
Comparison of 2D simulations of detached divertor plasmas with divertor Thomson measurements in the DIII-D tokamak

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Comparison of 2D simulations of detached divertor plasmas with divertor Thomson measurements in the DIII-D tokamak


A modeling study is reported using new 2D data from DIII-D tokamak divertor plasmas and improved 2D transport model that includes large cross-field drifts for the numerically difficult low anomalous transport regime associated with the H-mode. The data set, which spans a range of plasma densities for both forward and reverse toroidal magnetic field (B\textsubscript{T}), is provided by divertor Thomson scattering (DTS). Measurements utilizing X-point sweeping give corresponding 2D profiles of electron temperature (T\textsubscript{e}) and density (n\textsubscript{e}) across both divertor legs for individual discharges. The simulations focus on the open magnetic field-line regions, though they also include a small region of closed field lines. The calculations show the same features of in/out divertor plasma asymmetries as measured in the experiment, with the normal B\textsubscript{T} direction (ion V\textsubscript{B} drift toward the X-point) having higher n\textsubscript{e} and lower T\textsubscript{e} in the inner divertor leg than outer. Corresponding emission data for total radiated power shows a strong inner-divertor/outer-divertor asymmetry that is reproduced by the simulations. These 2D UEDGE transport simulations are enabled for steep-gradient H-mode conditions by newly implemented algorithms to control isolated grid-scale irregularities.

1. Introduction

The transport of plasma across the magnetic field B in fusion energy devices is caused by turbulence and Coulomb collisions. Classical cross-field drifts of ions and electrons owing to gradients in B and the electrostatic potential can influence the level of turbulent and collisional transport, and they can also directly contribute to transport. This paper focuses on the impact of these particle drifts on plasma transport spanning the magnetic separatrix region and the open field-line scrape-off layer (SOL) for tokamaks with a poloidal magnetic divertor. Here the competition between transport across and along the open B field lines determines the profile of plasma fluxes striking divertor plates. For the single-null divertors considered here, key issues are differences in plasma density and temperature profiles across the inner and outer divertor plates as low temperature plasma detachment conditions are reached and how these differences change when the toroidal magnetic field changes sign. These profiles help determine the peak heat flux to each plate, which is composed of incident plasma kinetic energy, the potential energy released by ion-electron recombination within the plate, and radiation from the SOL plasma.

Recent studies of future high-power devices directed toward fusion power plants find that substantial impurity seeding of the edge plasma must radiate most of the exhaust power to limit the peak heat flux on materials to the acceptable range of \(~ 10 MW/m\textsuperscript{2}\), e.g., [1–3]. In the optimization of power removal through this radiative channel, the electron temperature at the divertor plate is reduced to \(~ 1\) eV, and plasma recombination becomes important. Such conditions are referred to as detached divertor plasma operation. Consequently, it is important that the stable operation of detached divertor plasmas in present-day devices be understood, which is one of the focuses of this paper.

The effort to predict and measure plasma asymmetries in the SOL and divertor regions goes back at least 30 years to the work of Harbour [4], and Hinton and Staebler [5]. The comprehensive

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picture of the various flows in the SOL and a plasma equation set for 2D transport codes is given in [6]. Early implementation demonstrated that plasma flow under the magnetic X-point can provide large particle transport between the inner and outer divertor legs, thus affecting the asymmetry [7,8]. Simultaneously reciprocating probe measurements showed that such flows exist and can be large [9]. The importance of the SOL particle content for predicting plasma detachment (in each leg) is demonstrated by 2D simulations in [10], where recombination is demonstrated to be a key process. The impact of magnetic field direction (and thus cross-field drifts) on the L-H power threshold as well as SOL flows has been discussed in some detail by LaBombard [11]. Over the last 15 years, there have been a number of SOL/divertor simulations reported that include cross-field drifts, e.g., [12–14], though typically such cases used strong “L-mode” anomalous (turbulent) cross-field diffusion coefficients, while the “H-mode” cases with small anomalous diffusion have been numerically difficult. Simulations showing the role of cross-field drifts to increase the density in the inner divertor leg region on ASDEX-U are reported in another paper at this conference [15].

Measurements of plasma conditions have been made by a variety of diagnostics, including Langmuir probes (reciprocating and fixed at the surface of the target plate), thermocouples, bolometry, various optical measurements, infrared cameras (IRTV), and Thomson scattering. This paper concentrates on comparisons of divertor plasma profiles from 2D UEDGE transport simulations with profiles from the Divertor Thomson Scattering (DTS) diagnostic on the DIII-D tokamak [16,17].

