Theoretical Research in Turbulence and Transport

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Purpose

- Highlights from the Past Year
- Propose Theory Department Plan
- Well Focused Portfolio of Theory Projects to Achieve MFE Goals

FESAC Goal

Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

5 Year Turbulence and Transport Goal

Advance understanding of turbulent transport to the level where theoretical predictions are viewed as more reliable than empirical scalings in the best understood systems.

Outline

1. **Ion Temperature Gradient Turbulence with Zonal Flows**
2. Electron Dynamics and Electromagnetic Fluctuations
3. Collaborations with Other Theory Groups

Tools for Turbulence Studies

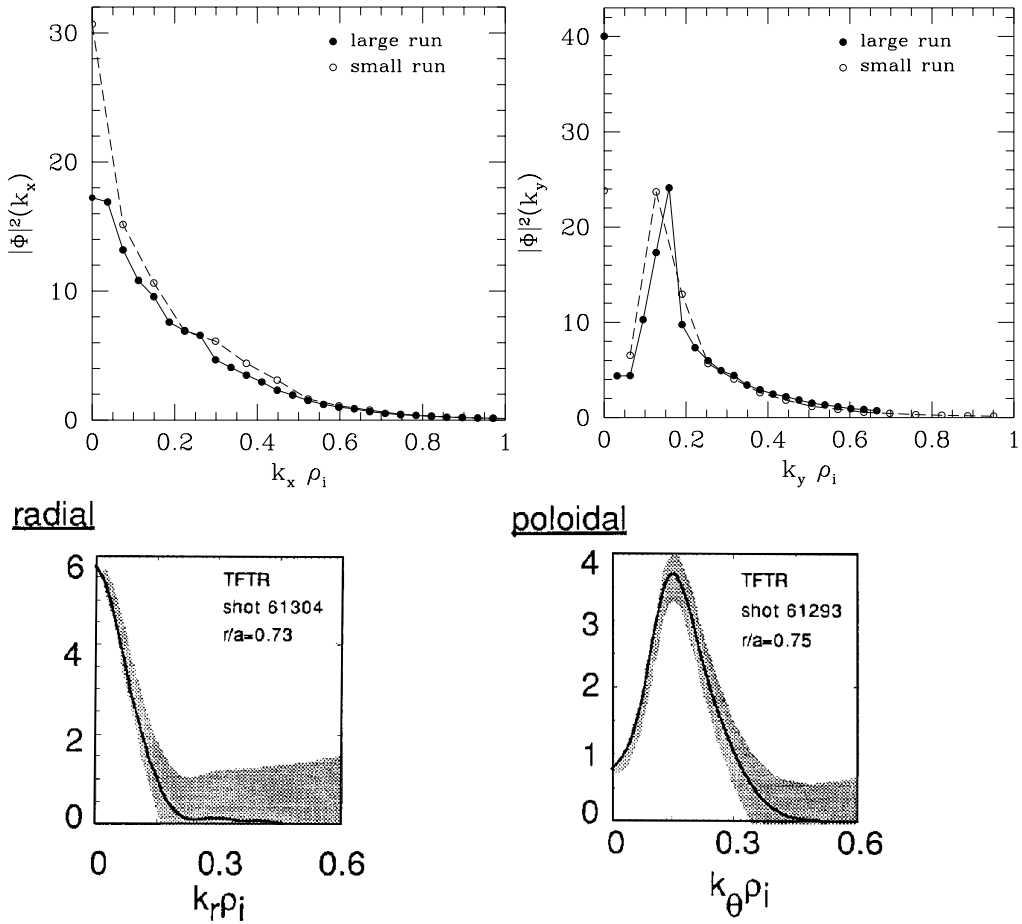
Gyrokinetic Particle-In-Cell Simulations in Full Torus

- Less approximations
- More nonlinear kinetic effects
- Easier to study meso-scale structures
  and transport scalings with machine size

Gyrofluid Simulations in Flux Tube

- Affordable long term simulations $\rightarrow$
- Statistically more meaningful
  frequency spectrum and correlation functions
- Easier to compare with theory

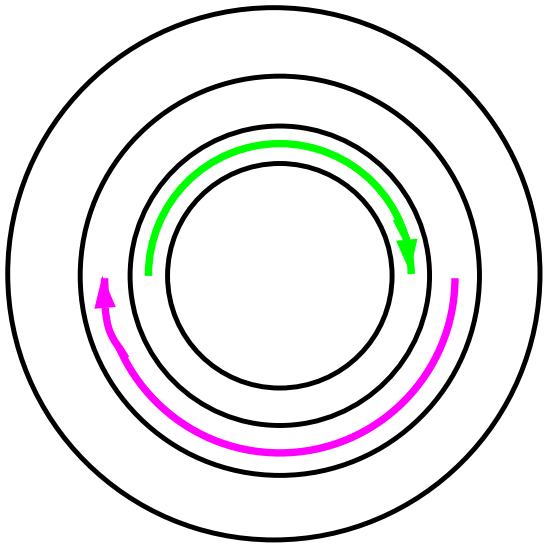
NONLINEAR SIMULATIONS WITH ZONAL FLOWS PRODUCE SPECTRA SIMILAR TO EXPERIMENTS



• **Nonlinear gyrofluid simulations (M. Beer et.al.) qualitatively similar to TFTR Data (Fonck et.al. PRL, 1993). (electrostatic simulations not done with exact experimental parameters. similar results from nonlinear gyrokinetic simulations.)**

