DEPENDENCE OF GLOBAL CIRCULATION LAYER INSIDE TEXTOR-94 SEPARATRIX ON MAGNETIC FIELD ORIENTATION AND IMPURITIES

R. Zagórski[1], H.Gerhauser[2], M.Lehnen[2]

[1]*Institute of Plasma Physics and Laser Microfusion, P.O.Box 49, 00-908 Warsaw, Poland*

[2]*Institut für Plasmaphysik, Forschungszentrum Jülich GmbH,*
EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany

1 Introduction

The 2D multifluid code TECXY [1-4] is a useful tool for investigating specific physical questions in the plasma edge of limiter tokamaks. In the present paper we use an updated version of TECXY to study in more detail the formation or destruction of a global circulation layer (GCL) just inside the separatrix of the TEXTOR-94 tokamak and its dependence on the magnetic field orientation (normal or inverted) and the presence of carbon impurities. In this GCL with a width of 1-2 cm the poloidal plasma velocity goes all around the poloidal circumference, which is connected with an electric field spike (negative for normal orientation) and a corresponding local channel of the perpendicular (binormal) electric drift velocity.

2 Physical Model

The 2D boundary layer code TECXY [1-3] is primarily based on the classical transport equations derived by Braginskij [6]. The transport along field lines is assumed to be classical, whereas the radial transport is assumed to be anomalous with prescribed radial transport coefficients of the order of Bohm diffusion. The dynamics of deuterium and impurity neutrals in the SOL is described by an analytical model, which accounts in a self-consistent way for recycling of plasma ions as well as for sputtering processes at the limiter plates. Moreover the present version of the code incorporates drift motions and currents in a fully self-consistent way with plasma and impurity dynamics in a real curvilinear geometry of the limiter tokamak boundary layer, and the radial electric field and plasma potential in the transition layer inside the separatrix are derived from an ordinary differential equation which ensures global ambipolarity of the radial electric current. For every ion species we solve the continuity, parallel momentum and energy equations. The momentum equation and the equations for drifts and currents are in detail described in [7], whereas for the energy balance equations we refer to [5]. In the present paper we focus our consideration to the equation for the electric field, which is obtained from the global ambipolarity constraint:

$$
\begin{aligned}
0 \; &= \; -\oint \frac{h_z h_x}{B}\left[\frac{b_z}{h_x}\left(2p+\sum_a (b_a + m_a n_a V_{a\|}^2)\right)\frac{\partial}{\partial x}\ln\left(h_z b_z\right) + \sum_a m_a c_s^a b_x P_2^a\right] dx \\
&+ \; \oint \frac{h_z h_x}{B}\left[\sum_a m_a V_{a\perp}\left(P_1^a + S_n^a\right) + \sum_a m_a n_a \left(V_{ax}\frac{1}{h_x}\frac{\partial}{\partial x} + V_{ay}\frac{1}{h_y}\frac{\partial}{\partial y}\right) V_{a\perp}\right] dx \\
&- \; \oint \frac{h_z h_x}{B}\frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left(\frac{\sqrt{g}}{h_y^2}\sum_a \eta_\perp^a \frac{\partial V_{a\perp}}{\partial y}\right) dx \qquad (1)
\end{aligned}
$$

depending linearly on $V_{a\perp}$. Here $h_x,\ h_y,\ h_z$ are the metric coefficients ($\sqrt{g} = h_x h_y h_z$), and $b_x,\ b_z$ are components of the unit vector parallel to the total magnetic field $\mathbf{B}$. The source term from the momentum transfer by cx with neutrals has been written as: $S_{V\perp}^a \equiv -m_a V_{a\perp} P_1^a + m_a c_s^a b_x P_2^a$, where c_s^a is the sound speed, and P_1^a, P_2^a are given.
Let us denote $\Phi = \Phi^* + \widetilde{\Phi}$, where $\Phi^* = \Phi^*(y) = \Phi\left(x_{bis}, y\right)$ and $\widetilde{\Phi} = \widetilde{\Phi}\left(x, y\right)$ with $\widetilde{\Phi}\left(x_{bis}, y\right) \equiv 0$. The condition for a unique electrostatic potential $\oint d\Phi = \oint \partial\Phi/\partial x\, dx = \oint \partial\widetilde{\Phi}/\partial x\, dx = 0$ means that $\widetilde{\Phi}\left(x, y\right)$ can be found for every y by integrating the parallel Ohm's law along x. At the separatrix Φ^* and $\frac{d\Phi^*}{dy}$ are given by the values obtained in the SOL. At the core boundary we use

