# Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas (GPS-TTBP)

PSACI-PAC Meeting-PPPL 6/5-6/2008

UCSD

# i.) PERSONNEL

- **P.H. Diamond, Principal Investigator, UCSD**
- **Fred L. Hinton, Senior Research Scientist, UCSD**

- Dr. John Mandrekas, DOE OFES - **Office of Science Program Officer**

**Collaborating Institutions/P.I.'s**
- Taik-Soo Hahm (institutional co-PI), Weixing Wang, Gregory Rewoldt, Stephane Ethier, PPPL
- Wendell Horton (institutional co-P.I.), Francois Waelbroeck, U TX*, Austin*
- Zhihong Lin (institutional co-PI), Liu Chen, Yong Xiao, Igor Holod, Wenlu Zhang, UCI
- Scott Klasky (institutional co-P.I.), *ORNL*
- Viktor Decyk (institutional co-P.I.), *UCLA*
- Kwan-Liu Ma (institutional co-P.I.), *UC Davis*
- Mary Hall (institutional co-P.I.), *USC*
- Mark Adams (institutional co-P.I.), *Columbia U*

**Domestic Collaborators**
- George Tynan, Ozgur Gurcan, Christopher Holland, Stefan Mueller, Christopher McDevitt (UCSD),
- C.S. Chang (*New York University*), Keith Burrell (*General Atomics*),
- Stanley Kaye, Daren Stotler (PPPL)

**International Collaborators**
- Jiaqi Dong, Jiangang Li (*China*) • Yanick Sarazin, • Virgina Grandgirard (*France*)
- Sanae-I Itoh (*Japan*) • Gyung Su Lee, Hyeon Park (Korea)

**Embedded Scientific Application Partnership (SAP):**
**Scientific Data Management Technologies to Accelerate Fusion Scientific Discovery**
- Arie Shoshani (PI), *LBNL*

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## ii.) ORGANIZATION

→ **Executive Committee (monthly teleconference)**

**P.H. Diamond, UCSD - P.I., Physics**

**Z. Lin, UCI - Computation**

**T.S. Hahm, PPPL - Physics**

**W. Wang, PPPL - Computation**

**Y. Xiao, UCI - GTC Code Development**

**S.Klaskly, ORNL**
**S.Ethier, PPPL** **- High Performance Computing**

**S. Kaye, PPPL - Validation**

**G. Tynan, UCSD - Validation**

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# Project Advisory Committee

**C.-S. Chang, C.I.M.S./N.Y.U. - Chair**

**X. Garbet, C.E.A., Cadarache**

**K.H. Burrell, G.A.**

**Y. Idomura, J.A.E.A.**

**T.-H. Watanabe, N.I.F.S.**

**M. Norman, U.C.S.D.**

## → GPS leverages off and collaborates with:

- Base program at: PPPL, UCI, UCSD

**- G.S.E.P. (Lin)**
**- C.P.E.S. (Chang)**
**share 8M hr. INCITE Award with GPS**

→ Postdocs Supported by GPS:

- **Yong Xiao, UCI**
- **Igor Holod, UCI**
- **Wenlu Zhang, UCI**
- **Kazuhiro Miki, UCSD (arrived 5/08)**
- **1 offer pending, UCSD**
- **Other recruitment in progress**

## → GPS Computing

- independent but interactive streams of code development and physics studies within:

  GTC FRAMEWORK

- West: Irvine, et al. (Lin)

  GTC Code, etc.

  East: PPPL, et al. (Wang)

  GTC - S Code, etc.

→ common:

physics program

analysis tools

supporting theory program

supporting HPC program

# GPS-TTBP Computing Resources

- Joint INCITE proposal by GPS-TTBP, GSEP & CPES awarded 8M hours of Jaguar @ORNL
- ORNL Jaguar CPU hours: 3.7M (INCITE + Director's)+4.5M (250TF pioneer application)
- NERSC Franklin MPP hours: 9.5M (~1.5M ORNL hours)
- TACC at U. Texas Lonestar & Ranger ?

## iii.) SCIENTIFIC PROGRAM

1.) Physics Studies in Drift Wave Turbulence and Transport

2.) GTC Framework Development

3.) High Performance Computing

4.) Validation of Gyrokinetic Models

# 1.) Physics Program

a.) Turbulent transport of toroidal momentum

- motivated by intrinsic rotation phenomena

- goal: understanding of off-diagonal toroidal momentum flux $\rightarrow$ pinch and residual stress

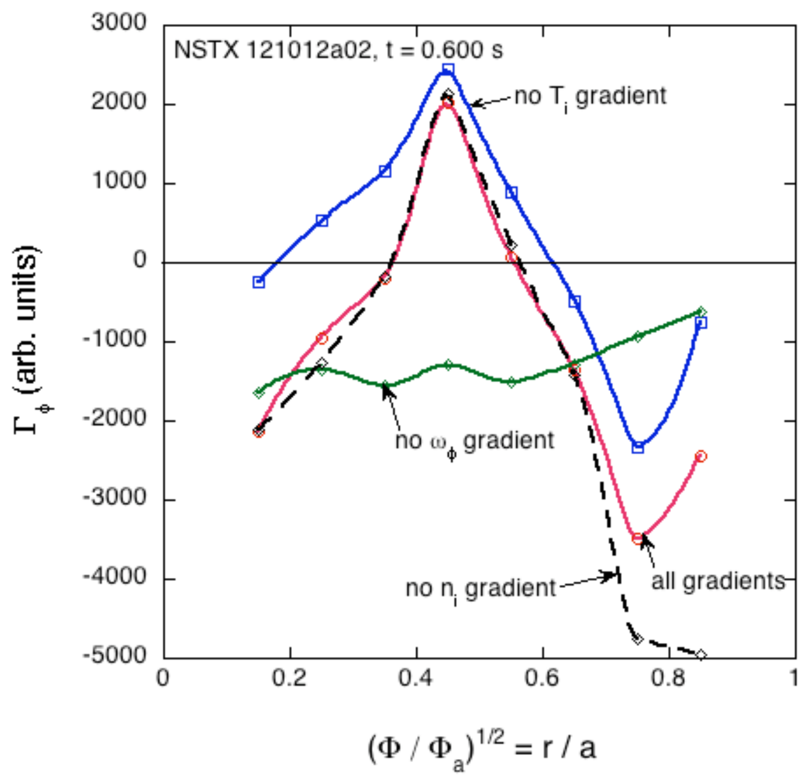
- special attention to:
  - relation of $v_\phi$ and *n* pinch

  - $\langle v_E \rangle'$ and neoclassical effects

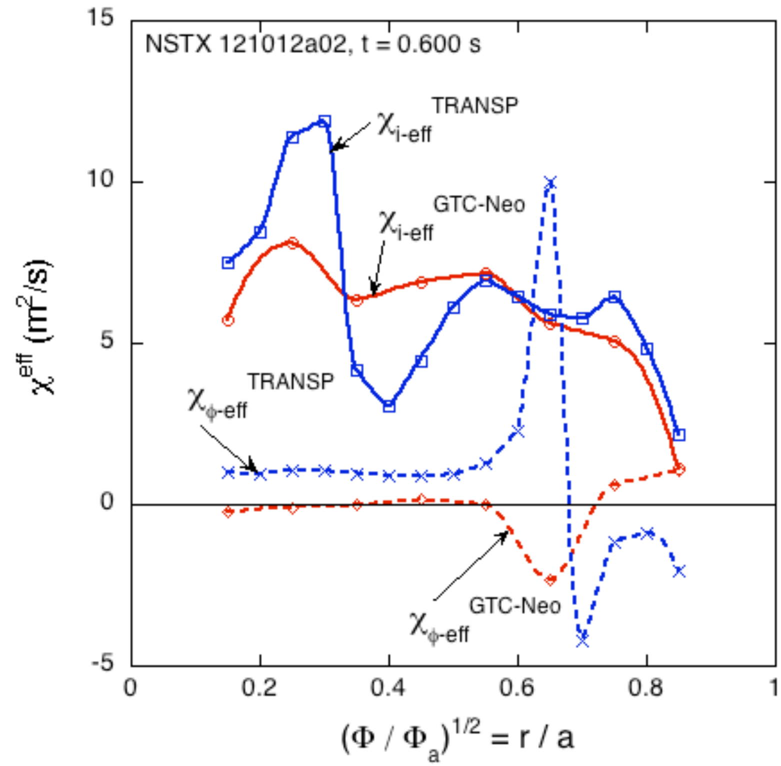
  - anomalous momentum transport in electron channel-dominated regimes (i.e. NSTX)

# Plans & Progress for GTC-Neo (W.X. Wang, G. Rewoldt, …)

• GTC-Neo is a global $\delta$f gyrokinetic particle-in-cell code, including finite-orbit-width (banana width) effects, which make the transport nonlocal. GTC-Neo can calculate neoclassical particle, momentum, and energy fluxes, along with $E_r$, $E_\theta$, $j_b$, etc. The code is now routinely applied to experiments (NSTX & DIII-D).

