Gyrokinetic Investigations of Turbulence Driven Plasma Current and Shear Flow Driven Turbulence

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in collaboration with

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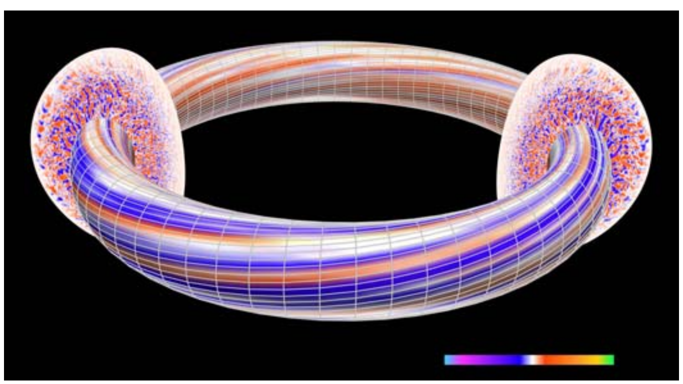

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Gyrokinetic Tokamak Simulation (GTS) code: simulate turbulence and transport in fusion experiments

- Solving modern gyrokinetic equation in conservative form for $f(Z,t)$

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

(see, e.g., Brizard & Hahm, Rev. Mod. Phys. '07)

- Using δf method (based on importance sampling) – $\delta f \equiv f - f_0$

$$\frac{\partial \delta f_a}{\partial t} + \frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}} B^* \delta f_a) = -\frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}}_1 B^* f_{a0}) + \sum_b C^l(\delta f_a)$$

– f_0 = neoclassical equilibrium satisfying:

$$\frac{\partial f_{a0}}{\partial t} + \frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}}_0 B^* f_{a0}) = \sum_b C[f_{a0}, f_{b0}]$$

– $f_0 = f_{\rm SM}$ for ions; $f_0 = f_{\rm SM}$ or $(1 + e\delta\Phi/T_e) f_{\rm SM}$ for electrons

$\dot{\vec{Z}} \equiv \dot{\vec{Z}}_0 + \dot{\vec{Z}}_1$; $\vec{Z}_1$ – drift motion associated with fluctuations $\delta\Phi$, $\delta \vec{A}_\parallel$

(Wang et al,. PoP'06, PoP'10)

GTS uses δf Particle-In-Cell approach

- Particle-in-cell approach – solving marker particle distribution $F(Z, w)$ in extended phase space:

$$\frac{\partial F}{\partial t} + \frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}} B^* F) + \frac{\partial}{\partial w}(\dot{w} F) = 0; \qquad \delta f = \int w F dw$$

$(1/B^*)\nabla_Z \cdot (\dot{\vec{Z}} B^* F) \Longrightarrow \dot{\vec{Z}} \cdot \nabla_Z F$; taking $Z = \{r, \theta, \phi, v_\|, \mu\}$

– Lagrangian equations in general flux coordinates for G.C. motion:

$$\frac{d}{dt}\left(\frac{\partial}{\partial \dot{x}_i} L\right) - \frac{\partial}{\partial x_i} L = 0, \tag{1}$$

$L(\mathbf{x}, \dot{\mathbf{x}}; t) = (\mathbf{A} + \rho_\| \mathbf{B}) \cdot \mathbf{v} - H;\quad H = \rho_\|^2 B^2/2 + \mu B + \Phi$ (Littlejohn PF'81)

– Weight equation

$$\dot{w} = \frac{1-w}{f_0}\left[-\frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}}_1 B^* f_{a0})\right] + \frac{w - \langle w \rangle}{f_0}\left[-\frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}}_1 B^* f_{a0})\right]$$

to ensure incompressibility: $(\partial/\partial w)\dot{w} = 0$!

Major numerical and physical features

- Real space field solvers with field-line-following mesh

  – retains all toroidal modes and full channels of nonlinear energy couplings

$$\frac{e}{T_i}(\Phi - \widetilde{\Phi}) = \frac{\delta \bar{n}_i}{n_0} - \frac{\delta n_e}{n_0} \quad -\text{integral form (Lee}'83)$$

$$-\nabla_\perp \cdot \frac{Z_i n_{i,0}}{B\Omega_i} \nabla_\perp \Phi = \bar{n}_i - n_e \quad -\text{PDE form (Dubin et.al.}'83)$$

- Fully kinetic electrons (both trapped and untrapped electron dynamics)
- Linearized Fokker-Plank operator with particle, momentum and energy conservation for i-i and e-e collisions; Lorentz operator for e-i collisions
- Interaction with neoclassical physics with two options

  i) include both turbulent and neoclassical physics self-consistently

  ii) import GTC-NEO result of equilibrium E_r into GTS
- Full geometry, global simulation

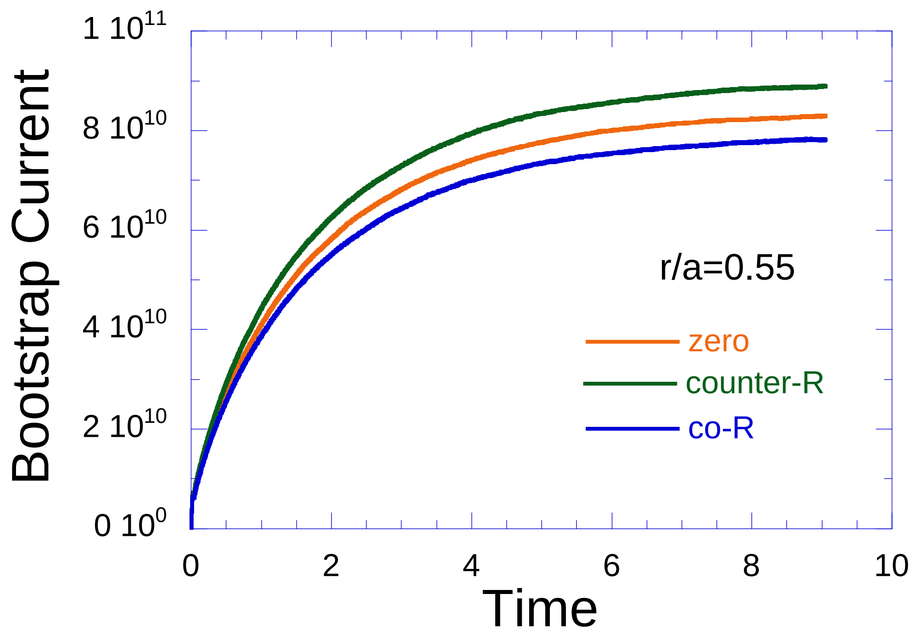
Can turbulence drive plasma current or change bootstrap current?

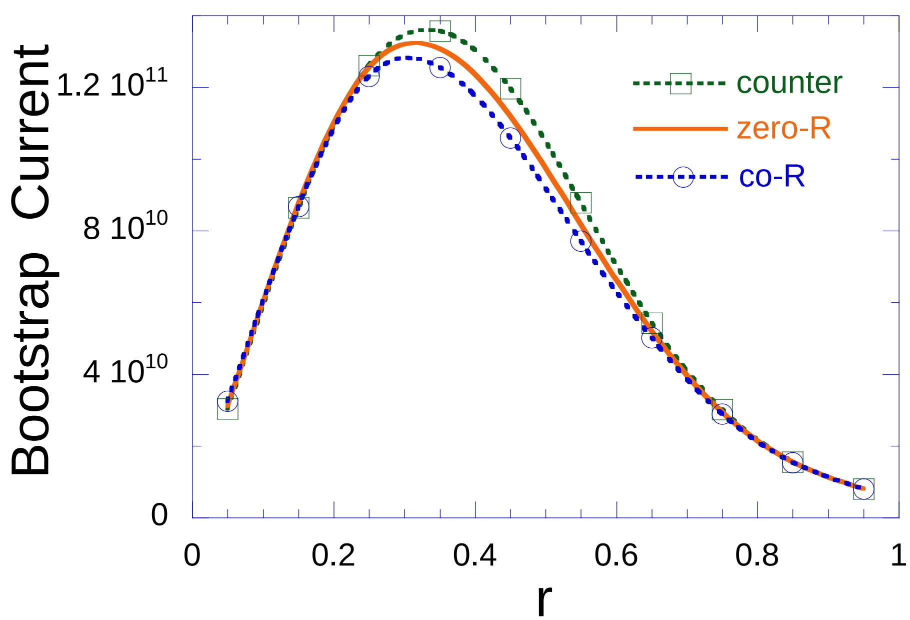
- Plasma self-generated non-inductive current is of great importance
  - NTM physics, ELM dynamics, overall plasma confinement
- Bootstrap current J_{bs} – a well known non-inductive current
  - driven by pressure and temperature gradients in toroidal geometry
  - associated with existence of trapped 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
- Current generation by turbulence is investigated using nonlinear global gyrokinetic simulations with GTS code
  - focus on electron transport dominated regime – CTEM turbulence
  - neglect electromagnetic effect (Hinton et. al., PoP’04)

