Search for zonal structures on the radial electric field and Reynolds stress profiles on COMPASS

O. Grover[1,2], J. Seidl[1], J. Adamek[1], M. Imrisek[1,3], P. Vondracek[1,3], M. Tomes[1,3], J. Havlicek[1], V. Weinzettl[1], M. Hron[1], R. Panek[1] and the COMPASS team[1]

[1] *Institute of Plasma Physics, The Czech Academy of Sciences, Prague, Czech Republic*

[2] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic*

[3] *Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic*

Introduction

Since the observation of stationary zonal-like structures on the radial profile of the radial electric field E_r in the E_r well of the JET tokamak [1] no other device is known to have reproduced similar results (at least within published research). The perpendicular Reynolds stress force (not measured in the JET experiments) $-\partial_r\langle\tilde{v}_r\tilde{v}_p\rangle$ due to the perpendicular Reynolds stress (RS) $\langle\tilde{v}_r\tilde{v}_p\rangle$ has been identified in recent models and experiments [2] as a likely driver of poloidal zonal flows which are expected to play a key role in the L-H transition.

This contribution summarizes the efforts to observe similar structures on the E_r profile in the COMPASS tokamak [3] simultaneously with RS measurements in order to assess any zonal flow drive. Due to its modest size and heating methods in comparison to JET, it is possible to measure the radial profiles of E_r and other related quantities in the plasma edge directly via reciprocating manipulators featuring electrostatic probes under the assumption that the edge plasma turbulence fluctuations are of a dominantly electrostatic character, i.e. $v_p \approx E_r/B_\phi$ and $\langle\tilde{v}_r\tilde{v}_p\rangle \approx \langle\tilde{E}_r\tilde{E}_p\rangle/B_\phi^2$. The so called "Reynolds stress" probe head described in detail in [4] is routinely used for such purposes.

Measurements with the Reynolds stress probe head

The "Reynolds stress" probe described in [4] is a slight modification of the design in [5]. The probe head is equipped with both Langmuir (LP) and ball-pen (BPP) [6] probes in similar geometric configurations. The probes are fixed in a boron nitride bulk, which enables small distances between the probes. The radial E_r and poloidal E_p electric fields are calculated from differences of floating or plasma potentials measured by neighboring LPs or BPPs, respectively. This enables fast (5 MS/s), simultaneous, local measurements of electric fields with and without the strong influence of the electron temperature T_e, thereby enabling a direct investigation of T_e influence on derived quantities like the RS. The probe head was inserted into the edge plasma for

~ 70 ms on a reciprocating manipulator. The inward and outward profiles enable an assessment of stationarity of any observed phenomena.

The results presented below come from ohmic L-mode discharges with a low ohmic heating power at plasma currents below $I_{pl} < 150\,\text{kA}$ and higher magnetic fields $B_\phi \in [1.38, 1.5]$ T and a moderate range of line-average densities $n_e \in [4, 8] \cdot 10^{19}\,\text{m}^{-3}$. These configurations had a purposefully high $q_{95} > 6$ in order to mitigate saw-teeth and other MHD instabilities as much as possible.

Bootstrapped kernel regression of fluctuation statistics

A statistical method of performing the averaging $\langle \cdot \rangle$ was used instead of the more common method of lowpass filtering in time for reasons demonstrated below. The method consists of two statistical procedures: Kernel regression for obtaining the averaged nonparametric radial profiles and the so called bootstrap for establishing confidence bounds for the obtained profiles. Prior to the application of these methods the data is decimated to a sampling frequency of 500 kS/s in order to decrease the computation complexity and because no significant ambient turbulence contributions are observed beyond 250 kHz in the signal spectra.

