Recent Progress in Gyrokinetic Particle Simulations of Turbulent Plasmas

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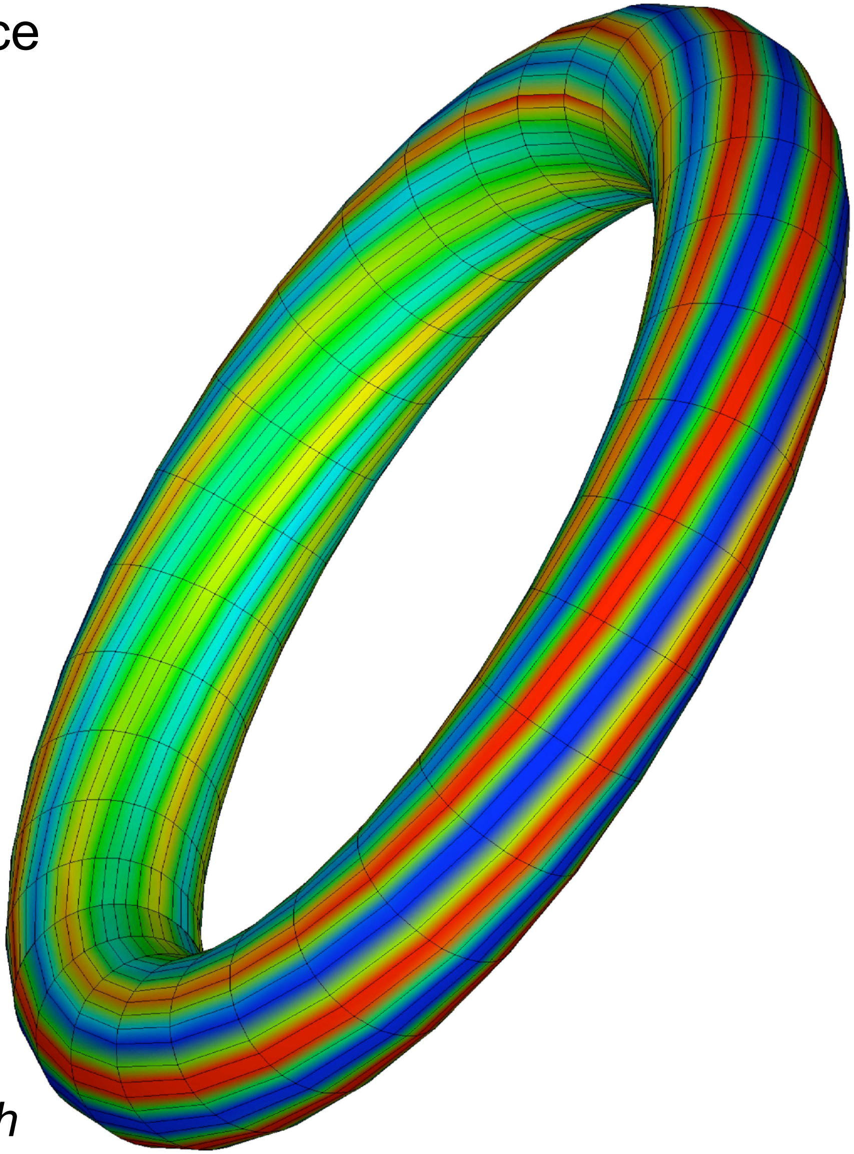
Global Gyrokinetic Toroidal Code (GTC)

