Turbulence, intermittence and low order rational surfaces in the TJ-II stellarator

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An important aspect of turbulent transport in fusion plasmas is its bursty nature, or intermittence. In the past, intermittence has been characterised by means of the Kurtosis, but we note that this quantifier only accurately indicates 'burstiness' under very specific assumptions. Chaos theory provides a more accurate quantifier of turbulence intermittence, namely the multifractal intermittence parameter *C(1)*, as was shown in recent work [1].

Near dominant low order rational surfaces, modes with the corresponding helicity tend to dominate fluctuations, leading to a local reduction of the degree of multifractality. Based on the results from turbulence simulations, we found that the parameter *C(1)* is also affected by the (poloidal) zonal flow. Comparing results with preceding work on the analysis of heat transport using the transfer entropy [2], we also found that radial minima of *C(1)* correspond to maxima of the transfer entropy, which were identified with 'trapping zones' for radial heat transport. Therefore, minor radial heat transport barriers ('trapping zones'), often associated with low order rational surfaces, have an effect on the intermittent character of the turbulence via zonal flows. Thus, the intermittence parameter provides valuable indirect information about the interaction of turbulent fluctuations, zonal flows, and the magnetic topology of fusion plasmas, not accesible via other techniques.

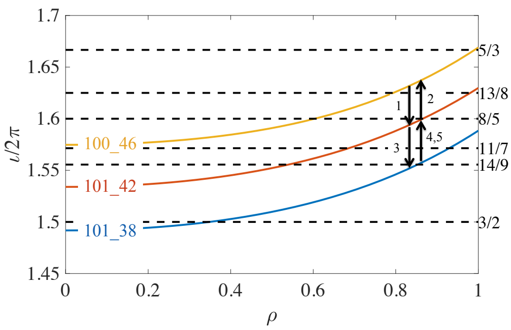


Fig. 1 – Rotational transform scans

We performed a series of dynamic configuration scans in low density ECR heated plasmas (nominal power: 2×250 kW) by varying the rotational transform at the edge, slowly and linearly in time (by modulating the external coil currents), while using plasma current control to keep currents inside the plasma small ($|I_p| < 0.5$ kA). Due to the low current and low plasma pressure ($\beta < 0.1\%$), Shafranov shifts of the flux surfaces are insignificant.

Thus, the magnetic configuration was very tightly controlled, particularly in the external part of the plasma, $\rho = r/a > 0.8$, where the influence of plasma currents on the magnetic configuration is weak. Fig. 1 shows the iota profiles of the five dynamical scans, each scan being repeated a number of times to confirm reproducibility.

Fig. 2 shows a combined graph of experimental results at low electron density (electron root conditions) and results from a calculation of a resistive MHD model. The horizontal axis is the local rotational transform, which is varied continuously as the rotational profile is scanned, while the Langmuir probe remains at a fixed position in the plasma edge. The black points correspond to the intermittence *C(1)* calculated from the floating potential of the probe.

The red line is a result obtained from the resistive MHD model. Performing a rotational transform scan similar to that of the experiment is very expensive, so instead, we took a single numerical calculation and moved the synthetic probes radially though the modelling domain.

