The role of magnetic islands in modifying long range temporal correlations of density fluctuations and local heat transport

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Abstract
This work explores the relation between magnetic islands, long range temporal correlations and heat transport. A low order rational surface ($\iota = 3/2$) was purposely scanned outward through an electron cyclotron resonance heated (ECRH) plasma in the TJ-II stellarator. Density turbulence and the poloidal flow velocity were characterized using a two channel Doppler reflectometer. Simultaneously, the ECRH power was modulated to characterize heat transport, using measurements from a 12 channel electron cyclotron emission diagnostic. A systematic variation of the poloidal velocity was found to be associated with the $\iota = 3/2$ rational surface. Near the rational surface, the Hurst exponent, quantifying the nature of long-range correlations, was reduced below 0.5 (indicating subdiffusion), while at radii smaller than that of the rational surface, it was found to be significantly enhanced (superdiffusion). In the latter region, heat transport was enhanced as well, thus establishing a link between density fluctuations and anomalous heat transport. The observed variation of the Hurst exponent was consistent with a magnetohydrodynamic turbulence simulation.

Keywords: fusion, stellarator, turbulence, transport

(Some figures may appear in colour only in the online journal)

1. Introduction

In this work, we study the relation between rational surfaces, long range temporal correlations and heat transport in the low shear stellarator TJ-II. The relationship between rational surfaces and heat transport has been explored in a number of earlier works, both at TJ-II [1–3] and other stellarator devices [4]. In tokamaks, low order rational surfaces are often associated with Internal Transport Barriers or the reduction of (heat) transport [5, 6]. However, very little is known about the relation between rational surfaces and the Hurst exponent [7], and this work will focus specifically on this issue. The Hurst exponent is a measure of the degree of long range temporal correlations [8–10], and hence an important quantifier of anomalous transport.

In the experiments presented here, the position of the rational surfaces is slowly scanned outwards by means of the external induction of Ohmic current [11], allowing the exploration of various quantities as a function of the rotational transform by diagnostics observing at a fixed position. Doppler reflectometer (DR) measurements show that a rational surface corresponding to a low order rational (3/2) is associated with a localized variation of the radial electric field. Here, we will report that the Hurst exponent obtained from the DR density fluctuation amplitude is also modified significantly.
In the same discharges, we also characterize heat transport using the modulation of centrally deposited Electron Cyclotron Resonance Heating (ECRH) combined with radially distributed Electron Cyclotron Emission (ECE) temperature measurements. We observe that heat transport is locally enhanced when the Hurst exponent, calculated from density fluctuations, is increased. Eight similar discharges are analyzed, showing that the obtained results are systematic and reproducible.

The reported observations establish a clear link between (a) the modification of density fluctuation properties near a rational surface in the gradient region, associated with long range memory effects, and (b) enhanced heat transport.

The interpretation of these observations finds support from a model [12], showing that the radial electric field structure and the Hurst exponent are both modified close to the rational surface.

This paper is structured as follows. In section 2, the experimental setup is discussed. In section 3, we present the experimental results. In section 4, we present the modeling results and interpretation. In section 5, we discuss the results, and in section 6, we draw some conclusions.

2. Experimental set-up and techniques used

In this work, we study discharges heated by Electron Cyclotron Resonant Heating (ECRH). In these discharges, the plasma has a relatively low line average electron density of \(n_0 \approx 5.1 \times 10^{19} \text{ m}^{-3}\), so that it is slightly below the critical density of the electron to ion root confinement transition at TJ-II [13, 14].

2.1. Modulated ECRH and ECE measurements

The ECRH system consists of two gyrotrons with a frequency of 53.2 GHz, allowing the injection of up to 2 \(\times\) 300 kW of heating power [15]. In the ECRH experiments, both ECRH systems were launching into the core of the plasma; the half width of the deposition profile being \(w_{\text{ECRH}} \approx 3 \text{ cm}\) [16]. One was providing continuous injection of approximately 250 kW, whereas the second system was modulated at low power (\(\approx 50 \text{ kW}\)), at a modulation frequency of 360 Hz and with a duty cycle of 30%, in order to allow quantifying heat transport.

