Electron Heat Transport Studies Using Transient Phenomena In ASDEX Upgrade.

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Abstract. Experiments in tokamaks suggest that a critical gradient length may cause the resilient behavior of T_e profiles, in the absence of ITBs. This agrees in general with ITG/TEM turbulence physics. Experiments in ASDEX Upgrade using modulation techniques with ECH and/or cold pulses demonstrate the existence of a threshold in R/L_{Te} when $T_e>T_i$ and $T_e \leq T_i$. For $T_e>T_i$ linear stability analyses indicate that electron heat transport is dominated by TEM modes. They agree in the value of the threshold (both T_e and n_e) and for the electron heat transport increase above the threshold. The stabilization of TEM modes by collisions yielded by gyro-kinetic calculations, which suggests a transition from TEM to ITG dominated transport at high collisionality, is experimentally demonstrated by comparing heat pulse and steady-state diffusivities. For the $T_e \approx T_i$ discharges above the threshold the resilience, normalized by $T_e^{3/2}$, is similar to that of the TEM dominated cases, despite very different conditions. The heat pinch predicted by fluid modeling of ITG/TEM turbulence is investigated by perturbative transport in off–axis ECH-heated discharges.

1. Introduction

Micro-turbulence theory predicts for electron heat transport two main candidates: the TEM modes, generally coupled to the ITG modes, and the ETG modes. The ETG modes excite very small scale turbulence and significant transport is believed to be driven only if larger cells, so-called streamers, can develop [1]. The TEM and ETG modes have respective thresholds in R/L_{Te} ($1/L_{Te} = -\nabla T_e/T_e$) above which they become unstable and drive transport, as discussed in a companion paper [Peeters IAEA04]. Indeed, during the recent years numerous observations [2] in tokamaks suggested the existence of well localized changes in the electron heat transport occurring at a threshold in R/L_{Te} in very different experimental conditions. It appears thus natural to assume that, at the exact position of the transition, some mode becomes unstable; this particular circumstance gives the opportunity to check turbulence theory against plasma parameters measured at the point of mode transition from stable to unstable.
Theory studies of ITG/TEM modes indicate that it is useful to distinguish between cases with dominant electron heat flux ($T_e>T_i$ and $R/L_{Te} > R/L_{Ti}$) and comparable heat fluxes in each channel ($T_e \leq T_i$ and $R/L_{Te} \leq R/L_{Ti}$). In the former cases the ITG modes are only weakly excited and electron heat transport is dominantly driven by the ETM modes above the TEM threshold. The TEM threshold and driven transport depend mainly on R/L_{Te}, R/L_n , magnetic shear and safety factor, [Peeters IAEA04]. In cases with comparable heat flux in the electron and ion channels, electron heat transport cannot be considered as driven by the TEM modes alone, the ITG contribution is important or even dominant. To cope with these theory predictions our experiments on electron heat transport are divided into two classes: i) discharges with dominant electron heating, performed at low density heated with ECH; ii) discharges with NBI heating, with comparable heat fluxes and temperature profiles for

electrons and ions. In these cases ECH is used as additional tool to investigate specifically electron heat transport.
Fluid modeling of ITG/TEM turbulence predicts the existence of convective heat fluxes either due to the off-diagonal contribution of the ∇n_e term or to truly convective terms driven by the magnetic field in homogeneity (∇B). Dedicated experiments have been performed to address this question. The experiments presented here were performed in deuterium in the usual parameter range of the ASDEX Upgrade tokamak (R=1.65m, a=0.5m, κ =1.7). The 140 GHz ECH system delivers up to 2 MW absorbed at the second harmonic in the X-mode ensuring 100% single-pass absorption. The position of the deposition can be varied according to the experimental requirements for on-axis or off-axis heating. The ECH deposition width is about 3 cm, i.e. much smaller than the minor radius.

