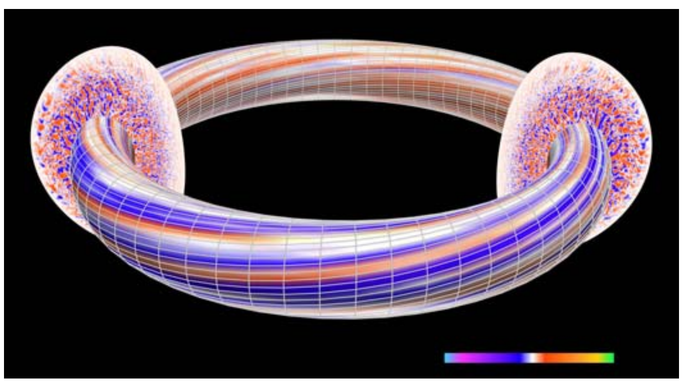
Fluctuation Driven Plasma Current, Poloidal Rotation and Flow Structure

W. X. Wang

in collaboration with

S. Ethier B. Grierson Y. Ren T. S. Hahm (SNU, Korea)
P. H. Diamond (UCSD & NFRI, Korea) F. L. Hinton (UCSD)
E. Startev J. Chen E. Feibush

Princeton Plasma Physics Laboratory



7th Festival de Théorie

8 - 26, July 2013

Aix-en-Provence, France

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

Outline

- Gyrokinetic simulation model
- Anomalous poloidal flow driven by fluctuations
- Fluctuation-induced plasma current generation
- Interesting GAM structure and implications
- Summary

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

$\dot{\vec{Z}} \equiv \dot{\vec{Z}}_0 + \dot{\vec{Z}}_1$; $\dot{\vec{Z}}_1$ – 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:

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

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

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

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

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

– Weight equation

$$\dot{w}=\frac{1-w}{f_0}\left[-\frac{1}{B^*}\nabla_Z\cdot(\dot{\vec{Z}}_1B^*f_{a0})\right]+\frac{w-\langle w\rangle}{f_0}\left[-\frac{1}{B^*}\nabla_Z\cdot(\dot{\vec{Z}}_1B^*f_{a0})\right]$$

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

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

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

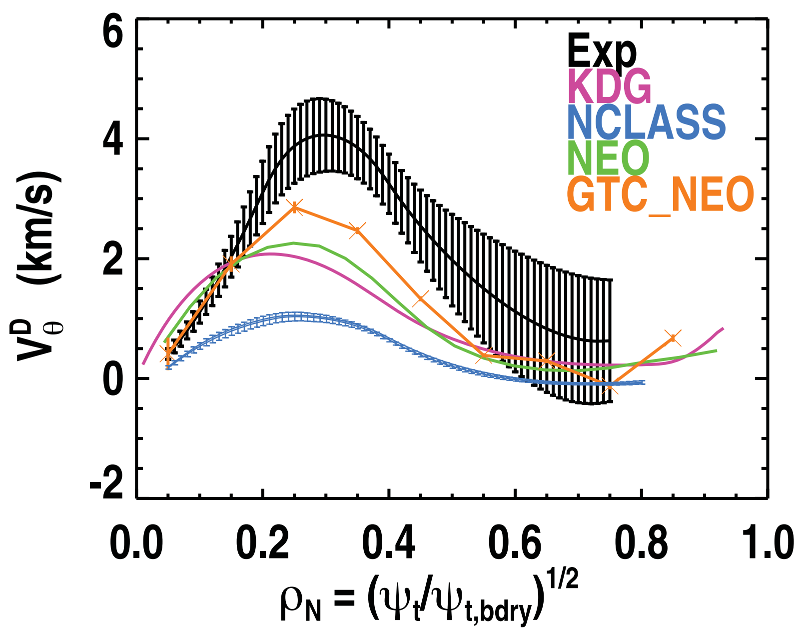
- Fully kinetic electrons (both trapped and untrapped electron dynamics)
- Linearized Fokker-Plank operator with particle, momentum and energy conservation for i-i and e-e collisions; Lorentz operator for e-i collisions
- Interaction with neoclassical physics with two options
  i) include both turbulent and neoclassical physics self-consistently
  ii) import GTC-NEO result of equilibrium E_r into GTS
- Full geometry, global simulation

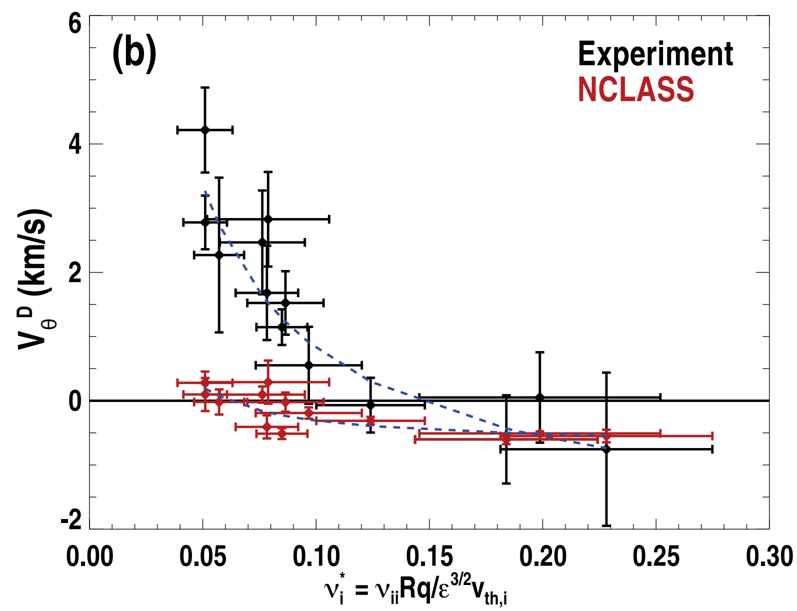
Observation of anomalous poloidal flow and impact on ITER confinement performance

- Significant v_θ contribution to E_r likely in ITER

$$E_r = \frac{1}{ne}\frac{\partial p}{\partial r} + \frac{1}{c}(B_\theta V_t - B_t V_\theta)$$

- Large difference in poloidal flow between DIII-D exptl. and NC value in low-collisionality regime with steep ∇T_i (B. Grierson, 2013)





- Associated $\mathbf{E} \times \mathbf{B}$ shear may significantly impact ITER confinement

