Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas*

SciDAC - Advanced Simulation of Fusion Plasmas

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

Mission

- Development of global gyrokinetic particle simulation capabilities
  - Codes: GTC, GTC-neo, GEM
  - Code validation: GT3D(Japan), LORB5(Switzerland), PG3EQ(LLNL), GYRO(GA), and GS2(Maryland).
- Simulations of burning plasmas: Turbulent and neoclassical transport simulations in the core
- Collaborations
  - Fusion theory and experiements
  - Applied mathematics: efficient parallel Poisson solvers
  - Computer sciences: data management, visualization, code optimization and team coding
- Foundation for future capabilities
  - Core-edge integrated simulation by extending GTC to the edge
  - Turbulence-MHD integrated transport time scale simulation

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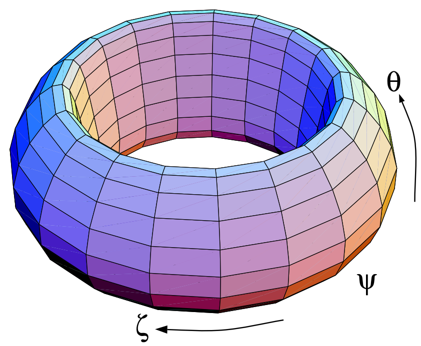
Management Plan

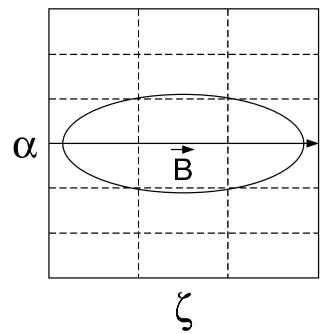
- Budget: SciDAC: $800K/yr$ for 3 yrs + $40K/yr$ for 2 yrs; SAPP: $160K/yr$ for 2 yrs
- Personnel: 7 institutions with 16 researchers, and with additional postdocs and students
- Executive committee: Lee, Parker, Lin and Keyes
- Collaborative activities
  - Tele/video conferences when necessary
  - Evening discussion sessions at Sherwood and APS/DPP
  - Bi-annual on-site meeting in Princeton, Boulder or Irvine
  - Short term individaul visits
  - Long term individual visits
  - Outreach activities

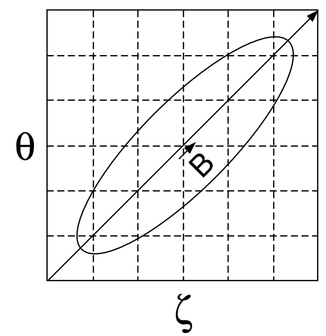
Global Gyrokinetic Toroidal Particle Simulation Code: GTC

[Z. Lin, T. S. Hahm, W. W. Lee, W. M. Tang and R. B. White, *Science* (1998)]



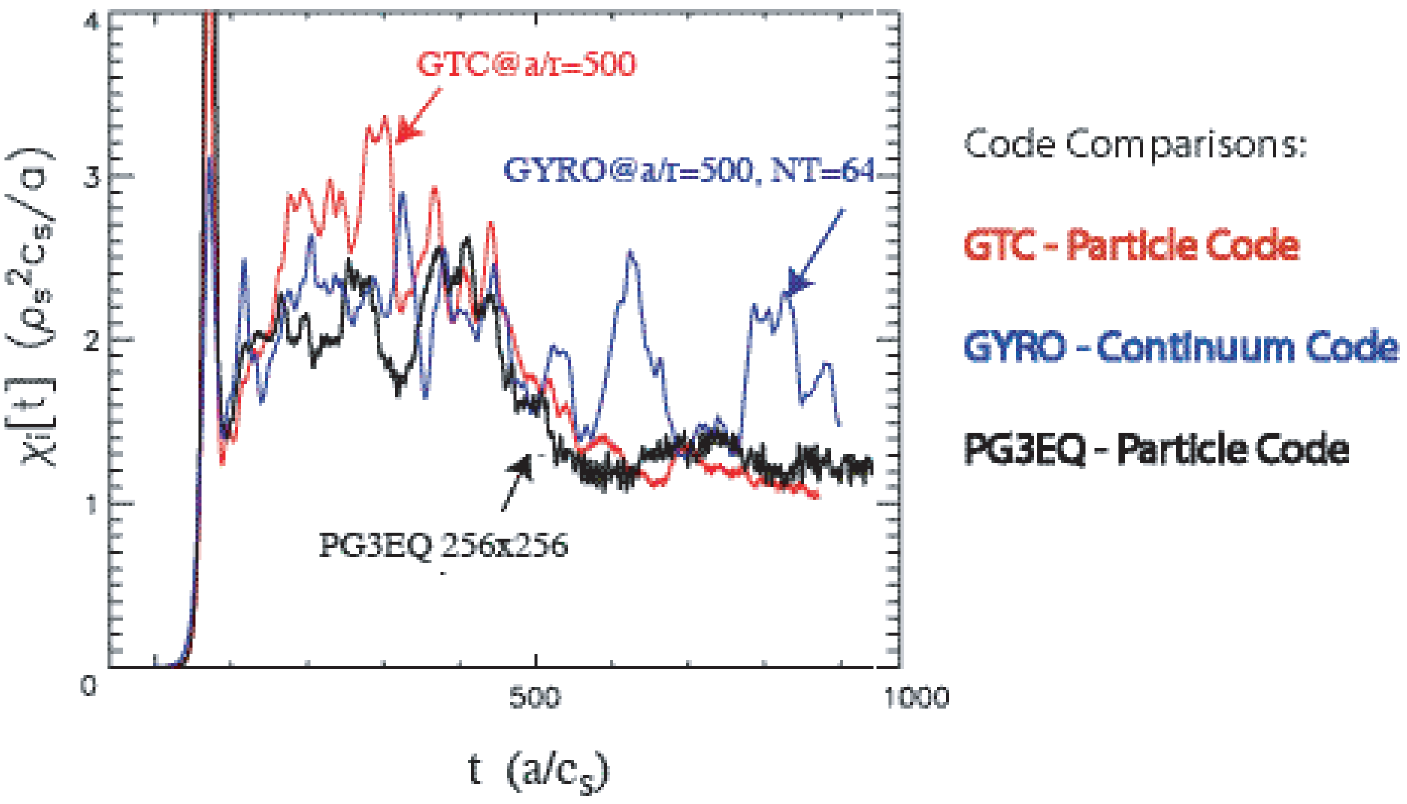
- Magnetic coordinates (ψ, θ, ζ) [Boozer, 1981]
- Guiding center Hamiltonian [Boozer, 1982; White and Chance, 1984]
- Non-spectral Poisson solver [Lin and Lee, 1995]
- Global field-line coordinates: $(\psi, \alpha, \zeta), \alpha = \theta - \zeta/q$
  - Microinstability wavelength: $\lambda_\perp \propto \rho_i$, $\lambda_\| \propto qR$
  - With field-line coordiantes: Grid # $N \propto a^2$, a: minor radius, $\triangle\zeta \propto R$
  - Without field-line coordinates: grid # $N \propto a^3$, $\triangle\zeta \propto \rho$
  - Larger time step: no high $k_\|$ modes
- Collisions: e-i and i-i





