MHD STUDIES IN FTU PLASMAS WITH LOW AND NEGATIVE MAGNETIC SHEAR

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Abstract

Fast current ramps with central ECRH and pellet injection in ohmic plasmas allowed to study several kinds of MHD instabilities in plasmas with peaked pressure profile and low or negative magnetic shear. Double tearing modes were systematically observed when the minimum q value crossed the $q_{min}=2$ value; such modes either ended into full core reconnection, or saturated at a large amplitude, with a displacement involving more than one third of the plasma radius. Macroscopic fluctuations clamp the peak temperature during central ECRH; the cause of such fluctuations is attributed to MHD modes that are excited when q_{min} is close to a low order rational value; gaps in the distribution of such values can explain the effective transport barriers observed near integer q_{min} values. When $q_{min}\approx1$ either sawteeth or saturated internal kink modes are observed.

1. INTRODUCTION

Plasma configurations with extremely peaked pressure profile and negative or low magnetic shear in the plasma core are obtained in the FTU tokamak by 140 GHz ECRH during fast current ramps [1, 2] or by deep deuterium pellet injection in ohmic discharges [3]. In both cases the MHD behavior is a relevant issue as it affects the core confinement properties; this is not surprising, since the low magnetic shear ($s=rq'/q$) reduces the line bending stabilizing effect, and the local poloidal beta reaches values $\beta_P>3$.

Current ramps are particularly interesting as the minimum q value (q_{min}) slowly decreases from $q_{min}>3$ to $q_{min}=1$. The main aspects of MHD activity in such conditions can be seen in Fig. 1. The major feature is a wide scale profile rearrangement associated to a double tearing mode at $q_{min}\approx2$ (see Section 2). Besides this well identified event, erratic T_e fluctuations with 2÷5% amplitude are present during most of the ECRH pulse; the possible connection between these fluctuations and MHD activity will be discussed in Section 3. At t=140 ms, i.e. 10 ms before the onset of sawtooth relaxations, saturated m=1 oscillations set in. Such oscillations are not localized at the sawtooth inversion radius, on the contrary all the plasma within that radius is affected by a nearly uniform displacement. A similar mode is also observed after pellet injection; in this case, either the mode precurs the sawtooth crash, or it survives for a long time at a large, saturated amplitude (Section 4).

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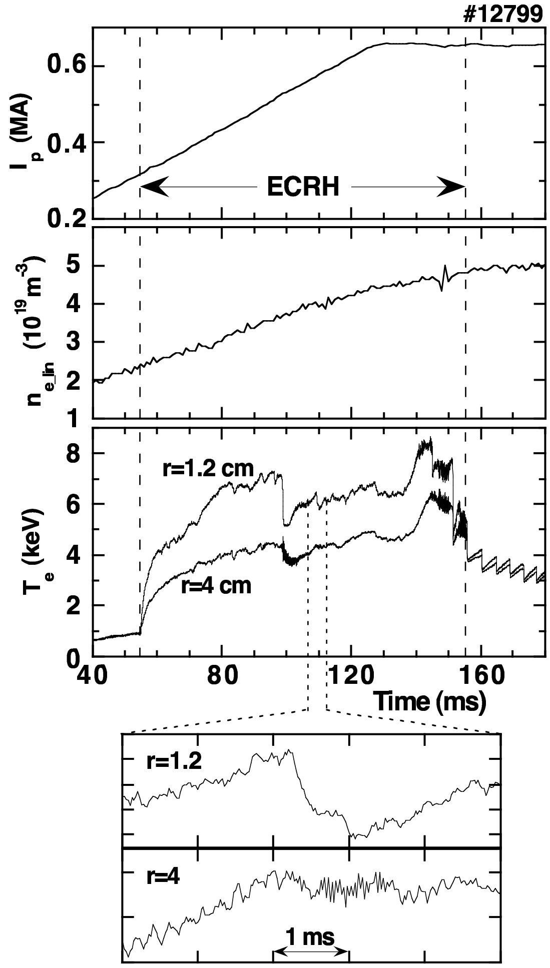

FIG. 1. Fast current ramp time traces, pulse #12799, 360 kW ECRH: plasma current (I_p), central line averaged density ($n_{e\ lin}$), electron temperature (T_e) from ECE polychromator at r=1.2 cm and r=4 cm. The expanded trace at r=4 cm shows that macroscopic fluctuations of the central temperature are correlated with MHD rapid oscillations (see Sect. 3).

