Non-Diffusive Momentum Transport and Intrinsic Rotation in Tokamaks

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in collaboration with

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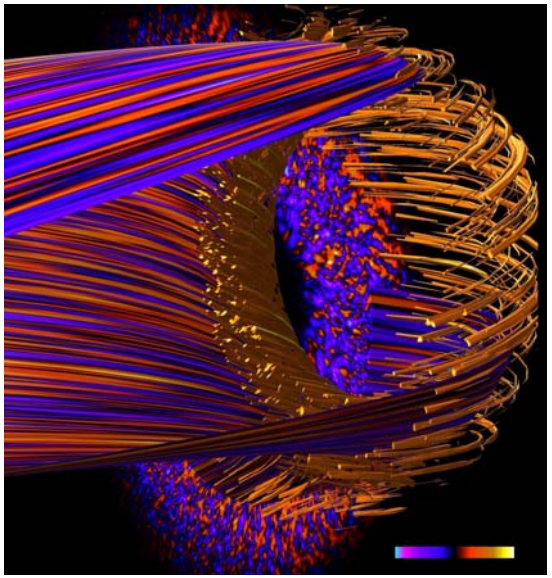

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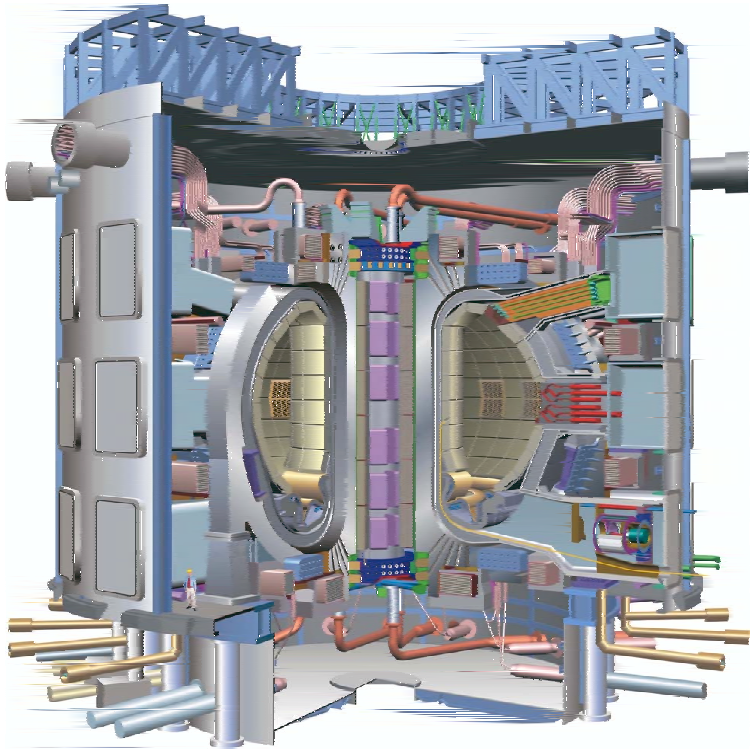
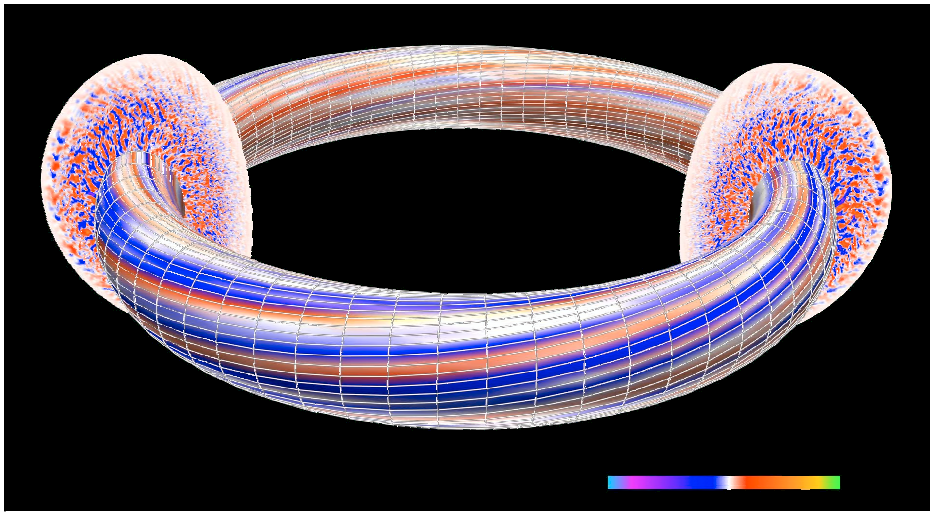
Momentum transport and plasma flow generation are of great importance in magnetic confinement fusion

An optimized plasma flow is critical for high quality plasma confinement:

- control large-scale (macroscopic) plasma stability
- reduce energy loss due to plasma microturbulence: H-mode, ITB
- extremely critical for ITER

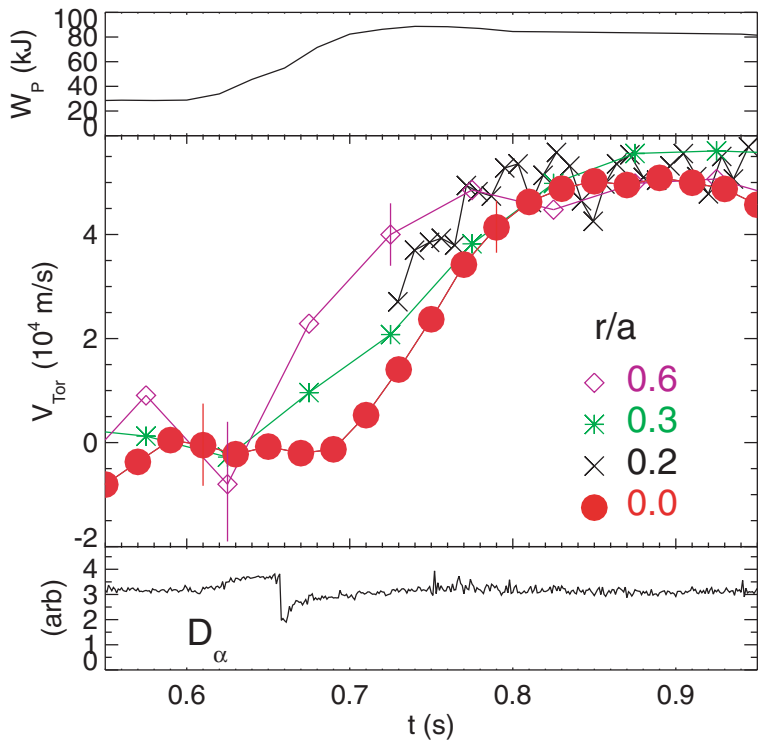




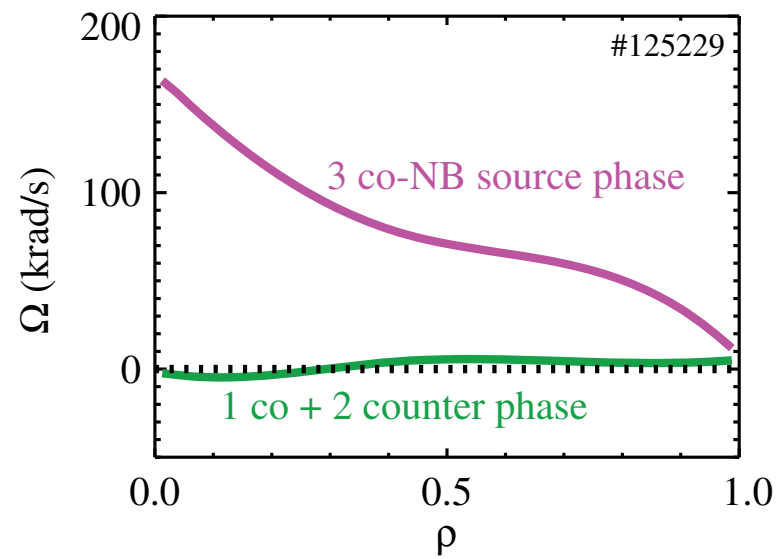
Momentum transport and plasma flow generation are very complex transport phenomena

Intrinsic or spontaneous rotation observed in nearly all tokamaks:

- Toroidal plasmas can self-develop rotation without an external torque!
- A "negative viscosity phenomenon"



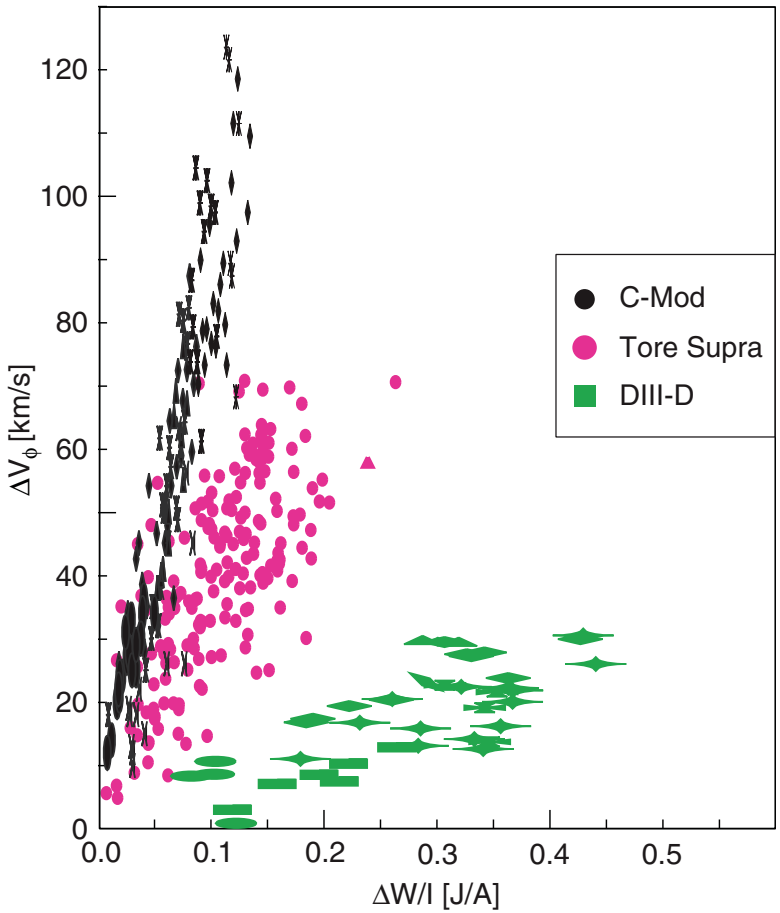
(Rice et al. '04)