The plan of the paper is as follows: the plasma and neutral models used in the 2D UEDGE simulation code are explained in Section 2; the experimental setup and diagnostic systems used to generate data sets are described in Section 3; comparisons between the data and the simulations are presented in Section 4, where subsections focus on different parameter variations; the implications of the results and the conclusions are given in Section 5.

2. Simulation model

The basic UEDGE plasma model, including drifts, is described in [8]. Transport equations are evolved for the plasma density, parallel ion velocity, separate ion and electron temperatures, and the electrostatic potential from the current continuity equation \( \nabla \cdot \mathbf{J} = 0 \). The transport along the magnetic field is taken from the collisional model of Braginskii where transport fluxes of energy and momentum are limited to a fraction (0.15 for energy and 0.71 for momentum) of their free-streaming thermal values in regions where the mean-free path becomes long as taken from kinetic Monte Carlo charged-particle simulations [18]. Transport across the magnetic field is a combination of assumed anomalous (turbulence-driven) transport and cross-field magnetic and electric drifts for ions and electrons. Specifically, for an axisymmetric tokamak with a dominant toroidal magnetic field, the general expression of ion particle-flux due to magnetic drifts given in [6] can be approximated as

\[
\mathbf{n}_i \mathbf{V}_{ib} \approx -(P_i + m_i n_i V_{\perp i}^2) \mathbf{B} \times \nabla B / (eB) \\
\approx -(P_i + m_i n_i V_{\perp i}^2) / (eRB_i) \mathbf{i}_e,
\]

where \( P_i \) is the ion pressure (assumed isotropic here), \( V_{\perp i} \) is the ion drift velocity along \( \mathbf{B} \), \( e \) is the electronic charge, \( R \) is the major radius, and \( B_i \) is the toroidal magnetic field. For electrons, the magnetic drift flux is

\[
\mathbf{n}_e \mathbf{V}_{eb} \approx P_e \mathbf{B} \times \nabla B / (eB^2) \approx P_e / (eRB_i) \mathbf{i}_e,
\]

where the curvature parallel-drift term (\( \propto m_e v_{\perp e}^2 \)) is ignored owing to the small electron mass. These magnetic drifts are approximately vertical in tokamaks because of the dominant toroidal magnetic field varying as \( 1/R \) as indicated by the unit vector \( \mathbf{i}_e \), and are oppositely directed for ions and electrons.

The electric drifts across B-field lines are identical for ions and electrons in the strong magnetic field limit (with negligible variation over the particle gyro-orbits), and are given by

\[
\mathbf{V}_{ld} = \mathbf{E} \times \mathbf{B}/B^2,
\]

where \( \mathbf{E} \) is the electric field. For the transport simulations to follow, these classical drifts are added to the anomalous ion and electron fluid velocity used to model turbulent transport, which is given by

\[
\mathbf{V}_d = -D \frac{\partial n_i}{\partial \mathbf{r}} \mathbf{i}_e,
\]

where \( \mathbf{i}_e \) is the unit vector normal to the magnetic flux surface, and \( r \) measures the distance in this direction. As described in more detail in [8], the model also has cross-field ion and electron thermal diffusivities and kinematic viscosities applied to both the parallel and perpendicular ion velocities. The perpendicular anomalous (turbulence) viscosity for the ion velocity gives rise to a net current across flux surfaces, adding to the current from the oppositely directed ion and electron magnetic drifts [8]. The numerical implementation of the transport terms takes advantage of the only retaining divergence-free terms [6,8] except at the domain boundaries.

The present simulations also include 4th order diffusion-like terms for the radial (\( r \)) direction to damp any strong variations on at the shortest unresolved grid-scale length for the ion density and two temperature equations. This technique [19] also allows more accurate central-difference scheme to be used rather than the strongly diffusive upwind difference scheme typically used in edge transport codes (comparison between differencing schemes is beyond the scope of this paper; see [20]). When steady-state solutions are obtained, these added diffusive terms are reduced to show that they have only minor impact on the solution obtained. Another method for reducing some of the numerical diffusion from the large vertical drifts \( V_{ld} \) is discussed in [21].

