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The Energy Confinement Scaling Based on Microturbulence Transport and Neoclassical Conductivity in a Tokamak

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Based on the neoclassical electric conductivity and the anomalous transport models due to trapped electron modes and ion temperature gradient modes, the scaling law of the global energy confinement time in a tokamak has been theoretically studied, under the electron temperature profile constraint. The entropy production rate method, developed by W. M. Tang, has been employed to evaluate the electron temperature at the magnetic axis. The calculations has been performed in the wide range of the surface safety factor q_a of 2 to 7 and the inverse aspect ratio a/R of 0.2 to 0.6 Results are $\tau_E \propto n_e q_a^{0.9} a^{0.9} R^{1.9} B^{-0.3}$ for joule heated plasmas and $\tau_E \propto n_e^{0.6} I_p^{1.16} a^{0.15} R^{1.7} B^{-0.36} P^{-0.6}$ for additionally heated L-mode plasmas, respectively. The trapped particle effect, or neoclassical effect, on electric conductivity has been shown to increase the dependence of q_a on τ_E, compared with the results for Spitzer conductivity case. Both scaling laws for joule and additionally heated plasmas are similar to those obtained in experiments.

Keywords: Tokamak, Microturbulence, Energy Confinement Time, Profile Consistency, Toroidal Ion Temperature Gradient Mode, Trapped Electron Mode, Neoclassical Conductivity

微視的乱流輸送理論および新古典電気伝導度理論にもとづくトカマク・エネルギー閉じ込め比例則

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捕捉電子モードおよびイオン温度勾配モードによる異常輸送と新古典電気伝導度にもとづいて，電子温度分布相似則のもとに，トカマクにおけるエネルギー閉じ込め比例則を解析した。中心電子温度を評価するために，Tang によって導入されたエントロピー生成率法を用いた。広範囲のパラメータ領域（安全係数：2－7，逆アスペクト比：0.2－0.6）でエネルギー閉じ込め時間の解析を行い，低密度ジュール・プラズマでは，$\tau_E \propto n_e q_a^{0.9} a^{0.9} R^{1.9} B^{-0.3}$ ，また，追加熱Lモード・プラズマでは，$\tau_E \propto n_e^{0.6} I_p^{1.16} a^{0.15} R^{1.7} B^{-0.36} P^{-0.6}$ の比例則が得られた。電気伝導度に対する捕捉粒子効果（新古典効果）は，閉じ込め時間の安全係数依存性を強めることが示された。これらの理論的比例則は，実験的に得られた比例則と同様の依存性を示している。

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1. Introduction

It is well accepted that the energy confinement in a tokamak is largely enhanced from the prediction of the neoclassical transport theory and is governed by the anomalous transport processes, which are considered to be due to microtubulences excited by electrostatic or electromagnetic instabilities in a plasma. Numerous theoretical models have been proposed and the validity of the models have been tested to understand the energy confinement observed in experiments. Transport theory gives the local expression of the thermal conductivity and, in order to check the validity of the model, we need to solve the transport equations based on the microturbulence model. However, we have some difficulties in this procedure. Even though the transport process due to the underlined turbulence model would be dominant in the major part of the plasma, the plasma is also affected by many other physics, like the plasma-surface interactions, MHD activities and so on. As the result, the parameter dependence of the global energy confinement may differ from the one predicted only from the anomalous transport theory. For example, the electrostatic microtubulences theory gives the strong dependence of the toroidal magnetic field on the thermal diffusivity, while the experimental observations of energy confinement does not show such strong dependence. First approach to resolve this problem has been given by Perkins. He evaluated the scaling of the global energy confinement time based on the trapped electron mode under the assumption that the underling transport model does work only in the good confinement region between q=1 and q=2[1]. Tang extended this approach to more rigorous formulation, where the electron temperature profile is assumed to obey the experimentally observed profile constraint and the electron thermal diffusivity works "as the average" in the good confinement region in the sense of the volume averaged entropy production rate[2]. By this analysis, he succeeded to recover the neo-Alcator scaling of ohmic discharges and also discussed the confinement in auxiliary heated tokamaks. Romanelli argued the global scaling laws derived from the variety of transport models by the rather phenomelogical argument[3]. In these analyses, however, the electric conductivity in a tokamak is assumed to be classical.

