Enhanced $\vec{E}\times\vec{B}$ Drift Effects in the TCV Snow Flake Divertor

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Enhanced $\vec{E} \times \vec{B}$ drift effects in the TCV snowflake divertor

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Abstract.

This work reports on the effect of the $\vec{E} \times \vec{B}$ particle drift on the edge plasma transport in TCV snowflake (SF) divertor configurations. Plasma boundary transport simulations using the EMC3-Eirene code show that the poloidal gradients of the kinetic profiles in the vicinity of the null-point of a SF divertor are substantially larger than those of a conventional single-null configuration. These gradients are expected to drive larger $\vec{E} \times \vec{B}$ flows in the SF divertor and are thought to be responsible for the formation of the double-peaked particle and heat flux target profiles observed experimentally. Experiments in forward and reversed toroidal magnetic field directions further support this conclusion. The formation of such a double-peaked profiles is enhanced at higher plasma densities and may have beneficial effects on the divertor heat loads since they lead to broader target profiles and lower peak heat fluxes.

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1. Introduction

In the demonstration power plant DEMO [1], and in future tokamak-based fusion power plants, the heating power is expected to be 4-5 times higher than in ITER [2]. However, as these devices will be only about 50% larger than ITER, unacceptably high values of power are expected on the plasma facing components of the divertor. The solution for this problem currently relies on a combination of core and divertor radiation with the edge power flow sufficiently above the H-mode transition threshold. Assuming that the constraints of the DEMO divertor will be similar to those of the ITER divertor, about 70-90% of the power exhausted must be radiated inside of the last closed flux surface (LCFS) [3]. However, it is not clear if these conditions can be sustained or will even be sufficient to maintain operation in the H-mode in reactor-sized machines [1]. To mitigate the risk that highly radiating regimes may not extrapolate towards devices like DEMO, alternatives to the conventional divertor are being researched. One of several magnetic divertor configurations that have been proposed is the “snowflake” (SF), which is characterized by a second order null-point [4]. In practice, the currents in the poloidal field (PF) coils required for creating an exact SF configuration always differ slightly from their exact values resulting in a SF configuration with two nearby first order null-points. The SF divertor has a hexagonal structure, with four divertor legs, and a lower poloidal magnetic field in the vicinity of the null-point, $B_{\theta,npt}$, than a conventional single-null (SN) divertor. In such a quasi-SF configuration, the primary x-point determines the LCFS while the secondary one can be located either in the private flux region (PFR) of the primary separatrix, usually referred to as snowflake plus (SF+), or in its common flux region, usually referred to as snowflake minus (SF-) [5]. The proximity of a divertor configuration to an exact SF can be characterized by the parameter $\sigma$, defined as the distance between the two nearby x-points, $d_{xpt}$, normalized with the plasma minor radius, $a$.

The SF configuration is expected to reduce the wall heat loads due to its geometrical properties in the vicinity of the null-point [4, 5, 6], namely a larger flux expansion, $f_{exp}$, larger divertor volume, which is usually associated with larger radiative losses and a greater energy transfer to neutrals [7], and a longer connection length, $L_{||}$, which is usually associated with a lower electron temperature at the divertor target and easier access to detachment [8]. The SF divertor configuration was first demonstrated experimentally in the TCV tokamak [9, 10] and has since also been obtained in the NSTX spherical torus [11, 12, 13] and in the DIII-D tokamak [14]. Experiments in these devices have shown that a substantial decrease of the peak heat flux on the divertor plates can be achieved. It was also shown that the SF configuration facilitates the access to detachment [12, 14], whilst keeping the energy confinement, L-H threshold and H-mode pedestal height similar to those obtained in similarly shaped SN diverted plasmas.

In medium-sized devices, like TCV, the aforementioned enhanced geometrical properties are limited to the inner part of the scrape-off layer (SOL) closest to the...
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separatrix [15]. In DEMO-sized devices, however, the SF properties are expected to be enhanced across the entire SOL. Even though in TCV the SF properties are enhanced only in a small part of the SOL, previous studies based on particle, momentum and energy transport simulations, using the EMC3-Eirene code [16], have shown that changes in the field line geometry alone with diffusive cross-field transport are not enough to explain the observed power distribution among strike points (SPs) nor the shape of the target profiles [17, 18]. This observation suggests the existence of an additional cross-field transport in the SF divertor.

