Experiments on Electron Temperature Profile Resilience in FTU Tokamak with Continuous and Modulated ECRH

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Abstract. Experiments performed on FTU tokamak, aiming at validation of physics-based transport models of the electron temperature profile resilience, are presented. ECRH is used to probe transport features, both in steady state and in response to time-varying heating, while LHCD is used for current density profile shaping. The experiments clearly show resiliency in the electron temperature profile response to localized ECRH. Central, low gradient plasmas are characterized by low stiffness, in the sense that the temperature gradient can change with conducted heat flux, and low electron thermal diffusivity. Strong stiffness, in the sense that the temperature gradient length $1/L_T$=- T/T does not change significantly even with largely different heating profiles and intensity, and high diffusivity are found in the confinement region ($0.15<r/a<0.5$). A particular attention is given to the experimental investigation of the transition layer between low-high diffusivity (and low-high stiffness) regions, which is found at the EC deposition radius r_{dep} in case of powerful ECRH. A transition layer, well identified by heat waves launched by modulated ECH, is found also in plasmas with dominant ohmic heating, showing that it is a local plasma feature, and not merely a consequence of a step-wise increase in the conducted heat flux at r_{dep}. A novel experimental technique providing localized modulation of the temperature gradient shows strong dependence of heat diffusivity on L_T at the transition layer. All observations fit well with a critical temperature gradient length modelling of local electron heat transport.

1. Introduction

The experiments described in this paper have been performed for testing electron heat transport models, in particular the critical temperature gradient length approach. ECRH is used not only to shape the heating profile, but also to probe transport by heat waves launched by modulated ECH.

Electron Cyclotron Resonance Heating is applied to FTU plasmas by launching up to four millimetre-wave beams at the frequency of f_{ECH}=140 GHz, fundamental EC resonance. Each one is poloidally and toroidally steerable, and transmits up to P_{ECH}=400 kW of r.f. power. The EC beams are launched from the low field side of the tokamak, polarized for optimum coupling to the Ordinary mode into the plasma. Being the cut-off density for this mode $n_{e,c.o.} = 2.4\ 10^{20}\ m^{-3}$, high-density target plasmas with a peak value $n_{e,0} \approx 1.5\ 10^{20}\ m^{-3}$ are routinely used during ECRH. Typical plasma current in these experiments is I_p≈400 kA, q_a≈6, with an ohmic input power of P_{OH}≈500 kW, dropping to P_{OH} ≈250 kW during EC heating. In these conditions it is not unusual that during ECRH the local electron power balance at steady state, including ion coupling and radiation losses, is negative everywhere but at the very localized EC deposition layer. This emphasizes the fact that the steady-state electron temperature profile shape is completely dominated by heat transport processes inside the plasma column, and stresses the potential of ECRH in studying energy confinement.

It is a merit of ECRH experiments to have pointed out clearly the property of the electron temperature profile stiffness, in FTU [1,2] and other tokamaks [3,4]. When the heat continuity condition $\nabla\cdot(-n_e\chi_e\nabla T_e)=P_{heating}$ at steady state is considered, the experimental observation of profile stiffness with ECRH is that an accumulation of the heating power density $P_{heating}$ at the EC waves deposition radius r_{dep} might not cause a change in the T_e profile curvature $\nabla^2 T_e$. Profile stiffness implies that the electron heat diffusivity χ_e must adjust itself during ECRH to keep the gradient ∇T_e flat, much beyond any smooth dependence of χ_e with local plasma parameters.

The experimental observation of profile stiffness has been analyzed both on the basis of profile consistency arguments [5,6], and of electron heat transport driven by turbulence with a threshold on L_T [7,8,9]. Although in both approaches the profile shape shows invariant features, it is worth noticing that in the first case of consistency χ_e is derived from general thermodynamic constraints, while in the second case χ_e is a quantity describing a local plasma response of the profile shape to a given heat flux.

2. Local and global aspects of profile stiffness

Unique features, observed in most experiments with ECRH, characterize profile stiffness: gradient length $L_T=-T_e/\nabla T_e$ saturation, at least in the confinement region of the plasma column, and a step-wise radial dependence of the electron thermal diffusivity $\chi_{e,PB}=-\Phi_{heat}/n_e\nabla T_e$ at r_{dep}. In spite of a wide range of heating intensity (P_{OH}=200÷1000 kW; P_{ECRH}=100÷200 kW) and distribution, in FTU tokamak the inverse gradient length $1/L_T$ of the steady profile in the region 0.15<r/a<0.5 is compressed in a narrow band around $1/L_{T,c}\approx 10\ m^{-1}$.

