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IMPROVEMENT OF PLASMA CONFINEMENT DUE TO ELECTRON LANDAU DAMPING IN TOKAMAKS

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Improvement of Plasma Confinement due to Electron Landau Damping in Tokamaks

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It is shown that the $\vec{E}_{rf} \times \vec{B}_{\theta}$ drift for resonant electrons in tokamaks does not cancel and forms an inward flux during rf heating with a travelling wave type spectrum when an exact treatment of Landau damping in the presence of the magnetic field is performed as an initial value problem, where $\vec{E}_{rf}$ is rf electric field and $\vec{B}_{\theta}$ is poloidal magnetic field. This effect could be the basis of the phenomenon that the plasma confinement is improved during low density lower-hybrid current drive in tokamaks.

Keywords: $\vec{E}_{rf} \times \vec{B}_{\theta}$ Drift, Resonant Electrons, Landan Damping Lower Hybrid Current Drive, Initial Value

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トカマクに於ける電子ランダウ減衰による閉じ込めの改善

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上原和也

（１９８７年１０月１４日受理）

磁場中のランダウ減衰の問題をDawsonの手法に基づいて，初期値問題として正確に解いた場合，トカマク中の共鳴粒子の$E_{rf} \times B_{\theta}$ ドリフトが，波動が進行波で且つプラズマが温度効果を持つ場合，キャンセルアウトしないことが導びかれる。この効果はトカマクに於いて，低密度領域での低域混成波による電流駆動で観測されている閉じ込め時間が改善される現象の基礎的描像を与える。

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1. Introduction

The deterioration of the plasma confinement during supplementary heating in tokamaks is the most serious problem that must be solved in order to attain the ignition state of thermonuclear fusion. When the high additional heating power,such as the neutral beam injection (NBI) or radiofrequency (RF),has been injected into the tokamak,the confinement scaling versus the input power shows a distinct deterioration (" L mode ") in almost all tokamaks. Even the relatively good confinement time of the "H mode" have only twice that of the "L mode" and it still decreases with the input power with the exception of the JT-60 LHCD experiment [1].

It should be noted that the break even condtion can be attained if only we keep the same confinement time during joule heating. So the confinement characteristics of the joule heated tokamak is better than that of supplementary heated tokamaks. From this point of view we must reconsider why tokamaks have so much better confinement characteristics during joule heating. For the joule heated tokamak,the plasma current generated inductively is flowing in the plasma to yield the poloidal field $\vec{B}_\theta$ for plasma confinement. Let's remember Ohkawa multipole experimemt that we,torus people,were saved by the inner current to escape from the "Purgatory" [2]. After that,we have kept the advantage of the poloidal field for plasma confinement with the tokamak discharge. When the plasma current is flowing in a material conductor as in the multipole experiment,there's no electric field in the plasma. However,in the case of the tokamak discharge,an inductive electric field $\vec{E}_\Omega$ is generated in the plasma and all electrons feel the force $e\vec{E}_\Omega$. The resulting inward $\vec{E}_\Omega \times \vec{B}_\theta$ drift confines the plasma, although microscopic and/or macroscopic fluctuations driven by the plasma current may cause an anomalous electron thermal conductivity much larger than the neoclassical prediction. This centrifugal drift velocity $v_d (= E_\Omega B_\theta / B^2)$ is small because the toroidal magnetic field B_z is large, where $B = (B_z^2 + B_\theta^2)^{1/2}$. However, it should be noted that this drift acts on every electron. So the inward flux caused by this $\vec{E}_\Omega \times \vec{B}_\theta$ drift cannot be neglected relatively to the outward flux $-D\partial n/\partial r$, even when we take the anomalous electron diffusion coefficient in tokamaks as the value of D. In fact, while v_d is only of the order of 10^{-2} m/sec, the flux nv_d is of the order of $10^{17} m^{-2} sec^{-1}$, which is often comparable to the outward flux $-D\partial n/\partial r$ at the central region when the value of D is given by the anomalous diffusion coefficient such as Alcator or Kaye-Goldston scaling, where n is the plasma density. This should be called to be an initial pinch in joule heated tokamaks.

It is strange that the simulation people should not include this initial pinch term in the tokamak code. They introduce the anomalous inward term[3)] or Ware pinch term to be different from the initial pinch in order to suppress the density clamping that often occurs at the central region in the simulation of tokamak codes. What is the physical meaning of this anomolous inward term ? Is the Ware pinch really confirmed by the experiments ? Can this tokamak code including this anomalous inward term predict that the plasma confinement in the additional heating of tokamaks is improved by raising the plasma current ? If the initial pinch term is introduced into the tokamak code the density clamping is suppressed effectively[4] and the importance of the poloidal field in the magnetic confinement of tokamaks due to the plasma current is confirmed.

Thus, the initial pinch in tokamaks seems to be one of reasons why joule heated tokamaks show better confinement characteristics. We must keep these better confinement characteristics of the joule tokamak even when the additional heating power is injected into tokamaks. The initial pinch may be one of reasons togather with a large minor radius that JET tokamak should attain the good energy confinement time of 0.9 sec at the plasma current I_p of 5 MA during joule heating and that the energy confinement time τ_E in the additional heating is gradually improved by increasing of I_p.[5]

In the case of travelling wave type rf heating where the rf electric field is parallel to the toroidal direction ,resonant particles receive the momentum and the resultant force $\vec{F}_{wave}$ from the travelling wave and may feel the effective DC field $\vec{E}_{rf}$ from the wave by Landau damping,where $\vec{F}_{wave}=e\vec{E}_{rf}$.

This force is in the toroidal direction and resonant electrons form an inward or outward flux due to the $\vec{F}_{wave} \times \vec{B}_\theta$ drift depending on the direction of $\vec{E}_{rf}$. In previous paper,we show that the pinch effect may occur in the lower hybrid current drive in tokamaks to yield the improvement of the particle confinement time.[4] However,the physical validity that the $\vec{E}_{rf} \times \vec{B}_\theta$ drift is not really cancelled out to bring the inner DC flux in the radial direction is not given in the simulation. As the same manner in the joule heating case,the DC plasma current $\vec{J}_{rf}$ flows in the toroidal drection and it is probable to yield $\vec{J}_{rf} \times \vec{B}_\theta$pinch also in the case of LHCD. In the method of ray tracing the rf electric field in plasmas is in the direction of the combination of the toroidal and poloidal magnetic field. Conversely speaking,it is not necessary to consider the effect of the magnetic field in the calculation of the rf heating using the parallel electric field since the $\vec{E}_{rf} \times \vec{B}_\theta$ seem to cancell out in the radial direction. However,in the appearance of the current drive the situation become to be different. The poloidal magnetic field caused by electrons acceralated due to the rf electric field may be caused in the azimuthal direction and the magnetic field yielded by rf always shadows in the perpendicular direction to the rf travelling wave. This situation indicates that we must reconsider the problem of Landau damping in the presence of the magnetic field in the calculation of the LHCD in tokamaks.

