

NEW INTERPRETATION OF SLOW HEAT PULSE PROPAGATION DURING ITB FORMATION IN TOKAMAKS

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Introduction

Understanding of properties of internal transport barrier (ITB) is of importance for the fusion research of toroidal magnetic confinement. In T-10, ITB has been recently recognized by means of analyses of heat pulse propagation (HPP) induced by central ECRH-onset and cold pulse propagation (CPP) by off-axis ECRH cut-off in a sawtooth-free plasma created by off-axis ECRH [1-3]. The cold pulses propagate slowly and diffusively with dynamic electron heat diffusivity $\chi_e^{\text{HP}} \sim 0.1 \text{ m}^2/\text{s}$. It is known by many years, that in L-mode, $\chi_e^{\text{HP}} \approx 2-4 \chi_e^{\text{PB}}$ (so called “enhanced” HPP). At present, this relationship is usually explained by “critical gradient model”. In the present report, we focus at fully opposite cases with $\chi_e^{\text{HP}} < \chi_e^{\text{PB}}$. For the first time, this case was found in T10 many years ago [3] and called “self-deceleration of heat wave”, or, in a contrast with L-mode, “reduced” HPP. Non-local confinement bifurcations (jump of core transport at $\sim 0.3-0.4r/a$ region inside and around ITB in a ms timescale) was found in various JT-60U normal and RS plasmas and called ITB-events [4-6]. At the same time, HPP is diffusive between the non-local bifurcations of the transport [2,4]. Slow outward HPP induced by ITB-event was observed in JT-60U [4].

Interpretation of the pulse propagation analysis at T-10 and JT-60U

Regarding the perturbations of the heat sources and density, HPP/CPP is analysed using a simplified transport equation for δT_e , as usually (e.g. see [1-4] for detail):

$$1.5n_e \partial \delta T_e / \partial t = \text{div}(n_e \chi_e^{\text{HP}} \nabla \delta T_e) \quad (1)$$

with the various initial and boundary conditions. Important experimentally measured characteristic of the CPP is the index of the relative sharpness of a heat wave (Sh) (see [1-4]):

$$\text{Sh} = |(\delta \nabla T_e / \delta T_e) / (\nabla T_{e0} / T_{e0})|. \quad (2)$$

The value of Sh characterizes the sensitivity of the diffusive term ($\chi_e^{\text{HP}} \delta \nabla T_e$) to the terms proportional to δT_e such as convective and convective-like terms (electron-ion exchange sources perturbations, dependence of χ_e on T_e , etc.) In the experiments described below, the value of Sh exceeds 5, and the role of convective terms is negligible.

Regarding the perturbations of the heat sources, density and convective heat flux, the transport of $\delta T_e(r,t)$ is described by full equation :

$$1.5n_e \partial\delta T_e / \partial t = \text{div}(\delta\Gamma_e), \quad \delta\Gamma_e = n_e (\chi_{e0} \nabla\delta T_e + \delta\chi_e (\nabla\delta T_e + \nabla T_{e0})) \quad (3),$$

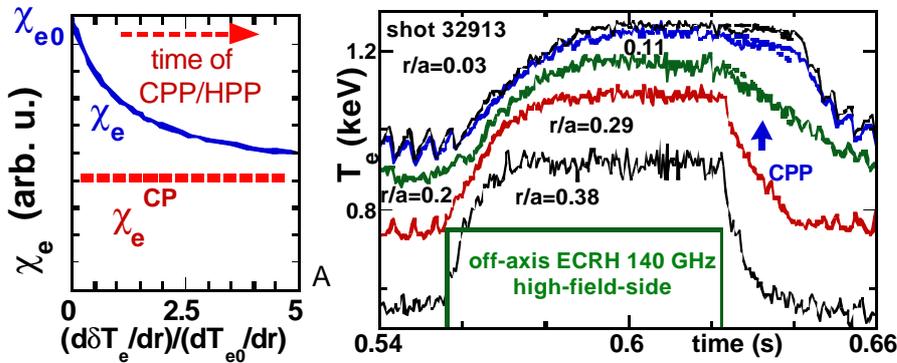
where $\delta\Gamma_e$ is the variation of the electron heat flux, χ_{e0} is background power balance electron heat diffusivity, ∇T_{e0} is T_e gradient before HPP, and $\delta\chi_e$ is the variation of power balance electron heat diffusivity during HPP. Comparison of equations (3) and (5) gives follows:

