Upstream and downstream properties of turbulent transport at tokamak COMPASS

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Edge plasma turbulence is an important topic in current tokamak research. To investigate the edge turbulence, probes are often employed because of their simple design and high spatial and temporal resolution. On the other hand, one of their disadvantages is that single Langmuir probes cannot measure the principle transport variables, the electron density n_e and the electron temperature T_e, with sufficient temporal resolution to study turbulence properties. The electron temperature may be inferred by sweeping the probe biasing voltage, but this inherently limits the temporal resolution. The electron density can be approximated by the ion saturation current

$$I_{sat} = \frac{1}{2} e A_{probe} n_e \sqrt{\frac{k_B T_e}{m_i}}, \tag{1}$$

which is collected at the probe sampling frequency, but its $\sqrt{T_e}$ contribution is difficult to estimate or remove without the appropriately time-resolved T_e measurement. As a result, I_{sat} fluctuations have been used to represent n_e fluctuations, while the resulting uncertainties in the inferred turbulent transport characteristics have remained unknown.

In this article, we exploit the high temporal resolution measurements of T_e performed by the combination of a Langmuir probe and a ball-pen probe [1] to quantify the differences between the I_{sat} and n_e fluctuations in L-mode. We use trios of probes, a floating ball-pen probe, a floating Langmuir probe and a Langmuir probe in the I_{sat} regime, to calculate T_e and n_e with temporal resolution $\sim 5\mu s$ (limited by the ball-pen probe suppression of frequencies above 200 kHz) and spatial resolution $\sim$ 5 mm in the poloidal direction (given by the probe distance). The probes are installed at two locations: on a reciprocating manipulator located at the outer midplane (OMP) (Figure 1) and in a divertor probe array (Figure 2), providing measurements of T_e, n_e and I_{sat} both at upstream and downstream (Figure 3). Furthermore, we have investigated two discharges representing a low-collisionality plasma (#13813, $I_p = 180$ kA, $\overline{n_e} = 2.5 \times 10^{19}$ m^{-3}, $\nu^* = \frac{n_u L}{T_u^2}$ = 2-5 throughout upstream SOL) and a high-collisionality plasma (#13826, $I_p = 180$ kA, $\overline{n_e} = 8 \times 10^{19}$ m^{-3}, $\nu^* =$ 12-33 throughout upstream SOL), but we have found no significant differences, and so we present only the high-collisionality discharge.

To gauge the difference between n_e and I_{sat} fluctuations character, let us first discuss their

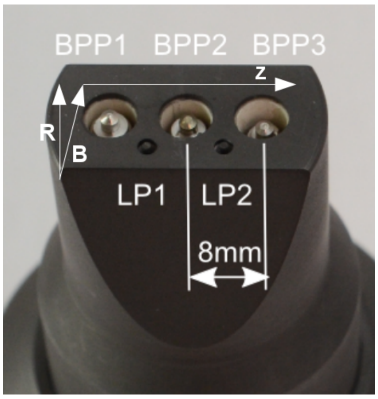

Figure 1: Horizontal reciprocating probe (HRCP) head. [2]

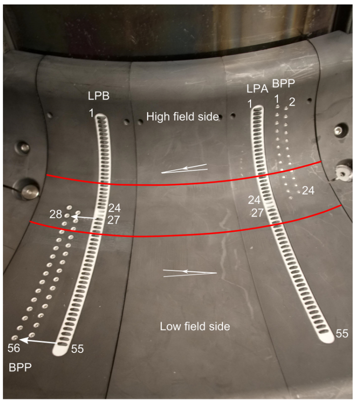

Figure 2: Divertor probe array. [3]

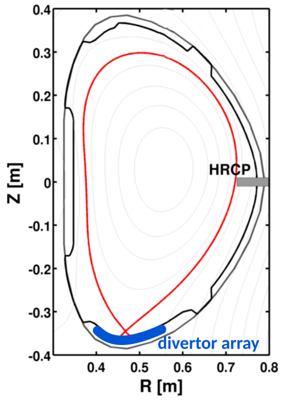

Figure 3: Diagnostics location in the poloidal cross-section.

mathematical relation. The ion saturated current $I_{sat} \propto n_e\sqrt{T_e}$ is afflicted by a T_e contribution; the question is whether removing this contribution significantly changes its fluctuations properties. The answer critically depends on the relation between T_e and I_{sat}, or T_e and n_e, fluctuations. Figure 4 hints that this relation may differ between upstream and target: upstream T_e and I_{sat} fluctuate together (phase shift close to 0), while at downstream they fluctuate opposite one another (phase shift close to $\pm\pi$). In this article, we show that I_{sat} fluctuations are quantitatively representative of n_e fluctuations at upstream but *not* at downstream, and we explain this conclusion by the different relation between n_e and T_e fluctuations.

