*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-2.054 (2002)*

Fast Reconnection and Saturated m=1 Modes in FTU Tokamak

P. Buratti, E.Giovannozzi, L. Panaccione, O. Tudisco

EURATOM-ENEA Association, C.R. Frascati, CP 65, 00044 Frascati, Italy

1. Introduction

The dynamics of kinked structures with dominant m=1 mode component (m=1 modes hereafter) is a long-debated problem in tokamak plasma physics, the main questions being the trigger of fast sawtooth collapses, the saturation mechanism underlying partial reconnection and mode rotation dynamics.

2. m=1 modes and sawtooth precursors

Sawtooth precursors are usually identified as oscillations due to growing and rotating m=1 modes. Careful analysis of FTU data shows that mode rotation is not an essential feature of the precursor, in fact a purely growing m=1 precursor can be identified in apparently precursorless collapses, provided that adequate resolution is used (fig. 1). The precursor growth rate is in close agreement with the linear growth rate in the semicollisional regime $\gamma_\rho = (2/\pi)^{2/7} (\rho_s /r_1)^{4/7} (\delta_\eta/r_1)^{3/7} \omega_A$, where ρ_s, δ_η, r_1 and ω_A are the ion sound Larmor radius, the resistive layer width, the q=1 radius and the shear-Alfvén frequency respectively.

The semicollisional regime is characterized by the ordering $\rho_s > \delta_\eta > d_e$, where d_e is the collisionless skin depth. During the precursor phase the hot core displacement ξ is in the early non-linear regime $\rho_s < \xi << r_1$; continued exponential growth at the linear rate is expected in this regime due to electron pressure effects [1]. Rotating precursors also grow exponentially, but their growth rate is typically smaller by an order of magnitude (fig. 2); this can be understood as reconnection slowing-down by diamagnetic rotation.

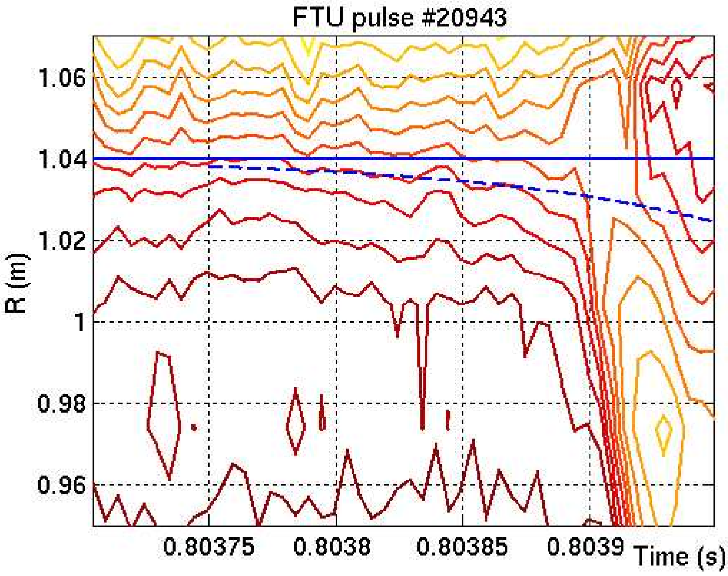

Fig. 1. Temperature contours evolution at the sawtooth crash. A growing displacement is evident before the fast collapse phase. The dashed line represents an exponentially growing displacement at the linear growth rate, the e-folding time being 97 µs.

Both purely growing and rotating precursors are followed by very fast collapses, in which the displacement speed reaches a significant fraction (up to 20%) of the shear-Alfvén velocity r_1/ω_A.

The observation of precursors growing at the linear growth rate helps to elucidate the relationship between m=1 instability and sawtooth trigger mechanism. In these cases, it is clear that the precursor is the early non-linear stage of the instability (the linear stage being buried in noise). In the fast collapse phase, the growth rate increases by an order of magnitude within half a growth time [2], while the spatial structure is still well described by a rigid displacement of the hot core, leaving room to a large m=1 island [2]. The fact that temperature inside the shrinking hot core does not change in this phase tends to exclude the occurrence of secondary instabilities, and points to a dramatic increase of the reconnection rate. During the precursor phase the resistive layer shrinks as $\eta/(\mu_0 d\xi/dt)$ and consequently the δ_η/d_e ratio drops from 4 to 0.6; this suggests that the fast collapse phase is triggered by a non-linear transition from the semicollisional regime to the collisionless one, where super-exponential growth is expected [3, 4].

