Island Structure and Rotation after Pellet Injection in FTU

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abstract. Pellet injection with ablation near the q=1 surface triggers the fast growth of an island with dominant m=1 poloidal number. As the island reaches a large amplitude, magnetic reconnection mixes the plasma center with the q=1 pellet fuelled region, so enhancing the effective pellet deposition depth. Long-lived m=1 island show higher harmonics (m/n=1 with m>1) near the q=1 surface. Progressive phase shift observed in the phases is attributed to island deformation by sheared viscous flow. Coupling between m=1 and m=2 islands is observed. Reconnection at the q=2 surface is driven by a toroidal sideband of the m=1 island; coupling provokes strong braking of both islands.

1. Introduction

Understanding the mechanisms behind rotation of nonlinear magnetic islands is one of the key issues in the study of internal kink and neoclassical tearing mode stability. Saturated large islands are commonly observed in FTU near the q=1 and q=2 magnetic surfaces. The injection of frozen deuterium pellets has a strong influence on island dynamics. The phenomenology observed in the pellet injection experiments is compared with models of island evolution. The fast growth of an m=1 island will be shown to be the leading mechanism that takes the density to the plasma center when pellet deposition is off-axis. Pellet injection provokes an initial acceleration of island rotation, which is followed by a phase of slow or inverted (in the ion drift direction) rotation. Islands triggered by pellet injection can give rise to long-lived "snakes"; in this case, due to accumulation of particles at the o-point, the island becomes a bright x-ray emitter, so that its shape can be analyzed in detail. The island structure is asymmetric, possibly due to sheared rotation. The island rotation tends to reach the electron diamagnetic frequency, unless braking via coupling with an m=2 structure occurs. In this case both m=1 and m=2 islands can get locked to the wall.

2. Fast growth of m=1 islands during pellet ablation

According to NGPS ablation code deuterium pellets injected into high current FTU plasmas are completely evaporated at about one third of the minor radius, the foot of the ablation profile being near the location of the q=1 surface.

Pellet ablation there induces the sudden growth of a large island, which gives rise to mixing between the pellet fuelled region and the central region, and then to effective central fuelling (fig. 1). The island is observed as a strong in-out asymmetry of the temperature profile (fig. 2). Temperature profiles are taken by a fast ECE diagnostic every 5 μs for some shots dedicated to pellet penetration studies. The ECE diagnostic is located at 90° toroidal distance from the pellet injection port. Pellets are injected from the low field side and the position of impact on the q=1 surface is magnetically connected with the upright top position at the ECE toroidal location. In consequence, at first the impact region is not intercepted by the (equatorial) ECE line of sight. Following island rotation in the electron diamagnetic direction, the impact region enters the ECE line of sight at the high field side, where a striking temperature depression is observed, whereas temperature at the low field side is nearly unchanged.

Simulations performed by a modified version of the M1TEV code explain the main features of the phenomenon [1]. The model assumes a Kadomtsev like reconnection where the helical

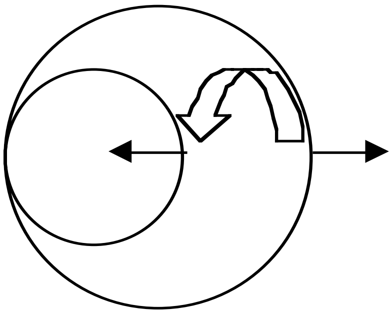

FIG. 1. Schematic diagram of the reconnection process: while the island is enlarging the density is taken from outside to the center.

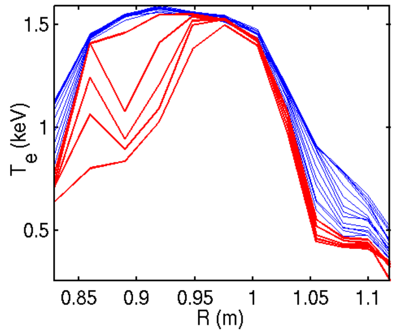

FIG. 2. Temperature profiles taken every 5 µs during pellet ablation. The blue ones correspond to the first 70 µs after the beginning of pellet ablation; the red ones to the following 25 µs.

and the toroidal flux of the reconnected surfaces are conserved. Due to the fast time scale of the phenomenon (~50 µs) perpendicular transport is negligible. Parallel conductivity could be important instead, if magnetic shear is low enough, in fact a cold plasma tube of significant size and lifetime can be formed around the q=1 field line intercepted by the pellet trajectory. This mechanism is likely to be the basis for island formation; at the present it is not included in the code and the island growth and rotation are externally imposed in order to mimic as close as possible the temperature behaviour.