Possible new mechanisms for poloidal flow generation

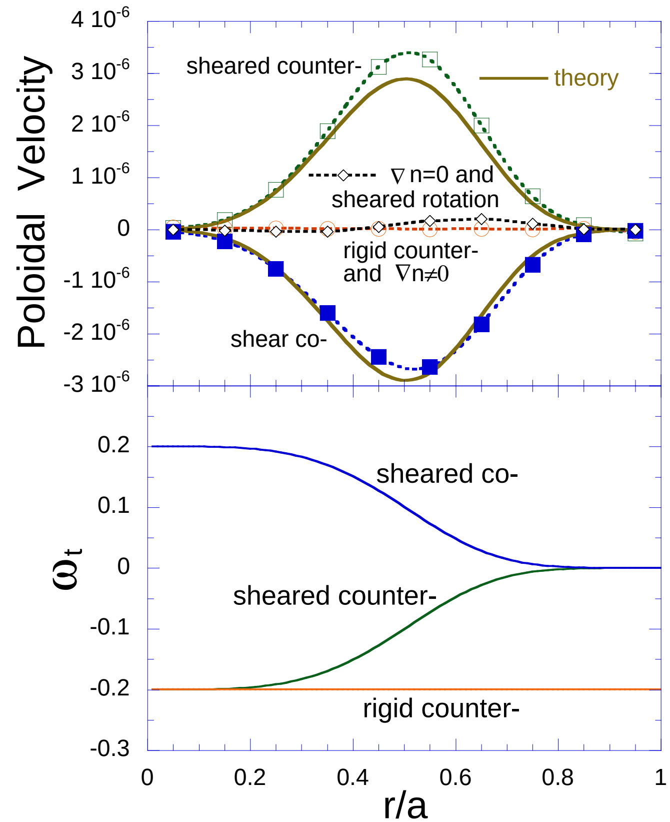
- Nonlocal NC EQ in collisionless regime:

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

- Additional poloidal flow due to finite orbits identified by GTC-NEO:

$$\langle u_\theta \rangle = u_{\theta,0} - \frac{1}{2}\left\langle \rho_{i\theta}^2 \right\rangle \frac{B_\theta}{B}\left\langle \frac{I}{B}\right\rangle \frac{\partial \ln p_i}{\partial r}\frac{\partial \omega_t}{\partial r}$$

(Wang et.al., '06; Kolesnikov et.al., '10)

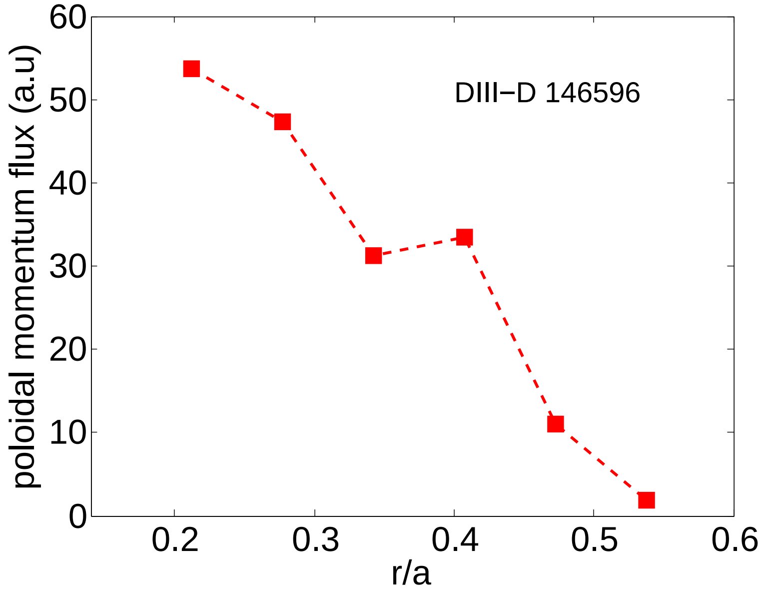


- Poloidal flow generation by turbulence((Diamond & Kim, '91; Pif-Pradalier et.el., '09; McDevitt et. al., 10)

  torque induced by poloidal Reynolds stress: $\Pi^{\mathrm{RS}}_{r,\theta} \sim \langle \tilde{v}_r \tilde{v}_\theta \rangle$

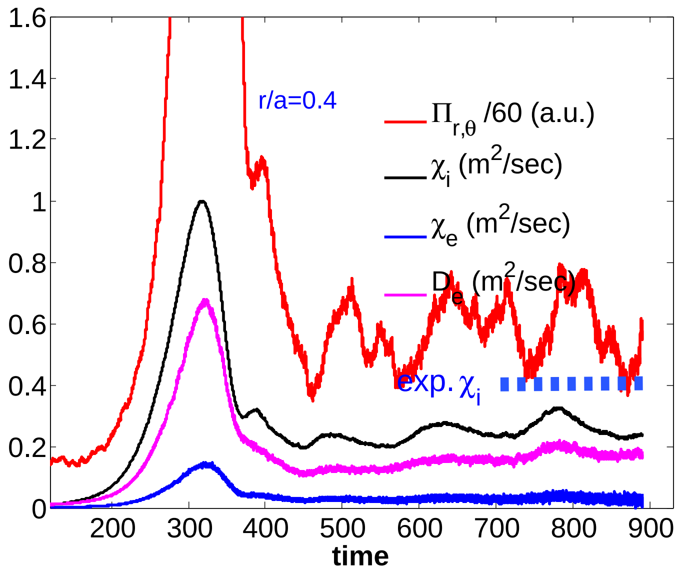
- Examine characteristic dependence using large exptl. database: $(u_\theta^{exp} - u_\theta^{th})$ vs. $\delta\tilde{n}$, $\nabla\omega_t$, ∇p

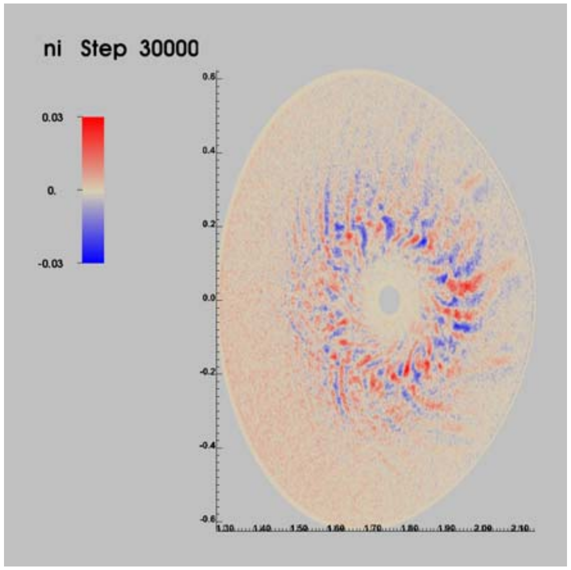
Fluctuation-induced torque is shown at right location & in right direction for driving poloidal flow

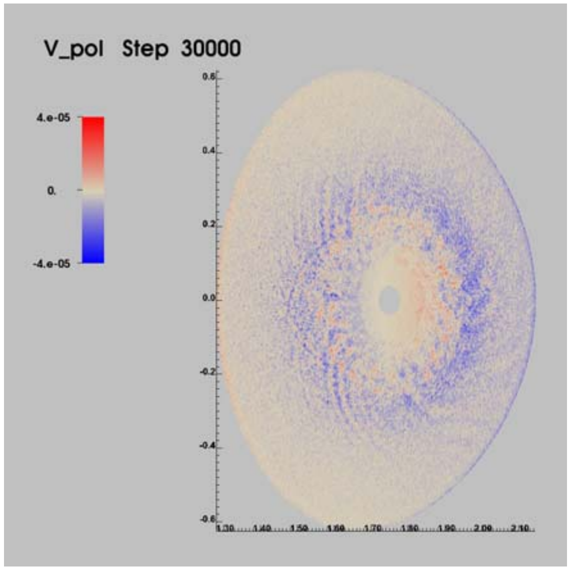


Simulation incl. kinetic electron & NC phys.