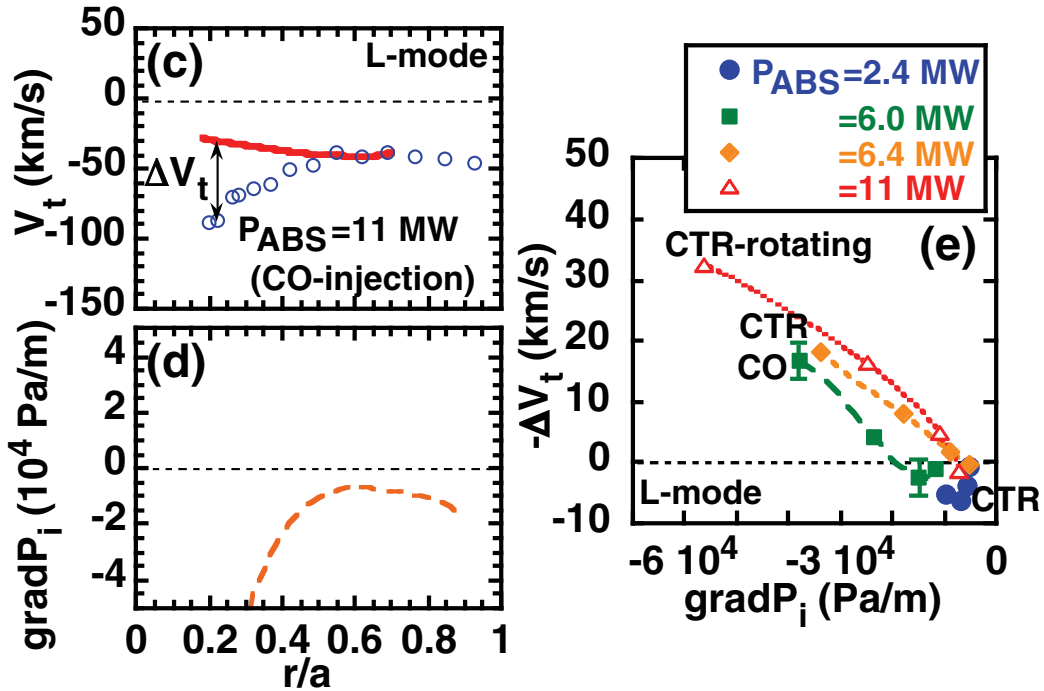
(Solomon et al. '07)

Particularly important for ITER – intrinsic rotation will dominate

Empirical scalings of intrinsic rotation obtained in multiple fusion devices



(Rice et al. '07)

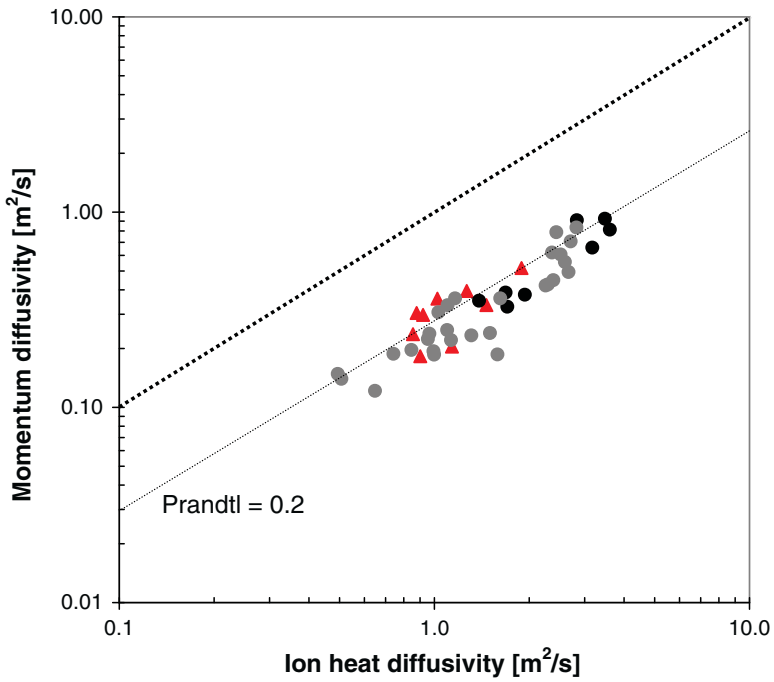


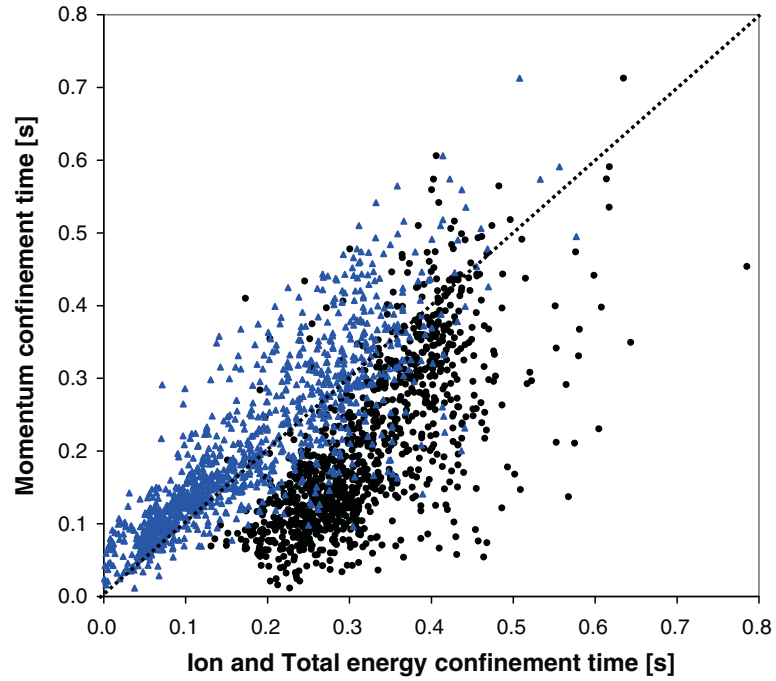
(JT-60U – Yoshida et al. '08)

- $\Delta V_\phi \sim \Delta W / I_p$ (Rice Scaling)
- $\Delta V_\phi \sim \nabla P_i$
- Mostly in co-current direction
- What are underlying physical origins

Micro-turbulence is a key player in determining toroidal momentum transport and plasma rotation

- Coulomb collision induced neoclassical momentum transport negligible small $\sim 10^{-1} - 10^{-2}$
- Momentum-energy transport closely coupled via microturbulence as a "medium"





(de Vries et al. '06)

Toroidal momentum transport is highly anomalous for its high level & non-diffusive, nonlocal nature

- Radial flux of toroidal angular momentum:

$$\Gamma_\phi \propto -\chi_\phi \frac{\partial U_\phi}{\partial r} + V_p U_\phi + \Pi^{\mathrm{rs}}_{r,\phi}$$

- Different physics origins under turbulence circumstances
- Qualitatively distinct effects on flow formation

  Diffusion and pinch move mechanical momentum and rearrange profile

  But pinch can be in either direction, up- or down-gradient
- Residual Stress $\Pi^{\mathrm{rs}}_{r,\phi}$ has fundamentally distinct effect on rotation profiles
- All are observed in experiments

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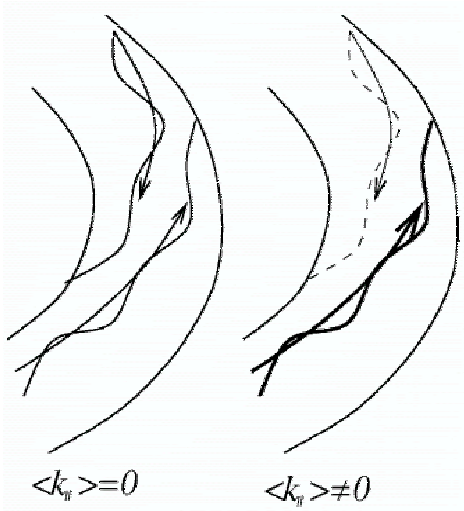
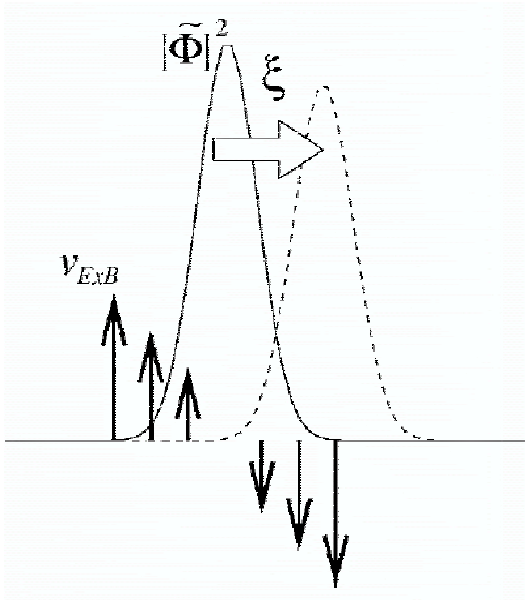
Simple picture of turbulence driven residual stress





