Publ. Astron. Obs. Belgrade No. 84 (2008), 447 - 450 *Contributed Paper*

BLOBS IN THE TOKAMAK SCRAPE-OFF LAYER

D. JOVANOVIĆ[1], P. K. SHUKLA[2] and F. PEGORARO[3]

[1]*Institute of Physics, P. O. Box 57, 11001 Belgrade, Serbia*
E–mail: djovanov@phy.bg.ac.yu

[2]*Institut für Theoretische Physik IV, Ruhr–Universität Bochum,*
D-44780 Bochum, Germany
E–mail: ps@tp4.rub.de

[3]*Dipartimento di Fisica Universitá di Pisa, largo Pontecorvo 3, 56127 Pisa, Italy*
E–mail: pegoraro@df.unipi.it

Abstract. A three-dimensional model for the warm-ion turbulence at the tokamak edge plasma and in the scrape-off layer is proposed. It is based on the nonlinear interchange mode, coupled with the nonlinear resistive drift mode, in the presence of the magnetic curvature drive, the density inhomogeneity, the electron dynamics along the open magnetic field lines, and the electron-ion and electron-neutral collisions. Numerical solutions indicate the collapse of the blob in the lateral direction, followed by a clockwise rotation and radial propagation. The symmetry breaking, caused both by the parallel resistivity and the finite ion temperature, introduces a poloidal component in the plasma blob propagation, while the overall stability properties and the speed are not affected qualitatively.

The transport in the scrape-off layer is mostly intermittent, due to the coherent filamentary plasma structures, or "blobs". They are elongated along the magnetic field and small (cm-sized) in the perpendicular direction, propagating radially with a velocity in the thermal range. They are usually an order of magnitude, or more, denser and hotter than the surrounding plasma. Blobs and SOL turbulence are usually studied within the interchange paradigm, see the recent review (Krasheninnikov et al., 2008). We include the effects of parallel electron dynamics and finite ion temperature, using the standard hydrodynamic equations of continuity and momentum, in a purely electrostatic regime. The collision frequency is below the ion gyrofrequency, and the electron and ion dynamics are expressed in the drift aproximation. The equations are further simplified for a weakly inhomogeneous tokamak magnetic field, $\vec{B} = B_0(1 - x/R)[\vec{e}_z + (x/L_s)\vec{e}_y - (z/R)\vec{e}_x]$ where the coordinates x, y, and z correspond to the radial, poloidal and toroidal distances. We consider electrons to be isothermal, and alow for finite ion temperature, $T_i \leq T_e$. Finally, we assume a weak variation along the magnetic field, $\nabla_\| \ll \nabla_\perp$, which allows us to neglect the nonlinear convection along the magnetic field. Neglecting the polarization and finite Larmor radius effects, the electron continuity equation, can be written as

$$\left[\frac{\partial}{\partial t} + \frac{1}{B_0}\left(\vec{e}_z \times \nabla\right)\cdot\nabla\right] n + \frac{\gamma_{e,i}\, n^2}{\Omega_e B_0}\, \frac{T_e+T_i}{e}\, \nabla_\perp^2 \ln n$$
$$-\frac{\gamma_{e,n}^{(sc)}\, n n_n}{\Omega_e B_0}\, \nabla_\perp^2\left(\phi - \frac{T_e}{e}\ln n\right) + \nabla_\|\left(n v_{e_\|}\right) = \gamma_{e,n}^{(ion)}\, n n_n, \qquad (1)$$

where we used $n_e = n_i \equiv n$, and we neglected the gradients of temperature, electron-ion and electron-neutral collision frequencies across the SOL. $\gamma_{\alpha,n}^{(sc)} n_n$ is the effective frequency of the scattering collisions between the particle species α and the neutrals. The particle source term $\gamma_{e,n}^{(ion)} n_e n_n$ comes from the electron impact ionization of the neutrals. $\gamma_{e,i}\, n_e$ is the electron-ion collision frequency.

Subtracting the ion- and electron continuity equations, we obtain the ion vorticity equation which in the Boussinesq approximation (we neglect the terms $\nabla_\perp n_\alpha$ compared to $n_\alpha \nabla_\perp$) takes the form

$$-\tfrac{T_e+T_i}{eB_0}\left(\tfrac{1}{L_s}\tfrac{\partial}{\partial z} - \tfrac{2}{R}\tfrac{\partial}{\partial y}\right) n_i + \nabla_\parallel \left[n \left(v_{i_\parallel} - v_{e_\parallel} \right) \right]$$
$$+ \tfrac{n}{\Omega_i B_0} \nabla_\perp \cdot \left\{ \left[\tfrac{\partial}{\partial t} + \tfrac{1}{B_0} \left(\vec{e}_z \times \nabla \phi \right) \nabla - \eta_i \nabla_\perp^2 + \gamma_{i,n}^{(sc)}\, n_n \right] \nabla_\perp \left(\phi + \tfrac{T_i}{e} \ln n \right) \right\} = 0. \quad (2)$$