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2. Energy Confinement in Low Density Joule Heated Plasmas

In this section, we consider the ohmic discharges, where the electron loss channel is dominant, and we assume the ion temperature is equal to the electron temperature. We also assume the electron anomalous transport is caused by the microturbulence of the dissipative trapped electron mode. The first step to evaluate the global energy confinement is to specify the electron temperature profile. Based on the experimental observations in JT-60[?], in this paper, we employ the powered parabolic profile as the constraint to the T_e-profile;

$$T_e(r) = T_{e0} \{ 1 - (r/a)^2 \}^{\alpha_T} \qquad (1)$$

where a is the plasma minor radius and α_T is the profile parameter, respectively. Another constraint on the electron temperature profile, obtained by experiments is

$$r_1 = \frac{a}{q_a}, \qquad (2)$$

where r_1 and q_a are the position of q=1 surface and the q-value at the plasma surface, respectively. This constraint gives the relation between α_T and q_a through the current density profile. In the steady state, the plasma current profile is given as follows;

$$J_{//}(r) = \sigma_{//}(r)\, E_{//} \qquad (3)$$

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$$J_{//}(r) = \sigma_{//}(r)\, E_{//} \qquad (3)$$

where $E_{//}$, $\sigma_{//}$ and Z_{eff} are the parallel electric field and the parallel electric conductivity and the effective charge of a plasma, respectively, and $\sigma_{//}$ is the numerical constant. Functions, $\Lambda(Z_{eff})$ and f^{NC}, are the Z_{eff} correction factor and the neoclassical correction factor, respectively, which are expressed in the following forms[6];

$$\Lambda(Z_{eff}) = 3.4 \cdot \frac{1.13+Z_{eff}}{2.67+Z_{eff}},$$

$$f^{NC}(r) = \left(1 - \frac{f_T}{1+\xi\nu_{*e}}\right)\left(1 - \frac{C_R f_T}{1+\xi\nu_{*e}}\right), \qquad (4)$$

$$f_T = 1 - \frac{(1-\varepsilon)^2}{\sqrt{1-\varepsilon^2}\cdot(1+1.4\sqrt{\varepsilon})}, \ \varepsilon = \frac{r}{R},$$

$$\xi = 0.58 + 0.2\, Z_{eff},\ C_R = \frac{0.56}{Z_{eff}}\frac{3.0-Z_{eff}}{3.0+Z_{eff}}$$

ν_{*e} is the effective collision frequency of electron and f_T is the fraction of trapped particles. In present day tokamak experiments, ν_{*e} is quite small except near the plasma center and in the peripheral region, so that, in the following, we set $\nu_{*e} = 0.$ for simplicity. Also we assume that Z_{eff} is constant in space. We note that $f^{NC} = 1$ and $\Lambda(Z_{eff}) = 1$ correspond to the classical conductivity case and, hereafter, the superscript "CL" denotes values evaluated by using the classical conductivity in order to distinguish from the neoclassical case. By using these expressions, the equation (2) can be rewritten as

$$q_a = \frac{I(1, \alpha_T, \varepsilon_0)}{I(1/q_a, \alpha_T, \varepsilon_0)}, \qquad (2')$$

$$I(x, \alpha_T, \varepsilon_0) = \int_0^x dtt(1-t^2)^{3\alpha_T/2} f^{NC}(\varepsilon_0 x),\ \varepsilon_0 = \frac{a}{R}$$

Numerical results of Eq.(2') can be fitted by the following simple relation between α_T and q_a;

$$\alpha_T \approx \frac{2}{3}(1 - 0.55\sqrt{\varepsilon_0})[q_a - (0.5 + \frac{7}{3}\varepsilon_0)], \qquad (2'')$$

in the range of ε_0 of 0. - 0.3 and q_a of 2. - 8.. It can be seen that the neoclassical effect of the conductivity brings the broader electron temperature through the constraint Eq. (2); for example, $\alpha_T(\varepsilon_0=0.3) / \alpha_T(\varepsilon_0=0.) \sim 0.5$ for $q_a = 3.0$.