the condition, that the total poloidally circulating ion current from perpendicular ion motion vanishes: $\oint \sqrt{g} b_z j_{i\perp} dx|_{y=0} = \oint \sqrt{g} b_z \sum_a e_a n_a V_{a\perp} dx|_{y=0} = 0$, which yields $d\Phi^*/dy\ |_{y=0}$. In the following we consider all quantities including $V_y, V_x, V_{||}$ as given. The expression for $V_{a\perp}$ can then be written in terms of the unknown radial electric field as $V_{a\perp} = \left(G_a - \frac{d\Phi^*}{dy}\right)/Bh_y$, where

$$G_a = \frac{1}{e_a n_a}\left[-\frac{\partial}{\partial y}(p_a - b_a) + \left(3b_a + m_a n_a V_{a||}^2\right)\frac{\partial}{\partial y}\ln(h_z b_z)\right] - \frac{\partial\widetilde{\Phi}}{\partial y} \tag{2}$$

Now, the ambipolarity constraint (eq.1) is easily transformed into a linear differential equation of third order for Φ^* (second order for $d\Phi^*/dy$):

$$B(y)\frac{d\Phi^*}{dy} + C(y)\frac{d^2\Phi^*}{dy^2} + D(y)\frac{d^3\Phi^*}{dy^3} = A_0(y) + A_1(y) \tag{3}$$

where all coefficients $B(y)$, $C(y)$, $D(y)$, $A_0(y)$ and $A_1(y)$ are known functions of the plasma parameters. Especially $A_0(y)$ is given by the expression in the first line of eq.(1). We have split the right hand side of eq.(3) into 2 parts, because only the coefficient $A_0(y)$ contains contributions from free forces acting on the plasma, whereas all terms in the coefficient $A_1(y)$ have corresponding parts on the left hand side of eq.(3) (see [7]) and describe compensating or counteracting forces during the system evolution, e.g. from inertia and anomalous perpendicular shear viscosity. The remaining free driving forces in $A_0(y)$ can be associated to the pressure force $(2p + \sum_\alpha b_\alpha)$, centrifugal force $(\sum_\alpha m_\alpha n_\alpha V_{\alpha||}^2)$ and momentum input due to neutrals $(\sum_\alpha m_\alpha c_s^\alpha b_x P_2^\alpha)$.

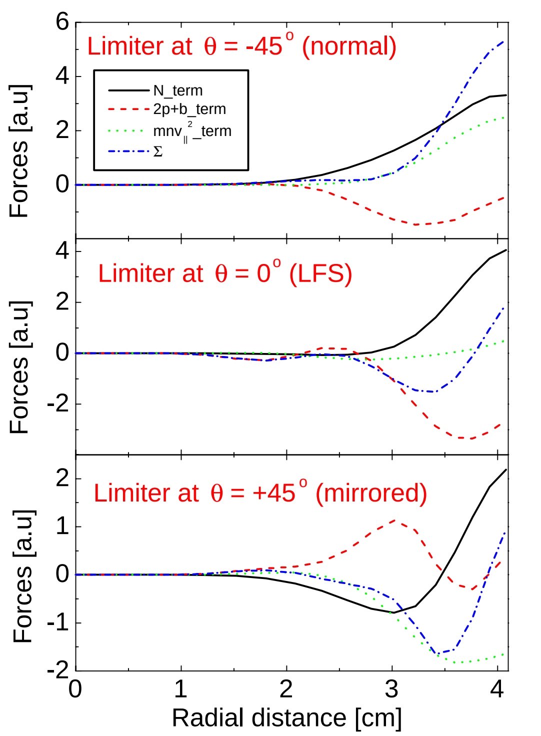

Figure 1: *Forces for different limiter positions*

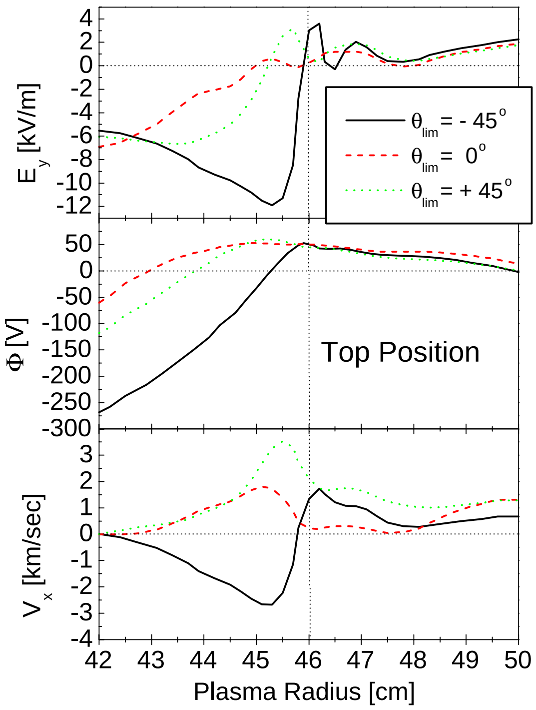

Figure 2: *Electric field, plasma potential and poloidal plasma velocity for 3 limiter positions*