Recent PMP Code Comparisons

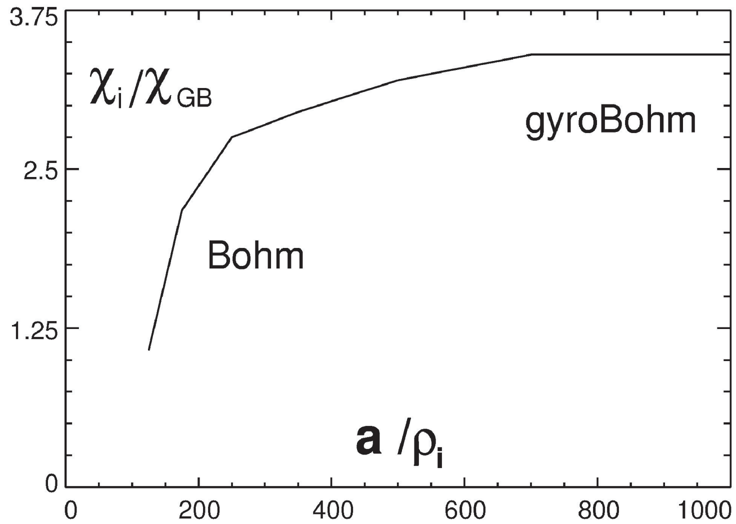
(W. M. Nevins, 04)



Size Scaling of ITG Turbulent Transport

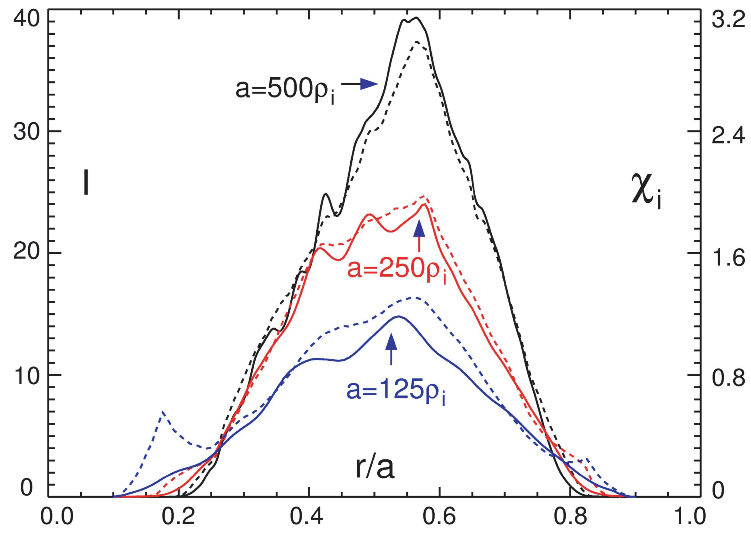
(Lin et al., PRL2002, IAEA2002)

- A critical issue for reactor design
- GyroBohm regime: turbulence eddy size remains the same as devise sizes increase
- Mixing length transport modeling based on $\gamma/^{2}_{\perp}$ is no longer valid



Turbulence Spreading and Transport Scaling

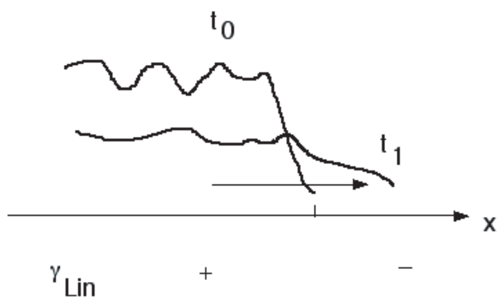
- Radial profile of heat conductivity (χ_i) matches with the profile of fluctuation density (I)
- Turbulence spreading from unstable to stable regions postulated as a mechanism for Bohm to gyroBohm transition [Lin and Hahm, PoP2004]
- GTC simulations motivate analytic models for turbulence spreading [Hahm et al. 2004, Chen et al. 2004]



Theoretical Model of Turbulence Spreading

Hahm, Diamond, Lin *et al.*, Plasma Phys. Control. Fusion **46**, A323 (2004)

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



I: turbulence intensity, $\gamma(x)$ is "local" growth rate,

α: a local nonlinear coupling, $\chi_0 I = \chi_i$ is a turbulent diffusivity

$$\frac{\partial}{\partial t}\int_{x-\Delta}^{x+\Delta} dx' I(x',t) \sim \chi_0 I \frac{\partial}{\partial x} I]_{x-\Delta}^{x+\Delta} + \ldots$$

Profile of Fluctuation Intensity crucial to its Spatio-temporal Evolution.