• **Recent work started more detailed comparisons (parameter scans, etc. with more complete physics) (collab. w/ IFS-UT, U. Md., U. Wisc., DIII-D and C-MOD)**

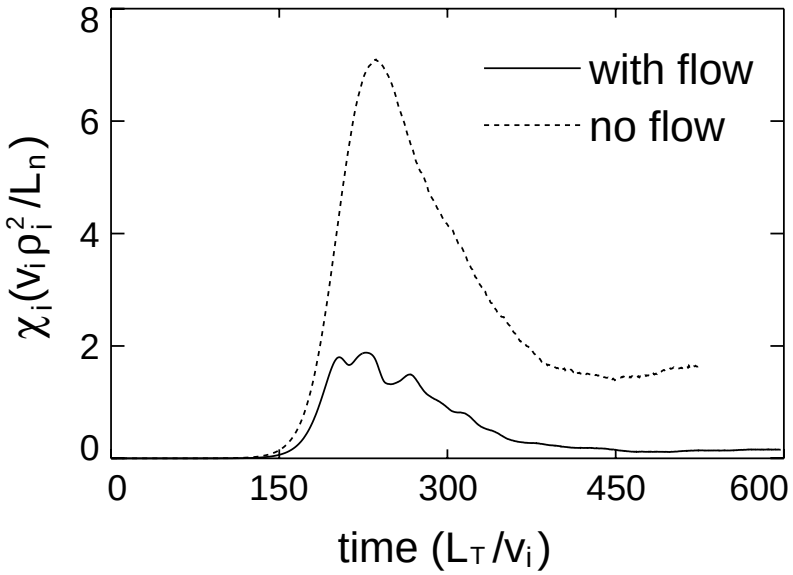
Time-varying Self-generated Zonal Flows



Radially Localized
Axisymmetric $\mathbf{E} \times \mathbf{B}$ Flows

Zonal Flows Reduce Ion Heat Transport

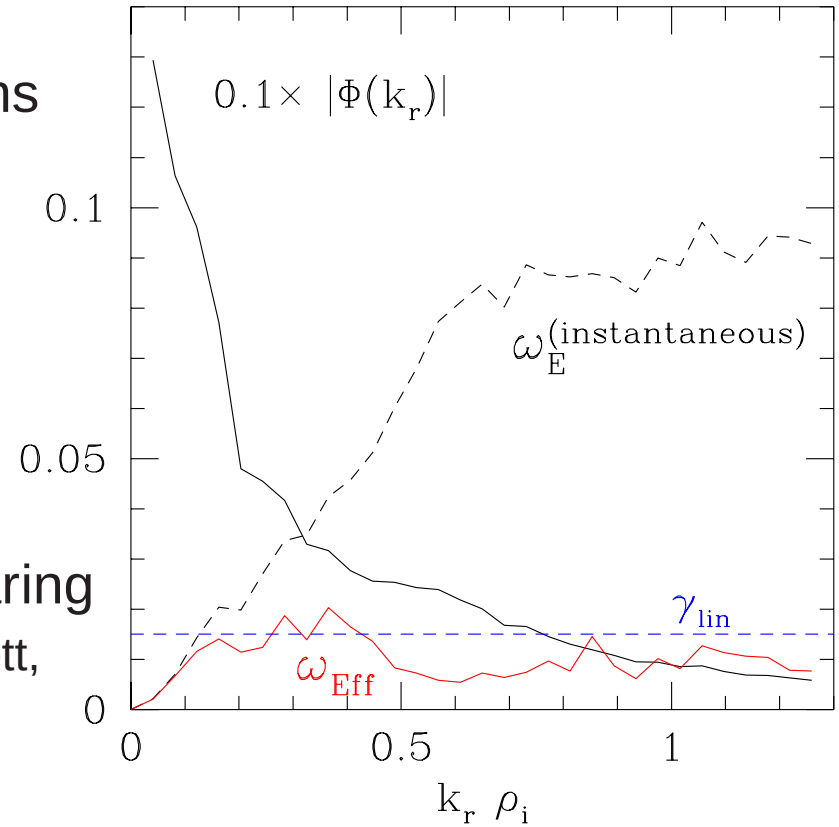
[Lin, Hahm, Lee, Tang, and White, *Science* **281**, 1835 (1998)]