Minor correction due to finite orbit neoclassical effect

- Nonlocal neoclassical equilibrium solution in collisionless regime:

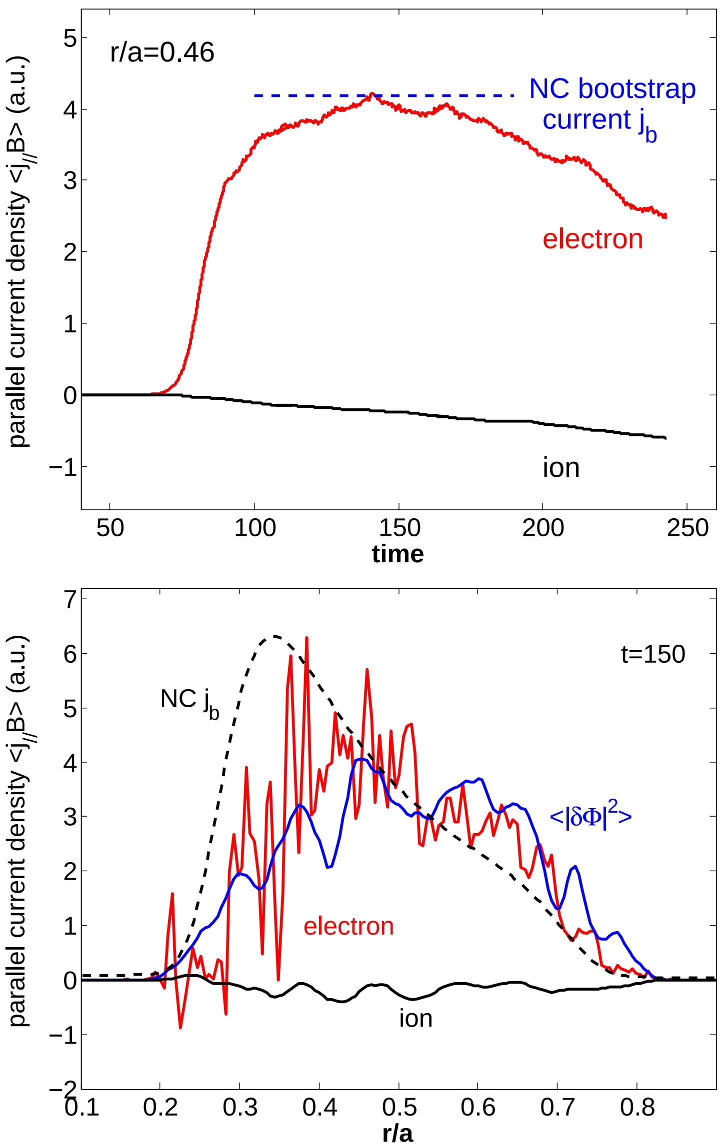
$$\Delta u_{i\|} \simeq -\frac{m_i c}{e}\left\langle \frac{I^2}{B^2}\right\rangle \frac{cT_i I}{eB}\frac{\partial \ln n_i}{\partial \psi_p}\frac{\partial \omega_t}{\partial \psi_p}.$$





(Wang et. al., '06)

Earlier GK turbulence simulations excluding neoclassical physics show significant quasi-stationary electron current generation by CTEM fluctuations



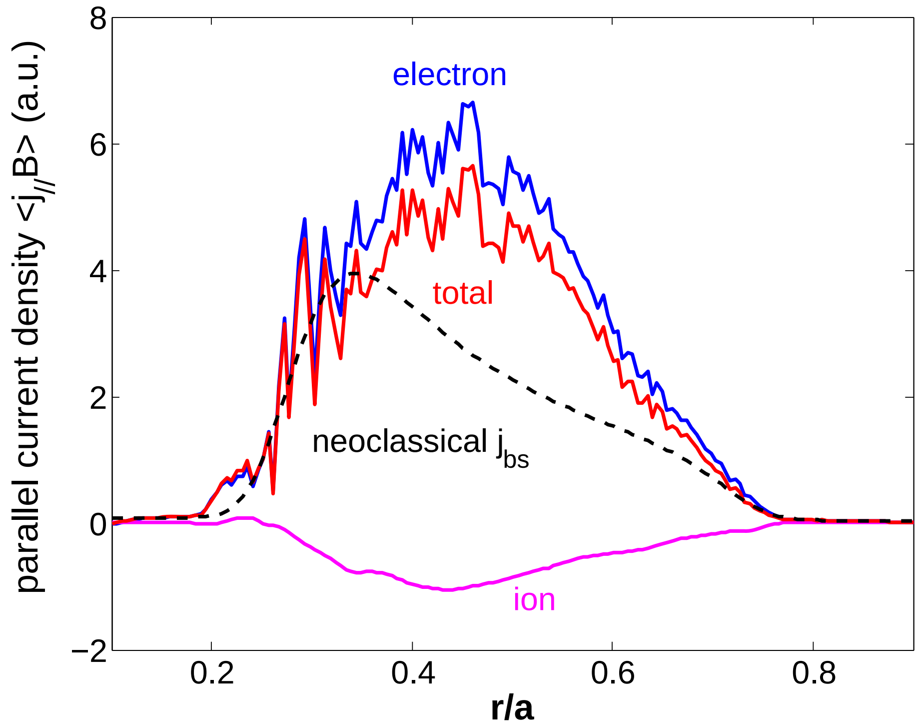
$$\langle j_{\parallel} B \rangle = \langle e \int v_{\parallel} B \delta f d^3 v \rangle$$

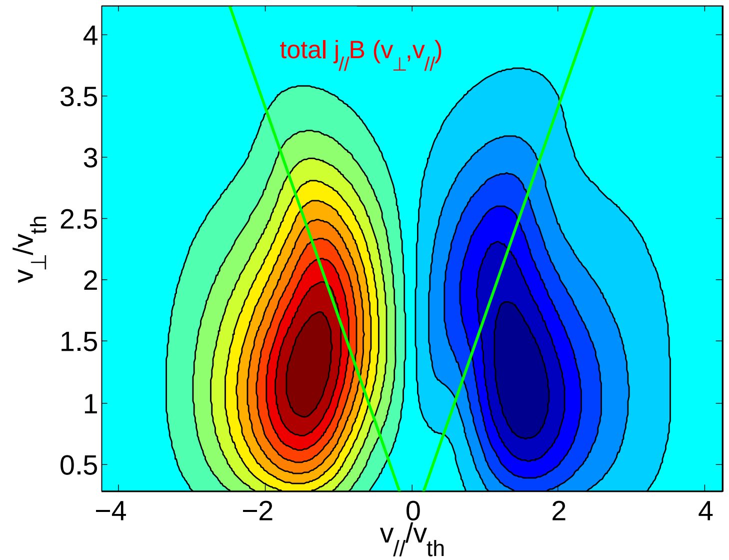
DIII-D size geometry;
$R_0/L_{T_e} = R_0/L_n = 6$;
$R_0/L_{T_i} = 2.4$; initially rotation free;
mean $\mathbf{E} \times \mathbf{B}$ included

