

Application of Modulated ECH to Electron Heat Transport Study on FTU Tokamak.

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Introduction

Perturbative and steady state heat transport properties have been investigated by means of Electron Cyclotron Heating of FTU tokamak during steady state and current ramp-up operations. Modulated Electron Cyclotron Heating is performed during current ramp-up operations in a wide range of the parameter s/q ($0.1 < s/q < 0.4$) in high density FTU plasmas ($n_e \geq 10^{20} \text{ m}^{-3}$). The accurate feed-back control of the total current evolution of FTU tokamak (major radius $R=0.93$ m, minor radius $a=0.3$ m) together with an appropriate programming of the neutral gas injection rate allows a gross control of the current density profile shape $J(r)$ in the ramp-up phase. Discharges can be programmed to evolve with a peaked, high shear profile or, alternatively, with a flat-hollow J profile. This provides the target for experiments probing electron energy transport in terms of magnetic shear by modulated ECH (140 GHz, fundamental resonance, O-mode, Low Field Side launch and absorption). In this work it is shown that both perturbative and steady state [1,2] transport experiments are coherent with a electron heat conduction which switches from low to high values when the electron temperature gradient length reaches a threshold value $1/L_{Tc}$. Experimental findings are compared to predictions of a empirical model based on the assumption of a threshold gradient length, L_{Tc} ($1/L_T = |\nabla T_e/T_e|$), in the electron temperature T_e below which electron thermal conductivity, χ_e , switches from low to high values [3].

The threshold value $1/L_{Tc}$, determined by means of a new technique which makes use of perturbative transport, is shown to be dependent on the ratio s/q .

1. Plasma target for modulated ECH during current ramp-up.

Current density and electron temperature profiles of three representative shots (#20144, #20145, #20146) are very different in the three cases, shots #20144 and #20146 representing

two opposite extremes. The electron temperature evolution on axis, and at the position of EC wave absorption, is shown in fig.1 for the two discharges.

Although the strong MHD activity introduces further complexity in the dynamics of the discharge, its presence is most valuable in bench-marking current density reconstruction by a current diffusion code. Modulated ECH is applied to these targets, at a position $r_{dep} \approx 0.06$ m. The modulation frequency is 160 Hz.

Radial profiles of modulation amplitude of the discharges analyzed are shown together with the solution of the heat diffusion equation:

$$(3/2 i \omega + 1/\tau) T_{\omega}(r) - 1/n(r) \nabla \cdot [n(r) \chi_{HP}(r) \nabla T_{\omega}(r)] = P_{\omega}(r) \quad (1)$$

in the frequency domain in Fig.2. Experimental amplitudes and phases are well reproduced by a simple “two levels” χ_{HP} model shown together with EC power deposition profiles P_{RF} in Fig. 3. This χ_{HP} model, which is the simplest model to fit the data of this experiment, allows to draw few important conclusions:

- a) extremely different levels of perturbative electron heat conduction (more than a factor 10) are observed in different zones of the plasma column in analogy with previous ECH steady state experiments in FTU tokamak [2].
- b) The relative radial position of r_{dep} and of the transition of χ_{HP} from low to high values is different in different discharges: transport properties are not directly induced by the RF injection.

It is also important to remind here that high frequency high phase velocity heat waves are insensitive to the presence of a heat pinch; this implies that, in general, low χ_{HP} zones are zones of real low heat transport and not of high transport with a heat pinch overlapped. This, differently from findings of ref.[4], is the case of present experiment. The last is an important piece of information: it helps to separate and scale the different physical mechanisms that drive transport.

