Particle-in-Cell Simulations of Electron Transport from Plasma Turbulence: Recent Progress in Gyrokinetic Particle Simulations of Turbulent Plasmas

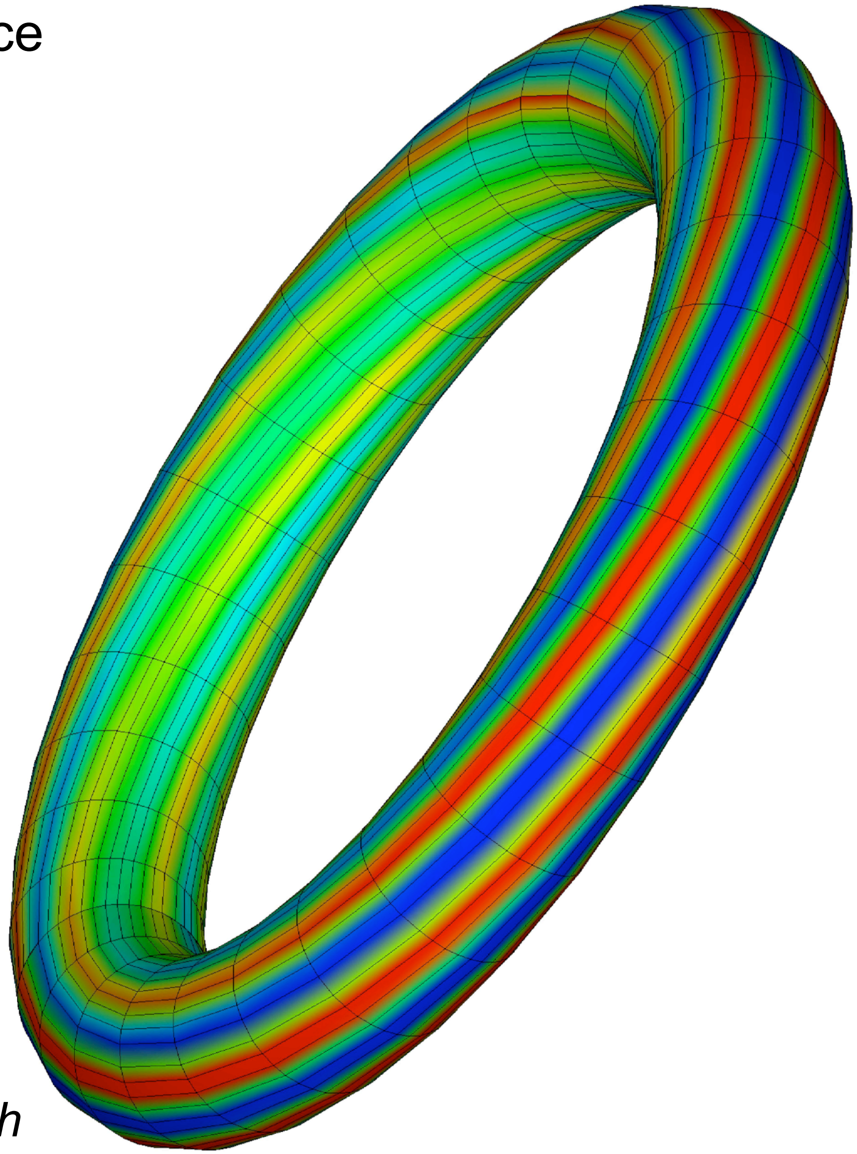
Z. Lin,[1] G. Rewoldt,[2] S. Ethier,[2]
T.S. Hahm,[2] W.W. Lee,2
J.L.V. Lewandowski,[2] Y. Nishimura,[1]
W.X. Wang[2]
[1]University of California, Irvine
[2]Princeton Plasma Physics Laboratory, Princeton University

UCIrvine

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Global Gyrokinetic Toroidal Code (GTC)

- Gyrokinetic particle simulation
  - Efficient sampling of *5D* phase space
- GTC global field-aligned mesh:
  - Respects physical periodicity
  - Efficient for toroidal eigenmode
  - # of computation ~ $(a/\rho)^2$
  - Reduces computation by $n{\sim}10^3$
- Massively parallel computing
  - Reactor scale plasmas
  - Keeps all toroidal modes $n{\sim}10^3$
- Resources: US DOE SciDAC