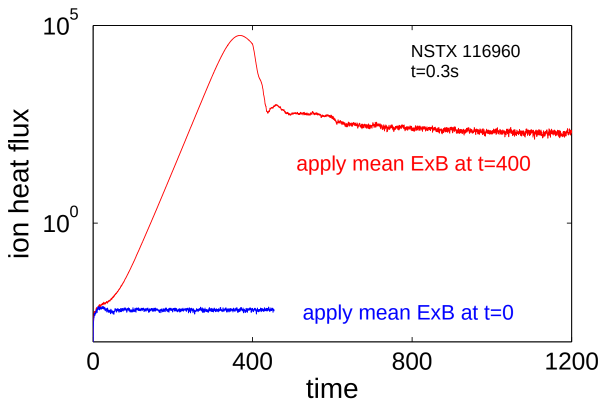


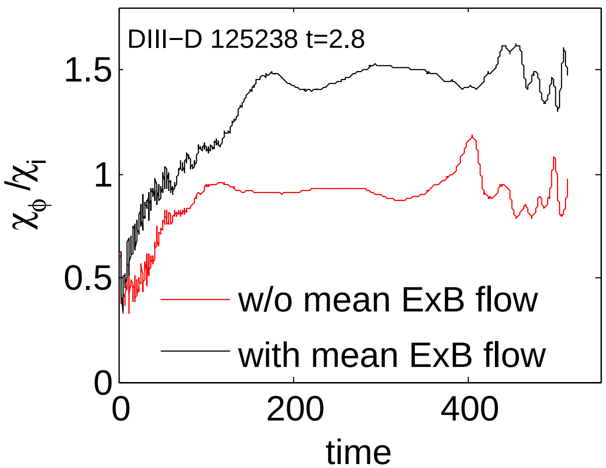

• Here $\Gamma_\phi$, the radial flux of toroidal angular momentum, is shown for an NSTX case (in internal code units) versus r/a. The $n_i$ gradient contribution is small, the $T_i$ gradient contribution is moderate and is always inward (pinch!), and the $\omega_\phi$ gradient contribution is largest, and has both signs.




• Here we show $\chi_{I\text{-eff}}$ and $\chi_{\phi\text{-eff}} = \Gamma_\phi / [R^2 n_i m_i (d\omega_\phi/dr)]$ (in m² / s) versus r/a for the same NSTX case. Ion energy transport is comparable to neoclassical (so anomalous ion energy transport is small), yet angular momentum transport is much larger than neoclassical (so anomalous angular momentum transport is dominant)!

# GTS/GTC-NEO validation excise: co-existence of normal ion heat transport and anomalous momentum transport




- Neoclassically $\chi_\phi/\chi_i \sim 0.01-0.1$, and neoclassical contribution to toroidal momentum transport is negligibly small
- GTS simulations verified strong coupling between ion momentum and heat transport for ITG turbulence: $\chi_\phi \sim \chi_i$
- Finite residual turbulence can survive strong mean $\mathbf{E}\times\mathbf{B}$ shear flow induced damping, and drive an insignificant ion heat flux and a finite momentum flux significantly higher than neoclassical level
- Equilibrium $\mathbf{E}\times\mathbf{B}$ flow shear is found to reduce turbulence driven transport for energy more efficiently than for momentum
- These may explain experimental observations of near neoclassical ion heat and anomalous momentum transport

# Various Physics Mechanisms exist for Nondiffusive Flux

Generic:

[Itoh, PFB '92], [Diamond, IAEA'94], [Coppi, NF 02], [Diamond, et al., PoP '08],…

E x B Shear:

[Dominguez et al., PFB '93], [Garbet et al., PoP'02], [Gurcan et al., PoP '07]

Wave Particle Resonant Interaction:

[Chen, JGR '99], [Shaing, PRL '01], [Diamond et al., PoP '08]

Magnetic Curvature:

[Hahm et al.,PoP '07, '08][Gurcan et al., PRL '08]

Coriolis Drift:

[Peeters et al., PRL '08]

It's likely:

*A combination of two or more mechanisms is necessary to reproduce basic features of experiments.*

Eg., Simple Transport Model [Gurcan, Diamond, Hahm et al., submitted '08] for H-mode plasmas in terms of Pinch and Residual Stress:

- V can be obtained by magnetic curvature [Hahm et al., PoP '07]
- S can be obtained ExB shear [Gurcan et al., PoP '07]
- Also, include simple ExB shear reduction [Hinton, PFB '91]

# GTC Simulation of Toroidal Momentum Transport

*UCI*

- Recent tokamak experiments observed spontaneous toroidal rotation and inward pinch of toroidal momentum *[Rice et al, NF07; Ida, PRL01]*
- Momentum flux is measured for shifted Maxwellian plasma in GTC global simulation of ion temperature gradient (ITG) turbulence
- Simulation with rigid toroidal rotation find inward flux of toroidal momentum, independent of rotation direction
- Simulation with sheared toroidal rotation find both diffusive and off-diagonal momentum fluxes. Measured $\chi_\phi/\chi_i$=0.2-0.7
- Quasilinear calculation using measured fluctuation spectrum shows that resonance occurs at particle energy higher than temperature and thus $\chi_\phi/\chi_i$=0.7

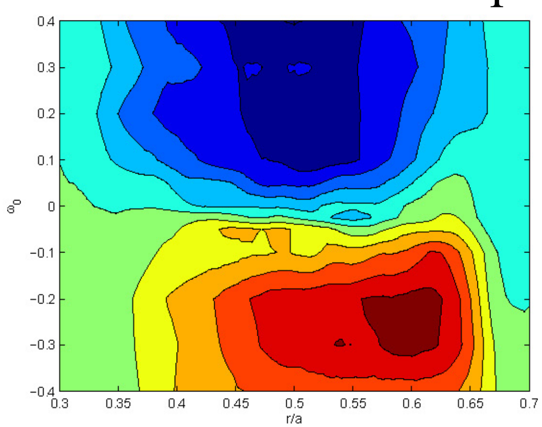
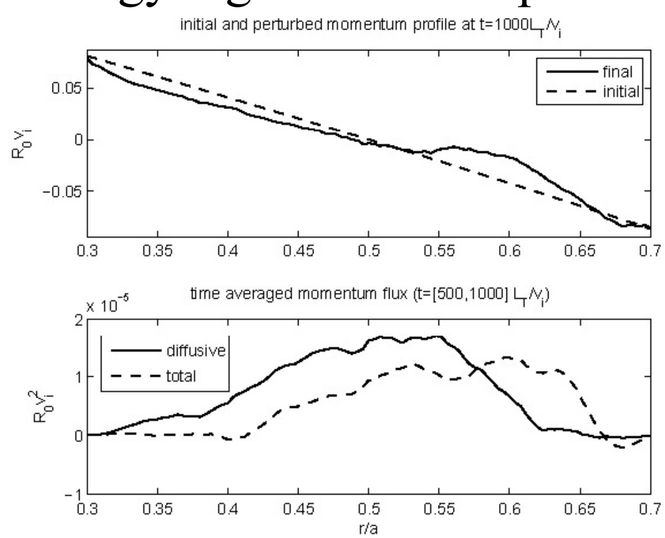
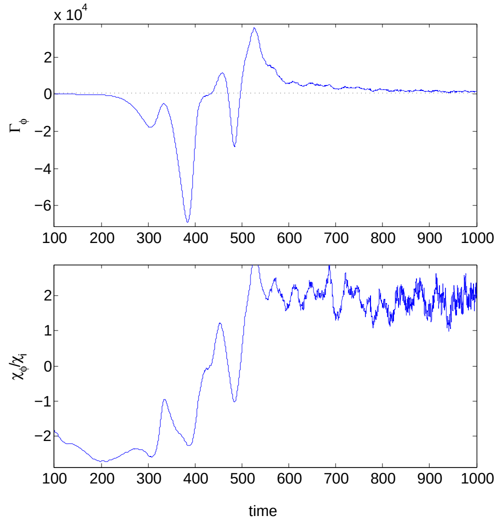


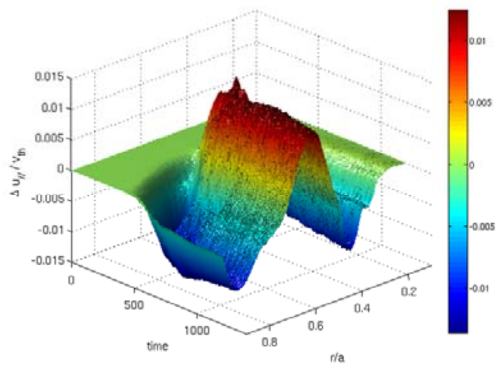

Fig. 6. Off-diagonal part of the momentum flux

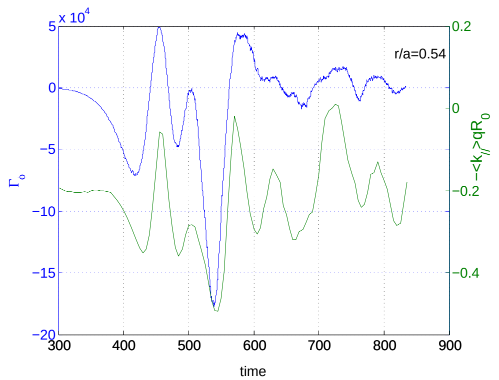



*[Holod & Lin, TTF08]*

# Gyrokinetic turbulence drives off-diagonal and diffusive momentum transport – from GTS simulations




- A robust, large inward $\Gamma_\phi$ is found in post-saturation phase of ITG turbulence (in the direction opposite to momentum diffusion for this case)
- Core plasma spins up with $\Delta u_\| \sim$ a few % of $v_{th}$ (no momentum source at edge)
- Mechanism: generation of residual stress due to $k_\|$ symmetry breaking induced by self-generated ZF shear

$$\langle k_\| \rangle (r) = \frac{1}{qR_0} \frac{\sum (nq - m)\delta\Phi^2_{mn}}{\sum \delta\Phi^2_{mn}}$$

