JULY 1975 MATT-1136

COMMENTS ON ENERGY CONFINEMENT OF TOKAMAKS IN THE TRAPPED ELECTRON REGIME

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Comments on Energy Confinement of Tokamaks in the Trapped Electron Regime

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ABSTRACT

Some discussion is made to estimate the energy confinement properties of large Tokamak devices in the trapped electron regime based on the experimental results of the spherator. The generalized empirical formula of the spherator predicts in the trapped electron regime the energy confinement time τ_E is independent of ohmic heating current I_{OH} and the electron temperature T_e, and depends only on the size of the plasma radius a. The electron temperature T_e is increased with an increase of I_{OH}. These predicted formulas are $\tau_E \simeq 0.5\ a^2$ (m) I_{OH}^{0} (MA) T_e^{0} (keV) and T_e (keV) $\simeq 2.0\ a^{-1}$ (m) I_{OH} (MA). We predict without additional heating the energy confinement time for PLT will be 70 ~ 90 msec with T_e ~ 4 keV and the value for TCT to be 300 ~ 400 msec with T_e ~ 7 keV.

In order to design large Tokamak devices, we have to face the most difficult problem, that is, the prediction of scaling law in the new parameter range without sufficient information. Here, it has been attempted to predict the scaling law of the large Tokamaks based on the spherator experiments. The spherator, an internal ring device, has restrictions on the plasma parameter range and the magnetic field configurations different from the current carrying plasma. However, it has to be noted that in the collisional regime where the electron collision frequency ν_e is higher than the electron bounce frequency ω_{be} between mirror trapping, so-called pseudoclassical scaling law[1] formulated from the spherator experimental results was also observed in Tokamaks[2] and some stellarator devices[3], although the cause of anomalous transport could differ in these devices. Here, based on the recent spherator experimental results[4,5] of the electron heat conductivity in the electron trapped regime, some predictions are made for the large Tokamak devices. The detail of the measurement is discussed in Ref. 4 and 5. First, summary of the parameter range and the experimental result is briefly described, and later the comments on the large Tokamaks are presented.

Figure 1 shows the parameter range of the electron thermal conductivity $K_\perp$ measurement in the comparison with the dependence of the particle confinement time τ_p on the plasma density n_e and the electron temperature T_e[6]. The transition condition between the pseudoclassical scaling regime and the collisionless regime is plotted in the (n_e, T_e) diagram. These transition conditions roughly follow a relation $n_e \sim cT_e^2$, which is consistent with the assumption that the electron collision frequency is equal to the electron bounce frequency; $\nu_e/\omega_{be} \cong 1$, (which also provides $n_e \propto T_e^2$). The obtained proportional constant c from Fig. 1 agrees with the value estimated with the connection length of spherator $L \sim 0.5$m. Thus the collisionless regime could be called a trapped electron regime. The figure 2(a) and 2(b) shows the results of the dependence of $K_\perp$ and $D_\perp$ on the electron temperature and the magnetic shear length. From these experimental results the electron thermal conductivity is formulated by

$$\begin{aligned} K_\perp &\sim \left(\frac{1}{400} \sim \frac{1}{800}\right) \frac{L_s}{a} \frac{T_e}{16B} \; (> D_\perp) \\ \frac{L_s}{a} &\sim \frac{B_T^2 + B_p^2}{B_T B_p} \end{aligned} \qquad (1)$$

where B_T is the toroidal magnetic field component and B_p is the poloidal magnetic field component. For Tokamaks ($B_T >> B_p$), the empirical formula (1) can be expressed by

$$K_\perp = \frac{1}{f_o} \frac{T_e}{16B_p} \quad \left(B_T >> B_p, \frac{L_s}{a} \approx \frac{B_T}{B_p}, \; f_o = 400 \sim 800\right) \qquad (2)$$

which is similar to the experimental results obtained by GA.[7]

