Radial electric field generated by resonant trapped electron pinch with radio frequency injection in a tokamak plasma

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(Received 10 May 2011; accepted 16 July 2011; published online 19 August 2011)

Radial electric fields in tokamaks can be generated by charge accumulation due to a resonant trapped electron pinch effect. The radial field can then drive a toroidal flow. This resonant pinch effect was evaluated for the current-drive scheme that diffused electrons in the direction parallel to the toroidal field. It was found that, for typical tokamak parameters, to generate a radial electric field on the order of 100 kV/m, an rf power density on the order of $\mathrm{kW/m^3}$ is required. This power, absorbed by trapped electrons, is a small fraction of rf power density for current drive which is absorbed by passing electrons. However, according to the Landau resonant mechanism, the fraction of the momentum to trapped electrons decays exponentially with the square of the parallel phase velocity of the wave; therefore, the power absorbed at lower resonant velocities is the key. On the other hand, the redistribution of the current profile, due to rf current, decreases the local poloidal field and may reduce the particle transport significantly. It can relax the requirement of momentum deposited to trapped electrons, and, at the same time, contribute to explain the strongly correlation between the rotation and the driven current observed in experiments. © *2011 American Institute of Physics*. [doi:10.1063/1.3624494]

I. INTRODUCTION

Toroidal plasma flow in tokamaks may be advantageous for confinement.[1–3] However, momentum input by neutral beam injection alone to produce this flow may not suffice to meet the flow required in ITER or future reactors. Therefore, it is of great interest to investigate methods of flow drive without significant momentum input, such as may occur during rf current drive. While the physics of the rf current drive effect itself has been well understood,[4] what is not well understood is why toroidal rotations were observed in many rf experiments.[5–8] Since the rotation was usually observed in early ion cyclotron resonant heating (ICRH) experiments, theories based on the orbit of energetic particles were developed.[9–11] However, similar rotations were found later in electron cyclotron resonant heating (ECRH) plasma and Ohmic plasmas. Then, theories were developed from the view of neoclassical[12] or turbulence transport.[13–16] Also, a comprehensive description[17] of many processes of toroidal flow generation and transport was provided in sequential time scales. In addition, an inter-machine comparison of intrinsic toroidal rotation was conducted.[18]

One of the significant characteristics of the so-called "intrinsic rotation" is that the rotation is proportional to the stored energy but inversely proportional to the plasma current. At present, a theory[19] based on the turbulent momentum transport seems to be promising, since the rotation from a residual stress was confirmed by recent experiment at cylindrical laboratory plasma.[20] However, recent experiment on mode conversion flow drive in C-Mod (Ref. 21) showed different behavior, where the flow is significantly larger than the empirical scaling law of the intrinsic rotation and is rather sensitive to different rf-plasma interactions. Another recent experiment in C-Mod (Refs. 22 and 23) indicated that a toroidal flow can be generated by lower hybrid wave (LHW) injection, where the flow seems to be closely associated with the rf driven current. Because of the large space of wave parameters explored and to which this effect appears to be sensitive, this discovery of toroidal rotation produced by the LHW is likely important for understanding rotation production in general.

While the lower hybrid current drive physics has been clear,[24,25] the physical mechanism of toroidal flow generation by the LHW is an open issue. A negative radial electric field, near the peak of the electron profile, was observed[22,23] which may imply an electron pinch effect. It is expected that this pinch process is similar to the Ware pinch,[26] but due to the rf-electron resonance. This rf-induced pinch effect has been mentioned in the scheme of low frequency current drive,[27] where in the steady state, the bootstrap current might compensate the current lost in trapped electrons. However, the charge separation due to this pinch of electrons would generate a radial electric field, which would then drive rotation. Therefore, it is of great interest to investigate whether this electron pinch effect induced by rf waves is relevant to producing a significant radial electric field and then driving the plasma rotation.