- ECH-induced H-mode plasma
- anomalous V_θ observed in $r/a \sim 0.2$ - 0.6
- mild heat transport produced by ITG
- significant poloidal RS produced $\nabla \cdot \Pi^{RS}_{r,\theta} \rightarrow$ positive torque for V_θ
- Poloidal torque density $\sim$ Nt/m^3

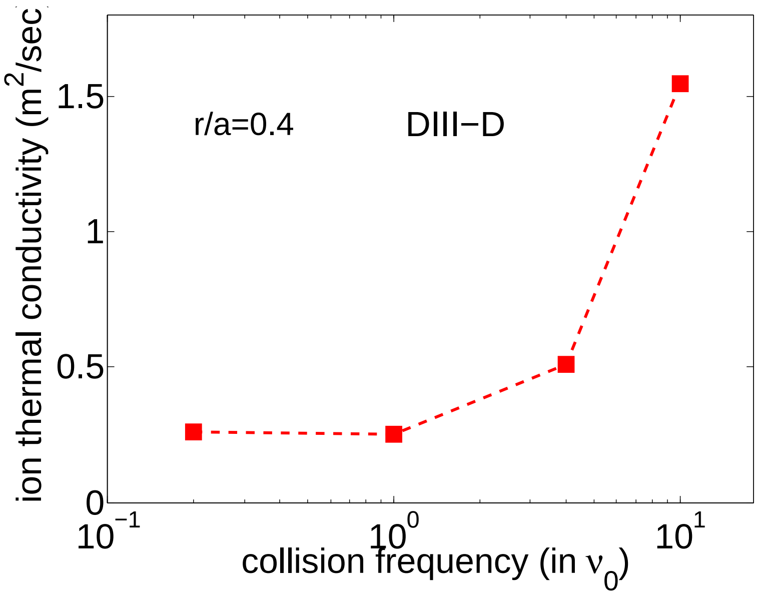






PPPL

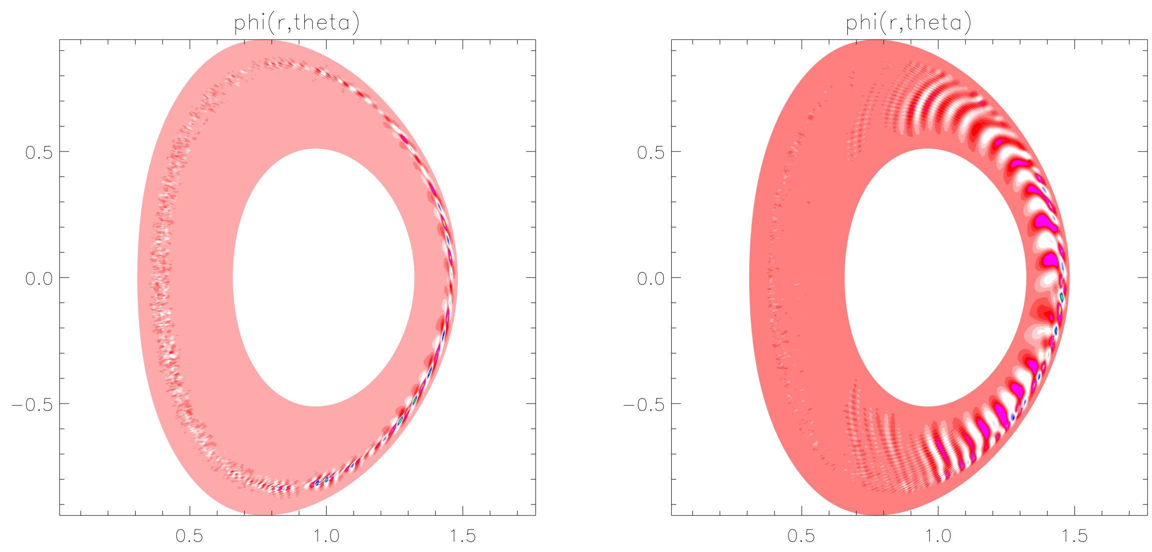
How collisionality dependence comes in

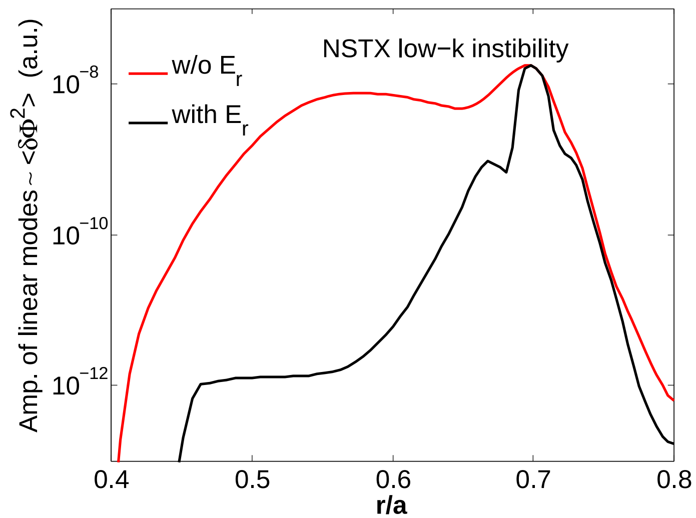


ν_* effects on fluctuations & transport

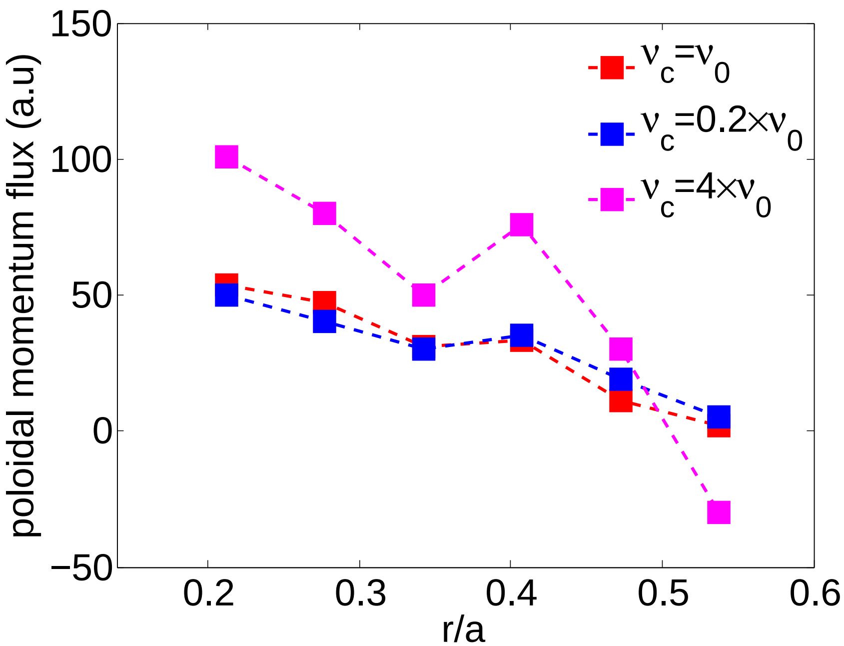
- Collisional zonal flow damping
- Strong ν_* dependence of ITG driven χ_i
- Same behavior likely for ETG driven χ_e
  $\rightarrow$ a possible origin for confinement scaling observed in NSTX $\sim 1/\nu_{*,e}$

