Measurements of density profile and density fluctuations in Tore Supra with reflectometry

R. Sabot 1), F. Clairet 1), P. Hennequin 2), S. Heuraux 3), A. Sirinelli 1), L. Vermare 1), J.M Chareau 1), J.C. Giaccalone 1), C. Honoré 2), G. Leclert 4), D. Molina 1), J.L. Ségui 1), A. Truc 2), F. Da Silva 5), E. Manso 5)

1) Association EURATOM/CEA, CEA/DSM/DRFC, CEA-Cadarache, 13108 Saint-Paul-lez-Durance, France
2) Laboratoire de Physique et de Technologie des Plasmas, CNRS (UMR-7648), Ecole Polytechnique, 91128 Palaiseau, France
3) Laboratoire de Physique des Milieux Ionisés, Université Henri Poincaré, BP 239, 54506 VANDOEUVRE Cedex, France
4) LPIIM, CNRS (UMR 6633) - Université de Provence,13397 Marseille Cedex 20, France
5) Associação EURATOM/IST Centro de Fusão Nuclear, Instituto Superior Técnico, 1046-001 Lisboa, Portugal

e-mail contact of main author: roland.sabot@cea.fr

Abstract Tore-Supra is now running with a set of reflectometers using three different techniques. A 50-110 GHz X-mode fast and continuously scanning frequency set-up that routinely measures the density profile, a stepped fixed frequency X-mode set-up operating between 105–160 GHz for plasma core measurements which is also able to perform slow sweeps and a 50-75 GHz O-mode Doppler reflectometer with k-spectra determination. This collection of diagnostics can thus achieve complementary measurements from the low to the high field side of the discharge. Reflectometers provide reliable and accurate measurements of the density profile from the edge to the center even during large and fast profile evolution. Central MHD modes are observed with high radial and temporal resolution. Thus, valuable information can be given onto the safety factor profile to be compared with equilibrium code calculations. Detecting MHD modes with two reflectometers at different toroidal location allows to estimate the mode toroidal velocity. The fluctuation poloidal velocity is measured with Doppler reflectometry. The radial profile of small scale density fluctuations can be retrieved from fast FM-CW phase reflected signal. It shows a minimal level in the center, and a strong increase toward the edge.

1. Introduction

Density is a key parameter governing the performances of magnetically confined plasmas: particles confinement studies ask for a precise density profile, coupling of radio-frequency power is determined by edge density values, fast events like sawtooth or pellet injection generate large density perturbations. The micro-instabilities that are thought to cause anomalous transport generate also small scale density fluctuations.

Derived from radar principle, reflectometry is a common diagnostic for density measurements in magnetic fusion devices [1,2]. It measures the round-trip time of a microwave reflected inside the plasma at a position that depends on the wave frequency and the local density. Sweeping the frequency source is the standard method for density measurements, a method called FM-CW for Frequency Modulation-Continuous Wave. Large bandwidth and fast sweeping rate allow profile measurements with high spatial and temporal resolution. The resolution, the modest requirement for plasma accessibility, the possibility to move the electronic components far from the vacuum vessel make reflectometry an ideal tool for ITER. High density and magnetic field in ITER will demand frequencies up to 200 GHz [3].

In this paper we present various results obtained with Tore-Supra reflectometers. These reflectometers are built on the same original microwave scheme presented in section 2. In section 3, we show that reflectometry gives robust and reliable profile measurements. Measurements of MHD modes are presented in section 4. Measurement of poloidal rotation with Doppler reflectometry are presented in section 5. In section 6, we show that density fluctuations profiles could be obtained from fast FM-CW reflectometry. Concluding remarks follow in section 7.

