

Analysis of the 3D nature of the density in QSH plasmas at MST

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The Madison Symmetric Torus (MST) experiment ($R=1.5\text{m}$, $a=0.52\text{m}$) is equipped with a 11 chords FIR interferometer divided between 2 toroidal locations (5 chords at $\phi = 250^\circ$ and 6 chords at $\phi = 255^\circ$), covering more than 70% of the plasma poloidal cross section. The spatial and temporal resolution of the interferometer (acquisition frequency is 375 kHz) allows us to resolve the density fluctuations which are associated with quasi single helicity (QSH) magnetic structure, both in locked or in rotating cases. Rotating and locked QSH have been observed routinely in $F\sim 0$, $I_p=400\text{ kA}$ standard MST discharges, hence our analysis has been concentrated over this kind of plasma pulses.

1. Rotating QSH: phenomenology and inversion techniques.

Signatures of the rotating structures are seen as oscillations in the experimental integral line density N_e^{exp} : figure 1(a) displays a contour plot of density integral measurements, where the vertical axis is the impact parameter of each line of sight versus the time. The density follows an $m=1$ pattern: the measure is dominated by

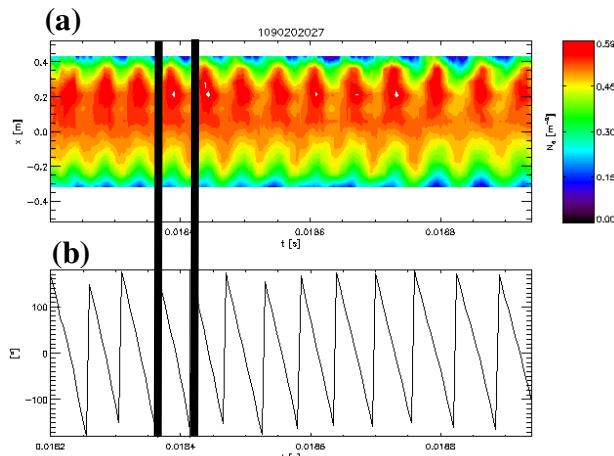


Figure 1: (a) contour plot showing the time evolution of the line integrated density signal as a function of time and chords impact parameter. (b) phase of the $m=1$ $n=-5$ tearing mode that is the dominant harmonic of the Fourier spectrum of the magnetic perturbation. The two black thick lines limit one rotation cycle of the magnetic structure and the corresponding oscillation of the plasma column. Data of shot 1090202027.

a $\nu_{ne} \sim 10\text{ kHz}$ oscillation of about 10% of N_e^{exp} which is in counter phase in the inner and outer section of the plasma. The oscillation rate is equal to the rotation frequency of the innermost resonant mode ($m=1$, $n=-5$), the one that generates the QSH structure in the plasma. Figure 1(b) shows the phase of that mode as a function of the time: for each rotation of the magnetic structure, one oscillation is observed in the density pattern. The interferometric measurements collected during a single period of the dominant mode rotation have been used to obtain a 2D map of the density by an Abel inversion algorithm.

The hypothesis underlying such procedure is that the rotating density structure does not change during one single period of rotation.

In this way a tomography of the density structure has been performed. The Abel inversion has been computed feeding the algorithm with $11 \times 90 = 990$ virtual signals, collected in one

complete rotation, of the density fluctuation \tilde{N}_e^{exp} . In

order to consider the toroidal displacement of the two interferometric fans, the relative position between the chords and magnetic structure has been computed for an $m=1$, $n=-5$ helical structure inside the plasma, hence the two fans are tilted by 25 degrees on the poloidal plane. The result is shown in figure 2: the plot (a) shows a poloidal contour plot of the density computed as the inverted fluctuation density map summed to the bulk or unperturbed density (that is the density profile obtained averaging the data over many periods). A dense structure is clearly visible off-axis of about 20 cm with respect to the geometrical centre of the vacuum chamber, whereas the usual Shafranov shift is about 5 cm. The white dashed line and the arrows represent the horizontal view shown in plot (b): the total density profile (in black continuous line) is compared with the density average profile (in red dashed line). The density structure corresponds to a bulging of the profile. It is important to remember that this inversion technique does not rely on any magnetic information but the rotation velocity of the dominant mode hence the position of the density structure is not due to any ad-hoc shift but only to the interferometric data.

