Theoretical Research in Turbulence and Transport

Presented by **T.S. Hahm**

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Outline

Analytic theory activity with an emphasis on interaction with simulation experts, and experimentalists

- Physics of E x B Zonal Flows
- Physics of Turbulence Spreading
- Theoretical Foundations and Statistical Properties of Nonlinear Gyrokinetic Systems

Conclusions

Our Research in Turbulence and Transport

FESAC Priorities Panel Topical Research Questions include:

"How does turbulence cause heat, particles, and momentum to escape from plasmas?"

"How are large scale electromagnetic fields and mass flows generated in plasmas?"

ITPA High Priority Items Include:

"Encourage tests of simulation predictions via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings"

Role of ExB Shear in Reducing Turbulence

- ExB shear decorrelation in cylinder [Biglari, Diamond, Terry '90, Shaing '90,…]

$$\omega_E > \Delta\omega_T$$

- Turbulence quenching in gyrofluid simulation [Waltz, Kerbel, Milovich, Hammett, PoP '94]

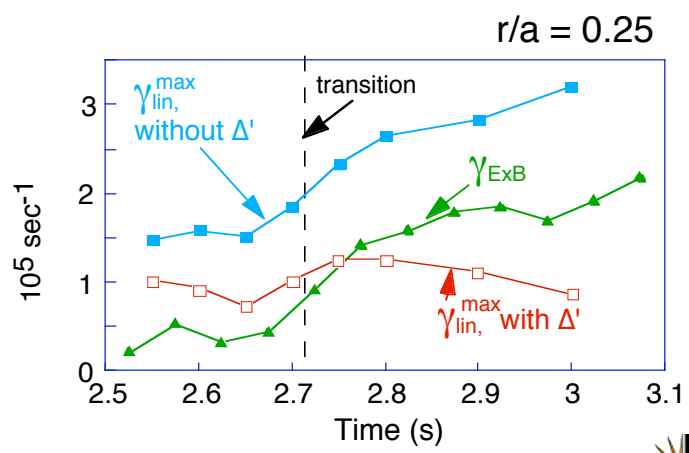
$$\omega_E > \gamma_{lin}$$

- ExB Shearing Rate in **General Toroidal Geometry** [Hahm-Burrell, PoP'95]

$$\omega_E = \frac{\Delta r_0}{\Delta \ell_\perp} \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi}\left(\frac{E_r}{RB_\theta}\right)$$

- Made possible by developments of experimental diagnostics for E_r and B_θ (MSE, CHERS, …)

- Widely used for experimental results analysis (TFTR, DIII-D, JET, JT60-U, AUG, Textor, NSTX, MAST, LHD, W7-AS,…) with linear growth calculations via FULL, Gryffin (Beer's GF code), GS2,…



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E x B Shearing by time-dependent Zonal Flow

[Hahm, Beer, Lin, Hammett, Lee, Tang, PoP '99]

- Gyrofluid Simulations observed that instantaneous $\omega_E(t) >> \gamma_{\text{lin}}$ while turbulence was at L-mode level and transport was anomalous.
- Effective E x B shearing rate has been analytically derived to take into account the time dependence of zonal flows
- From GF simulation data analysis, $\omega_E^{\text{eff}} \sim \gamma_{\text{lin}}$ has been observed:
  - -- Shearing due to GAM is predicted to be ineffective for core turbulence.
  - -- High k_r of GAM also contributes to this effect in Dimits' GK simulation [Nevins, APS-Invited '00].
- Gyrokinetic simulations demonstrated broadening of k_r due to zonal flows indicating eddy shearing quantitatively.

