Investigation of Mechanisms for the Generation of Blobs/holes at the Boundary of the HL-2A Tokamak


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Abstract. Experimental investigation of mechanisms for the generation of blobs/holes has been performed in the edge and scrape-off layer (SOL) of the HL-2A tokamak. Whereas the blobs present across the entire plasma boundary, the holes emerge only locally outside the last closed flux surface (LCFS). The results show three distinctive regions with multiple driving mechanisms responsible for the development of the blob and hole dynamics: (i) inside the LCFS, the local density gradient is high and the blobs are driven by drift-wave turbulence; (ii) outside but nearby the LCFS, blobs and holes coexist. The features are close to interchange drive instabilities; (iii) in the far SOL where the local density gradient is very low, the turbulence spreading appears to play a key role in dominating the blob dynamics. It has been found that in the region with holes, the turbulence transfers energy into the macro-scale flow via Reynolds stress, resulting in reduction of local turbulence power and build-up of poloidal $E \times B$ flows. As a consequence, the inward motion of holes fades in the vicinity of the LCFS.

1. Introduction

“Blob-filaments”, or simply “blobs”, denote radial convection of coherent plasma structures, which transport plasma mass and energy across the open magnetic field line region known as the scrape-off-layer (SOL) and enhance the plasma interaction with the boundary materials, and consequently, lead to serious wall erosion or recycling problems for future fusion reactors [1]. The mechanisms for the blob origination have been investigated for many years. Experiments and theories/simulations have showed that the formation of blobs can be linked to a variety of driving regimes, such as the drift-wave regime, interchange instability, conducting wall instability and the turbulence spreading, etc. The drift-wave paradigm indicates that the blobs are due to drift-Alfven-wave turbulence, which is usually developed in the confined plasma region with a non-zero parallel structure length ($k_{\parallel} \neq 0$). Observed signatures are that density and potential fluctuations are nearly in phase [2, 3]. The interchange instability suggests that density blobs arise from the nonlinear saturation of linear instabilities at the plasma edge. For example, curvature-driven interchange drift waves and ballooning modes all tend to arise
near the maximum of the linear growth rate. The small initial positive and negative density perturbations of the interchange mode both grow and eventually disconnect as part of the turbulent saturation process, forming approximately equal numbers of blobs and holes, respectively [4, 5]. The conducting wall instability is driven by electron temperature gradient. Fluctuations of the parallel current are induced by electron temperature fluctuations via the Bohm criterion. Then, the fluctuations in the parallel current couple electron temperature and plasma potential fluctuations [6]. The turbulence spreading has always been investigated in the low density gradient region. It constitutes an energy exchange between the confined plasmas with the plasma in the SOL, and a substantial energy drive for fluctuations in the far SOL [7, 8].

In this work, we have made an experimental survey on the spatial distribution of blobs (and holes) as well as their driving mechanisms in the edge and SOL of the HL-2A tokamak. The results reveal that, depending on spatial locations at the plasma boundary, multiple mechanisms are responsible for the development of the blob and hole dynamics. Besides, a nonlinear energy transfer from local turbulence to macro-scale flows is observed in the hole-dominant area, leading to suppression of holes as well as their inward convective motion.

2. Experimental set-up

The experiments were carried out in ohmically heated deuterium plasmas in the HL-2A tokamak [9]. Typical discharge parameters are \( R = 1.65 \) m, \( a = 0.38-0.40 \) m, \( B_t = 1.2-1.4 \) T, \( I_p = 150-170 \) kA and the line-averaged density \( \bar{n}_e = (0.8-1.4) \times 10^{19} \) m\(^{-3}\). In this study, edge equilibrium density (\( n_e \)), electron temperature (\( T_e \)), floating potential (\( V_f \)) and their fluctuations are measured by a reciprocating Langmuir probe array installed at the midplane of the low field side. The radial scanned distance is 8.0 cm, covering both the plasma edge and the SOL [10]. The probe data were digitized at a rate of 1 MHz. Two pins of the array are DC-biased to record the ion saturation current (\( I_s \)). The radial electric field \( E_r \) is inferred from the radial derivative of the plasma potential \( V_p = V_f + \alpha T_e \), where \( \alpha = 2.8 \) for deuterium plasmas.

