Tokamak Plasma Self-driven Current Generation in the Presence of Turbulence

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in collaboration with

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

- Plasma self-generated non-inductive current is of great importance
  - NTM physics, ELM dynamics, overall plasma confinement
- Bootstrap current J_{bs} – a well known non-inductive current
  - driven by pressure and temperature gradients in toroidal geometry
  - associated with existence of trapped particles
  - predicted by neoclassical theory (see, e.g., Hinton & Hazeltine, '76);
  - discovered in experiments (Zarnstorff & Prager, '84)
- Total current rather than local current density measured in exptls.
  - $\sim J_{\mathrm{bs}} \pm 50$ % in core
  - significant deviations seem to appear in edge pedestal

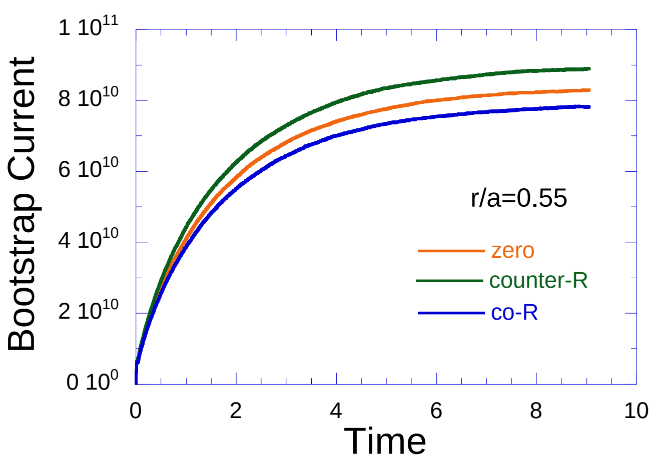
    (Coda et.al., IAEA-FEC'08; Kikuchi-Azumi, PPCF'95)
- However, fusion plasmas are usually not turbulence-free
  - how fluctuations affect self-driven current generation
  - a largely unexplored, but important issue

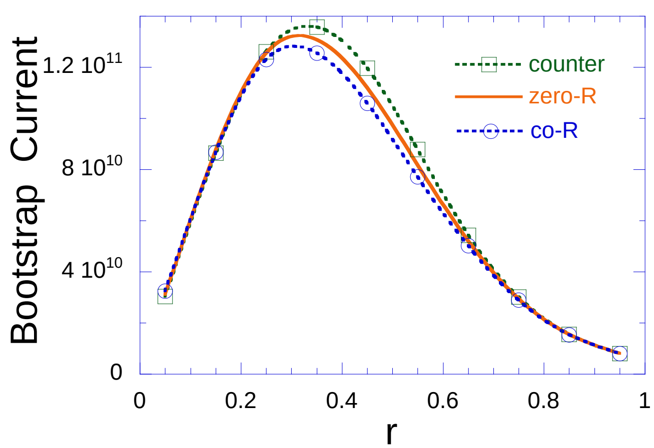
Additional bootstrap current associated with strong toroidal rotation gradient – finite orbit neoclassical effect

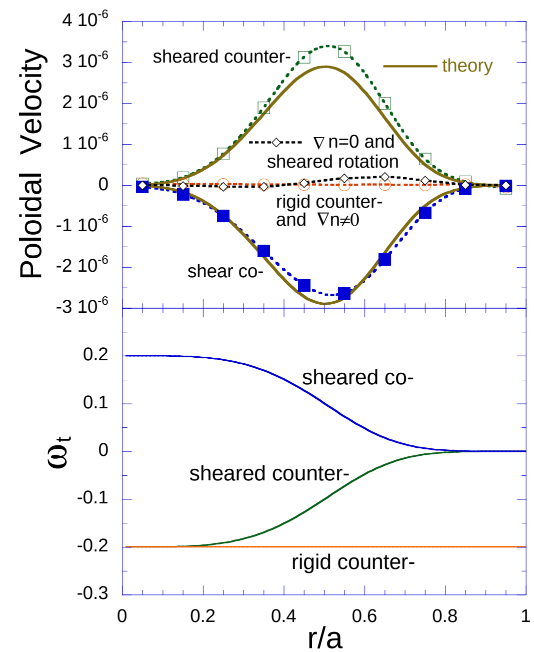
- Nonlocal neoclassical equilibrium solution in collisionless regime:

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

- Due to finite orbit neoclassical effect – higher order correction



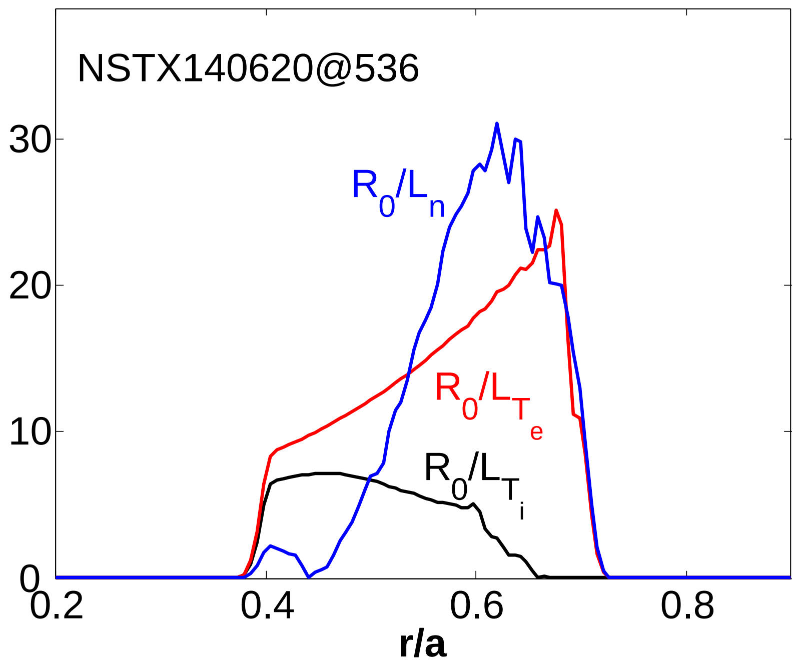




(Wang et. al., PoP'06)