- $k_{\|}$ and $-k_{\|}$ are equally excited $\rightarrow$ balanced wave population
- KEY: $k_{\|} \leftrightarrow -k_{\|}$ symmetry breaking $\rightarrow$ net parallel acceleration
- mean $\mathbf{E} \times \mathbf{B}$ velocity shear $\Rightarrow \langle k_{\|} \rangle \neq 0 \rightarrow \Pi^{\mathrm{rs}}_{r,\phi}$
  (Gurcan et al. '07, Dominguez et al. '93, ...)
- Residual Stress provides an ideal mechanism to drive intrinsic rotation

  acts as internal (intrinsic) torque $-\nabla \cdot \mathbf{\Pi}^{\mathrm{rs}}_{r,\phi}$

  via wave-particle momentum exchange (Diamond et al. 08)

Global gyrokinetic simulations elucidate origin of intrinsic rotation in tokamaks

Discovery of important nonlinear flow generation process by turbulence

Critical issues closely coupled to experimental and theoretical studies include:

- mechanisms for turbulence driving residual stress
- mechanisms for $k_{\|}$ symmetry breaking
- characteristic dependences of intrinsic rotation on plasma parameters
  $\Longrightarrow$ what is underlying physics governing empirical scalings in experiments
- directional tendency of the rotation

Finding of a striking "flow pinch" phenomenon in CTEM regime

$\Longrightarrow$ elucidation of flow penetration in well known perturbation experiments

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

- Generalized gyrokinetic simulation model; δf PIC approach; realistic magnetic geometry, global simulation (Wang et al,. PoP'06)
- Interfaced with MHD equilibrium codes and experimental data base via TRANSP
- Fully kinetic electrons
- Field-line-following mesh and configuration space field solver using PETSc
- Linearized Fokker-Plank operator with particle, momentum and energy conservation for i-i and e-e collisions; Lorentz operator for e-i collisions
- GTS turbulence simulation is interfaced with GTC-NEO simulation

  GTC-NEO $\Longrightarrow$ NC EQ. f_0, Φ_0 and transport (Wang et al,. CPC'04)

  Non-local physics associated with large ion orbits and steep gradients
- $\{\langle n(r,\theta)\rangle$, $T(r)$, $\Phi_0(r)$, and $\omega_t(r)\}$ $\Longrightarrow$ turbulence & transport

  (energy, particle and momentum flux)

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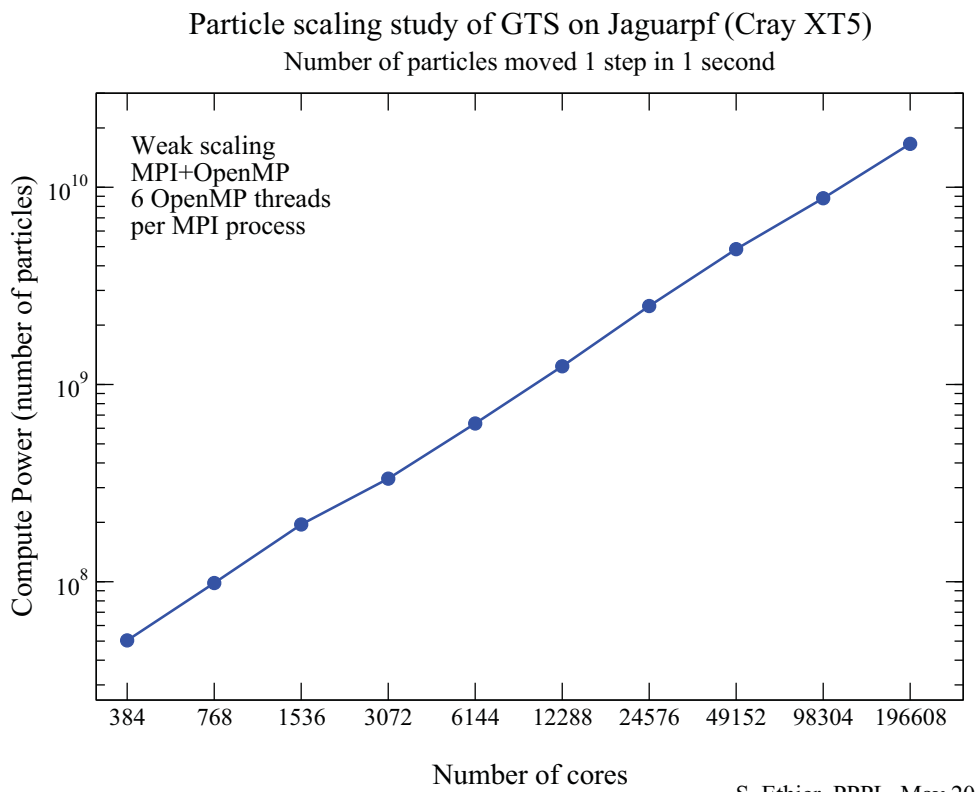
GTS: parallelization algorithm and scalability

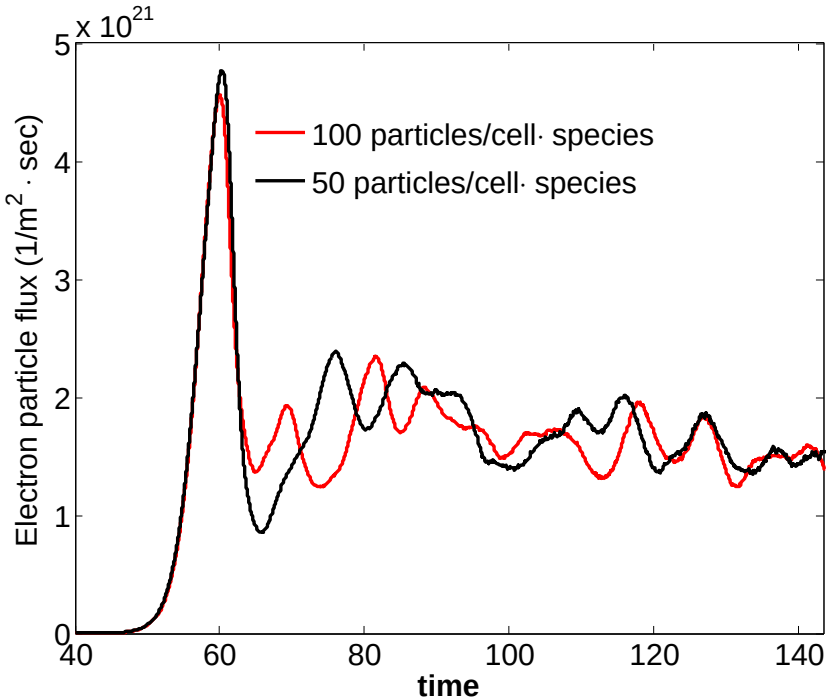
3 levels of parallelism make GTS massively parallel and highly scalable

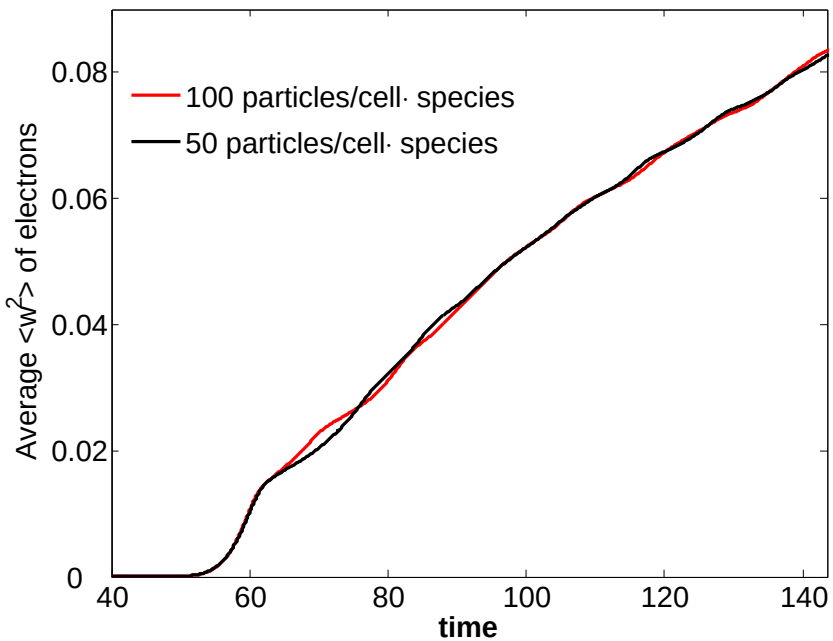
- 1D domain decomposition in toroidal direction for both grids and particles
- particles distributed across processors within each domain
- loop-level multi-threading



