On the origin of anomalous radial transport in the tokamak SOL

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Abstract. Turbulent transport in the scrape-off layer of TCV has been investigated by probe measurements and direct comparison with two-dimensional fluid simulations of interchange motions at the outer midplane. The experiments demonstrate that the fluctuation statistics in the region where plasma profiles are broad are invariant with respect to changes in the line-averaged core plasma density. Good agreement is found between measurements and an interchange turbulence simulation at high density, indicating that the turbulent transport is dominated by the radial motion of field-aligned plasma filaments. Moreover, the plasma flux onto the main chamber wall at the outer midplane scales linearly with the local particle density, implying that the particle flux at the wall radius can be parameterized in terms of an effective convection velocity. Strong ballooning of the edge turbulence would also result in toroidal field direction independent transport-driven parallel flows in the scrape-off layer. The magnitude of this flow estimated from pressure fluctuation statistics in the simulations is found to compare favorably with the measured flow offset obtained when averaging data obtained from flow profiles observed in matched forward and reversed field discharges.

1. Introduction

The high rate of cross-field transport in the tokamak scrape-off layer (SOL) is commonly attributed to turbulence, but typically only in a qualitative sense. By comparing statistical analysis of particle density fluctuations and fluctuation-driven cross-field turbulent flux measurements in the SOL of TCV with that of time series from two-dimensional interchange turbulence simulations, this paper demonstrates, quantitatively, that turbulent particle transport in the SOL may be ascribed to interchange motions [1–6].

Interchange dynamics has long been regarded as a source of the turbulence and anomalous transport which are universally observed at the boundary of magnetically confined plasmas. However, substantial advances in describing the collective motions have been limited until recently by the assumptions of the flux–gradient paradigm (in which the fluxes of particles and heat are assumed to be proportional to the local profile gradients) and sheath-dissipation in two-dimensional models (which implies that the turbulence structures are perfectly field-aligned and subject to strong sheath currents at material surfaces) [7–11].

TABLE I: A LIST OF THE TCV PULSES CONSIDERED IN THIS PAPER, SHOWING THE PULSE NUMBER, PROBE RECIPROCATIONS USED FOR THE ANALYSIS, LINE-AVERAGED DENSITY, AND THE SYMBOLS USED IN THE SUBSEQUENT FIGURES.

Pulse number	Reciprocation	$\overline{n}_e$ $[10^{19}\,m^{-3}]$	Symbol
24530	2	11	▲ (red)
26092	1 & 2	8.4	▲ (green)
26060	1 & 2	6.5	♦ (black)
26084	1 & 2	4.8	▼ (blue)
24530	1	4.4	▼ (magenta)
ESEL			—●— (grey)

Analysis of probe measurements from the outboard midplane region of a wide range of TCV Ohmic L-mode discharges show that the particle density and turbulent flux probability distribution functions (PDFs) exhibit a high degree of statistical similarity. At the SOL–main chamber interface, the fluctuations are self-similar over a wide frequency range, with both particle and turbulent flux density PDFs found to be universal in shape. The implication, confirmed by observation, is that both the absolute flux and the fluctuation amplitude must scale with the local mean density near the wall [1, 2].

A fundamental result of this scaling is that the turbulent particle flux in the wall region can be parameterized in terms of an effective convection velocity. Here it is shown from the experimental measurements that this is indeed the case, although there does not seem to be any simple flux parameterization which is valid through the whole SOL region and for all plasma densities. It is also shown that the particle flux density at the wall radius scales with the square of the line-averaged density, providing a link between a main operating parameter and the turbulence driven wall flux. Finally, a simple estimate of the transport driven parallel flow component in the SOL is shown to be in good agreement with the experimental measurements. The favorable comparison achieved with ESEL turbulence simulations across a range of profile information, fluctuation statistics and flows, indicates that both the radial transport and a significant component of the parallel flows are due to radial interchange motions of plasma filaments [12, 13].

2. Turbulent fluctuations

In this paper we present results from a set of ohmically heated, single null lower (SNL) diverted TCV pulses with a plasma current of 340 kA and varying line-averaged core plasma density $\overline{n}_e$. Fluctuation statistics are derived from measurements with a five-pin probe head reciprocating twice into the plasma for each pulse at a distance 23 cm below the outer midplane. The probe time series have been analyzed and compared with results from an ESEL interchange turbulence simulation for a high density case. Figure 1 in Ref. [3] illustrates the magnetic equilibrium of the SNL discharge together with the probe reciprocation trajectory.