The initial condition assumed in the code is a hollow density profile calculated by ablation code and the temperature profile shown by the solid line in figure 3, which is the profile measured just before the pellet reaches the q=1 surface. Density and temperature evolution are calculated by the code assuming that energy and particles content in the reconnected flux surfaces are conserved. Temperature profiles calculated after 25 µs are shown in fig. 3 together with corresponding experimental data. The main result is that temperature asymmetry is reproduced by an island that grows in 25 µs and rotates at 10 kHz (fig. 3). In addition to producing asymmetric temperature profiles the island growth takes density from the ablation fuelled region to the plasma center (fig. 4).

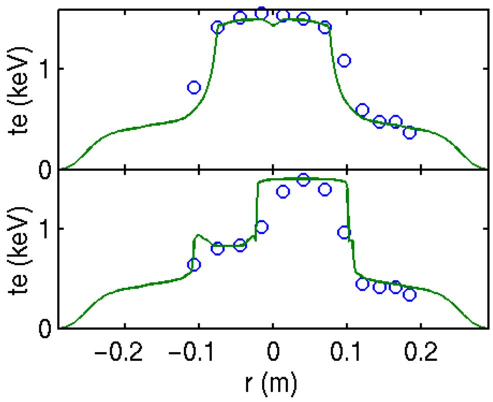

FIG. 3. Temperature profiles when the pellet reaches the q=1 surface (a) and 25 µs later (b). Circles are experimental data, the continuous line is the code output

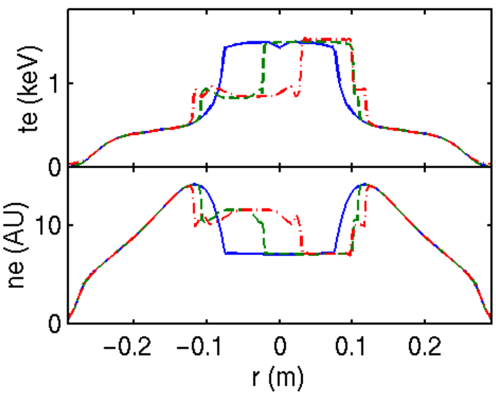

FIG. 4. Temperature (a) and density (b) evolution during the reconnection process. The profiles are taken at 0 (solid), 25 (dashed) and 50 µs (dot dashed) after pellet reaches the q=1 surface

3. Long-lived kinked structures

All the discharge with pellet injection on FTU develop the island described in the previous section, provided that a q=1 surface is present in the plasma.

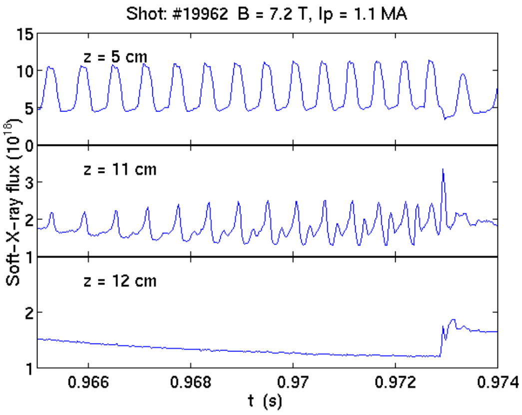

FIG. 5. Soft-X-ray traces showing snake evolution before a sawtooth collapse. The chord at z = 5 cm intercepts the island o-point. The chord at z = 11 cm is nearly tangent to the island separatrix. The chord at z = 12 cm is just outside the separatrix and it shows that the magnetic perturbation has a very sharp boundary.

About one third of these discharges also develop long lived kinked structures (possibly remnants of the pellet triggered island). The lifetime of kinked m=1 structures observed after pellet injection is typically comparable with the density decay time, which in turn can exceeds the plasma current diffusion time (this happens in FTU discharge with plasma current I_p>0.7 MA). This long lifetime is associated with the accumulation of well-confined impurities at the island o-point (the so-called snake phenomenon).