3. Experimental results and discussion

3.1 Identification of blobs/holes in the edge plasmas

In the near SOL (\( r/a \geq 1 \)) of the HL-2A tokamak, a lot of positive and negative bursts are observed in the ion saturation current (\( I_s \)) signals, as shown in Figs. 1(a) and (e), respectively. Since the \( I_s \) fluctuations are roughly equal to density fluctuations, these large
positive and negative spikes essentially reflect bursts in the plasma density. They are called blobs and holes, respectively. The bursty behavior implies a departure from a random diffusive process in fluctuations. This has been verified in Figs. 1(b) and (f), where the probability distribution functions (PDFs) both deviate from the Gaussian distribution and the PDF shows a positively and negatively skewed tail, respectively. In order to discriminate the coherent structures of blobs/holes from ambient turbulence, we have made an auto-conditional averaging of the intermittent bursts in $I_s$ and a cross-conditional averaging on the $E_\theta$ data by selecting burst amplitudes larger than $\pm 2.5$ times of the standard deviation in the $I_s$ signal. Here the $E_\theta$ is measured by the potential difference on two poloidally spaced probes. The technical details on the conditional averaging have been described in refs. [11, 12]. The results clearly show existence of the blobs and holes with a life time of about $(30-40) \mu s$, as illustrated by a large positive spike in Fig. 1(c) and a negative one in Fig. 1(g), respectively. The corresponding $E_\theta$ is positive for the blob and negative for the hole, suggesting a radially outward convection for the blob and an inward transport for the hole as the radial speed $V_r$ is dominated by

![Fig. 1 Identification of blobs (positive bursts) and holes (negative bursts) in density fluctuations at the plasma edge of HL-2A. (a, e) time history of ion saturation currents $I_s$; (b, f) PDF of $I_s$ signals normalized by the standard deviation; (c, g) auto-conditional averaged $I_s$ signal; (d, h) cross-conditional averaged $E_\theta$ signal for blob (left column) and hole (right column) coherent structures.](image)
3.2 Multiple mechanisms for the development of blobs and holes at different locations

In this study, we have surveyed the characteristics of blobs and holes in a wide range of the plasma boundary, including the plasma edge \((r/a \leq 1)\) and the SOL \((r/a > 1)\). Figure 2(a) plots the raw data of \(I_s\) measured in the edge and SOL. In the figure, the \(\Delta r\) \((=r_{\text{probe}} - r_{\text{LCFS}})\) denotes the radial distance between the Langmuir probe and the LCFS (marked by the vertical blue solid line). Figure 2(b) shows the corresponding skewness of \(\bar{I}_s\), which reflects the degree of asymmetry of the probability distribution of a signal with respect to its mean value [12]. Thus, the positive (negative) skewness implies blobs (holes) in \(I_s\) fluctuations. Figure 2(c) further illustrates the spatial distribution of blob and hole numbers, selected by burst amplitudes exceeding a factor of \(\pm 2.5\) of the standard deviation in the \(I_s\) signal. Figure 2(d) plots the radial profile of electron density (black curve) and its scale length \(L_n^{-1} = |\nabla n_e|/n_e|\) (red curve). The phase shift between density
and potential fluctuations has been calculated and drawn in Fig. 2(e). It appears that the spatial location of the blobs/holes can be characterized in three distinctive regions. (i) Inside the LCFS ($\Delta r < 0$), the skewness is positive, suggesting blobs are dominant in this region. The local density gradient is high and the phase shift between $I_s$ and $V_f$ is about zero. Thus, it points to the drift-wave driving mechanism, similar to that observed in the TJ-K stellarator [2, 3]. (ii) In the far SOL ($\Delta r > 35$ mm), the local density (and temperature) gradient is very low, however, the value of skewness is even higher ($S > 1$). This region is related to turbulence spreading and will be discussed in section 3.4 in this paper. (iii) Between the above two regions, the blobs and holes coexist and exhibit obvious interchange-type feature. At $\Delta r = 11$ mm (vertical blue dashed line), the density scale length $L_n^{-1}$, which is equivalent to the linear growth rate of curvature-driven interchange and ballooning modes, reaches its maximum value. Meanwhile, the phase shift between $I_s$ and $V_f$ is closes to $-\pi/2$. The local skewness at $\Delta r = 11$ mm is nearly 0, consistent also with the interchange drive [4, 5], i.e., the initial small positive and negative density perturbations of the interchange mode both grow and eventually disconnect as part of the turbulent saturation process, forming approximately equal numbers of blobs and holes. Therefore, the position of $S = 0$ can be regarded as the origin zone of the blobs and holes. At one side of the formation zone ($0 < \Delta r < 10$ mm) the holes prevail ($S < 0$), whereas at the other side (15 mm $< \Delta r < 30$ mm) the blobs become dominant ($S > 0$) and almost no hole exists. After the generation of blobs and holes, the charge polarization induced by curvature (effective gravity) causes these newly-formed coherent objects to move: the enhanced-density blobs move outwards (down the density gradient) while the reduced-density holes move inwards (up the density gradient), in agreement with the $E_\phi \times B$ drift depicted in figures 1 (d) and (h).