- 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

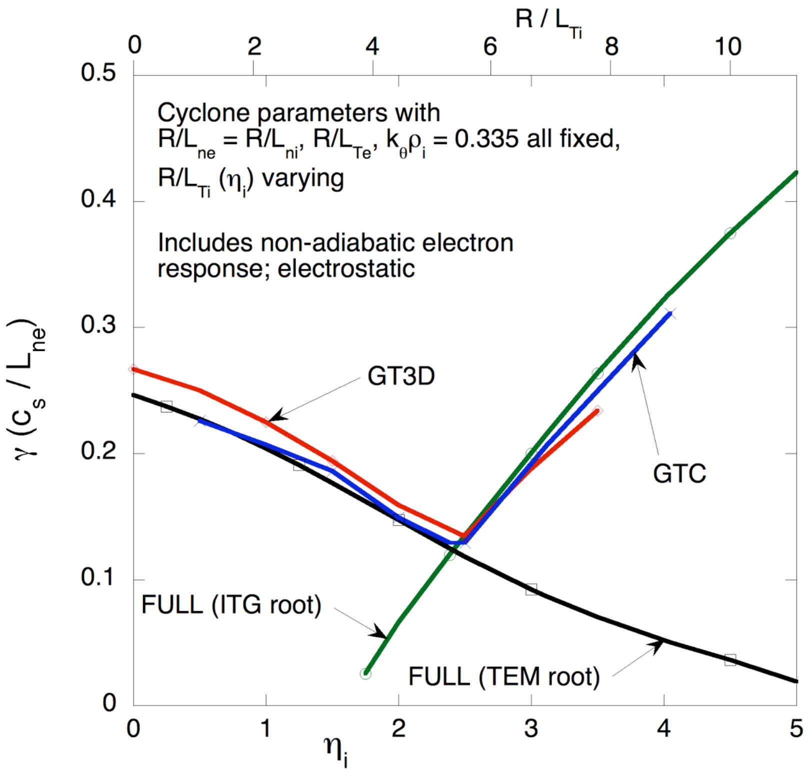


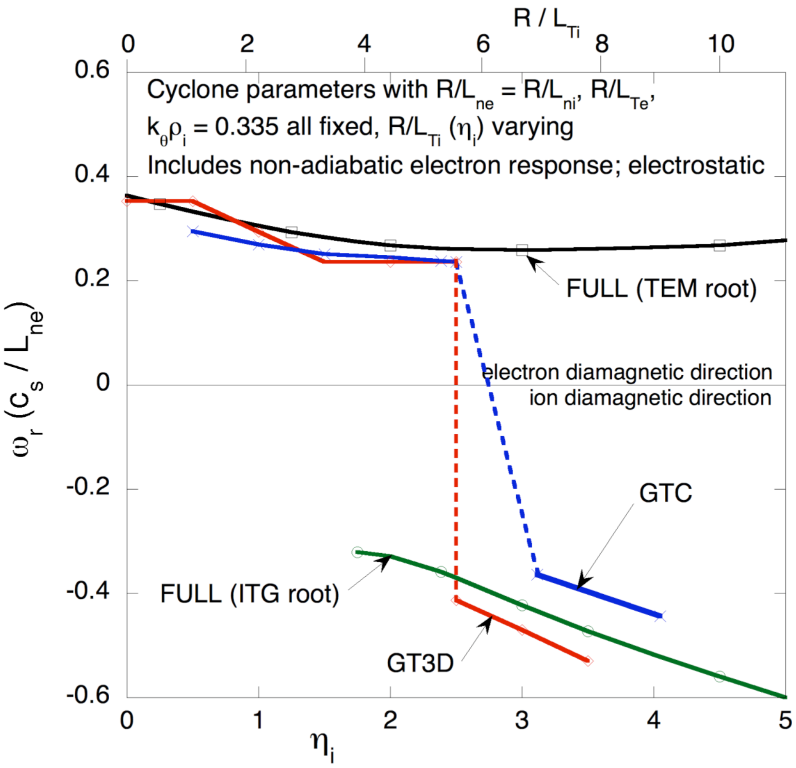
GTC mesh

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