- Substantial reduction (up to an order of magnitude) of steady state χ_i by turbulence-generated $\mathbf{E} \times \mathbf{B}$ flows
- However, turbulence is not totally suppressed, and ion thermal transport is still anomalous

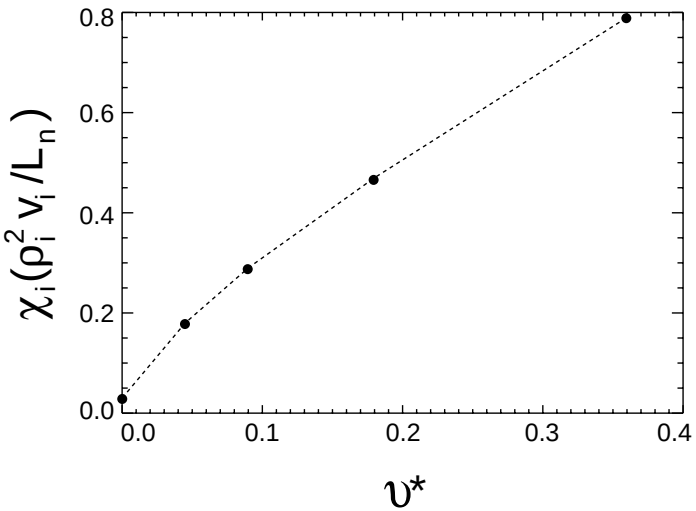
Effective Shearing Rates at Nonlinear Saturation

- Long term Gyrofluid simulations produce statistically reliable turbulent spectra.
- Using simulation zonal flow spectrum and zonal flow time history to calculate $\tau_{\mathrm{corr}}(k_r)$ [Beer & Hammett, APS 1998], we estimate the effective shearing rate ω_{Eff} [Hahm, Beer, Lin, Hammett, Lee, & Tang, PoP **6**, 922 (1999)] and find close to γ_{lin}



Collisional Effect on Transport

- Nondimensionally similar experiments: $\chi_{\rm eff} \sim \nu^{\alpha}$
  - $\rightarrow$ DIII-D H-mode: $\alpha \sim 0.5$; L-mode: $\alpha \sim 0$
    [*Petty and Luce 1999*]
  - $\rightarrow$ C-Mod H-mode: $\alpha \sim 1$
    [*Greenwald et al. 1998*]



- Transport increases with collision frequency
  [*Z. Lin, T. S. Hahm, W. W. Lee, W. M. Tang, and P. H. Diamond, Phys. Rev. Lett. , 1999*]
- Collisional effect on linear growth rate is negligible ($< 1\%$)

Plans on ITG Turbulence

Gyrokinetic Simulations

- More user friendly version of the GTC code
  Facilitate further dissemination [in addition to ORNL, NYU, and UCLA]
- Ion gyroradius scaling of confinement, roles of zonal flows, streamers, avalanches, and intermittency
- $(\nu_*, R/L_{Ti})$-scan; mixing length scaling recovered far away from ITG-marginality?
- Massive parallelization of the GTC code with multi-dimensional decomposition
  (in collaboration with CPPG)

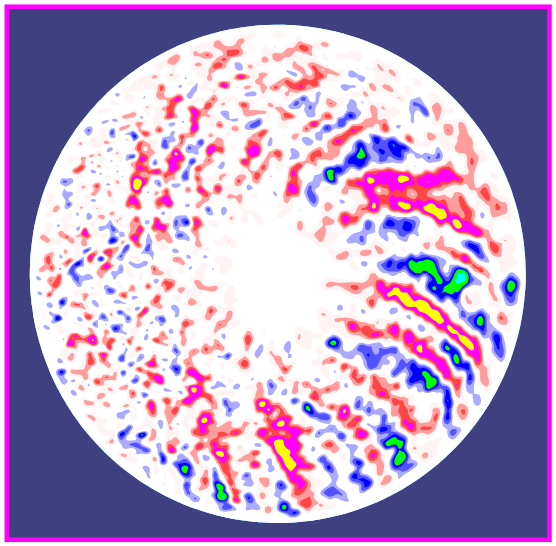
Plans on ITG Turbulence

- Comprehensive simulation diagnostics and visualization package for turbulence characteristics and spectral transfer (in collaboration with CPPG as part of PSACI)
  Modeling of experiments (eg., Reflectometry measurements)
- Inclusion of the externally driven $\mathbf{E} \times \mathbf{B}$ shear in nonlinear GF/GK simulations $\rightarrow$
  Comparison with the experiments [to be shown in presentations on collaborations]

