Intrinsic current driven by electromagnetic electron temperature gradient turbulence in tokamak plasmas

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Abstract
The mean parallel current density evolution equation is presented using the electromagnetic (EM) gyrokinetic equation. There are two types of intrinsic current driving mechanisms resulting from EM electron temperature gradient (ETG) turbulence. The first type is the divergence of residual turbulent flux including a residual stress-like term and a kinetic stress-like term. The second type is a residual turbulent source, which is driven by the correlation between density and parallel electric field fluctuations. The intrinsic current density driven by the residual turbulent source is negligible as compared to that driven by the residual turbulent flux. The ratio of intrinsic current density driven by EM ETG turbulence to the background bootstrap (BS) current density is estimated. The local intrinsic current density driven by the residual turbulent flux for mesoscale variation of turbulent flux can reach about 80\% of the BS current density in the core region of an ITER standard scenario, but there is no net intrinsic current on a global scale. Based on this, the local intrinsic current driven by EM micro-turbulence and its effects on local modification of the profile of the safety factor may need to be carefully taken into account in future devices with high $\beta_e$, which is the ratio between electron pressure to magnetic pressure.

Keywords: intrinsic current, ETG turbulence, residual turbulent flux, residual turbulent source, electromagnetic effects

1. Introduction
The current density profile is of great importance for tokamak plasmas since it can affect both confinement time and a variety of magnetohydrodynamic (MHD) instabilities, such as the kink mode and the tearing mode. The current density profile can be strongly affected by the current driving mechanism. Until now, various current driving mechanisms have been proposed, such as an inductive current drive, a neutral-beam-injection current drive [1], a lower hybrid drift instability current drive [2], an electron cyclotron current drive [3], the poloidally asymmetric fueling current drive [4], and so on.

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One of the particularly efficient and economical mechanisms is the bootstrap (BS) current driven by the pressure gradient, which has been predicted by the neoclassical theory [5]. It has been demonstrated to be consistent with the predictions of the neoclassical theory in some experiments [6–8]. Nonetheless, deviations from the neoclassical theory are also observed in some cases [9, 10]. Inspired by the turbulent-driven intrinsic rotation, naturally, intrinsic current driven by turbulence can be taken into account similarly.

In fact, current driven by drift waves in a slab geometry was proposed many years ago [11]. It showed that a residual current flux could be caused by the electrostatic (ES) fluctuations in the presence of $k_\parallel$ (parallel wave number of drift wave) symmetry breaking. A more systematic model for current driven by...
turbulence has been done by Garbet [12], where two kinds of current sources from the gyrokinetic equation were proposed. Both require $k_{||}$ symmetry breaking and may contribute about 10% of the BS current density in the edge region of tokamak plasmas. Similarly, an extended Ohm’s law modified by magnetic turbulence has also been studied by using the self-consistent action-angle transport theory [13]. In this model, turbulence results in three different kinds of resistances in Ohm’s law. Ohm’s law has been modified by two types of current sources from electromagnetic (EM) turbulence [14]. One is the momentum source and the other is radial flux of the parallel current driven by magnetic flutter. Though the momentum source term can result in a little change in the local current density, it contributes a nonzero total current. In contrast, the flux source term can result in a small change in the local current density. Although the contribution to the total net current is neglected, the local modification of the current density profile due to EM ETG turbulence could play a significant role in future devices.

The remainder of this paper is organized as follows. In section 2, the derivation of the mean parallel current density evolution equation is presented. The quasi-linear estimation of intrinsic current density driven by EM ETG turbulence and the comparison between the intrinsic current density and the BS current density are also presented. Finally, our conclusions and a discussion are given in section 3.

2. Quasilinear estimate for an intrinsic parallel current drive

We start from the nonlinear EM gyrokinetic equation [23],

$$\frac{\partial (F_e B_e^* \parallel)}{\partial t} + \nabla \cdot \left( \frac{\partial R}{\partial v ||} F_e B_e^* \parallel \right) + \frac{\partial}{\partial v ||} \left( \frac{\partial v ||}{\partial F_e B_e^* \parallel} \right) = 0,$$

with the electron gyro-center equations of motion in the symplectic formulation, i.e. $v ||$ representation

$$\frac{dR}{dt} = v || B^* \parallel \frac{c b}{-e B^*\parallel} \times [(-e \nabla \delta \phi + \mu \nabla B)]$$

and

$$\frac{dv ||}{dt} = -B^* \frac{c m_e}{e \mu c \parallel} \cdot (-e \nabla \delta \phi + \mu \nabla B) + \frac{e \partial \delta \parallel}{m_e c \parallel}.$$

Here, $F_e = F_e (R, \mu, v ||, t)$ is the electron gyro-center distribution function where $\mu$ is the magnetic moment of electron, $b = B / B$ is the unit vector of equilibrium magnetic line, $B^* \parallel = b \cdot B^*$ is the Jacobian of the transformation from the particle phase space to the gyro-center phase space with $B^* = B + \delta B \perp + \frac{c m_e}{e} v || \nabla \times b$. $c$ is the speed of light, $m_e$ is the electron mass, and $e$ is the elementary charge. $\delta \phi$ is the ES potential fluctuation. $\delta B \perp \approx -b \times \nabla \delta A \parallel$ is the perturbed magnetic field. In this paper, the index || refers to the components parallel to the equilibrium magnetic field, and the index \perp refers to the components perpendicular to the equilibrium magnetic field. Only the shear component of magnetic perturbation, i.e. $\delta A \parallel$, is considered, and $\delta B \parallel$ is not included in this work. This simplified model has also been widely adopted in previous works on the investigation of EM ETG [24–26]. However, for a spherical tokamak where $\beta$ can reach 10% or even higher, neglecting $\delta B \parallel$ will lead to an underestimation of the growth rates of ETG as well as that of ITG [27].