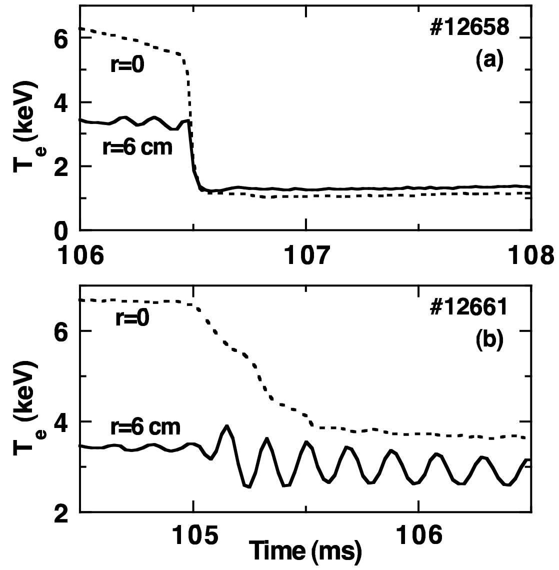

FIG. 2. T_e evolution during double tearing modes: (a) core crash; (b) saturated mode.

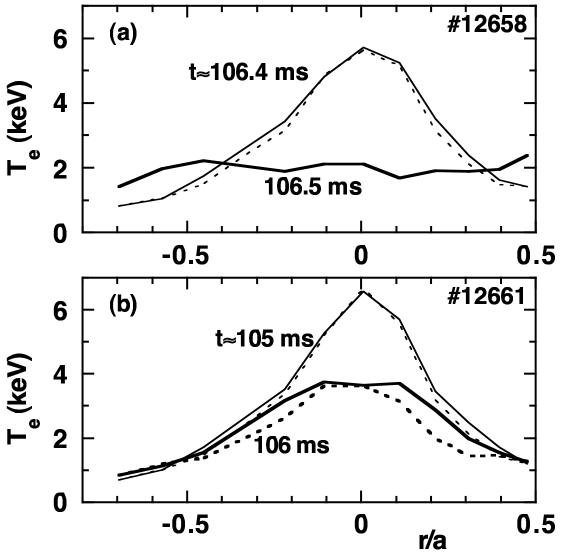

FIG. 3. T_e profiles during the precursor (thin lines) and after the mode growth (thick lines).

2. DOUBLE TEARING MODES AT $q_{min}\approx 2$

The evolution of m/n=2/1 double tearing modes during current ramps with ECRH features a clear branching: a precursor oscillation, lasting for 0.5 ms, is followed by a sudden growth acceleration, leading either to full reconnection in less than 25 μs, or to a large saturated oscillation that reduces the central temperature but leaves a peaked profile (Figg. 2, 3). The structure of precursor and saturated oscillations is a displacement with even parity, which affects more than one third on the plasma radius; in the example shown in Fig. 2b, the displacement increases from 7 mm in the precursor phase to a maximum value of 27 mm in the saturated one (Fig. 3b). The fast time scale and the global nature of the perturbation imply that the mode must be ideally unstable, or at least marginally stable [4]. The full reconnection case is similar to a sawtooth crash (apart from the wider radial extent), while the saturated oscillation resembles the so called subordinate sawtooth relaxation, with the remarkable exception that the mode structure is m/n=2/1 (the mode numbers can be unambiguously identified as the large oscillation is detected by the Mirnov coils).

