3D modeling of blobs with the BOUT++ code*

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I. Introduction.

The edge region in a tokamak during L-mode is characterized by strong fluctuations of plasma parameters, in particular, on the outer side of the torus. Occasionally, so-called "blobs" (filamentary structures extended along the magnetic field and having radially and poloidally isolated bumps on plasma density profile) are formed in the vicinity of core-edge boundary and propagate to the SOL (e.g. see Ref. 1 and the references therein). Blobs contribute ~50% of plasma particle transport in some vicinity of the last closed flux surface [2]. However, an increase of relative amplitude of intermittent fluctuations further into SOL [3] suggests that blobs dominate in far SOL plasma transport and plasma-wall interactions.

There is a large body of theoretical papers devoted to the study of dynamics of individual blobs (e.g. see Ref. 4 and the references therein). However, practically all of these studies adopt 2D fluid approach for blob governing equations by invoking different schemes for closure of 3D plasma dynamic equations in the direction parallel to the magnetic field lines. On our best knowledge only in Ref. 5, 6 3D dynamics of individual blobs was considered in 3D with PIC and BOUT codes respectively, but with no detail analysis of the results (although blobs were observed in edge plasma turbulence simulations, e.g. [7]). Meanwhile 3D features can have a very important impact on blobs. For example, the variation of blob's plasma parameters along the magnetic field can result in electrostatic potential variation, which can spin up plasma and, therefore, alter blob propagation dynamics [4]. In addition, inhomogeneity of plasma parameters along and across the magnetic field can result in the development of plasma instabilities (e.g. dissipative drift [8], $\nabla_\perp T_e$ [9], and $\nabla_{||}(\vec{E}\times\vec{B})$ [10-12] instabilities).

Here we consider 3D blob dynamics in the electrostatic approximation and present both analytic estimates and initial results of 3D electrostatic simulation of the blob using the BOUT++ code [13].

II. Equations

We adopt simple slab geometry with magnetic field $\vec{B}=\vec{e}_z B$ in z-direction and effective curvature of the magnetic field lines $\vec{\kappa}=\vec{e}_x / R$ in x-direction. We assume that plasma is localized along the field lines at $0<z<L_{||}$ and limited by material targets at the boundaries. To describe plasma dynamics we use vorticity and continuity equations:

$$\nabla\cdot\frac{d}{dt}\left(\frac{nMc^2}{B^2}\nabla_\perp\varphi\right)=\frac{2cT}{B}\left(\vec{e}_z\times\vec{\kappa}\right)\cdot\nabla n+\nabla_{||}j_{||}, \quad (1)$$

$$\frac{dn}{dt}=0, \quad (2)$$

where n is the plasma density, M is the ion mass, c is the light speed, φ is the electrostatic potential, $d(...)/dt=\partial(...)/\partial t+(c/B)\left(\vec{e}_z\times\nabla\varphi\right)\cdot\nabla(...)$, T=const. is the electron temperature (we assume zero ion temperature),

$$j_{||}=\sigma_{||}\left(\frac{T}{e}\nabla_{||}\ell n(n)-\nabla_{||}\varphi\right), \quad (3)$$

$\sigma_{\parallel}$ is the plasma conductivity, and e is the elementary charge. At the boundaries the parallel current and potential are related by sheath boundary condition

$$j_{sh} = en_t C_s \left\{1 - \exp\left(-e(\varphi_t - \varphi_f)/T\right)\right\}, \tag{4}$$

where $\varphi_f \propto T$ is the floating potential corresponding to a zero sheath current, $C_s = \sqrt{T/M}$, n_t and φ_t are the density and potential at the target.

III. Analytic estimates

Before we discuss the simulation results let us make some analytic estimates. First we notice that potential variation along the magnetic field line caused by parallel current is smaller than potential jump due to effective sheath resistivity for [14]

$$\frac{\lambda_e}{L_{\parallel}} > \sqrt{\frac{m}{M}\frac{n_t}{n_b}}, \tag{5}$$

where m is the electron mass, n_b and λ_e are the plasma density and electron mean in the bulk of the blob. For edge plasma conditions inequality (5) is usually fulfilled (we are not considering very low temperature regimes like MARFE and detached divertor where inequality (5) can be violated). In this case the only important potential variation along $\vec{B}$ can be due to electron pressure/density variation.

As a result, for large $\sigma_{\parallel}$ from Eq. (3) we find

$$\varphi = \varphi_t + \frac{T}{e}\ell n\left(n_b / n_t\right). \tag{6}$$

As one can see from Eq. (6), electrostatic potential depends on the blob density n_b and, therefore, can be inhomogeneous in both parallel and perpendicular directions. As a result, both plasma polarization and corresponding blob dynamics can be altered by $\vec{E}\times\vec{B}$ plasma rotation. Similar effects can be caused by inhomogeneous electron temperature [10]. Following Ref. 15 (see also Ref. 4) and considering torpedo-like shape of blob density extended along $\vec{B}$ with cross-field scale δ_b we find that the $\vec{E}\times\vec{B}$ rotation becomes important for blob's dynamics for

$$\frac{n_b}{n_t} > \frac{\rho_s}{L_{\parallel}}\left(\frac{\delta_b}{\rho_s}\right)^4. \tag{7}$$

However, this estimate is somewhat superficial because the impact of plasma instabilities can be even more important for blob dynamics than plasma rotation.

