Influence of Plasma Turbulence on Tokamak Self-driven Current

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Plasma current is a fundamental component for tokamak operation

- Tokamak relies on toroidal plasma current for generating poloidal magnetic field, unlike stellarator

- Toroidal current can be driven inductively by means of transformer
  - plasma acts as secondary winding
  - finite flux swing + finite resistivity $\rightarrow$ pulsed tokamak operation
Plasma self-driven current is of great importance to tokamak operation

- Steady state tokamak operation requires fully non-inductive current
  - by RF waves; NBI etc. \(\text{(Fisch, Rev. Modern Phys. (1987))}\)
  - external non-inductive drive is expansive
- **Bootstrap current** \(J_{bs}\) – a well known plasma self-driven current
- Originated from diamagnetic effect of drift orbits + collisions
  - driven by pressure and temperature gradients in toroidal geometry
  - associated with existence of trapped particles
Plasma self-driven current is of great importance to tokamak operation

- Predicted by neoclassical theory (Galeev & Sageev, ’68)

\[ \langle j_b \cdot B \rangle = \frac{1}{n_e} L_{e31} \frac{dp_e}{d\psi_p} + \frac{1}{n_i} L_{i31} \frac{dp_i}{d\psi_p} + L_{e32} \frac{dT_e}{d\psi_p} + L_{i32} \frac{dT_i}{d\psi_p} \]

- Discovered in experiments (Zarnstorff & Prager, ’84)

\[ J_{\parallel}, \text{ (A cm}^{-2}) \]

on Wisconsin Levitated Octupole Experiment
Experimental evidences in tokamaks show deviation of plasma self-driven current away from bootstrap current

- Total current (sum of all current contributions) rather than local current density measured in present fusion experiments
  - difficult to directly measure plasma self-driven current
  - $\sim J_{bs} \pm 50\%$ in core
  - more significant deviations seem to appear in edge pedestal

  (Coda et.al., IAEA-FEC’08; Kikuchi-Azumi, PPCF’95)
  - on TCV full bootstrap discharges, total $J$ is (28 - 37)$\%$ higher
Can turbulence drive plasma current or change bootstrap current? and how?

- However, fusion plasmas are usually not turbulence-free
  - turbulence $\rightarrow$ EMF $\rightarrow$ dynamo current
  - a relatively unexplored, but important issue
  
  earlier attempt in theory and simulations (exptl. study missing):
  Itoh & Itoh, Phys. Lett. A’88; Nunan & Dawson, PRL’94; Hinton et. al., PoP’04; Wang et. al., IAEA-FEC’12; ...

- Physics links to electron momentum transport and flow generation

$$\frac{\partial f_a}{\partial t} + \frac{1}{B^*} \nabla \cdot (\dot{Z} B^* f_a) = \sum_b C[(f_a, f_b)]$$

$$\frac{\partial \langle j_{||,e} \rangle}{\partial t} + \nabla \cdot \langle \delta v_{EB} \delta j_{||,e} \rangle - \nabla \cdot \langle \frac{e}{m_e} \hat{b}_r \delta p_{||,e} \rangle$$

$$= -\frac{e^2}{cm_e} \langle \frac{\partial \delta A_{||}}{\partial t} \delta n_e \rangle - \frac{e^2}{m_e} \langle \hat{b} \cdot \nabla \delta \phi \delta n_e \rangle$$

- Fluctuations also provide effective collisions for scattering and detrapping of trapped electrons $\rightarrow$ anomalous bootstrap current (toroidal effect)
Additional bootstrap current associated with strong toroidal rotation gradient – a finite orbit neoclassical effect

- Nonlocal neoclassical equilibrium solution in collisionless regime:
  \[
  \Delta u_i \parallel \simeq -\frac{m_i c}{e} \left\langle \frac{I^2}{B^2} \right\rangle \frac{c T_i I}{e B} \frac{\partial \ln n_i}{\partial \psi_p} \frac{\partial \omega_t}{\partial \psi_p}.
  \]

- Due to finite orbit neoclassical effect – higher order correction

(Wang et. al., PoP’06, Kolesnikov et. al., PoP’10)

- In some regime, pronounced trapped electron contribution was also noted
  (Wang et. al., PoP’06; Hager & Chang, PoP’16)
This study employs a global gyrokinetic model (GTS code) with self-consistent turbulence + neoclassical phys.

- Describe a consistently coupled evolution of toroidal plasmas
  \( \Rightarrow \) NC equilibrium state (for electrons) \( \Rightarrow \) steady state turbulence
  - gyrokinetic ions + drift kinetic electrons
  - consistent electric field from GK Poisson equation
  - initial Maxwellian ions and electrons

- Simulations use plasma conditions relevant to current experiments
  - NSTX H-mode core plasma profiles
  - Real DIII-D or NSTX geometry/equilibrium
  - \( \nabla n \)-driven CTEM (DTEM) turbulence for DIII-D (NSTX)

- Follows plasma evolution for much longer than electron collision time
- Focus on mean electron current
Parallel current structure is largely changed from neoclassical phase to turbulence phase

- Distinct phases are shown in electron current generation during simulation

Electron parallel current (only contributed by non-adiabatic electrons):

\[ j_{e,\parallel B} \equiv e \int v_{\parallel} B \delta f_e d^3v \]

\[ t = 3.4\tau_{ei} \]  
(neoclassical phase)

\[ t = 10.1\tau_{ei} \]  
(turb. growing phase)

\[ t = 30\tau_{ei} \]  
(well-developed turb. phase)
Plasma self-driven macroscopic current can be significantly modified in the presence of turbulence.

