Tomographic reconstruction of the core density profile during sawtooth oscillations

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1. Introduction

In tokamaks, the core magnetic configuration is periodically reorganised by sawtooth oscillations [1]. Sawteeth are characterized by a slow (tens of milliseconds) rise of parameters like temperature or density followed by a fast crash (hundred microseconds) that flattens the profiles in the core. 2-D images like those obtained with soft-X rays or ECE temperature measurements [2, 3, 4] highlight the evolution and reconnection of magnetic surfaces and can be used to test sawtooth models.

In this work, we present the first 2-D reconstruction of plasma density during ohmic sawtooth oscillations. On Tore Supra, the density profiles are measured with X-mode reflectometry with very good radial resolution and high sensitivity. First simulations with a bi-fluid MHD mode with diamagnetic reconnection produce image looking very similar.

2. Dynamic of density profile

On Tore Supra, the D-band (100-155 GHz) reflectometer measures the density profile in the equatorial plane from the low to the high field side (HFS) [5]. Figure 1 shows an example of density profile dynamic in an ohmic shot (TS44634, B=3.8T, I_p=1.2 MA). The reflectometer is swept in 45 µs with a dead time of 5µs between two profiles. The density peaking in the center appears clearly as well as the density plateau that extand beyond the q=1 surface. Density peaking is explained by the Ware pinch and reduced diffusion inside the q=1 surface [6].

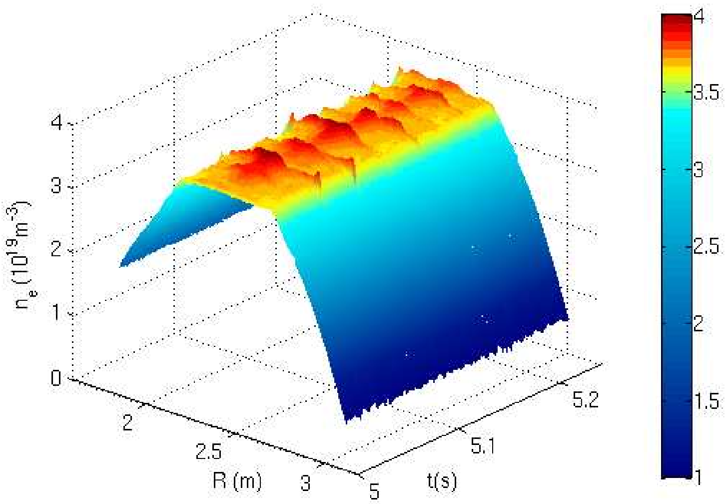

Fig. 1: Density profile dynamic

The precision of the density profile is sufficient to detect profile displacement and density perturbations inside the q=1 surface (figure 2): coherent oscillation up to $10^{18}m^{-3}$ (2.5 %) are detected at r/a=0.1. Weaker oscillations are detected at r/a=0 or 0.2.

