Density response to modulated EC Heating in FTU Tokamak.

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Introduction.

The empirical analysis of the electron density time evolution during modulated Electron Cyclotron Heating (ECH) in FTU L-mode ohmic discharges shows that the density drop and the resulting flattening of the density profile is not a by-product of plasma heating. Fourier analysis of density and temperature time traces clearly shows, in fact, that the density drop and the temperature rise in low collisionality plasmas are synchronous. This implies that the RF heating method is the common cause of both the electron heating and the density drop, but the lack of delay between the time evolution of the density and the temperature excludes that the electron temperature T_e or the measured ratio T_e/T_i are the cause of the flattening of n_e profile.

The generation of an energetic tail in the electron distribution function sustained by the RF injection likely determines a spatial diffusion of the energetic electrons [1]. This would suggest that collisions, rather than density or T_e/T_i, are the key parameter of the density profile response to the ECH heating. Indeed we observe that, in FTU discharges with effective collisionality $\nu_{eff}\propto(z_{eff}\langle n\rangle R/\langle T_e\rangle^2)<1$, the density profile peaking, $n_0/\langle n\rangle$, which in general increases by decreasing ν_{eff} [2,3], is seriously degraded by the ECH injection. When ν_{eff} is close to 1, on the contrary, the density peaking recovers its ohmic behaviour and the ECH power, by increasing T_e, reduces ν_{eff} and builds more peaked density profiles.

Plasma target and experimental results.

Plasma line density has been varied in the range $0.5 \leq n_e \leq 1.0\ 10^{20}\ m^{-3}$ and the EC power is injected at ~5 cm (ρ_{dep}~ 0.16) from the low field side as a ordinary wave at the fundamental harmonic (140 GHz). The RF power (~700 kW) with deposition depth of ~1 cm is 100% modulated with a 50% duty cycle at 20 Hz for about 300 ms i.e. for 6 complete cycles.

For all the FTU discharges of this experiment the toroidal field was 5.4 T and the plasma current I_p = 500 kA.

Plasma density is reconstructed with a time resolution better than 62 ms and space resolution of 1 cm by making use of a scanning interferometer [4] which works in the infrared range (λ=10.6 μm). Electron temperature is given by a fast ECE polychromator calibrated against a Michelson interferometer. Electron density and temperature are measured also by a Thomson scattering (TS) diagnostic with a spatial resolution of ~2 cm in the central region of the plasma and sampling frequency of 60 Hz. Peak ion temperature is computed by making use of the integral neutron emission and the density profile. In Fig.1 time traces of central electron and ion temperature together with peak plasma density are shown and compared to RF power modulation for a "low" ($n_{e0} \approx 0.51 10^{20} m^{-3}$) density discharge. It can be seen that both ion temperature and density decrease when RF power is injected in the plasma; the electron temperature is raised by the power injection. The decrease of the plasma density (see reconstructed profiles in Fig.2), commonly said "density drop", is a well known effect associated to the EC heating in low density discharges, the decrease of the ion temperature is also often observed and it is due to the reduction of the electron-ion collisions and the consequent lowering of the power flowing from the electrons to the ions. Numerical Fourier transforms of the time traces of Fig.1 allow a clear comparison, in the phases space, of the timing of the rise or drop of the physical plasma parameters under investigation. In Fig.3 cross phases with respect to the RF power at the fundamental harmonic (20 Hz) of density and temperature are shown. Density and temperature are in phase opposition ($\Delta\varphi$=180 deg) for the reason that the density drops while the electron temperature rises and synchronous. It is of critical importance to note here that, in spite of the fact that theese physical figures are synchronous, both the electron temperature and the density experience a finite and well detectable delay of ~60 deg (8.3 ms) with respect to the RF power. The RF heating is the common cause of the electron heating and the density drop, the lack of delay between the time evolution of the temperature and the density excludes that the electron temperature T_e or the measured ratio T_e/T_i (also shown in Fig.3) are the cause of the flattening of the n_e profile.