This study employs a global gyrokinetic model coupling self-consistent turbulence + neoclassical dynamics

- 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

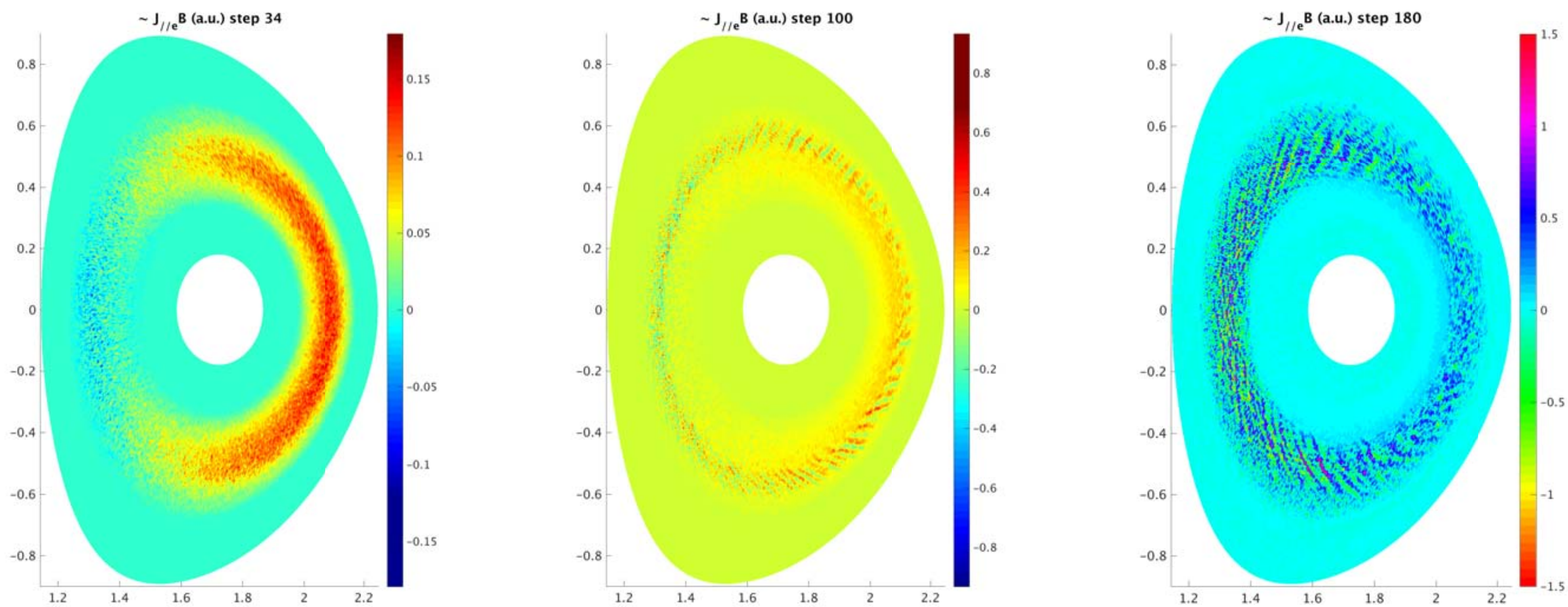
Parallel current structure is largely changed from neoclassical phase to turbulence phase

- Distinct phases are shown in electron current generation during simulation

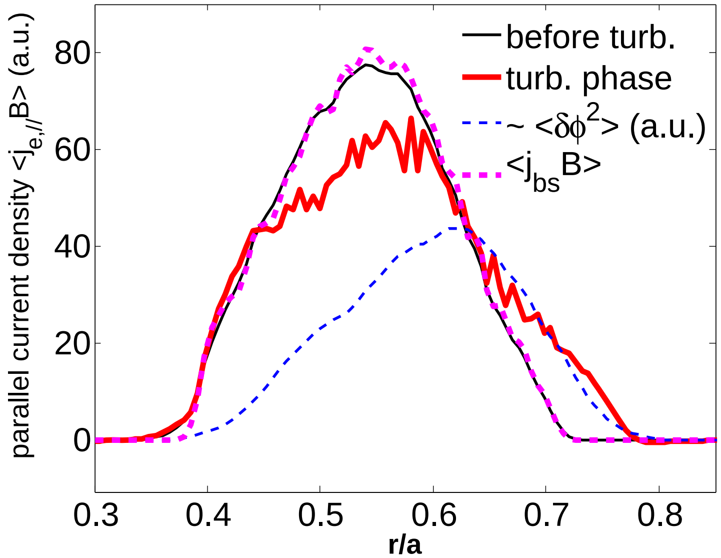
  Electron parallel current (only contributed by non-adiabatic electrons):