Recently,Xia and Wu have pointed out from the calculation of the ray tracing that the average flux due to $E_z \times B_\theta$ drift is negligible comparing with the average flux due to $E_\theta \times B_z$ drift,where E_z and E_θ are the toroidal and the poloidal component of rf electric field,respectively.[6] The problem must be set,however,whether the component of rf electric field of the travelling wave really forms the DC component of flux by coupling to the magnetic field when we consider Landau damping of travelling wave in the presence of the magnetic field. This problem must be never treated since the energy transfer from waves to particles is only considered in the usual calculation of Landan damping.

In this paper,it is shown that there still remains a part of $\vec{E}_{rf} \times \vec{B}_\theta$ that does not cancel out in the LHCD of tokamaks in section 2,and that the energy confinement time in the LHCD may bring out by the pinch effect in sction 3. Discussion and conclusion are shown in section 4.

2. $\vec{E}_{rf} \times \vec{B}$ drift in the LHCD

In order to explain whether the quantity of $\vec{E}_{rf} \times \vec{B}_\theta$ cancell out or does not cancel out, the following cartesian coordinates are adopted, where x is the radial direction, y is the poloidal direction and z is the toroidal direction, which is the direction of the travelling wave. The components are $E(E_x\cos(k_x x-\omega t), E_y\cos(k_y y-\omega t), E_z\cos(k_z z-\omega t))$ and $B(0, \pm B_\theta, B_z)$, where the sign ± of B_θ denotes the direction of the plasma current. The equations of motion are

$$m dv_x/dt = eE_x\cos(k_x x-\omega t) + e(v_y B_z - v_z B_\theta) \quad (1)$$

$$m dv_y/dt = eE_y\cos(k_y y-\omega t) - e\, v_x B_z \quad (2)$$

$$m dv_z/dt = eE_z\cos(k_z z-\omega t) \pm e v_y B_\theta \quad (3)$$

The zero order solutions for x, y and z on the velocity and the displacement are obtained putting $E_x=0, E_y=0, E_z=0$, $B_\theta= 0, B_z=0$ and $x=x_0, y=y_0, z=z_0, v_x=v_{x0}, v_y=v_{y0}, v_z=v_{z0}$ at $t=0$ in eqs. (1), (2) and (3)

$$x = x_0 + v_{x0} t \quad (4)$$

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$$x = x_0 + v_{x0} t \qquad (4)$$

$$y = y_0 + v_{y0} t \tag{5}$$

$$z = z_0 + v_{z0} t \tag{6}$$

In the first order solution $\vec{v} \times \vec{B}$ is neglected and these are obtained substituting eqs.(4) - (6) into eqs.(1) - (3), where we set $v_{x1}=0, v_{y1}=0$ and $v_{z1}=0$ at $t=0$ since Landau damping is an initial value problem.[7]

$$v_{x1} = eE_x[\sin(k_x x_0 + \alpha_x t) - \sin k_x x_0]/m\alpha_x \tag{7}$$

$$v_{y1} = eE_y[\sin(k_y y_0 + \alpha_y t) - \sin k_y y_0]/m\alpha_y \tag{8}$$

$$v_{z1} = eE_z[\sin(k_z z_0 + \alpha_z t) - \sin k_z z_0]/m\alpha_z \tag{9}$$

and

$$x_1 = \int_0^t v_{x1} dt = (eE_x/m\alpha_x)\{-[\cos(k_x x_0 + \alpha_x t) - \cos k_x x_0]/\alpha_x - t \sin k_x x_0\} \tag{10}$$

$$y_1 = \int_0^t v_{y1} dt = (eE_y/m\alpha_y)\{-[\cos(k_y y_0 + \alpha_y t) - \cos k_y y_0]/\alpha_y - t \sin k_y y_0\} \tag{11}$$

$$z_1 = \int_0^t v_{z1} dt = (eE_z/m\alpha_z)\{-[\cos(k_z z_0 + \alpha_z t) - \cos k_z z_0]/\alpha_z - t \sin k_z z_0\} \tag{12}$$

where

$$\alpha_j = k_j v_{j0} - \omega \qquad (j=x,y,z) \qquad (13)$$

Substituting $x=x_0+ v_{x0}t+x_1, y=y_0+v_{y0}t+y_1$ and $z=z_0+v_{z0}t+z_1$ into the combination of eqs.(1),(2) and (3),we can obtain the sum of 1st and 2nd order equation,

$$d^2(v_{1x}+v_{2x})/dt^2+\omega_c^2(v_{1x}+v_{2x})=(eE_x\omega/m)\sin[k_x(x_0+x_1)+\alpha_x t]$$
$$+(eE_y\omega_{cz}/m)\cos[k_y(y_0+ y_1)+\alpha_y t]\mp(eE_z\omega_{c\theta}/m)\cos[k(z_0+z_1)+\alpha_z t] \qquad (14)$$

where, $\omega_{cz}= eB_z/m$, $\omega_{c\theta}=eB_\theta/m$ and $\omega_c=(\omega_{cz}^2+\omega_{c\theta}^2)^{1/2}$. Equation (14) is a nonlinear differential equation. We can solve this equation using the following procedure,which is well defined in the derivation of Landau damping[8]. The R.H.S. of eq.(14) can be expanded using the relation $\cos k_j j_1=1$ and $\sin k_j j_1=k_j j_1$ when $k_j j_1 \ll 1$ since j_1 is an infinitestimal term of the 1st order. Averaging in space all terms of eq.(14) on x_0, y_0 and z_0 we get

$$d^2\langle v_{1x}+v_{2x}\rangle_{x_0,y_0,z_0}/dt^2+\omega_c^2\langle v_{1x}+ v_{2x}\rangle_{x_0,y_0,z_0}=-(e^2E_x^2\omega k_x/2m^2)d(\cos\alpha_x t/\alpha_x)d\alpha_x$$
$$-(E_y^2\omega_c^2\omega_{cz}k_y/2B^2)d(\sin\alpha_y t/\alpha_y)d\alpha_y\mp(E_z^2\omega_c^2\omega_{c\theta}k_z/2B^2)d(\sin\alpha_z t/\alpha_z)d\alpha_z \qquad (15)$$

First term in R.H.S. of eq.(15) is the 2nd order perturbation of E_x component and second term is due to $E_y \times B_z$ drift and third term is due to E_z

x B_θ drift . Using the relation as a means of the time average, $\lim_{t\to\infty} \sin(kv-\omega)t/(kv-\omega)=\pi\delta(v-\omega/k)/k$, where $\delta(x)$ is Dirac's delta function, and multiplying a distribution function $f(\vec{v})$ and integrating on $\vec{v}$ $(=v_x v_y v_z)$

$$\frac{d^2}{dt^2}\int\langle v_{1x}+v_{2x}\rangle_{x_0,y_0,z_0} f(\vec{v})d\vec{v} + \omega_c^2\int\langle v_{1x}+v_{2x}\rangle_{x_0,y_0,z_0} f(\vec{v})d\vec{v}$$

$$=(E_y^2\omega_{cz}\omega_c^2\pi/2B^2k_y)df(v_y)/dv_y\Big|_{v_y=\omega/k_y} - (E_z^2\,\omega_{c\theta}\omega_c^2\pi/2B^2k_z)df(v_z)/dv_z\Big|_{v_z=\omega/k_z} \quad (16)$$

where we set v_{j0} to v_j and $\int_{-\infty}^{\infty} f(v_j)dv_j=1$. It is noted that E_x term in eq.(15) is cancelled out since the integrant is odd function. Equation (16) is no longer nonlinear and we get as the flux term in the radial direction.