Strong $\mathbf{E} \times \mathbf{B}$ shear wipes out most of low-k fluctuations in NSTX





Where collisionality dependence comes from



- Weak ν_* dependence in low collisionality regime due to time scale separation
- ν_* dependence in CTEM regime?
  – competing between ZF damping & CTEM weakening

- Collision effect on poloidal flow dissipation
  – magnetic pumping induce viscous damping $\sim \nu_{ii} V_\theta$
  – viscous heating (kinetic energy $\rightarrow$ thermal energy)
  – mean V_θ determined by balance $\nabla \cdot \Pi^{\mathrm{RS}}_{r,\theta} \sim \nu_{ii} V_\theta \rightarrow \nu_*$ dependence

Strong correlation shown between fluctuation driven V_θ and V_ϕ generation

Correlation coefficients: $R[\Pi^{RS}_{r,\theta}, \Pi^{RS}_{r,\phi}] > 0.7$; $R[\tilde{v}_\theta, \tilde{v}_\phi] > 0.9$;

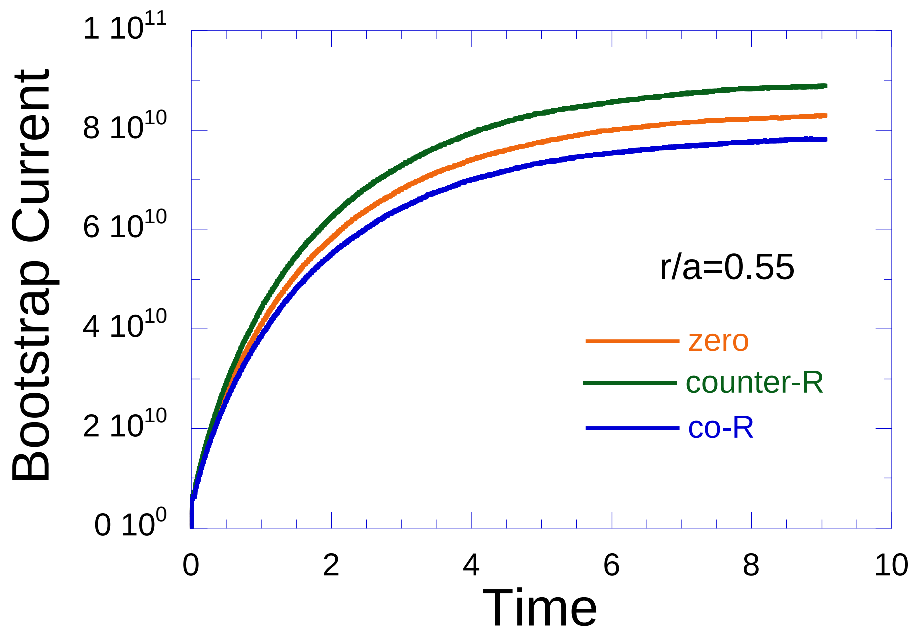
Can turbulence drive plasma current or change bootstrap current?

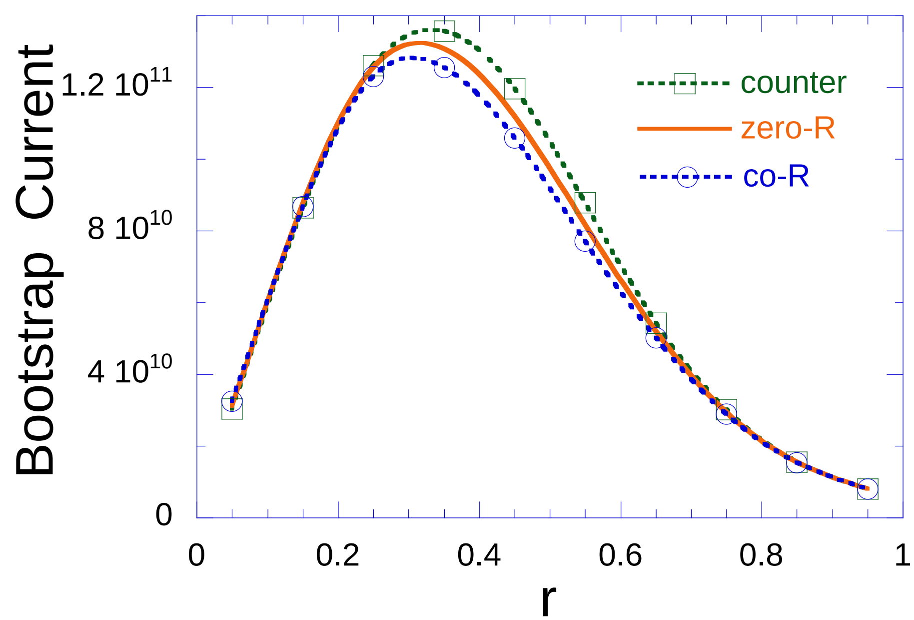
- Plasma self-generated non-inductive current is of great importance
  - NTM physics, ELM dynamics, overall plasma confinement
- Bootstrap current J_{bs} – a well known non-inductive current
  - driven by pressure and temperature gradients in toroidal geometry
  - associated with existence of trapped 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:

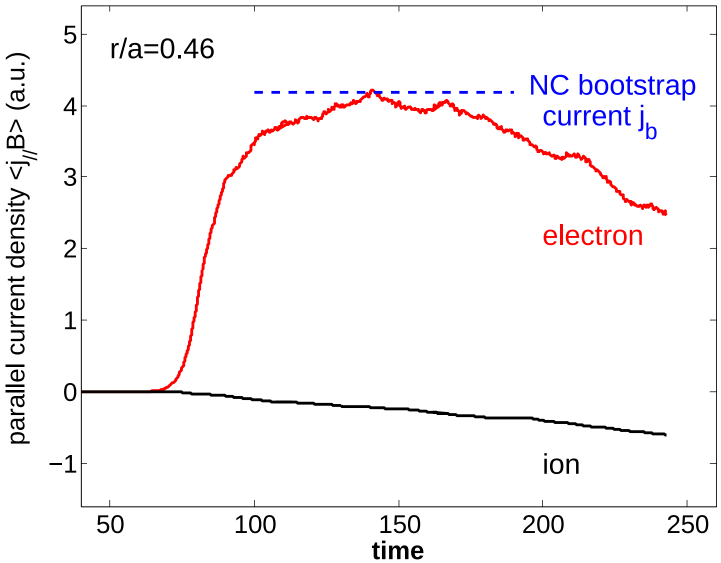
$$\Delta u_{i\parallel} \simeq -\frac{m_i c}{e} \left\langle \frac{I^2}{B^2} \right\rangle \frac{cT_i I}{eB} \frac{\partial \ln n_i}{\partial \psi_p} \frac{\partial \omega_t}{\partial \psi_p}.$$