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

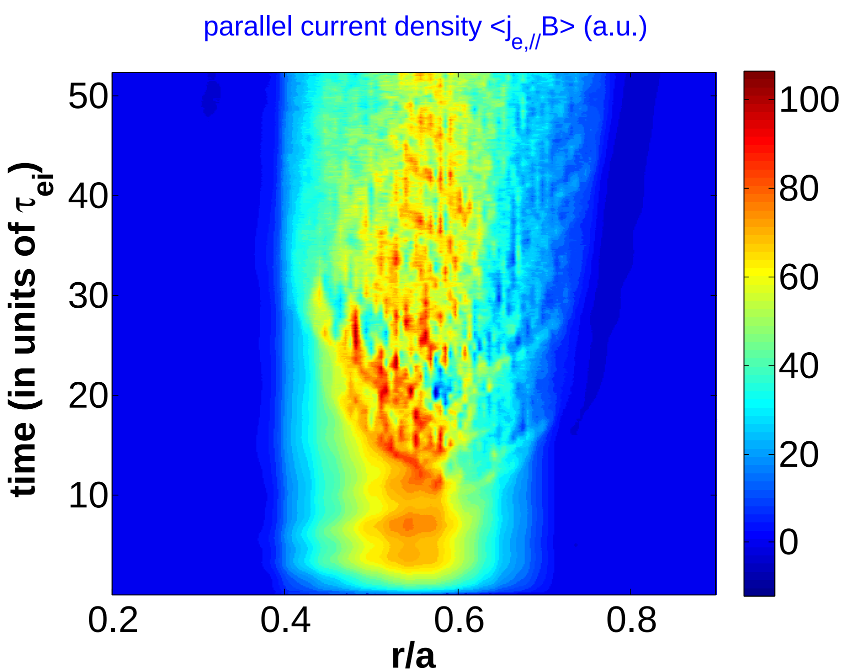
$t = 3.4\tau_{ei}$	$t = 10.1\tau_{ei}$	$t = 30\tau_{ei}$
(neoclassical phase)	(turb. growing phase)	(well-developed turb. phase)

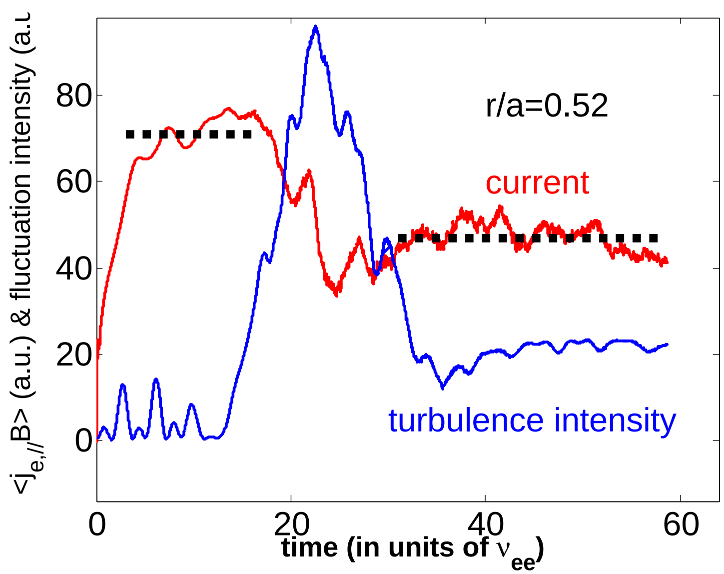


Plasma self-generated macroscopic current can be significantly modified in the presence of turbulence

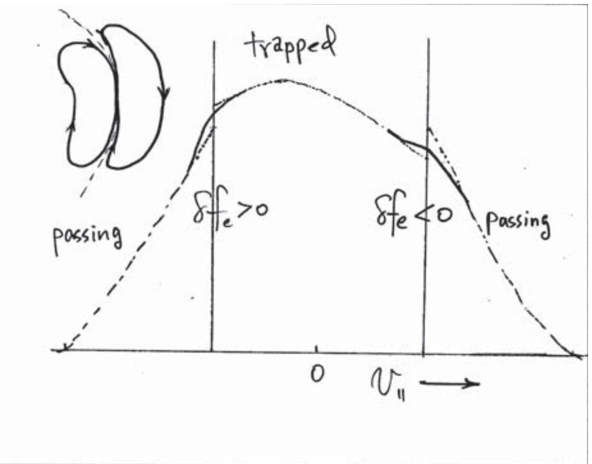


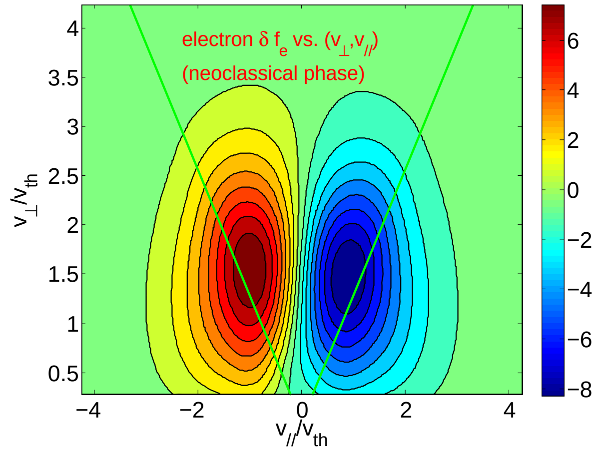
- simulation shows three distinct phases for current development
- current profile significantly modified – total current can be changed too
- fine radial scales presented in electron current