Neutral atoms and molecules are modeled as two separate fluid species. Owing to strong charge-exchange collisions with ions, the atoms have a parallel momentum equation similar to the ions [22] where charge-exchange collision provides a direct momentum exchange with the ions and a flux-limited viscosity coefficient describes elastic scattering with ions and neutrals. The atom velocities in the two orthogonal directions normal to the magnetic are given by

\[
\mathbf{V}_{d,na} = -D_{na} \frac{\partial n_a}{\partial \mathbf{r}} \nabla \cdot n_a \mathbf{i}_e,
\]

where \( D_{na} = (T_a/m_a)^{1/2}/v_{\text{cx}} \), which is flux-limited to keep \( V_{d,na} \) no larger than the local free-streaming thermal velocity, and \( v_{\text{cx}} \) is the neutral charge-exchange frequency with ions. Because of strong charge-exchange coupling between ions and neutral atoms, their temperatures are assumed to be very similar, i.e., \( T_a \approx T_i \). The energy equation for neutral atoms is thus added to that for the ions, yielding a combined energy equation that is solved for a mean ion/atom temperature \( \bar{T} \). The molecules that form the recycling flux from walls are assumed to have a temperature of 0.2 eV owing to some heating by ions and atoms based on limited Monte Carlo neutral simulations, and their fluid velocity is computed in a manner similar to the atoms, except \( D_{\text{num}} \) has the elastic collision frequency in the denominator determined by rate coefficient of \( 5 \times 10^{-16} \text{ m}^2/\text{s} \) for collisions with both ions and atoms, instead of \( v_{\text{cx}} \).

The magnetic drifts are essentially vertical and oppositely directed for ions and electrons, and their magnitude scales as
$T/(eBR)$, where $T$ is the temperature for ions or electrons. On the other hand, the electrostatic potential is of order $T_e/e$, such that the electric drift scales as $T_e/(eBR)$, where $L_p$ is the scale-length of the plasma gradient, either poloidal and radial. Because $R \gg L_p$, the electric drifts are expected to dominate, though they produce no net current, while the magnetic drifts do modify the current. The directions of the various drifts are shown in Fig. 1 for the divertor region of DIII-D.

3. Experimental setup and 2D DTS profiles

The experiments are performed on the DIII-D tokamak [23] at General Atomics in San Diego, CA. The divertor plates and chamber walls are carbon. A poloidal cross-section of the divertor region is shown in Fig. 1 where the toroidal plasma current is into the plane of the paper. When the toroidal magnetic field, $B_t$, is out of that plane, the ion $V_B$-drift is directed toward the X-point. This configuration is termed the forward $B_t$ (positive) case, while the opposite-sign of $B_t$ corresponds to the reversed $B_t$ (negative) case. The DTS system has 8 channels in a vertical line located at a major radius of $R = 1.49$ m, rising approximately 0.25 m above the target surface. This location in major radius is approximately at the outer strike point shown in Fig. 1. The DTS measures a series of snapshots of the electron density and temperature, $n_e$ and $T_e$, at each channel location.

In order to obtain a set of 2D profiles, the H-mode magnetic X-point is slowly swept outwards in $R$ over a 3 s period, with the DTS being fired over 100 times. The signals are then mapped onto a static magnetic equilibrium by shifting points radially by the difference between the instantaneous X-point and the reference X-point. During these series of discharges, all parameters are kept fixed with the exception of a changed gas-puffing rate to provide a density scan. More details are available in [16,17]. Results of the DTS scan for one of our base cases (shot 161005) for forward $B_t$ are shown in Fig. 2, where the separatrix electron density, $n_{sep}$, is used to characterize outer midplane conditions.

For forward $B_t$, the inner divertor plasma is detached ($T_e < 2$ eV), while for reverse $B_t$, it is attached (see Fig. 3). In the forward $B_t$ configuration, the inner divertor plasma typically has high density and low temperature, while the outer divertor has comparatively low density and high temperature. Upon reversal of $B_t$, the inner and outer divertor leg $T_e$ profiles are much more symmetric. Furthermore, this reversal produces a pronounced shift in the maximum divertor density from the inner leg to the outer leg.

In addition to profiles of $n_e$ and $T_e$ from DTS, experimental/simulation comparisons will also be made with the bolometer system that provides a 2D map of the total power emanating from the divertor region, including line radiation and charge-exchange neutrals [24].