3 Results of calculations and discussion

We used standard boundary conditions in our calculations. The computational domain extends poloidally from one limiter side to the other limiter side and radially from $r = 42\ cm$ to $r = 50$

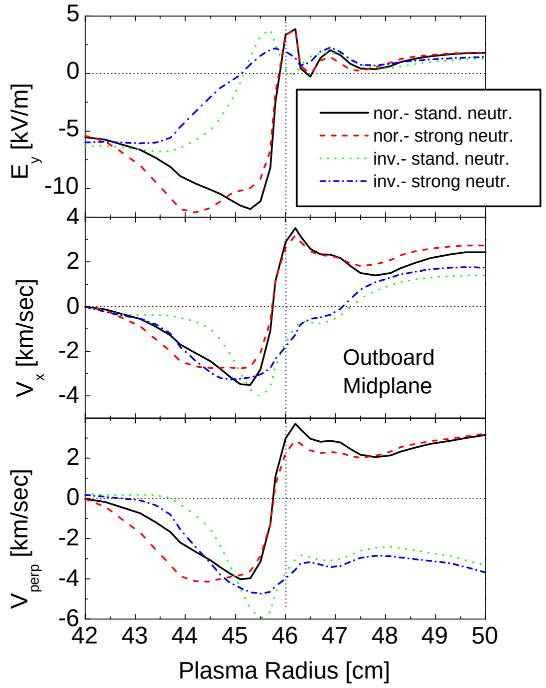

Figure 3: *Electric field, poloidal and perpendicular plasma velocity for different neutral models and field orientations (LFS)*

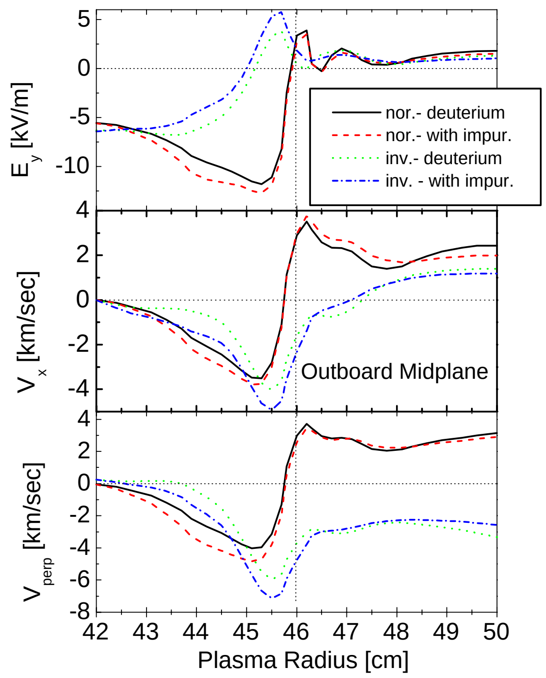

Figure 4: *Electric field, poloidal and perpendicular plasma velocity for pure deuterium case and for case with impurities at LFS (both B-field orientations)*

cm with the separatrix at $a = 46\ cm$. At the core boundary a total power input and a total particle input flux are specified. At the wall we have used decay lengths as boundary conditions. At the limiter $V_x^a = \pm b_x c_s$ for the momentum equations and $q_x^e = \delta_e n_e V_x^e T_e$, $q_x^a = \delta_a n_a V_x^a T_i$ for the energy equations. At the auxiliary boundary, which continues the limiter sides into the transition layer, we have assumed that all quantities are continuous and poloidally periodic.