S. Ethier, PPPL, May 2010

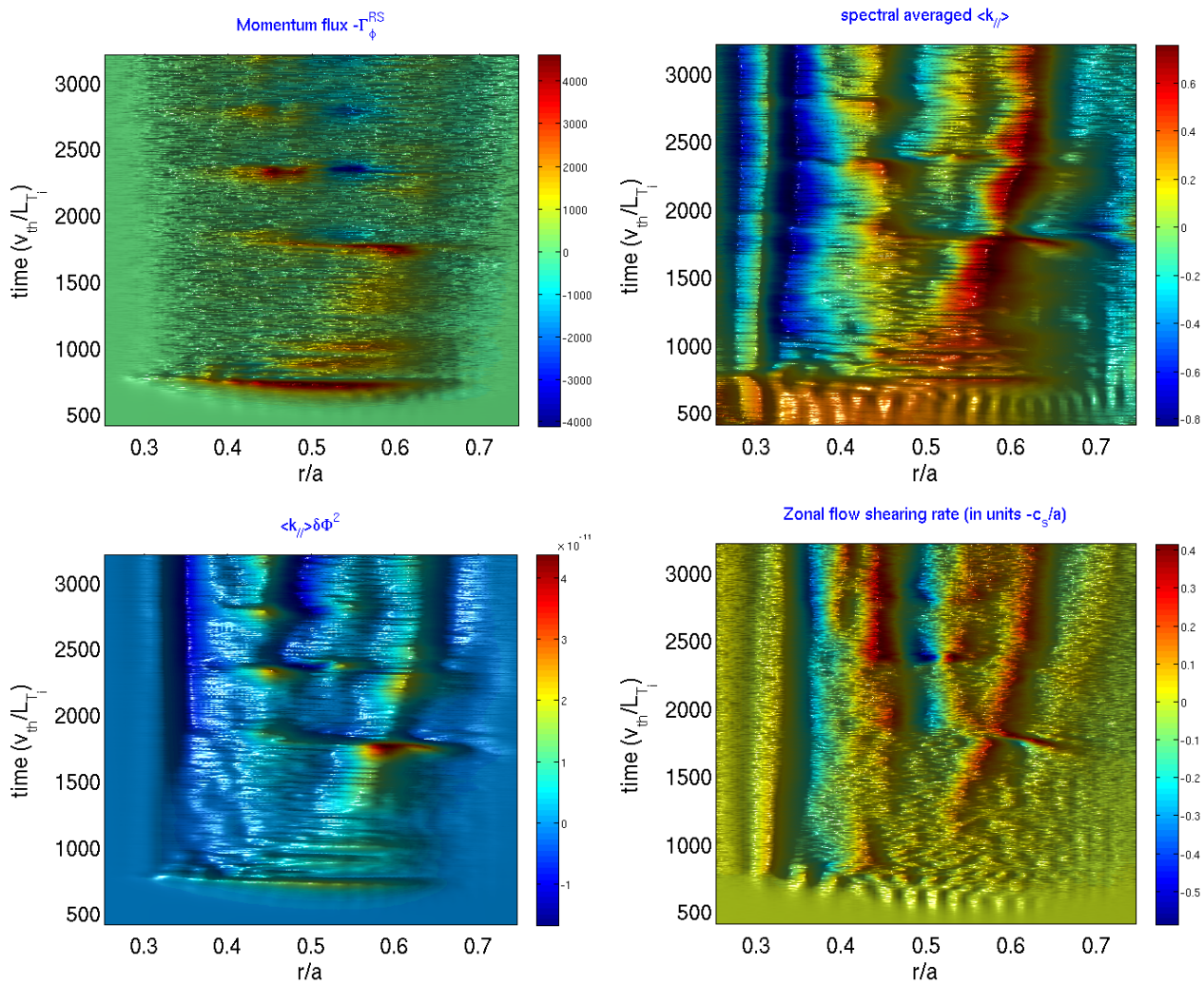
Particle noise is low and does not impact physical results





Simulation of trapped electron mode (TEM) turbulence

Residual stress is nonlinearly generated due to zonal flow shear in ITG turbulence

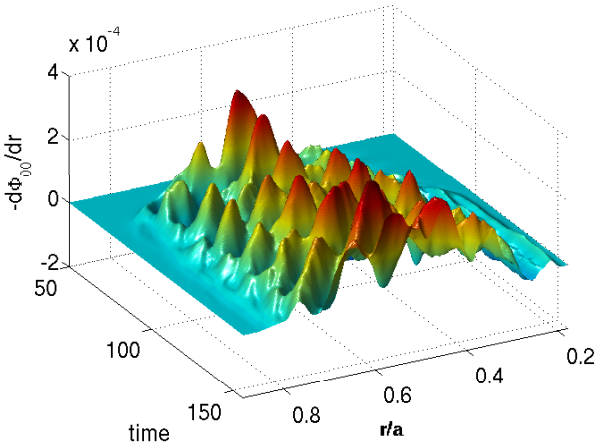


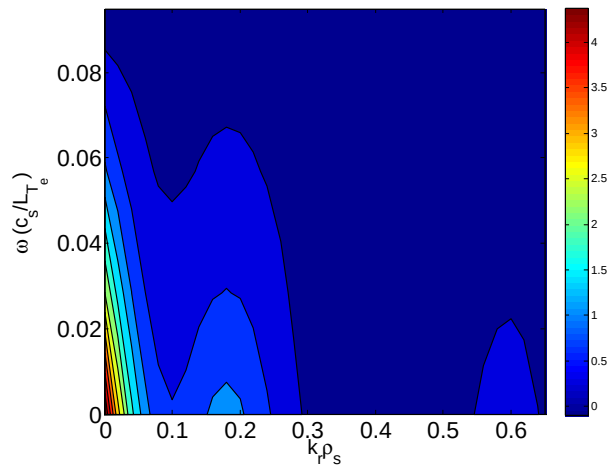
- ITG marginal: $R_0/L_{T_i} = 5.3$
- adiabatic electrons
- initially rotation free
- mean $\mathbf{E} \times \mathbf{B}$ excluded

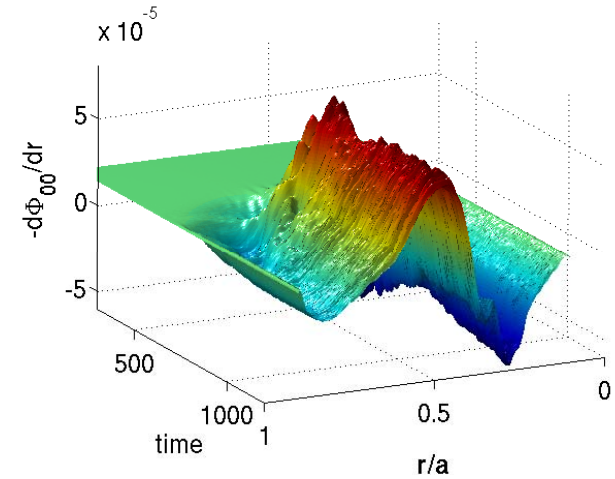
(Wang et al., PRL'09)

- Residual stress driven by fluctuation intensity
- Self-generated low frequency zonal flow shear is a key mechanism for $k_{||}$ symmetry breaking

Distinctive zonal flow characteristics in CTEM turbulence

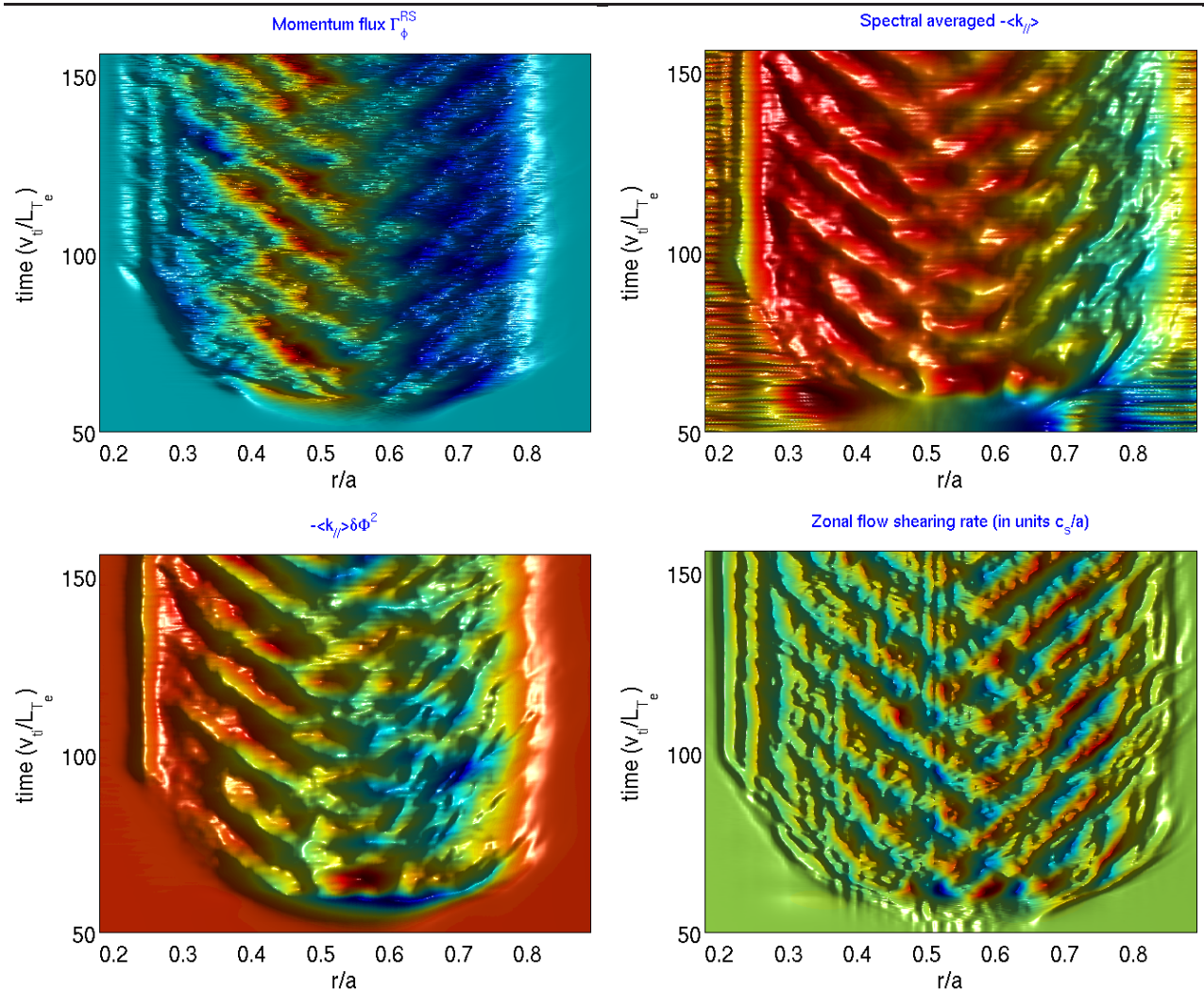






- Fine scales generated compared to typical ITG case
- Zero frequency dominated with certain extension to low frequency
- $\mathbf{E} \times \mathbf{B}$ shearing rate is high

