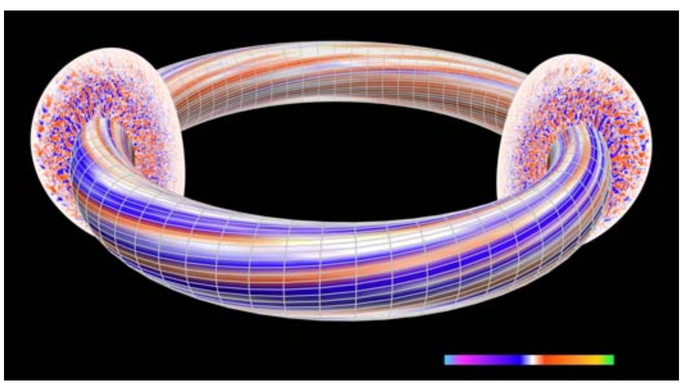
Toroidal Flow Shear Driven turbulence and Transport

W. X. Wang

in collaboration with

S. Ethier F. L. Hinton (UCSD) T. S. Hahm (SNU, Korea)
P. H. Diamond (UCSD & NFRI, Korea) W. M. Tang
Z. Q. Li (ZJU, China) E. Feibush

Princeton Plasma Physics Laboratory



54^{th} APS - DPP
Oct. 29 - Nov. 2, 2012
Providence, Rhode Island

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

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

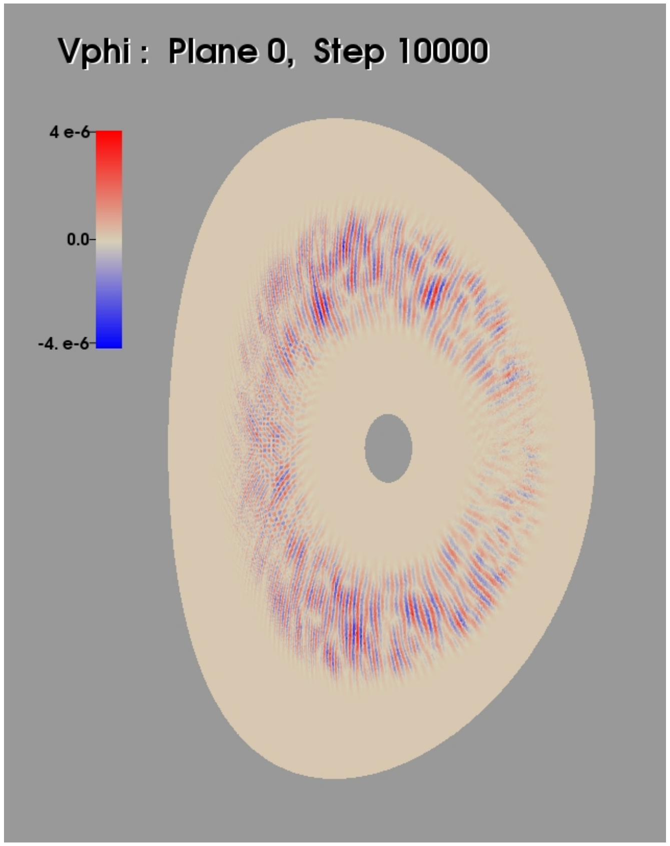
  (Diamond et. al., NF'09)
- Both achievable amplitude and flow structure are important
- Free energy in flow gradient may drive its own instability and turbulence
  - velocity shear drive Kelvin-Helmholtz instability in fluid
  - in plasmas, flow shear may drive a negative compressibility mode

    (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

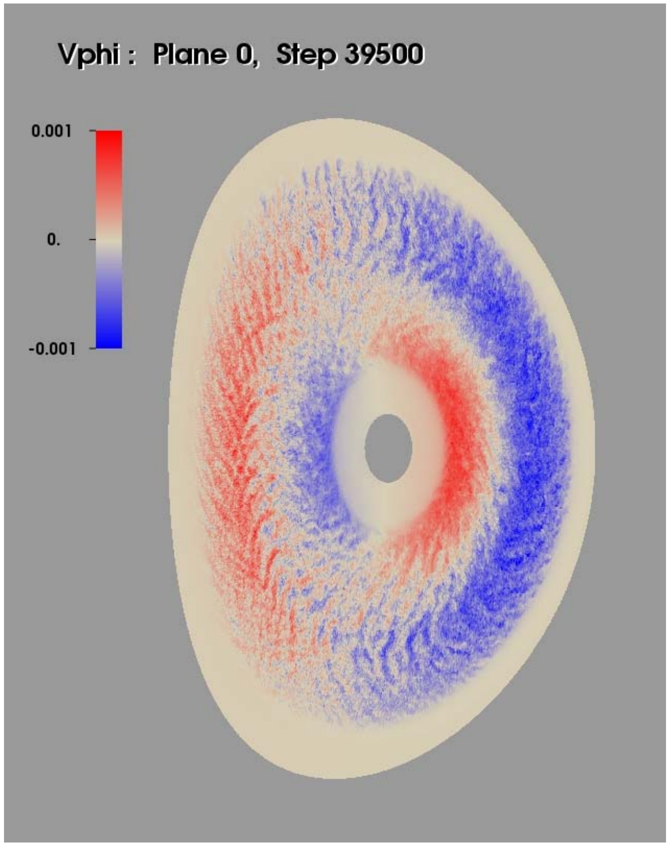
Turbulence generated flow shows strong poloidal variation

- First order (in ρ_i) plasma flow:
  $\mathbf{V} = \omega(\psi)R\hat{\phi} + K(\psi)\mathbf{B}$; $\quad V_\phi(\psi,\theta) = \omega(\psi)R(\psi,\theta) + K(\psi)B_\phi(\psi,\theta)$
  Arguments involved: i) flow within magnetic surface; ii) incompressible
- CTEM driven rotation: dominated by $(m,n) = (1,0)$ and zonal mode (0,0)
- To test in experiments and to understand its impact on turbulence