Multiplying equation (1) by $-\frac{2}{m_e} e v ||$ and integrating in the velocity space, the evolution equation of parallel current density can be obtained,

$$\frac{\partial \rho_{db}}{\partial t} + \nabla \cdot \left( 3v_{dc} J || + v_{dV} \nabla J || + \delta V_{EBx} B J || + 2U_0 J || b^* - e U_0^2 m_c \frac{\partial B^*}{\partial t} \right)
+ \left( \frac{e b^* \cdot \nabla \delta \phi}{m_e} + \frac{e}{m_e} \frac{\partial \delta A \parallel}{\partial t} \right) n_e
+ \left( -\frac{c b^*}{m_e} \cdot \nabla P || \right) + \frac{c b^*}{m_e} \cdot \frac{\nabla B}{B} (P || - P \perp) = 0.$$

Although the contribution to the total net current is neglected, the local modification of the current density profile due to EM ETG turbulence could play a significant role in future devices.

The remainder of this paper is organized as follows. In section 2, the derivation of the mean parallel current density evolution equation is presented. The quasi-linear estimation of intrinsic current density driven by EM ETG turbulence and the comparison between the intrinsic current density and the BS current density are also presented. Finally, our conclusions and a discussion are given in section 3.
Here, we assume the current is mainly carried by electron. \( J_\parallel = -e \int F_e v || d^3v = -en_e U || \) is the parallel current density with \( n_e \) being the density of the electron and \( U || \) being the parallel speed of the electron fluid. \( P || = m_e \int F_e (v || - U ||)^2 d^3v \) is the parallel electron pressure. \( P \perp = \int F_e \mu_B B \delta n d^3v \) is the perpendicular electron pressure. \( \delta b \perp = \delta B \hat{b} \) with \( \delta B = \delta \mathbf{B} = \frac{\delta \mathbf{E} \times \mathbf{B}}{\mathbf{B}} \) is the fluctuating \( E \times B \) drift velocity. \( \nu_{\text{CRT}} = \frac{e}{mc} B \times \nabla B \) is the magnetic gradient drift velocity, and \( \nu_{\text{de}} = \frac{e}{mc} B \times (\hat{b} \cdot \nabla) \hat{b} \) is the magnetic curvature drift velocity. The magnetic drift velocity will be neglected in the mean parallel current density equation, since they are higher order terms \( O(\omega_{\text{de}}/\omega) \) as compared to \( E \times B \) drift velocity [28]. For the same reason, all the terms in equation (4) related to magnetic gradient will be neglected. The terms related to the equilibrium electron fluid velocity \( U_0 \) will also be neglected because of \( U_0^2 \ll \nu_{\text{he}}^2 \) where \( \nu_{\text{he}} = \sqrt{\frac{T_e}{m_e}} \) is the electron thermal velocity with \( T_e \) being the electron temperature. Taking the flux-average of equation (4), the evolution of the parallel current density can be obtained,\n\n\[ \frac{\partial \langle J || \rangle}{\partial t} + \nabla \cdot \langle \nu_{\text{CRT}} J || + \nu_{\text{de}} J || \rangle = -\nu_{\text{CRT}} \nu_{\text{de}} \langle \delta J || \rangle. \] (5)\n
Here, \( \delta J || = -e \int \delta f_e v || d^3v \) is the perturbation of the parallel current density with \( \delta f_e \) being the perturbed electron distribution function. \( \delta P || = m_e \int \delta f_e (v || - U ||)^2 d^3v \) is the perturbation of the parallel electron pressure. The two terms under the divergence on the left-hand side of equation (5) are the turbulent flux of the current density. Similar to the intrinsic rotation drive in [22], the first one is a Reynolds stress-like term, and the second is a kinetic stress-like term denoting dynamo effects. The terms on the right-hand side (RHS) are turbulent source terms, which are analogous to the momentum source for the ion [29]. The source terms are driven by the correlation between density and parallel electron field fluctuations including an inductive electric field. Equation (5) seems to be similar to equation (3) derived from the fluid model in [18]. However, the ES limit was adopted in the quasilinear calculation of the intrinsic current drive in [18]. Both the EM v and toroidal effects are kept in our quasilinear calculation, which will be shown later. Then, equation (5) can be rewritten as

\[ \frac{\partial \langle J || \rangle}{\partial t} + \nabla \cdot \Gamma || = S, \] (6)

where \( \Gamma || \) is the turbulent flux of the current density, and \( S \) represents the turbulent source. The turbulent flux can be usually divided into the diffusive term, convective term, and residual term, i.e.,