$$\int_{-\infty}^{\infty}\langle v_{1x}+v_{2x}\rangle_{x_0,y_0,z_0} f(\vec{v})d\vec{v}=A_1\sin(\omega_c t+\theta)+(E_y^2\omega_{cz}\pi/2B^2k_y)df(v_y)/dv_y\Big|_{v_y=\omega/k_y}$$

$$\mp(E_z^2\omega_{c\theta}\pi/2B^2k_z)df(v_z)/dv_z\Big|_{v_z=\omega/k_z} \quad (17)$$

First term in R.H.S.is only a cyclotron motion in the total magnetic field which becomes zero after the time arevaging and second and third term are drift term,that is,the DC flux in the radial direction still remind. In the lower hybrid current drive,E_y is not initially excited and even if this component may be excited in the plasma the second term in eq.(17) can be nglected since E_y is very small and k_y is large. Third term in R.H.S. of eq.(17) forms a inward drift flux Γ_{pinch} in the LHCD in tokamaks,which becomes,

$$\Gamma_{pinch} = \mp(\pi e E_z^2 \ B_\theta / 2 m k_z B^2) df(v_z)/dv_z \Big|_{v_z=\omega/k_z} \tag{18}$$

where the sign of R.H.S. is depending on the direction of the plasma current. This estimation differs by only $2/\pi$ from our first prediction[4]. It is noted that the DC drift is outward at the anti-direction palsma current as shown in the sign of eq.(17).

3. Improvement of the plasma confinement due to pinch effect

3.1 Procedure of formation

Since it is shown that the DC inward flux occurs in the LHCD ,we want to consider the behaviour of energy confinement time in the following. We consider that the particle flux is reduced by the inward flux of eq.(18) to form the effective flux in the following

$$-D\partial n_1/\partial r - \Gamma_{pinch} = -D_{eff} \partial n_2/\partial r \tag{19}$$

where the notation of n_1 means the density before the pinch effect occurs and n_2 is after the pinch occurs. The electron thermal conductivity χ_e can be connected to the particle diffusion component may be excited in the plasma the second term in eq.(17) can be nglected since E_y is very small and k_y is large. Third term in R.H.S. of eq.(17) forms a inward drift flux Γ_{pinch} in the LHCD in tokamaks, which becomes,

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where the notation of n_1 means the density before the pinch effect occurs and n_2 is after the pinch occurs. The electron thermal conductivity χ_e can be connected to the particle diffusion

$$\chi_e = \beta D_{eff} / \sqrt{q} \tag{20}$$

,where β is a constant and q is safety factor. The energy confinement time of electron is

$$\tau_{Ee} = a^2 / \chi_e \tag{21}$$

According to Kadomtsev[9], τ_{Ee} can be related with the gross energy confinement time τ_E during supplementary heating by

$$\tau_E = 2\tau_{Ee} (1 + \gamma\ n^{1/3} R^{2/3}\ I_P^{-2/3} P_{IN}^{1/3}\ )^{-1} \tag{22}$$

This relation is based on the fact that the ion thermal conductivity χ_i is neoclassical and only χ_e is anomalous, where the plasma density n is in units of $10^{13}\mathrm{cm}^{-3}$,R is the major radius in meters,I_p is the plasma current in MA,P_{IN} is the supplementary heating power in MW and γ is a constant. In the calculation to get E_{rf} in eq.(18),the rf power P_{RF} in the radial direction is essential[4] ,that is,the local rf power $P_{RF}(r,n_z)$ of the slow wave propagating in the - r direction is expressed in one dimensional WKB approximation,as

$$\frac{dP_{RF}(r,n_z)}{dr} = -2k_{QL} P_{RF}(r,n_z) \tag{23}$$

here k_{QL} is quasi-linear damping rate [10]. We assume the Gaussian as the n_z spectrum of the slow wave, and the accessibility condition $n_z > n_{za} = (1+(\omega_{pe}/\omega_{ce})^2)^{1/2} + \omega_{pi}/\omega_{ci}$ should be satisfied for $r < a$. The integration on n_z must be performed at each point in solving eq.(23): $P_{rf0} = \int_{-\infty}^{\infty} P_{rfa} dn_z$ at $r=a$, $P_{RF} = \int_{n_{za}}^{\infty} P_{RF}(r, n_z) dn_z$ at $r < a$. It is noted that the spatial damping of D_{QL} which must be included in k_{QL} is considered. The stationary quasi-linear distribution function is used for f in eq.(18). A slab model is used in this calculation including a simple toroidal correction to n_z given by $n_z = n_{zc}(R+a)/(R+r)$, where n_{zc} is injected n_z at the launcher [10].

Since τ_E is gross energy confinement time, we calculate the radial profile of P_{rf} at first and then we get a spatial average of D_{eff}, χ_e and τ_E. The density profile of n_1 is assumed to be $(1-(r/a)^2)^{\alpha_1}$ and n_2 is $(1-(r/a)^2)^{\alpha_2}$. We get D corresponding to Kaye-Goldston scaling [11] using $D = a^2/\beta\tau_{Ee}$ by substituting the value of τ_E in Kaye-Goldston scaling (K-G Scaling) into eq.(22). The physical basis in this simulation is how χ_e in Kaye-Goldston scaling is improved through the particle diffusion D.

3.2 Simulation results

The value of τ_E is calculated against n_{zc} , T_{e0}, $\bar{n}_e$ and P_{rf0} as shown in Figs.1,2,3 and 4,respectively,where T_{e0} is the central electron temperature, $\bar{n}_e$ average plasma density and the temperature profiles are paraboloic $(1-(r/a)^2)^2$. The parameters of the simulation is taken JT-60 LHCD case. Figure 1 shows that τ_E is improved at a certain value of T_{e0} and with increase of n_{zc} the optimum value of τ_E increases and shifts to the lower temperature side. As the same manner in Fig.1, the optimum τ_E is improved at a certain value of n_{zc} and with increase of T_{e0} the optimum value of τ_E decreases and shifts to the lower n_{zc} side as shown in Fig.2. Figure 3 shows that τ_E has also a optimum value on $\bar{n}_e$ and τ_E has gentle peak on $\bar{n}_e$. Many data that the confinement is improved at the low density region are included in this simulation. Figure 4 shows that τ_E does not deteriorate even when P_{rf0} increases if T_{e0} has a certain value. The value of τ_E is improved even when the density profile is peaking as shown in eq.(19),which corresponds to the case at $\alpha_1 < \alpha_2$ as shown in the padestal of τ_E in Figs.2 and 3. Peaking parameter α_1 and α_2 are as follows; $\alpha_2 = \alpha_1 + 1 \times 10^{-3} P_{rf}^{0.33}$ It is already shown that the density profile is peaking during LHCD[4]. This parameter is based on the simulation. The pinch effect in LHCD occurs when the large plasma current flows in plasmas and the strong poloidal field by rf causes. It should be noted as the case of current drive that the optimum value of τ_E is obtained when the values of n_{zc}, T_{e0} and $\bar{n}_e$ take a certain value,respectively. The most interesting calculation is the power dependence, that is, τ_E does not deteriorate against the input power in a certain parameters although τ_E is still in "L mode" of the scaling when the parameters are not optimized.