Nonlinear residual stress generation by fluctuation intensity is clearly demonstrated in CTEM turbulence

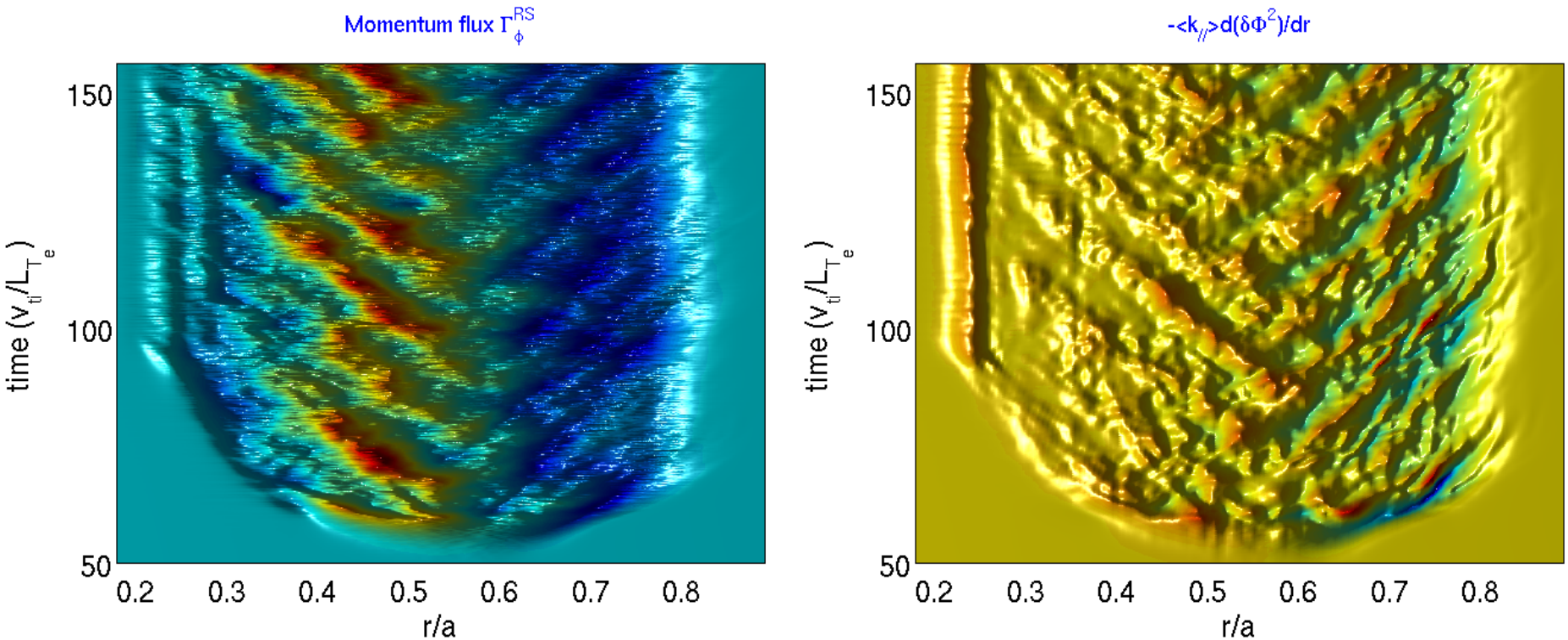


- typical DIII-D parameters
- initially rotation free
- mean $\mathbf{E} \times \mathbf{B}$ included
- real DIII-D geometry

(Wang et al., PoP'10)

- Residual stress driven by fluctuation intensity (particularly for $r/a \lesssim 0.55$)
- $k_{||}$ symmetry breaking caused by self-generated zonal shear
- Turbulence intensity effect insignificant for $r/a \gtrsim 0.55$

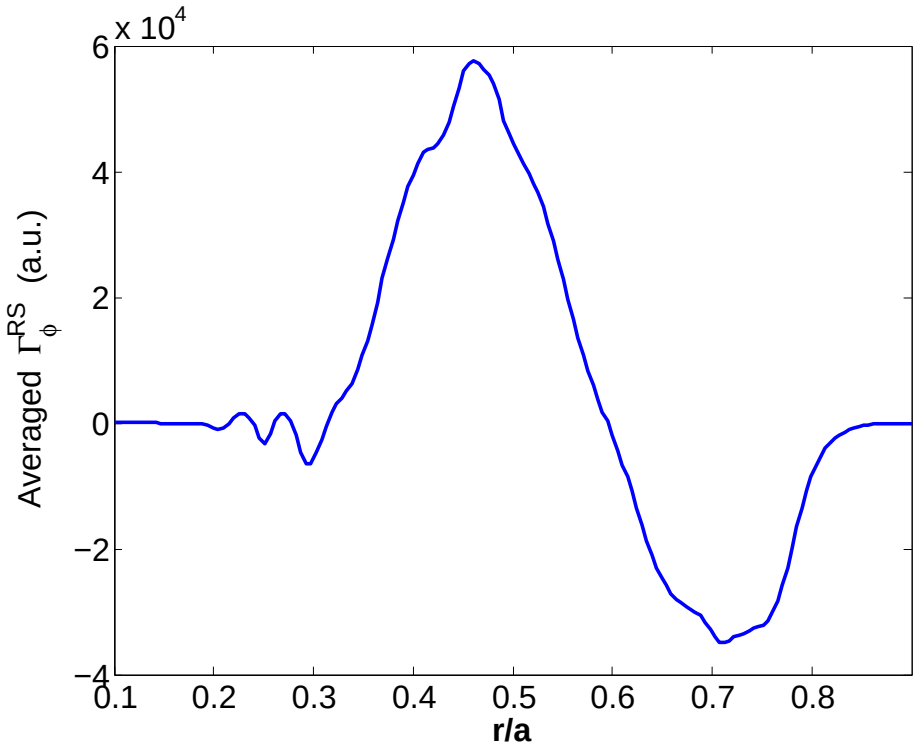
Turbulence intensity gradient driving residual stress is also identified

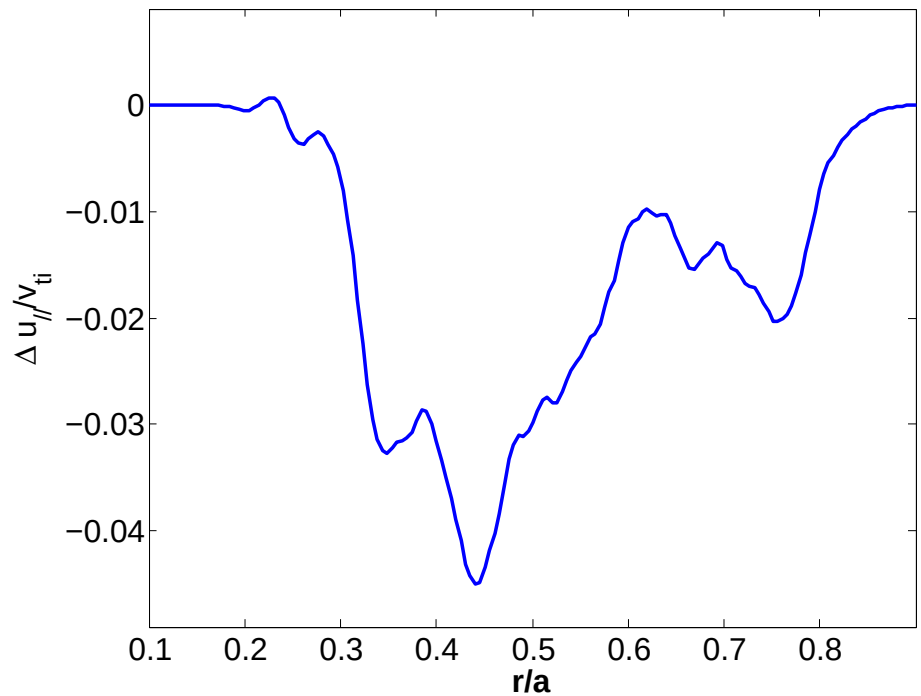


(Wang et al., PoP'10)

- Residual stress driven by $\sum \partial(\delta\Phi^2)/\partial r$ acting with zonal flow shear
- $\sum \partial(\delta\Phi^2)/\partial k_r$ driving RS also predicted (Diamond et al. '08)

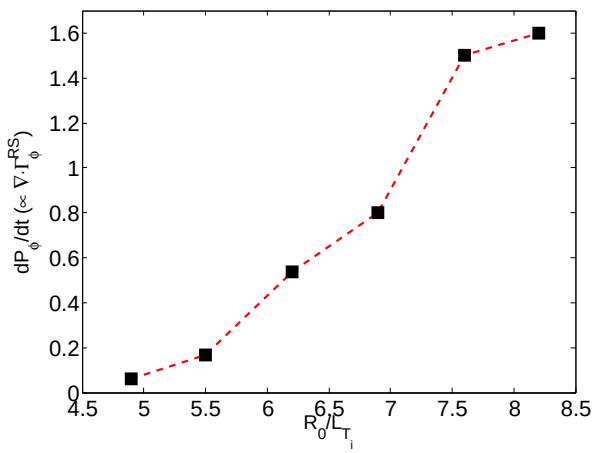
Nonlinear residual stress in CTEM can drive toroidal rotation effectively

