# A possible model for non-local electron heat transport

Wang A.K.[1)], Wang H.[1)], Jiang H.B.[1)], and Wang Z.T.[1)]

1) Southwestern Institute of Physics, P.O.Box 432, Chengdu 610041, P.R.China

akwang@swip.ac.cn

**Abstract.** In the present model, the non-local electron heat transport is theoretically studied from both microphysics (electromagnetic electron temperature gradient instability) and macrophysics (global power relation). The conditions of core electron temperature rise in low density plasmas are obtained and compared with experiments. Qualitatively, the present results are in good agreement with those observed in experiments.

## 1. INTRODUCTION

It has been widely observed in the non-local electron heat transport experiments [1-13] that the core electron temperature ($T_e$) increases in response to the edge cold pulse in the low density plasmas and inversely the core $T_e$ decreases in response to the edge heat pulse in the high density plasmas. Up to now, the physical mechanism causing the non-local electron heat transports remains unknown.

In the present model, both the core $T_e$ rise in response to the edge cold pulse in the low density plasmas and the core $T_e$ drop in response to the edge heat pulse in the high density plasmas are attributed to the electromagnetic electron temperature gradient (ETG) modes in the core region of plasmas. An important fact is that magnetic fluctuation is observed in both core and edge regions of plasmas after non-local effect takes place [1-5]. Thus, it is reasonable to assume that the magnetic field fluctuation $\delta\mathbf{b}$ is excited by the edge perturbation and it propagates into the core plasma in an Alfvén velocity. In response to the magnetic field fluctuation $\delta\mathbf{b}$ of core plasma, the electromagnetic ETG modes are excited in the core plasmas without any changes in the thermodynamic variables. On the one hand, the electromagnetic ETG instabilities induce the turbulent resistivity ($\eta^t$) and turbulent electron viscosity ($\nu^t$) [14]. On the other hand, the instabilities lead to the anomalous electron heat transport. Here it is found that in low density plasmas, the short wavelength ($k_\perp \rho_e >> 1$) instabilities are excited in the response to cold pulse. Thus, the dominant effects of the core electromagnetic instabilities are determined by the turbulent $\eta^t$ and $\nu^t$ because the anomalous thermal diffusion coefficient of electrons $\chi_e \propto k_\perp^{-2}$ is small. As a result, the turbulent $\eta^t$ and $\nu^t$ in the core region heat the electrons [15] locally and lead to the core $T_e$ rise. Inversely, in high density plasmas the long wavelength ($k_\perp \rho_e << 1$) electromagnetic instabilities are excited in the response to heat pulse. Consequently, the anomalous electron heat transport plays a dominant role and it leads to the core $T_e$ decrease. The present results show that there exists a temperature threshold and when the electron temperature is larger than the threshold the core $T_e$ rise takes place in response to the edge cold pulse in low density plasma. The above conclusions are in good agreement with the experimental tendency. Here the $\delta\mathbf{b}$, excited by the edge perturbation and then propagated to the core region, plays a role of the bridge linking the edge and the core, triggering the electromagnetic ETG instabilities in the core region of plasmas.

Furthermore, a macrophysics parameter equation for non-local effects, including the turbulent power, ohmic power and the applied powers (such as edge auxiliary heating power), has been developed to tokamak from reversed pinch plasma theory. Correspondingly, the power conditions for the core $T_e$ rise in low density plasmas and drop in high density plasma are obtained. In addition, it is found that the edge heat pulse reduces the core $T_e$ rise in low density plasma. The conclusion is supported by the experiment [1-3]. In addition to the non-local heat transport experiments in ohmic discharges of tokamaks, we use the macrophysics parameter equation to analyze those in both the full non-inductively discharge of tokamak and the helical system without net plasma current. It shows that the collsional dissipation power (collisionality) of electrons in a helical system reduce the core $T_e$ rise in low density plasma, which is qualitatively in agreement with the experimental observation [13].