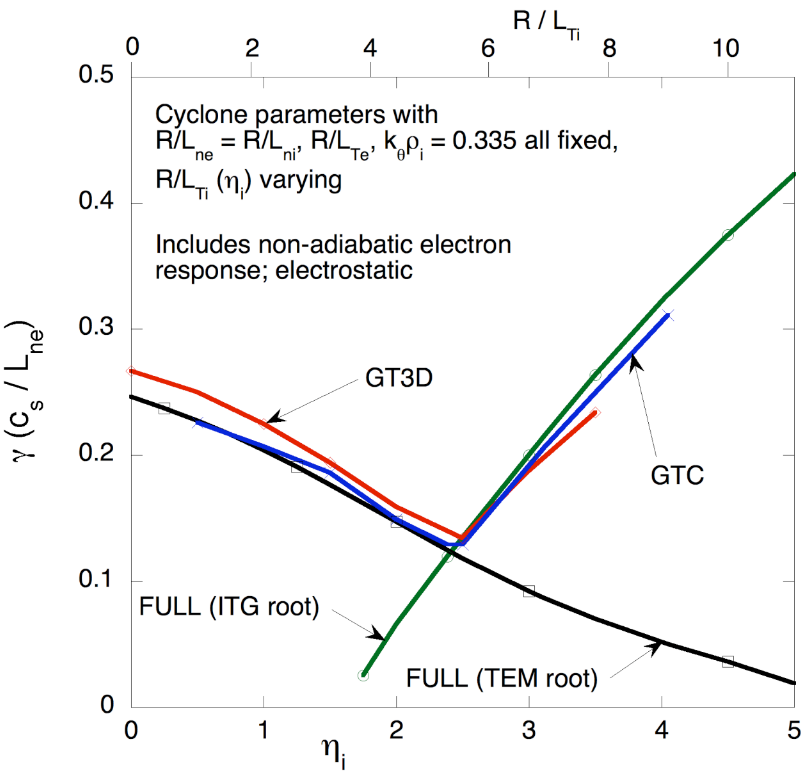


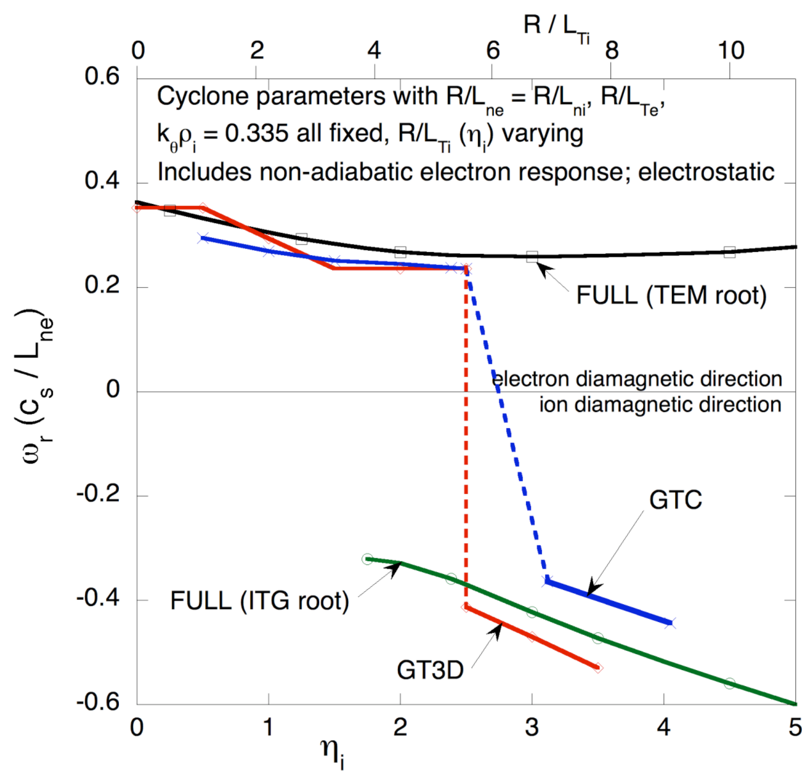
GTC mesh

G. Rewoldt, Z. Lin, Y. Idomura (JAERI)

Linear Frequency Comparison: GTC, GT3D,FULL R / L_{Ti} (η_i) Scan with Trapped Electrons

- FULL: local only, GTC fixed density and temperature values but varying gradients; GT3D varying density and temperature values and gradients (different profile shapes)
- Vary R/L_{Ti} (and η_i) at fixed R/L_{Te} = 6.92, R/L_n = 2.22, and $k_\theta \rho_i$ = 0.335 (on reference surface) with trapped electrons