To quantitatively demonstrate the differences between I_{sat} and n_e fluctuations, we plot their probability distribution function (PDF) moments profiles in Figure 5. At upstream, n_e and I_{sat}

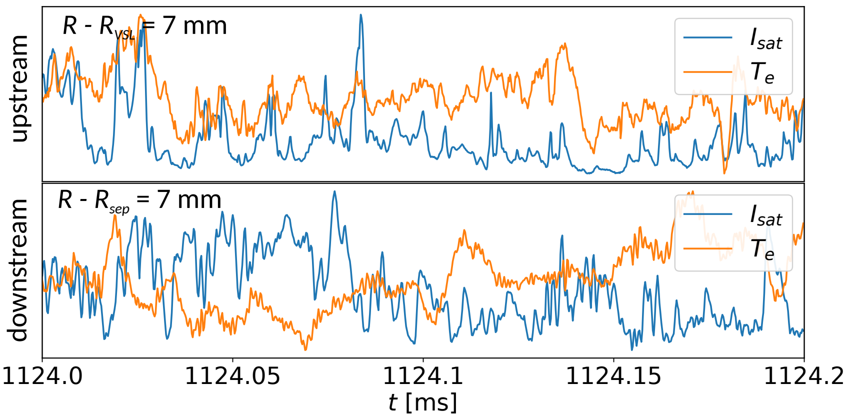

Figure 4: Electron temperature T_e and ion saturated current I_{sat} temporal evolution on the fluctuations scale. The frequency components below 1 kHz were removed with a highpass filter, removing most notably sawtooth fluctuations at 700 Hz.

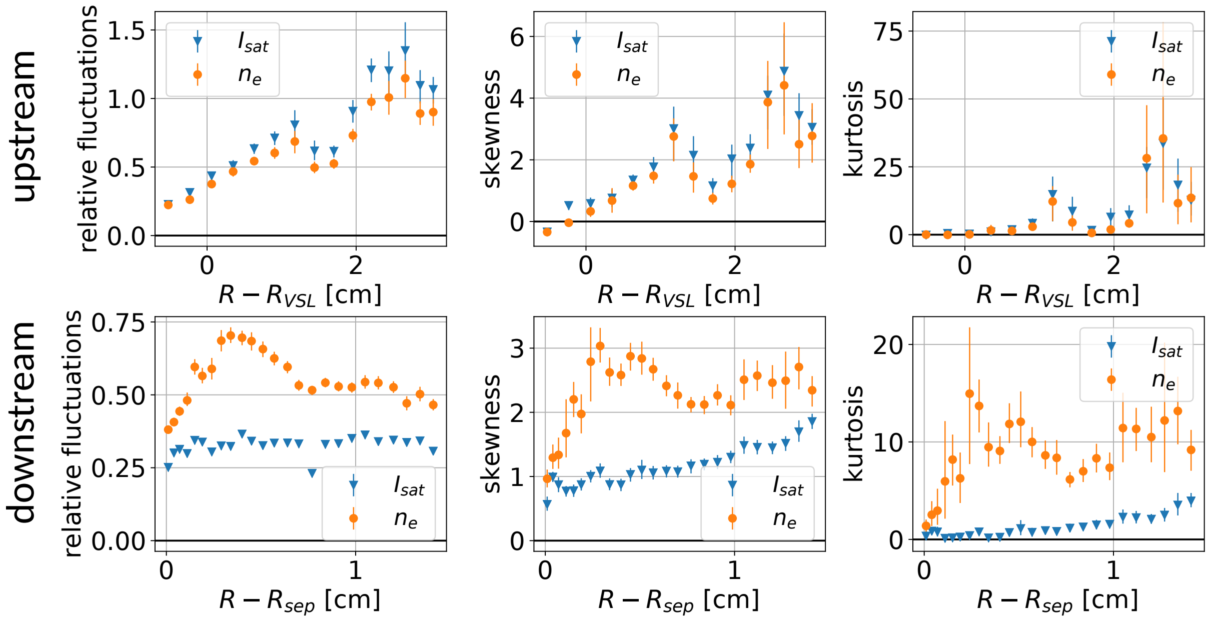

Figure 5: Profiles of I_{sat} and n_e distribution function moments. Errorbars correspond to 95% percentiles. Upstream profiles are taken relative to the velocity shear layer (VSL) position, detected as the plasma potential peak, and downstream profiles are mapped to the OMP and taken relative to the magnetically reconstructed separatrix.

