Turbulence measurements by ultra-fast sweeping reflectometry in Tore Supra

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Introduction

The ultrafast frequency sweep X-mode heterodyne reflectometer used in this work operates in the V and W bands. The frequency bands are simultaneously swept in 2 μs with a 1 μs dead time, giving a temporal resolution of 3 μs [1]. The frequency sweeping provides a continuous radial scan from the edge to the center of the plasma with a relative radial resolution of the millimeter range. This diagnostic can thus provide radial properties of the turbulence (correlation lengths), its frequency spectrum as well as its temporal dynamics. The characterization of turbulence properties is indeed crucial for the understanding and control of anomalous transport, which can seriously affect nuclear reactor performances.

Statistical analysis

Quantitative properties of the signal fluctuations are extracted through a cross-correlation analysis. The cross correlation function $CCF(r,\Delta r,\Delta t)$ is computed on two arbitrary time series measured at different radial positions, quantifying the similarity between data measured at different positions and times.

$$\boldsymbol{CCF(r,\Delta r,\Delta t)} = \frac{\overline{\left(X(r,t)-\overline{X(r,t)}\right)\left(X(r+\Delta r,t+\Delta t)-\overline{X(r+\Delta r,t)}\right)}}{\sigma_{X(r)}\sigma_{X(r+\Delta r)}}$$

where $\overline{X(r)}$ and $\sigma_{X(r)}$ denote the mean and standard deviation over the times series. The statistics is performed over each burst of sweeps (typically from 2000 to 3000 sweeps, i.e. over 6 to 9 ms). The CCF computed for $\Delta r=0$ is the autocorrelation function (ACF). The correlation time t_c is defined as the ACF full width at half maximum. The radial correlation length L_r is evaluated as the CCF full width at half maximum, for $\Delta t=0$. It has to be noted that the correlation length evaluated from the reflectometry signal might be underestimated close to the separatrix because of strong non-linear interactions between the probing electromagnetic waves and the plasma, occurring when density fluctuations exceed 1%, i.e. for r/a> 0.8 [2]. Here we therefore focus the analysis on the core-edge (r/a > 0.6) and far scrape-off layer (SOL) regions (> 2cm outward the last closed flux surface LCFS).

Core-edge plasma

Parametric dependences of the core-edge fluctuation characteristics have been studied on two sets of ohmic discharges: in the first set the line average density is continuously ramped up from nl = 2.4 to 4.5 10^{-19} m^{-2}, at constant plasma current, Ip = 1 MA; the second measurements are performed during successive plasma current plateaus ranging from 0.5 to 1.4 MA keeping the density constant (nl = 2.7 10^{-19} m^{-2}). A reduction of the measured fluctuation correlation lengths is observed (Fig. 1) over a large radial extent in the edge (more pronounced for r/a < 0.75), for increasing collisionality.

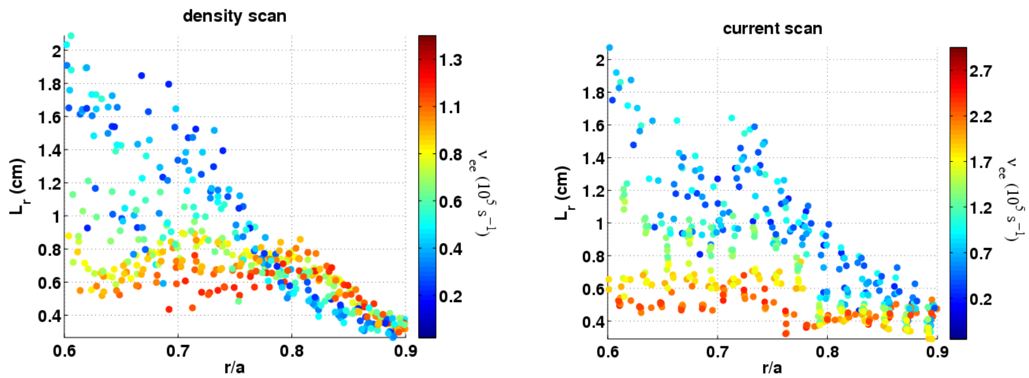

Figure 1: Measured correlation length profiles for the density ramp set of 9 discharges (#47169:47174; #48100:48102) (left) and for the plasma current scan set of 6 discharges (#47670:47675) (right). The color bar represents the values of electron collisionality (radially averaged over r/a =0.6-0.9).