- Enhanced understanding beyond kinematic models:

[Krommes, Kim, Phys. Rev. E. '00] Hasegawa-Mima System

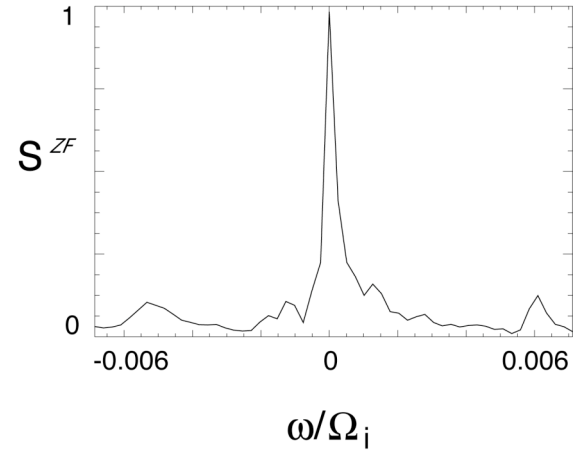
[Kim, Diamond, Hahm, PoP '04] Interchange and ITG models

Characterization of Zonal Flow Properties Motivated Experimental Measurements

[Hahm, Burrell, Lin, Nazikian, Synakowski, PPCF '00]

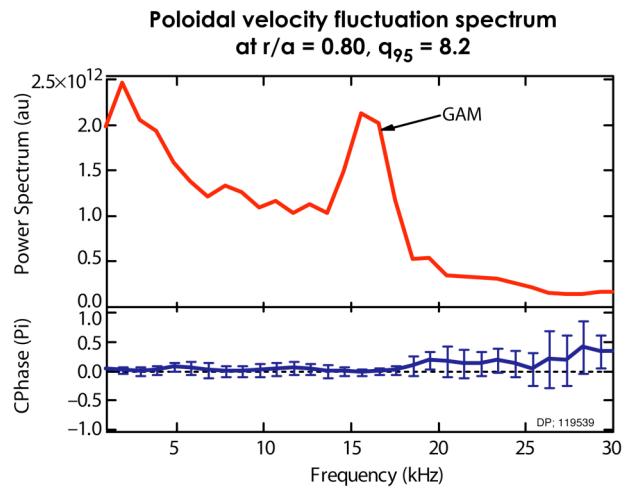
From gyrokinetic simulations:

- n=0, m=0, broad k_r, potential fluctuation
- Broad-band zero-freq ZF & GAM
- Properties of associated density fluctuations



Experiments:

DIII-D (BES, PCI, Langmuir Probe)
TEXT, JFT-2M, JIPPT-IIU (HIBP),
AUG, (Doppler Reflectometry),
…



New results from McKee, et al., on DIII-D [presented by Burrell, IAEA-TM, Sept. '05]

Theory on Nonlinear Upshift of ITG Threshold

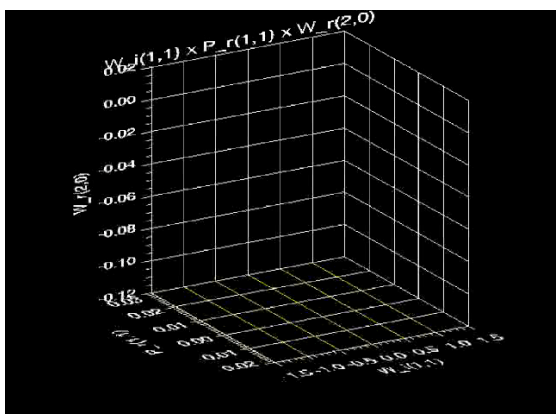
- **Nonlinear up-shift** due to self-generated Zonal Flows [Dimits et al., PoP '00] (Product of Cyclone Project)

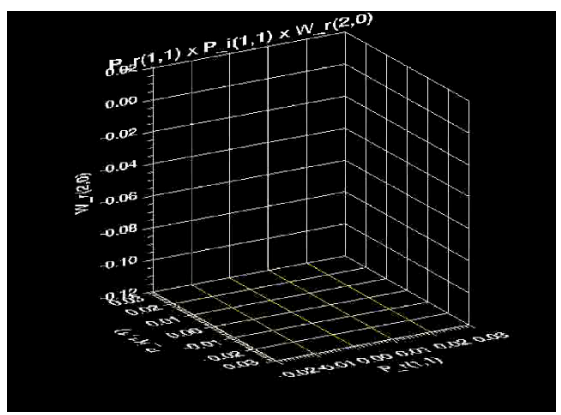
- First serious analytical calculation of the nonlinear up-shift in ITG turbulence using center manifold theory relatively unfamiliar to MFE community
[Kolesnikov -Krommes, PRL, PoP '05]