## 2. MICROPHYSICS OF NON-LOCAL EFFECTS

It is the key to understand how the electromagnetic ETG instabilities in the core region of plasmas are excited in respond to the $\delta\mathbf{b}$ ($\delta\mathbf{b}_\perp$, $\delta\mathbf{b}_{//}$). Thus, we need to study the coupling of the ETG modes to the perpendicular and parallel magnetic field perturbations, equivalently, to the $\delta\mathbf{A}_\perp$ and $\delta\mathbf{A}_{//}$, where $\delta\mathbf{b} = \nabla\times\delta\mathbf{A}$. Similar to the Ref.(16), we consider the correcting of $\delta\mathbf{A}_\perp$ in the $\mathbf{E}\times\mathbf{B}$ drift $\mathbf{v}_E = -\vec{\mathbf{b}}\times\mathbf{E}_\perp / B$ and the polarization drift $\mathbf{v}_{pe} = -(B\Omega_e)^{-1}(\partial/\partial t + \mathbf{v}_{de}\cdot\nabla)\mathbf{E}_\perp$, where $\mathbf{E}_\perp = -\nabla\phi + c^{-1}\partial\mathbf{A}_\perp/\partial t$ and $\mathbf{v}_{de} = -\mathbf{b}\times\nabla p_e / eBn_e$. Then, the model equations for the microphysics of non-local effects consist of the electron continuity equation, the parallel equation of motion and the pressure equation:

$$\frac{\partial n_e}{\partial t} + (\mathbf{v}_E + \mathbf{v}_{de})\cdot\nabla n_e + n_e\nabla\cdot(\mathbf{v}_E + \mathbf{v}_{de}) + n_e\cdot\nabla\mathbf{v}_{pe} + n_e\nabla_{//}v_{//e} = 0\,, \tag{1}$$

$$\frac{\partial v_{//e}}{\partial t} + \mathbf{v}_E\cdot\nabla v_{//e} = \frac{e}{m_e}\left(\nabla_{//}\phi + \frac{1}{c}\frac{\partial A_{//}}{\partial t}\right) - \frac{\nabla_{//}p_e}{m_e n_e} - \frac{\nabla A_{//}\times\mathbf{b}}{cm_e n_e B}\cdot\nabla p_e\,, \tag{2}$$

$$\frac{\partial p_e}{\partial t} + \mathbf{v}_E\cdot\nabla p_e + \frac{5}{3}p_e\nabla\cdot\mathbf{v}_E + \frac{5}{3}\mathbf{v}_{De}\cdot\nabla p_e + \frac{5}{3}n_e\mathbf{v}_{De}\cdot\nabla T_e + \frac{5}{3}p_e\nabla_{//}v_{//e} = 0\,. \tag{3}$$

We obtain from linearizing Eqs.(1)-(3)

$$\begin{aligned}&\omega\tilde{n}_e + (\omega_{De}-\omega_{*e})\tilde{\phi} - \omega_{De}\tilde{p}_e + \rho_e(2R^{-1} - L_n^{-1})\omega\tilde{A}_\perp - (\omega - \omega_{*pe})\\ &\times(k_\perp^2\rho_e^2\tilde{\phi} + k_\perp\rho_e\omega\tilde{A}_\perp/\omega_{ce}) + k_{//}\rho_e(k_\perp\lambda_s)^2\omega_{ce}\tilde{A}_{//} = 0\end{aligned}\,, \tag{4}$$

$$k_{//}\rho_e\omega_{ce}(\tilde{p}_e - \tilde{\phi}) + [(1 + k_\perp^2\lambda_s^2)\omega - \omega_{*pe}]\tilde{A}_{//} = 0\,, \tag{5}$$

$$\begin{aligned}&(\omega - \frac{5}{3}\omega_{De})\tilde{p}_e - (\omega_{*pe} - \frac{5}{3}\omega_{De})\tilde{\phi} - \frac{5}{3}\omega_{De}\tilde{T}_e - \rho_e(L_P^{-1} - \frac{10}{3}R^{-1})\omega\tilde{A}_\perp\\ &+\frac{5}{3}k_{//}\rho_e(k_\perp\lambda_s)^2\omega_{ce}\tilde{A}_{//} = 0\end{aligned}\,, \tag{6}$$

where $\omega = \omega_r + i\gamma$, $\omega_r$ is the real frequency of the mode, $\gamma$ is the growth rate, and the other physical quantities are traditional. Based on the experimental facts [1-5] that there are no obvious changes in electrostatic fluctuations (both density and electrostatic potential) after non-local effect takes place, we consider the limit case that $\tilde{\phi} = 0$ and $\tilde{n}_e = 0$ in Eqs.(4)-(6).

