La réflectométrie : un outil pour détecter les modes MHD dans les plasmas du tokamak Tore-Supra.

Detection of MHD modes in Tore-Supra tokamak with reflectometry.

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Inspirée des radars ionosphériques, la réflectométrie est un diagnostic mesurant la densité électronique des plasmas de fusion magnétique. La réflectométrie peut détecter les déformations du profil de densité provoquées par des instabilités MHD macroscopiques. En utilisant la rotation du plasma, il est possible de reconstruire une image tomographique bidimensionnelle du profil de densité pendant les oscillations MHD dites en dents de scie. En travaillant à fréquence fixe, la réflectométrie détecte les oscillations de la couche de coupure provoquées par des modes MHD comme les modes excités par les particules rapides. Pour les modes BAE (Beta Alfvén Eigenmodes) qui sont excités par des ions rapides, un bon accord a été obtenu entre observations et prédictions théoriques. Toutefois, l'évolution temporelle (baisse puis augmentation rapide) de la fréquence et de la structure d(séparation en plusieurs modes) de ces modes au cours d'une dent de scie sort du cadre de la théorie linéaire.

Based on ionospheric radar, reflectometry is a diagnostic that measures the electron density in magnetic fusion devices. Reflectometry can detect the perturbations on the density profiles caused by macroscopic MHD instabilities. Using plasma rotation, a 2-D image of the density profile can be reconstructed during sawtooth, a core MHD relaxation. Running in fixed frequency mode, reflectometers detect the cut-off layer oscillations induced by MHD modes as fast particles driven MHD modes. For BAE (Beta Alfvén Eigenmodes) which are excited by fast ions, a good agreement was obtained between observations and theoretical predictions. However, the temporal evolution of the frequency (slowing down followed by a fat rise) and the structure (frequency splitting) of these modes during a sawtooth goes beyond linear theory.

Diagnostic pour les plasmas de fusion, Réflectométrie, MHD, Modes d'Alfvén.

Fusion plasma diagnostic, reflectometry, MHD, Alfvén modes

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1 Introduction

MHD instabilities are one of the key issues for magnetic fusion in particular for ITER where the slowing-down of α particles generated by fusion reactions will be the dominant heating source. Development of MHD modes can cause a redistribution of the plasma current leading to partial or complete loss of confinement [1]. In burning plasmas, the velocity of α particles created by fusion reactions is comparable to the Alfvén velocity. These fast particles can destabilize a wide variety of MHD modes [2]. These modes can cause large α particle losses that would reduce the plasma self-heating and hence the performances and would also represent a potential threat for first wall components.

MHD modes are detected from the perturbations they induce on plasma parameters like magnetic field, plasma density or temperature. Reflectometry relies on the propagation properties of electromagnetic waves in plasmas to measure the local electron density or properties of density fluctuations. Its high sensitivity and good spatial and time resolution make reflectometry an essential diagnostic for MHD studies in fusion plasmas.

In this article we present recent results on MHD modes obtained with reflectometry on Tore-Supra. Reflectometry principles are first introduced. The first tomographic reconstruction of the core density profile during MHD sawtooth oscillations is then presented. The fourth paragraph concerns the excitation of Beta Alfvén Eigenmodes (BAE) by fast ions.

2 Reflectometry principle

2.1 Cut-off frequencies

In non-magnetized plasmas, an electromagnetic wave in the plasma frequency range propagates only if the wave frequency is higher than the plasma frequency. This property has been exploited since the 30's to probe the ionosphere [3]. Launched from the ground, the wave propagates in the sky up to the ionosphere where it is reflected back to the antennas. The wave frequency gives the ionosphere electron density and the elevation is recovered from the time delay between emission and reception.

Reflectometry is based on this principle [4,5,6]. Fusion plasma densities being roughly 1 million time denser than ionosphere, frequencies in the microwave range (30-300 GHz) are appropriate. Short distance imposes also different techniques to measure the time delay.

Fusion plasmas being strongly magnetized, waves launched perpendicular to the magnetic field can propagate with two polarizations. The Ordinary-mode (O-mode) with **E//B** (where **E** is the wave electric field and **B** the tokamak magnetic field) has a cut-off frequency corresponding to the plasma frequency f_p (as in non magnetized plasma):

$$f_p = \frac{1}{2\pi}\left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{0.5} \tag{1}$$

where n_e is the electron plasma density, m_e the electron mass, e the electron electric charge and ε_0 the vacuum dielectric constant.