$$n_e \chi_e^{\text{HP}} \nabla\delta T_e \approx n_e (\chi_{e0} \nabla\delta T_e + \delta\chi_e (\nabla\delta T_e + \nabla T_{e0})) \quad (4).$$

since calculations with simplified equation (1) describe experiments rather well [1-4]. The evolution of $\chi_e \equiv \delta\chi_e + \chi_{e0}$ is described by the following expression derived from eq. (4):

$$\chi_e \approx (\chi_e^{\text{HP}} \nabla\delta T_e / \nabla T_{e0} + \chi_{e0}) / (1 + \nabla\delta T_e / \nabla T_{e0}) \quad (5).$$

Fig. (1) shows the dependence of χ_e in eq. (5) which describes diffusive HPP with $\chi_e^{\text{HP}} < \chi_{e0}$.



In T-10, the slow inward CPP was induced by turning-off of the off-axis ECRH. Figure 2 displays the timetraces of T_e .

Fig. 1 Dependence of χ_e on $\nabla\delta T_e / \nabla T_{e0}$ (see eq. 5) dashed lines— calculations with $\chi_e^{\text{HP}} = 0.08 \text{ m}^2/\text{s}$.

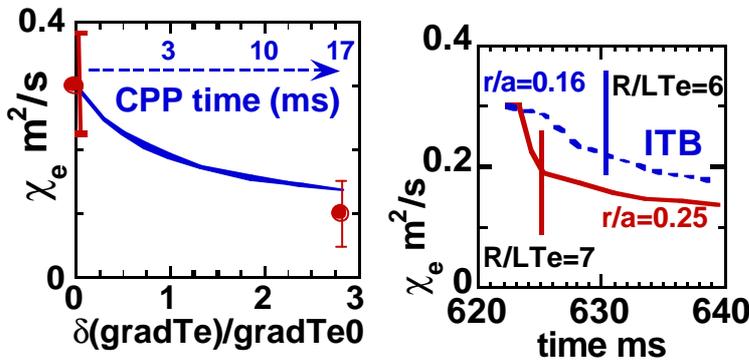


Fig.3 T-10- (a) Dependence of χ_e on $\nabla\delta T_e / \nabla T_{e0}$ (see eq. 5) at $r/a=0.25$, circles- power balance values (b) Timetraces of χ_e at $r/a=0.25$ and $r/a=0.16$

from power balance calculations before CPP (χ_{e0}) and in the end of CPP [1]. The reconstructed decay of χ_e fits well the value of χ_e in the end of CPP. Figure 3(b) shows the timetraces of χ_e at $r/a=0.25$ and $r/a=0.16$. At $r/a=0.25$, the value of χ_e falls quickly and $R\nabla T_e / T_e = R/L_{Te}$ reaches critical value in two ms (R/L_{Te} reaches 17 in the end of CPP). At $r/a=0.16$, the value of χ_e falls slowly and $R\nabla T_e / T_e = R/L_{Te}$ reaches critical value only in the middle of CPP.

In JT-60U RS experiments [4-5], ITB-events A and C reduces transport and form stronger ITB. Figures 4(a-b) shows the timetraces of $T_{e,i}$. ITB-event C creates diffusive outward ion and electron HPP with $\chi_e^{HP} \sim 0.1 \text{ m}^2/\text{s}$, $\chi_i^{HP} \sim 0.14 \text{ m}^2/\text{s}$ [5]. Figure 4(c) represents the evolution of χ_e (with two values of χ_{e0}) at $r/a=0.63$ taken from eq. (5). The evolution of χ_i is similar. The decay of $\chi_{e,i}$ during HPP is correlates with the rise of ∇P_i and ∇V_t .