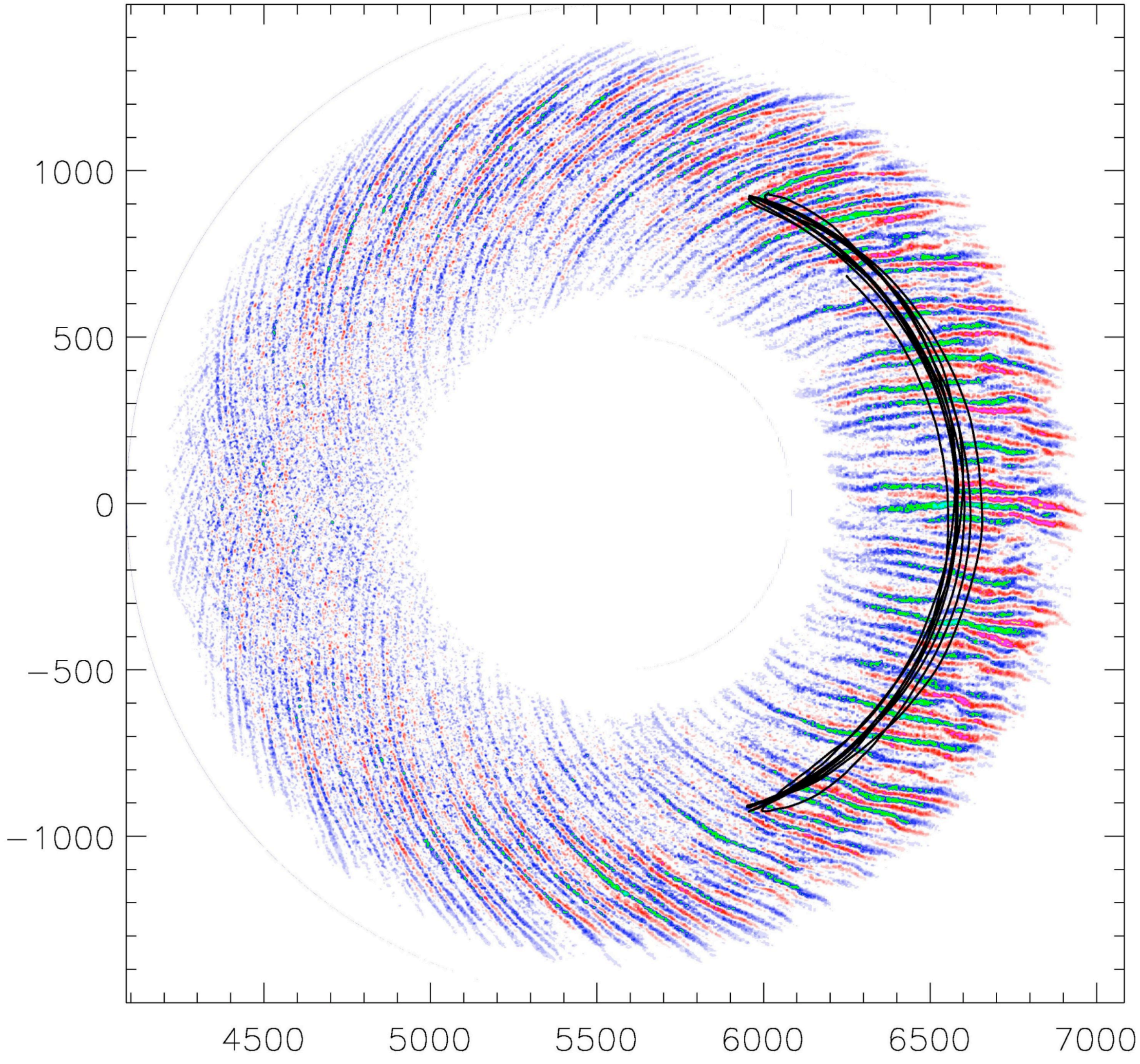




Z. Lin

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

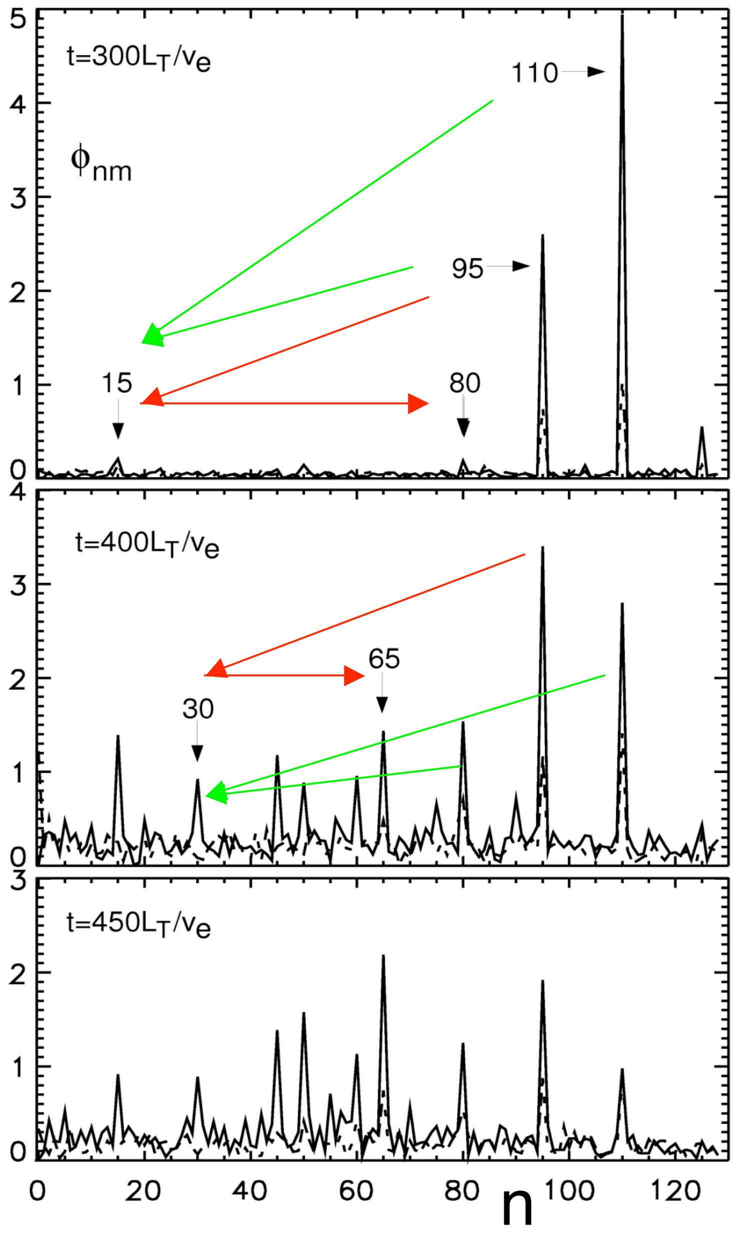
- 1st step: generation of low-*n* quasi-mode

