The Effect of Drifts on the DIII-D Boundary Plasma

G. D. Porter 1), T. D. Rognlien 1), M. E. Rensink 1), N. S. Wolf 1), T. W. Petrie 2), W. P. West 2), P. C. Stangeby 3), and the DIII-D team 2)

1) Lawrence Livermore National Laboratory, Livermore, CA, USA
2) General Atomics, La Jolla, CA, USA
3) University of Toronto, Toronto, Canada

e-mail contact of main author: porter2@llnl.gov

Abstract

The effect of E×B and diamagnetic drifts on the boundary plasma of a diverted tokamak is examined by comparing simulations obtained from the 2D fluid code UEDGE with data from the DIII-D tokamak. The effect of drifts on a single null L-mode configuration is determined by comparing the measurements with two simulations which are identical except that only one includes drifts. The dominant effect is seen on the high B–field side of the divertor where the plasma density is a factor of two higher when drifts are included. This effect occurs because a radial electric field associated with steep electron temperature radial gradients along the separatrix between the X-point and strike points drives a poloidal flow from the outer to inner divertor in the private region. The higher density yields higher radiation power, moving line radiation zones further off the divertor plate. The simulated profiles of both D_α and CIII radiation obtained with drift effects included are more consistent with measurements. The drifts also affect the in/out asymmetry of both divertor heating power and divertor ion flux. The effect of drifts on the up/down asymmetry of double null plasma configurations is also considered, although not in as much detail. The up/down asymmetry of the divertor heat flux which is measured in double null plasmas on DIII-D is consistent with that obtained in UEDGE simulations which include the effect of drifts. Drift effects can be important in determining the profile of divertor heating powers, and the distribution of recycling neutrals, and therefore should be included in the design of divertor structures for future fusion devices.

1. Introduction

Divertors of future tokamaks must effectively exhaust the power and particles flowing across the separatrix to avoid damage of plasma facing materials, and to maximize fusion power. Efficient design of divertors should include the asymmetry of divertor heating power and neutral recycling current observed in operating tokamaks. In single null (SN) configurations the divertor power is generally observed to be much lower on the high field side of the divertor and recycling much higher. Some proposed burning plasma devices anticipate using double null configurations (DN) as a means of minimizing the divertor heat flux. Current experiments find that the up/down power balance is very sensitive to the magnetic asymmetry of the DN equilibrium shape. These in/out and up/down asymmetries must be included to effectively design divertor structures to exhaust power and baffle recycling neutrals.

Divertor design is typically guided by simulation of the boundary plasma with 2D fluid plasma codes[1-3]. The physics models in these codes have been extensively validated against data obtained in tokamaks throughout the world. The effect of drifts in the edge and SOL has recently been included in these codes although these effects are not yet included in divertor design efforts[4-6]. It is generally believed that divertor asymmetries are determined in part by the effect of the ion ∇B and E×B drifts. The purpose of this paper is to describe the effect of these drifts on simulations of DN and SN plasma configurations of the DIII-D tokamak.

2. Drift equations

The 2D fluid plasma code UEDGE solves the hydrogen[7] plus impurity species[8] equations for the plasma density, momentum, and energy flows in the poloidal plane of a tokamak plasma. Drift effects appear in both the poloidal and radial velocities, as shown in Equation 1, where subscript *x* is the poloidal direction, and *y* is the radial direction. The velocities, $v_{i,E}$ and $v_{i,\nabla B}$ are the E×B and ∇B drifts, respectively, and $v_{i\|}$ is the parallel ion velocity. The parameter B is the magnetic field, D_a is the radial particle diffusivity, and n_i the ion density. The effect of the drift terms on the fluid equations is described in detail elsewhere[5]. Drifts create radial and poloidal flows which affect the density, momentum, and temperature profiles directly. The transport equations couple all the plasma variables, hence changes in the plasma flows affects all quantities. Drift effects tend to be large in regions of large gradients.

$$u_{ix} = \frac{B_x}{B} v_{i\|} + v_{ix,E} + v_{ix,\nabla B}$$

$$u_{iy} = -\frac{D_a}{n_i}\frac{\partial n_i}{\partial y} + v_{iy,E} + v_{iy,vis} + v_{iy,\nabla B}$$

Equation 1

Note that the velocity u_I differs from the plasma velocity in that it does not include the divergence free drift velocities from the pressure and temperature gradient. The divergence free drift velocity terms are included when specifying boundary conditions.

3. Results

The effect of the drift terms has been assessed by simulating plasma operation in two magnetic configurations on DIII-D, single null and double null. All configurations considered here have the ion ∇B drift direction downward, i.e. toward the X-point for the SN configuration. The results of these simulations are described in this section.