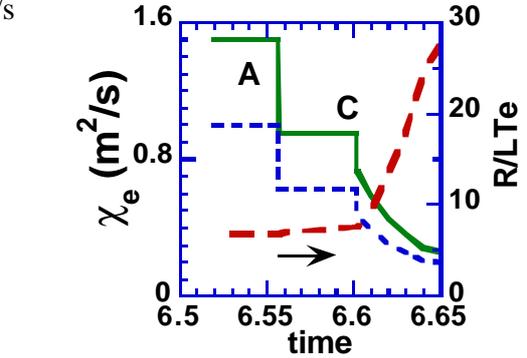
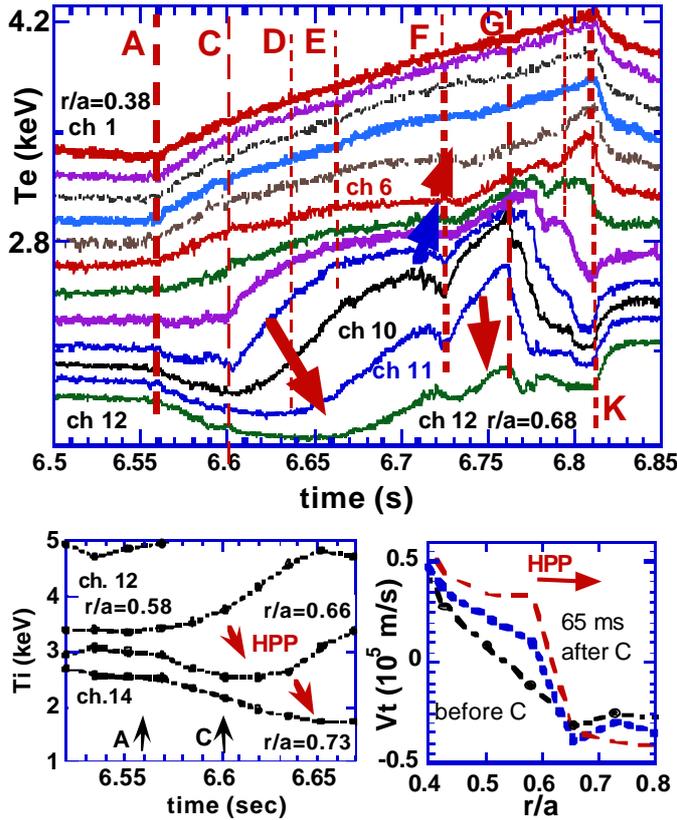


Fig.4- JT-60U (a-b) Timetraces of $T_{e,i}$ at ITB-events A,C and outward HPP induced by event C. (c) profiles of toroidal V_t . (d) Timetraces of χ_e at $r/a=0.63$ for two values of χ_{e0} (power balance errors) taken from eq. (5) and evolution of R/LT_e (dotted line).

Now we discuss the behavior of eq. (5) in extreme cases. χ_e decreases almost linearly at small values of $\nabla\delta T_e / \nabla T_{e0}$ since $\chi_e \approx \chi_{e0} - (\chi_{e0} - \chi_e^{HP}) \nabla\delta T_e / \nabla T_{e0}$ at $\nabla\delta T_e / \nabla T_{e0} \ll 1$. We used this qualitative explanation of slow HPP during ITB formation

earlier [1-4]. The opposite case is the interpretation of HPP/CPP experiments with strongly rising T_e gradients ($\nabla\delta T_e / \nabla T_{e0} \gg 1$) on the heat (cold) wave front. In these cases equation (5) may be rewritten as $\lim_{\nabla\delta T_e / \nabla T_{e0} \rightarrow \infty} \chi_e = \chi_e^{HP}$. (see an obvious limit $\chi_e = \chi_e^{HP}$ in figure (1)). In this case slow HPP/CPP indeed represents low transport with $\chi_e \approx \chi_e^{HP}$ in the end of HPP.

