TRANSPORT STUDIES DURING ECRH IN MONOTONIC-q AND SHEAR-REVERSED FTU PLASMAS

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1. Introduction

The heating system at the Electron Cyclotron Resonance on FTU tokamak can deliver to the plasma up to 1.6 MW of millimeter-wave power at 140 Ghz in four gaussian beams. Each beam has a waist of 28 mm in vacuum and is steerable both in the toroidal and poloidal directions. Operation at the fundamental resonance, O-mode, with $B_{tor} \approx 5$ T, allows ECRH experiments with a peak electron density up to 2.4×10^{20} m^{-3}. A series of experiments performed with one beam at 0.35 MW is reported, aimed at probing thermal confinement in a variety of configurations by taking advantage of the good localization of ECRH, the radial width of the heated layer being $\delta r = 0.2a$ at worst. In particular, heat transport in steady-state at 350 kA, $q_a = 8$, and in shear-reversed configuration during current ramp-up at 5÷7 MA/s was studied.

2. Steady state (monotonic-q) vs. current ramp-up (shear-reversal)

The most apparent difference between steady-state and current ramp-up at similar current and electron density is the presence in the former of sawteeth, which affect transport in the plasma core. Furthermore, improved confinement conditions may establish during current ramp-up, as the electron temperature increases while the heat source remains constant [2,3].

Steady-state discharges are mostly sawtoothing, even at moderately low current (350 kA) and high q_a values (6÷8). In a few cases, off-axis ECRH quenched sawteeth[1] for enough time to allow the evaluation of transport parameters. $P_{ecrh}= 350$ kW exceeded $P_{oh}=230$ kW in

these cases (Fig.1), and near-central absorption (r_{abs}=0.2 a) determined an ECRH heat flux much larger than OH over a considerable portion of the plasma column (Fig.2) outside the absorption radius, up to r/a≈0.4. According to a time dependent transport analysis, χ_e in this region is as low as 0.5 m^2/s (Fig.3). At centre, ECRH power density is not dominant over ohmic heating and power balance can be affected by large errors. In this case, χ_{e0} can be given

by $\chi_{e,0} \cong \dfrac{3r_1^2 \, \partial \tilde{T}_0 \big/ \partial t}{16T_0}$, r_1 and T_0 being respectively the radius and the peak temperatureof the

sawtoothing ohmic plasma [4]. The value $\chi_{e,0}$=0.2 m^2/s confirms the good core confinement found with transport analysis. The $\Delta T_e(r)$ profile due to ECRH flattens inside r<r_{abs} after the initial heating phase, and no heat pinch is evident (Fig.4). The e-i energy exchange is modest, only ≈10% of the ECRH power being transferred to the ions because of the relatively low density and the large T_e/T_i ratio [5].

During current ramp-up, peaked electron temperature profiles with central values above 8 keV are achieved before the start of sawteeth during on-axis ECRH at n_e≈0.35 10^{20} m^{-3} and I_p≈350 kA, rising at 5÷7 MA/s rate. Transport analysis performed on discharges with on-axis and off-axis ECRH [6] shows that also in this phase the electron thermal diffusivity is ≈0.2 m^2/s at centre and ≈0.4 m^2/s up to r/a≈0.4, as it is observed in sawtooth-free steady-state conditions. The persistence of this low central diffusivity and central localized ECRH determine the formation of peaked temperature profiles (Fig.5), which do not degrade the local confinement properties.

3.Transitions

The central temperature collapse at the start of sawteeth when the minimum q≈1 sets in is clearly seen in Fig.6, showing a discharge with ECRH at 220 kW, lasting for 0.3 s from the early phase of current ramp-up up to almost steady-state. Larger portions of the plasma are progressively interested by the reconnection process, until the inversion radius of a purely ohmic discharge at the same current is reached (Fig.7) and a broad temperature profile is established. In spite of the dramatic fall in local central temperature, partly due to the still increasing electron density, the total energy content appears not much affected by the onset of sawtooth activity, which do not correspond to a real transition in the overall confinement.

A more effective event on heat accumulation appears to occur earlyer than sawteeth in the ramp-up phase. After ≈20 ms from ECRH start, the slope of thermal energy build-up, formerly consistent with the heating power, sharply decreases in coincidence with the appearance of thermal fluctuations also in the plasma core (Fig.8), while sink/source terms continue undisturbed. The change involves maximum gradients of temperature and pressure as well.

