Major progress in high spatial and spectral resolution of reflectometry in Tore Supra: density peaking and fluctuation measurements

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Abstract The development of complementary reflectometry systems on Tore Supra allows for high resolution wide spatial coverage measurements for turbulent transport detailed analysis. Combining density profile and fluctuation measurement, it was found that the localised core peaking of the density profile results from a particle pinch inside the q=1 surface close to neo-classical value and a small turbulent diffusion in agreement with a low level of density fluctuations. Dedicated β scaling experiments showed no change in the fluctuation levels on Tore-Supra, in agreement with the observation of weak confinement degradation with increasing β. Finally, complementary spectral sensitivity, from low to medium or high wave-number k for fluctuation measurements permits to address the question of ion or electron transport channel and dominant modes.

1. Introduction

Turbulence determines the quality of confinement in tokamak plasmas. Therefore detailed fluctuations measurements provide key insight for understanding the turbulent transport. Derived from radar principle, reflectometry is a versatile density diagnostic using microwaves [1]. This non-perturbative technique is able to provide detailed density profile and quantitative density fluctuation measurements overall the plasma. This paper presents some recent results obtained with reflectometry on particle, thermal transport, and turbulence in Tore Supra.

Particle transport has aroused a large theoretical and experimental effort since predicting the density profile in ITER remains a subject of debate [3]. While there is strong evidence that a turbulent particle pinch exists in the gradient zone of tokamak plasmas, the behaviour of the plasma core is still unclear. In Tore Supra, high resolution profile reflectometry has revealed the existence of a localised density peaking in the plasma core over a flat region larger than the $q = 1$ surface. The dynamics of this spontaneous peaking shows the combined effects of neo-classical and turbulent transport.

Confinement prediction for the next step machines remains challenging for transport models, and relies on extrapolations of scaling laws based on multi-machine data base [2]. The dimensionless form of these scaling laws should reveal the underlying mechanisms of turbulent transport, each of the dimensionless parameters involved being linked with a particular aspect of turbulent transport. Fluctuation measurements provide key elements for validating the confinement dependence with non dimensional parameters.

Finally, complementary spectral sensitivity, from low to medium or high k is required for identifying the dominant instabilities. In particular, the role of small scale turbulence could be important for electron transport, which should be central when electron heating dominates, as this will be the case in burning plasmas.

2. Reflectometry systems

Tore Supra is equipped with a set of four reflectometers for measuring density profiles and density fluctuations properties with good spatial resolution [4]. Fast swept reflectometers provide accurate density measurements over the whole profile: two FM-CW reflectometers operating in the band 50-78 GHz and 72-116 GHz in X-mode polarisation are dedicated to edge density profile measurements in usual operating conditions. Each bandwidth is swept in 20 μs, which determines the time measurement per profile. Core profile is now measured with a 105-160 GHz (D-band) reflectometer [5]. Its sweeping time varies between 40 to 100 μs, depending on plasma conditions. Operating in X mode, it covers, in usual plasma conditions, an area from mid-radius on the low field side (LFS) to the plasma edge on the high field side (HFS) in the equatorial plan ($Z = 0$). The high spatial sensitivity permits detailed density profile measurements, which has been used for detailed observation of MHD modes [6, 7]. However errors in magnetic field for instance can lead to a localisation uncertainty of the order of 5 mm.

The D band X-mode reflectometer can also operate at fixed frequencies, which is the classical method to detect large scale fluctuations ($k_r < 2$ cm^{-1}) with a high sensitivity. Radial profiles of density fluctuations shown in this paper are obtained with this system.

