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# Density Fluctuations Measured with Fast Frequency Swept Reflectometry

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# Density fluctuations measured with fast frequency swept reflectometry

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Plasma turbulence is known to induce an anomalous heat and particle transport responsible of a strong degradation of the plasma energy confinement, and we present recent achievements to provide precise measurements of density fluctuations using the microwave reflectometry diagnostic. In this work, the turbulence measurements are retrieved from the fluctuations of the reflected signals of frequency swept systems. This method, first tested on Tore Supra [1], offers the great advantage to provide a localized and continuous radial determination of the density fluctuation level from their radial wavenumber power spectra $S(k_r)$. The fast sweep capability offers the possibility to study the plasma turbulent events with a high time resolution. Using the complete set of the JET X-mode fast sweeping heterodyne reflectometers (KG10) [2] we can provide fluctuation profiles from the edge to the center over a wide variety of plasma discharges in terms of density and magnetic field.

**Determination of the density fluctuation profile**

While the phase of the reflected signal is commonly used to calculate a radial density profile, the plasma density fluctuations are extracted from its phase fluctuations. Thanks to the profile reconstruction we can retrieve the radial dependency of these phase fluctuations $\delta\phi(r)$ and calculate their wavenumber spectra by performing a FFT through a radial window $\Delta r$ (providing a minimum accessible wavenumber $k_{min} = 2\pi/\Delta r$). The relationship, or transfer function, between the phase fluctuations and the density fluctuations spectra is given by a 1D Helmholtz code which simulates the propagation of the probing electromagnetic wave into fluctuating plasma given the experimental density and magnetic field profiles of the discharge. The reflected signal records the plasma fluctuations through Bragg backscattering physical processes, where $k_{fluc} = 2k_{wave}$, of the probing electromagnetic wave with $k_{wave}$ varying from $k_0$ ($2\pi F/c$) at the edge to 0 at the cut-off (Fig. 1).

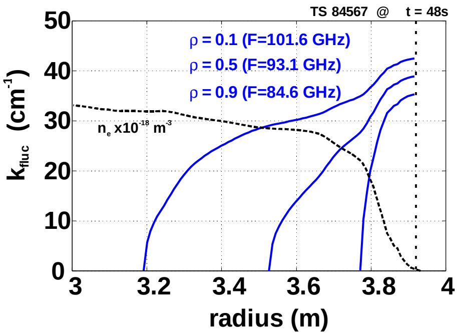

Fig. 1 : Probing wavenumbers of the plasma fluctuations according the probing frequency.

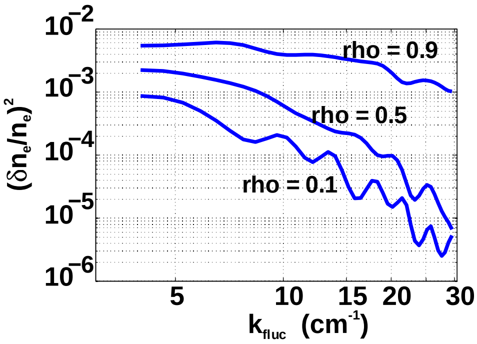

Fig. 2 : Wavenumber density fluctuation spectra calculated at the cut-off positions of Fig. 1 with an integrated radial window of 3.14 cm ($k_{min}$=2cm$^{-1}$).

The fluctuation levels are calculated from the integrated spectra (Fig. 2) for $k_{min} < k_{fluc} <$ 10cm$^{-1}$ ($k_{min}$ depends on the integrated radial window) in order to preserve the radial localisation of the measurement.

## H-mode discharge

This technique has been applied to the JET 84567 discharge (Fig. 3) with a time resolution of 300 µs (phase spectra averaged from 5 sweeps) and a radial integration of Δr=1.57 cm. It exhibits the time evolution of the density fluctuation radial profile around the LH transition in the entire plasma, from the edge to the center (Fig. 4). The turbulence reduction arises at about 48.65s and has been evaluated to occur first near the edge (ρ ~ 0.95) which then propagates toward the center. Much of the turbulence reduction is noticeable up to mid-radius and has no noticeable influence further in the plasma center.

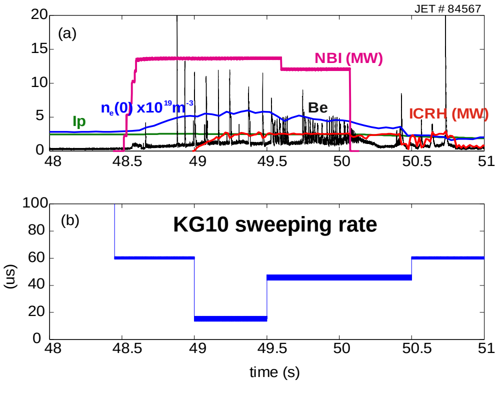

Fig. 3 : (a) Time trace of the H-mode discharge scenario and (b) delay between consecutive frequency sweeps of the reflectometers.