In this paper, we evaluated this effect of resonant trapped electron pinch and its relevance to the radial electric field needed to drive the flow. It was found that two key processes influence this effect strongly. One is the division of rf power into passing and trapped electrons. It was found that, for

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typical tokamak parameters, to generate a radial electric field on the order of 100 kV/m needs an rf power density on the order of $\mathrm{kW/m^3}$ deposited on trapped electrons, which is only a small fraction of the rf power density for heating and/or current drive. However, according to the Landau resonance mechanism, the fraction of momentum to trapped electrons decays exponentially with the square of the parallel phase velocity of the wave, so that a low frequency wave, for example, an ion cyclotron frequency range (ICRF) fast wave or an Alfven wave, easily provides enough momentum to trapped electrons to build a significant electric field. However, for a higher frequency wave, for example, a LHW, the large parallel wavenumbers in power absorbed spectrum, rather than the wavenumbers that dominate current drive, is expected to play the key role in flow drive. The other important issue in this mechanism is the secondary effect due to the redistribution of current profile due to the rf current. The current profile distribution can decrease the local poloidal field and may reduce the particle transport significantly. It can loosen the requirement of momentum deposited to trapped electrons, and, at the same time, contribute to explain the strong correlation between the rotation and the driven current observed in experiments.

The paper is organized as followed. A physical model of resonant trapped electron pinch is presented in Sec. II. The magnitude of electric field driven by this mechanism is estimated in Sec. III, where possible processes to increase the fraction of momentum to trapped electrons are discussed. Section IV is devoted to the effect of the redistribution of current profile due to rf current, which may explain the correlation between flow drive and current drive. Finally, conclusions are given in Sec. V.

II. PHYSICAL MODEL

We will evaluate the pinch effect due to rf-plasma resonant interaction for the parallel-drive scheme. First, suppose that, during the time interval Δt, the electrons obtain the momentum Δp, parallel to the magnetic field from the rf wave. This momentum gain is allocated to circulating electrons and trapped electrons separately, as $\Delta p = \Delta p_c + \Delta p_t$. For circulating electrons, a parallel current, $J_\parallel$, is determined by balancing the wave driving effects and the collision dragging effects

$$\frac{\Delta p_c}{\Delta t} = \frac{\nu_e m_e J_\parallel}{e}, \tag{1}$$

where ν_e is the collision rate of resonant circulating electrons. However, the resonant trapped electrons, which absorb the parallel momentum as well, do not contribute to the current since the parallel velocity of the trapped particle reverses its sign at the bounce points. Instead, the vector potential changes to keep the conservation of canonical annular momentum such that a radial electron flux is produced. The mechanism is the same as the well-known Ware pinch[26] except that the parallel momentum is provided by the rf-electron resonance rather than by the inductive eclectic field. Then, we have

$$\frac{\Delta p_t}{\Delta t} = -e n_t v_r B_\theta \equiv -e B_\theta \Gamma_{re}, \tag{2}$$

where n_t and v_r are the density and radial drift velocity of trapped electrons, and $\Gamma_{re} = n_t v_r$ denotes the radial electron flux. This inward radial electron flux causes the negative charge accumulation. The saturation mechanism is related to the particle transport process, which is the mixture of diffusion and convection. However, for simplicity, we may consider the radial particle transport as an "effective" diffusion process by defining an effective diffusion coefficient $D_n = D_{diff} + L_n V_{conv}$, where D_{diff} is the diffusion coefficient, V_{conv} is the convection velocity, and L_n is the scale length of density. Then, we can estimate the value of D_n from the particle confinement time in experiments and need not consider the details of anomalous diffusion and convection, which is still an open question. (Of course, we can also consider the particle transport as an effective convection process in the same way.) In this picture, the charge density is determined by the balance between the rf-induced pinch flux and the outward diffusion flux due to the slight increase in electron density gradient

$$\Gamma_{re} = D_n \frac{\Delta q}{e L_n}, \tag{3}$$

where $\Delta q = e \Delta n$ is the accumulated charge. Here, it is assumed that the density gradient does not change too much so the change of density gradient is proportional to the change of electron density. Finally, the radial electric field, E_r, is decided by the Possion's equation

