THEORY OF ELECTROMAGNETIC (EM) TURBULENCE DRIVEN INTRINSIC CURRENT IN TOKAMAK PLASMAS

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Abstract

- Evolution equation of parallel current density is derived
- Intrinsic current driven by EM ETG turbulence in core plasmas
  - The turbulent flux driven intrinsic current density can reach about 80% of the local bootstrap (BS) current density
  - Less than 1% from turbulent source
- Intrinsic current driven by EM electron DW turbulence in pedestal plasmas
  - Adiabatic kinetic stress is the dominant drive; Non-adiabatic ES contributions are strongly cancelled by the EM effects
  - Scaling of intrinsic current to BS current is predicted

Background

- Current density profile important for MHD instability: NTM (core), ELM (pedestal)
- Measurements of bootstrap current NOT always consistent with neoclassical theory [De Bock et al, PPCF 2012]
- Intrinsic flow: self-generated rotation without external momentum input is of great interest - explained by turbulence [Diamond et al, NF 2013]
- Ion momentum ←→ electron momentum per electron mass (current)
- Turbulence driven intrinsic current? [Itoh PLA 1988; Hinton PoP 2004; McDevitt PRL 2013; Garbet JPCS 2014; Yi PoP 2016; Wang, NF 2019]
- Onset threshold of neoclassical tearing mode affected by intrinsic current has been found [Cai, NF 2019]
- Self-consistent EM effects on intrinsic current drive are missing

Evolution equation of parallel current density

- **Starting from conservative form of EM drift-kinetic equation**

$$\frac{\partial\left(F_e B_\parallel^*\right)}{\partial t} + \nabla\cdot\left(\frac{d\boldsymbol{R}}{dt}F_e B_\parallel^*\right) + \frac{\partial}{\partial v_\parallel}\left(\frac{dv_\parallel}{dt}F_e B_\parallel^*\right) = 0$$

- **Mean parallel current equation**

$$\frac{\partial\langle J_\parallel\rangle}{\partial t} + \nabla\cdot\langle\delta v_{E\times B,r}\delta J_\parallel\rangle - \nabla\cdot\langle\frac{e}{m_e}\delta \boldsymbol{b}_r\delta P_\parallel\rangle = -\frac{e^2}{m_e}\langle\hat{\boldsymbol{b}}\cdot\nabla\delta\phi\delta n_e\rangle - \frac{e^2}{cm_e}\langle\frac{\partial\delta A_\parallel}{\partial t}\delta n_e\rangle$$

✓Turbulent flux terms: $\Gamma = \Gamma_1 + \Gamma_2$ enter this equation by their divergence

- $\Gamma_1 = \langle\delta v_{E\times B,r}\delta J_\parallel\rangle$, **Reynold Stress-like** term
- $\Gamma_2 = -\frac{e}{m_e}\langle\delta b_r\delta P_\parallel\rangle$, **Kinetic Stress-like** term

✓Turbulent source terms $S = S_1 + S_2$ can't be written as a divergence of stress, so act as a local source or sink of parallel current

- $S_1 = -\frac{e^2}{m_e}\langle\hat{\boldsymbol{b}}\cdot\nabla\delta\phi n_e\rangle$ driven by **electrostatic** electric field
- $S_2 = -\frac{e^2}{cm_e}\left\langle\frac{\partial\delta A_\parallel}{\partial t}\delta n_e\right\rangle$ driven by **inductive** electric field

- **Balance the negative divergence of residual turbulent flux and residual turbulent source with the collisional friction force**

$$-\nabla\cdot\Gamma_r^{res} + S^{res} - v_{ei}J_{turb} \approx 0$$

- **The length scale of variation of the residual turbulent flux is taken as mesoscale** L

✓Turbulent flux driven: $J_{turb}^{\Gamma} = \mp\frac{\Gamma_r^{res}}{v_{ei}L}$

✓Turbulent source driven: $J_{turb}^{S} = \frac{S^{res}}{v_{ei}}$

- **Compare to the neoclassical BS current**: $J_{BS} \simeq 5\sqrt{\frac{1}{\varepsilon}}\frac{cqn_0T_e}{BL_P}$

Intrinsic current driven by EM ETG turbulence (core)