2. Tore-Supra reflectometer microwave scheme

Four reflectometers are now in operation on Tore-Supra. Two FM-CW reflectometers operate in the frequency ranges 50-75 GHz and 75-110 GHz in X-mode polarisation, and are dedicated to density profile measurements [4]. A 105-160 GHz X-mode reflectometer, that can operate either at fixed frequencies or in slow FM-CW mode, addresses plasma core measurements [5]. A 50-75 GHz O-mode Doppler reflectometer measures the poloidal velocity and density fluctuations at poloidal wavenumber $k_{\perp}$ between 3 and 15 cm^{-1} [6]. FIG 1a. shows the cut-off radial dependence at high magnetic field (B=3.8 T). The 50-110 GHz set-up measures the edge density profile, the 105-160 GHz reflectometer probes the core from mid-radius up to the edge on the high field side. At B=3 T, the 50-110 GHz set-up measures up to the centre (FIG 1b) . The Doppler reflectometer probing zone depends only on the density profile.

These reflectometers are built on an original microwave set-up presented FIG. 2. The microwave source is broadband in the range 12 to 20 GHz. The source signal is split in a probing and reference arm. On the probing arm, a single sideband modulator (SSBM) shifts the frequency for heterodyne detection ahead of a frequency multiplier. On the reference arm, a second multiplier is the local oscillator of a balanced or sub-harmonic mixer. A quadratic demodulation gives the amplitude and the phase of the reflected signal. The microwave source makes the main difference between the 50-110 set-up and the two other reflectometers. Because of fixed frequency measurements, the 105-160 GHz and the Doppler reflectometers are built with a frequency synthesiser that offers a very low phase noise instead of a more agile VCO (Voltage Control Oscillator).

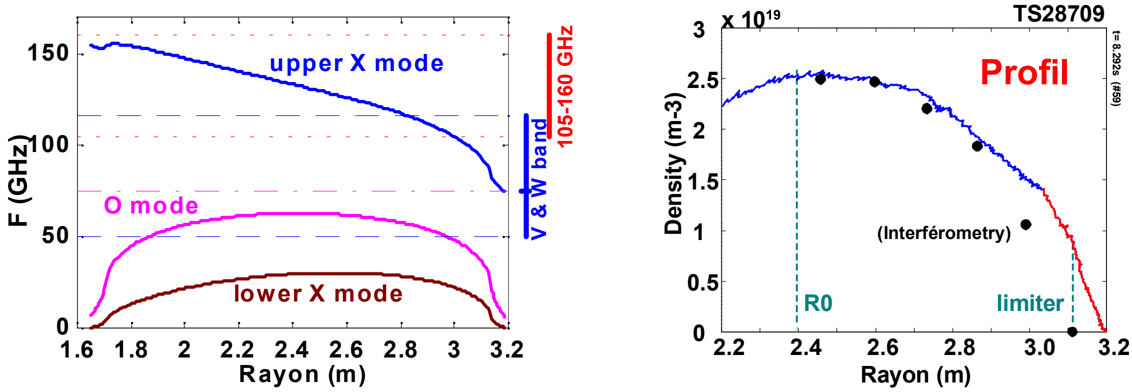


FIG. 1: a) Radial dependence of cut-off frequencies for $n_e = 5.10^{19}\left(1-(r/a)^2\right)^{0.6} m^{-3}$*, B=3.8T. b) Density profile from the 50-110 set-up at B=3T and comparison with interferometry (dot). The discrepancies near the edge comes from the interferometry assumption of a zero density at the edge.*

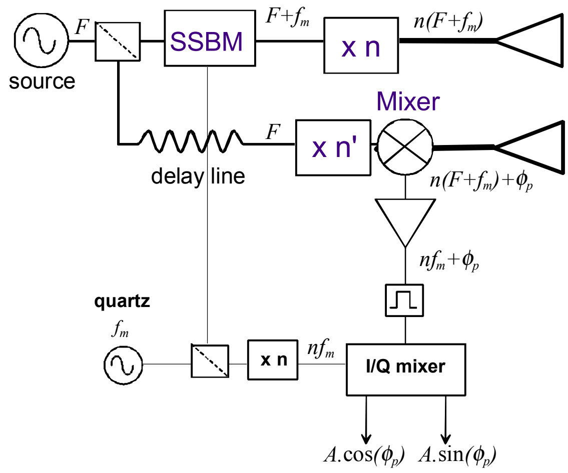


FIG. 2: Set-up of the Tore-Supra reflectometers.