- Smaller $\Gamma_\phi$ in long-time steady state is likely diffusive with effective $\chi_\phi/\chi_i$ on order of unit, consistent with experiments and early ITG theory

## b.) Collisonless Trapped Electron Mode (CTEM) and Electron Temperature Gradient Driven (ETG) Turbulence (Early Appl. Topic)

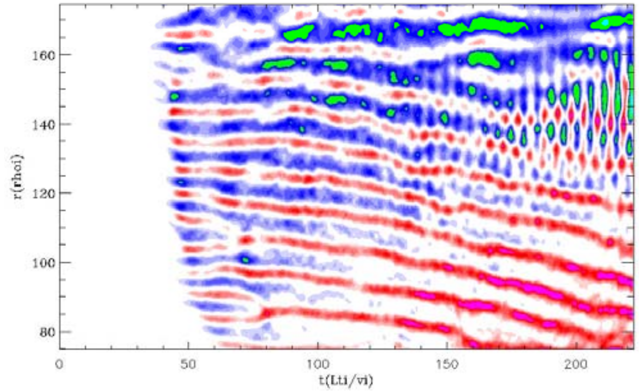
- motivated by electron thermal, particle transport
- goal: - understand saturation mechanisms and transport with strong resonance coherency
  - compare/contrast with ETG studies (ongoing at PPPL)

- special attention to:
  - zonal flow, corrugation effects
  - resonance detuning, distortion
  - CTEM turbulence spreading
  - related EPM avalanching (GSEP)

# GTC Simulation of CTEM Turbulence & Transport

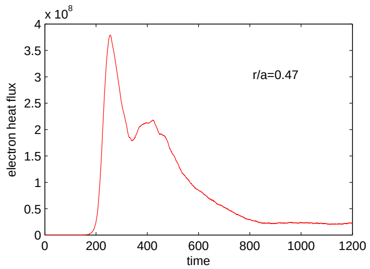
*UCI*

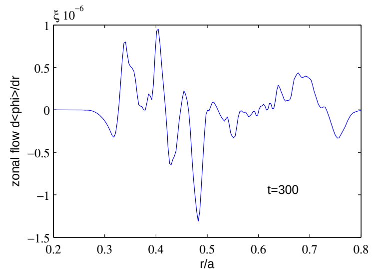
- CTEM instability driven by toroidal precessional resonance, detuning of which is weak; QLT has not been verified for electron heat transport in CTEM
- GTC simulation find that CTEM saturation amplitude increases an order of magnitude when zonal flow is suppressed *[Xiao & Lin, TTF08]*
- Characteristic time scale of CTEM close to inverse ZF shearing rate
- GTC simulation of CTEM scheduled for pioneer application on ORNL computer

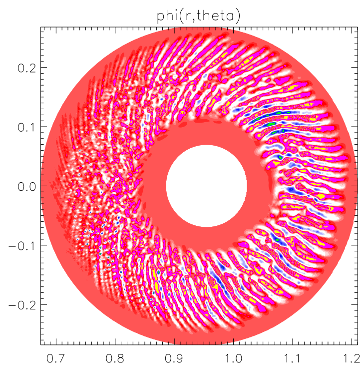



| $[\frac{L_{ne}}{v_i}]$ | $\tau_{wp} = \frac{4\chi}{3\delta v_r^2}$ | $\tau_{\parallel} = \frac{1}{\Delta k_{\parallel} v_i}$ | $\tau_{\perp}$ | $\tau_{eddy}$ | $\tau_{rb}$ | $\tau_{au}$ | $\tau_s$ | $\frac{1}{\gamma}$ |
|---|---|---|---|---|---|---|---|---|
| $ETG$ | 1.3 | 1.7 | 2.5 | 13.4 | 139 | 110 | | 11 |
| $ITG(A)$ | 1.6 | 1.7 | 2.2 | 4.9 | 23 | 15 | 1.4 | 9.1 |
| $ITG(k)$ | 1.6 | 1.8 | 1.64 | 3.6 | 12.6 | 6.6 | 0.87 | 5.0 |
| $ITG(k)$ | 0.7 | | 8.8 | | 67 | | | |
| $CTEM(i)$ | 0.26 | 1.91 | 7.7 | 1.82 | 19.3 | 9.27 | 0.65 | 4.0 |
| $CTEM(e)$ | 0.61 | | 7.8 | | 19.6 | | | |

# GTS Getting Ready for Global ETG Simulation for NSTX

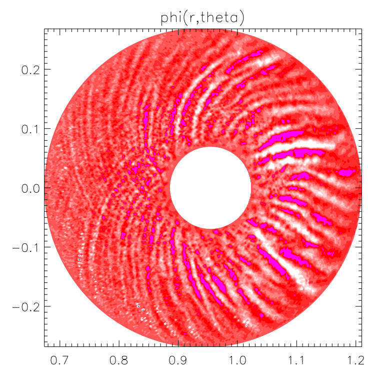



t=300

(nonlinear stage)




t=600

(nonlinear stage)

Test Simulation:

– $m_i/m_e = 100$,

– $0.2 \le r/a \le 0.8$,

– 0.28M grids/plane,

– 20 electrons/cell,

– low-$\beta$ numerical equilibrium

– 2432 cores of Franklin,

– wall clock time: 7 hours

- Streamers are sustained after nonlinear saturation
- Clear zonal flow structure is generated, but too weak to break streamers
- Real NSTX simulation $> (50 - 100)\times$ more expensive – very challenging!

# Study of ETG Turbulence in NSTX

- NSTX shot #124901a02 at t = 300 msec was identified as well-diagnosed in the core plasma.
  - Tangential scattering measurements were carried out at r/a~0.3
- In GTS, the number of grid points on a flux surface depends on the local value of the gyroradius, which is determined from the experimental temperature profile
  - The grid resolution needs to be at the electron gyoradius level
  - Require a very large number of grid points
- The mixed-model MPI-OpenMP capability of the code is being used to maximize the amount of memory per MPI process
  - Multi-threading is used within each quad-core socket to parallelize the work at the loop level
- Full system (31,232 cores) global ETG simulations with real electron mass

## c.) Nonlocality in Turbulence and Transport

- motivated by $\rho_*$ scaling, edge-core coupling

- goal: understand physics and mechanism of departure from quasi-local GB model

- special attention to:
  - $\rho_*$ - $\nu_*$ interplay, via shear flows
  - testing models of spreading
  - edge - core spreading/coupling
  - physics model for turbulence intensity profile

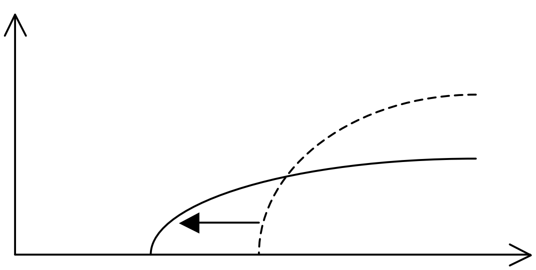
# Turbulence spreading is reduced by E x B shear

GTS nonlinear simulation of ITG turbulence exhibits significant turbulence spreading into the linearly stable zone

[Wang, Hahm, Lee et al., PoP 14, 072306 '07]

With ExB shear, spreading extent, $\Delta$ is reduced as expected from simple analytic nonlinear diffusion model

[Hahm, Diamond, Lin et al., PPCF 46, A323 '04]:

