Evidence for High-m Secondary Islands Induced by Large Low-m Islands in a Tokamak Plasma

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Small-scale structures with high poloidal mode numbers ($m = 10$–20) have been observed in the TEXTOR tokamak plasma with pulsed radar reflectometry and an electron cyclotron emission diagnostic, in conjunction with large $2/1$ and $1/1$ islands. The small islands have a peaked density profile, similar to that of the simultaneously observed large-scale $2/1$ islands. This together with the observation that high-frequency density and temperature fluctuations are very pronounced near the X points of the large islands hints to a strongly perturbed magnetic topology around the X points.

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Magnetohydrodynamic (MHD) modes in a tokamak usually occur on helical magnetic field lines with a low-order rational winding number m/n (number of toroidal turns / number of poloidal turns). From linear MHD stability analyses (Δ' calculations) it is known that for standard current density gradients in a tokamak plasma, tearing modes with a poloidal mode number m are inherently stable [1]. For the destabilization of tearing modes nonlinear destabilization mechanisms are required. At high β a well-known mechanism is the so-called neoclassical tearing mode (NTM) with low m numbers. High values of edge radiation can modify the current density gradient near the winding number $q = 2$ leading to $2/1$ islands and in extremum to a density limit disruption. In this Letter it will be demonstrated that MHD modes with high m numbers ($m = 10$–20) can exist in plasmas in conjunction with large low m number islands. These plasmas are typically at $\beta_N \sim 1$–1.5, which is much less than the threshold value of $\beta_N > 3$ needed for NTM destabilization. The large $2/1$ and $1/1$ islands are in these cases deliberately generated by too fast a current ramp in the beginning of the discharge. Wall stabilization is prevented by balancing the power ratio of neutral beam injection (NBI) in the cocurrent and countercurrent directions, such that the toroidal plasma rotation is close to zero. The presence of the high m-number modes then opens the discussion for the existence of additional nonlinear destabilization mechanisms.

During a research program on the TEXTOR tokamak ($R/a = 1.75/0.46$ m, $B_T = 2.25$ T, $I_p = 350$ kA), which was devoted to the simultaneous observation of large $m/n = 1/1$ and $2/1$ MHD modes, with m and n the poloidal and toroidal mode numbers, surprisingly small-scale structures with high m numbers were observed in the region between the large islands. The measurements were done with pulsed radar reflectometry [2] and with various heterodyne electron cyclotron emission (ECE) systems [3] in discharges with NBI. To be able to understand especially the pulsed radar signals that will be shown below, the principle of island observation by pulsed radar measurements is shown in Fig. 1 for a shot with a clear $2/1$ mode. Because the islands have a three-dimensional helical shape and rotate with the plasma in the toroidal direction, they are observed by diagnostics that are located at one position along the torus as a periodically varying signal. In pulsed radar reflectometry short (~ 1 ns) microwave pulses are launched into the plasma. Their flight time to the critical density layer and back is measured with a repetition rate of up to 10 MHz. The measurements reported in this paper were done at 5 MHz. In the case of Fig. 1 the pulsed radar channel was probing a density that was slightly below the peak density of the island, but higher than the density at the edge of the island, resulting in the typical garland structure in the time of flight versus time. The fact that the pulses reflect from a layer within the island is indicative of a peaked internal density profile [4]. This density peaking, which is also clearly observed with high-resolution Thomson scattering [see Fig. 1(b)] has been explained by

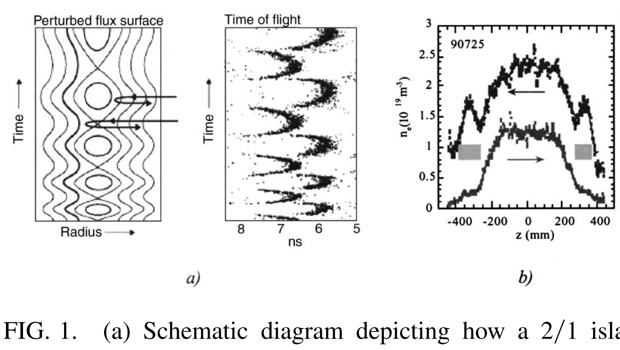

FIG. 1. (a) Schematic diagram depicting how a $2/1$ island, with a peaked internal density profile, is observed by the pulsed radar reflectometer. Because the mode rotates with the plasma, the microwave pulses are reflected alternating by the critical density layer in the island and by a density layer behind the island, causing a typical garland structure in the flight time measurements. (b) Density and temperature profiles measured with multiposition Thomson scattering in the same shot. The gray bars indicate the radial position of the $m = 2$ island.

