THE SIMULATION OF DRIFTS EFFECT ON THE EDGE PLASMA OF SMALL SIZE DIVERTOR TOKAMAK

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Received Date: 16 July 2019; Accepted Date: 22 August 2019; Published Date: 28 August 2019.

ABSTRACT

A systematical study of switch on / off (E×B and diamagnetic) drifts effects is reported based on the analysis of simulations by B2SOLPS5.0 2D multifluid transport code. It shown that, electron, ion temperatures and plasma density asymmetry are established due to switching on drifts. The existing plasma density, electron, ion temperatures and heat flux asymmetry is amplified by accounts these drifts. The simulation demonstrated that, the switching on drifts result in formation of edge transport barrier (ETB), which corresponding reduction of transport coefficients inside this barrier. Also at switch on drifts leads to there is no source of charge particles due to ionization of neutrals inside edge transport barrier (ETB). The simulation predicted the switching on / off drifts did change significantly the profile of parallel (toroidal) velocity and there is linear correlation between toroidal velocity $V_\parallel$, ion plasma temperature $T_i$ and poloidal magnetic field $B_x$ at switch on drifts. Also the simulation predication is switching on drifts has significant influence on the radial electric field which is of order of (or close to) neoclassical radial electric field and leads to torque generation, this torque spins down the parallel (toroidal) rotation.

Keywords: E × B drift, Diamagnetic drift, ETB
PACS: 52.25.Fi
INTRODUCTION

The role of drifts ($E \times B$ and diamagnetic drifts) in the tokamak edge plasma was discussed in (Rozhansky et al., 2013; Stangeby et al., 2000; Rozhansky et al., 2006; Pitts et al., 2005; Pitts et al., 2005; Rozhansky et al., 2003). One possibility is that, the radial $E \times B$ drifts play the main role due to the radial flows from low field side (LFS) divertor to high field side (HFS) for single null (SN) divertor configuration. Other authors considered the poloidal $E \times B$ drifts as the main sources of asymmetries. The divertor asymmetry has been observed experimentally in several tokamaks with SN divertor configuration (Hutchinson et al., 1995; Tsois et al., 1999; Pitts et al., 2005; Ou et al., 2007; Bekheit & Gaber, 2010). Moreover, the degree of in / out divertor asymmetries depends on the line averaged density (Hutchinson et al., 1995; Tsois et al., 1999; Bekheit & Gaber, 2010). The outer / inner divertor energy asymmetry increases with the heating power from core plasma for normal direction of toroidal magnetic field. Classical particle drifts from $E \times B$ and $\nabla B$ (including curvature) drifts are believed to be important for understanding tokamak edge/scrape off layer (SOL) transport even in the presence of turbulent transport simulations with 2D codes were not able to give an unambiguous answer since the role of the drifts was masked by usual LFS-HFS divertor asymmetry. Study the effects of switching on drifts effects in edge plasma of small size divertor tokamak are reported based on the analysis of simulations performed using B2SOLPS5.0 2D meltfluid transport code (Rozhansky et al., 2001; Rozhansky et al., 2000), including the calculation of radial electric field “$E_r$” on both side of separatrix. This paper demonstrated switching on drifts causes amplification of divertor asymmetry.

SIMULATION OF SOL PLASMA

The B2SOLPS5.0 2D multifluid transport code is used for present simulation. The code employed to solve the full two dimensional fluid equations (Rozhansky et al., 2001) (Braginskii transport equations) uses an edge geometry and input assumption for plasma transport based on a comparison with experimental data from other tokamaks. Multifluid plasma consists of neutral particles, ions and electrons with various physical processes, for example, ionization and recombination. For small size divertor tokamak (SSD) have parameters given in (Table 1).