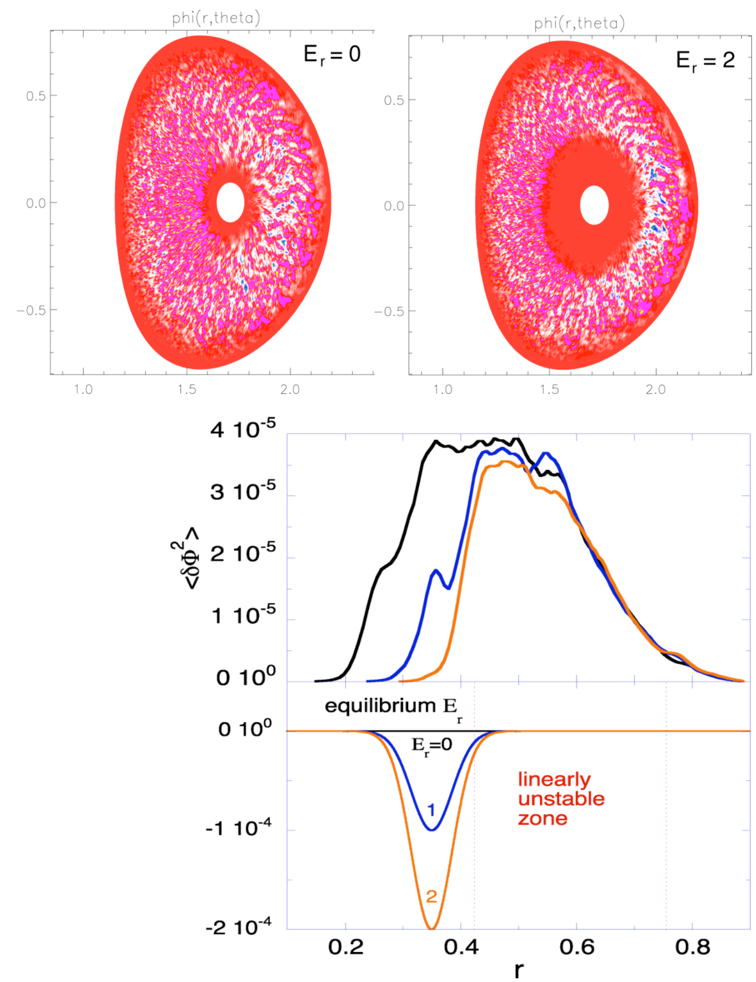


Balancing propagation time to damping time,

$\Delta / V_s \sim 1/|\gamma'|\Delta \Rightarrow \Delta \sim (V_s / |\gamma'|)^{1/2}$

$\omega_{ExB}$ increases damping rate slope $|\gamma'|$ and reduces fluctuation intensity locally.

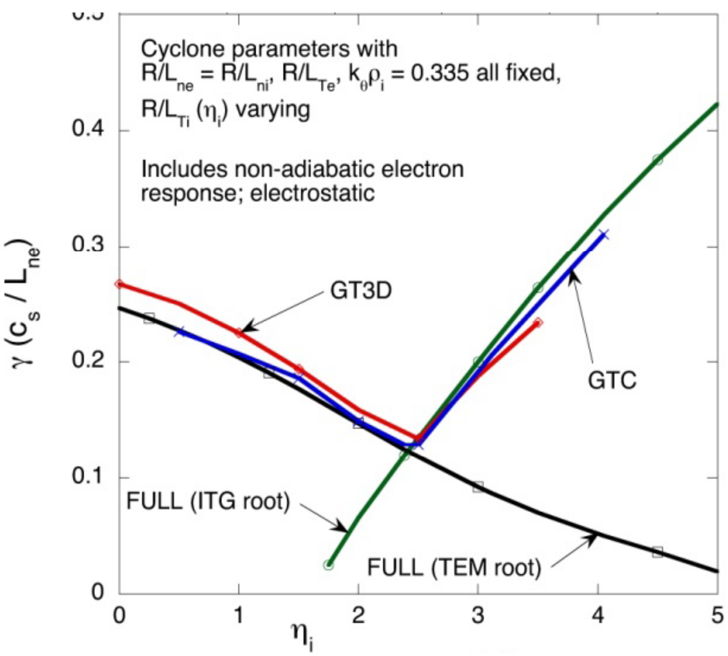
Spreading speed $V_s$ gets reduced with fluctuation intensity.



# GTC Simulation of CTEM Bursting & Spreading

***UCI***

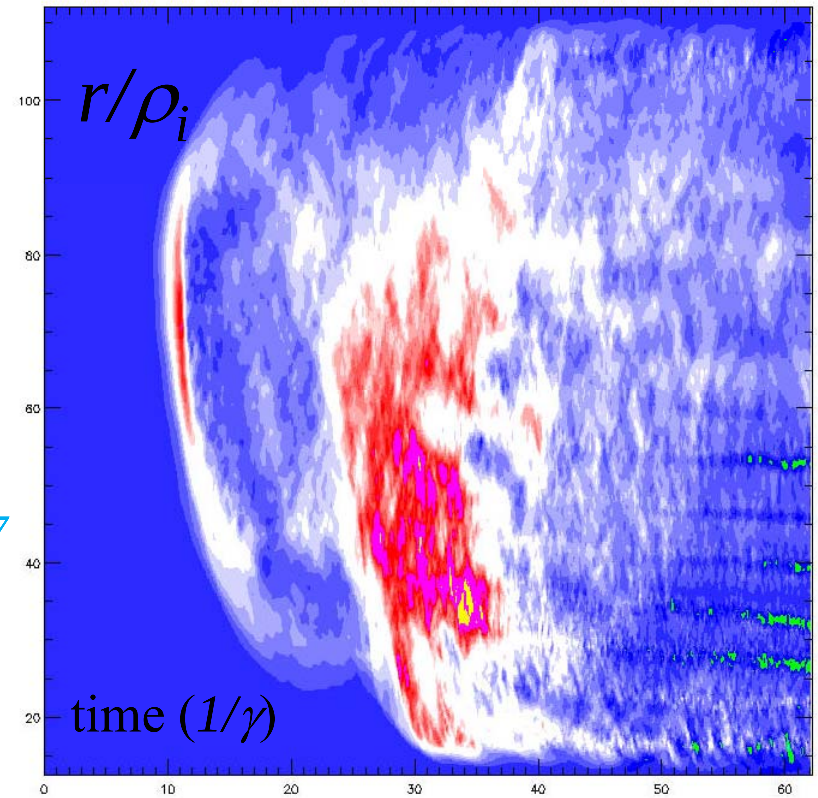
- Collisionless electron mode (CTEM) turbulence has been identified in some experiments as probable candidate for electron transport
- GTC linear simulation of CTEM benchmarked with GT3D & FULL
- GTC nonlinear simulation finds bursting originates at maximal drive, spreading both inward & outward
- Inward spreading ballistic with a speed close to drift velocity




*[Rewoldt, Lin & Idomura, CPC07*

*Lin, APS07]*

Electron transport



## d.) Secondary Structure Dynamics

- motivated by critical role of self-generated flows, structures in regulating turbulence, now universally acknowledged

- goal: elucidate detailed physics of flow structure, evolution, feedback-especially in collisionless regimes

- special attention to:
  - collisionless ZF saturation
  - spreading - ZF interaction
  - space-time flow structure
  - mean flow - zonal flow interplay

# Short Term Plans on Physics and Validation

- Nonlinear Simulations of Turbulence Driven Momentum Transport:

  Identify non-diffusive flux (pinch and residual stress),

  Compare with theory predictions,

  Relevance of transients ? Is time-averaged flux more meaningful?

  Study turbulence modification of mean flows (plenty of examples exist where neoclassical predictions fail, when supposed to work)

- Role of Trapped Electrons in Core Turbulence

  Detailed characterization of ZF: ($\omega$, $q_r$) spectra, shearing rate,…

  Phase-space info: Distortion of “f” due to precession resonance

  Plot $\delta T_e$ as well as density fluctuations

  Look for evidence of T.E. Particle pinch from TEP theory

- Radial Dependence of Turbulence and Transport

  High fluctuation towards the edge ---> Revisit Turbulence Spreading

- Validation

  Develop Synthetic BES, CECE, High-k Scatt. Diagnostics

  Develop and use formula which quantifies the degree of agreement in flux, fluctuation amplitudes (density, temperature), correlation function,…

# 2.) GTC FRAMEWORK

# GTC Physics Module Developed for Specific Application

*UCI*

- Perturbative (δf) method for ions
- Fluid-kinetic hybrid electron model for electrons
  - Collisionless trapped electron mode (CTEM) turbulence
  - Electromagnetic turbulence with kinetic electrons
  - Shear Alfven wave (SAW) excited by energetic particle
- Multi-species via OO Fortran
  - Energetic particle diffusion by microturbulence
- Guiding center Hamiltonian in magnetic coordinates
- Global field-aligned mesh: truly global geometry
- General geometry MHD equilibrium using spline fit
- Fokker-Planck collision operators via Monte-Carlo method