\[ \Gamma || = -\chi || \frac{\partial}{\partial r} \langle J || \rangle + V_c \langle J || \rangle + \Gamma ||^\text{res}, \] (7)

where \( \chi || \) is the diffusion coefficient of the parallel current density, \( V_c \) is the convective velocity of the parallel current density, and \( \Gamma ||^\text{res} \) is the residual turbulent flux. The residual turbulent flux is independent of the parallel current density or its gradient, so it can provide an intrinsic current drive. This is analogous to the intrinsic rotation driven by residual stress [29, 30]. The turbulent source term can be divided into residual turbulent source and non-residual turbulent source terms, similarly. The residual turbulent source is also independent of the parallel current density or its gradient, and so can provide an intrinsic current drive, too. This is also analogous to the intrinsic rotation driven by momentum source [29].

Next, we make a quasi-linear estimation for the turbulent flux and the residual turbulent source. Therefore, the linear calculations of \( \delta n_e, \delta J ||, \) and \( \delta P || \) are required. The electron density fluctuation can be obtained using the quasi-neutrality condition \( \delta n_e = \delta n_i \) and adiabatic ion approximation \( \delta n_i = -\frac{\nu_{\text{de}}}{\nu_{\text{he}}} n_0 \) for the EM ETG mode. The adiabatic ion model is often employed in studying ETG turbulence [25, 26]. Especially, the validity of the adiabatic ion model used for ETG turbulence at low magnetic shear was demonstrated via a parameter scan in magnetic shear in [31]. The \( i \delta \) model is used in [18, 24], which is analogous to the \( i \delta \) model for electrons used in ITG turbulence. Assuming the equilibrium electron distribution function to be shifted Maxwellian \( F_{e0} = n_e \left( \frac{m_e}{2\pi k_{B} T_{e}} \right)^{3/2} \exp \left( -\frac{m_e v^2}{2 k_{B} T_{e}} \right) - \frac{v^2}{2} \right) \) where \( n_0 \) is the equilibrium electron density, the linearized EM perturbed electron distribution function in Fourier space can be written as

\[ \delta f_e = \frac{1}{i \rho_{e} \Omega_{e}} \left( \frac{m_e}{2\pi k_{B} T_{e}} \right)^{3/2} \exp \left( -\frac{m_e v^2}{2 k_{B} T_{e}} \right) \right] \]
\( x_\perp = \sqrt{\frac{\eta_T}{\omega}} \cdot \omega_{ce} = \frac{v_b}{\sqrt{\omega}} \cdot \nabla \ln n_0 \cdot k \) is the diamagnetic drift frequency of the electron with \( k \) being the wave vector, \( \omega_{L_e} = \frac{eB_k \nabla U_0}{\rho_e} \) is the frequency related to the gradient of background electron fluid velocity, \( \omega_{de} = \frac{eB_k \nabla \cdot \mathbf{b}}{\rho_e} \approx \frac{v_b}{\sqrt{\omega}} \cdot \nabla \nabla \cdot \mathbf{b} \cdot k \approx \frac{v_b}{\sqrt{\omega}} \cdot \nabla \) is the drift frequency due to a magnetic gradient or curvature. This is equivalent to taking the position at the outboard midplane. It should be pointed out that the complex poloidal angle dependence of the magnetic drift frequency is neglected for simplicity. Here, \( \mathbf{b} \times (\mathbf{b} \cdot \nabla \mathbf{b}) \approx \mathbf{b} \times \nabla \ln B \) is used and is justified even for the high beta case as long as \( \beta \ll 1 \). \( \eta_e = \frac{\eta_e}{\eta_{te}} \) with \( \eta_{te} = -(\nabla \ln T_e)^{-1} \) and \( \eta_{n_e} = -(\nabla \ln n_e)^{-1} \) being the electron temperature gradient length scale and electron density gradient length scale, respectively. On the RHS of equation (8) the first term comes from the ES contribution, and the second term is the \( \kappa \) being the drift frequency due to a magnetic gradient or curvature. This should be pointed out that the complex poloidal angle dependence of the magnetic drift frequency is neglected for simplicity.

The lowest order of the non-resonant part will be kept. Taking the first order moment of equation (8), i.e. \( \delta J_\parallel = -e \int \delta f_e v_\parallel d^3v \) we can obtain the perturbed parallel current density

\[
\delta J_\parallel = eU_0 \tau n_0 \delta \rho_e + \frac{U_0 \omega_{de} - \omega_e + \kappa v_\parallel}{\omega_e} \eta_0 v_\parallel \delta \rho_e \nabla \phi_k \\
+ \frac{\omega_{ce} (1 + \eta_e) - \omega_k + U_0 \omega_e}{\omega_k} \eta_0 v_\parallel \delta \phi_k \\
- \frac{3 \sqrt{3 \pi}}{8} \frac{U_0 \omega_{de} - \omega_e + \kappa v_\parallel}{\omega_{de}} \eta_0 v_\parallel \delta \phi_k \\
- \frac{3 \sqrt{3 \pi}}{8} \frac{\omega_k \omega_{de}}{\omega_{de}} \left[ 1 + \eta_e \left( \frac{3 \omega_k}{4 \omega_{de}} - \frac{3}{2} \right) \right] - \omega_k \\
- \frac{\omega_k}{\omega_{de}} \exp \left( -\frac{3 \omega_k}{4 \omega_{de}} \right) \eta_0 v_\parallel \delta \phi_k.
\]

where \( \tau = \frac{T_e}{\omega_e} \) is the ratio of the electron temperature to the ion temperature. Here, the assumption \( 2x_\parallel - x_\perp \) has been used for calculation of the resonant part. The first two terms in equation (10) result from the non-resonant ES contribution, the third term comes from non-resonant EM effects, and the last two terms are caused by resonant effects.