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>The main parameters of SDD tokamak for B2SOLPS5.0 2D simulation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius, $R$ (m)</td>
<td>0.3</td>
</tr>
<tr>
<td>Minor radius, $a$ (m)</td>
<td>0.1</td>
</tr>
<tr>
<td>Toroidal magnetic field $B$ (tesla)</td>
<td>1.7</td>
</tr>
<tr>
<td>Plasma density ($m^{-3}$)</td>
<td>(4-6)$\times 10^{18}$ and $1\times 10^{20}$</td>
</tr>
<tr>
<td>Temperature heating (eV)</td>
<td>387,403.5, 497.25</td>
</tr>
</tbody>
</table>

Preliminary operation, multifluid plasma in B2SOLPS5.0 2D simulation only includes hydrogen atoms, hydrogen ions and electrons for hydrogen discharge. The computational region for simulation is based on SN and covers the outer SOL and the divertor below the midplan plus a small segment region of closed flux surface and private flux region. In the computation region the coordinate which vary in the direction along the flux surface ($x$-coordinate) start at midplan, which is assumed to be symmetry boundary, and end at the target plate, and the coordinates which vary in the direction across the flux surfaces ($y$-
coordinate) start at the interface between the computation region and core plasma, (i.e. the core-SOL interface), and end at the outer wall. The computation mesh is divided into 96×24 units where the x-coordinate varies along flux surfaces (-1 ≤ x ≤ 96), y-coordinate varies perpendicular to flux surface (-1 ≤ y ≤ 24) and z- is the toroidal direction coordinate (Figure 1). The metric coefficients are $h_x = 1/||\nabla x||$, $h_y = 1/||\nabla y||$, $h_z = 1/||\nabla z||$ and $\sqrt{g} = h_x h_y h_z$. One can replace $h_z$ by $2\pi R$. The physical components of vectors are used. The ions of single species are considered with $Z=1$ so that $n_e = n_i = n$. The subscript ‘⊥’ denotes the direction perpendicular to both the magnetic field "B" and "y" axis $b_x = B_x/B$ and $b_z = B_z/B$ and $B = \sqrt{B_x^2 + B_z^2}$. The boundary conditions in the computational region are presented in (Rozhansky et al., 2001).

\[ FIGURE 1 \]

**COORDINATE SYSTEM AND SIMULATION MESH: X IS THE POLOIDAL COORDINATE; Y IS THE RADIAL COORDINATE ORTHOGONAL TO THE FLUX SURFACES. THE DIRECTIONS OF MAGNETIC FIELD AND PLASMA CURRENT CORRESPOND TO NORMAL OPERATION CONDITIONS OF SSD TOKAMAK (∇B DRIFT OF IONS DIRECTED TOWARDS THE X-POINT).**

**THE MAIN RESULTS OF SIMULATIONS**

Presented below are the results from the simulations of small size divertor tokamak. The anomalous transport coefficients were: diffusion coefficient $D = 0.5 \text{ m}^2/\text{sec}$, heat thermal conductivity coefficient $\chi_e = \chi_i = 0.7 \text{m}^2/\text{sec}$. The perpendicular viscosity was taken in the form $\eta = n m_i D$.

The main results of simulation are:

1. The first result of simulation show that, the switching on/off drifts did change the poloidal profiles of plasma density, ion and electron temperatures in edge plasma of this tokamak significantly as shown in (Figures 2-4) we can see that, switch on drifts at the HFS plates the plasma density becomes larger than the density at LFS plates. The temperatures asymmetry is opposite to the plasma density asymmetry, the denser divertor corresponding to lower temperature and vice versa. At HFS side the higher density corresponds to the case when the poloidal $E\times B$ drifts is directed away from HFS plates towards the LFS plates as shown in (Figure 2). Above result is interesting since they might show that, the poloidal drifts
have strong influences the plasma density, electron, ion temperatures electron and ion heat fluxes. Figure 5 show that, most part of electron heat flux and small part of ion heat flux arrive at divertor plates. This result consistent with the results given by (Hutchinson et al., 1995; Tsois et al., 1999; Ou et al., 2007; Bekheit et al., 2010).
Also this result shows that, the radial electric field and corresponding poloidal $E \times B$ drift velocity is larger due to formation of edge transport barrier (ETB) in the edge plasma of this tokamak. The poloidal $E \times B$ drift is directed from outer to inner plates as shown in (Figure 6). It clearly seen in (Figure 6) that, the parallel velocity to large extent compensates the poloidal $E \times B$ drift velocity near outer plate. Since the poloidal $E \times B$ drift velocity is larger in case of formation ETB of than L-mode, the parallel velocity is also larger.

