Study of electron heat and density flux structure during some transient processes created by ECRH in T-10 tokamak

S.V. Neudatchin, A.A Borshegovskii, V.V. Chistyakov, E.P. Gorbunov, S.G. Maltzev, T.B. Myalton, D.S. Sergeev, D.A. Shelukhin

NRC "Kurchatov Institute", 1 Kurchatov sq, 123182 Moscow, Russian Federation

The heat flux in the outer part of plasma column in L-mode T-10 experiments with central ECRH (or outside of EC resonance position at off-axis heating) represents L-mode transport (besides cases with ITB-formation, see e.g. [1] and references therein). In the present report, we focus on the analysis of three transient transport processes in the central part of plasmas with ECRH at 2nd harmonic with 130/140 GHZ gyrotrons and power up to 3 MW.

1**. Analysis of inward heat pulse propagation induced by off-axis ECRH imposed on sawtooth-free background created by off-axis ECRH**

First, we analyze inward electron heat pulse propagation (HPP) on a sawtooth-free background with low shear and q near 1 created by 0.5 MW off-axis ECRH in 180 kA/2.33 T shot 32913 (major radius R=150 cm, limiter radius a_L=29 cm). The inward HPP was created by switch-on of additional off-axis ECRH with 0.35 MW power. Figures 1 (a-b) show T_e timetraces (ECE measurements) at r/a= -0.25 and r/a= -0.05. A time delay of 5 ms is clearly observed at T_e(r/a=-0.05). The bold line in figure 1(b) represents the result of calculations with "dynamic" electron heat diffusivity coefficient χ_e^{HP} ≈0.25 m^2/s (T_e(r/a= -0.25) is boundary condition, see details of similar calculations in [1]). Slow and diffusive inward heat pulse propagation has been observed for both sides of the plasma column simultaneously (-0.25<r/a<0.3) with χ_e^{HP} ≈0.4 m^2/s at LFS of the plasma column. The influence of the Joule term decay has been estimated as 10%. The values of χ_e^{HP} in a similar shot 32907 are equal to 0.2 m^2/s at HFS and 0.3 m^2/s at LFS. The value of electron heat diffusivity coefficient obtained from the power balance χ_e ≈0.3 m^2/s. The obtained value of "dynamic" electron heat diffusivity is similar to the power balance value, while the so-called "heat pinch" is either absent or very small. In our previous similar experiments with the 1st harmonic heating [2] the narrow central zone (0<r/a<0.15) has been studied. Similar conclusion was made after analysis of the inward HPP at JET, created by off-axis ICRH switched-on [3].

2. Analysis of sawtooth density oscillations

Analysis of sawtooth density oscillations was performed in one ohmic T-10 regime earlier [4] (I_p= 200 кA, B_z =1.5 T, $n_e(0) = 2\cdot 10^{19}$/m^3). The build-up of n_e in the centre between the crashes was explained by the presence of neoclassical electron pinch velocity. Figure 2 (a-b) shows timetraces of line-averaged density $n_eL(r)/L(r)$ in OH phase of shot 31491 (240кA/

2.36T, q_L=2.8 NL/L(0)=3.3x10^{19}/m^3) and in the ECCD phase with almost stabilized sawtooth in 280кA/2.3T discharge 32452 (period up to 25 ms).

Within the errorbars of the neoclassical theory, pinch velocity is nearly linear in the central part of plasma column (V_p= αr) and $\delta n_e = 2\alpha t n_e$ between the crashes. We estimate the value of α from simple expression δn_e (4cм)/ n_e (4cм) = {L(4cm)/ (r_s -4cm)(geom)}·
[δ(nL(4cм))/ L(4cm)]/ n_e (4cm) = 2αt , where r_s is inversion radius, geom. – geometrical parameter of $\delta n_e(r)$ profile (e.g. equal to 0.5 for linear profile at 4cm<r< r_s, and equal to 0.7 in our calculations). For example, V_p= -0.06 m/s at r/a=0.2 in shot 32452 with ECCD.

