Plasma Flow, Turbulence and Magnetic Islands in TJ-II

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Abstract:

The effect of magnetic islands on plasma flow and turbulence is experimentally investigated in TJ-II plasmas. A characteristic signature of the n/m = 3/2 magnetic island as it crosses the Doppler Reflectometer (DR) measurement position is clearly detected, showing a modulation in the perpendicular flow that changes twice its direction. As the magnetic island crosses the DR measurement position two peaks appear in the DR signals spectra. The double peak reflects the vortex around the magnetic island O-point. An increase in the low frequency flow oscillations is measured at the magnetic island boundaries together with a reduction in the density fluctuation level. Further studies have been performed to characterize the radial correlation properties of the density fluctuations in the presence of magnetic islands, both numerically and experimentally in TJ-II. The analysis of the density fluctuations simulated using a MHD code shows that in the presence of a magnetic island the coherence profile shows a characteristic asymmetry. This asymmetry is also detected by a Doppler reflectometer synthetic diagnostic and in the experiments, where the asymmetric coherence profiles can be interpreted to be due to magnetic islands.

1 Introduction

Low order rational surfaces are found to ease the the transition to High confinement mode (H-mode) in helical devices [1, 2, 3, 4]. These results have been interpreted in terms of local changes in the radial electric field and zonal flow development near low order rational surfaces which may result in a reduction of plasma turbulence [5, 6, 7]. To date, however, a detailed experimental study of the flow and turbulence modification in the presence of a magnetic island and the impact on transport and confinement has not yet been completed. The present work describes the effect of magnetic islands on the plasma perpendicular flow (as reported in [8]), and on turbulence, both turbulence level and radial correlation length. The main diagnostic used in this work is a Doppler reflectometer [9] that allows the measurement of the perpendicular rotation velocity of the turbulence and density fluctuations with good spatial and temporal resolution [10]. Besides, a synthetic Doppler reflectometer, which combines a 2D full-wave code [11] and the turbulence simulated by a non-linear MHD resistive code [7], is used to explore the effect of the magnetic islands on the radial correlation length of the fluctuations.

2 Plasma Flow & Magnetic Islands

To characterize the plasma flow in the vicinity of magnetic islands, Ohmically induced magnetic configuration scans have been carried out sweeping the radial position of the low order rational $n/m = 3/2$. The experiments have been performed in ECH heated, low density plasmas ($\langle n_e \rangle = 0.5 - 0.6 \times 10^{19}$ m^{-3}). DR measurements are performed keeping the probing beam direction and frequencies fixed during the discharge, $f_{CH1} = 34$ GHz and $f_{CH2} = 36$ GHz, such that the corresponding cut-off densities are kept constant. An example is displayed in figure 1. This figure shows the time evolution of the plasma density (a), the spectrogram of the DR signals measured at $\rho = 0.75$ (b), the perpendicular rotation velocity (c), and the net plasma current (d). In the time interval between $t \sim 1140$ - 1170 ms, the spectrogram of the DR signals shows a modification in the Doppler peak frequency, i.e. in the plasma perpendicular flow, changing the flow direction twice. These changes can hardly be related to changes in the plasma density. The time evolution of the electron density profile is displayed in the right panel in figure 1. These profiles, reconstructed using a Bayesian analysis method [12] applied to the interferometer and AM reflectometer data [13], show no clear flattening associated to the magnetic island. The change in the flow measured in the time interval $t \sim 1140$ - 1170 ms, represents a characteristic signature of the magnetic island as it crosses the DR measurement position. As explained below, the fast reversal in the plasma flow, indicated in figure 1 with a broken black line, is interpreted to be linked to the magnetic island centre while the island boundaries should be allocated nearby the grey vertical thick lines.