Some predictions can be made by assuming the Eq. (2) is applicable for the Tokamak devices in the trapped electron regime. The energy balance between ohmic heating and energy loss in the equilibrium provides,

$$\left\{ \begin{aligned} \eta_e \, I_{OH}^2 &= \frac{n_e T_e \gamma}{\tau_E} \\ \tau_E &= \frac{a^2}{K_\perp} \end{aligned} \right. \qquad (3)$$

where η_e is resistivity and γ is the correction due to energy transfer to ions. The equations (2) and (3) yield

$$\begin{cases} T_e = I_{OH}^{\frac{6}{7}} \, a^{-\frac{6}{7}} \left(\dfrac{n_e \, e \, 2\pi^3 \gamma}{f_o \, \mu_o \, \eta_o Z_{eff}} \right)^{-\frac{2}{7}} \\ \tau_E = a^{1\frac{6}{7}} \, I_p^{\frac{1}{7}} \dfrac{(f_o \mu_o)^{\frac{2}{3}}}{2\pi} \left(\dfrac{2\pi^3 \gamma \, e \, n_e}{\eta_o \, \mu_o \, f_o} \right)^{\frac{2}{7}} \end{cases} \qquad (4)$$

where $\mu_o = 4\pi \times 10^{-7}$, $\eta_o = 5.10^{-4}$, and Z_{eff} is the effective Z. By inserting numerical numbers and neglecting 1/6 ~ 1/7 power dependence, the Eq. (5) can be approximately given by

$$\begin{cases} T_e \text{ (keV)} \cong 2 \, a^{-1} \text{ (m) } I_{OH}\text{(MA)} \; (n_e/2 \times 10^{13} \text{ cm}^{-3})^{-1/3} \\ \tau_E \text{ (sec)} \cong 0.5 \, a^2 \text{(m) } I_{OH}^{o} \, T_e^{o} \; (n_e/2 \times 10^{13} \text{ cm}^{-3})^{1/3} \end{cases} \qquad (6)$$

Where the average plasma radius is assumed 60% of the total plasma radius, Z_{eff} is 2, γ is 1.5 and f_o is 400. It must be noted that the energy confinement time τ_E is almost independent of the plasma current I_{OH} or T_e and depends only on the plasma radius a. The electron temperature increases linearly with an increase of ohmic heating current. The figure 3 shows the comparison of the prediction by Eq. (5) with the experimental results in TFR.[8] In their experimental parameters it is reasonable to assume that their experimental parameter range belongs to the trapped electron regime. Although there is some ambiguity about the effective Z and ion temperature collection factor γ, the contribution of these terms to Eq. (5) is relatively weak. Not only magnitude, but also the observed flat dependence of τ_E vs I_{OH} can be explained by the empirical law obtained from the generalized spherator experiments. The figure 4 shows the comparison of the predicted value of τ_E based on the Eq. (6), with the Tokamak experimental results. It is not clear whether T3, ST Tokamaks, reached to the trapped electron regime. Thus the comparison may not be justified, particularly for the case of TM-3. However, this empirical formula may provide the upper limit of the confinement time, which is the case for the spherator. (See the left side of Fig. 1) This empirical formula predicts the energy confinement time of ~ 70 msec with T_e ~ 4 keV for PLT and ~ 300 msec for TCT device with T_e ~ 7 keV.

The study of anomalous transport in toroidal devices is still in the primitive stage, though internal kink MHD instability in Tokamaks and an indication of trapped particle instability in the spherator have been reported. Thus, the establishment of empirical scaling law with large devices, PLT (a = 45 cm), TCT (a = 85 ~ 90 cm), and even larger devices will be essential to the success of fusion study.

ACKNOWLEDGMENT

This work was supported by U. S. Energy Research and Development Administration USERDA Contract E(11-1)-3073.

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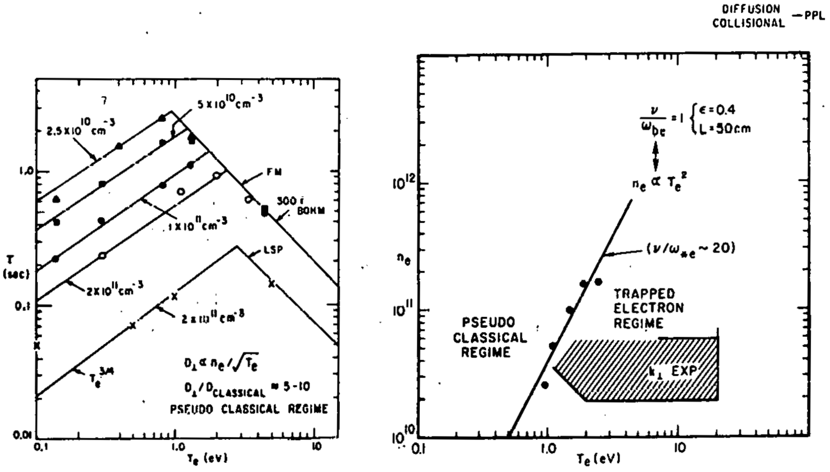