By using Eq.(2), the electron energy confinement time for the ohmic discharge is expressed as follows;

$$\tau_{Ee} = \frac{\frac{3}{2}\int_0^a n_e(r)T_e(r)rdr}{E_{//}I_p} = c\,\frac{n_{e0}T_{e0}^{5/2}R^2q_a^2\Lambda(Z_{eff})}{Z_{eff}B^2}\cdot\frac{I(1,\alpha_T,\varepsilon_0)}{1+\alpha_n+\alpha_T}, \qquad (5)$$

where we have assumed the density profile of $n_e(r)=n_{e0}(1-(r/a)^2)^{\alpha_n}$ and c is the numerical constant. Remaining problem is to determine T_{e0}. To do this, we employ the Tang's model; that is, the entropy production by the prescribed transport model of microturbulence is assumed to be the same as that by the profile consistency model, where the entropy production is defined by the following;

$$S = \int \chi_e(r)\left[\frac{d}{dr}lnT_e\right]^2 rdr \qquad (6)$$

The integration is performed in the region between the q=1 surface and q=2 surface, where more than 75% of the total stored energy is confined under the profile consistency model for $2 < q_a < 7$. Assuming that the electron conduction loss is the dominant loss channel, the local electron energy balance equation for the temperature profile of Eq(1) gives the electron thermal conductivity χ_e of the following form;

$$\chi_e(r) = \chi_{e0}\,F(r) \qquad (7)$$

$$\chi_{e0} = \frac{Z_{eff}B^2a^2}{n_{e0}T_{e0}^{5/2}R^2q_a^2\Lambda(Z_{eff})}$$

$$F(r) = \frac{I(r/a,\,\alpha_T,\,\varepsilon_0)}{\alpha_T I^2(1,\,\alpha_T,\,\varepsilon_0)r^2/a^2(1.-r^2/a^2)^{\alpha_n+\alpha_T-1}}$$

Now, we consider the anomalous transport caused by the dissipative trapped electron mode, the local thermal conductivity of which is expressed by

$$\chi_e^{TE} = c^{TE}\frac{\varepsilon^{1.5}(\omega_{*e}^2\eta_e+\omega_{*e}^P\omega_{De})}{\nu_{ei}k_\perp^2}, \qquad (8)$$

where $\omega_{*e}=k_\perp T_e/eBL_n$, $\omega_{*e}^P=\omega_{*e}(1+\eta_e)$, $\omega_{De}=\omega_{*e}L_n/R$, $\eta_e=L_n/L_T$ with $L_n=n_e/(\partial n_e/\partial r)$ and $L_T=T_e/(\partial T_e/\partial r)$. ν_{ei} is the electron-ion collision frequency. For the electron temperature profile given by Eq(1), the explicit radial dependence of $\chi_e^{TE}(r)$ is given by

$$\chi_e^{TE}(r) = \chi_{e0}^{TE}\, G(r), \tag{8'}$$

$$\chi_{e0}^{TE} = 5.03 c_\mu \frac{a^{0.5} T_{e0}^{3.5}}{R^{2.5} B^2 n_{e0} Z_{eff}},$$

$$G(r) = r^2/a^2\,(1-r^2/a^2)^{3.5\alpha_T-\alpha_n-2}\left[2(\alpha_T+\alpha_n)(1-r^2/a^2)+\frac{4\alpha_T\alpha_n}{\varepsilon_0}\frac{r}{a}\right].$$

