*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.020 (2005)*

Anomalous radial convection and flows in tokamak scrape off layer plasma

S. I. Krasheninnikov, A. Yu. Pigarov, and G. Q. Yu

University of California at San Diego, La Jolla, CA, USA

I. Introduction. There is vast experimental evidence of an important role of anomalous convection of a meso-scale structures in the tokamak edge plasma transport: the structures extended along the magnetic field lines, which often called “blobs”, are advected coherently into the far scrape-off layer (SOL) on a distance ~10 cm and even more; recent data suggest that the dynamics of Edge Localized Modes (ELMs) in the SOL plasma is very much similar to that of blobs, and result in large plasma particle and energy fluxes into far SOL. Rather simple models of blob propagation [1], based on the effective plasma gravity caused by magnetic curvature describe many essentials of nonlinear evolution and radial advection of such meso-scale structures as blobs and ELMs. Recently [2] it was shown that the drives caused by $\nabla_\perp T_e$ and the parallel shear of $\mathbf{E}\times\mathbf{B}$ velocity can also result in convective radial motion of the coherent structures. Integrated modeling of a tokamak edge plasma transport with 2D code UEDGE shows that the outward convective plasma velocity, which mimics the blob propagation, is needed to reproduce experimental data in the SOL [3]. Here we present our results of 2D turbulence modeling of nonlinear evolution of step-like electron temperature profile in the SOL caused by $\nabla_\perp T_e$ instability. We study the formation and advection of the coherent structures and investigate their role in the temperature transport. We also present the results of 2D edge-plasma modeling with transport code UEDGE focused on the macroscopic plasma poloidal and parallel velocities. We demonstrate numerically the existence of large parallel plasma flows with Mach number up to unity in the inner SOL region and show that the B-field variation can be an important ingredient in the formation of such flows.

II. Convective structures driven by the $\nabla_\perp T_e$ instability. The nonlinear plasma evolution related to the $\nabla_\perp T_e$ instability (see for example Ref. 4) can be described by the electron temperature advection equation $d_t T_e = 0$ and the condition of zero divergence of electric current integrated along the magnetic field between the material surfaces with the sheath effects taken into account, which gives

$$\nabla_\perp \cdot ((n/M\Omega_i^2) d_t \nabla_\perp (e\varphi)) = (2n/L_c)\sqrt{T_e/M}\left(1-\sqrt{M/2\pi m}\exp(-e\varphi/T_e)\right), \qquad (1)$$

where $d_t(\ldots) \equiv \partial_t(\ldots) + \mathbf{v}_E \cdot \nabla(\ldots)$, $\mathbf{v}_E = -C_s\rho_s\left(\nabla e\varphi/T_0 \times \mathbf{e}_z\right)$, L_c is the connection length, and other notations are standard. To simplify the problem we assume constant plasma density and relatively small variation of plasma temperature so that $T_e = T_0 + \delta T_e$ and $\varphi = \varphi_0 + \delta\varphi$, where $\varphi_0 \propto T_0 \equiv \text{const.}$ correspond to ambipolar plasma flow to material surfaces, and $|\delta T_e| < T_0$ and $|\delta\varphi| < \varphi_0$. Then introducing dimensionless variables $t \to t/t_*$, $\mathbf{r} \to \mathbf{r}/r_*$, $r_* = (\rho_s^3 L_c/2)^{1/4}$, $t_* = (\rho_s L_c/2)^{1/2}/C_s$, $\phi = e\delta\varphi/T_0$, $\vartheta = \delta T_e/T_0$, we find

$$d_t \nabla_\perp^2 \phi = \phi - \vartheta, \qquad d_t \vartheta = 0, \qquad (2)$$

where $d_t(\ldots) \equiv \partial_t(\ldots) + \mathbf{w}_E \cdot \nabla(\ldots)$ and $\mathbf{w}_E = -\nabla\phi \times \mathbf{e}_z$. In Ref 2 nonlinear long wavelength approximation of (2) was derived, assuming that $\partial_t(\ldots) << \mathbf{w}_E \cdot \nabla(\ldots)$,

$$\partial_t \phi = \mathbf{w}_E \cdot \nabla(\mathbf{w}_E \cdot \nabla(\nabla_\perp^2 \phi)) \qquad (3)$$

and then shown that Eq. (3) has solutions in the form $\phi(x,y,t) = (x+Ut)^\alpha F(y/(x+Ut)^\beta)$, describing traveling wedge, where α and β are the adjustable parameters and both function $F(\eta)$ and wedge convection velocity U can be found from the nonlinear equation (3).