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Fig. 1 The parameter range of pseudoclassical regime and trapped electron regime based in Ref. 6. The bounce frequency is estimated by assuming connection L ~0.5 m and ε = 0.4, ω_e^* is estimated by $k_\perp \rho_i \simeq 1$.

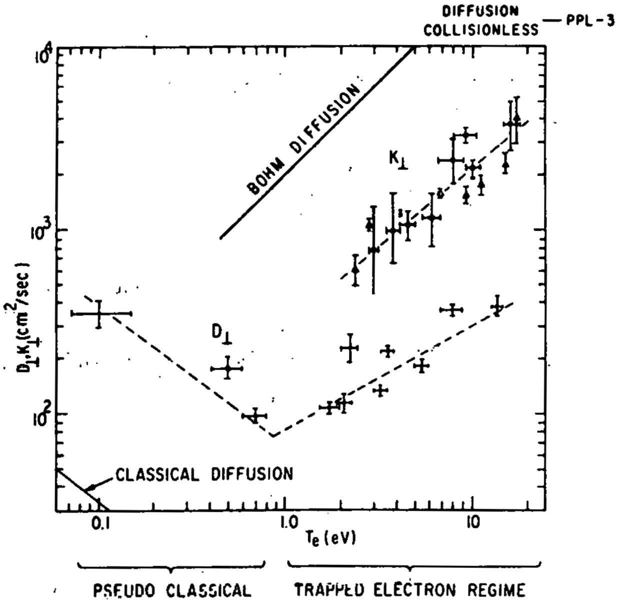

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Fig. 2. $D_\perp$ and $K_\perp$ dependence on T_e

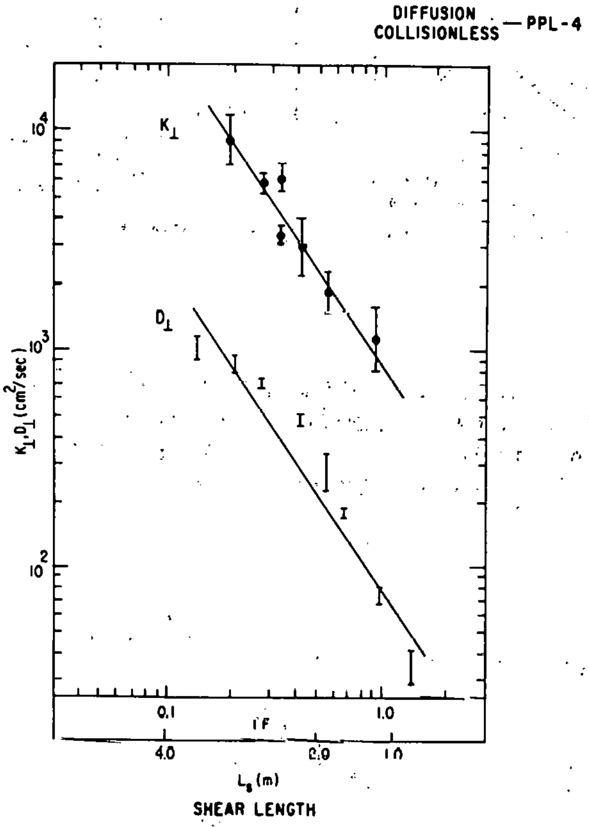

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Fig. 3. $D_\perp$ and $K_\perp$ dependence on L_s