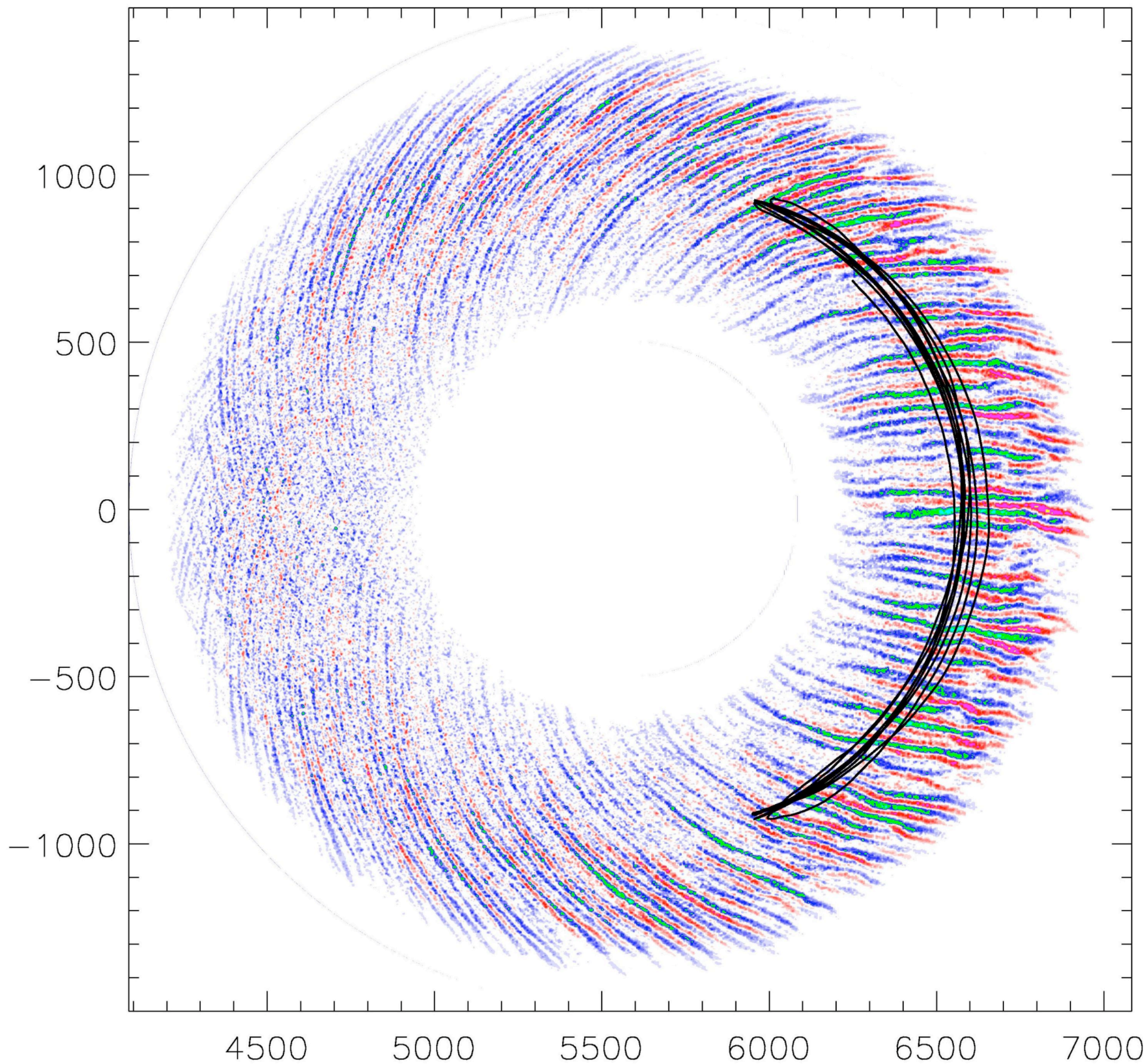




Z. Lin

Electron Transport Insensitive to ETG Streamer Length

- At $t=20/\gamma_0$ after saturation
- Streamer length scales with device size
- Eddy turnover time $\tau \sim 16/\gamma_0$
  - $\gamma_{nl} << \gamma_0$
- Electron does not rotate with streamers
- Transport driven by wave-particle interaction
- Mixing length estimate inaccurate



Z. Lin

Nonlinear Toroidal Couplings Regulate ETG Turbulence

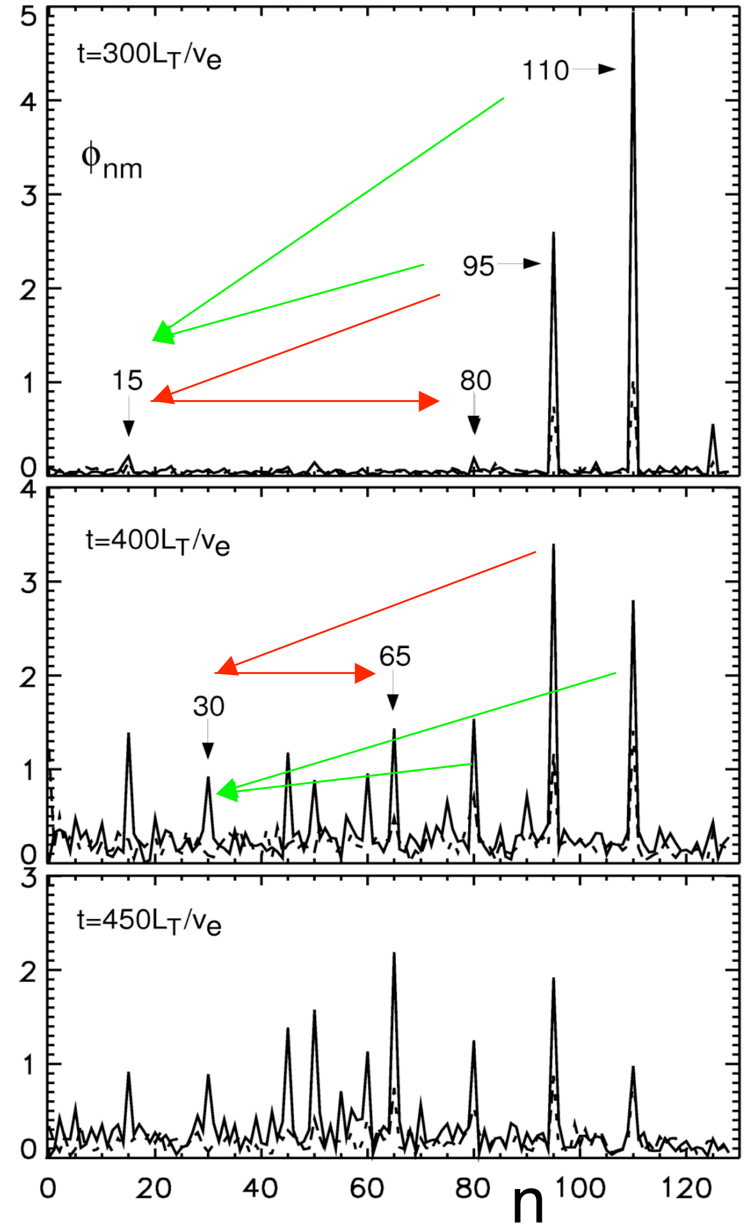
- 1st step: generation of low-*n* quasi-mode