$$\nabla \cdot \mathbf{E_r} = -\frac{\Delta q}{\varepsilon_0}. \tag{4}$$

Now, let us connect the electric field to the rf power deposited into plasma. For parallel drive with the resonant velocity $v_\parallel$, the transferring energy is $\Delta W = v_\parallel \Delta p$, so that the wave power density, P_D, is connected to the momentum gain

$$P_D = v_\parallel \Delta p / \Delta t. \tag{5}$$

Combining Eqs. (2) and (5), we get

$$\frac{E_r}{P_D} = -\frac{L_E L_n \kappa_t}{\varepsilon_0 D_n B_\theta v_\parallel}, \tag{6}$$

where $\kappa_t \equiv \Delta p_t / \Delta p$ is the fraction of momentum into trapped electrons and L_E the radial scale length of electric field. (Here, we assume that E_r at the edge is zero and then $\nabla \cdot \mathbf{E_r} \sim -E_r/L_E$.)

From Eq. (1), we can obtain the relation between the rf-driven current density and the power density as

$$\frac{J_\parallel}{P_D} = \frac{(1-\kappa_t)e}{m_e v_\parallel \nu_e}. \tag{7}$$

We can also connect the radial electric field to $J_\parallel$ by the relation

$$E_r = -\frac{\kappa_t}{1-\kappa_t} \frac{L_E L_n \nu_e}{\varepsilon_0 D_n \Omega_\theta} J_\parallel, \tag{8}$$

where Ω_θ is the electron cyclotron frequency at the poloidal field. Then, if the poloidal rotation and the pressure profile are not changed too much due to the rf injection, the change of the toroidal rotation accompanying the rf current drive may be written as

$$\Delta V_\phi = E_r / B_\theta. \tag{9}$$

Thus, counter-current rotation is expected. In Sec. III, we will estimate the magnitude of the radial electric field produced by this mechanism.

III. ESTIMATION OF THE MAGNITUDE OF RADIAL ELECTRIC FIELD

Let us examine Eq. (6). The scale length of density, L_n, is of the order of the major radius. The scale length of the electric field, L_E, may be estimated to be a fraction of the minor radius. The parallel resonant velocity $v_\parallel$ is of the order of the electron thermal velocity v_{te} but its precise value depends on whether fast electrons or slow electrons are driven. (We will be using the normalized resonant velocity, $\hat{v}_\parallel = v_\parallel / v_{te}$.) The poloidal magnetic field B_θ is on the order of a Tesla, but the local field is changed by the re-distribution of the current profile due to the off-axis current driven, for example in the low hybrid current drive (LHCD). At the same time, this re-distribution of the current profile may influence transport, so it should be related to the particle diffusion coefficient D_n. However, as mentioned before, the understanding of D_n is still an open problem in tokamak plasmas. While leaving further discussion for Sec. IV, here, we simply use some typical values of D_n. For example, we can take the parameters: $L_n = 0.3\,\text{m}$, $L_E = 0.3\,\text{m}$, $B_\theta = 0.5\,\text{T}$, $T_e = 3\,\text{keV}$, and $D_n = 1\,\text{m}^2/\text{s}$ which approximate the measured experimental values in C-Mod LHW experiment[22,23] and are also roughly comparable to parameters of other relevant experiments. (In typical medium-size tokamaks, the scale lengths of density and temperature are similar to those in C-Mod but the poloidal field is a little bit weak; while in large-size tokamaks, the scale lengths of density and temperature are somewhat larger.) Since the effective diffusion coefficient D_n is difficult to estimate, a typical value of anomalous diffusion coefficient in tokamak is chosen here. (The case of neoclassical transport level will be discussed separately.) Then, substituting these parameters in Eq. (6), the generated electric field E_r is related to the power density as follows:

$$\frac{E_r[\text{kV/m}]}{\kappa_t P_D[\text{kW/m}^3]} = \frac{0.9 \times 10^2}{\hat{v}_\parallel}. \tag{10}$$