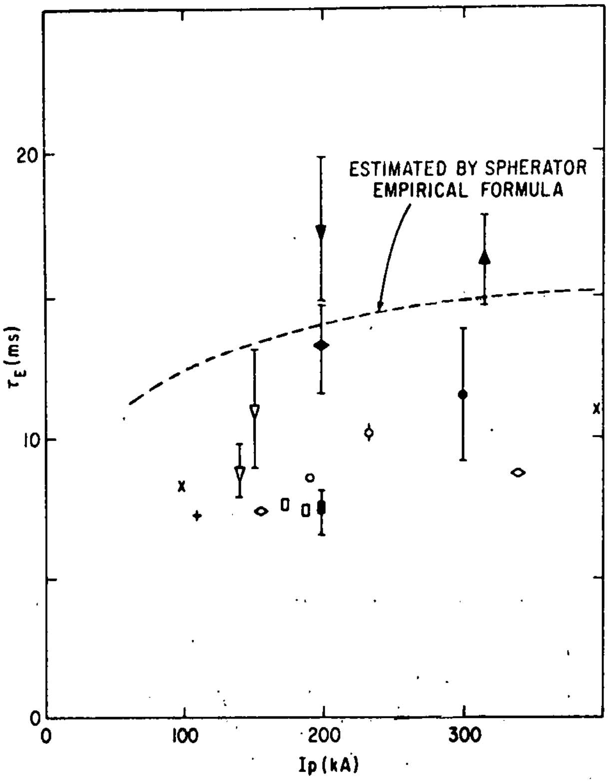

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Fig. 4(a) Comparison of TFR results (τ_e vs I_p) with the Eq. (4).

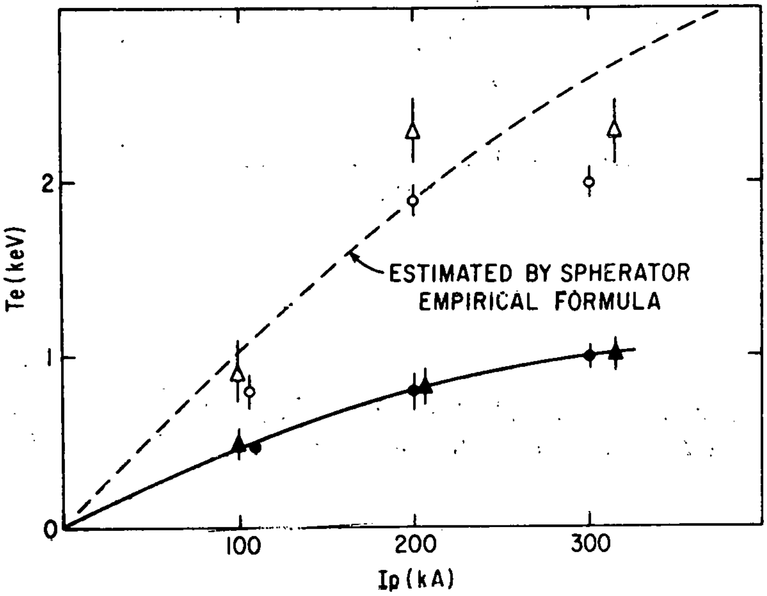

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Fig. 4(b) Comparison of TFR results (τ_E vs I_p) with the Eq. (4)

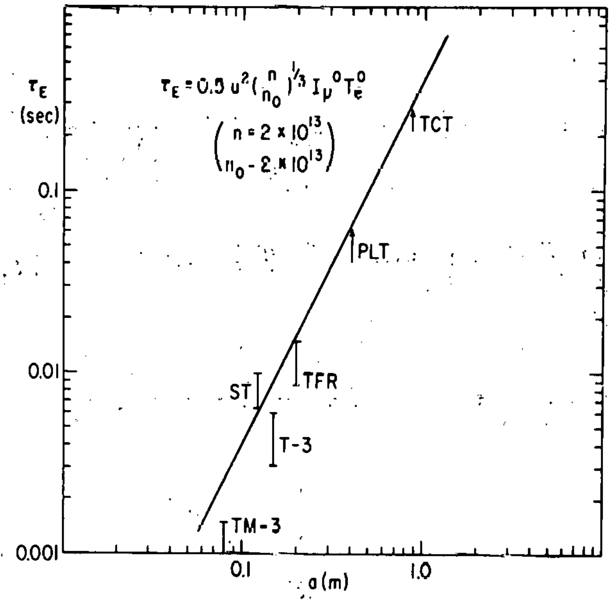

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Fig. 5. Comparison of the Eq. (5) with the observed τ_E in various devices, PLT for a = 45 cm, TCT for a = 90 cm.