Correction of turbulent flow moments measured by Langmuir probes in the vicinity of the L-H transition in COMPASS

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Introduction

The analysis of turbulent flows in the edge region of tokamak plasmas requires the measurement of time-averaged turbulent stresses and fluxes such as the Reynolds stress (RS), which has been identified in recent models and experiments [1] as a likely driver of poloidal zonal flows expected to play a key role in the L-H transition. However, the common method of using floating potential fluctuations measured by Langmuir probes (LP) $\tilde{V}_{fl}^{\rm LP}$suffers from being contaminated by electron temperature fluctuations $\tilde{T}_e$[2, 8]. For the interpretation of such experiments it is worth-while to seek a correction of $\tilde{V}_{fl}^{\rm LP}$statistics by the exploitation of additional knowledge of $\tilde{T}_e$statistics offered by e.g. the combination of LP with ball-pen probes (BPP) [9].

Decomposition of turbulent moments measured by probes into covariances

Turbulent moments of interest such as the radial-poloidal component of the Reynolds stress $\langle \tilde{v}_r \tilde{v}_p \rangle$, turbulent energy in the respective components $\langle \tilde{v}_r^2 \rangle$ and $\langle \tilde{v}_r^2 \rangle$ are often measured under the assumption of the electrostatic ($\langle \tilde{B} \rangle = 0$) velocity fluctuations being dominantly due to the $\tilde{v}_i \approx \tilde{E}_j \times B$ drift. Under these assumptions the problem is transformed into the measurement of electric field fluctuations and their variance $\langle \tilde{E}_j^2 \rangle = \mathrm{var}(E_j)$ and covariances $\langle \tilde{E}_j \tilde{E}_i \rangle = \mathrm{cov}(E_j, E_i)$. It is worth noting that these second-order statistical moments are centered, i.e. independent of the mean value $\langle E_j \rangle$.

The electric field components and their fluctuations are typically approximated by finite differences between appropriately positioned electrostatic probes $E_i \approx -(V^{(l)} - V^{(k)})/d_{lk}$ measuring a floating potential $V^{(l)}$ and separated by a distance d_{lk}. For simplicity the factor $-1/d_{kl}$ will be omitted in the following discussion. The electric field variance (and similarly covariance) then separates due to its bilinearity into

$$\mathrm{var}(E_j) \propto \mathrm{var}(V^{(k)}) - 2\mathrm{cov}(V^{(k)} V^{(l)}) + \mathrm{var}(V^{(l)}) \tag{1}$$

Unfortunately, probes such as Langmuir or ball-pen probes in so called floating mode do not measure directly the plasma potential ϕ, but a floating potential $V = \phi - \alpha T_e$ which is offset from the true plasma potential by a factor linearly dependent on the electron temperature T_e (here in eV) with the proportionality constant α, which can be large, e.g. 2.8 in magnetized Deuterium plasma for a typical Langmuir probe. Therefore, the statistical moments of the floating potential also separate into extra terms (the probe indices are left out for clarity)

$$\mathrm{var}(V) \propto \mathrm{var}(\phi) - 2\alpha \mathrm{cov}(\phi T_e) + \alpha^2 \mathrm{var}(T_e) \tag{2}$$

Combining (1) and (2) would result in a complicated expression with 9 terms, of which only the terms relating to the potential $\mathrm{var}(E_j) \propto \mathrm{var}(\phi^{(k)}) - 2\mathrm{cov}(\phi^{(k)}\phi^{(l)}) + \mathrm{var}(\phi^{(l)})$ are actually of the interest, all the other 6 terms involving T_e only obscure the sought value. Therefore, it is necessary to find a way of cancelling or separating out the 6 extra terms.

Reconstruction of potential covariances from floating point measurements

Using experimental data measured with both Langmuir and ball-pen probes on the so-called modified "Reynolds stress" probe head [3] in the COMPASS tokamak [4] it was found that the turbulent moments measured by ball-pen probes can be approximated by an appropriate linear combination of variances and covariances of floating potentials measured by Langmuir probes. Since the ball-pen probes have $\alpha \approx 0.6$, it is assumed that they measure the potential and associated turbulent moments very close to the true plasma potential. The idea to reconstruct ball-pen probe moments from Langmuir probe moments is based on the notion that the turbulent state of the edge plasma exhibits temperature and potential fluctuations which are somewhat correlated in space and time, so a combination of their statistical moments such as in (1) and (2) may result in the terms being linearly dependent.

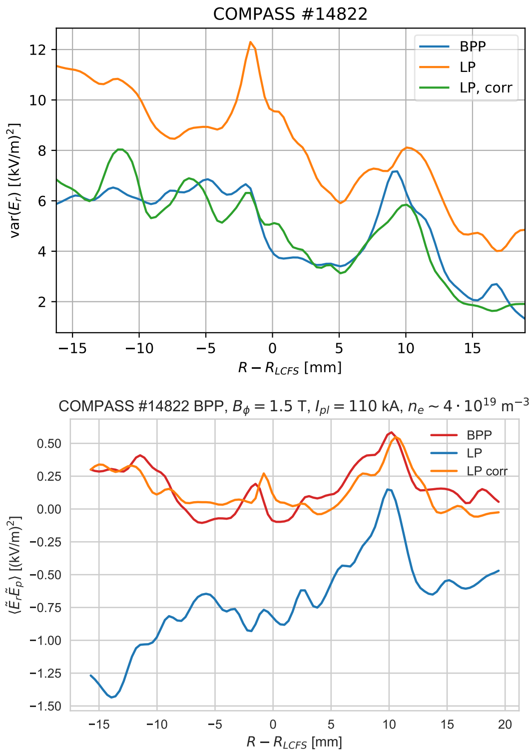

Figure 1: Radial profiles of $\mathrm{var}(E_r)$ and the Reynolds stress as measured by ball-pen (BPP) and Langmuir probes (LP) and a correction from LP moments in the discharge #14822.