It is easily showed in the frame of electron magnetohadrodynamics (EMHD), [17] equivalently, under the conditions of $\mathbf{v}_i \equiv 0$, $\delta n_i = 0$, $\delta n_i = \delta n_e$, and $\delta n_i = -e\delta\phi / T_i$ that it gets $\tilde{\phi} = 0$ and $\tilde{n}_e = 0$. In the EMHD, ions are fully decoupled from electrons, a phenomena which has been observed in the non-local experiments.[3] It indicates that the EMHD is available to describing the non-local electron heat transport. Finally, we derive the following dispersion relation from Eqs.(4)-(6),

$$A_1\omega^3 + A_2\omega^2 + A_3\omega + A_4 = 0 \tag{7}$$

where $A_1$, $A_2$, $A_3$, and $A_4$ are the functions of $k_\perp$, $k_{//}$, $\rho_e(T_e$ and $B)$, $\lambda_s(n_e)$, $L_T$, $L_n$, and $R$. The electromagnetic ETG instabilities can easily be obtained by solving the Eq.(7). Before solving the Eq.(7), we recall the turbulent resistivity ($\eta^t$) and viscosity ($\nu^t$), induced by the electromagnetic turbulence, [14]

$$\eta^t = 0.2K^2 / \varepsilon \tag{8}$$

$$\nu^t = 0.07K^2 / \varepsilon \tag{9}$$

with

$$K = (1/2)\left[\overline{(\delta\mathbf{b})^2} + \overline{(\delta\mathbf{u})^2}\right], \tag{10}$$

$$\varepsilon = \eta\overline{\left(\frac{\partial\delta b^a}{\partial x^b}\right)\left(\frac{\partial\delta b^a}{\partial x^b}\right)} + \nu\overline{\left(\frac{\partial\delta u^a}{\partial\delta x^b}\right)\left(\frac{\partial\delta u^a}{\partial x^b}\right)}, \tag{11}$$

where $\eta$ is the collisional resistivity, $\nu$ the collisional electron viscosity, and $\delta\mathbf{u}$ the fluctuation of electron toroidal flow $\delta\mathbf{u} = -\nabla\times\delta\mathbf{b} / n_e$. Here note that the electrostatic ETG turbulence can not produce the turbulent resistivity and viscosity. Thus, we believe that electromagnetic effect instead of kinetic effect plays a decisive role in the turbulence heating of electrons even in the short wavelength regime ($k_\perp\rho_e >> 1$)。 That is, electromagnetic turbulent heating of electrons can be described by the electromagnetic fluid theory, such as the EMHD, even in the short wavelength regime.

First we use Eqs.(8)-(11) to analyze qualitatively the relation between the size and injection velocity of cold pulse and the velocity and magnitude of core $T_e$ rise. It is assumed that under the same thermodynamic variables, a cold pulse with large size or / and fast injection velocity induces the magnetic fluctuation $\delta\mathbf{b}_1$ with large amplitude in the core plasma and another one with small size or/ and slow injection velocity does $\delta\mathbf{b}_2$ with smaller amplitude than that of $\delta\mathbf{b}_1$. Corresponding to the $\delta\mathbf{b}_1$ and $\delta\mathbf{b}_2$, we have $\eta_1^t$ and $\nu_1^t$ and $\eta_2^t$ and $\nu_2^t$. The $\eta_1^t$ and $\nu_1^t$ heat the electrons and lead to an increases of core $T_e$, $\delta T_{e1}$, and accordingly the $\eta_2^t$ and $\nu_2^t$ do $\delta T_{e2}$. Because the amplitude of $\delta\mathbf{b}_1$ is larger than that of $\delta\mathbf{b}_2$ for the same plasma parameters, we immediately obtain from Eqs.(8)-(11)