In this work, a new set of experimental measurements and calculations using the EMC3-Eirene code are presented and compared in order to provide an improved understanding of the edge plasma transport in SF+ configurations. In the following section, the experimental setup will be presented. In section 3, the effects of $\sigma$, plasma density and direction of the toroidal magnetic field, $B_\phi$, on the target profiles and power distribution among SPs are presented. In section 4, the experimental measurements are compared with EMC3-Eirene simulations. A non-self-consistent estimate of the $\vec{E} \times \vec{B}$ drift is used to explain the discrepancies between the experiment and the simulations. Conclusions are presented in section 5.

2. Experimental Setup

The experiments described in this work were carried out in Ohmically heated L-mode discharges with the primary x-point placed near the centre of the TCV vessel in order to separate the null-point region from each of the four strike points. In these experiments, the toroidal magnetic field was set to 1.45 T, the plasma current ranges from 220 to 250 kA and the ion $\vec{V}B$ drift is directed towards the primary x-point, usually referred to as the “forward” direction. In these experiments, the plasma density is sufficiently low to keep the divertor legs in the attached regime and thus to exhaust most of the power entering the SOL in the vicinity of the SPs [19]. The discharges were prepared using the free-boundary equilibrium code FBTE [20] that calculates the currents in the PF coils required to create a prescribed magnetic configuration. The experimental equilibria are reconstructed, mainly from magnetic measurements, using the fitting code LIUQE [21].

In the following sections, the experimental measurements in SF+ configurations, figure 1(a), are compared with those obtained in a reference configuration, defined as a SF+ configuration with $\sigma = 1.5$, figure 1(b). The latter configuration is used for any future comparison and will be referred to as SN for simplicity. The SPs in any SF configuration are usually labelled in a counter clock-wise direction from one to four (SP1 to SP4) starting at the highest strike point on the HFS wall of TCV. In the SF+ configuration, SP1 and SP4 are the primary SPs while SP2 and SP3 are in the PFR, figure 1(a).
3. Experimental Observations

In this section, the measurements at the divertor targets are presented and the effects of $\sigma$, line averaged electron density, $n_{e,l}$, and direction of the toroidal magnetic field on the target profiles and power distribution among SPs are discussed. The target profiles are shown with respect to the reconstructed position of the separatrix using LIUQE. The target profiles at all four SPs of the SF are measured by wall mounted Langmuir probes. Small sweeps of the SP position across multiple Langmuir probes were used to increase the experimental spatial resolution.

3.1. Effect of $\sigma$ on the shape of the target profiles

Previous TCV experiments have shown an increase of the power distribution to the secondary SPs of a SF+ when the distance between x-points decreases [15]. This enhanced power distribution among SPs is accompanied by changes in the shape of the target profiles at the primary SP1 that cannot be explained by modifications of the field line geometry alone. While the target profiles measured at SP4 are not substantially affected when $\sigma$ decreases, the conventional single-peaked plasma density profile at SP1, figure 2(a), is replaced by a double-peaked profile, figure 2(b). Decreasing $\sigma$ also affects the electron temperature, $T_e$, profile at SP1, which becomes more peaked.
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near the separatrix and with lower values in the far-SOL, compared with those in a SN configuration, figures 2(c-d). Experimental observations of double-peaked target profiles have already been reported in conventional single-null configurations [22, 23]. A possible explanation arises from the similarities between experimental observations in JET and modelling, using the EDGE2D code with particle drifts included [24]. This study shows that the appearance of double-peaked target profiles can be caused by plasma transport due to the $\vec{E} \times \vec{B}$ drift. The TCV measurements shown in figure 2, therefore, suggest that the effects of the $\vec{E} \times \vec{B}$ drift could be enhanced in SF configurations.