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

  - "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

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

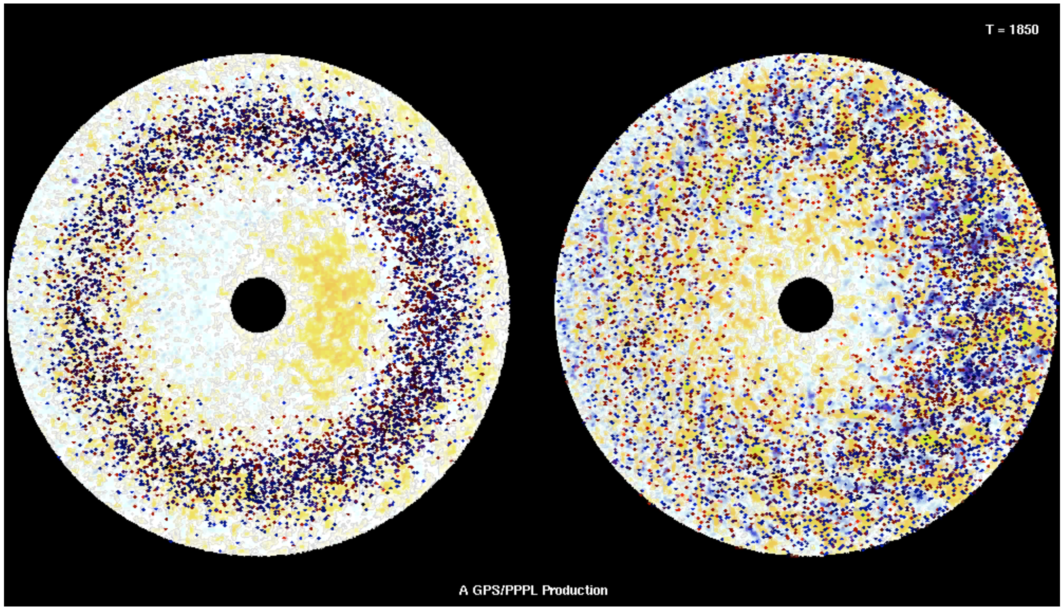
  - Streamers nonlinearly generated
- Spectral transfer facilitated by quasi-modes
  - Nonlocal in *n*-space, "Compton Scattering"
  - Streamer coupling: toroidal geometry-specific
- Need to keep all toroidal modes
  - Sufficient channels for spectral transfer