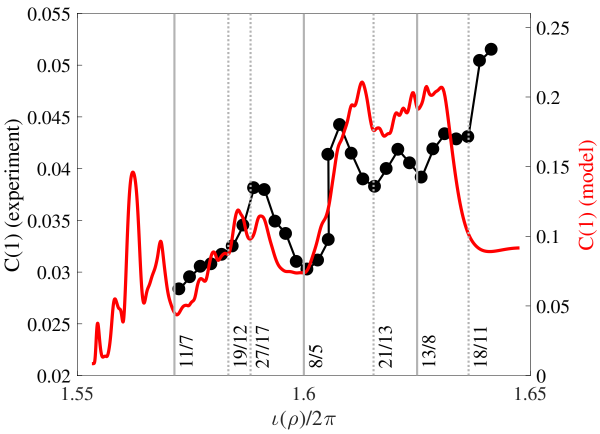
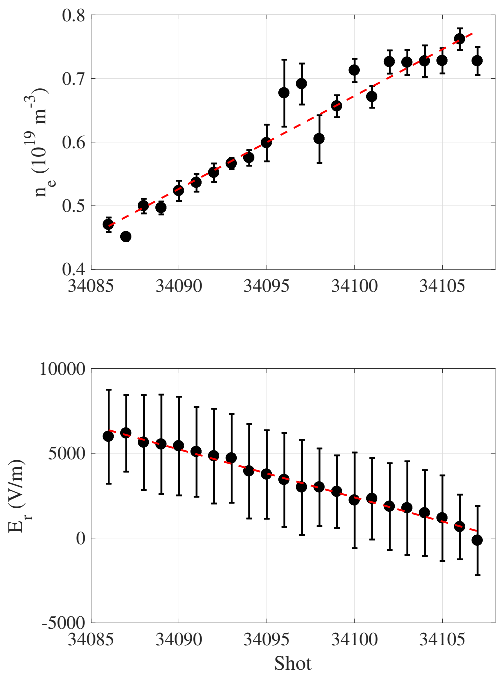


Fig. 2 – Intermittence from iota scan experiments (black dots) and the R-MHD model (red line)

This implies that the local conditions are different between experiment and model – in particular, the gradients. Nevertheless, one observes that the overall trend is similar in the experiment and the model between the rationals 11/7 and 13/8. Also note the significant dip in intermittence near the major rational surface 8/5. The drop of the model curve for $\iota/2\pi > 1.63$ is a boundary effect of the simulation.



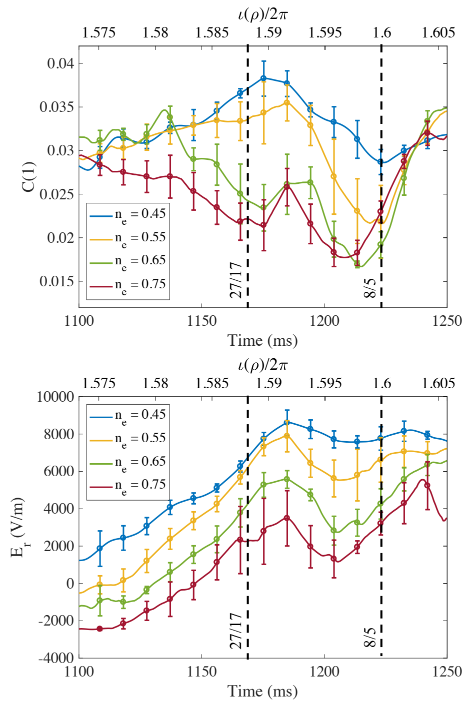


Fig 3 – Mean line averaged electron density, ne and radial electric field, E_r, and their standard deviations, for the discharges of the density scan, as a function of shot number. In each discharge, the rotational transform is scanned as described in the text. The red dashed lines merely serve to guide the eye.

Fig. 4 – Profiles versus iota of (top) the intermittence parameter, C(1), and (bottom) the radial electric field, Er, as a function of n_e (indicated in the legends, in units of 10^{19} m^{-3}). Vertical dashed lines indicate the location of the 8/5 and 27/17 rational surfaces.

One of the scans involved a set of discharges in which the electron density was raised slowly on a shot by shot basis, to study the effect of the electron-ion root transition on the intermittence. Fig. 3 shows the densities and the mean radial electric field at the probe location. Error bars indicate the variation during each discharge.

As the density increases, so does the density gradient and the turbulence drive. Nevertheless, the turbulence does not necessarily increase everywhere, as the turbulence may locally produce zonal flows that break up the turbulent eddies. We observe that the intermittence parameter gradually develops two clear local minima as the density rises. The first minimum appears close to the location of the most important low order rational surface in this range, iota = 8/5. It is already present when $n_e \approx 0.45 \cdot 10^{19}$ m^{-3} and deepens as the density is raised. The second minimum, near the low order rational surface of iota = 27/17, is absent at low density but becomes visible gradually for $n_e \approx 0.65 \cdot 10^{19}$ m^{-3}. We note also that this second minimum at 27/17 is apparent as a small dip in the theoretical curve shown in Fig. 2.

