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Density fluctuations measurements in Tore-Supra core with X-mode reflectometry

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1. Introduction

Density fluctuations are a key element to qualify plasma performances of magnetic fusion devices: destabilized MHD (Magneto Hydro Dynamic) modes could end enhanced regimes, the micro-instabilities thought to cause anomalous transport generate also small scale density fluctuations.

Reflectometry is a common diagnostic to measure density profiles and fluctuations with high spatial and temporal resolution [1,2]. The microwave launched from the edge is reflected back to the antenna at a cut-off layer where the refractive index N becomes zero.

Density fluctuations are often measured at a fixed frequency F. The phase variation of the wave acts as a motion monitor, which displays the time density perturbations in the plasma. The main part of the fluctuating phase comes from the vicinity of the cut-off layer [3]. The modelling of the phase variations can be made under the Born approximation. Different authors [4,5] have derived an expression connecting the phase fluctuations to the density perturbations for a single mode density perturbation $\delta n = \delta n_0 \exp\left(ik_x (x - r_c)\right)$:

$$\delta\phi = M\sqrt{\pi}\left(\frac{k_0^2 L_\varepsilon}{k_x}\right)^{0.5}\left(\frac{\delta n_0}{n}\right) \tag{1}$$

with $\varepsilon = N^2$, $L_\varepsilon = \left(\frac{\partial N^2}{\partial r}\right)^{-1}$, $M = n\left(\frac{\partial \varepsilon}{\partial n}\right)$ ($M=1$ in O-mode, $M\sim 2$ in X-mode), $k_0=2\pi F/c$.

2. The 105-155 GHz fluctuation reflectometer

From the expression (1), it follows that the phase should be accurately measured for evaluating the fluctuations amplitude.

2.1 Microwave scheme

The set-up previously developed for density profiles [6] was modified for achieving fluctuation measurements. A 13-20 GHz frequency synthesiser, step tuneable in few milliseconds makes a very stable source. A frequency octupler increases the frequency to the band 105-155 GHz for in X mode measurements. The core, both on low (LFS) and high field side (HFS) is reached at high magnetic field (B>3.4T). Before the multiplier, a single sideband modulator provides the frequency shift for heterodyne detection [7]. On the reference arm, a quadrupler and 2nd harmonic mixer make the detection system (fig. 1).

The wave is launched though a 18 cm diameter fused-quartz window. Due to thermal constraints during long pulses, the vacuum window was moved 2 m away from the plasma centre. High gain gaussian antennas were preferred to boost the detected signal due to the distance and the multiplier low output power (<0dBm). Two antennas are used to minimised parasitic reflections. The waist is ~5cm and the beam is slightly diverging (HPHW 1°).

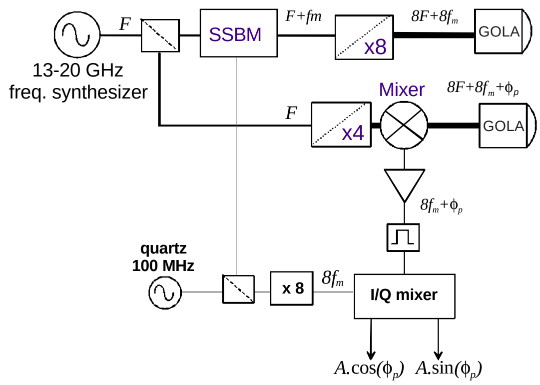

Figure 1: the 105-155 GHz reflectometer microwave scheme

After the I/Q demodulator, the signal is low-pass filtered and amplified before acquisition. Thanks to an amplifier working from DC to 500 kHz, the constant part of the signal which is crucial for phase measurement, is conserved. The acquisition system uses a 12 bit, 4 MHz, 4Mo, VME card. A radial scan of 20 frequencies can be performed in 300 ms.