![Figure 2](image2)
**FIGURE 2**
THE POLOIDAL DISTRIBUTION OF PLASMA DENSITY IN EDGE PLASMA OF THIS TOKAMAK.

![Figure 3](image3)
**FIGURE 3**
THE POLOIDAL DISTRIBUTION OF ION TEMPERATURE IN EDGE PLASMA OF THIS TOKAMAK.
(2) The electron and ion poloidal heat flux associated with drift velocities consist of two parts (Rozhansky et al., 2001):

\[ q_{jx} = \frac{3}{2} n \, T_j \, V^E_{\perp} + \frac{5}{2} n \, T_j \, V^{\text{dia}}_{\perp} = \frac{3}{2} n \, T_j \left( V^E_{\perp} + \frac{5}{3} V^{\text{dia}}_{\perp} \right), j = e, i \quad (1) \]

Where \( V^E_{\perp} = \frac{1}{B} \frac{\partial \phi}{\partial y} \), is \( E \times B \) drift velocity \( \phi \) is electrostatic potential and

\[ \vec{V}^{(\text{dia})}_{\perp \, j} = \frac{T_j \, B_z}{e b_z} \frac{\partial}{\partial y} \left( \frac{1}{B^2} \right) \]

is the diamagnetic drift velocity. In most cases when the divertor temperatures are low enough the conducting heat flux is directed away from HFS towards to LFS as shown in (Figure 5).

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**FIGURE 4**

THE POLOIDAL DISTRIBUTION OF ELECTRON TEMPERATURE IN EDGE PLASMA OF THIS TOKAMAK.

**FIGURE 5**

THE POLOIDAL OF ELECTRON AND ION HEAT FLUXES IN EDGE PLASMA OF THIS TOKAMAK.
Switching on drifts in SOL makes the plasma more asymmetric due to the additional electron heat flow from HFS plate to LFS plate equation (1). A Poloidal electron heat flux flow with switch on/off drifts was plotted as shown in (Figure 5). (Figure 5) shows that, the switching on drifts further amplify in-out asymmetry in poloidal electron heat flux. In general the switching on all drifts amplifies the asymmetry between divertor plates and leads strong influence on the distribution of poloidal ion heat flux which is smaller than electron heat flux as shown in (Figure 5).

FIGURE 6
PARALLEL (TORIDAL) AND POLOIDAL E×B DRIFT VELOCITIES IN EDGE PLASMA OF THIS TOKAMAK.

FIGURE 7
THE RADIAL DISTRIBUTION OF KINETIC PRESSURE IN EDGE PLASMA OF THIS TOKAMAK AT SWITCH ON DRIFTS.

(3) The third result of simulations shows that, switching on drifts leads to the formation of edge transport barrier (ETB) in the edge plasma of this tokamak as shown in
(Figure 7). The radial profiles of transport coefficients which have been chosen to obtain the calculated profiles are presented in (Figures 8-10). The values of the anomalous transport coefficients are the same for switching on/off all drifts. As shown in (Figures 8-10), we used the forms of the classical transport coefficients for given density and temperature calculated by code for certain temperature heating $\text{"Heating" } = 497.25$ eV in my article and plot the resulting classical transport coefficient, we were found the reduction of transport coefficient at formation of ETB as shown in (Figures 8-10). (Figures 8-10), show that, the switch on/off drifts have influence on the radial profile of classical transport coefficients. As seen from those figures the electron heat thermal conductivity coefficient has to be reduced by factor: "2.4" and ion heat thermal conductivity has reduced by factor "2.8" inside the edge transport barrier while the reduction of diffusion coefficient is of order "2.20" inside this barrier. A reduction of electron and ion heat thermal conductivity coefficients would lead to larger electron temperature gradient.