We may roughly consider the quantity $\kappa_t P_D$ as the power density deposited on trapped electrons. Then, Eq. (10) indicates that, to drive an electric field on the order of 100 kV/m, an rf power density on the order of kW/m^3 deposited on trapped electrons is required. In present devices, the plasma volume is typically of the order of m^3 and the injected rf power is of the order of MW. The total power density should be larger than MW/m^3 due to the localized deposition of the rf power. The typical observed electric field is about 30–50 kV/m. Therefore, only a small fraction of rf power for heating or current drive deposited on trapped electrons is enough to explain the radial electric field in experiments.

Now, we turn to examine the fraction of momentum to trapped electrons κ_t. For the resonant absorbing mechanism at given resonant phase velocity $v_\parallel$, the value of κ_t is the same as the fraction of trapped particles. Considering a tokamak with a low inverse aspect ratio $\varepsilon \ll 1$, the trapping condition of the particle is $v_\perp^2 \geq v_\parallel^2(1-\varepsilon)/(2\varepsilon)$; therefore, the fraction of the trapped particles at a given $v_\parallel$ can be roughly written as

$$\kappa_t \equiv \int_{\hat{v}_\parallel^2(1-\varepsilon)/(2\varepsilon)}^{+\infty} \exp(-\hat{v}_\perp^2)\, d\hat{v}_\perp^2 = \exp[-\hat{v}_\parallel^2(1-\varepsilon)/(2\varepsilon)]. \tag{11}$$

Here, we neglect the poloidal dependence of trapped condition and the corresponding magnetic surface average, which decreases the magnitude of κ_t but not by much. Clearly, κ_t decreases exponentially with the square of resonant velocity. Figure 1(a) shows the dependence of $\kappa_t/\hat{v}_\parallel$ on $\hat{v}_\parallel$ for $\varepsilon = 1/6$. It implies that the expected electric field driven efficiency can be obtained in the scheme of thermal or sub-thermal electron drive. For example, only a few kW/m^3 power density deposited on the thermal electrons is needed to generate a radial electric field on the order of 100 kV/m [the black dotted line in Fig. 1(b)]. If the rf power is deposited on trapped electrons directly, hundreds of watts are enough to drive the expected electric field [the green dash-dotted line