$$(n_1,m_1)+(n_2,m_2)\Rightarrow(\Delta n,\Delta m)=(n_2-n_1,m_2-m_1)$$

  - "Meso-scale: optimal mode number $\Delta n \sim n_1^{1/2}$
  - No ballooning structure: $\lambda_{||}\sim qRn_1^{1/2}$
- 2nd step: energy transfer to nonlinear mode

$$(n_1,m_1)+(\Delta n,\Delta m)\Rightarrow(n_1-\Delta n,m_1-\Delta m)$$

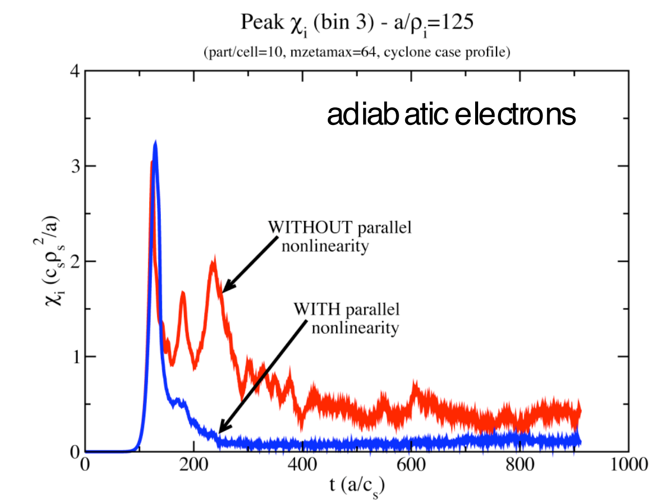
  - Streamers nonlinearly generated
- Spectral transfer facilitated by quasi-modes
  - Nonlocal in *n*-space, "Compton Scattering"
  - Streamer coupling: toroidal geometry-specific
- Need to keep all toroidal modes
  - Sufficient channels for spectral transfer

