Topic: EX-D

On the origin of anomalous radial transport in the tokamak SOL

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It has long been recognised that the cross-field transport of particles and energy in the tokamak scrape-off layer (SOL) occurs at rates several orders of magnitude in excess of that expected on the basis of classical collisional diffusion. And yet, it is common practice in SOL fluid code modelling, for example, for the cross-field fluxes to be described in terms of Fick's law diffusive ansatz, using "anomalous" transport coefficients chosen to fit the observed radial profiles. Of late, it has become experimentally clear that SOL density profiles, particularly at high density, have a tendency to flatten, requiring the "effective" diffusivity to be a increasing function of radial distance in the SOL. Indeed, long tails in the density profile, extending far into the main SOL and increasing recycling in the main chamber to levels which can match those in the divertor of X-point configurations, mean that the diffusive description must often be abandoned in favour of a purely convective approximation. Measured on a sufficiently fast timescale, time series of the SOL density exhibit extremely large fluctuations, of order $\tilde{n}/n \sim 1$, revealing a "bursty" or intermittent nature with skewed probability distribution functions (PDFs). By comparing straightforward statistical analysis of experimental single point density fluctuation and ExB driven cross-field turbulent flux measurements in the low field side SOL of the TCV tokamak with similar analysis of time series from state-of-the-art 2D fluid turbulence simulations, this contribution will demonstrate, quantitatively, that the fundamental origin of convective SOL transport may be ascribed to turbulent interchange motions.

Using a fast reciprocating, multi-pin Langmuir probe diagnostic, radial profiles of particle flux and electric potential at MHz acqusition rates have been acquired in the outboard midplane vicinity of the low field side SOL of a wide range of ohmic TCV discharges. The database comprises variations in plasma shape and configuration (divertor/limiter), plasma current, confinement mode (L and H), plasma density, toroidal magnetic field direction and plasma fuel species (D and He). Analysis of the database in terms of density and ExB driven turbulent flux PDFs (and their moments) demonstrates a remarkable degree of similarity in the statistics [1]. The strength of turbulence, quantified in terms of the relative fluctuation level, σ_n/n or σ_Γ/Γ (with n, Γ the density and flux and σ_n, σ_Γ their respective standard deviations) is in reasonable agreement, across the entire SOL width, with the Lognormal and Gamma distributions. Both of these analytic PDFs can be characterised uniquely in terms of the relative fluctation level and are known to describe turbulent, avalanche like processes. Alternative analytic PDFs, such as the extreme value Gumbel or BHP distributions, which have in the past been identified as candidates approximating measured SOL turbulence data, do not vary with the relative fluctuation level and so cannot adequately describe the TCV data (Fig. 1).

In the vicinity of the outer midplane SOL-main chamber interface, where particles interact with the walls, the density fluctuations exhibit clear evidence of self-similarity over two orders of magnitude in frequency. Both density and cross-field flux PDFs are found to be universal in shape, with $n/\sigma_n \sim 1.7$ and $\Gamma/\sigma_\Gamma \sim 0.4$ respectively. Together with the observed constancy of the correlation between density and poloidal electric field fluctuations (which combine to provide the net turbulent outflux), this universal flux PDF implies that both the absolute flux and the fluctuation amplitude must scale with the local mean density near the wall. This is indeed observed. The local density is also is found to scale with the square of the line averaged density, providing a link between a main tokamak operating parameter and the turbulent driven wall flux. The observation on other tokamaks and by other means (not invoking turbulence measurements), of a total particle outflux also scaling with the square of line average density therefore suggests the cross-field turbulence drive in the SOL to be the origin of the radial outflux [2].

Careful comparison of particular cases (in particular for varying separatrix density) inside the experimental database with 2D fluid turbulence simulations of the outboard midplane TCV SOL using the ESEL code [3] has shown a remarkable level of agreement between theory and experiment when the simulation output time series is analysed in exactly the same way as that applied to the measured data [4]. Although the model contains a number of simplifying approximations, notably the description of parallel losses along open field lines in the SOL using a simple linear damping term, the match with experiment is remarkably close (Fig. 1).