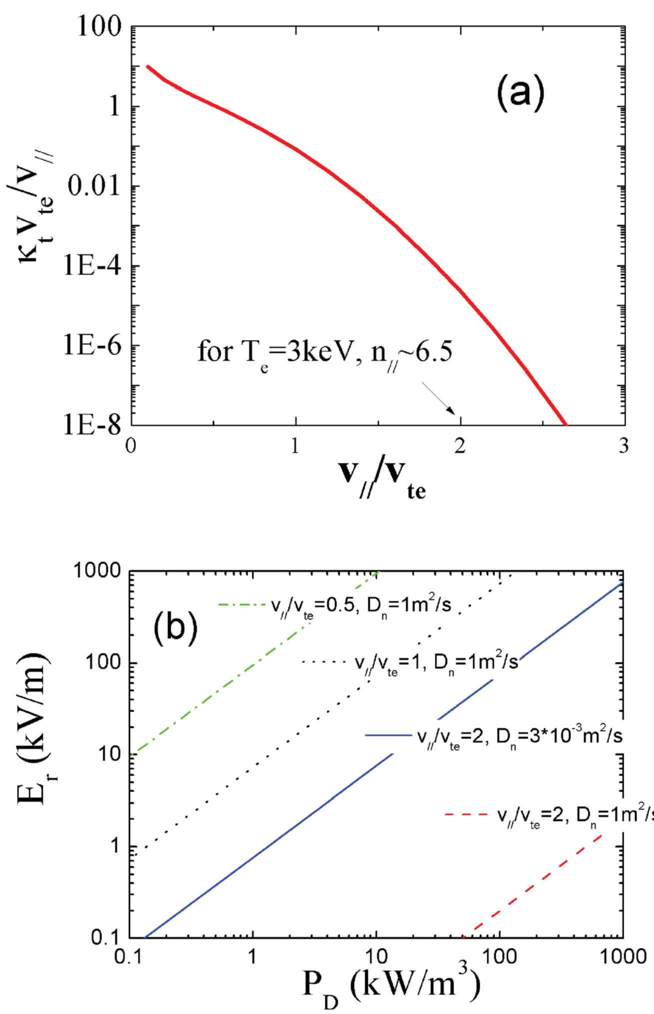

FIG. 1. (Color online) (a) The factor $\kappa_t/\hat{v}_\parallel$, which is proportional to the electric field drive efficiency by $\kappa_t/\hat{v}_\parallel = [(\varepsilon_0 D_n B_\theta)/(L_E L_n)](E_r/P_D)$, as functions of resonant velocity at $\varepsilon = 1/6$; (b) the magnitude of the driven electric field as functions of the power density for different resonant velocities and diffusion coefficient at typical parameters at $L_n = 0.3\,\text{m}$, $L_E = 0.3\,\text{m}$, $B_\theta = 5\,\text{T}$, $T_e = 3\,\text{keV}$, and $\varepsilon = 1/6$.

in Fig. 1(b)]. However, the efficiency of generating E_r decreases dramatically as the resonant velocity increases. This dependence implies that a low frequency wave, for example, an ICRF fast wave or an Alfven wave, can easily provide enough momentum to trapped electrons to build a significant electric field. However, the tendency is quite opposite for the LHCD case. For a typical LHCD experiment, the parallel phase velocity is several times of the electron thermal speed. For example, the spectrum $n_\parallel = 2$ corresponds to $\hat{v}_\parallel = c/(n_\parallel v_{te}) \sim 6.5$ for $T_e = 3\,\mathrm{keV}$. Therefore, the momentum deposited to trapped electrons is negligible. The phenomena of so-called $n_\parallel$ spectrum upshift or spectral gap[28] observed in LHCD may help produce some momentum deposition to electrons with lower velocity. However, even for $\hat{v}_\parallel = 2$ [the red dash line in Fig. 1(b)], $\kappa_t/\hat{v}_\parallel \sim 2 \times 10^{-5}$, which means the $\mathrm{MW/m^3}$ rf power density can drive a field of only 2 kV/m. Therefore, for the LHCD case, it is key to consider the possible processes to increase the momentum deposition to trapped electrons.

In practice, the grill antenna system generates a LHW power spectrum with multi-peaks in $n_\parallel$ besides the dominant peak. Neglecting the fine structure of each peak, the power spectrum can be written as $P_D \approx P_D \sum_j f_{Dj}\delta\ (n_\parallel - n_{\parallel j})$, where f_{Dj} is the weight function of the peak of $n_{\parallel j}$. The subpeaks have small fractions in power spectrum, therefore, may make a negligible contribution to current drive. However, the rf power with large $n_\parallel$ is deposited to electrons with lower velocities and then increase the efficiency for electric field generation. The total generated electric field can be described as

$$E_r \approx \eta P_D \sum_j n_{\parallel j}\kappa_t(n_{\parallel j}) f_{Dj}\delta(n_\parallel - n_{\parallel j}), \tag{12}$$

where $\eta = L_E L_n v_{te}/(c\varepsilon_0 D_n B_\theta)$ is about $8\mathrm{kV\cdot m^2/kW}$ for the parameters in Eq. (10). Then, the "dominant" peak for generating E_r depends on the value of $n_{\parallel j}\kappa_t(n_{\parallel j})f_{Dj}$. Since $\kappa_t(n_\parallel)$ grows rapidly, but f_D decays with an increasing $n_\parallel$, this value is sensitive to the details of rf power spectrum. Therefore, driving flow requires certain specific features for the antenna system.