a much better confinement of the plasma inside an island than that of the plasma surrounding the island. The peaking becomes more pronounced if there are particle sources inside the island, for instance, by neutrals from edge recycling or from NBI [4].

The pulsed radar reflectometry data of the 39 GHz channel for a TEXTOR discharge with simultaneously large and coupled 2/1 and 1/1 modes are shown in Fig. 2. The cutoff density (1.89×10^{19} m^{-3}) of the pulsed radar system was slightly below the peak density of the 2/1 island, but higher than the density at the edge of that island (as in Fig. 1). In this discharge a minor disruption occurred at 1.394 s. Immediately after that a 3/2 mode is observed until it becomes invisible at about 1.445 s. During a relatively short period in the TEXTOR discharge from 1.445–1.455 s, i.e., shortly after the 3/2 mode has vanished, it is seen that the reflection from the layer behind the island suddenly breaks up in a fine structure, with small garlands that are very reminiscent to the structures observed for the main 2/1 island. To be able to see the small structures by means of reflectometry, their internal density profile must also be peaked, very similar to the profile in the large islands. Thus in fact the small islands look like smaller copies of the large 2/1 island as far as the density is concerned. The particle sources in these small islands could come from NBI.

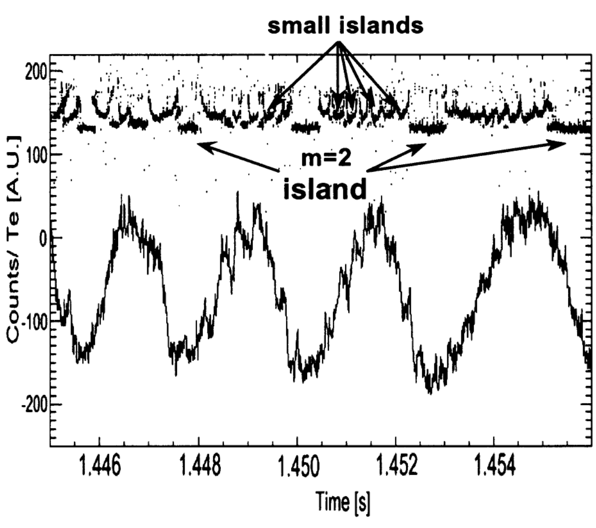

FIG. 2. Top trace: measurements with a pulsed radar reflectometer system (operating at 39 GHz in *O* mode). The reflections by the 2/1 island are indicated by arrows. The other reflections are originating from a layer behind the main island. It is clearly seen that the time-of-flight diagram has a pronounced garland structure as in the case of the main island. This proves the presence of a chain of small structures with a peaked density profile. Bottom trace: temperature variation of the 142 GHz channel that is probing the layer just behind the 2/1 mode. On top of the modulation of the large 2/1 mode, one can see a much faster modulation caused by a chain of small structures.

The bottom trace in Fig. 2 shows the temperature variation measured by means of ECE at 142 GHz (2nd harmonic *X* mode). This specific ECE channel is probing the layer between the 2/1 and 1/1 islands. The large oscillation is due to the 2/1 island. On top of the large oscillation, a much faster and smaller oscillation is observed, which is in phase with that of the pulsed radar reflectometer, demonstrating that the structures are also clearly visible in the temperature trace. The radial spacing of the ECE system was not sufficient to be able to detect whether the temperature profile in the small islands is slightly peaked, as is the case for the large islands [5]. The small modes could not be detected on the magnetics, because they are located too deep in the plasma.

