Influence of Plasma Turbulence on Tokamak Self-driven Current

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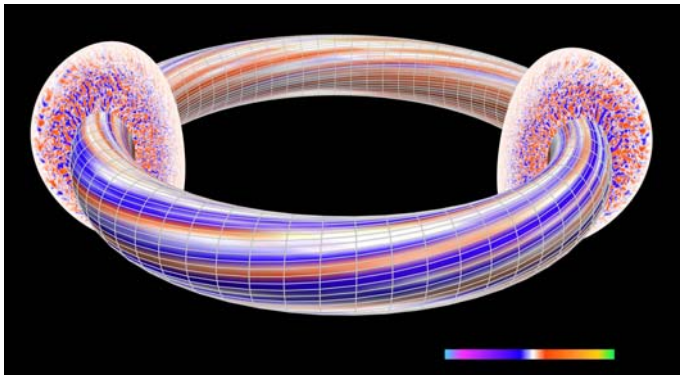
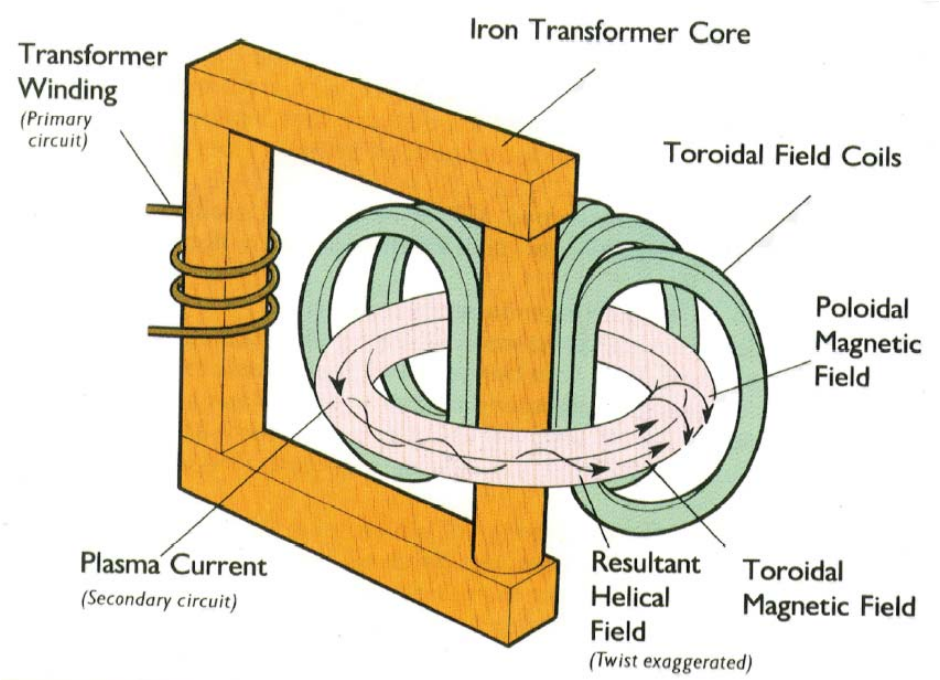


Theory Dept. Research & Review Seminar
June 30, 2020

Ack: U.S. DOE Contract DE-AC02-09-CH11466
SciDAC TDS project

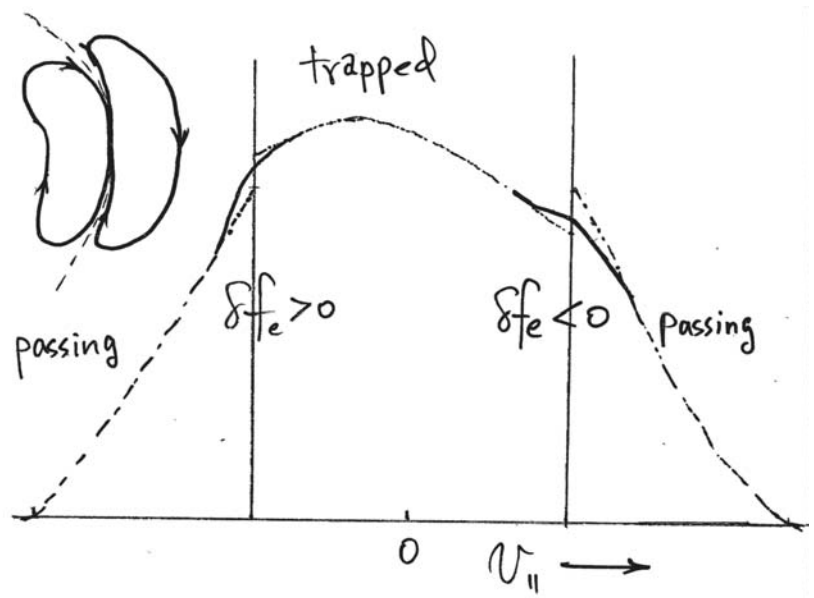
Plasma current is a fundamental component for tokamak operation

- 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 → 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. (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

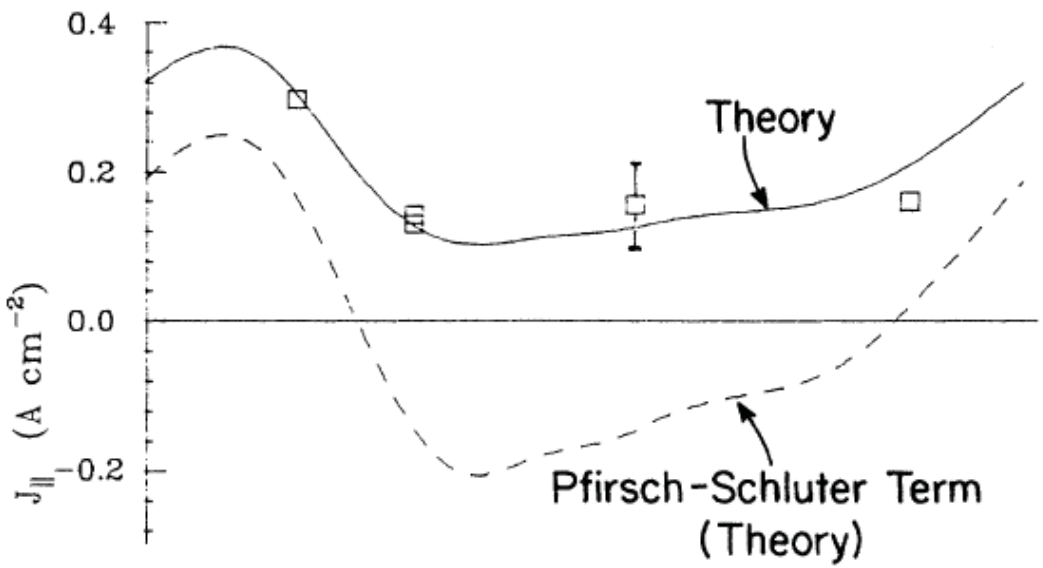


Plasma self-driven current is of great importance to tokamak operation

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

$$\langle \mathbf{j}_b \cdot \mathbf{B} \rangle = \frac{1}{n_e} L_{31}^e \frac{dp_e}{d\psi_p} + \frac{1}{n_i} L_{31}^i \frac{dp_i}{d\psi_p} + L_{32}^e \frac{dT_e}{d\psi_p} + L_{32}^i \frac{dT_i}{d\psi_p}$$

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

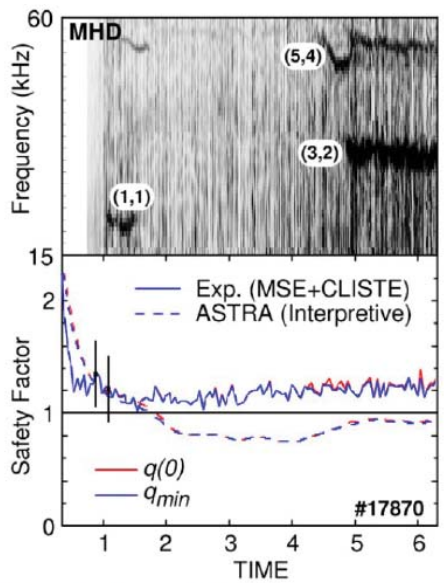


on Wisconsin Levitated Octupole Experiment

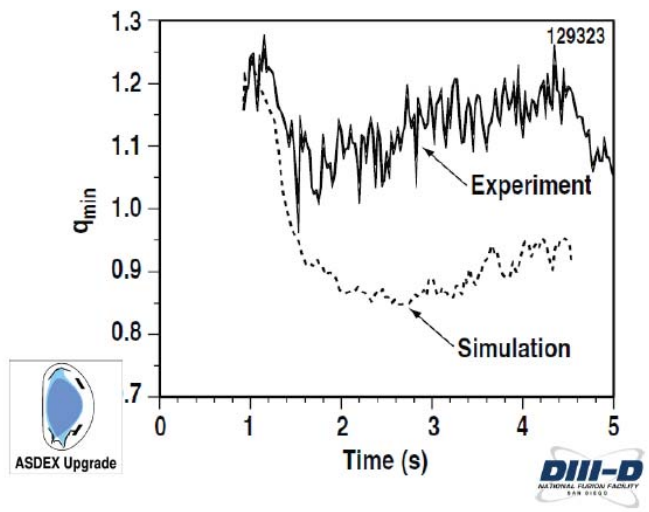
Experimental evidences in tokamaks show deviation of plasma self-driven current away from bootstrap current

- 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
  - $\sim J_{\rm bs} \pm 50$ % 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



[Yong-Su Na et al, Nucl. Fusion 46 232 (2006)]



[C.C. Petty et al, Nucl. Fusion 56 016016 (2016)]

Can turbulence drive plasma current or change bootstrap current? and how?