3.3 Simulation in the simultaneous injection of LHCD and NBI of JT-60

Since the simulation results in the previous section indicates that the value of n_{zc} and T_{e0} are very critical parameters we can find out the probable parameters that can explain the results of the simultaneous injection of LHCD and NBI in JT-60. Using the data of additional heating case, we can get the emprical scaling of T_{e0} and T_{i0} in JT-60 case, that is, $T_{e0} = (4.6\ P_{NB} + 23.3)/(3\ \bar{n}_e + 14)$ and $T_{i0} = (9\ P_{NB} + 15)/(3.5\ \bar{n}_e + 17.5)$, where T_{e0} and the central ion temperature T_{i0} are in keV, the NBI power P_{NB} in MW and $\bar{n}_e$ in cm^{-3}. These are based on the experiments in JT-60.[12] The simulation result in the case that τ_E does not deteriorate against the rf power and the average density are shown in Figs.5 and 6, respectively. The values of P_{NB} $\bar{n}_e$ and n_{zc} are the key parameters in order to get the optimum τ_E. Simulation results show that the improved τ_E can be obtained even for high density ($\bar{n}_e = 1 \times 10^{13}\ cm^{-3}$)and high current (I_p= 2.7 MA) case with high heating power (P_{RF}=5 MW and P_{NB}=12 - 15 MW) as shown in Fig.7. As shown in Fig.1, when n_{zc} is fixed T_{e0} is more sensitive to τ_E so that τ_E can meet an optimum value on T_{e0} through P_{NB} from the way to increasing P_{NB} . This is because T_{e0} increases with P_{NB}. It should be noted that we must find out te optimum parameters of $n_{zc}, T_{e0}, \bar{n}_e, P_{RF}$ and P_{NB} and so on if we want to improve the confinement.

4. Discussion and conclusion

The validity of the pinch effect in the travelling wave type current drive is estimated by the exact treatment of Landau damping in the presence of the magnetic field. We can also derived the same result as eq.(18) using a simple consideration as treated by Spitzer.[13] These are shown in Appendix I. The essential point in the calculation of the pinch effect in the current drive tokamaks is that the wave is travelling. If the wave is only oscillating without moving, the $\vec{E}_{rf} \times \vec{B}$ drift is cancelled out after time averaging as the same manner in the estimation of Landau damping. Since it has been already confirmed that the lower hybrid wave really drives the plasma current,[14] it is probable that the momentum is transfered to electrons from wave and in resonant electrons receive force $\vec{F}_{wave}=e\vec{E}_{rf}$ from wave to form a DC $\vec{j}_{rf} \times \vec{B}_\theta$ pinch as the same manner in joule heating $\vec{j}_\Omega \times \vec{B}_\theta$ pincn.

In this paper, three components of E_{rf} are all reminded, however, the y component of the rf electric field can be neglected in the derivation of eq.(17) since E_y becomes only oscillating term in LHCD case if we consider the propagating of the lower hybrid wave on the standpoint of the the dispersion relation. These are shown in Appendix II. In such three dimensional analysis like this the coupling theory indicates that the displacement in the y direction can be neglected ($\partial/\partial y=0$) and the fast wave te optimum parameters of $n_{zc}, T_{e0}, \bar{n}_e, P_{RF}$ and P_{NB} and so on if we want to improve the confinement.

4. Discussion and conclusion

The validity of the pinch effect in the travelling wave type current drive is estimated by the exact treatment of Landau damping in the presence of the magnetic field. We can also derived the same result as eq.(18) using a simple consideration as treated by Spitzer.[13] These are shown in Appendix I. The essential point in the calculation of the pinch effect in the current drive tokamaks is that the wave is travelling. If the wave is only oscillating without moving, the $\vec{E}_{rf} \times \vec{B}$ drift is cancelled out after time averaging as the same manner in the estimation of Landau damping. Since it has been already confirmed that the lower hybrid wave really drives the plasma current,[14] it is probable that the momentum is transfered to electrons from wave and in resonant electrons receive force $\vec{F}_{wave} = e\vec{E}_{rf}$ from wave to form a DC $\vec{j}_{rf} \times \vec{B}_\theta$ pinch as the same manner in joule heating $\vec{j}_\Omega \times \vec{B}_\theta$ pincn.

In this paper, three components of E_{rf} are all reminded, however, the y component of the rf electric field can be neglected in the derivation of eq.(17) since E_y becomes only oscillating term in LHCD case if we consider the propagating of the lower hybrid wave on the standpoint of the the dispersion relation. These are shown in Appendix II. In such three dimensional analysis like this the coupling theory indicates that the displacement in the y direction can be neglected ($\partial/\partial y=0$) and the fast wave component (E_y) is small in the usual lower hybrid wave current drive. It is shown in Table 1 of ref. 6) that the value of k_y becomes large . It may correspond to the flux control discussed by Itoh that the second term in eq.(17) becomes to be effective,however,this drift is not generated because no momentum input of the poloidal direction is in the LHCD case.[15] It is interested to make a poloidal phase difference in the case of fast wave heating. In this case the pinch effect may be further enhanced by the $E_y \times B_z$ drift togather with $E_z \times B_\theta$ drift since the second term of R.H.S. in eq.(17) reminds. Recently,MIT group reports that τ_p is not improved at the anti-current drive case[16] ,which seems to be supported by this pinch effect as shown in the sign of the second term of R.H.S. in eq.(18).

The physical background that τ_E is improved at the low density region is a feature of the quasi-linear effect,that is,this is the same physics as the fact that the driving rf current increases with decrease of the average plasma density,which comes from the fact that E_{rf} and D_{QL} decreases with increasing the density due to strong Landau damping at the main plasma region.

The radial profile of the rf electric field,that is,the calculation of E_{rf} in eq.(18) is important. At first,the rf power in the radial direction is obtained by the quasi-linear damping method,and the variation of n_{zc} is simple toroidal effect due to small single path damping,which may be almost correct when the density is lower. The value of τ_E in K-G Scaling is gross confinement time,which is defined as,$\tau_E=\int n(T_e+ T_i)dV/P_{IN}$,however,in the simulation it is represented by the spatial average in each point. It is natural that τ_E is improved at a certain parameter of n_{zc} and T_{e0} when we consider the feature of the quasi-linear theory,which is coming from the effect of the penetration of the rf electric field in the radial direction that is most sensitive to the value of v_z/v_{the} ,where v_{the} is the electron thermal velocity. General featrure of the calculation indicates that the better confinement is obtained when the current drive occurs effectively,that is ,the peak point of τ_E corresponds to the case when the largest plasma current flows by LHCD. Simulation in this paper is performed what values of the parameters are the best fitting to the experiment,however,the validity of the decision of them must be further considered.

