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Study of Electron Heat Pulse Propagation induced by ECRH/on-off on T-10 and LHD

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Abstract

Internal Transport Barrier (ITB) has been found at T-10 earlier by means of heat pulse propagation (HPP) and cold pulse propagation (CPP) analysis in target sawteeth-free plasma created by off-axis ECRH. Regimes with higher current (up to 0.22 MA) and density (central electron line-averaged density $\bar{n}_e$ up to $2.7\times10^{19}/m^3$), and various input power of the non-central ECRH are described in the present paper. Outward HPP was created by switching on the on-axis ECRH. Inward CPP was created by turning-off the off-axis ECRH. In both cases, $R/L_{Te}=R\nabla T_e/T_e$ rises significantly (up to 23) above Ohmic value on heat (cold) wave front, meanwhile dynamic electron heat diffusivity χ_e^{HP} values are low (0.06–0.25 m^2/s). CPP analysis shows important new feature. χ_e^{CP} values increase by ~3 times (from minimum level ~0.1 m^2/s inside $r/a < 0.4$ either by variation of the resonance position at the same off-axis power or by increase of power level. In all cases stronger redistribution (increase of wideness) of $T_e(r)/T_e(0)$ profile (normalized to OH level) leads to the increase of χ_e^{CP}. Probably, $\chi_e^{CP} \approx 0.1$ m^2/s corresponds to some "optimal" profile of safety factor q with low shear zone and $q(0)$ slightly above 1; χ_e^{CP} values rise under higher values $q(0)$.

Results of HPP/CPP study at LHD low density discharges show that HPP/CPP propagate in non-diffusive manner. In contrast, purely diffusive HPP ($\chi_e^{HP} \approx 1.5$ m^2/s at $0.2 < r/a < 0.4$) is observed in some LHD shots with moderate density and NBI power.

Keywords:

heat pulse propagation, cold pulse propagation, electron cyclotron resonance heating, internal transport barrier, dynamic electron heat diffusivity

1. Introduction

In the previous T-10 experiments [1], target sawteeth-free plasma was created either by high-field-side (HFS) off-axis electron cyclotron resonance heating (ECRH) with 140 GHz frequency or by low-field-side (LFS) off-axis ECRH (130 GHz) at $r/a \approx$ +/- (0.45). Regimes with 0.18MA/2.3–2.5T, limiter radius a_L= 0.29m, major radius R=1.5m, central line-averaged electron density $\bar{n}_e$ varied from 1.4 to $2.1\times10^{19}/m^3$ (normalized to camera radius 0.38m) were studied. Outward heat pulse propagation (HPP) with dynamic electron heat diffusivity $\chi_e^{HP} \approx$ 0.2–0.3 m^2/s at $0.2 < r/a < 0.37$ was created by on-axis ECRH (130 or 140 GHz) imposed on the target created by off-axis ECRH. At HPP front, $R/L_{Te}=R\nabla T_e/T_e$ rises up to 23 (Ohmic value of R/L_{Te}=10). These data confirm our old similar result [2]. Inward cold pulse propagation (CPP) was created by turning off the off-axis ECRH. At the cold wave front R/L_{Te} value rises up to 17. Slow inward CPP is well described by $\chi_e^{CP} \approx 0.1$ m^2/s at $r/a < 0.3$ in a ~20 ms time interval limited by the appearance of the first sawteeth oscillation. The combination of large gradients with low transport indicates the presence of Internal Transport Barrier (ITB) formed in low magnetic shear region with q (safety factor) slightly above 1. Nowadays, the dependences of χ_e^{PB} on $R/L_{Te}=R\nabla T_e/T_e$ and $\nabla T_e/T_e$ are usually discussed ("critical gradient" models). In the context of a "critical gradient" model, Ohmic value of R/L_{Te} lies above the "critical" one because enhanced HPP (induced by sawteeth or on-axis ECRH) is observed at all tokamaks at Ohmic background. In present paper, we analyse CPP and HPP characteristics in wider parametric range (0.18–0.22 MA shots with $\bar{n}_e$ up to $2.7\times10^{19}/m^3$) at various level of ECRH power and resonance position.