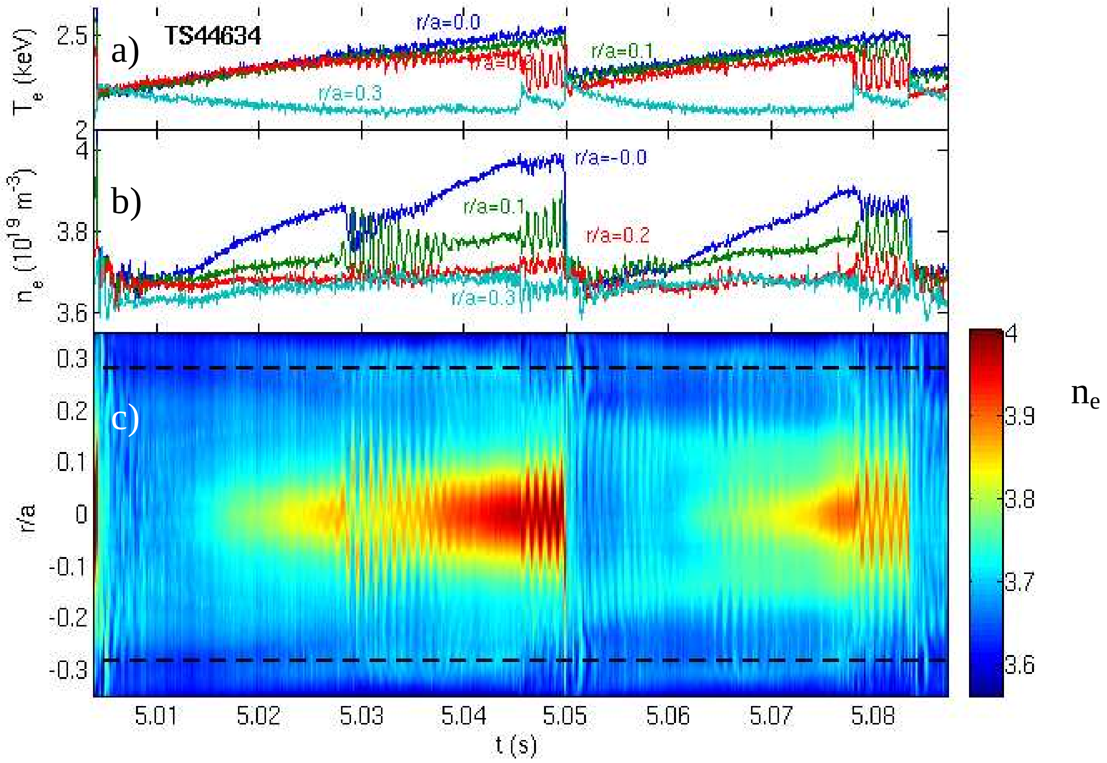

Fig. 2) c) Contour view of the density ($10^{19}m^{-3}$) during the first two sawteeth of figure 1. The dotted line shows the position of temperature inversion radius. The density and temperature at normalized radius ρ=r/a=0, 0.1, 0.2, and 0.3 on low field side are shown in b) and a).

3. 2-D image reconstruction

Using plasma rotation, a 2-D image can be reconstructed in a poloidal section [7]. This technique requires a profile measurement frequency much higher than the rotation frequency. Plasma rotation is equivalent to a poloïdal rotation of the diagnostic if plasma rotation is much faster than the characteristic time of profile evolution.

A density 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. However, because the profiles evolves in time, the density profile $n_e(\theta_i, t_0, \rho)$ at normalized radius ρ, a poloidal angle θ_i and $t=t_0$ is obtained by interpolating measurements performed at $t = t_0 - \theta/\omega$ and $t = t_0 + (\pi - \theta)/\omega$ or half turn latter since X-mode reflectometry measures the density profile on both sides of the magnetic axis:

$$n_e(\theta_i, t_0, \rho) = \frac{(\pi - \theta_i) \cdot n_e(0, t_0 - \theta_i/\omega, \rho) + \theta_i \cdot n_e(0, t_0 + (\pi - \theta_i)/\omega, \rho)}{\pi} \qquad 1)$$

In the ohmic shot shown on figure 1 & 2, the density perturbations at various radii exhibit an opposite parity between the LFS and HFS as expected for a m=n=1 structure. Their frequency is around 1.1 kHz and do not vary much during the sawtooth. The rotation velocity was then assumed to be constant in time and radius (rigid body rotation). Figure 3 shows the tomography reconstruction at different time during the two sawteeth shown previously.