![Figure 2. Langmuir probes measurements of the electron density and temperature target profiles at SP1 in a (a,c) SN and in a (b,d) SF+ configuration with $\sigma = 0.4$ and $n_{e,1} \approx 3 \times 10^{19} \text{ m}^{-3}$.](image)

**3.2. Effect of the plasma density on the power distribution and shape of the target profiles**

Langmuir probe measurements at SP1 show that the amplitude of the second peak appearing in the plasma density profile increases with $n_{e,1}$. This effect can also be seen on the ion saturation current, $J_{\text{sat}}$, and heat flux, $q$, profiles, which change from a single-peaked to a double-peaked shape as $n_{e,1}$ increases, figures 3. The measurements show that, along with the appearance of a second peak, the target profiles broadens and leads to a decrease of the peak heat flux on the divertor plates. For $n_{e,1} \geq 5 \times 10^{19} \text{ m}^{-3}$, the amplitude of the second peak exceeds the amplitude of the peak near the SP location and, for even higher values of $n_{e,1}$, the second peak dominates the profile shape changing
it back to a single-peaked one. The measurements also show that, along with an increase of \( n_{e,l} \), a decrease of the power detected at SP2 and SP3 is observed, figure 4. This may suggest that the plasma transport responsible for the appearance of the double-peaked profiles at the SP1 target also leads to less cross-field transport into the PFR.

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\vec{E} \times \vec{B} \text{ drift effects in the TCV snowflake divertor}
\]

3.3. Effect of reversing \( B_\phi \) on the shape of the target profiles

Since a possible explanation for the observed shape of the target profiles in SF configurations is based on particle drifts [24], reversing the direction of \( B_\phi \) is expected to have a significant effect on the edge plasma transport and on the shape of the target profiles [25]. To further investigate the importance of particle drifts on the formation of these double-peaked profile at SP1, experiments with reversed \( B_\phi \) were carried out in TCV. The measurements show that the double-peaked target profiles in forward \( B_\phi \), figure 5(a), are replace by single-peaked profiles in reversed \( B_\phi \), figure 5(b). In addition, note that the original peak value of the density profile in forward \( B_\phi \) occurs in the PFR side of SP1 whereas, in reversed \( B_\phi \), it occurs in the SOL side. Reversing \( B_\phi \) also affects the electron temperature profile, figure 5(c-d).
temperature profile near the separatrix, observed in forward $B_\phi$, is replaced by a flatter profile when $B_\phi$ is reversed. This dependence on the direction of $B_\phi$ strongly indicates that particle drifts indeed have a significant and stronger influence on the edge plasma transport in the SF divertor than in a SN divertor. Langmuir probe measurements indicate that both primary strike points (SP1 and SP4) remain attached for the entire range of investigated plasma densities for both forward and reversed $B_\phi$ configurations, figure 6, and no significant changes are observed on the profile shapes at SP4.

4. The $\vec{E} \times \vec{B}$ Drift in the Snowflake Divertor

Studies using the EMC3-Eirene code to model the plasma transport in the edge of SF+ configurations show that diffusive cross-field transport alone is insufficient to explain the experimentally observed power distribution to the secondary SPs as well as the target profiles shape [15, 17, 18]. One possible explanation for these discrepancies is that particle drifts are not included in the EMC3 model and, as shown in the previous section, they are expected to have a significant effect on the edge plasma transport in SF configurations. In this section, the importance of particle drifts on the EMC3-Eirene simulations will be investigated in order to provide a better understanding of the plasma transport in the edge of SF+ configurations.

4.1. Description of the particle drifts

Two alternative approaches can be used to investigate the effects of particle drifts on the plasma transport: the fluid or the average guiding centre approach [25]. In the fluid approach, the single-fluid momentum conservation equation is used to calculate the total particle flux which, under stationary conditions, is given by [26]
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Figure 5. Langmuir probe measurements of the electron density and temperature at SP1 in (a,c) forward and (b,d) reversed $B_\phi$ with $n_{e,1} \approx 3 \times 10^{19} \text{ m}^{-3}$.

Figure 6. Langmuir probe measurements of the recycling current measured at the SP1 and SP4 targets of a SF+ configuration with $\sigma = 0.4$ in (a) forward and (b) reversed $B_\phi$.