4. Simulation results and comparison with data

For simulations in this paper, only a small region inside the magnetic separatrix is included because the focus is on changes in the divertor region plasma profiles as $n_{sep}$ is varied and as the sign of $B_t$ is changed. Thus, there is no attempt here to describe the pedestal region in any detail, say with a transport barrier, and...
the transport coefficients are simply taken as uniform radially. The inner boundary of most of the simulations is taken at a normalized poloidal flux of $\psi = 0.99$ to allow for nonuniform plasma density in the vicinity of the magnetic X-point to fully develop across the separatrix as will be seen in the results. Placing the core boundary further inward has only a modest effect on the associated poloidal variation of density and temperature near the separatrix for the cases presented, though a transport barrier very near the separatrix could influence the results. Simulations including transport barriers can be done, but often require significantly more simulation time.

Two cases of experimental conditions are considered, one being a series of similar high-power discharges with H-mode core confinement and scrape-off layer conditions, and the second being low power discharges in the L-mode. In the modeling, these two types of discharges are distinguished by different levels of anomalous transport diffusivity coefficients and input power, with the “H-mode” confinement having comparatively high power and small transport such that strong radial plasma gradients can develop in the divertor region, driving strong classical cross-field drifts, while the comparison “L-mode” case has lower power and anomalous transport coefficients that are 3–5 times larger. Because these two experimental cases are H- and L-mode discharges, we use these labels for the corresponding simulations, though they can also be viewed as comparing high-power, low diffusivity conditions to low-power, high diffusivity conditions.

4.1. H-mode conditions: 2D profiles

The simulations are performed on a flux-surface mesh corresponding to one discharge in the series being studied, namely shot 160997 (at 4 s). The simulation mesh in the divertor region is shown in Fig. 4, though a full single-null mesh links the inner and outer divertor legs around the top of the machine (not shown). Because the DTS measurements compared to the simulations are all collected at the major radius of $R = 1.49$ m where the divertor target is horizontal, we perform the simulations with a horizontal plate at $Z = -1.15$ across the whole domain. The simulation domain begins slightly inside the magnetic separatrix (a normalized poloidal flux of $\psi = 0.99$) to an outer boundary in the SOL of $\psi = 1.07$. Even for this high power, low diffusivity case, results for two sets of spatially-constant anomalous transport coefficients are compared, one having $D = 0.15$ m$^2$/s and $\chi_{ie} = 0.40$ m$^2$/s for ion and electron energy transport; the second set doubles all coefficients to show sensitivity of the solutions to modest changes in diffusivities. There is also a gas puff at the outer radial boundary near the top of the machine of $2.5 \times 10^{21}$ particles/s (0.4 kA-equiv). The main-chamber wall pumps atoms with an albedo of 0.99 with escaping ions and remaining atoms recycled as molecules at 100%. For the first set of simulation results shown in Figs. 5–8, a fixed 2% concentration of carbon is assumed with the radiation corresponding to coronal equilibrium in the presence of deuterium charge-exchange.

For a set of discharge with conditions the same as shown in Section 3, an outer midplane separatrix density scan has been performed at a neutral beam power of 4 MW where the X-point is
swept across the DTS over a 3 sec period while other conditions remained the same [16,17]. The data corresponds to times in the range of 50–90% between the occurrence of edge-localized modes (ELMs).

The UEDGE simulation for forward $B_1$ is shown in Fig. 5, and as in the experiment, the inner/outside divertor plasma asymmetry is strongly evident. The plasma flow driven by the $\mathbf{E}_p \times \mathbf{B}_i / B_i^2$ velocity diagnosed from the simulation directly under the X-point transports $6.3 \times 10^{23}$ particles/s (1 kA-equiv) from the outer divertor region to the inner divertor. This flow is approximately the same value as that entering the outer divertor leg across the SOL at the X-point height. Such strong flows were also identified in early cross-field drift simulations [7]. In the regions where $T_e \gtrsim 10$ eV, the radial width of the DTS profiles are generally substantially broader than those from UEDGE, suggesting that a large anomalous transport coefficients are needed to better fit the DTS data.

Upon reversal of $B_1$, UEDGE shows a strong reversal of the in/out divertor asymmetries, with the inner leg now attached, while the outer leg is detached. These contours are shown in Fig. 6 and can be compared to the DTS data of Fig. 3. Again the plasma flow under the X-point, now from the inner divertor region to the outer, is an important component in determining the characteristics of the UEDGE solution. The DTS, on the other hand, shows more balanced in/out divertor plasmas with respect to density and temperature. Again, the comparison suggests that the anomalous diffusivities should be increased, at least in the divertor legs, to better match the experimental data. A related model, not considered here, is strong outward convection caused by filamentary plasma blobs [25].