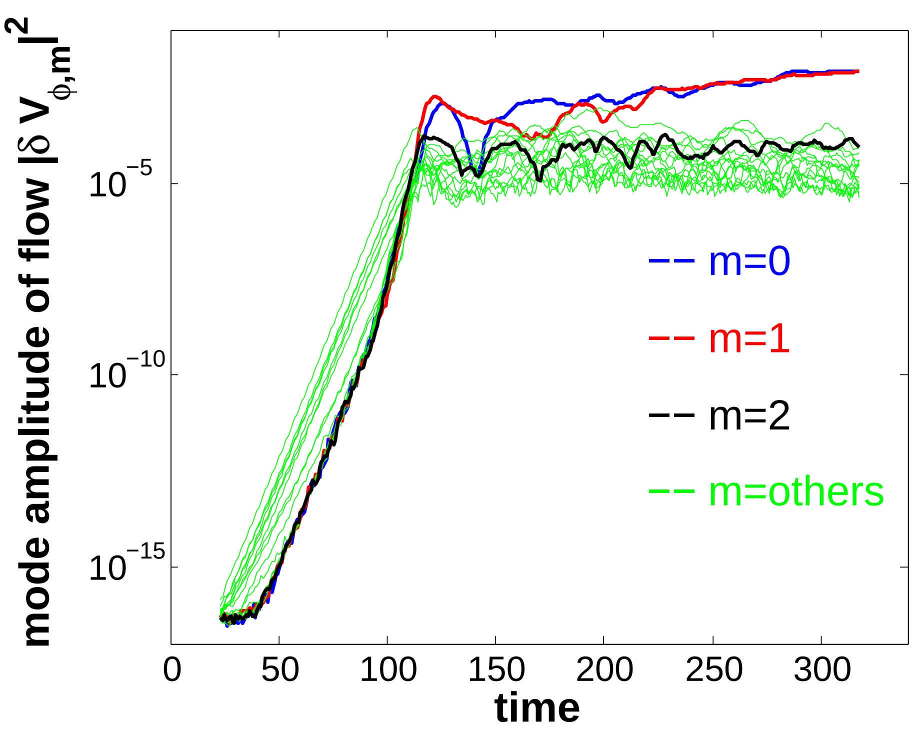


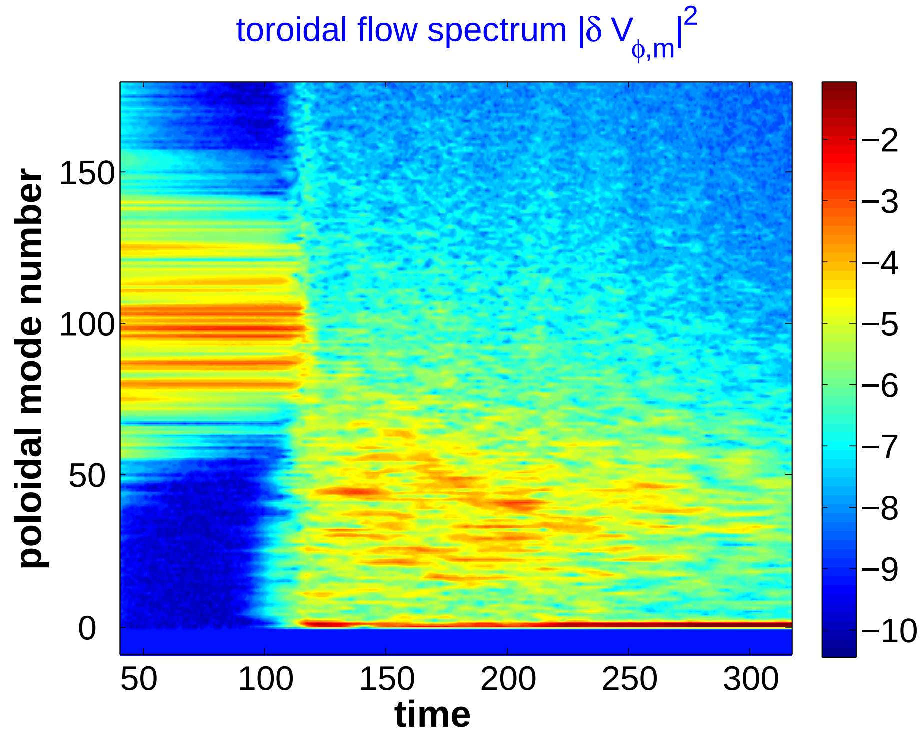
Toroidal Component of Plasma Flow V_ϕ

(E. Feibush)



Nonlinear process for flow structure formation

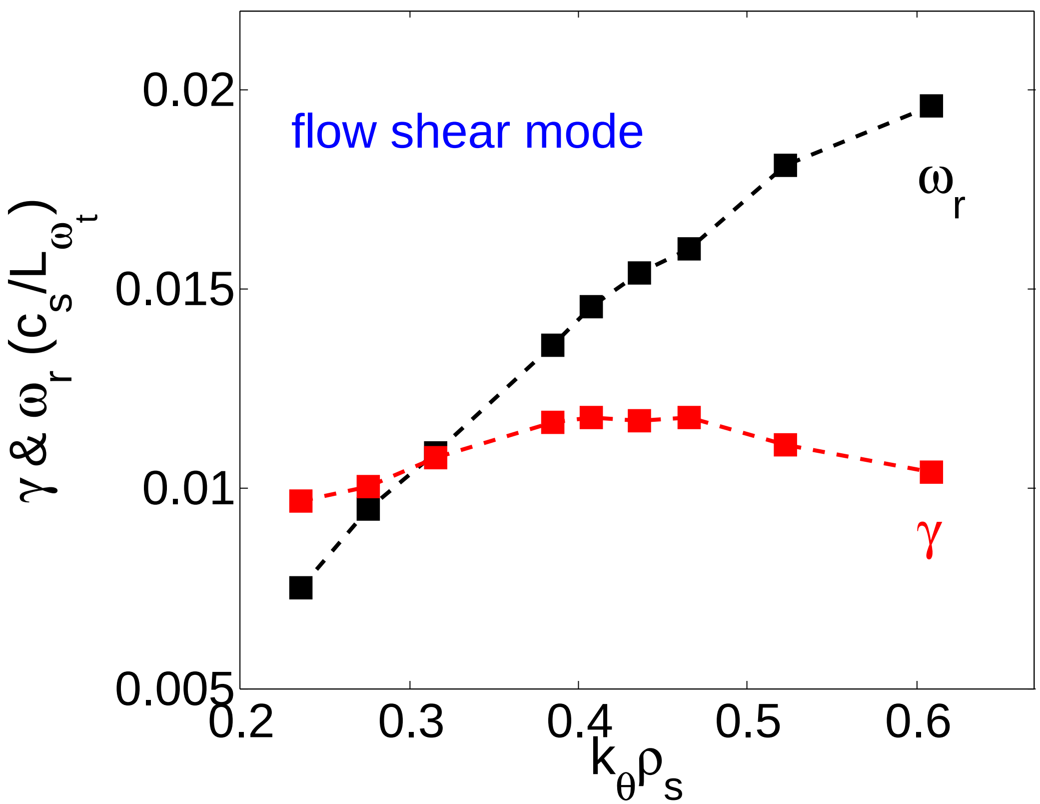


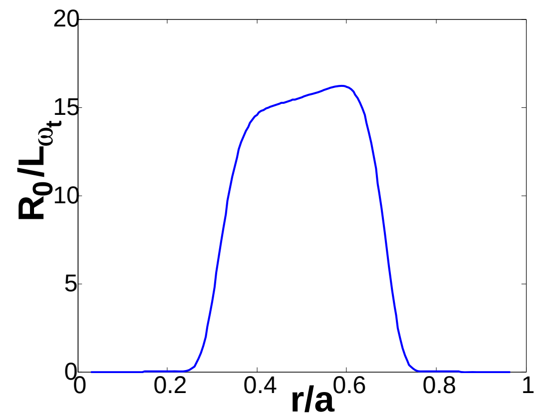


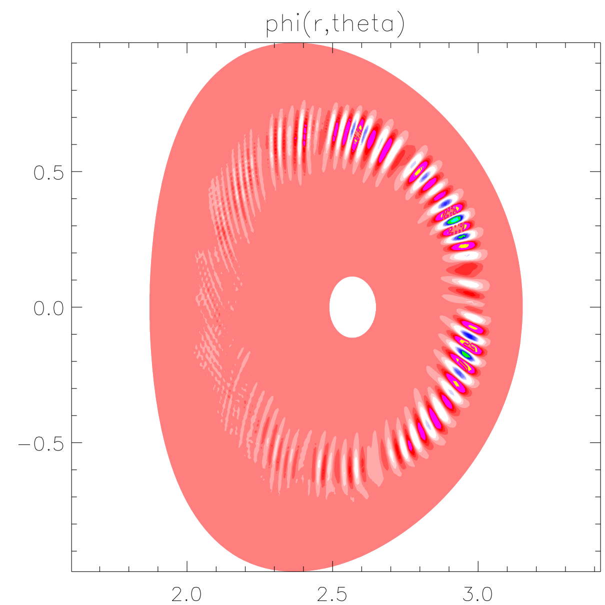
- Amplitudes of (1,0) and (0,0) components are comparable and much larger than others
- Nonlinear toroidal mode couplings transfer energy of flow fluctuations from small to large scale