# GTC Numerical Method Designed for Parallel Computing

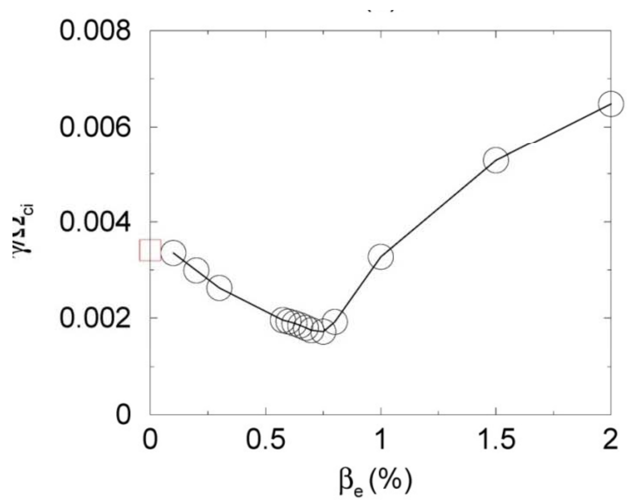
*UCI*

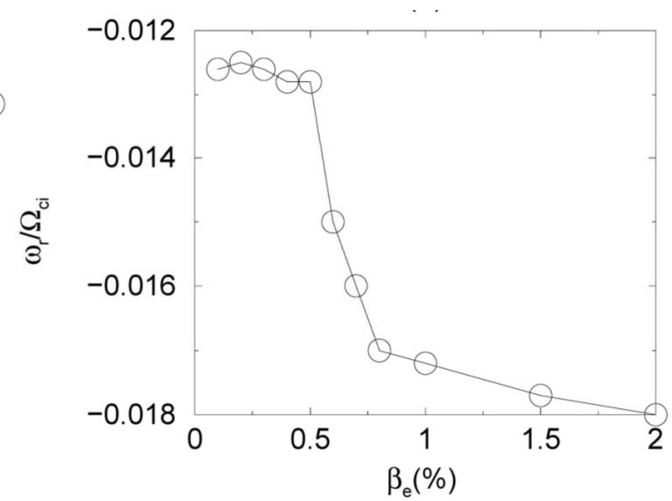
- Finite difference & finite element elliptic solvers
  - Iterative method for electrostatic simulation
  - Sparse matrix solver (PETSc) for direct solver
  - Pade approximation & integral gyrokinetic Poisson equation
- Multi-level parallelism
  - Particle-field domain-decomposition via uni-directional MPI
  - MPI-based particle decomposition
  - Loop-level parallelization with OpenMP efficient for multi-core
- PIC optimization includes electron sub-cycling & vectorization
- Statistical analysis of fluctuations/particles, and noise control *[Holod & Lin, PoP2007]*
- Visualization of 3D fluid and 5D particle data for physics insights

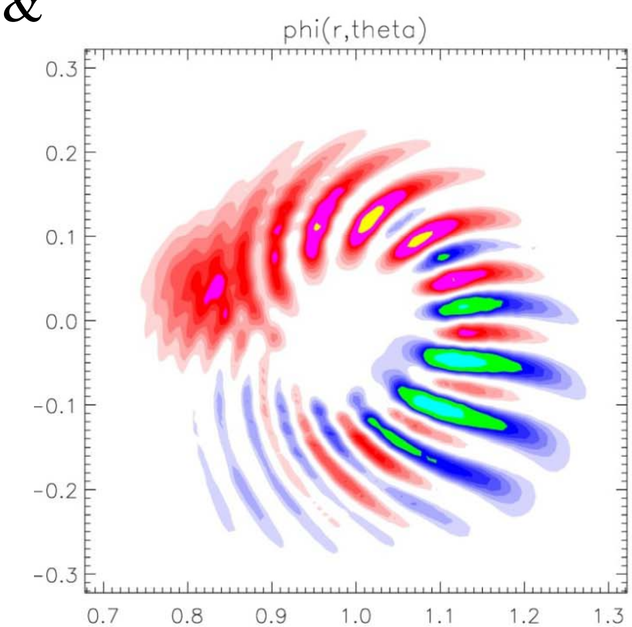
# GTC Simulation of Electromagnetic Turbulence with Kinetic Electron

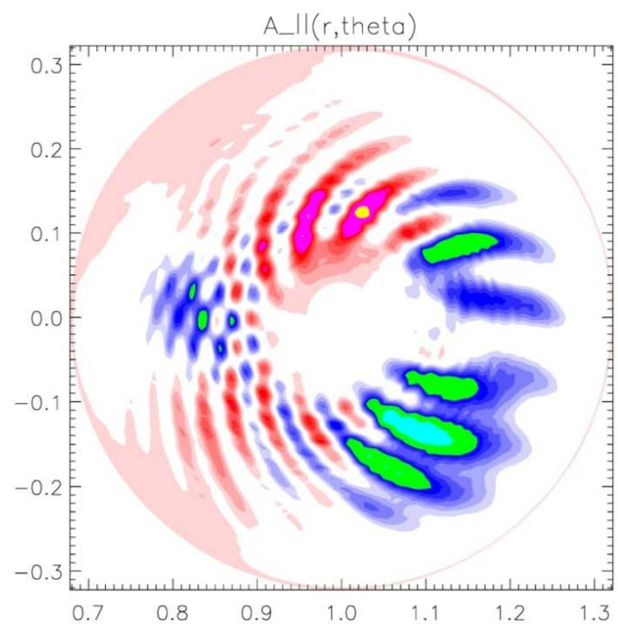
*UCI*

- Global GTC simulation using fluid-kinetic hybrid electron model
- Stabilization of ITG mode by finite beta
- Excitation of kineitc ballooning mode
- Enhancement of ITG & KBM growth rate by kinetic electrons




*Nishimura, Lin & Wang, PoP07*

*Lin et al, PPCF07*

*Nishimura, Lin & Chen, CiCP08*

# GTC Plan

UCI

- Version integration & control (with *Decyk*)
- Physics modules
  - Full-f ion & profile evolution
  - GTC-XGC core-edge coupling (with CPES), turbulence-Alfven wave coupling (with GSEP), & turbulence-neoclassical coupling
- Particle noise analysis and control
  - Characterization of particle noise in full-f
  - Deterministic collision operator (with *Hinton*)
- Particle-field domain-decomposition for 100,000+ cores
- PIC optimization for multi-core (with *Hall* of PERI & *Wichmann* of Cray, *Either*)
- Visualization of particle-field interaction (with *Ma* of IUSV)
- Parallel I/O, data streaming, workflow, & dashboard (with *Klasky* of SDM)
- Synthetic diagnostics (with *Holland* & *Tynan*)

# GTS turbulence simulation capabilities for tokamak experiment

- Gyrokinetic Tokamak Simulation (GTS) code: generalized gyrokinetic particle simulation model
- Shaped cross-section; experimental profiles; consistent rotation and equilibrium $\mathbf{E} \times \mathbf{B}$ flow; linear Coulomb collisions; $\cdots$
- Interfaced with MHD equilibrium codes (based on ESI interface) and TRANSP data base
- Kinetic(electrostatic) electrons via the split-weight scheme
- Switches to control physics modules: ITG, ETG, kinetic electrons (TEM, ITG-TEM), ...
- Linear coupling with neoclassical simulation by GTC-NEO

# GTS and GTC-NEO Development

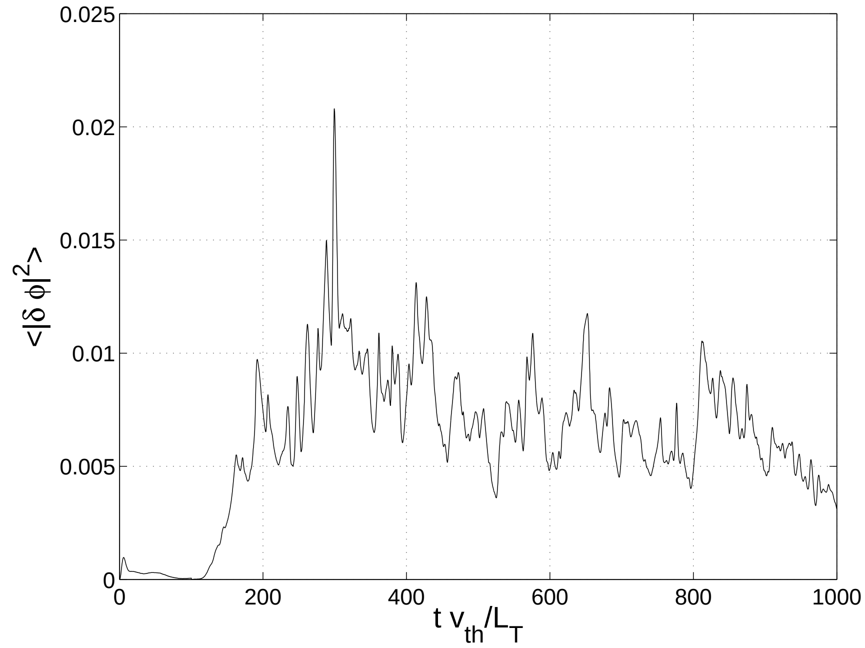
- A new algorithm based on expanding ion distribution around the collisionless neoclassical equilibrium and corresponding linear collision operators are being developed for $\delta f$ simulation (in collaboration with Hinton at UCSD).
  - huge weight associated with high energy ions and steep $T_i$ gradient in existing $\delta f$ scheme
  - this advanced scheme overcomes difficulties for simulating neoclassical physics of high temperature, steep gradient plasmas and impurities
  - approach to integrated $\delta f$ simulation capability with nonlinear interplay between neoclassical and turbulent dynamics
  - start to implement into GTC-NEO
- A web-based user interface for GTS/GTC-NEO is under development
- Multi-ion species in GTS/GTC-NEO to be developed

# GTS and GTC-NEO Development

- A full-f version of GTS is being tested
  - preliminary ITG simulation test:

    1000 particles/cell

    (0,0) components of electric field (both NC and ZF) zeroed out




  - more careful debugging and benchmarking are required

# Short and long term plans for PPPL codes

- A web-based user interface is being developed
- full-f capability is being tested (with Kolesnikov and Lee)
- multi-ion species to be developed
- EM to be developed (with Lee and Startsev)
- multi-ion species into GTC-NEO with a new $\delta f$ scheme and collision operator (with F. L. Hinton)
- integrated $\delta f$ simulation capability with nonlinear interplay between neoclassical and turbulent dynamics

# 3.) High Performance Computing

# Advances in High Performance Computing for the GTC framework

**Problem**

- Run on more than 10K processors.
- Grids getting larger.
- 128-bit floating-point capabilities enable each processor to simultaneously execute up to four floating-point operations per core.
- Target more end-users.