This system presents the following advantages:

- The same microwave source is used as a probing and reference signal. The sweeping time is not constraint by a phase lock loop, it is determined by the source sweeping rate (up to few GHz/µs for VCO). Decreasing the sweeping time to the microsecond range ‘‘freezes’’ the turbulence and substantially improve the profile reconstruction [7].
- The SSBM high rejection level allows heterodyne measurement at fixed frequency without frequency image overlapping [8].
- Different sources can be used in sequence in the same reflectometer: a stable source for fixed frequency measurements and a fast swept source for profile reconstruction.

3. Density profile measurements

The 50-110 GHz set-up are built with agile VCOs. The bands 50-75 GHz and 75-110 GHz are fully swept in 20 microseconds. The reconstruction algorithm uses an automatic detection procedure to initialise the profile without relying on other density measurements [9]. It provides radial electron density profiles routinely and automatically on the shot to shot basis. Up to 5000 (12 000) profiles can be recorded during a shot. A burst mode allows a profile measurement every 25µs for fast profile evolution, MHD or turbulence studies.

For two years now (since the start of the CIEL project) the data are accessible from the TS database few minutes after the discharge with nearly 100 % success with good agreement with interferometry (FIG. 1b). A high dynamic sensitivity associated with fast sweep capabilities, ensures robustness and versatility of the measurements. For example, it is possible to track the profile evolution during fast and large density perturbation like a Massive Helium Injection experiment (IMH) up to the disruption limit with high temporal resolution (Δt = 25 µs). The IHM aims to terminate a pre-disruptive discharge without the generation of run-away electrons [10]. It is also possible to record profiles during long duration (a few minutes) plasma discharge such fully non inductive current drive experiment [11].

Detailed knowledge of edge profile is crucial for the coupling of RF additional power to the plasma. The cut-off position of the fast wave during ion cyclotron resonance heating (ICRH) has been determined experimentally from the edge density profile measured by reflectometry. The coupling efficiency was shown to decrease exponentially with the distance between the ICRH antenna and the RF cut-off position [12].

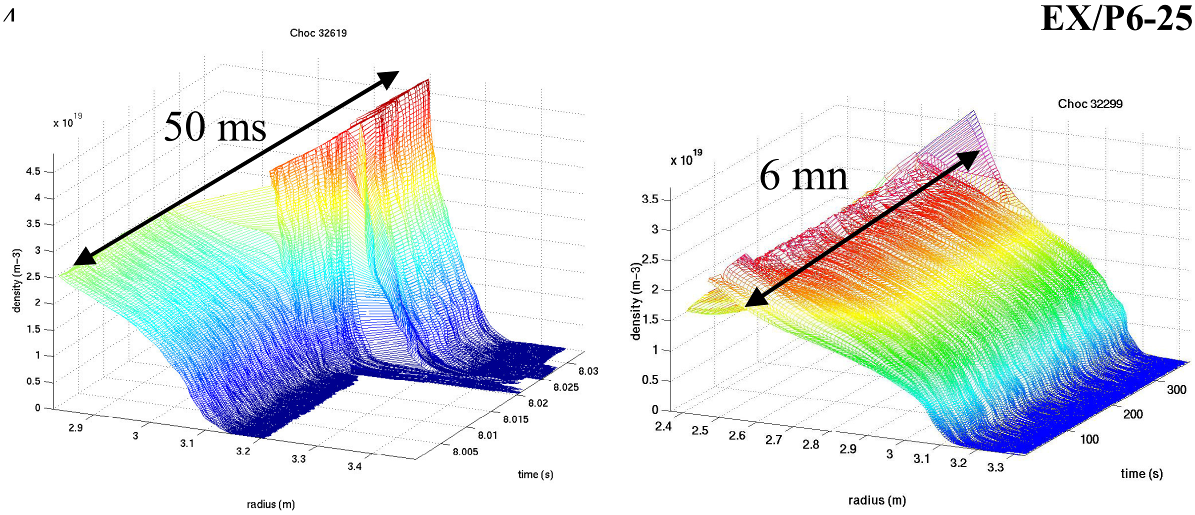


FIG 3: a) Fast acquisition performance (one profile every 25 µs) of the 50-110 GHz set-up during a massive helium injection. b) Standard profile acquisition procedure during a long pulse operation.