\[
\vec{\Gamma} = n \vec{u}_\parallel + \frac{\vec{f}_{\text{fric}} \times \vec{B}}{e B^2} + \frac{\vec{B} \times \vec{\nabla} p_\perp}{e B^2} + \frac{\left(p_\parallel - p_\perp + n m_i u_\parallel\right)}{e B^3} \vec{B} \times \left[ \left( \frac{\vec{B} \cdot \vec{\nabla}}{B} \right) \frac{\vec{B}}{B} \right] + n \frac{\vec{E} \times \vec{B}}{B^2}.
\] (1)
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In this equation, $n$ is the plasma density, $\vec{u}_{||}$ is the parallel fluid velocity, $e$ is the elementary electric charge, $m_i$ is the ion mass, $\vec{E}$ is the total self-consistent electric field, $f_{\text{fric}}$ is a friction force density due to the interaction between ions and neutrals, $p_{||}$ is the parallel plasma pressure and $p_{\perp}$ the perpendicular plasma pressure (see [26] for more details). The parallel and perpendicular directions are defined with respect to the total magnetic field, $\vec{B}$. In equation 1, the first term represents the usual parallel particle flux while the others represent the particle transport due to various particle drifts. The second term accounts for the cross-field transport due to collisions between ions and neutrals, and can be neglected in almost the entire SOL as it is significant only for temperatures $\lesssim 5\text{ eV}$ [27]. The third term represents the diamagnetic drift, which do not significantly influence the plasma transport since it is largely divergence-free. The fourth term accounts for the contribution from both the curvature and gradient of the total magnetic field, which scales inversely with the major radius. The last term corresponds to the $\vec{E} \times \vec{B}$ drift and, as it scales with the local scale length of the kinetic profiles, it is usually the dominant drift term among the others [28]. The effect of particle drifts in the null-point region of conventional SN divertor configurations, in particular the $\vec{E} \times \vec{B}$ drift, was already investigated numerically [28, 29] and experimentally [30, 31]. Since the $\vec{E} \times \vec{B}$ is the leading order term among the other drift terms, only its effect will be considered in the following analysis of the plasma transport in the SOL of SF+ configurations.

4.2. The edge plasma transport caused by the $\vec{E} \times \vec{B}$ drift

The effect of the $\vec{E} \times \vec{B}$ drift is described using a coordinate system $(\rho, s_\theta, \phi)$ with a radial direction, $\hat{e}_\rho$, perpendicular to the flux surfaces and a poloidal direction, $\hat{e}_\phi$, parallel to the flux surfaces in the poloidal plane, figure 7. The toroidal direction, $\hat{e}_\theta$, remains as usual.

In this coordinate system, the steady state electric field, $\vec{E} = E_\rho \hat{e}_\rho + E_\phi \hat{e}_\phi + E_\theta \hat{e}_\theta$, and magnetic field, $\vec{B} = B_\rho \hat{e}_\rho + B_\phi \hat{e}_\phi + B_\theta \hat{e}_\theta$, are used to evaluate the $\vec{E} \times \vec{B}$ drift velocity,

$$\vec{u}_{\text{E} \times \text{B}} = \left( \frac{E_\phi B_\rho - E_\rho B_\phi}{B^2} \right) \hat{e}_\rho - \frac{E_\rho B_\phi}{B^2} \hat{e}_\theta + \frac{E_\phi B_\theta}{B^2} \hat{e}_\phi.$$  

(2)

The toroidal component of the electric field, $E_\phi = V_{\text{loop}}/(2\pi R)$ is determined by the loop voltage, $V_{\text{loop}}$, with $R$ being the major radius coordinate. The poloidal component of the electric field, $E_\theta = B E_{||}/B_\theta$, can be calculated using the parallel electron momentum balance equation,

$$E_{||} = \frac{J_{||}}{\sigma_{||}} - 1.71 \frac{\partial T_e}{\partial s_{||}} - \frac{T_e}{n} \frac{\partial n}{\partial s_{||}}.$$  

(3)

Here, $E_{||}$ is the parallel electric field, $J_{||}$ is the parallel current density, $\sigma_{||}$ is the parallel plasma electric conductivity and $s_{||}$ is a coordinate in the parallel direction. Estimates of $E_{||}$ using equation 3 show that the $J_{||}/\sigma_{||}$ term is negligible compared with the other terms. To estimate the importance of the $\vec{E} \times \vec{B}$ drift on the edge
plasma transport, the particle flux calculated by EMC3-Eirene, $\Gamma_{||}$, is compared with the particle flux induced by the $\vec{E} \times \vec{B}$ drift, $\vec{\Gamma}_{E \times B}$, which is estimated using the kinetic profiles calculated by EMC3-Eirene. According to equation 2, the radial component of the $\vec{E} \times \vec{B}$ drift velocity depends on the poloidal electric field that, by neglecting the parallel current and using the relation $\frac{\partial}{\partial s_{||}} = \frac{B_{\theta}}{B} \frac{\partial}{\partial s_{\theta}}$, can be rewritten as:

$$E_\theta (\rho, s_\theta) = -1.71 \frac{\partial T_e (\rho, s_\theta)}{\partial s_\theta} - \frac{T_e (\rho, s_\theta)}{n (\rho, s_\theta)} \frac{\partial n (\rho, s_\theta)}{\partial s_\theta}.$$  