S/N is around 25 dB between 115 and 145 GHz, slightly less at both band end due to lower octupler output. Electron cyclotron emission (ECE) sizes the noise level. Noise increases by one order of magnitude or more during LH heating due to supra-thermal electron emission.

2.2 <u>Signal correction for phase measurement</u>

The window reflection although very low (20 dB below the plasma reflection) is eliminated by pulse compression technique [8]. Imbalance of the I/Q modulator is corrected. An automatic algorithm suppress most of the remaining phase jumps. Derived from the algorithm proposed by A Ejiri, et al. [9], wavelets are used to localise the jumps. The phase of the reflected wave is thus precisely measured under the following requirements: very stable source, narrow beam almost parallel, removed parasitic reflection, correction of I/Q errors, full signal needed (constant and fluctuating) and suppression of phase jumped.

3. Observation of MHD modes

Reflectometry as a motion monitor is illustrated by cut-off oscillations caused by a MHD mode (fig. 2). In this shot, a m=2 at mode 0.7 kHz was detected by magnetic coils. The cut-off is located at a position where the mode is also detected by ECE. Large (±2π) oscillations are observed at 0.7 kHz corresponding to a cut-off displacement of the order of 0.5 to 1 cm.

The mode also modulated the reflected amplitude. The amplitude changes at a doubled frequency: amplitude is highest when the phase oscillation is maximal corresponding to the mode O and X point and minimal when the field line distortion is the largest. Such large amplitude losses (20 to 30 dB) due to 2-D effects and antenna high gain emphasise the requirement for an heterodyne signal and a good S/N.

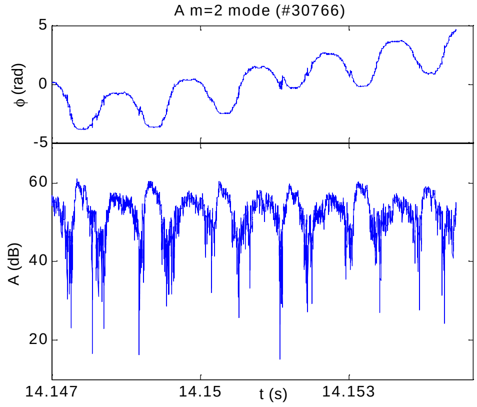

Figure 2: temporal evolution of the phase and amplitude in presence of a m=2 mode

The density fluctuations generated by the q=1 mode in sawtooth discharges could also be probed. The reflected signal from a cut-off near the q=1 surface exhibits a sawtooth evolution, similar to the temperature evolution (fig.3). The amplitude of the mode at f= 2kHz increases 1-2 ms before the crash and decreases in 1ms after the crash with a change in the mode frequency. 10 ms later, the amplitude increase for 5ms with the mode frequency rising back to 2 kHz. This transient increase is sometimes associated with a partial temperature crash. Observation of the mode during the whole sawtooth period means that the magnetic reconnection is probably not complete.

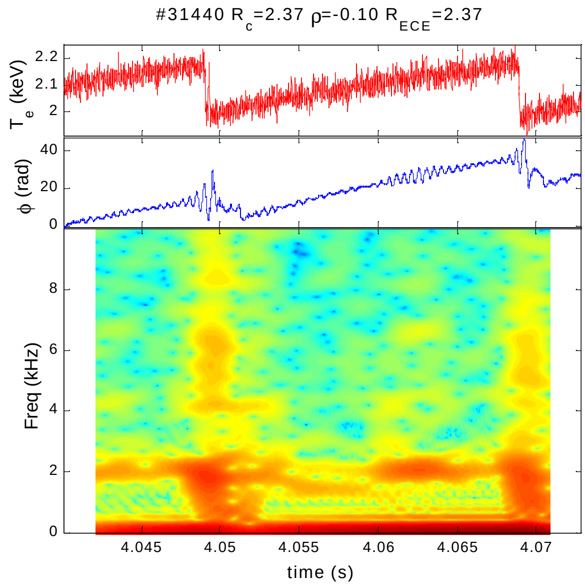

Figure 3: c) Spectrogram of the reflected phase b). Temperature evolution at the same radius a).