The whole profile but the very edge on the high field side can be measured by combining the 50-110 GHZ and 105-160 GHz reflectometers. Until now, the frequency synthesiser has limited the performances to a slow (5 ms) sweep from 105 and 129 GHz. The density profile from the 50-110 reflectometers is used for the profile initialisation. The FIG 4 shows the evolution of the density obtained with these reflectometers in an ICRH modulated discharge (B=3.2 T). When the RF power is applied, the core density increased while the edge density is less affected.

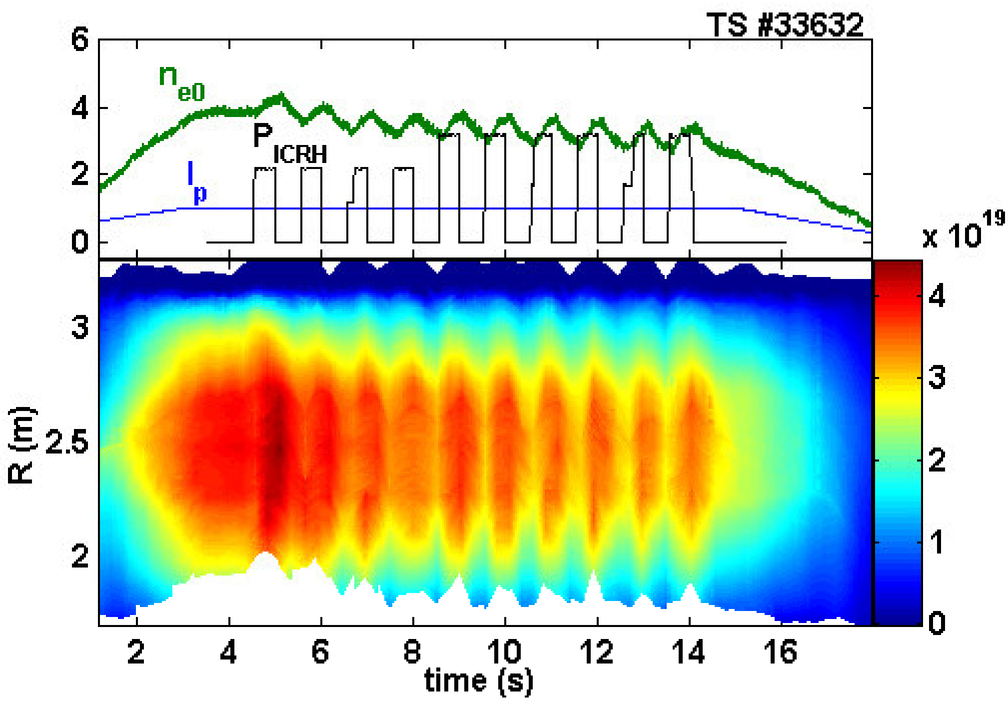


FIG. 4: Top) Density evolution in a shot with 2 then 3 MW of ICRH power modulated at 1Hz.

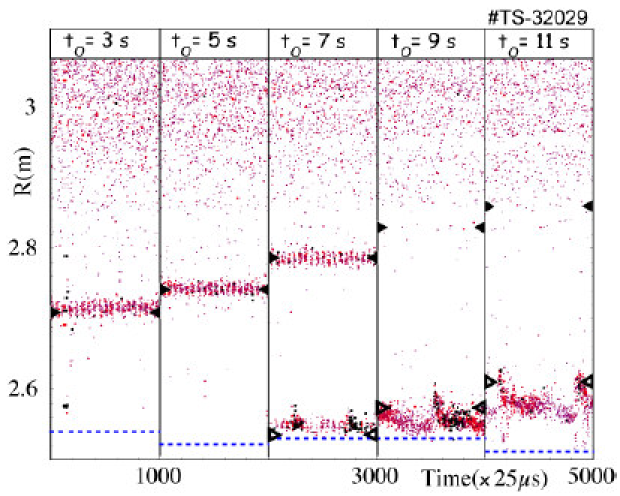


FIG. 5: Time evolution of the amplitude of the time of flight jumps versus the radial position, The triangles show the radial position of the q=2 and q=1 surface from the CRONOS code.