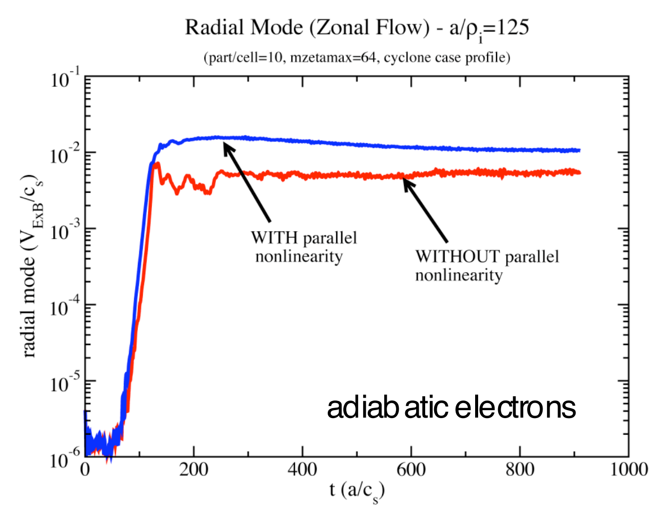


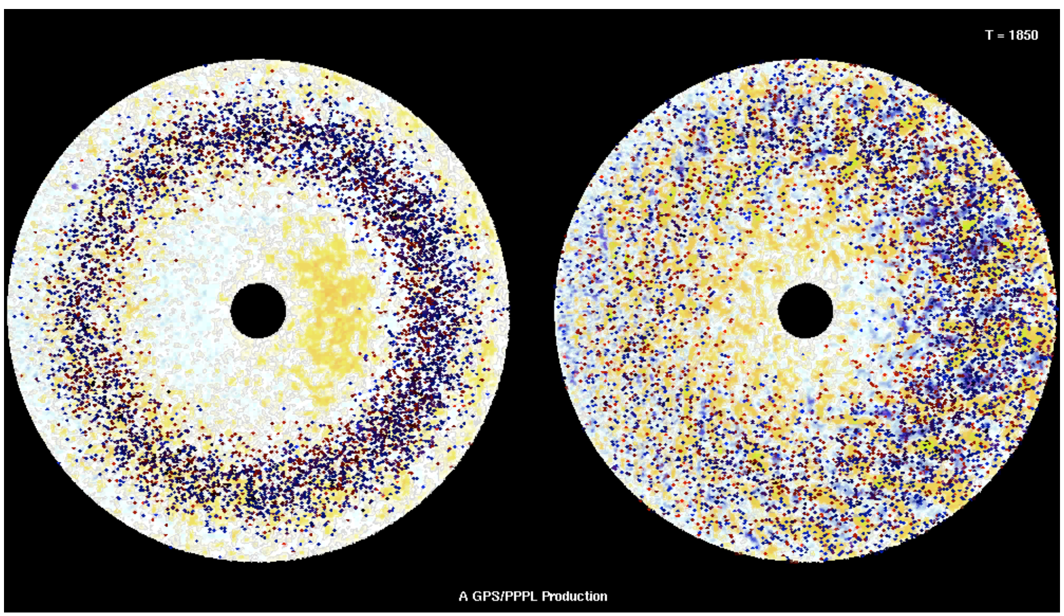
W.W. Lee & J.L.V. Lewandowski

Particle Diffusion Due To Toroidal ITG Modes With/Without Parallel Velocity-Space Nonlinearity

- $(q/m)\, E_{||}\, (\partial\, \delta f / \partial\, v_{||})$ term in GTC
- Additional channel to reach steady state
- Different (test particle) diffusion pattern (and scaling)?





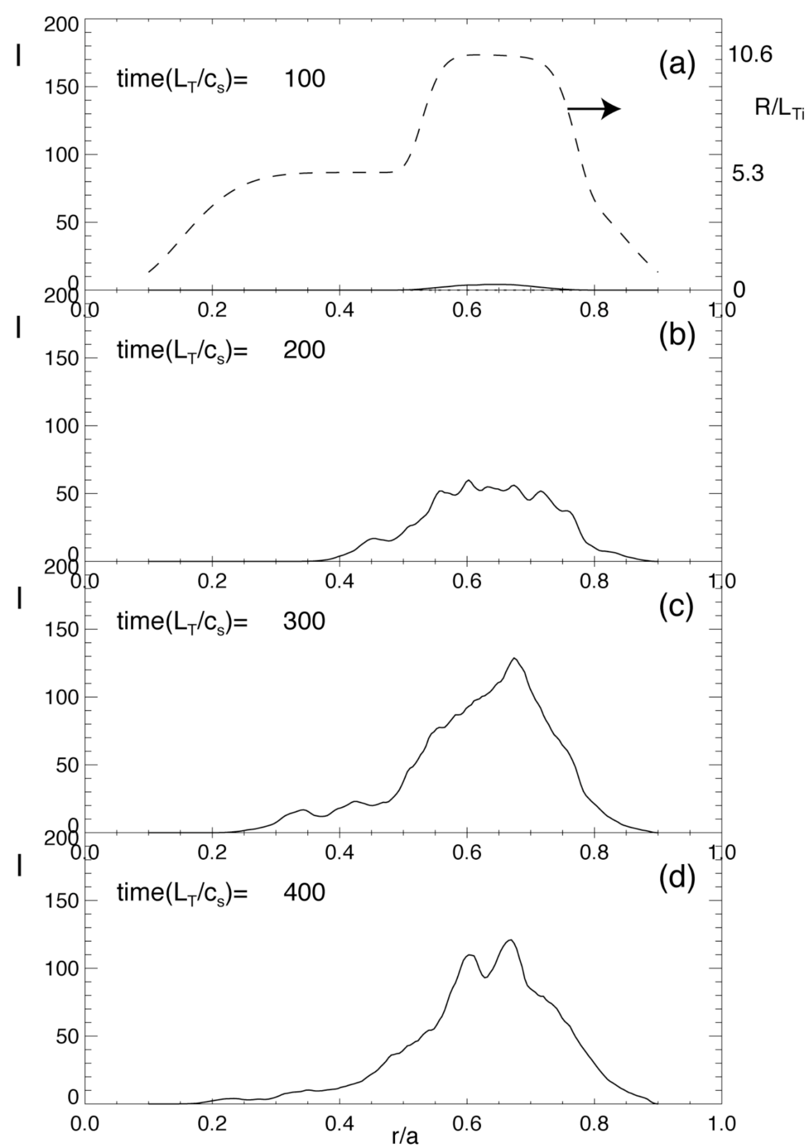


with

without

Turbulence Spreading from Edge to Stable Core

T.S. Hahm, et al., to appear, Phys. Plasmas '05



- Nonlinear GTC Simulations of Ion Temperature Gradient Turbulence

  $\frac{R}{L_{Ti}}$ = 5.3 at core

  (within Dimits shift regime)

  $\frac{R}{L_{Ti}}$ = 10.6 at edge

- Initial growth at edge

  → Penetration into stable core

  (Lin, Hahm, Diamond, PRL '02, PPCF, PoP '04)

