REDUCED TRANSPORT IN THE CORE OF THE T-10 AND TEXTOR PLASMAS AFTER OFF-AXIS ECRH SWITCH-OFF

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It has been observed in the T-10 tokamak that immediately after off-axis ECRH switch off, the core electron temperature stays constant for some time, which can be as long as several tens of ms, i.e. several energy confinement times before it starts to decrease. Whether or not the effect is observed depends critically on the local magnetic shear in the vicinity of the q=1 rational surface, which should be close to zero. It is assumed that small shear can induce the formation of an internal transport barrier. Measurements of the density fluctuations in the transport barrier with a correlation reflectometer show immediately after the ECRH switch-off a clear reduction of the fluctuation level corroborating the above results. The delayed temperature decrease has also been observed in similar discharges in the TEXTOR tokamak.

Introduction

Shortly after ITB's have been discovered in JT-60U [1], the existence of multiple ITB regions were found in RTP experiments in the vicinity of low order rational q-surfaces [2]. More recently T-10 experiments with ECCD [3] led to the following criterion: the necessary condition for the appearance of zones with reduced transport is a low value of $dq/d\rho$ in the vicinity of rational q-surfaces with low m and n-numbers. A very interesting phenomenon, connected to the above findings has been observed in some T-10 regimes with off-axis ECRH [4]. After the off-axis ECRH switch-off, the core electron temperature, T_e, does not decrease immediately and continuously in time towards the ohmic value. Instead, the core T_e first stays constant during several tens of ms (Fig. 1) before it starts to decrease. Sometimes even a slight increase of the core energy content is observed. The fact that the central electron temperature remains constant for some time after ECRH switch off, while the off-axis temperature decreases at the same time (and hence ∇T_e increases) under the action of constant internal (only OH) power deposition, leads to the conclusion that the transport coefficients must be reduced. The aim of this paper is to investigate the phenomenon of delayed T_e decrease after the off-axis ECRH switch off, and to study whether there is a connection between the heat transport coefficients and the local value of $dq/d\rho$. This research is done at the T-10 and TEXTOR tokamaks, under rather similar discharge conditions.

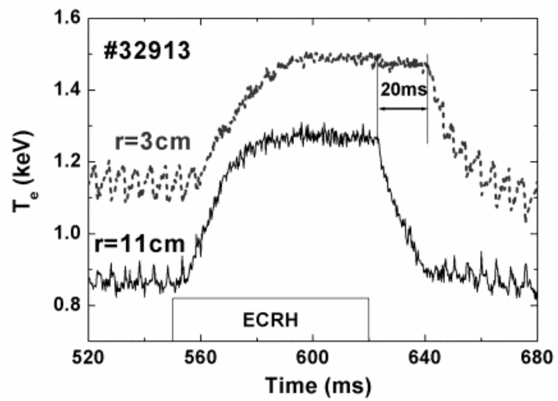

Figure 1: Delayed decrease of the core electron temperature in T-10 after ECRH switch-off at 620 ms; B_t = 2.33 T, I_p = 180 kA, n = 1.5 ×10^{19} m^{-3}, P_{ECRH} = 400 kW;

Experimental set up

For T-10 (R = 1.5 m, a_{lim}= 0.3 m, circular plasma) the basic plasma scenario used in this study had a plasma current I_p = 180 kA and a toroidal magnetic field B_t = 2.33 T. The total power of four ECRH gyrotrons (f = 140 GHz) was varied up to 900 kW. The ECRH power deposition radius, ρ_{ECRH}, was varied by changing B_t. It was observed that the power of only two gyrotrons (P_{ECRH} = 400 kW) is already sufficient for sawtooth stabilization in the given plasma scenario, provided that ρ_{ECRH} is located slightly outside the sawtooth inversion radius, ρ_S. The electron temperature profile, $T_e(\rho)$, was measured by a 25-channel electron cyclotron emission (ECE) diagnostic. The value of Z_{eff} was derived from the absolute intensity of the Bremsstrahlung in the visible region. In shots with sawtooth oscillations a rude estimation of Z_{eff} at $\rho \leq \rho_s$ and for a given B_t, could also be derived from $T_e(0)$, the loop voltage, V_l, and the ρ_S values.

The density fluctuation spectra in T-10 were measured as a function of time by a heterodyne O-mode correlation reflectometer [5]. A radial scan of the reflection layer was obtained from shot to shot, by a small variation of the discharge density within a ±7% range. The signals received by two antennas, poloidally separated by an angle of 5.8º were analysed. The value of the phase fluctuations and the integral coherency of the two signals were processed as described in [5].