Analytic prediction for radial spreading into linearly stable zone $\rightarrow 18\rho_i$

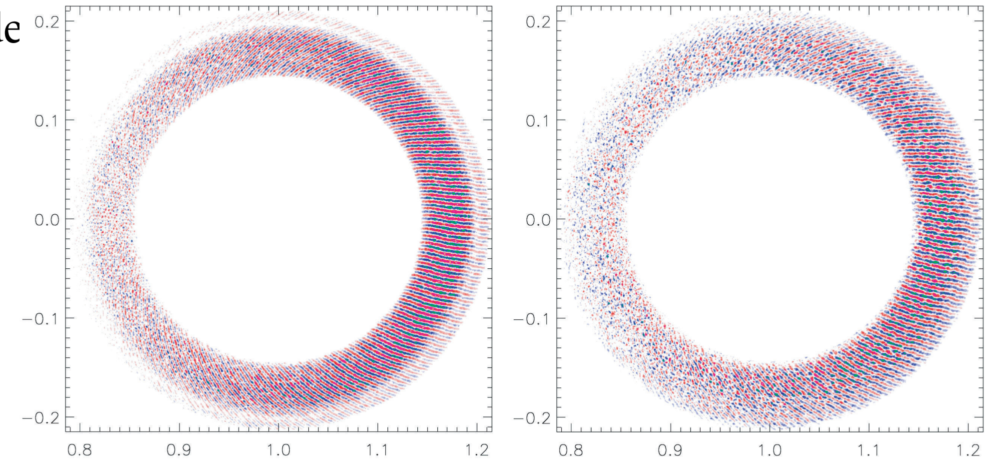
when the values from simulation used.

From GK simulation using GTC: $\simeq 25\rho_i$.

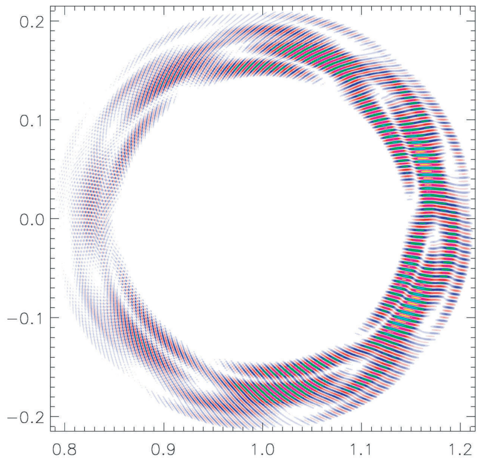
Electron Temperature Gradient Drift Instability Simulations

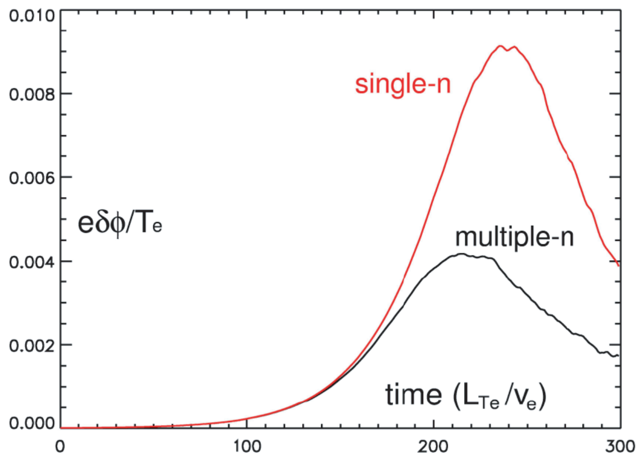
[Z. Lin et al., Sherwood (2004)]