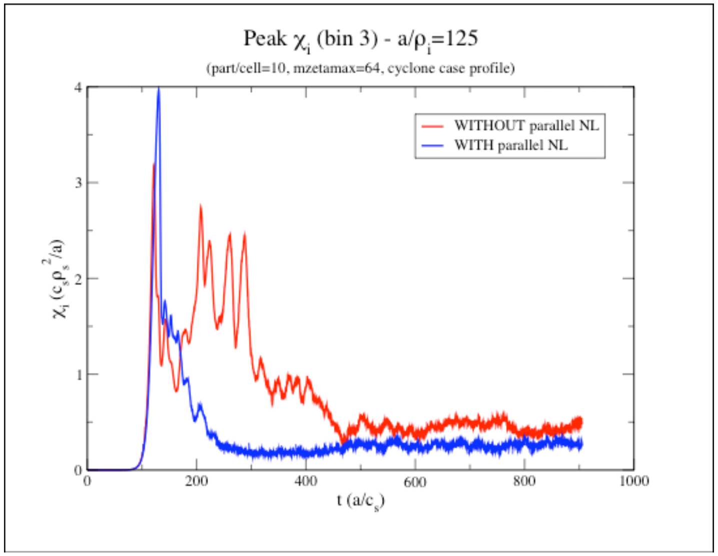
W.W. Lee & J.L.V. Lewandowski

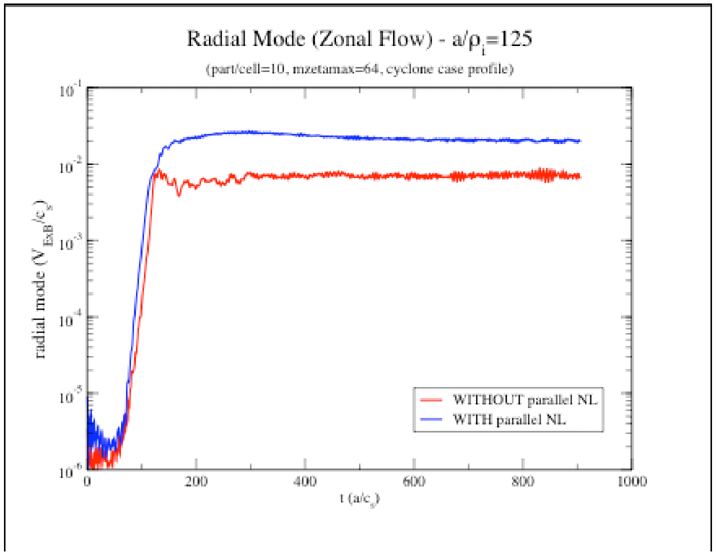
Particle Diffusion Due To Toroidal ITG Modes With/Without Parallel Velocity-Space Nonlinearity

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



with without

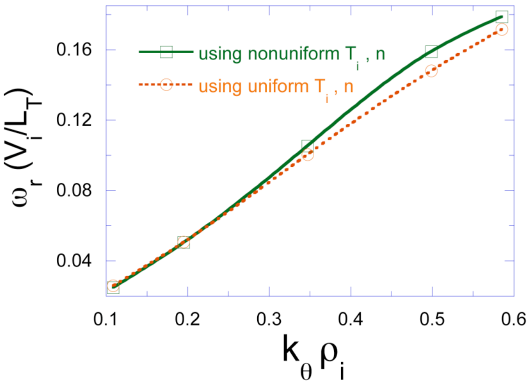


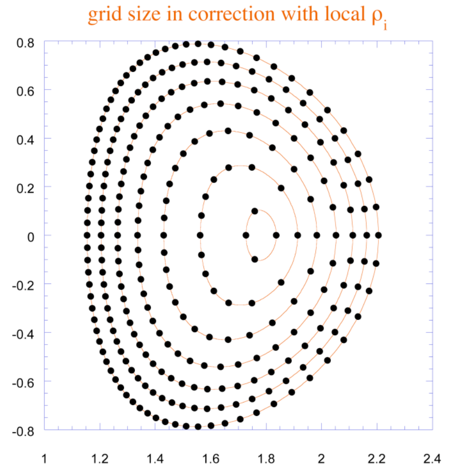


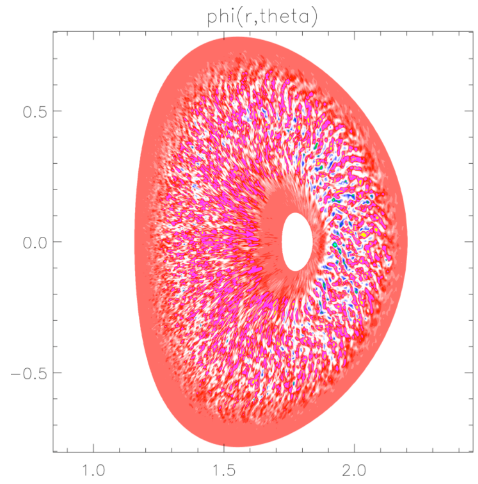
Gyrokinetic Simulation of Microturbulence for Shaped Plasmas

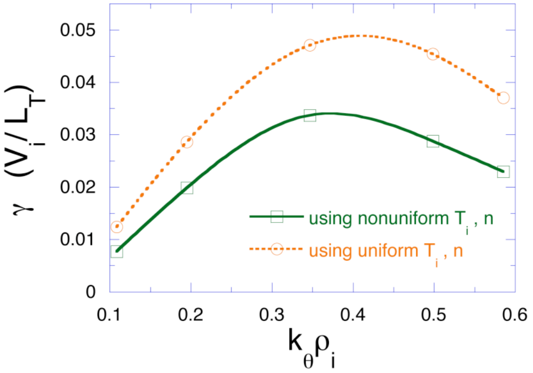
W.X. Wang

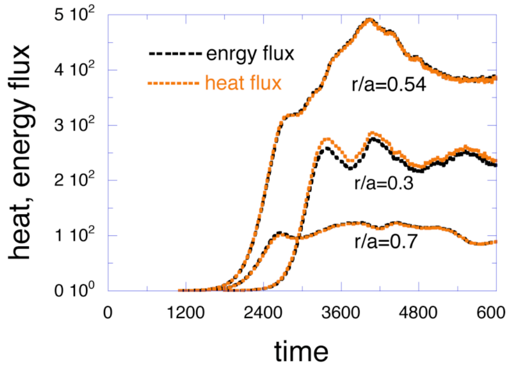
- General Geometry GTC developed with generalized and extended features: realistic plasma profiles and MHD equilibrium(ESC, JSOLVER…); systematic treatment of plasma rotation and equilibrium **ExB** flow (calculated from GTC-Neo); nonuniform mesh in correlation with local gyroradius; accurate gyrokinetic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