TJ-II disposes of a 12 channel Electron Cyclotron Emission (ECE) detection system to measure the local electron temperature \(T_e\) at up to 12 different radial positions along the midplane on the high magnetic field side of the plasma (at a toroidal angle of \(\phi = 315^\circ\)), covering a significant part of the plasma minor radius, with a radial resolution of about 1 cm [17]. The local modulation amplitude and phase (relative to a central ECE channel) are determined using a Fourier analysis of the \(T_e(r, t)\) data (\(r\) being the minor radius and \(t\) the time).

Assuming transport is diffusive it is possible, in principle, to extract diffusive transport parameters (such as the effective diffusivity and convective velocity) from these data. However, we refrain from doing so, as the uncertainties introduced by assuming a specific transport model, as well as the ill-posed nature of the problem, do not allow obtaining a clear and unambiguous interpretation of the transport processes inside the plasma from such an inversion [18, 19]. Instead, we will represent the amplitude and relative phase directly, noting that the gradient of the relative phase is directly linked to the speed of the transport [20, 21].

2.2. Doppler reflectometry

The two-channel Doppler reflectometer of TJ-II [22] is located in a top viewport at a toroidal angle of \(\phi = 337^\circ\). In Doppler reflectometry, a finite tilt angle is purposely introduced between the incident probing beam and the normal to the reflecting cut-off layer, and the Bragg back-scattered signal is measured [23]. The amplitude of the recorded signal is a measure of the intensity of the density fluctuations, \(\tilde{n}\). As the plasma rotates in the reflecting plane (a flux surface), the scattered signal experiences a Doppler shift. The size of this shift is directly proportional to the rotation velocity of the plasma turbulence perpendicular to the magnetic field lines, \(v_\perp\), and therefore to the plasma background \(E \times B\) velocity, provided the latter dominates over the phase velocity of...
density fluctuations [24]. The Doppler reflectometer signals, sampled at 10 MHz, allow determining $\dot{\eta}$ and $v_\perp$ with high temporal and spatial resolution at two radial positions [25]. In the discharges analysed here, channel 1 is characterized by: $\rho \approx 0.75, k_\perp \approx 6 \text{ cm}^{-1}$ and channel 2 by: $\rho \approx 0.68, k_\perp \approx 6.7 \text{ cm}^{-1}$. Here, $\rho = r/a$ is the normalized minor radius and $k_\perp$ is the perpendicular wavenumber.

2.3. Sweep and tracking of rational surfaces

In these ECRH experiments, a number of magnetic configurations were used with similar (low) magnetic shear, but a slightly different value of rotational transform, $\omega = \iota/2\pi = 1/q$, where $q$ is the safety factor. By inducing an Ohmic current in the plasma, the rotational transform profile is modified, as shown in figure 1. Different magnetic configurations are identified by a label that is constructed from the values of the currents flowing in the external field coils. The induced Ohmic current moves the rational surfaces (such as $\iota = 3/2$) outward. Simultaneously, the magnetic shear is enhanced, although it remains rather low.

For the interpretation of experimental data obtained in such discharges, a reconstruction of the actual rotational transform profile (and the location of the rational surfaces) during the sweep of the Ohmic current is useful. This is obtained by iteratively updating equilibria calculated by VMEC [26], using a separate publication. An example result is shown in figure 2, with respect to a reference time $\Delta \tau = 0$ to be defined in the following. However, this evolution will depend on the precise shape of the plasma current profile, which is not measured directly, leading to some uncertainty in the calculation. The interpretation of the data reported in the following will therefore not rely on this calculation in detail, although it serves as a guide to what one may expect to find in the experimental situation.

In this work, we will focus mainly on the $\iota = 3/2$ rational surface. Figure 3 shows Poincaré plots for the vacuum configuration 100_36 (see figure 1), in planes of constant toroidal angle, $\phi$, indicating the positions of the ECE diagnostic (left) and the DR diagnostic (right). The major radius is $R_0 = 1.5$ m.