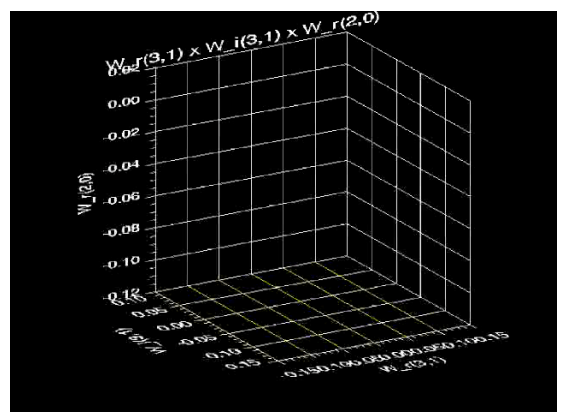
$$\partial_t \begin{Bmatrix} \omega_1 \\ P_1 \end{Bmatrix} = \mathcal{L}_1 \begin{Bmatrix} \omega_1 \\ P_1 \end{Bmatrix} + \{\text{ZF's shearing the ITG's}\}$$

$$\partial_t \begin{Bmatrix} \omega_3 \\ P_3 \end{Bmatrix} = \mathcal{L}_1 \begin{Bmatrix} \omega_3 \\ P_3 \end{Bmatrix} + \{\text{Sideband generation via ZF's}\}$$

$$\partial_t \begin{Bmatrix} \omega_Z \\ P_Z \end{Bmatrix} = \{\text{Generation of Zonal vorticity, pressure via Reynold's stress}\}$$







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Zonal Flow Generation in Alfvénic Turbulence

- In high-β plasmas (eg., ST's), turbulence becomes electromagnetic (Alfvénic)
- Imperfect cancellation between Reynolds' stress and Maxwell stress due to dissipation in Alfvénic turbulence [Kim, Hahm, Diamond, PoP '01]

  Related to Transport Barriers near rational q surfaces observed in Experiments ? (JET, TJ-II, TFTR Type-II ERS, …)

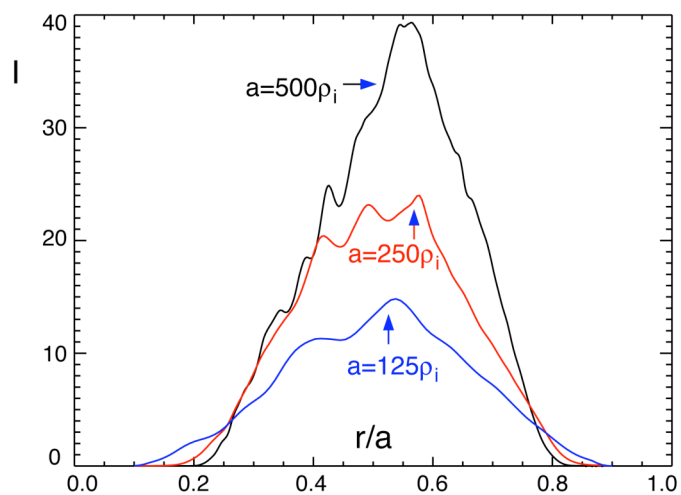
- Partial cancellation and weaker Zonal Flow generation also predicted from Gyrokinetic analysis of Alfvénic ITG turbulence [Chen, Lin, White, Zonca, PoP '01]