By equating the entropy productions of the profile consistency model and the anomalous transport model; that is,

$$\chi_{e0}\int_{r_1}^{r_2} F(r)\left[\frac{d}{dr} ln T_e\right]^2 r dr = \chi_{e0}^{TE}\int_{r_1}^{r_2} G(r)\left[\frac{d}{dr} ln T_e\right]^2 r dr \tag{9}$$

we have the scaling for the electron temperature at the axis and the electron energy confinement time as follows;

$$T_{e0} = \tilde{c} q_a^{1/3} Z_{eff}^{1/3} B^{2/3} R^{1/12} a^{1/4}\left(\frac{\hat{c}}{c_\mu}\right)^{1/6} \tag{10}$$

$$\tau_{Ec} = \tilde{c} n_{e0} q_a^{7/6} Z_{eff}^{-1/6} B^{-1/3} R^{53/24} a^{5/8}\left(\frac{\hat{c}}{c_\mu}\right)^{5/12} \cdot \frac{I(1, \alpha_T, \varepsilon_0)}{1+\alpha_n+\alpha_T} \tag{11}$$

The coefficient $\hat{c}$ is determined by

$$\hat{c} = \int_{r_1}^{r_2} r dr F(r)\left[\frac{d ln T_e}{dr}\right]^2 \Big/ \int_{r_1}^{r_2} r dr G(r)\left[\frac{d ln T_e}{dr}\right]^2 \tag{12}$$

The $\hat{c}$ is the complicated function of q_a, α_n and ε_0 so that we numerically evaluate Eqs.(10) and (11) in the range of q_a=3-7, α_n=0.5-2.0 and ε_0=0.2-0.6, and obtain the power law expressions for T_{e0} and τ_{Ec} by using the least square fitting method. For the neoclassical conductivity case, resultant scaling laws are

$$\begin{aligned} T_e(r_1) &= 0.701 q_a^{0.12} Z_{eff}^{0.30} B^{0.67} a^{0.40} R^{-0.07} \alpha_n^{-0.14} c_\mu^{-0.17} \\ \tau_{Ec} &= 0.04 n_{e0} q_a^{0.90} Z_{eff}^{-0.05} B^{-0.33} a^{0.93} R^{1.91} \alpha_n^{-0.63} c_\mu^{-0.42} \end{aligned} \tag{13}$$

Here we have calculated the electron temperature at the q=1 surface instead of T_{e0}, because the electron temperature is flattened inside of this surface by sawteeth activities. For the classical conductivity case,

$$T_e^{CL}(r_1) = 0.753 q_a^{0.07} Z_{eff}^{0.33} B^{0.67} a^{0.38} R^{-0.04} \alpha_n^{-0.12} c_\mu^{-0.17}$$
$$\tau_{Ee}^{CL} = 0.14 n_{e0} q_a^{0.33} Z_{eff}^{-0.17} B^{-0.33} a^{0.94} R^{1.91} \alpha_n^{-0.52} c_\mu^{-0.42} \quad (14)$$

The neoclassical conductivity case gives the similar parameter dependence as the neo-Alcator scaling of electron energy confinement time. It is very interesting that even though the neoclassical correction comes from the aspect ratio, the main difference of τ_{Ee} between the neoclassical and classical cases is the q_a dependence. This is due to the reason that the neoclassical effect comes in the τ_{Ee} evaluation through the change of the electron temperature profile and the direct effect of aspect ratio on τ_E itself is small in the practical range of aspect ratio. In the original paper of Tang[2], he derived the neo-Alcator scaling of τ_{Ee} by using the classical conductivity and his conclusion seems to contradict with ours. This difference is not due to the different functional form of the electron temperature profile which is employed for the profile consistency . In order to confirm this, we have also evaluated the scaling of τ_{Ee} by using the Tang's model of Gaussian electron temperature profile and classical conductivity, and obtained the results similar to Eq.(14) as follows ;

$$T_e^{Tang}(r_1) = 0.769 q_a^{0.08} Z_{eff}^{0.33} B^{0.67} a^{0.37} R^{-0.04} \alpha_n^{-0.12} c_\mu^{-0.17}$$
$$\tau_{Ee}^{Tang} = 0.16 n_{e0} q_a^{0.31} Z_{eff}^{-0.17} B^{-0.33} a^{0.93} R^{1.91} \alpha_n^{-0.53} c_\mu^{-0.42} \quad (15)$$

The difference of q_a dependence of τ_{Ec} between Eq.(14) and Tang's result may come from the range of q_a, which is used in the evaluation of τ_{Ee}. We have recovered the strong q_a dependence of τ_{Ec} even for the classical conductivity case when we fit the numerical data by restricting q_a in the range of q_a=2-3.

