Comparison of Plasma Response to ECRH at the First and Second Harmonics at T-10 Tokamak

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In T-10, ECRH at first harmonic has been widely used since 1980. Gyrotrons at two different frequencies have been employed to heat plasma simultaneously (e.g. see [1] and references therein). Later (since 1992), new gyrotrons (130/140 GHZ) have been installed. Increased frequency has allowed us to heat plasma at the second harmonic only.

Profiles of absorbed ECRH power are wider at ECRH at first harmonic compare with the heating at the second harmonic [2]. The physics of the absorption of EC-waves at the second harmonic is complicated and strongly depends on plasma parameters (e.g. electron temperature T_e). The main task of the present paper is the comparison of not-stationary processes occurred in T-10 under ECRH at different harmonics.

1. Internal Transport Barrier Formation at on-axis ECRH imposed at sawteeth-free background formed by off-axis heating

It is well-known that, in L-mode, occurs enhanced heat pulse propagation (HPP). Enhanced HPP describes with “dynamic” electron heat diffusivity coefficient $\chi_e^{HP} \approx 2\text{-}4\chi_e$ (χ_e - electron heat diffusivity coefficient obtained from power balance). Enhanced HPP was explained by the rise of χ_e together with the increase of $\nabla T_e/T_e$ during HPP [3].

The fully opposite case with ($\chi_e^{HP} < \chi_e$, χ_e^{HP} =0.14 m^2/s , χ_e =0.35 m^2/s) was found during slow and diffusive HPP induced by central ECRH-onset (0.36 MW) in a sawtooth-free plasma created by off-axis ECRH (0.9 MW) [4] at T-10 with first harmonic ECRH. We interpreted this phenomenon as the decay of χ_e during the rise of $\nabla T_e/T_e$ [4]. The density profile was constant within 15ms after central ECRH-on.

Similar slow HPP (χ_e^{HP} =0.2 m^2/s , χ_e =0.3 m^2/s) has been observed at ECRH at second harmonic [5]. Figure 1a) shows the evolution of Te (r/a=0.07) at three shots 32914 [5], 32917, 32918 with $P_{on\text{-}axis}$ = 0.55, 0.3, 0.22 MW at sawteeth-frre background created by off-axis heating with $P_{off\text{-}axis}$ = 0.5 MW. HPP analysis shows smilar values of χ_e^{HP} =0.2 m^2/s in three shots. A simple expression to evaluate $\chi_e(r,t)$ variation during slow HPP have been proposed in [6]: $\chi_e \approx (\chi_e^{HP}\ \nabla\delta T_e\ /\ \nabla T_{e0} + \chi_{e0})\ /\ (1+\nabla\delta T_e\ /\ \nabla T_{e0})$, index zero represents steady-state values before HPP. Figures 1b-c) represents the evolution of χ_e

during slow formation of ITB with ECRH at the first and second harmonic heating. The gradual decay occurs in both cases.

Another not-stationary process is a so-called “density pump-out” at central ECRH well known at the heating on the first [7] and second harmonic heating. The variation of normalized line-averaged electron density δLn(r/a)/ Ln(r/a) at 10 ms interval in shots 32914 and 32917 ($P_{on-axis}$ / $P_{on-axis}$ =1.1, 0.6) is shown in figure 1d). The decay of density strongly depends on the value of $P_{on-axis}$ / $P_{on-axis}$ and nearly absent in shot 32918 with $P_{on-axis}$ / $P_{on-axis}$ =0.4 (small variations not shown). The absence of n_e evolution in shot 32918 is similar to experiments with first harmonic heating and $P_{on-axis}$ / $P_{on-axis}$ =0.4.

2. On-axis ECRH in L-mode with sawteeth oscillations

At ECRH on first harmonic, density pump-out strongly depends on the value of ECRH power in the regimes with high values of q [8] (I_p= 180 kA, B_t=3T, a_L=32 cm, q_L=6).