3. MACROSCOPIC TEMPERATURE FLUCTUATIONS

The erratic T_e fluctuations observed during central ECRH play a role in heat transport, in fact, as the temperature evolution reverts from fluctuating to monotonically increasing at $q_{min}\approx 1$ (t=135 ms in Fig. 1, i.e. 5 ms before the onset of sawteeth), the thermal energy in the plasma core increases at a rate amounting to 60÷70% of the local heating power. This indicates that an effective transport barrier sets in when the fluctuations are suppressed. Profile evolution shows that the barrier extends throughout the plasma core (Fig. 4). Time dependent transport analysis gives a factor two reduction of the heat diffusivity during the temperature rise.

The existence of a pause of fluctuations at $q_{min}\approx 1$ points to a causal role played by MHD modes excited at $q_{min}=m/n$ resonances with relatively low m, n, in fact the distribution of such resonances features gaps around integer q values; as an example, the distribution of resonances with $n\leq 9$ is shown in Fig. 5. As the poloidal magnetic field increases in the central region on the resistive diffusion time scale, the resonances diagram is scanned leftwards, and gaps and resonances sequentially enter the plasma (the wider the gap, the stronger the resonance); when q_{min} is close to a resonance, a small temperature drop occurs, while, if q_{min} is in a gap, the peak temperature rises since the modes are effective only if they resonate in the zero shear region. This view is enforced by the observation that a transient temperature rise is also observed at $q_{min}\approx 2$ when the 2/1 double tearing mode is weak [5]. Furthermore, in some cases, MHD oscillations are directly observed in conjunction with temperature drops (Fig. 1). The concept of effective transport barriers associated with the larger gaps around integer q values is only valid in the shearless region, since, with monotonic q, modes with m>3 are not likely to affect transport.

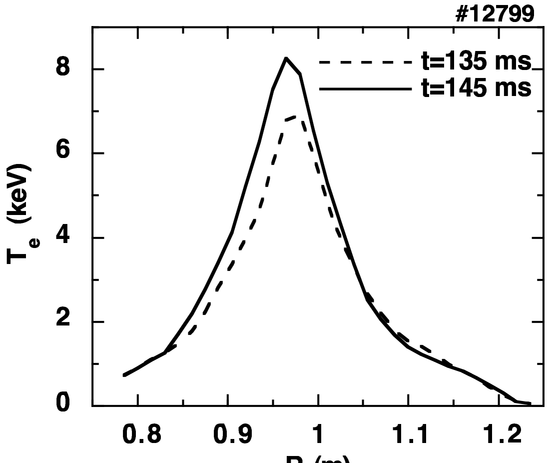

FIG. 4. Profile variation during the temperature rise at $q_{min}\approx 1$. The time traces at R=.954 (r=1.2 cm) and R=.926 (r=4 cm) are shown in Fig. 1.

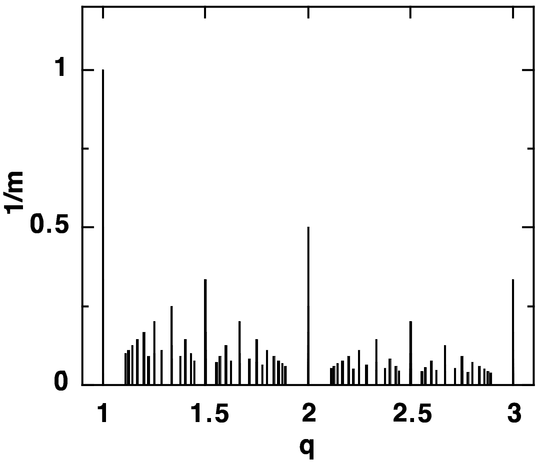

FIG. 5. Rational $q=m/n$ values with $n\leq 9$. The bar height is 1/m in order to highlight the resonances with smaller line-bending effect.