For the description of the parallel dynamics, we average the parallel momentum equations along the magnetic field. We seek an elongated, quasi 2-D solution that is tilted by the angle θ relative to the toroidal axis (z axis), and whose projection on the tokamak cross-section (x, y plane) makes the angle ϑ with the radius (x axis), for which we may write $\nabla_\parallel = \partial/\partial z' + \tan\theta\; \vec{p}_\perp(x) \cdot \nabla_\perp$, where $\vec{p}_\perp(x) = \vec{e}_x \cos\vartheta + \vec{e}_y (x/L_s + \sin\vartheta)$. Neglecting the electron inertia, after the multiplication of the parallel electron momentum equation by $\nabla_\parallel$ and integration along the z axis from the wall ($z = 0$) to $z = L_\parallel$, where the average parallel velocity is equal to zero, we have

$$v_{e_\parallel}(0) = \frac{e/m_e}{\gamma_{e,i}\, n + \gamma_{e,n}^{(sc)}\, n_n} \left[\left(\frac{\partial}{\partial z'} + 2\, \tan^2\theta\; \vec{p}_\perp \cdot \nabla_\perp \right) \left(\phi - \frac{T_e}{e} \ln n \right) - \gamma_{e,i}\, n\, v_{i_\parallel} \right]_{L_\parallel}^{0}. \quad (3)$$

The electron velocity at the plasma-wall interface is determined from kinetic considerations. When the magnetic field is perpendicular to the the wall, we have

$$v_{e_\parallel}(z=0) = n\, c_s\, \exp\left\{ (e/T_e) \left[\phi_0 - \phi\,(z=0) \right] \right\}, \quad (4)$$

where c_s is the acoustic velocity, $c_s = [(T_e + T_i)/m_i]^{\frac{1}{2}}$ and ϕ_0 is the unperturbed plasma potential $\phi_0 = \phi^{wall} + (T_e/e)\, \ln\{[T_e/(T_e+T_i)](m_i/m_e\sqrt{2\pi})\}$. The ion velocity at the plasma-sheath boundary is found by the integration of the 1-D ion momentum equation, since the sheath thickness is typically much smaller than the perpendicular scale of turbulence. The sheath is a thin (Debye sized) layer, that is created at the plasma-conducting wall interface, due to the different rates of escape of the electrons and ions. When the magnetic field is perpendicular to the wall, we have $v_{i_\parallel} = c_s$. Then, approximating the z-averaged flows by their local values, the divergence of the parallel flows in Eqs. (1) and (2) can be written as

$$\nabla_\parallel v_{e_\parallel} = \frac{c_s}{L_\parallel} \exp\left[-\frac{e\tilde{\phi}\,(z=0)}{T_e} \right] + \frac{(e/m_e)\, \tan^2\theta}{\gamma_{e,i}\, n + \gamma_{e,n}^{(sc)}\, n_n} \left(\vec{p}_\perp \cdot \nabla_\perp \right) \vec{p}_\perp \cdot \nabla_\perp \left(\phi - \frac{T_e}{e} \ln n \right), \quad (5)$$

and $\nabla_\parallel v_{i_\parallel} = c_s/L_\parallel$, where $\tilde{\phi} = \phi - \phi_0$ is the variation of the potential at a given point from the background plasma potential ϕ_0. In the rest of the text, for simplicity, tilde will be omitted. Now, using above equations and appropriate normalizations, we can rewrite our basic Eqs. (1) and (2) in a dimensionless form as

$$\left[\frac{\partial}{\partial t} + \left(\vec{e}_z \times \nabla \phi \right) \cdot \nabla \right] n - D \nabla_\perp^2 n = -\sigma n, \quad (6)$$