As proof-of-principle example the variance of the electric field $\mathrm{var}(E_r)$ measured by ball-pen probes was used as the turbulent moment representing poloidal turbulent kinetic energy. This variance measured by a pair of radially separated ball-pen probes was then approximated by a linear combination of the floating potential variance and covariance terms appearing in (1) of a pair of Langmuir probes with the same radial separation. The linear approximation offers surprising accuracy as seen in Figure 1 with the same combinations coefficients holding over a wide radial range covering both the SOL and inside the LCFS across several discharges.

A similar correction possibility was found for the measured Reynolds stress itself as a linear combination of Langmuir probe moments, with an additional term $\sqrt{\mathrm{var}(E_r^{\mathrm{LP}})\mathrm{var}(E_p^{\mathrm{LP}}}$ representing the offset due to missing Langmuir probes with respect to the ball-pen probes geometry.

Comparison with HESEL simulations

In order to understand how the physical moments in (2) may be related the output of simulations by the fluid HESEL code [5, 6] for comparable COMPASS parameters [7] was analyzed. Radially separated synthetic probes $V_{fl,i}$ and ϕ^{BPP} were constructed by the appropriate combination of recorded time-traces of ϕ and T_e. Then the averaging for obtaining statistical moments at each radial location was done over the stationary part of the time traces.

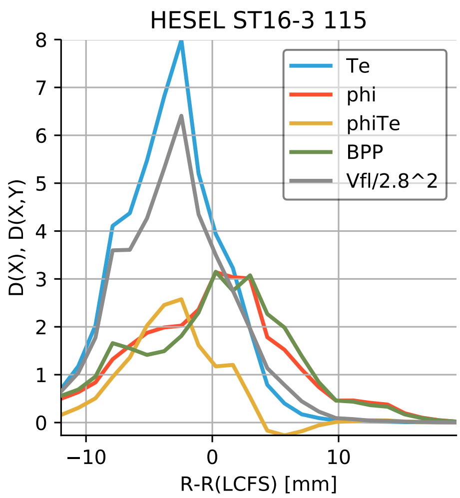

Figure 2: Radial profiles of $D(X)$ radial difference terms of plasma quantities and the corresponding combinations representing E_r variances as measured by ball-pen and Langmuir probes in HESEL simulation.

Defining $D(X) := \mathrm{var}(X_i) - 2\mathrm{cov}(X_i,X_j) + \mathrm{var}(X_j)$ and $D(X,Y) := \mathrm{cov}(X_i,Y_i) - \mathrm{cov}(X_i,Y_j) - \mathrm{cov}(X_j,Y_i) + \mathrm{cov}(X_j,Y_j)$ then leads to the variances observed by the synthetic probes to be given by $\mathrm{var}(E_r^{\mathrm{BPP}}) \propto D(\phi) - 2\cdot 0.6D(\phi,T_e) + 0.6^2 D(T_e)$ and $\mathrm{var}(E_r^{\mathrm{LP}}) \propto D(\phi) - 2\cdot 2.8D(\phi,T_e) + 2.8^2 D(T_e)$. These terms and their combinations are shown in Figure 2 Due to the very different α factors and in the case of $D(T_e)$ the square of α it becomes clear that while ball-pen probes likely observe values very close to the true E_r electrostatic variance (with deviations where $D(\phi,T_e)$ is large), but the Langmuir probes would observe mostly just the dominant term $D(T_e)$.

A linear regression of $D(\phi)$ on the Langmuir probe moments $\mathrm{var}(V^{(k)}), \mathrm{cov}(V^{(k)}V^{(l)}), \mathrm{var}(V^{(l)})$ showed that it is possible to obtain a good fit in the SOL region, but not so easily inside the LCFS. A linear regression over the whole radial extent (SOL and inside the LCFS) does not result in such a good fit as for the experimental data, the best fit is obtained by approximately rescaling the $\mathrm{var}(V^{(k)})$ component by $1/(1-2\alpha_{LP}+\alpha_{LP}^2)$, i.e. assuming $D(\phi) \sim D(\phi T_e) \sim D(T_e)$. An inspection of the decomposition of the regressed V terms according to (2) (i.e. multiplied by te regression coefficients and appropriate α factors) for the SOL case reveals that the T_e and ϕ, T_e terms partially cancel each other with the residual building up to $D(\phi)$.

Conclusions

Turbulent moments measured by Langmuir probes may be strongly influenced by $\mathrm{var}(T_e)$ and $\mathrm{cov}(\phi, T_e)$ (and covariance similarly) terms as evidenced by experimental and simulation results. A comparison of experimental ball-pen and Langmuir probe measurements suggests the possibility of correcting moments measured by Langmuir probes as a linear combination of moments of individual Langmuir probe measurements. Comparison with HESEL simulation results suggests that such a correction could be indeed possible at least in the SOL due to the T_e moments and covariances between ϕ and T_e partially cancelling with an appropriate linear combination. The simulations further suggest that ball-pen probes are affected by $\mathrm{var}(T_e)$ nearly at all and only a little by $\mathrm{cov}(\phi, T_e)$ terms.

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