Moreover, based on the arguments of the stability of such structures it was concluded that the structures with dimensionless scale of the order of 1 are the most stable one. However, it was not clear how $\nabla_{\perp}T_e$ driven plasma turbulence would affect such structures. To verify these analytic conclusions and understand the impact of plasma turbulence we perform 2D modeling based on the equations (2) and present some preliminary results here. We also should note that modeling of the $\nabla_{\perp}T_e$ instability has been done in Ref. 5, but without particular emphases on coherent structures.

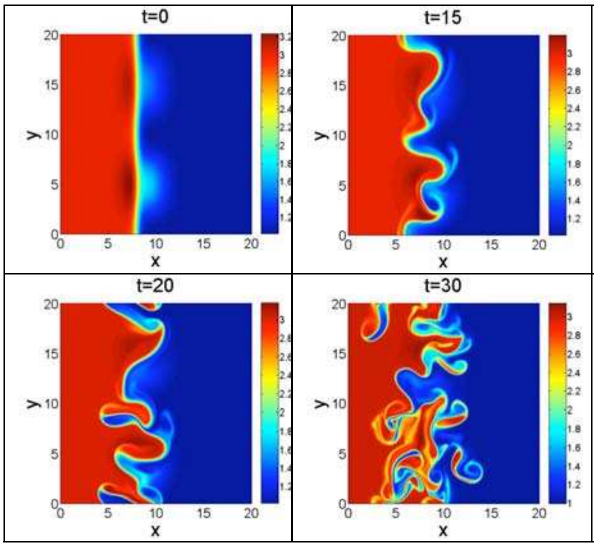


Fig. 1. δ=0.5

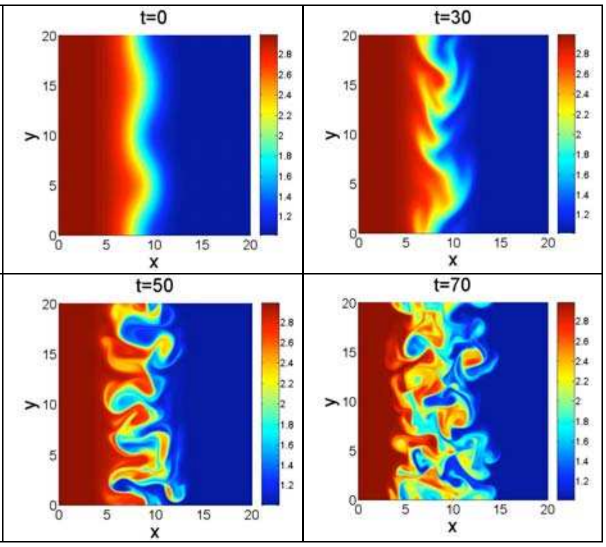
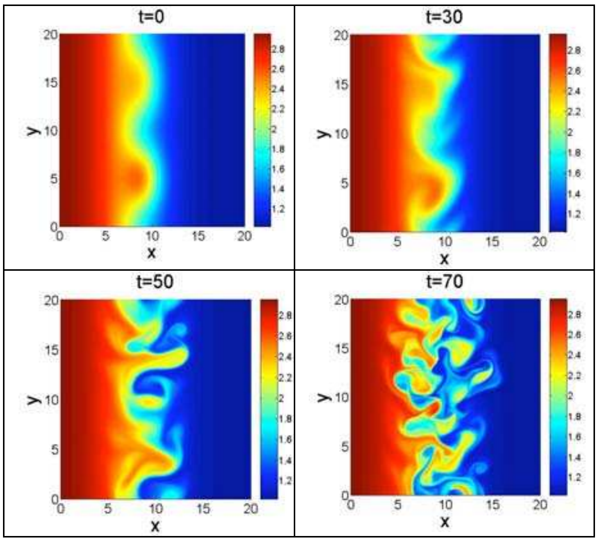


Fig. 2. δ=2

In Figs. 1-3 we show time evolution of the step-like temperature profile (in x-direction temperature ϑ drops from 2 to 1 on the scale length δ). As one sees, wedge-like structures indeed are developing on the nonlinear stage of the evolution. They propagate in radial direction on significant distance, which in real units corresponds to the distance ~5 cm. The characteristic dimensionless spatial scale of these structures is of the order of unity regardless on initial sharpness of the step. However, transition of temperature profile evolution to fully developed (which occurs faster in the case of small initial δ) turbulent regime break the most pronounced of these structures. We will continue our numerical study to see statistics of wedge like structures in the fully turbulent stage.



δ=4 Fig. 3.