Flow shear can drive drift wave unstable 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

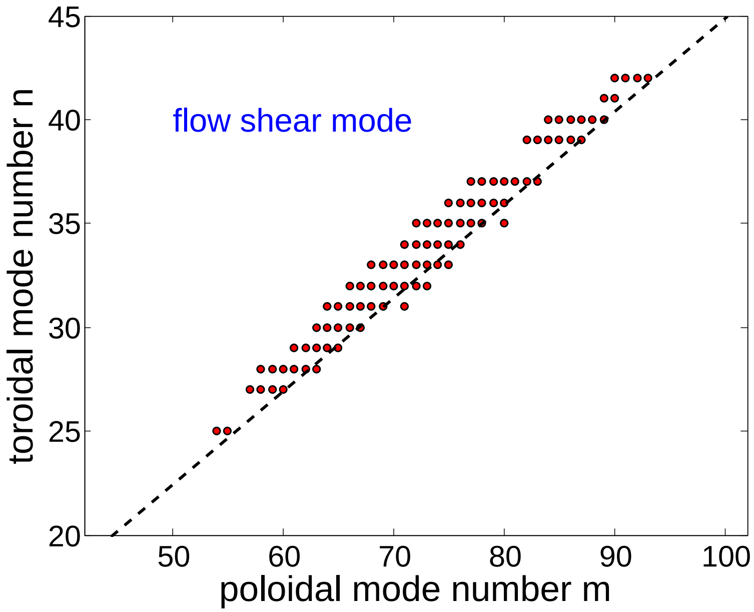






- Low-k mode (in same range of ITG mode)
- Smaller but almost constant growth rate

Distinct linear features of flow shear instability

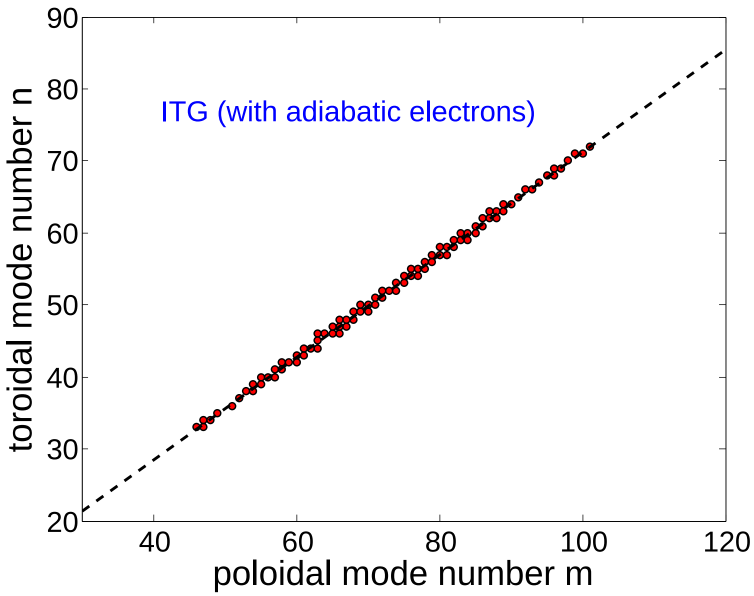


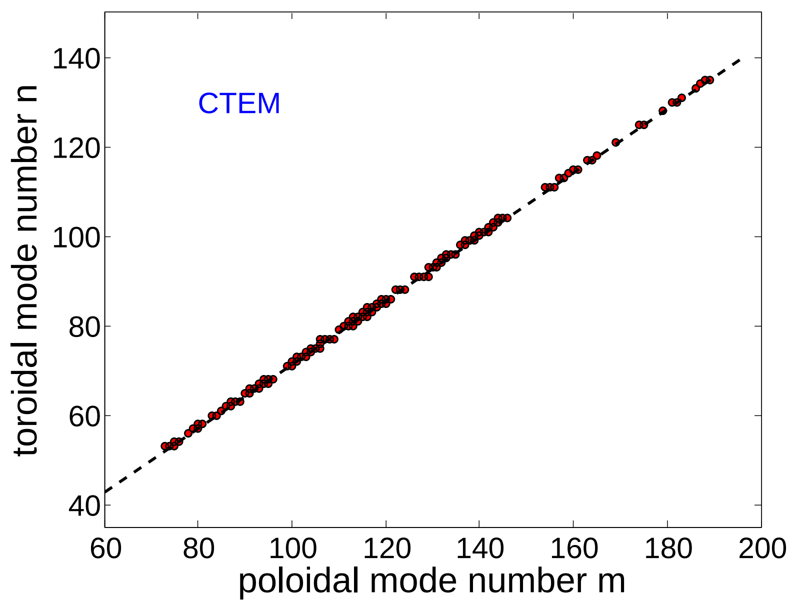
- significant finite $k_{\|}$

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

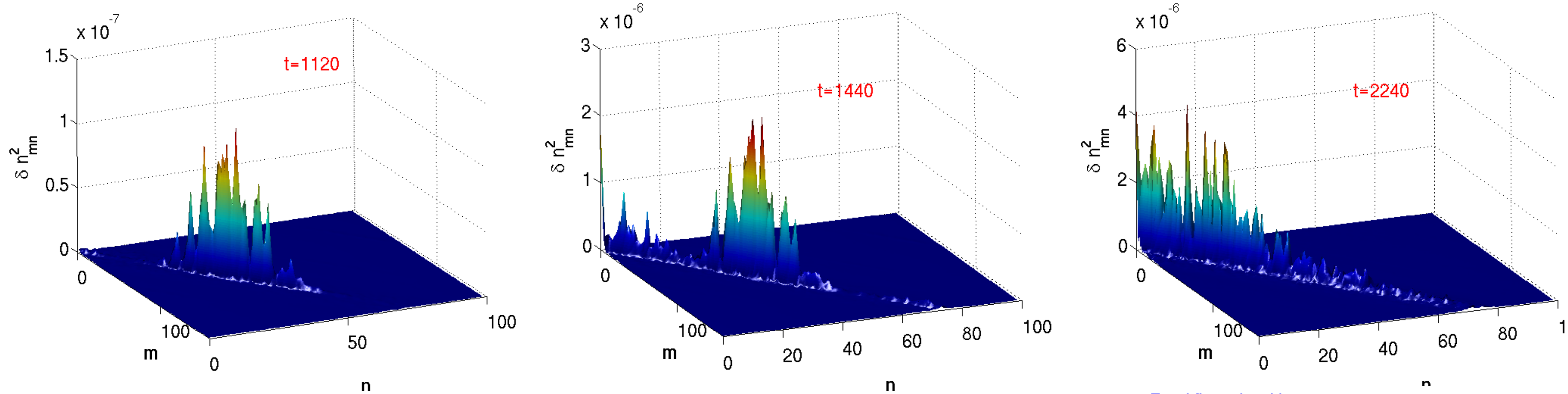
- asymmetry (impact on residual stress generation)