3.3 Energy transfer between the holes and the $E_r \times B$ flow in the near SOL ($r/a \geq 1$)

The interplay between the blobs and the plasma flow has been reported in several devices [1, 12, 13]. In this work, we have found new experimental evidence of the energy transfer between the turbulent holes and the mean $E_r \times B$ flow in the near SOL ($r/a \geq 1$). As depicted in Fig. 3(a), the radial profile of the radial electric field ($E_r$) shows a peak value outside the LCFS ($\Delta r = 5$ mm), indicating a strong $E_r \times B$ flow in the near SOL. It is interesting to notice that the maximum of the $E_r \times B$ flow always presents in the hole-dominant region (see Fig. 3(c)), where the skewness is negative. Concurrently, the amplitudes of density and poloidal electric field fluctuations, as well as the fluctuation-induced radial particle flux all decrease considerably in the $S < 0$ region, as shown in Figs. 3 (d, e, f). The dynamic interaction between turbulence and flows can be
written as follows:

\[
\frac{\partial v_{\text{turb}}^2}{\partial t} = \gamma_{\text{eff}} v_{\text{turb}}^2 - \gamma_{\text{decor}} v_{\text{turb}}^2 + \frac{\partial \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\partial r} V_{\text{flow}} \\
\frac{\partial V_{\text{flow}}^2}{\partial t} = -\frac{\partial \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\partial r} V_{\text{flow}} - \mu_{\text{flow}} V_{\text{flow}}^2
\]

Because the Reynolds stress \( \langle \tilde{v}_r \tilde{v}_\theta \rangle \) is associated with the tilting of turbulence eddy structure and hence \( E_r \) shear (\( E'_r \)), the coupling term \( -\frac{\partial \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\partial r} V_{\text{flow}} \) is proportional to \( -E''_r E_r \). In figure 3(b), the \( -E''_r E_r \) shows also an apex at the location of \( \Delta r \approx 5 \) mm, revealing a strong energy transfer from ambient turbulence to the macroscopic flow, leading to a local reduction in fluctuation level and maintenance of the strong \( E_r \times B \) flow.

In order to validate this conclusion, we have made statistic studies for many shots. Figures 4(a) and (b) plots the magnitude of density fluctuations and \( -E''_r E_r \) as a function of skewness in the \( I_s \) signal. The statistic results clearly show that in the hole-dominated zone (skewness < 0) the density fluctuation level is the lowest while the \( -E''_r E_r \) value is the highest. As such, the magnitudes of holes are suppressed in that region along with fading of their inward convection. Figure 3(g) shows that in the hole-dominant region the frequency spectrum is the broadest, implying that the coherent structures of holes are broken up gradually.

![Figure 4](image)

**Fig. 4** (a) Density fluctuation levels and (b) \( -E''_r E_r \) values as a function of skewness in the \( I_s \) signal.

3.4 Effect of turbulence spreading in the far SOL (\( t/a \gg 1 \))

As already shown in Fig. 2(b), in the far SOL (\( \Delta r > 35 \) mm) the blobs remain
existent along with high values of skewness (S>1). However, the local density gradient is very low in comparison with the inner region. This means that in this area it is almost impossible for the drift-wave or interchange instabilities to drive the local blob generation. According to relevant theories [7, 8], the evolution of turbulence free energy can be written as:

\[
\frac{\partial}{\partial t} \left( \frac{1}{2} \langle n^2 \rangle \right) = -\frac{\partial \langle n \rangle}{\partial r} \langle v_r n \rangle - \frac{1}{2} \frac{\partial}{\partial r} \langle v_r n^2 \rangle
\]

where \( \vec{v}_r \) is the fluctuating \( E_\theta \times B \) velocity. The first term at the right side of the equation indicates a local drive by density gradient, which transfers the free energy to the turbulent field. The second term is independent of local gradient and represents the turbulence spreading regime. It is a divergence and preferentially transports the fluctuation energy from unstable to stable regions. The rates of local drive (\( \omega_D \)) and turbulence spreading (\( \omega_s \)) can therefore be written by

\[
\omega_D = -\frac{\partial \langle n \rangle}{\partial r} \langle v_r n \rangle \quad \text{and} \quad \omega_s = -\frac{1}{2} \frac{\partial}{\partial r} \langle v_r n^2 \rangle
\]

respectively. The radial profiles of \( \omega_D \) and \( \omega_s \) are depicted in Fig. 5 along with their fluctuations.
ratio of $\omega_s/\omega_D$. It is noticed that in the far SOL the ratio of $\omega_s/\omega_D$ goes up considerably, as shown in figure 5(d). This result suggests that the turbulence spreading regime plays a key role for the blob dynamics in the far SOL. Similar simulation results have been reported in reference [8].

4. Conclusion

In conclusion, experimental investigation of mechanisms for the generation of blobs/holes has been executed in the edge and SOL of the HL-2A tokamak. The blobs appear in the entire plasma boundary, but the holes exist only in the near SOL. The results show three distinctive regions with various mechanisms governing the blob and hole dynamics: (i) inside the LCFS, the local density gradient is high and the blobs are driven by drift-wave turbulence; (ii) outside but nearby the LCFS, blobs and holes coexist. They are driven by the interchange instability; (iii) in the far SOL where the local density gradient is very low, the turbulence spreading plays a crucial role for blob dynamics. It is found that in the region of holes, the turbulence transfers energy into the macroscopic flow, resulting in reduction of local turbulence level and build-up of poloidal $E\times B$ flows. As a result, the holes and their inward motion are suppressed nearby the LCFS.

Reference: