Density fluctuations measurements on Tore Supra tokamak plasma : radial profiles and spectra

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Abstract

Up to now, turbulent processes in fusion plasmas are not clearly identified, then innovative and comprehensible diagnostic measurements are required. Fast-sweep heterodyne reflectometry is always suitable for precise measurement of density profiles but can also be used to reconstruct fluctuation density profiles. A closed-loop upgrade of the method developed in [1] , based on comparisons between simulated and experimental reflected signals, allows us to extract from shot to shot on Tore Supra tokamak the density fluctuations radial wavenumber spectra $S(k_r)$ from the fluctuating phase signal of the X-mode fast-sweep V and W band reflectometers.

In this paper we focus on the application of this experimental method of extracting the spatial evolution of the wavenumber spectra and radial density fluctuation profiles of the Tore Supra tokamak plasma. Then we exhibit a density fluctuations scaling with the electronic density gradient length L_{n_e}.

1 Introduction

Turbulence is responsible for a strong degradation of the energy confinement time of the plasma in magnetic fusion devices. However, turbulent processes are not clearly identified, then innovative and comprehensible diagnostic measurements are required.

The sweep frequency reflectometry system of Tore Supra has been designed to perform density profile measurements. In standard configuration the density profile reflectometer launches a probing wave on the extraordinary mode polarization (X-mode). Located at the low field side of the torus and in the equatorial plane, it covers the frequency ranges $50-75$ GHz (V-band) and $75-110$ GHz (W-band) in a 20 μs sweeping time [2].

This reflectometry system can operate in burst mode, i.e. sweeps are performed repeatedly every 25 μs in order to keep all plasma parameters (density, temperature, plasma current...) as constant as possible during the analysis. Usually 5000 sweeps are recorded into the memory storage of the acquisition system. We suppose that the reflectometer signal fluctuations are essentially due to the plasma density fluctuations, apart from all electronic and hardware noises. The goal of this paper is to present the first application of a method of extraction of plasma density fluctuations profiles and radial wavenumber spectra leading to a scaling of $\delta n_e(r)/n_e(r)$ with L_{n_e}.

2 Extraction of plasma density fluctuations

Phase signal extracted from the reflectometry complex signal carries different information on the plasma density : a slow evolution linked with the average density profile and MHD events,

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and a rapidly varying one regarded as turbulence signature on the measured signal. We focus in this article on the turbulent phase signal, whose time scales are approximately below a few milliseconds. As the probing wave propagates through the plasma, the phase of the reflected signal records all the fluctuations of the refractive index. In addition to the main contribution coming from the reflection at the cut-off, the Bragg backscattering processes provide information on the density fluctuation wavenumber k_r up to 2 k_0, where k_0 corresponds to the vacuum wave number ($10 - 23\ \mathrm{cm}^{-1}$).

Bragg backscattering guarantees that density fluctuation effects on the reflected phase signal are localized between the cut-off layer and $5\ \mathrm{cm}$ in front of this layer, if the phase fluctuations wavenumbers remain below $10\ \mathrm{cm}^{-1}$. Furthermore local analysis allows to access plasma local behaviours, i.e. density fluctuations close to the cut-off layer. Plasma conditions vary radially quickly from the edge to the gradient zone : a sliding-windows approach allows to locally distinguish radial plasma behaviour. Phase fluctuations extraction is mainly based on a time scale separation. Mean phases are computed on a few milliseconds windows, suppressing slow signal variations from the turbulent phases. For a precise data processing discussion, refer to [2, 3].

Relative density fluctuation profiles ($\delta n_e/n_e$) are defined on relative density fluctuation spectra ($S_{\delta n}$) , on the 1-10 cm^{-1} range :

$$\overline{\frac{\delta n_e(r)}{n_e(r)}}\Big|_k = \frac{1}{N}\sqrt{\sum_{\substack{i=1\ldots N\\ k_i\in[1,10]}} S_{\delta n}(k_i)} \tag{1}$$

The method is designed to rapidly provide the absolute values of density fluctuation profiles and k_r spectra from fast-sweeping reflectometry [4]. By comparing phase fluctuations local power spectra from experimental and simulated data, with a mono-dimensionnal full-wave propagation code ^{5}, respectively $S^{exp}_{\delta\phi}$ and $S^{sim}_{\delta\phi}$, created by known density fluctuations spectra ($S^{sim}_{\delta n}$), we can define a transfert function leading to an estimation of experimental density fluctuations spectra :

$$f_t(k_r,r) = \frac{S^{sim}_{\delta n}(k_r,r)(k_r,r)}{S^{sim}_{\delta\phi}(k_r,r)(k_r,r)} \quad , \quad S_{\delta n}(k_r,r) = f_t(k_r,r)\ S^{exp}_{\delta\phi}(k_r,r) \tag{2}$$

The estimation of $S^{exp}_{\delta n}$ is then reinjected into the simulation, providing a more precise transfert function, until the convergence of the loop.