Both statistical procedures assume that the measured dataset is dense enough to provide an accurate estimate of the joint probability of measuring the observed values. In the simplest case of E_r measurements at given radial positions with respect to the LCFS $x = R - R_{LCFS}$ the dataset $\mathscr{D} = \{(x_i, E_{r,i})\}_{i=0}^{N}$ is assumed to represent a probability distribution $p(x, E_r)$. The average radial E_r profile is then obtained as an expectation conditional on x: $\langle E_r \rangle(x) = \mathbf{E}(E_r \mid x)$. The expectation is calculated using the so called Nadaraya-Watson kernel regression [7]
$\mathbf{E}(E_r \mid x) = \sum K_i(x) \cdot E_{r,i} / \sum K_i(x)$ where $K_i(x)$ is a kernel $K_i(x) \propto \exp\left(-\left(\frac{x - x_i}{h}\right)^2\right)$ with bandwidth h. Therefore, the average E_r value at a given x location is a weighted sum of the closest measured $E_{r,i}$ points with weights given by the distance from the measurement locations x_i. The bandwidth is determined by least-squares cross-validation and effectively acts as a smoothing parameter. The smoothing corresponds to the assumption that the true probability density $p(x, E_r)$ is smooth.

The bootstrap procedure then attempts to simulate additional repetitions of the experiment under the same distribution $p(x, E_r)$ by randomly resampling with replacement the same number of points from the original dataset $\mathscr{D}$, thus forming a new bootstrap dataset sample
$\mathscr{D}^* = \{(x_{I_i}, E_{r,I_i})\}_{i=0}^{N}$ where I_i is a random integer from 0 to N. About ~ 1000 of such $\mathscr{D}^*$ bootstrap samples are formed and for each the kernel regression is performed. The point-wise 2.5% and 97.5% percentiles of the obtained $\mathbf{E}(E_r \mid x)$ profiles define the point-wise 95% confidence intervals. Therefore, the bootstrap procedure effectively estimates the robustness of the result

with respect to omitting and/or duplicating some of the measured points.

This procedure can be easily extended to the Reynolds stress calculation by assuming a probability distribution $p(x, E_r, E_p)$ on the dataset $\mathscr{D} = \{(x_i, E_{r,i}, E_{p,i})\}_{i=0}^N$ and then calculating $\langle \tilde{E}_r \tilde{E}_p \rangle(x) = \mathrm{cov}(E_r, E_p \mid x) = \mathbf{E}(E_r \cdot E_p \mid x) - \mathbf{E}(E_r \mid x) \cdot \mathbf{E}(E_p \mid x)$.

Stationary zonal-like structures

In Figure 1 the radial profiles of E_r and $\langle \tilde{v}_r \tilde{v}_p \rangle$ in discharge #14822 measure with BPP are shown. Statistically significant (straight line cannot be drawn within confidence bounds) zonal-like structures are observed on the $\langle \tilde{v}_r \tilde{v}_p \rangle$ profile around $x \sim 5$ mm inside the E_r well. These structures appear to be near-stationary as they change only a little from the inward to the outward reciprocation. Their radial scale is between 0.5 cm and 1 cm while the ion gyroradius is estimated to be almost $\rho_i \sim 1$ mm, which agrees quite well with the observations in JET where the radial scale of the structures was $\sim 10\rho_i$ [1].

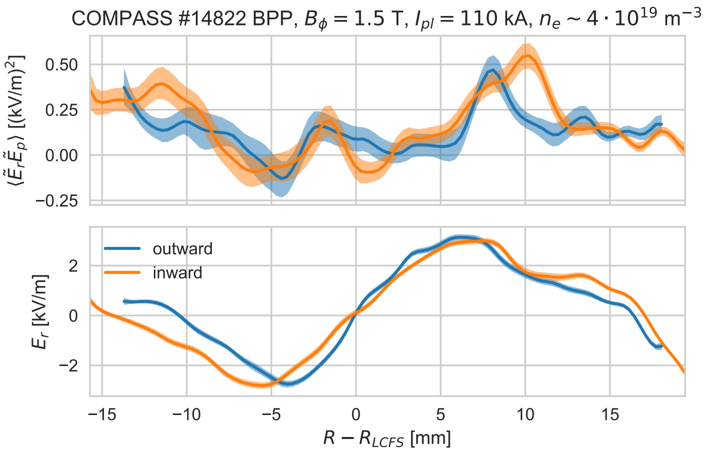

Figure 1: Radial profiles of $\langle \tilde{v}_r \tilde{v}_p \rangle$ and E_r during the inward and outward reciprocations in the discharge #14822.