$$\eta_1^t > \eta_2^t \text{ and } \nu_1^t > \nu_2^t. \tag{12}$$

Consequently, we have $\delta T_{e1} > \delta T_{e2}$ for the same heating period and thus $(\partial\delta T_{e1} / \partial t) > (\partial\delta T_{e2} / \partial t)$. That is, the injected-cold pulse with large size or / and fast velocity will lead to the larger increase of core $T_e$ in a shorter time compared with that the injected-cold pulse with small size or slow velocity does, as observed in the experiments[ 1-6, 13].

Now we analyze the electromagnetic ETG instabilities by solving the dispersion relation (7) numerically. At first, we investigate the electromagnetic ETG instabilities in low density plasma ($\lambda_s >> \rho_e$). For this purpose, we use the TFTR experimental data ($R = 2.36m$, $B = 4.9T$, $T_e(0) = 4.5kev$, and $n_e(0) = 1.7\times10^{19} m^{-3}$, where $\lambda_s = 39\rho_e >> \rho_e$). *FIG.1* shows the change of growth rate with $k_{//}\rho_e$ for the different $k_\perp\rho_e$. It can be seen that the larger the $k_\perp\rho_e$, the larger the growth rate and, vice versa. In the range of $k_\perp\rho_e < 0.5$, we

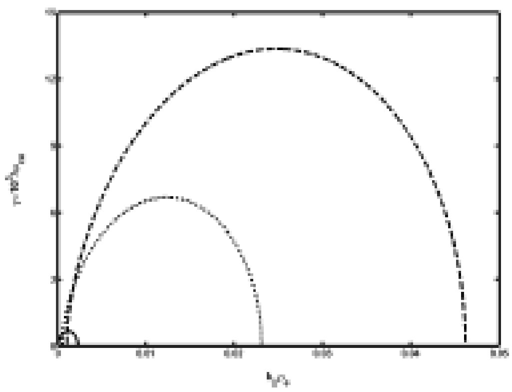

*FIG.1 The growth rate versus $k_{//}\rho_e$ for the different $k_\perp\rho_e$. Solid line : $k_\perp\rho_e$ =5; the dotted line: $k_\perp\rho_e = 50$; the dashed line: $k_\perp\rho_e = 100$. $L_T = L_n = 0.6$.*

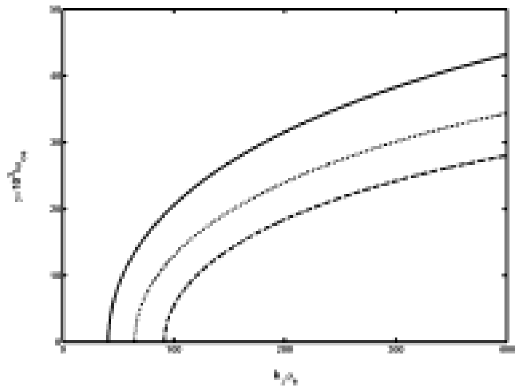

*FIG.2 The growth rate versus $k_\perp\rho_e$ for the different $L_T$ and $L_n$. The solid line: $L_T = L_n = 0.4$; the dotted line: $L_T = L_n = 0.6$; the dashed line: $L_T = L_n = 0.8$; $k_{//}\rho_e = 0.03$.*

have the $k_{//}$ spectrum of zero growth rate. It is showed that growth rate changes with $k_\perp\rho_e$ for the different electron density and temperature gradient scale lengths in *FIG.2*. We have the conclusion from Figs.1 and 2 that the dominant instabilities are the short wave length ones ($k_\perp\rho_e >> 1$) in the low density plasma. In such short wavelength regime, the anomalous transport can even be neglected compared the turbulent heating, induced by the instabilities. That is, totally the effect of electromagnetic ETG instabilities is the turbulent heating. Furthermore, the time scale of turbulent heating is $1/\gamma \sim \omega_{ce}/10^3 \sim 10^{-7}s$ from Figs.1 and 2. Hence, the larger the growth rates of instabilities, the larger the growth velocity and magnitude of core $T_e$ rise. Also *FIG.2* indicates that the growth rate reduces with the increase of electron temperature and density gradient scale length. The experiment [13] shows that the delay time of core electron heating increase with increase of electron temperature gradient scale length. The present result seems be in agreement with the experiment tendency. Subsequently，we investigate the growth rate versus the $T_e$ (or $\rho_e$) under the other parameters , such as the magnetic field