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Contradictory picture given by the results of HPP/CPP analysis in low density LHD plasma is described and discussed. The evidences of ITB existence (laser data) are observed in these shots after application of nearly central ECRH (e.g. see [3-5]). At higher density, HPP is fully diffusive.

2. Analysis of HPP/CPP in T-10

The variation of CPP characteristics with the shift of resonance position will be our initial concern. The inward CPP in cases described below is induced by the reduction of the off-axis ECRH in two steps. Fig. 1(a) displays the timetraces of $T_e(0)$ and ECRH power $P_{ECRH}(t)$ in 0.18 MA shots 34573 and 34575 ($\overline{n}_e \approx 2.1\times10^{19}/\mathrm{m}^3$, safety factor at limiter q_L=4, all parameters are the same besides B_t). The resonance lies at $r/a \approx -0.45$ for shot 34573 (toroidal magnetic field B_t=2.34 T) and at $r/a \approx -0.38$ for shot 34575 (B_t=2.38T). $T_e(0)$ response to first reduction of power at t=0.86s is obviously lower in shot 34575, thus the position of resonance lies closer to the plasma centre. CPP is analysed with numerical solution of the simplified transport equation for δT_e, as usually, with boundary condition taken from experiment at r/a=0.3 (see details e.g. in [1,6]). Slow inward CPP with $\chi_e^{CP} \approx 0.1$ m^2/s inside $r/a < 0.3$ is found in shot 34575 for 23 ms time interval. Faster CPP with $\chi_e^{CP} \approx 0.3$ m^2/s is obtained for 15 ms time interval in shot 34573. Later, sawteeth oscillations appeared in shot 34575 but were not observed in shot 34573. Analysis of CPP after final power switching-off at t=0.955s in shot 34573 shows the reduction of χ_e^{CP} in 2–3 times inside r/a=0.3 in comparison with t=0.86s. R/L_{Te} rises at cold wave front up to 14 (1.4 OH value at r/a=0.26) instead of the increase up to ~7 (below OH value) during the same 15ms time interval analysed after t=0.86s. The variation of CPP characteristics with ECRH power was studied in various plasmas. Fig. 1(b) displays the timetraces of $T_e(0)$ and $P_{ECRH}(t)$ for another pair of shots (0.18 MA/ 2.34T, $\overline{n}_e \approx 2.1\times10^{19}/\mathrm{m}^3$) with different P_{ECRH} (~0.45 MW in shot 35762 and ~0.25MW in 35764). $T_e(0)$ responds to power cut-off in obviously different manner. CPP with $\chi_e^{CP} \approx 0.1$ m^2/s (shot 35764) and ~0.3 m^2/s (shot 35762) inside $r/a <$ 0.3 is found in 15 ms time interval (with R/L_{Te} ar r/a=0.27 rises up to 11 in both cases). Estimations show that $q(0)$ (q value in the centre) for shot 35762 is higher, and the analysis with ASTRA transport code [7] is in progress. The decay of $T_e(0)$ stops before first sawteeth crash in shot 35762 (see interruption of diffusive CPP observed as disappearance of decay at time shown by second vertical line in Fig. 2). In many shots with $\chi_e^{CP} \approx 0.3$ m^2/s, after the period of T_e decay, the rise of T_e in the central region (inside r/a < 0.15) is observed before the first sawteeth crash. The rise of T_e could be explained by abrupt reduction of χ_e in the central region (estimated level of χ_e variation $\delta\chi_e \approx -0.12$ m^2/s at r/a=0.15). Probably, q reaches the value of 1 at the time of χ_e reduction.

The redistribution of T_e profile at ECRH shown in Fig.