4.Discussion

The thermal response of FTU plasmas to localized ECRH heating, in the limit $P_{ecrh}/P_{oh} \leq 1$, is consistent with a diffusive character of heat transfer, with a local electron thermal diffusivity as low as ≈ 0.2 m^2/s at centre and ≈ 0.4 m^2/s up to r/a≈ 0.4 transport, both in monotonic-q and shear-reversed configurations, in spite of the large differences in T_{e0} and $(\nabla T_e)_{max}$.

Sawteeth average the energy distribution in the plasma core and broaden the profiles, but do not necessarily reduce the overall confinement.

Improved confinement is temporarilty observed during current ramp-up, which is degraded when thermal fluctuations appear also in the plasma core.

References
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[2] F.Romanelli, this Conference
[3] P.Buratti et al., this conference
[4] M.Soler, J.D.Callen, Nuc. Fus. 19, 703 (1979)
[5] S.Cirant et al., this Conference
[6] P.Buratti, et al., Plasma Phys. Contr. Fusion 39, B383 (1997).
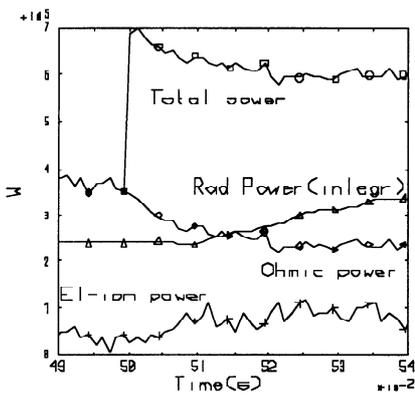
Fig.1 - Power balance during off-axis ECRH (ρ=0.2) in steady-state at I_p =350 kA.
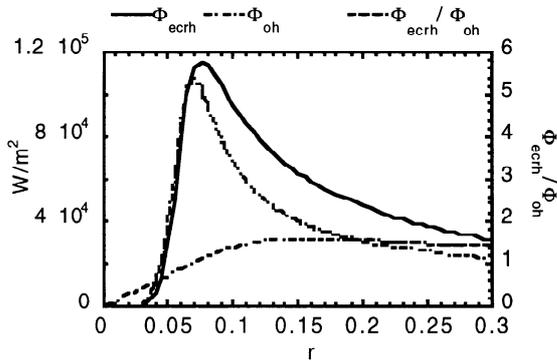

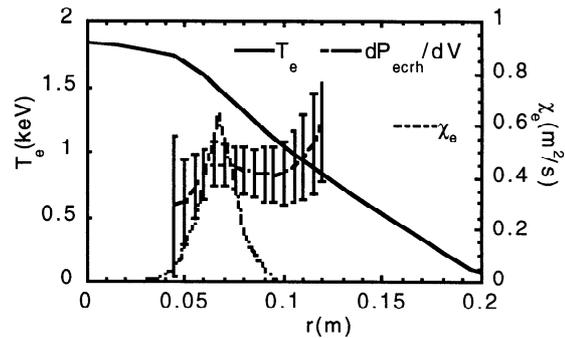Fig.2 - ECRH and OH heat fluxes during off-axis heating (ρ=0.2) in steady-state at I_p =350 kA.

Fig.3 - Electron temperature, ECRH power density and electron thermal diffusivity χ_e. The error bar on χ_e corresponds to 100% error in the estimate of ohmic heating power.
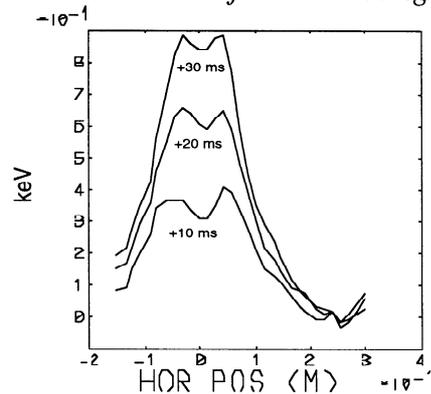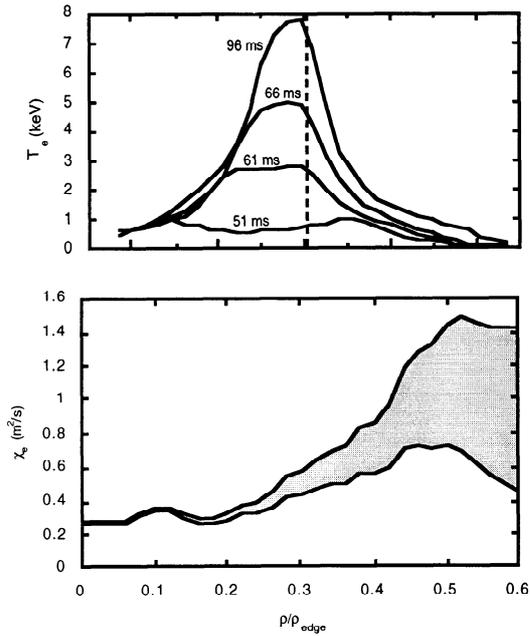

Fig.4 - $\Delta Te(r)$ during off-axis ECRH (ρ=0.2).