Considering stability of plasma slab with plasma density inhomogeneity scale-length δ_b in electrostatic local approximation using Eq. (1-3) and boundary condition (4) assuming no plasma density variation along the magnetic field we arrive to the following dispersion equations

$$\omega^2 + \omega_g^2 + i\omega_{sh}\omega = 0 \quad \text{for l=0 and} \quad \omega^2 + \omega_g^2 + i\omega_{\sigma}(\omega - \omega_*) = 0 \quad \text{for } l \geq 1, \tag{8}$$

where l is the integer number, $\omega_{sh} = (2C_s / L_{\parallel})\left(\rho_s k_{\perp}\right)^{-2}$, $\omega_g^2 = 2C_s^2 / R\delta_b$, $\omega_* = C_s \rho_s k_{\perp} / \delta_b$, $\omega_{\sigma} = \nu_{ei}\left(2\pi l \lambda_{ei} / L_{\parallel}\right)^2 \left(\rho_s k_{\perp}\right)^{-2}$, $k_{\perp}$ is the perpendicular wave number, ρ_s is the effective ion gyro-radius, ν_{ei} is the electron-ion collision frequency, λ_{ei} is the electron mean free path, and R is the tokamak major radius.

We are interested in the mode with $l \geq 1$, since the mode with l=0 can be seen in 2D modeling and was considered before. For $l \geq 1$ the maximum growthrate, γ_{max}, depends on the ratio $x_{g*} \equiv \omega_g / \omega_*$. For $x_{g*} < 1$ ($x_{g*} > 1$) $\gamma_{max} \sim \omega_*$ ($\gamma_{max} \sim \omega_g$) is reached for $\omega_\sigma \sim \omega_*$ ($\omega_\sigma \sim \omega_g$) and the mode has dissipative drift (interchange) nature. For plasma parameters used in our 2D and 3D simulations (plasma density 10^{13}cm^{-3}, electron temperature 30 eV, B=30 kG, R=100 cm, $L_{||} = 10^3\text{cm}$) we have $x_{g*} > 1$ so that the unstable mode suppose to have an interchange structure.

IV. 3D modeling results

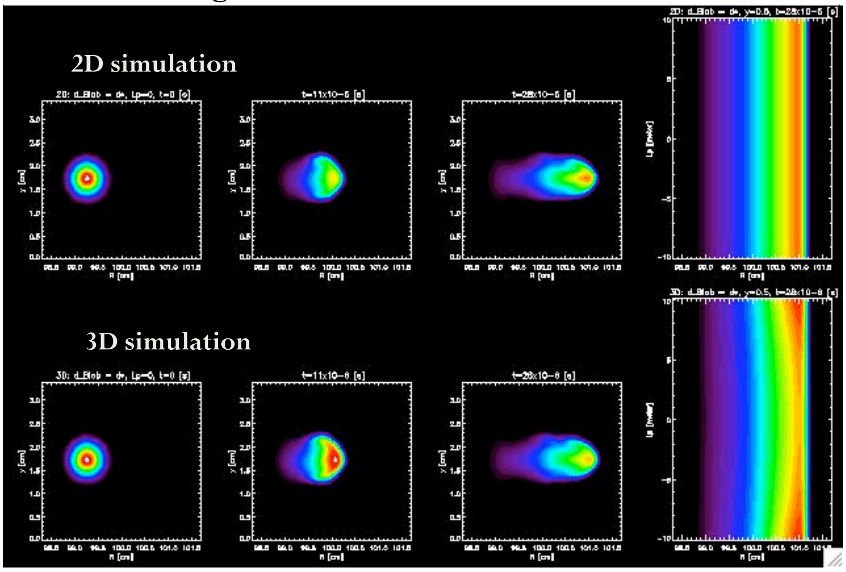

Fig. 1.