At moderate magnetic field (B~3.4T), the 50-110 GHz profile reflectometers can also probe the q=1 surface. Observation of the q=1 mode with two reflectometers which are positioned at different toroidal angles allows to determine the mode toroidal velocity [10].

4. Amplitude of density fluctuations

The level of fluctuations can derived from equation (1). k_x is taken constant over the whole plasma. The assumed value, $k_x=1$ cm^{-1}, corresponds to a saturation in the k-spectrum of density fluctuations and it's also a medium value: $k_x \geq 2\pi/a \sim 0.1$ cm^{-1} and $k_x < 6$ cm^{-1} [11]. A high pass filter (>10 kHz) is applied to remove MHD activity signatures at low frequency.

Radial evolution of density fluctuations is shown figure 4. Fluctuations are around 2% at the center (ρ=r/a=0). Taking k_x=0.1 cm^{-1}, equation (1) would provide density fluctuations below 0.7% at the centre. As expected, the profile is minimal in the centre and increases toward the edge both on low field side (LFS) and high (HFS). The fluctuations amplitude is 1.5 to 2 times lower on the high field side. An error on the cut-off position due to a 10% incertitude on the density profile could not explain this asymmetry which could be a signature of a ballooning effect. Fluctuations increase with additional heating (LH and ICRH).

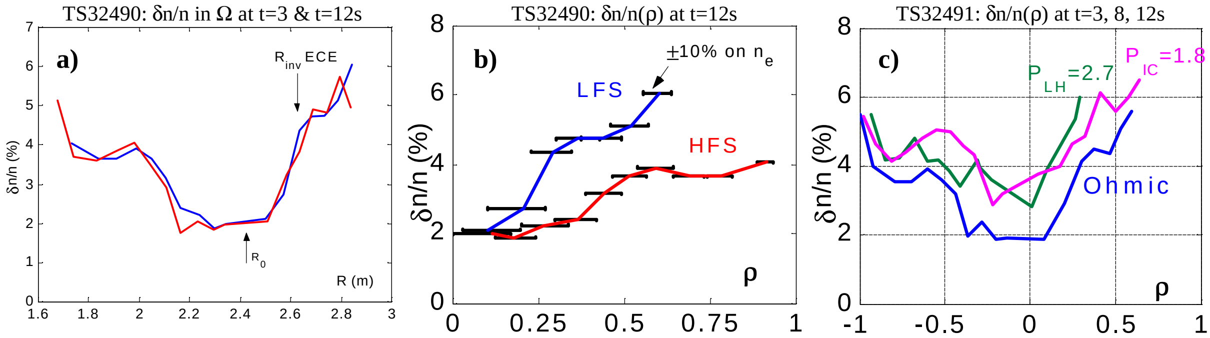

Figure 4: a) Density fluctuation profiles in ohmic phase (t=3, 12s, same parameters) plotted on R
b) The profile at t=12 shown as a function of ρ=r/a.
c) Profiles with additional heating (P_{LH} =2.7 MW, P_{ICRH}=1.8 MW) in a shot with similar plasma parameters.

5. Conclusions

On Tore-Supra, reflectometry has been designed to measure the density fluctuations from LFS to HFS and runs as shown here. This system can also access to MHD activity with high accuracy in time and space, which can provide a measurement of the toroidal velocity.

More interesting fact is that the reflectometry system provides a density fluctuations profile over the plasma core. As expected, density fluctuations are lowest at the centre (ρ=0) and increase in different way for LFS and HFS. Density fluctuations seem higher on LFS than HFS and increase with additional heating. These points need further studies.

To obtain the absolute value of fluctuation amplitude numerical simulations should be done with accurate profiles to assess the relation connecting phase and density fluctuations .

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