Finally, a 50-75 GHz O-mode Doppler reflectometer detects fluctuations at selectable poloidal wave numbers ($3 < k < 20$ cm^{-1}) [8]. It is based on the possibility to separately detect the field back-scattered on fluctuations along the beam path from the field reflected at the cut-off layer (standard reflectometry), by launching the probing beam in oblique incidence with respect to the cut off layer. Fluctuations whose wave-number matches the Bragg rule are selected $\vec{k} = -2\vec{k}_i$, where $\vec{k}_i$ is the *local* probing wave-vector. The probing beam wave-vector is determined by the angle α of the beam to the normal to the iso-index layer. In addition to the fluctuation level at k, the perpendicular fluctuation velocity in the laboratory frame is obtained from the Doppler shift of the frequency spectrum $\Delta\omega = kv_\perp$. The Doppler reflectometer probing zone depends only on the density profile, typically $.5 < r/a < .95$.

3. Localised density peaking in the plasma core

High resolution profile reflectometry has shown the existence of a localised density peaking inside the $q = 1$ surface [9]. As shown on figure 1 it consists of a very local steepening of the profile over a very flat central region. It can represent up to 10 % of the central density, with a typical width less than 15 cm.

This central peaking is commonly observed in ohmic discharges, and is not caused by plasma fuelling (gas puff at the periphery). It is not associated with a similar structure on the temperature profile, as can be seen on the ECE temperature profile.

To follow the time evolution of this structure, profiles were recorded at high repetition rate, with a dwell time of $5\,\mu$s between 2 profiles. The build up of the structure is clearly seen on figure 2 in the 30 ms sequence (around 1000 profiles) covering a sawtooth period.

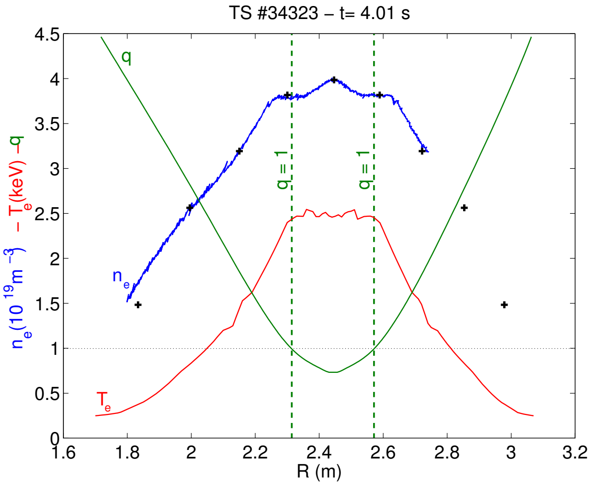

Figure 1: *the density profile (in blue) is flat over a region larger than the $q = 1$ surface, except in the very centre; also shown are the electron temperature (red) and q-profile (green).*

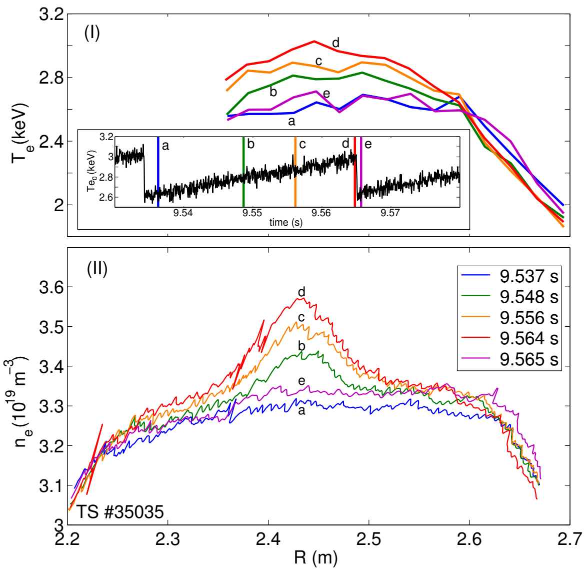

Figure 2: *Temperature (I) and density (II) profiles at different times (abcde) during the ramp phase of a sawtooth (T_e time evolution in the box).*

5 profiles are partially represented on figure 2. The central density value increases quasi-linearly in time. Conversely to temperature profile, the density profile raise is more local than the temperature one, leaving the flat plateau on both sides of the bump practically unchanged. The plateau width is larger than the $q = 1$ surface, and the bump width smaller. The link with the $q = 1$ radius has been observed by scanning the plasma current; however the bump width rapidly saturates when $r_{q=1}$ is increased [9].