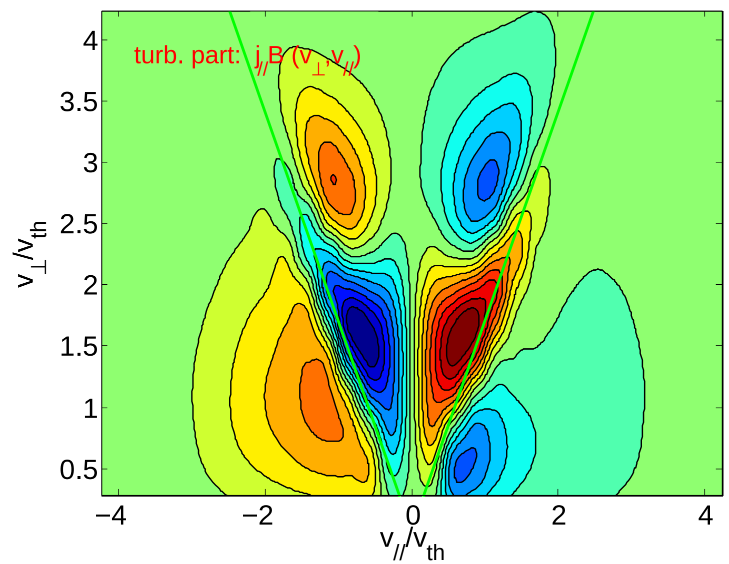
- electrons carry most of current in $+\mathbf{B}$ direction
- ions carry small current in $-\mathbf{B}$ direction
- fine radial scales presented in electron current
- Much weaker current generation by ITG

Bootstrap current generation can be significantly modified in the presence of turbulence

- New sim. incl. both turb. & NC physics simultaneously in CTEM regime

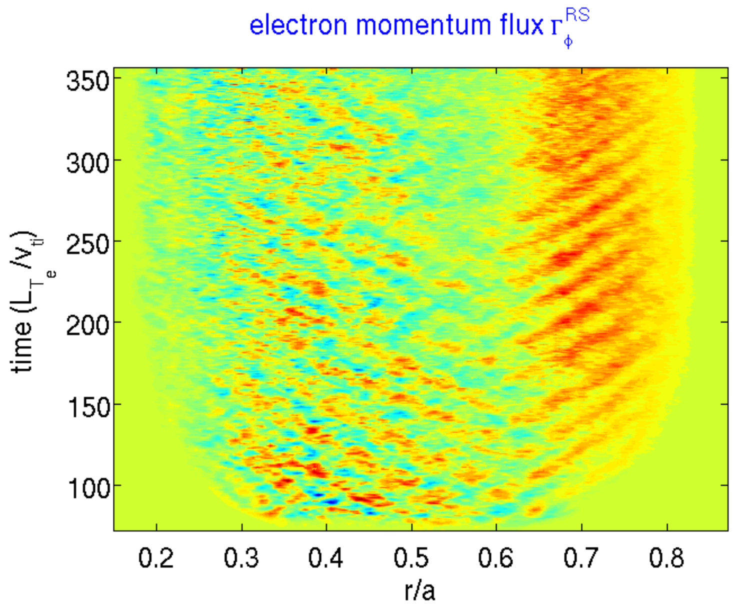






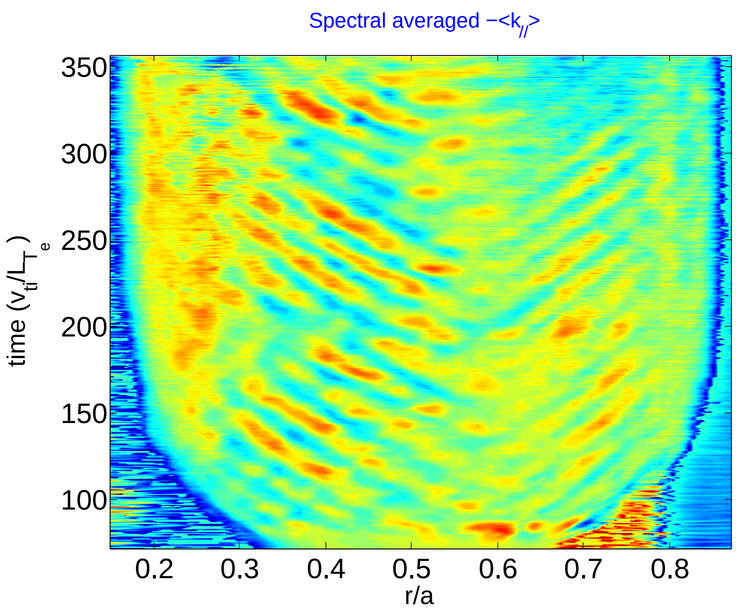
- Results consistent with turb.-only sim.
- Total J_{bs} mainly carried by passing e^-
- Turb. contr. dominated by trapped e^-

Fluctuation-induced current is associated with nonlinear electron flow generation

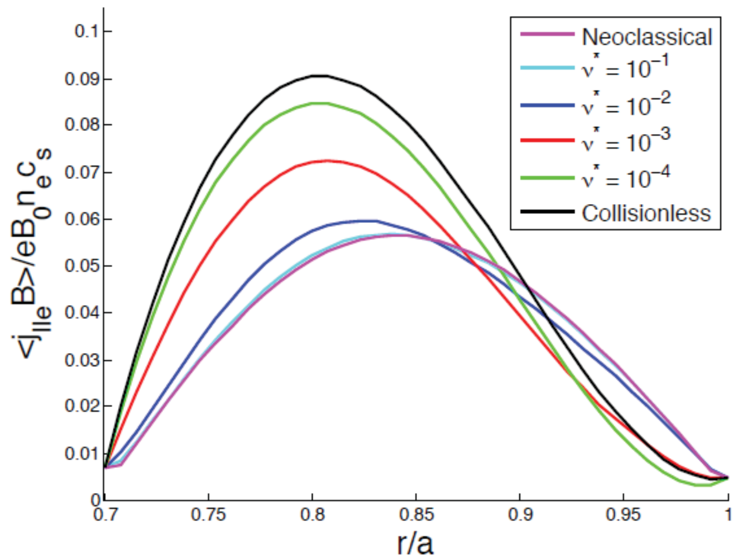


$$\langle j_{\|} B\rangle = e\langle n(u_{i\|} - u_{e\|})B\rangle$$

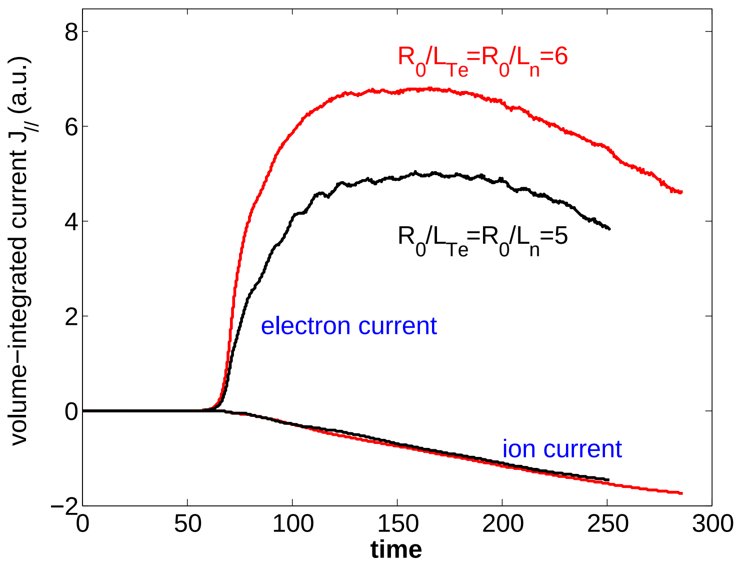
- Electron flow generation by turb. residual stress due to $k_{\|}$ symmetry breaking
- Turbulence acceleration of electrons ?