III. Modeling of large parallel plasma flows in tokamak SOL. The traditional picture of plasma transport in the scrape-off layer suggests the total (plasma-and-neutrals) pressure variation along the magnetic field lines to be small (e.g., due to rapid parallel electron heat conduction and small diffusive cross-field transport) and, as a result, the quiescent (i.e. substantially subsonic) parallel plasma flows. However, recent experiments on several tokamaks showed the strong cross-field plasma convection (due to intermittency) as well as the existence of large-Mach-number parallel plasma flows in the SOL. For instance, as reported in [6], in the single null magnetic configuration such flows originated from the outboard mid-plane accelerated to about sound speed toward the inboard mid-plane and the inner divertor. The detailed experimental characterization of plasma flows on Alcator C-Mod lead the authors to conclusion that the driving mechanism of these flows was the strong inboard/outboard asymmetry in the cross-field plasma transport.

To confirm the existence and driving mechanism of large flows and to investigate the effect of flows on divertor detachment, impurity transport, and main chamber recycling, we perform the multi-fluid 2D simulations of edge plasma and neutral gas transport with the UEDGE code. We employ the multi-ion diffusive-and-convective model for anomalous cross-field plasma transport that has been discussed in [3]. Our model introduces the asymmetric (e.g. ballooning-like) 2D profiles for transport coefficients. We also assume the poloidal variation for wall pumping and for some other parameters prescribing the boundary conditions at the main chamber and private flux region walls (in particular, the cross-field gradient scale length of plasma density at the walls).

The UEDGE calculations were performed for typical L-mode shot 109033 (at 350ms into the discharge, low single null (LSN) magnetic configuration) in the NSTX tokamak. In the obtained solutions, the cross-field transport in SOL is largely due to anomalous convection. The inboard/outboard asymmetries in convective transport are taken to be 1:3 at the mid-plane. No plasma drift terms were switched on.