In the pulsed radar measurements, density fluctuations show up as a spread in the time of flight of the pulses, firstly because the distance to the critical density layer is varying from pulse to pulse and secondly due to changes in the local density gradient. Because of the high repetition rate of the pulsed radar system (0.2 μs for the present measurements) it is possible to measure fluctuations up to very high frequencies. Figure 3 shows the frequency spectrum of the density fluctuations up to 500 kHz as a function of time measured for a plasma featuring a clear 2/1 island during the same period. The white trace shows the time-of-flight data. It is clear that the fluctuations above 50 kHz are strongly suppressed when the pulse is reflected from a position inside the island (corresponding to the garlands with the shortest flight time in the white curve). When the pulse reflects from a layer behind the main island, a strongly enhanced fluctuation level up to 400–500 kHz is observed.

With wavelet techniques the temperature fluctuations, measured by means of ECE, in the vicinity of the *O* point and the *X* point of the 2/1 island, have also been analyzed

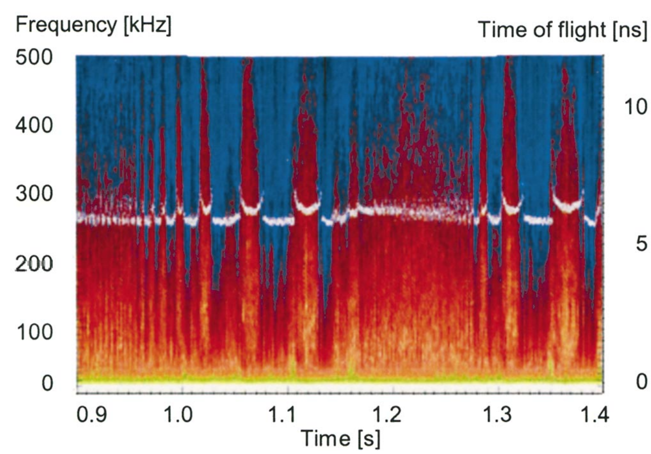

FIG. 3 (color). Measurement with the pulsed radar reflectometer of a rotating 2/1 island in the TEXTOR plasma. The white curve depicts the flight time of the radar pulses as a function of time. The colored spectrum gives the fluctuations in the flight time (indicative of density fluctuations) as a function of time.

(see Fig. 4). Clearly the fluctuations in the vicinity of the X point have higher frequencies and higher amplitudes than those near the O point of the island.

A final interesting observation is that the frequency of the small island structures in Fig. 2 strongly increases as a function of time, in a period of the TEXTOR discharge when the rotation of the tightly coupled $1/1$ and $2/1$ islands slowly decreases (see Fig. 5). This could mean that either the $3/2$ mode, which is manifest until 1.445 s and which is located between the $1/1$ and $2/1$ islands, is suddenly spinning up in velocity, or that the higher frequency originates from a breaking up of the $3/2$ mode into smaller islands with a higher spatial periodicity. The first of these explanations is thought to be less likely since the small islands are in the region between the $1/1$ and $2/1$ islands, which rotate toroidally as one rigid structure and moreover slow down. The local electron diamagnetic drift frequency ω_e^* at the position of the $3/2$ mode as derived from the n_e and T_e gradients in Fig. 1(b) is $2.5 \times 10^4\ \mathrm{s}^{-1}$. If the $3/2$ mode were spinning with this drift frequency we would have expected a frequency of more than 10 kHz while we observed at most 3.5 kHz. There are no indications for very localized zonal flows at the position of the small structures that could cause a differential rotation of the small structures in respect to the toroidal spinning of the large islands. Therefore, it is concluded that most likely the small islands must have a high m number locked to the large islands and therefore rotate with the same toroidal velocity.