- Single toroidal Mode



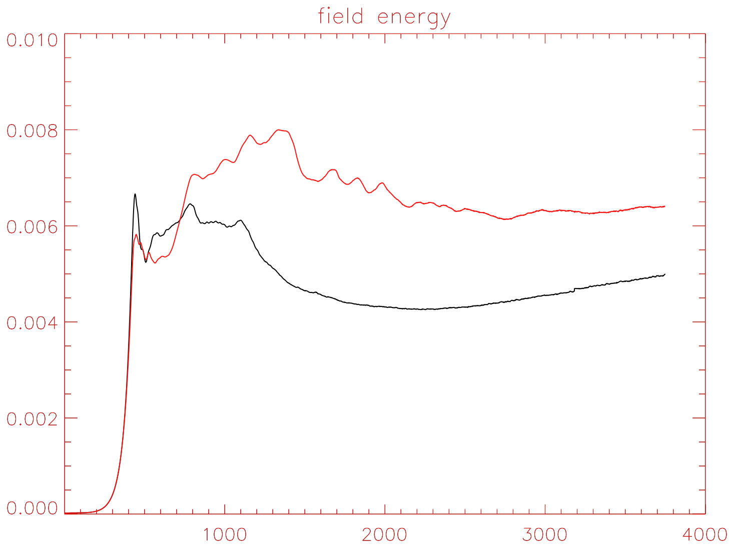
- Multiple toroidal modes

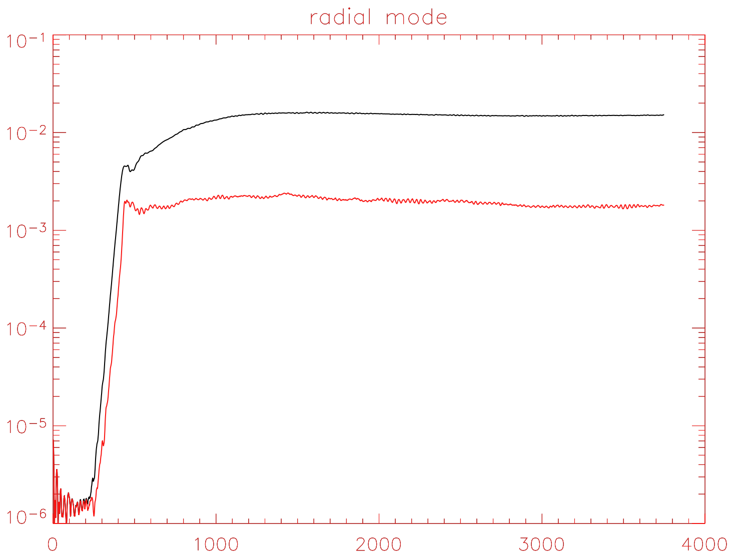


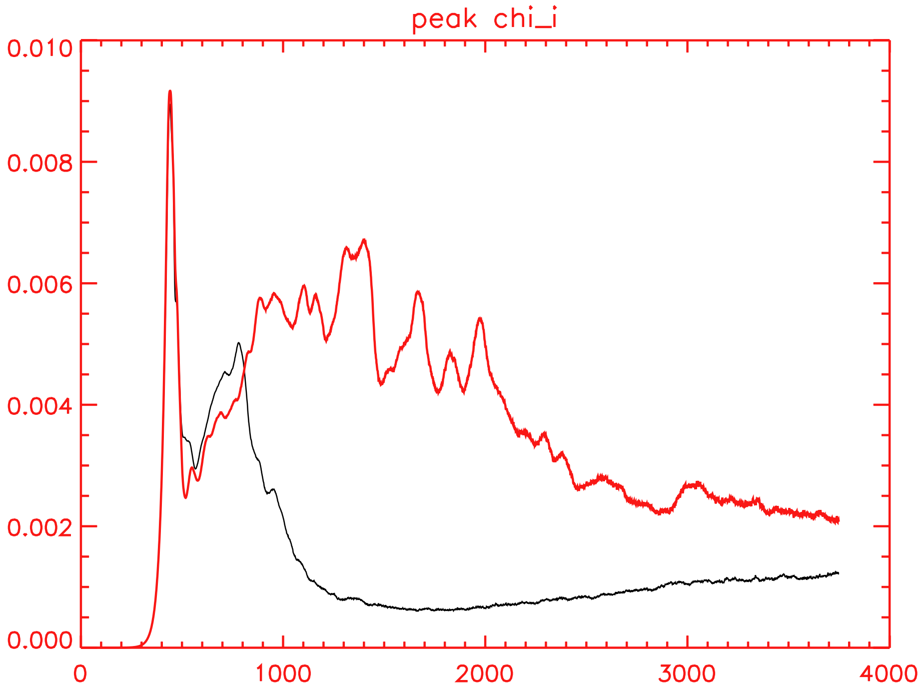


Velocity Space Nonlinearities on Toroidal ITG Modes

(W. W. Lee et al., Sherwood '04)







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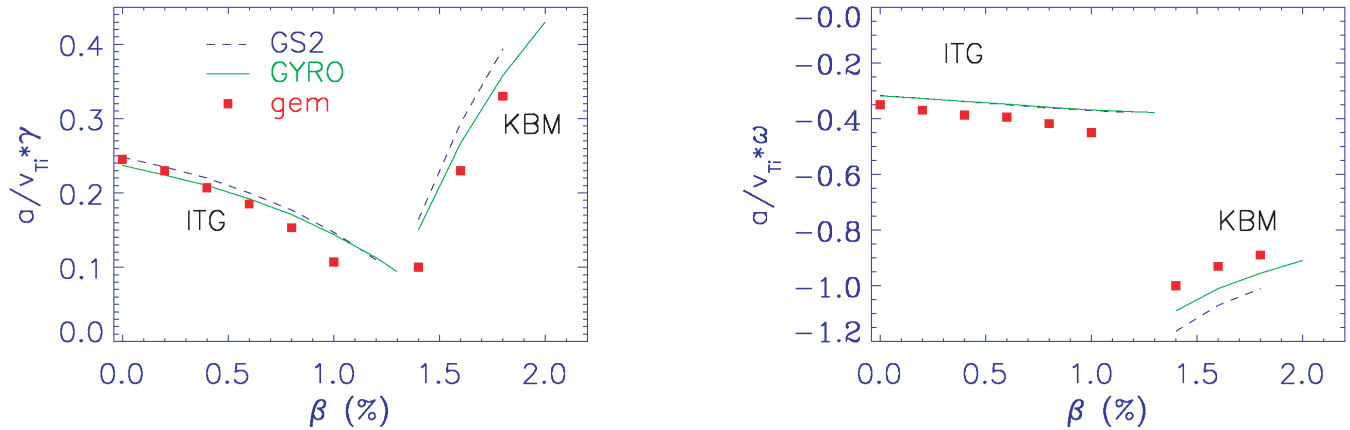
[Chen and Parker]