**Solution**

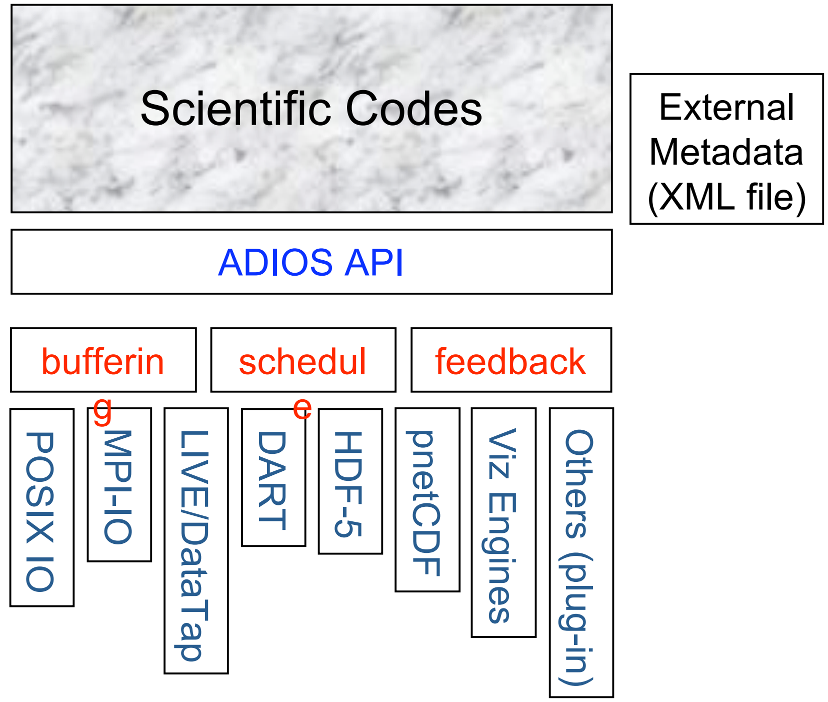
- Replace current IO strategy with ADIOS and use particle domain decomposition.
- Use OpenMP + MPI.
- Vectorize key points in code to use SSE3 instruction set.
- Develop an easy to use analysis framework.

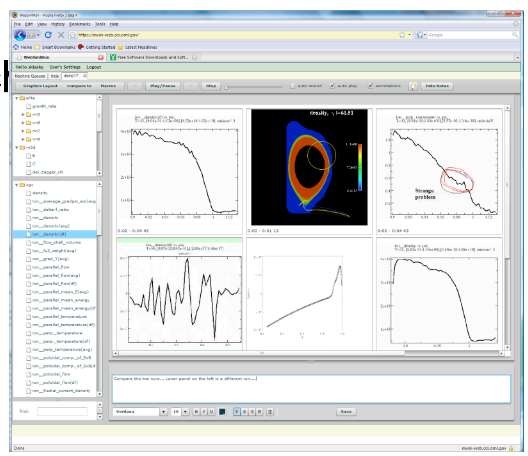
# Performance Issues for GTC framework

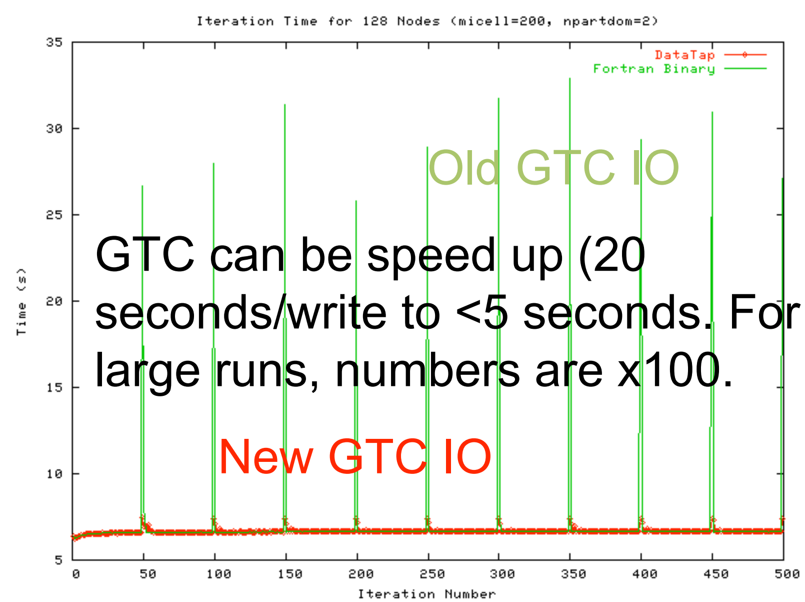
- Now 4 cores per nodes, petaflop upgrade will give us 8 cores per node.
  - GTC uses OpenMP. Latest runs will use OpenMP infrastructure.
- Latest upgrade moves from 19,320 to 31,000, and finally to 111,000 cores.
  - 64 bit bus, moves to 128bit bus.
    - Most vectorize code using SSE instructions.
    - Latest results from GTC with TEM gives significant performance boost.
  - Old GTC IO breaks down on >12,000 cores.
    - Move to the Adaptable IO System.
- Data output increases from 10 TB/simulation to 200TB/simulation.
  - Need advanced workflow technology + ADIOS to manage the data.

# ADIOS + Dashboard

- ADIOS is an IO componentization allowing one interface for many implementations.
- ADIOS allows users to change the implementation at runtime, and has shown to get 50% of peak IO performance on the Cray at ORNL.
- Dashboard + Kepler workflow is scalable to thousands of processors, and GTC is being incorporated into this enterprise technology.
  - MySQL, Apac





# 4.) Validation of Gyrokinetic Models

$\rightarrow$ definition: GPS-TTBP Workshop on Physics and Validation; UCSD: 2/29, 3/1

- Participants from PPPL, UCI, UCSD, Univ. TX, UCLA, G.A., NYU
- Mix of simulation, theory, experiment
- Intensive informal group discussion

$\rightarrow$ Outcome:

- Validation focus:

  $\delta f$ gyrokinetic models of ion thermal and particle flux with "dynamic edge boundary conditions"

$\rightarrow$ rationale:

- $\rightarrow$ validation should follow "front" of physics studies
- off diagonals (pinch) important, so choice:
  - stresses $\chi_i$; D and V
  - breaks flux $\leftrightarrow$ diffusion identity
  - n.b. caution: particle source ambiguous
- dynamic b.c. $\Rightarrow$ incorporate inward spreading from edge to boost intensity levels at $\rho > .6$!?

Other Issues:

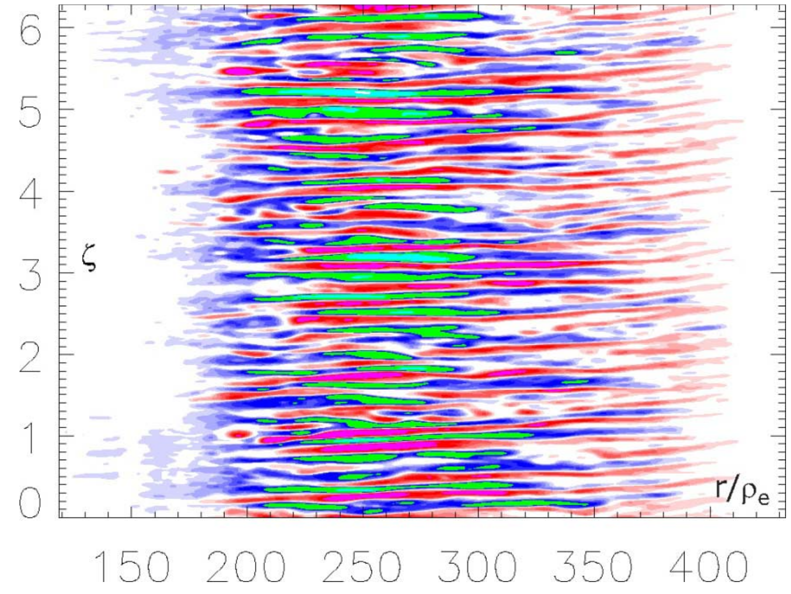
- explore low-*n* modes (i.e. trapped ion) excluded in flux tube schemes
- validation metric should:
  - reward success with flux *and* fluctuations
  - account for noise?!
- need to quantitatively characterize profile stiffness

# GTC Simulation of Foundation for Transport Model *UCI*

- Prediction of ITER confinement requires accurate transport model; Most existing transport models assume some forms of quasilinear theory
- GTC simulation of toroidal electron temperature gradient (ETG) turbulence dominated by radial streamers for examining the validity of quasilinear theory
- Comprehensive analysis of spatial and temporal scales find that electron heat transport is diffusive with a characteristic time scale of electron parallel decorrelation time
- Wave-particle decorrelation, not eddy mixing, regulate electron heat transport in ETG turbulence; Quasilinear transport theory in tokamak successfully tested