The theoretical explanation of the physical mechanism acting on particle confinement is beyond the scope of this work. Here we just remind that the particle diffusion induced by an unstable energy distribution function sustained by the EC heating has been addressed [1] as cause of the enhanced particle transport since from the early ECH experiments [5, and references there in]. In high density discharges (n_0~1.5 10^{20} m^{-3}), on the contrary, not only the density drop induced by the ECH disappears, but a clear increase of the central particle density shows up each time that the RF is injected (see Fig.4). Once again in Fig.5 cross phases of n_e and T_e with respect to the RF power are shown in polar coordinate; the cross phase of the ratio T_e/T_i (not shown in the figure) is almost overlapped to the one of T_e. In this high density case the n_e delay ($\varphi \sim 120$ deg) is about a factor two the T_e delay; in other words we see that the density reacts with its time constant, not differently from the previous low density case. In the high density case, however, T_e or T_e/T_i can be the cause of the density rise. The experiment made on FTU suggests that collisions are the key parameter of the density profile response to the ECH heating. Indeed we observe that in FTU discharges with low effective collisionality ($\nu_{eff} \propto z_{eff} \langle n \rangle R / \langle Te \rangle^2 < 1$), the density profile peaking, defined as the ratio between the peak and the mean density ($n_0/\langle n \rangle$), which has been shown to increase by decreasing ν_{eff} [2,3], is degraded by the ECH injection. When ν_{eff} is close to 1, on the contrary, the density peaking recovers its "ohmic" behaviour and the ECH power creates more peaked density profiles as shown in Fig.6. Theory of ion temperature gradient (ITG) and trapped electron modes (ETG) seem to cope with L and H-mode experiments in ASDEX-Upgrade [6]; in this reference the density drop happens in ETG dominated discharges due to a change of the T_e/T_i ratio induced by the ECH. High density ITG dominated discharges show no effect or small peaking in reaction to the EC heating. The interpretation of FTU and ASDEX-Upgrade experiments agree in the high density regimes while at low density the physical interpretation in terms of ETG modes fails in FTU experiments since it would be in contradiction with the cause-effect principle.

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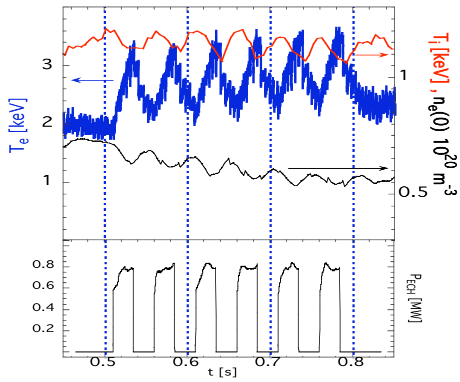

Fig.1. Electron, ion temperature and density peak values of shot #33177 vs time are shown together with ECH power.

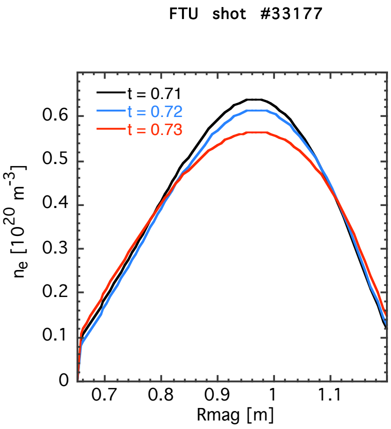

Fig.2. Electron density profiles at different time intervals of the ECH power pulse beginning at t=0.71 s.

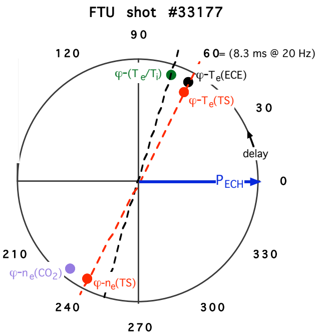

Fig.3. Cross phases, φ, (with respect to ECH power) of peak electron temperature and density (see Fig.1) measured by means of ECE (black dot), Thomson scattering (red), infrared interferometer (purple) and, in green, ratio of electron to ion peak temperatures.

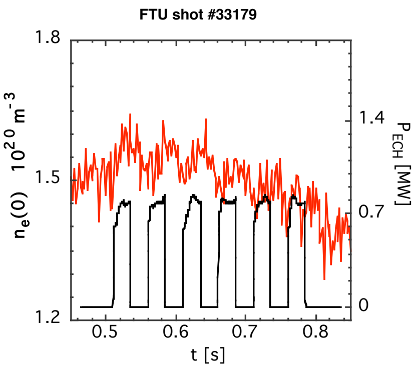

Fig.4. Peak density time traces of "high density" discharge #33179 is shown together with ECH power time distribution.

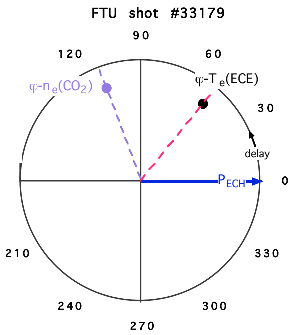

Fig.5. Cross phases, φ, (with respect to ECH power) of the peak density of Fig.4 and of the electron temperature as measured by the CO_2 interferometer (purple) and ECE (black dot) diagnostics in shot #33179.

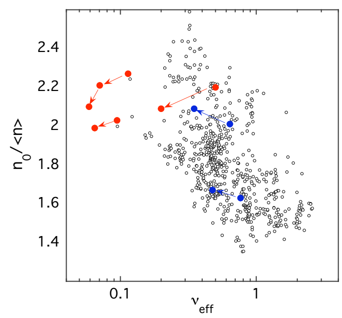

Fig.6. Density peaking of Ohmic FTU discharges B_T=6T I_p = 550 kA (gray symbols) vs ν_{eff} is shown together with EC heated discharges. Arrows point from OH to RF heated regimes