- For typical ITER parameters in core region: $q = 1$, $R/L_{Te} = 4$, $R/L_n = 1.5$, $\hat{s} = 0.3$, $\varepsilon = 0.16$, $R = 6.2\text{m}$, $B = 4.85\text{T}$, $\tau = 1$, $n_e = 1.3\times10^{20}/\text{m}^3$, $T_e = 12\text{keV}$, $v_{ei} = 5.8\times10^3\text{Hz}$, $\rho_e = 5.4\times10^{-5}\text{m}$, $\beta_e = 2.67\%$
- Typical ETG turbulence scale: $k_\theta\rho_e \simeq 0.4$, $\gamma_k/\omega_{kr} = 3/10$, $w_k = \frac{1}{k_\theta}$, $\sum_k I_k = 10^{-4}$, $L_I = L_n$

✓Ratio of turbulent flux driven current to BS current: J_{turb}^{Γ}/J_{BS}

J_{turb}^{Γ}/J_{BS}	non-resonant contribution	resonant contribution
ES contribution	$\mp17.4\%$	$\mp59.6\%$
EM contribution	$\mp(9.9\%)$	$\pm3.7\%$

✓Ratio of turbulent source driven current to BS current: $J_{turb}^{S}/J_{BS} < 1\%$

[Wen He, Lu Wang, et al., Nucl. Fusion 58 106004 (2018)]

Intrinsic current driven by EM DW turbulence (pedestal)

- For parameters in pedestal region @ DIII-D & ITER

Ratio of intrinsic current density to BS current density	ES contribution		EM contribution	
	DIII-D	ITER	DIII-D	ITER
$\langle\delta v_{E\times B,r}\delta J_\parallel^{NA}\rangle$	$\mp0.58\%$	$\mp14.3\%$	$\pm0.34\%$	$\pm14.3\%$
$\langle-\frac{e}{m_e}\delta b_r\delta P_\parallel^{A}\rangle$			$\pm4.06\%$	$\pm66.1\%$
$\langle-\frac{e}{m_e}\delta b_r\delta P_\parallel^{NA}\rangle$			0	$\mp1.46\%$
Total turbulent flux	$\mp0.58\%$	$\mp14.3\%$	$\pm4.40\%$	$\pm78.9\%$
$\langle-\frac{e^2}{m_e}\hat{\boldsymbol{b}}\cdot\nabla\delta\phi\delta n_e^{NA}\rangle$	-0.52%	-7.81%	0.30%	7.84%
$\langle-\frac{e^2}{cm_e}\frac{\partial\delta A_\parallel}{\partial t}\delta n_e^{A}\rangle$			0.38%	1.81%
$\langle-\frac{e^2}{cm_e}\frac{\partial\delta A_\parallel}{\partial t}\delta n_e^{NA}\rangle$			4.16×10^{-4}	-0.38%
Total turbulent source	-0.52%	-7.81%	0.72%	9.27%

✓ Scaling for the ratio of the intrinsic current to the BS current:

- Turbulent flux driven: $\frac{J_{turb}^{\Gamma}}{J_{BS}} = \mp\frac{2\sqrt{\varepsilon}\Gamma}{5v_{ei}\sqrt{\rho_s L_n}}\frac{L_P}{en_e v_{the}q\rho_e} \propto \frac{T_e^{3/4}T_i}{n_e}$
- Turbulent source driven: $\frac{J_{turb}^{S}}{J_{BS}} = \frac{2\sqrt{\varepsilon}S}{5v_{ei}}\frac{L_P}{en_e v_{the}q\rho_e} \propto \frac{T_eT_i}{n_e}$

[Wen He, Lu Wang, and Ge Zhuang, PPCF 61, 115016 (2019)]

CONCLUSION

- For EM ETG turbulence in core region:
  - ✓ The turbulent flux driven intrinsic current density can reach about 80% of the local bootstrap current density
  - ✓ Less than 1% from turbulent source
- For EM electron DW turbulence in pedestal region:
  - ✓ Adiabatic kinetic stress driven intrinsic current is dominant as compared to the source driven part
  - ✓ Non-adiabatic contributions are strongly cancelled by the EM effects
  - ✓ Effects of ExB shear are not self-consistent in this work

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