Gyrofluid Simulations

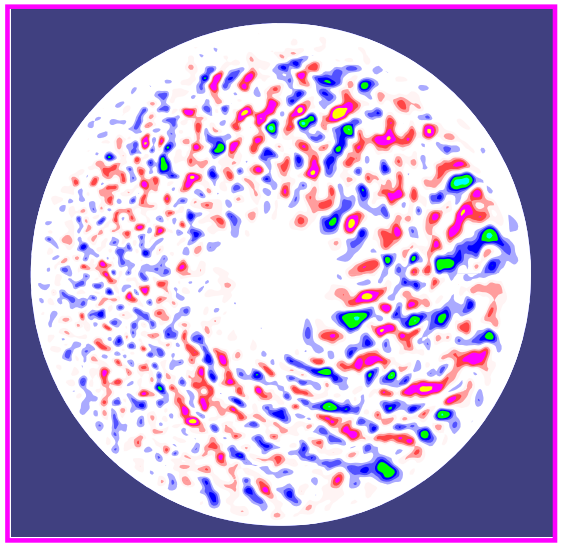
- Completion of the code parallelization with UMd and dissemination to UT and GA $\rightarrow$
  Improvements to the gyrofluid closures

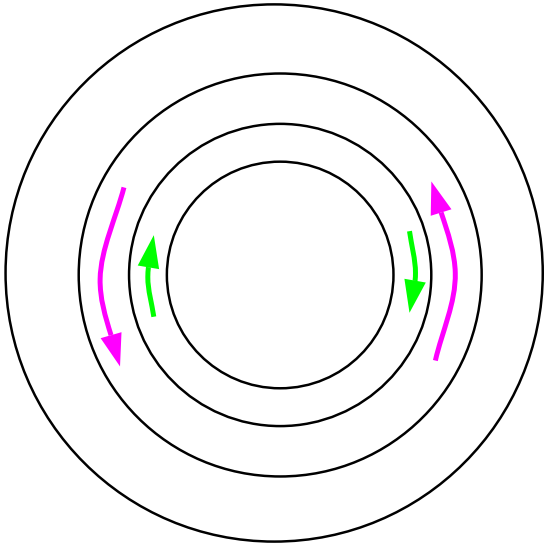
ITG Turbulence-Zonal Flow System



Random Shearing

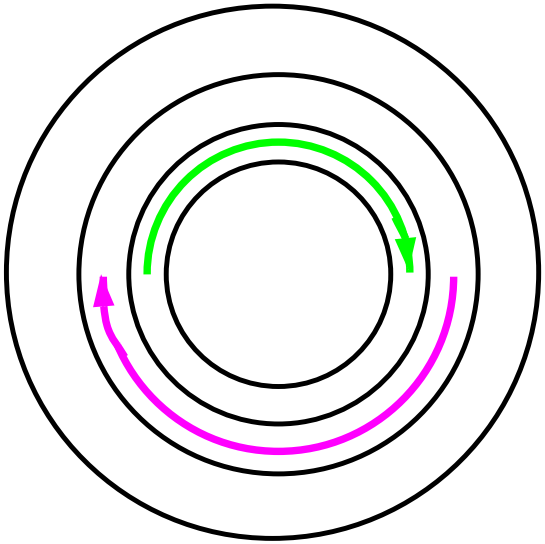
$\Longrightarrow$





Flow Generation

$\Longrightarrow$



Often χ_e remains highly anomalous,
although FULL and GS-2 calculations predict
NO linearly unstable modes with toroidal mode numbers
in the rough range of $10 < n < 100$.

Plans on Electron Dynamics and Electromagnetic Fluctuations

- Extend the linear stability calculations to longer wavelengths ($n < 10$) using global comprehensive kinetic code (KIN-2d; low n FULL) to study elusive electron thermal transport mechanism.
- Strengthen collaboration with IPP-Garching and UMd, on the c/ω_{pe}-scale fluctuations driven by electron temperature gradient using the gyrokinetic continuum code.
- Continue collaborations on submarginal turbulence with CEA Cadarache, UCSD, ORNL, and UAF.

