Reynolds stress and fluctuation measurements with Langmuir and ball-pen probes in the vicinity of the L-H transition on COMPASS

O. Grover[1,2], J. Seidl[2], J. Adamek[2], P. Vondracek[2,3], M. Tomes[2,3],
V. Weinzettl[2], M. Hron[2], R. Panek [2] and the COMPASS team
[1] *Faculty of Nuclear Physics and Engineering, Czech Technical University in Prague, Prague, Czech Republic*
[2] *Institute of Plasma Physics, The Czech Academy of Sciences, Prague, Czech Republic*
[3] *Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic*

Introduction

The Reynolds stress force $-\partial_r\langle\tilde{v}_p\tilde{v}_r\rangle$ due to the Reynolds stress (RS) $\langle\tilde{v}_p\tilde{v}_r\rangle$ has been identified in recent models and experiments [1] as a likely driver of poloidal zonal flows which are expected to play a key role in the L-H transition and the associated limit cycle oscillations (LCO) [2] in the predator-prey-like interaction of zonal flows with turbulence.

One common method of measuring the RS is to measure fluctuations of electric fields with arrays of Langmuir probes. However, such measurements may be influenced by the fluctuations of the electron temperature. Similar probe head arrangements have been also used to investigate the dynamics of density fluctuations and electric fields during LCO [2]. In order to investigate the role of temperature fluctuations and LCO dynamics, two similar probe heads equipped with both Langmuir (LP) and ball-pen (BPP) [3] probes in similar geometric configurations were developed, installed and used at the COMPASS tokamak [4]. This contribution reports on the results of measurements with these probe heads, specifically on the comparison of RS profiles obtained with BPP and LP and the investigation of limit cycle oscillations during the L-H transition on COMPASS.

Reynolds stress probe heads with Langmuir and ball-pen probes

The two (original and modified version) probe heads were constructed from a boron nitride (BN) support in which the probes are directly embedded. This removes the need for extra shielding and in conjunction with the triangle-mesh-like placement enables placing probes very close to each other. A detailed description of the original probe head geometry and an assessment of its measurement properties, e.g. the α coefficient of the 2 mm BPPs used, electric field measurement properties, can be found in [5]. Figure 1 shows the schematic of the modified probe head design derived from the original design. The radial separation between probes is 2.5 mm and the poloidal separation is ~ 4 mm and the separations are nearly the same in both designs.

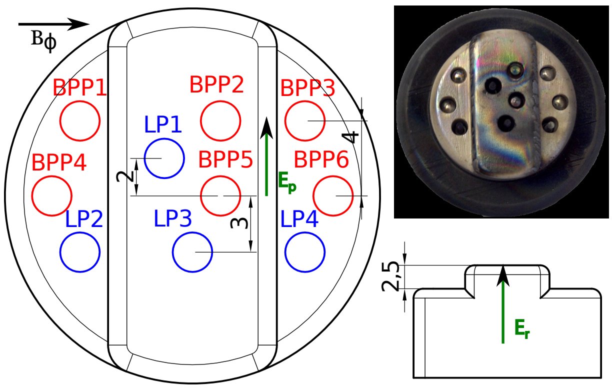

Figure 1: Schematics and a picture of the modified Reynolds stress probe head containing Langmuir (LP, blue) and ball-pen (BPP, red) probes. All dimensions are in mm. The directions of the toroidal magnetic field B_ϕ, the radial E_r and poloidal electric field E_p are also displayed.

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 main differences between the modified and original designs are the addition of BPP4 and BPP6 in the new design and the use of purer BN material for its construction. The former change enables the calculation of both the electric fields with BPPs at the same virtual point, removing the risk on any phase shift between separated measurement points. The latter change resulted in almost no plasma cooling or perturbation in comparison to the original probe head which significantly cooled the plasma and often led to disruptions as was reported in [5].

Radial profiles of the Reynolds stress measured with Langmuir and ball-pen probes

Radial profiles of the RS simultaneously measured with BPP and LP were obtained with the original RS probe head. The measured RS profiles are significantly different for either probe type, although they have some similarity in their general shape as can be seen in Figure 2. The RS obtained with BPP is generally higher than from LP. The spectral composition of the RS suggests that the lower or even negative values for LP originate from negative contributions of higher frequency ($f > 100$ kHz) fluctuations which may be related to temperature fluctuations. Details of this analysis can be found in [5].