Another issue is that, we used an anomalous particle diffusion coefficient above. If the particle confinement is improved, the requirement on the $n_\parallel$ absorbing spectrum will be relaxed. We may consider a neoclassical diffusion coefficient $D_n \sim 3 \times 10^{-3}\,\mathrm{m^2/s}$ (assuming $n = 1 \times 10^{20}\mathrm{m^{-3}}$, $B = 5\,\mathrm{T}$, $q = 3$). In this case, the efficiency for electric field generation is improved to $E_r/P_D = 3 \times 10^4(\kappa_t/\hat{v}_\parallel)$ $[\mathrm{kV\cdot m^2/kW}]$. Comparing to Eq. (10) at the anomalous transport level, the dependence on the resonant velocity does not change but the magnitude increases by about 300 times. In Figure 1(b), the blue solid line indicates this case, where $v_\parallel = 2v_{te}$ and $D_n = 3 \times 10^{-3}\,\mathrm{m^2/s}$. It is shown that tens of $\mathrm{kW/m^3}$ power density can drive tens of kV/m electric field. This improved confinement is consistent with the evolution of the radial electric field and/or the re-distribution of current profile due to the off-axis current drive. We will leave the discussion in Sec. IV.

Other mechanisms beyond the Landau absorbing can also contribute to the increase of the momentum percentage to trapped electrons. For example, anomalous Doppler broadening effect due to the interaction between LHW and fast electrons may scatter the momentum to the perpendicular direction,[29,30] and hereafter, Cherenkov mechanism could increase the momentum of trapped electrons.[31] However, if this mechanism was effective, the relevance of the radial electric field to the runaway behavior should be shown in the experiment. It was also known that the LHW can couple to low frequency fluctuations through the parametric decay,[32] which was considered as one of the explanations for the phenomena of spectral gap.[28] Recent study also[33] showed that the trapped electron mode (TEM) could be destabilized by the parametric processes induced by the low hybrid injection and then induces an inward transport. However, it is problematic to investigate whether the direct turbulence-induced diffusion is ambipolar or not. In this case, the turbulent energy (or momentum) dissipation should be considered. If the dissipation is different in the ion and electron channel, it will contribute the charge separation and then the generation of the radial electric field. Another process might be the momentum redistribution due to the collisions. The LHW serves as a continuous momentum pump, and collisions redistribute the momentum to bulk plasma over the relaxing time of fast electrons. The momentum on trapped electrons at the steady status may be

$$\kappa_t|_\infty \approx f_t \frac{\nu_{ee}}{\nu_{ee} + \nu_{ei}} = \frac{\sqrt{2\varepsilon}}{1 + 0.5Z}, \tag{13}$$

where ν_{ee} and ν_{ei} are the electron-electron and electron-ion collision frequencies, and Z is the effective charge number. This fraction is independent to the resonant velocity but seems much larger than the value required. Further consideration on the momentum distribution is still required.

IV. DISCUSSION OF THE CORRELATION WITH RF CURRENT DRIVE

Considering the division of parallel momentum into circulating and trapped electrons, the two roles of rf, i.e., current drive and flow (or radial electric field) drive, are indeed competitive. Although the mechanisms beyond the dominant peak absorbed, which are stated in the above section, may cause the fraction of momentum to trapped electrons, κ_t, independent on the dominant $n_\parallel$ value, the strong dependence of the current driven efficiency on the resonant velocity still remains. However, in the C-Mod experiment,[22,23] the strong correlation between the increasing rotation and the decreasing internal inductance were observed and this correlation changed a little as $n_\parallel$ varied. Both the current and the rotation increased with the decrease of $n_\parallel$. Moreover, the rotation seemed to lag behind the re-distribution of the current, which may indicate causality. Therefore, it is necessary to consider the effect of rf current drive on the generation of radial electric field and the corresponding toroidal rotation. In Sec. III, it has been mentioned that two factors, B_θ and D_n, can be changed by the redistribution of the current profile due to the off-axis current driven. In this section, we will discuss these effects in details.