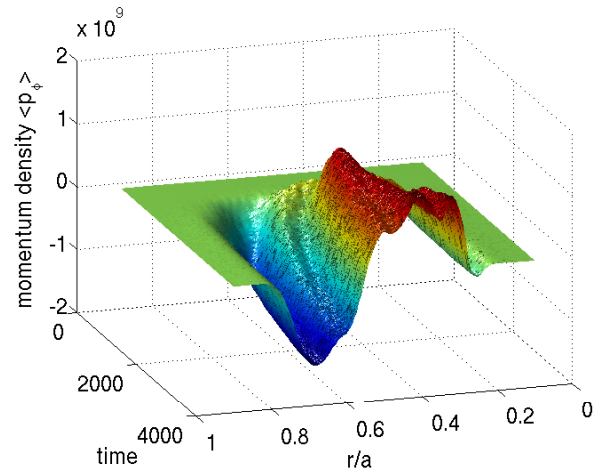


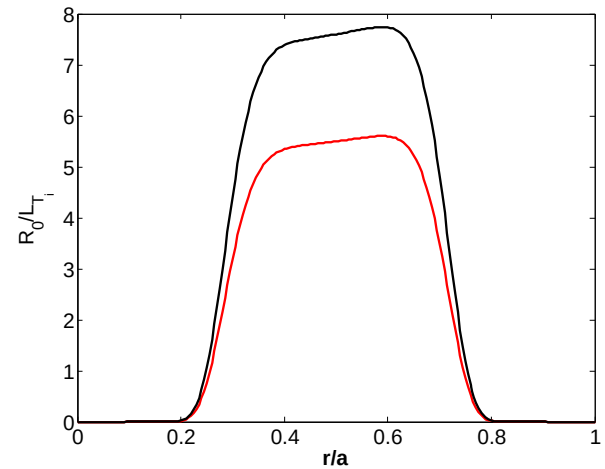


- Plasma initially rotation-free and momentum-source-free
- a net toroidal rotation produced in whole turbulence region
- in co-current direction, consistent with experimental trend
- $u_{\|} \sim 5\% \times v_{ti}$ at end of simulation
- Indicating momentum transfer from waves to particles

ITG driven intrinsic torque $\nabla \cdot \Gamma_\phi^{\rm RS}$ scales with ∇T_i through dependence of turbulence intensity and zonal flow shear



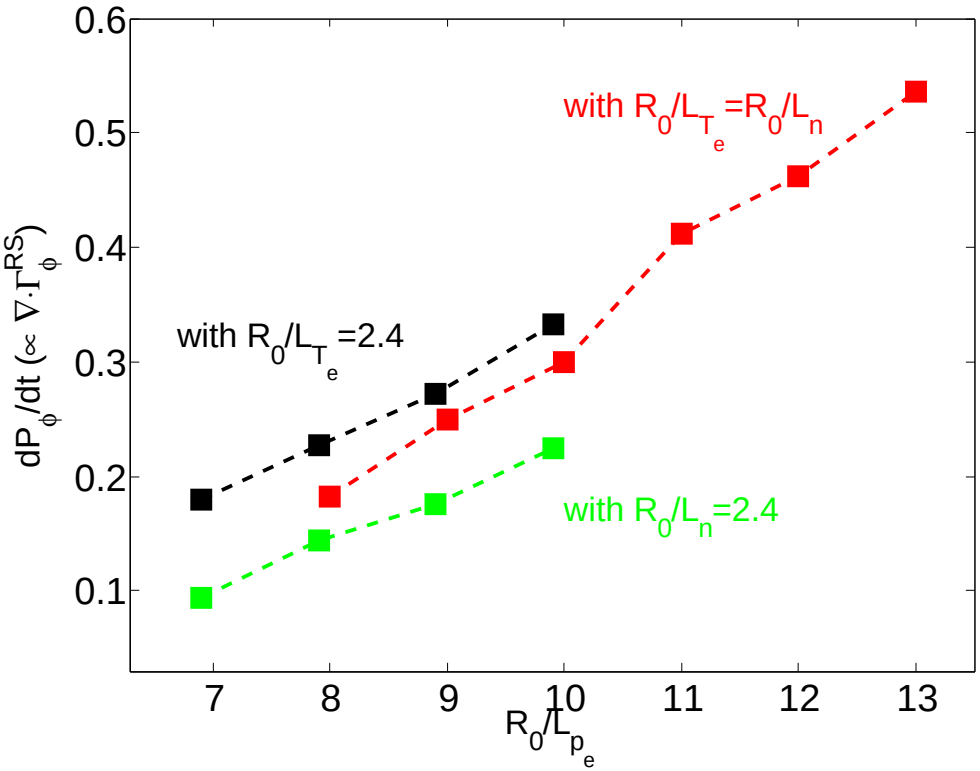




- Integrated intrinsic torque $\sim (R_0/L_{T_i} - R_0/L_{T_i}^{\rm crit})$ (Wang, APS-DPP'09)
- RS nonlinearly generated due to ZF shear (equilibrium $\mathbf{E} \times \mathbf{B}$ excluded)
- Consistent with experimental observations
  - $\Delta V_\phi \sim \Delta W_p / I_p$ in H-mode plasmas of multiple devices (Rice et al. '07)
  - $V_{\phi,\rm central} \sim \nabla P_{\rm edge}$ in C-MOD (Rice, APS-DPP'09)
  - intrinsic rotation increases with pressure gradient

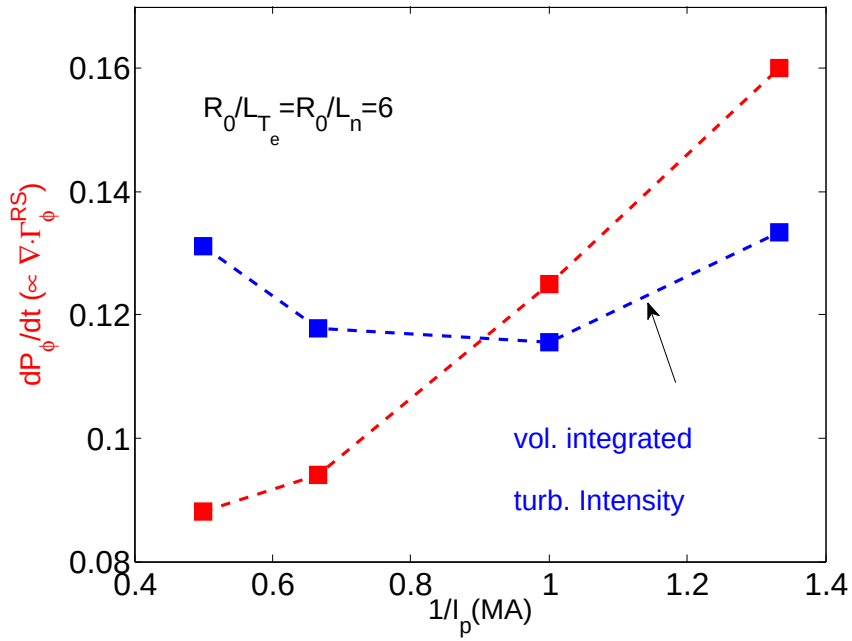
    in JT-60 (Yoshida et al. '08); in LHD (Ida et al. '10); $\cdots$

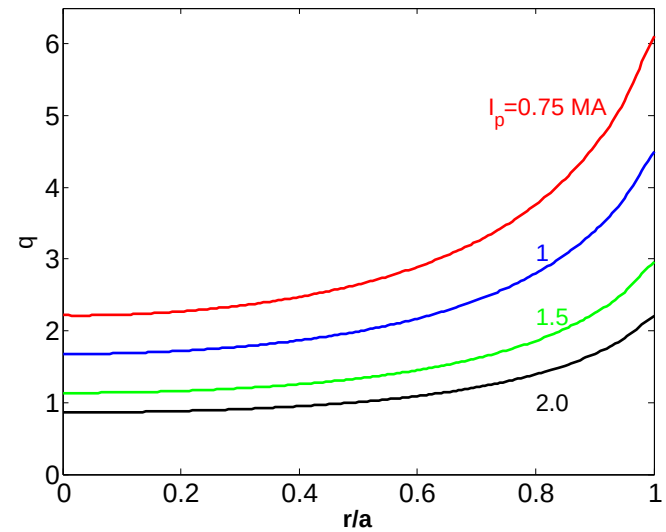
Intrinsic torque $\nabla \cdot \Gamma_\phi^{\mathrm{RS}}$ scales with ∇p_e in CTEM dominated regimes

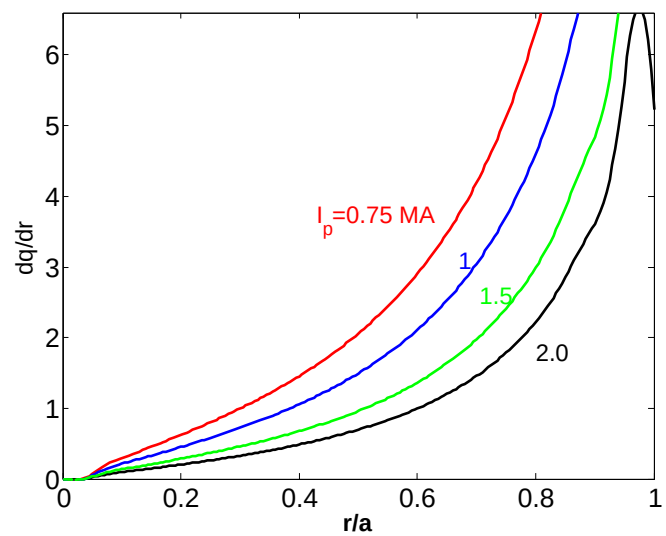


- Integrated intrinsic torque $\sim R_0/L_{p_e}$ linearly
- RS nonlinearly generated due to ZF shear (mean $\mathbf{E} \times \mathbf{B}$ shear effect small)
- Via turbulence intensity and ZF shear dependence on drive R_0/L_{p_e}
- Highly interesting to test in experiments – good for validation study

Turbulence nonlinearly driven intrinsic rotation is predicted to inversely scale with plasma current