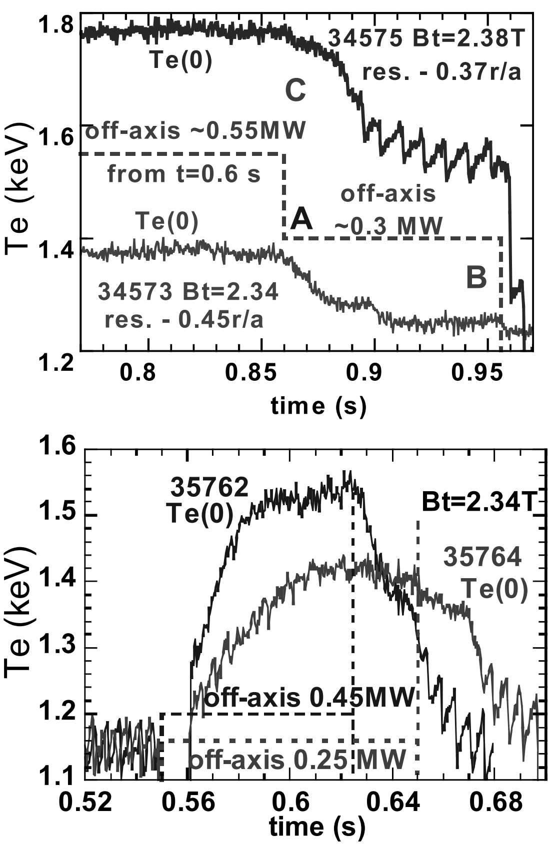

Fig. 1 (a) Variation of $T_e(0)$ response with resonance position. (b) Same with ECRH power.

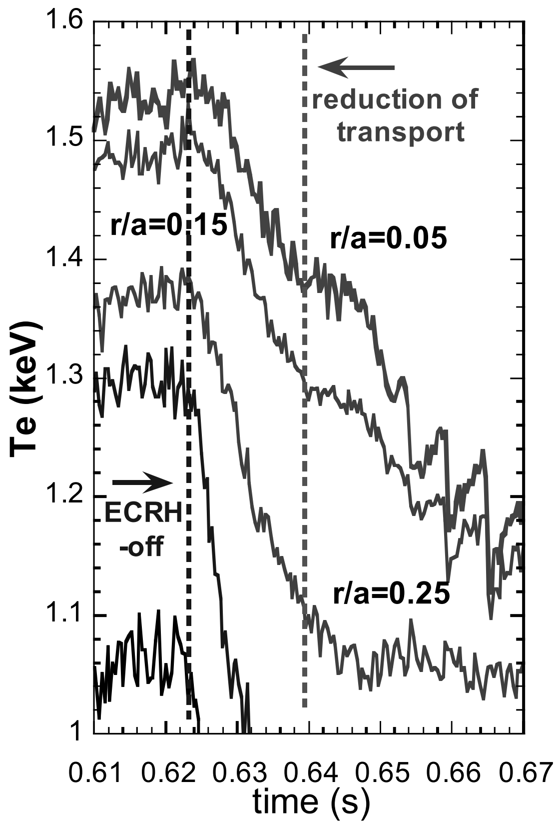

Fig. 2 Interruption of diffusive CPP by abrupt decrease of transport in central zone (observed as disappearance of decay at time shown by second vertical line).

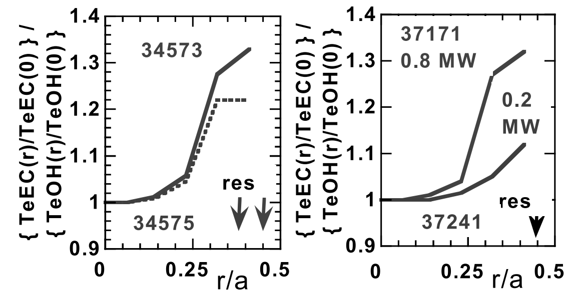

Fig. 3 Comparison of T_e wideness factor for (a) 0.18MA shots 34573 and 34575 (see Fig. 1(a)). (b) 0.22MA shots 37241 ($\chi_e^{CP} \approx 0.1$ m^2/s) and 37171 ($\chi_e^{CP} \approx 0.25$ m^2/s) with different power.