The presence of impurities inside the island allows a fine reconstruction of its structure from soft-X ray emissivity. It turns out that several harmonics (i.e. m/n=1 with m>1 components) are present and that the rotation velocity of these harmonics is sheared, in fact, as shown in fig. 5, the relative phase progressively changes between sawtooth collapses. Soft-X ray emission along chords intercepting the island o-point is nearly sinusoidal and its amplitude is essentially unchanged at sawtooth collapses; in contrast emission along chords nearly tangent to the island separatrix has a rich harmonic content. The magnetic perturbation has a very sharp boundary, in fact no oscillations are detected one centimeter beyond the separatrix, excepting of course heat waves at sawtooth collapses. The sheared rotation of the harmonics could be an indication of island deformation due to effects of sheared viscous flow outside the island that introduces a radial dependence in the island phase.

4. Island rotation

The m=1 island behaviour changes when sawteeth disappear, in particular higher harmonics inside the q=1 radius disappear, while an m=2, n=1 toroidal sideband starts reconnecting at the q=2 surface (fig. 6).

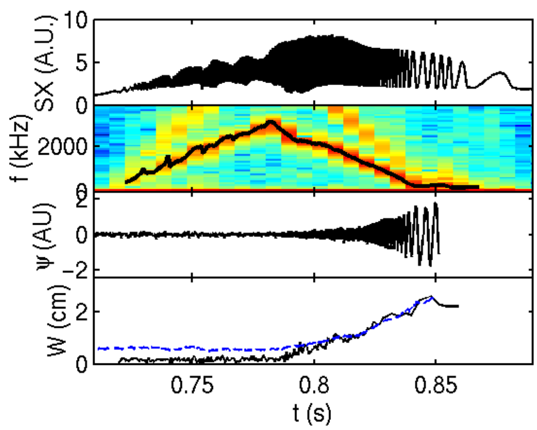

FIG. 6. Shot #18106, a) Soft X ray signal at z = 5 cm. b) m=1 rotation frequency. c) Magnetic signal due to the m=2 island. d) Amplitude of the island from the ECE temperature oscillation (W = δT/grad(T)), and from the magnetic signal; the latter has a baseline due to noise.

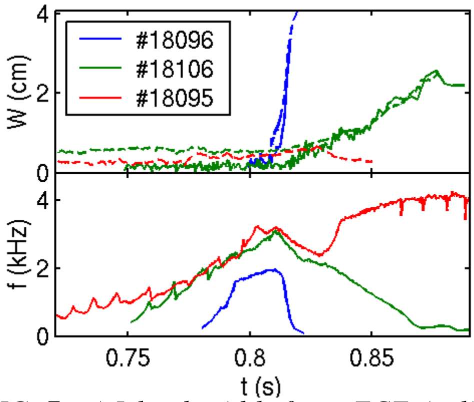

FIG. 7. a) Island width from ECE (solid lines) and from magnetics (dashed lines). b) Frequency evolution. Times are shifted to align the m=2 mode onset.

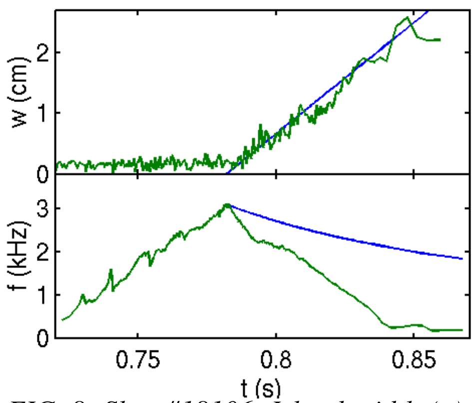

FIG. 8. Shot #18106. Island width (a) and rotation frequency (b). Green lines represent experimental data; the blue lines in (a) and (b) are a fit and the inertial effect calculation respectively.

In the following we compare three discharges (#18095, #18096 and #18106) showing different behaviour (fig. 7). Discharges #18095 and #18096 have a magnetic field of 5.5T and a plasma current of 750 kA (q_{edge}=3.7), while discharge #18106 is a 7 T, 800kA one with q_{edge} = 4.3. All the discharges have a strong m=1 oscillation that couples with an m=2 island. In discharge #18095 the sawtooth activity is transiently stabilized by ECRH near the q=1 radius; a small m=2 appears and rotation frequency decreases. The m=2 mode subsequently disappears and frequency increases towards its "natural" value. On the contrary in discharge #18096 the m=2 mode grows very fast and provokes locking to the wall in less then 10 ms. Discharge #18106 has a behaviour intermediate between the two previous ones, in fact it begins like #18095, but afterwards the two modes remain locked and stop rotating in 60 ms. The island width increases linearly, and the frequency decreases almost linearly. The central m=1 displacement is nearly constant (about 4 cm) for all the three discharges. The rotation frequency of the m=2 mode is the same as that of the m=1 mode, at least at the times when the m=2 mode is visible beyond the noise in the ECE and magnetic diagnostics.