Similar experiments have been performed in five different magnetic configurations with slightly different rotational transform in combination with two different OH current intensities. Figure 2 summarizes the results. The time evolution of the perpendicular plasma flow measured using DR channel 1 is shown together with the plasma density and net plasma current, for strong (left) and weak (centre) OH current intensity. Each magnetic configuration is represented with a different color. The corresponding rotational transform profiles in vacuum are represented in the right panel together with a *generic* profile modified by the OH current. The plasma current at which the magnetic island is detected by the DR depends on the magnetic configuration, i.e. on the value of the rotational transform in vacuum. The higher the rotational transform the stronger the OH intensity needed to radially move the magnetic island towards the DR measurement position. The results presented in figure 2 seem to indicate that the time it takes the magnetic island to cross the DR measurement position depends on the magnetic configuration. However, this is just a consequence of the time evolution of the plasma current: the temporal variation rate decreases along the plasma discharge slowing down the radial propagation of the magnetic island. The island width has been estimated to be close to 3 cm as it crosses the radial position probed by DR channel 1 ($\rho \sim 0.75$). This value is

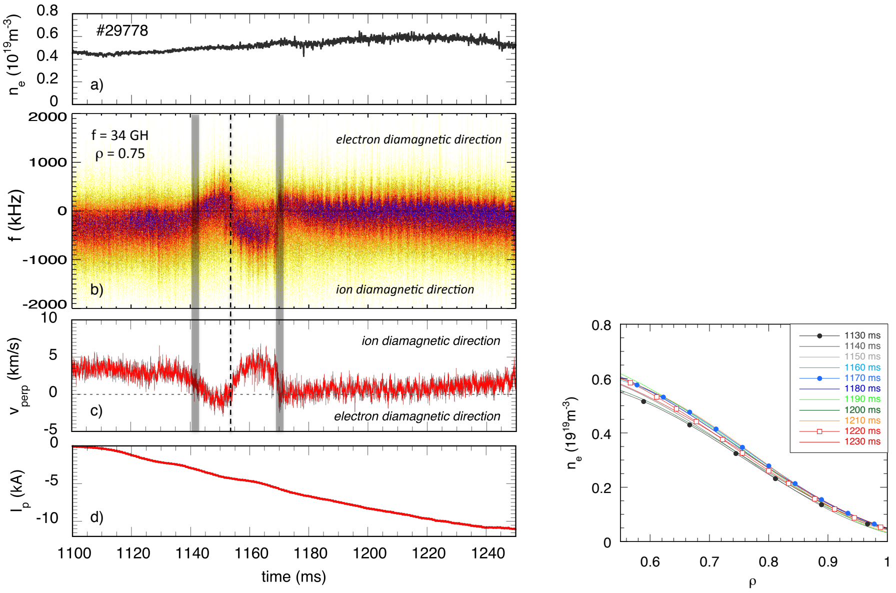

FIG. 1: Left: The time evolution of line density (a), spectrogram of the DR signals measured using channel 1 at $\rho \sim 0.75$ *(b), perpendicular rotation velocity calculated from the centre of gravity of the spectrogram (c), and net plasma current (d). The vertical lines indicate the expected location of the boundaries and centre of the magnetic island. Right: The time evolution of the electron density profile reconstructed using a Bayesian analysis method applied to the interferometer and Amplitude Modulated reflectometer data.*

very similar in all configurations.

A closer look at the time evolution of the DR spectrogram allows a detailed study of the perpendicular flow across the magnetic island. The DR spectrogram shown in figure 3.top has been chosen to illustrate this point. As the magnetic island approaches the DR measurement position the perpendicular flow gradually changes from the ion to the electron diamagnetic drift direction (between $\sim 1180 - 1200$ ms). At a later time, the flow reverses again and stays in the ion diamagnetic drift direction (from ~ 1230 ms on), however, this is not a gradual change: during several milliseconds ($\sim 1210 - 1225$ ms) two peaks appear simultaneously in the spectrum. To interprete this result one has to take into account that the radial resolution of the measurements is finite ($\Delta r \lesssim 1$ cm [9]) and the spectrum can be influenced by different velocities when the velocity changes abruptly within the measurement volume. In these cases two peaks related to two different velocities can be detected in the spectrum provided the reflectometer has an optimum spectral resolution as it is the case for the TJ-II DR; otherwise a single broader peak would appear [14]. In [14] the double peak arises as a consequence of a strong flow shear associated to the H-mode. In the present case, however, the double peak reflects the vortex around the magnetic island O-point. This has been schematically represented in figure 3.bottom. It shows the flow along the flux surfaces inside the magnetic island and the corresponding spectra. Within this interpretation, the reported DR spectra are compatible only with a static and large (larger than the DR radial resolution) magnetic island.