Electron detrapping by drift wave turbulence (McDevitt et. al. '13)

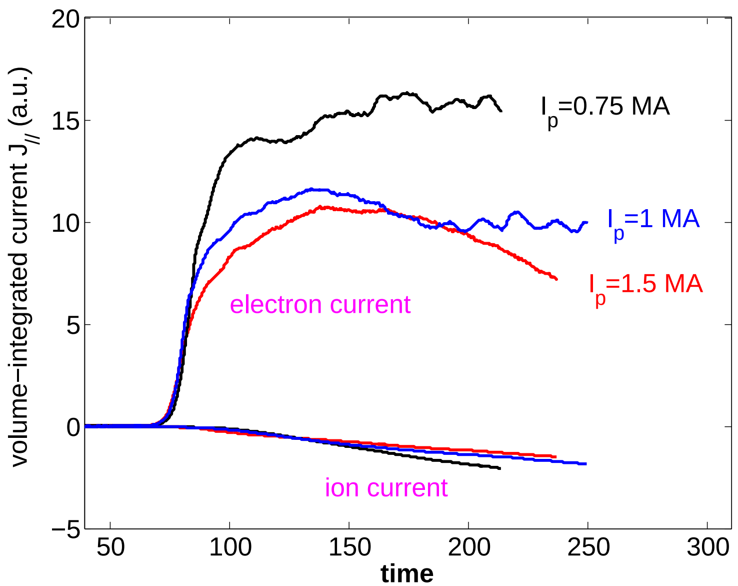


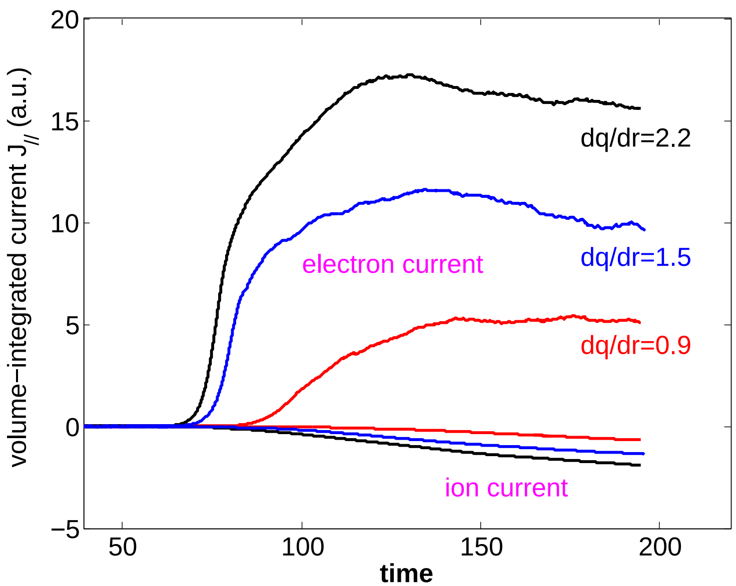
Characteristic dependence of fluctuation-induced current generation



Share similarity wth conventional bootstrap current, but with different physics origins

- increases with ∇p
- decreases with B_p
- increases with magnetic shear dq/dr
- collisionality dependence





Optimized flow is of great importance in fusion plasmas

- Control macroscopic stability; reduce micro-turbulence and energy loss
- Turbulence generation of global intrinsic rotation is critical in ITER
  - turbulent residual stress driven by ∇T, ∇n produces a local torque
  - interplay of turbulent torque and edge boundary conditions/effects

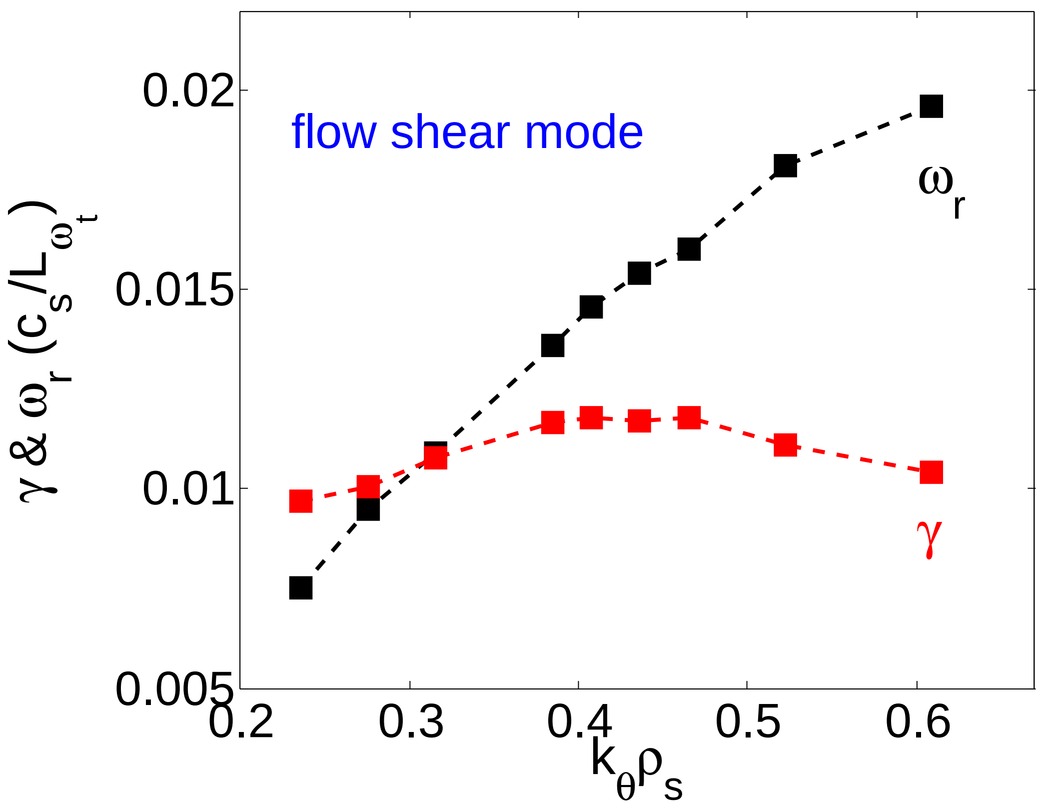
    (Diamond et. al., NF'09)
- Free energy in flow gradient may drive its own instability and turbulence
  - velocity shear drive Kelvin-Helmholtz instability in fluid
  - in plasmas, flow shear may drive a negative compressibility mode

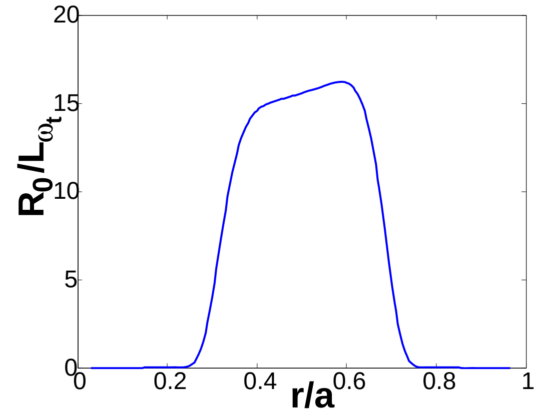
    (Catto *et al.*, '73; Matter & Diamond, '88; Artun & Tang, '92 ...)
  - observed in linear machines.
  - largely ignored and unexplored in tokamaks

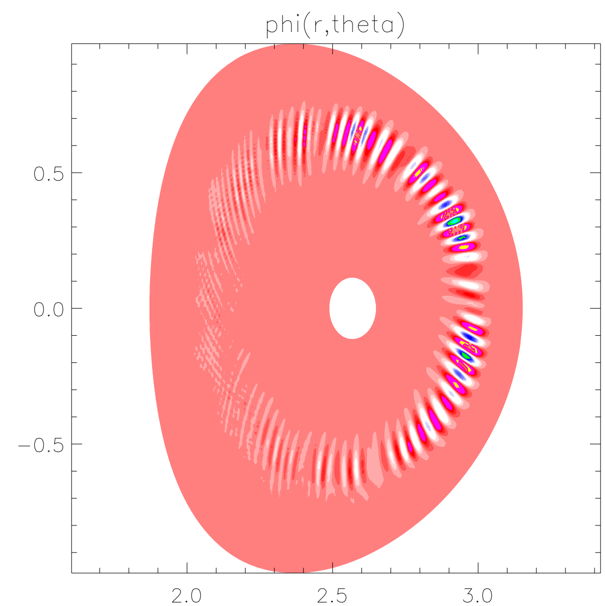
    (presumably assumed hardly unstable due to magnetic shear effect)
- First results of flow shear driven turbulence and transport from nonlinear global GK simulations [with GTS code (Wang *et al.*, PoP'06)] are reported

Strong flow shear can drive micro-instability in tokamak

- Global GK simulation with kinetic electrons
- DIII-D-size geometry
- $R_0/L_{T_i} = R_0/L_{T_e} = R_0/L_n = 1.2$ – ITG and TEM are stable