In conclusion,we must not deteriorate the confinement time below the value for the joule heated plasma when additional heating power is injected into tokamaks. The rf heating due to electron Landau damping with travelling waves may enhance the good confinement characteristics of the centrifugal $\vec{E} \times \vec{B}$ drift that the joule heated tokamak has for all charged particles by replacing E_Ω with E_{rf} for resonant elecrons, resulting in the improvement of the plasma confinement in the slow wave current drive. It has been said for a long time that the anomalous diffusion of electron determines the gross confinement in tokamaks. The theoretical understanding of this is not given yet in satisfactory and the solution how suppress the anomalous diffusion is not also given yet,however,on the appearance of the current drive by the travelling wave we may be able to find out the suppression method of the anomalous diffusion of electron to confine plasmas in tokamaks .

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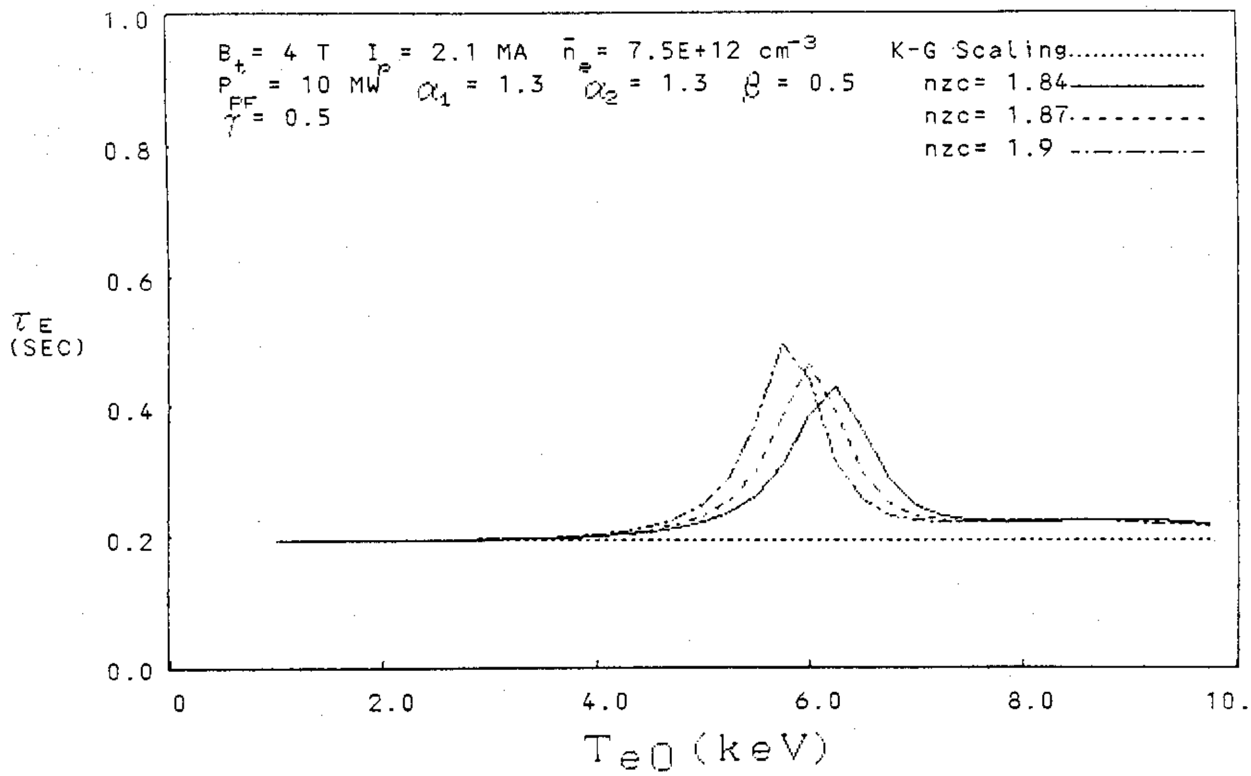


Fig.1 Energy confinement time τ_E against T_{e0} putting n_{zc} as a parameter.

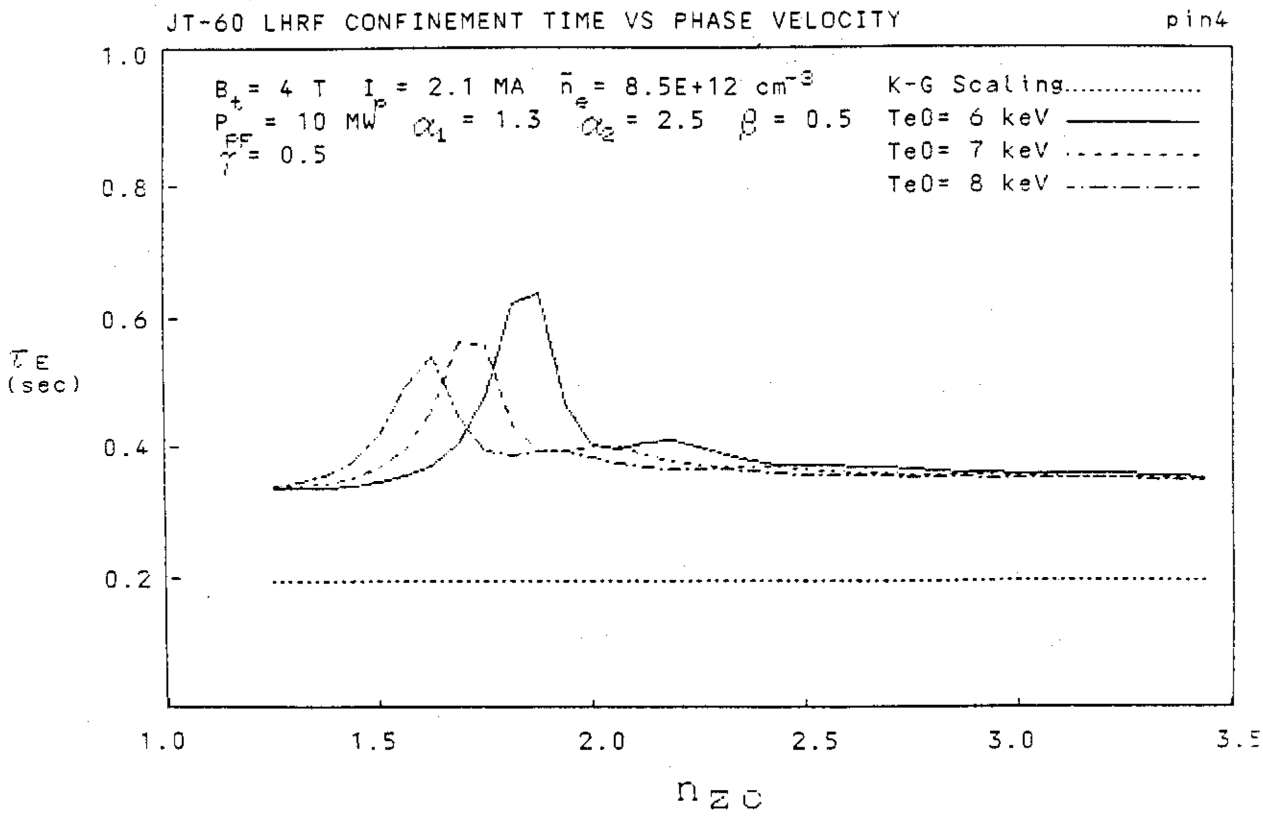


Fig.2 Energy confinement time τ_E against n_{zc} puttung T_{e0} as a parameter.