Split-Weight δf Particle Simulation Scheme

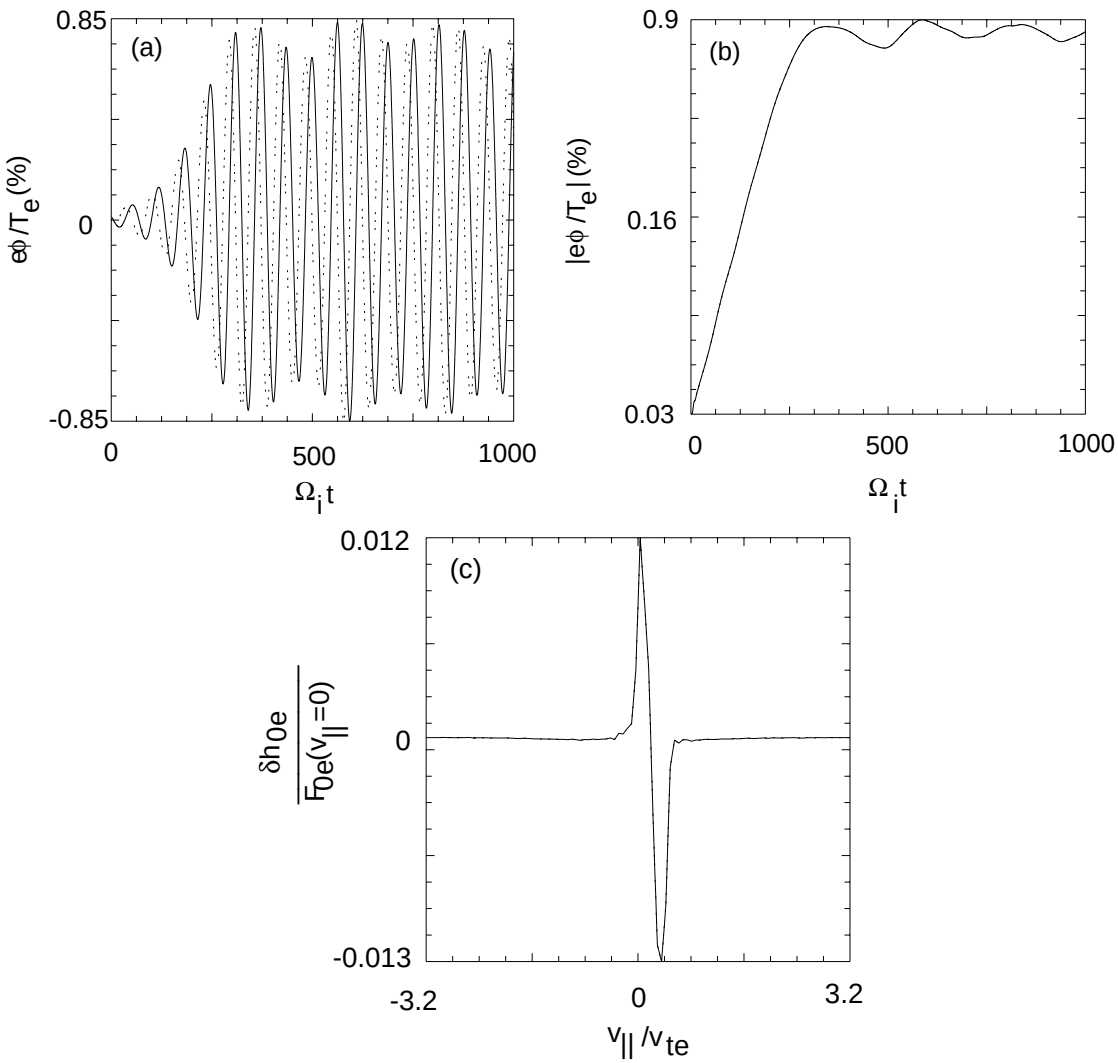
- δf scheme : $F = F_0 + \delta f$ *[Parker and Lee (PFB '93)]*
  - $w \equiv \delta f / F$ is followed dynamically.
  - Advantages: noise reduction and easy access to linear and nonlinear regimes.
  - Courant condition: fast particles limit the time steps
- Split-weight δf scheme: $\delta f = \phi F_0 + \delta h$

  [Manuilskiy and Lee (PoP '00)]
  - $w^{NA} \equiv \delta h / F$ is followed dynamically.
  - Courant condition can be circumvented.
- Finite-β Split-weight δf scheme: $\delta f = \psi F_0 + \delta h$

  [Lee et al., in preparation]
  - $\frac{\partial \psi}{\partial x_\parallel} = \frac{\partial \phi}{\partial x_\parallel} + \frac{1}{c}\frac{\partial A_\parallel}{\partial t}$

Simulation of Electrostatic Drift Waves using Split Weight Scheme for the Electrons

- 1D drift instability: (linear: $\omega\Delta t \approx 0.72, k_{||}v_{te}\Delta t \approx 2.7$)