The local poloidal magnetic field is determined by the current inside the local flux surface. Since the current keeps constant in discharges, the inside current will decrease when the off-axis current driven by rf increases. For simplicity, we assume an rf driven current profile with a constant density $J_\parallel$ and an effective diffusion width Δ_w outside the local surface $r = r_0$. (If considering a more realistic current density profile, the Δ_w can be estimated by the relation $\int_{r_0}^{a} j_\parallel(r) r dr = J_\parallel r_0 \Delta_w$. For the linear dependence of $j_\parallel(r) = J_\parallel (r-a)/(r_0 - a)$ and $r_0 = a/2$, it is easy to find $\Delta_w = a/3$.) The decrease of inside current should be $J_\parallel 2\pi r_0 \Delta_w$, and therefore, the modified poloidal magnetic field is $B'_\theta = B_\theta - \mu_0 J_\parallel \Delta_w$.Then, using Eqs. (7)–(9), we can get

$$\frac{\Delta V_\phi}{J_\parallel} = \frac{m L_E L_n \nu_0 \kappa_t}{e \varepsilon_0 B_\theta^2 D_n \hat{v}_\parallel^3 (1-\kappa_t)} \left(1 - \frac{\mu_0 \Delta_w e P_D \hat{v}_\parallel^2}{m_e v_{te} \nu_0 B_\theta}\right)^{-2}. \quad (14)$$

Here, the simple 1-D model is employed to calculate the current driven efficiency in Eq. (7), i.e., $\nu_e = \nu_0 \hat{v}_\parallel^{-3}$, where ν_0 is the electron-ion collision frequency for thermal electrons. Considering the same parameters in Eq. (10) and $P_D = 1\,\mathrm{MW/m^{-3}}$, $\Delta_w = 0.05\,\mathrm{m}$, and $n = 10^{20}\mathrm{m^{-3}}$, the term in the parentheses in Eq. (14) becomes $1 - 0.03\hat{v}_\parallel^2$. If the κ_t and D_n are constants, the modification of the poloidal field can partially compensate the strong dependence of ν_e on the resonant velocity. As a result, the ratio of rf-driven flow to rf-driven current is not very sensitive to the resonant velocity. This trend is shown in Fig. 2, where the $\Delta V_\phi / J_\parallel \sim \hat{v}_\parallel^{-3}(1 - 0.03\hat{v}_\parallel^2)^{-2}$ changes not too much in a large regime of $\hat{v}_\parallel$.

Another possible process is that the particle transport might be strongly influenced by the off-axis current drive. It is mentioned that the diffusion coefficient D_n used here is an effective parameter. It may include both diffusion and convection (pinch) through neoclassical and turbulence processes. The well-accepted conclusion[34–36] on the particle transport is that the curvature induced "turbulence-equipartition" effect[37,38] always induces an inward flux, but that the "thermo-diffusion" term[39–42] can either be inward when the ion temperature gradient mode (ITG) is dominant and outward when the TEM is dominant. Therefore, the reduction of particle transport can be realized by the weakness of outward transport or by the enhancement of inward transport, depending on different situations. However, the particle transport, which is closely related to the generation of radial electric field, is still an open question. Here, we just do some qualitative analysis based on experimental facts. Experiments[43–46] have identified that the transport may be reduced dramatically when the q profile becomes weak shear or negative shear. The reduction of magnetic shear is related to the off-axis rf driven current $\Delta(\hat{s}/q) \sim J_{rf} \propto \hat{v}_\parallel^2$, and then the effective diffusion coefficient D_n decreases with the increase in rf-current. This effect may influence the dependence of $\Delta V_\phi / J_\parallel$ on $\hat{v}_\parallel$, together with the change of B_θ due to the rf-induced current. Moreover, it has been mentioned in Sec. III that the reduction of D_n relaxes the requirement of the momentum to trapped electrons. Since the particle transport can be greatly improved, typically from anomalous to the neoclassical level, the Landau absorbing with the up-shifted $n_\parallel$ spectrum is enough to drive the significant flow as shown in Fig. 1(b) of Sec. III. It might contribute to understand the plausible causality between the flow drive and current drive in the C-Mod experiment.[22,23]