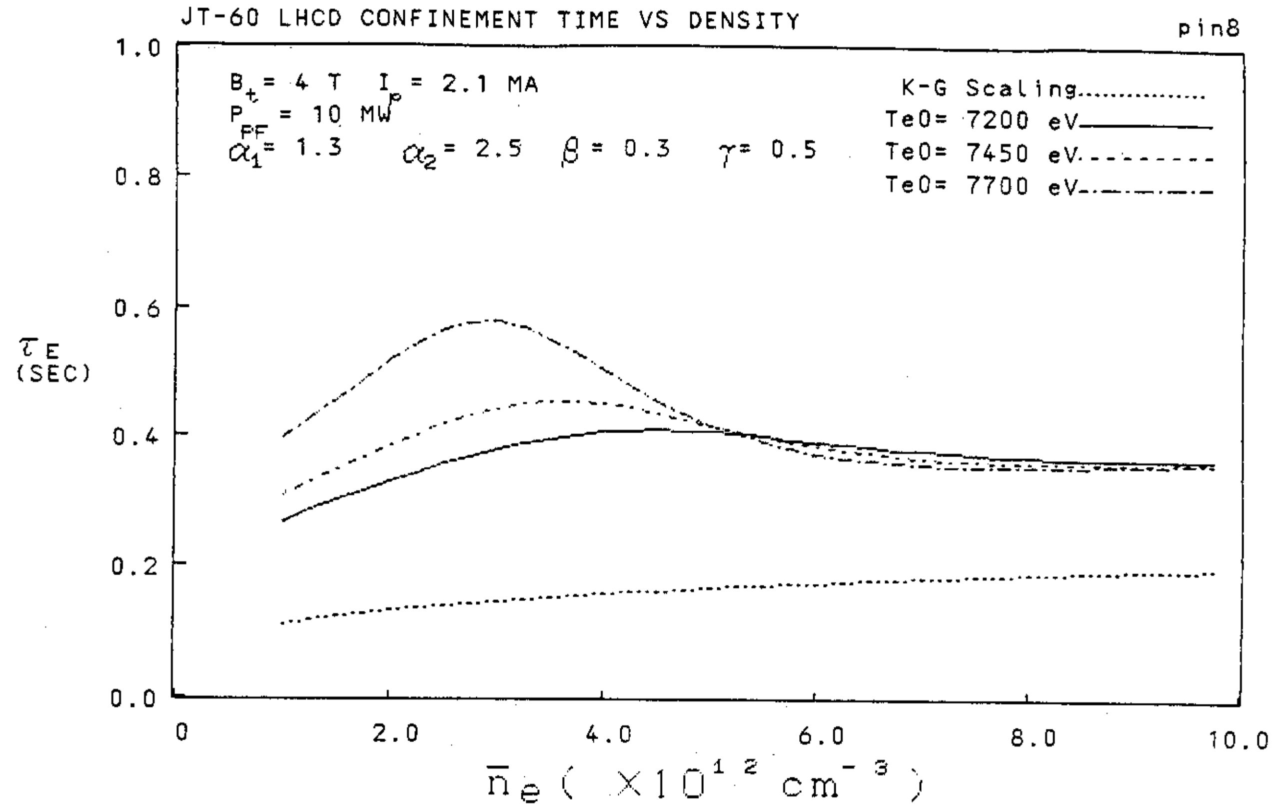


Fig.3 Energy confinement time τ_E against $\bar{n}_e$ putting T_{e0} as a parameter.

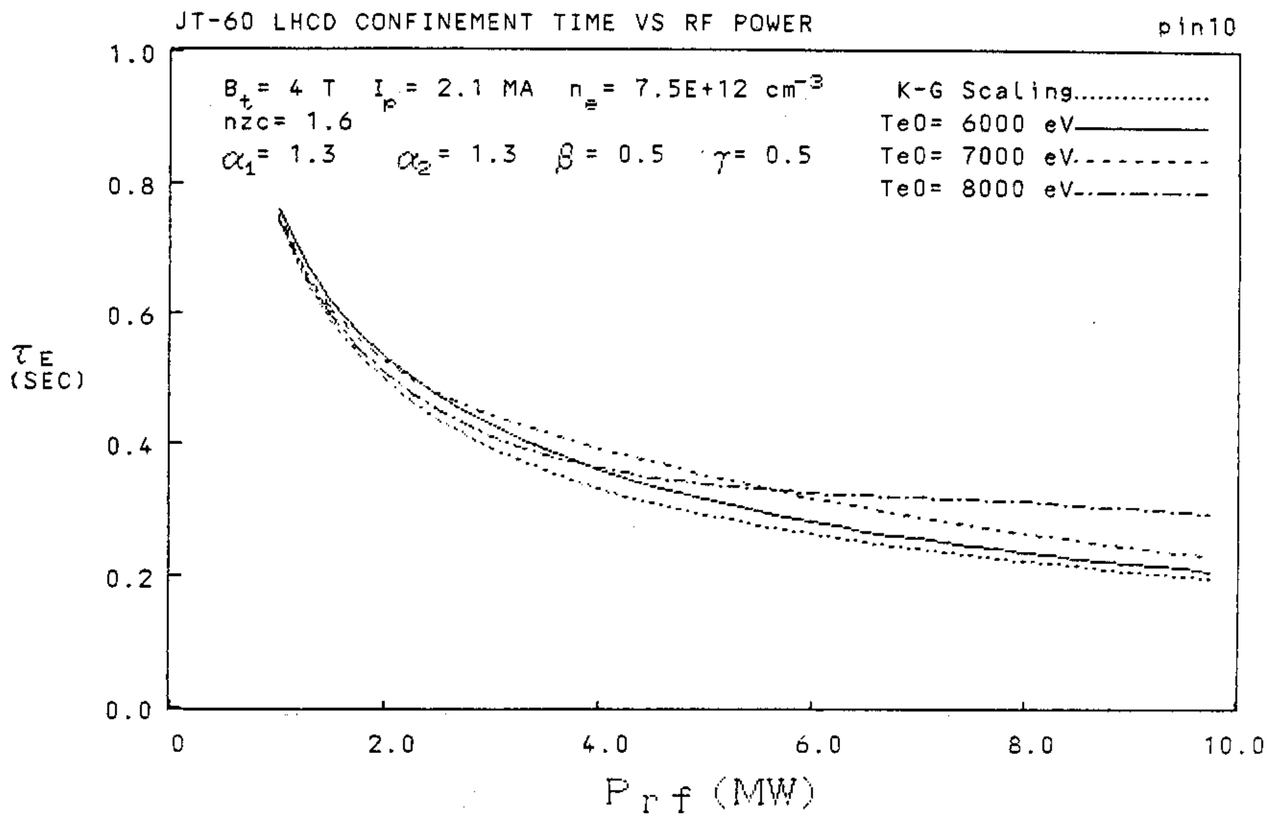


Fig.4 Energy confinement time τ_E against P_{rf} putting T_{e0} as a parameter.