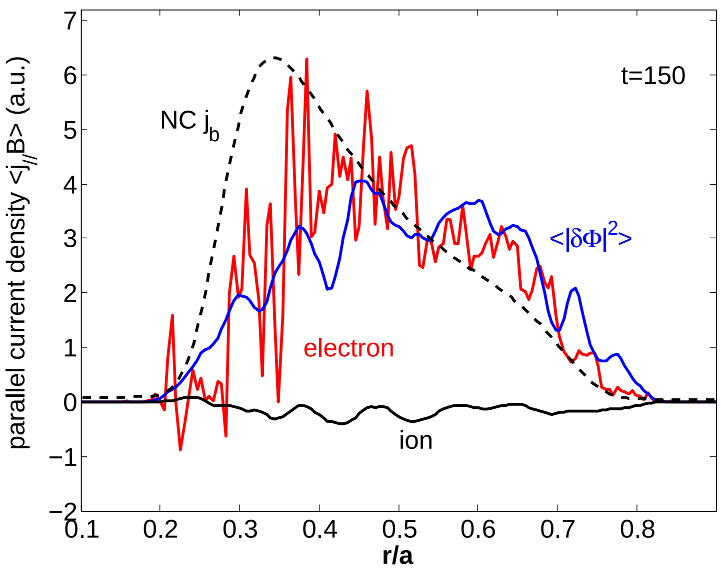




(Wang et. al., '06)

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





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

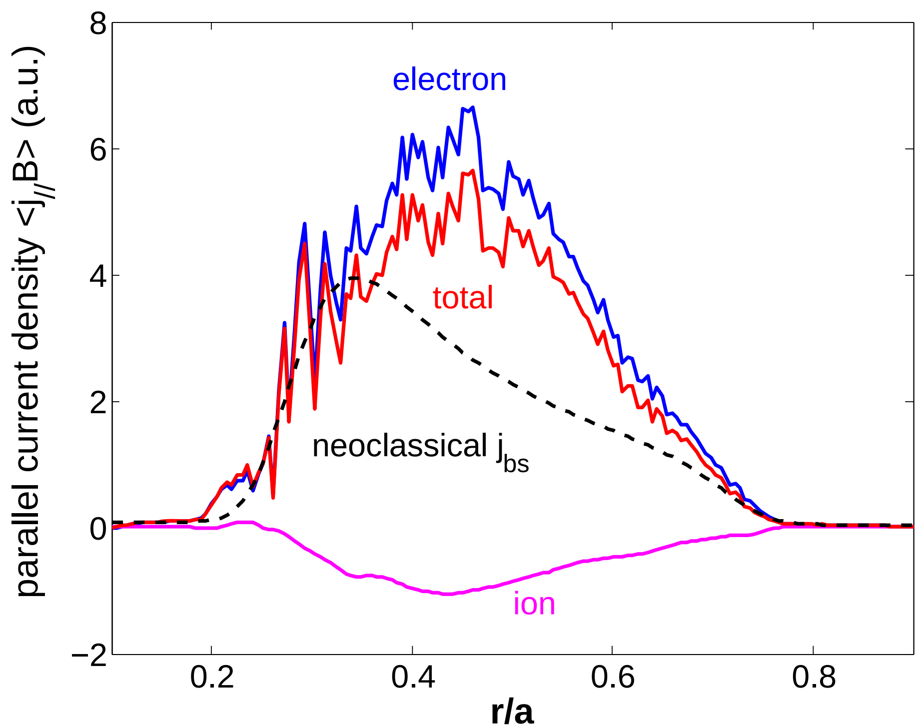
DIII-D size geometry;
$R_0/L_{T_e} = R_0/L_n = 6$;
$R_0/L_{T_i} = 2.4$; initially rotation free;
mean $\mathbf{E} \times \mathbf{B}$ included

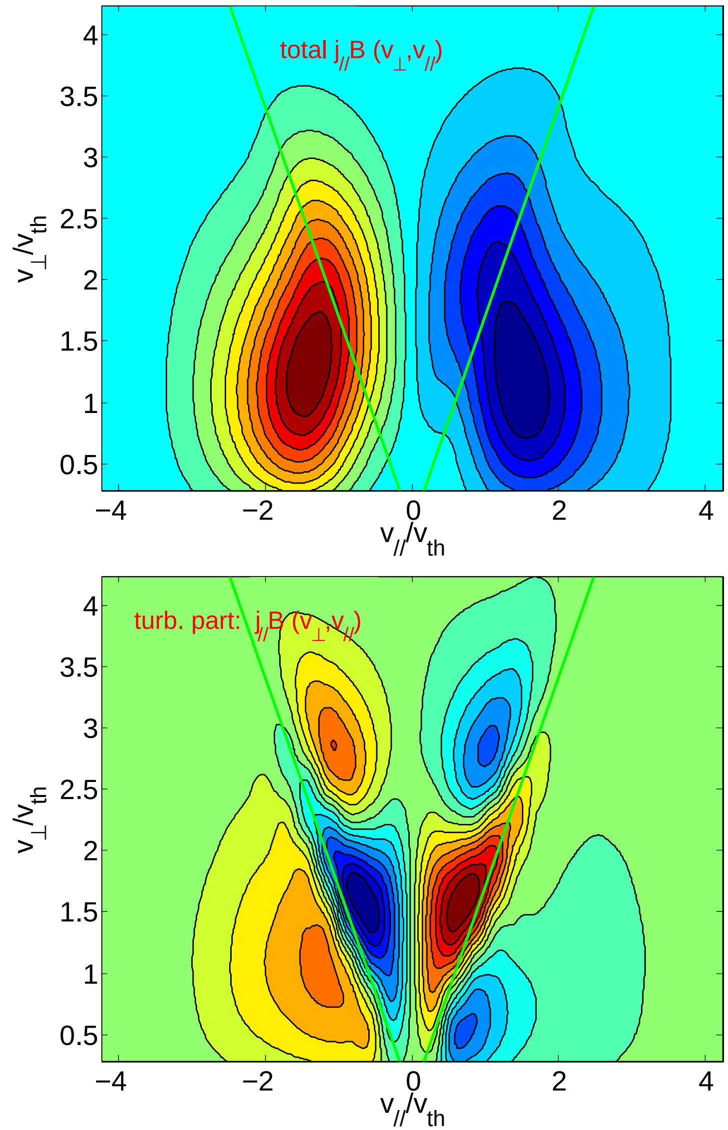
- electrons carry most of current in $+\mathbf{B}$ direction
- ions carry small current in $-\mathbf{B}$ direction
- fine radial scales presented in electron current
- Much weaker current generation by ITG