Taking the second order moment, i.e. \( \delta P_{\perp} = m_e \int \delta f_e (v_\perp - U_0)^2 d^3v \approx m_e \int \delta f_e (v_\perp - U_0)^2 d^3v \), we can obtain the perturbed electron pressure

\[
\delta P_{\perp,k} = \frac{1}{A} \left[ \omega_{ce} \left( 1 + \frac{\eta_e}{\omega_{de}} \right) - 4 \omega_{de} \right] \eta_0 T_e \delta \phi_k \\
- \omega_{ce} \left( 1 + \eta_e \right) \ln U_0 \frac{\eta_0 T_e \delta \phi_k}{\omega_e} \\
- \frac{\omega_{ce} \eta_e}{\omega_e} \exp \left( -\frac{3 \omega_k}{4 \omega_{de}} \right) \eta_0 v_\parallel \delta \phi_k \\
+ \frac{1}{\omega_{de}} \exp \left( -\frac{3 \omega_k}{4 \omega_{de}} \right) \eta_0 v_\parallel \delta \phi_k.
\]

Similar to equation (10), the first two terms on the RHS of equation (11) are non-resonant parts, and the last two terms are resonant parts.

We take \( \omega_k = \omega_{\parallel} + \gamma_k \) with \( \omega_{\parallel} \) being the real frequency and \( \gamma_k \) being the linear growth rate, respectively. The higher orders of \( \gamma_k \) will be neglected because of \( |\gamma_k|^2 \ll \omega_{\parallel}^2 \), which justifies the quasi-linear theory. Then, using \( \delta v_\parallel \times B = \sum_{k} i k_\parallel \rho_k v_\parallel \delta \phi_{-k} \), \( \omega_k = -k_\parallel \rho_k \frac{\partial \phi}{\partial r} \), \( \omega_{de} = k_\parallel \rho_k \frac{\partial n_0}{\partial r} \), \( \delta \phi_{-k} = i k_\parallel \rho_k \delta \phi_{-k} \), we can calculate the turbulent flux terms and the turbulent source terms. The details of the calculation are presented in the appendix. Here, we just directly write the expressions,
\[ \Gamma_r = -\sum_k \frac{2}{\nu} k_0^2 \mu_0^2 \nu_{\text{the}}^2 \left( \left| \delta \phi_k \right|^2 + 3 \left| \delta \tilde{A}_{||k} \right|^2 \right) \frac{\partial \nu_{\text{the}}}{\partial t} \]
\[ - \sum_k \frac{3 \sqrt{\pi}}{8} k_0^2 \mu_0^2 \nu_{\text{the}}^3 \left( \frac{\omega_{\text{de}}}{2} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left( \left| \delta \phi_k \right|^2 + \frac{1}{2} \frac{\nu_{\text{de}}}{\nu_{\text{the}}} \left| \delta \tilde{A}_{||k} \right|^2 \right) \frac{\partial \nu_{\text{de}}}{\partial t} \]
\[ - \sum_k \frac{2}{\nu} k_0 \mu_0 \nu_{\text{the}} \left( \omega_{\text{de}} + \omega_{\text{ce}} \right) \left| \delta \phi_k \right|^2 + (\omega_{\text{de}} + 2 \omega_{\text{ce}} - \eta_k \omega_{\text{ce}}) \left| \delta \tilde{A}_{||k} \right|^2 \langle J \rangle \]
\[ - \sum_k \frac{3 \sqrt{\pi}}{8} k_0 \mu_0 \nu_{\text{the}} \left( \frac{\omega_{\text{de}}}{2} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left( \left( \frac{\omega_{\text{de}}}{\nu_{\text{the}}} + \frac{\nu_{\text{de}}}{\nu_{\text{the}}} \right) \left| \delta \phi_k \right|^2 \right) \langle J \rangle \]
\[ - \left\{ \frac{\omega_{\text{de}}}{\nu_{\text{the}}} \left[ 1 + \eta_k \left( \frac{3}{\nu_{\text{the}}} - \frac{3}{\nu_{\text{de}}} \right) \right] - \frac{1}{\nu_{\text{the}}} \left[ \frac{1}{\nu_{\text{de}}} \right] \right\} 3 \left| \delta \tilde{A}_{||k} \right|^2 \langle J \rangle \]
\[ + \sum_k \frac{2}{\nu} \left( 1 - \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) k_0 \mu_0 \nu_{\text{the}} \Im \left\{ \langle \delta \tilde{A}_{||k} \delta \phi_{-k} \rangle \right\} \]
\[ + \sum_k \frac{\eta_1 (2 \omega_{\text{ce}} + 4 \omega_{\text{de}})}{\nu_{\text{de}}} k_0 \mu_0 \nu_{\text{the}} \Re \left\{ \langle \delta \tilde{A}_{||k} \delta \phi_{-k} \rangle \right\} \]
\[ + \sum_k \frac{2 \sqrt{3 \pi}}{8} k_0 \mu_0 \nu_{\text{the}}^2 \left( \frac{\omega_{\text{de}}}{2} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left| \delta \phi_k \right|^2 \]
\[ + \sum_k \frac{5 \sqrt{\pi}}{8} k_0 \mu_0 \nu_{\text{the}} \left( \frac{\omega_{\text{de}}}{2} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left( \frac{\omega_{\text{de}}}{\nu_{\text{the}}} \right) \left[ 1 \right] \]
\[ + \eta_k \left( \frac{3}{\nu_{\text{de}}} \left[ \frac{3}{\nu_{\text{de}}} - \frac{3}{\nu_{\text{de}}} \right] - \frac{1}{\nu_{\text{de}}} \right) \] Re \left\{ \delta \tilde{A}_{||k} \delta \phi_{-k} \right\} \right) \right) \]
\[ (12) \]