4. MHD measurements

MHD modes generate density perturbations that could be detected by reflectometry. On Asdex, the cut-off oscillations observed at fixed frequency have been used to locate rational surfaces [13]. On Tore-Supra, the q=1 surface has been observed with higher sensitivity and better temporal resolution than ECE or magnetic coils [14].

When the frequency is swept, the time of flight exhibits jumps at the density plateau associated to the MHD mode. The high repetition rate of Tore-Supra 50-110 GHz set-up allows to locate the modes and measure their frequency up to 20 kHz [15]. On FIG 5 we show that the time of flight jumps are located at the radius of the q=2 or q=1 surface given by the CRONOS code. During the discharge (B0=3.4 T, $n_0 \sim 2.5\ 10^{19} m^{-3}$), the plasma current is increased from 0.5 to 1 MA, the mode moves outward before disappearing at t=9s. From t=7s, the q=1 mode enters the reflectometer probing zone [16].

Simultaneous observation of a MHD mode with the 50-110 GHz and the 105-160 GHz reflectometers that are at different toroidal angles (~120° apart) gives details on the mode structure. From successive profile measurements, we can measured the mode radial structure while the mode frequency can be precisely evaluated with the 105-160 GHz reflectometer working at fixed frequency. The mode toroidal velocity can also be measured from the delay of the phase oscillation between the two reflectometers [17] (FIG. 6).

5. Poloidal velocity profiles

Backscattering of a microwave beam launched in oblique incidence makes possible measurement of density fluctuations close to the cut-off layer with a selected wave-number $k_\perp=-2\ k_i$, where k_i is the beam wave-vector at the reflection layer. On the system installed on Tore Supra in 2003, the incidence of the gaussian beam is controlled thanks to a motorized monostatic antenna. The choice of a 50-75 GHz band and O mode polarization is appropriate for typical ITB enhanced plasma regimes on Tore Supra (n_0 = 3 to 7 $10^{19}\ m^{-3}$). Both the scattering wave-number $k_\perp$ and the scattering localization r/a can be changed during a shot, owing to the tuneable probing frequency and the motorized antenna (tilt angle 0 to10°). The

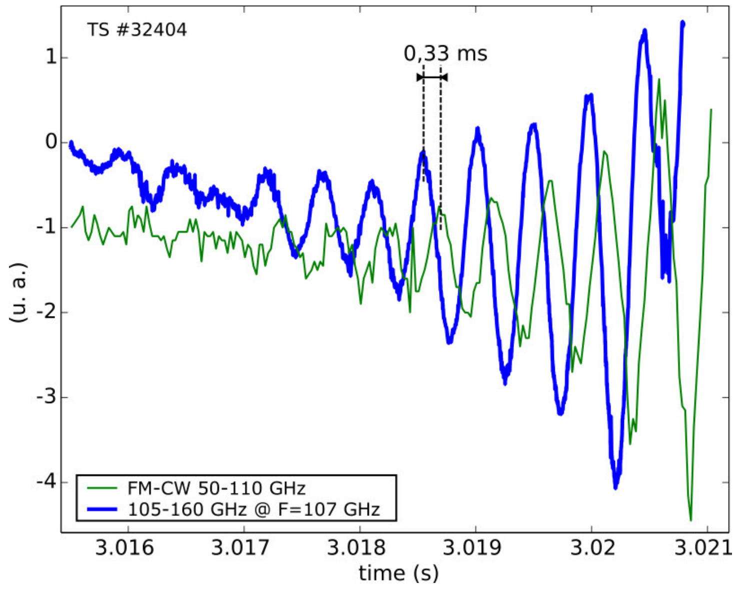
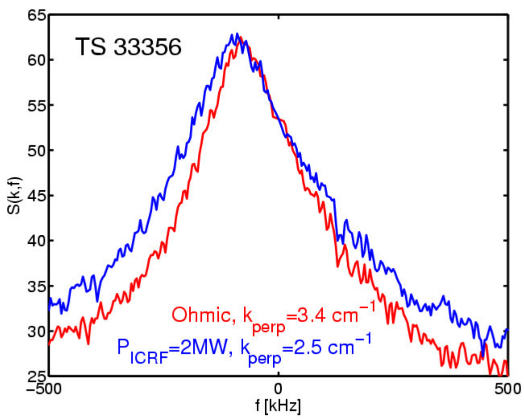