![Figure 8](image1)

**FIGURE 8**

**THE RADIAL DISTRIBUTION OF ELECTRON HEAT THERMAL CONDUCTIVITY COEFFICIENT IN EDGE PLASMA OF THIS TOKAMAK AT SWITCH ON/OFF DRIFTS.**

![Figure 9](image2)

**FIGURE 9**

**THE RADIAL DISTRIBUTION OF ION HEAT THERMAL CONDUCTIVITY IN EDGE PLASMA OF THIS TOKAMAK AT SWITCH ON/OFF DRIFTS.**
(4) Fourth result of simulation shows that, the ion particle flux profile at the outer midplane for switch on/off case is shown in (Figure 11). One can see that, the switching on drifts leads to increasing the ion particle flux inside barrier region. Therefore, inside the separatrix the switching on all drifts leads to too small source of charge particles due to ionization of neutrals inside the edge transport barrier as show in this figure, where the ion particle flux over the flux surface decreasing towards separatrix is shown. Outside the barrier region in the SOL the switch on drifts leads to decrease the radial particle flux, which indicates to there is no source of charged particle in SOL. A noticeable particle flux flow to the far SOL is significant, where positive values of ion particle flux corresponds to radially outward and the negative values corresponds to radially inward.

\[
E^{(NEO)} = \frac{T_i}{e} \left( \frac{1}{h_y} \frac{d \ln n}{dy} + \frac{k_T}{h_y} \frac{1}{d \ln T_r} \right) - b_z \frac{\sqrt{g V_B}}{\sqrt{g}} dx
\]

(2)

FIGURE 10
THE RADIAL DISTRIBUTION OF DIFFUSION COEFFICIENT IN EDGE PLASMA OF THIS TOKAMAK AT SWITCH ON/OFF DRIFTS.

(5) Fifth result of simulation shows that, inside and near the separatrix switching on drifts leads to the radial electric field for this tokamak is close to(or of order of ) the neoclassical radial electric field given in (Rozhansky et al., 2004) by equation:

FIGURE 11
THE RADIAL DISTRIBUTION OF ION AND NEUTRAL FLUX FLOWS THROUGH THE FLUX SURFACES FOR THIS TOKAMAK AT SWITCH ON DRIFTS.
Where \( k_T \) is constant equal 2.7 and \( V_\parallel \) is parallel (toroidal) velocity as shown in (Figure 12), while switch off drift the radial electric field is not of order neoclassical radial electric field, as shown in (Figure 13), Also (Figure 12), shown that, the radial electric field in all calculation of switch on drifts can be estimated by equation (2) with exception of dip in the separatrix vicinity as in the previous simulation (Rozhansky et al., 2001; Rozhansky et al., 2004).

**FIGURE 12**
THE DISTRIBUTION OF RADIAL ELECTRIC FIELD IN EDGE PLASMA OF THIS TOKAMAK, WHEN DRIFTS ARE SWITCHING ON DRIFTS.

**FIGURE 13**
THE DISTRIBUTION OF RADIAL ELECTRIC FIELD IN EDGE PLASMA OF THIS TOKAMAK, WHEN ALL DRIFTS ARE SWITCHING OFF.

The negative radial electric field on the core side of computational domain is determined by balance between negative contribution from density and ion temperature gradients (first term on RHS of equation (2)) and positive contribution from co-current (negative) toroidal (second term on RHS of equation (2)). For hot regime of the B2SOLPS5.0 2D code in the core region the agreement between the neoclassical and code electric field is fairly good for the case of switch on drifts. However in the SOL the contribution of the parallel (toroidal) velocity,
which generated in the SOL and transport to the core region, is large. This parallel (toroidal) velocity changes the neoclassical electric field and influences the result of B2SOLPS5.0 2D simulations, of electric field. The parallel (toroidal) rotation in the core is (-0.882, -0.0069) km/s and its negative contribution in the radial electric field is of order (-5.6, -6.31, -8.45) kV/m at different plasma density as shown in (Figure 14).

![Figure 14](image)

**FIGURE 14**
THE DISTRIBUTION OF RADIAL ELECTRIC FIELD IN EDGE PLASMA OF THIS TOKAMAK AT DIFFERENT DENSITY AND \( T^{(heating)} = 306 \) eV FOR SWITCH ON DRIFTS.

![Figure 15](image)

**Figure 15**
THE DISTRIBUTION OF PARALLEL (TOROIDAL) VELOCITY IN EDGE PLASMA OF THIS TOKAMAK AT DIFFERENT DENSITY AND \( T^{(heating)} = 306 \) eV FOR SWITCH ON DRIFTS.