4.2. H-mode: density scan and detachment

As mentioned in Section 3, the density in the experiment is varied over a set of otherwise identical shots, and the maximum DTS electron temperature on the channel nearest the divertor plate is plotted versus $n_{sep}$. To model this density scan, the boundary value of density at the $\psi = 0.99$ flux surface is varied. Two comparisons with diagnostics have been considered, first, the in/out asymmetry in the 2D bolometer reconstructions of radiated power, and then the peak plate $T_e$, both versus $n_{sep}$. All of these simulations are steady-state solutions.

The DIII-D bolometer system [24] gives a detailed 2D map of the radiated power distribution. For these density scans, the signal is grouped into the fraction coming from regions with major radius $R$ smaller than its X-point value and the fraction coming from regions outside the X-point radius. The experimental data has been reported in [16,17] and is reproduced here. Both the experiment and the simulations show the same strong change in the in/out asymmetry of this radiation as the direction of $B_1$ is changed as seen in Fig. 7. Note that this power asymmetry is large at lower density and decreases at higher density, presumably because high densities have lower $T_e$ and thus the cross-field drifts become weaker.

Turning to the peak electron temperature on the divertor plates versus $n_{sep}$ from the simulations, variation on each divertor plate is shown in Fig. 8 for both signs of $B_1$. As the core plasma density increases, both divertor legs become detached and evolve to steady-state conditions without producing a radiative collapse of the core. The figure shows results for the higher H-mode diffusivity set with $D = 0.3$ m$^2$/s, while calculations for a factor of 2 reduction in the diffusivities show only a modest ~20% increase in the density for detachment.

The simulations sometimes find two solutions near the $n_{sep}$ threshold for detachment as shown explicitly in the forward $B_1$ curve in the right panel of Fig. 8. Thus, depending on the direction of approach - i.e., whether starting from initial conditions with a low density and moving to a higher density, or vise versa, one might arrive at different steady-state solutions as denoted by 1 and 2 on the figure. Alternately, one can begin at solution 1, and imagine a prompt injection of gas into the outer leg. Then allowing UEDGE to evolve the new plasma/neutral non-steady state in a time-accurate manner can lead to steady-state solution 2. Such bifurcations in the divertor plasma solution have been studied previously, most recently in [26]. As discussed in the next section, recent simulations for L-mode conditions in DIII-D do not show a bifurcation. Thus, a detailed understanding of the conditions for the occurrence of such bifurcations and whether they can explain the sudden drop observed in some data near detachment is the subject of current research.

As can be seen from the experimental $T_e$ contour plots (Figs. 2 and 3), the peak temperature generally occurs on the outer divertor plate for forward $B_1$, while for reverse $B_1$, the inner plate $T_e$ can
be comparable to that on the outer plate, but not larger. On the other hand, the simulations with fixed-fraction carbon find that for reverse $B_t$, the inner plate has a higher $T_e$ shown in Fig. 8, and that it is the last one to detach as $n_{sep}$ is increased.

The DTS data for the peak divertor electron temperature on the outer plate versus $n_{sep}$ is shown in the left panel of Fig. 9, where the reverse $B_t$ case is seen to detach at a lower density than the forward $B_t$ case [16,17]. This measurement is qualitatively consistent with the outer plate simulation data shown in the right panel of Fig. 8, but again, the reverse $B_t$ simulations show detachment at a lower $n_{sep}$ on the outer divertor than on the inner divertor, unlike the experiment.

The discrepancy between the experimental DTS data and simulations can be improved by introducing a full multi-charge state carbon impurity model where the carbon source is chemical and physical sputtering from the divertor plates. These calculations are described in a separate paper at this conference by Jaervinen et al. [27]. The results of the simulations are reproduced here for the peak $T_e$ on the outer plate, and are shown in the right panel of Fig. 9. Here, the substantial separation of the values of $n_{sep}$ where the peak $T_e$ reaches $\sim 2$ eV for the forward and reverse $B_t$ curves seen in the fixed-fraction results for the outer plate in Fig. 8 is greatly reduced, now being closer to the separation shown in the DTS data in the left panel of Fig. 9.

Finally, a few fixed-fraction carbon calculations have been performed with changes in the main-chamber wall albedo from the base-case value of 0.99. The pumping action of the walls is not well understood, so this can be considered a parameter to explore. It is found that decreasing the albedo to 0.975 provides a more balanced peak $T_e$ on the inner and outer plates for the reverse $B_t$ case compared to that shown in Fig. 6, while having only a small effect on the in/out asymmetry of the forward $B_t$ case. However, this lower albedo also increases the density needed for complete detachment, which is related to the need to have a certain particle content in each divertor leg to enable detachment [10].

