Intrinsic current driven by electromagnetic electron drift wave turbulence in the tokamak pedestal region

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Abstract
The local intrinsic parallel current density driven by electron drift wave (DW) turbulence including electromagnetic (EM) effects is analytically studied. The scalings of the ratios of intrinsic current density driven by residual turbulent flux and by a turbulent source to the bootstrap (BS) current density with electron density and temperature are predicted to be $T_e^{-1/4}n_e$ and $T_eT_i/n_c$, respectively. Based on the typical parameters in the DIII-D pedestal region, the local intrinsic current density driven by both the residual turbulent flux and the turbulent source is negligible. However, despite the negligible turbulent source driven current, the residual turbulent flux driven local intrinsic current density by EM DW turbulence can reach about 66% of the BS current density for International Thermonuclear Experimental Reactor (ITER) pedestal parameters due to much lower collisionality in ITER than in DIII-D. Moreover, the contributions from adiabatic ES parts, non-adiabatic ES parts, and non-adiabatic EM parts of the plasma response to EM fluctuations are analyzed. It is found that there is a strong cancellation between the non-adiabatic ES response and the non-adiabatic EM response for the ITER pedestal case, and thus the kinetic stress contributed by the adiabatic ES response of parallel electron pressure dominates the intrinsic current drive. This is different from the ES electron DW case. Therefore, the EM effects on turbulence driven intrinsic current density should be carefully considered in the future reactor with a high ratio of electron pressure to the magnetic pressure and steep pressure profile.

Keywords: intrinsic current density, electromagnetic effects, electron drift wave turbulence, turbulent flux, turbulent source

1. Introduction

A current density profile is closely related to magnetohydrodynamic (MHD) instability in tokamaks, such as the neo-classical tearing mode (NTM) in the core region and edge localized mode (ELM) in the pedestal region. The neo-classical bootstrap (BS) current has attracted wide attention [1–4]. This is not only because it provides an economic way of driving the plasma current, but it also has a strong impact on the MHD instability. It has been discovered that the ubiquitous turbulence in tokamaks can also affect the current density profile via hyper-resistivity and anomalous resistivity [5, 6]. Moreover, by making an analogy between the collisional scattering and the resonant electron scattering by drift wave (DW) turbulence, the turbulence driven BS current has been proposed [7]. It has been found that the onset threshold of the NTM can be significantly affected by the turbulence or turbulence driven current density [8, 9]. The interaction
between micro-turbulence and the tearing mode has been investigated via both a self-consistent theoretical model [10, 11] and Landau-fluid simulations [12, 13]. These may be relevant to the effects of micro-turbulence on the onset and recovery of the NTM observed on JT-60U and DIII-D [14, 15]. Therefore, the study of intrinsic current density driven by micro-turbulence is helpful for a comprehensive understanding of the multi-scale interaction between micro-turbulence and MHD instability.

The idea of intrinsic current driven by an electrostatic (ES) electron DW in a sheared magnetic field in the presence of radial variation of the fluctuation level was proposed in [16]. The intrinsic current density induced by a finite value of averaged $k_{||}$ (parallel wave number of the DW) is very similar to the intrinsic rotation driven by residual stress due to $k_{||}$ symmetry breaking. Later, the intrinsic current drive by various types of micro-turbulence in a tokamak, e.g., the electron temperature gradient (ETG) [17, 18], ion temperature gradient (ITG) [19], and trapped electron mode [20] has been investigated. In these works, ES turbulence results in the change of the local current density profile by at least 10% as compared to the BS current density profile without considering electromagnetic (EM) effects. However, in the pedestal region where the pressure profile is very steep so that $\beta = (qR/L)_{||}^2$ can be above unity with $\beta$ being the ratio of thermal pressure to magnetic pressure, $q$ being the safety factor, $R$ being the major radius, and $L_\parallel$ being the mean pressure profile scale length across the magnetic flux surfaces, the EM effects on micro-turbulence is of great importance [21]. Hence, the EM effects on turbulence driven current should be carefully considered in the pedestal region. Although there are some works on EM turbulence driven current density [22–24], a general model with explicit contributions from ES effects and EM effects using the relationship between ES potential and magnetic vector potential fluctuations is missing. The intrinsic current driven by ETG turbulence including explicit EM effects has been studied recently [25], where the estimation is based on the parameters of tokamak core plasmas. Therefore, the goal of this work is to study the intrinsic current driven by EM electron DW turbulence in the pedestal region.

In this paper, the intrinsic current density driven by EM electron DW turbulence is estimated. The ratios of turbulence driven intrinsic current density from quasi-linear estimation to the BS current density based on the DIII-D and International Thermonuclear Experimental Reactor (ITER) pedestal parameters are presented. The intrinsic current density driven by EM DW turbulence may be too small to affect the current density profile in the DIII-D pedestal region. However, the local intrinsic current density driven by residual turbulent flux can reach about 66% of the BS current density in the ITER pedestal due to much lower collisionality. Moreover, an important finding is that the non-adiabatic EM effects strongly cancel the non-adiabatic ES effects, thus the dominant contribution to intrinsic current drive comes from the adiabatic ES response of parallel electron pressure induced kinetic stress. This indicates the necessity of considering the EM effects on intrinsic current driven by turbulence in a future reactor with relatively high $\beta$ and a steep pressure profile region.