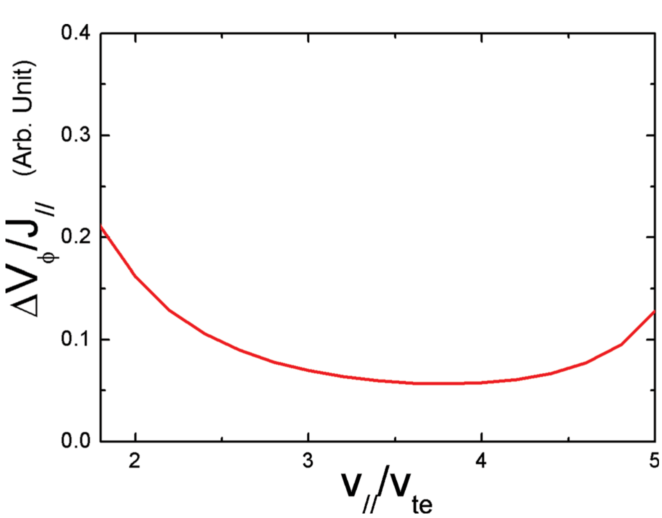

FIG. 2. (Color online) The correlation between flow drive and current drive: $\Delta V_\phi / J_\parallel$ as functions of resonant velocity at $P_D = 1\,\mathrm{MW/m^{-3}}$, $\Delta_w = 0.05$ m, $n = 10^{20}\,\mathrm{m^{-3}}$, and other parameters same as in Fig. 1.

V. CONCLUSIONS

Radial electric fields in tokamaks can be generated by charge accumulation due to the pinch effect of trapped electrons, when they resonantly obtain parallel momentum from the injecting rf wave. This radial field can then drive the toroidal flow. Two processes influence this mechanism strongly. One is the allocation of rf power into passing and trapped electrons. At typical tokamak parameters, to generate a radial electric field on the order of 100 kV/m needs an rf power density on the order of $\mathrm{kW/m^3}$ deposited on trapped electrons. This power, absorbed by trapped electrons, is a small fraction of rf power density for current drive which is absorbed by passing electrons. However, according to the Landau resonance mechanism, the fraction of the momentum to trapped electrons decays exponentially with the square of the parallel phase velocity of the wave; therefore power absorbed at lower resonant velocities is important. For example, for low hybrid wave injection, those sub-peaks with larger $n_\parallel$'s, rather than the main peak with a small $n_\parallel$, dominate the generation of the radial electric field. Therefore, the efficiency for electric field generation might be very sensitive to the fine structure of the rf power spectrum. Some mechanisms beyond the Landau absorbing, including anomalous Doppler scattering, parametric decay, and collisional redistribution, also have the possibilities to be involved. The other important issue in this mechanism is the secondary effect due to the redistribution of current profile due to the rf current. The redistribution of current profile is expected to decrease the local poloidal field and reduce the particle transport significantly. It may contribute to explain the strongly correlation between the rotation and the driven current observed in experiments and, at the same time, relaxes the requirement of momentum deposited to trapped electrons.

For fast electron drive, the above critical conditions should be satisfied to generate the radial electric field desired. Otherwise, this effect becomes too weak. However, for low frequency rf waves, the current drive efficiency is weakened due to the enhanced electron trapping at lower phase velocities, but the generation of electric field is expected to be of higher efficiency. Therefore, the flow drive mechanism of resonant trapped electron pinch may be observed easily when injecting an ICRF fast wave or an Alfven wave into plasma.

ACKNOWLEDGMENTS

The authors gratefully thank Professor S. J. Wang for extensive discussion and helpful suggestions. Discussion with Professor X.T. Ding, Professor J.Q. Dong, Professor J.Q. Li, Professor H. Sugama, and Professor B.N. Wan are gratefully acknowledged as well. This work is supported by NSFC, under Grant Nos. 10990214 and 10875122, and MOST of China, under Contract Nos. 2009GB105000 and 2008GB717804.

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