Turbulence Spreading

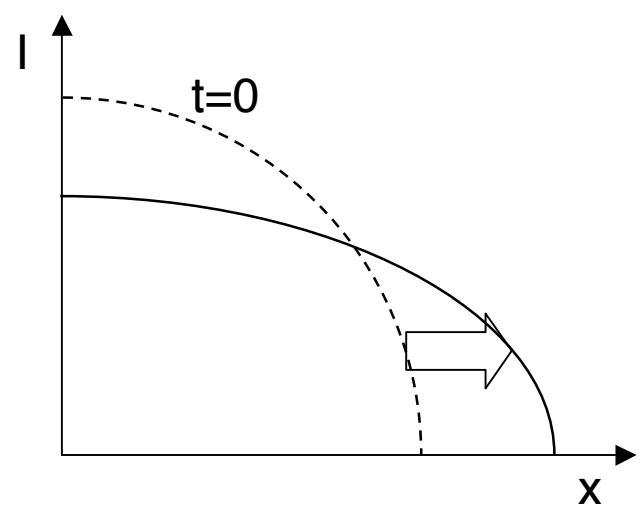
[Hahm,Diamond,Lin,Itoh,Itoh, PPCF '04]

- Garbet et al., '94 discussed spreading in the context of transient transport.
- Widely observed in many global gyrokinetic simulations.
- Theoretical Research motivated by GK simulations reporting deviation from "gyroBohm" scaling for moderate system size

[Lin, Ethier, Hahm, Tang, PRL '02]



Range of fluctuation spreading into linearly stable zone: GK simulation: $\Delta \approx 25\ \rho_i$



Nonlinear diffusion model: $\Delta \approx 18\ \rho_i$ for simulation parameters

Turbulence Spreading Theory I

[Hahm,Diamond,Lin,Rewoldt,Gurcan,Ethier, PoP '05]

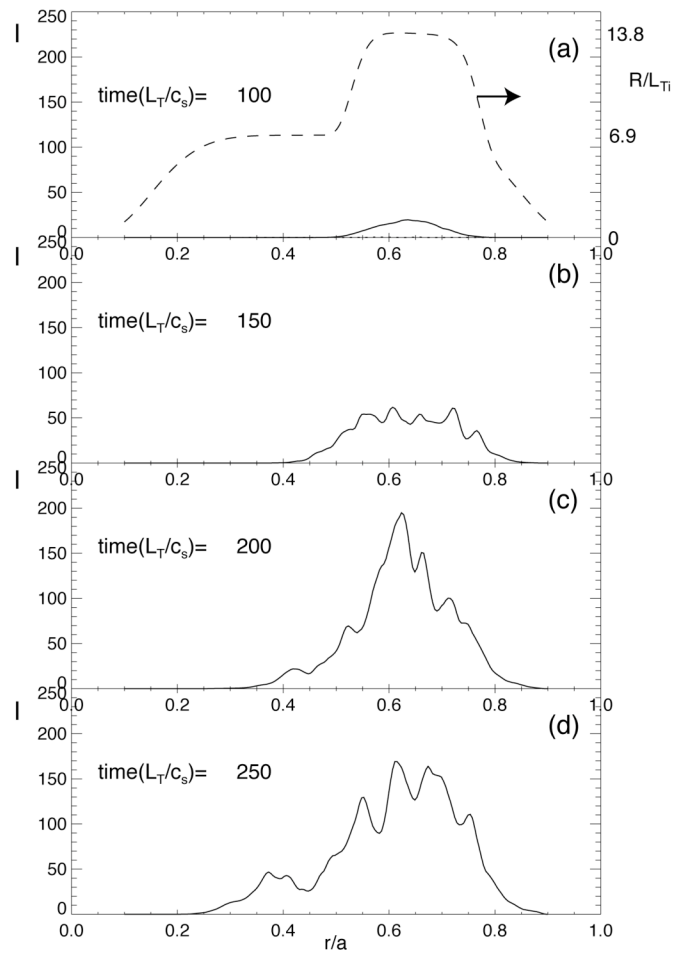
- A model nonlinear diffusion equation

$$\frac{\partial}{\partial t} I = \gamma(x) I - \alpha I^2 + \chi_0 \frac{\partial}{\partial x}\left(I \frac{\partial}{\partial x} I \right)$$