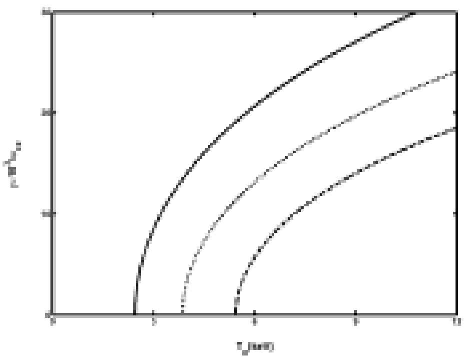

*FIG.3 The growth rate versus $T_e$ for the different $L_T$ and $L_n$. The solid line: $L_T = L_n = 0.4$; the dotted line: $L_T = L_n = 0.6$; the dashed line: $L_T = L_n = 0.8$; $n_e = 1.7\times10^{19} m^{-3}$ $k_{//} = 10^3 m$, and $k_\perp = 10^5 m$.*

($B = 4.9T$), the major radius ($R = 2.36m$), and the density [$n_e(0) = 1.7\times10^{19} m^{-3}$], are fixed. There exists the a threshold or down limit ($T_e^{th}$) of the electron temperature, i.e., the electromagnetic ETG modes are unstable only when $T_e > T_e^{th}$. In other world, the non-local effect occurs only when $T_e > T_e^{th}$. The TFTR experiments [2,3] indicate that non-local effect takes place when the condition $n_e(0)/T_e(0)\,[\times10^{19}/kev]$ < 0.6 is satisfied. For the fixed density [ $n_e(0) = 1.7\times10^{19} m^{-3}$ ], the experimental condition can be rewritten as $T_e > T_e^{th} \approx 2.83$. In *FIG.3*, the minimum threshold $T_e^{th} \approx 2.5$. Qualitatively, the present result is in agreement with the experimental result.

Moreover, we investigate the electromagnetic ETG instabilities in high density plasma ($\lambda_s >$ or ~ $\rho_e$). For this purpose, we take $\lambda_s = \lambda_s/4$ artificially, where the $\lambda_s$ in right hand is determined by the TFTR experimental data. In the case, the $k_{//}$ spectrum of growth rate for the different $k_\perp\rho_e$ is showed in *FIG.4*, and the $k_\perp$ spectrum for the different $L_T$ and $L_n$ are showed in *FIG.5*. We find that when $k_{//}\rho_e$ is very small, there exist discrete modes with the growth rate $\gamma\times10^4/\omega_{ce} \sim 10^{-2} - 10^{-3}$ near $k_\perp\rho_e \approx 0$. On the other hand, when $k_{//}\rho_e$ is very large the instabilities appear with $k_\perp\rho_e >> 1$. Thus, there exist at the same time the instabilities with $k_\perp\rho_e << 1$ and $k_\perp\rho_e >> 1$ in high density plasma. The former mainly induces the anomalous transport while the latter mainly contribute to the turbulent heating. That is, there is the competition between the turbulent heating and turbulent cooling (anomalous transport, equivalently, negative turbulent resistivity). The present model can not give the core $T_e$ drop but it shows a possible physics of the core $T_e$ drop in high density plasma. In what follows, we will see that the edge auxiliary heating plays important role in determining the core $T_e$ rise in low density and the core $T_e$ drop in high density plasma.