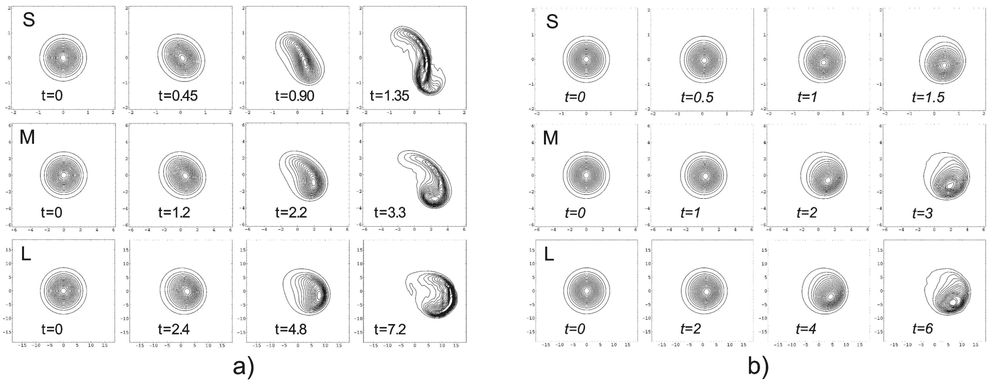

Figure 1: a) The effect of the parallel electron dynamics. **Collisional** regime, with cold ions and negligible perpendicular collisional effects. The parameters are $\chi_{2_\parallel} = 1$, $\vartheta = 0$, $D = 10^{-3}$, $\chi_0 = 2 \times 10^{-3}$, $\chi_{2_\perp} = \chi_4 = \gamma = \sigma = \tau = 0$. b) The effect of the finite ion temperature in the **inertial** regime. We used $D = 10^{-3}$, $\chi_0 = 2 \times 10^{-3}$, $\chi_{2_\perp} = \chi_{2_\parallel} = \chi_4 = \gamma = \sigma = 0$, while $\tau = 1, 3$ and 12 for the S, M, and L structures.

$$\begin{aligned}&\left[\tfrac{\partial}{\partial t} + (\vec{e}_z \times \nabla\phi)\cdot\nabla\right]\nabla_\perp^2\,(\phi + \tau\, n) - \tfrac{\partial n}{\partial y} + \tau\left(\vec{e}_z \times \nabla \tfrac{\partial \phi}{\partial x_i}\right)\cdot\nabla\tfrac{\partial n}{\partial x_i}\\ &= \chi_0\,\phi\,(z=0) + \chi_{2_\parallel}\,(\vec{p}_\perp\cdot\nabla_\perp)^2\, n + \left(\chi_{2_\perp}\nabla_\perp^2 - \chi_4\,\nabla_\perp^4\right)(\phi + \tau n)\,. \qquad (7)\end{aligned}$$

The expressions for $\sigma, D, \chi_0, \chi_2, \chi_4$, and τ depend on our choice of the normalizations, i.e. on the appropriate scaling laws. We can distinguish four different orderings with respect to the intensities of various dissipation mechanisms, to the blob's temporal and spatial scales, and to the amplitude of electrostatic potential.

Inertial regime is realized when all dissipations can be neglected and, with the accuracy to leading order, we have $\chi_0 = \chi_{2_\parallel} = \chi_{2_\perp} = \chi_4 = \sigma = D = 0$.

In the **sheath resistivity** regime the dominant dissipation mechanism is the current loss to the wall, when we have $\chi_0 = 1$, $\chi_{2_\parallel} = \chi_{2_\perp} = \chi_4 = \sigma = 0$, $\tau = \tau_i\,(\nu_{sink}^3\Omega_i/\nu_{_{RT}}^4)^{\frac{1}{5}}$, $D = [(D_{e,i} + D_{e,n})/\rho_s^2](\nu_{sink}^3/\nu_{_{RT}}^4\Omega_i^4)^{\frac{1}{5}}$. Here we introduced the notations $\rho_s = (1/\Omega_i)(T_e/m_i)^{\frac{1}{2}}$, $\tau_i = T_i/T_e$, $\nu_{src} = \gamma_{e,n}^{(ion)}\,n_n$, $\nu_{i,n} = \gamma_{i,n}^{(sc)}\,n_n$, $\nu_{_{RT}} = 2\Omega_i(1+\tau_i)(\rho_s/R)$, $\nu_\parallel = |\Omega_e|\,\Omega_i\,\tan^2\theta/(\gamma_{e,i}\,n + \gamma_{e,n}^{(sc)}\,n_n)$, $\nu_{sink} = c_s/L_\parallel$, $D_{e,n} = (m_e/m_i)\rho_s^2\,\gamma_{e,n}^{(sc)}\,n_n$, $D_{e,i} = (m_e/m_i)(1+\tau_i)\rho_s^2\,\gamma_{e,i}\,n$.

Collisional regime is realized if the electron-ion and ion-neutral collisions are the dominant dissipation mechanisms, when we have $\chi_{2_\parallel} = 1$, $\chi_{2_\perp} = (\nu_{i,n}/\nu_{_{RT}})(\nu_\parallel/\Omega_i)^{\frac{1}{2}}$, $\chi_0 = \chi_4 = 0$, $\sigma = (\nu_\parallel/\Omega_i)^{\frac{1}{2}}(\nu_{sink} - \nu_{src})/\nu_{_{RT}}$, $\tau = \tau_i\,\nu_{_{RT}}\Omega_i^{\frac{1}{2}}/\nu_\parallel^{\frac{3}{2}}$, and $D = \nu_{_{RT}}\,(D_{e,i} + D_{e,n})/(\rho_s^2\nu_\parallel^{\frac{3}{2}}\Omega_i^{\frac{1}{2}})$.