- predicts **Ballistic Front Propagation** with

$$U_x = \gamma^{1/2} \times \left(\frac{\chi_0 I}{2} \right)^{1/2}$$

- From simulation, initial turbulence growth at the edge is followed by ballistic front propagation into core
- Front speed increases with R/L_T
- Related to Sudden Core confinement improvement after H-mode transition in JET, JT-60U, … [Cordey, Neudatchin, et al., NF '94]



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Turbulence Spreading Theory II

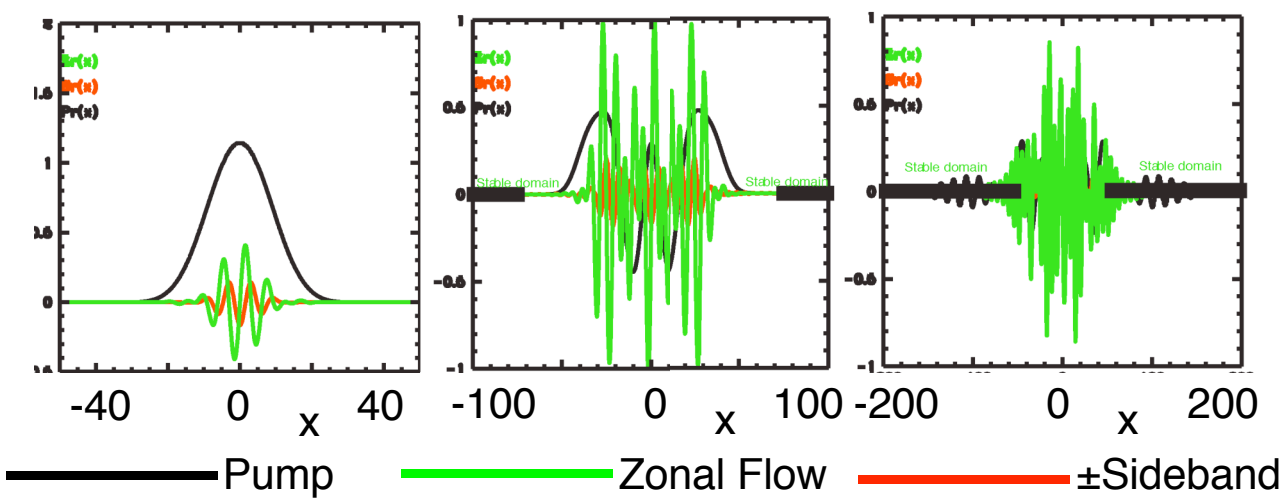
[Zonca,White,Chen, PoP '04, White,Zonca,Chen, PoP '05]

- Profile variations introduced to 4-wave model to include linearly stable zone.
- Numerical solutions of nonlinear envelope equation exhibit:

Self-generated Zonal Flows act as anti-potential well on the drift wave, and expel it.

Turbulence spreading occurs in a bursty manner.

Simple estimation based on simulation parameters predicts Bohm to GyroBohm transition as observed in GTC [Lin and Hahm, PoP '04].



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PPPL Theory played a Lead Role in Paradigm Shifts

- **Toroidal ITG eigenmodes**:

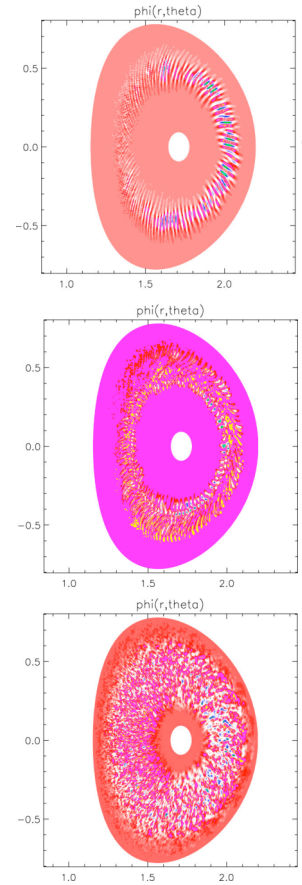
[Horton-Choi-Tang, PF '82],…
[Parker-Lee-Santoro*, PRL '93],…