(Figure 14) indicates the radial electric field, as well as the neoclassical electric field, is dependent the parallel velocity, density and temperature gradients is close to the neoclassical nature of equation (2). The maximum radial electric field shear is found at low plasma density near separatrix. The reason for deviation of parallel velocity in the case of core
plasma density \((6 \times 10^{19})\) \(m^{-3}\) shown in (Figure 15) might be due to the fact that most of the unbalanced parallel particle flux caused by the radial flux from the core plasma goes to the outer plates. The negative gradient contribution is comparable but bigger. At the same time the rise of density leads to decreases of the ion temperature, so the change of the contribution of the density and temperature gradients is only about 12%. One would expect the strong dependence of radial electric field at the core side on the collisionality.

**FIGURE 18**
The Distribution Of Ion Temperature And Ion Parallel (Toroidal) Velocity As Function Of Radial Coordinate When All Drifts Are Switch On.

**FIGURE 19**
The Distribution Of Ion Temperature And Ion Parallel (Toroidal) Velocity As Function Of Radial Coordinate When Drifts Are Switch Off.

In the SOL the positive radial electric field is larger than in the L-regime, here the radial electric field is determined by electron temperature divided by the radial density and temperature scale length: \(E_r \sim T_e / \epsilon_e L\). The radial electric field and corresponding \(E \times B\) are larger due to formation of ETB (Rozhansky et al., 2004). Therefore, the switch on drifts has
strong influence on the distribution of radial electric field as shown in (Figure 16). Also this figure indicates that, when the all drifts are switch on the additional radial electric field generated in the plasma core of this tokamak.

![Figure 20](image1)

**FIGURE 20**
The Distribution Of Parallel (Toroidal) Torque As Function Of Radial Coordinate When All Drifts Are Switch On/Off.

![Figure 21](image2)

**FIGURE 21**
The Distribution Of Parallel (Toroidal) Velocity As Function Of Radial Coordinate When Drifts Are Switch On/Off.

(6) Sixth result of simulation show that, switching on/off drifts has strong influence on the poloidal distribution of parallel (toroidal) velocity in edge plasma of this tokamak at HFS and LFS mid plane is show in (Figure 17). This figure show that, switching on/off drifts leads to parallel velocity is directed towards the plates; however in principle it might be directed away from the plates provided large enough $E \times B$ drifts is directed to plates, at case of switching on drifts. According to Rozhansky et al., 2013; the change in parallel velocity
caused by drifts requires the corresponding pressure gradient to accelerate or decelerate plasma to or away from the plates. An example is shown in (Figure 1), at the HFS plate the density increasing towards the plate. In contrast, at LFS plate the plasma density decreasing from the plate towards the X-point. For high temperature plasma heating \( T_{\text{heating}} = 497.25 \) eV inputs into the electron and ion components the radial electric field in the core is larger, as shown in (Figure 16). For switch on drifts. We can see from (Figure 16). The radial electric field at separatrix is different for switch on / off drifts and is of the order of the local temperature, which also different for switch on / off drifts. On the other hand, at switch on drifts the electric field dip in core should be of order of ion temperature divided by characteristic scale length of ion temperature, since it should be determined by neoclassical effects. We conclude that at switch on drifts the radial electric field is of order of neoclassical radial electric field. According to Rozhansky et al., 2001; switching on drifts leads to density and temperature increase near the divertor plates with the direction of poloidal drifts. An asymmetry of the parallel (toroidal) velocity between the divertor legs and the upper part of SOL was observed, in (Figure 17). Parallel (toroidal) velocity here is directed towards to the HFS if the drifts are switched off. Switching on drifts leads to a further increase of the parallel velocity, because the poloidal projection of parallel velocity compensates poloidal \( E \times B \) drifts, so that poloidal rotation roughly remains the same. The exception is the region close to separatrix where the contribution from poloidal \( E \times B \) to the poloidal rotation is the largest.