2. Transient Transport Experiments in Plasmas with Dominant Electron Heat Flux

The space and time behaviour of a temperature perturbation combined with time averaged analyses gives a direct insight of plasma heat conduction properties. The perturbed thermal diffusivity χ_{HP}, defined as the derivative of the heat flux with respect to ∇T_e is a rather good indicator of the radial position of the threshold in R/L_T [3]. In fact, if we assume that the electron diffusivity can be empirically described [4] as $\chi_{PB}=\chi_0+\alpha\,(T_e)^{3/2}(R/L_{Te}-R/L_{Tc})$ then χ_{HP} will show a sharp change at the radial position where R/L_{Te} crosses its critical value R/L_{Tc}. Here χ_{PB} is the steady-state heat transport coefficient, χ_0 represents a purely diffusive 'background' heat transport for $R/L_{Te}< R/L_{Tc}$ and $(T_e)^{3/2}$ reflects the gyro-Bohm assumption; the term $(R/L_{Te}- R/L_{Tc})$ mimics the transport due to turbulent modes. An example of sharp transition in χ_{HP} in ASDEX Upgrade has been presented for ECH power modulation in [2].
In the experiments presented here, repetitive cold pulses, induced by a laser ablation of Silicon (LBO), have been used to induce a cyclic (negative) temperature perturbation at the plasma boundary. The plasma is heated with 800kW of ECH deposited off-axis at $\rho_{dep}\sim 0.5$, where ρ is the normalized toroidal flux radius. Figure 1, which illustrates the Te perturbation at different radii, indicates that it "travels" with two different "speeds" outside and inside of the ECH deposition. As pointed out in [5] for the ECH induced heat pulses, this means that the ECH splits the plasma column into 2 parts with very different transport properties. Indeed here also, it can be seen by eyes that the temperature perturbation experiences two definitely different χ_{HP} on the two sides of ρ_{dep}. Therefore 2 different methods used to probe transport yield the same results. A possible interpretation of the observed behaviour is offered by the model mentioned above assuming a threshold behaviour. In the radial region $\rho > \rho_{dep}$ the ECH power, well in excess of the residual Ohmic contribution (~ 200 kW with a total plasma current of 400 kA), forces the electron temperature profile above R/L_{Tc}: there turbulent modes are unstable. In the plasma section extending from ρ_{dep} to the core, on the contrary, the temperature profiles drops below R/L_{Tc} , the modes are stable and the electron heat transport is low. The presence of a threshold can also be observed by cyclically inducing, in a given radial part of the plasma, a gradient length variation extending over a range of values which includes the threshold one. This will induce a time (and space) modulation of the electron heat conduction and, in turns, the time behaviour of the temperature perturbation should reflect the presence of the threshold.
A 100% square wave power modulation has been applied with 800 kW of ECH to plasma. This vigorous modulation induces simultaneously a strong modulation of both temperature and R/L_{Te}.
The analysis indicates that the time of flight, i.e. the time needed by a peak (or a deep) of T_e to diffuse over a radial extent is different at the switch on or off of the ECH power. 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. This behavior is summarized by plotting in FIG.2 the delay time (relative to the ECH switch-on or switch-off time points) of the peak (or deep) of T_e as a function of the distance from ρ_{dep}. Data of perturbations traveling to the centre or to the boundary of the plasma at the RF switch-on or at the switch-off group on three well resolved branches. At the RF switch-off a slow wave moves to the plasma centre while a fast one goes to the boundary. A single branch of intermediate speed collects the pulse behavior in both directions at RF switch-on. Two branches for a perturbation traveling to the center or to the boundary at the RF switch-off mean that the plasma heat diffusivity has been split in two different levels during the "on" phase of the ECH pulse. On the contrary at the RF switch-on plasma heat conduction has recovered its smooth radial profile and the delay time settles on a single branch both for pulses traveling to the centre and to the boundary. The change in χ_e starts with a delay of ~ 5 ms from the RF switch on but occurs in a time which is shorter than half modulation period i.e. in less than 15 ms. This together with the sharp separation of the different branches represents a strong indication of the presence of a threshold gradient length.