3.1 Single null configuration

The single null configuration considered here is derived from DIII-D operation in a “Simple as Possible Plasma” (SAPP) mode to permit thorough diagnosis of the edge and scrape-off layer (SOL) plasmas[9]. The plasma is kept in L-mode with reduced neutral beam heating power and is swept radially to permit 2D diagnosis of the divertor region. Several identical discharges are taken to permit spectroscopic diagnosis with several visible and UV lines. These plasmas are analyzed using UEDGE simulations which include the effect of both drifts and intrinsic carbon impurity evolved from the plasma facing components by physical and chemical sputtering. The effect of ∇B and E×B drifts is quantitatively assessed by comparing simulations with and without the drift terms. The simulations assume the perpendicular flow of thermal energy and plasma particles is diffusive with spatially constant diffusivity. The diffusivity is determined by creating consistency between the simulated upstream radial profile of the electron density and temperature and that measured with the Thomson scattering diagnostic, as has been previously done[10]. The best fit for the SAPP discharge described here is obtained with $D_\perp$=0.2 m^2/s, and χ_I=χ_e=0.8 m^2/s for both simulations with and without drifts. The effect of the drifts on the electron density in the divertor region is shown in Figure 1. The radial electric field created by the radial gradient in the electron temperature along the separatrix between the X-point and the inner and outer strike points, creates a significant poloidal flow of plasma in the private region, from the outer to inner divertor. This flow increases the plasma density by about a factor of two on the inner divertor.

Although the poloidal drift in the private region is an effective transport mechanism to move ions away from the outer strike point, the peak density on the outer divertor also increases when drift effects are included in the simulation. This arises because the increased density on the inner divertor, together with radiated power, cools the inner plasma, moving the location of the ionization front (T_e=3 to 5 eV) further off the divertor plate. This enhances volume recombination because the parallel flow velocity is reduced and a large volume with T_e~1 eV is created, permitting recombination before ions reach the plate.

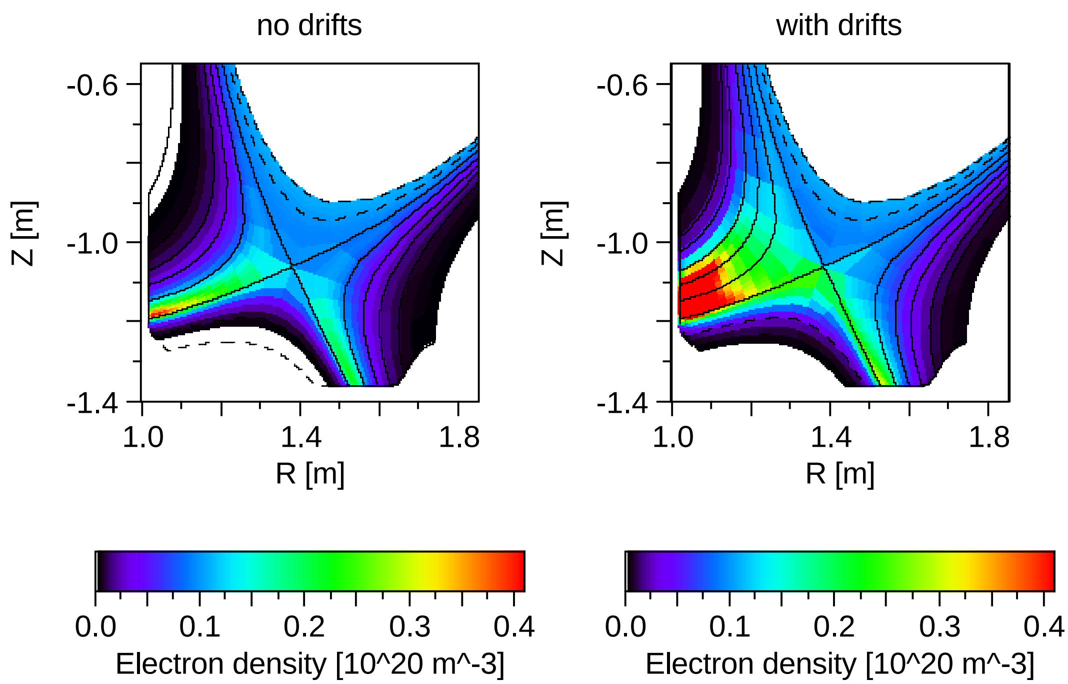

Figure 1 Comparison of simulated electron density in the divertor region with and without drift effects.

The enhanced recombination increases the neutral density throughout the divertor region. Thus there is increased ionization sources throughout the divertor, and the electron density is seen to increase both inside and outside.