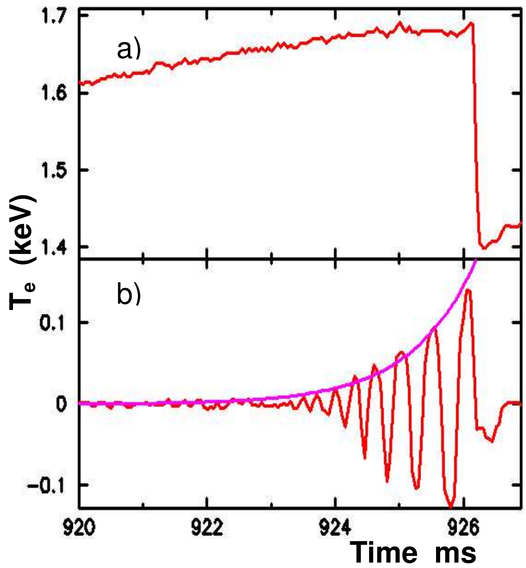

Fig. 2. Sawtooth crash with oscillating precursor (pulse #21802). a) central T_e. b) T_e oscillations near the inversion radius, and exponential with 1 ms e-folding time.

3. Partial reconnection and islands lifetime

The observation of post-cursor oscillations left by sawtooth collapses is a clear evidence of partial reconnection. In FTU discharges with high plasma current one or two partial reconnection events are typically observed interleaving full collapses. Each partial reconnection closely resembles a fast, full collapse, the only difference being that the displacement saturates at some intermediate amplitude. After fast growth, the island decays on a longer time-scale, as shown in fig. 3. Saturation amplitude tends to increase with time elapsed from the previous full collapse, i.e. with the accumulated magnetic energy. The saturation mechanism is not known at present; the presence of a second q=1 surface inside the inversion radius would explain the results, but q-profile measurements on other tokamaks tend to exclude this possibility.

The island lifetime becomes very long if metallic impurities accumulate around the o-point and cause a helical temperature depression by radiation. This may occur either spontaneously if the onset of sawteeth is delayed, or in consequence of deuterium pellet injection (the latter is the so-called snake phenomenon). In these cases the island can survive across sawtooth crashes, and its lifetime can exceed the global resistive diffusion time. This robust island stability can be explained by the helical temperature depression, which plays the same role of helical bootstrap current perturbation in neoclassical tearing modes.

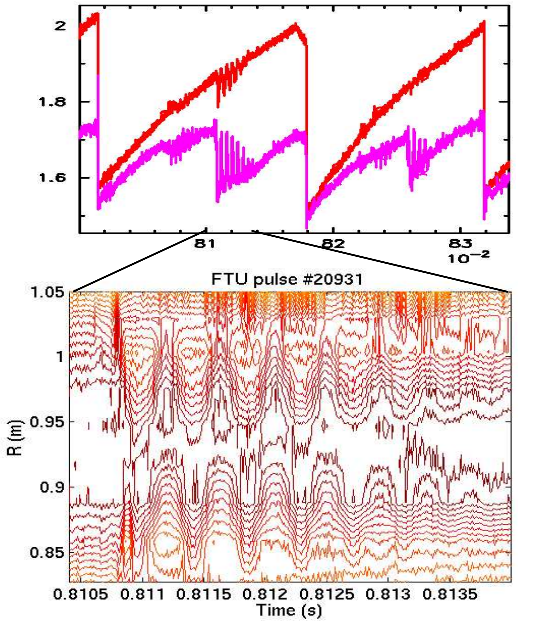

Fig. 3. Sawtooth cycles interleaved by small and large partial reconnection events. Lower frame: temperature contours showing that the displacement suddenly grows just before t=0.811.

4. m=1 mode rotation

The rotation of m=1 modes generally agrees in sign and magnitude with the electron diamagnetic velocity [5]. When a long-lived m=1 mode coexists with sawteeth, its amplitude is nearly unperturbed by sawtooth crashes (fig. 4); there is evidence of the development of higher harmonics, up to m=4, n=4, but the mode is well confined inside the sawtooth inversion radius.