Current Features of GEM

- Passing + trapped kinetic electrons, electromagnetic perturbations
- $p_{\|}$ formulation, split-weight scheme and finite-β Ampere solver
- Field-line-following coordinates for Miller equilibrium
- Periodic and fixed boundary conditions with arbitrary profile variation
- Lorentzian electron-ion collisions
- 2-D domain decomposition, in radius and along field line

[Chen and Parker]

Linear Benchmark with Continuum Codes Shows Good Agreement

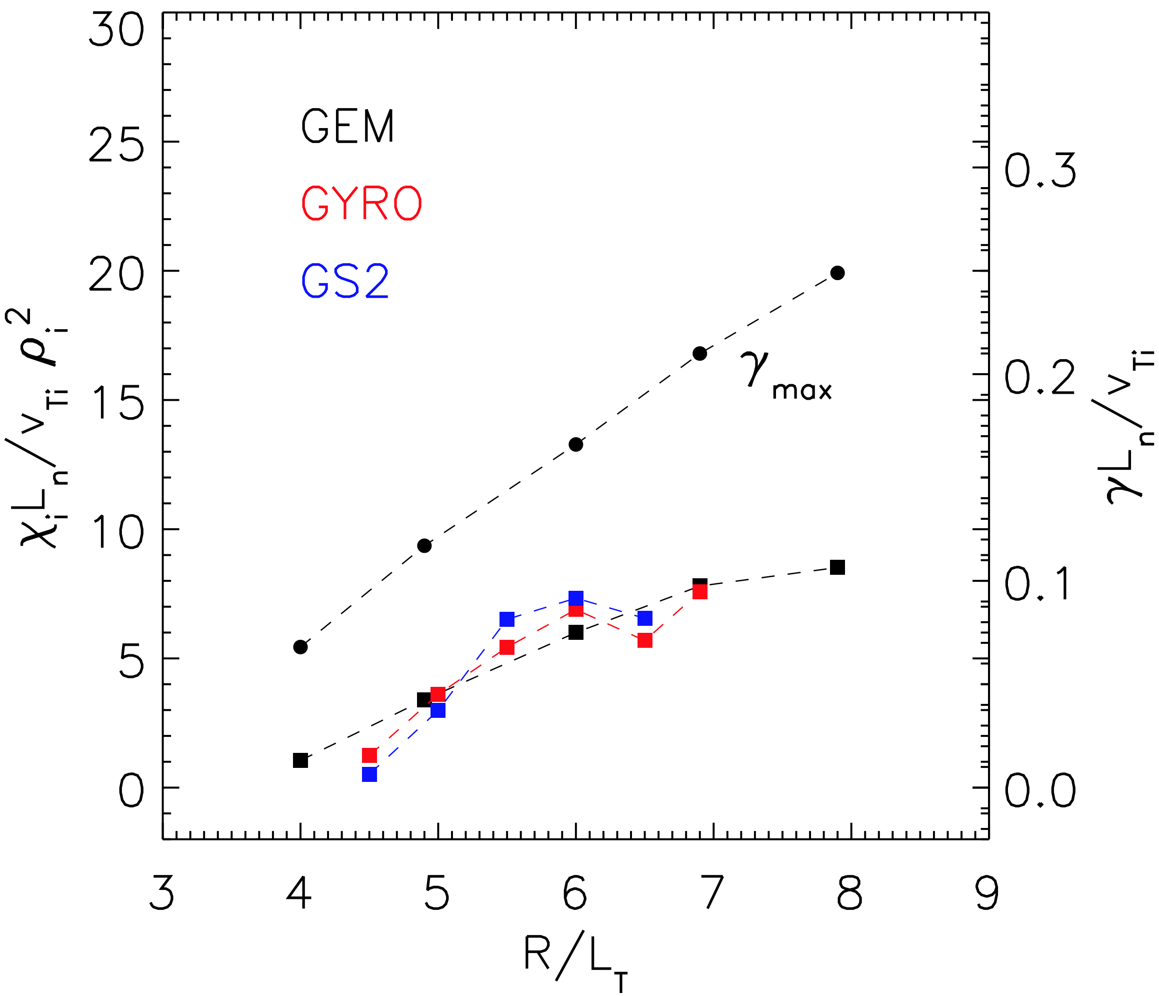


- $k_y \rho_i = 0.3$. Deuterium plasma with $R_0/L_T = 9$, $\eta_i = 3$, $q = 2$, $\hat{s} = rq'/q = 1$

Candy and Waltz, JCP 186(2), 545 (2003)
Dorland, 18th IAEA (2000)

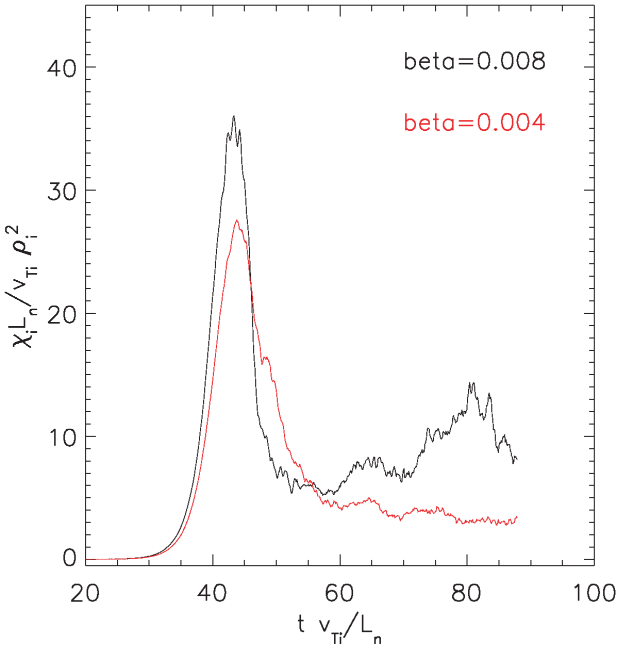
[Chen and Parker]