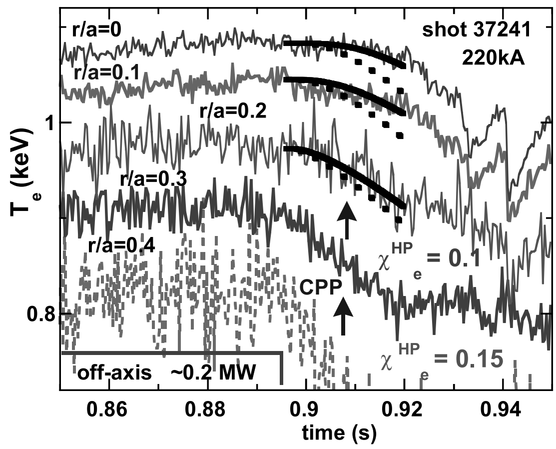

Fig. 4 CPP at 0.22MA/2.33T, $\bar{n}_e \approx 2.7\times10^{19}$/m^3, bold and dotted lines represent calculations with χ_e^{CP} = 0.1 m^2/s and 0.2 m^2/s.

1(a) could be presented by the profile with the wideness of $\{T_{e\,EC}(r)/T_{e\,EC}(0)/\}/\{T_{e\,OH}(r)/T_{e\,OH}(0)\}$ shown in Fig. 3 (a), which is higher in shot 34573. It seems that χ_e^{CP} values vary due to difference in q profiles, which should have higher $q(0)$ values at t=0.86s in shot 34573 in comparison with shot 34575 and in shot 34573 at t=0.955s (Z_{eff} profiles are not well known for these pulses).

The dependence of CPP characteristics on ECRH power is observed also in 0.22MA/2.33T shots (q_L=3.3) with $\bar{n}_e \approx 2.7\times10^{19}$/m^3. The wideness of T_e shown in Fig. 3 (b) is visibly higher in shot 37171 (0.8 MW) compared with shot 37421 (~0.22 MW of ECRH power). Figure 4 shows the timetraces of T_e in shot 37421. Calculations with χ_e^{CP} = 0.1 m^2/s inside r/a < 0.3 are shown by bold solid lines in Fig. 4 (dotted bold lines are calculated with χ_e^{CP} = 0.2 m^2/s) and $\chi_e^{CP} \approx 0.15$ m^2/s at 0.3 < r/a < 0.4. 2.5 times higher values of χ_e^{HP} (inside r/a=0.3) are found in similar shot 37171 with ~0.8 MW of ECRH power.

In the case of HPP induced by central ECRH-on, according to our observation χ_e^{HP} does not depend on density (at $\bar{n}_e$ = 1.4–2.7×10^{19}/m^3) or on the level of on-axis power.

3. Analysis of HPP/CPP in LHD

First, we analyse ECE (electron cyclotron emission) data in low-density LHD shots 28614 and 28615 with neutral beam injection (NBI). In this case ITBs were formed in the central part of plasma column after application of nearly central ECRH [3-5] into NBI-heated (28615) and ECRH+NBI heated (28614) plasmas. T_e timetraces of these shots are shown elsewhere (e.g. [3-5]). The profiles of $|\delta T_e|$ (absolute value of the variation of T_e) created by ECRH/on-off in shot 28615 (after 4.5ms) are shown in Fig. 5(a) by bold and thin solid lines ($|\delta T_e|$ by ECRH-on in shot 28614 is shown by dashed curve). In general, CPP/HPP looks non-diffusive for these shots since $|\delta T_e|$ does not decay monotonically. The example of HPP analysis in shot 28614 is given in Fig. 5(b). Analysis shows $\chi_e^{HP} \approx 1.2$ m^2/s between r/a=0.39 and 0.434, $\chi_e^{HP} \approx$ 1.3 m^2/s between r/a=0.434 and 0.475, and rise of χ_e^{HP} up to ~3 m^2/s between r/a=0.475 and 0.566. The calculations performed with χ_e^{HP} =1.3 m^2/s are shown by dotted lines in Fig. 5(b). Anyway, diffusive HPP is not able to describe the rise of δT_e value at r/a=0.599. Moreover, the delay is absent