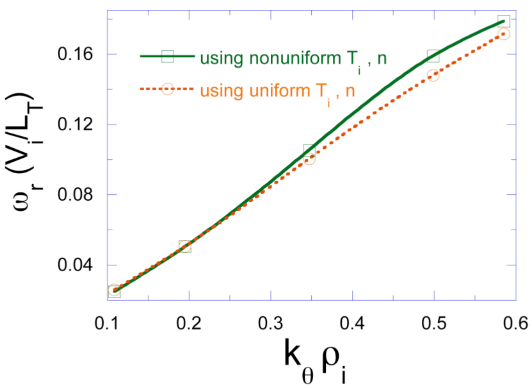
- Saturation level at core:

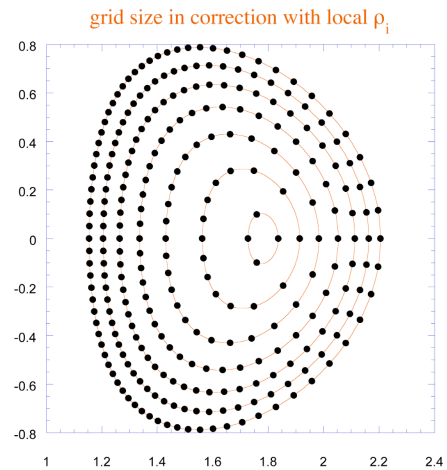
$$\frac{e\delta\phi}{T_e} \approx 3.6\frac{\rho_i}{a} \rightarrow \nabla \cdot \Gamma_I >> \gamma_{local} I$$

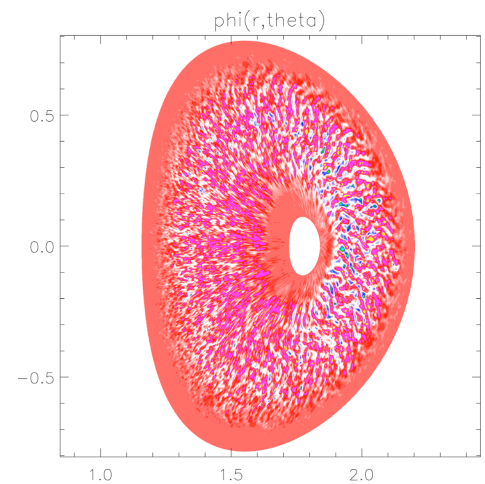
Gyrokinetic Simulation of Microturbulence for Shaped Plasmas

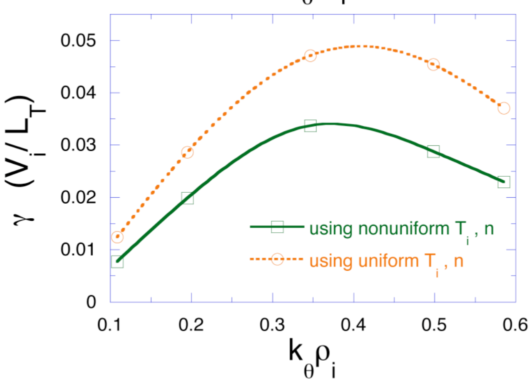
W.X. Wang

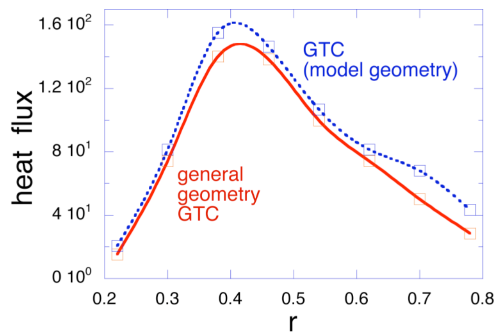
• General Geometry GTC developed with generalized and extended features: realistic plasma profiles and MHD equilibrium(ESC, JSOLVER…); systematic treatment of plasma rotation and equilibrium **ExB** flow (calculated from GTC-Neo); nonuniform mesh in correlation with local gyroradius; accurate gyrokinetic transformation; ES with adiabatic electrons (tested); trapped electrons via higher order correction (to be tested).

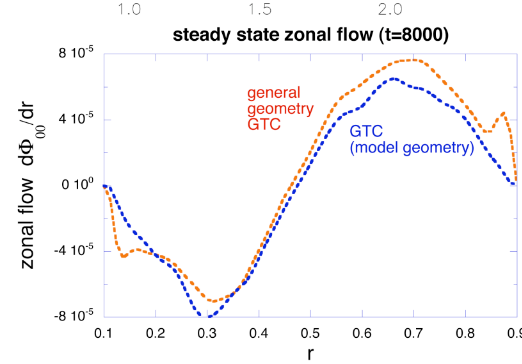












To do: update field solver; incorporate split-weight scheme for electron dynamics; fully develop and deliver EM general geometry capability for turbulence simulations;
Physics: TEM, Alfvenic ITG (KBM), micro-tearing, ITB dynamics …