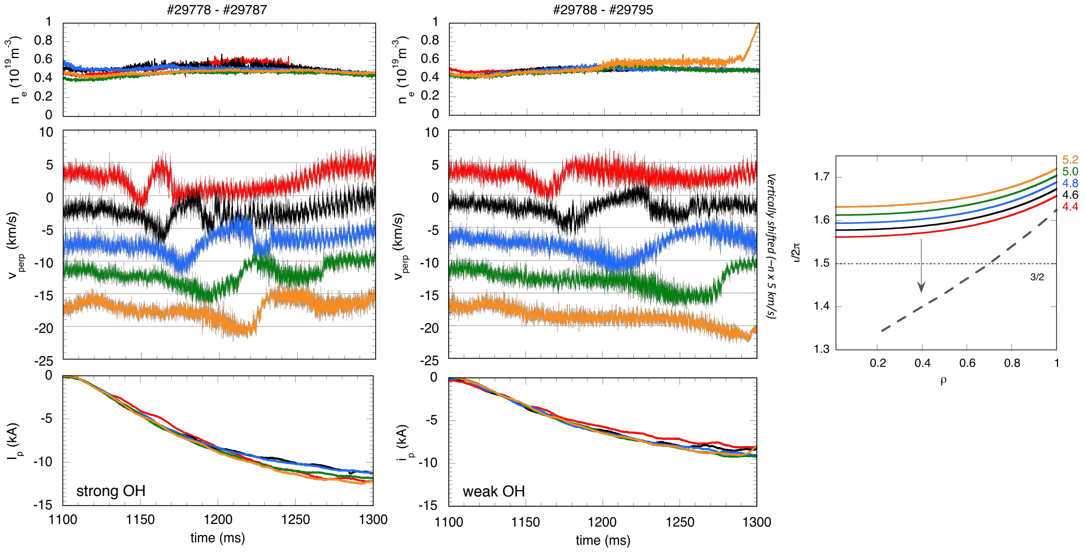

FIG. 2: The time evolution of the line density (top), perpendicular rotation velocity (middle) and net plasma current (bottom) measured at five different magnetic configurations -whose rotational transform profiles are shown in the right panel- for strong (left) and weak (centre) OH current intensity. Each magnetic configuration -represented with a different color- is characterized by the current in the helical coil that changes from 4.4 kA (in red) to 5.2 kA (in yellow).

3 Turbulence & Magnetic Islands

3.1 Turbulence Level

DR allows the measurement of plasma flow fluctuations and density turbulence with good time and spatial resolution. These two quantities have been measured during the present experiments in order to study the possible influence of the 3/2 magnetic island. An increase in the flow fluctuation intensity is measured at the outer and inner boundaries of the magnetic island; the increase being more pronounced for low frequencies (below ∼ 50 kHz). Synchronous with the increase in the flow fluctuations, a reduction in the density fluctuation level is measured. This reduction is more pronounced in the inner boundary of the island, i.e. when the island is overpassing the DR measurement region, where the E_r-shear is stronger [8].