In another discharge #14825 with different plasma parameters similar structures were observed as well. Figure 2 shows a comparison of time traces of core SXR radiation displaying saw-teeth crashes and the $\langle \tilde{v}_r \tilde{v}_p \rangle$ calculated by the kernel regression (x mapped to time of probe measurement) and the common lowpass averaging approach. The $\langle \tilde{v}_r \tilde{v}_p \rangle$ structures display not obvious coherency with the saw-teeth crashes, specifically, their time scale increases as the probe head decelerates form $\sim$ 1 mm/ms at 1110 ms to 0 mm/ms at 1140 ms, further suggesting that these are structures in

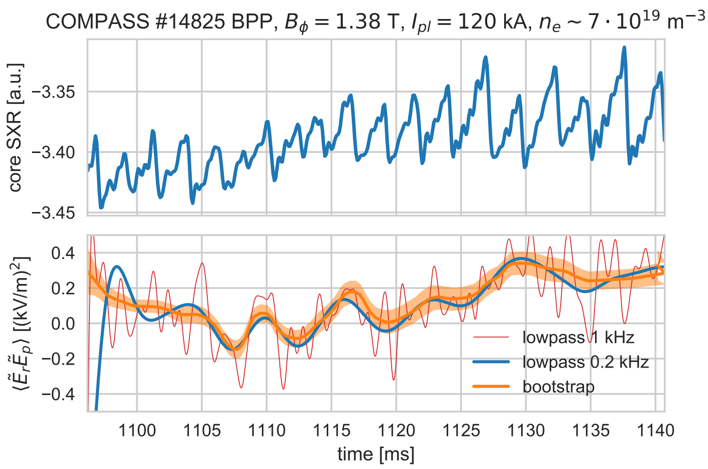

Figure 2: Time traces of core SXR radiation and $\langle \tilde{v}_r \tilde{v}_p \rangle$ during the inward reciprocation in the discharge #14825.

space, not in time. The comparison with the common method of lowpass filter averaging in time clearly displays its disadvantages. Firstly, the assumption of strict time scale separation and ergodicity requires a selection of a rather arbitrary cut-off frequency. However, typical edge plasma turbulence spectra do not feature such a clear frequency cut off between zonal flows and ambient turbulence. Secondly, the ergodicity requires local stationarity which is hard to fulfill in the time domain as the movement of the probe with respect to the plasma is not constant for all points. Thirdly, the lowpass filter may fail in averaging region boundaries. Finally, a simple lowpass filter gives no estimate of the uncertainty in the obtained average, hampering a clear judgment on the significance of any structures.

Summary

The bootstrapped method of kernel regression was applied to measurements of electric fields with ball-pen and Langmuir probes located on a reciprocating probe head. The advantages of this method over the more common method of lowpass filter averaging in time were demonstrated. Statistically significant, near-stationary zonal-like structures on the Reynolds stress profile have been found in the E_r well. The structures appear to be of a spatial character as they are not coherent with saw-teeth crashes.

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References

[1] J.C. Hillesheim et al., *Phys. Rev. Lett.* **116**, 065002 (2016)

[2] G. R. Tynan, I. Cziegler, P. H. Diamond, et al., Plasma Physics and Controlled Fusion **58**, 044003 (2016)

[3] R. Pánek, J. Adamek, M. Aftanas, et al., *Plasma Physics and Controlled Fusion* **58**, 014015 (2016)

[4] O. Grover, J. Seidl, J Adamek, et al. *Nucl. Fusion* `https://doi.org/10.1088/1741-4326/aabb19` (2018)

[5] O. Grover, J. Adamek, J. Seidl, et al., *Review of Scientific Instruments* **88**, 063501 (2017)

[6] J. Adamek, H. W. Müller, C. Silva, et al., *Review of Scientific Instruments* **87**, 043510 (2016)

[7] J. S. Racine, Nonparametric Econometrics: A Primer, Now Publishers Inc., (2008)