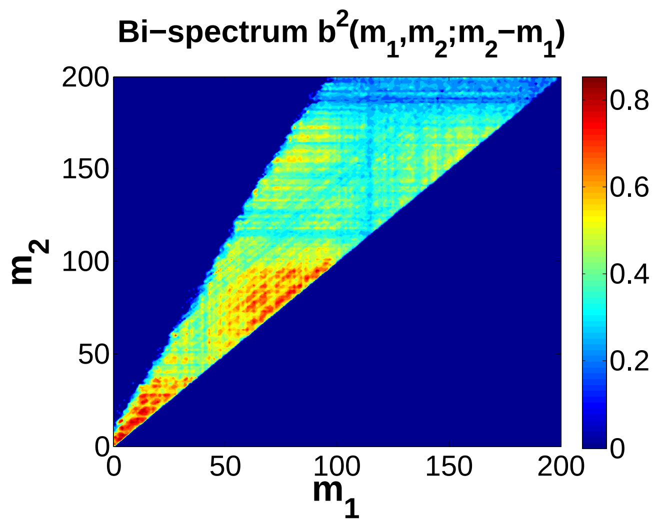
- broad poloidal mode coupling

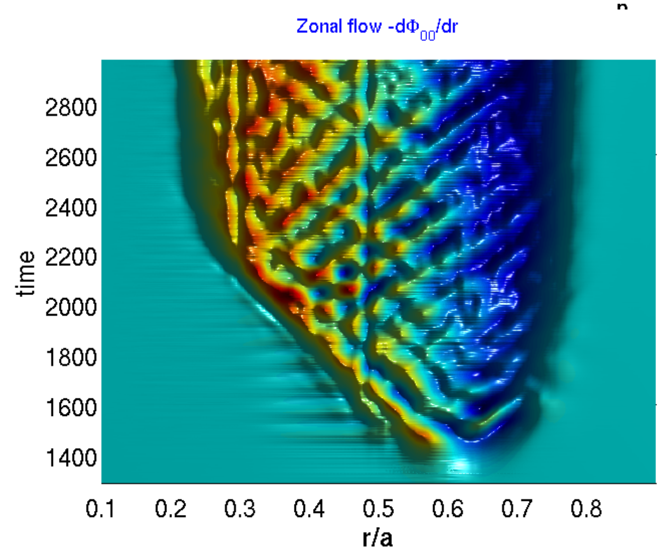




Nonlinear toroidal mode couplings play a key role to cause flow shear turbulence saturation



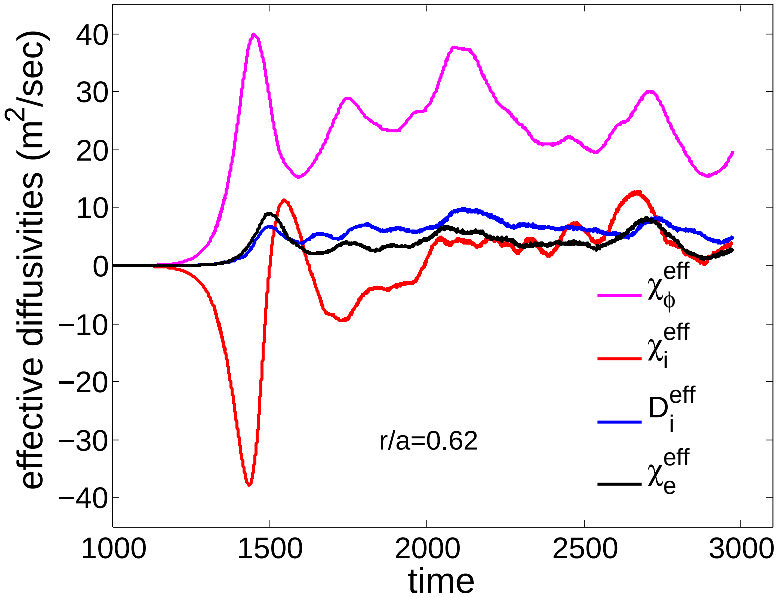


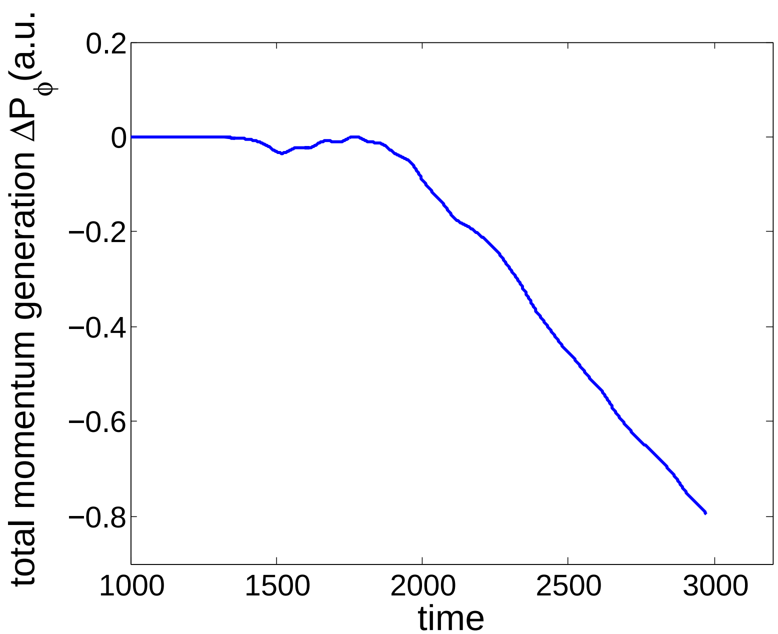


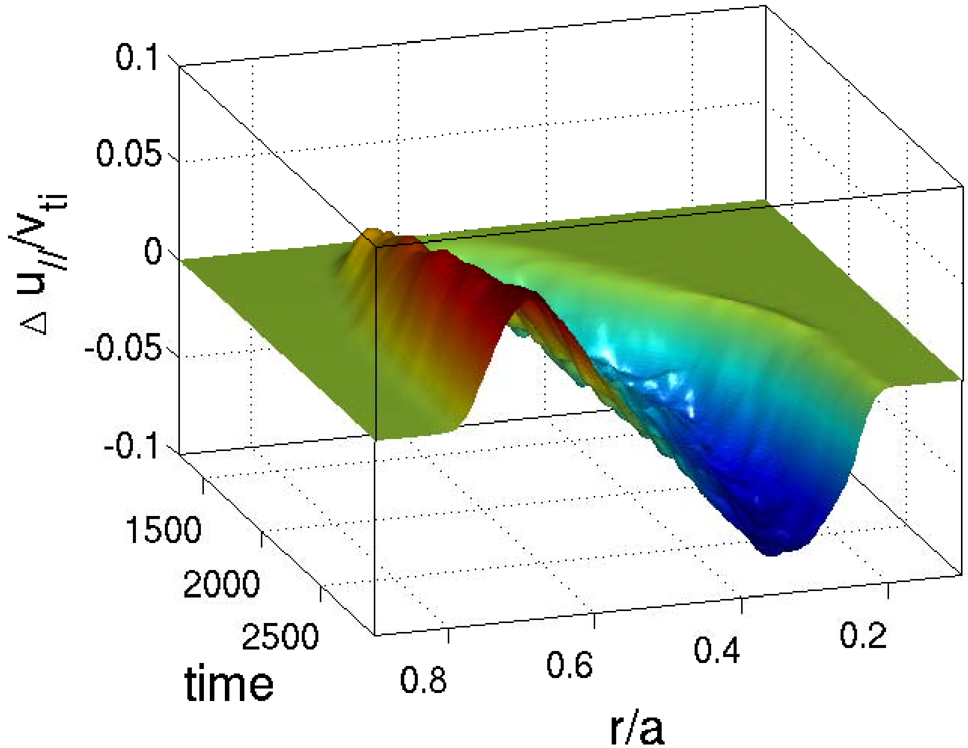
- Nonlinear energy transfer to longer wavelength modes via toroidal mode couplings
- Strong zonal flows and GAMs generation