3. Energy Confinement in High Density Joule Heated Plasmas

Increasing the plasma density, the coupling between electrons and ions becomes important and the energy confinement time tends to saturate. This saturation is con-

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3. Energy Confinement in High Density Joule Heated Plasmas

Increasing the plasma density, the coupling between electrons and ions becomes important and the energy confinement time tends to saturate. This saturation is considered to be due to the anomalous energy loss of ions. The possible candidate of the ion anomalous loss is the microturbulence caused by the toroidal ion temperature gradient modes (toroidal η_i modes). In the medium and high density regime, the equipartition is dominant and we can use the single energy transport equation with $T_i(r) = \tau T_e(r)$, where τ is the ratio of ion temperature to electron one. And again we employ the constraint on the electron temperature profile Eq.(1). The toroidal η_i mode turbulence causes not only the ion thermal loss but also the electron one. In the following, for the simplicity, we assume the electron thermal diffusivity is the same as the ion one and solve the following equation;

$$\frac{1}{r}\frac{\partial}{\partial r} r n_e(1+\tau)\chi_i \frac{\partial T_i}{\partial r} + E_{//}\cdot J_{//} = 0\,, \qquad (16)$$

where we have assumed $n_i = n_e$. For the electron temperature profile of Eq.(1), this equation gives the ion thermal diffusivity of the similar form as Eq.(7);

$$\chi_i(r) = \chi_{i0}\, F(r)\,, \quad \chi_{i0} = \frac{Z_{eff} B^2 a^2 \tau}{n_{e0} T_{e0}^{5/2} R^2 q_a^2 \Lambda(Z_{eff})(1+\tau)} \qquad (17)$$

The function F(r) is the same as Eq.(7). The thermal diffusivity of toroidal η_i mode is given by

$$\chi_i^{ITG} = \frac{(\omega_{*i}^T \omega_{Di} \tau)^{1/2}}{k_\perp^2}\,, \qquad (18)$$

where $\omega_{*i}^T = k_\perp T_i / e_i B L_{Ti}$ and $\omega_{Di} = \omega_{*i} L_{Ti}/R$, and the explicit radial dependence of χ_i^{ITG} is .

$$\chi_i^{ITG}(r) = \chi_{i0}^{ITG}\, F(r)$$

$$\chi_{i0}^{ITG} = 10.8\, c_\mu \frac{T_{i0}^{3/2}}{B^2 (Ra\tau)^{1/2}}\,, \quad H(r) = (2\alpha_T r/a)^{1/2}\, (1 - r^2/a^2)^{\alpha_q - 1/2} \qquad (18')$$

By using the same procedure as the previous section, we obtain the following scaling laws of electron temperature and energy confinement time

$$T_e(r_1) = 1.47 n_e^{-0.25} q_a^{-0.49} Z_{eff}^{0.20} B a^{0.73} R^{-0.48} \alpha_n^{0.09} c_\mu^{-0.25} \tau^{0.75} (1+\tau)^{-0.25}$$
$$\tau_E = 0.276 n_{c0}^{0.38} q_a^{-0.64} Z_{eff}^{-0.30} B^{0.5} a^{1.76} R^{0.86} \alpha_n^{-0.05} c_\mu^{-0.63} \tau^{0.88} (1+\tau)^{0.37} \quad (19)$$

It is clearly shown that the energy confinement in this density range has the week dependence on the plasma density and the degradation due to the reduction of q_a. It is also interesting to see that the dependence on the plasma size is very different from the low density case Eq.(13). For the classical conductivity case, the scaling laws become

$$T_e^{CL}(r_1) = 1.13 n_e^{-0.25} q_a^{-0.45} Z_{eff}^{0.25} B a^{0.63} R^{-0.38} \alpha_n^{0.11} c_\mu^{-0.25} \tau^{0.75} (1+\tau)^{-0.25}$$
$$\tau_E^{CL} = 0.375 n_{c0}^{0.38} q_a^{-0.98} Z_{eff}^{-0.38} B^{0.5} a^{1.56} R^{1.06} \alpha_n^{0.06} c_\mu^{-0.63} \tau^{0.88} (1+\tau)^{0.37} \quad (20)$$

