INTERNAL MHD MODES IN FTU PLASMAS WITH HIGH CORE CONFINEMENT

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1. Introduction

Internal electron transport barriers have been found in plasmas with negative or low magnetic shear either near the minimum q radius [1], or close to integer and half-integer q values [2]. In this paper we present results on the formation of effective transport barriers in ECRH and pellet injection experiments on the FTU tokamak.

2. ECRH experiments

The application of central Electron Cyclotron Resonance Heating (ECRH) at 350 kW during current ramp-up transiently produces magnetic shear reversal [3]. The electron . temperature (T_e) rises from 1 to 8 keV in 20÷25 ms, while the discharge remains sawtooth free for measurements reveal that the plasma core is affected by macroscopic fluctuations. Fig 1 shows two examples in which all the relevant features can be identified. In both discharges the plasma current is ramped from 0 to 700 kA and the central magnetic field is B =5 T (the heating frequency being 140 GHz).

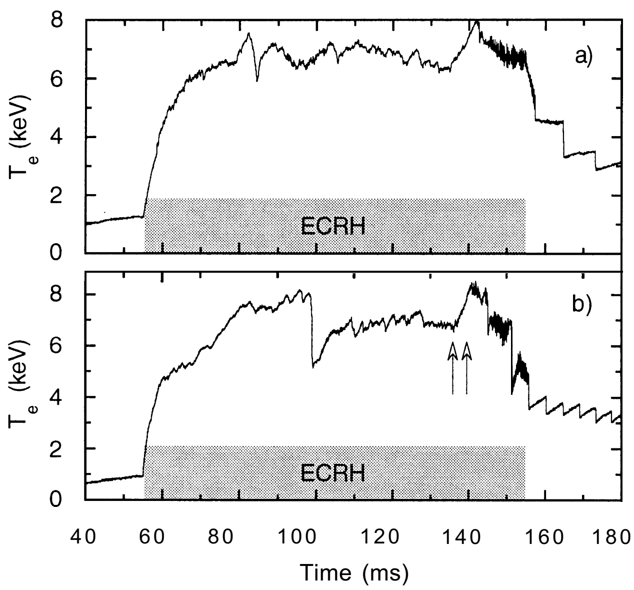

Fig. 1. Time traces of $T_e(0)$ for FTU pulses: a) #12608 with P_{ECRH} = 293 kW and b) #I2799 with P_{ECRH} =360 kW. The arrows mark the times for the profiles shown in Fig. 2.

Erratic T_e fluctuations with 5÷10% amplitude are present during most of the ECRH pulse. At t ≈ 135 ms (a short time before the appearance of m=l sawtooth precursors, i.e. when the minimum q value q_{min}≈1), the temperature evolution reverts from fluctuating to monotonically increasing, and consequently the thermal energy in the plasma core increases at a rate amounting to 60+70% of the local heating power. This indicates that the mechanism underlying T_e fluctuations plays a role in heat transport, and an effective transport barrier sets in when these fluctuations are suppressed. Profile evolution shows that the barrier extends throughout the plasma core (Fig. 2). Transport analysis performed with moderate time resolution (10 ms) gives low values of the electron thermal diffusivity (χ_e ≈0.2+0.3 m^2/s, comparable with typical ohmic values) in the presence of fluctuations, and a reduction by a factor 2 during the temperature rise.

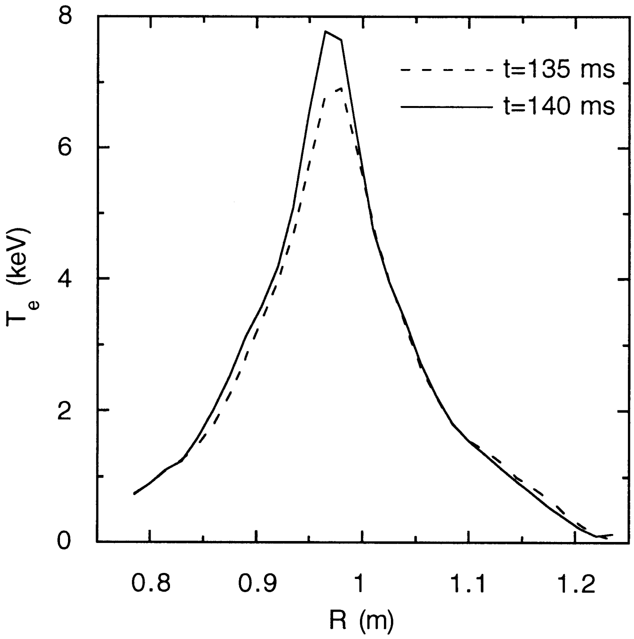

Fig. 2. Temperature profiles before and during the T_e rise at q_{min} ≈1 for FTU pulse #12799.