2.4. The Hurst exponent

In this work, we will be using the Hurst exponent as a measure of long-range correlations. This coefficient provides an estimate of the degree to which transport deviates from normal diffusive transport. The calculation of the Hurst exponent is based on the rescaled range statistic $(R/S)$ proposed by Mandelbrot and Wallis [8]. This statistic is defined as the ratio between the maximal range of the integrated signal $X_n$ normalized to the standard deviation, denoted by $S(n)$ for a signal of length $n$. Thus [28]

$$ R(n) = \frac{\max(0, W_1, W_2, \ldots, W_n) - \min(0, W_1, W_2, \ldots, W_n)}{\sqrt{\lambda(n)}} $$

where $W_i = X_1 + X_2 + \cdots + X_k - k \overline{X}(n)$, $\overline{X}(n)$ being the mean of the signal. For phenomena exhibiting long-range time dependence properties, the expected value, $E$, of $R/S$ scales as $E[R(n)/S(n)] \rightarrow \lambda n^H$, where $H$ is the Hurst exponent.

We recall that the Hurst exponent lies in the range $0 \leq H \leq 1$. When $H = 0.5$, one has ordinary diffusive transport; when $0 \leq H < 0.5$, one has antipersistence of the fluctuations, associated with subdiffusive transport, and when $0.5 < H \leq 1$, persistence of the fluctuations, associated with superdiffusive transport [9, 10].

The Hurst exponent is calculated from the density fluctuation amplitude, $|\dot{\eta}|$, measured using the DR. We calculate the rescaled range graph of $R/S$ using overlapping time windows with a length of 10 ms, and evaluate $H$ from the logarithmic slope of $R(\tau)/S(\tau)$ over the time lag range of $0 \leq \log_{10} \tau \leq 1$ ($\tau$ in ms). The value of $H$ thus obtained corresponds to asymptotic times, close to the confinement time of the plasma. Note
that the DR sampling rate is 10 MHz, so that 10 ms of data corresponds to $10^5$ data points, providing ample statistics for the determination of the Hurst exponent. Even though the plasma state is varying constantly due to the ramped plasma current, these changes are sufficiently slow to consider the density fluctuation amplitude measurement to be essentially in steady state during the analysis time windows of 10 ms. Modifying the length of these time windows by a factor of two hardly affects the results, confirming this statement. External Mirnov pick-up coils give no indication of strong MHD (magneto-hydrodynamic) mode activity, and likewise no strong evidence for such activity is seen in the $R/S$ graphs.

3. Experiments

3.1. Doppler reflectometry results

Figures 4 show examples of the analysis of Doppler reflectometry signals. Here, $v_\perp$ is computed from the raw complex signal using 64-point bins [25]. The figures show $v_\perp$ itself (smoothed to remove noise), showing the mean perpendicular rotation velocity at the observation point, and the Hurst exponent, $H$, calculated as described in section 2.4. The 360 Hz modulation seen in $v_\perp$ is a consequence of the modulated ECRH power.

The Hurst exponent tends to be slightly above $H = 0.5$ on average, although during specific time intervals, the value is lower or higher, which may be related to the passage of rationals by the observation point. In figure 4, $H$ is particularly low for discharge 29 782, 1175 < $t$ < 1185 ms, coincident with $v_\perp \approx 0$. Similarly, for discharge 29 786, $H$ is low for 1205 < $t$ < 1220 ms, again coincident with $v_\perp \approx 0$. The dip in $H$ is somewhat less clear for discharge 29 787. As will be clarified in section 4, the periods of $H < 0.5$ are associated with subdiffusion occurring in ‘trapping zones’, typically associated with a low order rational surface. On the other hand, in figure 4, $H$ is high for 1210 < $t$ < 1220 ms in discharge 29 782, and for 1225 < $t$ < 1250 ms in discharges 29 786 and 29 787.