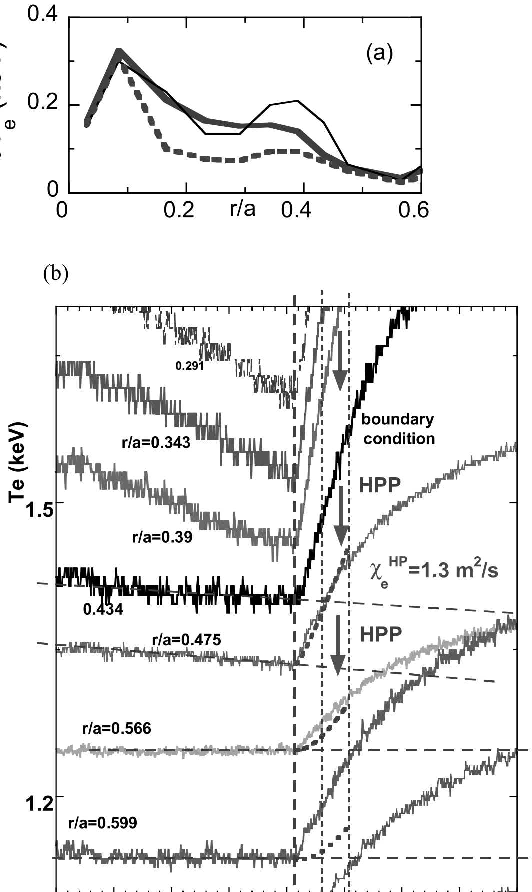

Fig. 5 (a) Profiles of $|\delta T_e|$ created by ECRH/on-off in LHD shot 28615 (after 4.5ms) - bold and thin solid lines, same by ECRH-on in shot 28614 is shown by dashed curve. (b) Example of HPP, dotted line -calculations.

even at r/a=0.566. In the case of CPP in shot 28614, $\chi_e^{HP} \approx$ 0.5 m^2/s is found between r/a=0.434 and 0.475. Nevertheless, low values of χ_e^{CP} could not be treated as reliable.

The HPP induced by ECRH-on in shot 45475 (2.3MW

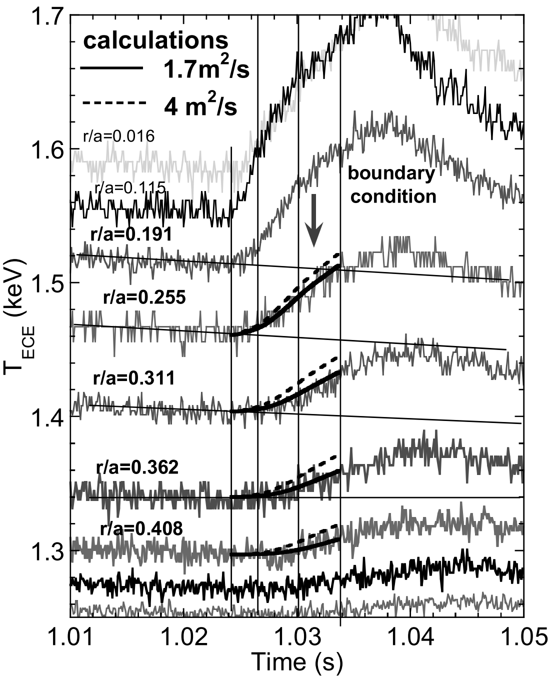

Fig. 6 Diffusive HPP created by ECRH-on in LHD shot 45475.

NBI injected power, $\overline{n}_e \approx 1.8\times10^{19}/\mathrm{m}^3$) looks totally different. Figure 6 clearly shows the decay of amplitude and rising delay of HPP during outward propagation of heat wave. The results of calculations with $\chi_e^{HP} = 1.7\ \mathrm{m}^2/\mathrm{s}$ are shown in Fig. 6 with bold lines (r/a=0.191 is taken as boundary condition). These calculations fit the experimental data. The results of calculations with $\chi_e^{HP} = 4\ \mathrm{m}^2/\mathrm{s}$ are shown in Fig. 6 by dashed lines; they obviously disagree with experiment.

With the increase of NBI power, HPP looks faster (with χ_e^{HP} around 5 m^2/s), and even more fast in some shots. Clear delay is not observed in some shots even at r/a~0.6.