- However, fusion plasmas are usually not turbulence-free
  - turbulence → EMF → 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

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

$$\frac{\partial \langle j_{\parallel,e} \rangle}{\partial t} + \nabla \cdot \langle \delta v_{E\times B} \delta j_{\parallel,e} \rangle - \nabla \cdot \langle \frac{e}{m_e} \delta \hat{b}_r \delta p_{\parallel,e} \rangle$$

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

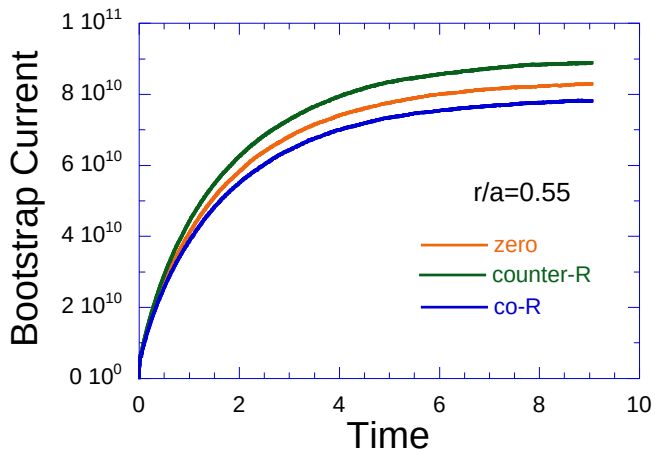
- Fluctuations also provide effective collisions for scattering and detrapping of trapped electrons → anomalous bootstrap current (toroidal effect)

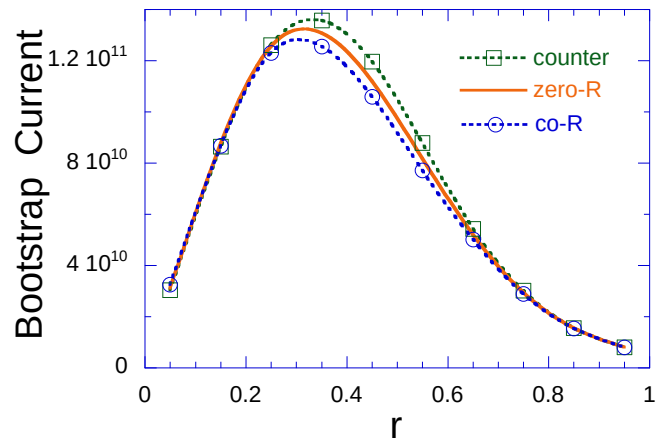
Additional bootstrap current associated with strong toroidal rotation gradient – a finite orbit neoclassical effect

- Nonlocal neoclassical equilibrium solution in collisionless regime:

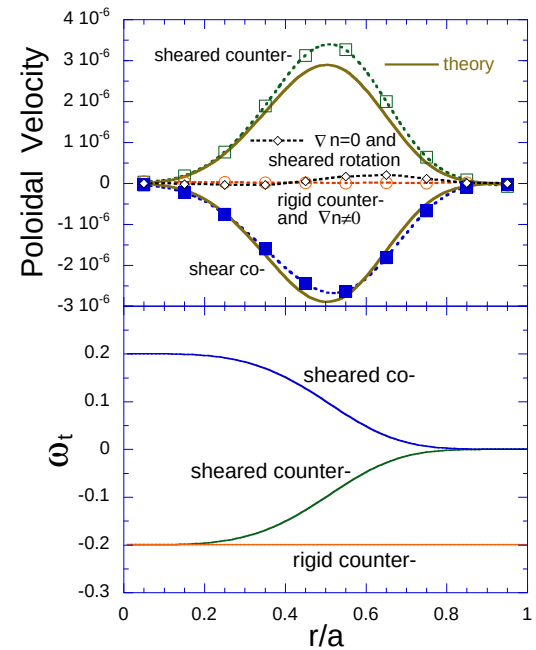
$$\Delta u_{i\|} \simeq -\frac{m_i c}{e}\left\langle \frac{I^2}{B^2}\right\rangle \frac{cT_i I}{eB}\frac{\partial \ln n_i}{\partial \psi_p}\frac{\partial \omega_t}{\partial \psi_p}.$$

- 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.

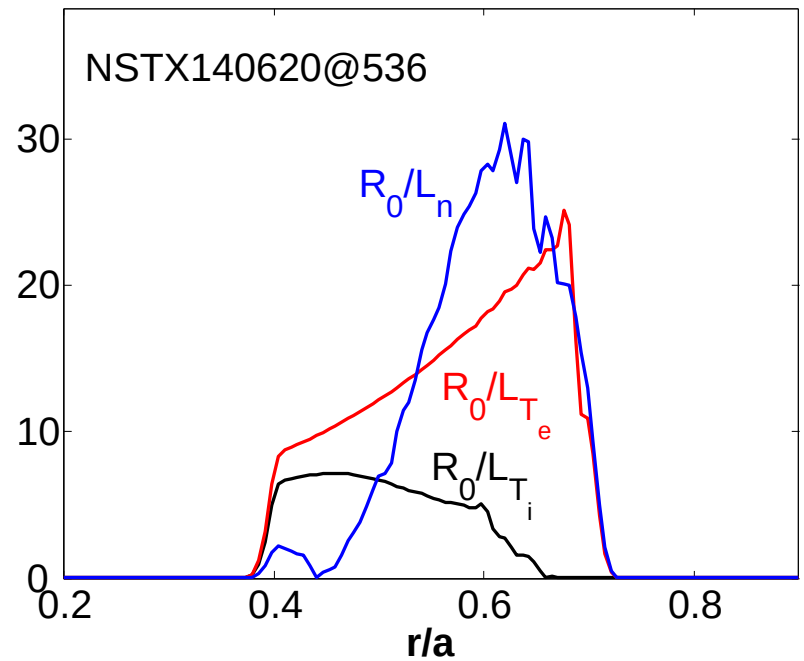
- Describe a consistently coupled evolution of toroidal plasmas

  $\Longrightarrow$ NC equilibrium state (for electrons) $\Longrightarrow$ 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
  – ∇n-driven CTEM (DTEM) turbulence for DIII-D (NSTX)