In the extraordinary polarization (X-mode) for **E⊥B** waves, the cut-off frequency depends also on the magnetic field. There are two cut-off frequencies named upper f_R and lower f_L cut-off:

$$f_{R/L} = \frac{1}{2}\left(\sqrt{f_{ce}^{\,2} + 4 f_p^{\,2}} \pm f_{ce}\right) \tag{2}$$

where the electron cyclotron frequency is defined by: $f_{ce} = \dfrac{1}{2\pi}\dfrac{eB}{m_e}$.

The radial profile of cut-off frequencies in Tore-Supra are shown on fig. 1. Tore-Supra is a medium size tokamak (major radius R_0=2.4m, minor radius a=0.8m) with a high magnetic field (B ≤ 3.9 T). This offers a gives a good accessibility to ordinary (O-mode) and extraordinary (X-mode) polarizations (fig. 1).

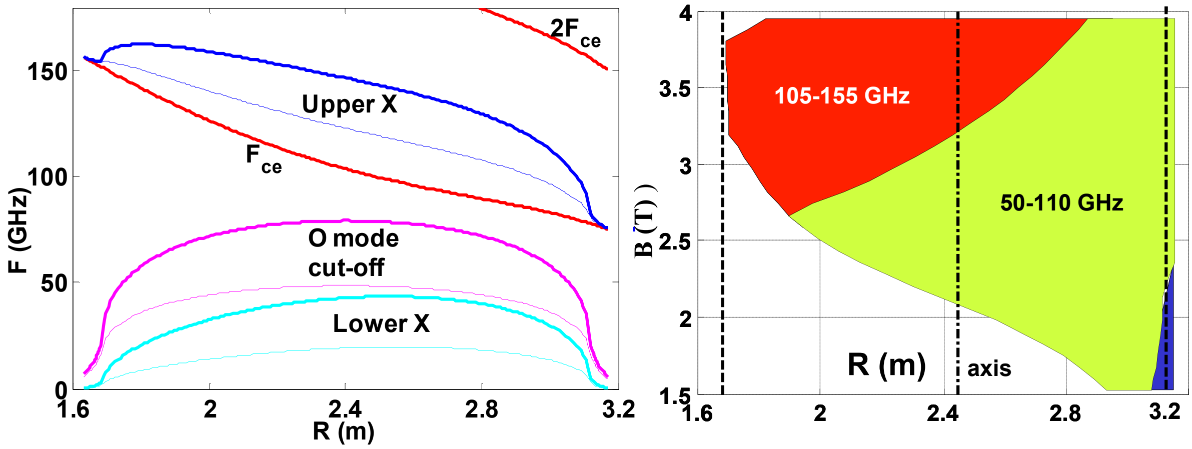

Figure 1 a) Plasma frequencies on the equatorial plane for high ($n_e(0)=8.10^{19}m^{-3}$) and low ($n_e(0)=3.10^{19}m^{-3}$, thin line) central density at B=3.8T. b) Accessibility with the magnetic field B at moderate density ($n_e(0)=4.10^{19}m^{-3}$) for X-mode reflectometers covering the band 33 to 155 GHz.

In O-mode, the accessibility does not depend on the magnetic field but the edge where cut-off frequencies are very low and the center where density profile is flat cannot be probed. The upper X-mode cut-off does not fall to zero; as a consequence, the edge density can be measured with a centimetre resolution. For sufficient magnetic field (B>2.5T), the core and the inner side are also accessible (fig. 1b) since the upper branch X-mode cut-off frequency continues to increase beyond the center. In a tokamak, the toroidal magnetic field decrease as $B \propto 1/R$, R being the radiusto the torus vertical axis.

Phase and amplitude variations due to round trip into the plasma are monitored by comparison with a reference signal. The phase ϕ_p is the main quantity of interest while the amplitude shows the reflectivity variation due to geometrical effects.

2.2 Profile measurements

Increasing the frequency F makes the wave to be reflected deeper inside the plasma. A sweep in frequency allows not only to probe the plasma from edge to core but also to measure the time delay induced by the wave's path in the plasma as for FW-CW radars. The time of flight can also be recovered from a frequency chirp:

$$\tau(F) = \frac{1}{2\pi} \cdot \frac{\partial \phi_p}{\partial t} = f_b \left(\frac{\partial F}{\partial t} \right) \tag{3}$$

where the beat frequency $f_b = \frac{1}{2\pi} \frac{\partial \phi_p}{\partial t}$ can be seen as the frequency of the detected signal.