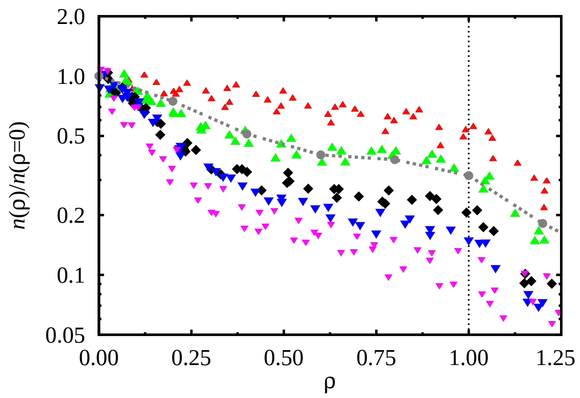

FIG. 1. Radial profile of the particle density normalized to the separatrix values.

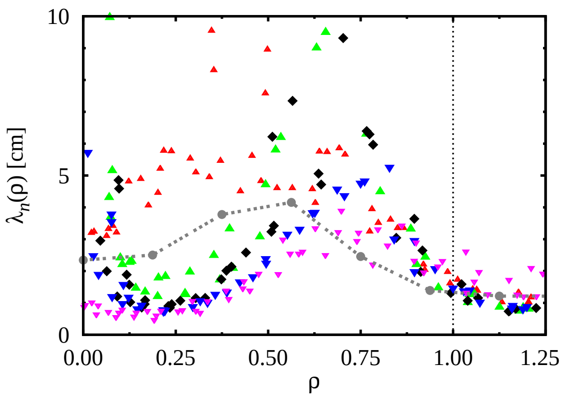

FIG. 2. Radial variation of the exponential particle density scale length.

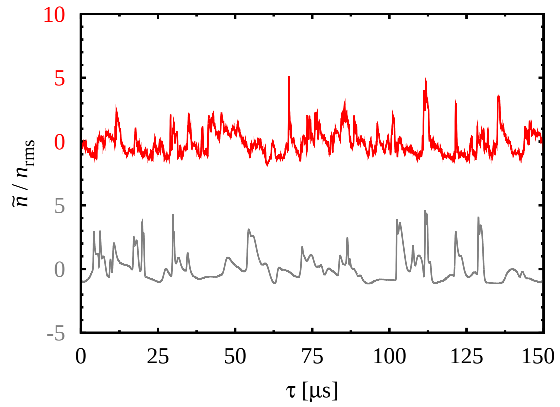

FIG. 3. Time series of the particle density at the wall radius from experiment and simulation.

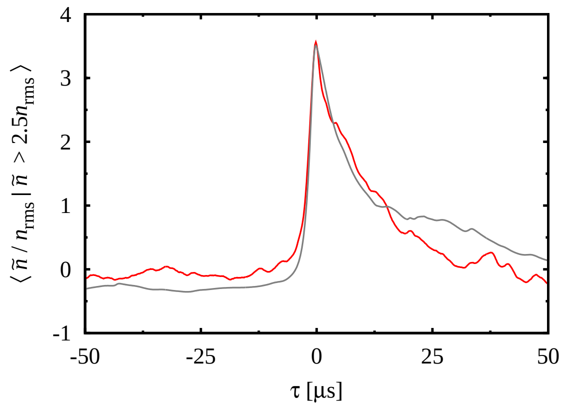

FIG. 4. Conditional average of the particle density at the wall radius from experiment and simulation.

Table I lists the TCV pulses considered in the present contribution, and the symbols used in the following figures. It should be noted that pulse 24530 is a density ramp discharge with the first probe reciprocation at low line-averaged density and the second reciprocation at high density. In the following we apply a normalized radial coordinate ρ, defined such that $\rho = 0$ at the separatrix and $\rho = 1$ at the wall radius when mapped along flux surfaces from the probe position to the outboard midplane. The separatrix to wall clearance is approximately 3 cm for the TCV pulses considered here. Further description of the experiments and the interchange turbulence simulation can be found in Refs. [1–6].