- Follows plasma evolution for much longer than electron collision time

- Focus on mean electron current

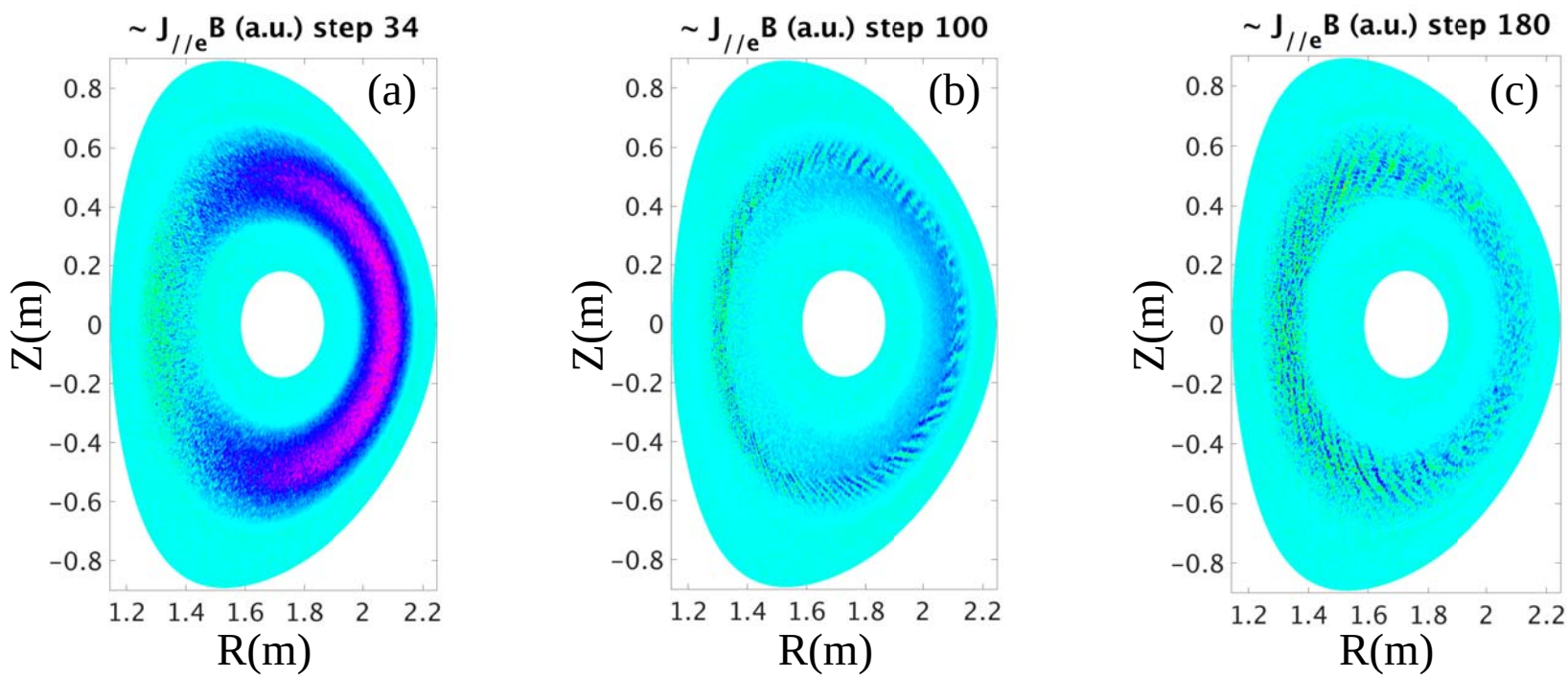
Parallel current structure is largely changed from neoclassical phase to turbulence phase

- Distinct phases are shown in electron current generation during simulation

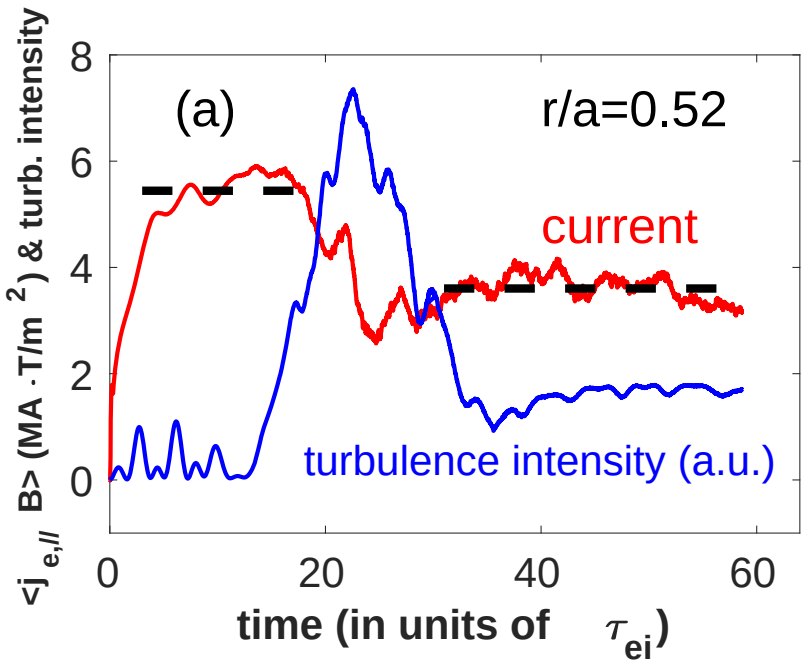
Electron parallel current (only contributed by non-adiabatic electrons):

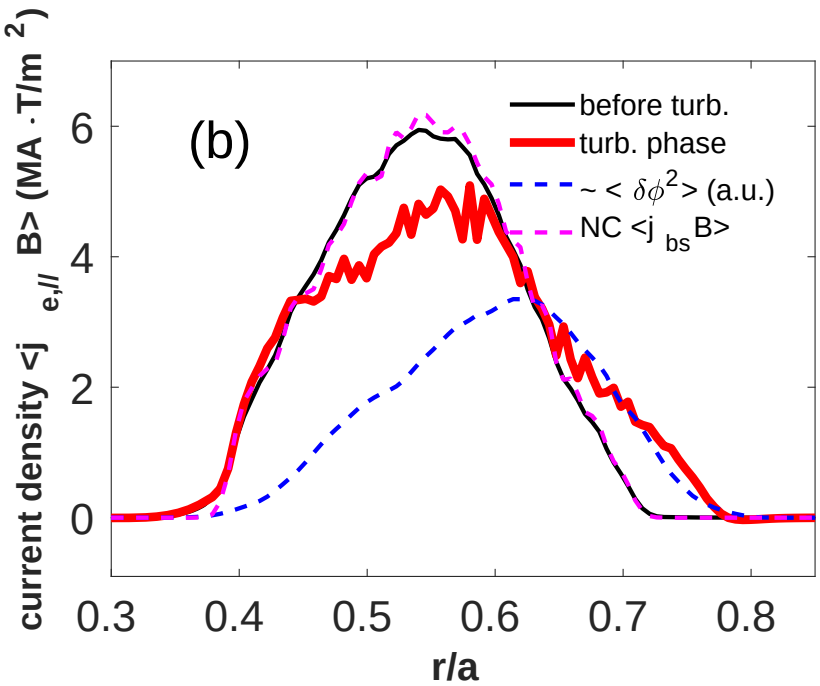
$$j_{e,\|}B \equiv e\int v_\| B\delta f_e d^3v$$

$t = 3.4\tau_{ei}$	$t = 10.1\tau_{ei}$	$t = 30\tau_{ei}$
(neoclassical phase)	(turb. growing phase)	(well-developed turb. phase)



Plasma self-driven macroscopic current can be significantly modified in the presence of turbulence