Nonlinear Benchmark (GEM)



[Chen and Parker]

Finite β Enhances Transport well below Ballooning Limit

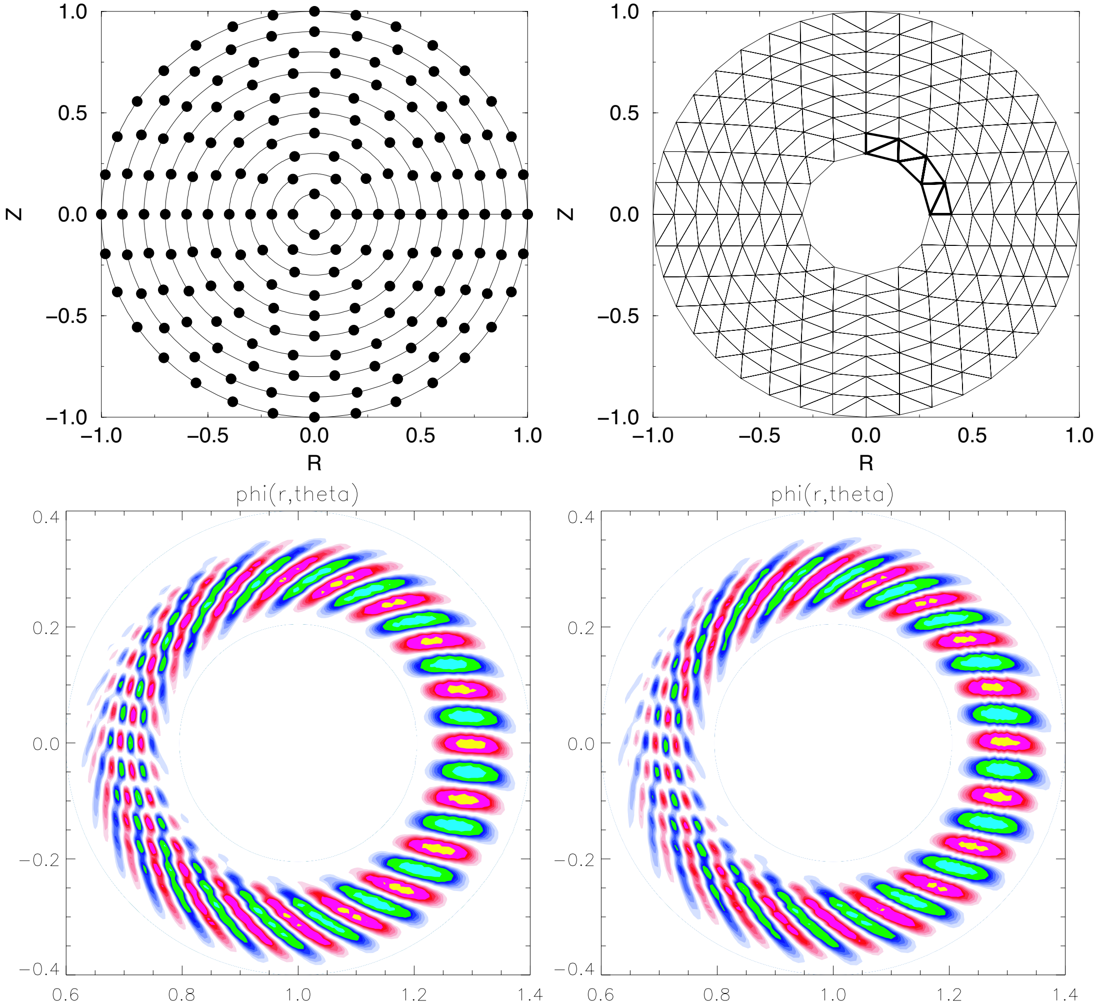


- Cyclone base case parameters. $R/L_T = 6.9$, $R/L_n = 2.2$, $\hat{s} = 0.78$.
- Collisionless.
- $m_i/m_e = 1837$
- $(L_x, L_y) = (100\rho_i, 64\rho_i)$, $NX = 128$, $NY = 64$ $NZ = 16$. $\Omega_{\rm ci}\,\triangle t = 5$.
- $4,194,304$ particles per species.
- Transport increases rapidly with β well below ideal ballooning limit ($\beta_{\rm crit} \sim 0.024$)