Viscosity regime corresponds to $\chi_4 = 1$, $\chi_0 = \chi_{2_\parallel} = \chi_{2_\perp} = \sigma = 0$, $\tau = \tau_i\,\rho_s^2\Omega_i/\eta_i$, and $D = (D_{e,i} + D_{e,n})/\eta_i$.

Equations (6) and (7) are numerically solved in all above regimes. We used the method of lines, with a finite difference discretization of the spatial variables x and y, with 32×32 points. We set to zero the plasma source and sink, as well as the collision frequency with the neutrals. The initial condition was adopted as $\phi\,(t=0) = 0$, and

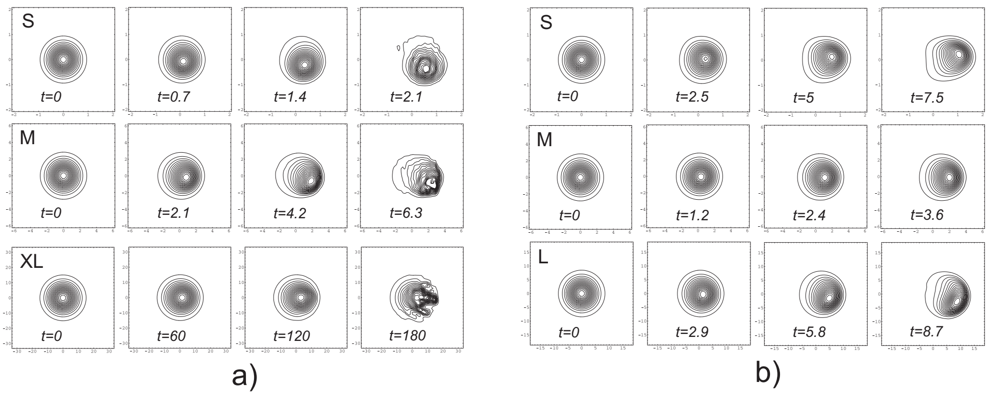

Figure 2: a) The effect of the finite ion temperature in the **sheath connected** regime, in the vicinity of the wall of the vessel. We used $D = 10^{-3}$, $\chi_0 = 1$, $\chi_{2_\perp} = \chi_{2_\parallel} = \chi_4 = \gamma = \sigma = 0$, with $\tau = 1, 5$ and 5 for the S, M, and XL structures. b) The effect of the ion temperature in the **sheath connected** regime. We used $D = 10^{-3}$, $\chi_4 = 1$, $\chi_2 = \chi_{2_\perp} = \chi_{2_\parallel} = \gamma = \sigma = 0$, while $\tau = 2, 5$, and 12 for the S, M, and L structures.

$n_i\,(t=0) = n_{i_{SOL}} + n_{i_{max}} \exp\left[-(x^2+y^2)/L_\perp^2\right]$, which corresponds to a Gaussian blob, injected at $t = 0$, into a background SOL plasma whose density is $n_{i_{SOL}}$. We studied four characteristic blob sizes, labelled as S (Small, $L_\perp = 0.5$), M (Medium, $L_\perp = 1.5$), L (Large, $L_\perp = 4.5$), and XL (eXtra Large, $L_\perp = 8.5$). The peak blob density was taken five times larger than the background plasma density, $n_{i_{max}} = 5\, n_{i_{SOL}}$. The coupling with nonlinear drift modes introduces a fundamentally different behavior compared to its 2-D counterparts (Jovanović et al., 2007). Due to the presence of the resistive drift drive,the collapse of the oblique blobs in the lateral direction is followed by a clockwise rotation and radial propagation, see Fig. 1 a). The finite ion temperature effects in the *inertial*, *sheath connected* and *viscous regime*, are shown in Figs. 1 a), 2 a) and 2 b), respectively. The symmetry breaking introduces a poloidal component in the blob velocity, while its overall stability properties and the speed are not affected qualitatively.

References

Jovanović, D., de Angelis, U., Fedele, R. and Pegoraro, F.: 2007, *Phys. Plas.*, **14**, 3704.

Krasheninnikov, S. I., D'Ippolito, D. A. and Myra, J. R.: 2008, *J. Plasma Phys.*, **74**, published online, doi: 10.1017/S0022377807006940.