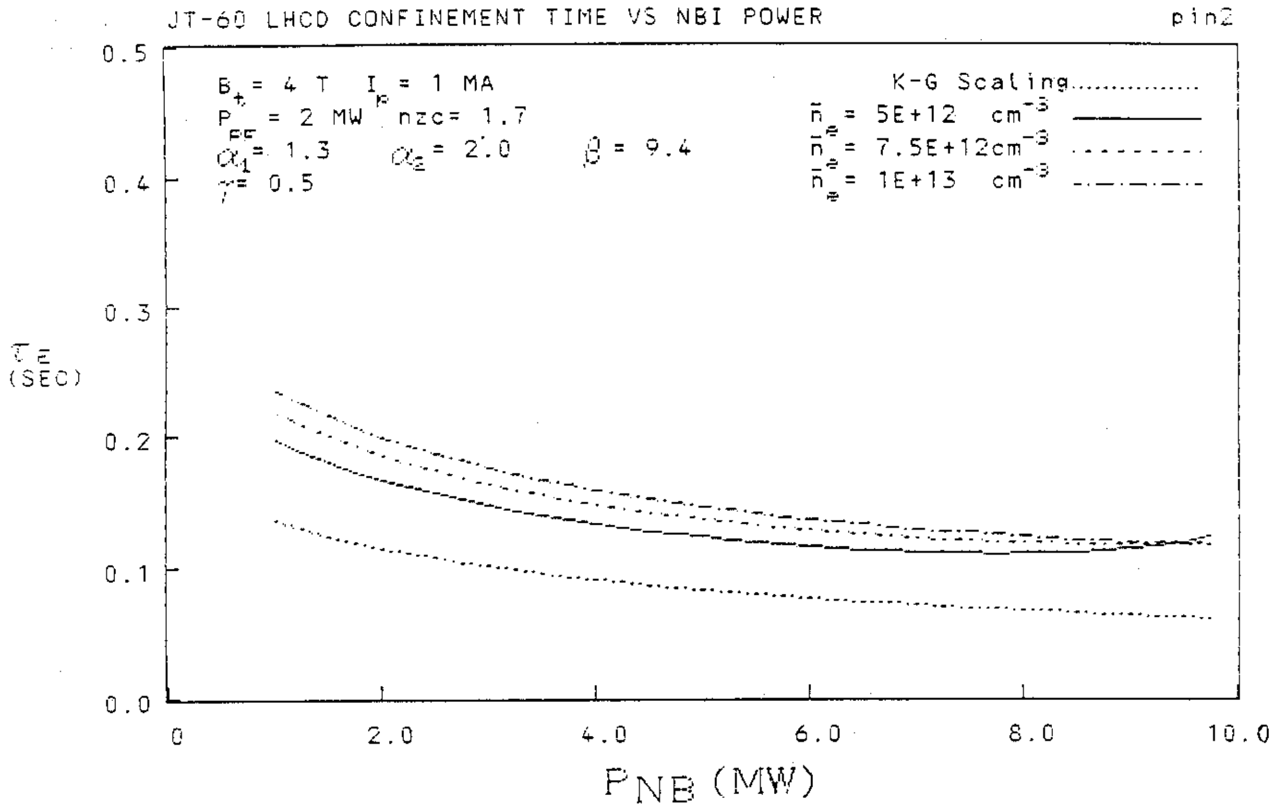
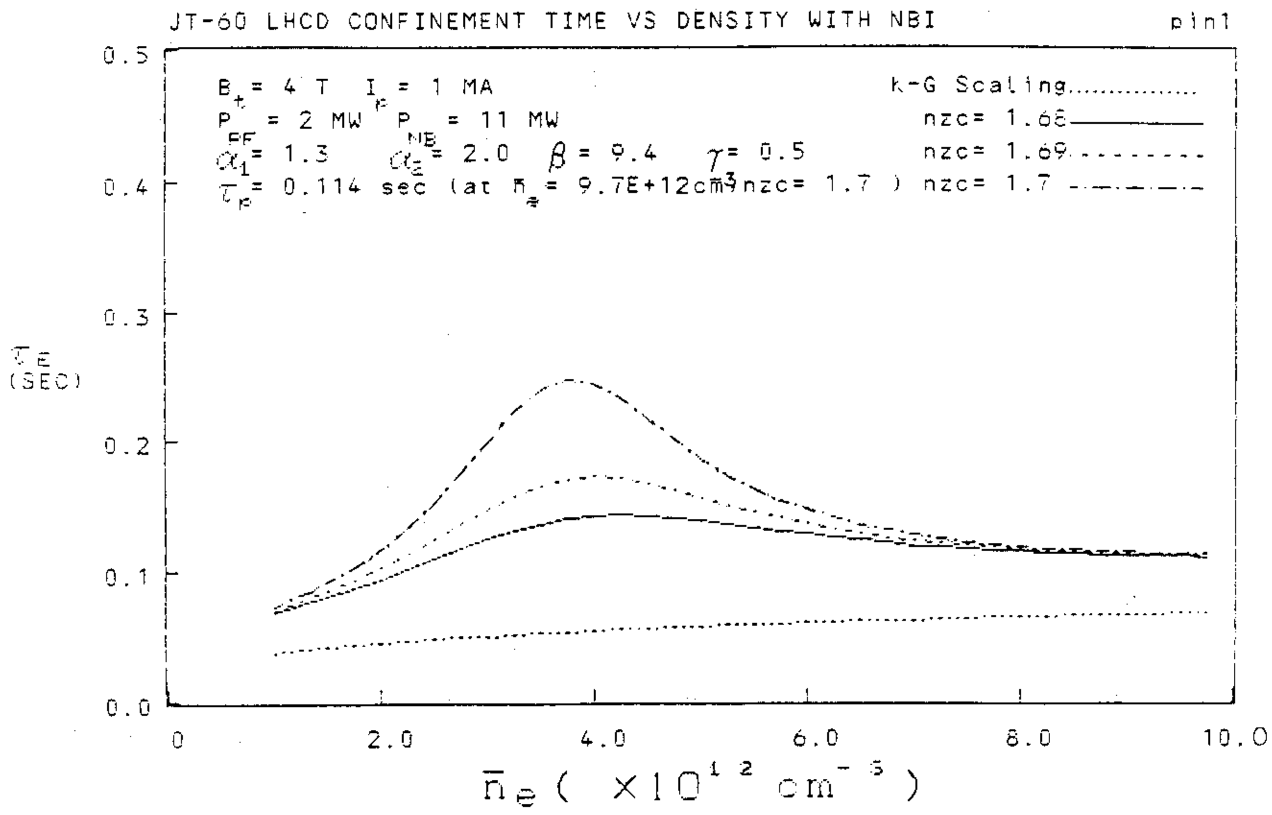


Fig.5 Energy confinement time τ_E against P_{NB} putting $\bar{n}_e$ as a parameter in JT-60 LHCD and NBI case.



Fg.6 Energy confinement time τ_E against $\bar{n}_e$ putting n_{zc} as a parameter.