cf. poster, Weixing Wang, Wed. evening

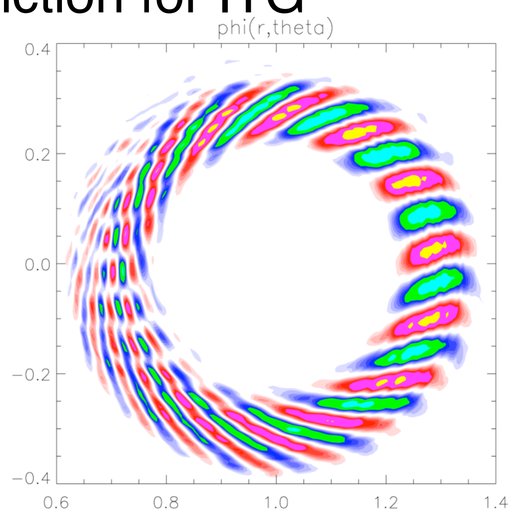
Y. Nishimura

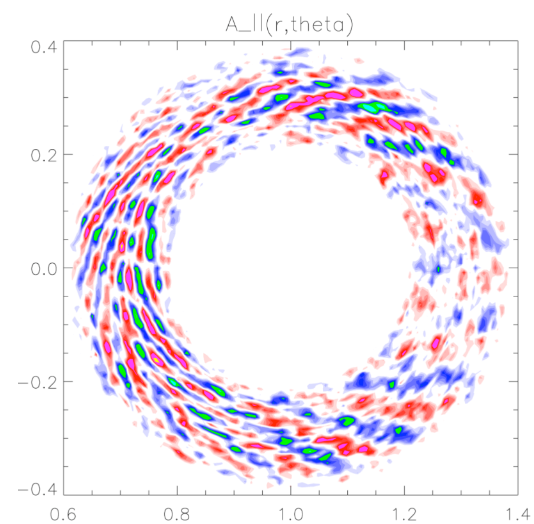
Finite beta effects in the massless limit are investigated

• A finite element method (FEM) elliptic solver has enabled kinetic electron studies using the split-weight scheme (Lee, et al '01) and also using the hybrid model (mass-ratio expansion) (Lin & Chen '01)

• Electromagnetic effects currently being studied. AITG/KBM and TAE modes expected to be unstable for sufficient beta and gradient of energetic particles. Two steps: (1) massless electron limit (solve fluid equations for electrons), (2) kinetic electrons

• Initial results: Left: 2D plot of $\tilde{\Phi}$ (electrostatic potential) exhibiting the eigenmode for the ITG instability; Right: Corresponding $A_{||}$ eigenfunction for ITG

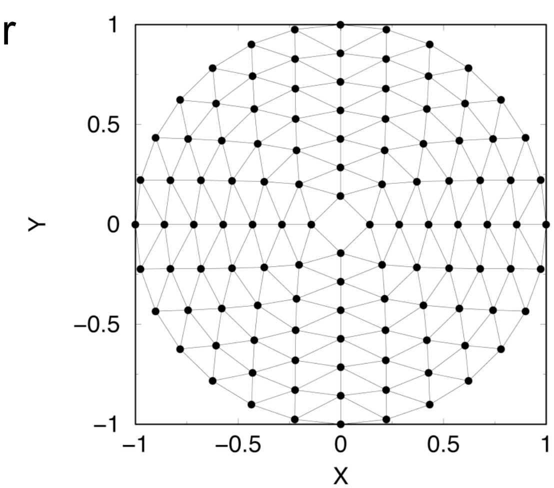


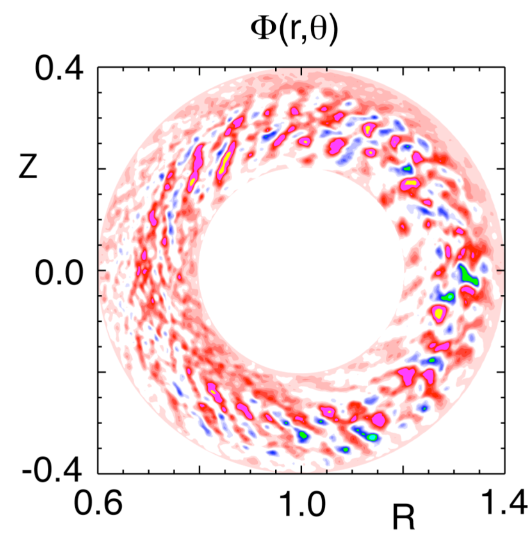


J.L.V. Lewandowski

Split-weight Scheme for Toroidal, Kinetic PIC Simulations with Kinetic Electrons

- Remove the adiabatic electron response analytically, and solve for non-adiabatic response numerically - currently ES but later EM (solve GK Poisson equation & Ampere's law)
- I-D simulations showed: (1) more accurate linear growth rate, (2) cleaner power spectrum, and(3) better conservation properties even for few electrons, $N_e << N_i$.
- Splitting scheme for toroidal plasmas: $F_e = F_M \exp(e\Phi/T_e) + h$, and solve for non-adiabatic weight $w = h/F_e$.
- Split-weight scheme for non-adiabatic electron response only (allows for turbulent & collisional friction between trapped & untrapped electrons).
- Current density and other scalar quantities deposited on structured (but not logically rectangular) grid every timestep, and inversion of field equation carried out using finite-element method, with triangular elements.
- Global finite-element Poisson solver used to invert $A\ \partial \Phi/\partial t = S$ (32 or 64 different Stiffness matrices A, on different poloidal planes)
- Numerical method is stable for large time step $\Delta t = (5 - 10) / \omega_{ci}$