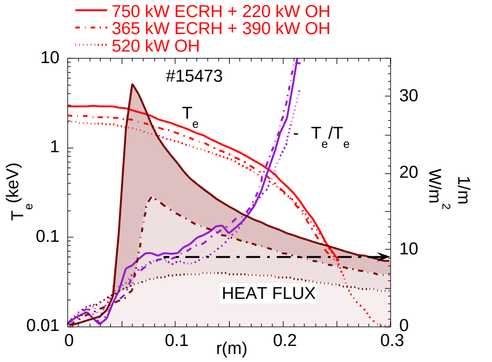

Fig.1 - Electron temperature, gradient length and heat flux vs. radius for different levels of ECRH intensity. The electron temperature gradient length does not increase with stronger heating.

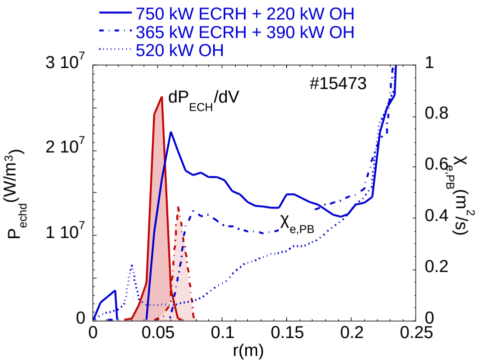

Fig.2 – In order to maintain the temperature gradient length L_T constant also during ECRH, the electron thermal diffusivity χ_e develops a step at deposition radius r_{dep}, larger with stronger heating.

An example of this behaviour is shown in Fig.1, in which a 5-times increase in the heat flux in the same shot does not change L_T at all. Oppositely to the outside of the EC absorption layer, where the heat flux strongly increases with ECRH, on the inside it drops significantly because of loss of ohmic heating due to T_e increase. Since L_T does not change in either regions inside and outside r_{dep}, it follows that $\chi_{e,PB}$ has a step-wise radial dependence at the deposition radius. This response is clearly shown in Fig.2, and it represents a distinctive marker of profile stiffness in tokamaks. This step in χ_e is also detected by heat wave propagation experiments performed both on the current flat-top [10,11] and during current ramp-up [9], which also excludes that the low-high transition in $\chi_{e,PB}$ is an apparent effect of an heat pinch.

There is no way to explain this behaviour with a dependence of $\chi_{e,PB}$ with T_e alone. Instead, it would be indeed a direct consequence of profile consistency complying with global equilibrium, stability and thermodynamic requirements [5], or of a thermal diffusivity strongly dependent on T_e, with a threshold on L_T [8,9]. In this second case, ASDEX Upgrade experiments have shown [7] that both steady state and transient response to ECRH is well described by the empirical relation:

$$\chi_e = \chi_0 + \lambda T_e^{\alpha} \left(- \ T_e/T_e - \kappa \right)^{\beta} H\left(- \ T_e/T_e - \kappa \right) \qquad (1)$$

H being the Heavyside function of argument ($1/L_T$-κ). A similar relation has been successfully used to model FTU steady state discharges [8].

3. Transition layer

Equation (1) contains the key features of profile stiffness observed so far in experiments: a) the saturation of the temperature gradient length L_T, which the model suggests to occur where $1/L_T$ approaches κ into the plasma; b) the step-wise behaviour of χ_e (and particularly $\chi_{e,HP}$ [7,9]) at r_{dep} with strong ECRH. However, independently of ECRH, equation (1) suggests that the step in χ_e should be found in ohmic plasmas as well, since the experiments indicate that χ_0 is so low that the ohmic heating flux alone would be sufficient to force $1/L_T$ towards κ somewhere into the plasma.