After calculating $E_\theta$, the plasma potential $\Phi$ can be estimated by

$$\Phi (\rho, s_\theta) = \frac{T_e (\rho, 0)}{2} \ln \left\{ \frac{m_i}{2 \pi m_e} \left[ 1 + \frac{T_i (\rho, 0)}{T_e (\rho, 0)} \right]^{-1} \right\} - \int_0^{s_\theta} E_\theta (\rho, s_\theta') \, ds_\theta'.$$

The first term on the right hand side of equation 5 is the sheath potential calculated at the LFS target ($s_\theta = 0$) for each flux tube [32]. Since ambipolar transport is assumed in EMC3 ($J_{||} \equiv 0$ at each location on the wall), the HFS target can equally be used to calculate the plasma potential without affecting the final result. With $\Phi (\rho, s_\theta)$, the radial electric field can be calculated, $E_\rho (\rho, s_\theta) = -\nabla \Phi \cdot \hat{e}_\rho$.

As an example, the electric potential, and the poloidal and radial electric fields in the common flux region of a SF+ configuration with $\sigma = 0.1$ are shown in figure 8(a-c). These calculations were performed using the plasma density and electron temperature poloidal distributions from a EMC3-Eirene simulation of the TCV discharge #43418 [18]. In this simulation, the Ohmic heating power at the inner simulation boundary is
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consistent with that from the experiment, $P_{in} = 238$ kW, and equal power distribution between electrons and ions is assumed. The plasma density at the inner simulation boundary was changed until the plasma density at a point in the separatrix, farthest away from the primary x-point, reaches $n = 2.5 \times 10^{19}$ m$^{-3}$, which is the value measured by the Thomson scattering diagnostic. The cross-field particle, $D_{\perp}$, and heat, $\chi_{\perp}$, diffusivities were adjusted to $D_{\perp} = \chi_{e,\perp} = \chi_{i,\perp} = 0.6$ m$^2$/s in order to match the heat flux profile measured at SP1 using Langmuir probes.

**Figure 8.** (a) Poloidal electric field, (b) electric potential and (c) radial electric field for a SF configuration with $\sigma = 0.1$. Ratio between (d) the radial and (e) the poloidal component of the particle flux due to the $\vec{E} \times \vec{B}$ drift with the poloidal projection of the parallel plasma flux for a SF configuration with $\sigma = 0.1$.

Using equation 2, the particle flux due to the $\vec{E} \times \vec{B}$ drift, $\vec{\Gamma}^{E \times B} = n \vec{u}_{E \times B}$, can be estimated and compared with the poloidal projection of the parallel particle flux calculated by EMC3-Eirene, $\Gamma_\theta = \Gamma_{||} B_\theta / B$. In this investigated case, the particle fluxes $\Gamma_\theta$, $\Gamma_\rho^{E \times B}$ and $\Gamma_\rho^{E \times B}$ are of the same order of magnitude in some regions of the SOL, figures 8(d-e). The radial component of $\vec{\Gamma}^{E \times B}$ is larger than $\Gamma_\theta$ in most of the null-point region and its poloidal component is larger than $\Gamma_\theta$ in almost the entire SOL. Therefore, the kinetic profiles calculated by EMC3-Eirene are expected to cause an $\vec{E} \times \vec{B}$ drift that locally alters the convective transport in both poloidal and radial directions. The
absence of this mechanism in the EMC3 model could explain the observed discrepancies between measured and simulated target profiles.