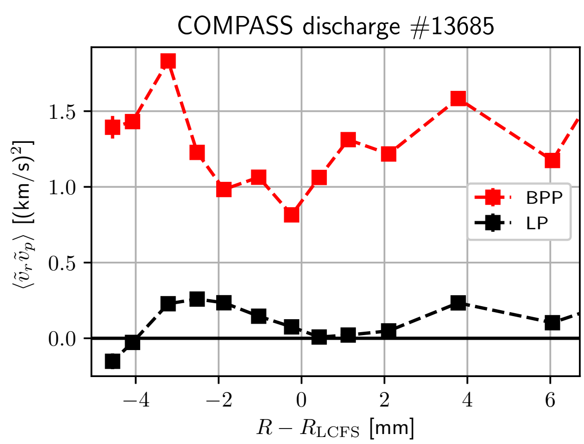

Figure 2: Radial profiles of the Reynolds stress $\langle \tilde{v}_r \tilde{v}_p \rangle$ measured with ball-pen (BPP, red) and Langmuir probes (LP, black). The radial LCFS position is taken with respect to the E_r velocity shear layer.

Candidate limit cycle oscillation measurements with probes

The modified RS probe head was used to investigate 3-5 kHz oscillations often appearing during the L-H transition in the COMPASS tokamak which were suspected of being LCO and are referred to as candidate LCO (cLCO). These oscillations were observed to modulate the intensity of density fluctuations std(n) related to the turbulence intensity and also the radial electric field E_r related to the poloidal flows decorrelating turbulent structures. The modulation of these quantities was measured using the modified probe head in Figure 1 while it was inside the LCFS. Conditionally averaged waveforms of $\sim$ 180 LCO cycles are shown in Figure 3. The poloidal velocity $v_p = E_r/B_\phi$ and its radial shear appear to be strongly correlated with the radial pressure gradient $\partial_r p_e$ and decrease in response to the flattening of the pressure profile.

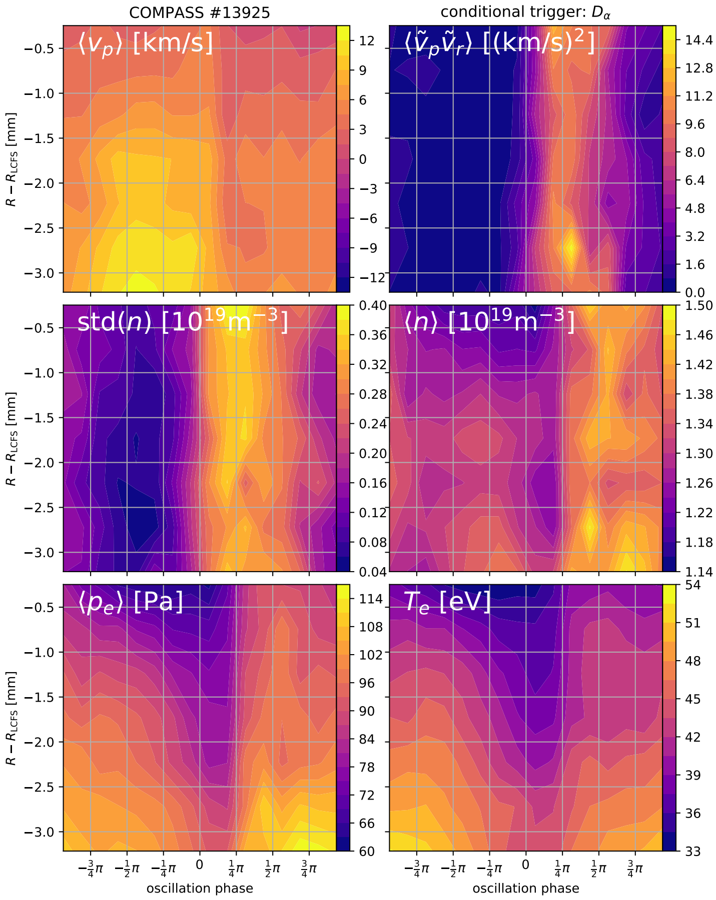

Figure 3: 2D-histogram-like conditional averages of cLCO.