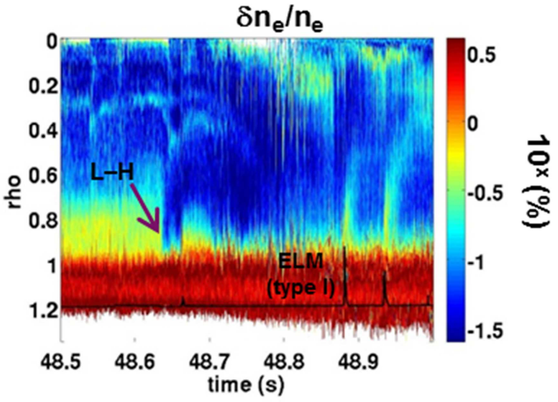

Fig. 4 : Time evolution of the density fluctuation radial profile. The black line accounts for edge Be emission.

## Wavenumber spectra

Along with a decrease of the turbulence in H-mode, a substantial steepening of the spectra is clearly evidenced (Fig. 5) and can be seen from the edge to the center (Fig. 6). The modification of the spectral slope can be related to non-linear effects of the density fluctuations onto the phase fluctuations of the reflected signal. This is particularly true at the edge where the plasma turbulence is high, however, the linear relationship between phase and density fluctuations should be more solid toward the center where the fluctuation level is low (δn/n< 1%).

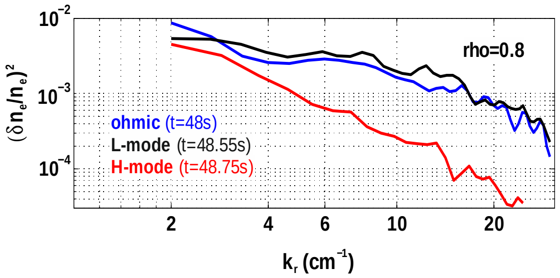

Fig. 5 : Wavenumber density fluctuation spectra comparison between ohmic, L-mode and H-mode.

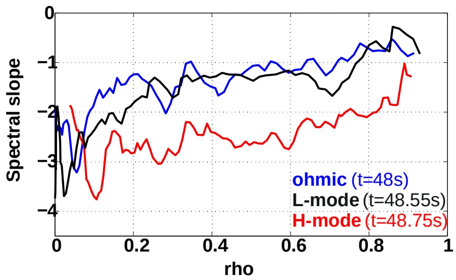

Fig. 6 : Spectral slope comparison between ohmic, L-mode and H-mode. The slopes are calculated between 2 and 10 cm$^{-1}$

## ELM crash

An ELM of type I (Fig. 7 and 8) provides a strong plasma perturbation with considerable fluxes hitting the inner wall. It offers the advantage of having a long inter ELM

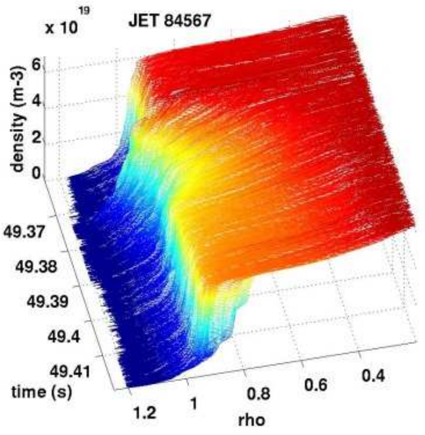

Fig. 7 : Density profile evolution during a type I ELM event.

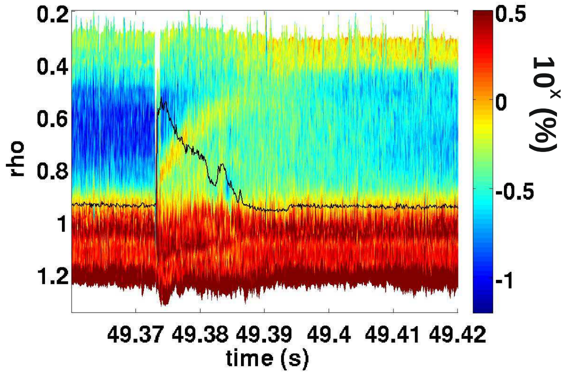

Fig. 8 : Time evolution of the density fluctuation radial profile. The black line account for edge Be emission.

period and can be thus more easily studied individually. Before the ELM crash, no precursor is observed. At the crash onset, a substantial increase of the density fluctuations is observed starting from the edge accompanying the strong plasma expulsion toward the edge. During the crash a turbulent wave front propagates toward the plasma center at about 30m/s accompanying a density collapse. Once the turbulent wave front disappears, the plasma density relaxes to its former state.

## Conclusion

In this work, we demonstrate that the fast swept reflectometry is a powerful tool to analyze the plasma density fluctuations. While fixed frequency systems provide a substantially better signal to noise ratio, the sweeping systems provide a continuous radial measurement of the plasma turbulence from the edge to the center. Thanks to the fast sweeping capabilities the turbulent changes during the L-H transition as well as the ELM crash which can be extremely well temporally observed. The density fluctuation level can be determined with very few sweeps (~ 5 to 10), the wavenumber spectra require much more (100 to 200) and is still subject to substantial nonlinear interaction between the probing electromagnetic wave and the plasma fluctuations which may alter its spectral shape.

## Acknowledgments

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**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

[1] L. Vermare et al. Nucl. Fusion 46, S743–S759 (2006)

[2] A. Sirinelli et al. Rev. Sci. Instrum. 81, 10D939 (2010)