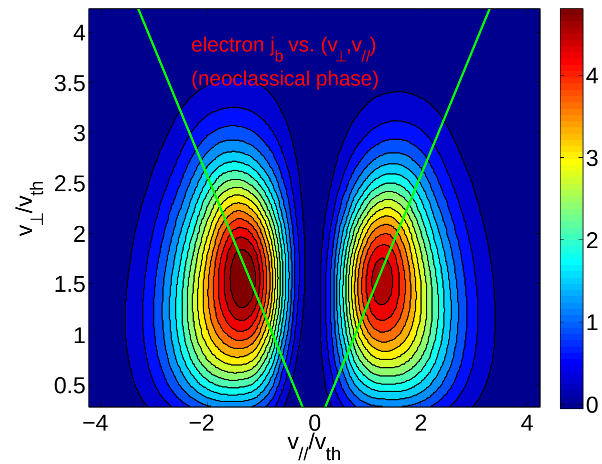




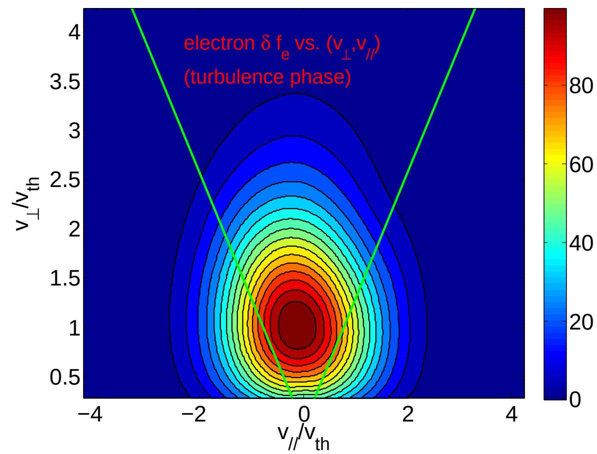
Phase space structure of electron current density is largely changed by turbulence

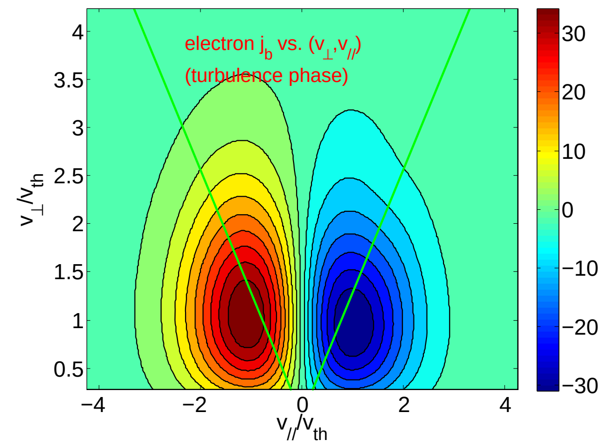






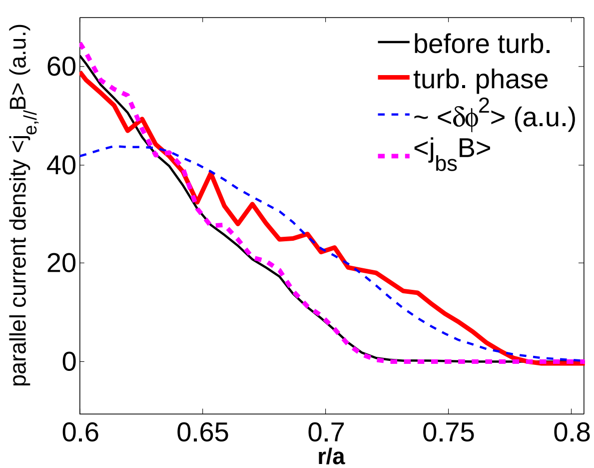
Turbulence Phase $\Longrightarrow$

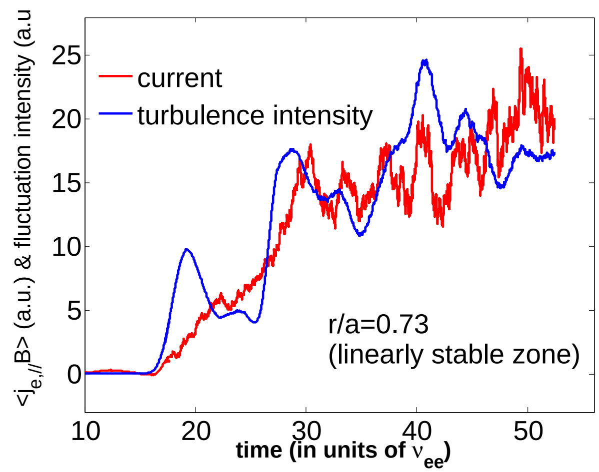


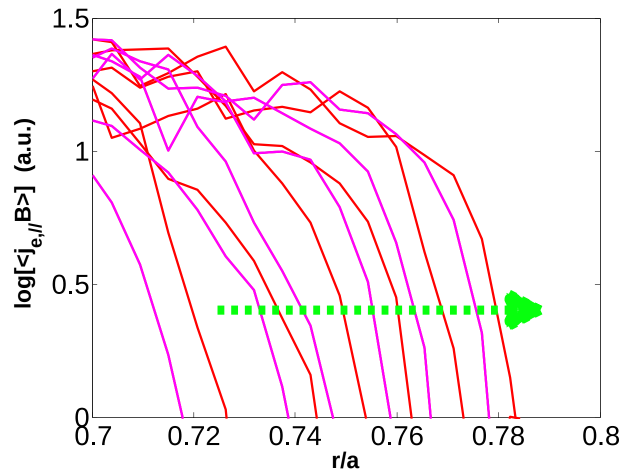


- Current is mainly carried by electrons around trapped-passing boundary
  - mostly contributed by passing particles
  - considerable contribution from trapped electrons

Significant current can be generated in flat pressure region – nonlocal effect due to turbulence spreading







- Current diffusion via turbulence spreading
- 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 physics may link to electron momentum transport and flow generation

- Generalized NC Ohm's law (see Hinton et.al.,'04; Gatto-Chavdarovski,'11)

$$\langle (j_{\|} - j_{bs})B\rangle = \sigma_{neo}\langle E_{\|}^{\rm ind} B\rangle + \langle j_{dyn} B\rangle$$

