Propagation Velocity Analysis of a Single Blob in the SOL

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Nonlinear simulation of plasma blob propagation in the tokamak scrape-off layer is reported. Three types of model equations are introduced and the simulation results are compared. It is found that in the parameter regime where the interchange instability appears during the propagation process, the theoretical model of propagation velocity determined by the initial blob size provides a good approximation of the simulation results. In the regime where the Kelvin-Helmholtz instability appears, however, the blob velocity saturates at a lower value.

Keywords: plasma blob, scrape-off layer, interchange instability, Kelvin-Helmholtz instability

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Plasma transport in the tokamak scrape-off layer (SOL) has attracted attention. Recent experimental research indicates non-diffusive convective transport in the edge region, such as a "plasma blob," which is a magnetic-field-aligned plasma filament that propagates in the radial direction [1–3]. It causes radiation damage at the first wall, ejecting impurities into the core plasma. Thus, research on blob transport in the SOL is crucial for the development of a thermonuclear fusion reactor such as ITER. The theoretical model for plasma blob propagation was proposed by S.I. Krasheninnikov [4]. The basic mechanism behind the rapid convection appears to be the following: Any macroscopic clump of particles in a toroidal plasma tends to be polarized as a result of species-dependent drift due to ∇B and curvature. In the core plasma with its closed flux surface, this charge separation is short circuited by free-streaming electrons. In the SOL, however, a finite potential can be supported on the open fields, due to sheath formation and resistivity at the end points. A poloidal electric field thus formed, coupled with the toroidal magnetic field, then leads to a rapid $\boldsymbol{E}\times\boldsymbol{B}$ drift of the blob to the first wall. In the theoretical model, the blob is assumed to be a magnetic-field-aligned flux tube in the SOL, connected to the divertor plates at each end (Fig. 1) [4].

2D Hasegawa-Wakatani-type model equations are introduced, based on the theoretical model in [5]. We derive the equations by averaging along the magnetic field line and taking the sheath boundary conditions at the end of the tube into consideration. Detailed derivation of these equations in which the energy conservation relation is taken into consideration is presented in [6]. These equations are as follows:

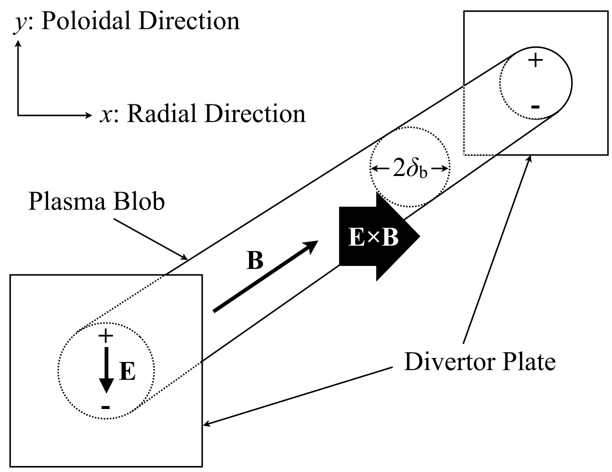

Fig. 1 Blob theoretical model and geometry.

$$\frac{\partial}{\partial t}\nabla_\perp^2\varphi + \left[\varphi, \nabla_\perp^2\varphi\right] = \alpha\varphi - \frac{\beta}{n}\frac{\partial n}{\partial y} + \mu\nabla_\perp^4\varphi, \quad (1)$$

$$\frac{\partial n}{\partial t} + [\varphi, n] = -\alpha n + \beta\left(n\frac{\partial\varphi}{\partial y} - \frac{\partial n}{\partial y}\right) + D\nabla_\perp^2 n, \quad (2)$$

where x is the radial direction and y is the poloidal direction, $[\varphi, f] = \hat{z}\cdot(\nabla_\perp\varphi\times\nabla_\perp f)$ is the Poisson bracket, n is the plasma density, φ is the electrostatic potential, μ is the ion viscosity and D is the diffusion coefficient. The characteristic parameter $\alpha = 2\rho_s/L_\parallel$ is a measure of the net parallel current into the divertor plates, and $\beta = 2\rho_s/R$ is a measure of the strength of the curvature drift. ρ_s is the ion Larmor radius, c_s is the ion acoustic speed and Ω_i is the ion cyclotron frequency. R is the major radius, $L_\parallel = qR$ is the connection length of the magnetic field line in the SOL, and q is the safety factor. The other parameters have their usual meanings. The length and time are normalized to ρ_s and Ω_i^{-1}, respectively. This model con-

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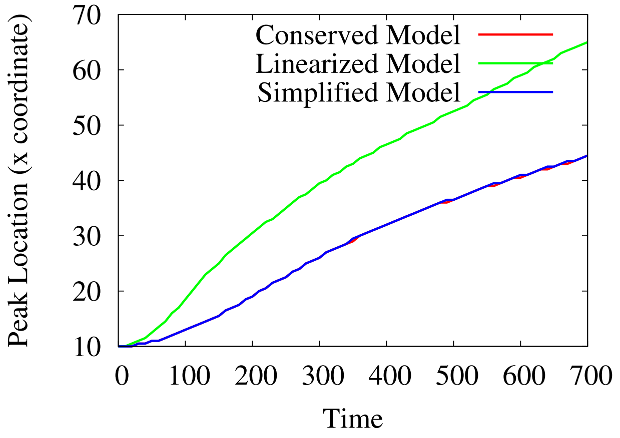

Fig. 2 A time evolution of the peak location of $m = 0$ mode using three models. The length and time are normalized to ρ_s and Ω_i^{-1}.