Particle transport coefficient and pinch velocity can be derived from the dynamics of this peaked profile. The particle flux $\Gamma(r,t)$ is estimated at several radii at the different times $\Gamma(r,t) = -\frac{1}{r}\int_0^r r'\partial_t n_e \, \mathrm{d}r'$ (particle conservation law in absence of particle source). For each radius, the electronic particle transport coefficient (D) and the pinch velocity (V) are determined from the dependence of the particle flux $\Gamma(r,t)$ on density and density gradients: $\Gamma/n_e = -D\nabla n_e/n_e + V$ by a linear fit on their time evolution.

In the local density peaking zone, V and D are very low: at $r = 4$ cm, $V = -0.088 \pm 5.10^{-3}$ m/s and $D = 0.074 \pm 7.10^{-3}\,\mathrm{m}^2/\mathrm{s}$. The pinch velocity V appears to be close to the neo-classical value, as confirmed by the comparison of the experimental profiles with the outputs of the neo-classical transport code NCLASS [10] integrated in the CRONOS [11] package. As usually observed in tokamak plasmas, the measured diffusion coefficient D is larger than the neo-classical one D_{neo}; the latter is governed by electron diffusion that is very low (10^{-2} m^2s^{-1}). However, D is around 3 times lower than the particle diffusion observed in the gradient zone, which is known to be anomalous.

The raise of the local density peak thus reveals a low turbulent zone, where some of the neo-classical features of the transport are expressed. This picture is confirmed by density fluctuation profile measurements (fig. 3 a) on the one hand, and the effect of heating on the local density peak (fig.3) on the other hand.

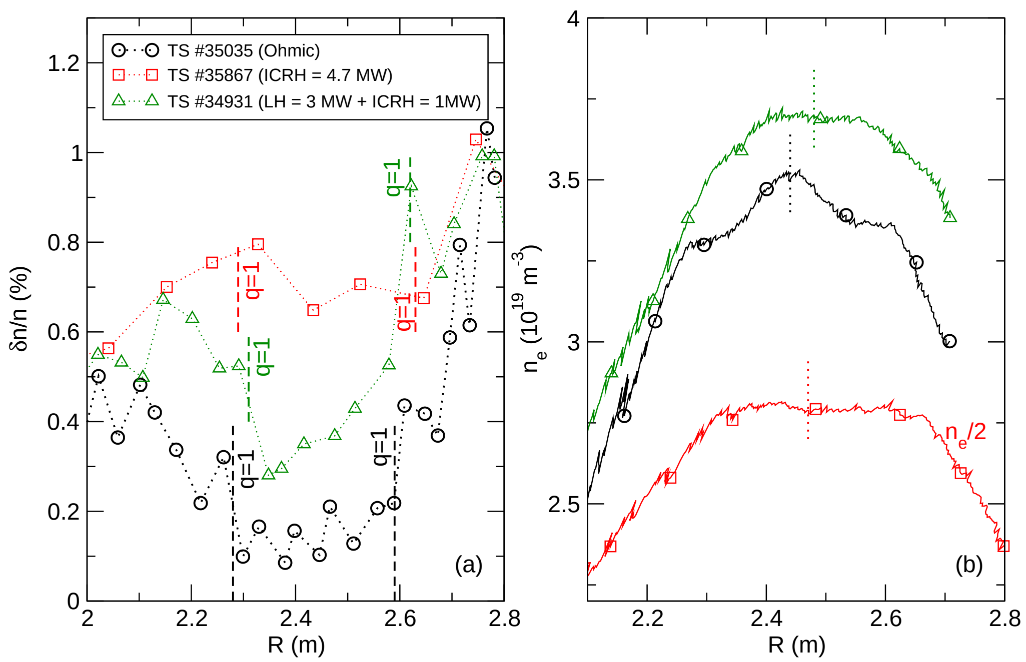

Figure 3: *Density fluctuation profile (a) from the fluctuation reflectometer, and density profile (b) measured in ohmic discharge (black), during ICRH (red) and LHCD (green)*