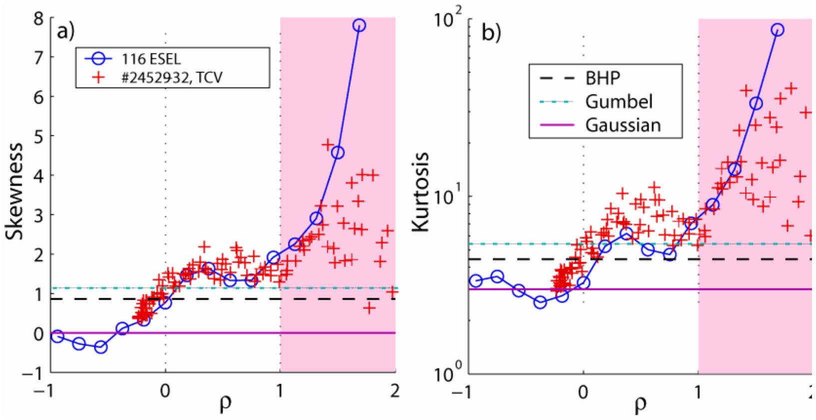

***Fig.1** Excellent agreement is found between experimental TCV data from a high density ohmic plasma (+) and ESEL turbulence code (○) output for the radial profiles of the 3rd (Skewness) and 4th (Kurtosis) moments of the density PDF. The radial distance, ρ, is expressed in terms of normalised distance from the separatrix (ρ = 0) mapped to the outside midplane with ρ = 1 the wall radius. Gaussian statistics are a good approximation near the separatix in both cases, but the extreme value BHP and Gumbel PDFs cannot match the observed (and simulated) radial dependence*

In fact, the success of this code-experiment comparison has stimulated the development of a physics based derivation of the coefficients representing perpendicular diffusion and parallel losses in the ESEL model equations [5]. These coefficients had previously been selected somewhat arbitrarily to provide the best match with experiment [6]. Quantitative agreement between theory and measurement has been found for radial profiles of mean values, fluctuation levels, PDF shapes, timescales and power spectra of both density and turbulence driven flux throughout the main SOL and even partially inside the separatrix. This level of agreement also implies that the code output conforms quite closely to the Gamma and Lognormal distributions satisfied in experiment. Indeed, deep in the wall shadow, where experimental data are unavailable due to the very low signal levels there, the code yields time series with PDFs which approximate the Gamma distribution extremely well. A further important conclusion of this work has been the demonstration that the experimentally derived magnitudes of cross-field fluxes are perfectly consistent with the simulated values. The crucial inference here is that nominally perturbing solid probes can be used with impunity to estimate the turbulence driven flux.

The time series of density and cross-field particle flux can be straightforwardly used to estimate the radial variation of the effective radial particle diffusivity, $D_\perp = \Gamma/\nabla n$ and the convective velocity $v_\perp = \Gamma/n$, both of which are required inputs to edge fluid code simulations. Agreement is again excellent in both magnitude and radial variation, with $D_\perp$ at high plasma density rising from ~3 m^2s^{-1} near the separatrix to a peak of ~10 m^2s^{-1} in the main SOL and $v_\perp$ similarly increasing from separatrix values of ~100 m s^{-1} to 200 m s^{-1} at the wall. Such behaviour is perfectly consistent with the picture of radially advecting plasma filaments propagating at substantial fractions of the local acoustic speed out into the far SOL from a formation location in the region of the transition from closed to open field lines. What these simulations reveal, that a single sensor sampling time series at a fixed poloidal location cannot, is the truly rich two-dimensional structure contained within the fluid interchange motions that are clearly responsible for the cross-field SOL transport in TCV.

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