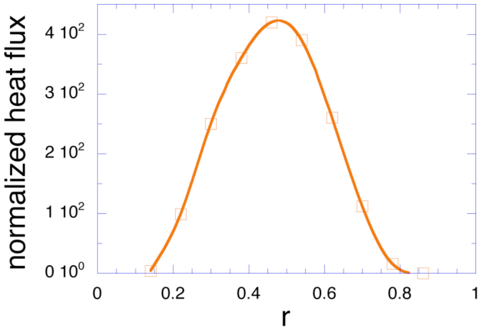








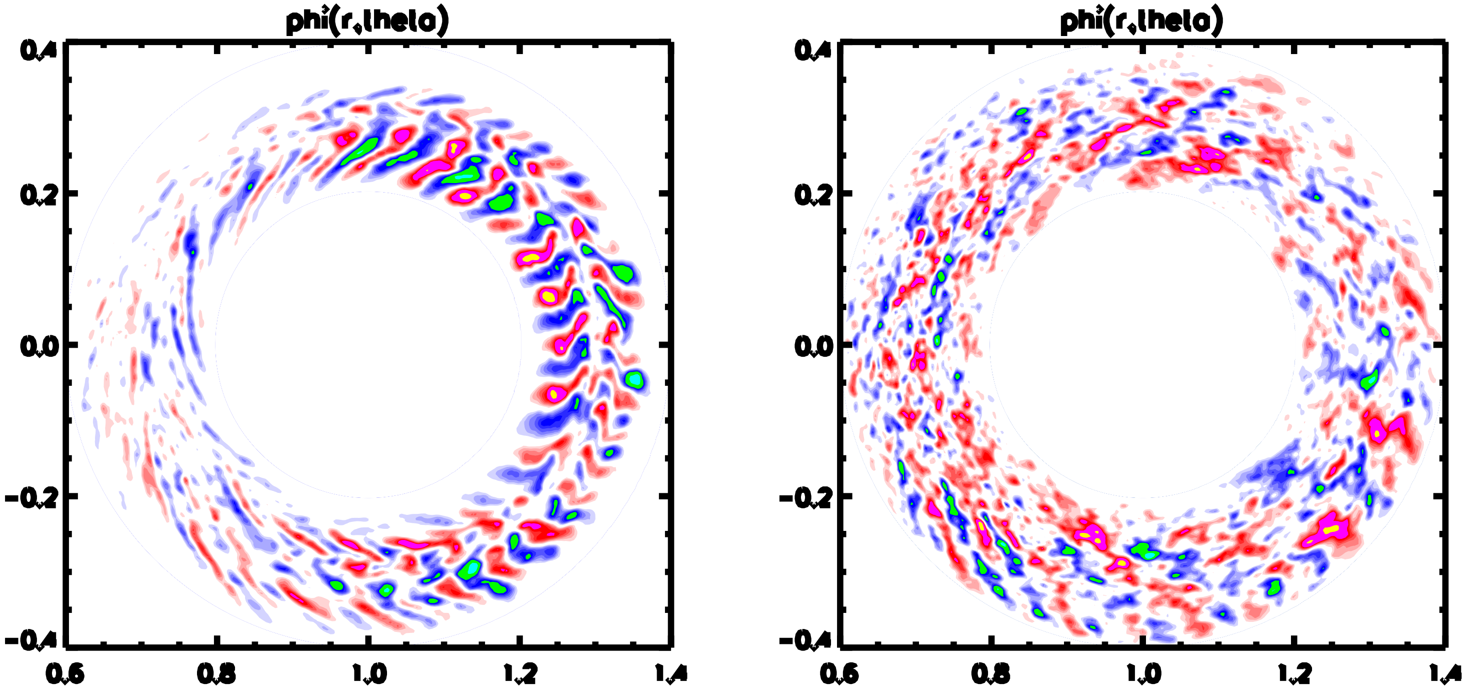




To do: update field solver; incorporate split-weight scheme for electron dynamics; fully develop and deliver EM general geometry capability for turbulence simulations;
Physics: TEM, Alfvenic ITG (KBM), micro-tearing, ITB dynamics …