Our previous conclusions are confirmed in the present study in various regimes (I_p up to 300 кA, B_z =2.3-2.5 T, $n_e(0)$ up to 5x10^{19}/m^3). In Ohmic regimes, in regimes with central ECRH with small power and in experiments with ECCD to damp sawtooth oscillations (with period of oscillations up to 30 ms), the value of V_p is close to neoclassical value in the central part of plasma column (0.05-0.1 m/s at r/a=+/- 0.2).

3. Electron density pump-out at ECRH with power up to 3 MW

The electron density profile n_e flattens after ECRH-on (so-called "density pump-out") and "pump-out" rises with power. Figure 3(a-b) shows the profiles of n_e (r) before and 13 ms after ECRH with 1.2, 2.1 MW (240 kA/2.36T) and 3 MW (200 kA/2.4T) power. The variation of the outward n_e flux (averaged by 12 ms time interval) rises two times with the increase of P_{ECRH} from 1.2 MW to 2.1 MW at 2^{nd} harmonic heating reminding that observed at 1^{st} harmonic [5]. Under P_{ECRH} > ~ 1.5 MW, the n_e profiles become hollow (or flat within the errorbars) at r/a<0.5 (probably due to appearance of outward convective n_e flux). The rise of outward n_e flux could be explained with the appearance of outward convective pinch velocity δV_p (r/a=0.4) = 0.5 m/s, 1 m/s , 1.2 m/s at 1.2 MW, 2.1 MW and 3MW heating (averaged at 12 ms time interval, the rise of diffusivity and neutral influx is not taken into account). The δV_p values should be treated as underestimated especially at 3MW shot with smaller density and stronger rise of neutral influx.

Figure 3(c) presents sawtooth density oscillations at 2.1 MW heating (see profiles in fig. 3(a)). Oscillations look like crashes with inverted phase (rise at r=+/- 4cm and decay at r=12 cm) and are observed in many shots. The presence of the inverted phase independently confirms the existence of hollow n_e profiles and outward V_p in steady-state phase of discharges with P_{ECRH} > ~ 1.5 MW.

Pump-out increases significantly with the inward shift (within sawtooth inversion radius) of the resonance position under low q_L. Figure 4 shows the evolution of $T_e(0)$ and $n_eL(0)/L(0)$ in shots 57446 (240kA/2.3T, q_L=2.8) and 57454 (240kA/2.17T, q_L=2.64) with resonance position shifted inside by 8 cm. The value of $n_eL(0)/L(0)$ decays stronger in shot 57454.

4. Conclusions

1. First, we analyzed inward electron heat pulse propagation (HPP) on a sawtooth-free background with low shear and q near 1 created by off-axis ECRH. The inward HPP was created by switch-on of additional off-axis ECRH. Slow and diffusive inward heat pulse

propagation was observed for both sides of the plasma column simultaneously (-0.25<r/a<0.3). The obtained value of “dynamic” electron heat diffusivity is similar to power balance value (~0.3 m^2/s) while the so-called “heat pinch” is either absent or very small.

2. In the present study in various regimes (I_p up to 300 кA, B_z =2.3-2.5 T, $n_e(0)$ up to 5 $10^{19}/m^3$) the build-up of n_e in the centre between the crashes is explained by the presence of neoclassical electron pinch velocity. In the OH regimes, in the regimes with central ECRH with small power and in the experiments with ECCD current drive to damp the sawtooth oscillations (with the oscillation period up to 30 ms), the electron pinch velocity value is close to the neoclassical one in the plasma centre (from -0.05 to -0.1 m/s at r/a=+/- 0.2).