The cut-off layer position can be recovered from the time delay or the phase. The frequency wave gives the density at the reflecting layer to give the radial density profile. A frequency sweeping in tens of microsecond, a time comparable to characteristic time of plasma turbulence, helps overcome the phase jamming caused by plasma turbulence [7].

2.3 Fluctuations measurements

Density perturbations modify the optical path length between plasma edge and the reflecting layer. The phase variation of a fixed-frequency (CW) reflectometer acts as a monitor of the cut-off motion, which displays the time density perturbations in the plasma. The main part of the fluctuating phase comes from large scale fluctuation (radial wave number k_r<3 cm^{-1}) at the vicinity of the cut-off layer. This method can detect small density fluctuations ($\delta n/n$<0.1%). The contribution from back scattering all along the beam path is usually negligible [8,9]. For the latter, the density fluctuation wave number k_f satisfies the Bragg rule $k_f = 2k(x)$ where $k(x)$ is the wave number of the probing wave.

2.4 Tore Supra reflectometers

All Tore Supra reflectometer are built on the same microwave scheme: a low frequency source (12-18 GHz) follows by frequency multipliers (fig 2). The same source serves as local oscillator for the mixer. A Single Side Band modulator shifts the frequency for heterodyne detection. The multiplier power decreases from 20 dBm in the 33-50 GHz band to few dBm above 110 GHz.

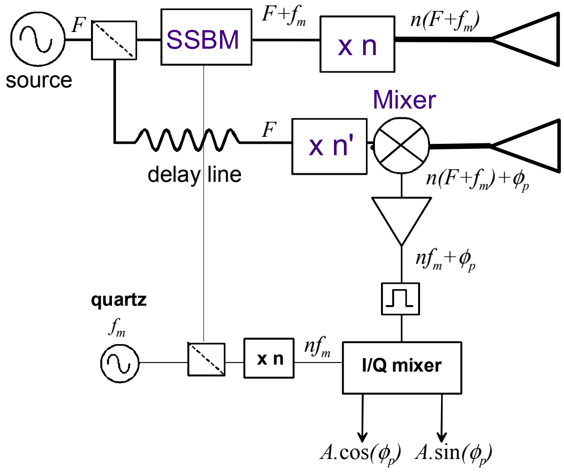

Figure 2: Microwave set-up of the Tore-Supra reflectometers.

On Tore Supra, six reflectometers are in operation, covering the range 33 to 155 GHz. The density profile is measured with X-mode reflectometry from 33 to 155 GHz in four bands [10]. The D-band reflectometer can also run in frequency step mode to measure the density fluctuations [11]. Two other reflectometers operate with an oblique incidence [12]. They rely on Bragg diffusion to measure small scale density fluctuations and the poloidal rotation velocity by Doppler Effect [13, 14].

3 Tomographic reconstruction of core density profile during sawtooth

3.1 Detection of macroscopic mode

Macroscopic MHD instability like kink (flux surface displacement) or tearing (flux surface reconnection) modes can be large enough to distort locally the density profile. Such irregularities can be detected with reflectometry. On raw data, a density flattening appears as a jump in the time of flight caused by the sharp variation of the phase on the density plateau. On the reconstructed profile, the poloidal and toroidal structures and the plasma rotation produce a periodic oscillation of the local density [15].

3.2 Measurement of the core density profile

The core of tokamak plasma is usually affected by a periodic MHD instability that redistributes the plasma current [16,1]. Sawtooth oscillations have two phases: a growth of the core parameters (temperature, density) during tens milliseconds followed by a fast (100 µs) reconnection a fattening of core profiles. The affected region is enclosed in a particular flux surface corresponding to the safety factor q=1. On this surface, he magnetic field line (that is the center guide of plasma particles motions) returns at is initial position after exactly one turn around the torus (one turn also in the poloidal direction)..

Owing to the precision of the reflectometry, we have observed that the density profile in the center is not smooth but presents a Mexican hat structure (fig 3a) with a peak around the center that grows linearly during the sawtooth crash surrounded by a plateau that extends slightly further than the q=1 surface [17].

Fig 3 a) shows the evolution of the density profile during two consecutive sawteeth in ohmic plasma. The first sawtooth exhibits a strong oscillation of the dense core around the magnetic axis just before the crash. In the second sawtooth, the oscillation before the crash is much smaller.