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

$$j_{\|,turb} \sim \tilde{E}_{\|}\tilde{n}^* e^2/m_e\nu_{ei} \sim \langle k_{\|}\delta n_k^2\rangle$$

- Divergence of radial flux of parallel electron momentum (Hinton et.al., '04)

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

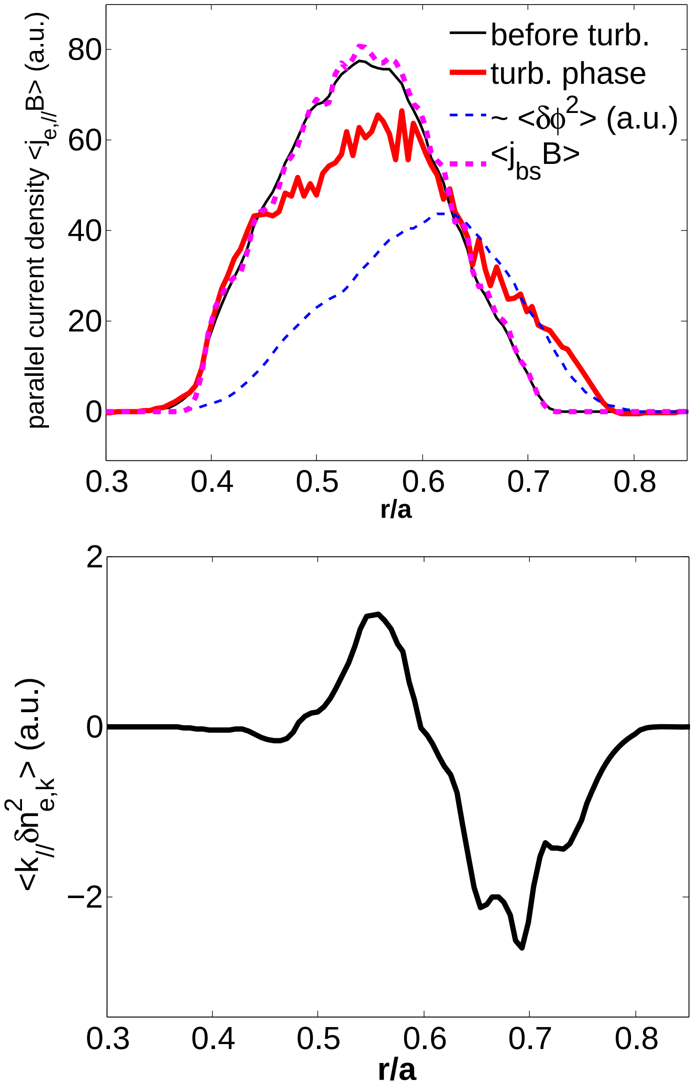
- Significant residual stress contribution $\Pi_{r,\|}^{\rm RS} \sim \langle k_\theta k_{\|}\delta\phi_k^2\rangle$

  (Wang et.al., IAEA-FEC'12; McDevitt et. al., PoP'17)

  – link to $k_{\|}$-symmetry breaking (Diamond et.al., NF'09)

- Finite $\langle k_{\|}\rangle$ is needed for both parallel acceleration and residual stress

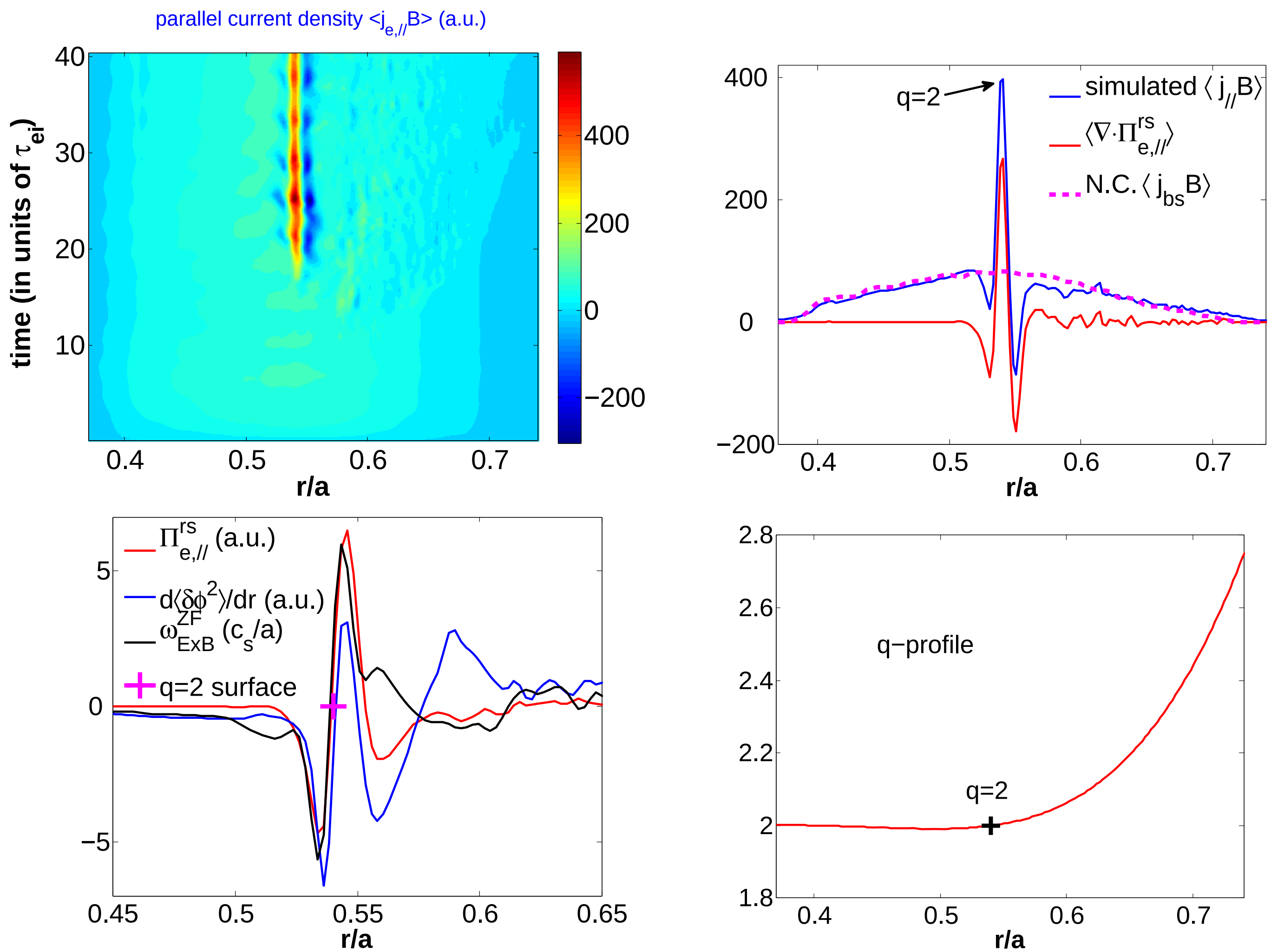
Turbulence-induced parallel acceleration seems to drive anomalous current in a large scale