Figure 5 shows the spectrum of a bolometry channel (ABOL7) for discharge 29 786, also shown in figure 4 [29]. One observes several modes, including a mode with a frequency of $\sim 30$ kHz, visible in the time interval 1170 < $t$ < 1220. The mode frequency is modulated by the ECRH modulation frequency (360 Hz). The mean frequency of the mode sweeps down slowly because the rational surface is moving outward (to parts of the plasma that are rotating more slowly) [30].

To get a clearer view of the temporal evolution of the various quantities, we will use 8 similar discharges to compute averages. These discharges are listed in table 1. The starting configurations are different, having vacuum profiles as shown in figure 1, meaning (mainly) that the time of occurrence of the passage of the rational surface past the Doppler reflectometry observation point is different for each discharge. Also, the sweep rates of the OH current vary slightly. To be able to average over such discharges, we must define a reference time, which we take to be the time of steepest slope of $v_\perp$, i.e. the times indicated by the vertical dashed lines in figure 4. The reference times are different for each channel, as channel 1 (further outward) responds some 15 ms after channel 2.

Figure 6 shows the mean evolution of $H$ in a time window centered about the reference time. The mean Hurst exponent of channel 1 is close to the value for uncorrelated random noise (diffusion), $H \approx 0.5$, for $\Delta t < 0$, and attains a peak of about $H = 0.65–0.7$ lasting about 25 ms after the steepest descent point of $v_\perp$. The dip in $H$ for $-25 < \Delta t < -10$ ms is
clear, although $H$ does not drop far below 0.5 due to the mentioned variability of the discharge conditions; but the rise in $H$ seen at $\Delta t > 0$ appears to be quite robust to the averaging procedure. Channel 2 (further inward) does not show a clear temporal evolution of $H$.

To understand this situation, figure 7 shows the mean electron density profiles reconstructed from AM reflectometer [31] and interferometer data, using a Bayesian technique described elsewhere [32]. The density profiles evolve only little in the relevant time interval. Clearly, when the rational $\iota = 3/2$ is located at a position $\rho < 0.65$, the density gradient

![Figure 5. ABOL7 spectrum. The overall slowdown of the frequency is due to the rising OH current, slowly moving the rational surfaces outward. The modulation of the mode frequency (at 360 Hz) is due to ECRH modulation (discharge 29 786).](image)

**Table 1.** Discharges and DR reference times.

| Discharge number | Starting configuration (see figure 1) | Reference time (channel 1) | Reference time (channel 2) |
|------------------|--------------------------------------|----------------------------|----------------------------|
| 29 771           | 100_44_64                            | 1160                       | 1150                       |
| 29 780           | 100_46_65                            | 1170                       | 1160                       |
| 29 782           | 100_48_65                            | 1195                       | 1185                       |
| 29 783           | 100_48_65                            | 1185                       | 1175                       |
| 29 784           | 100_50_56                            | 1210                       | 1190                       |
| 29 785           | 100_50_56                            | 1200                       | 1180                       |
| 29 786           | 100_52_66                            | 1225                       | 1200                       |
| 29 787           | 100_52_66                            | 1225                       | 1205                       |

![Figure 6. The mean Hurst exponent (calculated from $|\tilde{\eta}|$ for 8 discharges) for Doppler reflectometry channels 1 and 2. The red dashed line indicates the smoothed trend (channel 1).](image)

![Figure 7. Mean electron density profiles for the eight discharges analyzed in this work. The profiles are averaged over $-100 \leq \Delta t \leq 100$ ms; in this time window, temporal variations are only slight.](image)

![Figure 8. ECE data $T_e(\rho, t)$ obtained in an ECRH modulation experiment: discharge 29 786 at $\rho = -0.75, -0.52, -0.20, -0.079, 0.11$ (bottom to top).](image)
at the rational surface is low, whereas it is much higher for \( \rho > 0.65 \). As island growth and the development of sheared flows are related to local gradients, we surmise that the corresponding island or flow perturbation is initially small, but grows when the rational surface reaches the gradient region, \( \rho > 0.65 \). The rational surface is associated both with a dip in \( H \) and \( v_\perp \approx 0 \) (see figure 4). After passage of the rational, \( H \) clearly increases for channel 1 (well inside the gradient region at \( \rho \approx 0.75 \)), while it remains modest at channel 2 (at \( \rho \approx 0.68 \)).