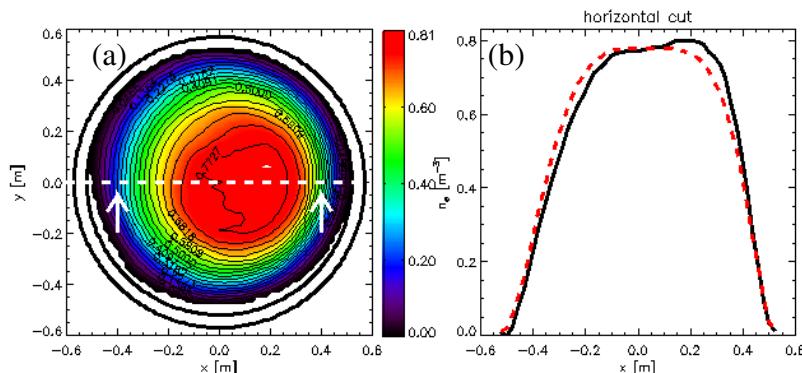


Figure 2: (a) Abel reconstruction of the poloidal electron density map, peaked off-axis for the interferometric data shown in figure 1. The white line shows the horizontal view (b) of the total density profile, with the 20 cm off-axis structure (black continuous line), compared with the unperturbed density profile (red dashed line).

2. Locked QSH: magnetic reconstruction, SXR emissivity and density profile.

The presence of a density structures in phase with the dominant mode suggests that the density is attached to the magnetic flux surface: our hypothesis is that the density behaves as a flux function, being constant on the flux surfaces. Mimicking the analyses already performed at RFX-mod, where the kinetic quantities as electron temperature and density are well mapped over the helical flux χ [1] (computed combining the axisymmetric equilibrium fields and the dominant harmonic of the MHD spectrum), the helical equilibrium has been computed for MST with the SHEq code [4]. In order to perform this computation the force-free model for the solution of the Newcomb's equation in toroidal geometry developed at

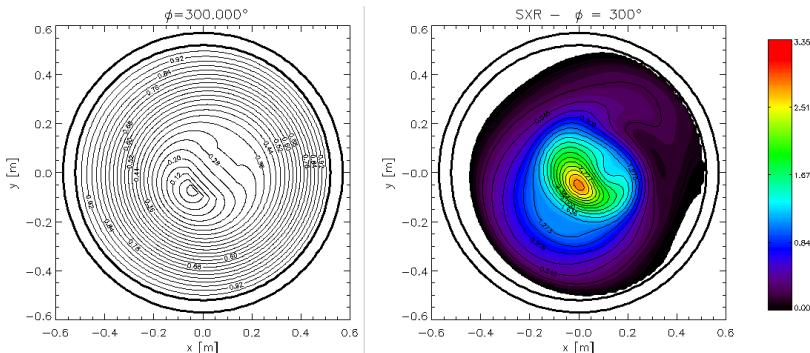


Figure 3: (a) poloidal view at $\phi = 300^\circ$ of helical flux reconstruction for shot 1090604127 at 27ms. (b) SXR emissivity inversion for the same shot and time.

RFX-mod [2] has been adapted to MST. Furthermore the $\alpha\theta_0$ model[3] to compute the unperturbed magnetic field has been adopted. The model has been generalized introducing one more free