Code Development - Poisson Solver

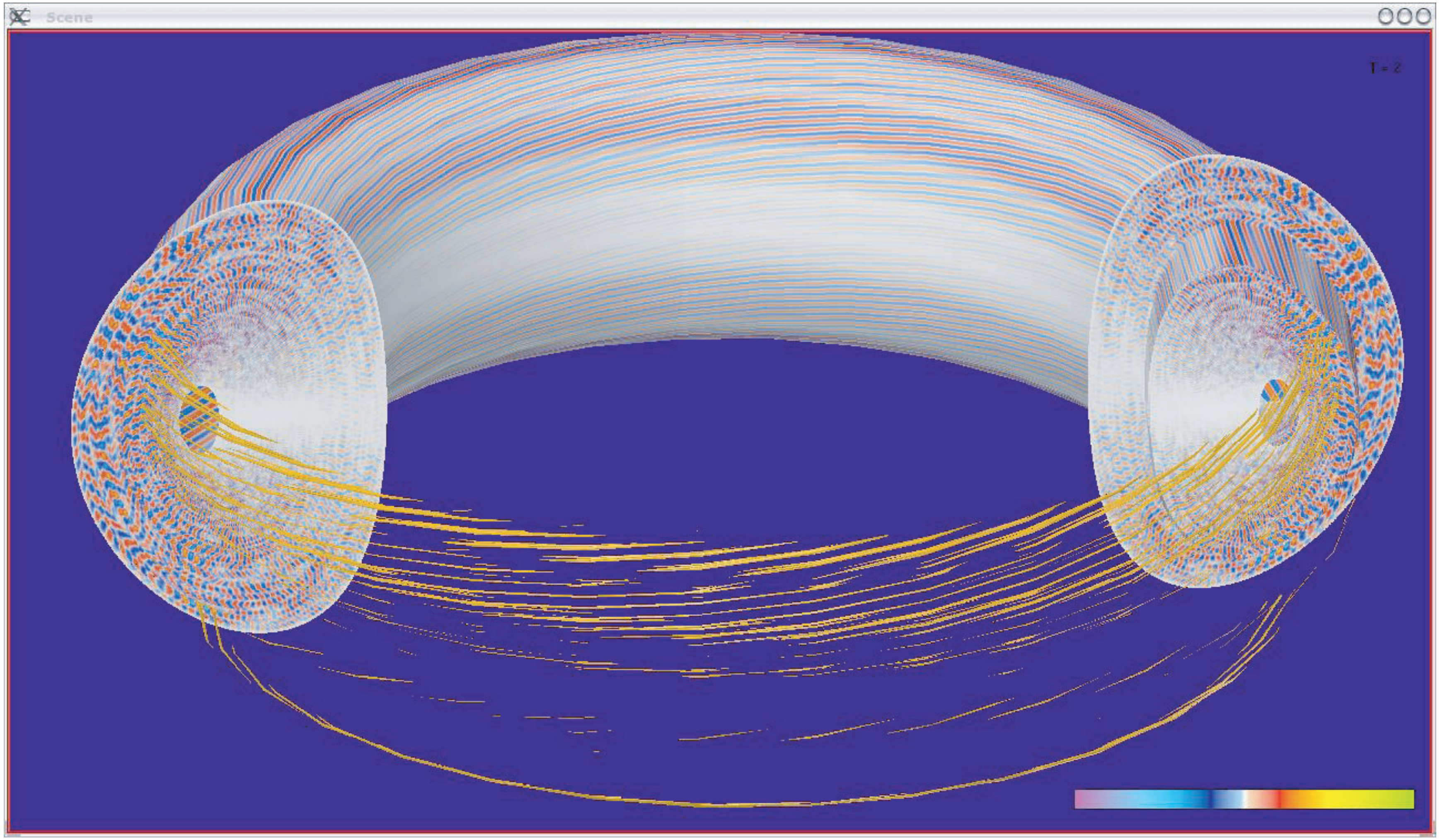
Old GTC solver vs. New GTC solver

[Nishimura, Lewandowski]



Code Development - Shaped Plasmas

[Wang, Klasky]



Code Development - Electron Dynamics and Finite-β effects

- Split-weight Scheme [Lee et al., PoP (2002)]

$$F = F_0 + \psi F_0 + \delta h$$

- Electron Hybrid Scheme [Lin and Chen, PoP (2002)]