PPPL

Flow shear turbulence can drive significant momentum and energy transport

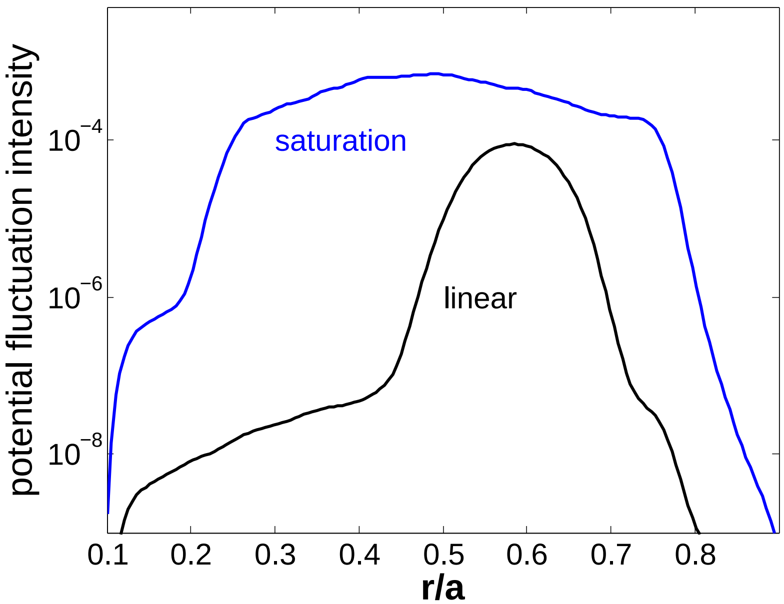


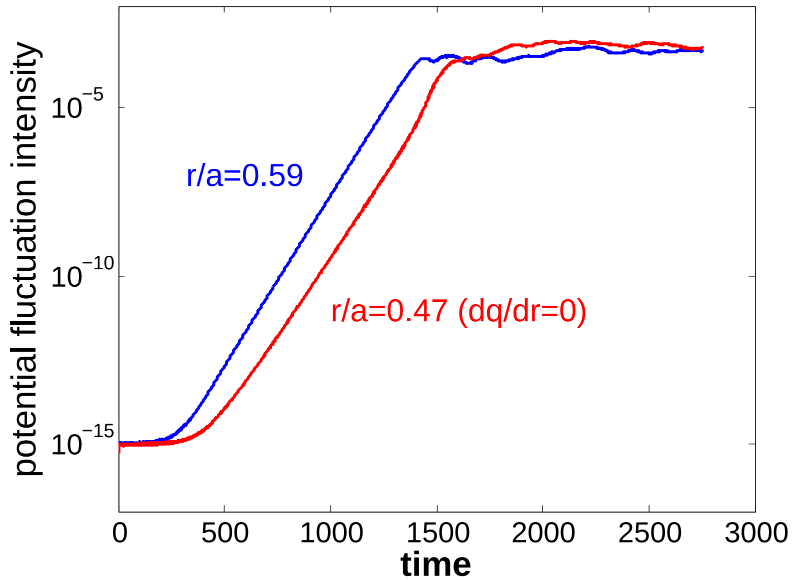


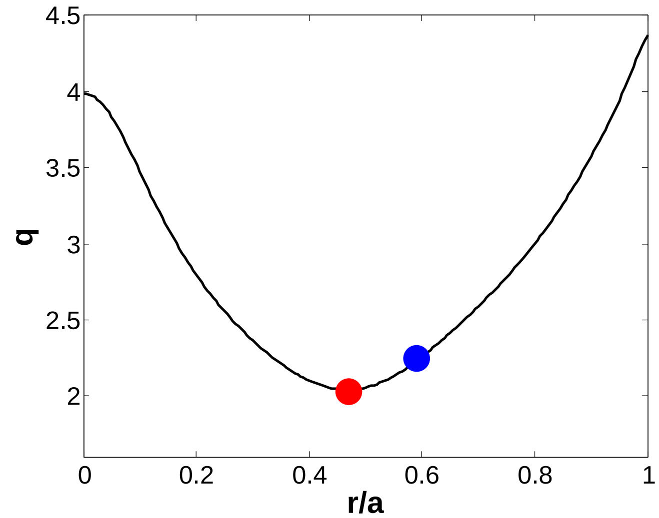


- Observation of turbulent intrinsic torque in co-current direction

Effects of q-profile structure

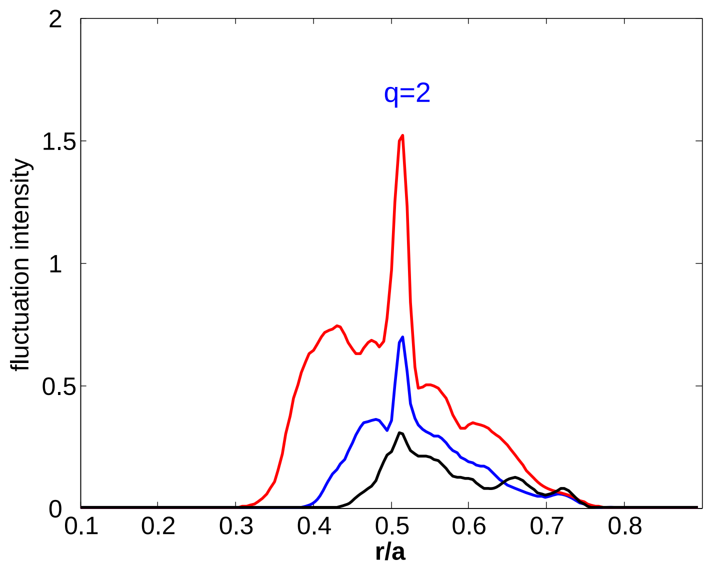


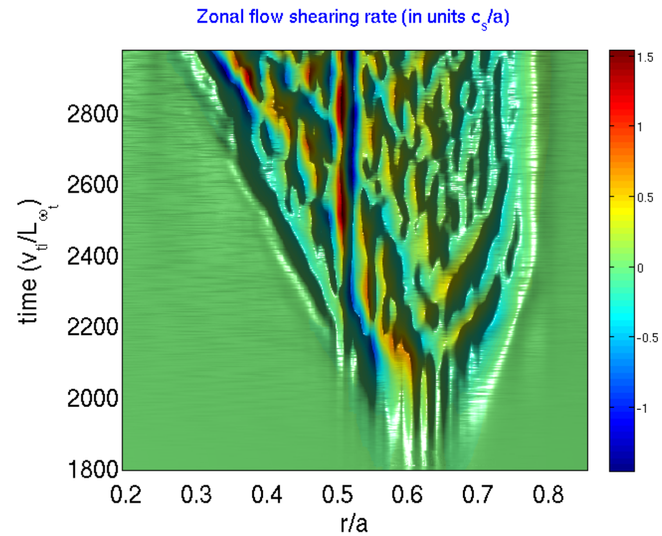


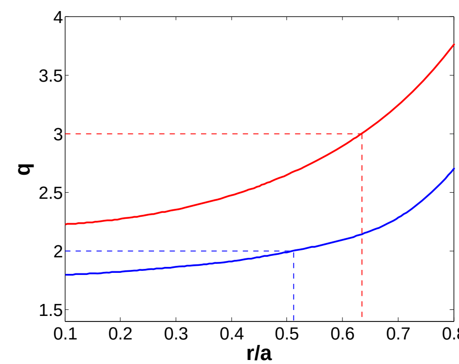


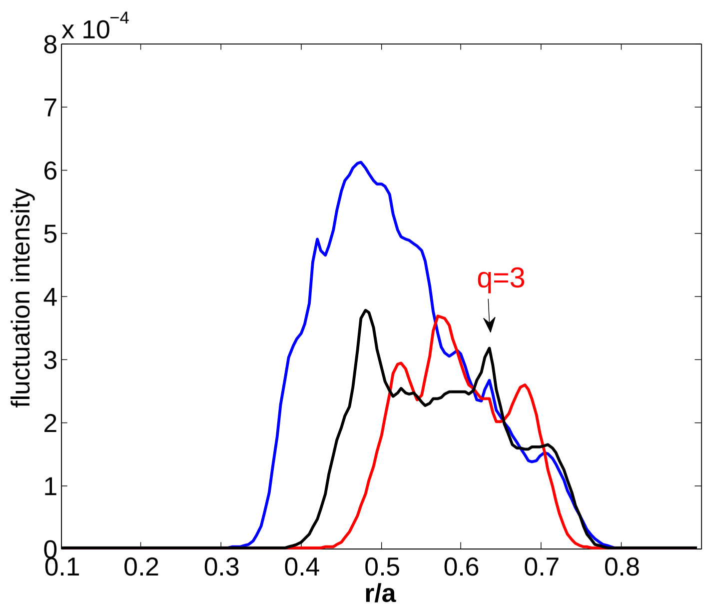
- Magnetic shear shows no suppression effect on flow shear instability in tokamak plasmas!

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