3. The electron density profile n_e flattens after ECRH-on (so-called “density pump-out”) and “pump-out” rises with power. For example, the variation of the outward n_e flux (averaged by 12 ms time interval) rises two times with the increase of P_{ECRH} from 1.2 MW to 2.1 MW at 2nd harmonic heating reminding that of at 1st harmonic [5]. At P_{ECRH} > ~ 1.5 MW, the n_e profiles become hollow (or fully flat within the errorbars) at r/a<0.5 (probably by the appearance of outward convective n_e flux). Pump-out strongly depends on the q_L value [6] and increases significantly with the inward shift (within sawtooth inversion radius) of the resonance position under low q_L. At P_{ECRH} > ~ 1.5 MW, we frequently observed sawtooth density oscillations which look like oscillations with inverted phase (rise at r=+/- 4cm and decay at r=12 cm). The presence of the inverted phase independently confirms the existence of hollow n_e profiles and outward V_p in steady-state phase of discharges. Nevertheless, we should further study the density pump-out and sawtooth oscillations at higher density during new experimental T-10 campaign in autumn 2012. Authors are grateful to Drs. N.A. Kirneva and D.A. Kislov for fruitful discussions. The research was supported by grants N 16518.11.7004 by Rosnauka and N H4x.45.90.12.1023 by Rosatom.

[1] Neudatchin S V., Kislov A. Ya, Krupin V. A. et al 2003 Nucl. Fusion 43 1405
[2] Bagdasarov A. A., et al 1990 17th EPS Conf. on Contr. Fus. and Pl. Ph. (Venice,) v.I, p 83
[3] Balet B., Boucher D., Cordey J.G., Muir D.G., Neudachin S.V., Shmidt G.1992 19th EPS Conf. on Contr. Fus. and Pl. Ph. (Innsbruck) v.I, p 59
[4] Dnestrovskij Yu.N., Neudachin S.V., Pereverzev G.V. Sov. J. Plasma Physics 1984 p 236
[5] Vasin N.L. et al 1985 12th EPS Conf. on Contr. Fus. and Pl. Ph. (Budapest) v.2, p 68
[6] Neudatchin S.V. et al 2011 38th EPS Conf. on Contr. Fus. and Pl. Ph. (Strasbourg) P 4.132

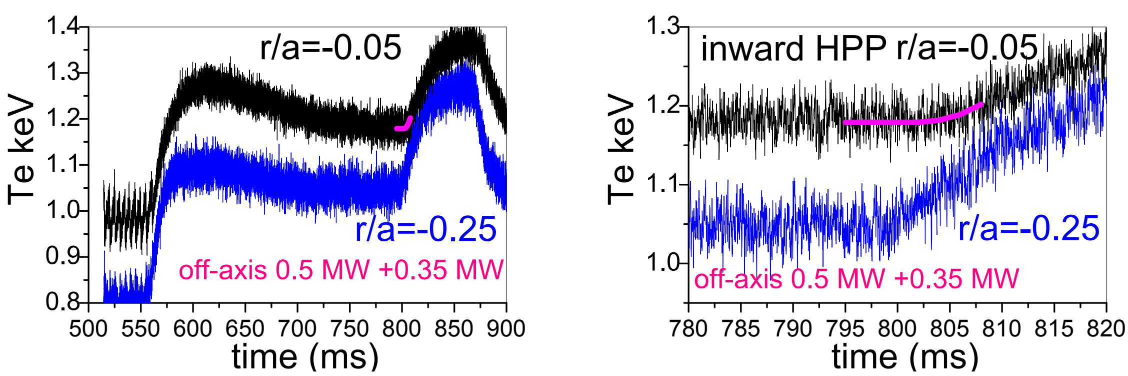


Fig 1(a-b). T_e timetraces at r/a= -0.25 and -0.05, bold line- calculations with χ_e^{HP} =0.25 m^2/s