3.2 Radial Correlation Length

The effect of magnetic islands on the radial correlation length of the density fluctuations and the possibility of measuring this effect using Doppler reflectometry have been numerically studied using a synthetic DR diagnostic. This combines a 2D full-wave code [11] and the density fluctuations simulated using a MHD resistive code [7]. The radial correlation length, L_r, at a given radial position is usually calculated as the radial separation at which the mean coherence drops to $1/e$. This radial separation can be chosen either towards the plasma edge or towards the plasma core and, in plasma regions where the turbulence

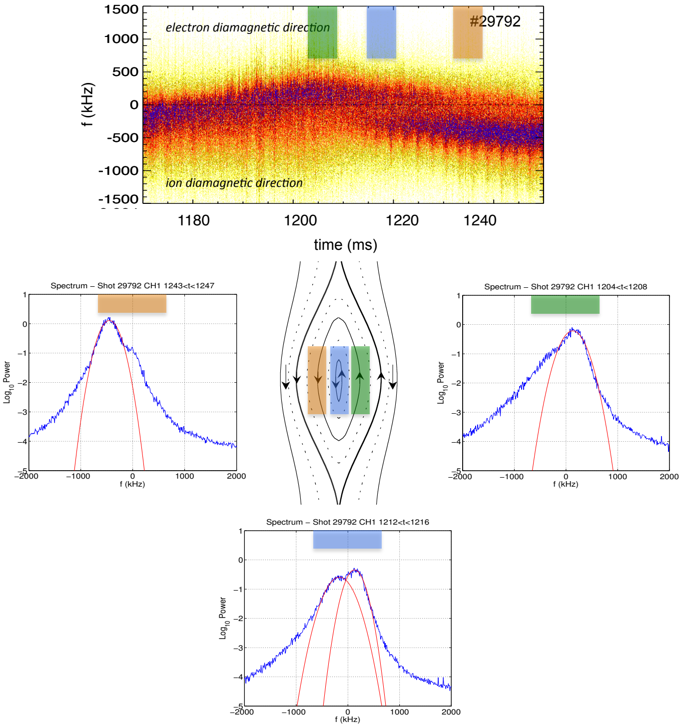

FIG. 3: Top: Spectrogram of the DR signals showing the evolution of the Doppler peak frequency as the magnetic island crosses the measurement region. Bottom: Schematic representation of the flux surfaces inside a magnetic island with the direction of the flow represented by the arrows. The corresponding DR spectra are represented, reflecting the evolution of the flow across the flux surfaces inside the 3/2 island.

is radially homogenous, both approaches provide similar values for L_r. In other words, the mean coherence calculated at r_0 is a symmetric function of $\Delta r = r - r_0$. However, in a plasma region with a magnetic island this is not longer the case, a pronounced asymmetry is detected in the mean coherence. Figure 4 summarizes the correlation results obtained for the density fluctuations simulated using the MHD code. The upper figure shows the L_r values obtained along the radial region where the 8/5 magnetic island is located. Two L_r curves have been measured at different radial positions for positive and negative values of Δr (in black and red, respectively). The mean coherence as a function of Δr is also represented for six radial positions (from A to F) across the magnetic island. The selected radial positions are indicated in the upper figure with vertical lines marked with the corresponding capital letters. Two Gaussian functions have been plotted in each case following the drop in the mean coherence at either side of r_0: in pink the function that fits the symmetric part of the mean coherence and in blue the function that fits the asymmetric one. Outside the magnetic island ($r < 0.105$ m and $r > 0.13$ m) the radial correlation length of the density fluctuations is $L_r \sim 0.6$ cm for both positive and negative Δr. As the outer boundary of the magnetic island is approached (A and B), a pronounced asymmetry in the mean coherence is detected, increasing the value of L_r up to ~ 2.2 cm for $\Delta r < 0$, i.e., towards the island center. Similarly, at the inner island boundary (F and E) the asymmetry reverses yielding values of Lr up to ~ 2.2 cm for $\Delta r > 0$. Closer to the magnetic island center (C and D), the asymmetry is less pronounced and intermediate values of L_r ($\sim$ 1 and 1.7 cm) are obtained. Finally, a symmetric coherent profile is found (between C and D) at the center of the magnetic island with $L_r \sim 1.3$ cm.