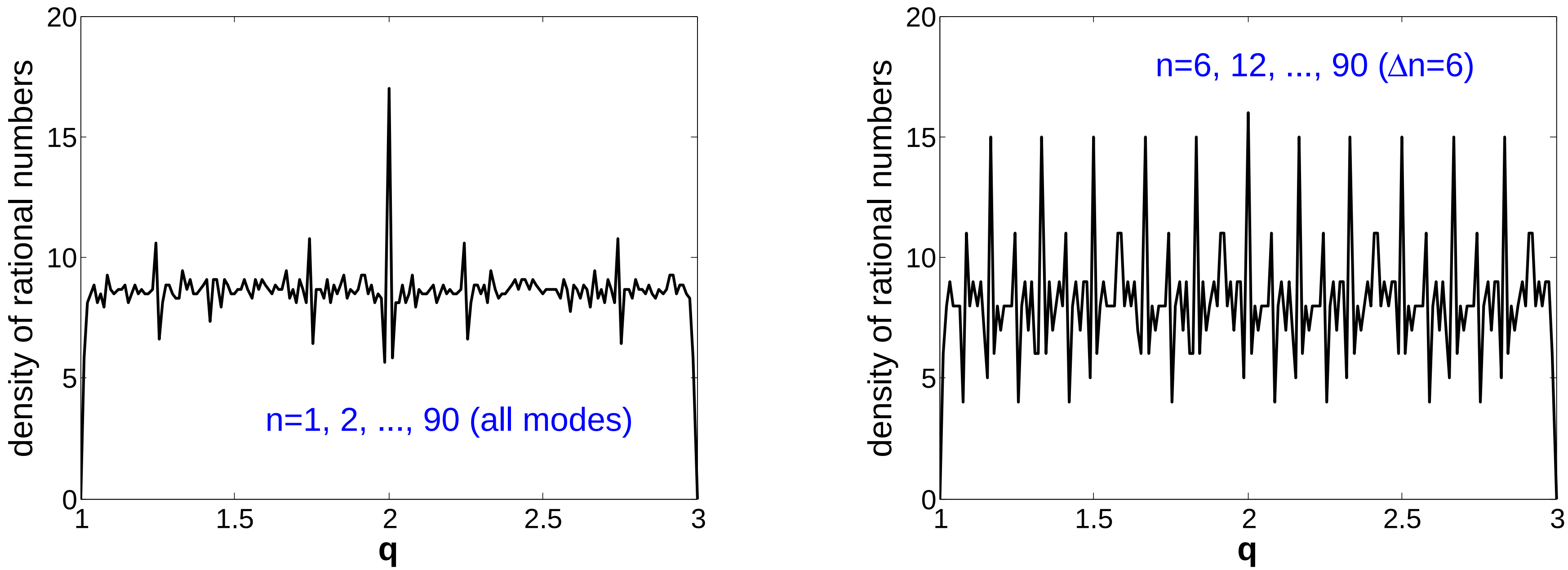




- Fluctuations peak at lowest-order rational surface $q = 2$ (and $q = 3$) (only in nonlinear phase)
- Zonal flow shear shows corrugated structure at the same location

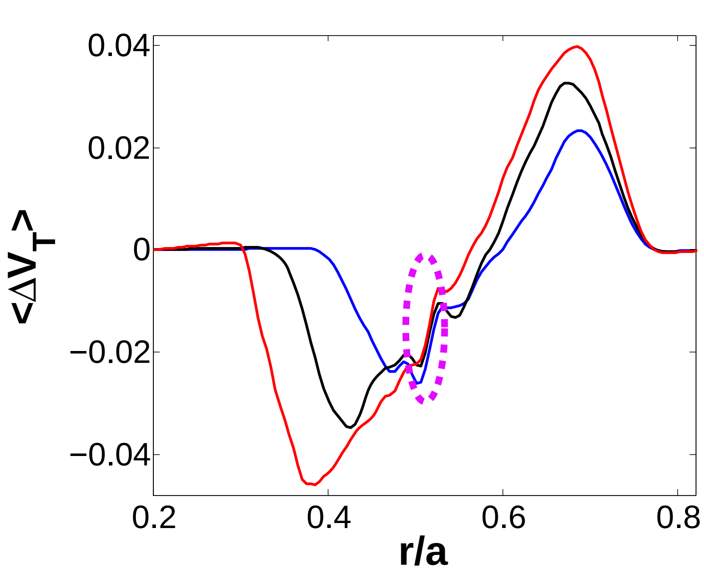
Why fluctuations peak at lowest-order rational surfaces with integer-q number – a theoretical explanation

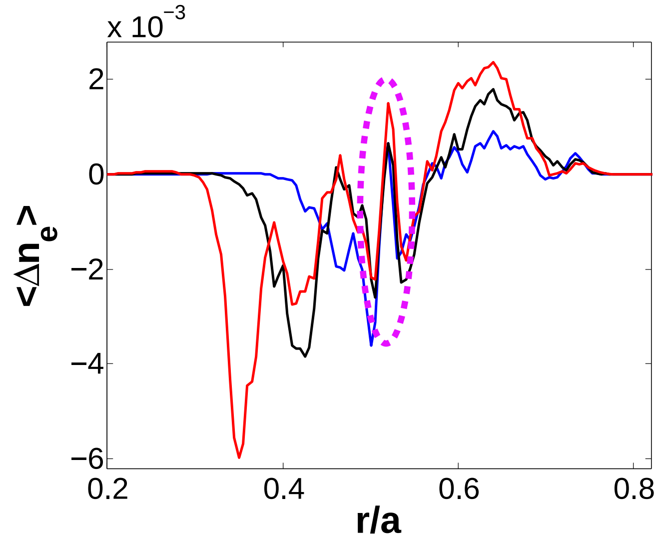
- Due to minimum Landau damping at $k_{\|} = 0$, $\phi_{m,n}$ peaks at $q(r) = m/n$
- $I(r) = \sum_{m,n} |\phi_{m,n}|^2 d_{m,n}(r) \sim \sum_{m,n} d_{m,n}(r)$ assuming $\phi_{m,n}$ same for all MRSs
- Example with $q = 1 + 2(r/a)^2$