- Simulation shows distinct phases for current development.
- Current density profile significantly modified.
  - Total current can be changed too.
- Fine radial scales presented in electron current.

(Wang et. al., NF’19)
Phase space structure of electron current density is largely changed by turbulence

- Current is mainly carried by electrons around trapped-passing boundary
  - mostly contributed by passing particles
  - considerable contribution from trapped electrons
Significant current can be generated in flat pressure region – nonlocal effect due to turbulence spreading

- Current penetration via turbulence spreading into linearly stable zone
- Anomalous current fully driven by fluctuations
- Not associated with local profile gradients

- Possible source for seed current near magnetic axis (?)
- May drive current inside magnetic island (?) → impact NTM dynamics
Underlying mechanisms link to electron momentum transport and flow generation by turbulence

- Generalized neoclassical Ohm’s law

\[
\langle j_B \parallel B \rangle = \sigma_{\text{neo}} \langle E_{\text{ind}}^\parallel B \rangle + \langle j_{\text{bs}} B \rangle + \langle j_{\text{NBI,RF}}^\parallel B \rangle + \langle j_{\text{dyn}} B \rangle
\]

\[
\frac{\partial \langle j_{\parallel e} \rangle}{\partial t} + \nabla \cdot \langle \delta v_E \times B \delta j_{\parallel e} \rangle = -\frac{e^2}{m_e} \langle \hat{b} \cdot \nabla \delta \phi \delta n_e \rangle
\]

- Parallel acceleration driving a current against resistive decay
  (Itoh & Itoh, Phys. Lett. A ’88; Sugama, PoP’95; Hinton et. al., PoP’04)

\[
\langle j_{\parallel turb} \rangle \sim \langle \delta E_{\parallel} \delta n_e \rangle \frac{e^2}{m_e \nu_{ei}}
\]

- originated from turbulence-induced momentum exchange with ions

- From quasilinear analysis (Garbet’14; McDevitt’17; He’19)

\[
\langle \delta E_{\parallel} \delta n_e \rangle \sim \sum_{m,n,\omega} \frac{k_{\parallel}}{|k_{\parallel}|} \frac{e^{-\phi_{mn\omega}}}{T_e} \omega_0 \int d\mu B[(\omega - \omega_0) f_{e,M}] v_{\parallel} = \frac{\omega}{k_{\parallel}}; \quad k_{\parallel} = \frac{m - nq}{qR_0}
\]

- Sensitive to asymmetry in fluctuations between $|\phi_{k_{\parallel}}|^2$ and $|\phi_{-k_{\parallel}}|^2$!
Underlying mechanisms link to electron momentum transport and flow generation by turbulence

- **Divergence of radial flux of parallel electron momentum** (Hinton’04)

\[ j_{||, \text{turb}} \sim \nabla \cdot \Pi_{r,||}/m_e\nu_{ei} \]

\[ \Pi_{r,||} = -\chi\phi \frac{\partial u_{||,e}}{\partial r} + V_p u_{||,e} + \Pi^\text{RS}_{r,||} \]

- Significant residual stress contribution \( \Pi^\text{RS}_{r,||} \)

(Wang et. al., IAEA-FEC’12)

- From quasilinear analysis (McDevitt’17; He’19)

\[ \Pi^\text{RS}_{r,||} \sim \sum_{m,n,\omega} \frac{m}{r} \frac{1}{|k||k'||} \frac{e\delta\phi_{mn\omega}}{T_e} \int d\mu B[(\omega - \omega_e)f_{e,M}]v_{||} = \frac{\omega}{k||} \]

- again, links to \( k|| \)-symmetry breaking physics! (Diamond et.al., NF’09)

- Electron \( \Pi^\text{RS}_{r,||} \) strongly localized about rational surface

\[ \omega - k||v|| = 0 \Rightarrow \text{electron Landau layer } \Delta x \sim (L_s/L_n)\sqrt{m_e/m_i}\rho_s \]

\( \Rightarrow \) drive fine scale corrugation in \( j_{e,||} \) around rational surface

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A central physics for turbulence-driven flow is $k_{||}$-symmetry breaking: i) $\mathbf{E} \times \mathbf{B}$ shear

- In idea case $k_{||}$ and $-k_{||}$ are equally excited $\rightarrow$ balanced wave population
- Shear flow, in particular, $\mathbf{E} \times \mathbf{B}$-induced shear flow