Plans on Electron Dynamics and EM fluctuations

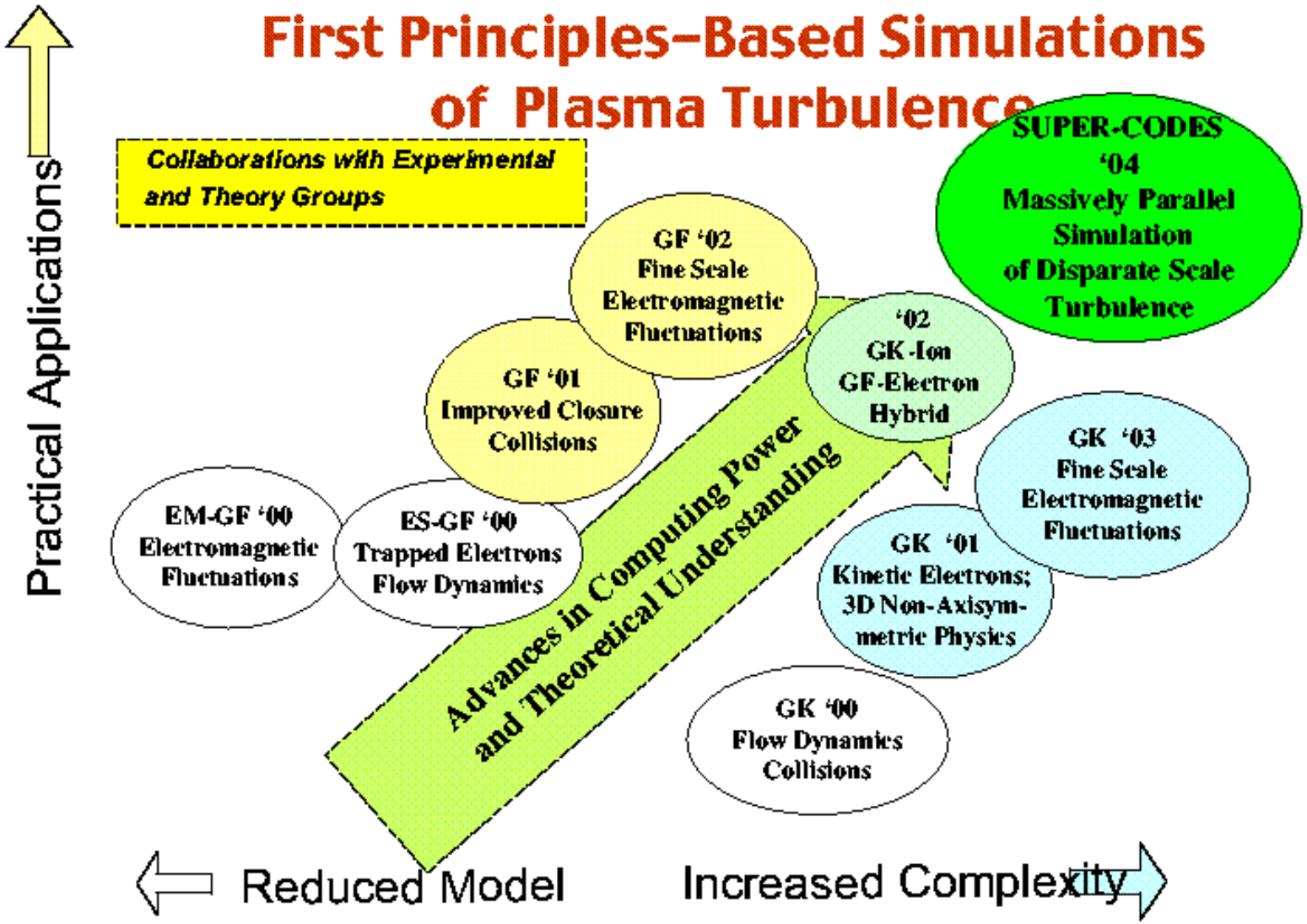
Gyrokinetic Simulations

- Implement electrostatic split-weight scheme to GTC code
- Initiation of electromagnetic simulations to address β-scaling of transport (PSACI)

Gyrofluid Simulations

- Role of trapped electron dynamics in spectral transfer (Forward Cascade?) and zonal flow generation
- Zonal flow dynamics in electromagnetic simulations (role of Maxwell stress?), further extension of gyrofluid simulations to larger system size, finer resolution as a bridge between MHD and fully kinetic simulations

First Principles–Based Simulations of Plasma Turbulence



Outline

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2. Electron Dynamics and Electromagnetic Fluctuations
3. **Collaborations with Other Theory Groups**

Contributions to Transport Models

- Gyrofluid simulations provide the nonlinear physics basis for both IFS-PPPL[*Kotschenruether, Dorland*, **Beer, Hammett**, *Phys. Plasmas '95*] and GLF-23 [*Waltz*,...**Hammett**..., *IAEA '96*] transport models
- FULL calculations provide some linear physics basis for Multi-mode transport model

  [*Redd, Kritz, Bateman*,**Rewoldt, Tang**, *Phys. Plasmas'99*]
- Both computational and analytic contributions to leading models of confinement enhancement

  [**Beer, Hammett, Rewoldt**,... *Phys. Plasmas '97*]

  [*Diamond*,...**Hahm, Tang, Rewoldt**..., *Phys. Rev.Lett. '97*]

  [*Ernst*,...**Hammett**,... *Phys. Plasmas '98*]

Self-Organized-Criticality Paradigm

- The first application of SOC paradigm to transport in magnetically confined plasmas [*Diamond and* **Hahm**, *Phys, Plasmas '95*] as a candidate to reconcile the ion gyroradius scale fluctuations and Bohm-like transport.
- [Carerras,Politzer] point out possible relations of SOC to numerous experimental observations of nonlocal transport and $1/f$-spectrum.
- An example of non-SOC turbulence system which also produces $1/f$-spectrum has been found.