- **Self-regulation by Zonal Flows**:

In alphabetical order:
Beer*, Dorland*, Hahm, Hammett, Krommes, Lee, Lin, Rewoldt, Tang, White
with
Chen, Diamond, Dimits, Hinton, Itoh, Itoh, Kim, Rosenbluth, Waltz, Zonca

- **Role of turbulence spreading in confinement scaling and edge-core coupling**

[Hahm, Diamond, Lin et al., PPCF '04, PoP'05]
[White, Zonca, Chen, PoP '05]



$t=150\ v_{ti}/L_T$

$t=210\ v_{ti}/L_T$

$t=1260\ v_{ti}/L_T$

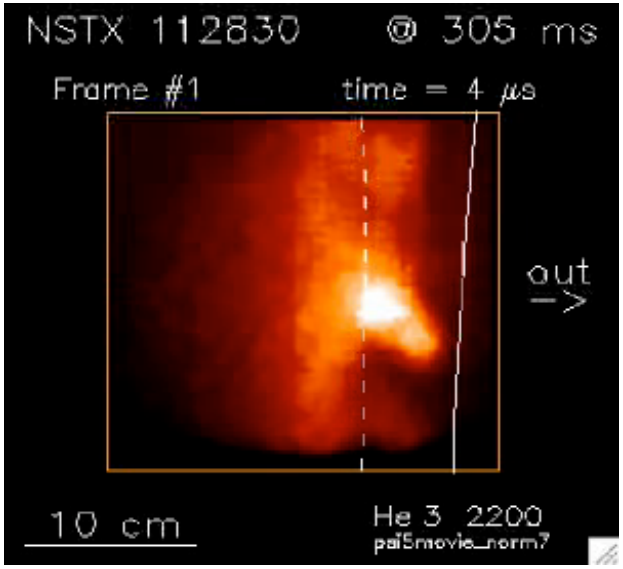
Density fluctuations from a GTC simulation of a shaped plasma with typical DIII-D core parameters [W. Wang, *et al.,* submitted to PPCF `05]