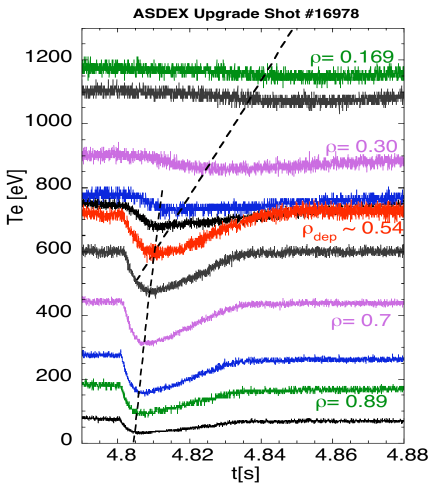

FIG.1. Time traces of a cold pulse of shot #16978 are shown for different radial positions. ECH power is injected at $\rho_{dep} \approx 0.5$; damping and speed of the pulse change dramatically in the region $\rho \leq 0.5$. The dotted lines indicate the positions of minima.

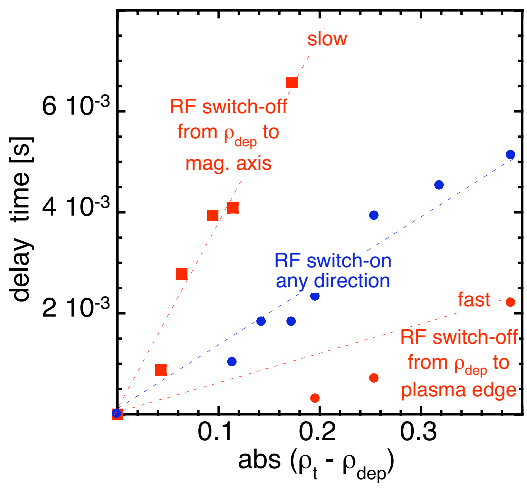

FIG.2. Delay time (measured from the switch-on or off of ECH power) of the peaks or deeps of temperature perturbation is plotted in function of the radial distance from ρ_{dep} . The two branches (slow and fast) group data taken at RF switch-off. The slow branch gives the delay of pulse diffusing to the centre, while the fast one gives time for diffusion to the boundary. Data taken at the switch-on lay on a single branch.

2.1. Threshold of TEM Driven Transport

As mentioned above and in [Peeters IAEA04], at low collisionality the TEM turbulence is a very probable candidate for electron heat transport. The TEM modes are expected to become unstable above a threshold which depends on several plasma parameters, in particular on R/L_{Te}. The data available so far [6] clearly indicated that transport is decreasing to very low values for finite values of R/L_{Te}, strongly suggesting the existence of a threshold. However, the residual Ohmic power and the decreasing transport as the threshold is approached did not allow R/L_{Te} to cross the threshold. The experiments described in the previous sections also suggest the existence of a threshold but did not yield its value. The threshold in R/L_{Te}, has been addressed in new experiments using ECH deposited at 2 radial positions, ρ_{tor} = 0.35 and ρ_{tor} = 0.55, allowing to vary $\nabla T_e/T_e$ in this radial region. The existence of a threshold is reflected in a jump-like change of the heat pulse propagation around the threshold, see above and [3]. This property can be used to monitor the actual existence of a threshold defined here as a clear change of the quantity $\partial q_e/\partial \nabla T_e$. The set of new experiments presented in this section were carried out at low Ohmic power and allow to produce T_e profiles which obviously went below the threshold with enough off-axis ECH. An additional ± 10% power modulation provide the required heat pulses propagating towards the plasma center and therefore through the region where R/L_{Te} could be varied from below to above the threshold. The results of the analyses is shown in FIG.3 which shows the heat pulse propagation speed deduced from the amplitude and phase of the Fourier transform of the T_e modulation, according to references [7,8]. It clearly shows a jump on χ_{Amp} at R/L_{Te} around 3. In general one expects $\chi_{Amp} \leq \chi_{Phase}$ for a diffusive transport with the form $q_e \approx \nabla T_e^{\alpha}$. The present results are explained by the experimental method and by the existence of a threshold. In fact, the heat pulses launched by the outer ECH deposition propagate toward the inner ECH deposition. If the region between the 2 depositions is below the threshold the transport properties may be close to purely diffusive. Indeed FIG. 3 shows $\chi_{Amp} \approx \chi_{Phase}$ for $R/L_{Te}<3$. Therefore, each heat pulse

arriving at that point will modify $\nabla T_e/T_e$ there and create a variation of χ_e and χ_{HP}. Similarly to the effect described in section 2, this periodic variation of the transport coefficients is similar to an apparent power modulation that creates a secondary heat wave which propagates from that point toward the plasma edge. The interference with the initial heat wave can strongly distort the Fourier profiles of amplitudes and phase. Transport simulations using the empirical model mentioned in the introduction indicate that this effect is indeed occurring, leading in particular to $\chi_{Amp} > \chi_{Phase}$ as soon as the T_e profile is above the threshold in this region.