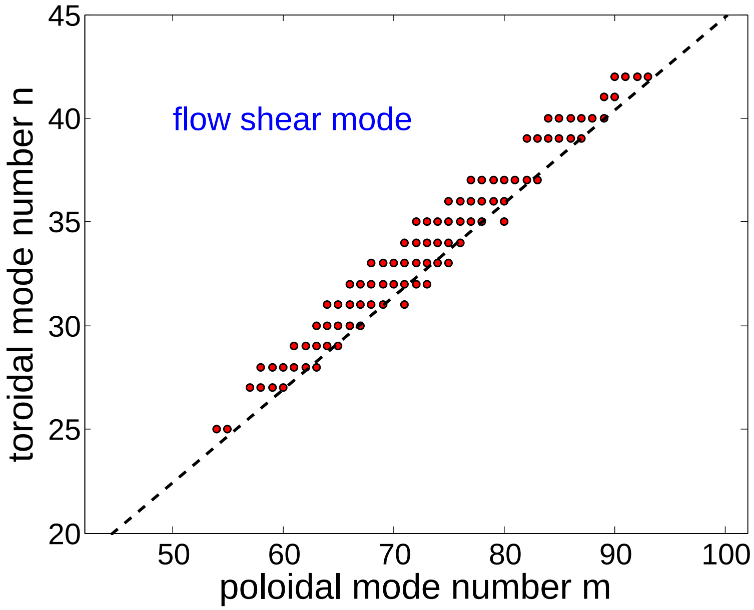






- Low-k mode (in same range of ITG mode)
- Smaller but almost constant growth rate

Distinct linear features of flow shear instability



- significant finite $k_{\parallel}$

  $k_{\parallel} \sim \hat{b} \cdot \nabla\theta(m - nq)$

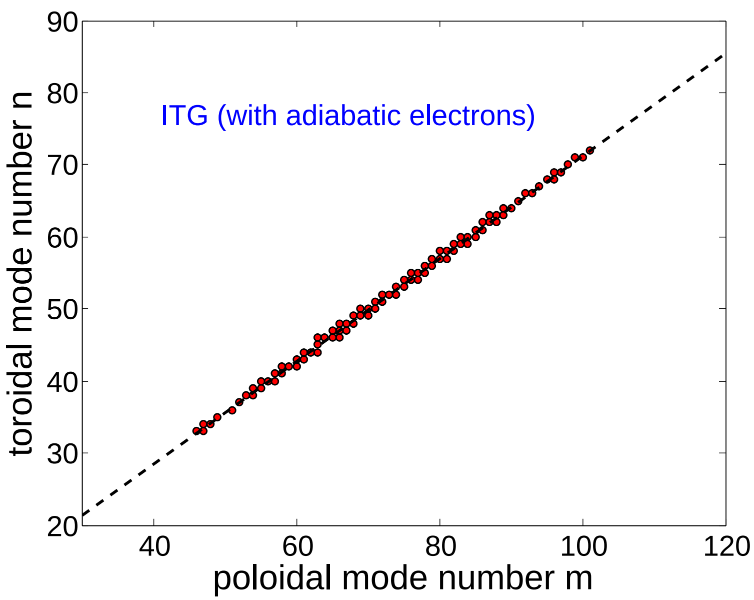
- stronger Landau damping

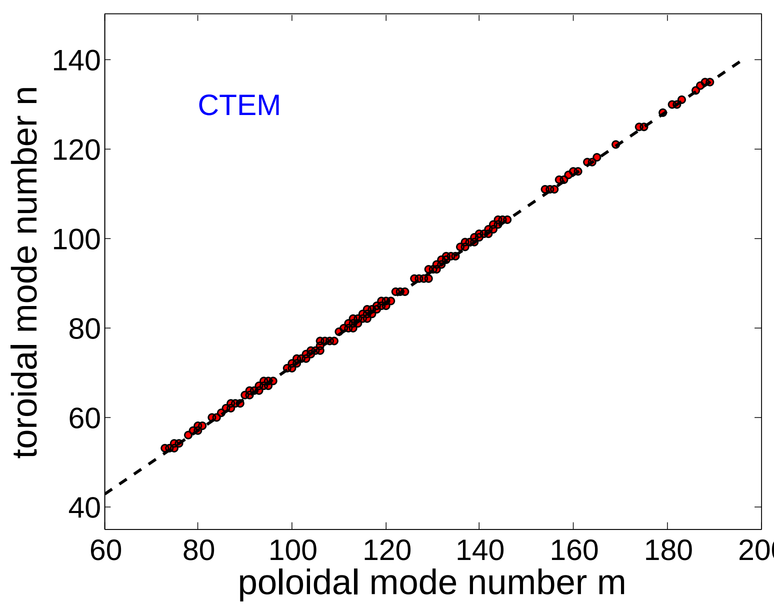
  $\rightarrow$ increase instability threshold

  $R_0/L_{\omega_t} > R_0/L_{T_i}$ (for ITG)

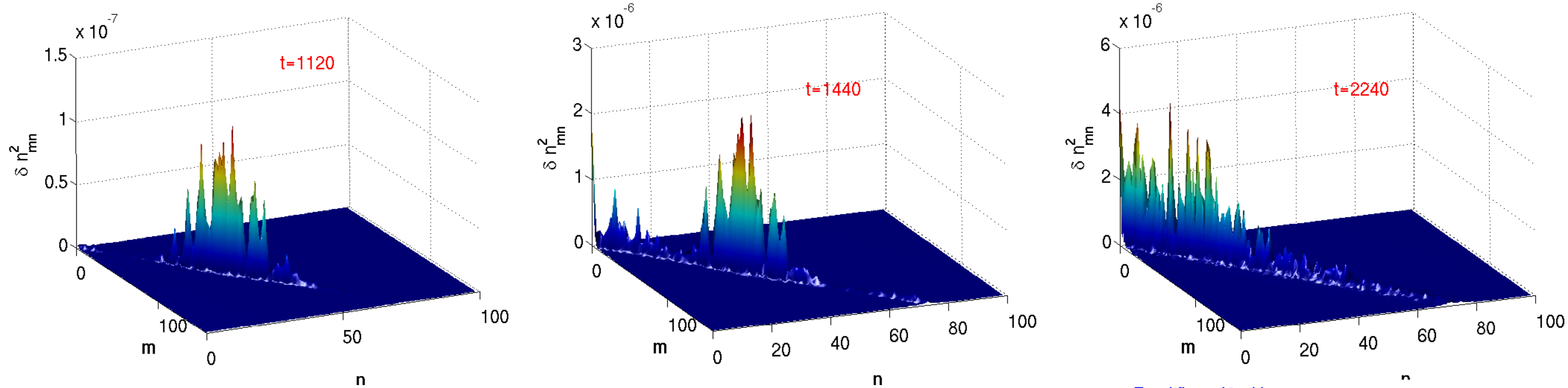
  $R_0/L_{\omega_t} > R_0/L_{T_e,n}$ (for TEM)

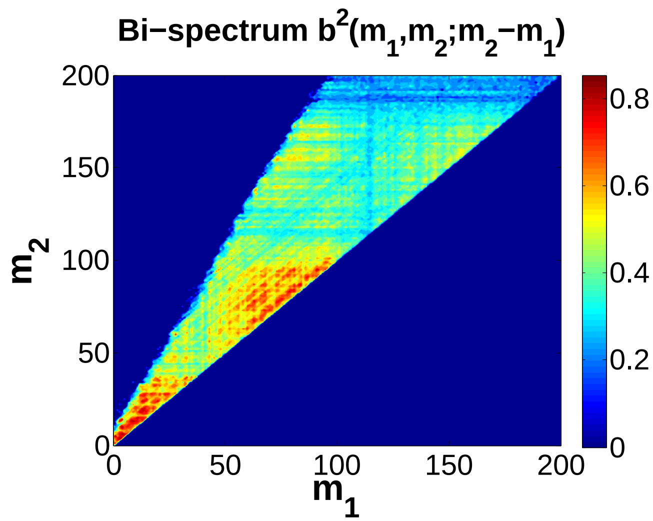
- asymmetry (impact on residual stress generation)