The remainder of this paper is organized as follows. In section 2, a detailed quasi-linear derivation of the residual turbulent flux and the turbulent source driven by EM electron DW turbulence is presented. Besides, based on the DIII-D and ITER pedestal parameters, the ratio of intrinsic current density to the BS current density is estimated. Finally, a summary and discussion are given in section 3.

2. Quasi-linear estimate for intrinsic parallel current density

We will use the mean parallel current density evolution equation derived from the EM gyrokinetic equation [25]

$$\frac{\partial (\mathcal{J}_||)}{\partial t} + \nabla \cdot (\mathcal{E}_E \times \mathcal{B}_r) + \mathcal{J}_|| = -\left\langle \frac{e^2}{m_e} \mathcal{b} \cdot \nabla \mathcal{b} \mathcal{o} \mathcal{n}_e \right\rangle + \left\langle \frac{e^2}{c m_e} \frac{\partial \delta \mathcal{A}_1}{\partial t} \mathcal{o} \mathcal{b} \mathcal{n}_e \right\rangle. \tag{1}$$

Here, $\mathcal{J}_||$ is the parallel current density, $\mathcal{E}_E \times \mathcal{B}_r = \frac{i}{2} \times \nabla \mathcal{b} \mathcal{n}_e$ is the fluctuating $\mathbf{E} \times \mathbf{B}$ drift velocity, $\mathcal{b} = \mathcal{B} / B$ is the unit vector of equilibrium magnetic line, $\mathcal{o} \mathcal{n}_e = \int \mathcal{b} \mathcal{d}^3 \mathcal{v}$ is the perturbed electron density with $\mathcal{b}$ being the perturbed electron distribution function, $\mathcal{J}_|| = -e \int \mathcal{b} \mathcal{v} \mathcal{d}^3 \mathcal{v}$ is the perturbation of the parallel current density, $\mathcal{P}_f = m_e \int \mathcal{b} \mathcal{v}^2 \mathcal{d}^3 \mathcal{v}$ is the perturbation of the parallel electron pressure, $\mathcal{b} \mathcal{b} / \mathcal{c}$ is the ES potential fluctuation, $\mathcal{c}$ is the speed of light, $m_e$ is the electron mass, $e$ is the elementary charge, and $\mathcal{b} \mathcal{b} / \mathcal{c}$ is the normalized fluctuating perpendicular magnetic field where $\mathcal{b} \mathcal{B}_e \approx -\mathcal{b} \times \nabla \mathcal{A}_1$ is the perturbed perpendicular magnetic field. We only consider the shear component of magnetic perturbation, i.e., $\mathcal{A}_1$, and the compressional component $\delta \mathcal{B}_1$ is not included. The $\left\langle \cdot \right\rangle$ in this paper represents the flux average. On the left-hand side, the terms under the divergence are turbulent flux $\Gamma_1$ with $\left\langle \mathcal{b} \mathcal{E}_E \times \mathcal{B}_r \mathcal{J}_|| \right\rangle$ being the Reynolds stress-like term and $-\left\langle \frac{e^2}{c m_e} \frac{\partial \mathcal{A}_1}{\partial t} \mathcal{b} \mathcal{n}_e \right\rangle$ being the kinetic stress-like term. On the right-hand side (RHS), the turbulent source are driven by the correlation between density and parallel electric field fluctuations including both the ES field $\mathcal{S}_1 = \left\langle \frac{e^2}{m_e} \mathcal{b} \cdot \nabla \mathcal{b} \mathcal{o} \mathcal{n}_e \right\rangle$ and the inductive electric field $\mathcal{S}_2 = \left\langle \frac{e^2}{c m_e} \frac{\partial \mathcal{A}_1}{\partial t} \mathcal{o} \mathcal{b} \mathcal{n}_e \right\rangle$. In this work, we focus on the intrinsic current drive which is independent of the mean parallel current density or its gradient. This is analogous to the intrinsic rotation drive by the residual stress, kinetic stress, and turbulent source [26–28].

2.1. Residual turbulent flux and turbulent source

The quasi-linear estimation for the residual turbulent flux and turbulent source requires the calculation of the linear response of $\delta \mathcal{n}_e$, $\delta \mathcal{J}_||$ and $\delta \mathcal{P}_f$ to the EM fluctuations. By linearizing the
EM drift equation of electrons, the linearized perturbed electron distribution function in Fourier space decomposed into adiabatic and non-adiabatic parts can be written as

\[
\delta f_k = \frac{e\delta \phi_k}{T_e} F_M + \delta g_k = \frac{e\delta \phi_k}{T_e} F_M - \frac{m_e}{2\pi T_e} \left( \frac{m_e}{k^2} \right)^{3/2} \exp \left( -\frac{\gamma_k}{k} \right) v_n \left( \gamma_k \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right).
\]

(2)

Here, \( F_M \) is the Maxwellian distribution function of electrons, \( \delta g_k \) represents the non-adiabatic part of the perturbed electron distribution function, \( \nu_k = \frac{v_n}{v_{th}} \) is the diamagnetic drift frequency of electron with \( k \) being the wave vector, \( \omega_k = k v_n \) is the electron transit frequency with \( k \) being the parallel wave number, \( v_{th} = \frac{\sqrt{T_e}}{m_e} \) is the electron thermal velocity with \( T_e \) being the electron temperature, \( v_n = \frac{v_n}{v_{th}} \) is the normalized electron parallel velocity, \( \nu_k = \frac{v_n}{v_{th}} \) is the normalized electron perpendicular velocity, and \( \eta_k = \frac{v_n}{v_{th}} \) is the non-adiabatic part of the perturbed electron distribution function in Fourier space decomposed.