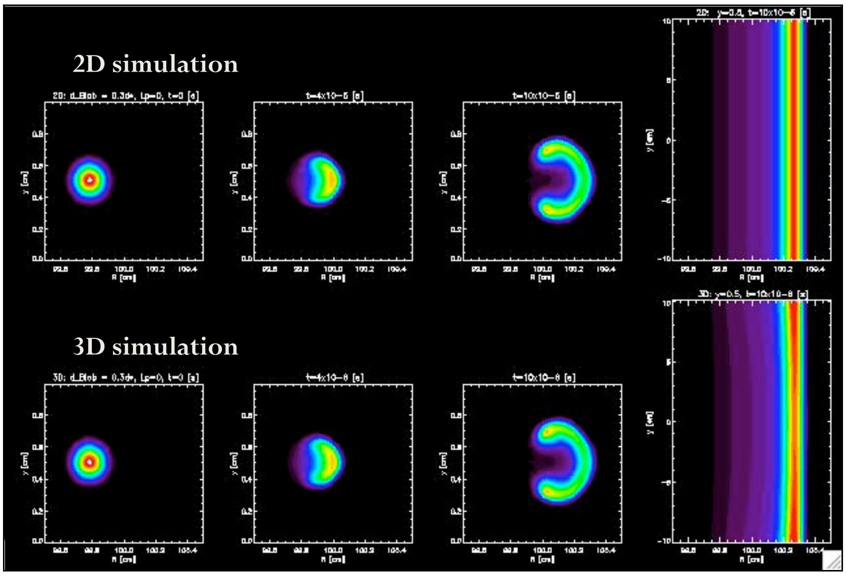

Fig. 2.

Before we proceed with the discussions of our numerical simulations we should remind that according to 2D theoretical estimates and numerical modeling the most structurally stable (in 2D case) blob size corresponds to $\delta_b \sim \delta_* = \rho_s \left(L_{||}^2 / \rho_s R \right)^{1/5}$. Smaller (bigger) blobs are the subjects of KH (RT) instability which causes the mushrooming (fingering) of the shape of the blob.

In order to verify our 3D numerical simulation with 2D numerical results we neglect pressure term in the Ohm's law. By that we eliminate an impact of the drift waves and corresponding 3D instabilities. In Fig. 1 (Fig. 2) we present plasma density contours found in the result of 2D and 3D numerical simulations of blob dynamics with $\delta_b = \delta_*$ ($\delta_b = 0.3 \times \delta_*$) and no pressure term in Ohm's law. As we see we have coherent propagation of the blob in radial direction and for $\delta_b = \delta_*$ and a mushrooming for $\delta_b = 0.3 \times \delta_*$ due to nonlinear effects of the KH instability. In both cases we have a very good agreement between 2D and 3D results.

Next we study the effect of dissipative instability on blob dynamics and proceed with full Ohm's law equation (3). In Fig. 3 we show plasma density contours for blob with

$\delta_b = 0.3 \times \delta_*$ found from 3D numerical simulation. 3D structure of developed plasma instability is clearly seen in the simulation. However, blob still propagates radially with the speed observed in 2D simulations at least for the time where 3D simulation results are available. Unfortunately, further modeling is complicated by numerical problems. We notice that according local stability analysis the most unstable mode corresponds to l=3, meanwhile in 3D simulations we see mode structure with l~10. The reason for such discrepancy is not clear yet.

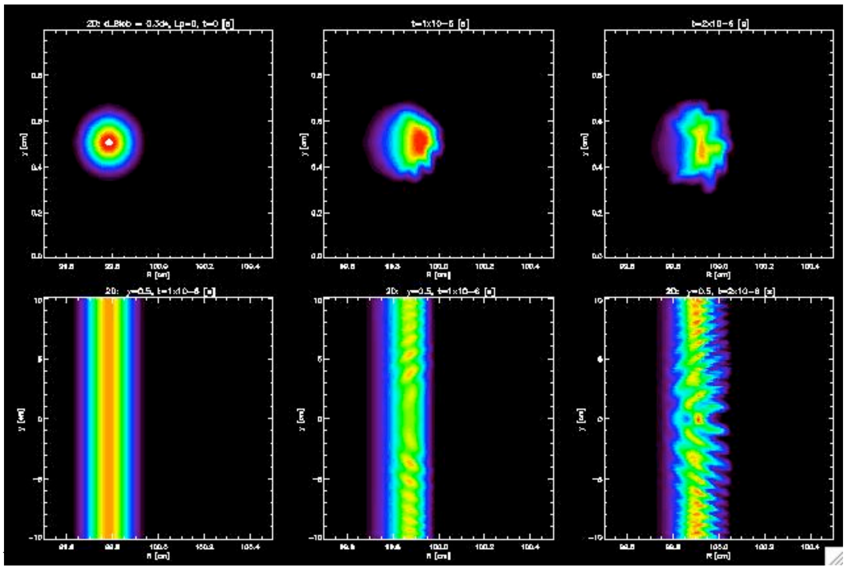

Fig. 3.

V. Conclusions

We repot preliminary results of 3D numerical simulation of blob dynamics with BOUT++ code. The main motivation was studying the impact of plasma instabilities on blob propagation speed and coherency. So far we limited ourselves by considering electrostatic approximation. We found that although instability develops, the blob still propagates radially with the speed corresponding to 2D approximation. However, the work is in progress and these conclusions should be considered as preliminary.

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