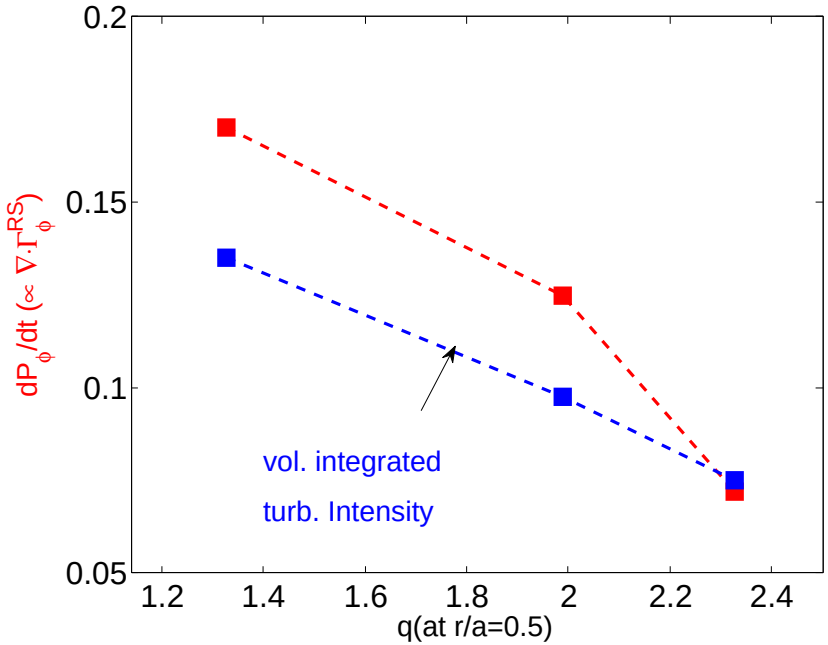


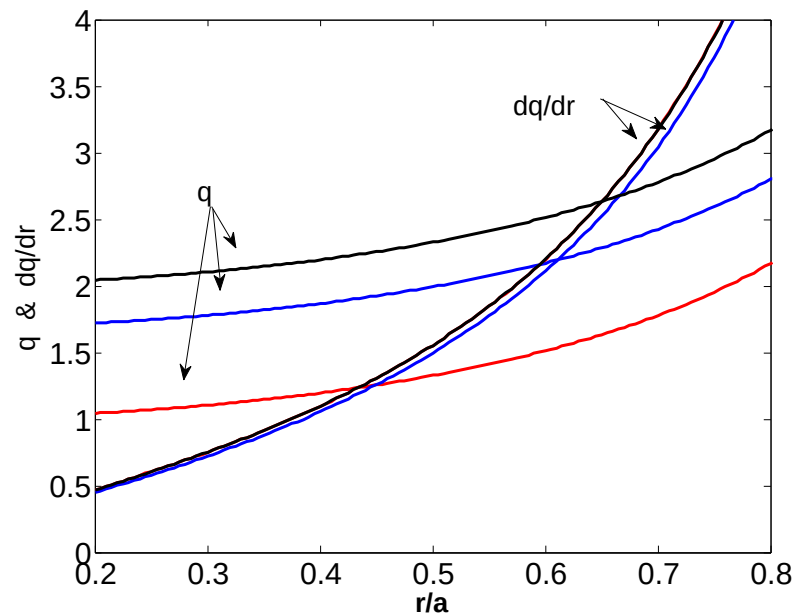




- I_p scan performed with CTEM turbulence
- Hold B_{ext} & P fixed, varying I_p (as expt. do)
- Empirical I_p scaling is reproduced
- Turbulence intensity and intensity gradient insensitive to I_p
- Due to difference in $k_{||}$ symmetry breaking
  – q or magnetic shear dq/dr ?

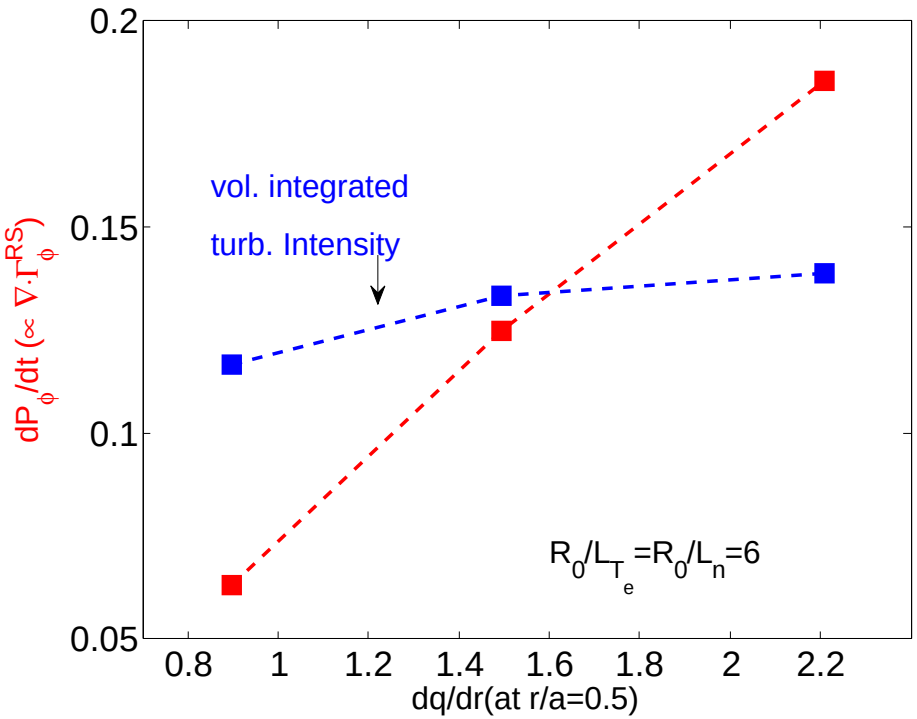
Current scaling of turbulence driven intrinsic rotation: dependence on safety factor

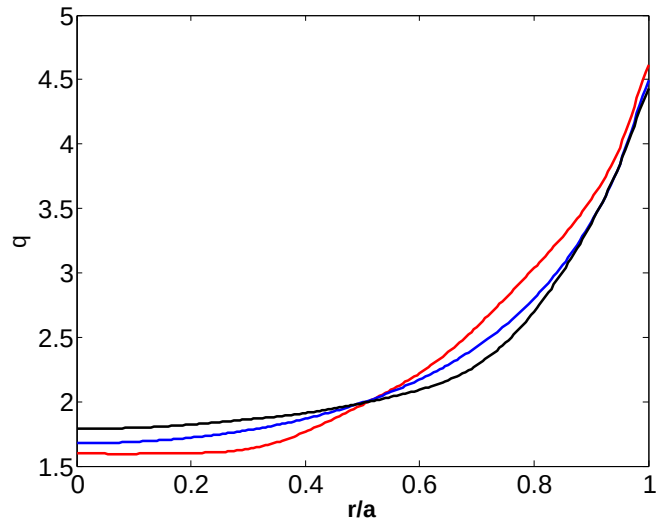


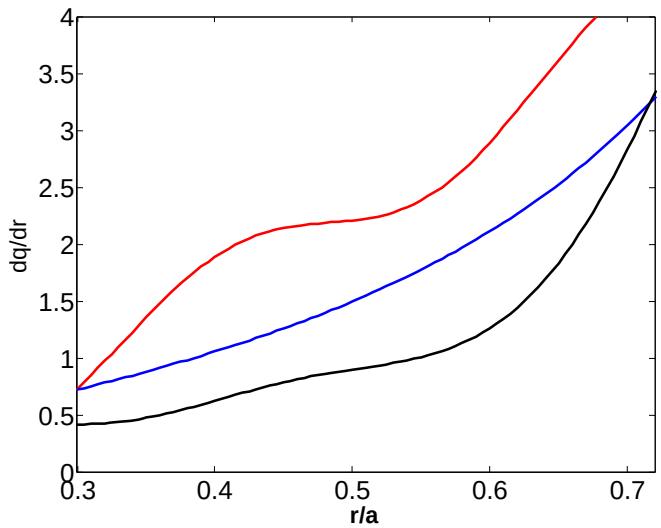


- Computational experiments performed hold dq/dr and boost q profile
- Dependence on q obtained here shows opposite trend with current scan