4. Discussion and conclusions

The existence of zones with improved transport near low-order-rational q values was reported for ECR-heated plasmas at RTP [8] and many other tokamaks. ITBs were found in plasmas with dominating electron heating at JT-60U [9] and LHD [3-5]. Recent analysis of HPP created by off-axis modulated ECRH in ASDEX-U and FT-U shows slow HPP under R/L_{Te} up to ~10 [10-11]. Low values of $\chi_e^{CP} \approx 0.3\ \mathrm{m}^2/\mathrm{s}$ were observed inside magnetic island in LHD [12]. Any perturbation imposed on Ohmic background (which increase R/L_{Te}) propagates in a fast manner in any tokamak ($\chi_e^{HP} \approx$ 0.6 m^2/s or more for T-10), and χ_e^{HP} value usually exceeds power balance value in 2 or more times (enhanced HPP). It means that the Ohmic value of R/L_{Te} lies already above the "critical" value of R/L_{Te}, and it was increased by more than 2 times by off-axis ECRH in T-10. Enhanced CPP was observed during inward propagation of cool wave induced by injection of C8H8 pellet at LHD [13].

In the present paper, the transport characteristics of sawteeth-free plasmas created by off-axis ECRH were studied by means of CPP and HPP analysis in wider parameter range (0.18–0.22MA shots with $\overline{n}_e$ up to $2.7\times10^{19}/\mathrm{m}^3$) comparing with [1]. Off-axis ECRH forms the region of the reduced transport in low-shear zone with q above 1. Later, q and shear reduce due to the current redistribution during CPP/HPP (see calculations in [1]). CPP analysis shows that χ_e^{CP} values increase by ~3 times (from minimum level ~0.1 m^2/s inside r/a < 0.4 with R/L_{Te} up to 1.5 times of OH level during CPP at shots with 0.22MA/2.33T, $\overline{n}_e = 2.7\times10^{19}/\mathrm{m}^3$) either by variation of the resonance position at the same off-axis power or by variation of power level. In all cases stronger redistribution (namely, the increase of wideness) of $T_e(r)/T_e(0)$ profile (normalized to OH level) leads to the increase of χ_e^{HP}. Probably, $\chi_e^{CP} \approx 0.1\ \mathrm{m}^2/\mathrm{s}$ corresponds to some "optimal" q profile with low shear zone and $q(0)$ slightly above 1. The similar value of $\chi_e^{HP} \approx 0.1\ \mathrm{m}^2/\mathrm{s}$ was observed at JT-60U inside strong ITB [6]. Reduction of the turbulence below OH level after ~15ms of CPP was measured with reflectometer at T-10 [14] in series of shots with $\chi_e^{CP} \approx 0.1\ \mathrm{m}^2/\mathrm{s}$. Moreover, the reduction of q during CPP with $\chi_e^{CP} \approx 0.3\ \mathrm{m}^2/\mathrm{s}$ brings interruption in diffusive CPP process by the decrease of transport in the central region (inside r/a=0.15). In our opinion, this improvement represents the influence of some "optimal" q value, which lies near 1.

Results of HPP/CPP study at LHD low density discharges ($\overline{n}_e \approx 0.4\times10^{19}/\mathrm{m}^3$) show that HPP/CPP propagate in non-diffusive manner. Low values of χ_e^{HP} obtained in some zones could not be treated as reliable. In contrast, purely diffusive HPP ($\chi_e^{HP} \approx 1.5\ \mathrm{m}^2/\mathrm{s}$ at $0.2 < r/a < 0.4$) is observed in some LHD shots with $\overline{n}_e \approx 1.8\times10^{19}/\mathrm{m}^3$ and 2.4 MW NBI power. Similar values of χ_e^{HP} were observed in T-10 (0.17MA/3T, $\overline{n}_e \approx 2.8\times10^{19}/\mathrm{m}^3$, 0.8 MW ECRH power [15]) and JET (3MA/3T, $\overline{n}_e \approx 2\times10^{19}/\mathrm{m}^3$, 2 MW NBI power [16]) in the same space region. HPP/CPP looks faster at higher NBI power and density in LHD (χ_e^{HP} order of 5–10 m^2/s).

The region of HPP analysis with "single wave" method presented in the present paper is strongly limited by small amplitude of heat wave in LHD shots with moderate density. The analysis of MECH experiments (modulated ECRH: periodical short-term ECRH/on-off) [17], in principle, allows studying wider region of plasma column. Each method has positive and negative features. Careful application of both "single wave" and MECH methods simultaneously should allow creating systematic scan of χ_e^{HP} dependency on plasma parameters at LHD.

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