2.2. Modulation Experiments at Constant Heating Power

Additional experimental support to the conclusion of the previous sections can be provided by provoking direct local modulation of ∇T_e [9]. In the experimental practice two ECH beams, absorbed at slightly different radii, are alternatively switched on and off. This produces a heat flux $q_{e,H}$ which is almost constant outside the two absorption layers, but strongly modulated in between. A ∇T_e modulation will follow, accordingly to the dependence of χ_e on ∇T_e itself, if any. In addition, if χ_e is modulated with ∇T_e, a heat wave is internally generated by periodical capture/release of the stored energy. Quantitative analysis of the experimental results is based on two relations: from $q_{e,H} = -\chi_e \nabla T_e$ it follows $\Delta\overline{\chi} = \left(\Delta\overline{q} - \Delta\overline{\nabla T}\right)/\left(1 + \Delta\overline{\nabla T}\right)$, where $\Delta\overline{\chi} = \Delta\chi/\chi$, $\Delta\overline{q} = \Delta q/q$ and $\Delta\overline{\nabla T} = \Delta\nabla T/\nabla T$ are the relative changes in χ_e, $q_{e,H}$ and ∇T_e respectively. Secondly, χ_e modulation creates an apparent source term in the heat diffusion equation with a strength given by $P_{n.l.} = \Delta\overline{\chi}P_0$, where P_0 is the steady state heating power density. The existence of this non-linear term is revealed experimentally by the appearance of $\tilde{T}_e$ oscillations between the two absorption radii, where out-of-phasing would cancel $\tilde{T}_e$ if χ_e were independent on ∇T_e. FIG.4 shows the effects of the $q_{e,H}$ modulation performed at ρ_{tor}=0.5, where $\Delta\overline{\chi} = 0.3 \div 1$. A non-linear heat wave is clearly observed, providing direct proof that χ_e depends on ∇T_e (or on $q_{e,H}$). At ρ_{tor}=0.3, where $\Delta\overline{\chi} = 0.1 \div 0.3$ (weak stiffness) the non-linearity is much weaker, although it was so far not possible to explore non-stiff regions. These experiments that use a localized $q_{e,H}$ modulation are in agreement with a critical gradient length transport modeling

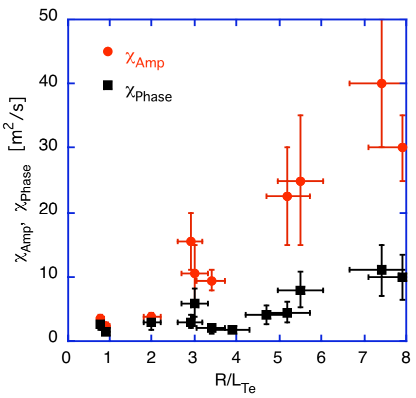

FIG.3. c_{Amp} and c_{Phase} versus R/L_{Te} showing the threshold around 3. The error bars for R/L_{Te} are relative, the absolute error bars are estimated to -1, +3 and lead a shift on the x-axis.

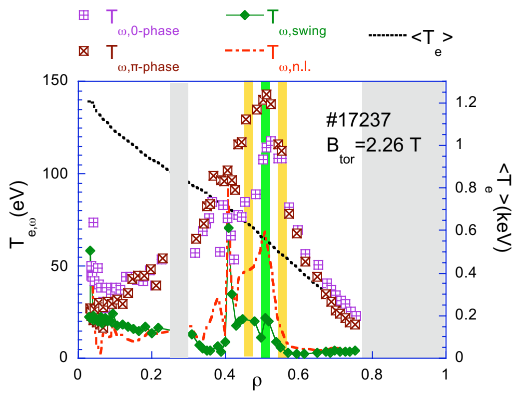

FIG.4 – Vertical lines mark r_{dep}s of EC beams modulated out-of-phase, each exciting an heat wave (squares). Linear combination would give a different result from actual measurement (diamond), because of the presence of a strong non-linear effect (dash-dot). Dashed line is the average T_e profile