The strongest effect of the drifts for these simple plasmas occurs on the high field side of the divertor. The primary diagnostic which can see the effect of the increased density is an array of visible light monitors which view the divertor from the top of the device. The fact that the plasma is swept during the discharge permits combining the data from each detector in the array to obtain a well resolved spatial profile of the emission seen in several visible lines. The profile seen in D_α and CIII emission is compared with simulations with and without the effect of drifts in Figure 2. The abscissa is the angle of the detector view from the horizontal. The location of the strike points is shown by two vertical dashed lines. The movement of the emission region for both D_α and CIII, which results from the enhancement of the electron density by the drifts, is seen as a shift of the peak emission on the inner divertor to the right. The peak of the CIII emission lies farther off the plate than that for the D_α emission because the CIII ion radiates at a higher electron temperature. Although differences still exist, the measured profile is more consistent with the simulation that includes the effect of drifts. Note there is very little effect of the drifts on the emission profile seen on the low field side of the divertor. The interpretation that the increased ion density on the inner divertor moves the radiation region of the D_α and CIII emission off the plate is consistent with data from cameras which view the divertor region tangentially. The simulated emission profile with drifts included agrees qualitatively with the data from these cameras. The enhanced density on the high field side of the divertor also increases the in/out power asymmetry. The inner divertor is predominately heated by re-absorbed radiation from carbon radiation near the 8 eV electron temperature contour. Since that contour moves further from the divertor plate as a result of the E×B drift enhancement of the inner divertor density, the heat load is reduced, and has a broader footprint. The in/out asymmetry of the peak divertor heating power is increased from 0.4/1.1 MW without drifts, to 0.2/1.1 MW when the drift effects are included.

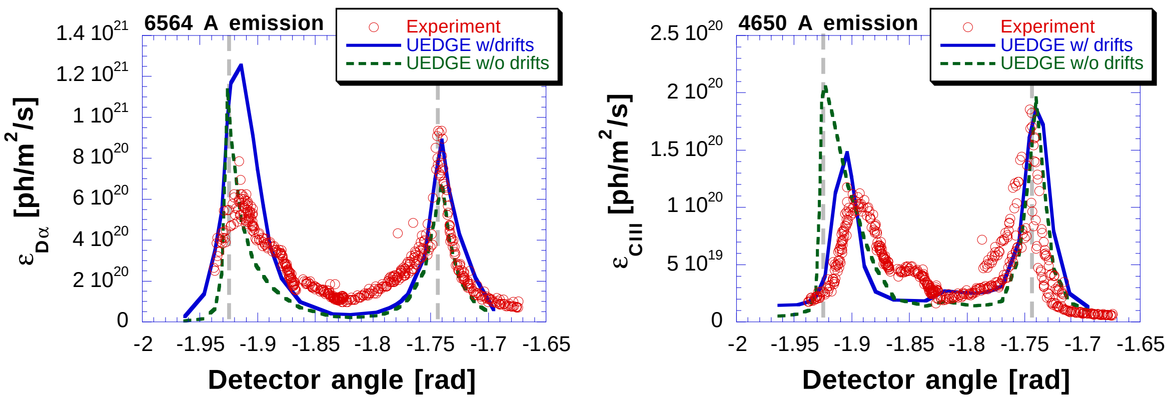

Figure 2 Comparison of simulated radial profile of D_α and CIII emission with experimentally measured profile.

The drifts appear to have less effect on the ion flux on the plates. The peak ion flux on the inner leg moves about 2 cm away from the strike point when drifts are included, but there is no effect on the magnitude of the peak on either divertor plate. The shift of the peak flux is associated with a radial drift arising from the poloidal electric field created by the steep electron pressure gradient at the ionization front on the inner leg.

3.2 Double null configuration

The effect of drifts in DN plasma configurations has been examined by simulating a set of DIII-D ELMing H-mode discharges in which the separation between the upper and lower X-point flux surfaces was varied to study the up/down power asymmetries[11].