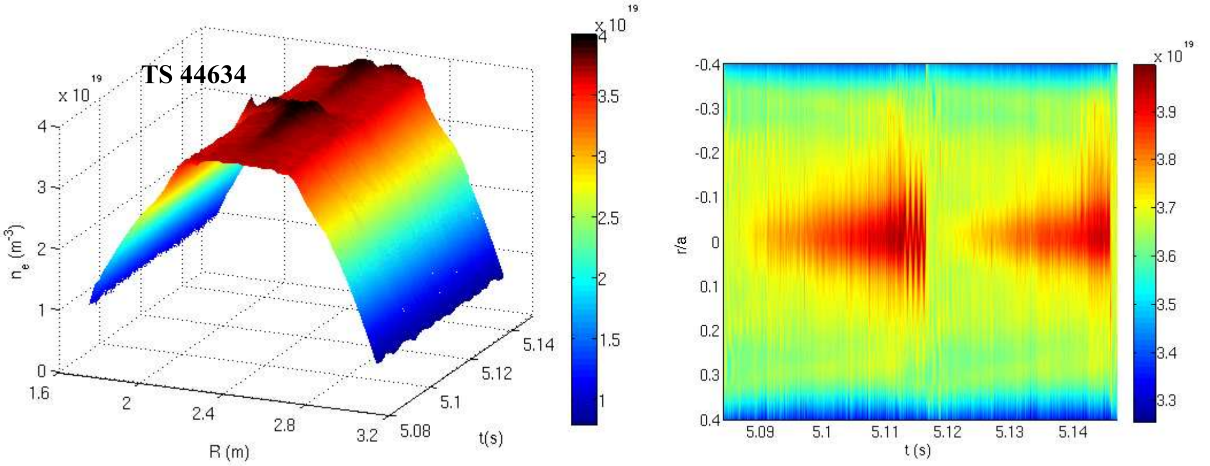

Figure. 3: a) Evolution of the density profile during an sawtooth ohmic disharge (the magnetic axis is at R~2.45 m, the minor radius a~0.72 m). b) Contour view of the same sawteeth shown in normalized radius (r/a).

3.3 Tomographic reconstruction of the density profile

The rotation of the plasma allows 2-D reconstruction in a poloidal (vertical) plane for parameters measured along a minor radius. Such tomographic reconstructions were already performed for soft-X-ray emission [18] or the temperature profile [19, 20]. To be applied, the measurement time should be much faster that the rotation period, this latter being much shorter than the evolution time of profiles. If these conditions are fulfilled, the plasma rotation is similar to a poloidal rotation of diagnostic. This reconstruction assumes that the geometric structure is not modified by the rotation, a reasonable assumption in Tore Supra where plasmas are circular.

For the first time, this method was applied to density profiles. The D-band (100-155 GHz) reflectometer measures the density profile in the center; the reflectometer is usually swept in 45 µs with a dead time between two profiles that can be reduced to 5 µs. The repetition rate, 50 µs, is then much shorter than the rotation time (0.5 to 1ms) while the sawtooth period last several tens of milliseconds.

For this reconstruction, the plasma is assumed to rotate as a rigid body at an angular velocity ω around the magnetic axis. A profile measurement done at $t=t_i$ gives also the density profile at an angle $\theta_i = \omega_\theta (t_0 - t_i)$ relative to the equatorial plane measurement at t = t0. To take account the temporal evolution of the mode, the density profile at the angle θ_i at $t=t_0$ is obtained by interpolating measurements performed at t = ti = ti and t= t + T/2 where T is the period rotation mode. The interpolation is done with the half-period since X-mode reflectometry measures the density profile on both sides of the magnetic axis :

$$n_e(\theta_i, t_0, r) = \frac{(\pi - \theta_i) \cdot n_e(0, t_0 - \theta_i/\omega, r) + \theta_i \cdot n_e(0, t_0 + (\pi - \theta_i)/\omega, r)}{\pi} \tag{4}$$

Fig. 4 shows the tomographic reconstruction during the final part of the first sawtooth shown of fig. 3. The rotation frequency is 1.1 kHz, corresponding roughly to 17.5 the repetition time of profile measurements . The oscillation of the dense core on the equatorial plane corresponds to the rotation of a kink dense core.

These reconstructions will be compared with non-linear bi-fluid MHD simulations obtained with the XTOR-2F code developed by H. Lutjens and co-workers [21]. We also want to improve the tomographic reconstruction to obtain details on the flat ring that surround the dense core. Very low amplitude density oscillations can be observed on the reconstructed profiles. This might gives information on the structure of the mode that is detected with fixed frequency reflectometry around the q=1 surface.