(7) Seventh result of simulation shows that, the switching on drifts leads to the simple model based on the idea that, the toroidal velocity is linearly proportional to the local ion temperature as shown in (Figure 18). This figure shows correlation between these two physical quantities. Conclusively it found that, the switching off drifts there is no correlation between the two quantities as shown in (Figure 19). According to the analysis performed in this article based on the modeling with B2SOLPS0.50 2D multfluid transport code the average parallel (toroidal) flow in the edge plasma of this tokamak is given by (Rozhansky et al., 2001; Rozhansky et al., 2004):

\[
\langle V_{i\parallel} \rangle = b_x(V_x - b_z V_{\perp}) \quad (3)
\]

Where \( V_x \) is poloidal velocity and \( V_{\perp} \) is given by:

\[
V_{\perp} = \left( V^{E \times B} + \bar{V}_{\text{dia}} \right) \quad (4)
\]

Where \( E \times B \) and diamagnetic drifts velocities are given (Rozhansky et al., 2001) and the \( \langle \cdot \rangle \) is average. According to (Rozhansky et al., 2001), \( E \times B \) drift velocity has stronger influence than on the diamagnetic velocity. Therefore, we can neglect the diamagnetic velocity with respect \( E \times B \) drift velocity. Hence the average parallel (toroidal) velocity becomes:

\[
\langle V_{i\parallel} \rangle = -(b_x(V_x - b_z(V^{E \times B} + \bar{V}_{\text{dia}}))) \quad (5)
\]

The radial electric field is of order of neoclassical electric field when drifts are switching on. Therefore, the radial electric field is given by:

\[
E_r \approx \frac{T_i}{e} \left( \frac{1}{L_n} + \frac{1}{L_T} \right) , \quad L_n = \left[ \frac{d \ln n}{h_y dy} \right]^{-1} \quad \text{and} \quad L_T = \left[ \frac{d \ln T}{h_y dy} \right]^{-1} \quad (6)
\]

Where \( L_n \) and \( L_T \) is the characteristic scale length for the plasma density and temperature. Under conditions \( L_T \gg L_n \) equation (6) becomes:
\[ E_r \approx \frac{T_i}{e} \left( \frac{1}{\lambda_n} \right) \]  

(7)

From equations (6,7) into equation (5) we obtain after some algebraic manipulation is expressed in form given by:

\[ \langle V_{\parallel} \rangle = -\langle A \frac{T_i}{B_x} \rangle \]  

(8)

Where \( \lambda_n = \frac{b_z}{eL_n^2} \), Equation (8) gives us the dependence of parallel flow on ion temperature \( T_i \) divided by poloidal magnetic field \( B_x \). This result consists with the results given by (Chatthong et al., 2011; Rozhansky 2012).

(8) Eighth result of simulation shows that, switch on drifts leads to additional parallel (toroidal) torque generated in edge plasma of this tokamak as shown in (Figure 20). The mechanism responsible for the toroidal momentum torque is illustrated in (Figure 20). In the upper part of torus the drifts transport negative toroidal velocity inward (Figure 21). Creating negative torque (Figure 20). This negative torque is balance mainly by the radial transport of toroidal momentum due to anomalous plasma viscosity and diffusion. One can see that, the plasma viscosity and diffusion play significant role of transport of ion parallel (toroidal) momentum in edge plasma of this tokamak.

**CONCLUSION**

A B2SOLPS5.0 2D multifluid transport code has been used and implemented for the simulation of edge plasma of small size divertor tokamak when drifts are switching on /off. It is demonstrated that, the switching on drifts leads to, the formation of edge transport barrier (ETB) in the edge plasma of this tokamak which corresponding to the diffusion coefficient inside this barrier is reduced by factor "2.20" with respect of L-mode value, while the electron heat thermal conductivity and ion heat thermal conductivity coefficients are reduced by factors "2.3" and "2.8". The \( E\times B \) and diamagnetic drifts are one of the sources which lead to divertor asymmetries. The power up-down asymmetry observed in edge plasma of this tokamak might be connected with the conductive electron energy flow established by \( E\times B \) and diamagnetic drifts flux flow. In edge plasma of this tokamak with normal direction of toroidal magnetic field the HFS-LFS asymmetry is amplified by switching on drifts. Switching on drifts did change the radial electric field profile significantly which is close to (or of order of) neoclassical radial electric field near separatrix while the switch off drifts. Result in the radial electric field is not close of neoclassical radial electric field. A switching on drifts leads to co-current ion parallel velocity which is proportional to the ion temperature and inversely proportional to the poloidal magnetic field. Also the simulation results show that, switching on drifts result in torque generation, this torque causes down the toroidal rotation.

**REFERENCES**