*[Lin et al, PRL07]*

| $\tau_{wp} = \frac{4\chi_e}{3\delta v_r^2}$ | $\tau_{\parallel} = \frac{1}{\Delta k_{\parallel} v_e}$ | $\tau_{\perp} = \frac{3}{4s^2\overline{\theta}^2\overline{k}_\theta^2\chi_e}$ | $\tau_{eddy} = \frac{L_r}{\delta v_r}$ | $\tau_{rb} = \frac{4L_r^2}{3\chi_e}$ | $\tau_{auto}$ | $\frac{1}{\gamma}$ |
|---|---|---|---|---|---|---|
| 4.2 | 5.3 | 8.0 | 42 | 437 | 346 | 33 |



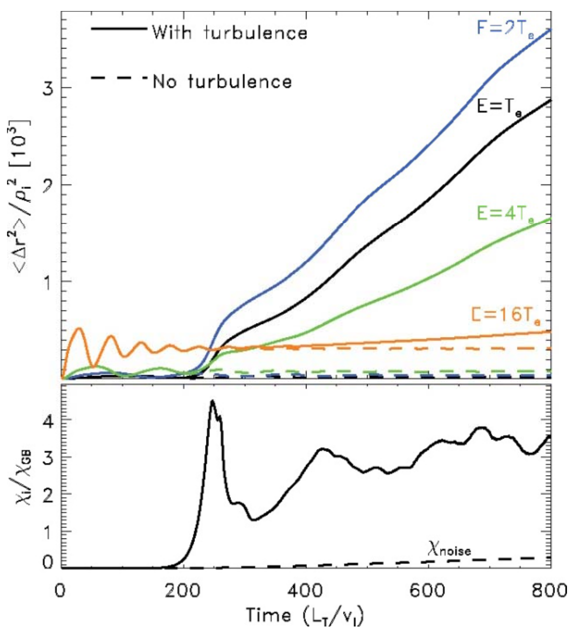
# GTC Simulation of Energetic Particle Transport

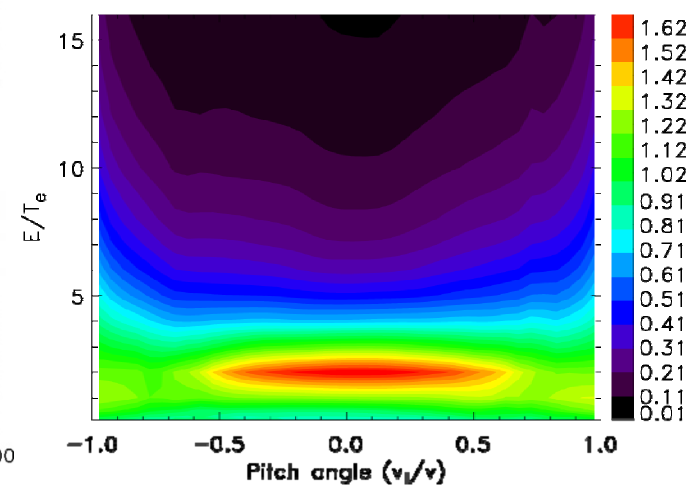
*UCI*

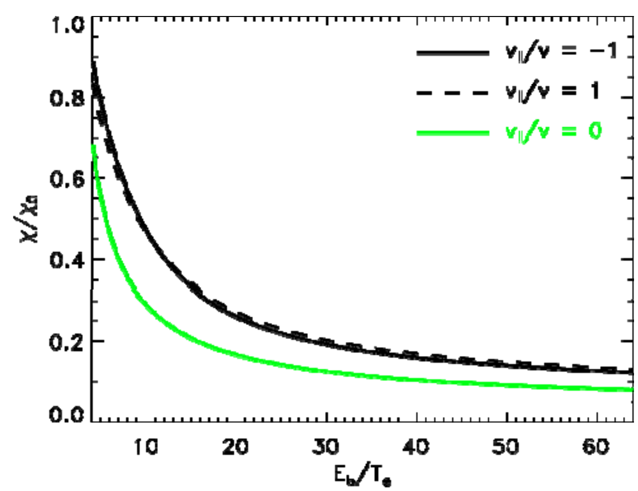
- Recent tokamak experiments revive interest of fast ions transport induced by microturbulence *[Heidbrink & Sadler, NF94; Gunter et al, NF07]*
- Radial excursion of test particles found to be diffusive in GTC global simulation of ion temperature gradient (ITG) turbulence
- Detailed studies of diffusivity in energy-pitch angle phase space
  - Diffusivity drops quickly at higher particle energy due to averaging effects of larger Larmor radius/orbit width, and faster wave-particle decorrelation
- NBI ions: lower diffusivity for higher born energy

*Zhang, Chen & Lin, TTF08*

*In collaboration with SciDAC GSEP*



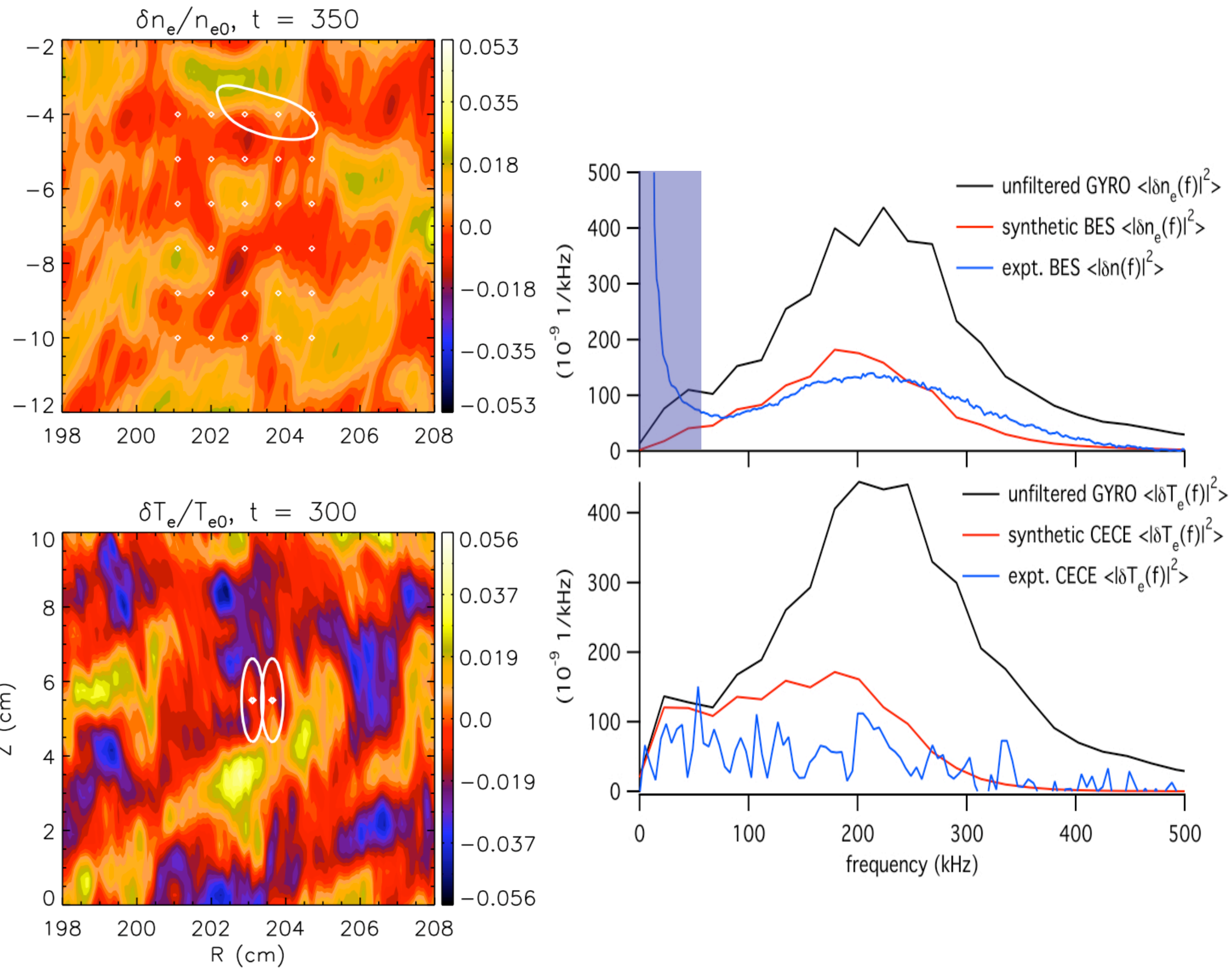



# New Synthetic Diagnostic Capability Allows Direct Comparisons of Simulated and Measured Turbulence Characteristics

- **Synthetic BES and CECE diagnostics have been developed as IDL post-processing tools for use with GYRO simulations**

- **Short term goal is to develop corresponding IDL interface for GTC which will use same tools**