3.2. ECE

Figure 8 shows an example of the measured ECE time traces of \( T_e(\rho, t) \). The corresponding power spectra are shown in figure 9. The frequency of the first three harmonics of the modulation frequency (360 Hz) is indicated by vertical dashed lines. The amplitude of the first three harmonics versus \( \rho \) is shown in figure 10. In this figure, negative \( \rho \) values refer to ECE channel positions with \( R > R_m \), where \( R_m \) is the major radius value of the magnetic axis in the ECE poloidal cross section, and positive values to positions with \( R \leq R_m \). As the modulated ECRH power is deposited centrally, the amplitude decays from the centre of the plasma towards the edge. The indicated error bars indicate the variation of the amplitude when the analysis is performed using successive time windows with a length of 10 ms. The phase of the first harmonic versus \( \rho \) is shown in figure 11, along with a straight line fit. For this purpose, a central ECE channel is taken as reference; evidently, for the selected reference channel the cross phase is zero. Generally speaking, the cross phase increases from the plasma core towards the edge, indicating a delayed response to the core modulation. It is understood that the effect of the modulation propagates outward as a consequence of heat transport.

Note that the phase does not increase monotonically from the centre towards the edge; in particular, for \( \rho < -0.4 \) the phase seems to decrease or at least remain constant. A priori,
this observation allows two alternative interpretations. First, the zone of nearly constant phase might correspond to the island region, as fast parallel transport within the topologically separate island might cause (partial) profile flattening [33, 34]. Second, this zone might correspond to a region with enhanced radial transport, possibly associated with field line stochastization [35]. In this respect, recall that the measured modulation amplitude and phase can be related to the effective heat diffusion coefficient via [20]:

$$\chi_e \propto \frac{\omega_0}{4} \left( \frac{\Lambda}{A} + \frac{1}{2A} + n' \right)$$

(2)

Thus, a drop in the radial derivative of the phase, $\phi'$, would imply an increase in local $\chi_e$.

The propagation analysis is quite reproducible for the set of 8 discharges cited above. Hence, we use the same reference times as in table 1, DR channel 1, and calculate discharge averaged values versus time and radius. Figure 12 shows the mean modulation amplitude and phase (relative to the central ECE channel).

Note the significant and short-lasting reduction of phase around $\Delta t \approx 0$ ms ($|\rho| \approx 0.65$). This time and place coincides rather well with the passage of the rational $\omega = 3/2$, see figure 2, and its entry into the density gradient zone. Figure 12 shows that the phase is nearly constant over a wide area, namely $0.3 < |\rho| < 0.7$, for a time period lasting several tens of ms around $\Delta t = 0$. The slight temporal variation of $\Lambda$ is mainly due to a small temporal variation of the line average electron density, $n_e$, leading to a corresponding small variation in absorbed ECRH power.

Figure 13 shows the time evolution of the measured electron temperature, $\langle T_e(\rho, t) \rangle$, averaged over the 8 mentioned discharges, and its temporal variation, $\Delta \langle T_e(\rho, t) \rangle = \langle T_e(\rho, t) \rangle - \langle T_e(\rho, t) \rangle$, where the overline indicates a time average taken over the time window $-50 \leq \Delta t \leq 0$ ms. By definition, this quantity is near zero for $-50 < \Delta t < 0$ ms, but a significant temperature drop ($|\Delta T_e| \approx 50$ eV) is visible for $\Delta t > 0$, starting at around $|\rho| = 0.35$ and propagating both inward and outward, suggesting a release of heat from the core towards the edge.

The area of constant phase at $\Delta t \approx 0$ is very wide ($0.3 < |\rho| < 0.7$, figure 12), so that the explanation for the observed modulation phase in terms of rapid parallel transport within a hypothetical island seems unlikely, as the required
island would be excessively large. The observed heat release from the core, along with the fact that no significant profile flattening is observed, seems to favor the interpretation in terms of locally enhanced radial transport in a zone associated with (inward from) the rational.