4.3. Transport into the private flux region of SF+ configurations

The EMC3 code is well suited to handle the complex magnetic geometry of the SF+ configuration with both primary and secondary x-points included in the simulation domain [18]. To investigate the effects of the $\vec{E} \times \vec{B}$ drift on the edge plasma transport of SF plasmas self-consistently, the EMC3 equations and boundary conditions would have to be modified accordingly. However, even though a version of the EMC3 code with particle drifts included in its model is not available yet, the previous EMC3-Eirene results can still be extrapolated to evaluate whether the discrepancies between simulated and measured target profiles can be qualitatively explained by the neglecting of the $\vec{E} \times \vec{B}$ drift. In this section, the influence of the $\vec{E} \times \vec{B}$ drift on the plasma transport into the PFR of SF+ configurations will be discussed.

![Figure 9.](image)

Figure 9. Poloidal profiles of the EMC3-Eirene simulated (a) electron and (b) ion temperatures, (c) plasma density and (d) poloidal electric field for a SN ($\sigma = 1.00$) and a SF+ configuration ($\sigma = 0.1$). The origin $s_\theta = 0$ corresponds to the LFS target (SP4) while the position $s_\theta = L_p \approx 2.5$ m corresponds to the HFS target (SP1).

According to equation 3, sufficiently large poloidal gradients of the kinetic profiles can cause the appearance of an additional transport due to the $\vec{E} \times \vec{B}$ drift. Calculations performed using the EMC3-Eirene code show that the poloidal gradients of the kinetic profiles in the null-point region of SF configurations are larger compared with those in
conventional SN divertors, figures 9(a-c). These larger poloidal gradients are caused by the longer parallel length of field lines within a certain poloidal interval in the null-point region of the SF divertor. The larger poloidal gradients of the kinetic profiles lead to higher values of the poloidal electric field, figure 9(d), which in turn are expected to cause a stronger $\vec{E} \times \vec{B}$ drift, thus leading to an additional radial transport.

At smaller values of $\sigma$, the distance between primary and secondary separatrices decreases and a larger fraction of heat and particles transported across the primary separatrix (SP4 divertor leg) is also able to cross the secondary separatrix, figure 10(a). This effect is enhanced by the $\vec{E} \times \vec{B}$ drift as its radial component depends on $E_\theta$, which is expected to increase when $\sigma$ is reduced. After crossing the secondary separatrix (SP4 divertor leg), the particles are convected towards SP3 by the poloidal component of the $\vec{E} \times \vec{B}$ drift. This predicted effect of the $\vec{E} \times \vec{B}$ drift is in qualitative agreement with the enhanced power distribution to SP3 observed in the experiments, which is underestimated in the EMC3-Eirene simulations. The $\vec{E} \times \vec{B}$ drift also provides an explanation for the asymmetric shape of the experimentally measured heat flux profile at SP3 in SF+ configurations, figure 10(b), while the EMC3-Eirene calculations predict a symmetric profile, figure 4 of [18].

The $\vec{E} \times \vec{B}$ flow along the SP3 divertor leg is expected to enhance the plasma flow in the LFS of SP3 while on the HFS it is directed against the plasma flow. The poloidal $\vec{E} \times \vec{B}$ drift is expected to convect heat and particles from the HFS of SP3 to the lower side of SP2 while, on the upper side of SP2, the poloidal $\vec{E} \times \vec{B}$ drift transports heat and particles towards SP1, figure 10(a). This effect is also in qualitative agreement with the observed lower values of power detected at SP2, compared with those detected at SP3, and with the observation that the peak of the density profile at SP1 is located in the PFR, figure 5(a).

![Figure 10](image_url)

**Figure 10.** Schematic showing the expected $\vec{E} \times \vec{B}$ drifts (a) in the null-point region and (b) along the SP3 plasma leg of a SF+ configuration with forward toroidal magnetic field.

To further investigate the importance of the $\vec{E} \times \vec{B}$ drift on the activation of the secondary SPs, the radial $\vec{E} \times \vec{B}$ particle flux was calculated in the common flux region of a SF+ configuration with $\sigma = 0.1$ for two different values of plasma density. At the lower plasma density, the region with increased radial transport due to the $\vec{E} \times \vec{B}$ drift
Enhanced $\vec{E} \times \vec{B}$ drift effects in the TCV snowflake divertor extends down to the divertor legs whereas, at the higher plasma density, the region with enhanced radial transport moves upstream, figure 11. The plasma transport across the SP4 divertor leg into the PFR due to the $\vec{E} \times \vec{B}$ drift is, therefore, expected to decrease as the plasma density increases, which agrees with the measurements shown in figure 4. These measurements also show that, for $n_{e1} \gtrsim 6 \times 10^{19} \text{ m}^{-3}$, the power distribution to SP2 and SP3 remains approximately the same. This could be explained by the fact that, at higher values of plasma density, the radial $\vec{E} \times \vec{B}$ drift does not contribute to the plasma transport into the PFR and the relatively smaller power distribution observed is provided by, e.g. diffusion.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig11.png}
\caption{Ratio between the calculated radial $\vec{E} \times \vec{B}$ particle flux and the poloidal projection of the EMC3-Eirene parallel particle flux in a SF+ configuration with $\sigma = 0.1$ and forward $B_\phi$ for (a) $n = 4 \times 10^{19} \text{ m}^{-3}$ and (b) $n = 8 \times 10^{19} \text{ m}^{-3}$.}
\end{figure}