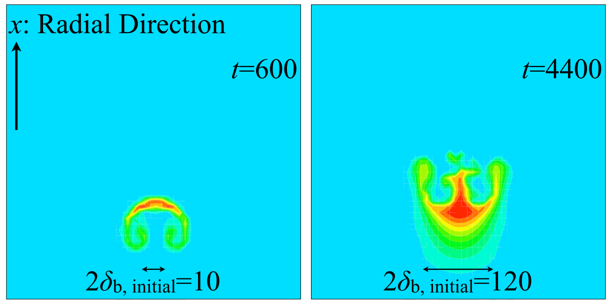

Fig. 3 Density contour snap shot of $\delta_b = 5$ and $\delta_b = 60$ in the conserved model. System size is 128×128 for $\delta_b = 5$ and 512×512 for $\delta_b = 60$. Blobs break and spread with the Kelvin-Helmholtz and interchange instabilities.

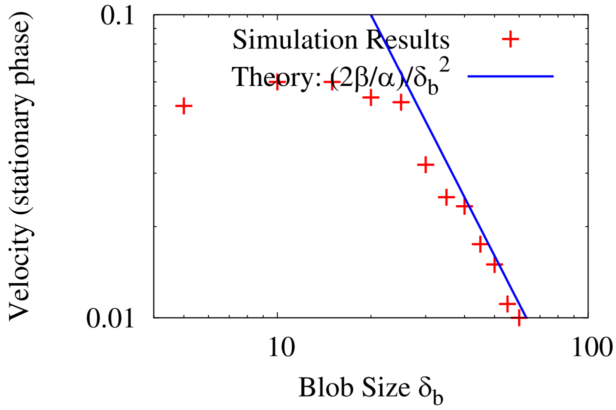

Fig. 4 Blob peak velocity of the $m = 0$ mode vs. initial blob size. A log scale is used on the vertical and horizontal axes. The critical size of the changing instability is $\delta_{crit} = 15$.

serves energy in the limit of $\alpha \to 0$, $\mu \to 0$, and $D \to 0$, i.e., $\langle H \rangle = \text{const.}$ where $H = |\nabla_\perp \varphi|^2/2 + (\log n)^2/2$ is the Hamiltonian, and the bracket implies the surface integral. In this model, the second term on the r.h.s. of Eq. (2) is balanced to the conserved quadratic energy (conserved model). We compare this model with two other models. In one model, the density nonlinear term is linearized by replacing it with $(\beta/n)(\partial n/\partial y) \to \beta\,\partial n/\partial y$ in Eq. (1) and $\beta n\,\partial\varphi/\partial y \to \beta\,\partial\varphi/\partial y$ in Eq. (2) (linearized model), so that the Hamiltonian reduces to $H = |\nabla_\perp\varphi|^2/2 + n^2/2$. Alternatively, the β term on the r.h.s. of Eq. (2) is ignored. This simplified model is the same as that used by Aydemir [7] (simplified model). The simulations are performed with the initial condition where the blob density distribution is assumed to be a 2D Gaussian: $n_b \exp\left[-(X/\delta_b)^2 - (Y/\delta_b)^2\right]$ where $X = x - 2\delta_b$ and $Y = y - L_y/2$. δ_b is the blob size, and L_y is the system size in the y direction. The simulation parameters are set as $\alpha = 3\times10^{-5}$, $\beta = 6\times10^{-4}$, $n_b/n_0 = 10$ and $\mu = D = 2\times10^{-3}$ (like in [7]), where n_0 is the initial background density. For the discretization, finite difference is used in the x direction and the pseudo-spectral method is used in the y direction. Figure 2 shows the motion of the peak positions of the poloidally-averaged $m = 0$ element of density versus time for $\delta_b = 5$. The simplified model agrees well with the conserved model, while the linearized model is quite different from the conserved model. The density nonlinearity in Eq. (1) has a more dominant effect than the one in Eq. (2) on the phase of nonlinear evolution. Hence, we focus on the conserved and simplified models in the following. Figure 3 shows the density contour plots for a small blob $\delta_b = 5$ and a large blob $\delta_b = 60$ in the conserved model. Reference [7] suggests that the Kelvin-Helmholtz instability appears for a small blob (because of the velocity shear accompanied by its rapid convection), but that the interchange instability appears for a large blob. The critical blob size, which categorizes the type of instability, is given in [7] as $\delta_{crit} = \rho_s\left(L^2/2\rho_s R\right)^{1/5}$=15. It should be mentioned that although the simplified model gives a good approximation for the conserved model for the parameters analyzed here, the traveling waveform assumption is violated when deformation of the blob is significant. This will be discussed in a forthcoming article. In the early stage of propagation, the peak velocity of each blob size progressively rises and reaches a stationary phase with the blob breaking and spreading, due to the instability. Figure 4 shows the plot of the initial blob radius and the peak velocity (stationary phase) of the $m = 0$ mode. The solid line represents the results calculated by the theoretical blob velocity $V_x = (2\beta/\alpha)/\delta_b^2$, which is derived assuming a traveling waveform [7]. In the regime where the blob is subject to the Kelvin-Helmholtz instability, the simulation results are quite different from the theoretical prediction. Blobs become spread over a broader area, and the velocity saturates at a value lower than predicted. On the other hand, the spreading is weak in the interchange regime, where the theoretical model gives a good approximation of the simulation results.

In summary, we investigated the motion of single blob by solving a Hasegawa-Wakatani-type model equation and found that, when the blob size is large, the propagation velocity of the blob scales as δ_{b}^{-2}. In contrast, when the initial blob is small, the blob is deformed strongly by the Kelvin-Helmholtz instability, which limits the blob velocity.

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