With the caveat that the small structures can be regarded as high m number islands rotating locked to the large islands, we can summarize the findings by the following: (1) Large $1/1$ and $2/1$ islands are locked to each other and positioned at $\rho = 0.25$ and 0.65 and widths of $w/a = 0.13$ and 0.27, respectively. Toroidal rotation is about 450 Hz. For the $2/1$ islands [Fig. 1(b)], $B_r^*/B_\Theta = 2.5 \times 10^{-2}$; between the X and O points, $\Delta T/T = 0.3$ and $\Delta n/n = 0.2$; between the separatrix and the secondary maximum in the center of the island, $\Delta T/T = 0.1$ and $\Delta n/n = 0.3$. The pressure peaking at the islands' O points is consistent with theoretical predictions [6]. (2) For small islands: $m = 10$–20, $n = 7$–10; if $m = 10$, $B_r^*/B_\Theta = 1.5 \times 10^{-2}$; between the X and O points, $\Delta T/T \approx 0.05$ and $\Delta n/n \approx 0.1$; between the separatrix and the secondary maximum in the center of the island, $\Delta n/n \approx 0.1$ and $\Delta T/T =$ unknown. With $\rho_s \approx 2$ mm one can give as estimates: $k_\Theta \rho_s = 0.15 \pm 0.05$ and $k_r \rho_s = 0.35 \pm 0.15$. (3) For high-frequency (>10 kHz) fluctuations (Fig. 4), $B_r^*/B_\Theta =$ unknown, $\Delta T/T \approx 0.03$, and $\Delta n/n \approx 0.1$.

The observations are consistent with theoretical predictions by Thyagaraja [7] who calculated that near X points of magnetic islands there can be a considerable level of ergodicity.

The question to be answered is which mechanism(s) could be responsible for the occurrence of islands with a high m number. The most likely explanation is that they are a side product of the nonlinear coupling between the large $1/1$ and $2/1$ modes mainly due to the toroidicity of the system. Field line equations can be written as a Hamiltonian system. When the Hamiltonian is perturbed by a small nonintegrable part, $\mathrm{H} = \mathrm{H}_0 + \varepsilon \mathrm{H}_1$ (i.e., a small coupling between the 2 degrees of freedom, the poloidal and toroidal angle), the phase space falls apart into three distinct regions: still unperturbed KAM tori (=flux surfaces), islands that themselves are made up of nested KAM tori, and regions in which the field lines behave chaotically. The larger the perturbation ε is, the larger are the areas with

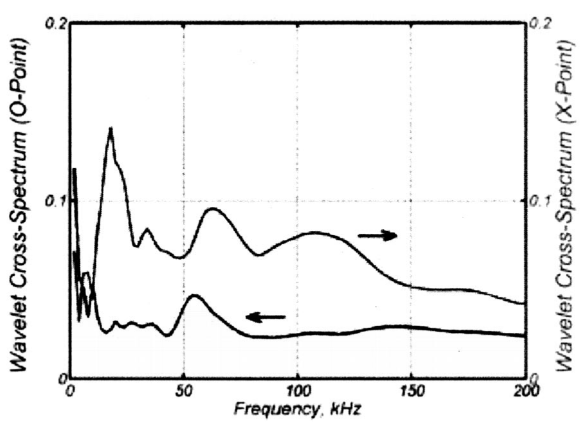

FIG. 4. Wavelet power spectra of the temperature fluctuations measured by means of ECE in the vicinity of the O point and of the X point of the $m/n = 2/1$ islands.