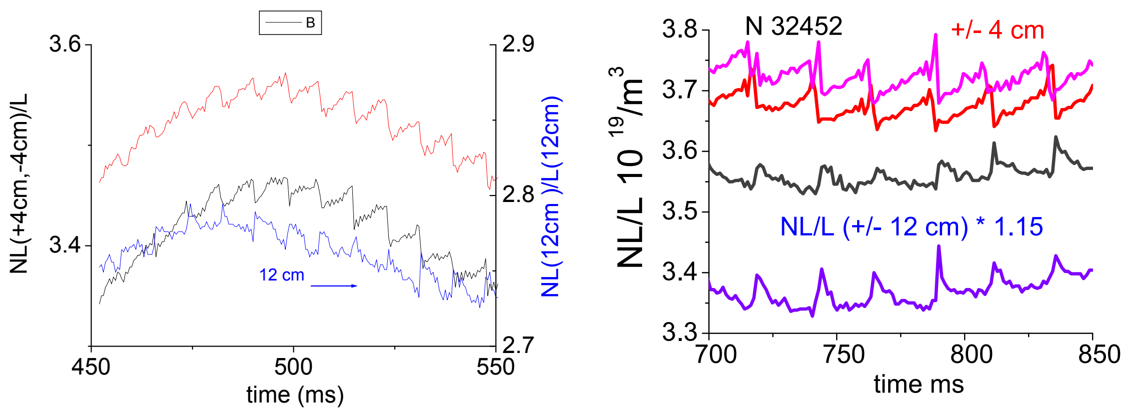
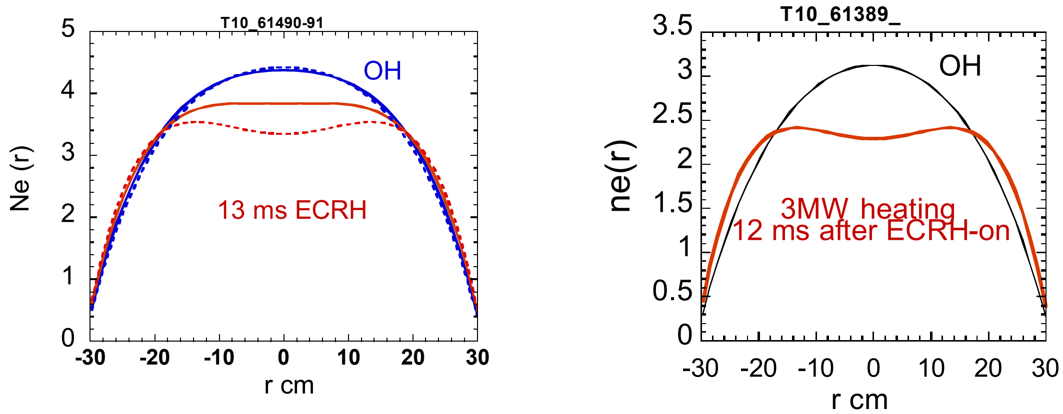


Fig. 2(a-b) Sawtooth density oscillations in OH plasmas and ECCD experiments



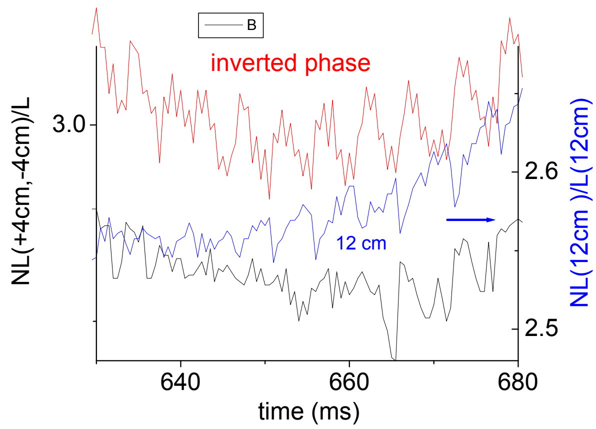


Fig. 3(a-c) a) n_e profiles in OH and after 13 ms of ECRH with 1.2 MW and 2.1 MW (dashed line). b) n_e profiles in OH and after 12 ms of ECRH with 3 MW. c) Sawtooth density oscillations with inverted phase at 2.1 MW ECRH (see fig. 3(a)).

Fig. 4. Evolution of Te(0) and central line averaged density $n_eL(0)/L(0)$ in shot 57446 (red and brown lines, central ECRH) and in shot 57454 black and blue lines, ECRH shifted inward at r/a=-0.3). The central density decays stronger while Te(0) rises weaker with the resonance position shifted inward.