In order to check whether the reported behavior in the coherence of the density fluctuations is still visible when the correlation length is measured using a Doppler reflectometer, the density fluctuations simulated using the MHD code have been incorporated into the 2D full-wave code. To obtain the L_r profile a large number of measurements at neighboring radial positions across the magnetic island are needed. Numerically these measurements have been obtained keeping the probing beam angle fixed at 7° and changing the probing frequency from 36.5 GHz to 43.2 GHz in steps of 0.1 GHz. At each probing frequency, the reflectometer synthetic signals are calculated for the 1024 density field time-steps. A very similar behavior is found when the coherence of the Doppler reflectometer synthetic signals is considered. It is worth mentioning that a detailed comparison shows shorter L_r values when measured by the synthetic diagnostic as compared with those of the density fluctuations. This disagreement, however, is not exclusive of the present numerical results. Similar discrepancies have been previously reported in theoretical and numerical studies [15, 16]. Different values of L_r can be measured depending not only on the turbulence conditions but also on the reflectometer set up, i.e. on the probing beam frequency and angle. This dependence has been also confirmed in previous TJ-II experiments [17]. In any case, the results obtained with the Doppler reflectometer synthetic diagnostic suggest that a Doppler reflectometry diagnostic should be able to capture the signature of a magnetic island. Motivated by these simulation results, a set of experiments was carried out in which the magnetic configuration was scanned by the induction of OH current as in the experiments reported in previous section. In the new experiments, however, once the plasma current reaches the desired value, the one that locates the magnetic island at the DR measurement position, is kept constant until the end of the discharge by properly adjusting the pre-programmed waveform of the current in the OH coils. An example is shown in figure 5. In the discharge #41620 (in pink), the plasma current increases (in absolute value) up

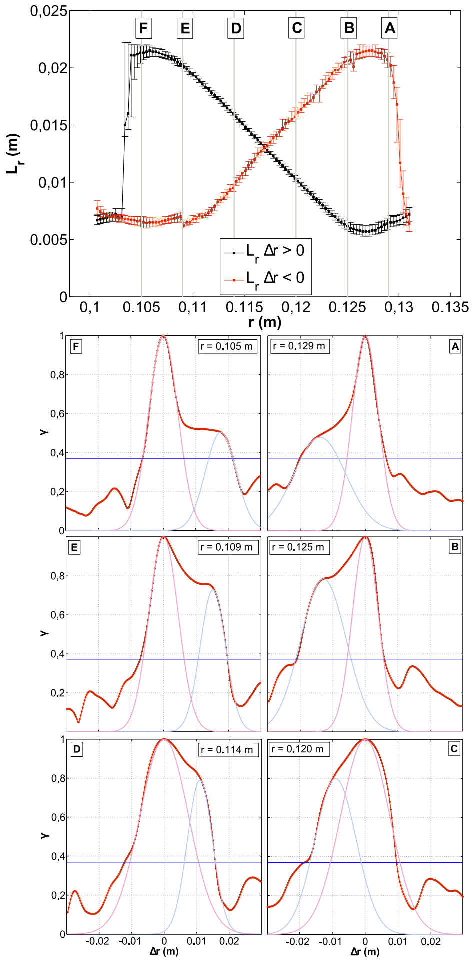

FIG. 4: Top: Radial correlation length L_r for $\Delta r > 0$ (towards the plasma edge, in black) and for $\Delta r < 0$ (towards the plasma core, in red), in the plasma region where the 8/5 magnetic island is. From A to F: Mean coherence as a function of Δr for different radial positions across the magnetic island.