The dependence of the measured fluctuation correlation lengths versus Larmor radius $\rho_s = \sqrt{T_e m_i}/eB$ is also investigated. Theoretical linear models for interchange or drift-wave type turbulence [3,4] predict that the convective cells size is limited by Landau damping. This condition, gives $\Delta r \sim \rho_s\, f(L_s, L_n, L_T)$ where the macroscopic gradient scale lengths dependence varies with the details of the models (slab/toroidal ITG, TEM). In all

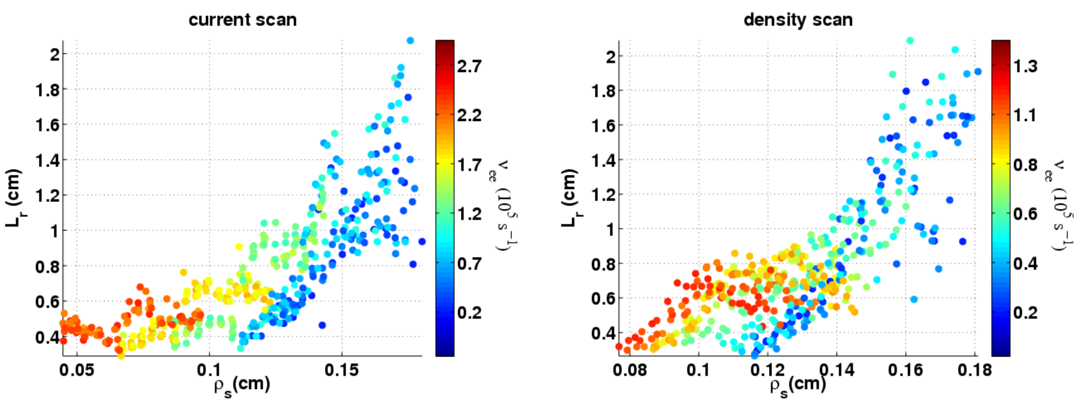

Figure 2: Correlation lengths Lr from the set of ohmic discharges as in Fig. 1 (left, density ramp; right current ramp) vs. the ion sound Larmor radius at different electron collisionality ν_{ee} (radially averaged over r/a =0.6-0.9).

cases the mode width is predicted to mainly scale with ion/sound Larmor radius, consistently with a Gyro-Bohm scaling of the transport. Previous experimental studies with reflectometry [5] report $L_r \sim$ 5-10 ρ_s consistently with a mesoscale scaling of eddies. In our measurements, L_r values are consistent with the above range; a linear scaling with ρ_s is only observed at low collisionality (Fig. 2), whereas the dependence of L_r appears more complex in the edge at high density as well as in the plasma current scan. In order to get more insight in the mechanisms occurring in the edge plasma during the density ramp up, a spectral analysis has thus been performed. The radial dependence of the spectra is obtained by performing an FFT at fixed radii of the temporal complex signal, from sweep to sweep, sampled at 333 MHz (sampling time of 3μs) (Fig. 3). This is equivalent to a signal analysis provided by fixed frequency reflectometry systems, though with less amplitude dynamics (15 dB instead of 40 dB) but it conveniently provides a fast and large radial coverage of the plasma. In the plasma edge (r/a > 0.8) the high turbulence level produces a uniformly flat and saturated spectrum whatever the plasma conditions. However, in the outer core (r/a ~ 0.7) at the lowest density, the frequency spectrum is clearly dominated by frequencies in the range 50-100 kHz with a characteristic M-shaped spectrum (Fig. 3, left). At higher density, this feature disappears and lower frequencies dominate (Fig. 3, right).