The discharges shown in Fig. 1 are differentiated by the behavior at q_{min}=2: Fig. la shows a temperature rise around 80 ms, followed by a mild drop, as typically occurs when the minimum q is close to the magnetic axis, whereas the sharp drop at t=99 ms that can be seen in Fig. lb is a wide-scale double tearing reconnection [3] that occurs at q_{min}≈2 when the negative shear region is wider. The former case is more interesting, in that it shows a single, well resolved T_e fluctuation. The sequence of events is shown in Fig. 3 for FTU pulse #12660 (similar to #12608

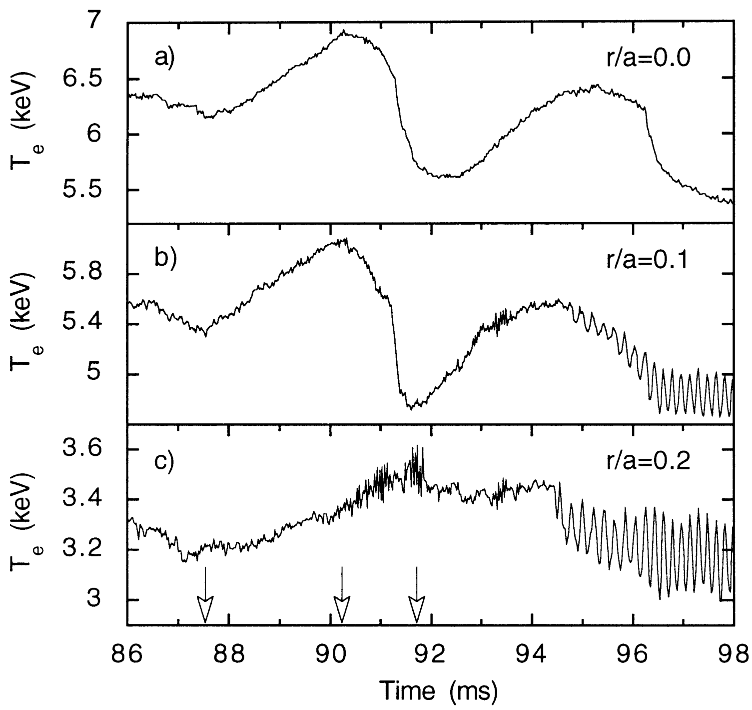

Fig. 3. T_e time traces for FTU pulse #12660. The arrows mark the times for the profiles shown in Fig. 4.

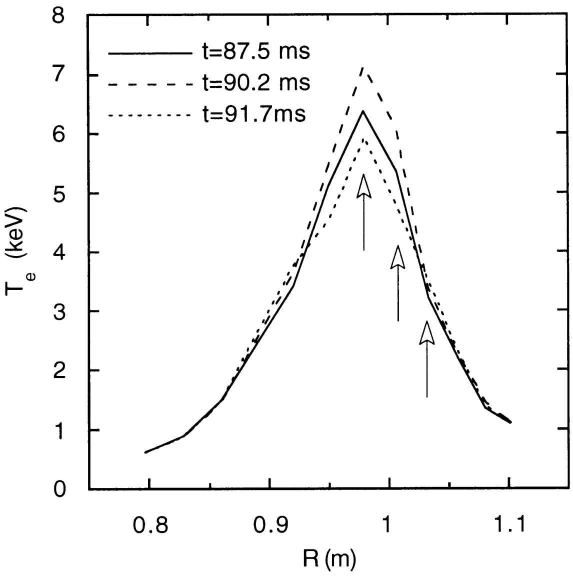

Fig. 4. T_e profiles during the fluctuation at q_{min}=2 in FTU pulse #12660. The arrows mark the positions of the channels shown in Fig. 3.

in this phase, but with full profiles at 40 kHz sampling rate). Two periods of temperature rise, lasting 2+3 ms can be clearly seen after t=88 ms. At the end of the first period, there is a temperature drop associated with the growth of 20 kHz oscillations with even poloidal mode number. The mode is detected at normalized radius r/a=0.2 and the effective transport barrier associated with the temperature rise is localized inside this radius (Fig. 4). Before the end of the second temperature rise, the mode frequency decreases and the plasma region affected by poloidal number can be unambiguously identified as m=2.