DIII-D NATIONAL FUSION FACILITY SAN DIEGO

THE UNIVERSITY of WISCONSIN MADISON

UCLA

UCSD

# Validation Plans for NSTX

- Low-k turbulence
  - Reflectometry
    - Implement a synthetic reflectometer diagnostic into the TORIC full wave code to determine density fluctuations from HHFW wave field
    - Use this information to determine change in plasma density fluctuation with onset of HHFW
  - BES
    - BES diagnostic will be implemented on NSTX for 2009
    - BES synthetic diagnostic will be built into GTS, GYRO codes to calculate density fluctuations in radius range r/a~0.4 to 0.8
      - Confirm hypothesis that ions are near neoclassical in H-mode plasmas
- High-k turbulence (high-k scattering)
  - Build synthetic high-k scattering diagnostic into GYRO, GTS codes to determine non-linear amplitudes/spectra of electron-scale turbulence (ETG and short-wavelength CTEM) for comparison to experiment

## → Outlook for GPS Validation Program

- GPS-TTBP validation effort will work closely with related DIII-D effort
- C. Holland and G. Tynan will help supervise postdocs working on validation
- Validation will require:
  - common, accessible toolkit for GTCF
  - report of noise monitoring
- Interviews for validation postdocs ongoing

## → Related Work: Tests of Physics Basics of Transport Models

→ Seeks to explore validity, self-consistency of standard modelling approximations (I.e. quasilinear theory)

→ Likely productive synergy with validation effort

# iv.) Recent Activities and Recognition

a.) Activities

$\rightarrow$ Two “Kick-Off Workshops”:

a.) GTC Framework - UCI, 1/24

b.) Physics and Validation - UCSD, 2/29-3/1

$\rightarrow$ Project Meeting at TTF: 3/28

b.) Achievements

$\rightarrow$ INCITE Award (joint with GSEP, CPES)

$\rightarrow$ 3 U.S. IAEA Selections:

P.H. Diamond, et al. - Toroidal Momentum Transport Physics

Z. Lin, et al. - Physics Basis Of Transport Models

W. Wang, et al. - Turbulence $\leftrightarrow$ Neoclassical Interaction

UCSD

# v.) Future Plans

a.) Near-term emphasis on:

- toroidal momentum transport, including $\left\langle V_E \right\rangle'$ and neoclassical effects/feedback
- CTEM physics
- initial validation studies

b.) Activities:

- meeting with International members of Project PAC at EPS, IAEA
- all hands meeting at APS
- possible small informal working meetings
  i.e. possible topic: secondary structures, flows and multi-scale interaction

## JOURNAL PUBLICATIONS and CONFERENCE PROCEEDINGS

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## BOOK CONTRIBUTION

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Diamond, P.H., "*Mechanisms of Edge-Core Coupling: Some Speculations on How SOL Flows Influence Intrinsic Rotation and the L-H Transition,*" 21st U.S. Transport Task Force Workshop, Boulder, CO, March 25-28, 2008.

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McDevitt, C.M., "*Transport of Parallel Momentum by Collisionless Electromagnetic Turbulence,*" 21st U.S. Transport Task Force Workshop, Boulder, CO, March 25-28, 2008.

Diamond, P.H., "*Physics and Modeling of Multi-Scale Interaction in Plasmas*," Invited Speaker, Kyoto University, Kyoto, Japan, March 3-4, 2008. (Unable to attend due to schedule conflicts)

Gurcan, O., "*Comment on Momentum Transport Physics - Theory Perspective*," Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas, La Jolla, CA, February 29-March 1, 2008.

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Diamond, P.H., "*Introduction to Transport Barriers and Related Mesoscale Phenomena*," Festival de Theory 2007, Aix-en-Provence, France, July 2-20, 2007.

Diamond, P.H., "*Theory of Turbulent Transport of Toroidal Momentum - Some New Thoughts on an Old Problem*," Festival de Theorie 2007, Aix-en-Provence, France, July 2-20, 2007.

Diamond, P.H., "*The Plasma Physics of Diffusive Shock Acceleration Beyond the Bohm Limit*," The First Asian Pacific Symposium on Astrophysical, Space and Laboratory Plasmas, Beijing, China, June 16-20, 2007.

Diamond, P.H., "*Physics of Drift Wave - Zonal Flow Turbulence in Confined Plasmas*," The First Asian Pacific Symposium on Astrophysical, Space and Laboratory Plasmas, Beijing, China, June 16-20, 2007.

Diamond, P.H., "*Turbulence in Diffuse Astrophysical Environments*," Invited Speaker, American Astronomical Society 210th Meeting, Honolulu, HI, May 2007 (Unable to attend due to schedule conflicts)

Diamond, P.H., "*Momentum Transport Working Group*," 12th US-EU Transport Task Force Meeting, San Diego, CA, April 17-20, 2007.

Diamond, P.H., "*Physics of Intrinsic Rotation and Transport of Toroidal Momentum: A Resonant Particle - Quasi-Particle Approach*," 12th US-EU Transport Task Force Meeting, San Diego, CA, April 17-20, 2007.

Diamond, P.H., "*Issues in Transport and Confinement Physics for ITER,*" Invited Speaker, 3rd IAEA Technical Meeting on the Theory of Plasma Instabilities," York, United Kingdom, March 26-28, 2007.

# Additional UCI GPS publications and talks

- **Publications**

*Statistical analysis of fluctuations and noise-driven transport in particle-in-cell simulations of plasma turbulence*, I. Holod and Z. Lin, Phys. Plasmas **14**, 032306 (2007).

*Electromagnetic global gyrokinetic simulation of shear Alfven wave dynamics in tokamak plasmas,* Y. Nishimura, Z. Lin, and W. X. Wang, Phys. Plasmas **14**, 042503 (2007).

*Nonlinear equilibria, stability and generation of zonal structures in toroidal plasma , L. Chen, F. Zonca, Nuclear Fusion 47, 886 (2007).*

*Full torus electromagnetic gyrokinetic particle simulations with kinetic electrons*, Y. Nishimura, Z. Lin, and L. Chen, Commun. Comput. Phys. **4**, 2008, in press.

- **Talks**

Lin, Z., "*Nonlinear dynamics of ETG and CTEM turbulence and their interaction with zonal flows*", invited talk, 34th European Physical Society Conference on Plasma Physics, Warsaw, Poland, 2007.

Lin, Z., "*Turbulent transport via wave-particle decorrelation in collisionless plasmas*", invited talk, 49th Annual Meeting of American Physical Society, Division of Plasma Physics, Orlando, 2007.

Lin, Z., "*Turbulent transport via wave-particle decorrelation in collisionless plasmas*", Joint U.S.-European Transport Task Force Workshop, San Diego, 2007.

Nishimura, Y., "*Alfven Continuum and Toroidal Gap Generation in Global Electromagnetic Gyrokinetic Simulations*", Joint U.S.-European Transport Task Force Workshop, San Diego, 2007.

Holod, I., "*Discrete particle noise in particle-in-cell simulations of plasma turbulence*", Joint U.S.-European Transport Task Force Workshop, San Diego, 2007.

Xiao, Y., "*Gyrokinetic Simulation of Trapped Electron Mode in Tokamak Edge Plasmas*", Joint U.S.-European Transport Task Force Workshop, San Diego, 2007.

Lin, Z., "*Global GTC simulation of ETG turbulence*", US-Japan Joint Institute of Fusion Theory Workshop, San Diego, 2007.

Nishimura, Y., "*Electromagnetic global gyrokinetic simulation of tokamak plasmas*", US-Japan Joint Institute of Fusion Theory Workshop, San Diego, 2007.

Nishimura, Y., "*Shear Alfven wave dynamics in gyrokinetic tokamak plasmas*", IAEA TCM on Theory of Plasma Instability, York, UK, 2007.

Lin, Z., "*Turbulent transport in collisionless plasmas: eddy mixing or wave-particle decorrelation?*", Theory Festival, Aix-en-Provence, France, 2007.

Nishimura, Y., " *Numerical properties of electromagnetic gyrokinetic particle simulations in a global tokamak geometry*", 20th International Conference on Numerical Simulation of Plasmas, Austin, 2007.

Holod, I., " *Discrete particle noise in gyrokinetic particle-in-cell simulations of plasma turbulence* ", 20th International Conference on Numerical Simulation of Plasmas, Austin, 2007.

Xiao, Y., *Short Wavelength Trapped Electron Mode* ", 20th International Conference on Numerical Simulation of Plasmas, Austin, 2007.

Lin, Z., "*Fusion Research on the Cray XT",* Cray Technical Workshop, San Francisco, 2008 .

*Lin, Z., "GTC simulation of turbulence and transport in tokamak plasmas"* Transport Task Force Workshop, Boulder, 2008.

*Nishimura, Y., "GTC full torus electromagnetic gyrokinetic particle simulations with kinetic electrons",* Transport Task Force Workshop, Boulder, 2008.

*Holod, I., "Gyrokinetic particle simulations of parallel momentum transport in tokamak",* Transport Task Force Workshop, Boulder, 2008.

*Xiao, Y., "CTEM Turbulence and Transport Dynamics",* Transport Task Force Workshop, Boulder, 2008.