  [**Krommes** *and Ottaviani, Phys. Plasmas '99*]
- LLNL team[Nevins '99] reported signature of nonlocal transport events from PPPL-GK simulations of ITG turbulence.

Utilization and Extension of PPPL Turbulence Codes

- Extension of GTC code to diverted geometry is underway by NYU team to study L-H transition physics
- Our global gyrokinetic simulation (GTC) results are being analyzed by LLNL team using a comprehensive diagnostics package as a part of PSACI activity
- IFS (the University of Texas) team will compare gyrofluid code simulation results to the density fluctuation spectra from Beam Emission Spectroscopy measurements on DIII-D plasmas, and planned for C-Mod
- Numerous application (throughout the world MFE community) of FULL and Gyrofluid codes for linear growth rate calculations.

Conclusions

- Accountable track record for producing seminal theories and reliable codes for Fusion Energy Science research
- Collaborations among transport experts and with other topical groups
- Partnerships with other theory groups and with experimental groups
- Key National/International Resource highly desirable investment for scientific challenging problems and many external collaborations

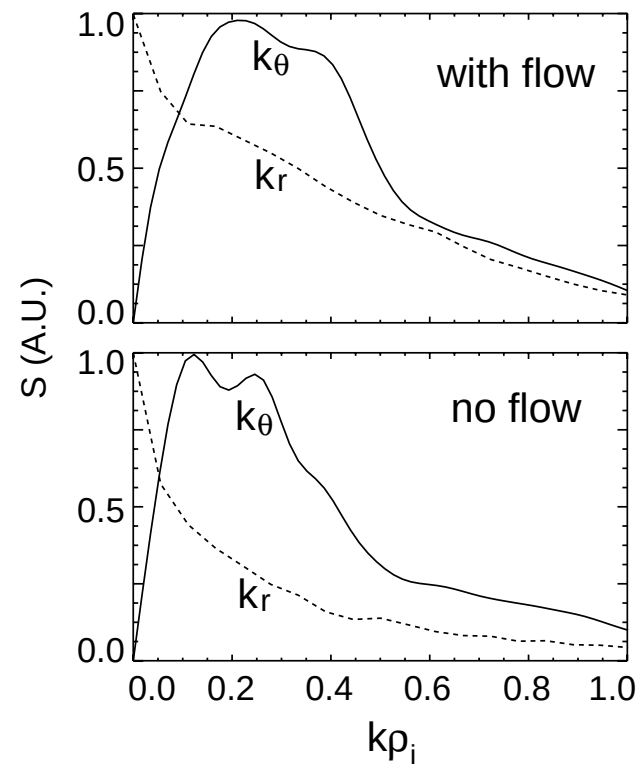
Broadening of k_r Spectrum by Zonal Flows

- Theory for $\mathbf{E} \times \mathbf{B}$ shear deccorelation of turbulence has been generalized to include time-dependence of zonal flows
  [*T. S. Hahm, M. A. Beer, Z. Lin, G. W. Hammett, W. W. Lee, and W. M. Tang, Phys. Plasmas, 1999*]

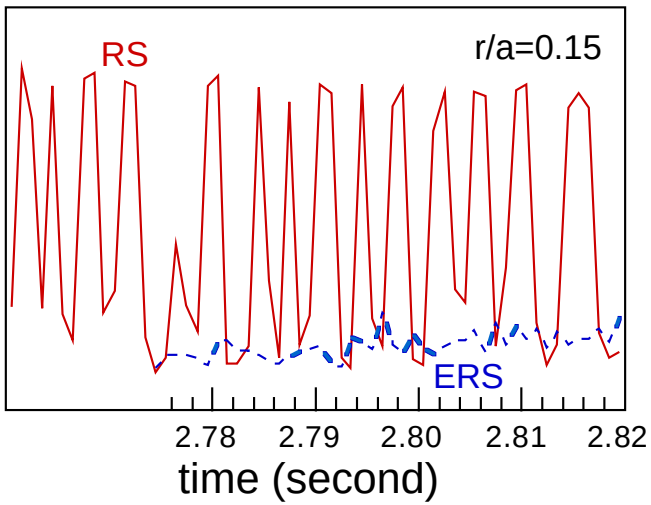
$$(\frac{\Delta r_0}{\Delta r})^2 = 1 + \frac{\omega_{Eff}^2}{\Delta\omega_T^2}$$

- Fast time-varying $\mathbf{E} \times \mathbf{B}$ flow is not effective in suppressing turbulence: flow pattern changes before eddies get distorted

$$\omega_{Eff} \simeq \omega_E^{(0)} \frac{\Delta\omega_T}{\sqrt{\Delta\omega_T^2 + 3\omega_f^2}}$$