At present experiments (analysis not completed yet), density pump-out strongly depends on the q_L value. Figures 2a) and 2b) shows the evolution of line-averaged densities and T_e(r/a=0.05) in shot 32913 (I_p= 180 kA, B_t=2.3T, a_L=30 cm, q_L=3.8, $P_{on-axis}$=0.55 MW) and in shot 57446 (I_p= 240 kA, B_t=2.3T, a_L=30 cm, q_L=2.8, $P_{on-axis}$=0.6 MW). Figure 2a) show immediate decay of central density while figure 3b) clearly demonstrates the time delay order of 10-12ms.

It was shown by us earlier [9], that the fast decay of sawteeth-induced rise of T_e represents the phase of enhanced transport after the crash [9] during 0.5 ms (P=1 MW) in T-10 and 1-2 ms in JET [10]. The method described in [10] allows us to analyze the approximate time behavior of χ_e after the crash. Figures 3a-b) represents the evolution of T_e(r/a=0.4, 0.5, 0.6) during crashes in shot 57446 (see fig. 2b). The series of similar shot with the variation of reflectometer channels position was produced. Surprisingly, the phase of enhanced transport has not been found and usual L-mode values χ_e^{HP}~1.5 m^2/s have been obtained. The reflectometer [7] data also do not show enhanced level of fluctuations shortly after the crash.

3. Summary

Dynamic of ITB formation induced by on-axis ECRH imposed on off-axis heated sawteeth-free background is similar in experiments with 1-st and 2-nd harmonic ECRH

Density pump-out induced by on-axis ECRH imposed on off-axis heated sawteeth-free background strongly depends on the level of on-axis power and is nearly absent at $P_{on-axis}/P_{off-axis}$=0.4 in experiments with 1-st and 2-nd harmonic heating.

At present experiments with central ECRH imposed at OH background with sawteeth oscillations(analysis not completed yet), density pump-out strongly depends on the q_L value and time delay of 10-12 ms has been observe in experiments q_L =2.8.

Analysis of the decay rate of the sawteeth-induced rise of Te shows value ceHP ~1.5 m2/s. Surprisingly, strong sawteeth oscillations (with the rise of T_e (0) up 40% between the crashes) do not create phase with enhanced transport. We expected to observe 300- 500 microseconds phase with an enhanced transport after a strong crash. The reflectometer data also do not show enhanced level of fluctuations shortly after the crash. These phases were observed in JET during 1-2 ms after crashes and in T-10 (0.5 ms with stronger heating at first harmonic) earlier. We should repeat these experiments with higher power.