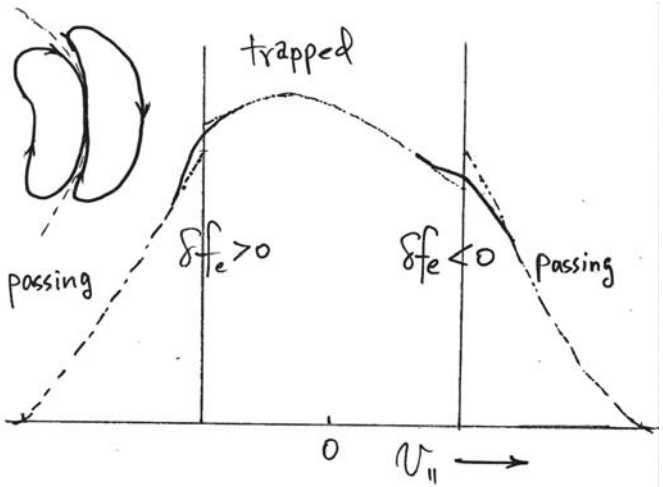




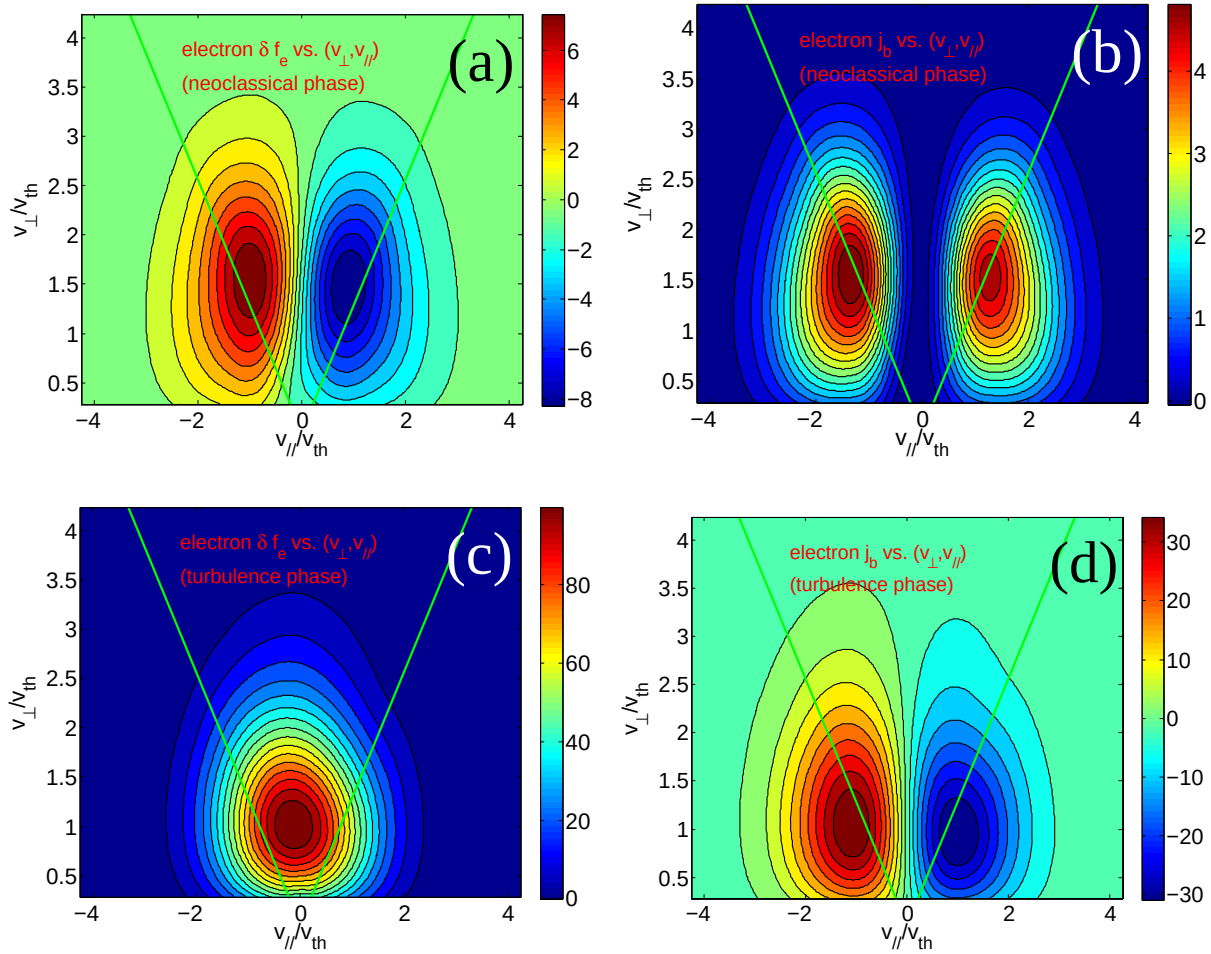
- simulation shows distinct phases for current development
- current density profile significantly modified
  - total current can be changed too
- fine radial scales presented in electron current

(Wang et. al., NF'19)

Phase space structure of electron current density is largely changed by turbulence

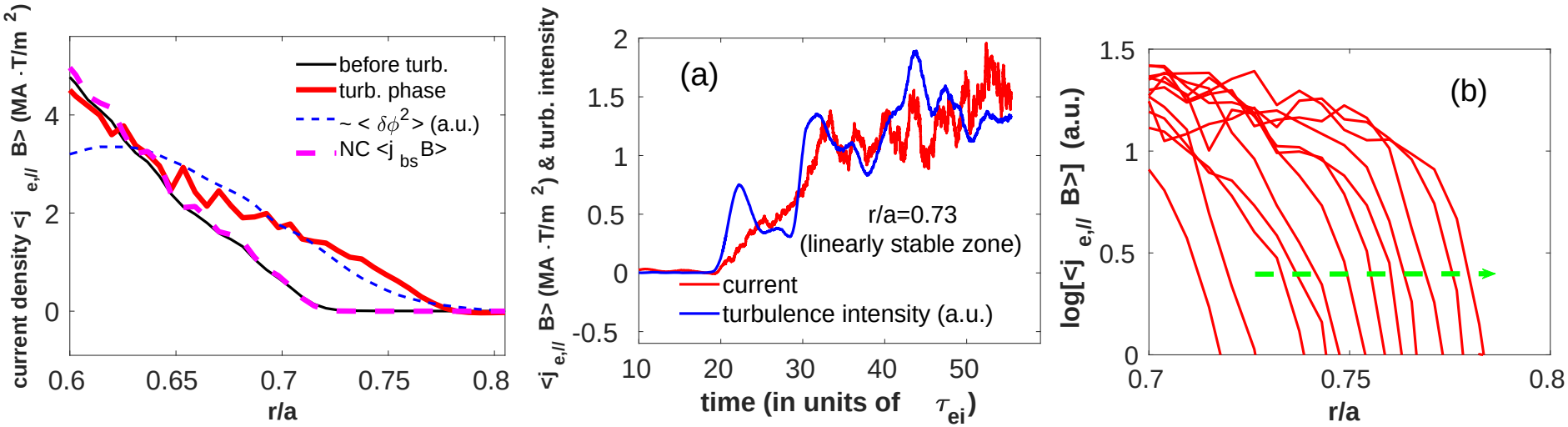


Turbulence Phase $\Longrightarrow$



- 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

$$\langle j_\| B\rangle = \sigma_{neo}\langle E_\|^{\rm ind} B\rangle + \langle j_{bs} B\rangle + \langle j_\|^{\rm NBI,RF} B\rangle + \langle j_{dyn} B\rangle$$

$$\frac{\partial\langle j_{\|,e}\rangle}{\partial t} + \nabla\cdot\langle\delta v_{E\times B}\delta j_{\|,e}\rangle = -\frac{e^2}{m_e}\langle\hat{b}\cdot\nabla\delta\phi\delta n_e\rangle$$

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

$$j_{\|,turb} \sim \langle\delta E_\|\delta n_e\rangle e^2/m_e\nu_{ei}$$

– originated from turbulence-induced momentum exchange with ions

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

$$\langle\delta E_\|\delta n_e\rangle \sim \sum_{m,n,\omega}\frac{k_\|}{|k_\||}|\frac{e\delta\phi_{mn\omega}}{T_e}|^2\int d\mu B[(\omega-\omega_e)f_{e,M}]_{v_\|=\frac{\omega}{k_\|}};\quad k_\| = \frac{m-nq}{qR_0}$$

- Sensitive to asymmetry in fluctuations between $|\phi_{k_\|}|^2$ and $|\phi_{-k_\|}|^2$!

Underlying mechanisms link to electron momentum transport and flow generation by turbulence

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

$$j_{\parallel,turb} \sim \nabla \cdot \Pi_{r,\parallel}/m_e\nu_{ei}$$

$$\Pi_{r,\parallel} = -\chi_\phi \frac{\partial u_{\parallel,e}}{\partial r} + V_p u_{\parallel,e} + \Pi_{r,\parallel}^{\mathrm{RS}}$$

- Significant residual stress contribution $\Pi_{r,\parallel}^{\mathrm{RS}}$

(Wang et. al., IAEA-FEC'12)

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

$$\Pi_{r,\parallel}^{\mathrm{RS}} \sim \sum_{m,n,\omega} \frac{m}{r} \frac{1}{|k_\parallel|} \frac{\omega}{k_\parallel} |\frac{e\delta\phi_{mn\omega}}{T_e}|^2 \int d\mu B[(\omega - \omega_e) f_{e,M}]_{v_\parallel = \frac{\omega}{k_\parallel}}$$

– again, links to $k_\parallel$-symmetry breaking physics! (Diamond et.al., NF'09)

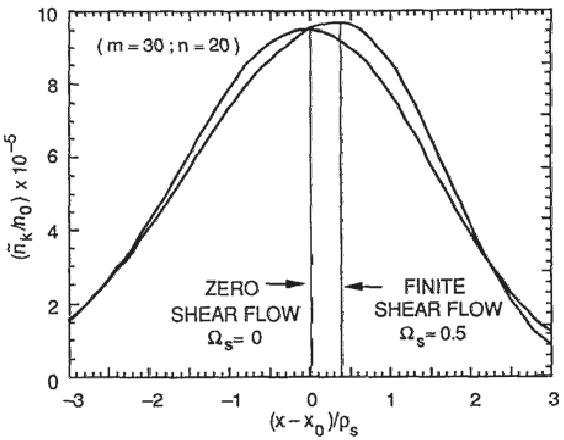
- Electron $\Pi_{r,\parallel}^{\mathrm{RS}}$ strongly localized about rational surface

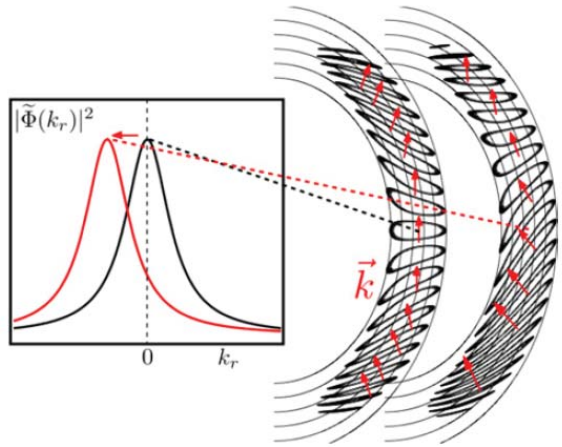
$\omega - k_\parallel v_\parallel = 0 \Rightarrow$ electron Landau layer $\Delta x \sim (L_s/L_n)\sqrt{m_e/m_i}\rho_s$