4. THE INTERNAL KINK MODE

The spatial structure of m/n=1/1 oscillations is a global displacement of the plasma core (Fig. 6). The displacement is nearly constant across 30% of the minor radius in discharges with pellet injection (25% in the ECRH case); its amplitude can overcome 10% of the minor radius. In spite of the large displacement, the profile peaking is not reduced; this indicates that no reconnection occurs. This observation, together with the one on spatial structure, leads us to identify the origin of the oscillations as a saturated internal kink mode. Such a mode can exist if the q profile has an off-axis minimum slightly above one [6,7]. The saturated m=1 mode is very similar to the sawtooth precursor (Figg. 7, 8); we conjecture that the sawtooth crash occurs if the $q_{min}=1$ condition is fulfilled, as in this case fast reconnection becomes possible, and then the line-bending saturation mechanism [6] is no longer effective.

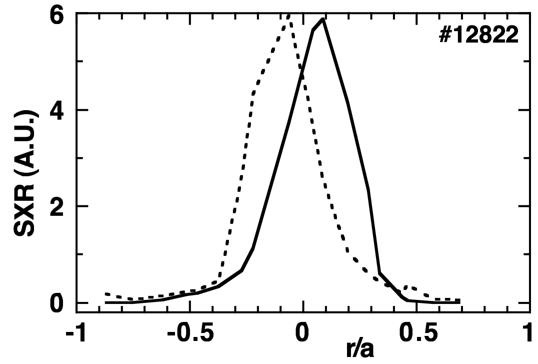

FIG. 6. Oscillation of the soft x-ray brightness profile during the saturated m=1 mode in pulse #12822. Dashed line: t=.81135; solid line: t=.81165.

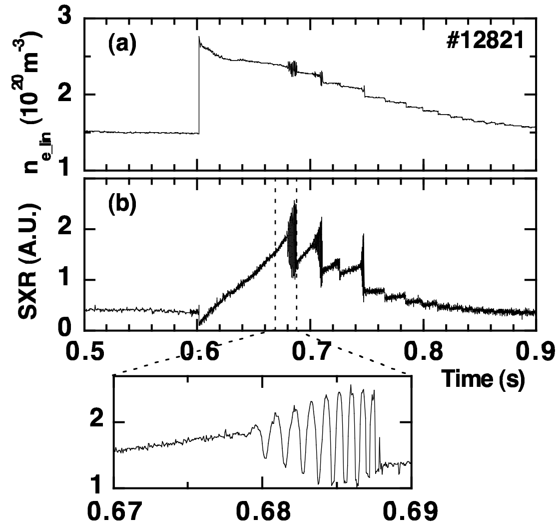

FIG. 7. Pellet injection followed by sawteeth. (a) line average density; (b) soft x-ray flux 5 cm above the midplane.

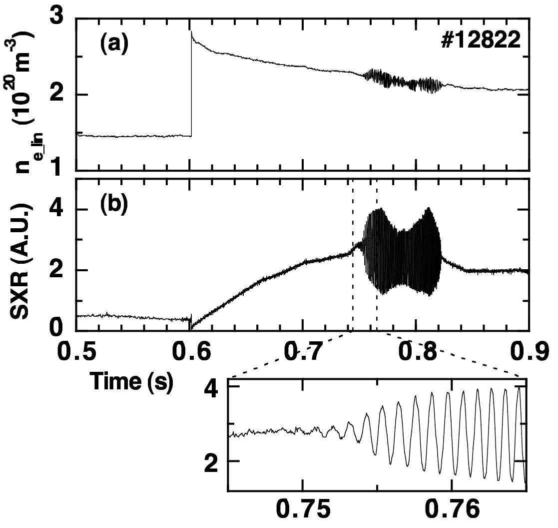

FIG. 8. Pellet injection) followed by a long-lived m=1 mode. (a) line average density; (b) soft x-ray flux 5 cm above the midplane.

5. CONCLUSIONS

Saturated MHD modes featuring a global plasma core displacement have been observed at $q_{min}=2$ and $q_{min}=1$; such modes can either lead to wide-scale reconnection or survive for a long time. The peak temperature during central ECRH is clamped by macroscopic fluctuations, and rises when q_{min} is close to an integer value. The fluctuations can be caused by modes excited at low order rational q_{min} values.

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