4. Energy Confinement of L-mode Plasmas

In a tokamak under the intensively additional heating, the energy confinement degraded with heating power. In this L-mode discharge, the plasma energy is lost mainly through the ion thermal conduction. Again, the toroidal η_i modes are the candidate of this anomalous energy loss. We employ the same assumptions as the previous section, though the joule heating profile $E_{//} \cdot J_{//}$ is replaced by the externally given profile, which is assumed as follows:

$$P_h(r) = P_T \frac{1+\alpha_h}{2\pi^2 R a^2} (1 - r^2/a^2)^{\alpha_h}, \quad (21)$$

where, P_T and α_h are the total heating power and the peakedness of the profile, respectively. By using the same procedure as the previous section, the scaling of the energy confinement time are given as follows

$$\tau_E = 9.17\times10^{-2} n_{c0}^{0.6} I_p^{1.16} P_T^{-0.6} B^{-0.36} a^{0.15} R^{1.70} \alpha_n^{-0.13} c_\eta^{-0.40} \tau^{0.2} (1+\tau)^{0.6} \quad (22)$$

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$$\tau_E^{CL} = 0.375 n_{e0}^{0.38} q_a^{-0.98} Z_{eff}^{-0.38} B^{0.5} a^{1.56} R^{1.06} \alpha_n^{0.06} c_\mu^{-0.63} \tau^{0.88} (1+\tau)^{0.37} \quad (20)$$

4. Energy Confinement of L-mode Plasmas

In a tokamak under the intensively additional heating, the energy confinement degraded with heating power. In this L-mode discharge, the plasma energy is lost mainly through the ion thermal conduction. Again, the toroidal η_i modes are the candidate of this anomalous energy loss. We employ the same assumptions as the previous section, though the joule heating profile $E_{//} \cdot J_{//}$ is replaced by the externally given profile, which is assumed as follows:

$$P_h(r) = P_T \frac{1+\alpha_h}{2\pi^2 R a^2} (1 - r^2/a^2)^{\alpha_h}, \quad (21)$$

where, P_T and α_h are the total heating power and the peakedness of the profile, respectively. By using the same procedure as the previous section, the scaling of the energy confinement time are given as follows

$$\tau_E = 9.17 \times 10^{-2} n_{c0}^{0.6} I_p^{1.16} P_T^{-0.6} B^{-0.36} a^{0.15} R^{1.70} \alpha_n^{-0.13} c_\eta^{-0.40} \tau^{0.2} (1+\tau)^{0.6} \quad (22)$$

and, for the corresponding classical conductivity case,

$$\tau_E^{CL} = 5.73\times10^{-2} n_{e0}^{0.6} I_p^{1.35} P_T^{-0.6} B^{-0.55} a^{-0.50} R^{2.15} \alpha_n^{-0.04} c_\eta^{-0.40} \tau^{0.2} (1+\tau)^{0.6} \qquad (23)$$

5. Summary

We have reexamined the scaling law of τ_E based on the microturbulence of dissipative trapped electron modes and toroidal η_i modes by using the neoclassical conductivity. We numerically evaluated τ_E in low density and high density joule heated plasmas and L-mode plasmas in the wide range of parameter (q_a = 3 - 7, a/R = 3 - 7, Z_{eff} = 1 - 5, α_n = 0.5 - 2) and obtained the scaling law in each regime by using the least square fitting method. The results show the similar parameter dependence of τ_E as experimental ones. The neoclassical effect on the electric conductivity increases the dependence of q_a on τ_E. This is because the electric conductivity affects the energy confinement mainly through the modification of electron temperature profile.

Acknowledgement

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