PDF moments are close and often identical within the errorbars. In contrast, at downstream n_e relative fluctuations, skewness and kurtosis are significantly higher throughout the SOL. This difference is illustrated in Figure 6, where the histograms of I_{sat} and n_e are plotted. Downstream n_e PDF has a longer tail (higher skewness) and it is more peaked (higher kurtosis). In comparison, upstream PDFs of I_{sat} and n_e are quite close. Thus we conclude that using I_{sat} as proxy for n_e is acceptable when investigating upstream turbulent fluctuations, but at downstream the same may introduce a significant error.

The different conclusion for upstream and downstream may be partly explained by the 2D n_e-T_e histograms plotted in Figure 7. Upstream n_e and T_e are weakly positively correlated (Pearson correlation coefficient is 0.26), while downstream n_e and T_e are non-linearly anticorrelated, their relation being nearly, but not quite, isobaric. This may be connected to the different energy and particle transport mechanisms. Upstream cross-field turbulent transport carries both energy and particles, which results in n_e and T_e fluctuations correlation when measured by probes. The perturbations then travel along the flux tube at characteristic times which are considerably shorter for parallel energy transport (electron heat conductivity) than for parallel particles transport (ion sound speed), which results in their decorrelation when they arrive at the divertor target. [4] However, this does not explain why downstream T_e and n_e should be anticorrelated.

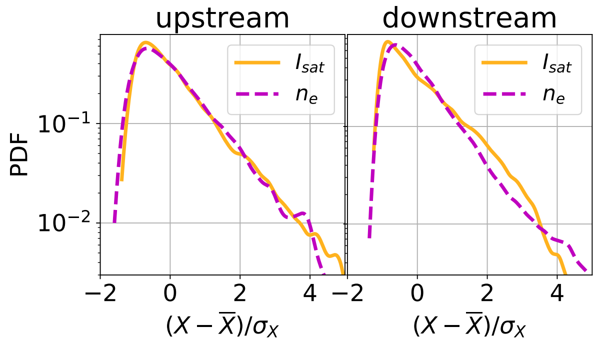

Figure 6: Histograms of n_e and I_{sat}, normed to zero mean and unit standard deviation and processed using gaussian kernels.

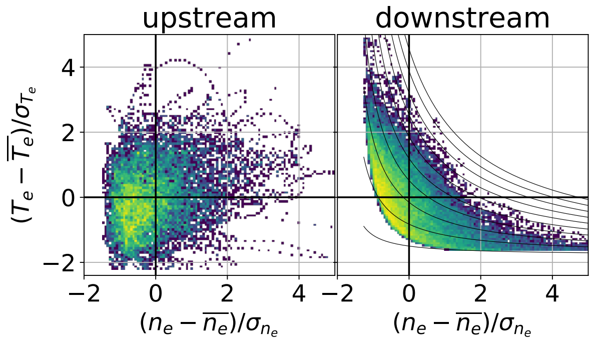

Figure 7: 2D histograms of n_e and T_e, normed to zero mean and unit standard deviation. Curved black lines are isobars.

Furthermore, due to uncertainties in probe alignment I_{sat} perturbations were observed to arrive at the divertor *before* T_e perturbations with the time lag smoothly increasing from 0.5μs at the strike point to 16μs in the far SOL. We conclude that the physical reasons for the difference in upstream and downstream n_e-T_e relation remain elusive; nevertheless, the differences in downstream I_{sat} and n_e PDFs can still be attributed to the n_e-T_e relation on an empirical basis.

In summary, we have shown that in L-mode I_{sat} fluctuations are representative of n_e fluctuations at upstream, but at downstream substituting I_{sat} for n_e may introduce significant errors in PDF shape and profile. The difference between upstream and downstream may be linked to the n_e-T_e fluctuations relation; however, their downstream anticorrelation could not be provided with a convincing physical explanation.

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