For the ohmic case (black), the fluctuation level ($\delta n/n$) drops by a factor of more than 2, near the magnetic axis ($R = 2.44$ m). This fluctuation hole is very well correlated with the position of the $q = 1$ surface and is always seen in Tore-Supra ohmic discharges. When the peaked feature is present (black density profile, fig. 3 b), the density fluctuations profile is always hollow inside the $q = 1$ surface, supporting the assumption of a very low level of turbulent transport inside the $q = 1$ surface.

Additional heating however deeply affects the peaking process either by decreasing the inductive field or by increasing the fluctuation level. Indeed, when Lower Hybrid Current Drive (LHCD), mostly used for sustaining long stationary discharges with non-inductive current-drive, is applied, the density peaking vanished (green curve, fig. 3 b). More precisely, the density profiles become flat when the loop voltage V_{loop} goes under 100 mV (a typical value for ohmic regime is about 900 mV). This observation supports the role of the neoclassical Ware pinch for driving the central peaking since the Ware pinch is proportional to the parallel (inductive) electric field.

Ion Cyclotron Resonance Heating (ICRH) also modifies the central density profile. Above 4 MW of ICRH power, the density peaking is no longer visible while V_{loop} is still higher than 400 mV. When applying ICRH, the density fluctuation level increases over the whole plasma, including the center (red curve, fig. 3a). This could lead to a higher turbulent diffusion. It likely explains the vanishing of the local central peaking when applying ICRH.

Though the local peaking itself is rather well described by a pure neo-classical effect, the presence of the large plateau on both sides of the peak, extending over the $q = 1$ surface is still not completely understood. These observations however show the concurrent effects of diffusion and pinch on particle transport, and the role of turbulence. The questions of particle transport and density peaking have deserved a lot of interest in the few past years since it is of crucial importance for burning plasma performance.

4. Weak fluctuation and transport dependence on β

The scaling of energy confinement time with dimensionless parameters is widely used with the aim of validating transport models and improving confidence in next step machines performance. It relies on the assumption that, if energy transport is dominated by plasma physics, transport coefficients, normalised to the Bohm value $\chi_B \equiv T/eB$, can be expressed as functions of three dimensionless parameters $\chi \equiv \chi_B F(\rho^*, \nu^*, \beta)$ at fixed safety factor q, plasma geometry, and ratio T_e/T_i [15]; $\rho^*(\equiv \rho_i/a)$ is the normalized gyroradius, ν^* the collisionality and β the ratio of kinetic to magnetic pressure. The latter is mainly linked to electromagnetic effects.

Discrepancies have been found between the ITER H-mode scaling law, which predicts a degradation of the energy confinement with β, and dedicated similarity experiments. JET [12] and DIII-D [13] have shown a very weak or even non-existent dependence with β while the JT-60U [14] results are closer to the original ITER scaling law: $B_0\tau_E^H \propto \beta^{-0.9}$ [2]. This contradiction remains unclear: in H-mode, the ELM physics is driven by MHD and is thus β dependent.

	high β shots (35900, 35873)	**low β shots** (36044, 36031)
B_0	3.8 T	3.2 T
I_p	0.95 MA	0.8 MA
$n_e(0)$	6.10^{19} m^{-3}	3.10^{19} m^{-3}
$T_e(0)$	4 keV	2.5 keV
P_{ICRH}	7 – 8 MW	1.5 – 2 MW
β_{th}	0.3 %	0.14 %
β_N	0.5	0.23

Table 1: *Main plasma parameters for the β series*

L-mode discharges in Tore-Supra are particularly suitable for studying the β dependence of turbulent transport without edge MHD (ELMs) and pedestal physics to interfere.