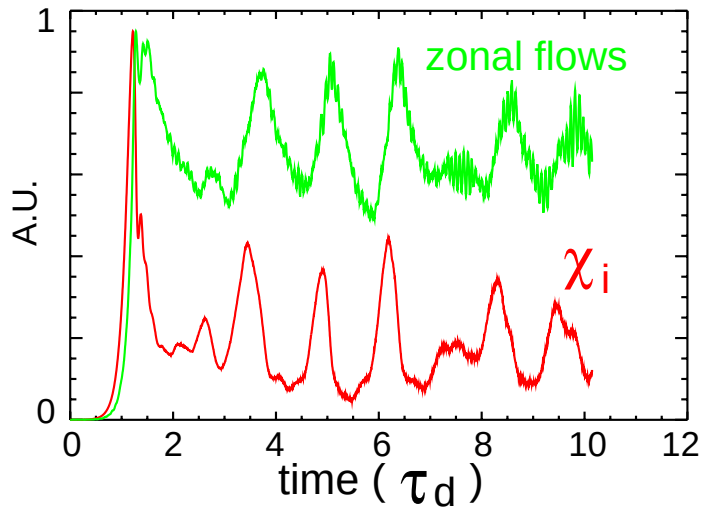


Bursty Behavior of Fluctuations and Transport



[Mazzucato, et al., PRL, 1996]

large bursts of fluctuation in TFTR RS plasmas observed period ~ collisional flow damping time



[Lin, et al., PRL, 1999]

collisional damping of zonal flows causes bursts of turbulent transport in gyrokinetic simulations

- Collisional flow damping causes oscillatory/bursty behavior

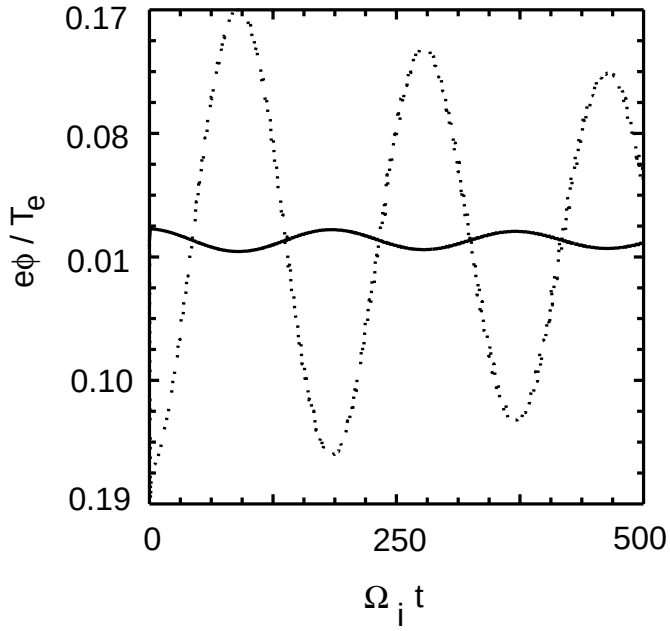
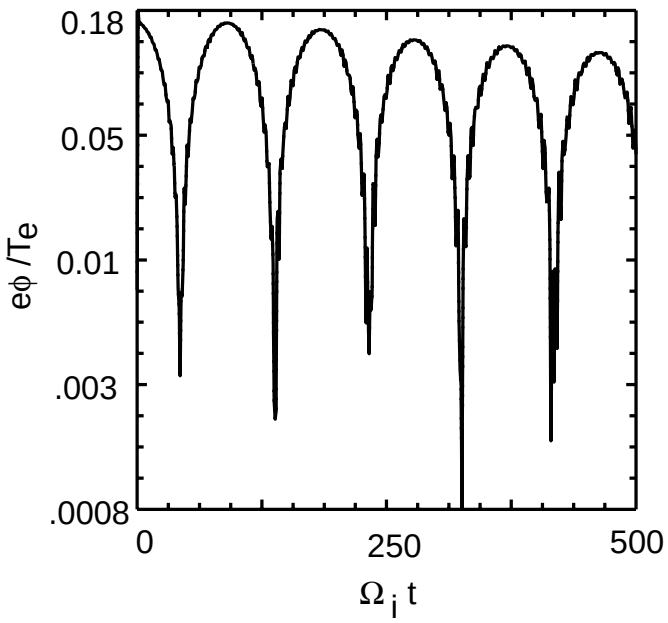
  [*Z. Lin, T. S. Hahm, W. W. Lee, W. M. Tang, and P. H. Diamond, Phys. Rev. Lett.* , *1999*]

  $\rightarrow$ oscillation period $\sim \tau_d$ zonal flow damping time

- Measured period of turbulence burst in TFTR RS plasma [*Mazzucato et al. 1996*] close to collisional flow damping time

Shear-Alfven Waves Simulation using Split-Weight Scheme

- One-Dimensional Simulation:

$$k_\perp \rho_s = 0.8, \beta = 10\%, k_{||}/k_\perp = 0.01, T_e/T_i = 1$$

- Split weight scheme: $\omega \Delta t \approx 0.033, k_{||} v_{te} \Delta t \approx 0.344$