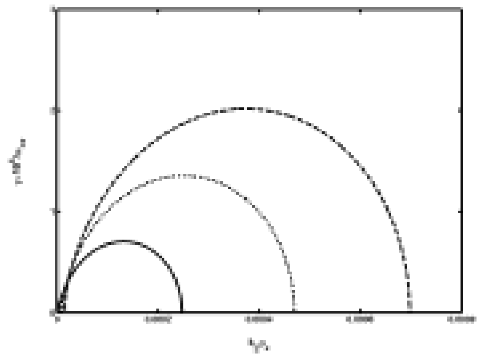

*FIG.4 The growth rate versus $k_{//}\rho_e$ for the different $k_\perp\rho_e$ . Solid line : $k_\perp\rho_e = 0.5$ ; the dotted line: $k_\perp\rho_e = 1.0$ ; the dashed line: $k_\perp\rho_e = 1.5$. $L_T = L_n = 0.6$.*

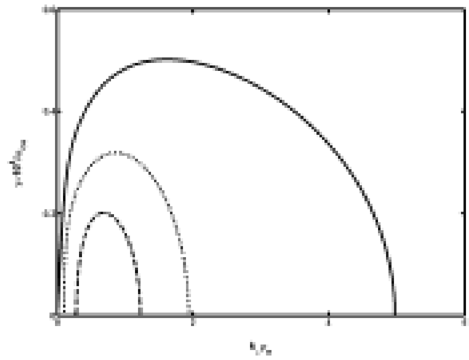

*FIG.5 The growth rate versus $k_\perp\rho_e$ for the different $L_T$ and $L_n$. The solid line: $L_T = L_n = 0.4$ ; the dotted line: $L_T = L_n = 0.6$ ; the dashed line: $L_T = L_n = 0.8$; $k_{//}\rho_e = 0.0002$.*

### 3. MACROPHYSICS OF NON-LOCAL EFFECTS

In order to understand the physics of "non-local" response deeply and explore the macrophysics condition for the core $T_e$ rise, it is necessary to find out the relations between the microphysics quantities ($\eta^t$ and $\nu^t$) and the macrophysics quantities (such as ohmic power, and edge auxiliary heating power and so on). For the quasistable state of reversed field plasma, such a energy (power) relation, is given.[15].

$$IV_L = <(\nu+\nu^t)\nabla\mathbf{U}:\nabla\mathbf{U}> + <(\eta+\eta^t)\mathbf{J}^2> - \Gamma_1 - <\nabla\cdot\mathbf{D}> \qquad (13)$$

with

$$\Gamma_1 = <\alpha\mathbf{B}\cdot\mathbf{J}> \text{ and } <\nabla\cdot\mathbf{D}> = <\alpha'\mathbf{U}\cdot\nabla\times\mathbf{U}>$$

where $I$ is the toroidal current, $V_L = V_{EL} + V_{IL}$ the total loop voltage including the applied $V_{EL}$ and the inductive $V_{IL}$, $\mathbf{J}$ the current density, $\mathbf{U}$ the toroidal flow of plasma, $\mathbf{D}$ the flow flux contributed by the dynamo-produced flow, and $< >$ represents an integral over the plasma volume. In the present case ($\mathbf{v}_i = 0$ and $\delta n_i = \delta n_e = 0$, i.e., the electron fluid obeying the quasi-neutrality, as stated previously), $\mathbf{U}$ is the toroidal flow of electron fluid and accordingly $\nu$ and $\nu^t$ are the collisional and turbulent viscosity of electrons. In tokamaks, the dynamo effects can be neglected. That is, both the dynamo-produced current term $<\alpha\mathbf{B}\cdot\mathbf{J}>=0$ and the dynamo-produced flow term $<\alpha'\mathbf{U}\cdot\nabla\times\mathbf{U}>=0$. But in it, the applied driven power ($P_{dr}$), such as low hybrid wave and electron cyclical wave, will drive current and electron flow. Equivalently, in tokamak plasma we replace the $<\alpha\mathbf{B}\cdot\mathbf{J}>$ and $<\alpha'\mathbf{U}\cdot\nabla\times\mathbf{U}>$ of reversed field pinch plasma with $P_{dr}$, i.e., $P_{dr} = <\alpha\mathbf{B}\cdot\mathbf{J}> + <\alpha'\mathbf{U}\cdot\nabla\times\mathbf{U}>$. Furthermore, in order to study the non-local effects, we should consider in Eq.(13) the cold pulse power ($P_{cold}$) and the auxiliary heating power of both edge ($P_{heat}$, such as heat pulse power) and core. Here the effect of cold pulse (cooling source) in the edge plasma is phenomenally treated as that of a negative resistivity (i.e., $P_{cold} = <\eta_- J^2>$) and the effect of applied heat source in the edge as that of a positive resistivity (i.e., $P_{heat} = <\eta_+ J^2>$) while the effect of applied heat source in the core plasma is included in the core $T_e$ of background plasma (i.e., the applied core heat source gives a high background plasma $T_e$ in the core region). Both physically and mathematically the terms $<\eta_- J^2>$ and $<\eta_+ J^2>$ are easily incorporated in Eq.(13). Similarly, the effects of anomalous transport, induced by the electromagnetic ETG turbulence, are included in $\eta^t$ and $\nu^t$ as negative turbulent resistivity and turbulent electron viscosity. Finally, in tokamak plasmas the Eq.(13) can be rewritten as,