As $\overline{n}_e$ increases, the time-averaged SOL particle density profile qualitatively changes shape. At low density, the profile has a steep gradient region in the vicinity of the magnetic separatrix and a significantly larger scale length in the outer part of the SOL. Note that beyond $\rho = 1$, the gradients increase substantially in all cases due to the strong wall sink. However, with increasing $\overline{n}_e$ the profile becomes broader in both radial extent and length scale. This is clearly seen from Figs. 1 and 2, showing the time-averaged particle density profile n and the corresponding scale length $\lambda_n = -1/(\partial \ln n/\partial r)$ for a range of TCV discharges with varying line-averaged densities, as well as from the turbulence simulation. At the highest density, the profile is roughly exponential with the same length scale throughout the SOL. Similar changes in the profile behavior have been observed in several other tokamak experiments [14–18].

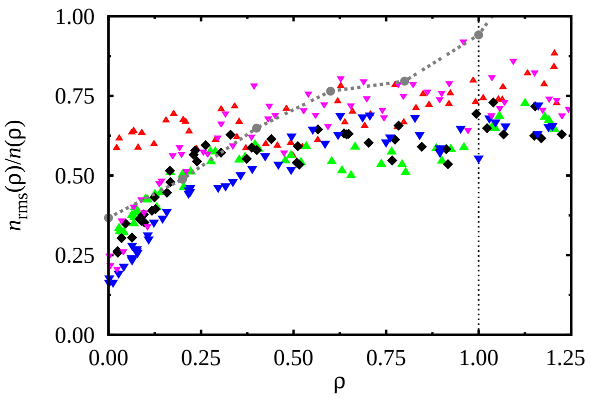

FIG. 5. Radial variation of the relative fluctuation level of the particle density fluctuations.

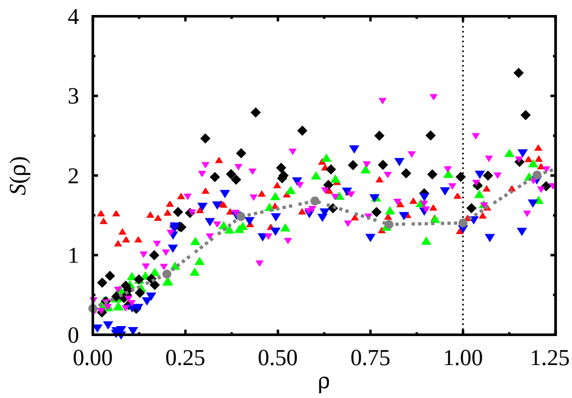

FIG. 6. Radial variation of the skewness of the particle density fluctuations.

Despite the significant changes in the time-averaged particle density profiles with increasing $\overline{n}_{\mathrm{e}}$, the plasma fluctuations show a remarkable degree of robustness. Fig. 3 shows the raw particle density time series at the wall radius from the high density reciprocation of TCV pulse number 24530 and a time series from the matched ESEL turbulence simulation. The similarity of these signals is striking, both characterized by occasional very large fluctuation amplitudes with a steep front and a trailing wake. This is even more clear from a conditional average of the time series, presented in Fig. 4. The large-amplitude and asymmetric wave form is believed to be due to the radial motion of field-aligned plasma filaments [12, 13].

Figures 5 and 6 present the radial variation of the relative fluctuation level and the skewness of the particle density fluctuations. In the SOL, the fluctuations are positively skewed, with a relative fluctuation level of order unity, reflecting the abundance of positive bursts in the time series as seen in Figs. 3 and 4. The universal property of plasma fluctuations in the region of broad profiles, seen by the same values and radial shapes for all statistical moments, clearly indicates that the underlying transport mechanism is the same for all values of $\overline{n}_{\mathrm{e}}$. Again, treating the simulation time series in exactly the same way as a real experimental time trace yields excellent agreement with regard to these statistical parameters.

3. Turbulent transport

Turbulent transport in magnetized plasmas is commonly described in terms of an effective diffusion coefficient, D_{eff}, for the particle flux density defined by $\Gamma = -D_{\mathrm{eff}}\partial n/\partial r = nD_{\mathrm{eff}}/\lambda_n$. In the experiments, the radial flux Γ is estimated from measurement of the floating potential by two probe pins separated poloidally by 1 cm, while it is calculated directly in the simulations [3]. The radial variation of D_{eff} from the turbulence simulation case and all experimental densities is presented in Fig. 7. At all values of $\overline{n}_{\mathrm{e}}$, the experimental D_{eff} has a pronounced peak in the outer half of the SOL. Due to the significant variation with radial coordinate and $\overline{n}_{\mathrm{e}}$, the turbulent particle flux clearly cannot be unambiguously parameterized in terms of an effective diffusivity on the basis of this experimental data.