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

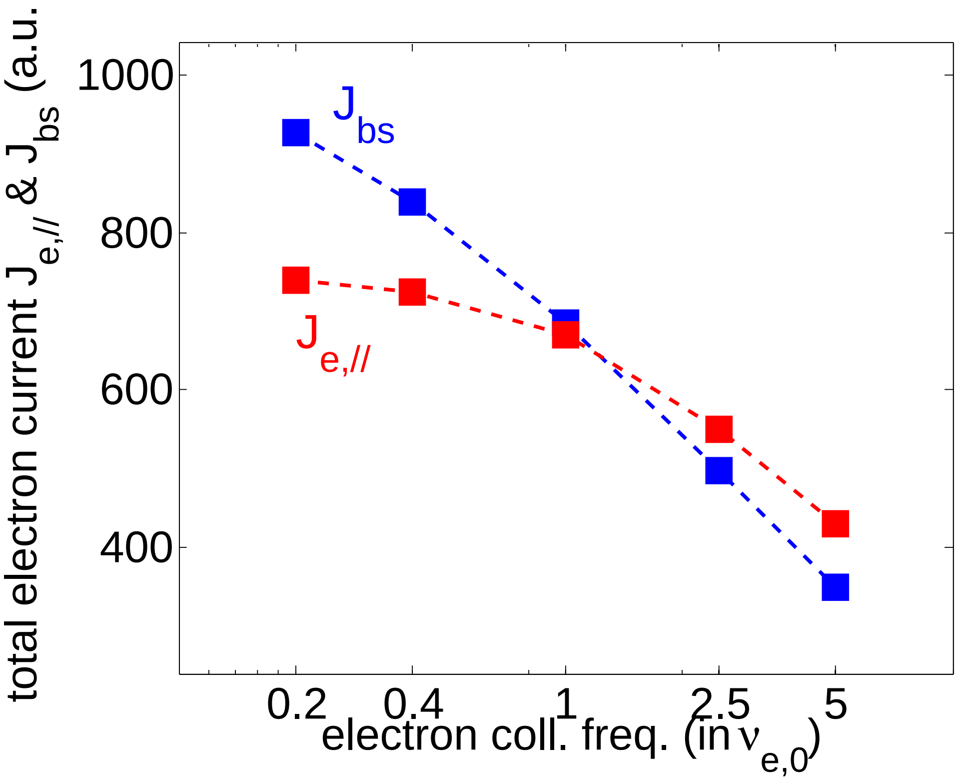
- $k_{\|}$-symmetry breaking can be caused by fluctuation intensity gradient
- $j_{\|,turb}$ direction may link to sign of $\langle k_{\|} \rangle$ and then turb. intensity gradient

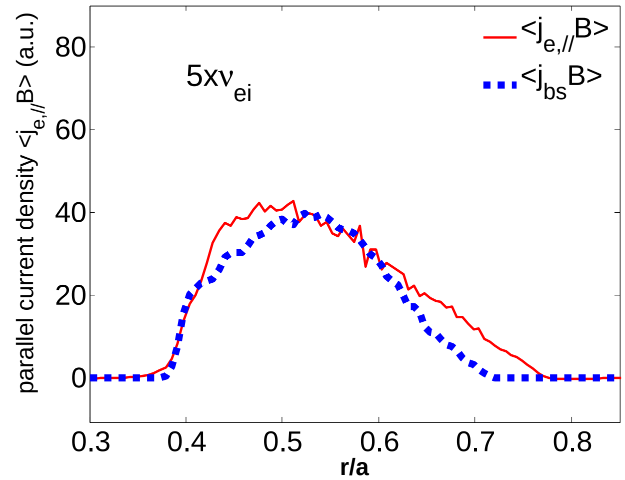
Turbulence-produced electron parallel Reynolds stress drives fine-scale anomalous current near rational surface