$$F \approx F_0 + \psi F_0 + \delta h(\propto \omega / k_{\|} v_{\|})$$

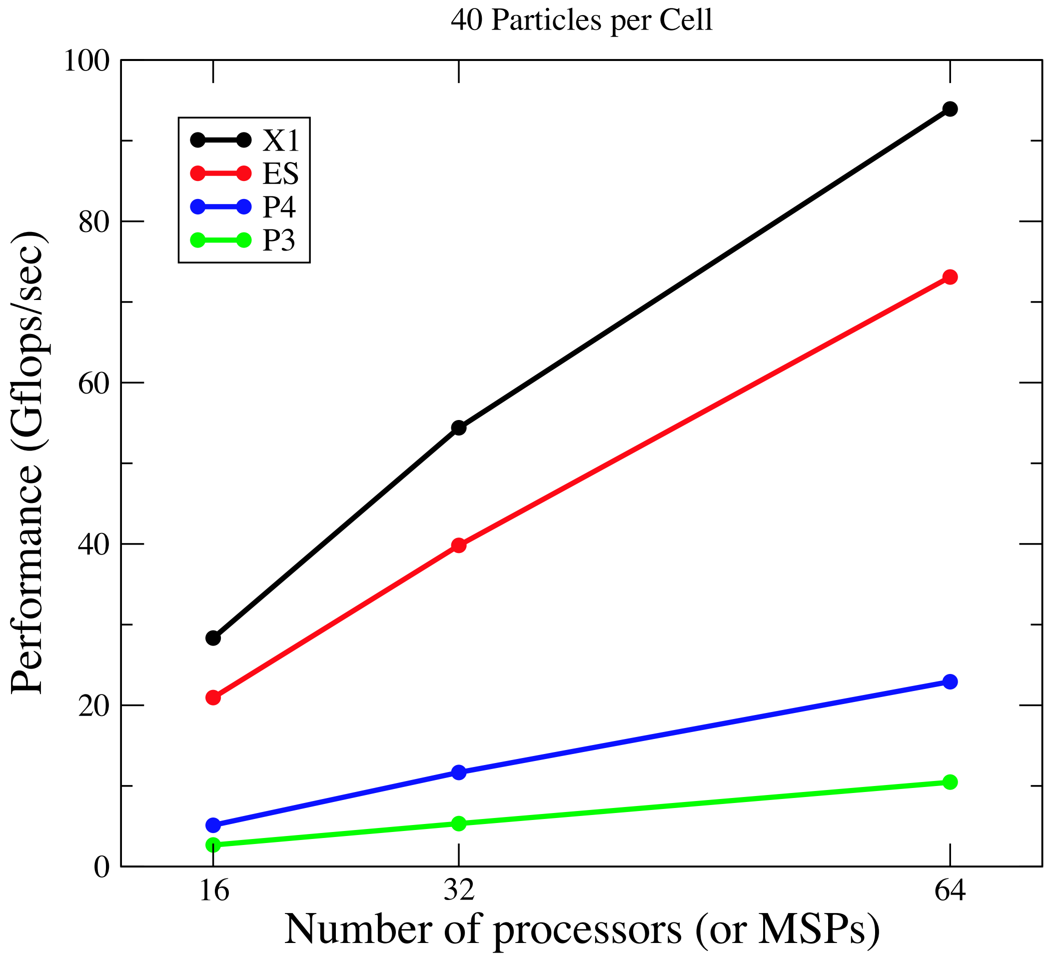
- Adiabatic response

$$\psi = \phi + \frac{1}{c} \int \frac{\partial A_{\|}}{\partial t} dx_{\|0}$$

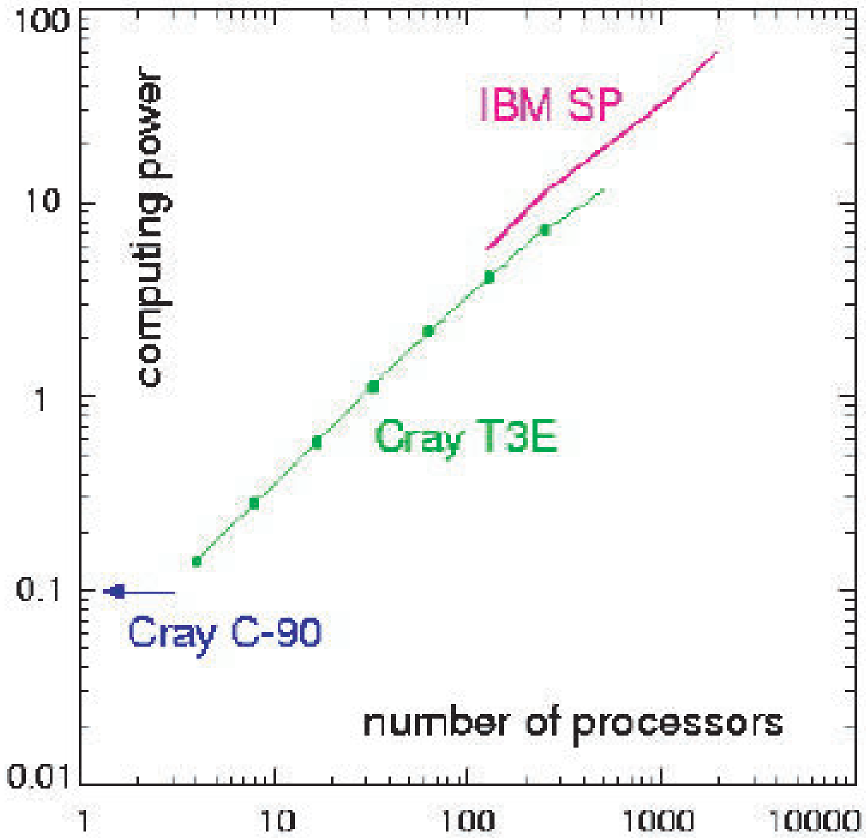
- Time step restriction for the electrons is determined by zero-th order orbit along the field line not $k_{\|} v_{\|} \Delta t < 1$.

GTC Performance on parallel platforms

[S. Ethier, '04]



GTC Scalable to a Large Number of processors



Y-axis: the number of particles (in milions) which move 1 step in 1 second

(Lin and Ethier)

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Single Processor Performance

Processor	Max speed (Mflops)	GTC test (Mflops)	Efficiency (real/max)	Relative speed (user time)
Power3 (Seaborg)	1,500	173.6	12 %	1
Power4 (Cheetah)	5,200	304.5	6 %	1.9
SX6 (Rime)	8,000	715.7	9 %	5.2
Earth Simulator			18%	10

(S. Ethier)

New Physics Issues

- Coherent Structures and Meso-scale Physics
  - Zonal flow/fields
  - Meso-scale phenomena
  - Conservation properties assciated with velocity-space nonlinearities and collisions in steady state simulations - energy, entropy . . . .
- Electron Transport
  - Electron thermal transport
  - Particle transport
  - Toroidal angular momentum transport
- Transport barrier physics
- Effects of energetic particles on turbulent transport

Integrated Simlations

- Development of GTC for core-edge integrated simulations:
  - Develop extended gyrokinetic Vlasov-Maxwell equations [Hahm and others]
  - Possible collaborations with Max-Planck-IPP [Bruce Scott]
- Development of transport time scale simulation capabilities: needs interface with MHD equilibrium codes and, possibly, transport codes. [Lee and Qin, PoP (2003)]

Other Center Activities

- Particle code optimization and team programming – Decyk (in collaboration with Ethier)
- Parallel Poisson Solver – Keyes (in collaboration with Nishimura and Lewandowski)
- Data mamagement – Beck (in collaboration with Klasky)
- Visualization – Ma (in collaboration with Klasky)

Conclusions

Let us carry on the dream of John Dawson,

who started it all in 1961 at PPPL.