The failure of the diffusion ansatz as a description of experimental measurements, together with the increasing experimental evidence for intermittent SOL transport caused by radial motion of plasma filaments, motivates the heuristic application of an effective convection velocity, V_{eff}, defined by $\Gamma = nV_{\mathrm{eff}}$, for parameterization of the turbulent particle flux density. Figure 8

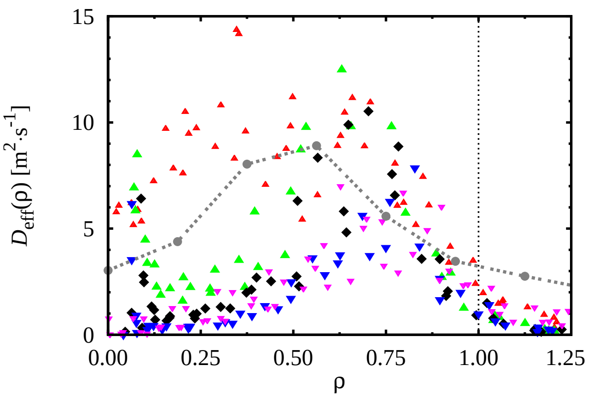

FIG. 7. Radial variation of the effective radial diffusion coefficient defined by $\lambda_n\Gamma/n$.

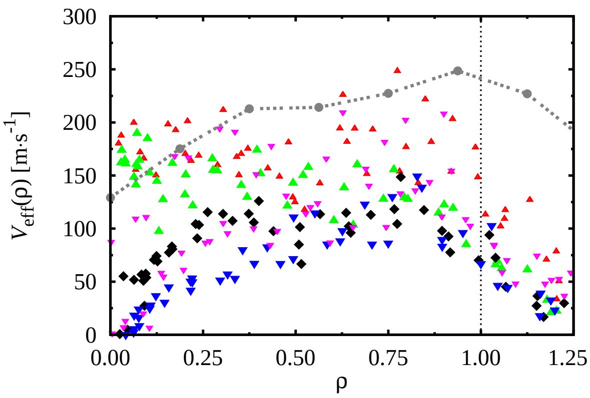

FIG. 8. Radial variation of the effective radial convection velocity defined by Γ/n.

demonstrates that $V_{\rm eff}$ varies significantly over the radial extent of the TCV SOL at low density. At high density, the effective convection velocity is roughly constant over the main SOL. It is interesting to note that in the region with broad particle density profiles, the experimental $V_{\rm eff}$ is roughly the same for all densities [4].

These results indicate that, for these TCV plasmas at least, no simple parameterization of the radial turbulent particle flux appears to exist if the transport is to be described purely in terms of an effective particle diffusivity or a convective velocity. However, Figs. 7 and 8 demonstrate that the convection ansatz has more robust features than the traditional diffusion approximation that underlies the flux–gradient paradigm and which is commonly used in transport modelling codes.

4. Transport scaling

The broadening of the particle density profile in the SOL with increasing $\overline{n}_{\rm e}$, clearly seen in Fig. 1, leads to large fluxes onto the main chamber surfaces. In fact, as shown in Fig. 9, these TCV experiments show that a factor 2 increase in $\overline{n}_{\rm e}$ yields a factor 4 increase in the particle flux density at the wall radius. The broken line in this figure corresponds to a fitted power law scaling with exponent 2.1. It is this strong quadratic scaling of wall flux with plasma density which is responsible for the main chamber recycling phenomenon first identified on the Alcator C-Mod tokamak and since found on other devices [14–18].

In a previous IAEA FEC contribution, LaBombard and co-workers have shown that the flux onto the limiters and main chamber walls for several tokamak experiments scales as the square of the line-averaged plasma density [14]. It should be noted that the plasma flux in these experiments was obtained by various methods, some of which were based on a consideration of global particle balance. Using estimates of the turbulent particle flux from probe measurements, Fig. 10 presents a similar scaling of the local particle flux density at the wall radius as function of $\overline{n}_{\rm e}$ for TCV. The broken line is a fitted power law function, yielding a scaling exponent of 2.2. For these Ohmic TCV discharges, there is thus an intimate link between the turbulence driven wall flux and a main operating parameter, namely the line-averaged plasma density.