The linearized perturbed electron distribution function is

\[
\delta n_{ek} = \frac{e\delta \phi_k}{T_e} n_e + \int \delta g_k d^3v = n_e \delta \phi_k - \sqrt{\pi} n_e \exp \left( -\frac{\gamma_k}{k} \right) \nu_k \left( \gamma_k \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right).
\]

(3)

The perturbed parallel current is

\[
\delta J_{ik} = \sqrt{\pi} \nu_k v_n \ell_{\text{the}} \zeta_k \exp \left( -\frac{\gamma_k}{k} \right) \frac{\gamma_k}{k} \nu_k \left( \gamma_k \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right).
\]

(5)

It is noted that the perturbed parallel current is produced by the non-adiabatic response, since the adiabatic ES response does not have a contribution. Similarly, on the RHS of equation (5), the terms relevant to \( \delta \phi_k \) and \( \delta A_{kj} \) result from the non-adiabatic ES and EM responses, respectively. Then, equation (5) can be rewritten as

\[
\delta J_{ik} = \delta J_{ik}^{\text{NA}_{\text{ES}}} + \delta J_{ik}^{\text{NA}_{\text{EM}}}.
\]

(6)

The perturbed parallel electron pressure is

\[
\delta P_{ik} = \frac{e \delta \phi_k}{T_e} n_e - \sqrt{\pi} \nu_k v_n \ell_{\text{the}} \zeta_k \exp \left( -\frac{\gamma_k}{k} \right) \frac{\gamma_k}{k} \nu_k \left( \gamma_k \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right).
\]

(7)

Here, the first term on the RHS comes from the adiabatic ES response. The other terms come from the non-adiabatic ES and EM responses, again. Then, equation (7) can be rewritten as

\[
\delta P_{ik} = \delta P_{ik}^{\text{A}_{\text{ES}}} + \delta P_{ik}^{\text{NA}_{\text{ES}}} + \delta P_{ik}^{\text{NA}_{\text{EM}}}.
\]

(8)

Based on equations (3)–(8), the calculations of residual turbulent flux and turbulent source are straightforward.

The detailed calculations of \( \langle \delta \phi_k, \delta \phi_k \rangle \) and \( \left\langle -\frac{\xi_k}{m_e} \delta \phi_k, \delta \phi_k \right\rangle \) can be found in the appendix. The expression of residual turbulent flux can be written as

\[
\Gamma_r = \sum_k \frac{1}{2} \sqrt{\pi} k_0 \nu_k v_n \ell_{\text{the}} \zeta_k \exp \left( -\frac{\gamma_k}{k} \right) \left( \frac{\omega_{kr}}{k} \right) \nu_k \left( \gamma_k \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right) \exp \left( -\frac{\gamma_k}{k} \right) \left( \nu_k \delta A_{kj} \right).
\]

Here, the first term on the RHS comes from the pure ES contribution from \( \delta J_{ik}^{\text{NA}_{\text{ES}}} \) to the Reynold stress. The other terms come from EM effects including both the contribution from the non-adiabatic EM response of the current \( \delta J_{ik}^{\text{NA}_{\text{EM}}} \) to the Reynold stress and the contribution from the non-adiabatic ES response of electron pressure \( \delta P_{ik}^{\text{NA}_{\text{ES}}} \) to the kinetic stress. Especially, the last term comes from the contribution from the adiabatic response of parallel electron pressure \( \delta P_{ik}^{\text{A}_{\text{ES}}} \) to the kinetic stress. If the ES limit is taken,
equation (9) will be reduced to the same form as equation (6) in [20]. In the same way, the expression of the turbulent source is

\[
S = -\sum_k \frac{\sqrt{2\pi} \epsilon n_e v_{th}^2}{2} \exp\left(-\xi_e^2\right) \left\{ \omega_{\nu k} - \frac{\omega_{\nu k}}{|k|} v_{th} \right\} \times \left[ 1 + \eta_e \left( \frac{|k|}{2} - \frac{1}{2} \right) \right] \frac{k}{|k|} |\delta_\nu k| - \frac{4\omega_{\nu k}}{v_{th}} \right\}
\times \text{Re}(\delta A_{\nu k} \hat{\nu} \delta_\nu k) + 2\eta_e \frac{\omega_{\nu k}}{v_{th}} \frac{v_{\text{th}}}{v_{\text{turb}}} \left| \delta_\nu k \right|^2 - \frac{4\omega_{\nu k}}{v_{th}} \right\}
\times |\delta A_{\nu k}|^2 - \sum_k \epsilon n_e v_{th} \left[ \omega_{\nu k} \frac{v_{\text{turb}}}{v_{\text{th}}} \right] \hat{\nu} \text{Re}(\delta A_{\nu k} \hat{\nu} \delta_\nu k)
\right]
\frac{\gamma_k}{\text{Re}(\delta A_{\nu k} \hat{\nu} \delta_\nu k)}.
\]