Experiments have also been done in the TEXTOR tokamak (R = 1.75 m, a_{lim} = 0.445 m, circular plasma cross-section) in which up to 800 kW of 140 GHz ECRH (≤3 s) was deposited at the high-field side. Changing the magnetic field B_t on a shot-to-shot basis was used to vary the ECRH power deposition radius. The response of the plasma temperature was measured by means of a number of heterodyne ECE systems [6] and SXR cameras (80 channels), each at a time resolution of 100 µs. Like in T-10, the value of Z_{eff} was derived from the absolute intensity of the bremsstrahlung in the visible region, and the Z_{eff} profile could be deduced from the value of the loop voltage, V_l, and that of ρ_S.

The experimental results of both T-10 and TEXTOR were analysed with the ASTRA transport code [7]. The COBRA code [8,9] was used to calculate the ECRH power deposition profile and to model the dynamics of the transport coefficient profiles at the end of the heating pulse. In all model calculations the experimental parameter profiles were used as input.

Experimental results

Fig. 2a shows the heat diffusivity calculations for the experiment presented in Fig. 1. The heat diffusivity χ_e, calculated by ASTRA for the OH case and off-axis ECRH phase is shown by dashed and solid line respectively. The dash-dotted line corresponds to the χ_e calculated by COBRA for the dynamic part of the process (t=20 ms) after the off-axis ECRH switch off. The value of χ_e reduces at all radii (compare with ECRH) and locally (ρ~0.17) it reaches the very low value of 0.1 m^2/s. Analysis of the influence of the accuracy of T_e measurements on the determination of χ_e was carried out in [9]. It was shown that the 20% stochastic errors in T_e lead to 10-15% errors in χ_e.

Estimations of $j(\rho)$ and $q(\rho)$ by ASTRA [8] for OH, end of the ECRH phase and during the existence of the constant temperature after ECRH switch-off are presented in Fig. 2b. The results are consistent with the earlier mentioned ITB formation criterion: soon after ECRH switch-off a zone with low shear appears near q=1 surface.

Let us also compare two T-10 shots with the same initial plasma parameters (B_t=2.33 T, I_p=185 kA, $\bar{n}_e$=1.4×10^{19} m^{-3}), but with different off-axis ECRH input powers: shot #35355 with two gyrotrons and shot #35358 with four gyrotrons (Fig. 3(a)). In the case of two gyrotrons, $T_e(0)$ remains constant during 25 ms after switch-off. In the case of four gyrotrons, $T_e(0)$ immediately decreases after switch-off until it reaches the same value as in the case of off-axis heating with two gyrotrons. Then it remains constant during 15 ms.

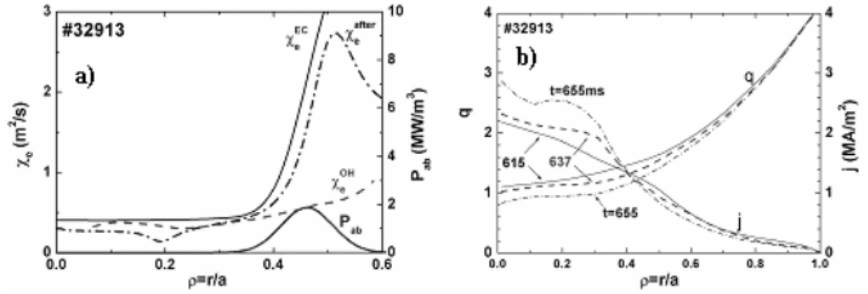

Figure 2: a) Electron heat diffusivity in the OH phase (dash), at the end of ECRH phase (solid) and during the T_e decay phase (dot-dashed). The retrieved ECRH power deposition profile P_{ab} is also shown.
b) The current density and q profiles during the ECRH phase and after ECRH switch off in T-10. One can see that dq/dr ≅ 0 near q = 1.

The results of ASTRA calculations that shots are shown in figures 7b and 7c, where r_s is a position of q=1 surface and dq/dρ is the dimensionless gradient of q at the radius of q = 1.25.

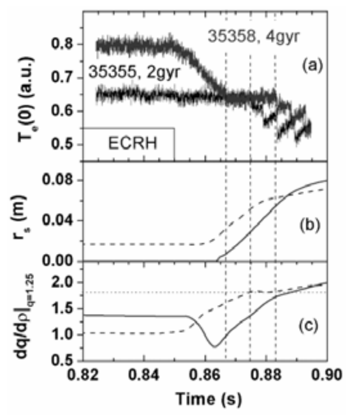

Figure 3: a) Evolution of the central temperature after ECRH switch-off for T-10 shots with higher and lower ECRH power.
b) Position of q=1 surface. Solid line – higher ECRH power, dashed line – lower.
c) dq/dρ value on q=1.25 surface.