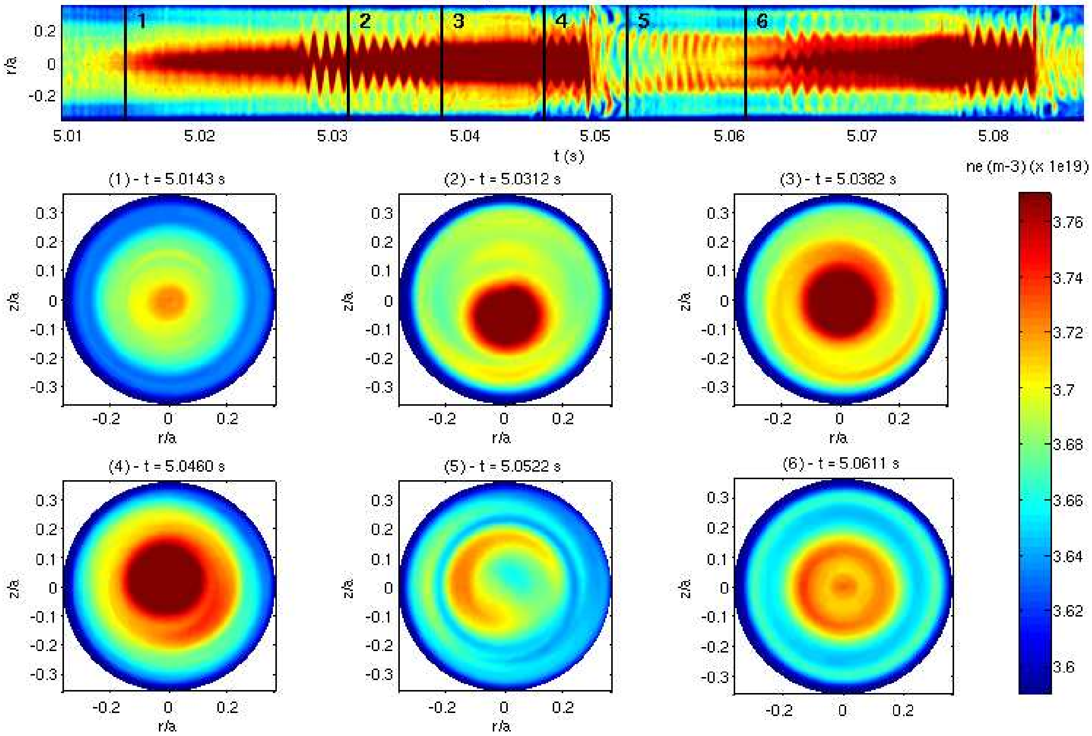

Fig. 3: 2-D image of density at 6 times during two consecutive sawteeth : times are shown by vertical lines on the contour view of density profile (top). The same color bar is used for the 2-D images and the contour view.

4. First numerical simulations

Using the experimental conditions of the shot shown above, first simulations were done with the XTOR-2F code [8]. The physical model implemented in the XTOR-2F code is fully toroidal and non-linear; it includes anisotropic thermal transport, resistivity, and viscosity as well as diamagnetic drifts. As shown on Figure 4, periodic oscillations are recovered [9]. The

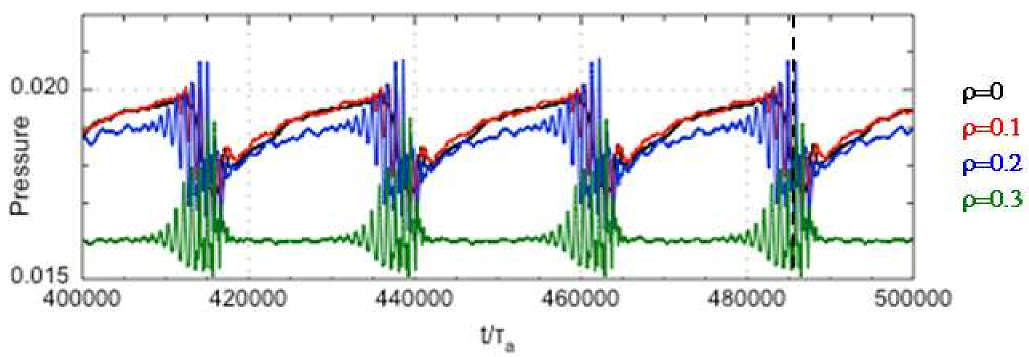

Fig. 4: Time evolution (normalized to Alfvén time) of the pressure (normalized to magnetic pressure) at various radial positions.

simulations reproduce also the oscillations just before and after the crash. The precursor oscillations are caused by poloïdal rotation. Postcursor oscillations are due to the redistribution of pressure/density after the crash.

The XTOR-2F code solves density diffusion and can thus produce 2-D images of density. The density peaking observed experimentally near the axis cannot be reproduced as the code does not include a density pinch term. If one excluded this core peaking, simulations produce images that present striking similarities with experimental density images as the example shown on figure 5. After the crash at t=485319.5 t_A (dotted line on figure 4), the density present an helix structure. The image looks like the image at t=5.0522 (5th 2-D image on figure 3) reconstructed 2 ms after the sawtooth crash.

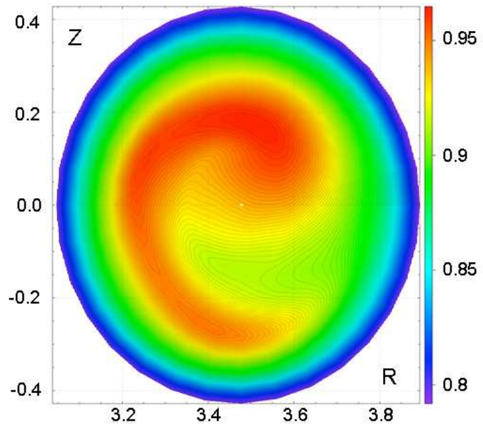

Fig. 5: Density contour at t=485319 t_A. Density is normalized to the density on axis at the beginning of the simulation.

5. Conclusion

The sensitivity of reflectometry and its radial resolution allows the 2-D reconstruction of plasma density inside the q=1 surface with great details. These images look similar to results of the bi-fluid XTOR-2F code.

Analysis of the density structure could also give information of the magnetic structure and q profile evolution during the sawtooth period. Analysis of faster rotating mode like with additional heating require higher frequency measurement for good temporal/angle resolution.

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