2.3. Stabilization of TEM Turbulence by Collisionality

Theory predicts the TEM modes to be stabilized by collisions. To investigate this question, experiments have been carried out in which collisionality of ECH heated plasmas has been varied by increasing density. The ECH power of about 800 kW was deposited at $\rho_{tor} = 0.38$, with a ±10% power modulation to study the propagation of heat pulses. The density has been increased in a ramp from 2 10^{19} m^{-3} to 4 10^{19} m^{-3} during the 2 seconds of the ECH pulse. The electron temperature and its gradient decreased with increasing density and R/L_{Te} remained constant at about 10. The density profile also evolved such that R/L_n remained about constant. The ion temperature decreased, somewhat weaker than T_e, with R/L_{Ti} remaining about constant within the large error bars. The time averaged electron heat transport from power balance, χ_{PB} , decreases with increasing density by a factor of about 2 keeping roughly its profile, see FIG. 5. In contrast, χ_{HP} yielded by the analysis of the heat pulses propagating from the ECH deposition toward the edge, exhibits a very strong decrease with density, as also shown in FIG. 5. It even reaches a point where $\chi_{HP} < \chi_{PB}$, which is reversed compared to the usual situation. This behavior starts at the plasma edge and propagates toward the center as density further increases. The behavior of the ratio χ_{HP}/χ_{PB} versus the effective collisionality, is shown in FIG. 6 and can be explained as follows. As discussed above, in [Peeters IAEA04] and yielded by the gyro kinetic calculations for these discharges, at the beginning of the density ramp the TEMs dominate electron heat transport. However, as collisionality increases during the density ramp, the TEMs are gradually stabilized. Towards the end of the density ramp the TEMs do not dominate electron heat transport because of the stabilization. The electron heat flux, which is strongly reduced at the end of the ramp is mainly driven by the ITG. This is indicated by our gyro-kinetic calculations. Indeed we find that, at the experimental value of $R/LT_e \approx 10$, the heat flux and its slope decrease with increasing collisionality.

Whereas at low collisionality the TEMs dominate the electron heat transport, at high collisionality it is dominated by the ITG modes. The calculations also indicate that, in the experimental conditions existing at the end of the density ramp, the electron heat flux driven by the ITG is significant and depends very weakly upon R/L_{Te}.

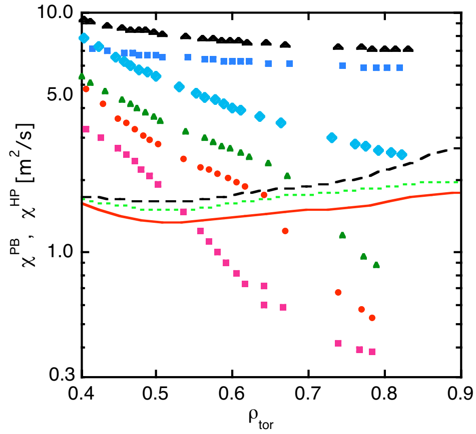

FIG. 5 χ_{PB} and χ_{HP} versus normalized radius for different time points during the density ramp. The ECH pulse was applied from 2 to 4 s.

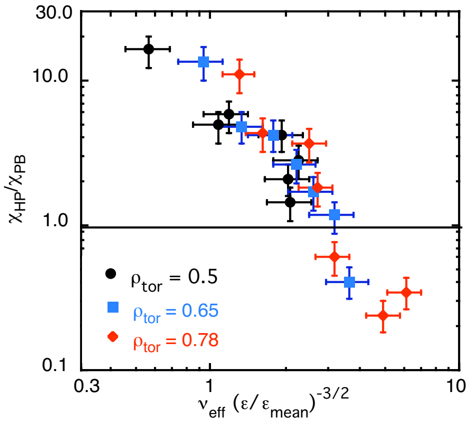

FIG. 6 χ_{HP}/χ_{PB} versus effective collisionality. The factor $(\varepsilon/\varepsilon_{mean})^{-3/2}$ is a rough normalization taking into account the dependence of collisionality on aspect ratio and the destabilizing effect of ε on the TEMs.