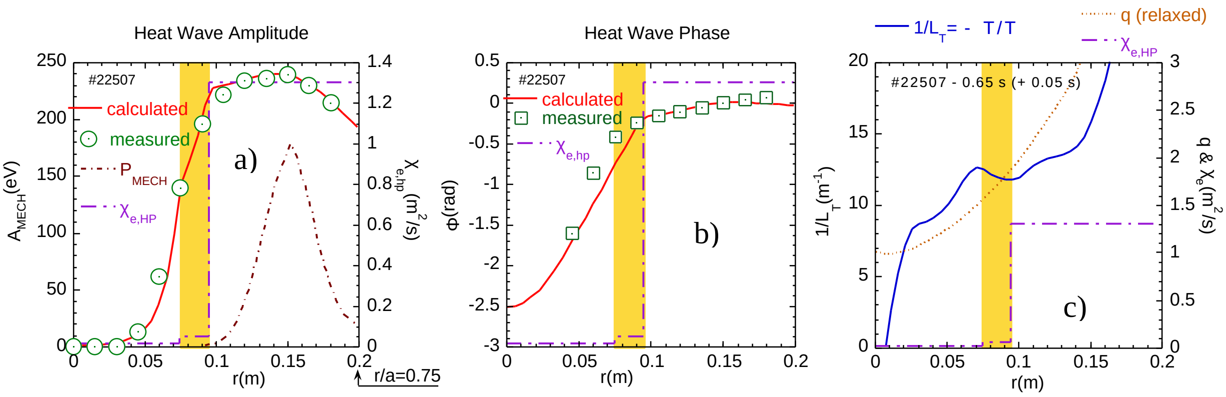

Fig.2 –Heat wave from modulated ECH deposited at r_{dep}≈0.6a (power deposition profile is the dotted peaked line in fig.a), and propagating up to the ohmically heated core. Markers in a) and b) are the experimental values measured with a 12-channels ECE polychromator (amplitude and phase respectively). The continuous line is the result of a diffusive calculation of the perturbed electron temperature assuming $\chi_{e,HP}$ constant in time, but with the step-wise radial distribution shown by the dashed line (in a), b) and c)). The wave clearly passes through a layer where $\chi_{e,HP}$ drops by an order of magnitude, as shown by the sudden slowing down of the phase velocity and the strong increase in the wave damping rate. The transition layer is well inside the deposition region, and it is located at the margin of the region where L_T saturates (figure c).

The model predicts that, as a general picture, the layer where $1/L_T$ approaches κ divides the plasma in two regions, one, central, non-stiff and with low diffusivity, and the other one, external, stiff and with enhanced transport. The fact that the step in $\chi_{e,HP}$ does not necessarily coincide strictly with r_{dep}, but rather with L_T saturation point, was preliminarily observed during modulated ECH experiments on current ramp-up on FTU tokamak [9], and now it has been confirmed with a series of experiments at current flat-top.

Absorption of the EC beam is kept as much as possible off-axis, in order to keep to a minimum level the effect of the average ECRH power on the ohmic plasma in the core. Data analysis is aimed particularly at the recognition of a singular point in the phase velocity and in the amplitude damping rate of the inward heat wave. Experimental data are compared with a calculation of the perturbed temperature distribution by using a simple model for $\chi_{e,HP}$ [9], in which thermal diffusivity is assumed to be constant in time, but with a step-wise radial dependence. The two levels of $\chi_{e,HP}$, and the position of the discontinuity, are free parameters to be adjusted for best fitting the experimental data.
A typical result, representative of many experiments all having the same behaviour, is shown in Fig.2. The heat wave propagation is observed on FTU at 12 radii by using a multi-channel ECE polychromator, tuned to 12 positions from r_{dep} up to the centre (outward heat wave is neglected). The important result of the analysis is that both the amplitude and the phase reveal that a sudden drop in diffusivity must occur at r=0.075÷0.095 m, well external to the EC deposition layer and well inside the ohmic plasma. Calculations suggest that the low and high diffusivities on the two sides of the transition are different by an order of magnitude, and that the transition is localized in a narrow layer. The figure shows (Fig.2c) that the transition is located at the margin of the region where L_T is saturated, which is very consistent with the implications of eq. (1).