Detailed calculations of \( S \) can also be found in the appendix. The first term on the RHS of equation (10) comes from the pure ES contribution, i.e., correlation between the non-adiabatic ES electron density response \( \delta n_{\nu \text{ES}} \) and the ES electric field fluctuation, which is consistent with the result in [22]. Here, it is noted that the adiabatic ES density response \( \delta n_{\nu \text{ES}} \) does not contribute to the pure ES turbulent source. The other terms are due to EM effects including the correlation between the non-adiabatic EM density response \( \delta n_{\nu \text{EM}} \) and both the ES and inductive electric field fluctuations and the correlation between the adiabatic ES density response \( \delta n_{\nu \text{ES}} \) and the inductive electric field fluctuation.

2.2. Intrinsic current density and comparison with BS current density

Up to now, the quasi-linear expression for the residual turbulent flux and the turbulent source has been written in terms of the EM fluctuations. Then, the explicit estimation of EM effects on intrinsic current drive requires the relation between \( \delta A_{\nu k} \) and \( \delta_\nu k \). Combining equation (5) with Ampère’s law, \( -\nabla^2 \delta A_{\nu k} = \frac{4\pi}{c} \delta J_{\nu} \), the relation can be written as

\[
\delta A_{\nu k} = \frac{C_{\nu}}{D} \frac{\gamma_{\nu k}}{v_{\text{th}}} \delta_\nu k.
\]

Here, \( C_{\nu} = F_1 \frac{k^2 \epsilon^2}{\beta_e} + 2\xi_e F_2^2 + 2\xi_e F_2 \), \( C_2 = F_2 \frac{k^2 \epsilon^2}{\beta_e} \), \( D = \left( \frac{k^2 \epsilon^2}{\beta_e} + 2\xi_e F_1^2 \right) + 4\xi_e^2 F_2^2 \) with \( F_1 = \sqrt{2\pi} \xi_e \exp\left(-\xi_e^2\right) \left[ \frac{\gamma_{\nu k}}{|k|} v_{\text{th}} \right] \), and \( F_2 = \sqrt{2\pi} \xi_e \exp\left(-\xi_e^2\right) \left[ \frac{\gamma_{\nu k}}{|k|} v_{\text{th}} \right] \), are all dimensionless. \( k \) is the perpendicular wave number, and \( \beta_e = \frac{\epsilon n_e}{\sqrt{2 m_e T_e}} \) is the ratio between electron pressure and the magnetic pressure. When the finite Larmor radius effects are neglected, equation (11) yields \( \delta A_{\nu k} = \frac{1}{2} k^2 \xi_e \frac{\gamma_{\nu k}}{\omega_e} \). Note that \( \delta A_{\nu k} = \frac{\delta \epsilon n_e}{\rho_e} \) and \( \delta_\nu k = \frac{\epsilon n_e}{\rho_e} \frac{\gamma_{\nu k}}{\omega_e} \) are normalized, so the ideal Alfven wave limit \( \delta A_{\nu k} = \frac{\epsilon n_e}{\rho_e} \delta_\nu k \), i.e., \( \delta E_1 = 0 \) can be reproduced. In this limit, the turbulent source which is proportional to \( \delta E_1 \) vanishes. The non-adiabatic responses in equations (3), (5), and (7) are all proportional to \( (\delta_\nu k - 2\xi_e \delta A_{\nu k}) \). From equation (11), we can obtain

\[
\delta_\nu k = 2\xi_e \delta A_{\nu k} = \frac{k^2 \epsilon^2}{\beta_e} + 2\xi_e F_2^2 + 2\xi_e F_2 \frac{k^2 \epsilon^2}{\beta_e} \frac{\gamma_{\nu k}}{\omega_e} \delta_\nu k.
\]

Substituting equation (12) into the residual turbulent flux and turbulent source, it is found that \( k \) symmetry breaking is required for a non-zero intrinsic current drive. This is very similar to the intrinsic rotation drive. Various symmetry breaking mechanisms have been proposed, such as \( E \times B \) shear [29, 30], intensity gradient [31], and so on [32, 33]. Symmetry breaking induced by \( E \times B \) shear will be taken in this work. The average of the parallel wave number induced by the \( E \times B \) shear for electron DW turbulence is \( k_{||} = k_{||} |\delta_\nu k|^2 / \sum |\delta_\nu k|^2 \approx \frac{q}{2\pi} k_0 \rho_1 \frac{\rho_1}{R L_p} \) [22] with \( L_p \) being the length scale of the pressure gradient. Considering \( \omega_{\nu k} = \frac{k_0 \rho_1}{2\pi} \) and \( \lambda_k = |\delta_\nu k|^2 \), then substituting equations (9)–(12), the residual turbulent flux can be written as