Appearing of q=1 surface in plasma stops the central temperature decreasing for the case of 4 gyrotrons switch-off (Fig. 3b, solid line, 1st vertical dotted line). The delay effect disappears for both cases then dq/dρ value on q=1.25 surface becomes larger than some ceiling value (Fig. 3c, 2nd dashed line for lower ECRH power and 3rd dashed line for higher one). The experimental results strongly point towards the conclusion that a low value of dq/dρ leads to a confinement enhancement only if the local value of q is near a rational value (in the present case when q is near unity).

On TEXTOR in series of discharges with HFS ECRH with ρ_{ECRH} just outside the q=1 radius (B_t = 2.32-2.36 T), four pulses of ECRH were applied with a length of 400, 200, 100 and 50 ms respectively. The ohmic phase between the pulses had a length of 500 ms, i.e. a few current diffusion times, to allow the current density profile to relax to its ohmic state. The strongest delay of the central T_e decay (~20 ms, i.e. ~$1\times\tau_E$) was observed after switch-off of the shortest ECRH pulse (Fig. 4a). As in the T-10 case, the heat is conserved inside the q = 1 region. Fig. 4b shows the results of analysis with the COBRA and ASTRA codes.

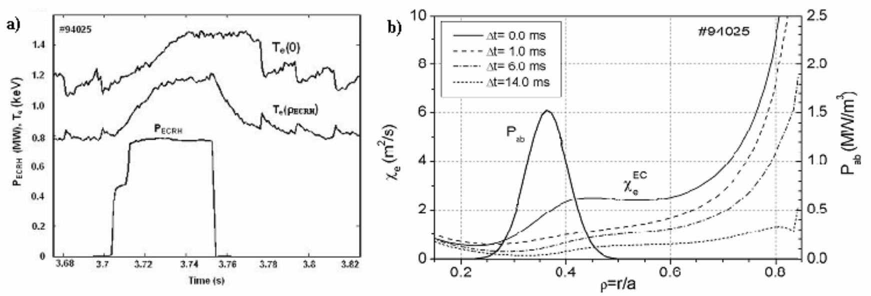

Figure 4: a) Electron temperature time traces for TEXTOR plasma core and for the ρ_{ECRH} region measured by ECE diagnostic
b) ECRH, 5-15 ms after ECRH switch-off and in ohmic phase.

Behaviour of turbulence in T-10 during improved confinement

The density fluctuations in T-10 have been measured by means of O-mode reflectometry. The radial dependence of the relative amplitude of density fluctuati-

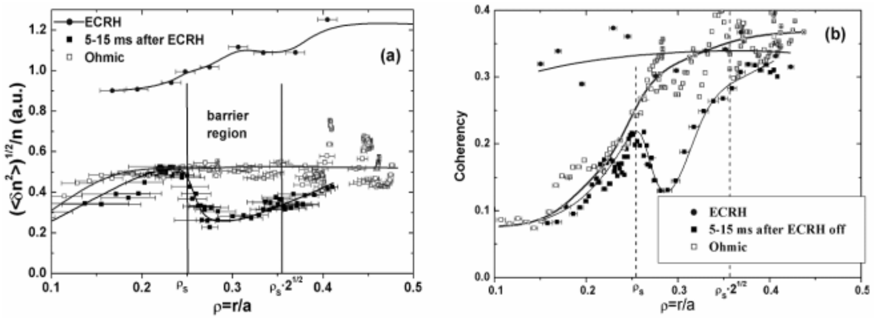

Figure 5: Relative density fluctuation level (a) and the spectral coherence (b) measured by reflectometer during ECRH, 5-15 ms after ECRH switch-off and in ohmic phase.

ons $\sqrt{<\delta n^2>}/n$ and the spectral coherence between two poloidally separated channels are presented in Fig.5a,b. The quantities were evaluated for the ECRH heating period, ohmic phase of the discharge and during the time window of 5-15 ms after ECRH switch off. A pronounced decrease of the relative density fluctuation level as well as of the spectral coherence are observed in the radial range $\rho_S<\rho<\rho_S\,2^{1/2}$. This is consistent with the considerable decrease of the electron heat conductivity seen in Fig. 2a.

Discussion

The experimental results strongly point towards the conclusion that a low value of $dq/d\rho$ leads to a confinement enhancement only if the local value of q is near a rational value (in the present case when q_r is near unity).

We still do not understand the physical processes at the rational surfaces, which determine the confinement changes. To improve our insight we need to perform further studies in which also the q-profile is measured as a function of time. These experiments are planned later this year in TEXTOR after the new Motional Stark Effect diagnostic has been commissioned.

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