4.4. The target profile shapes in forward and reversed $B_\phi$

In a fluid model, the net transport caused by the $\vec{E} \times \vec{B}$ drift can be treated as source terms. In the particle conservation equation, such a source term accounts for the net particle transport caused by the divergence of the $\vec{E} \times \vec{B}$ particle flux, $S_\rho^{\text{ExB}} = -\vec{\nabla} \cdot \left( \Gamma^{\text{ExB}} \right)$. The same procedure is performed on the electron and ion energy conservation equations by adding an energy source term that corresponds to the net energy transported by the divergence of the electron ($\alpha = e$) and ion ($\alpha = i$) $\vec{E} \times \vec{B}$ energy flux, $S_{\rho\alpha}^{\text{ExB}} = -\vec{\nabla} \cdot \left( \frac{2}{3} k_B T_\alpha \Gamma_\alpha^{\text{ExB}} \right)$. In order to investigate the effects caused by the $\vec{E} \times \vec{B}$ drift on the shape of the target profiles, these source terms were calculated for a SF+ configuration with $\sigma = 0.1$ and with forward $B_\phi$. The calculations show that the $\vec{E} \times \vec{B}$ drift is predicted to have a stronger effect in front of the SP1 target than
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in front of the SP4 target, figure 12. This is consistent with the fact that the target profile shapes at SP4 are not significantly affected by changing $\sigma$, plasma density or by reversing $B_{\phi}$. The calculations also show that the $\vec{E} \times \vec{B}$ drift reduces the particle source, $S_{p}^{E \times B}$, near the separatrix in front of SP1 and increase it in the far-SOL, figure 12(a). This in turn causes a decrease of the plasma density near the separatrix in front of the SP1 target and an increase in the far-SOL, which agrees qualitatively with the double-peaked profile shapes observed at SP1, figures 2(b) and 3. Concerning the total energy source, $S_{ee}^{E \times B} + S_{ei}^{E \times B}$, the calculations show that the $\vec{E} \times \vec{B}$ drift is expected to increase the amount of heat deposited near the separatrix in front of the SP1 target and reduce it in the far-SOL, figure 12(b). This would cause the electron temperature profile to peak near the separatrix at the SP1 target, which is also observed experimentally, figure 5(c).

To further investigate the importance of the $\vec{E} \times \vec{B}$ drift on the edge plasma transport in SF+ configurations, the particle and energy sources were calculated assuming a reversed $B_{\phi}$ and compared with the experimental measurements. In reversed $B_{\phi}$, the $\vec{E} \times \vec{B}$ drift is expected to increase the particle source, $S_{p}^{E \times B}$, near the separatrix in front of the SP1 target and reduce it in the far-SOL, figure 13(a). This would cause the plasma density profile at the SP1 target to have a conventional single-peaked shape rather than a double-peaked shape, which is in agreement with the measurements shown in figure 5(a-b). The $\vec{E} \times \vec{B}$ drift in reversed $B_{\phi}$ is also expected to reduce the total energy source, $S_{ee}^{E \times B} + S_{ei}^{E \times B}$, near the separatrix in front of the SP1 target and increase it in the far-SOL, figure 13(b), causing a flattening of the electron temperature profile at the SP1 target rather than a peaking, which was also observed in the experiments, figure 5(c-d). In addition, the calculations show that the $\vec{E} \times \vec{B}$ drift in reversed $B_{\phi}$ is expected to increase the particle source in the LFS part of the SOL and decrease it.