3.3. ECE modulation amplitude variations

Figure 14 shows the signals of the outermost 4 ECE channels in a specific discharge (top). The modulation signal ‘disappears’ in ECE channel 2 ($\rho = -0.64$), for $1165 < t < 1188$ ms, the time interval indicated by the vertical dashed lines, leaving only noise. The length of this time interval coincides with the half period of the velocity variation observed by DR (not shown for this discharge, but similar in shape to figure 4, discharge 29 782), suggesting that this phenomenon is likewise associated with the passage of the rational surface. Again, we note that no important profile flattening is observed, within the resolution of the ECE diagnostic [36].

To quantify the relative importance of noise and the modulation amplitude in the ECE signals, we define a statistic 
\[ R = R_1/R_2, \]
where $R_1$ is defined as the root mean square (RMS) amplitude of the measured $T_e(\rho, t)$ data, after high-pass filtering with a cutoff frequency of 2 kHz. $R_2$ is defined as the RMS amplitude of the measured $T_e(\rho, t)$ data, after band-pass filtering in the frequency range 0.1 $< f < 2$ kHz. Thus, $R_1$ is a measure of the noise amplitude while $R_2$ is a measure of the modulation amplitude (the modulation frequency being 0.36kHz). To show how systematic this reduction of the modulated component of $T_e$ is, we again calculate an average over the 8 mentioned discharges. Figure 15 displays the mean ratio $R$, a quantifier of the degree of isolation from the temperature modulation, versus time and radius.

Regions in figure 15 with high values of $R$ (i.e. low modulation amplitude) possibly correspond to regions with relatively high sheared flow, leading to increased mixing. Alternatively, a magnetic island with significant width could also account for this phenomenon, as the island O-point region is topologically separate from the main plasma, so that the penetration of modulation in this region could be small. Apparently, this is the case when the rational 3/2 surface (moving outward) reaches $|\rho| > 0.65$, which is the density gradient region. The zone of relatively high $R$ seen at $|\rho| \simeq 0.4$ is possibly associated with another rational ($\ast = 7/5$); see figure 2. Note that the total magnetic field, $|B|$, varies by less than 0.5% due to the varying plasma current, so that the radial locations of the ECE channels, inversely proportional to $|B|$, may be considered fixed.

4. Modeling

Topological analysis of the flow structures of plasma turbulence [37] has shown that typically, low order rational surfaces are associated with small transport barriers. These are created by zonal flows, induced by flow eddies associated with the rational surfaces. These small transport barriers tend to trap particles, leading to local subdiffusive behavior, as reported in [38]. Therefore, a reduction of the Hurst exponent below 0.5 is expected in the barrier regions. On the other hand, experimental studies have shown that $H$ is systematically large in the plasma edge region [9] and varies with the global gradients [39].

To study the correlation between the zonal flows associated with low order rationals and the Hurst exponent, we have performed a simulation of the magnetohydrodynamic turbulence induced by resistive interchange modes in a periodic cylinder. This is a single fluid MHD model [12] that does not include Neoclassical plasma flows [40]. While such flows may certainly be important, our present purpose is merely to illustrate the effect of rationals on the Hurst exponent calculated from density fluctuations. Likewise, the model does not include static magnetic fields [12], for the same reason. We have not attempted to match the experimental situation closely, due to the difficulty of reproducing a gradual modification of the rotational transform in time, induced by an increasing plasma current. Here, we limit ourselves to studying the possible relation
between low order rational surfaces, zonal flow generation and the Hurst exponent. For this purpose, we have taken one of the standard rotational transform profiles of TJ-II, the case labelled 100_46 in figure 1, using a pressure profile that is close to the experimental one. Because the rotational transform has low shear, the low order rational surfaces produce magnetic islands of a significant width, facilitating the detection of regions with potential subdiffusion.