Series of shots at two different magnetic field B were performed, where density and heating power were adjusted to keep $\rho*$ and $\nu*$ constant while inducing a variation of β by a factor of 2 [16]. The 4 shots selected matching these constraints are detailed in table 1. Attention have been paid in having homothetical profiles for the electron density n_e and temperature T_e in the gradient zone, as well as similar T_e/T_i profiles. The profile matching is good in the gradient area, while in the plasma centre ($\rho < 0.2$), a slight mismatch in noticeable due to a warmer core temperature for the high β shots. The same auxiliary heating was used, Hydrogen minority ICRH in a deuterium plasma and the frequency was adapted in order to have a central power deposit in both case.

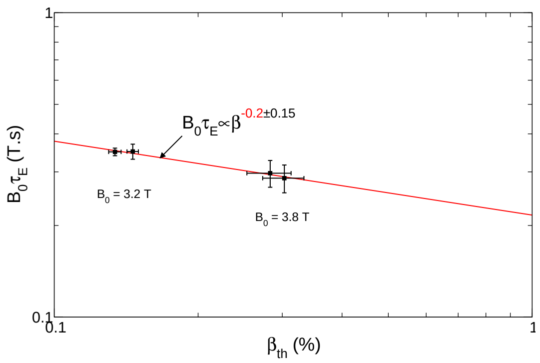

Figure 4: *Normalised confinement time of energy as a function of the average β for the dedicated scaling shots.*

The global energy confinement time τ_E shows a weak dependence on β: $B_0\tau_E \propto \beta^{-0.2\pm0.2}$ (fig 4). This dependence has to be compared to the ITER L-mode scaling law β: $B_0\tau_E^L \propto \beta^{-1.4}$. Global values of β and τ_E are evaluated from the magnetic probes, where a systematic error in the magnetic measurements due to fast ions contributions has been taken into account in the error bar; however CRONOS simulation have shown that the supra-thermal contribution in the energy measurements can be neglected. The local dependence of the the thermal diffusivity χ has been analysed thanks to the CRONOS code. The effective diffusivity ($\chi_{eff} = (n_e\chi_e + n_i\chi_i)/(n_e + n_i)$) has a scaling exponent rather low, of the order of $\alpha_\beta = 0.2 \pm 0.4$. This dependence is in good agreement with the scaling of the confinement time.

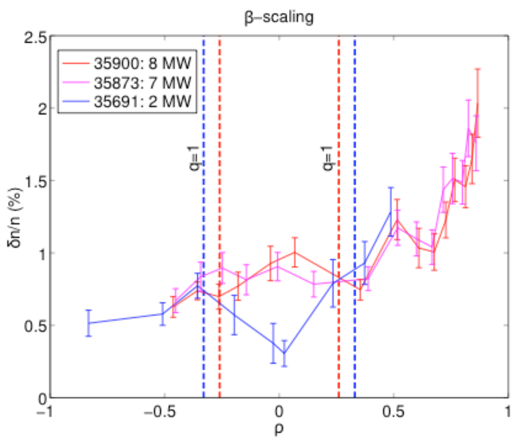

Figure 5: *density fluctuation profile at high and low β, with $\rho*$ and $\nu*$ kept constant.*

Finally the fluctuation level profile measured by the fast-hoping fluctuation reflectometer shows no or little dependence in the gradient zone, outside of the $q = 1$ surface (fig. 5). Inside the $q = 1$ surface, the hollow profile at low β (in blue), linked with the peaked central density (see above) disappears at high β (red). This could be due probably due to the mismatch of the ρ_* and ν_* profiles in this very central region, where temperature profile is much more peaked at high β (higher ICRH power).

In addition to global analysis of the energy confinement time τ_E, local analysis of transport as well as local turbulence measurements from reflectometry systems show a weak dependence on β in the L mode discharges in Tore supra. This is similar to the weak dependence observed in JET and DIIID in H mode, and suggests that discrepancies with JT-60 experiments could be due to edge pedestal effects. A statistical bias in the extraction of dimensionless scaling laws from databases [17] is invoked to explain the contradiction between statistical and these experimental observations.