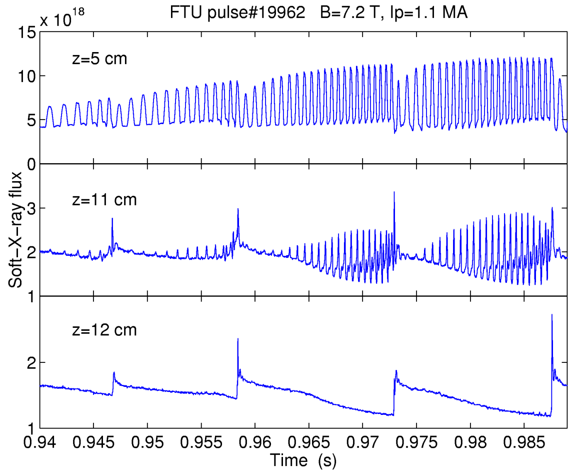

Fig. 4. Time traces showing nearly constant amplitude at z=5 cm, rich harmonic content at the inversion radius (z=11 cm) and no oscillations just outside (z=12 cm).

If sawtooth activity disappears, the mode domain broadens and an m=2, n=1 mode appears at the q=2 surface (fig. 5); rotation slows down and locking of both modes can take place. In this case the natural diamagnetic rotation is counteracted by the combined effect of toroidal mode coupling and wall braking [6].

Another significant rotation modification is observed after pellet injection with significant deposition inside the q=1 radius; in this case the mode transiently rotates in the ion direction. Rotation in the electron direction is subsequently restored on the re-heating time-scale (fig. 6) The origin of the torque that inverts mode rotation is not known at present. Linear theory predicts the existence of a branch that rotates in the ion direction when the ion temperature exceeds the electron one [7], but the frequencies of this branch are well below the observed ones.

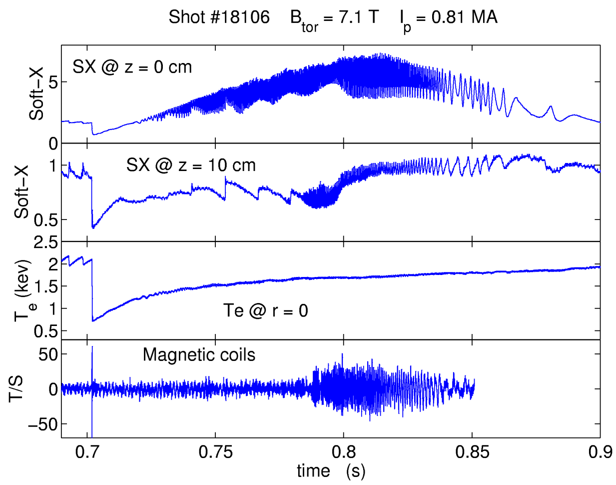

Fig. 5. X-ray traces showing that sawteeth stop and m=1 mode broadens at t=0.78. Magnetic coils show the m=2 mode development.

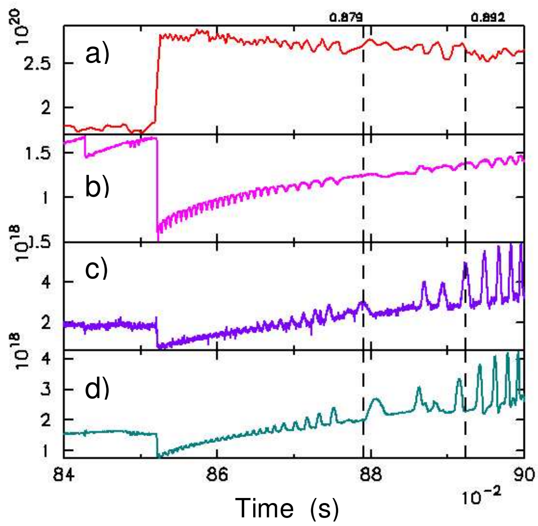

Fig. 6. a) Density; b) temperature; c), d) soft-x-ray emission along two lines at 90°, showing phase lag inversion. Pulse #20955.

5. Summary

Sawtooth precursors have been identified that grow at the semicollisional linear growth rate. The trigger for subsequent very fast collapse is likely to be a non-linear transition from collisional to collisionless reconnection. Large, long-lived m=1 islands have been observed. There is evidence that such islands are driven by a helical resistivity perturbation that plays the same role of bootstrap current perturbation in neoclassical tearing modes.

References

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