\[
\Gamma_{\nu e} = \frac{1}{2} \epsilon n_e v_{th} \left( 1 - 4\xi_e \frac{C_{\nu}}{D} + 4\xi_e^2 \frac{C_2^2}{D^2} \right) H_{\nu e}
\times \frac{\omega_{\nu k}}{|k|} \frac{\omega_{\nu k}}{v_{\text{th}}} \frac{q}{s} \frac{q}{s} \rho_1 \frac{\rho_1}{R L_p} \sum k
\left( \frac{C_{\nu}}{D} \frac{\gamma_{\nu k}}{v_{\text{th}}} \right) \left( \frac{C_{\nu}}{D} \frac{\gamma_{\nu k}}{v_{\text{th}}} \right)
\times \frac{q}{s} \frac{q}{s} \rho_1 \frac{\rho_1}{R L_p} \sum k.
\]

The turbulent source can be written as

\[
S = -\frac{\epsilon n_e v_{th}^2}{2 R} \left( \frac{1}{2} - \frac{C_{\nu}}{D} \frac{\gamma_{\nu k}}{v_{\text{th}}} \right) \left( \frac{C_{\nu}}{D} \frac{\gamma_{\nu k}}{v_{\text{th}}} \right)
\times H_{\nu e} \frac{k_{||} |\delta_\nu k|^2}{|\delta_\nu k|^2} \frac{q}{s} \frac{q}{s} \rho_1 \frac{\rho_1}{R L_p} \sum k
\times \frac{q}{s} \frac{q}{s} \rho_1 \frac{\rho_1}{R L_p} \sum k.
\]

It should be mentioned that although both the turbulent flux and source seem to diverge as they approach the rational surface, i.e., \( |k_{||}| \rightarrow 0 \) (\( e^{2/x} \rightarrow \infty \)), the factor of exponential convergence \( \exp\left(-\xi_e^2\right) \) will regularize the magnitude of the turbulent flux and source. This has been discussed in [20]. The transit resonance condition in cylindrical geometry, \( \omega_{\nu k} \approx \omega_{\nu k} \) implies \( \Delta x \approx \frac{1}{R} \frac{q}{\beta_e} \frac{\rho_1}{R L_p} \), where \( L_n = q R / \beta \) is the magnetic shear length with \( \beta \) being the magnetic shear. An interesting point is that the width of the electron Landau layer, \( \Delta \) could be several ion gyroradii for normal magnetic shear due to the very steep density gradient in the pedestal region. This will result in the radial variation of the turbulent flux and source around the rational surface being slower than that in the flat density gradient region [20]. In recent gyrokinetic simulation of a collisionless trapped electron mode (CTEM) turbulence driven current [34], the scale length of the corrugated
current profile around the rational surface was about 5–10 gyroradii where the density profile was relatively steep and the magnetic shear was weak. This is consistent with our theory.

Then, the negative divergence of residual turbulent flux can provide a turbulent force for driving the intrinsic current density. We take the length scale of the variation of the residual turbulent flux as mesoscale, i.e., $\sqrt{\rho L}$, which is larger than the ion gyroradius but smaller than the density gradient scale length. Then, the residual turbulent flux driven force is $\mp \frac{L}{\rho L}$. The sign of $\mp$ corresponds to a positive (negative) gradient of the turbulent flux. By balancing the turbulent flux driven force with the collisional friction force $-v_{\text{ei}} J_{\text{turb}}$, we can obtain the intrinsic current density driven by the residual turbulent flux

$$J_{\text{turb}}^{r} = \mp \frac{L}{\rho L}.$$ (15)

Similarly, balancing the turbulent source $S$ with the collisional force produces the intrinsic current density driven by turbulent source $S$

$$J_{\text{turb}}^{s} = \frac{S}{v_{\text{ei}}}. \quad (16)$$

Now, we compare the intrinsic current density driven by EM electron DW turbulence with the BS current density. The BS current density can be estimated as follows [22]:

$$J_{\text{BS}} = \frac{\frac{L}{\rho L} n_{e} \rho_{L}}{v_{\text{ei}}} \left[ \frac{L}{\rho L} + 4 \xi_{e} \right], \quad (17)$$

where $\xi_{e}$ is the reverse aspect ratio. Subsequently, the ratios of the intrinsic current density driven by residual turbulent flux and turbulent source to the BS current density can be written as

$$\frac{J_{\text{turb}}^{r}}{J_{\text{BS}}} = 1 - 4 \xi_{e} \frac{C_{1}}{D} + 4 \xi_{e}^{2} \frac{C_{2}}{D^{2}} \left[ H \frac{\omega_{\text{pe}}}{k_{\text{th}}} \frac{\omega_{k}}{v_{\text{th}}} \right] \frac{k_{0} \rho_{L}}{k_{0} \rho_{L}}, \quad (18)$$

and

$$\frac{J_{\text{turb}}^{s}}{J_{\text{BS}}} = - \frac{\sqrt{\rho_{L} L}}{v_{\text{ei}}} \frac{\rho_{L}}{s R} \left[ \frac{1}{2} - \frac{C_{1}}{D} \frac{\xi_{e}}{n_{e}} - \frac{C_{2}}{D^{2}} \frac{\xi_{e}^{2}}{n_{e}} \right] \frac{k_{0} \rho_{L}}{k_{0} \rho_{L}} \sum_{k} k_{0} \rho_{L} \sum_{k} \frac{k_{0} \rho_{L}}{k_{0} \rho_{L}}, \quad (19)$$