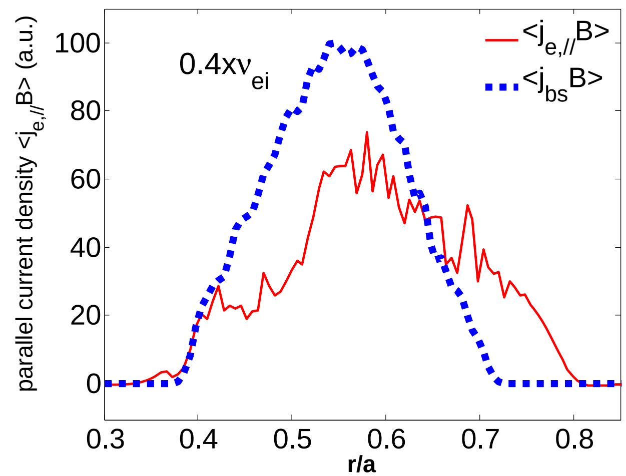


- Modify current density profile near a rational surface but not total current
- Radial scale of electron current corrugation $\sim$ a few ρ_s
- $\Pi^{rs}_{e,\|}$ closely correlates with both turbulence intensity gradient and ZF shear through their effects on $k_\|$-symmetry breaking

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





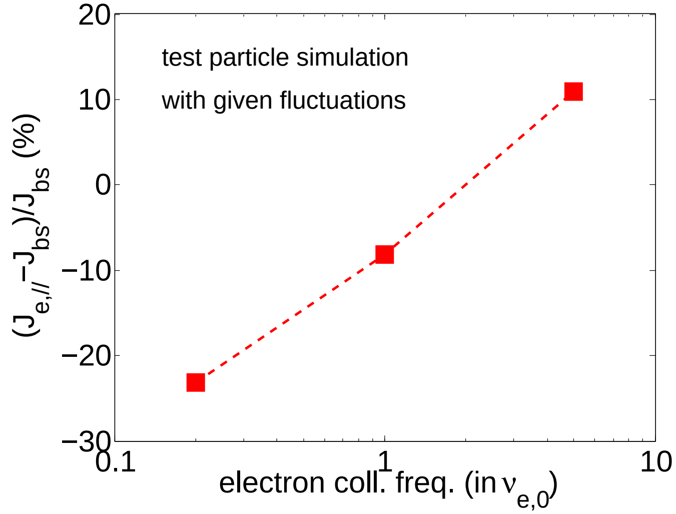


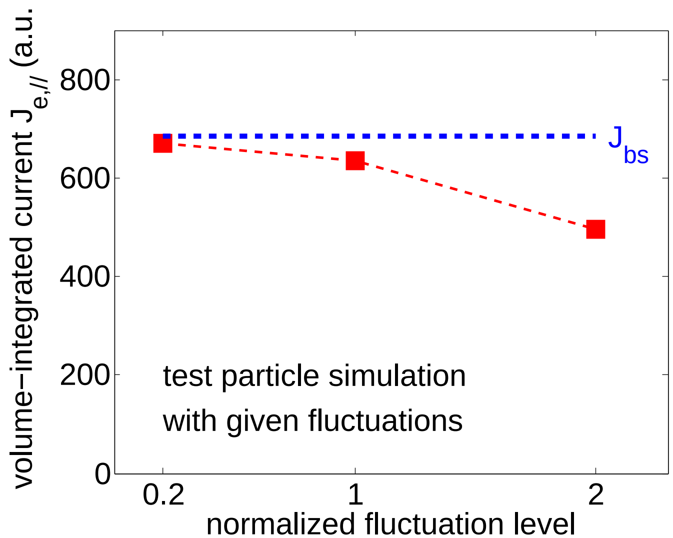
- A critical ν_e^* exists?
  (like intrinsic rotation reversal)

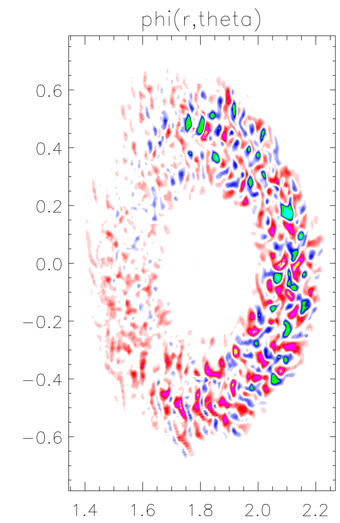
- Reduction of electron current relative to J_{bs} increases as ν_e^* decreases

- Possible impact on fully non-inductive steady state operation in burning plasma regime (?)