3 Density fluctuations measurements and L_{ne}

3.1 Experimental conditions

Eighteen ohmic discharges have been realized on the Tore Supra tokmaka, achieving a density scan from 1 to $4.2.10^{19}\ \mathrm{cm}^{-1}$, with a 3.1 T and 3.8 T magnetic field. Such plasma conditions allows a good coverage of the $50 - 110$ GHz fast-sweeping reflectometer, from $R = 3.1\ \mathrm{m}$ up to $R = 2.4\ \mathrm{m}$ ($\rho = r/a = 0.25-1$, $a = 0.72\ \mathrm{m}$ being the tokamak minor radius), for the whole scan. Each discharge was made up of three $5\ \mathrm{s}$ density levels, while the plasma parameters were kept constant. We performed 1500 frequency sweeps (1 sweep each $25\ \mu\mathrm{s}$) in burst mode for each density level.

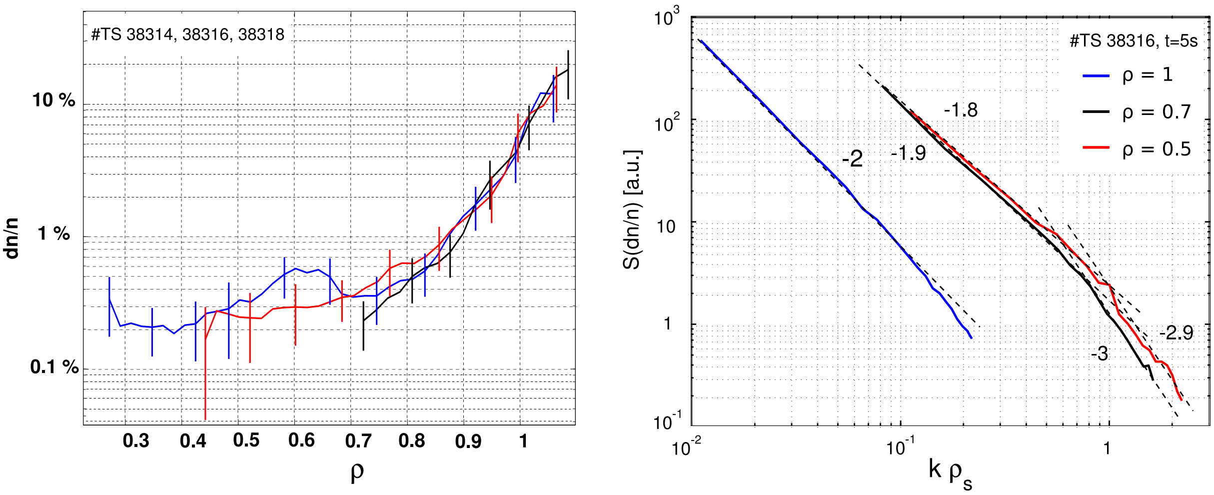

Figure 1: *left (a)* : density fluctuations profiles for a set of plasma discharges ($B = 3.8$ T, $I_p = 0.8$ MA), during a density scan : TS 38314, $n_e = 1.110^{19} m^{-3}$, (blue), TS 38316, $n_e = 1.510^{19} m^{-3}$ (black), TS 38318, $n_e = 3.410^{19} m^{-3}$ (red). *right (b)*: density fluctuations spectra for the TS 38316 plasma discharge, for $\rho = 1$ (blue), $\rho = 0.7$ (black), $\rho = 0.5$ (red).