and
\[ S = \sum_k \nu_{\text{the}} \nu_{\text{the}} \right) \left( \omega_{\text{de}} \Im \left\{ \langle \delta \tilde{A}_{||k} \delta \phi_{-k} \rangle \right\} \right) + \gamma_k \Re \left\{ \delta \tilde{A}_{||k} \delta \phi_{-k} \right\} \right) \] .
\[ (13) \]

Different from [12], the non-resonant parts are also calculated here. Moreover, we will consider the relation between \( \delta A_1 \) and \( \delta \phi \) in more detail to investigate the explicit EM effects. In the following, we will focus on the residual turbulent flux and the residual source, which contribute to the intrinsic current drive. Combining Ampere’s law with equation (10) and neglecting the terms related to \( U_0 \), the general relation between \( \delta \phi \) and \( \delta \tilde{A}_1 \) can be obtained,

\[ \delta \tilde{A}_{||k} = \frac{D_1 (C_1 - C_2) - (D_2 + D_3) (C_3 + C_4) - i \left[ (D_2 + D_3) (C_1 - C_2) + D_1 (C_3 + C_4) \right]}{C_1 - C_2} \delta \phi_k. \]
\[ (14) \]

Here, \( C_1, C_2, C_3, C_4 \) and \( D_1, D_2, D_3 \) are all dimensionless and independent of the parallel current density or the gradient of the parallel current density. Equation (14) is important for the explicit estimate of the EM effects. In [12], this relation is not mentioned, and the EM effects are not the focus. Besides, the spatial scale of turbulence is about ion gyroradius in [12]. The details of the calculation of equation (14) can be found in the appendix.

In the following, we assume \( \omega_{\text{de}} \approx \omega_{\text{ce}} \), which is appropriate for the ETG mode. The residual turbulent flux can be written as

\[ \Gamma_r^{\text{ins}} = \sum_k \frac{2}{\nu} k_0 \mu_0 \nu_{\text{the}}^2 \nu_{\text{the}} \nu_{\text{de}} \left| \delta \phi_k \right|^2 \]
\[ + \sum_k \frac{2}{\nu} \left( 1 - \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) k_0 \mu_0 \nu_{\text{the}} \Im \left\{ \langle \delta \tilde{A}_{||k} \delta \phi_{-k} \rangle \right\} \]
\[ + \sum_k \frac{\eta_1 (2 \omega_{\text{ce}} + 4 \omega_{\text{de}})}{\nu_{\text{de}}} k_0 \mu_0 \nu_{\text{the}} \Re \left\{ \langle \delta \tilde{A}_{||k} \delta \phi_{-k} \rangle \right\} \]
\[ + \sum_k \frac{2 \sqrt{3 \pi}}{8} k_0 \mu_0 \nu_{\text{the}} \left( \frac{\omega_{\text{de}}}{2} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left| \delta \phi_k \right|^2 \]
\[ + \sum_k \frac{5 \sqrt{\pi}}{8} k_0 \mu_0 \nu_{\text{the}} \left( \frac{\omega_{\text{de}}}{2} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left( \frac{\omega_{\text{de}}}{\nu_{\text{de}}} \right) \left[ 1 \right] \]
\[ + \eta_k \left( \frac{3}{\nu_{\text{de}}} \left[ \frac{3}{\nu_{\text{de}}} - \frac{3}{\nu_{\text{de}}} \right] - \frac{1}{\nu_{\text{de}}} \right) \] Re \left\{ \delta \tilde{A}_{||k} \delta \phi_{-k} \right\} .
\[ (15) \]