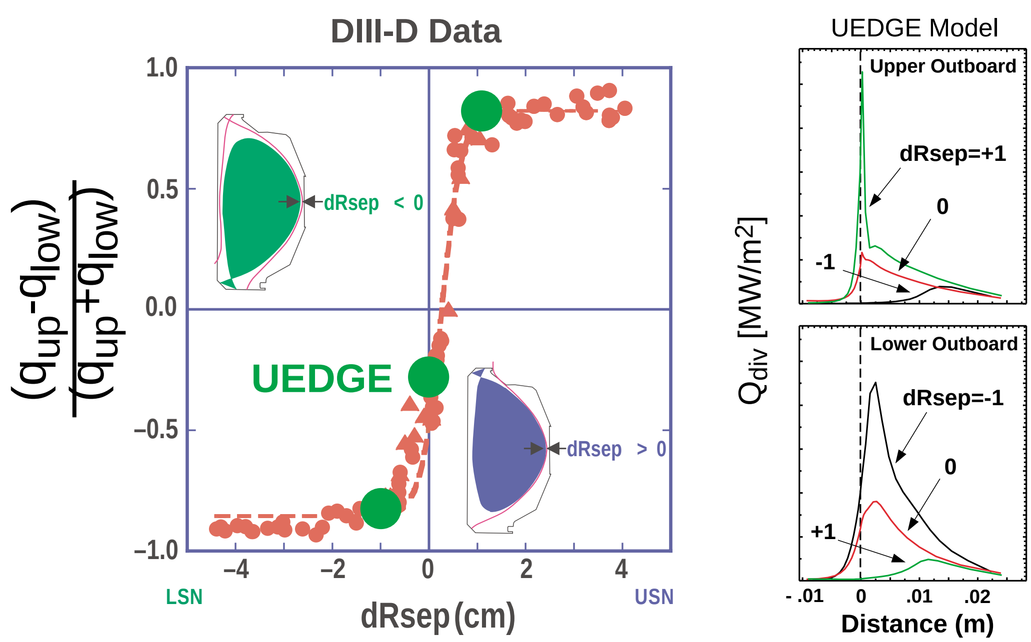

Figure 3 Comparison of simulated and measured up/down power asymmetry in the DIII-D tokamak.

Analysis of these plasmas require simulation of unbalanced DN configurations, a capability which has only recently become available[12]. UEDGE simulation of double null configurations is not as advanced as those of SN configurations because of the need for high grid resolution near all four divertor plates, rather than only two plates. The simulations done to date do not include the effect of intrinsic carbon radiation, and use a diffusive fluid neutral model. Three different DN configurations have been simulated. They are characterized by the parameter dR_{sep}, which measures the radial separation of the flux surfaces which pass through the two X-points. The separation is measured at the outer midplane of the plasma. The up/down asymmetry calculated for three different configurations are compared with those measured experimentally in Figure 3. The up/down asymmetry determined from three simulations with attached divertors agree well with the experiment. The up/down asymmetry is created largely by the effect of drifts, indeed there would be no asymmetry for a balanced DN configuration (dR_{sep}=0) without drifts.

4. Discussion

We have found that simulations of the boundary plasma in DIII-D that include the effect of drifts are more consistent with experimental data than those without. This result enhances confidence that the drift models are correct. The drifts have been shown to double the electron density on the high field side of a L-mode plasma because of an E×B flow in the private region. This flow is expected to be even more important for H-mode because the electron temperature gradients are higher, leading to larger radial electric fields in the divertor region. The private flux flow affects the in/out power asymmetry by moving radiation zones of a detached inner divertor further from the plate. These flows may have a larger effect in operation with attached inner divertors in that the flow could lead to detachment at lower powers. The flow which leads to higher density also is effective at transporting carbon ions obtained via physical sputtering at the outer divertor to the inner divertor region, and therefore enhances redeposition of carbon, in the inner divertor region and concomitant tritium co-deposition. We have also shown that drift effects are crucial to determining the up/down power asymmetry in DN configurations.

5. Acknowledgments

This work was supported at LLNL and General Atomics by the U.S. Department of Energy under contract Nos. W-7405-ENG48 and DE-AC03-99ER54463.

6. References

[1] R Schneider, D Reiter, H P Zehrfeld et al., J. Nucl Mat **196-198**, 810 (1992).
[2] A. Taroni, G. Corrigan, R. Simonini et al., J. Nucl. Mat. **220-222**, 1086 (1995).
[3] T D Rognlien, P N Brown, R B Campbell et al., Contr. Plasma Phys. **34** (2/3), 362 (1994).
[4] T D Rognlien, G D Porter, and D D Ryutov, J. Nucl. Mat. **266-269**, 654 (1999).
[5] T D Rognlien, D D Ryutov, N Mattor et al., Phys plasma **6** (5), 1851 (1999).
[6] A V Chankin, G Corrigan, S K Erents et al., J. Nucl. Mat. **290-293**, 518 (2001).
[7] S I Braginskii, in *Reviews of Plasma Physics*, edited by M A Leontovich (Consultants Bureau, New York, New York, 1965), Vol. 1, pp. 205.
[8] M Keilhacker, R Simonini, A Taroni et al., Nucl. Fus. **31** (3), 535 (1991).
[9] P C Stangeby, J A Boedo, B Bray et al., to be published in J. Nucl. Mat. (2002).
[10] G D Porter, R Isler, J Boedo et al., Phys. Plasma **7** (9), 3663 (2000).
[11] T. W. Petrie, C. M. Greenfield, R. J. Grobener et al., Journal of Nuclear Materials **290**, 935 (2001).
[12] M E Rensink, C J Lasnier, T W Petrie et al., Contrib. Plasma Phys. **42** (2-4), 181 (2002).