Perturbative Electron Transport Studies by means of Laser Blow Off Induced Cold Pulses In ASDEX-Upgrade.

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Introduction

Perturbative and steady state heat transport properties have been investigated by means of localized Electron Cyclotron Heating (ECH) in ASDEX-Upgrade experiments. Experimental findings, summarized in [1] (and references therein), have been successfully compared to predictions of a empirical model based on the assumption of a threshold gradient length, L_{Tc}, ($1/L_T = |\nabla T_{e0}/T_{e0}|$) in the electron temperature T_{e0} below which electron thermal conductivity, χ_e, switches from low to high values likely due to the onset of electromagnetic turbulence. In the experiment ECH power is used both to modify the steady state gradient length and to induce the transition from low to high electron heat transport. The radial position of the transition from turbulent to quiet plasma is also detected by means of perturbative transport performed through Modulated ECH (MECH) [1,2]; in fact the small amplitude heat wave induced by MECH acts as a probe of heat transport surfing in the different sections of the plasma column, with different speeds and damping determined by underlining electron heat transport [2].

Other perturbative techniques such as cold pulses (c.p.) induced by injection of radiating impurities at the plasma boundary gave in the past debated results [3] that brought to the so called 'nonlocal behaviour' paradox i.e. to an inversion of the sign of the temperature perturbation (from negative to positive) together with fast propagation times difficult to model in a single fluid description of heat diffusion. By increasing electron density, however, 'nonlocal behaviour' disappears [4] and c.p. can be used as independent method in perturbative transport studies.

In order to confirm that modulated heat transport experimental results obtained by means of MECH reflect a general behaviour of electron heat transport we made combined use of steady-state and MECH together with c.p. and compared MECH and c.p. experimental results.

Plasma target and experimental results.

Line density was kept constant $n_e \approx 2.3\ 10^{19}\ m^{-3}$ in all the discharges while ECH deposition radius has been changed between $0.4 < \rho_{dep} < 0.6$ by varying toroidal field $2.1 < B_T < 2.2$ T in combination with different angles of the launching mirror. A total plasma current $I_p = 400$ kA yields a safety factor $q_{95} \sim 9$ and a Ohmic power of about 300 kW that reduces to ~180 kW during the CW injection of 800 kW at 140 GHz. ECH (2nd harmonic X wave) power is 100% modulated with a 50% duty cycle at 30 Hz for 200 ms, after which it is kept constant at 800 kW. Cold pulses are induced by laser blow-off of Si which induces radiation pulses of ~ 300 kW at 4 Hz during the ~2 s ECH steady state (fig.1). In fig.2 it can be seen that there is a clear asymmetry in the duration of the raising and falling fronts of T_e measured by ECE diagnostic; the asymmetry is reversed in the region between ρ_{dep} and the plasma center compared to the region between ρ_{dep} and the plasma boundary. As a consequence the time of flight of the perturbation to the centre or to the plasma boundary is different at the switch-on or switch-off of the EC power. In fig.3 we see that MECH induces a (cyclic) change of the temperature gradient length which is modulated in phase opposition in the two sides near ρ_{dep}; to model experimental observations we assumed that also heat transport was cyclically pushed by MECH above and below a mean value switching to very low values in the region $\rho < \rho_{dep}$ and to higher values in $\rho > \rho_{dep}$. In fig.4 χ_e profiles (during the on-off phase of ECH) that allows to fit time traces of fig. 2 by means of ASTRA code. A fast switching of χ_e , already observed in W7-AS stellarator [5], gives the experimental measure of how fast reacts the mechanism that brings heat transport to turbulent levels. It is also important to note that at a frequency of 100-200 Hz we still observe a fast switching of χ_e. Current density profiles, however, cannot play a role at this frequency due its longer skin time. Some warning on the interpretation of modulated data from Fourier transforms techniques in the case of large temperature perturbations near threshold values of the temperature gradient length (i.e. in a strongly nonlinear case) are clearly raised by these experimental observations.