We performed calculations with the TECXY code for a high density auxiliary heated TEXTOR-94 discharge in pure deuterium ($a = i$) and also in the presence of carbon impurities ($a = j = 1, 2, ...6$). The belt limiter ALT-II is at $\theta = -45^o$ position, the total magnetic field $B = 2.25\,T$, the plasma current $I_p = 350\ kA$ and the Shafranov shift $\triangle = 6\,cm$. The anomalous transport in radial direction is determined by the coefficients $D_y = 1.5\ m^2/sec$, $\eta_y^a = \frac{1}{3} m_a n_a D_y$ and $\chi_y^e/n_e = \frac{3}{2}\chi_y^a/n_a = 2D_y$ (including an Alcator-like decrease with density towards the core). For the present case the input particle flux to the SOL was $\Gamma_{inp} = 5.5 \times 10^{21}\ s^{-1}$, and the power input $Q_{inp} = 1MW$. The recycling coefficient (the fraction of recycled neutrals reionized in the boundary layer) was $R = 0.75$. First we have investigated the role of different physical mechanisms for the formation of the global circulation layer (GCL). It appears that the strength and the direction of the plasma flow in the GCL is determined by the interplay between the different forces in the $A_0(y)$ coefficient. Also the toroidal geometry (metric factors and B-field structure) and the position of the limiter have a very strong influence on the resulting electric field. In Fig.1 we have plotted the poloidally integrated forces occurring in $A_0(y)$ for different limiter positions. It can be seen that for all limiter positions the momentum input due to interactions with neutrals recycled at the ALT-II limiter is essentially compensated by the pressure force term. Consequently the remaining centrifugal force term is mainly responsible for the strength and direction of the plasma flow in the GCL. For $\theta = -45^o$ there is a strong plasma circulation in counterclockwise direction (Fig.2), whereas for $\theta = +45^o$ the plasma flows in opposite direction because the projection of the centrifugal force on the poloidal direction changes sign. For $\theta = 0^o$ the centrifugal term is negligible, and in this case the electric field spike and the poloidal flow are relatively weak and driven only by an uncompensated top-bottom asymmetry of the pressure gradients. In order to consider the influence of the neutral model on the GCL structure we have made a sensitivity analysis by performing calculations with the standard neutral model [2] and with much stronger neutral source terms. We have done this for normal as well as inverted ($B_\phi \to -B_\phi$, $I_p \to -I_p$) magnetic field orientation. In Fig.3 electric field, poloidal and perpendicular velocities are shown at outboard midplane. We see that neutrals can affect only the width of the GCL but not the direction and the strength of the flow. If the momentum input due to interactions with neutrals is larger, then the plasma dynamics is such that the force due to neutrals is compensated by the pressure force, and consequently the centrifugal force defines the flow in the GCL. In Fig.4 the influence of impurities on the formation of the GCL is shown for both magnetic field orientations. Obviously impurities lead to a further shift of E_y profiles and as a consequence to a strengthening of the global circulation for both orientations, which indicates increased driving forces. We remind again the crucial role of the centrifugal force term near the limiter head, where the parallel velocity is related to the boundary sheath conditions at the limiter. For impurities the centrifugal force scales with the charge state j as $T_i + jT_e$, so that a few percent of admixed impurity leads already to a well visible increase of driving force. In Fig.5 we have shown calculated and measured values of plasma and impurity poloidal and perpendicular velocities. For normal as well as for inverted field the experimental points show the same behaviour as the calculated velocities and confirm the abrupt velocity reversal when radially passing through the separatrix. The high velocity shear at the separatrix and the global circulation layer just inside the separatrix are clearly produced by the characteristic shape of the perpendicular drift velocity $V_\perp$. We point out that an increase of the anomalous transport coefficients or a decrease of the particle input across the core boundary tends always to strengthen (deepen) the GCL layer.

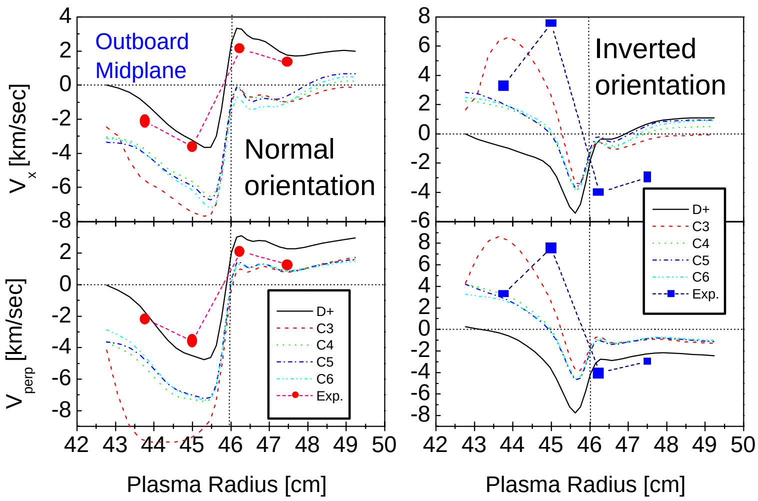

Figure 5: *Poloidal and perpendicular velocities at LFS for plasma and impurities together with experimental points (both B-field orientations)*

4 References

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