FIG. 6: Observation of an MHD mode with the 75-110 reflectometer (time of flight at F=107 GHz, green) and with the 105-160 reflectometer (phase oscillations at the same frequency, blue). The 0.33 ms delay gives a toroidal velocity around 15 km/s in agreement with CXSR.

wave-number range $k_\perp$ is 3 and 15 cm^{-1}, with a wave-number resolution around 2 cm^{-1}, and the localization from r/a~ 0.3 to 0.85, with a radial resolution around r/a=0.05, for a central density n_0=5.5 10^{19} m^{-3}. The Doppler effect allows to measure the perpendicular velocity profile for the same position range.

A typical double scan for tilt angle and probing frequency is achieved during a shot by programming several sets of frequency steps during a tilt angle sweep, sufficiently slow to ensure that the angle has not changed much during the acquisition time. FIG. 7a shows the modification of the frequency spectra between the ohmic phase and ICRH heating of a stationary plasma (B=3.7 T, I_p=1 MA, n_o=7 10^{19} m^{-3}). k has a larger value for the ohmic case for a slightly smaller the Doppler shift indicating a much smaller velocity. The fluctuation velocity estimated from the Doppler shift $f= k_\perp v_\perp$ and the spectrum broadening increase when heating is applied. Ray tracing calculation is required to determine the wave-number k and the location of the cut-off layer for each angle-frequency scan. The perpendicular fluctuation velocity profile obtained during an ohmic phase and ICRH heating is plotted on FIG. 7b. The



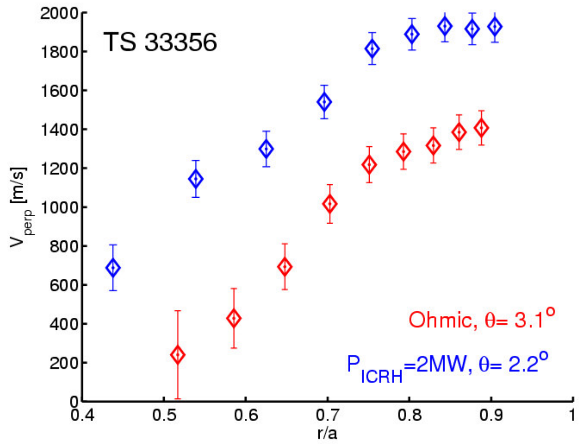


FIG 6. Doppler shift and radial poloidal rotation profile from the O-mode 50-75 Doppler reflectometer in ohmic (red) and with 2MW of ICRH power (blue).

perpendicular velocity slowly decreases as the scattering zone is located deeper in the plasma, consistently with previous observations [18].

6. Fluctuations measurements

Radial measurements of density fluctuations is crucial to evaluate plasma performance of discharges with Internal Transport barrier. The method proposed by S. Heuraux [19] has been applied to measure the density fluctuations from fast sweep reflectometer signals. It assumes that the phase fluctuations come from back-scattering on density fluctuations at a radial wavenumber twice the local reflectometry wavenumber. With a Fourier transform of the radial dependence of the phase fluctuations, we can access the radial wavenumber spectrum of density fluctuations. This method was assessed with full-wave simulations. The Fourier analysis of the phase fluctuations with sliding radial windows allows the determination of the local wavenumber spectrum of the fluctuations thus to the radial dependence of the density fluctuation level from the edge to the plasma core. FIG. 7 shows 3 fluctuation profiles with increasing density in an ohmic shot. The level of turbulence is low at mid-radius (R=2.7 m) and rises rapidly at the edge. It increases with the density at the edge but the gradient zone seems much less affected.
Fluctuations are also measured at fixed frequency reflectometer. The density fluctuations have been shown to increase with the additional heating power and to be higher on the low field side than on the high field side [14]. Numerical simulations are required for a better estimate of the level of density fluctuations from phase fluctuations at fixed frequency.