This explains the observation $\chi_{HP} < \chi_{PB}$. Thus these experiments and calculations demonstrate the stabilization of the TEMs by collisionality and a transition from TEM to ITG dominated transport.

3. Modulation Experiments in Ion Heated H-modes ($T_e \leq T_i$)

The electron heat transport in low density, NBI-heated, H-modes has been investigated in ASDEX Upgrade, using ECH, combining both steady-state and transient response analysis by applying modulated ECH (MECH) [10]. Under these conditions, the power delivered to the ions is $P_i > 0.6P_{NBI}$, while that going to the electrons is $P_e \sim 0.2P_{NBI}$. Due to the low collisional coupling, P_e is locally more than doubled by applying the ECH, while P_i is increased by less than 30%. The average ECH power varies from 0.4 MW during a first MECH phase to 1.2MW during a second MECH phase. The effect of the ECH on the main plasma parameters is weak. T_e increases to some extent only around the ECH deposition, while R/L_{Te} is unchanged. T_i and R/L_{Ti} are basically unchanged. In the confinement region, the T_e/T_i ratio varies between 0.5 and 0.7 in the NBI-only phase and between 0.8 and 1.0 when the ECH is also applied. Essentially no effect is observed in the density profile. The electron heat transport, assumed to be purely diffusive, is investigated with power balance (PB) and heat pulse (HP) propagation analyses based on the usual methods [2,3,5]. MECH power was deposited at 3 positions in ρ_{tor}= 0.1, 0.35, 0.55. Figures 7 and 8 summarize the results of both PB and HP analyses, performed at ρ_{an} = 0.25, 0.45. Figure 7 shows the dependence of q_e on $n_e\nabla T_e$ the ratio of which, by definition, yields χ_e^{PB}. The slope of the curve q_e versus $n_e\nabla T_e$ at each point is χ_e^{HP}, which is calculated from the HP analysis and is represented by segments at each full symbol. The points for the analyses made at the two different radial locations are clearly separated. Assuming for the heat transport a dependence on the gradient length, it is logical to plot q_e versus R/L_{Te}, as shown in figure 8. Here, the points from the two radial locations are clearly unified and the existence of a threshold or of a transition in the electron heat transport properties around $(R/L_{Te})_c$=6 is strongly suggested by the change of slope. A possible interpretation of these results is related to the most probable candidates believed to cause the anomalous transport, the coupled ITG/TEM and the ETG driven turbulence.

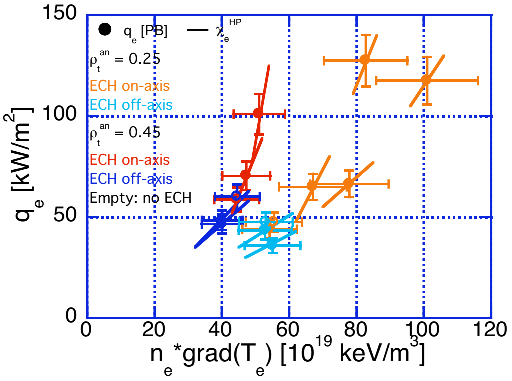

FIG. 7. Dependence of q_e on $n_e \nabla T_e$; the segments on the points are χ_e^{HP}.

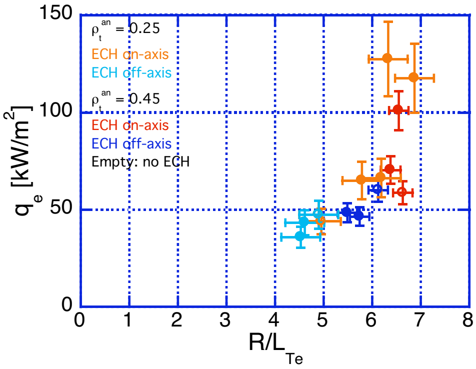

FIG. 8. Dependence of the q_e on R/L_{Te} for all discharges analyzed.