We take the typical pedestal parameters of DIII-D [35], $q = 3.6$, $R/L_{T_{e}} = 144$, $R/L_{n} = 64$, $s = 1$, $v_{\text{ei}} = 0.37$, $R = 1.77$ m, $n_{e} = 2.48 \times 10^{19} / \text{m}^{3}$, $T_{e} = 197$ eV, $T_{n} = 397$ eV, $v_{\text{ei}} = 3.88 \times 10^{15}$ Hz, $\rho_{L} = 2.82 \times 10^{-5}$ m, and $\beta_{e} = 0.07\%$. The typical EM electron DW turbulence scale in the pedestal region is taken as $k_{0} \rho_{L} \approx 0.28$ (with the toroidal mode number being 30), $k_{0}^{2} = 2 k_{0}^{2}$, $\gamma_{l} / \omega_{\text{pe}} = 1 / 10$, $\sum_{k} k_{0} \rho_{L} = 5 \times 10^{-4}$, $\sum_{k} k_{0} \rho_{L} = 5 \times 10^{-4}$, $\sum_{k} k_{0} \rho_{L} = 5 \times 10^{-4}$.
Table 1. Results of the estimation for the intrinsic current density driven by EM electron DW turbulence for typical pedestal parameters on DIII-D and ITER.

| Ratio of intrinsic current density to BS current density | ES contribution | EM contribution |
|--------------------------------------------------------|-----------------|----------------|
|                                                         | DIII-D          | ITER           |
|                                                         | ±0.58%          | ±14.3%         |
|                                                         | ±14.3%          | ±14.3%         |
|                                                         | ±4.06%          | ±66.1%         |
| Total turbulent flux                                     | −0.52%          | −7.81%         |
|                                                         | 0.38%           | 1.81%          |
|                                                         | 4.16 × 10⁻⁴     | −0.38%         |
| Total turbulent source                                   | −0.52%          | −7.81%         |
|                                                         | 0.72%           | 9.27%          |

\[ \frac{J_{\text{turb}}^S}{J_{\text{BS}}} = \mp(14.3\% - 24.3\% + 11.5\% - 66.1\%), \quad (24) \]

and

\[ \frac{J_{\text{turb}}^S}{J_{\text{BS}}} = -7.8\% + 13.3\% + 0.4\% - 6.3\%
+ (5.1\% - 3.3\%). \quad (25) \]

For this case, the intrinsic current density driven by turbulent flux can reach about 66% of the BS current density, and thus may be important for the modification of the local current density profile. But, the turbulent source driven current density is less than 2% of the local BS current density in the pedestal region, and can be neglected. The flux driven intrinsic current mainly comes from the kinetic stress due to the adiabatic ES response of parallel electron pressure. The contributions from the non-adiabatic responses are all small. This can be explained from equation (12). For the ITER pedestal parameters, equation (12) becomes \( \delta\phi_k - 2\xi_e \delta A_{jk} \). This indicates that the non-adiabatic ES and EM responses of \( \delta n_e, \delta J_e, \) and \( \delta P_t^\parallel \), i.e., equations (3), (5), and (7) become strongly canceled, and so the non-adiabatic contribution to the intrinsic current drive is small. The non-adiabatic contributions to the intrinsic current drive are significantly reduced if the EM effects are important. This is very different from previous works without careful treatment of EM effects. From equation (11), \( \delta A_{jk} \) will flip sign when ITG turbulence is considered. However, the non-adiabatic response is proportional to \( \delta\phi_k - 2\xi_e \delta A_{jk} \), and \( \xi_e = \frac{\nu_e}{k_{ij}\nu_p} \) will also flip sign for the ITG case. Therefore, the non-adiabatic EM response \( \sim -2\xi_e \delta A_{jk} \) will not flip sign. This implies that the EM effects still contribute a subtraction to the non-adiabatic response, and a reduction of the intrinsic current drive due to EM effects could be also expected for the ITG case. The results of the intrinsic current density based on the DIII-D and ITER pedestal parameters are summarized in table 1.

3. Summary

In this work, it is found that the EM effects on electron DW turbulence driven intrinsic current is significant for the ITER pedestal parameters. The non-adiabatic ES response of \( \delta n_e, \delta J_e, \) and \( \delta P_t^\parallel \) is strongly canceled by the non-adiabatic EM response, which results in the contribution from the non-adiabatic response to the intrinsic current drive being small. Only the kinetic stress associated with correlation between the radial magnetic fluctuation and the adiabatic ES response of \( \delta P_t^\parallel \) dominates the intrinsic current drive.