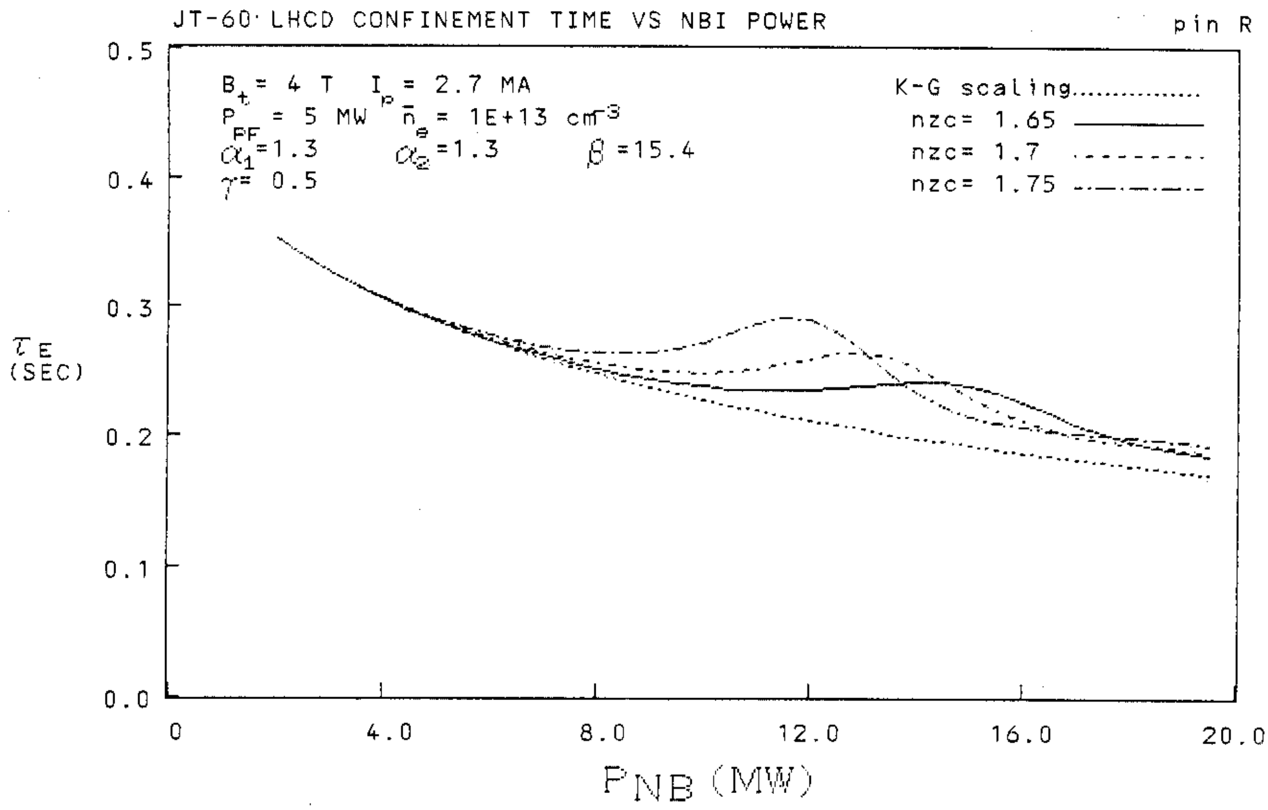


Fig.7 Energy confinement time τ_E against P_{NB} putting n_{zc} as a parameter for high density and high current with large additional power.

Appendix I

In this appendix,we want to derive eq.(18) by using a simple consideration as treated by Spitzer. The potential of wave is

$$\Psi=-\Psi_0\cos(kz-\omega t) \qquad \text{(A-1)}$$

On the coordinate moving with the phase velocity $V=\omega/k$,the displacement of electrons is

$$z'=z-Vt \qquad \text{(A-2)}$$

and eq.(A-1) becomes

$$\Psi=-\Psi_0\cos kz' \qquad \text{(A-3)}$$

which is an electrostatic potential. From the conservation law of energy,

$$\frac{1}{2}mv'^2+e\Psi=\frac{1}{2}mv_0'^2 \qquad \text{(A-4)}$$

where v_0' is the velocity at $\Psi=0$ and particles satisfying the condition

$$v_0' \leqq v_c = \sqrt{2e\Psi_0/m} \qquad \text{(A-5)}$$

are trapped by the wave. Since the rf field applies to this trapped particles as an effective DC electric field ,there exist an innward drift whose velocity is

$$v_D = E_{rf} B_\theta / B^2 \qquad \text{(A-6)}$$

where $E_{rf} = -\partial\Psi/\partial z'$. Trapped electrons move in the potential trough and are reflected at the potential wall. When trapped electron is reflected at the wall the velocity of electrons changes as $v' \to -v'$,where $v \to -(v-V)+V$ on the laboratory coordinate ,that is,the increment of the velocity is $\Delta v=2(v-V)=-2v'$. The time interval of the collision to the potential wall is $\lambda/2|v'|=\pi/k|v'|$,where λ is wave length of the wave. The force acting on the particles is $F=m\Delta v/\Delta t=-2mkv'|v'|/\pi$,which corresponds to eE_{rf}. Substituting E_{rf} into eq.(A-5),v_D becomes

$$v_D = -\frac{2}{\pi}\frac{m}{e} kv'|v'|\frac{B_\theta}{B^2} \qquad \text{(A-7)}$$

Multiplying the distribution function f(v) and integrates on v' we can get the inward flux Γ . When Ψ_0 and v_c are small,$f(V+v')=f(V)+v'\partial f/\partial v_{v=V}$ and the integration is performed from $-v_c$ to $+v_c$. The integration of $\int$

$v'|v'|dv'$ is zero since the integrand is odd function and $\int_{-v_c}^{v_c} v'^2 |v'|dv' = 2\int_0^{v_c}$

$v'^3 dv' = v_c^4/2 = 2e^2\Psi_0^2/m^2$. Finally, the average flux Γ becomes

$$\Gamma = -\frac{4}{\pi}\frac{e}{m}\frac{(k\Psi_0)^2}{k}\frac{B_\theta}{B^2}\frac{\partial f}{\partial v}\bigg|_{v=\omega/k} \qquad \text{(A-8)}$$

which is almost coincide to eq.(18) since $k\Psi_0 = E_{rf}$.

Appendix II

For simplicity, we consider the uniform plasma surrounded by a cylindrical wave guide. We assume that the majority of the spectral energy of Ψ is in the region $k_z \gg \omega/c$, so that an electrostatic approximation is valid. From cold plasma theory, Ψ is determined as the solution to

$$\mathrm{div}(\varepsilon_\perp + \varepsilon_{/\!/})\nabla\,\Psi = 0 \qquad \text{(A-9)}$$

where ε and ε are

$$\varepsilon_\perp = 1 - \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} \qquad \text{(A-10)}$$

and

$$\varepsilon_{/\!/} = 1 - \frac{\omega_{pe}^2}{\omega^2} \qquad (A\text{-}11)$$

in the frequency range of the lower hybrid wave,respectively. When we solve the eq.(A-9) by the cylindrical coordinate,we get

$$\Psi = A\ J_n(pr)\cos n\theta\ e^{-i(k_z z-\omega t)} \qquad (A\text{-}12)$$

where J_n denotes the modified Bessel function and $p^2 = -(\varepsilon_{/\!/}/\varepsilon_{\perp})k_z^2$. Thus,z direction is travelling wave,however,θ direction is only the oscillating component .