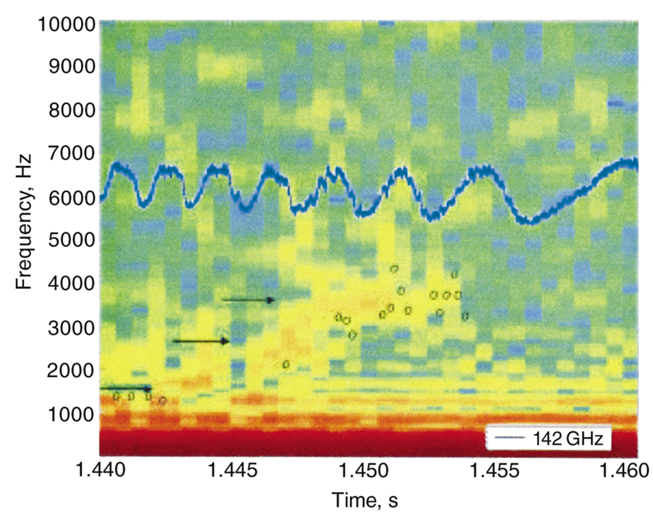

FIG. 5 (color). Frequency spectrum of ECE measurements as a function of time. The red colors depict high activity, whereas blue/green colors depict low activity. The blue trace shows the ECE signal at 142 GHz (identical to the curve of Fig. 3). One can see (blue trace) that the rotation of the $2/1$ island reduces, while the frequency of the small-scale structures increases (the orange-yellow cloud). The circles indicate the frequency measurements with pulsed radar reflectometry. Because the pulsed radar reflectometer cannot see the small islands when the main $2/1$ mode is in front of it, only discontinuous measurements can be made.

chaotic field lines. In cases when multiple island chains (with different m/n numbers) are simultaneously present in the plasma, the chaotic behavior of the magnetic field topology in the region between the island chains strongly depends on the overlap between the island chains. According to Chirikov, the unperturbed KAM tori that separate two individual chains of islands will disappear as soon as the separatrices of the islands (i.e., their outermost intact flux surfaces) come close to each other [8]. At lower values of the Chirikov parameter secondary islands appear between the two main island chains. The Chirikov parameter for the described experiments has been estimated to be 0.5 as the ratio between the sum of the experimental half widths and the radial distance between the $1/1$ and $2/1$ islands. Extensive calculations by de Rover and Schilham [9,10] on perturbed field line equations have demonstrated that indeed the magnetic field topology in a tokamak at such values of the Chirikov parameter is perturbed and shows secondary island chains. It should be pointed out that these calculations are magnetostatic. In fact the turbulence is a dynamic process that complicates matters. Moreover plasma particles are subject to more effects than just the magnetic field topology. The KAM theorem is only invoked here in order to illustrate that large islands can induce secondary island chains.

The observation that the frequency of the small mode increases in a short time can fit in the picture of a perturbed magnetic topology. Namely, the two main island chains are slowing down while at the same time the islands are still somewhat growing in size. As a result of that the Chirikov parameter of the two main island chains increases slightly. This can have a large effect on the field line behavior between the two main island chains. Small structures can suddenly appear, disappear, and come back with a different spatial periodicity. Indeed shortly after the $3/2$ mode becomes invisible at 1.445 s, another mode with a higher mode number comes back. On its turn the mode breaks up in islands with higher m number, however, with a ratio of m/n still between 1.5 and 2. Unfortunately, the statistics did not make it possible to see whether the frequency increase of the small mode occurs in small steps.

Although the trajectories of electrons are strongly determined by the magnetic field topology, they are also subject to $E \times B$ and curvature drifts. In cases when islands are significantly wider than ρ_s, it can be expected that electrons inside islands cannot escape except by collisions. This and the intact KAM tori inside the islands can explain the much lower fluctuation level inside the island and the better confinement. Outside the islands electrons are subject to both magnetic and potential fluctuations. However only around the X points the magnetic topology is strongly disturbed and could lead to enhanced fluctuation levels even when in the main plasma the magnetic component of turbulence can be neglected. This could explain that the level and frequency of turbulent fluctuations are modulated by the proximity to the main island X points as shown by the electron density fluctuations (Fig. 3), but also by the electron temperature fluctuations (Fig. 4).

In conclusion, we consider it very likely that secondary high m number islands have been observed in TEXTOR discharges in which the magnetic topology was strongly perturbed by the simultaneous occurrence of large $2/1$ and $1/1$ islands. The magnetic perturbations are largest at the main islands' X points, which could explain the modulation in level and frequency of high-frequency turbulent fluctuations by the proximity to X points. The next step, and part of the near future research program, is to try to map the characteristics of the structures with m numbers in detail by the use of a number of recently installed high-resolution diagnostics, including a 2D ECE imaging system and a microwave imaging reflectometer [11].

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