Based on the DIII-D pedestal parameters, the intrinsic current density driven by the residual turbulent flux and turbulent source is less than 2% of the local BS current density. However, an examination of the scaling of the intrinsic current density driven by turbulence with the electron temperature showed that the EM electron DW turbulence driven current may become considerable as compared to the BS current density for the high electron temperature case. Based on the ITER pedestal parameters, the local current density driven by EM electron DW turbulence can reach about 66% of the local BS current density due to the much lower collisionality. Therefore, we conclude that in high \( \beta \) fusion devices like ITER, the EM electron DW turbulence driven intrinsic current density may be important for the modification of the local current density profile in the pedestal region and the subsequent ELM control.

Finally, we discuss limitations of the model adopted in this work. The diffusive and convective components of the turbulent current flux are not calculated in the present work,
which may also be important for accurate prediction of a current density profile and thus the control of ELM in the pedestal region. Therefore, the effects of the diffusion and convection of the turbulent current flux induced by EM turbulence on the current density profile may be investigated in the future. It should be also mentioned that although the symmetry breaking caused by the equilibrium radial electric field $E_r$ shear has been considered, the effects of Doppler shift and $E \times B$ shear suppression of turbulence are absent. Self-consistently including the equilibrium $E \times B$ effects in the study of EM electron DW turbulence driven current is also worth exploring.

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Appendix. Calculations of the intrinsic current drive

The turbulent current flux consists of two terms. The Reynolds stress-like term can be calculated using equation (5),

$$\langle \delta n_{e,B_i} \delta J_i \rangle = \frac{1}{2} \sum_k \sqrt{\pi} k \psi_e e n_{e} v_{be}^2 \zeta_e \exp \left( -\xi_e^2 \right) \times \left\{ \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \right\}$$

(A1)

The kinetic stress-like term can be calculated using equation (7),

$$\langle \frac{e}{m_e} \delta P_i^{\ast} \delta h_i \rangle = - \sum_k \sqrt{\pi} k \psi_e e n_{e} v_{be}^2 \zeta_e \exp \left( -\xi_e^2 \right) \times \frac{\gamma_k}{|k||v_{be}|} \text{Im} \langle \delta A_{ik} \delta \phi_{ik} \rangle - \sum_k \sqrt{\pi} k \psi_e e n_{e} v_{be}^2 \zeta_e \exp \left( -\xi_e^2 \right) \times \left\{ \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \right\}$$

(A2)

The turbulent source also includes two components. The turbulent source driven by the ES field can be written as

$$S_1 = \sum_k - \frac{\sqrt{\pi}}{2} e n_{e} v_{be}^2 \exp \left( -\xi_e^2 \right) \times \left\{ \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \right\}$$

$$\times \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \times \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right]$$

$$\times \left\{ \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \right\}$$

(A3)

The parallel inductive electric field driven source is

$$S_2 = - \sum_k e n_{e} v_{be} \omega_{kr} \text{Im} \langle \delta A_{ik} \delta \phi_{ik} \rangle + \gamma_k \text{Re} \langle \delta A_{ik} \delta \phi_{ik} \rangle$$

$$+ \sum_k \sqrt{\pi} e n_{e} v_{be} \exp \left( -\xi_e^2 \right) \times \left\{ \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \right\}$$

$$\times \left\{ \frac{\omega_{kr}}{|k||v_{be}|} - \frac{\omega_{kr}}{|k||v_{be}|} \left[ 1 + \eta_e \left( \xi_e^2 - \frac{1}{2} \right) \right] \right\}$$

(A4)

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References

[1] Bickerton R J, Connor J W and Taylor J B 1971 Diffusion driven plasma currents and bootstrap tokamak Nat. Phys. Sci. 229 110
[2] Dunne M G, McCarthy P J, Wolfrum E, Fischer R, Giannone L and Burckhart A 2012 Measurement of neoclassically predicted edge current density at ASDEX upgrade Nucl. Fusion 52 123014
[3] Kikuchi M and Azumi M 1995 Experimental evidence for the bootstrap current in a tokamak Plasma Phys. Control. Fusion 37 1215
[4] Thomas D M, Leonard A W, Lao L L, Osborne T H, Mueller H W and Finkenthal D F 2004 Measurement of pressure-gradient-driven currents in tokamak edge plasmas Phys. Rev. Lett. 93 065003
[5] Strauss H 1986 Hyper-resistivity produced by tearing mode turbulence Phys. Fluids 29 3668
[6] Biskamp D 1984 Anomalous resistivity and viscosity due to small-scale magnetic turbulence Plasma Phys. Control. Fusion 26 311
[7] McDevitt C J, Tang X Z and Guo Z 2013 Turbulence-driven bootstrap current in low-collisionality tokamaks Phys. Rev. Lett. 111 205002

[8] Itoh S I, Itoh K and Yagi M 2003 Novel turbulence trigger for neoclassical tears modes in tokamaks Phys. Rev. Lett. 91 045003

[9] Cai H 2019 A mechanism of neoclassical tearing modes onset by drift wave turbulence Nucl. Fusion 59 026009

[10] McDevitt C J and Diamond P H 2006 Multiscale interaction of a tearing mode with drift wave turbulence: a minimal self-consistent model Phys. Plasmas 13 032302