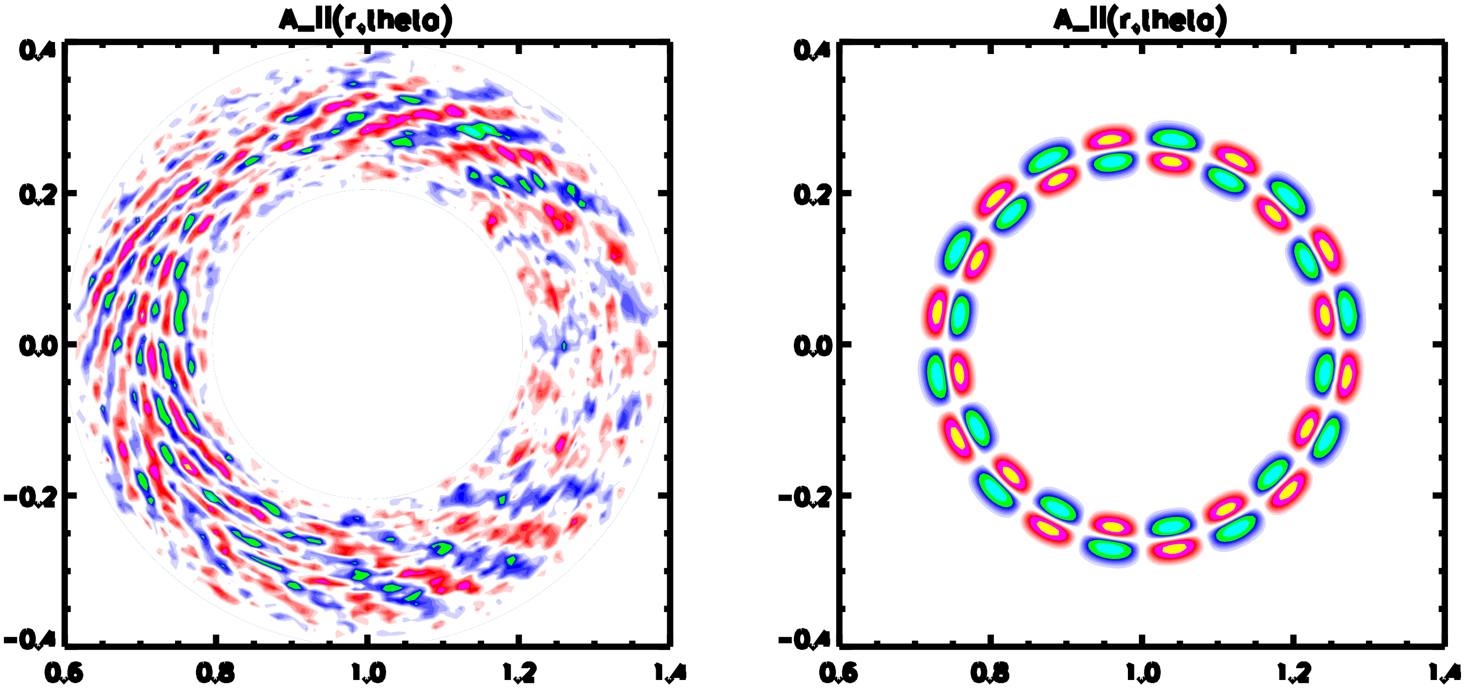
Y. Nishimura

Hybrid Model Employed for Nonlinear Simulations with Kinetic Electrons



- mass-ratio expansion - solve quasi-neutrality equation and induction equation
- Cyclone parameters, $\eta_i = \eta_e = 3.12$: Before (left) and after (right) saturation. Linear growth rate approximately twice as large as case with adiabatic electrons.

Testing Shear-Alfven Wave Propagation - Fluid-Kinetic Hybrid Electron Model

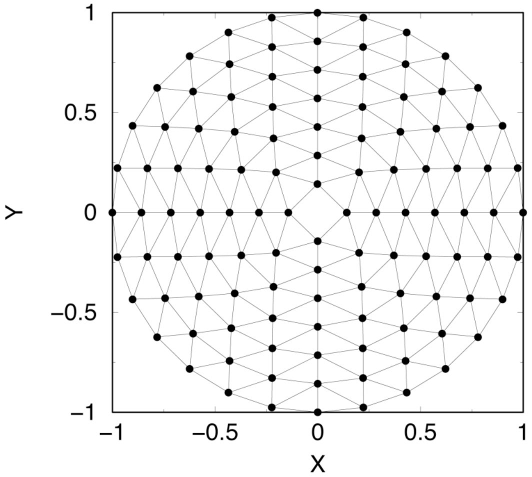


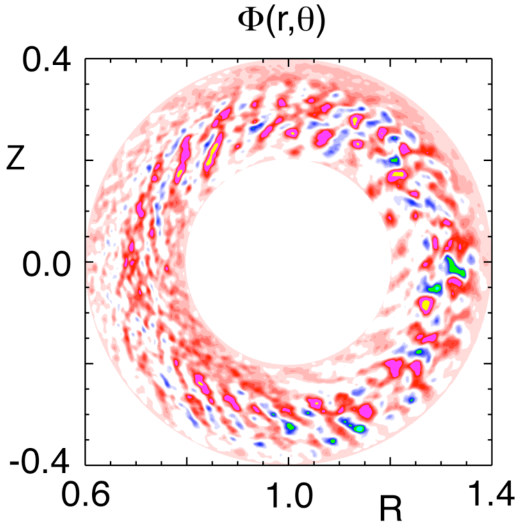
(Left) Evolution of $A_{\|}$ accompanied by a linear ITG instability, with $A_{\|} = 0$ as an initial condition. (Right) Perturbing a magnetic field line at t=0 in a uniform plasma with an odd parity mode for $A_{\|}$ at t=0.