Figure 12. (a) Particle and (b) energy sources due to $\vec{E} \times \vec{B}$ drift for a SF+ configuration with $\sigma = 0.1$ and forward $B_{\phi}$.

Forward Toroidal Magnetic Field

![Diagram showing particle and energy sources due to E x B drift for a SF+ configuration with σ = 0.1 and forward B_φ.](image_url)
in the HFS part of the SOL with respect to the forward $B_\phi$ configuration. This would cause an increase of the recycling current at SP4 and a decrease of it at SP1 in reversed $B_\phi$, compared with the values measured in forward $B_\phi$. These predictions are also in qualitative agreement with the recycling current measurements, figure 6.

The qualitative agreement between the experimental measurements and the expected effects of the $\vec{E} \times \vec{B}$ drift on the EMC3-Eirene simulations strongly suggests that the $\vec{E} \times \vec{B}$ drift is a relevant transport mechanism that has to be included in future simulations of the SF divertor in order to obtain more meaningful, reliable and predictive results.

5. Summary

The potential advantages of the snowflake (SF) divertor to alleviate the divertor heat loads arise from its enhanced magnetic properties that, in TCV, are limited only to a tiny region of the scrape-off layer (SOL) close to the separatrix [15]. However, even though such enhancement occurs in a small part of the SOL, previous studies have shown that changes in the field line geometry alone with diffusive cross-field transport are not enough to explain the observed power distribution among strike points (SPs) nor the shape of the target profiles [17, 18]. This observation strongly suggests the existence of an additional cross-field transport in the null-point region of the SF divertor. In this article, TCV experiments and EMC3-Eirene simulations of particle, momentum and energy transport in the boundary of SF plasmas are used to provide a better insight into the plasma transport in the TCV SF divertor.
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EMC3-Eirene simulations of the plasma transport in the edge of SF+ configurations show that larger poloidal gradients of the kinetic profiles develops in the null-point region as the distance between the x-points decreases. These gradients generate a poloidal electric field in the null-point region of the SF configuration that is significantly larger than that in a single-null (SN) configuration, thus driving considerably larger $\vec{E} \times \vec{B}$ particle flux in the edge of SF configurations. These fluxes are estimated to be of the same order of magnitude of the particle fluxes calculated by EMC3-Eirene, specially in the null-point region, and are thought to be responsible for the formation of the double-peaked particle and heat flux target profiles observed at SP1. It has to be pointed out that these estimates are not self-consistent but based on the kinetic parameters obtained from EMC3-Eirene calculations without including the $\vec{E} \times \vec{B}$ drift. The calculations show that, in a SF configuration with forward toroidal magnetic field direction, the $\vec{E} \times \vec{B}$ drift transports particles in front of the SP1 target from a region near the separatrix to a region more in the far-SOL, giving rise to the observed double-peaked target profiles. Comparisons between calculations and experiments in forward and reversed toroidal magnetic field directions further supports this conclusion. The formation of such a double-peaked profiles may have a beneficial effect on the divertor heat loads since they lead to broader target profiles and consequently lower peak heat fluxes.

The results presented in this article strongly suggest that the additional cross-field transport required to explain the measured power distribution to SP3, which is underestimated in the EMC3-Eirene simulations [18], is caused by the radial component of the $\vec{E} \times \vec{B}$ drift, which transports plasma across the SP4 leg into the PFR. This radial transport also explains the asymmetric shape of the particle and heat flux profiles measured at the SP3 target, in contrast to the symmetric profile shapes predicted by the EMC3-Eirene calculations. Furthermore, the results show that the smaller power distribution to SP3 observed at higher plasma densities is caused by a decrease of the poloidal gradients of the kinetic profiles in the null-point region, which leads to less $\vec{E} \times \vec{B}$ radial transport into the PFR. The same effect is expected to be observed in high power discharges with higher temperatures in the SOL. Due to the strong temperature dependence of the parallel electron heat conductivity [25], higher temperatures lead to a substantial decrease of the poloidal gradients of the electron temperature, which in turn decrease the $\vec{E} \times \vec{B}$ radial transport into the PFR and, consequently, the power distribution to SP3.

In this work, the $\vec{E} \times \vec{B}$ drift is identified as a key transport mechanism of the edge plasma transport in the TCV SF+ configurations and, therefore, has to be accounted in future numerical modelling in order to obtain more meaningful, predictive and reliable results.

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