[11] Sen A, Singh R, Chandra D, Kaw P and Raju D 2009 ETG turbulence effects on the evolution of an NTM Nucl. Fusion 49 115012

[12] Li J and Kishimoto Y 2012 Small-scale dynamo action in multi-scale magnetohydrodynamic and micro-turbulence Phys. Plasmas 19 030705

[13] Li J, Kishimoto Y and Wang Z X 2014 Response of microscale turbulence and transport to the evolution of resistive magnetohydrodynamic magnetic island Phys. Plasmas 21 020703

[14] Isayama A, Matsunaga G, Hirano Y and the JT-60 Team 2013 Onset and evolution of m/n = 2/1 neoclassical tearing modes in high-βp mode discharges in JT-60U J. Plasma Fusion Res. 8 1402013

[15] Bardóczi L, Rhodes T L, Carter T A, La Haye R J, Bañón Navarro A and McKee G R 2017 Shrinking of core neoclassical tearing mode magnetic islands due to edge localized modes and the role of ion-scale turbulence in island recovery in DIII-D Phys. Plasmas 24 062503

[16] Itoh S-I and Itoh K 1988 Anomalous bootstrap current due to drift waves Phys. Lett. A 127 267

[17] Singh R, Kaw P K, Singh R and Gürcan Ö D 2017 Intrinsic non-inductive current driven by ETG turbulence in tokamaks Phys. Plasmas 24 102303

[18] Yi S, Shang H and Kwon J M 2016 Gyrokinetic simulations of an electron temperature gradient turbulence driven current in tokamak plasmas Phys. Plasmas 23 102514

[19] Seiferling F, Peeters A G, Buchholz R, Grosshauser S R, Rath F and Weikl A 2018 On turbulence driven stationary electric currents in a tokamak Phys. Plasmas 25 102305

[20] McDevitt C J, Tang X-Z and Guo Z 2017 Turbulent current drive mechanisms Phys. Plasmas 24 082307

[21] Scott B 1997 Three-dimensional computation of drift Alfvén turbulence Plasma Phys. Control. Fusion 39 1635

[22] Garbet X, Esteve D, Sarazin Y, Dif-Pradalier G, Ghendrih P, Grandgirard V, Latt G and Smolyakov A 2014 Turbulent current drive J. Phys. Conf. Ser. 561 012007

[23] Hinton F L, Waltz R E and Candy J 2004 Effects of electromagnetic turbulence in the neoclassical Ohm’s law Phys. Plasmas 11 2433

[24] Gatto R and Chavdarovski I 2011 Current density equation in turbulent magnetized plasmas Open Plasma Phys. J. 4 1

[25] He W, Wang L, Peng S, Guo W and Zhuang G 2018 Intrinsic current driven by electromagnetic electron temperature gradient turbulence in tokamak plasmas Nucl. Fusion 58 106004

[26] Peng S, Wang L and Pan Y 2017 Intrinsic parallel rotation drive by electromagnetic ion temperature gradient turbulence Nucl. Fusion 57 036003

[27] Garbet X, Esteve D, Sarazin Y, Abiteboul J, Bourdelle C, Dif-Pradalier G, Ghendrih P, Grandgirard V, Lutk G and Smolyakov A 2013 Turbulent acceleration and heating in toroidal magnetized plasmas Phys. Plasmas 20 072502

[28] Wang L, Peng S and Diamond P H 2018 Gyrokinetic theory of turbulent acceleration and momentum conservation in tokamak plasmas Plasma Sci. Technol. 20 074004

[29] Dominguez R R and Stuebler G M 1993 Anomalous momentum transport from drift wave turbulence Phys. Fluids B 5 3876

[30] Gürcan Ö D, Diamond P H, Hahn T S and Singh R 2007 Intrinsic rotation and electric field shear Phys. Plasmas 14 042306

[31] Gürcan Ö D, Diamond P H, Hennequin P, McDevitt C J, Garbet X and Bourdelle C 2010 Residual parallel Reynolds stress due to turbulence intensity gradient in tokamak plasmas Phys. Plasmas 17 112309

[32] McDevitt C J, Diamond P H, Gürcan Ö D and Hahn T S 2009 A novel mechanism for exciting intrinsic toroidal rotation Phys. Plasmas 16 052302

[33] Camenen Y, Peeters A G, Angioni C, Casson F J, Hornsby W A, Snodin A P and Strintzi D 2009 Transport of parallel momentum induced by current-symmetry breaking in toroidal plasmas Phys. Rev. Lett. 102 125001

[34] Wang W X, Hahn T S, Startsev E A, Ether E S, Chen J, Yoo M G and Ma C H 2019 Self-driven current generation in turbulent fusion plasmas Nucl. Fusion 59 084002

[35] Liao X, Lin Z, Holod I, Xiao Y, Li B and Snyder P B 2016 Microturbulence in DIII-D tokamak pedestal. III. effects of collisions Phys. Plasmas 23 122507

[36] Angioni C, Peeters A G, Pereverzev G V, Bottino A, Candy J, Dux R, Fable E, Hein T and Waltz R E 2009 Gyrokinetic simulations of impurity, He ash and α particle transport and consequences on HER transport modelling Nucl. Fusion 49 055013