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 $\Delta t = (5 - 10) / \omega_{ci}$





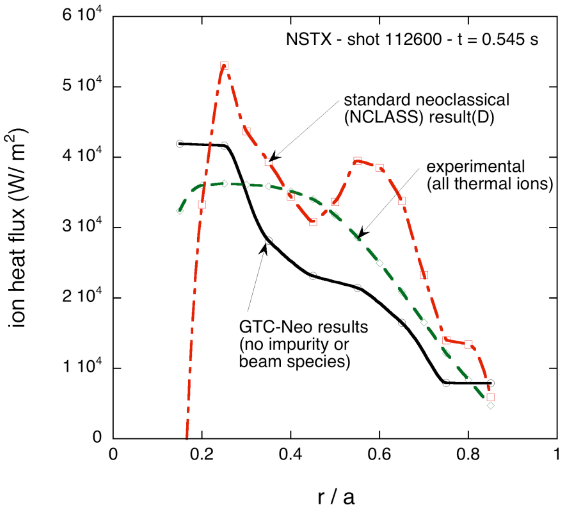
W.X. Wang, G. Rewoldt

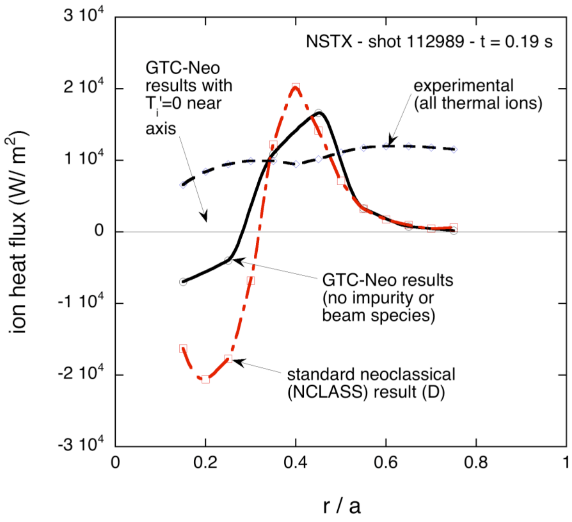
Neoclassical Transport Studies – GTC-Neo:

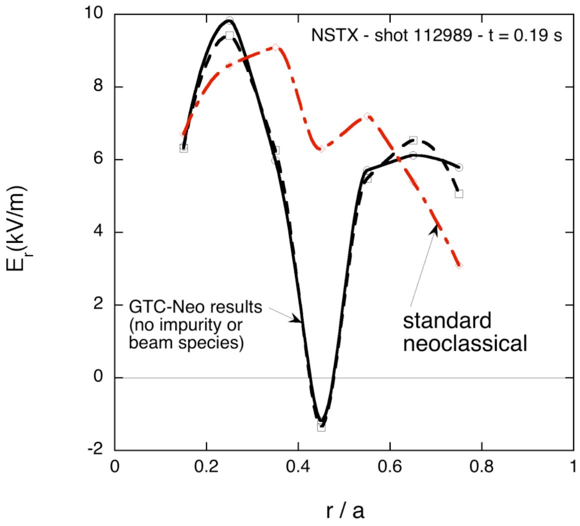
- global PIC code; ions + electrons; generalized tokamak geometry; self-consistent equilibrium E_r; finite orbit effects (nonlocal transport); systematic treatment of plasma rotation.

  $\{ T(r), n(r), \omega_t(r) \} \Longrightarrow q, \Gamma, j_b, E_r, \ldots$
- **Finite Orbit Transport** (with Tang, Hinton *et al.*)**:** nonlocal and nondiffusive property of ion thermal transport near magnetic axis; bootstrap current modified with large T_i gradient (not density gradient); additional bootstrap current, either positive or negative, driven by toroidal rotation gradient; additional poloidal flow driven by the toroidal rotation gradient.

Applications to NSTX and DIIID (by Rewoldt and Wang):







Doing and To Do: impurity physics by incorporating impurity and beam species into GTC-Neo; systematic inclusion of large gyro-orbit classical transport for low aspect ratio plasmas such as NSTX

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 [T.S. Hahm, this meeting]
- 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!