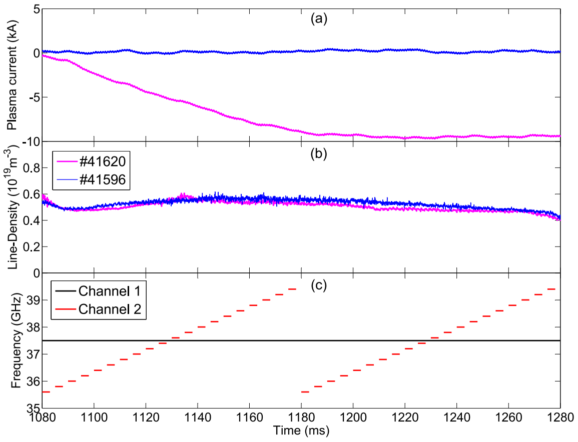

FIG. 5: The time evolution of (a) plasma current and (b) line density for two discharges, with and without OH induction, in pink and blue, respectively. (c) Doppler reflectometer probing frequency configuration for channel 1 (in black) and channel 2 (in red).

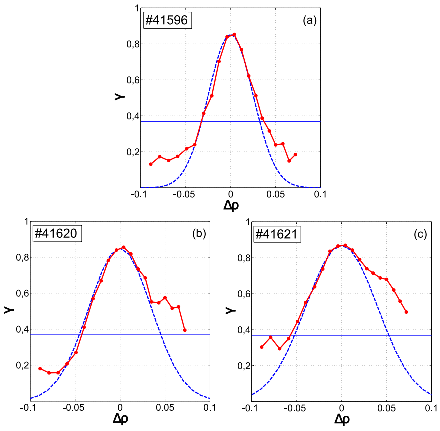

FIG. 6: Mean coherence vs. $\Delta\rho$ measured in three different discharges: (a) a reference discharge without OH induction, and (b) and (c) two similar discharges with the same OH current settings. The fitting curves (in blue) are included to highlight the asymmetries in the γ profiles

to ~ -10 kA along the first half of the discharge and then is kept constant. As a reference a second discharge in the same magnetic configuration but without OH induction is shown (#41596, in blue). The frequency of the second channel (shown in red in figure 5(c)) is scanned in steps of 200 MHz around the frequency of the first channel (in black) for coherence measurements. The coherence profiles measured during the second half of the discharges (in the interval t : 1180 - 1280 ms) are shown in figure 6. Three different discharges are represented, the reference one without OH induction #41596 (figure 6(a)) and two consecutive shots #41620 (figure 6(b)) and #41621 (figure 6(c)) with the same OH current settings (as the one showed in pink in figure 5(a)). The radial localization of the measurements is $\rho \sim 0.65$ in all cases. An almost symmetric γ profile is measured in the reference discharge (without OH induction) reflecting a rather homogeneous turbulence in this plasma region. On the contrary, in the discharges with negative plasma current a pronounced asymmetry is detected in the two cases. This asymmetry yields values of $L_r \sim 1.7$ cm for $\Delta\rho > 0$ and $L_r \sim 1.0$ cm for $\Delta\rho < 0$. The comparison of the γ profiles measured at TJ-II with those obtained in the simulations indicates that it is the inner part of magnetic island what is being detected by the coherence measurements. This is in agreement with the signature left by the magnetic island in the plasma flow measured by the fixed frequency channel.

4 Summary

The effect of magnetic islands on plasma flow and turbulence has been experimentally investigated in ohmically induced magnetic configuration scans using Doppler reflectometry at TJ-II. A characteristic signature of the 3/2 magnetic island as it crosses the DR measurement position is clearly detected, showing a modulation in the perpendicular flow that changes twice its direction. The perpendicular flow reverses at the center of the magnetic island and a flow shear develops at the island boundaries. An increase in the low frequency flow oscillations is measured at the magnetic island boundaries together with a reduction in the density fluctuation level. MHD resistive code simulations show that the radial correlation of density fluctuations has a pronounced asymmetry with larger values of L_r towards the island center. This asymmetry has been also detected by the DR synthetic diagnostic and also in TJ-II experiments where an asymmetry in the mean coherence profile is measured at a radial position that is in good agreement with the expected radial position of the 3/2 magnetic island. This asymmetry can provide a fingerprint of a magnetic island, useful to detect its presence and extension in a fusion plasma.

Acknowledgments

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