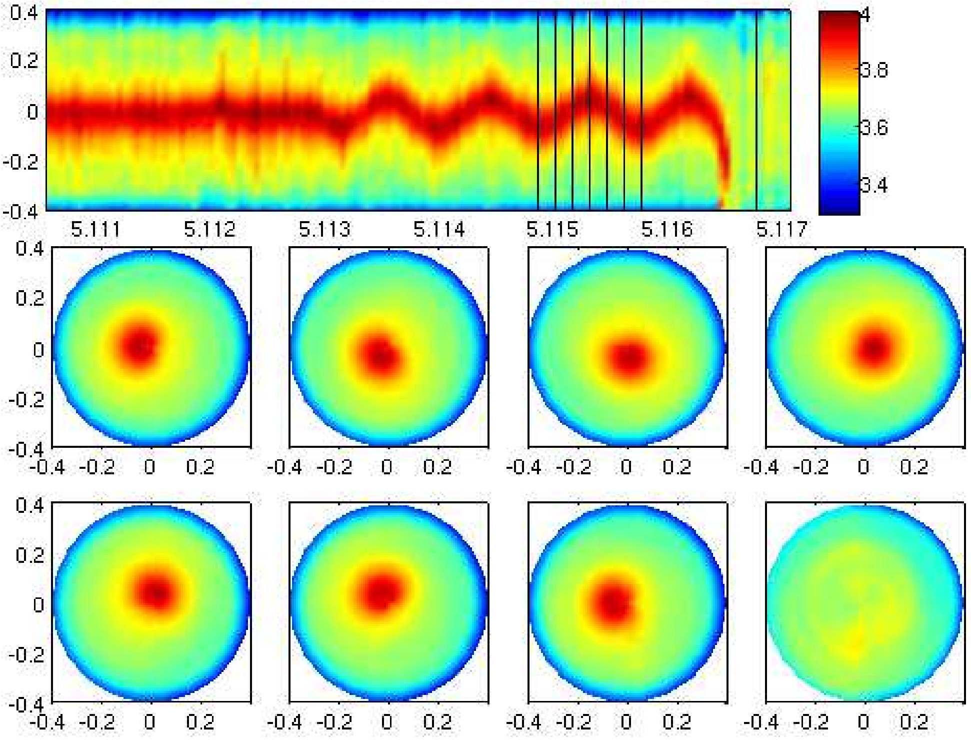

Figure. 4: Top : Contour view during the final part of the first sawtooth shown in Fig 3. Time of the tomographic are indicated by verticallines. Middle) Tomographic reconstruction in a poloidal plane for the first 4 times slices. Bottom) 4 last times slices. The same color axis is used for the contour view and the tomographic pictures.

4 Observation of Beta Induced Alfvén Eigenmodes

4.1 Excitation of Alfvén modes by fast particles

The energetic neutral beam or electromagnetic waves injected to heat the plasma to thermonuclear temperatures generate fast ions. They mimic the fusion-driven α particles and can couple to Alfvén waves to destabilize MHD modes.

On Tore-Supra, fast particles driven MHD modes are detected from the induced fluctuations on density [17] and temperature [22]. In ICRH heated plasma, two branches of Alfvén wave can be observed with the 100-155 GHz reflectometer [23]. Toroidal Alfvén Eigenmodes are detected above 100 kHz. TAE are Alfvén modes that can develop in a tokamak because of toroidal coupling. These modes are observed in many experiments and have been extensively studied [2]. In the acoustic frequency range, Beta Alfvén Eigenmodes are detected. BAE are the acoustic branch of Alfvén modes that can develop because of the finite plasma compressibility [24, 25]].

4.2 Beta Alfvén Eigenmodes excitation threshold

The linear excitation threshold of BAE has been calculated analytically and compared with experimental results [26]. A good agreement has been found between the predicted frequency and the observations. The observed threshold was in very good agreement with the prediction at high magnetic field. At B=3.2 T, modes were slightly more difficult to excite than predicted, this discrepancy being still under investigation.