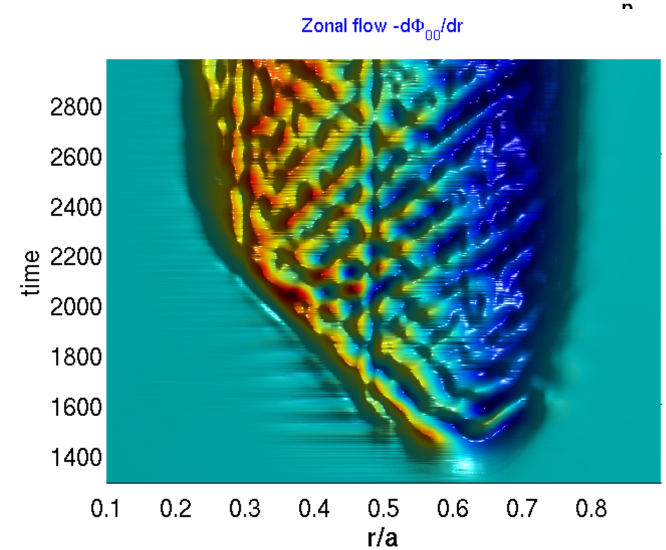




Nonlinear toroidal mode couplings play a key role to cause flow shear turbulence saturation

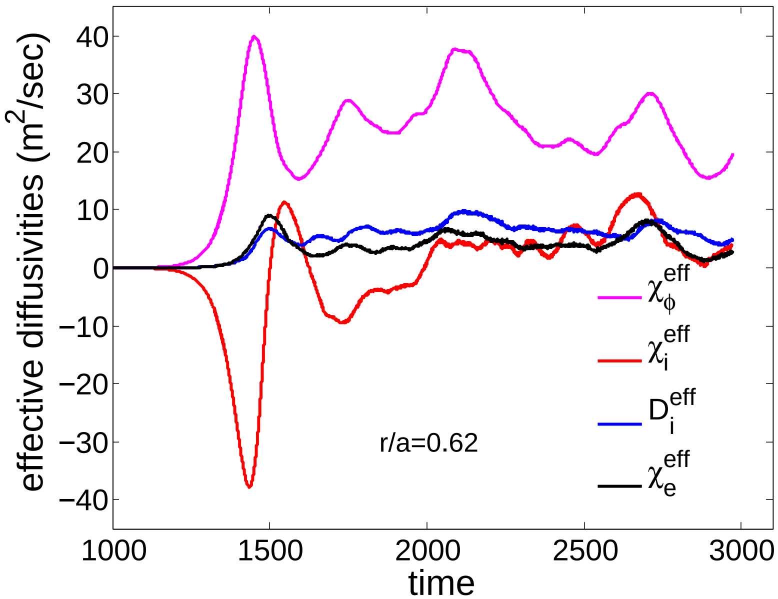


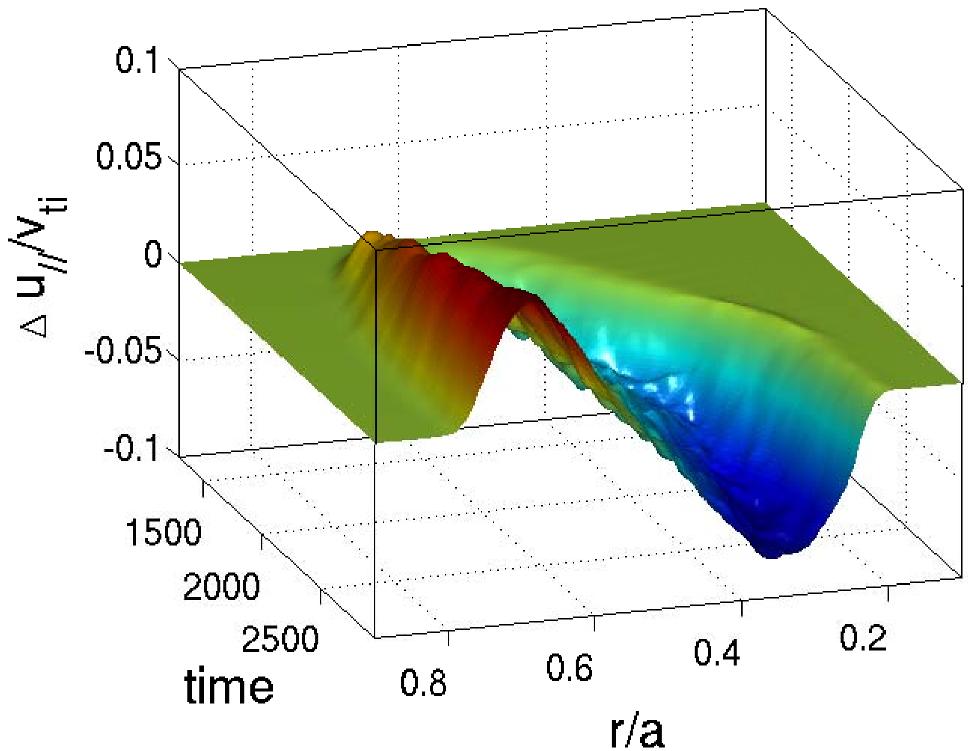


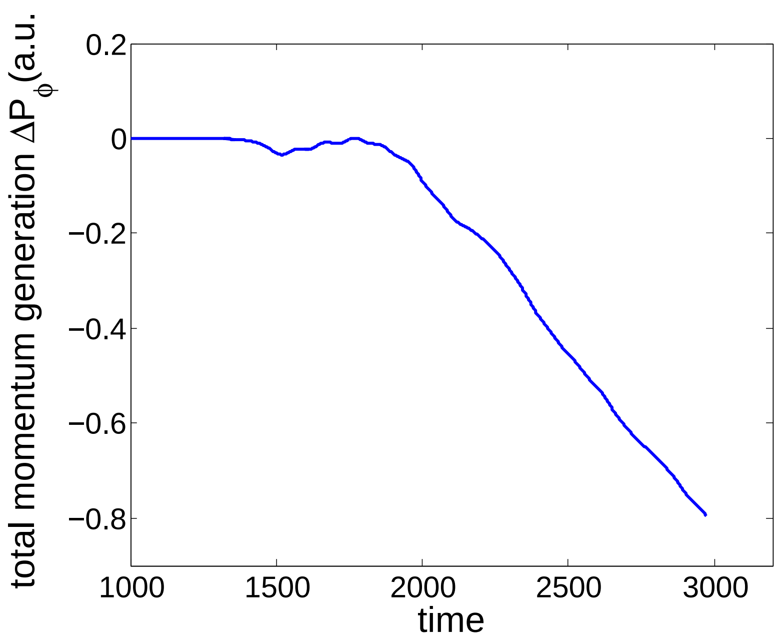


- Nonlinear energy transfer to longer wavelength modes via toroidal mode couplings
- Strong zonal flows and GAMs generation