PPPL

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

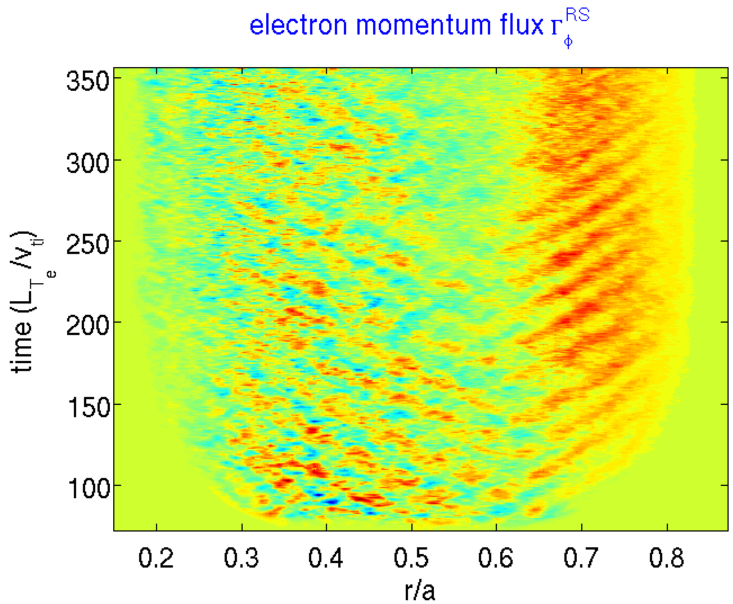
- New sim. incl. both turb. & NC physics simultaneously in CTEM regime





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

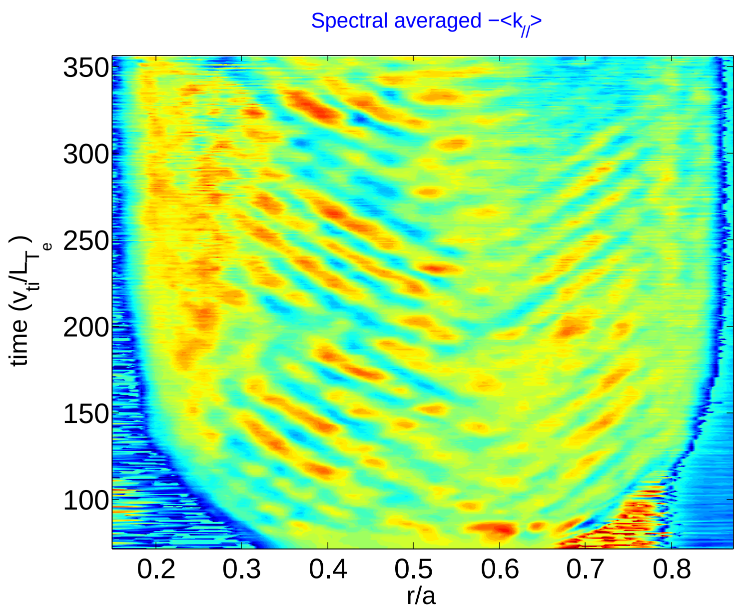
Fluctuation induced current is associated with nonlinear electron flow generation

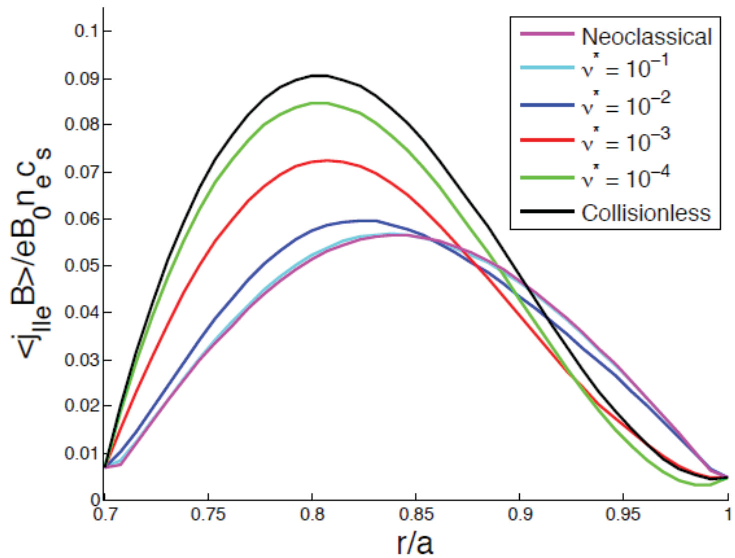


$$\langle j_\parallel B\rangle = e\langle n(u_{i\parallel} - u_{e\parallel})B\rangle$$

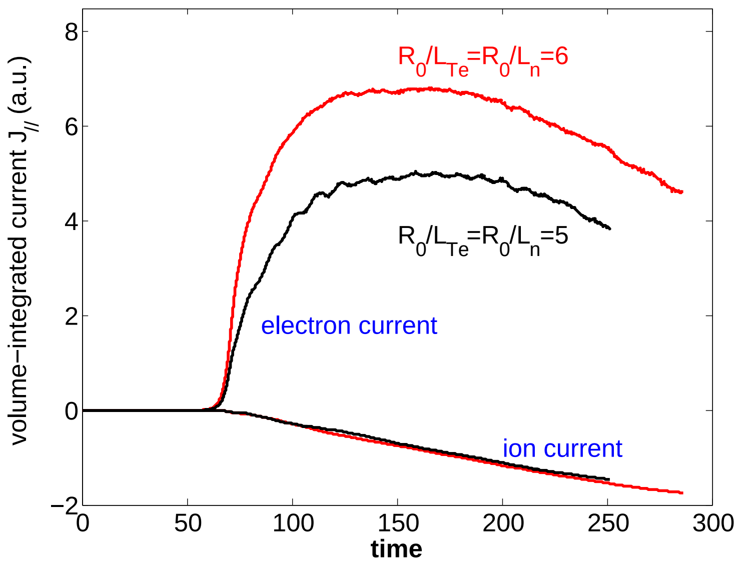
- Electron flow generation by turb. residual stress due to $k_\parallel$ symmetry breaking
- Turbulence acceleration of electrons ?