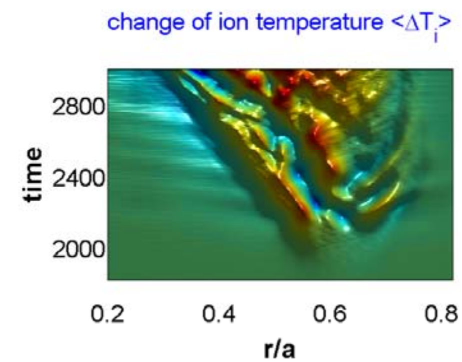


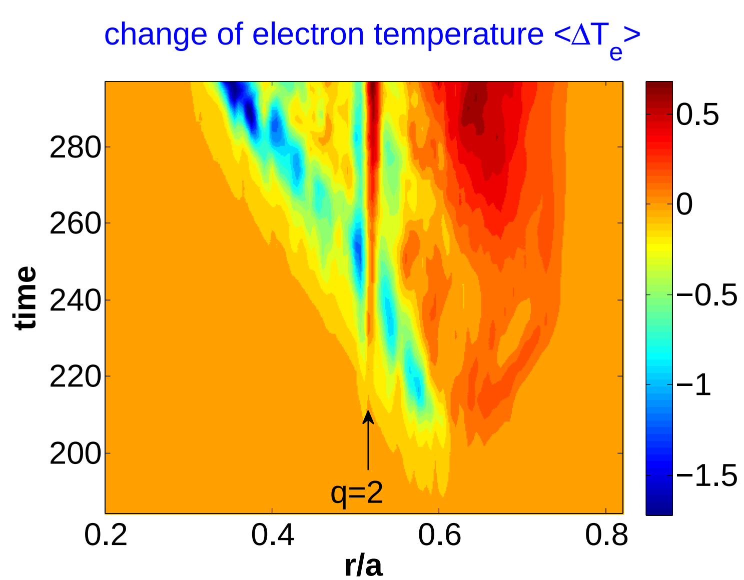
- Fluctuations peak at integer rational surfaces (rather than fractional!)
- Many spurious peaks at rational surfaces when using a subset of modes

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









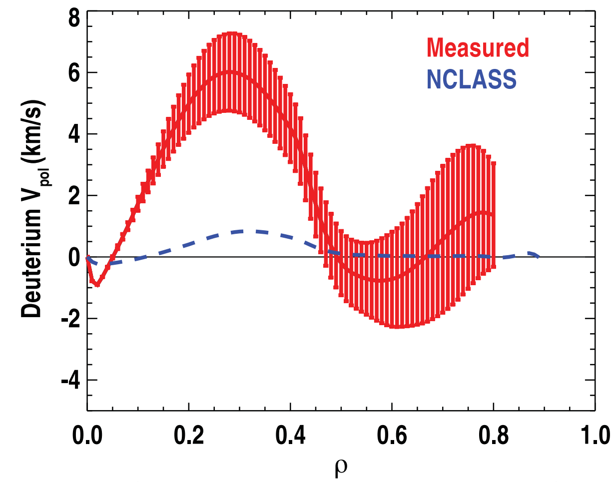
- Local "corrugations" generated in all radial profiles near integer rational surface: V_t, n_e, T_e and T_i
- Potential impact:
  - transport barrier formation near (integer) rational surface (Waltz et. al., PoP'06)
  - electron scale turbulence via nonlinear ETG excitation

Poloidal flow generation

- Significant v_θ contribution to E_r likely in ITER

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

- Mixing exptl. results compared to NC prediction – significant disagreement both in magnitude & in direction observed on DIII-D (with steep ∇T_i)



(Grierson, PoP'12)

- Poloidal flow generation by turbulence:

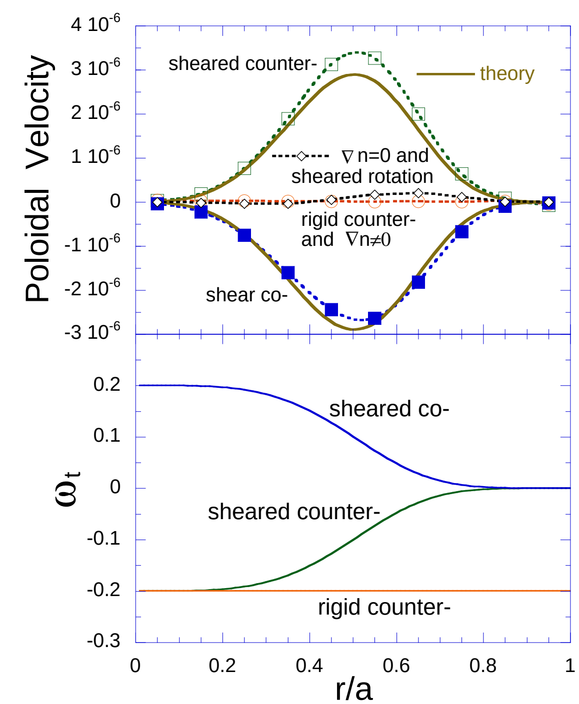
$$\Pi^{RS}_{r,\theta} \sim \langle \tilde{v_r}\tilde{v_\theta} \rangle$$

(Pif-Pradalier et. el., PRL'09)

- Nonlocal NC effect due to finite orbits:

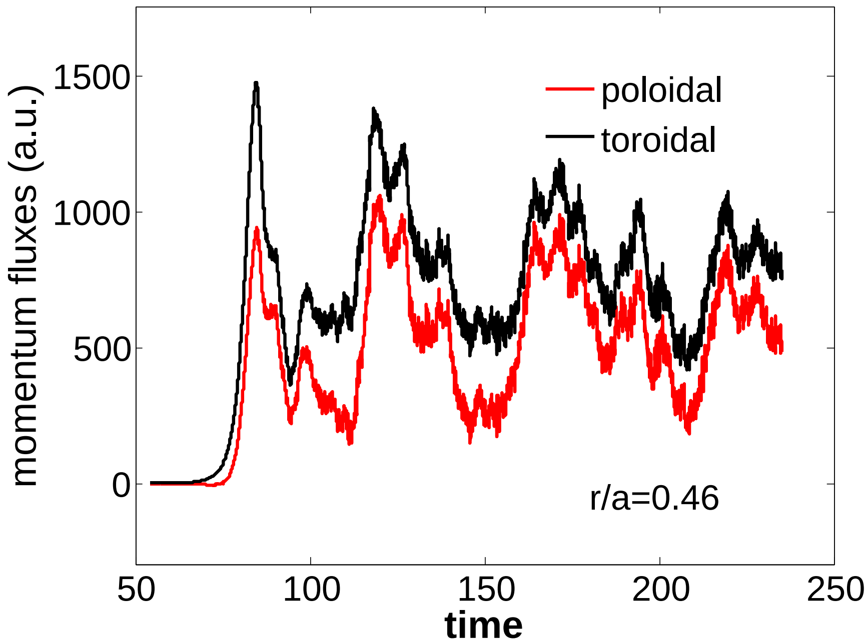
$$\langle u_\theta \rangle = u_{\theta,0} - \frac{1}{2}\left\langle \rho_{i\theta}^2 \right\rangle \frac{B_\theta}{B} \left\langle \frac{I}{B} \right\rangle \frac{\partial \ln p_i}{\partial r}\frac{\partial \omega_t}{\partial r}$$