In the case of the absence of HPP, i.e. with $\chi_e^{HP} \approx 0$ [6], when heat wave does not propagates at all, the eq. (5) appears as $\chi_e = \chi_{e0} / (1 + \nabla\delta T_e / \nabla T_{e0})$. Sawtooth-like crash creates outward HPP in RS shot. Profiles of T_e before and after the crash are shown in Fig. 5(a) by solid and dashed curves, respectively. Figure 5(b) shows shifted timetraces of T_e (ch. 9-12). Bold solid and dashed solid lines show calculations of HPP from ch.9 to ch. 11-12 with $\chi_e^{HP} = 0.1 \text{ m}^2/\text{s}$ (faster compare with experiment) and with $\chi_e^{HP} = 0.04 \text{ m}^2/\text{s}$.

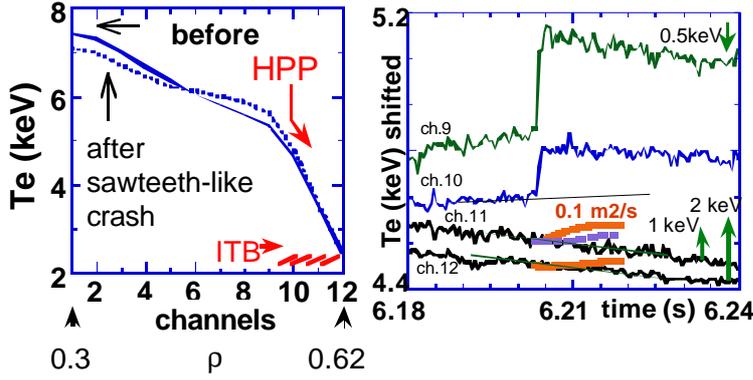


Fig 5 (a) T_e profiles before and after crash in RS JT-60U shot with NBI and ECRH. (b) Extremely slow HPP from ch. 10 to ch. 11,12 (bold solid and dashed lines – calculations with $\chi_e^{HP} = 0.1 \text{ m}^2/\text{s}$ and $0.04 \text{ m}^2/\text{s}$)

Heat wave does not propagate at ch. 11 and one cannot obtain χ_e^{HP} value but can only estimate its upper limit $\chi_e^{HP} < 0.03 \text{ m}^2/\text{s}$.

Discussion and conclusions

The heat flux is described by the following expression derived from equation (5):

$$\chi_e \nabla T_e \equiv \chi_e (\nabla T_{e0} + \nabla \delta T_e) \approx \chi_e^{HP} \nabla T_e + (\chi_{e0} - \chi_e^{HP}) \nabla T_{e0} \quad (6)$$

$$\text{or } \chi_e \nabla T_e \approx \chi_e^{HP} \nabla T_e + (\chi_{e0} - \chi_e^{HP}) \nabla T_{e0} (T_e/T_{e0}) \text{ at } \delta T_e/T_{e0} \ll \nabla \delta T_e/\nabla T_{e0} \quad (7).$$

We are not able to choose between equations (6) and (7) since the first term varies much stronger compare with the second term (e.g. in the end of CPP/HPP analysed above, $\delta T_e/T_{e0} = 0.03 \nabla \delta T_e/\nabla T_{e0}$ at JT-60U and $\delta T_e/T_{e0} = 0.07 \nabla \delta T_e/\nabla T_{e0}$ at T-10). The second term is convective term and its presence can be explained by the transport caused by global modes or fluctuations with large radial scale. (over $0.2r/a$ in T-10 and $0.1r/a$ in JT-60U).

The new method allows us to reconstruct approximate behaviour of $\chi_{e,i}(r,t)$ during slow electron and ion HPP. Important consequence of eq. (5) is that the value of χ_e remains above the value of χ_e^{HP} . In T-10, the reconstructed decay of χ_e fits well the value of χ_e at the end of CPP (obtained independently from the power balance). The fluctuations level measured by reflectometer [7] falls below the ohmic level in some shots with slow CPP in T-10. In J-60U, the decay of $\chi_{e,i}$ during HPP is accompanied by the rise of ∇P_i and ∇V_t . Depending on measurements available (reflectometer data, E_r variation etc), new method brings new possibilities to study physics of ITB formation in time and space.

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