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



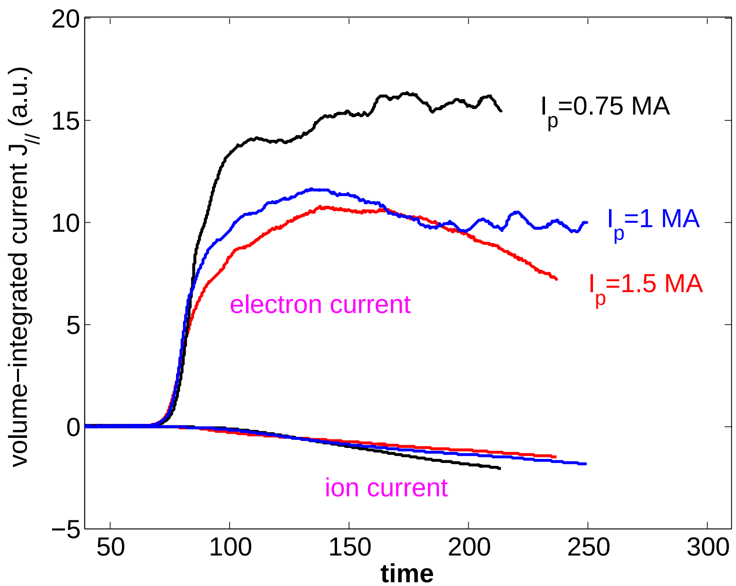


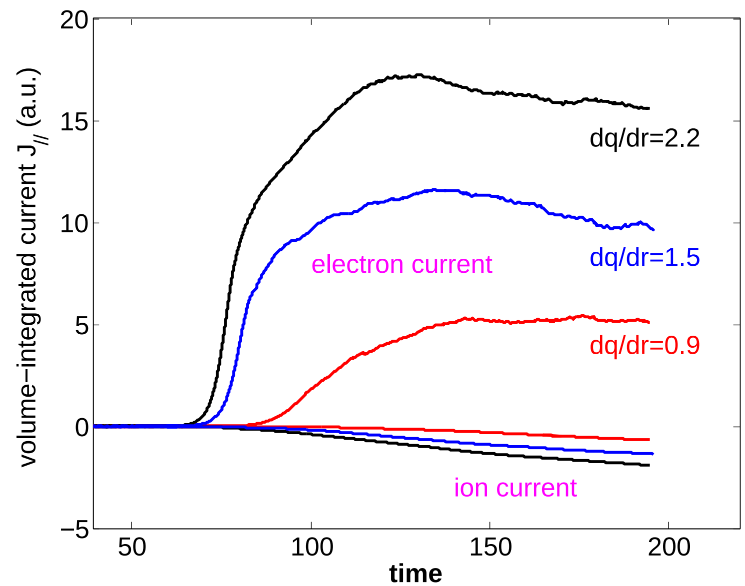
Characteristic dependence of fluctuation induced current generation



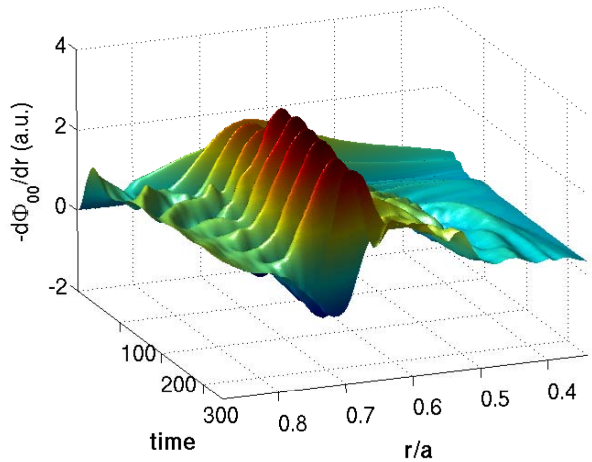
Share similarity wth conventional bootstrap current, but with different physics origins

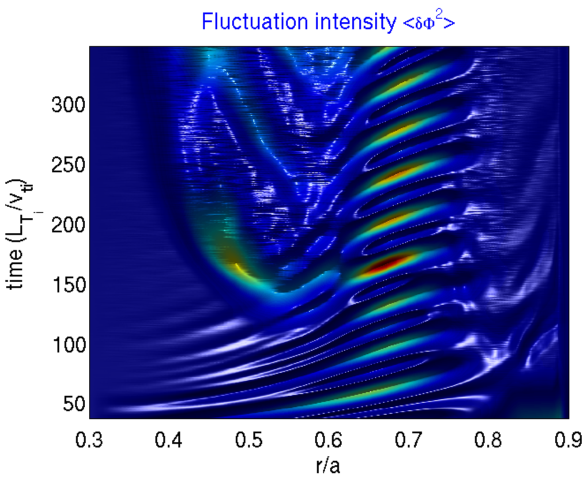
- increases with ∇p
- decreases with B_p
- increases with magnetic shear dq/dr
- collisionality dependence

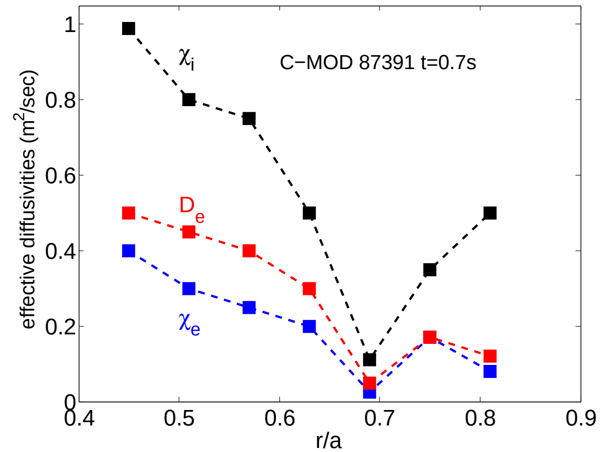


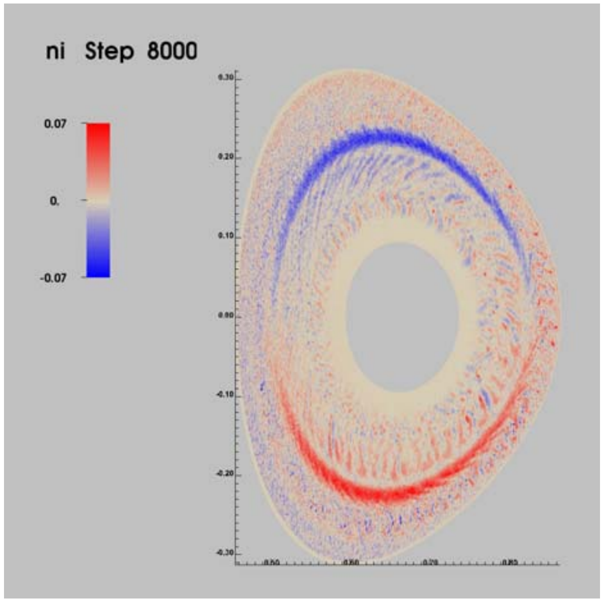


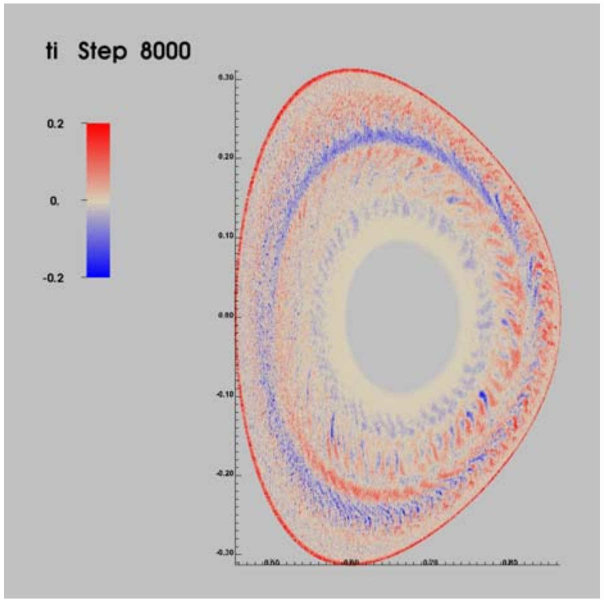
Dominant GAMs and impact in C-MOD L-mode phase