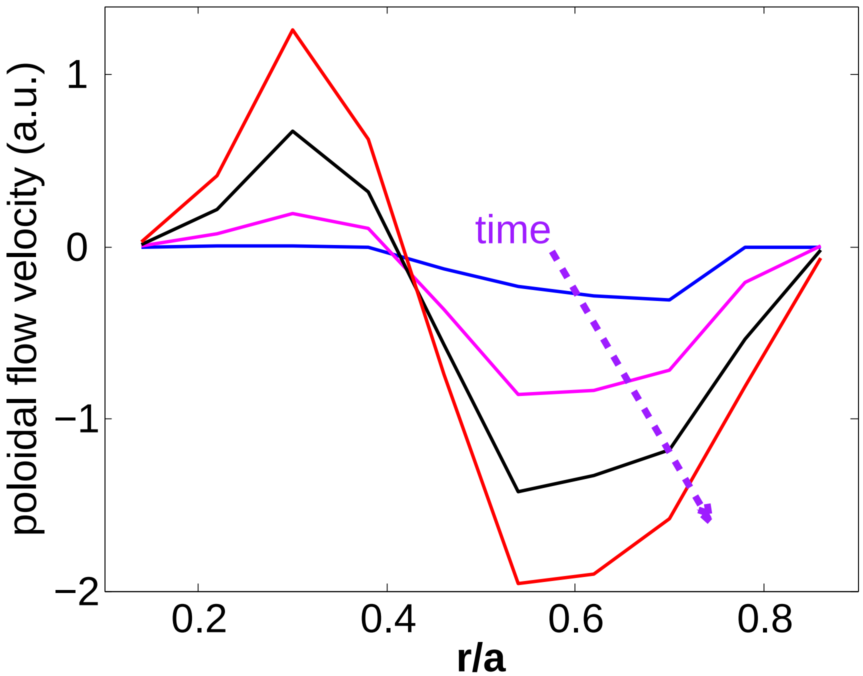
(Wang et. al., PoP'06;
Kolesnikov et. al., PPCF'10)



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

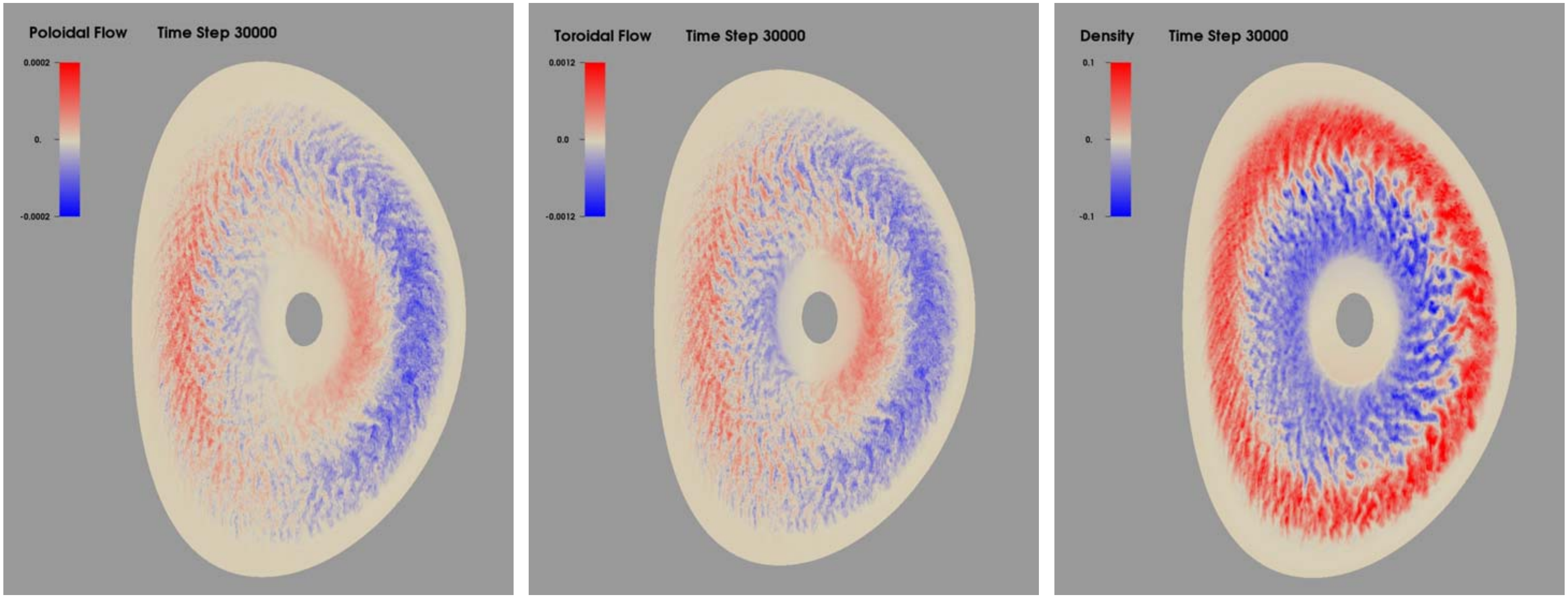
Poloidal flow generation by turbulence





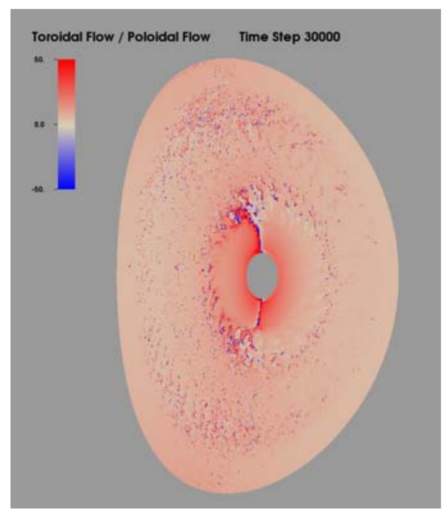
- Significant poloidal momentum generation observed in CTEM turbulence

Strong correlation shown between poloidal and toroidal flow generation



Correlation coefficients:

- $R[\Pi^{RS}_{r,\theta}, \Pi^{RS}_{r,\phi}] > 0.7$
- $R[\tilde{v}_\theta, \tilde{v}_\phi] > 0.9$
- $R[\langle\tilde{v}_\theta\rangle, \langle\tilde{v}_\phi\rangle] > 0.9$



Summary – Shear Flow Driven Turbulence & Transport in Tokamaks; and Turbulence-generated Flow Structure

- Strong flow shear may drive its own instability in tokamaks
  - low-k range as ITG; smaller, almost constant growth rate; finite $k_{||}$
  - saturation mechanism: nonlinear toroidal energy transfer to lower-k and strong ZFs and GAMs generation
- Flow shear turbulence impacts plasma transport
  - 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
- Turbulence driven toroidal flow shows strong poloidal variation
  - dominated by (m,n)=(1,0) along with zonal components
  - Nonlinear toroidal mode couplings play an important role in flow structure formation
- Significant poloidal momentum generation by CTEM turbulence, and in strong correlation with toroidal flow generation