For the turbulent source, \( S^{\text{ins}} = S \), which is also independent of the parallel current density or its gradient due to equation (14),

\[ \delta \tilde{A}_{||k} = \frac{D_1 (C_1 - C_2) - (D_2 + D_3) (C_3 + C_4) - i \left[ (D_2 + D_3) (C_1 - C_2) + D_1 (C_3 + C_4) \right]}{C_1 - C_2} \delta \phi_k. \]
\[ (14) \]

and so can provide an intrinsic current drive. The first term on the RHS of equation (15) represents the non-resonant ES contribution, the second term and the third term represent the non-resonant EM contribution, the fourth term represents the resonant ES contribution, and the last term represents the resonant EM contribution. We will use \( \omega_{\text{de}} \approx \omega_{\text{ce}} \) later. The terms related to \( \omega_{\text{de}} \) come from toroidal effects. Equation (13) shows that the residual turbulent source is only caused by EM effects, since the turbulent source driven by the correlation between density and ES field fluctuations vanishes for the adiabatic ion response. Both the residual turbulent flux and the
residual turbulent source require parallel symmetry breaking. Theoretical works have proposed various symmetry breaking mechanisms, such as $E \times B$ shear [32, 33], charge separation from polarization drift [34], intensity gradient [35], geometrical up-down asymmetries [36], etc. In [19], it is found that the contribution to the ETG turbulence driven current from symmetry breaking induced by the turbulence intensity gradient is more important than that by zonal flow shear from ES gyrokinetic simulations. We also take the symmetry breaking caused by the turbulence intensity gradient in this work. This is reasonable for a core region with a flat pressure profile where the $E \times B$ shear is not strong. The mean parallel wave number is $k_\parallel R \approx 3k_\parallel \frac{a}{T_e}$. From equation (21), it is shown that the resonant contribution is very important as compared to the non-resonant one. This is because the density profile is flat in the core region, making $\delta \hat{\phi}_k$ small. No experimental evidence exists for the length scale. The sign of $\mp$ corresponds to the positive (negative) gradient of the flux. In [18], only the ES part, namely the first term on the RHS of equation (15) is considered. While the toroidal effects, EM effects, and resonant effects are neglected in [18]. Similarly, the intrinsic current driven by residual turbulent flux can be written as

$$J^\text{Turb}_\text{intrinsic} = \mp \frac{\Gamma_{\text{res}}}{\nu_{ei} \sqrt{\beta_e L_a}},$$

where $L_a = L_p \sim 5 \nu_{ei} \sqrt{\frac{\rho_a T_e}{eB}} L_p$. No experimental evidence exists for the length scale. The sign of $\mp$ corresponds to the positive (negative) gradient of the flux. In [18], only the ES part, namely the first term on the RHS of equation (15) is considered. While the toroidal effects, EM effects, and resonant effects are neglected in [18]. Similarly, the intrinsic current driven by residual turbulent flux can be written as

$$J^\text{Turb}_\text{intrinsic} = \mp \frac{\Gamma_{\text{res}}}{\nu_{ei} \sqrt{\beta_e L_a}},$$

where $L_a = L_p \sim 5 \nu_{ei} \sqrt{\frac{\rho_a T_e}{eB}} L_p$. In this work, which may quantitatively modify the results and should be carefully considered in the future. The numerical results show that the linear growth rate of EM ETG increases with $k_0 \rho_e$ [25]. Then, the ratios can be written as

$$\frac{J^\text{Turb}_\text{intrinsic}}{J_{\text{BS}}} = \mp (17.3\% + 9.9\% + 59.6\% - 3.7\%),$$

(21)

$$\frac{J^\text{S}_{\text{intrinsic}}}{J_{\text{BS}}} < 1\%. $$

(22)

On the RHS of equation (21), the first term and the third term represent the non-resonant and resonant ES contributions, respectively. While the second term and the last term represent the non-resonant and resonant EM contributions, respectively. For this case, the intrinsic current density driven by residual turbulent flux can reach up to about 80% of the BS current density, but does not contribute to the total net current. On the other hand, the residual turbulent source can drive a nonzero total current, but the order of magnitude is less than 1% as compared to the BS current. Moreover, a rough estimation of the ratio of the ETG turbulence driven current density to the BS current density by taking similar parameters to those from [19] is about 10%, which is comparable to the ratio in [19]. In this paper, the contribution from magnetic drift resonance is calculated since a kinetic model is used. While in [18], only the non-resonant ES contribution was considered due to a fluid model in the pedestal region, and the toroidal effects were not taken into account, either. From equation (21), it is shown that the resonant contribution is very important as compared to the non-resonant one. This is because the density profile is flat in the core region, making

**Table 1. Results of the estimation for the intrinsic current density driven by EM ETG turbulence for typical core parameters of the ITER standard scenario.**

| Ratio of intrinsic current density to BS current density | Non-resonant contribution | Resonant contribution |
|--------------------------------------------------------|----------------------------|-----------------------|
| ES contribution                                       | $\mp 17.4\%$              | $+ 59.6\%$            |
| EM contribution                                       | $\mp (9.9\%)$             | $+ 3.7\%$             |
the characteristic frequency of ETG turbulence comparable to the magnetic drift frequency.