4. Modulation of the temperature gradient

A specific experiment has been performed in FTU with the aim of directly emphasizing the strong, non linear dependence of χ_e with T_e at the transition layer, foreseen by 1). Two EC beams, steered in a way to be absorbed at different radii $r_{dep,1}$ and $r_{dep,2}$, are switched ON alternatively in time. More exactly, they are ideally modulated almost out of phase, in a way that the two outward heat waves would cancel out if χ_e were constant in time. Because of the relative phasing, the EC heat flux is constant in time everywhere in the plasma (either one or the other beam is ON), except between $r_{dep,1}$ and $r_{dep,2}$, where the flux Φ_{heat} and T_e do oscillate at the modulation frequency. From 1) (with β=1), and from $\Phi^*_{heat} = \Phi_{heat}/n_e = -\chi_e \; T_e$, it can be shown that χ_e is modulated according to:

$$\frac{\delta\chi_e}{\chi_e} \approx \frac{\partial\chi_e}{\partial(1/L_T)} \frac{\delta(- \; T_e)}{\chi_e T_e} = \frac{\lambda T_e^{\alpha-1}\delta\Phi^*_{heat} H}{\chi_e^2 + \lambda T_e^{\alpha-1}\Phi^*_{heat} H} \tag{2}$$

This function is zero for $1/L_T<\kappa$, it has a maximum at $1/L_T \geq \kappa$ where $\chi_e \approx \chi_0$, and it falls everywhere else with $1/\chi_e^2$. An oscillating diffusivity should produce an heat wave, being the stored energy alternatively increased and released. The strength of this internal heat wave is given by $P_{int} \approx (\chi_{high}/\chi_{low} - 1)P_{heat} = (\delta\chi/\chi)P_{heat}$ [12], P_{heat} being the local heating power density responsible for steady-state T_e profile. A substantial internal heat wave is therefore expected when the swinging of r_{dep} occurs in the transition layer. The visibility of this internal wave is enhanced by the fact that the individual waves by the two gyrotrons can be cancelled out if the power in the two beams is properly adjusted. The result of the experiment is shown in Fig.3.

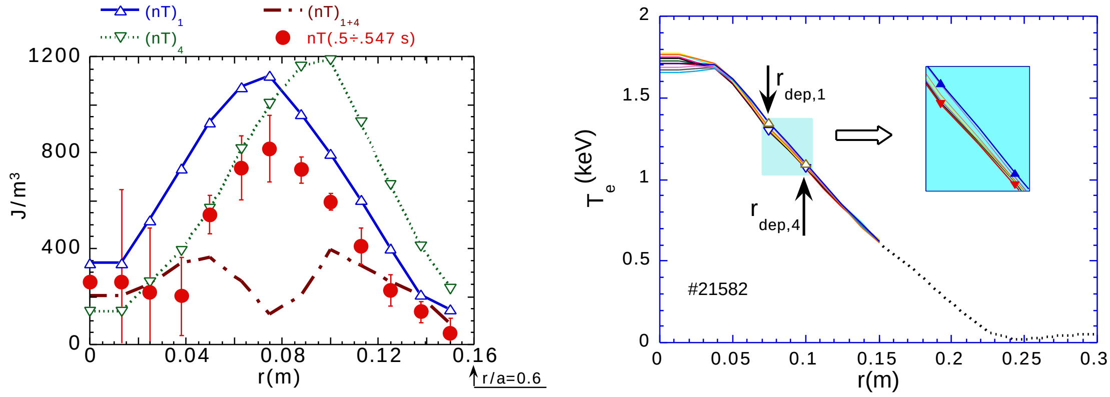

Fig.3 - Left: curves with triangles are the individual heat wave amplitude (nT_e) from the two beams (1&4) modulated out of phase. Dashed line is the vectorial sum, showing that substantial cancellation would occur with a linear response of the medium (χ_e constant in time). Dots are the measured heat wave amplitude, showing that a substantial internal heat wave is generated. Right: the electron temperature gradient does not change between the two deposition radii in spite of the oscillating heat flux.

Fig.3 shows that, as foreseen by 2), an intense internal heat wave is generated if swinging occurs at the transition layer. No heat wave is seen when the deposition is inside the non-stiff central region, while in the stiff region the heat wave is present but, as expected, with lower amplitude.

5. Summary

Experiments performed on FTU tokamak with ECRH, continuous and modulated for heat wave propagation and T_e modulation, are well in agreement with a critical gradient modelling of electron transport. They support the concept of χ_e as a physical quantity measuring confinement properties, dependent, although in a complex way, on local plasma features.

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