The main parameters used in these calculations are:

- \( \beta = 0.001 \), inverse aspect ratio \( \varepsilon = a/R_0 = 0.15 \), where \( R_0 \) is the major radius, and Lundquist number \( \tau = S/10R_A = 10^5 \). For these parameters, this configuration is unstable to resistive interchange modes. Here, \( \beta \) is the ratio of the plasma pressure, \( p \), and the magnetic pressure, \( \mu B^2/2 \), at the plasma axis:

\[
\beta = \frac{\mu p_0}{B^2/2} = \frac{\mu_0 B^2/2}{\mu_0 B^2/2} = 1,
\]

where \( \mu_0 \) is the vacuum permeability; \( \eta \) is the resistivity at the magnetic axis and \( \tau_\alpha \) is the Alfvén time, \( \tau_\alpha = R_0 p_0 m_i n_i / B^2 \), where \( m_i \) and \( n_i \) are the ion mass and density, respectively.

We have calculated the Hurst exponent at 100 equally spaced radial locations over a period of time of \( 4\tau_\alpha \), long enough to obtain asymptotic behavior. We also calculated the angular and time averaged poloidal flow. The Hurst exponent and the averaged poloidal flow are shown in figure 16.

At each of the main rational surfaces, the averaged poloidal flow has a minimum, while the flow has strong shear in the region of the magnetic island associated with each resonant surface. It is also clear that the \( H \) coefficient has a minimum in the same region, with values below 0.5. This is consistent with the idea that the region immediately surrounding a singular surface constitutes a ‘trapping zone’. The \( H \) coefficient increases above 0.5 as we move out of the region of the resonant surface. This structure is fairly systematic at all the low resonant surfaces present in the plasma and they are consistent with the measurements shown in figure 4. The experiment also shows a clear enhancement of \( H \) at radial positions inside from the rational surface, see figure 6.

When comparing with the experiment, one should remember that transport consists of both turbulent and collisional transport, the latter being induced by collisions [41]. Collisional transport has a diffusive nature and tends to dominate subdiffusive processes, making it difficult, in general, to observe significant regions with \( H < 0.5 \) in the experiment. Nevertheless, times with low values of \( H \) are visible in figure 4, and \( H \) is systematically moderate (of the order of 0.5 or slightly below) in a zone associated with the \( \approx = 3/2 \) rational, i.e. \( -25 < \Delta t < -10 \) ms in figure 6.

The averaged flow shown in figure 16, \( \langle V \rangle \), is calculated by averaging the poloidal flow over the poloidal and toroidal angles and over a period of time such that the dynamical calculation and the corresponding zonal flow are in steady state. The averaged flow near a rational surface, generated from the turbulence via Reynolds Stress, has a symmetric structure.

If we now compare the averaged flow to the instantaneous poloidal flow, see figure 17, one observes that the latter is not symmetric with respect to the singular surface, and that the asymmetry may vary. This is relevant for the interpretation of the perpendicular flow measured by DR in the experiment, which is instantaneous and local, and hence may be very sensitive to the precise poloidal and toroidal location of the measurement. In view of this, the perpendicular flow velocity obtained from Doppler Reflectometry may be asymmetric with respect to the rational surface.

The \( H \) coefficient is determined by at least two effects. One is the generation of long range correlations by avalanches, and the other is their suppression due to decorrelation by sheared flow. Avalanches are non-local phenomena, but in the plasma...
core region avalanches are relatively rare and they tend to correlate with the gradient, as they originate there. The edge, however, is crossed by many avalanches initiated in the entire plasma, so no relation is expected between the local gradient and the $H$ exponent. At the plasma edge, the $H$ exponent tends to be above 0.5 [9]. In figure 18 we show the gradient of the pressure, averaged over the flux surface and over time, as a function of the radius, together with the $H$ coefficient, to illustrate this situation. At the singular surface, the density gradient is low, and due to the presence of the islands and the associated average sheared flow, the $H$ coefficient is reduced below 0.5. Immediately outside the islands, where the sheared flow goes to zero, the density gradient is high, correlated with an increase of $H$ above 0.5, at least in the plasma core region.

