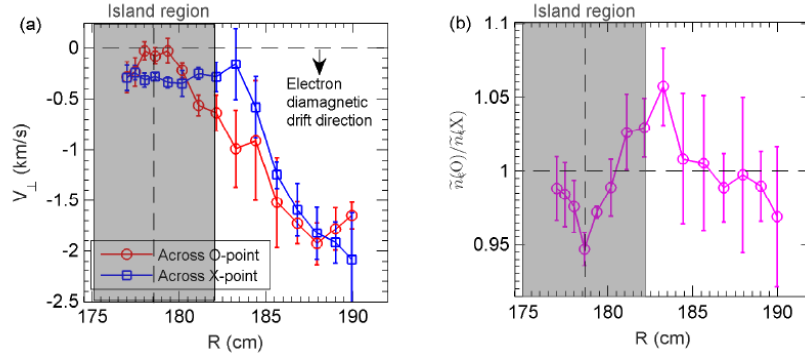

Figure 2. Radial profiles of the perpendicular flow velocity (a) and density fluctuations (b).

3.2 Modulation of electron temperature, perpendicular flow and density fluctuations by 2/1 island

Figure 3 shows the time evolution of local parameters (R_c=182 cm) with the island rotation. The $C(t_1)$ corresponds to the outer boundary of the island across the O-point, and $C(t_3)$ is near the X-point. It was found that all the local parameters such as T_e, $V_\perp$, $\tilde{V}_\perp$ and $\tilde{n}_e$ are modulated by the rotation frequency of the island. The perpendicular flows, flow fluctuations (up to 400 kHz), and turbulence levels (up to 400 kHz) were maximum at the boundary of the island ($C(t_1)$), while minimum at $C(t_3)$, probably due to the fact that gradients are elevated at the separatrices of the island compared with that of without island case.
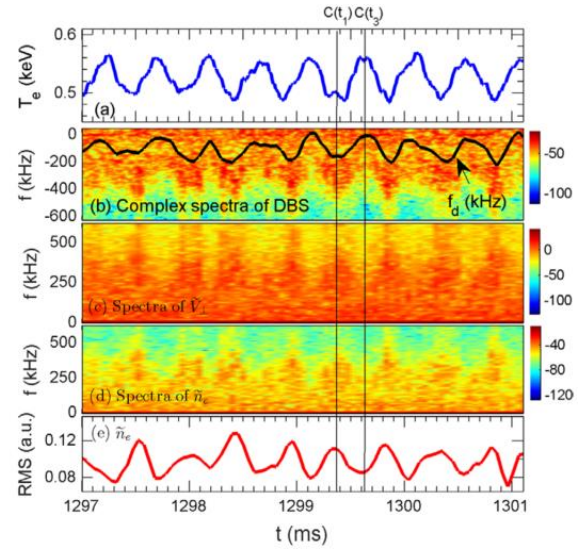

Figure 3. (a) Evolution of T_e at $R = 170$ cm, $Z = 8.06$ cm, located just inside the $q = 2$ surface; (b) complex spectra of DBS and the Doppler shift (black curve); (c) Spectrogram of $\tilde{V}_\perp$; ((d)–(e)) Spectrogram and RMS of $\tilde{n}_e$

To further investigate that whether the sheared flow induced by island would regulate the turbulent fluctuations as reported by the nonlinear gyrokinetic simulation [18], as a simplified first step we compared the inverse of shear rate ($\tau_s = \omega_s^{-1}$) with the auto-correlation time of the turbulence (τ_c). It was found that $\tau_c \ll \tau_s$, which suggests that the

sheared flow will not directly regulate the density fluctuations. To further validate this conclusion, we need to do bispectral analysis.

3.3 Cross-correlation between $V_\perp(R, t)$ and $T_e\left(R_{ref}, t\right)$

To identify in which area the perpendicular flow was modulated by the rotation of the island, the cross-correlation function between $V_\perp(R, t)$ and $T_e\left(R_{ref}, t\right)$, where the reference T_e was located at R = 170 cm, Z = −8.06 cm. The results show that strong correlation was observed inside and in the vicinity of the island, which implies that the $V_\perp$ was strongly modulated by the island rotation in those areas.

4. Summary

In this work, the multi-scale interaction between tearing mode, plasma perpendicular flows and density fluctuations has been investigated in the HL-2A ohmic plasmas. It was found that the perpendicular flow profile was quite flat and about zero near the center of the island, while both flow and flow shear enhanced dramatically towards the island boundary. Density fluctuations decreased at the O-point of the island while increased at the island boundary compared with the X-point of the island. The electron temperature, perpendicular flow (proportional to the radial electric field), flow fluctuations and density fluctuations were modulated by the rotation of the magnetic island. The cross-correlation analysis further indicates that these modulations occurred mainly inside and in the vicinity of the island.

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