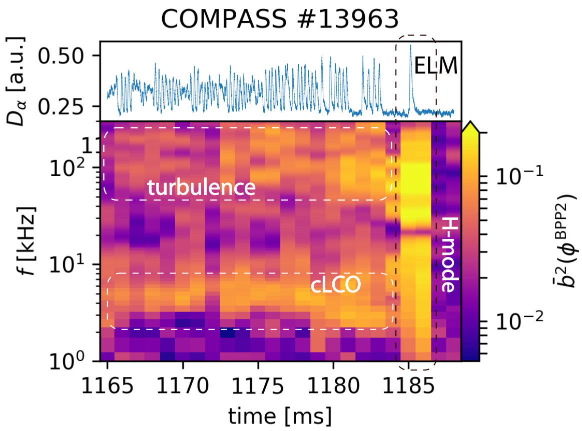

Figure 4: Evolution of summed squared bicoherence $\bar{b}^2(f)$ in plasma potential measured by BPP2.

Once the pressure profile flattens below a certain level the turbulence intensity (quantified by std(n)) quickly rises and the pressure profile and the velocity shear begins to rapidly decrease. The evolution of the density, electron temperature and pressure profiles suggests that the core plasma is ejected into the edge as the turbulence intensity approaches its maximum level. The RS $\langle \tilde{v}_p \tilde{v}_r \rangle$ is approximately proportional to the turbulence intensity. However, it appears to have little effect on v_p, likely due to the small radial gradient of the RS (i.e. the RS force). Altogether, the oscillations appear to be mostly driven by the modulation of the pressure gradient. This is consistent with type-J LCO observed on the HL-

2A tokamak [2] where the electric field was observed to decrease due to the plasma pressure gradient decreasing, after which the turbulence intensity began to rise.

Wavelet-based bicoherence analysis [6] was used to detect non-linear interaction and possible energy transfer between different frequency scales in the plasma potential during the cLCO. As seen in Figure 4, clear bicoherence between the cLCO frequency and a broad range of presumably turbulent fluctuations 50-250 kHz was observed inside the LCFS. Bicoherence analysis was also able to resolve the changing frequency of the cLCO during a slow L-H transition and showed a significantly different bicoherence signature for an ELM event preceding an ELM-free H-mode, during which no bicoherence was observed. This further suggests that these cLCO are not ELMs, even though some dynamics (e.g. pressure modulation) may appear to be similar [7].

Summary

Reynolds stress (RS) and candidate limit cycle oscillation (cLCO) dynamics were investigated with complex reciprocating probe heads containing both Langmuir and ball-pen probes on the COMPASS tokamak. The RS profiles calculated from the floating potential measured with Langmuir probes are found to be lower than those calculated from the plasma potential measured with ball-pen probes. Spectral analysis of the RS suggests that this is due to negative contributions from higher frequency fluctuations possibly associated with electron temperature fluctuations [5]. The investigation of cLCO during the L-H transition via probe measurements suggests that these are type-J LCO [2] where the turbulence intensity rises after the collapse of the velocity shear dominantly driven by the pressure gradient. Bicoherence between this mode and broadband turbulence was observed and it also differentiated these cLCO from ELMs.

Acknowledgment

This work received funding from the Czech Science Foundation projects GA16-25074S and GA15-10723S, MEYS projects 8D15001 and LM2015045 and grant no. SGS15/164/OHK4/2T/14 of the Grant Agency of the Czech Technical University in Prague.

References

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

[2] J. Cheng, J. Dong, K. Itoh, et al., Nuclear Fusion **54** 114004 (2014)

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

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

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

[6] B. Ph. van Milligen, E. Sánchez, T. Estrada, et al., Physics of Plasmas **2**, 3017 (1995)

[7] G. Birkenmeier, M. Cavedon, G.D. Conway, et al., Nucl. Fusion **56** 086009 (2016)