In the plasma edge region, $H$ tends to rise above 0.5 globally, while it is reduced below 0.5 only at the singular surfaces, mainly $\iota = 5/3$ in this case, without any clear correlation with the gradient.

5. Discussion

Doppler Reflectometry (DR) has detected a structure in $v_{\perp}$ (equivalent to $E_r$) that is systematically associated with a rational surface, which is purposely and slowly scanned outward in the experiments discussed here. We take the time of maximum temporal variation of $v_{\perp}$ as a reference time ($\Delta t = 0$); this time is closely associated with, though not identical to, the time of passage of the rational surface itself [42].

The Hurst exponent (DR channel 1) was found to be low ($H < 0.5$) for $-25 < \Delta t < -10$ ms and systematically high ($H \approx 0.65-0.7$) for $0 < \Delta t < 25$ ms (figure 6). This observation might be consistent with the systematic reduction of $H$ at rational surfaces observed in the model discussed in section 4. A reduction of $H$ is associated with subdiffusive transport, implying that possibly, the rational is associated with a (minor) transport barrier [43, 44], which in turn may be related to the relatively good heat confinement observed in figure 13 for $\Delta t < 0$.

For $0 < \Delta t < 25$ ms, the Hurst exponent is large ($H(\rho \approx 0.75) \approx 0.65-0.7$), while somewhat further inward, $H$ stays moderate ($H(\rho \approx 0.68) \approx 0.5$). As discussed above, this observation could be related to the location of the DR channels with respect to the density gradient region.

Specific radial zones are observed where the ECRH modulation appears to penetrate only weakly (figure 15), which is interpreted as a consequence of considerable velocity shear in those zones, leading to enhanced mixing.

A representation of the evolution of the mean ECE temperature ($T_e$) and its variation $\Delta T_e$ (figure 13) suggests heat loss occurs for $\Delta t > 0$, starting in the core and expanding outward, as visualized in the plot of $\Delta T_e$ as a dark blue area. Simultaneously, the $T_e$ modulation phase gradient ($d\phi/d\rho$) is reduced in the region $0.3 < \rho < 0.7$. We note that the (incremental) heat diffusivity is proportional to the inverse of the gradient of the phase [21], so that the decrease of $d\phi/d\rho$ suggests enhanced heat transport and stiffness in this region (inward from the rational). This enhanced transport zone matches the zone of enhanced Hurst exponent, thus establishing a clear link between (memory effects associated with) density fluctuations and heat transport.

6. Conclusions

In these experiments at TJ-II, an externally driven OH current was used to modify the rotational transform profile, $\iota(\rho)$, and slowly move the rational surfaces outward through the plasma. As a main rational moved past the DR observation points, the perpendicular propagation velocity of the turbulence, $v_{\perp}$—equivalent to the radial electric field, $E_r$—was found to experience a significant ‘wiggle’. Taking the time of strongest temporal variation of $v_{\perp}$ as a reference, 8 similar discharges were analyzed.
The Hurst exponent was found to be low ($H < 0.5$) near the rational surface (figure 4) and systematically high ($H \approx 0.65-0.7$) inward from the $\pm = 3/2$ rational surface (figure 6, DR channel 1, well inside the density gradient region). The analysis of ECE data revealed that radial heat transport was enhanced in the region inward from the rational.

Simulations of magnetohydrodynamic turbulence induced by resistive interchange modes reproduced some of these observations qualitatively, namely: (1) the variation of poloidal flow profiles associated with rational surfaces, and (2) the variation of the Hurst exponent associated with rational surfaces and local pressure gradients. Neoclassical contributions to the radial electric field were not considered in this simplified model, which mainly pretends to clarify the effect of rationals on the Hurst exponent.

Thus, this work establishes a clear correlation between density fluctuation long range temporal correlation properties (quantified via the Hurst exponent) and enhanced heat transport near a low order rational surface, possibly providing the first direct observation of the turbulent mechanism behind anomalous heat transport.

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