3. Pellet injection experiments

The injection of deuterium pellets penetrating inside the sawtooth inversion radius suppresses the sawtooth activity and leaves the plasma MHD-quiescent for at least one confinement time. This allows to study the diffusive heat transport in a wide plasma region of nearly zero magnetic shear. Transport analysis shows that the electron heat transport is virtually suppressed in this region [4, 5]**.**

The MHD-quiescent period is terminated by the growth of an m=l, n=l kink distortion of the plasma core [5]. According to resistive diffusion calculations, the central q rises slightly above the pre-pellet value during the quiescent period, and decreases again before the onset of the m=l mode. This indicates that the suppression of electron heat transport in the post-pellet phase is due to the same effective transport barrier that has been found in ECRH discharges for $q_{min}\approx 1$, but in this case the improved confinement is maintained for more than one confinement time.

4. Discussion

The observation of effective transport barriers associated with pauses in macroscopic fluctuations points to the existence of energy transport due to non-diffusive, intermittent phenomena, that play a role similar to sawteeth, although their period is erratic, and their amplitude is sufficient to clamp the peak temperature, but not to flatten the profile in the central region (so that the thermal diffusivity evaluated in the presence of fluctuations is relatively low). The nature of such intermittent phenomena can be identified when $q_{min}\approx 2$ and $q_{min}\approx 1$: the temperature drops following transient rises are clearly due to the growth of m=2 and m=l tearing modes respectively. The other, smaller fluctuations could be caused by tearing modes with relatively low mode numbers, that grow when the corresponding resonant q enters the plasma, owing to the presence of pairs of q=m/n resonances if the shear is negative [3], or to the large pressure gradient (the local poloidal beta $\beta_p(r)=2\mu_0(<p>-p(r))/B_p(r)^2$ can reach values β_p >3 in the central plasma region). As an example, Fig. 5 shows the distribution of resonant q values with n<l0 (this is roughly the number of temperature excursions that can be distinguished in Fig. 1 when q_{min} decreases from 2 to 1): the gaps about q=l and q=2 could be the reason for the existence of the effective transport barriers observed at q_{min}≈l and q_{min}≈2.

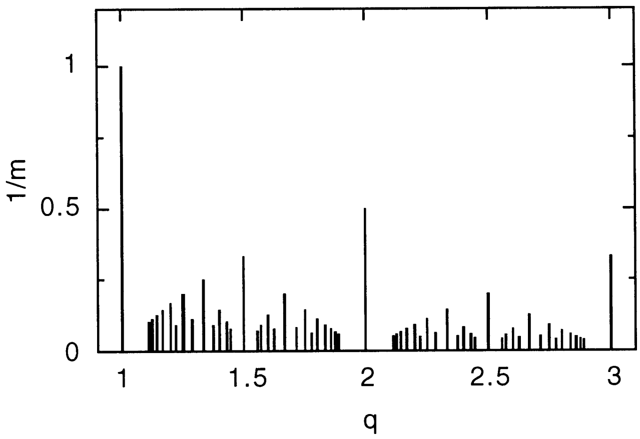

Fig. 5. Rational q=m/n values with n<10. The bar height is l/m in order to highlight the resonances with smaller line-bending effect

Improvements of the electron confinement associated with integer q values observed in other experiments have been attributed to a dramatic reduction of the electron thermal diffusivity [2]. On the other hand, increased transport due to the formation of magnetic islands has also been observed in several experiments with monotonic q profiles. The picture emerging from FTU results bridges the gap between those apparently contradictory observations: for inverted or flat q profiles, the purely diffusive electron heat flux is very low, but the temperature peaking is clamped by the sequential excitation of tearing modes occurring as q_{min} crosses low order rational values, while effective transport barriers appear near integer values. On the other hand, near-integer q values do not play any positive role where the q profile is monotonic and diffusive transport is strongly anomalous, so that only the adverse effect of islands at exactly integer q values is left.

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