Electron temperature profiles show up flat or even hollow in the region between ρ_{dep} and the plasma centre during steady-state ECH injection (see fig.6); on the contrary for $\rho \geq \rho_{dep}$ temperature profiles become similar one to each other assuming the well known 'stiff' behaviour [1]. Cold pulse changes suddenly its speed and damping while crossing ρ_{dep} as shown in fig. 5. The 24 Hz component of the c.p. shown in fig.6 together with temperature profiles undergoes a very strong damping, due to a very low heat transport, just after crossing ρ_{dep} in perfect agreement with a physical model of a plasma whose heat conduction is splitted in two levels by the injection of high ECH power. In the region $\rho \geq \rho_{dep}$ c.p. induces a factor 2 change in χ_e because of the change in ∇T_{e0} or $\nabla T_{e0}/T_{e0}$ produced by the perturbation. A quantitative analysis performed by means of ASTRA code shows that the radial position of the switch from high to low heat conduction is not changed by c.p. perturbation whose strength is not sufficient to modify the heat transport structure imposed by the strong ECH power. In fig.7 1st MECH harmonic and 6th harmonic of c.p. are compared; it can be seen that a "secondary" cold pulse, induced by the change of χ_e at ρ_{dep}, moves to the centre and to the boundary following the same damping and with the same speed of MECH induced heat pulse. Before reaching the boundary the primary and the secondary wave merge. The two waves can thus be clearly observed only in the case when RF is deposited far from plasma boundary i.e. far from the source of the c.p.. In a plasma with a heat conduction which changes in time over a portion of the plasma column of a factor γ the equation for the temperature perturbation T_e may be written as $3/2\, n_{e0}\, \partial_t\, T_e - \nabla . \{n_{e0}\, [\gamma\, (\rho,t)\, \chi_{e0} \nabla\, T_e]\} = p_{ext} + p_\chi$ [6] where n_{e0} , χ_{e0} are the steady state unperturbed quantities, p_{ext} an oscillating external power source, and $p_\chi \approx -[\gamma\, (\rho,t)\, -1]\, p_{e0}$ where p_{e0} is the steady-state power which is deposited into the electrons. It is worth noticing that in the case of intense and strongly localized p_{e0} as in the case of ECH heating of present experiment, p_χ can be comparable in strength to p_{ext} and localized at a different radial position i.e. in ρ_{dep}.

References

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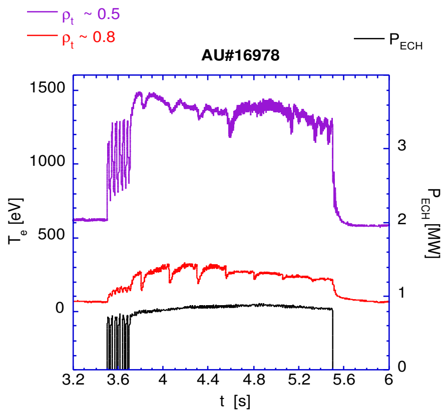

Fig.1 :*T_e time traces of AU shot #16978. ECH power is shown by the black line; red and purple traces give time evolution of the temperature at the boundary and at the deposition of RF ($\rho_{dep} \approx 0.5$). Before RF power reaches a steady-state a 30 Hz modulation allows both to determine the radial position of RF injection and to study the radial behaviour of temperature perturbation induced by MECH. During the ECH steady-state cold pulses are also performed and can be seen in the figure.*

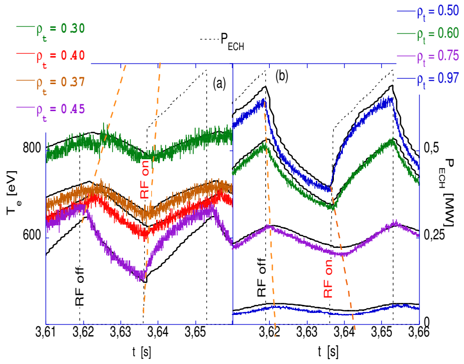

Fig.2: T_e *time traces together with simulations of shot #16978 (solid black lines) are shown from* ρ_{dep} *to plasma core in (a) and from* ρ_{dep} *to boundary in (b). Orange dotted lines show the delay of the perturbation at the switch on or at the switch off of the RF (dotted black lines).*