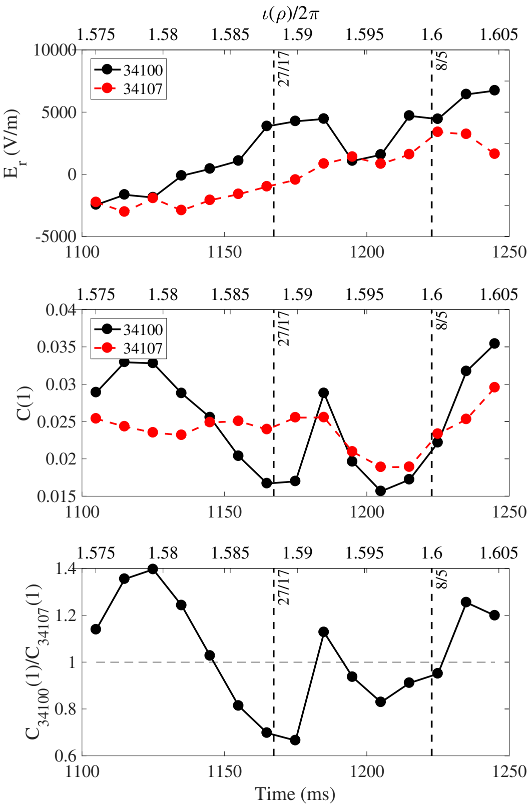


Fig. 5 - Profiles of (top) the radial electric field, E_r and (middle) the intermittence parameter, C(1), for two selected discharges with a similar value of n_e. Bottom: the ratio of the two curves of C(1) shown, highlighting the change of intermittence due to a change in E_r only.

In Fig. 5, we compare the profiles of Er and *C(1)* between shots 34100 and 34107, having a similar value of n_e, but a rather different value of E_r. At low E_r (red dashed curves), a minimum of *C(1)* can only be seen near the rational surface 8/5, and as E_r is increased (black continuous curves), the minimum near 8/5 deepens, while a new minimum near 27/17 appears. From these figures, we deduce that an increase of E_r leads to a decrease of *C(1)* around the corresponding low order rational surfaces, but not elsewhere.

Summarizing, in a first set of experiments, performed at low electron density in 'electron root' conditions, we observed variations of *C(1)* with iota, revealing minima at the locations of important low order rational surfaces. When these results were compared to the intermittence produced by the resistive MHD turbulence calculation in similar conditions, very good agreement was obtained. The locations of up to 4 low order rational surfaces could be identified inside the plasma, an unparalleled feat in plasma physics, to the best of our knowledge.

In a second set of experiments, we studied the variation of *C(1)* as the line average density was raised on a shot by shot basis. In doing so, the TJ-II plasma performed a gradual confinement transition from 'electron' to 'ion root' and the radial electric field E_r changed sign from predominantly positive to slightly negative. As the density was raised, we found that the intermittence at the rational surfaces decreased, while it increased at other locations.

A possible explanation is the increased drive (increased gradients) for instabilities, which would emphasize the monofractal properties at the rational surfaces, while increasing the generation of zonal flows and the associated mixing (leading to multifractality) away from the rational surfaces. The reduction of intermittence at rational surfaces led to the detection of a new low order rational (27/17) that had not been identified in the first set of experiments, performed at low density.

A subset of discharges from the second set of experiments (Section 3.3), at nearly constant line averaged electron density, n_e, allowed determining the specific effect of the radial electric field, E_r. on the intermittence parameter. We found that an increased radial electric field decreases the intermittence at the considered rational surfaces. Again, the response of the intermittence to an added electric field is fully consistent with the results of numerical calculations using the resistive MHD model.

In summary, we propose that the intermittence parameter constitutes a unique new tool to detect low-order rational surfaces in fusion plasmas. Their correct identification may be an important step forward in our understanding of the impact of rational surfaces on confinement in fusion devices. In addition, the study of intermittence may be helpful for the understanding of turbulence in general.

For more details regarding these results, please see [4].

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