parameter that allows the parallel current density profile to become zero at the edge with zero radial derivative. This modification has been introduced in order to have a good match with the external magnetic measurements in $F=0$ discharges. As a first test, the helical flux reconstruction has been compared with the soft X-ray (SXR) inversion as the high emissivity region corresponds to the core of the QSH structure [5]. The amplitude of the dominant harmonic of the poloidal magnetic field in rotating QSH is below 2.5mT, measured at the plasma edge, but exceeding that threshold the rotation slows down and the mode eventually locks at the wall, reaching amplitudes above 5.0mT. In order to have reliable SXR inversions, with a good signal over noise ratio, the locked case have been chosen because the structure is larger and the emissivity results higher than in rotating case. Figure 3 shows the very good match between the constant χ surfaces reconstruction (a) and the SXR inversion (b). The high emissivity core is bean-shaped and centred off-axis, at the resonance radius of the $m=1, n=-5$ MHD mode. Moreover the two structures have the same poloidal position with comparable radial and poloidal width, confirming that the helical flux surfaces are acting as confining surfaces in the plasma core. Exploiting the helical flux reconstruction, the density inversion is computed for the better diagnosed locked case, assigning at each magnetic surface the density value, and minimizing the differences between experimental and numerical line integral density. The density radial profile has been assumed to be a simple function of the effective radius $\rho = (\chi/\chi_0)^{0.5}$, where χ_0 is the helical flux at the plasma boundary. The parameterization provided to the inversion code is $n_e(\rho) = ((n_0 - n_1)(1 - \rho^\alpha)^\beta + n_1)$, where the four parameters n_0, n_1, α and β are varied in order to minimize the $\chi^2 = \sum \frac{(N_e^{\text{exp}} - N_e^{\text{sim}})^2}{\sigma_{n_e}}$ (where N_e^{sim} is the line

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integral density simulated, N_e^{exp} is the experimental one and σ_{n_e} is the measurement error where the sum is over all the chords). The results are shown in figure 4: panel (a) the density profile as a function of ρ , panel (b) the comparison of experimental and numerical integral

line density as function of the impact parameter of the measurements chords and panel (c) the poloidal map of the density . The profile results peaked in the core, with a gradient that extends from $\rho=0.2$ and $\rho=0.8$. The central region ($\rho<0.2$) appears almost flat: further analyses on the gradient region will be carried out to understand if, as happens in RFX-mod for the temperature profile, the internal transport barriers are located where the helical q has its maximum [6].

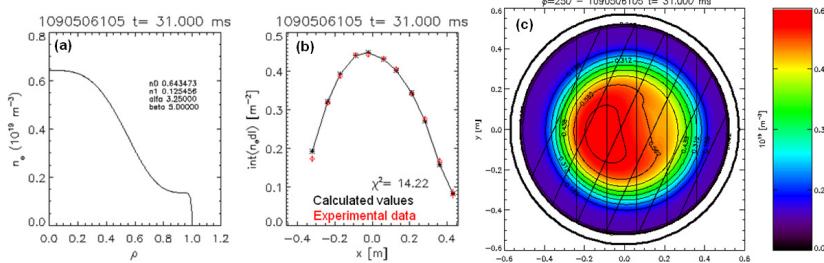


Figure 4: (a) density profile as a function of the effective radius ρ , (b) experimental line integral profile as a function of the impact parameter of the measurements chords. The black points connected with a continuous line are the simulated value corresponding to density profile in (a) where the experimental value are plotted in red, (c) poloidal map of the density with the geometry of the measurements chords, where the fan at $\phi = 255^\circ$ is rotated of 25° on the poloidal plane because of the helicity of the QSH structure.

The experimental line integral profile is asymmetrically displaced towards the high field side: this feature is well reproduced by the simulated values with a χ^2 that is about half with respect to the χ^2 obtained

with the usual inversion model that assumes shifted circular plasma surfaces. Hence the density appears to be constant over the flux surfaces, pointing out the magnetic structure of the plasma core: the iso-density surfaces are bean-shaped in the core and almost circular going toward the plasma edge. This is the first time that this behavior is observed to occur spontaneously. In fact at RFX-mod the iso dense, bean shaped surfaces have been pointed out with pellet injection, with an additional particle source in the core. With no added particle source, the density profile appears flat even in SHAx configuration. This is not the case of MST, where the neutral density n_n in the core is larger, reaching about 1% of n_n at the edge, as computed by NENE code [7]. The deeper penetration of particle source is mainly due to the lower density regime reached in MST.

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