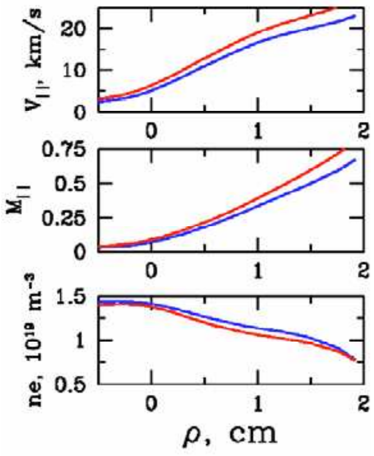


Fig. 4

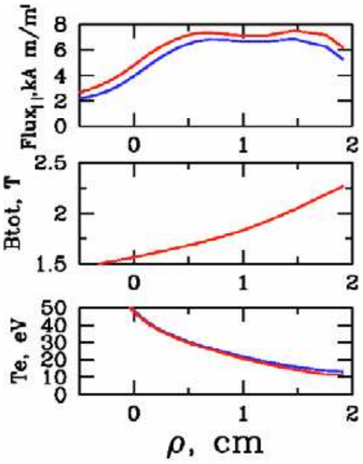


Fig. 5

The radial profiles at the inner mid-plane for parallel plasma velocity $V_{||}$, Mach number $M_{||}$, plasma density n_e and temperature T_e, and total magnetic field strength B_{tot} are shown on Fig.4,5. The coordinate ρ denotes the distance at the outboard mid-plane from the separatrix to the given magnetic flux surface in the SOL (note, the real inner-SOL width is ~3X larger). The Mach number is defined as $M_{||} = V_{||}/[(T_e + T_i)/M_D]^{1/2}$, M_D is the deuterium mass. The two curves on Fig.4,5 differ by some details in poloidal profile of anomalous convection. As seen, plasma in the entire SOL is moving in one direction, namely, toward the inner divertor plate. The parallel plasma velocity $V_{||}$ is 10-25 km/s. Both $V_{||}$ and $M_{||}$ are increasing toward the chamber wall. In the far SOL, the radial variation of T_e and T_i is relatively small due to fast cross-field convection and $M_{||}$ increases mostly because of increase in $V_{||}$. The averaged flux density is $Flux_{||}$~7 kA/m tends to be constant over the SOL width. The integral flux corresponds to few hundred Amperes flowing toward the inner divertor. It is much higher than the separatrix flux coupled to the inboard. The higher the B_{tot}, the higher is the $M_{||}$. The highest $M_{||} \approx 0.7 - 0.8$ is near the wall. The distribution of $V_{||}$, $M_{||}$, and $Flux_{||}$ along two magnetic flux surfaces: ρ≈0.9 (red curve) in the middle of SOL, and ρ≈1.8 (blue) near the chamber wall are shown in Fig. 6. Their positive values correspond to the direction toward the inner plate. The plot ordinate L_{mfl} is the normalized distance along the magnetic field line counted from the inner divertor plate (then, the outer plate corresponds to L_{mfl}=1). The green vertical lines correspond to locations of (from left to right) entrance to inner divertor, inboard mid-plane, plasma top, outboard mid-plane, and entrance to outer divertor. As seen, the parallel flow originates from the outer mid-plane. In this region the flow is rather quiescent, $V_{||}$=1-4 km/s, $M_{||}<0.05$. The flow continuously accelerates toward the inner mid-plane. The high $V_{||}$ values attained at the inner mid-plane are practically independent on the boundary conditions on the divertor plates (e.g. since the maximum $M_{||}$ is far in the SOL). In considered case, the inner divertor is detached. There are significant drop in plasma pressure between outer and inner mid-planes as well as a strong variation of the magnetic field strength that affect the $V_{||}$. On Fig.7 we display the poloidal profiles of plasma ion (red curve) and neutral atom (blue curve) fluxes through the separatrix. The ordinate L_p is the distance along the closed part of LSN separatrix line from X-point to X-point, clockwise. As seen, the plasma flux is due to ballooning-like anomalous convection on the outboard side ($L_p>0.4$). The neutral flux profile has three minimums (because of the negative values). The first minimum $L_p \approx 0.03$ is due to neutrals penetrating from inner divertor. The second one at $L_p \approx 0.23$ corresponds to the gas puff of 500A (plus the associated recycling) from the central stack location. The third, the deepest minimum is due to neutral recycling on the outboard of main chamber wall. The neutral flux from divertor is approximately equal to the total flux carried by parallel plasma flow along the SOL into the inner divertor. Thus, the "big picture" of large parallel plasma flows derived from the numerical experiment with UEDGE code is as follows. In the SN magnetic configuration has strong inboard/outboard asymmetry, so that up to 80% of particles and energy is coupled to the outboard part of torus. It is expected that cross-field transport is anomalous and ballooning-like. The ballooning-like transport both diffusive and convective (e.g. blobs) enhances the in/out asymmetry. Specific role of intermittent transport is in pushing plasma/ momentum/ energy into the **far** SOL. The far SOL is low-T_e, low-n_e and allows for large plasma pressure gradients (both $\parallel$ and $\perp$). The far SOL is typically coupled to the detached region in the divertor. The asymmetry in radial fluxes generates the parallel plasma flow from outboard to inboard. There is a strong variation in magnetic field strength along magnetic field lines. The far SOL plasma typically accelerates to large velocity in the regions with maximum poloidal flux expansion. The plasma stream ends in the inner divertor. Plasma recycles (and even can recombine) there. The equivalent amount of particles leaks from the inner divertor through the separatrix, hence, closing the large plasma flow loop.

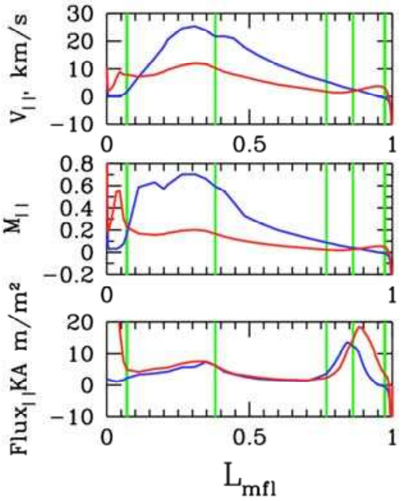


Fig. 6

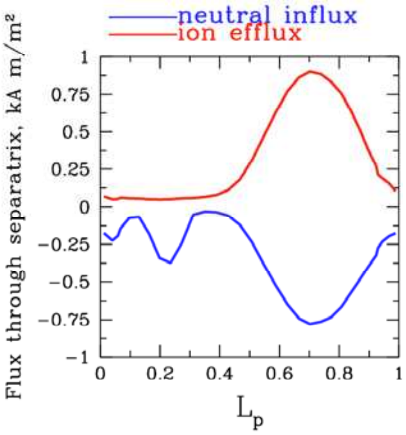


Fig. 7

This research was supported by the U. S. Department of Energy under Grant No. DE-FG02-04ER54739 at the University of California, San Diego.

References

[1] S. I. Krasheninnikov, Phys. Letters A, 283 (2001) 368; [2] S. I. Krasheninnikov, et al., Czechoslovak J. of Phys. **55** (2005) 307; Phys. Plasmas **12** (2005) July; [3] A. Yu. Pigarov, et al., Phys. Plasmas **9** (2002) 1287; A. Yu. Pigarov, et al., J. Nucl. Mater. **337-339** (2005) 371; [4] H. L. Berk, et al., Phys. Fluids B **3** (1991) 1346; [5] D. R. McCarthy, et al., Phys. Plasma **8** (2001) 750; [6] B. LaBombard, et al., Nucl. Fusion **44** (2004) 1047