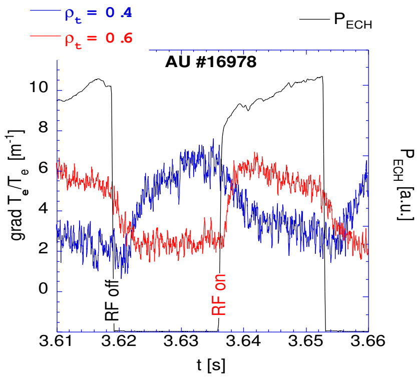

Fig.3: *$1/L_T = \nabla T_e / T_e$. vs. time is shown together with RF time trace (solid, black).*
When the RF is on $1/L_T$ decreases at $\rho_t < \rho_{dep}$ *(blue line) and increases for* $\rho_t > \rho_{dep}$ *(red line).*

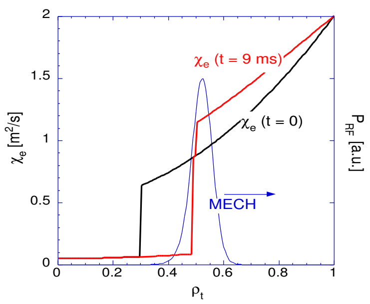

Fig.4:*Heat transport coefficient* $\chi\_$ *before RF switches on (black line) and after 9 ms from switch on (red). RF power deposition is also shown.* $\chi\_$ *drops just inside* ρ_{dep}.

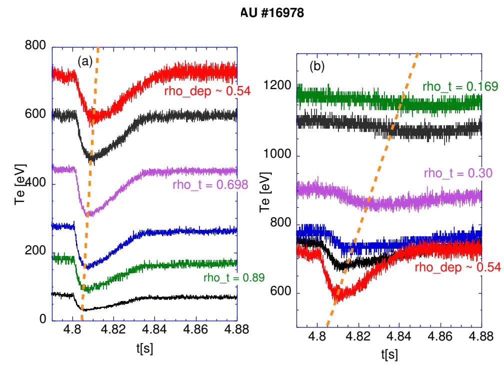

Fig. 5: *Te time traces showing c.p. propagation from the boundary (a) to* ρ_{dep} *(red) and in (b) from* ρ_{dep} *to plasma centre. The sudden change of speed and damping clearly shows that heat conduction drops in the central region of the plasma.*

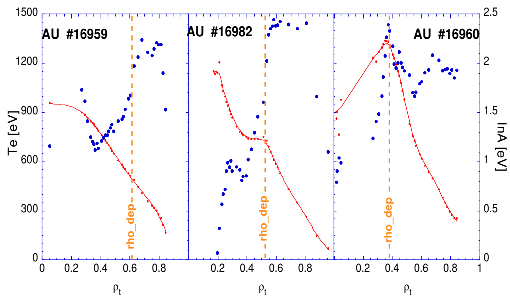

Fig.6: T_{e0} *profiles (red) for different* ρ_{dep} *are compared to the amplitude, A, of the 24 Hz component of c.p. perturbation (blue dots); orange dotted vertical line is at* ρ_{dep}.

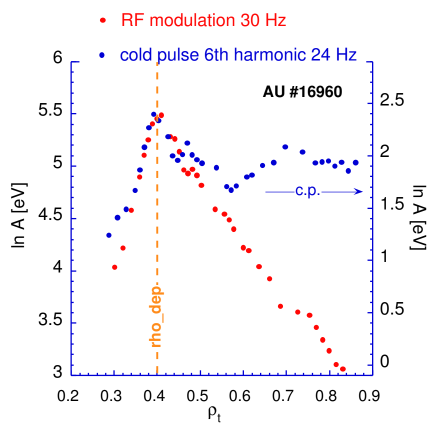

Fig.7: *Amplitude of c.p. (blue dots) and MECH (red dots) perturbations; a secondary cold pulse propagates from* ρ_{dep} *to the boundary and to the plasma centre.*