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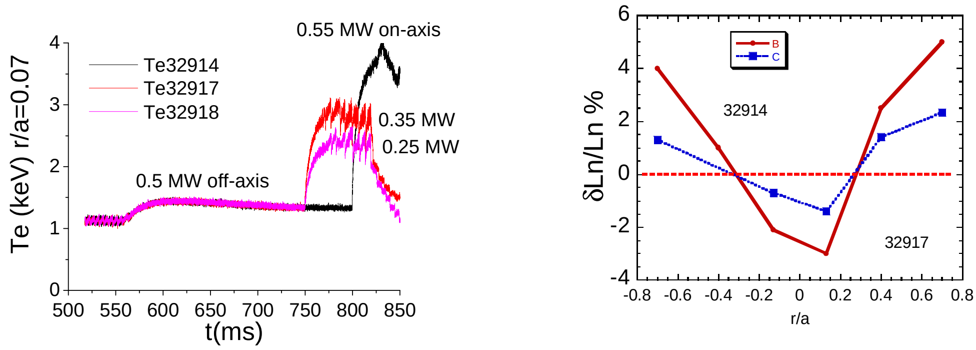
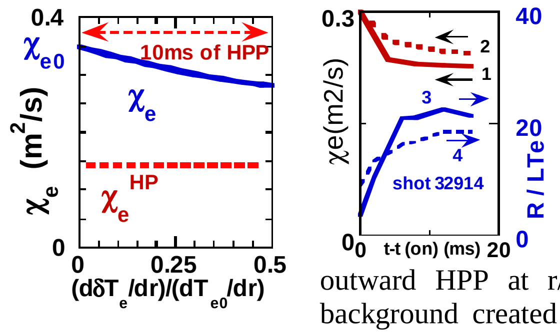
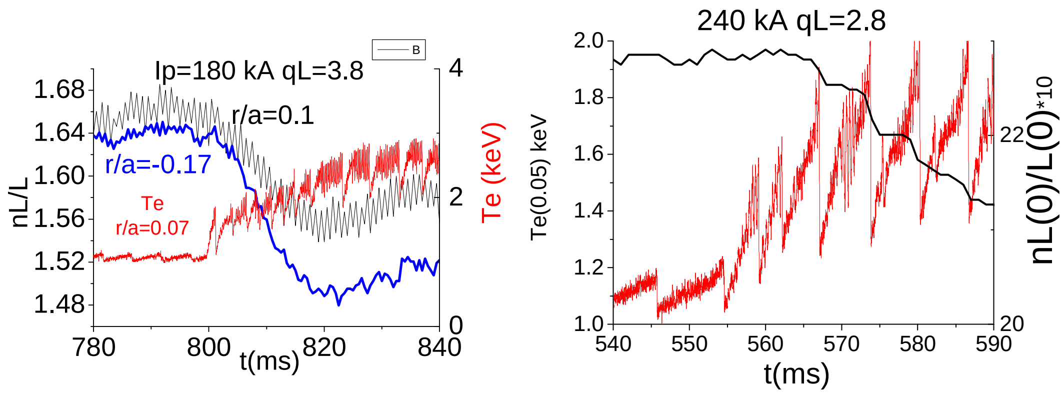
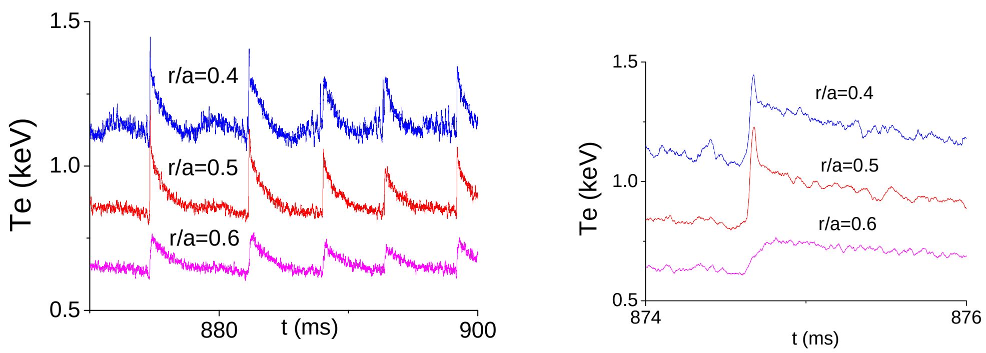




Figures 1. a) evolution of Te at three shots with $P_{on\text{-}axis}$ = 0.55, 0.3, 0.22 MW and $P_{off\text{-}axis}$ = 0.5 MW. b) The variation of normalized line-averaged electron density $\delta Ln(r/a)/ Ln(r/a)$ at 10 ms interval, small variation in shot 32918 not shown. c-d) Dependence of χ_e on $\nabla\delta T_e /\nabla T_{e0}$ during outward HPP at r/a=0.45 induced by central ECRH-on at the background created by off-axis ECRH [4](first harmonic heating) and in shot 32914 at r/a=0.27, 0.34 (second harmonic heating).



Figures 2a-b) evolution of line-averaged densities and $T_e(r/a=0.05)$ in shot 32913 (I_p= 180 kA, B_t=2.3T, a_L=30 cm, q_L=3.8, $P_{on\text{-}axis}$=0.55 MW) and in shot 57446 (I_p= 240 kA, B_t=2.3T, a_L=30 cm, q_L=2.8, $P_{on\text{-}axis}$=0.6 MW).



Figures 3a-b) the evolution of $T_e(r/a=0.4, 0.5, 0.6)$ during crashes in shot 57446 (see fig. 2b).