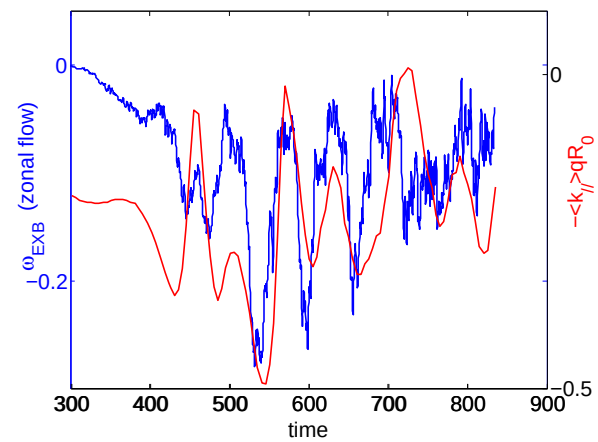
$\Rightarrow$ drive fine scale corrugation in $j_{e,\parallel}$ around rational surface

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





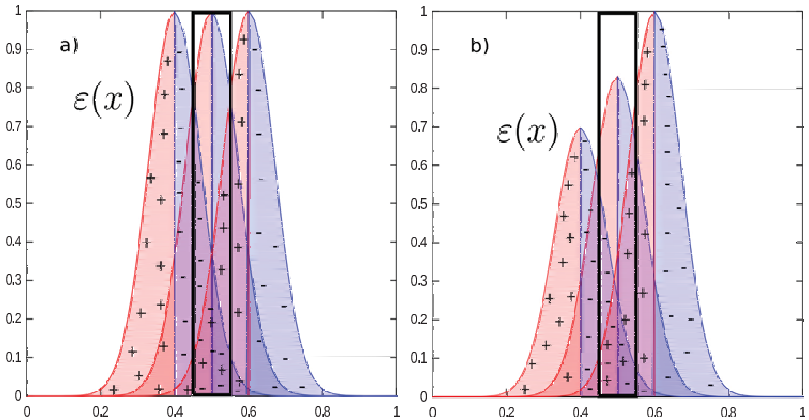


  - shift modes off resonant surfaces $\Rightarrow$ imbalance in wave populations with $\pm k_{\|}$ $\Rightarrow$ finite spectrum-averaged $\langle k_{\|} \rangle$
  - in ballooning space, $\mathbf{E} \times \mathbf{B}$ shear $\Rightarrow$ eddy shift and tilt; $\langle k_{\|} \rangle \Leftrightarrow$ eddy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

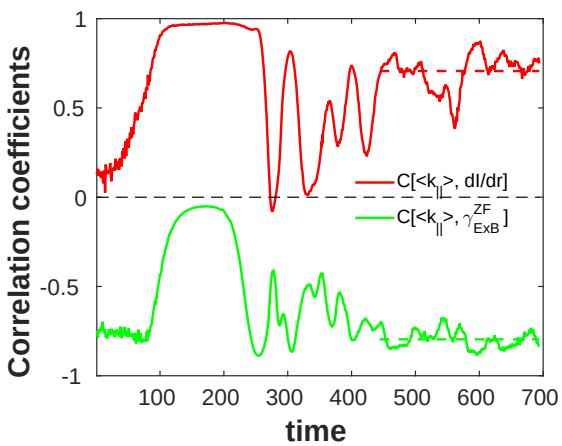
A central physics for turbulence-driven flow is $k_{\|}$-symmetry breaking: ii) turbulence intensity gradient

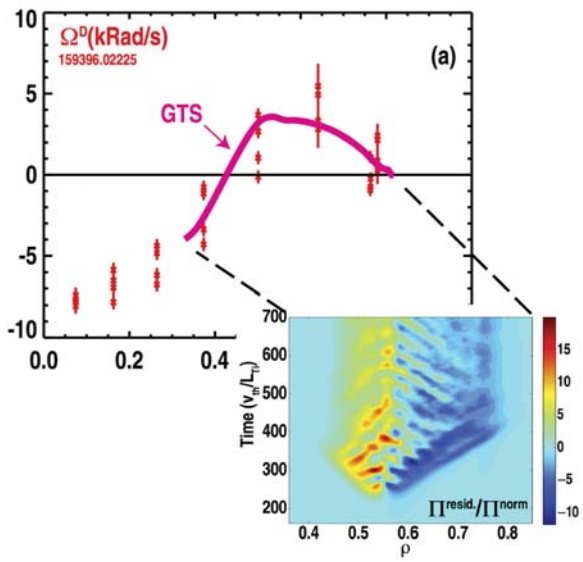
- Turb. intensity profile gradient $\Rightarrow$ finite $k_{\|}$ (an effect of global turbulence)



(Gurcan el.al., PoP'10)

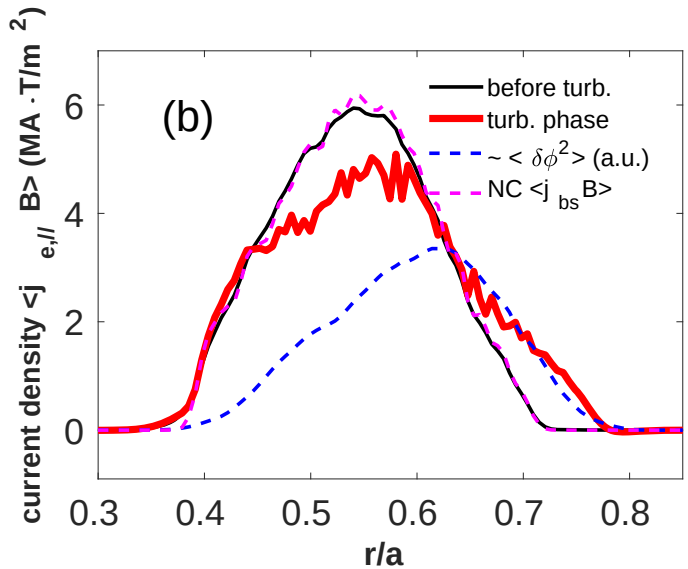
- Both ZF $\mathbf{E} \times \mathbf{B}$ shear & turbulence intensity gradient effects found important in driving intrinsic rotation in experiments

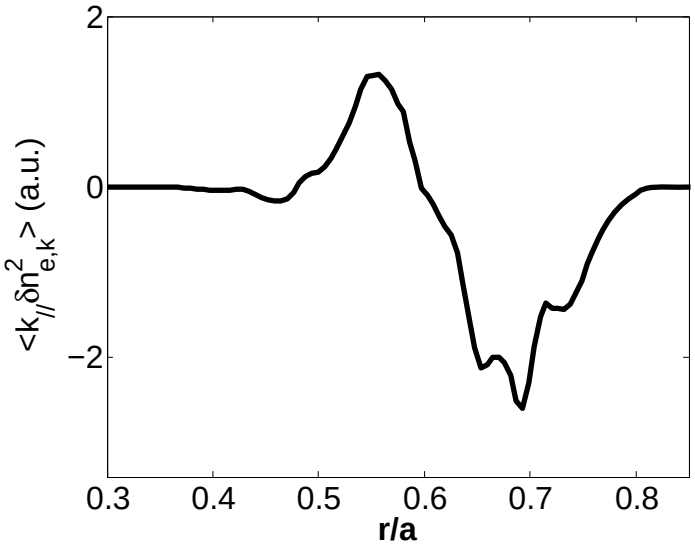




(Grierson et.al., PRL'17; Wang et.al., PoP'17)

Turbulence-induced parallel acceleration seems to drive anomalous current in a large scale