The current density profile may be locally modified on the length scale of $\sqrt{r_n L_n}$ (about hundreds of electron gyroradii or several ion gyroradii) by the EM ETG turbulence driven intrinsic current in the core region of tokamak H-mode plasmas. This may lead to the local modification of the $q$ profile, and hence affect the MHD behaviors. However, if the length scale of the residual turbulent flux is at macroscale, e.g. $L_n$, the ratio of the intrinsic current density driven by turbulent flux to the BS current density will reduce to 1/277 of that estimated for the mesoscale turbulent flux. Then, the ratio becomes less than 1%, and the intrinsic current density driven by ETG turbulence is thus negligible for this case. Therefore, the selection of the length scale of the residual turbulent flux is important and deserved to be verified in experiments. A brief summary of the result is given in table 1.

3. Summary

In this work, an evolution equation of mean parallel current density has been derived using EM gyrokinetic equations. There are two intrinsic current driving mechanisms. One is the residual turbulent flux and the other is the residual turbulent source. Both can provide intrinsic current drive and need $k_{\parallel}$ symmetry breaking, and the symmetry breaking caused by the turbulence intensity gradient is taken in the present work.

Although the net intrinsic current driven by EM ETG turbulence can be neglected, the local current density profile can be significantly affected. Quasi-linear estimations show that while the residual turbulent source may not contribute a lot to the current density as compared to the local BS current density, the residual turbulent flux can locally drive about 80% of the local BS current density by using the core parameters of the standard scenario of ITER. Therefore, we conclude that in the high beta fusion devices like ITER, the EM ETG turbulence driven intrinsic current density may significantly change the local current density profile, and thus may change the $q$ profile in the core region. This modification of the current density profile may be important for MHD instabilities. Particularly, the local modification of the current density profile in the narrow pedestal region might be important for edge localized modes, which will be considered in the future.

Until now, there has been no direct experimental observations for turbulence driven current. However, we expect that in a future fusion reactor with high beta the EM ETG turbulence driven intrinsic current density will be observed. We should point out that the diffusive coefficient and convective speed of current flux are not calculated in the present work. The diffusion and convection may be important for accurate prediction of the current density profile in the pedestal region. Moreover, the modification of the current density profile in the pedestal could affect the edge localized mode control. Therefore, extending this work from the core region to the pedestal region and considering the effects of diffusion and convection induced by EM turbulence on the current density profile may be investigated in the future. In addition, collisionless TEM turbulence is another prominent candidate for electron heat transport in high temperature plasmas. Now, we are also working on the intrinsic current driven by EM collisionless TEM turbulence.

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Appendix. Calculations of the intrinsic current drive and the relation between $\delta A_{\parallel k}$ and $\delta \hat{\phi}$

The turbulent current flux consists of two terms. The nonresonant Reynolds stress-like term can be calculated using equation (10),

$$
\langle \delta v_{\times B, \parallel} J_{\parallel} \rangle_{NR} = -\sum_k \frac{\gamma e k^4}{\omega_0} \left| \frac{\delta \hat{\phi}_k}{\omega_0} \right|^2 \left( \frac{3}{4} \frac{\omega_0}{\omega_{\text{de}}} \right) \left( \frac{\omega_0}{\omega_{\text{de}}} + \omega_\gamma \right) \left( \frac{\omega_0}{\omega_{\text{de}}} - \omega_\gamma \right) \left[ \frac{\omega_0}{\omega_{\text{de}}} + \frac{\omega_\gamma}{\omega_{\text{de}}} \right] \left( \frac{\omega_0}{\omega_{\text{de}}} - \frac{\omega_\gamma}{\omega_{\text{de}}} \right) \left( \omega_0 + \omega_{\text{de}} \right) \left( \omega_0 - \omega_{\text{de}} \right) \left( \omega_0 - \omega_\gamma \right) \left( \omega_0 + \omega_\gamma \right) \left[ \frac{1}{2} \frac{\omega_0}{\omega_{\text{de}}} - \frac{1}{2} \right] \right) \langle \delta A_{\parallel k} \delta \hat{\phi}_{-k} \rangle
$$