2. Temperature perturbations critical gradient length interpretative model.

Here we try to interpret the observed phenomenology within the frame of a critical gradient length theory assuming for the electron diffusivity:

$$\chi_{PB} = \chi_0 + \alpha T_e^{3/2} (1/L_T - 1/L_{TC})^{1/2} . \quad (2)$$

In this empirical model χ_{PB} is the steady state heat transport coefficient, χ_0 represents a 'background' heat transport for $1/L_T < 1/L_{TC}$, $T_e^{3/2}$ reflects the gyro Bohm assumption, L_T is

the temperature gradient length. The term $(1/L_T - 1/L_{Tc})^{1/2}$, which sets in for $1/L_T > 1/L_{Tc}$, mimics an extra transport possibly due to ETG modes.

Perturbed thermal diffusivity χ_{HP} , which, by definition, is the derivative of the heat flux with respect to ∇T_e [5], will show a sharp increase at the radial position where L_T becomes smaller than its critical value (see Fig.4). The radial position of the switch from low to high χ_{HP} , within this empirical model, is determined by the fact that the actual $1/L_T$ which becomes larger than its critical value $1/L_{Tc}$. In practice $1/L_{Tc}$ can be obtained by interpolating the experimental $1/L_T$ at the position of the step in χ_{HP} as shown in Fig.5. Perturbative transport is a rather good indicator of the radial position where the transition happens. The ratio s/q corresponding to the critical gradient length $1/L_{Tc}$, similarly to what done previously, can be obtained interpolating curves of Fig.10 at the radial position where χ_{HP} switches from low to high values. In Fig. 13 the stability parameter R/L_{Tc} is plotted versus s/q and compared with the same figures obtained in Tore Supra Tokamak as described in ref. [6]. A clear correlation between R/L_{Tc} and s/q is observed in spite of the large error bars mainly induced by the s/q reconstruction.

References

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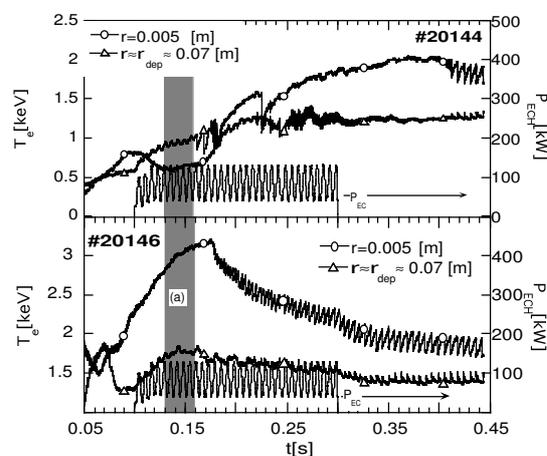


Fig.1 : T_e time traces of shot #20144 and #20146 are shown together with EC injected power. Shaded area shows the time interval of Fourier analysis. Time traces show electron temperature as measured by fast ECE at the plasma centre ($r=0.005$ m, open circle) and at a position close to the RF injection ($r_{dep}=0.075$ m, open triangles). Shot #20144 in the shaded time interval becomes hollow. In the following time a strong MHD activity, diagnosed as a double tearing mode, rearranges T_e profile to peaked.

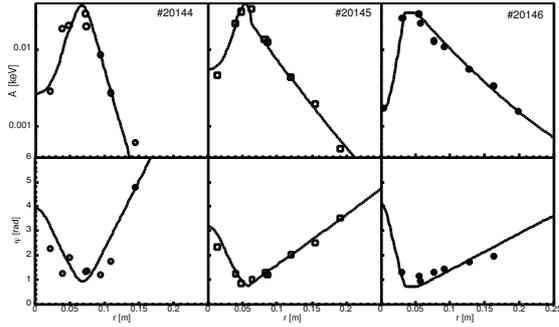


Fig.2: Experimental amplitude and phase profiles (160 Hz) from Fourier analysis of ECE polychromator time traces of different FTU shots are shown together with fits (solid lines) obtained with model assumption of Fig.3 for the different shots.