Using the GS2 gyro kinetic code, we have verified that in this experimental domain, the value $R/L_{Te} = 6$ does not correspond to an effective threshold for the TEM instability. This indicates that such value should rather correspond to the boundary between an instability domain in which the heat transport is weakly determined by R/L_{Te} (at $\rho = 0.25$, $R/L_{Te} < 6$, low heat flux) and a domain in which R/L_{Te} is a drive for the instability (at $\rho = 0.45$, $R/L_{Te} > 6$, high heat flux). This could in principle lead to a transition in the dominant modes governing the transport in the core and in the outer regions. Further investigation and experiments are needed in order to verify this possibility.

4. Heat Pinch Experiments

A number of experiments [11,12,13] have reported that, in conditions of localized off-axis electron heating, inward electron heat convection is observed. On the other hand, advanced fluid modelling of ITG/TEM turbulence predicts the existence of convective heat fluxes either due to the off-diagonal contribution of the ∇n_e term or to truly convective terms driven by the magnetic field in homogeneity (∇B) [14]. Detailed modulated ECH experiments with strong off-axis ECH power (P_{ECH}/P_{OH}>15) have been carried out in AUG [15] aiming at identifying the presence of an electron heat pinch both from the core power balance and from distortion of the heat wave amplitude profile at low frequency [8]. FIGs.9-10 illustrate the most remarkable results. The T_e profile (FIG.9) remains significantly peaked also when the whole ECH power (~1.6 MW) is located at ρ_{dep}~0.7 with an Ohmic power P_{OH}~80 kW. In these conditions using the available experimental information the core electron heat flux is estimated to be very close to 0, because the electron-ion power sink balances the Ohmic source. In addition, very flat amplitudes (FIG.10a) are observed at the lowest harmonics inside ρ_{dep}, opposite to the expectation of a stronger damping of the heat wave in low χ_e central regions, and at variance with the behaviour of the phases (FIG.10b) which rise sharply inside ρ_{dep}. Empirical simulations show that the results are consistent with the presence of a heat pinch v~2-4 m/s in the region inside ρ_{dep}. However first principle simulations using the Weiland model, although indicating the presence of a ∇n_e pinch driven by an ITG mode, do not yield a sufficient amount of pinch to reproduce the results [15]. In fact the intrinsic challenge of these experimental results is that they would require a significant amount of turbulence driven convection in a core region where the heat flux is small and therefore turbulence not fully developed. Further analysis and modelling work will hopefully lead to a full understanding of these experiments.

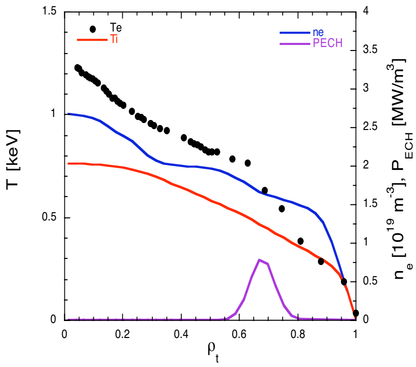

FIG.9. Time-averaged profiles of T_e, T_i, n_e during the stationary phase t=3.2-4 s..The ECH power deposition is also indicated.

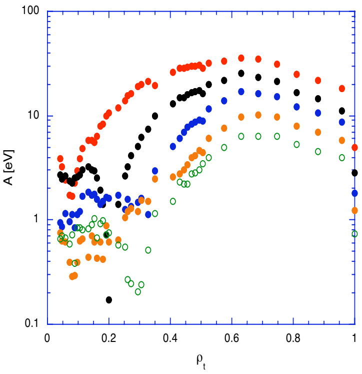

FIG.10a. Profiles of amplitude of the T_e heat wave at 5 harmonics of the modulation frequency (14.75 Hz).

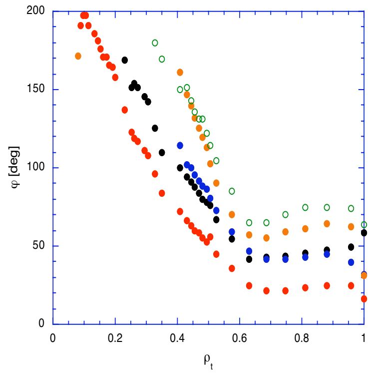

FIG.10b. Profiles of relative phase of the T_e heat wave with respect to power at 5 harmonics of the modulation frequency (14.75 Hz).

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