5. Fluctuation wave-number spectrum dependence on Larmor radius ρ_s

Scattering of electromagnetic waves is a powerful technique for the purpose of fine scale analysis, because it provides directly the space Fourier transform of the fluctuating density at a specified wave-number k. Though the most energetic part of the wavenumber spectrum lies at small k, higher k domain $k\rho_i >> 1$ has raised new interest because of its possible implication in the electron thermal transport. Several theoretical and numerical studies have recently shown that ETG modes have typical scale length larger than the electron Larmor radius due to the formation of long scale structures in the radial direction [18, 19] and thus could account for a significant part of electron transport [20]. Experimental observations in the high k range are still rare because of the very low level of fluctuations in this range requiring sensitive techniques [21, 22, 23].

High k range ($k\rho_i > 1$) has been investigated on the Tore Supra tokamak with the Doppler reflectometer system [24]. The power spectral density of the density fluctuations is plotted versus k on figure 7. It shows a fast decrease of the fluctuation level at high k. This observation is similar to previous observations in the plasma edge of Tore Supra using a CO_2 laser scattering experiment [21].

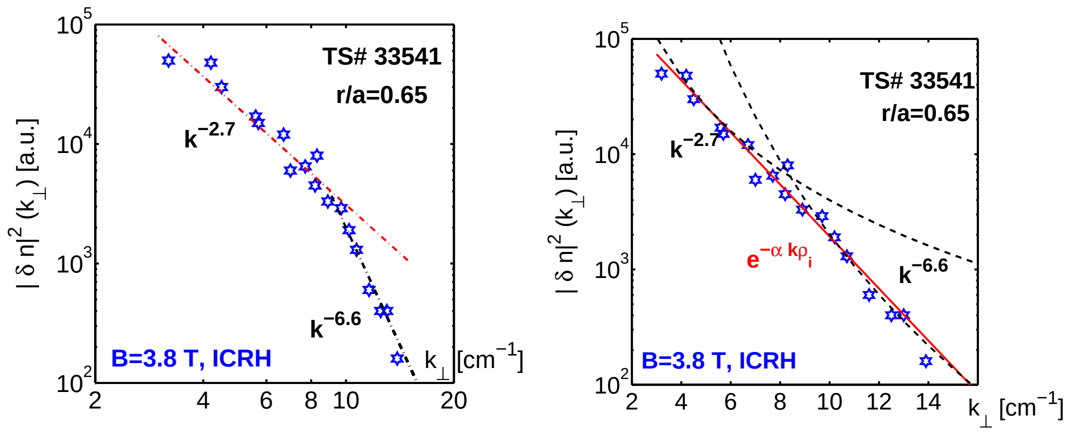

Figure 6: *k spectrum of the density fluctuations $|n(\vec{k})|^2$ as a function of k (a) logarithmic scales (b) semi-logarithmic scales, from Doppler reflectometry in Tore Supra with ICRH, $P = 3$ MW, $B = 3.8$ T, $n_l = 5\,10^{19}$ m^{-3}. The power laws are obtained by fitting the data on either side of the transition (dashed lines). (b) The $\exp^{-\alpha k}$ function (plain red curve) is fitted over the whole k range.*

The spectral index changes from the usual -3 to -7 when increasing the poloidal wave number $k_\perp$ above $k_\perp \rho_s \sim 1.5$, which means a drop of more than 3 orders of magnitude with respect to the small k level. This very low level of fluctuations at high k suggests a minor role of Electron Temperature Gradient driven modes.

The characteristic scale, which appears to be linked to the ion Larmor radius, is also clearly expressed when the spectrum is plotted in semi-logarithmic scale (fig 6 b). The spectrum is well fitted by $\exp^{-4\alpha k}$, with $\alpha \sim 4k\rho_i$ in all plasma conditions where these measurements could be performed, either with the CO_2 laser system or with the Doppler back-scattering system. The k spectrum deviation from usual power law prevailing in fluid turbulence, should indicate also a breaking of the self-similarity principle in inertial k range.

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