Flow shear turbulence can drive significant momentum and energy transport

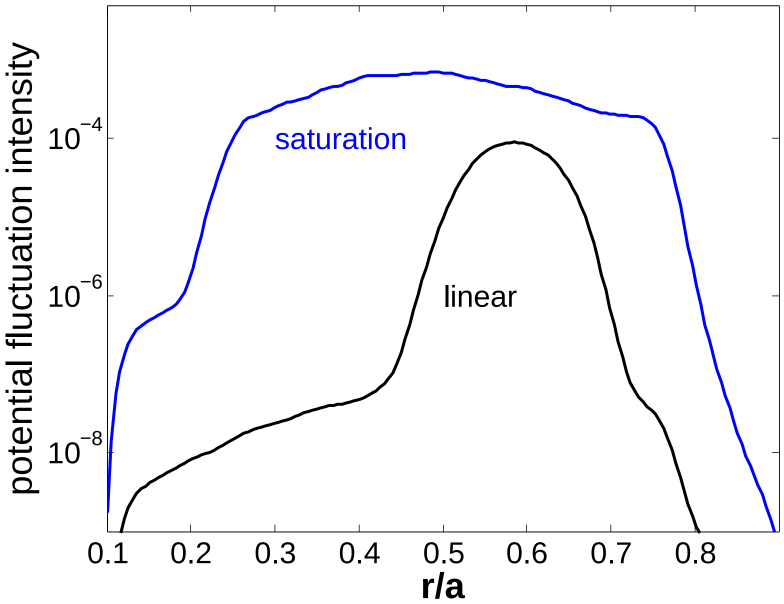


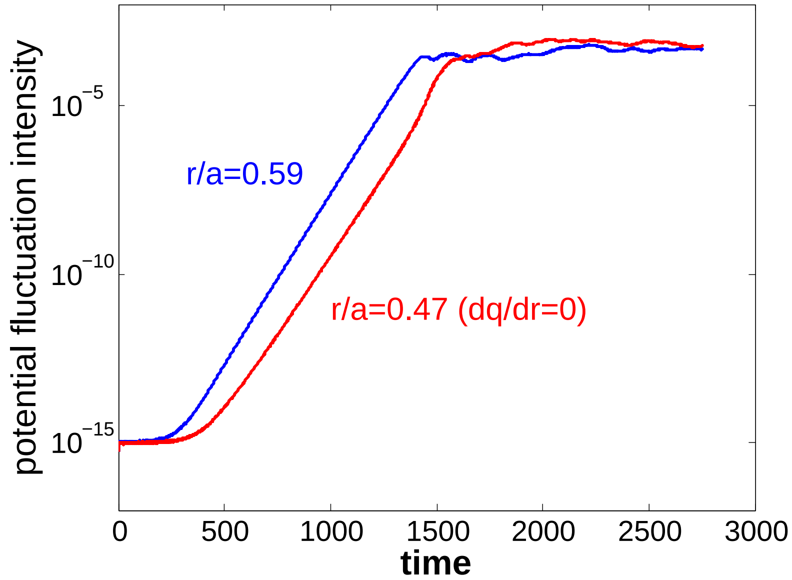




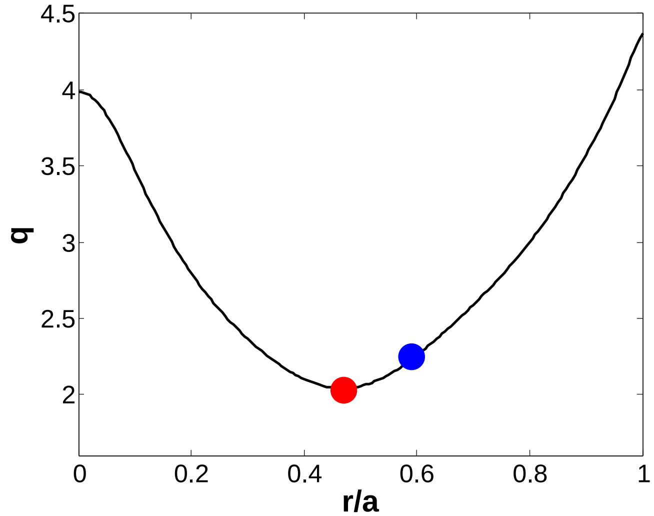
- Observation of turbulent intrinsic torque in co-current direction
- Limitation on de-stiffness seen in gyro-fluid simulation (Jhang, IAEA FEC '12)

Effects of q-profile structure

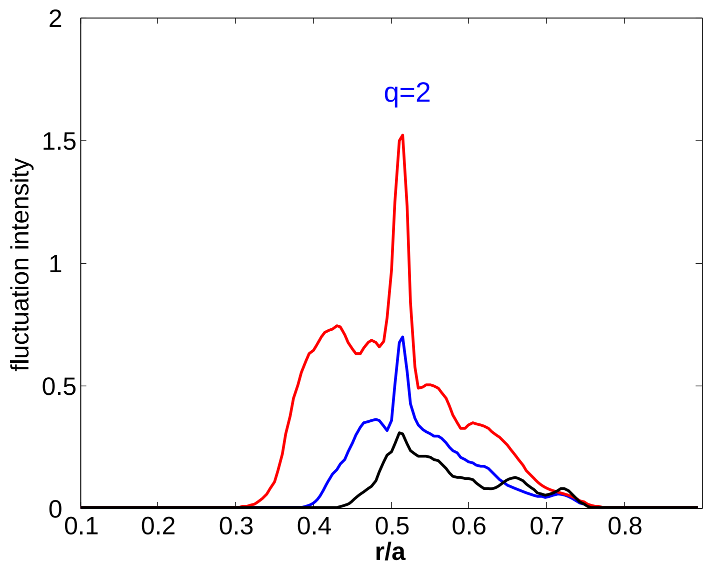


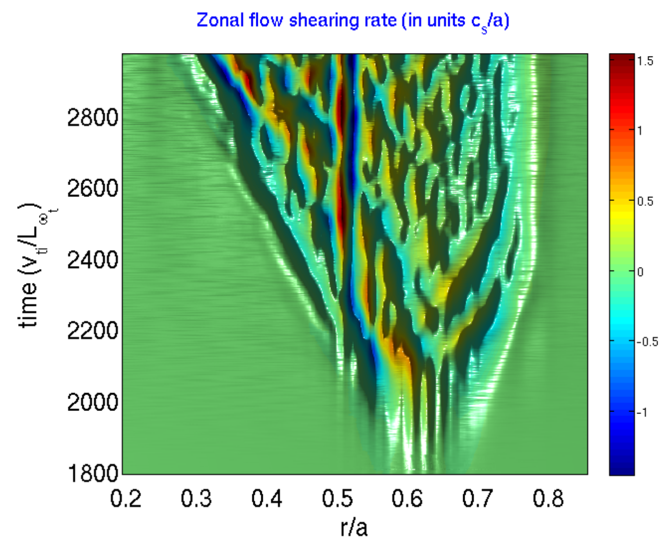


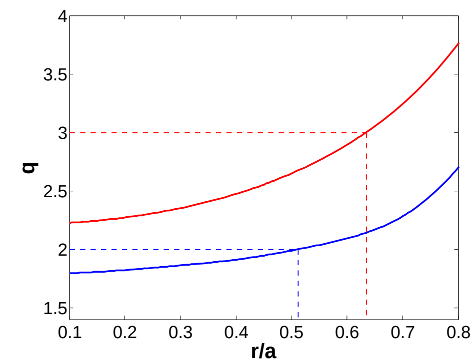
- Magnetic shear shows no suppression effect on flow shear instability in tokamak plasmas!

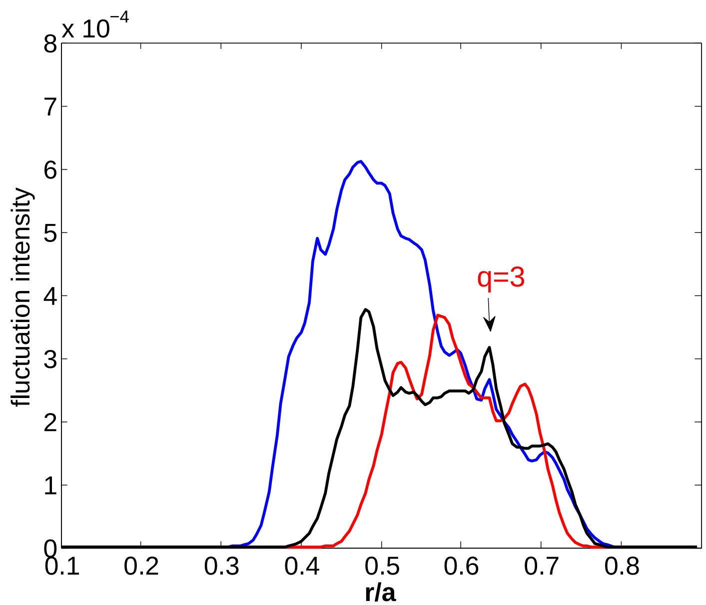


Effects of q-profile structure – what happens at rational surfaces with integer q-number?