Fig.5 - Electron temperature and the diffusivity with ECRH during current re up. $P_{ecrh}=350$ kW, $n_e \approx 0.5\ 10^{20}\ m^{-3}$. error in χ_e is due to errors on ohmic hea and radiation losses.
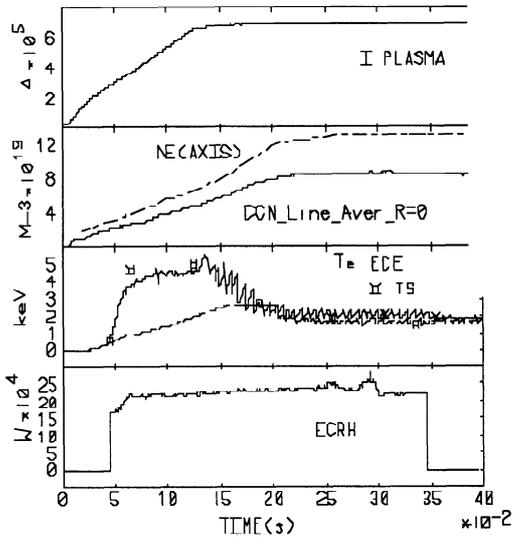

Fig.6 - Plasma current, electron density and temperature with Pecrh=220 kW during current ramp-up. T_e is compared with the one in a similar shot without ECRH.

Sawteeth start earlier with ECRH.

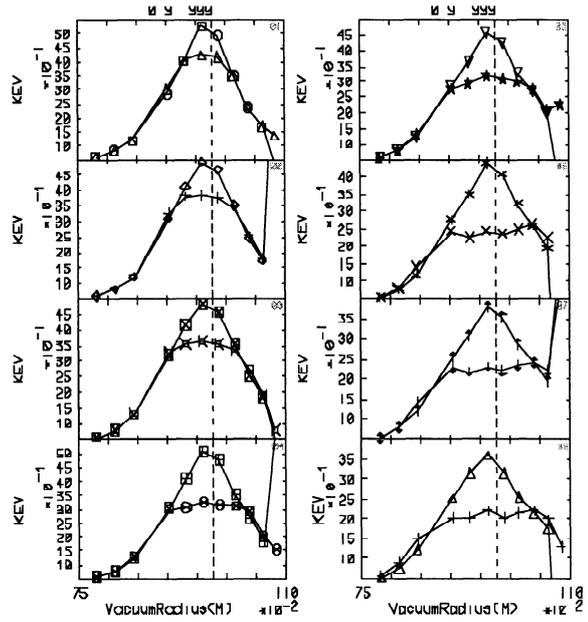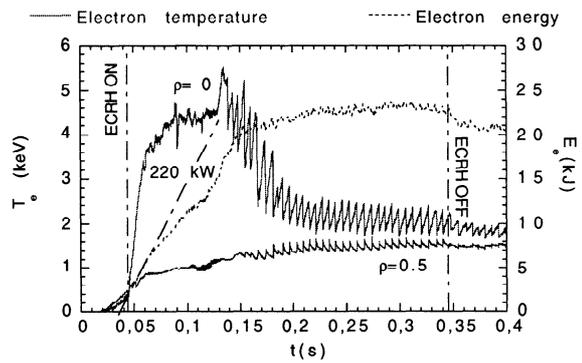Fig.7 - T_e profiles at first sawtooth after the

Fig.8a - T_e at centre and at half-radius, shown together with the electron kinetic energy vs. time.
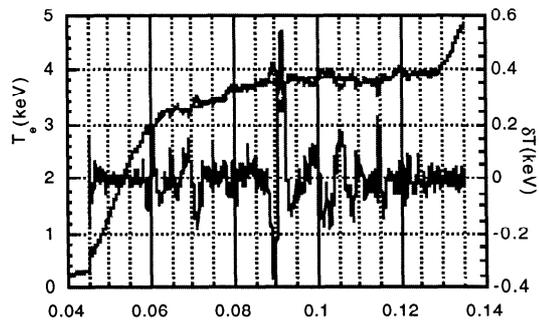

Fig.8b - Effect of fluctuations on the peak temperature, on T_{e0} increase and the energy accumulation rate (Fig.8a).