$$P_{tur} = \delta P_{OH} + P_{dr} + P_{cold} - P_{heat}, \qquad (14)$$

Where the increase of ohmic power (corresponding to that of total loop voltage) $\delta P_{OH} = P_{OH} - P_{coll}$ , the ohmic power $P_{OH} = IV_L$ , and the collisional power $P_{coll} = <\eta\mathbf{J}^2> + <\nu\nabla\mathbf{U}:\nabla\mathbf{U}>$; $P_{dr}$ is the applied current and flow drive power, $P_{heat}$ the edge auxiliary heating power (i.e., the edge heat pulse power ), $P_{cold}$ the cooling power of edge cold pulse, and $P_{tur}$ the turbulent heating or cooling power,

$$P_{tur} = <\eta^t\mathbf{J}^2> + <\nu^t\nabla\mathbf{U}:\nabla\mathbf{U}>. \qquad (15)$$

Here $\delta P_{OH} \geq 0$, $P_{apd} \geq 0$, $P_{cold} \geq 0$, and $P_{heat} \geq 0$ while $P_{tur} \geq 0$ for core $T_e$ increase and $P_{tur} \leq 0$ for the core $T_e$ decrease.

Now we use the equation (14) to analyze the dependence of the core $T_e$ rise ($P_{tur} > 0$) on the relations between the $\delta P_{OH}$, $P_{dr}$, $P_{cold}$, and $P_{heat}$. At first, for the cold pulse injection in ohmically heated tokamak plasmas, $P_{dr} = 0$ and the edge $P_{heat} = 0$, in the case we have

$$P_{tur} = \delta P_{OH} + P_{cold} . \quad (16)$$

Therefore, even $\delta P_{OH} = 0$, the core $T_e$ rise ($P_{tur} > 0$) always occurs if the condition $T_e > T_e^{th}$ is satisfied. There is a linear relation between $P_{tur}$ and $P_{cold}$ while $\delta P_{OH}$ enlarges the magnitude of $P_{tur}$, as observed in the experiments [1-5,9].

Subsequently, we consider the cold pulse injection in ohmically heated tokamak plasmas with the edge auxiliary heating $P_{heat}$. In the case we have, from Eq. (14),

$$P_{tur} = \delta P_{OH} + P_{cold} - P_{heat} . \quad (17)$$

From Eq.(17), we immediately see that the edge auxiliary heating $P_{heat}$ reduces the magnitude of the core $T_e$ rise, i.e., weakens the "non-local" effect, and even makes the phenomenon of core $T_e$ rise disappears [1-5] when $P_{heat} = \delta P_{OH} + \delta P_{heat}$. Moreover, for the ohmically heated tokamak plasmas with the edge auxiliary heating but without the edge cold pulse injection [9], Eq.(14) becomes