Current scaling is identified to originate from the effect of magnetic shear

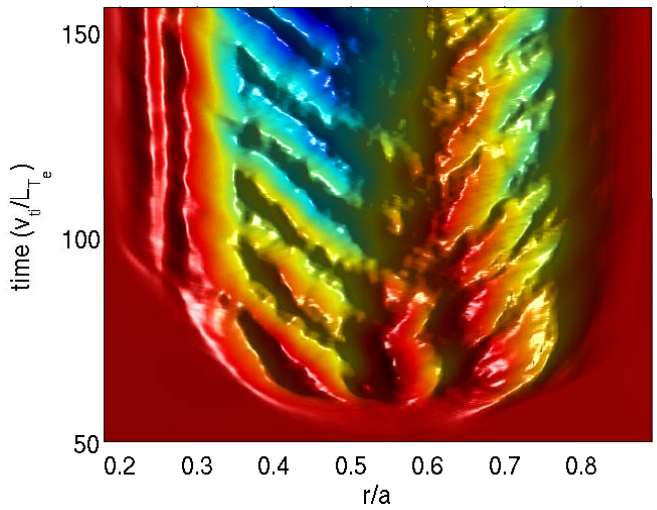


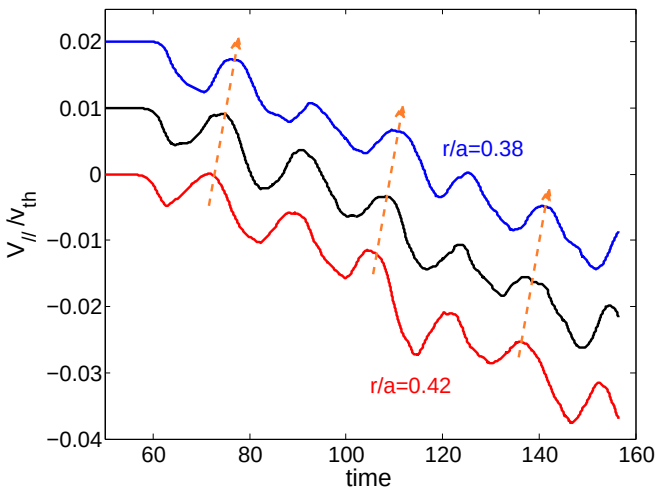


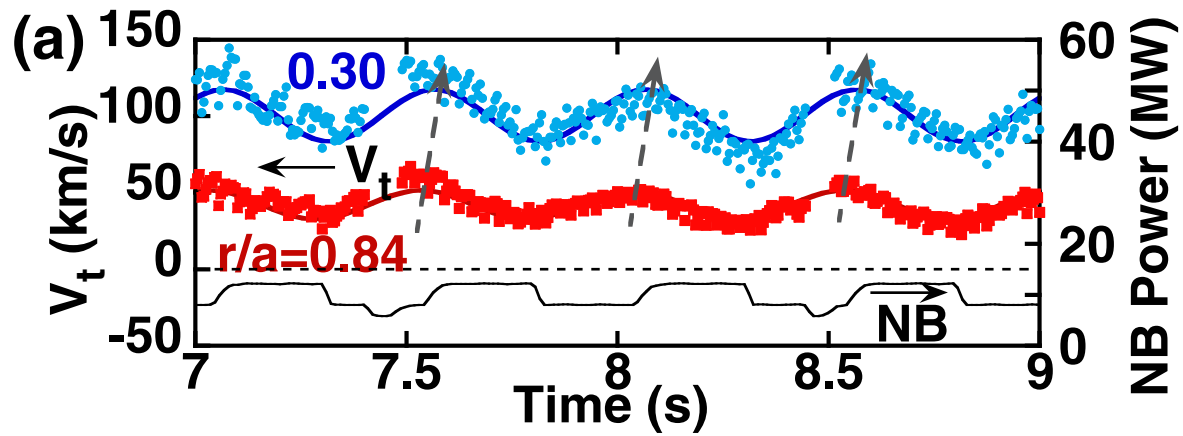


- Simulations vary dq/dr
- Intrinsic torque increases with dq/dr due to magnetic shear induced symmetry breaking
- Dependence of intrinsic torque on dq/dr accounts for current scaling

"Flow pinch" phenomenon found in CTEM turbulence is illuminating







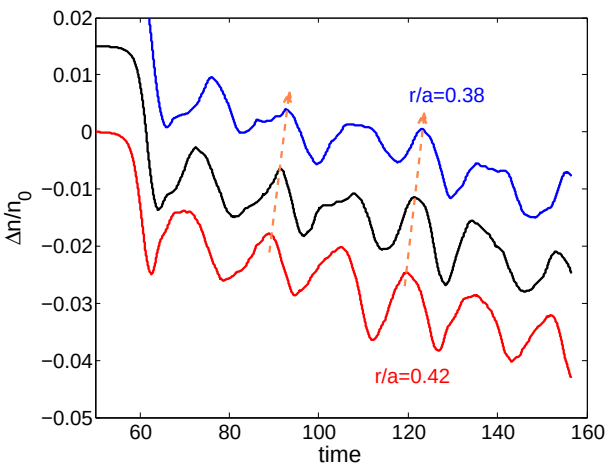
(From perturb. experiment, Yoshida et al. '08)

- Highly analogous to perturb. experiments
- $V_p \sim 7 \times 10^{-3} c_s, \quad f_p \sim 0.1 c_s/a$
- Flow perturbations generated locally in center

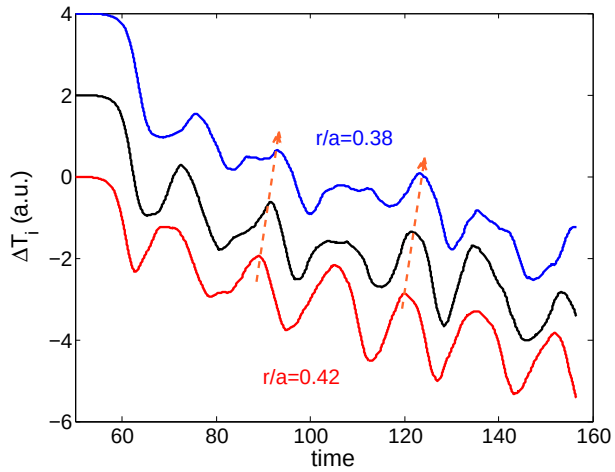
- An enlightening insight into underlying dynamics governing the radial penetration of modulated flows

CTEM turbulence also drives particle and heat pinch

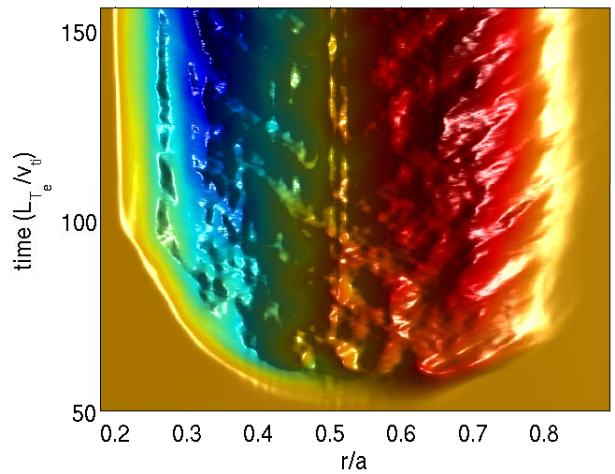
ion particle



ion heat

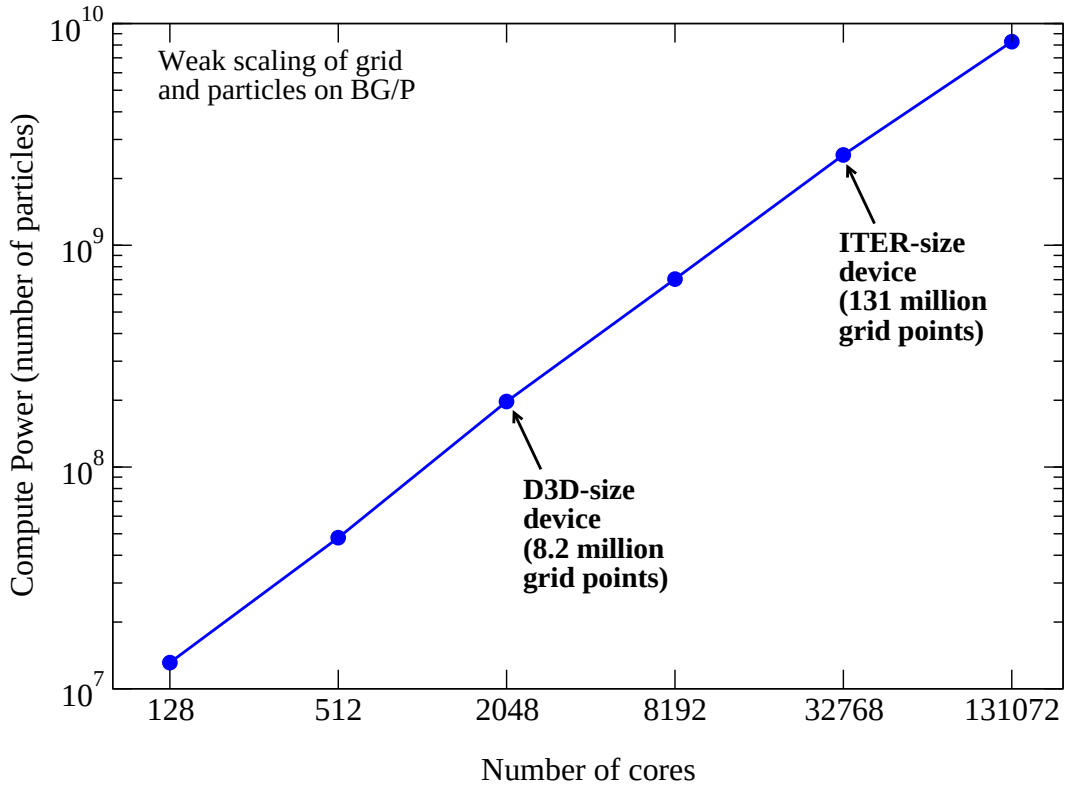


electron heat



- Meso-scale physics generic and important in determining plasma transport
- Flow, particle and heat pinch are in phase
- Particle and heat pinch can be tested by designing similar perturbative experiments to ones with modulated flows

Toward exascale



weak scaling of the new algorithm on BG/P (both particles and grids increased with cores)

- For an exascale system, memory/core will be fairly small
- Gyrokinetic PIC simulations face similar problem with Blue Gene. Only simulations of small devices could fit in memory
- To address this issue, we have added 2nd domain decomposition

- This enables ITER-size simulations with < 512MB/core by reducing memory footprint

Summary

State-of-the-art, first-principles-based global gyrokinetic simulations, which exploit leadership-class computational resources and cooperate with experimental and theoretical studies, are shown to lead to real advances in understanding some key physics issues in fusion science.

Global gyrokinetic simulations have discovered an important nonlinear flow generation process due to residual stress produced by micro-turbulence

- elucidate the origin of intrinsic rotation and formation of plasma rotation
- elucidate underlying physics governing experimental empirical laws of intrinsic rotation with respect to plasma gradients and current
- elucidate underlying dynamics governing the radial penetration of modulated flows in experiments
- important predictions made in regimes where experiments can validate

Acknowledgments: Simulations were performed on Franklin at the National Energy Research Scientific Computing Center (NERSC) and on Jaguar/pf at the National Center for Computational Sciences (NCCS).