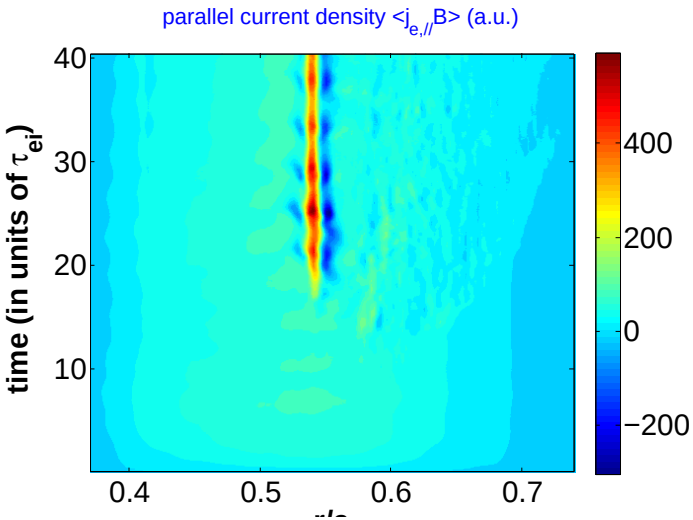


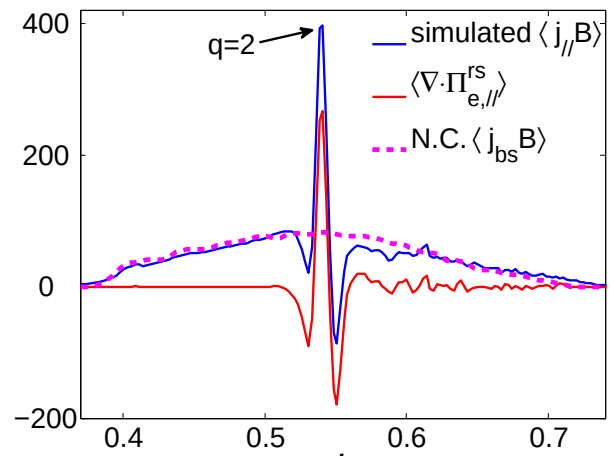


- Underlying process is turbulence-induced electron-ion momentum exchange
- Drive a net current but not change total momentum

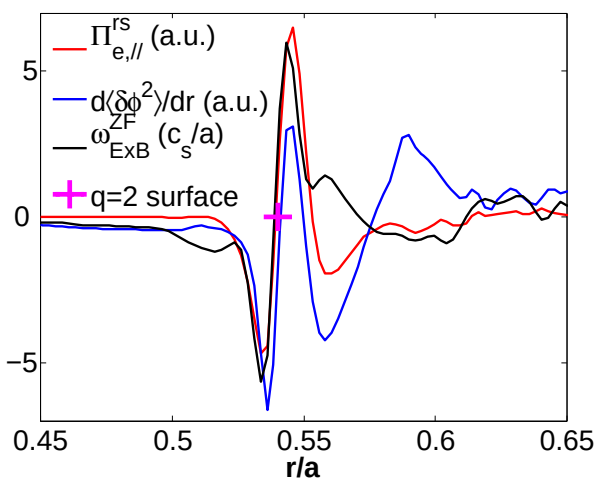
- $k_{||}$-symmetry breaking can be caused by fluctuation intensity gradient
- $j_{||,turb}$ direction may link to sign of $\langle k_{||} \rangle$ and then turb. intensity gradient

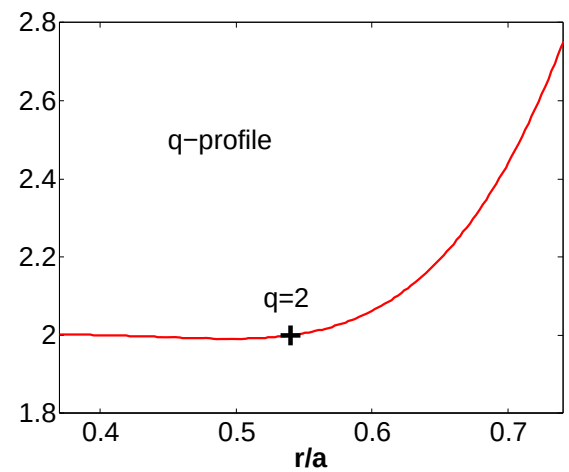
Turbulence-produced electron parallel Reynolds stress drives fine-scale anomalous current near rational surface





radial scale $\sim$ (5 - 10) ρ_s

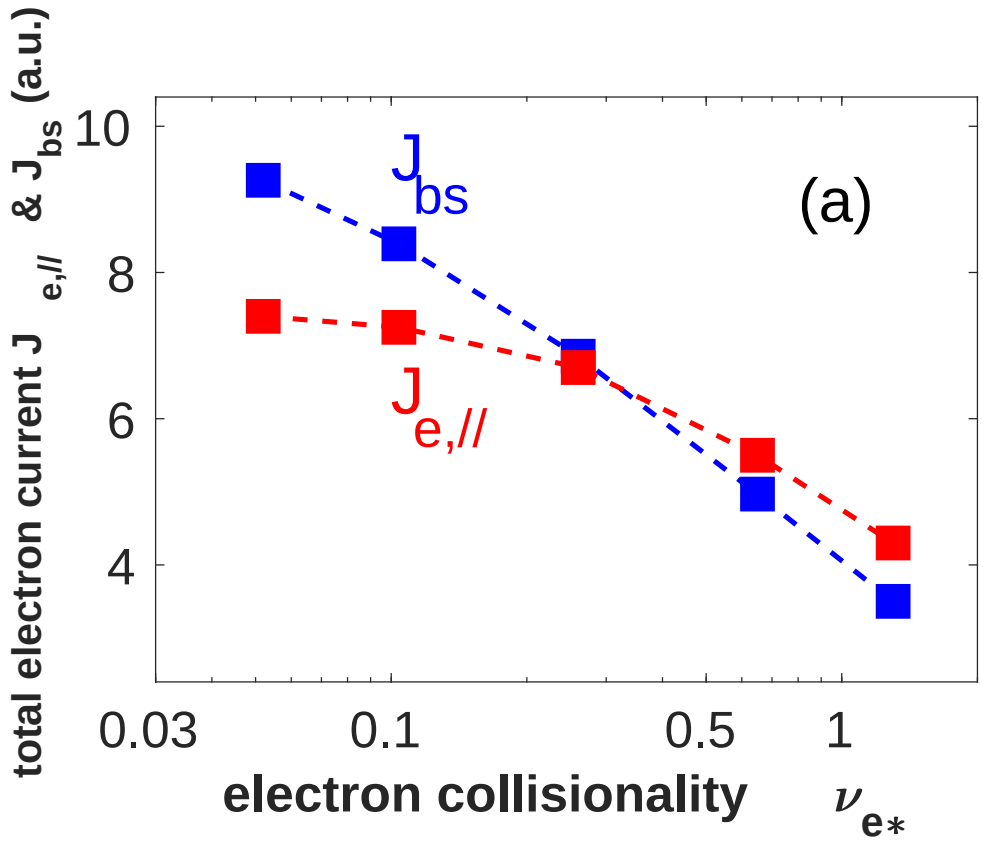


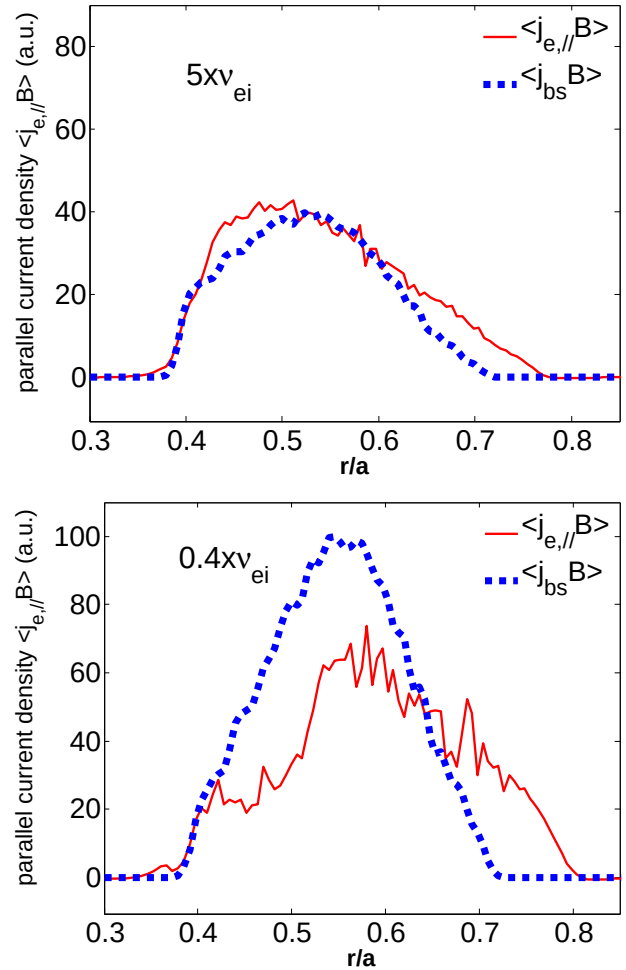


(Wang et. al., NF'19)