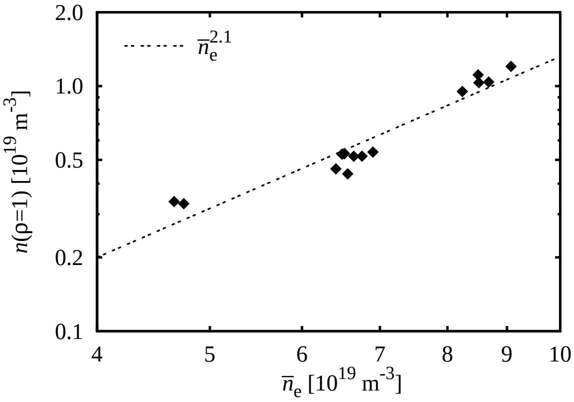

FIG. 9. Variation of the particle density at the wall radius with line-averaged density.

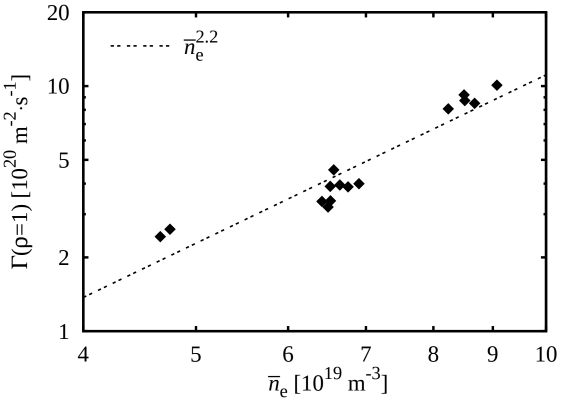

FIG. 10. Variation of the particle flux density at the wall radius with line-averaged density.

The quadratic scalings of particle and turbulent flux densities with $\overline{n}_e$ presented in Figs. 9 and 10 imply a linear relationship between the *local* SOL particle and flux densities at the wall radius. This is consistent with previous results presented in Ref. [1], and immediately suggests that the turbulent flux at the wall radius can be parameterized in terms of an effective convection velocity, found here to be $V_{\text{eff}}(\rho = 1) \approx 75\,\text{m}\cdot\text{s}^{-1}$, consistent with the clustering of points at $\rho = 1$ seen in Fig. 8.

5. Parallel flows

Mach probe measurements in the SOL of tokamaks with lower or upper single null divertor geometry, double null geometry, and both forward and reversed magnetic fields, have found a significant field direction independent parallel flow component directed poloidally away from the outer midplane [19–22]. One possible explanation for this "offset" component $V_{\parallel}$ is a parallel flow driven by turbulent radial plasma and heat transport which, due to its ballooning nature, enters the SOL predominantly on the outer midplane. The transient excess plasma pressure caused by the intermittent radial transport drains away along field lines, producing a parallel flow towards both the inner and outer divertors in single null geometries.

These transport driven flows have been investigated on TCV by making Mach probe measurements of parallel SOL flows in a series of discharges at various densities for both forward and reversed toroidal field direction [22]. Although the same SNL equilibrium is used as for the dedicated turbulence studies described in this paper, and therefore with the probe located 23 cm below the outside midplane, a slightly lower plasma current of 260 kA has been chosen to avoid transitions to Ohmic H-mode, which are easily obtained at higher plasma currents when operating in forward toroidal field. The result is a series of Ohmic L-mode discharge pairs in which plasma conditions are matched as closely as possible.

A dimensionless Mach flow profile is defined by $M_{\parallel} = V_{\parallel}/C_S$ where C_S is the ion acoustic speed, and a positive value corresponding to a flow directed towards the outer divertor target. Figure 11 compiles the normalized radial "offset" Mach flow profiles for a range of $\overline{n}_e$. The line-averaged densities for this set of matched discharge pairs are given by 1.7, 2.5, 4.2, 6.3, and 7.4 in factors of $10^{19}\,\text{m}^{-3}$, all at a plasma current of 260 kA. Its is emphasized that the data used in Fig. 11 are not taken from the same discharges as used for the other figures in this paper. The magnitude of the flow offset is in the range of $0.025 - 0.125$ in the central part of the SOL and is in the

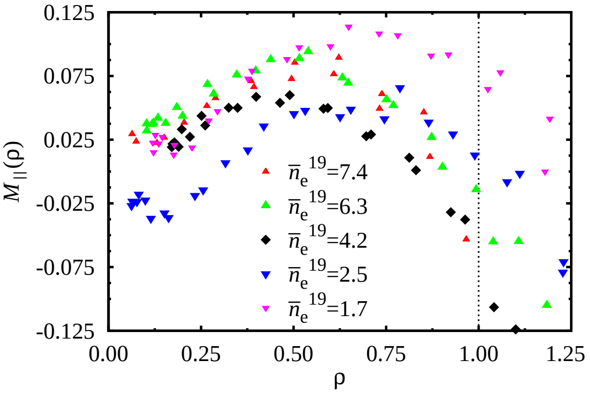

FIG. 11. Mach probe measurements of parallel flows in the SOL of TCV with plasma current 260 kA *and* $\overline{n}_e$ *given in factors of* $10^{19}\,\mathrm{m}^{-3}$.