- shift modes off resonant surfaces $\Rightarrow$ imbalance in wave populations with $\pm k_{||}$ $\Rightarrow$ finite spectrum-averaged $\langle k_{||} \rangle$
- in ballooning space, $\mathbf{E} \times \mathbf{B}$ shear $\Rightarrow$ eddy shift and tilt; $\langle k_{||} \rangle \Leftrightarrow$ eddy tilt (up-down asymmetry in global mode structure)
- $\langle k_{||} \rangle \propto \omega_{E \times B}$

- Turb.-driven zonal $\mathbf{E} \times \mathbf{B}$ shear found effective for $k_{||}$-symmetry breaking
  (Wang et.al., PRL’09)
A central physics for turbulence-driven flow is $k_\parallel$-symmetry breaking: ii) turbulence intensity gradient

- Turb. intensity profile gradient $\Rightarrow$ finite $k_\parallel$ (an effect of global turbulence)  
  \[ \varepsilon(x) \]

(Gurcan el.al., PoP’10)

- Both ZF $E \times B$ shear & turbulence intensity gradient effects found important in driving intrinsic rotation in experiments

(Grierson et.al., PRL’17; Wang et.al., PoP’17)
Turbulence-induced parallel acceleration seems to drive anomalous current in a large scale

- Underlying process is turbulence-induced electron-ion momentum exchange
- Drive a net current but not change total momentum

- $k_{\parallel}$-symmetry breaking can be caused by fluctuation intensity gradient
- $j_{\parallel, turb}$ direction may link to sign of $\langle k_{\parallel} \rangle$ and then turb. intensity gradient
Turbulence-produced electron parallel Reynolds stress drives fine-scale anomalous current near rational surface

- Modify current density profile near a rational surface but not total current
- $\Pi_{\parallel}^{rs}$ closely correlates with both turbulence intensity gradient and zonal flow shear through their effects on $k_{\parallel}$-symmetry breaking
- Potential to drive a magnetic island at rational surface

(Wang et. al., NF’19)
Turbulence may considerably reduce electron current from NC bootstrap level in low collisionality regime

- A critical $\nu_e^*$ exists?
  (like intrinsic rotation reversal)

- Reduction of electron current relative to $J_{bs}$ increases as $\nu_e^*$ decreases

- Potentially great impact on steady state operation in BP regime
  – how much self-driven current is expected in ITER?
Characteristic dependence of fluctuation induced current generation from test-particle-simulation is consistent

- Test particle simulations with given static fluctuations from NL GTS run
  - close to situations/assumptions that theory is derived
  - useful for developing and testing theory
  - feasible and efficient for parametric scan of multiple physics effects

- Turbulence induced current reduces bootstrap current in low-$\nu_*$ regime
  - consistent with fully nonlinear simulation result
Dissipative-TEM may be an important turbulence source for transport and confinement in ST experiments

- Capable to survive strong $E \times B$ shear in NSTX (CTEM strongly suppressed by collisions in STs)
- Drives experimentally relevant transport in NSTX
- DTEM driven-transport increases with $\nu_e$ (possible source for ST H-mode confinement scaling)

(Wang et. al., NF’15)
Dissipative-TEM turbulence may considerably modify plasma self-generated current in NSTX

- Increase total current in NSTX where collisionality is relatively high
A case of C-MOD discharge

- L-mode Ohmic discharge
- ITG-dominated turbulence
Turbulence effects on NTM include: – cross-field transport (against fast parallel streaming); – anomalous electron and ion viscosity

Turbulence-driven current in island region directly affects NTM evolution

\[ j_\parallel = \sigma_{neo} E_\parallel + j_{bs} + j_{turb} \]

\[ \frac{4\pi I_1}{c^2 \eta} \frac{dw}{dt} = \Delta' + \frac{G_1 \sqrt{\epsilon_s r_s}}{s L_n} \beta_\theta \left( \frac{w^2}{w^2 + w_{pol}^2} - \frac{w_{pol}^2}{w^2} + \frac{\sigma w_{turb}^2}{w^2} \right) \]
Summary

A new pathway for micro-turbulence to impact confinement & global stability:

- Turbulence can significantly affect plasma self-driven current generation
  – profile structure; – amplitude; – phase space structure
- Reduce current generation in collisionless regime
  – reduction of electron current relative to $J_{bs}$ increases as $\nu_e^*$ decreases
- Generate localized current profile corrugation near a rational surface
- Nonlocally drive a current in flat pressure region via turbulence spreading
- Mechanisms include i) electron parallel acceleration; ii) resid. stress drive
  – $k_\parallel$-symmetry breaking is needed and plays a critical role
  – $j_{\parallel,turb}$ profile may link to turbulence intensity and zonal flow profiles
    through the effects of their gradient on $k_\parallel$-symmetry breaking
  – residual stress drives current profile corrugation
- iii) turbulent detrappinga & scattering → anomalous $j_{bs}$

Experimental study of current generation by turbulence is called and critical!