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

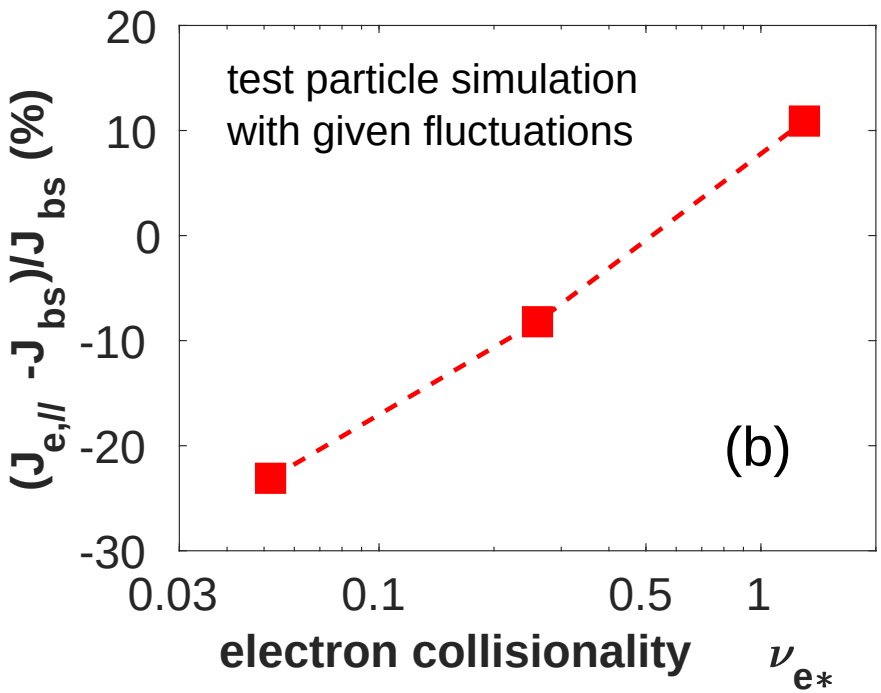
Turbulence may considerably reduce electron current from NC bootstrap level in low collisionality regime

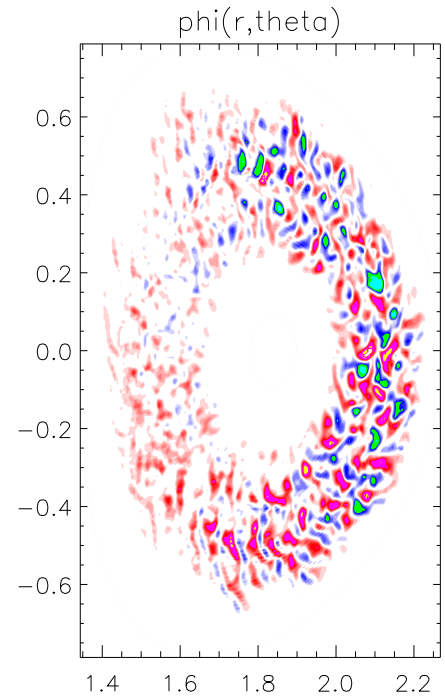




- A critical ν_e^* exists?
  (like intrinsic rotation reversal)
- Reduction of electron current relative to J_{bs} increases as ν_e^* decreases
- Potentially great impact on steady state operation in BP regime
  – how much self-driven current is expected in ITER?

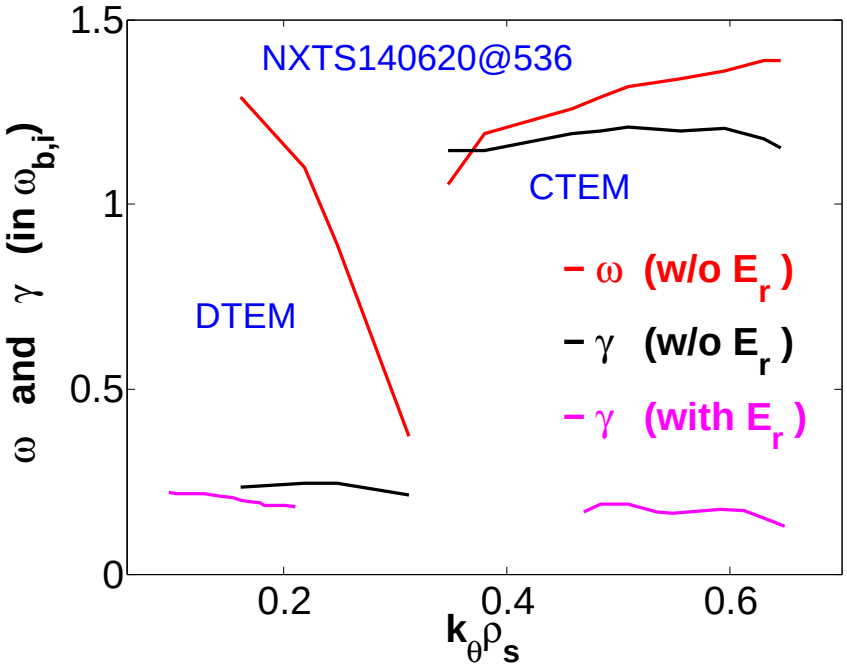
Characteristic dependence of fluctuation induced current generation from test-particle-simulation is consistent

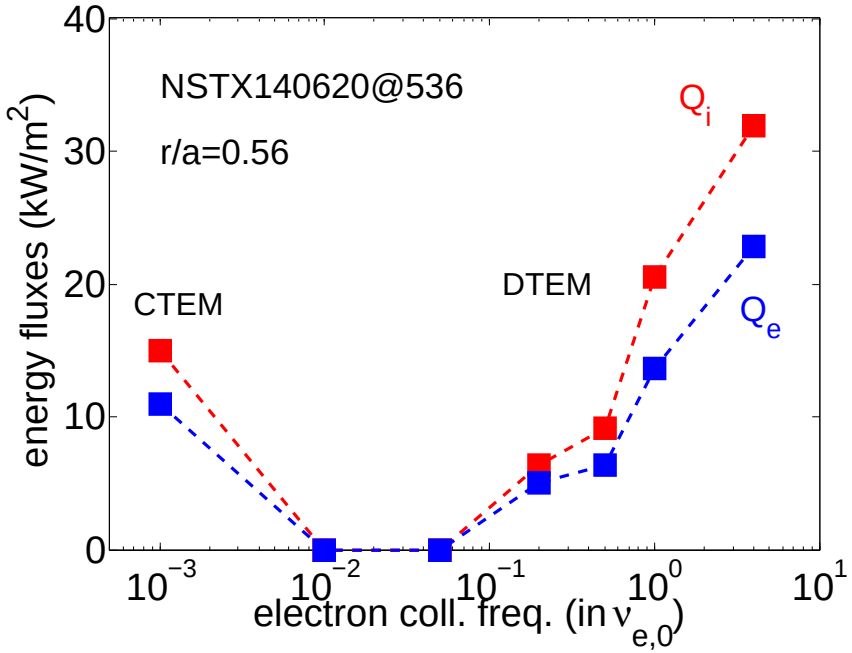




- Test particle simulations with given static fluctuations from NL GTS run
  - close to situations/assumptions that theory is derived
  - useful for developing and testing theory
  - feasible and efficient for parametric scan of multiple physics effects
- Turbulence induced current reduces bootstrap current in low-ν_* regime
  - consistent with fully nonlinear simulation result

Dissipative-TEM may be an important turbulence source for transport and confinement in ST experiments