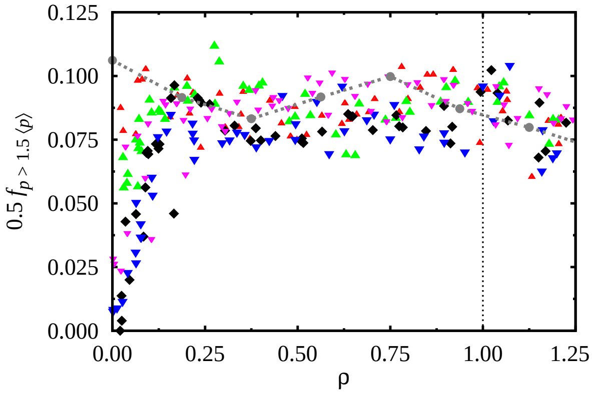

FIG. 12. Radial variation of the estimated Mach number from simulation and experiments with plasma current 340 kA.

direction towards the outer divertor target. This is what would be expected for a probe located below the main ballooning region if the flow were driven by radial transport.

A simple estimate of the time-averaged Mach number that would be expected from these transport driven flows can be obtained from the product of the sub-sonic value, taken to be approximately 0.5, and the fraction of the time that a significant parallel pressure gradient exists at any radial position, $M_{\shortparallel} \approx 0.5 f_{p>\alpha\langle p\rangle}$ [23, 24]. Here $\langle p\rangle$ is defined as the local time-averaged pressure, $\triangle t$ is the total duration of the time series, and $t(p > \alpha\langle p\rangle)$ is the time during which the local pressure exceeds the time-averaged value $\langle p\rangle$ by the factor α. Thus, $f_{p>\alpha\langle p\rangle} = t(p > \alpha\langle p\rangle)/\triangle t$ is the fraction of time that this condition is satisfied. The radial variation of the inferred parallel Mach number estimated using this ansatz for $\alpha = 1.5$ from the experiments listed in Table I and the turbulence simulation are presented in Fig. 12. This figure shows a significant parallel flow which is similar to that measured at lower plasma currents presented in Fig. 11 and whose magnitude is essentially independent of density. Once again, the turbulence simulation is in excellent agreement with the experimental data.

6. Conclusions

Probe measurements in the SOL of TCV have revealed that as the line-averaged core plasma density $\overline{n}_e$ increases, the particle density profile in the far SOL becomes broader in both radial extent and length scale. This increases the plasma density throughout the SOL, which leads to recycling on the main chamber walls. In the region where the profiles are broad, the fluctuation statistics remain robust in both magnitude and radial variation with respect to changes in $\overline{n}_e$.

Parameterization of the radial turbulent plasma flux in terms of an effective diffusion or convection coefficient reveals a significant variation of the inferred transport coefficients with both radial position and $\overline{n}_e$. As a consequence, no simple parameterization of the turbulent particle flux appears to exist for these TCV plasmas. However, at the wall radius there is a linear scaling of the local turbulent particle flux with respect to the particle density. This implies that the plasma flux at the wall intersection point can adequately be described in terms of an effective convection velocity, which is here found to be approximately $75\,\mathrm{m}\cdot\mathrm{s}^{-1}$.

Mach probe measurements in the SOL of tokamaks have found a significant field direction independent parallel flow component directed poloidally away from the outer midplane. Here it is shown that both the magnitude and direction of this “offset” component is consistent with estimates of a parallel flow driven by turbulent radial plasma and heat transport in the SOL.

A direct comparison of the experimental measurements with an interchange turbulence simulation at high density shows agreement with respect to magnitude and radial variation of statistical moments, temporal correlations, and the estimated transport-driven parallel flows. This clearly indicates that turbulent transport, main chamber recycling, and the parallel flow offset commonly observed in tokamak experiments are due to radial interchange motions of field-aligned plasma filaments in the SOL.

Acknowledgements

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