4.3 Frequency evolution of BAE during sawtoothld

Although the observed frequency of BAE is in agreement with expectations, we observed fast evolutions of the frequency during the sawtooth period. For a given position and ion mass, the BAE frequency depends only on the temperature:

$$f_{BAE} = \frac{1}{2\pi R}\sqrt{\frac{T_i}{m_i}\left(\frac{7}{2}+2\frac{T_e}{T_i}\right)} \qquad (5)$$

where R is the major radius, m_i the main ion mass, T_i (T_e) the ion (electron) temperature.

As can be seen on fig. 4, the BAE frequency decreases in the first phase of the sawtooth (t=14.12 to 14.16 s) while the temperature profile increases. Just before the sawtooth crash at t=14.2s, a frequency rise rapidly from 50 to 80 kHz while the temperature profiles does not change much (the central temperature saturates). Such behaviour does not fit with expression 5) obtained by linear theory.

A splitting of the modes in different frequency is also observed [27]. With the two channels of the D-band reflectometer set on opposite side of the magnetic axis we observed a change of phase between adjacent modes. As shown on figure c), the phase between of the two channels changes between negative (red) and positive (blue) values from one frequency to the upper one. This suggests a change of the mode structure.
Evolution of parameters like the current profile, the plasma rotation or the fast ions population might be needed in non-linear simulations to reproduce the evolution of the mode frequency

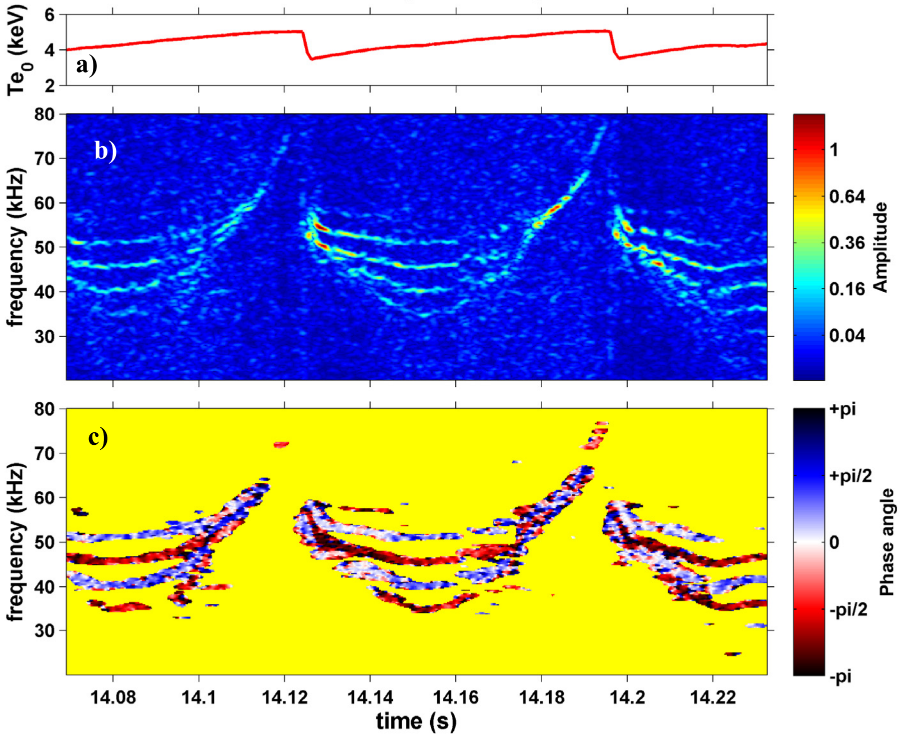

Figure 4: b) Evolution of the BAE frequency during sawtooth (TS 42039). c) Correlation between the two channels of the reflectometry localized on r/a ~ 0.4 on the inner side and r/a ~ 0.05 on the outer side. The evolution of the central temperature is shown in a).

5 Conclusion

Beyond is usual application for density profile measurement, reflectometry can also gives valuable information on MHD modes. Profile reflectometry can detect the perturbations induced by MHD modes on density profiles. Using plasma rotation, we perform the first 2-D tomographic reconstruction of the density profile. Recently, profile reflectomters were upgraded to be swept in few microseconds (<4µs). With this shorter sweeping time, a reconstruction with better angle resolution is expected as well as an application of this technique to higher frequency modes or to higher rotation velocity.
Fluctuations reflectometry is one of the most sensitive diagnostic to detect and localize MHD modes excited by fast particles. Observations of BAE excited by fast ions follow the theoretical predictions. More investigations are needed to understand the unexpected frequency evolution of these modes. Correlation at two radial positions or with other diagnostics should also give more information on the mode spatial structure.

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