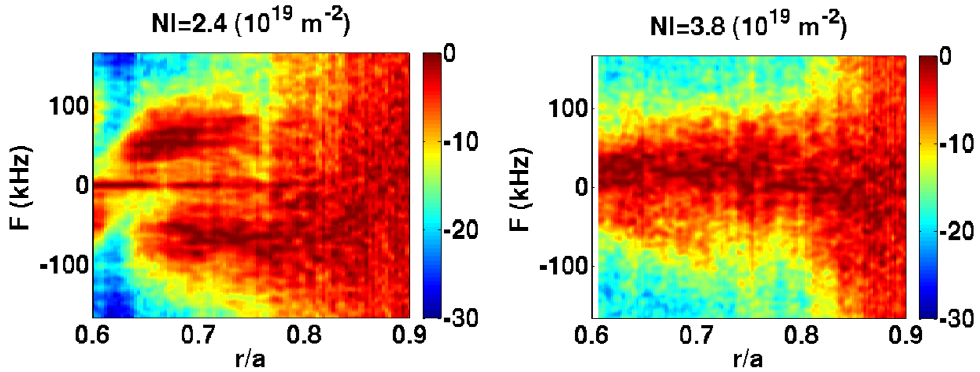

Figure 3: Radial dependence of the fluctuation power spectra of the for Tore Supra ohmic discharge #41802 at low (left) and high (right) density.

A stability analysis performed with the quasi-linear code, Qualikiz [6] using experimental data of shot #48102 suggests the presence of a Trapped Electron mode (TEM), dominant at r/a= 0.75 for low density and stabilized at higher density. A possible interpretation of the observed spectrum modification might thus be given in terms of TEM turbulence: linearly, TEMs are damped by collisions; non-linearly, saturation occurs through energy transfer towards lower frequencies [7]. A study of the impact of the latter on the turbulence fluctuation levels would require non-linear simulations.

SOL region

In ohmic plasmas, the far SOL exhibits an intermittent turbulent behavior with large correlation lengths in the centimeter range. By applying additional ICHR power, strong modifications of this blobby behavior are noticeable: a radial expansion of the plasma [8], due to fast radial displacement of plasma eddies of reduced correlation length and shorten correlation time compared to ohmic discharges (Fig. 4). To account for these observations, the effect of a rectified sheath potential on the SOL turbulence was invoked and tested by means of modeling with TOKAM code [9]. Local convective cells of potential created closely in front of the ICRH antenna were indeed measured by Langmuir probes [10].

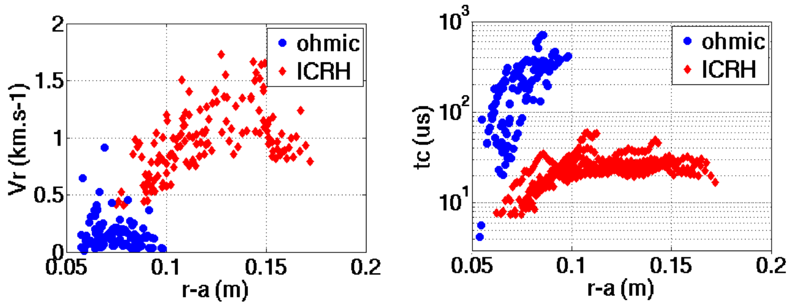

Figure 4: Comparison of the turbulence radial velocities and correlation times between ohmic and L-mode ICRH heated discharges (#46590, 46592:46597, 46599) as function of the distance from the separatrix.

Simulations show that the rectified potential produces a localized outward or inward particle transport, depending on the connection of the field line between the launcher and the reflectometer position. However, the reflectometer measurements always exhibit an outward stream, thus an additional non-local polarization might be invoked to interpret the observations.

Conclusion

Cross-correlation analysis of fast sweeping reflectometry data in Tore Supra provides quantitative estimates of fluctuation correlation lengths on a wide core-edge region and in the SOL. Collisionality reduces the turbulent structure size, which scales with ρ_s for low ν_{ee}. ICRH heating induces an expansion of the SOL plasma with increased structure velocity in the far SOL; non-local effects need to be invoked to account for this observed behavior.

References
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