3.2 Density fluctuations spectra and profiles – Scaling of $\delta n_e/n_e$

The $\delta n_e/n_e$ profiles are represented in fig 1 a for three different plasma conditions, each one corresponding one mean density value. What the method really computes are the radial wavenumber spectra of $\delta n_e/n_e$, in the range of 1-40 cm^{-1}, for each radial position : $\delta n_e/n_e$ values result from the integration of the spectra between 1-10 cm^{-1}. The $k_r \rho_s$ range depends on the spectra radial position. Error bars are estimated by computing the standard deviation for the whole set of 1500 $\delta n_e/n_e$ profiles. At the plasma edge and in the gradient zone ($0.7 < \rho < 1$), density fluctuations remain similar.

Previous measurements made by beam emission spectroscopy on DIII-D [6] found $\delta n_e/n_e \simeq 0.4\%$ around $\rho = 0.7$, evaluated from spectra between $0 < k_\perp \rho_s < 0.7$, in agreement with our measurement. Spectra shown in Fig 1 b exhibit different behaviours, according to their radial position : slopes for low k_r are almost identical, $S_{\delta n}(k_r, r) \sim k_r^{-2}$, for 1 cm^{-1} $< k_r <$ 10 cm^{-1} ($0.1 < k_r \rho_s < 1$, ρ_s being the electronic Larmor gyroradius). Some discrepancies appear while comparing with k_θ spectra previously extracted from the coherent forward Thomson scattering diagnostic [7], scaling with $k_\perp^{-3.5}$ for 6 cm^{-1} $< k_\perp$ 14 cm^{-1} ($0.5 < k_\perp \rho_s < 2.5$) and the Doppler reflectometry [8] , scaling with $k_\perp^{-3}$ for 3 cm^{-1} $< k_\perp <$ 20 cm^{-1} (0.15 <

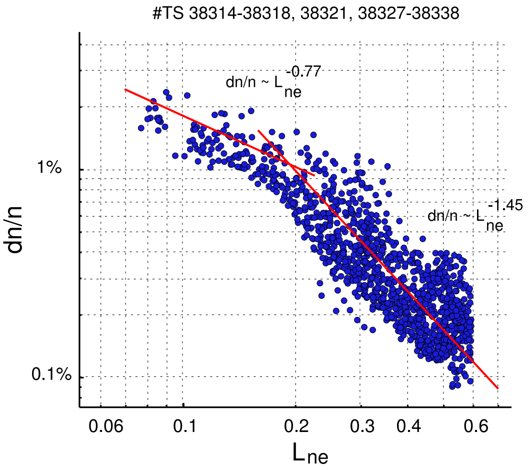

Figure 2: Fits of density fluctuations against local electronic density gradient length for the density scan shots.

$k_\perp \rho_s < 1$).

Gradients are generally supposed to drive the evolution of the plasma turbulence. Theory and experiments suggest that electron heat transport is governed by turbulence increasing above a threshold in a normalized gradient $R/L_{T_e} \equiv -R\nabla T_e/T_e$ or $R/L_{n_e} \equiv -R\nabla n_e/n_e$. We focuse here only on L_{n_e}. Previous experimental scaling of $\delta n_e/n_e$ with the density gradient length L_{n_e} roughly indicates $\delta n_e/n_e \sim \rho_s/L_{n_e}$ [9].

The global set of 54 ohmic plasmas give a precise estimation of radial $\delta n_e/n_e$ profiles, fitting well with the local electronic density gradient length L_{n_e}, computed from reflectometry density profiles. By selecting $\delta n_e/n_e$ values for $\rho < 1$ and $R0/L_{n_e} < 4$, R0 being the Tore Supra major radius (2.38 m), we underline the scalings $\delta n_e/n_e \sim L_{n_e}^{-0.77}$ ($0.07 < L_{n_e} < 0.2$) and $\delta n_e/n_e \sim L_{n_e}^{-1.45}$ ($0.2 < L_{n_e} < 0.6$). Dependences of the magnetic shear and temperature gradient length L_{T_e} contributions have to be investigated further.

4 Conclusion

The closed loop method is designed to be a tool rapidly providing an access to the absolute values of density fluctuation profiles and k_r spectra from fast-sweeping reflectometry. By comparing simulated and experimental phase signals, we are able to give an estimation of the plasma density fluctuations : radial profiles and radial wavenumber spectra are easily achievable on Tore Supra plasma discharges. Then a parametric analysis of density fluctuations dependences is achievable : this point is stressed by a double scaling of $\delta n_e/n_e$ with the local electronic gradient length L_{n_e}.

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