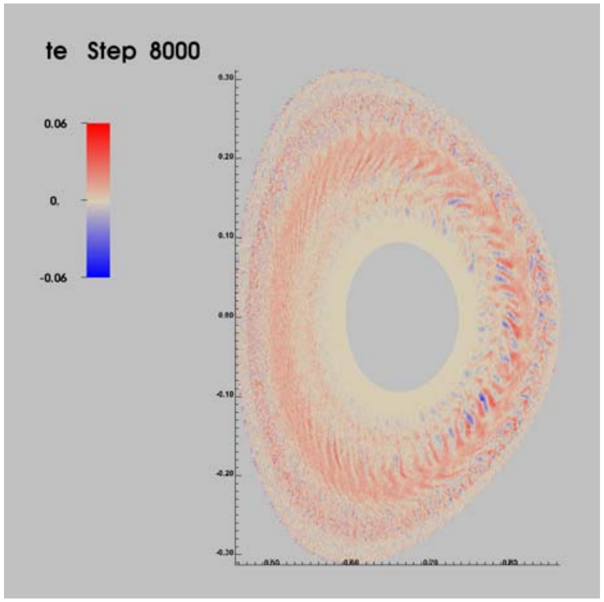








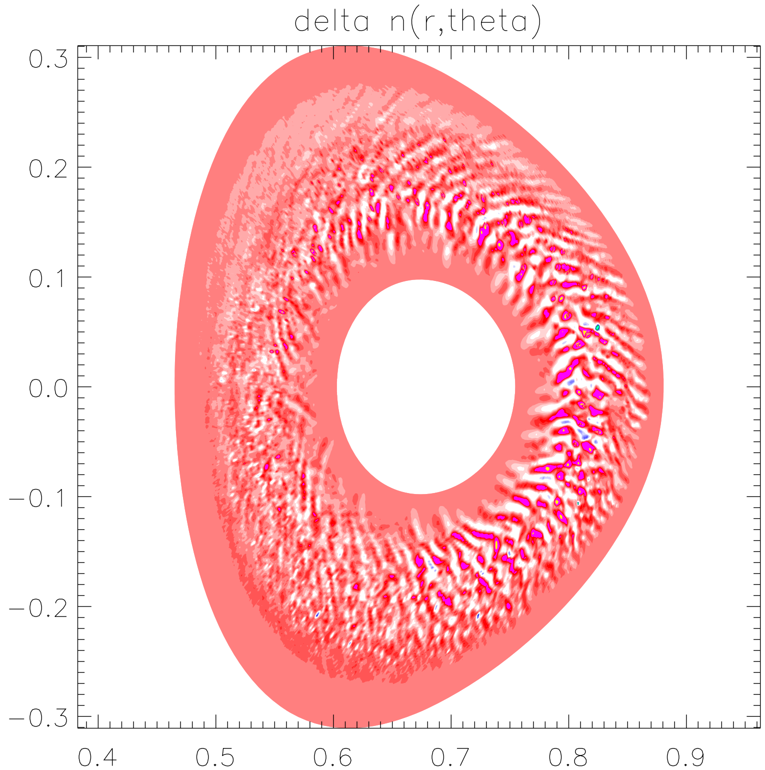




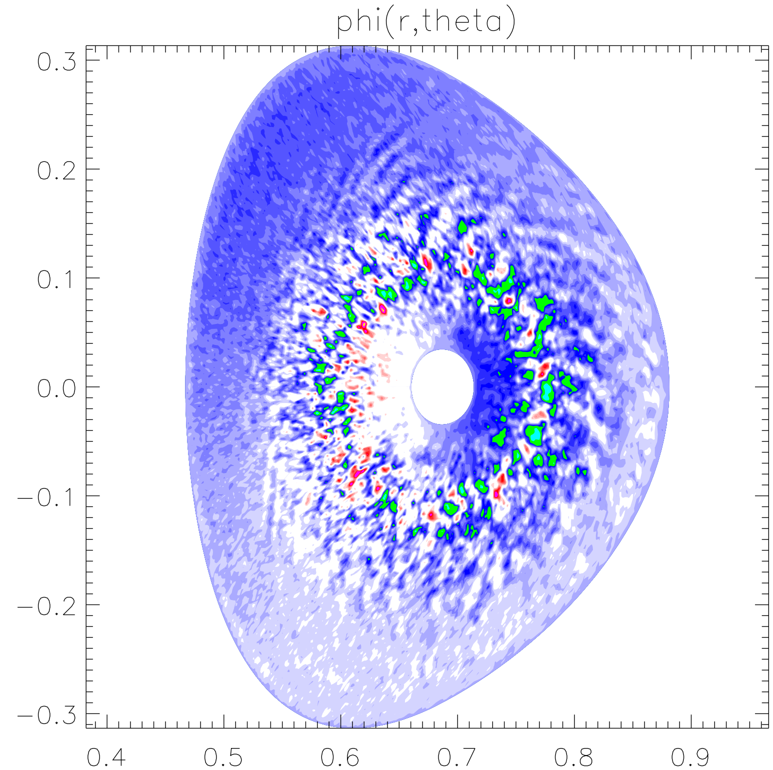
- GAMs dominate over zero-ω ZFs near $r/a \sim 0.7$ in L-mode phase
- Transport largely suppressed by GAMs locally with a max. ∇T_i presented

Dominant GAMs and possible implication (for discussion)

- No strong GAMs presented in I-mode phase & in sim. excluding NC phys.



L-mode sim. w/o NC physics



I-mode sim. incl. NC physics

- GAMs may play a dominant role over ZFs in edge as exptls. suggested
- GAM layer decouples inside & outside plasma $\rightarrow$
  rational reversals occur inside $q = 3/2$ surface in C-MOD Ohmic L-mode?

Summary

ITG fluctuation-induced poloidal Reynolds stress is shown to provide an effective torque for driving anomalous poloidal flow observed in DIII-D

- At right location, in right direction and with needed amplitude
- Fluctuation induced torque weakly depends on ν_* in collisionless regime
- Collisionality dependence of anomalous V_θ likely from viscous damping due to magnetic pumping

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

Dominant GAM structures and impact/implications suggested for C-MOD Ohmic L-mode phase