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

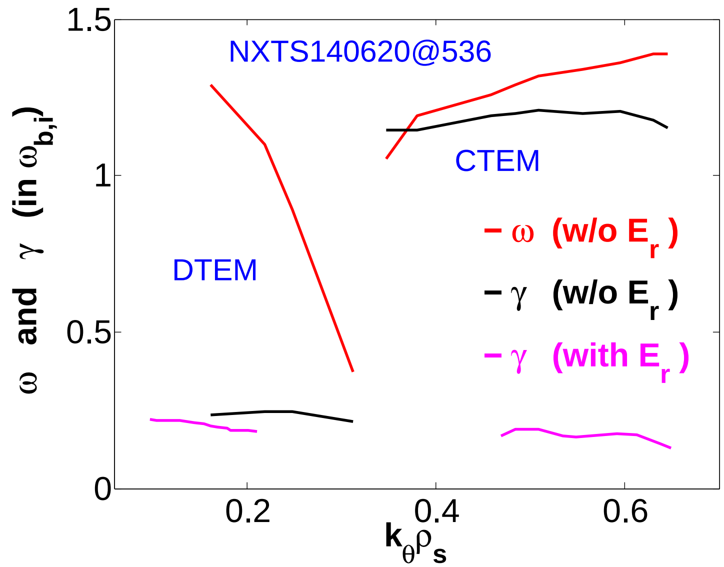


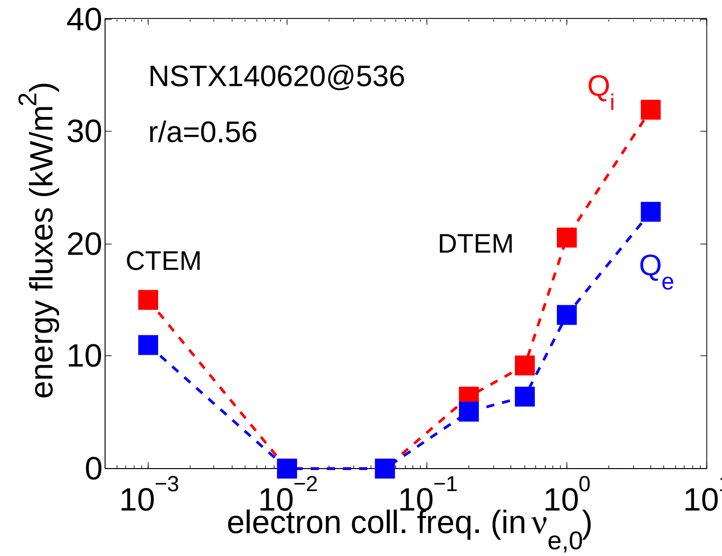




- Test particle simulations with given static fluctuations from NL GTS run
  - close to situations/assumptions that theory is conducted
  - useful for developing and testing theory
- Turbulence induced current reduces bootstrap current in low-ν_* regime
  - consistent with fully nonlinear simulation result
- Self-generated current is reduced as fluctuation level increases

Dissipative-TEM may provide a distinct, key turbulence source for transport and confinement in ST experiments

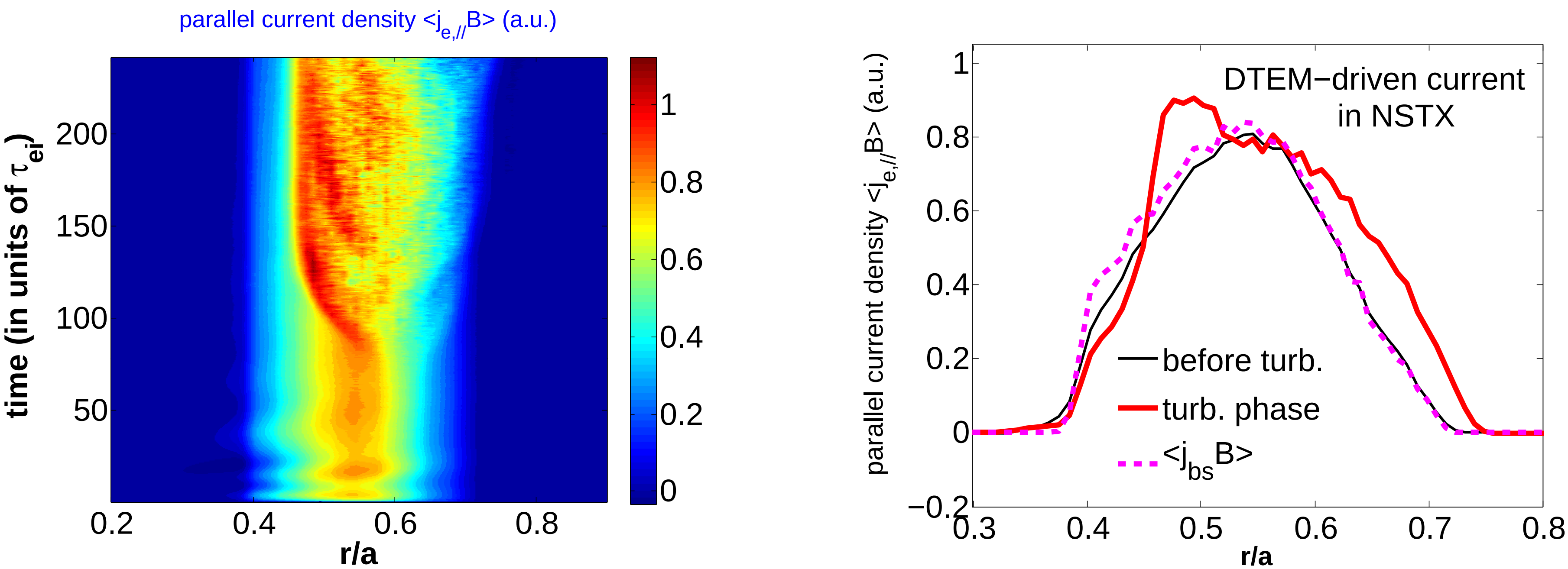




(Wang et. al., NF'15)

- 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)
- C/DTEM-free regime in low collisionality
  (possibly relevant to NSTX-U & ST-FNSF)

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



- Increase total current in NSTX where collisionality is relatively high

Summary

Nonlinear global gyrokinetic simulation with consistent turbulent and neoclassical dynamics is used to study plasma current generation

- Plasma self-generated current can be strongly modified by turbulence
  – profile structure; – amplitude; – phase space structure
- Current diffusion induced by turbulence spreading generates finite current in flat pressure region
- Mechanisms include i) electron parallel acceleration; ii) resid. stress drive
  – $k_{\|}$-symmetry breaking plays an important role
  – $j_{\|,turb}$ direction may link to sign of $\langle k_{\|} \rangle$, and then to turbulence intensity and zonal flow profiles
- Turbulence may enhance plasma self-generated current in high-ν_e^* regime, but deduct it in low-ν_e^* regime
  – reduction of electron current relative to J_{bs} increases as ν_e^* decreases
- Self-generated current is reduced as fluctuation level increases

Experimental verification is critical: to examine characteristic trend predicted