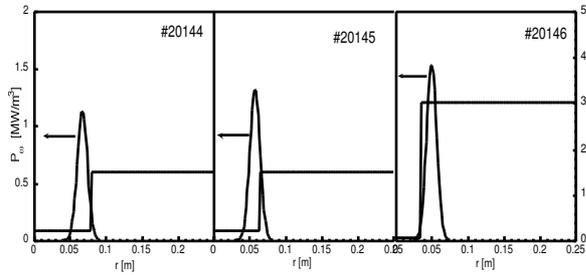


Fig.3: Model χ_{HP} and power deposition profile that give fits shown in Fig.2. The relative position of the switch from low to high χ_{HP} and the peak of power deposition are different in different shots.

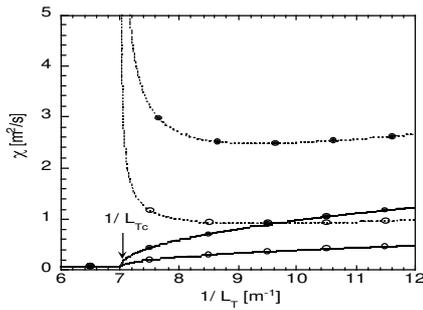


Fig.4: Heat transport coefficient χ for steady state (solid lines) and perturbative electron temperature (dashed lines) as given by the critical gradient length model of equation 2 at two electron temperatures ($T_e=1$ KeV and 2 keV, open and solid circles respectively) vs $1/L_T=\nabla T_e/T_e$. The heat conduction seen by a temperature perturbation (χ_{HP}) when $\nabla T_e/T_e$ is close to its critical value jumps to very high values.

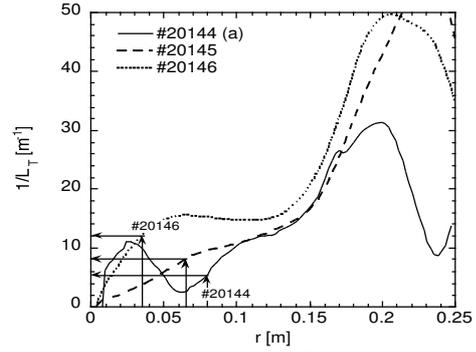


Fig.5: Actual $1/L_T$ from Michelson diagnostic. Arrows indicate the radial position of the step in χ_{HP} for each discharge and the interpolated $1/L_T$ value.

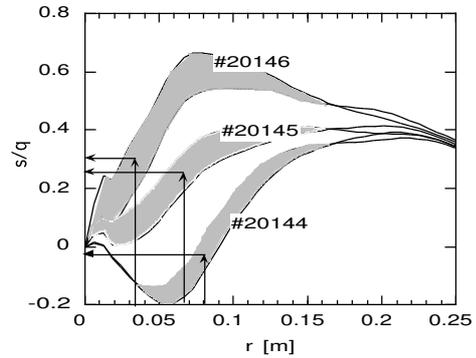


Fig. 6: Computed s/q . Shaded areas reflect uncertainties given by different model assumptions in the power balance analysis. Arrows indicate the radial position of the step in χ_{HP} for each discharge and the interpolated s/q value.

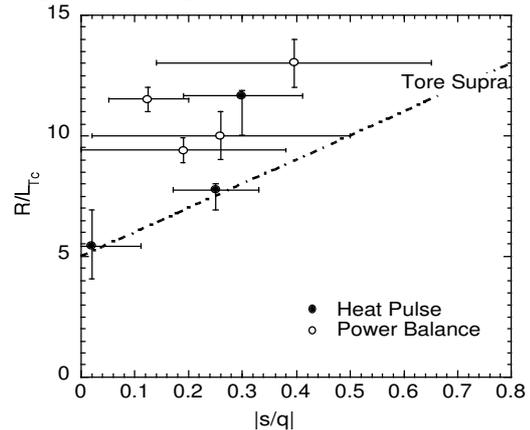


Fig. 7 : Dimensionless parameter, R/L_{Tc} , from FTU tokamak perturbative and power balance (open symbols) is shown vs the ratio s/q . The offset linear fit of Tore Supra [6] is also shown in the same figure for the sake of reference (dashed line) .