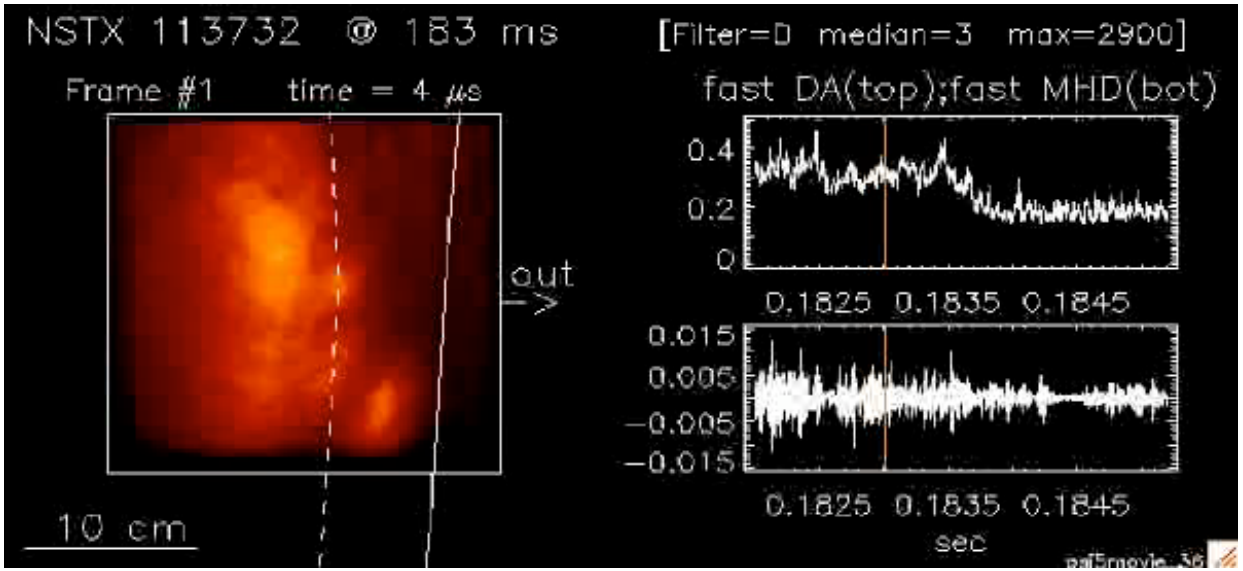
*Former graduate students at PPPL

Future Plans for Zonal Flows and Turbulence Spreading

- Include E x B Shear Effects in Turbulence Spreading Model in collaboration with UCSD and UCI, address turbulence behavior in the presence of transport barriers and possible experimental measurements of turbulence spreading [FY 06-07]
- Develop theoretical model for coherent structures in edge turbulence for use in comparison with GPI (gas puff imaging) data from NSTX and C-mod [FY 06-07]
- Study trapped electron effects in zonal flow dynamics, in particular, generation of short radial scale zonal flows in collaboration with UCI [FY 06-07]
- Pursue more realistic and quantitative analytic statistical theory of drift wave turbulence with zonal flows using center manifold theory [FY 06-07]
- Role of trapped electron precession shear in electron thermal transport barrier formation, in collaboration with UCSD [FY 07].

GPI Diagnostics of Edge Turbulence





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Theoretical Foundations for Nonlinear Gyrokinetics

- **Early Nonlinear Gyrokinetic Equations:**

  - Frieman, Chen, '82: for analytic applications
  - Lee '83: for particle simulations, identification of polarization density

  Lots of algebra, no consideration of conservation laws and Hamiltonian structure

- **Modern Nonlinear Gyrokinetic Formulations:**

  - Dubin*, Krommes, Oberman, Lee, '83:
    appreciation of Hamiltonian structure, systematic derivation of energy conservation, of polarization density
  - Hahm#, Lee, Brizard*, '88: generalization to electromagnetic case
  - Hahm# '88: generalization to toroidal geometry using phase-space Lagrangian, conservation of phase-space volume
  - Brizard* '90: fully electromagnetic toroidal NL GK using phase-space Lagrangian
  - Qin, Tang, '04: Differential geometry implications, extensions to high-frequency linear gyrokinetics

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Applications of Nonlinear GK and GF Theory

• Role of velocity space nonlinearity (crucial for energy conservation between particles and fields) in longer term dynamics [W.W. Lee's presentation]

• Nonlinear GK for core transport barriers with **High E x B Flow Shear** [Hahm PoP'96]:

*Implemented to FULL code and used for linear analysis of experiments [Rewoldt et al., PoP'98]

*Used for nonlinear GK particle simulations [Villard et al., PPCF '04]

• Nonlinear Gyrofluid Simulations:

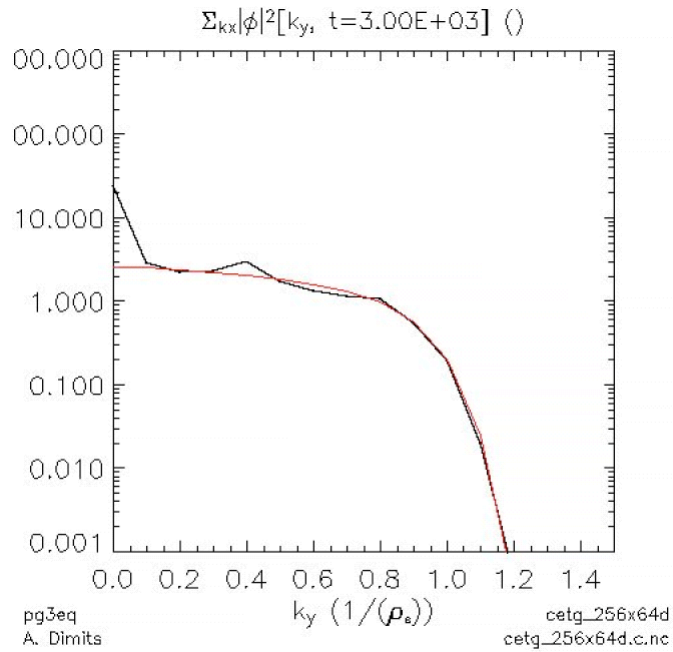
* First observation of self-generated short scale Zonal Flows in toroidal geometry [Hammett, Beer, Dorland, Cowley, Smith, PPCF '93]