GTC-Neo for Neoclassical fluxes with finite-orbit effects

- Global particle code GTC-Neo [W.X. Wang, *et al.,* Comp. Phys. Comm.**164**, 178 (2004)] calculates neoclassical fluxes of particles, momentum, and energy, as well as associated quantities such as radial electric field, bootstrap current, and poloidal velocity

- Intrinsically non-local over the scale-length of the ion banana width due to included finite orbit effects (implies smoothing)

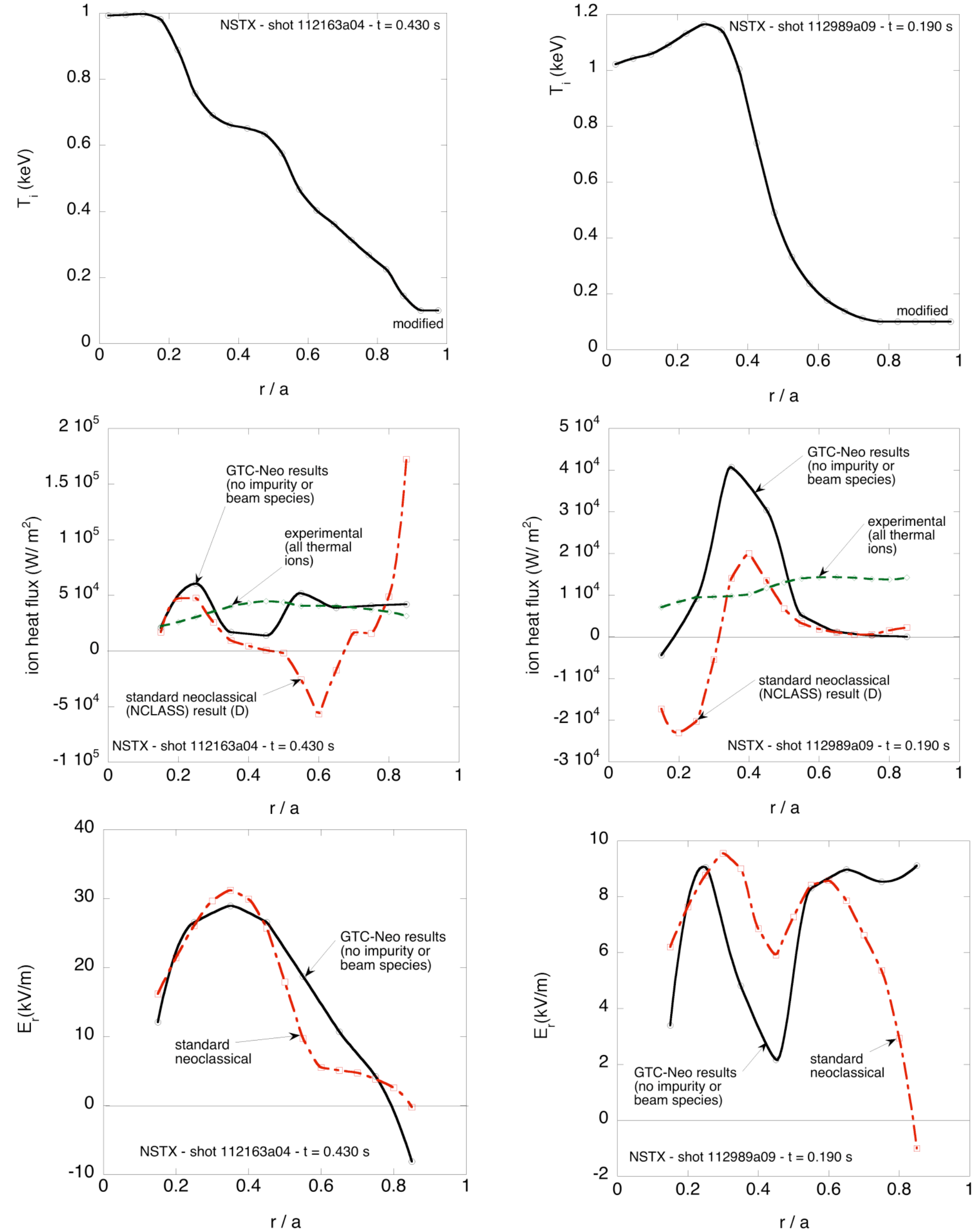
- Interfaced with MHD codes for the numerical MHD equilibrium and with TRANSP for experimental plasma profiles

- Runs currently on the massively-parallel IBM-SP computer at NERSC - 9 cases run for NSTX now

- Impurity and hot beam species to be added in future

Near-neoclassical(?) shot

ITB shot



W.X. Wang, G. Rewoldt

Conclusions

- Progress on many fronts for GTC code!
- GTC working now in ES limit, with circular concentric magnetic surfaces, including trapped electrons, producing physics results:
  - Linear and nonlinear benchmarking
  - ETG modes
  - Parallel nonlinearity
  - Turbulence spreading
- Non-circular-cross-section generalization beginning to produce results
- Two complementary approaches for EM generalization being investigated
- GTC-Neo code for neoclassical fluxes & E_r
- Still need to put everything together!