4.3. Comparison for L-mode conditions

A set of L-mode experiments have also been performed on DIII-D using the same X-point sweeping strategy to obtain 2D DTS profiles while other conditions remained the same [28,29]. Here small, 100 ms diagnostic neutral beam blips plus ohmic power add for a total of $\sim 1$ MW of input power, resulting in an L-mode discharge. The density is increased by gas puffing over a number of otherwise identical discharges (DIII-D shot numbers 160299–160302, 160323–160327). The peak electron temperature and corresponding density on the first DTS channel ($\sim 1$ cm above the divertor plate) are given in the left panel of Fig. 10 for both forward and reverse $B_t$. The corresponding UEDGE solutions [28,29] are shown in the right panel. The anomalous diffusivities used in the SOL for these L-mode conditions are $\chi_e = 2.6 \text{ m}^2/\text{s}$, $\chi_i = 0.75 \text{ m}^2/\text{s}$ for $T_e$, and particle $D$ rising from 0.2 to 2.5$m^2$/s in the outer SOL. Note that there is a smooth reduction in $T_e$ as $n_{sep}$ is increased, with no evidence of multiple solutions seen in H-mode simulations.

In comparing $n_{sep}$ Values needed for detachment in the L-mode and H-mode cases, the direction of $B_t$ that gives the lowest density threshold changes. Both the experiment and the multi-charge-state carbon simulations find that the L-mode detaches at a lower density for forward $B_t$ (see Fig. 10) than reverse $B_t$. However, for the H-mode, it is the reverse $B_t$ case that detaches first (Fig. 9 and the left panel of Fig. 8). A detailed analysis and explanation of this behavior is presented in separate papers [27,29].

5. Discussion and conclusions

The present set of simulations is motivated by recent detailed DTS measurements showing the 2D character of the electron density and temperature in the DIII-D divertor region by utilizing sweeping of the X-point position [16,17]. The onset of full divertor detachment is found to occur at a somewhat lower $n_{sep}$ for the forward $B_t$ configuration (with the ion V58-drift toward the X-point). These detached plasmas appear stable without a radiative collapse of the core plasma. However, the separatrix electron temperatures are reduced in these detached cases.

The simulations focus on understanding the role of the direction of $B_t$ on (1), the in/out divertor leg plasma asymmetries in the attached plasma regime, and (2), the $n_{sep}$ needed to induce plasma detachment at the divertor plate. The reverse $B_t$ case shows a decrease (increase) in the inner divertor $n_e$ ($T_e$) with the opposite in the outer divertor. These changes are traced to large $E_x \times B_t |B^2|$ poloidal particle flow under the X-point coupled with large $E_p \times B_t |B^2 |$ radial flows across the divertor legs, where $E_x$ and $E_p$ are the radial and poloidal electric fields, respectively. Such flows have been modeled previously for L-mode plasmas (high anomalous transport) [7,14] and measured by probes [9].

The simulations sometimes find multiple steady-state solutions for the same value of $n_{sep}$ when different initial conditions are used as illustrated by solution branches 1 and 2 in the right panel of Fig. 8. This type of behavior is attributed to a bifurcation of the solution to the strongly nonlinear plasma/neutral equation set, and it has been observed in a number of other divertor simulations and described by a reduced model [26]. Typically, one solution corresponds to an attached plasma and the other detached. Experimentally, such states might be observed as a hysteresis in the $n_{sep}$ value.
at the detachment transition compared to the back transition by first increasing $n_{sep}$ above the detachment threshold and then reducing $n_{sep}$ until the attached state returns. The signature of a bifurcation would correspond to maintaining the detached state to a lower density while decreasing $n_{sep}$ than is found when initially increasing it to enter the detached state.

UEDGE simulations for H-mode conditions reproduce the qualitative character of the in/out divertor asymmetries as the direction of the toroidal magnetic field is changed. However, the quantitative comparisons between simulation and experimental profiles show some significant differences when a simple fixed-fraction carbon model is used. The degree of detachment in one leg or another is often not well reproduced, with the impact of changing the sign of $B_t$ being larger in the simulations than the experiment. Also, the radial width of the plasma profiles is larger in the DTS data than in the simulations, indicating that enhanced anomalous transport is needed at least in the divertor legs to better fit the data. Adding a multi-charge state carbon model is shown to improve the fit to the DTS data, especially the $n_{sep}$ value required for reaching detachment as discussed in more detail in [27].

**References**