* ITG Turbulence nonlinear physics basis for IFS-PPPL [Kotschenruether, Dorland, Beer, Hammett PoP '95] and GLF-23 [Waltz, …, Hammett, et al., PoP '96] transport models

Theory of Discrete Particle Noise

- To investigate discrepancies between continuum & PIC simulations of ETG turbulence, calculated noise spectrum & noise-induced diffusion, building on fundamental work by Langdon, Krommes, …
- Gyrokinetic PIC application of Test-Particle Superposition Principle gives:

$$\left\langle \left| \frac{e\tilde{\Phi}_{noise,k}}{T} \right|^2 \right\rangle = \frac{\langle w^2 \rangle}{N_p} \frac{S_{filt}^2(\vec{k})\Gamma_0(k_\perp^2\rho^2)}{[2-\Gamma_0][2-(1-d_{\|}S_{filt})\Gamma_0]}$$



Excellent agreement of LLNL PIC simulations & noise theory (w/ no fitting) at late times.

- Noise can ↑ or ↓ χ. Elongated ETG eddies very sensitive to noise, ITG less so.
- First paper accepted for publication (Nevins, Hammett, Dimits, …) focusing on PIC confirmation of theory (effective LLNL/PPPL collaboration).

(Nevins, Hammett, Dimits, et al., to appear PoP '05, Hammett Sherwood invited '05, Nevins APS invited '05.)

Future Plans on Nonlinear Gyrokinetic Theory

- Finish writing a review article on the foundations of nonlinear gyrokinetic theory for publication in Rev. Mod. Phys. in collaboration with St. Michael's College [FY 06].

- Derive nonlinear gyrokinetic equations relevant to edge turbulence[FY 06-08] as a part of "Scidac-FSP Center for Plasma Edge Simulations"

- Study the effects of velocity space nonlinearity on zonal flows and transport, following the availability of comprehensive phase space diagnostics [FY 07].

Future Plans: Statistical Properties of Nonlinear Gyrokinetic Systems

- Pursue renormalized theory addressing turbulence interaction with background diffusion, address its implication on the noise issue [FY 06]

- Investigate methods of reducing noise in PIC algorithms (need the right balance: some dissipation, but not too much…).

- Turbulence extremely challenging & benefits from multiple algorithms:
  - -PIC methods and Continuum methods complement each other.
  - -Continue collaborating on continuum algorithms (GS2, GYRO, GENE, LLNL edge code), interact with PPPL experimentalists using these codes.

Review Articles

- ``Fundamental Statistical Descriptions of Plasma Turbulence in Magnetic Fields" [Krommes, Phys. Reports '02]

Reports three decades of research (a large amount conducted in PPPL theory) on the analytical description of turbulent fluctuations and transport in magnetized plasmas, including successful comparisons to direct numerical simulations

- "Physics behind Transport Barrier Theory and Simulations" [Hahm, Plasma Phys. Control. Fusion '02]

Based on several years of interaction with experimentalists at TFTR, DIII-D, JET, JT60-U, and NSTX, and with theorists at PPPL, UCSD, UCI, and GA

- "Physics of Zonal Flows - a Review" [Diamond,Itoh,Itoh,Hahm, PPCF '05, IAEA Overview '04]

Current status of theory, numerical simulations, and experiments, indicates directions for progress in future research

Conclusions

- Excellent track record for producing seminal theories and defining future direction of Fusion Energy Science Research

- Close interactions with simulation experts and experimentalists led to synergistic effects

- Partnerships with other theory groups

- Key National and International Resource, addressing scientific challenging problems and many external collaborations