$$P_{tur} = \delta P_{OH} - P_{heat} . \quad (18)$$

Thus, in the case we have the conclusion that the phenomenon of the core $T_e$ rise can occur only when $\delta P_{OH} > P_{heat}$ but it disappears when $\delta P_{OH} = P_{heat}$. In the present model, the edge auxiliary heating and the core auxiliary heating are completely different two things. The former weakens the rise of core $T_e$ in low density plasma and even makes the phenomenon disappears but the latter enhances the "non-local" response through increasing core electron temperature $T_e$ of background plasma. The high core $T_e$ is favorable to the "non-local" responses because the plasma condition of core $T_e$ rise is $T_e > T_e^{th}$. Moreover, when $P_{heat} > \delta P_{OH} + P_{cold}$ in Eq.(17) and $P_{heat} > \delta P_{OH}$ in Eq.(18), Eqs.(17) and (18) become, respectively

$$0 < P_{heat} - P_{OH} - \delta P_{cold} = -P_{tur} = -< \eta^t \mathbf{J}^2 > - < \nu^t \nabla \mathbf{U} : \nabla \mathbf{U} > , \quad (19)$$

$$0 < P_{heat} - \delta P_{OH} = -P_{tur} = -< \eta^t \mathbf{J}^2 > - < \nu^t \nabla \mathbf{U} : \nabla \mathbf{U} > . \quad (20)$$

Thus, we obtain the negative turbulent resistivity and viscosity (the negative $P_{tur}$), i.e., the core $T_e$ decreases. Therefore, when the heat pulse power is large enough the long wavelength electromagnetic ETG modes get ahead of the short wavelength ones between their competitions. As a result, the core $T_e$ reduces, as observed in the experiment [6]. For the full non-inductively driven tokamak plasmas [8], $P_{OH} = 0$ and thus Eq.(14) yields

$$P_{tur} = \delta P_{dr} + P_{cold} - P_{heat} , \quad (21)$$

where the increase of non-inductive drive power $\delta P_{dr} = P_{dr} - P_{coll}$. In the case we obtain the conclusions similar to Eqs.(16)-(20) of ohmically heated tokamak plasmas. Furthermore, for a helical system without net plasma current [13], $P_{OH} = 0$ and $P_{dr} = 0$. Thus, from Eq.(14) we have

$$P_{tur} = P_{cold} - P_{heat} - P_{coll} . \quad (22)$$

Eq.(22) shows that in addition to the edge auxiliary heating, the collisional power $P_{coll}$ (i.e., collisionality) weakens the core $T_e$ in low density plasma. The conclusion is qualitatively in agreement with the experimental observation in a helical system [13]. Moreover, Eq.(21) predicts the edge auxiliary heating $P_{heat}$ (heat pulse), together with the collisionality $P_{coll}$, always makes the core $T_e$ decrease for the high density plasma in a helical system if without the edge cold pulse injection.

## 4. SUMMARY

At first, non-local effects are investigated based on the electromagnetic ETG instabilities. It is found that in low density plasma, the short wavelength instabilities ($k_\perp \rho_e >> 1$) are excited while the long wavelength ones ($k_\perp \rho_e << 1$) are almost suppressed completely. Thus, the dominant effect of electromagnetic ETG instabilities is turbulent heating and it leads to core $T_e$ rise. Both the time scale of turbulent heating and the threshold condition of temperature for turbulent heating ($T_e > T_e^{th}$) are obtained numerically. However, in high density plasma the present results show that there exist not only the short wavelength instabilities with $k_\perp \rho_e >> 1$ but also the long wavelength ones with $k_\perp \rho_e << 1$. That is, there exists the competition between the long wavelength instabilities and short wavelength ones, i.e., that between the turbulent cooling and heating.

Subsequently, a power relation between turbulent power, applied current and flow drive power, cold pulse power, and edge auxiliary heating power is developed from reversed field pinch plasma to tokamak plasma. We use the relation to analyze the ohmically heated tokamak discharges with or without the edge auxiliary heating, the full non-inductively driven tokamak discharges, and the helical system discharges. It is obtained here that the edge auxiliary heating $P_{heat}$ weaken the non-local effect and even make the effect disappear in low density plasma and makes the core $T_e$ reduce in high density plasmas. Qualitatively， the results obtained in the present model are in good agreement with the experimental tendencies. Then, it is necessary to obtain quantitatively the anomalous transport and turbulent heating and compare them in the future work.

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