The island width evolution obtained from the magnetic signal at the edge is in very good agreement with the one obtained from the ECE temperature profiles.

The m=2, n=1 toroidal sideband of the m=1 island can drive reconnection at the q=2 surface. A large m=2 island can be formed there if the toroidal drive beats the differential rotation. This condition can be expressed as [2] $\xi_{cm} > 0.34(\omega_{*2} - \omega_{*1})$, where ξ is the m=1 displacement and $\omega_{*1,2}$ are the diamagnetic frequencies at the resonant q=1 and q=2 surfaces. For ξ ≈ 4 cm strong m=2 reconnection occurs below a difference in rotation frequency of about 2 kHz. The island amplitude with strong toroidal coupling at steady state is $W_{cm}^{max} \approx 1.6\sqrt{\xi_1}$; with $\xi_1 \approx 4$ cm $W^{max} \approx 3.2$ cm. The maximum island width that is observed in discharge #18106 is in reasonable agreement with this estimate.

During the m=2 island growth the m=1 amplitude is almost constant and both islands rotate at nearly the same frequency, therefore we model the island frequency evolution by [3,4]:

$$\left(I_\varphi^{(2)} + I_\varphi^{(1)}\right)\frac{d\omega}{dt} = -W_2^4 h_2^2 f_I(\omega) - \omega\frac{d(I_\varphi^{(1)} + I_\varphi^{(2)})}{dt} - I_\varphi^{(1)}\frac{1}{\tau_{t1}}(\omega - \omega_{*1}) - I_\varphi^{(2)}\frac{1}{\tau_{t2}}(\omega - \omega_{*2})$$

where the first term on right hand side arises from the wall braking torque, the second term represents the inertial ("ballerina") effect, and last terms are due to viscous torque. W_2 is the m=2 island width, $I_{\varphi}^{(1,2)}$ represents the inertial momenta of the two islands, τ_t are the viscous drag times, $f_I(\omega)$ is the wall drag term:

$$f_I(\omega) = \frac{4\pi^2 R_0 m}{\mu_0}\left(\frac{r_s}{d}\right)^{2m} \frac{\omega\tau_{wall}}{1+(\omega\tau_{wall})^2}$$

where r_s is the resonant radius, and h_2 is a factor connecting the perturbed flux ψ at the resonant surface with the island dimension:

$$\psi_2 = h_2 W_2^2 \quad h_2 = \frac{B_0 s}{16 R_0 q}$$

where s is magnetic shear. At first the m=2 island is small while its growth rate is finite; at this stage the inertial term should give the stronger contribution to rotation slowing down. In order to evaluate the inertial effect we calculated the frequency evolution neglecting wall braking and viscous drag. This is a very rough assumption, at least because the m=1 mode frequency was increasing before the m=2 mode onset; this means that viscous drag is not really negligible. The evolution equation takes the very simple form:

$$\frac{d\omega}{dt} \cong -\omega \frac{1}{(a+W_2)}\frac{dW_2}{dt} \qquad \text{that is solved by} \qquad \omega \cong \omega_0 \frac{a}{a+W_2}.$$

Here $a = W_2\, I_{\varphi}^{(1)} / I_{\varphi}^{(2)}$; if we evaluate the inertial momenta including only the island volumes, i.e. $I_{\varphi}^{(1)} = 2\pi^2 R_0^3 \rho_1 (2 r_{s(1)} \xi_1 - \xi_1^2)$ and $I_{\varphi}^{(2)} = 8\pi R_0^3 \rho_2 r_{s(2)} W_2$ (ρ being plasma mass density), we find that the inertial effect does not reproduce the experimental slowing down (see fig. 8). This indicates that the plasma region contributing to the inertial momentum is larger than m=2 island.

5. Conclusions

Enhanced central fuelling during pellet injection on FTU can be explained by a growing island that takes density from the off axis pellet ablation region towards the plasma center. A model that takes into account density and temperature evolution during magnetic reconnection reproduces very well experimentally observed helical temperature perturbations. Long lived internal kink perturbation are identified as magnetic island with dominant m=1 number. The island shape shows asymmetries that are likely to be due to sheared rotation.
Coupling between the m=1 island and a co-rotating m=2 island located at the q=2 surface has been observed. Strong slowing down associated with m=2 island growth indicates that the effective inertial momentum is larger than that of the plasma encircled by the island.

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