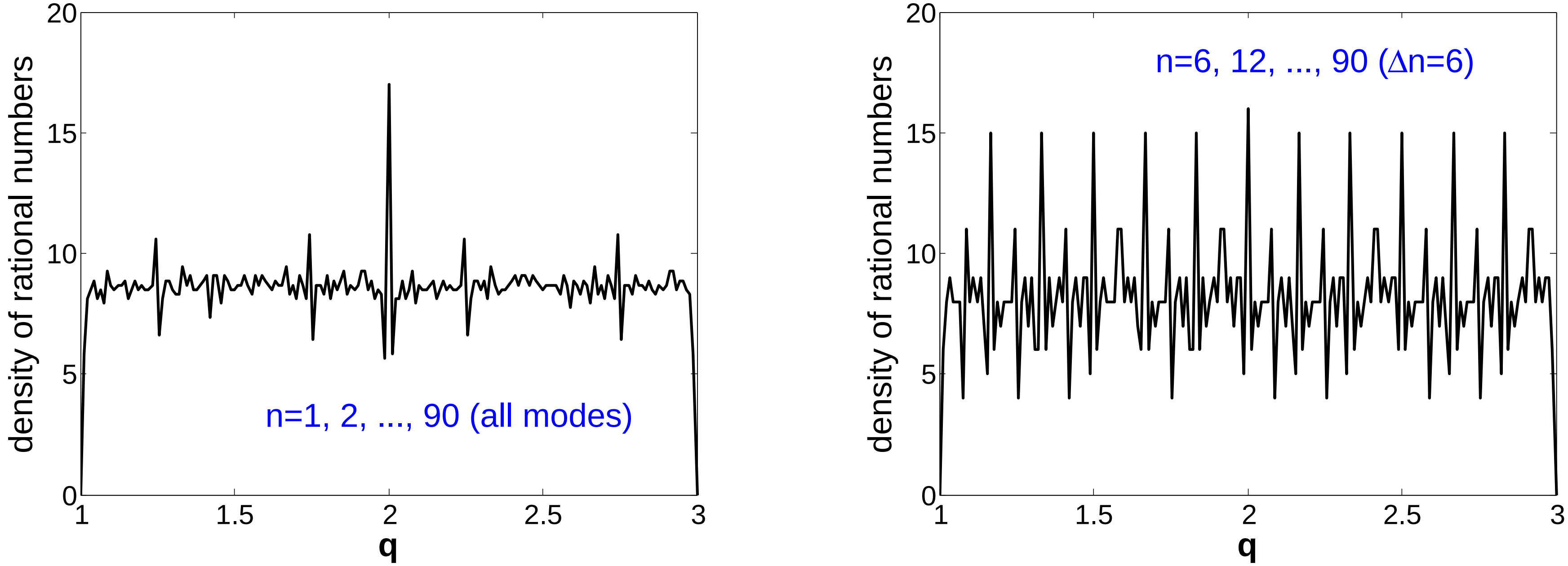




- Fluctuations peak at lowest-order rational surface $q = 2$ (and $q = 3$) (only in nonlinear phase)
- Zonal flow shear shows corrugated structure at the same location

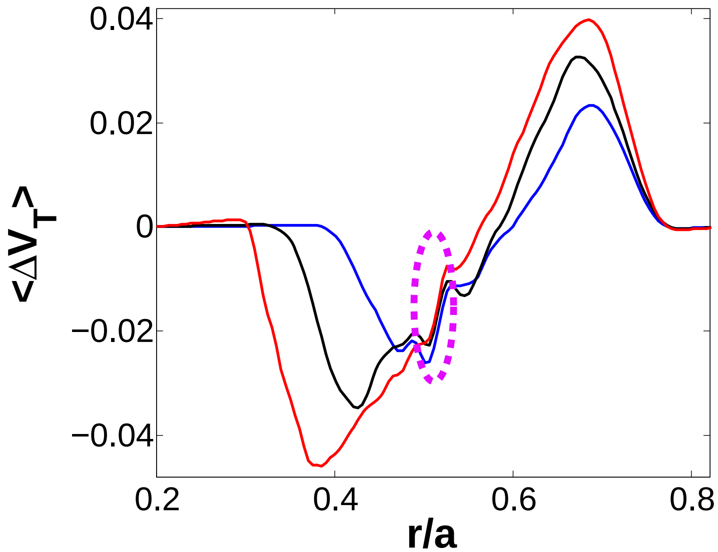
Why fluctuations peak at lowest-order rational surfaces with integer-q number – a theoretical explanation

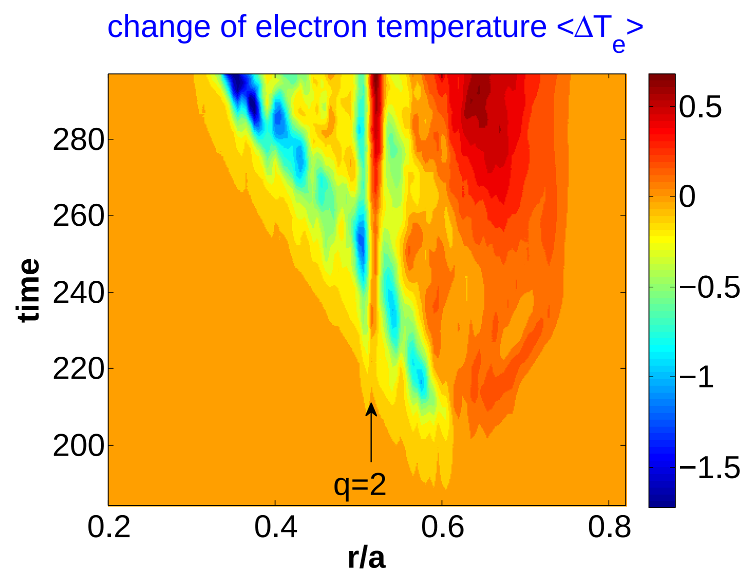
- Due to minimum Landau damping at $k_{\|} = 0$, $\phi_{m,n}$ peaks at $q(r) = m/n$
- $I(r) = \sum_{m,n} |\phi_{m,n}|^2 d_{m,n}(r) \sim \sum_{m,n} d_{m,n}(r)$ assuming $\phi_{m,n}$ same for all MRSs
- Example with $q = 1 + 2(r/a)^2$

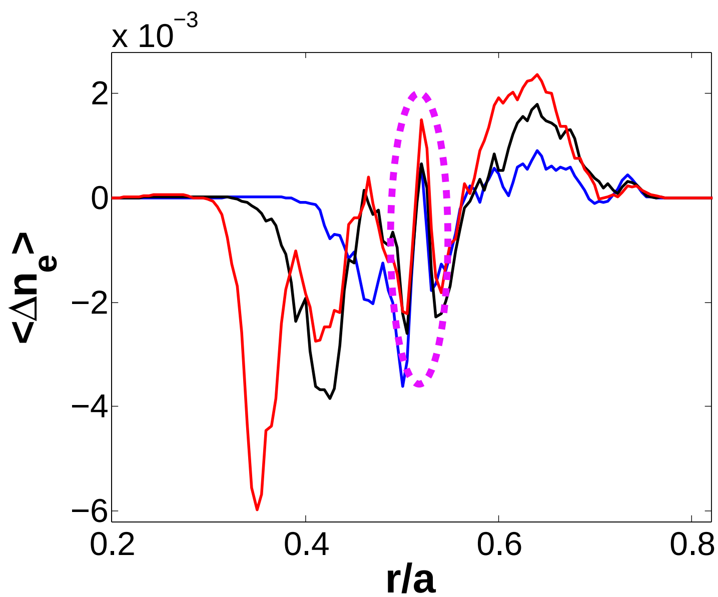


- Fluctuations peak at integer rational surfaces (rather than fractional!)
- Many spurious peaks at rational surfaces when using a subset of modes

Peaked fluctuations and transport impact plasma profile structure near integer rational surfaces







- Local "corrugations" generated in all radial profiles near integer rational surface: V_t, n_e, T_e and T_i
- Potential impact of profile corrugations:
  - transport barrier formation near (integer) rational surface (Waltz et. al., PoP'06)
  - electron scale turbulence via nonlinear ETG excitation

Summary

CTEM turbulence is found to drive a significant, quasi-stationary current

- Consistent results obtained between turb. sim. with and w/o NC physics
- Mainly carried by trapped electrons & driven by electron residual stress
- Similarity in characteristic dependence with neoclassical bootstrap current (but with different physics origins)
  – increases with ∇p; – decreases with equilibrium I_p (and B_p);
  – increases with magnetic shear dq/dr; – collisionality dependence

Strong flow shear may drive its own instability and turb. transport in tokamak

- Low-k range as ITG; smaller but almost constant growth rate; finite $k_{||}$
- Saturation via nonlinear toroidal energy transfer to lower-k modes and strong ZFs and GAMs generation
- Significant momentum & energy transport, including an intrinsic torque
- Fluctuations peak at integer (not fractional) rational surfaces
- local "corrugations" generated in all plasma profiles near the surfaces