Similarly, the resonant Reynolds stress-like term can be obtained,

$$
\langle \delta v_{\times B, \parallel} J_{\parallel} \rangle_{R} = -\sum_k \frac{\gamma e k^4}{\omega_0} \left| \frac{\delta \hat{\phi}_k}{\omega_0} \right|^2 \left( \frac{3}{4} \frac{\omega_0}{\omega_{\text{de}}} \right) \left( \frac{\omega_0}{\omega_{\text{de}}} + \omega_\gamma \right) \left( \frac{\omega_0}{\omega_{\text{de}}} - \omega_\gamma \right) \left[ \frac{\omega_0}{\omega_{\text{de}}} + \frac{\omega_\gamma}{\omega_{\text{de}}} \right] \left( \frac{\omega_0}{\omega_{\text{de}}} - \frac{\omega_\gamma}{\omega_{\text{de}}} \right) \left( \omega_0 + \omega_{\text{de}} \right) \left( \omega_0 - \omega_{\text{de}} \right) \left( \omega_0 - \omega_\gamma \right) \left( \omega_0 + \omega_\gamma \right) \left[ \frac{1}{2} \frac{\omega_0}{\omega_{\text{de}}} - \frac{1}{2} \right] \right) \langle \delta A_{\parallel k} \delta \hat{\phi}_{-k} \rangle
$$
The non-resonant kinetic stress-like term can be calculated using equation (11),
\[
\left\langle \frac{\delta \rho \mathbf{b}}{\rho} \right\rangle^\text{NR} = \sum_k \frac{3 \sqrt{2} k^2 e^2}{8} \left( \frac{\omega}{\omega_c} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega}{\omega_c} \right) \delta \mathbf{A}_{||} \left\langle \hat{\mathbf{j}}_i \right\rangle^{2} + \sum_k \frac{1}{2} \frac{\omega}{\omega_c} - \frac{1}{2} \left( \frac{\omega}{\omega_c} \right)^{2} \delta \mathbf{A}_{\|} \left\langle \hat{\mathbf{j}}_i \right\rangle \left( \hat{\mathbf{j}}_i \right) \left\langle \hat{\mathbf{j}}_i \right\rangle + \sum_k \frac{3 \sqrt{2} k^2 e^2}{8} \left( \frac{\omega}{\omega_c} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega}{\omega_c} \right) \delta \mathbf{A}_{\|} \left\langle \hat{\mathbf{j}}_i \right\rangle \left( \hat{\mathbf{j}}_i \right) \left\langle \hat{\mathbf{j}}_i \right\rangle + \frac{1}{\omega_c} \text{Re} \left\langle \delta \hat{\mathbf{A}}_{\|} \delta \hat{\mathbf{b}}_{--} \right\rangle.
\]
(A.4)

Similarly, the resonant kinetic stress-like term can be also obtained,
\[
\left\langle \frac{\delta \rho \mathbf{b}}{\rho} \right\rangle^\text{R} = \sum_k \frac{3 \sqrt{2} k^2 e^2}{8} \left( \frac{\omega}{\omega_c} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega}{\omega_c} \right) \delta \mathbf{A}_{\|} \left\langle \hat{\mathbf{j}}_i \right\rangle^{2} + \sum_k \frac{1}{2} \frac{\omega}{\omega_c} - \frac{1}{2} \left( \frac{\omega}{\omega_c} \right)^{2} \delta \mathbf{A}_{\|} \left\langle \hat{\mathbf{j}}_i \right\rangle \left\langle \hat{\mathbf{j}}_i \right\rangle + \sum_k \frac{3 \sqrt{2} k^2 e^2}{8} \left( \frac{\omega}{\omega_c} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega}{\omega_c} \right) \delta \mathbf{A}_{\|} \left\langle \hat{\mathbf{j}}_i \right\rangle \left\langle \hat{\mathbf{j}}_i \right\rangle + \frac{1}{\omega_c} \text{Re} \left\langle \delta \hat{\mathbf{A}}_{\|} \delta \hat{\mathbf{b}}_{--} \right\rangle.
\]
(A.5)

The turbulent source also includes two components. The turbulent source driven by the parallel inductive electric field can be written as
\[
\frac{e^2}{cm_e} \left\langle \frac{\delta \mathbf{A}_{\|}}{\partial t} \right\rangle = -\sum_k \epsilon_0 \nu_0 \tau \left[ \frac{1}{2} \frac{\omega}{\omega_c} \right] \left\langle \hat{\mathbf{j}}_i \right\rangle \left\langle \hat{\mathbf{j}}_i \right\rangle \left\langle \hat{\mathbf{j}}_i \right\rangle + \frac{1}{\omega_c} \text{Re} \left\langle \delta \hat{\mathbf{A}}_{\|} \delta \hat{\mathbf{b}}_{--} \right\rangle.
\]
(A.6)

This is because the adiabatic ion response was used in this work.

The general relation between $\delta \mathbf{A}_1$ and $\delta \phi$ can be obtained through Ampere’s law
\[
-\nabla^2 \delta \mathbf{A}_1 = \frac{4\pi}{c} \delta \mathbf{J}_i.
\]
(A.7)

Neglecting the $U_0$ related terms in equation (10) and putting them into equation (A.7), after some algebra, we can obtain
\[
\delta \hat{\mathbf{A}}_{\|} = D_1 (C_1 - C_2) - (D_2 + D_1) (C_3 + C_4) - i \left[ (D_2 + D_1) (C_1 - C_2) + D_1 (C_3 + C_4) \right] \delta \hat{\mathbf{b}}_{--}.
\]
(A.8)

Here, $C_1 = \frac{2\pi}{\omega_c} \nu_0 \tau$ with $k_\perp$ being the perpendicular wave number and $\beta_e = \frac{8\pi T_e}{B}, C_2 = \frac{\omega}{\omega_c}, C_3 = \gamma_0 \omega_c (1 + \nu_0), C_4 = \frac{3 \sqrt{2} e^2}{8} \left( \frac{\omega}{\omega_c} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega}{\omega_c} \right), D_1 = \frac{k_\perp \nu_0}{\omega_c}, D_2 = \frac{\gamma_0 \omega_c (1 + \nu_0)}{\omega_c}, D_3 = \frac{3 \sqrt{2} e^2}{8} \left( \frac{\omega}{\omega_c} \right)^{3/2} \exp \left( -\frac{3}{2} \frac{\omega}{\omega_c} \right)\frac{1}{\omega_c}.$

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