7. Conclusion

A wide set of reflectometers devices is installed on Tore-Supra tokamak. It covers the frequency band from 50 to 160 GHz, close to the highest frequency required in ITER. They rely on three techniques to measure different parameters: FM-CW for density profile, fixed frequency steps, and Doppler reflectometry for poloidal rotation and poloidal k-spectrum of fluctuations.

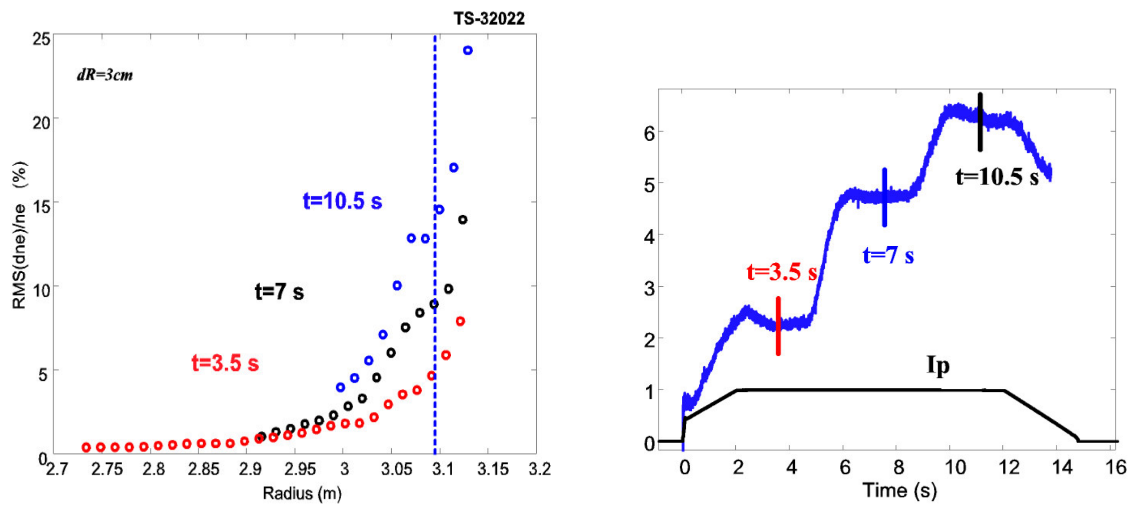


FIG. 7: Radial profile of density fluctuations at different density. b) shot scenario with 3 burst acquisitions (1000 profiles every 25µs) at 3.5, 7 and 10.5 s during central density plateaux.

Reflectometry is now a reliable diagnostic for density profiles. Automatic reconstruction algorithm enables profile measurements on every discharges even with large density perturbation. The 105-160 GHz reflectometer is under modification to run with two sources sequentially and to measure the density profile up to the high field in few tens of microseconds.

These reflectometers based on 3 different methods offers a multiple-heads tool to analyse density fluctuations from MHD to micro-instabilities, from the outer edge to the high field side and from very low k up to k=15-20 cm^{-1} for both the poloidal and radial wavenumbers. We are able to measure at the same time the density fluctuation amplitude at low and high wavenumber and the poloidal rotation. These are key parameters in Internal Transport Barrier (ITB) regime, where a reduction of density fluctuation is observed together with an increase of poloidal rotation [20].

Better simulation of anomalous transport is essential to reduce uncertainties in ITER performances. The complementary information obtain from these reflectometers will be crucial to test and improve transport models.

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