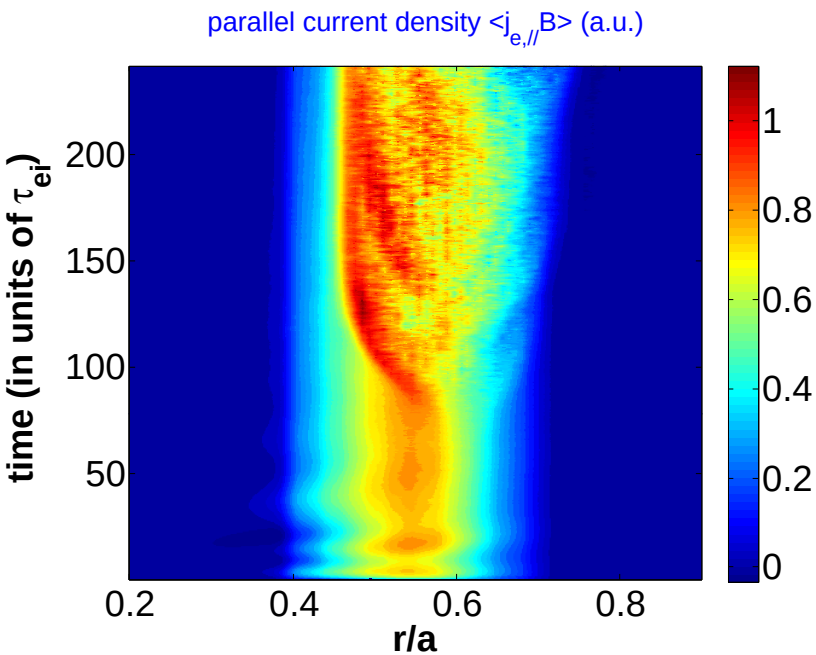


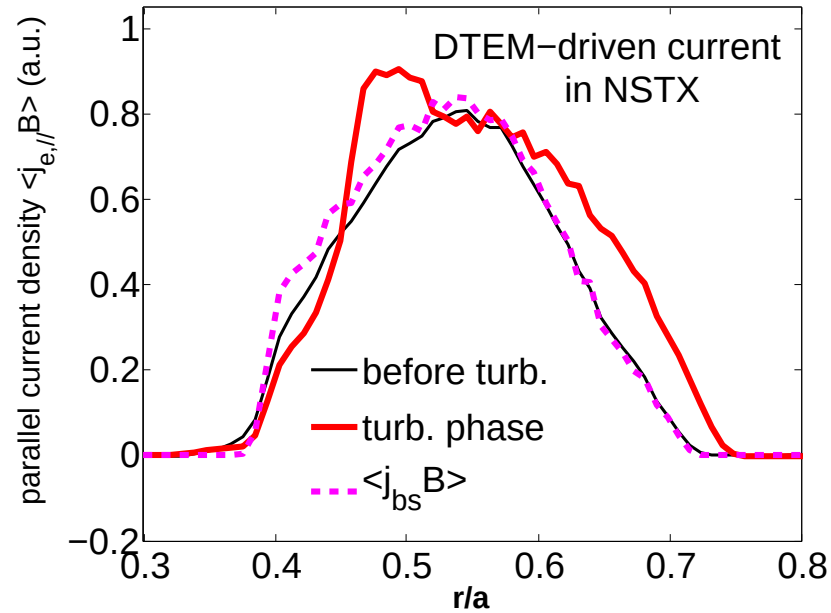


(Wang et. al., NF'15)

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

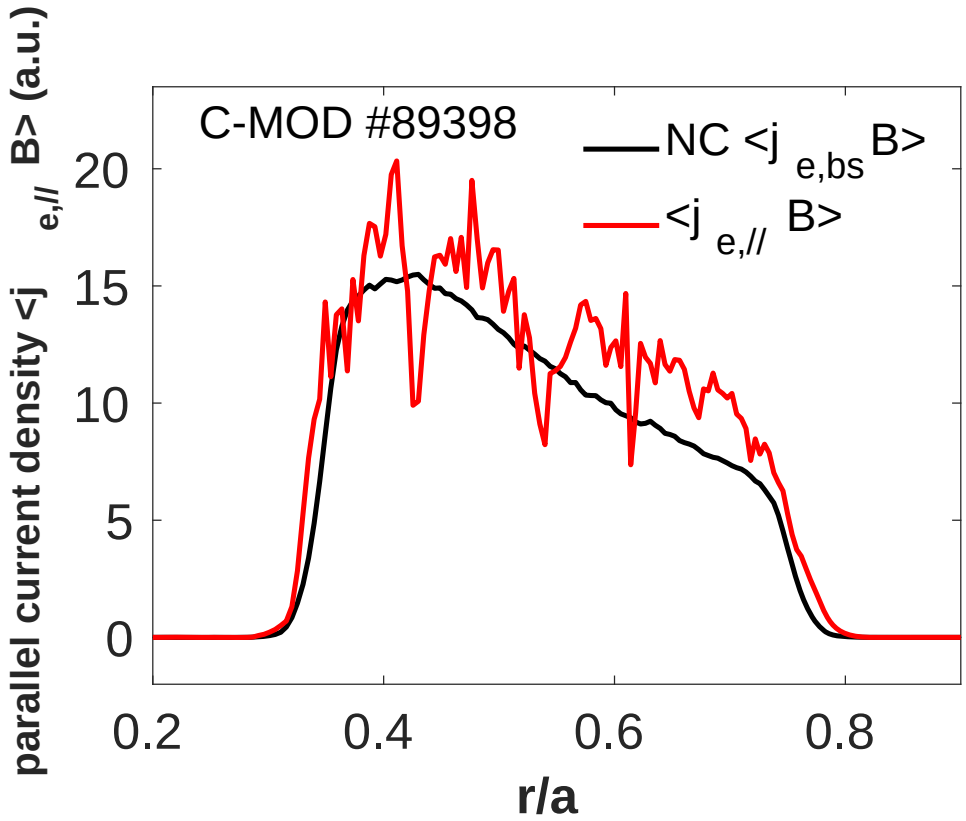
Dissipative-TEM turbulence may considerably modify plasma self-generated current in NSTX





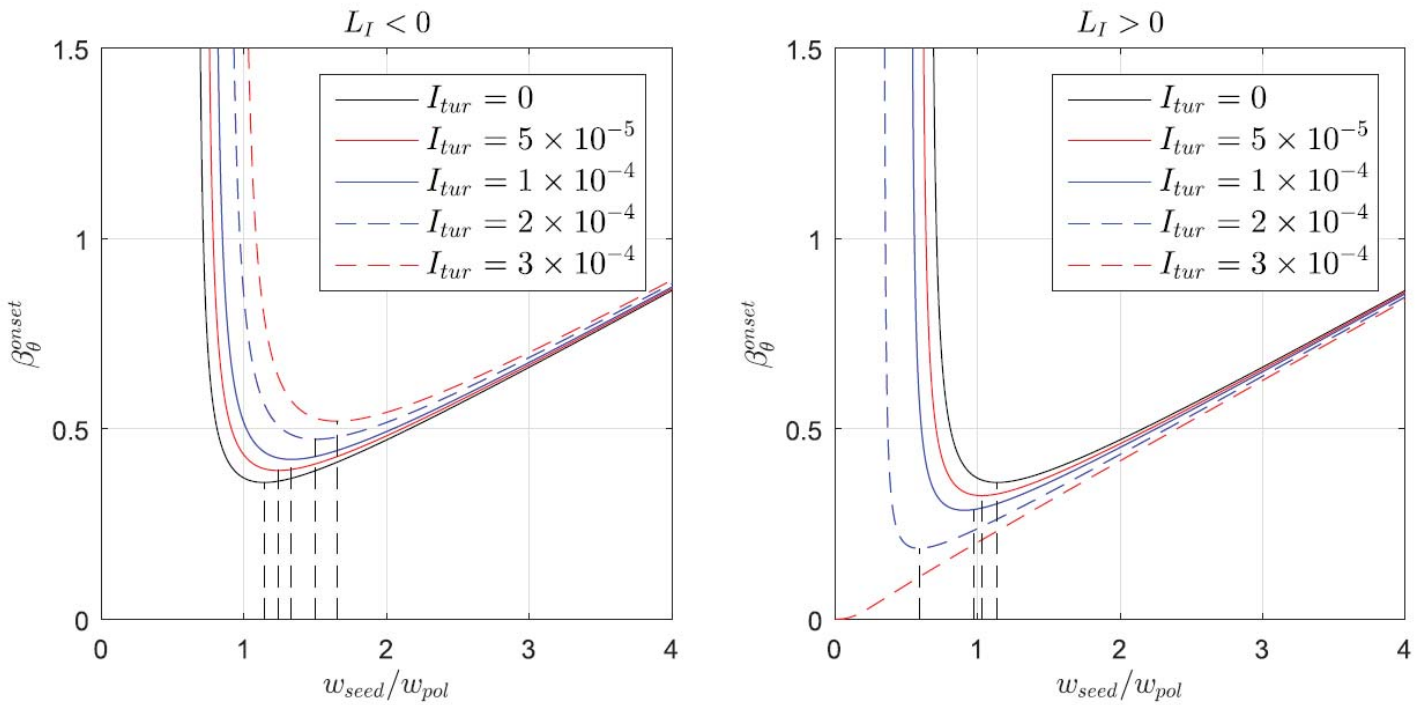
- Increase total current in NSTX where collisionality is relatively high

A case of C-MOD discharge



- L-mode Ohmic discharge
- ITG-dominated turbulence

Effect of turbulent current on neoclassical tearing mode



(Cai, NF'19)

- 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

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

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

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 ν_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
  – $k_{||}$-symmetry breaking is needed and plays a critical role
  – $j_{||,turb}$ profile may link to turbulence intensity and zonal flow profiles through the effects of their gradient on $k_{||}$-symmetry breaking
  – residual stress drives current profile corrugation
  iii) turbulent detrappinga & scattering $\rightarrow$ anomalous j_{bs}

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