Steady State Global Simulations of Microturbulence

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of Turbulent Transport in Burning Plasmas

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Outline

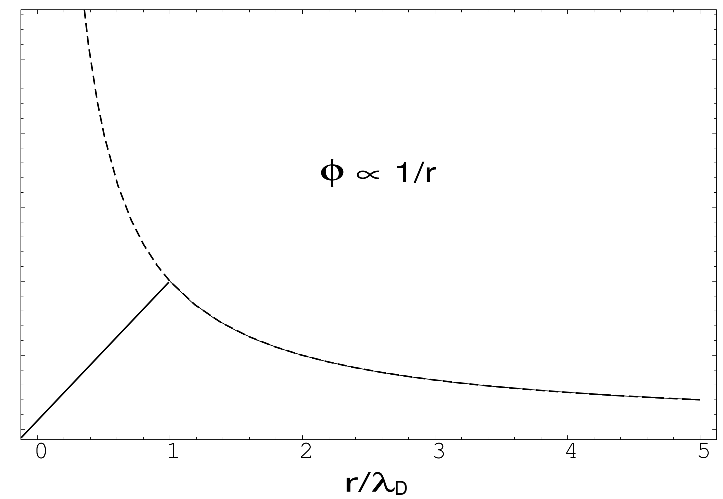
- Basics of Gyrokinetic Particle Simulation
  -- Finite size particles
  -- Decoupling of gyromotion and polarization effects
  -- Governing equations

- Gyrokinetic Particle Simulation of Microturbulence
  -- Simulation using the Gyrokinetic Toroidal Code (GTC)
  -- Scalability on MPP machines
  -- Influence of Parallel Velocity-Space Nonlinearity on Steady State Microturbulence

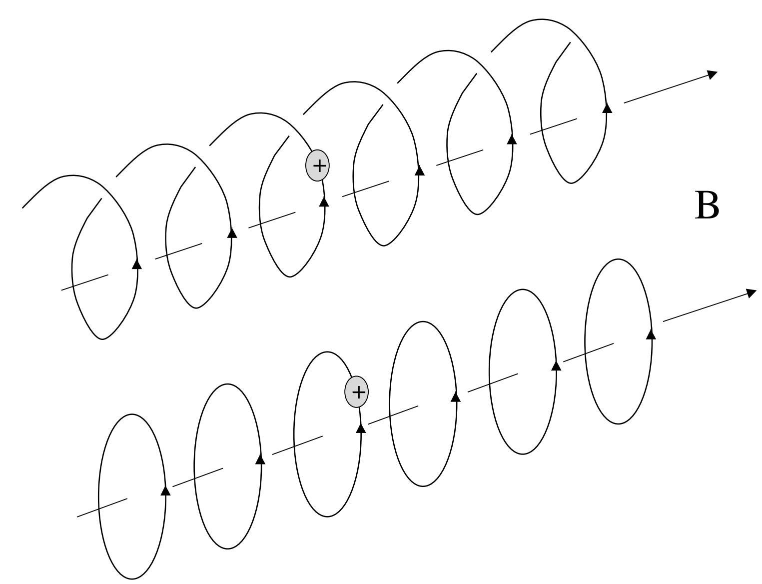
- Integrated Plasma Simulation
  -- Core-Edge Simulations
  -- Transport Time Scale Simulations

Basics of Gyrokinetic Particle Simulation

• Finite-size particles
[Dawson et al. '68; Birdsall et al. '68]
-- Coulomb interactions are collisionless
-- Collisional effects are subgrid phenomena



• Gyrokinetic particles
[Lee PF '83]
-- Gyromotion becomes motion of rotating charged rings
-- Polarization Effects in the field equations



• Efficient numerical methods to account for finite Larmor radius effects
[Lee JCP '87; Lee and Qin PP '03]

Gyrokinetic Vlasov-Maxwell Equations in Toroidal Geometry

- GK Vlasov equation - in gyrocenter coordinates

[Lee PF '83; Hahm et al. PF '88; Hahm PF '88; Brizard PF '88; Brizard J. Plas. Phys. '89; Qin et al. PoP '99; Qin et al. PoP '00; Qin et al., PoP '00; Lee and Qin PoP '03]

$$\frac{\partial F_{\alpha gc}}{\partial t} + \frac{d\mathbf{R}}{dt} \cdot \frac{\partial F_{\alpha gc}}{\partial \mathbf{R}} + \frac{dv_\parallel}{dt} \frac{\partial F_{\alpha gc}}{\partial v_\parallel} = 0,$$

$$\frac{d\mathbf{R}}{dt} = v_\parallel \mathbf{b}^* + \frac{v_\perp^2}{2\Omega_{\alpha 0}} \hat{\mathbf{b}}_0 \times \nabla ln B_0 - \frac{c}{B_0} \nabla \bar{\phi} \times \hat{\mathbf{b}}_0$$

$$\frac{dv_\parallel}{dt} = -\frac{v_\perp^2}{2} \mathbf{b}^* \cdot \nabla ln B_0 - \boxed{\frac{q_\alpha}{m_\alpha} \left(\mathbf{b}^* \cdot \nabla \bar{\phi} + \frac{1}{c} \frac{\partial \bar{A}_\parallel}{\partial t} \right)}$$ -- Velocity Nonlinearity

$$\mu_B \equiv \frac{v_\perp^2}{2B_0} \left(1 - \frac{mc}{e} \frac{v_\parallel}{B_0} \hat{\mathbf{b}}_0 \cdot \nabla \times \hat{\mathbf{b}}_0 \right) \approx cons.$$

$$\mathbf{b}^* \equiv \mathbf{b} + \frac{v_\parallel}{\Omega_{\alpha 0}} \hat{\mathbf{b}}_0 \times (\hat{\mathbf{b}}_0 \cdot \nabla) \hat{\mathbf{b}}_0, \quad \mathbf{b} = \hat{\mathbf{b}}_0 + \frac{\nabla \times \bar{\mathbf{A}}}{B_0}$$

$$\begin{pmatrix} \bar{\phi} \\ \bar{\mathbf{A}} \end{pmatrix} (\mathbf{R}) = \langle \int \begin{pmatrix} \phi \\ \mathbf{A} \end{pmatrix} (\mathbf{x}) \boxed{\delta(\mathbf{x} - \mathbf{R} - \rho)} d\mathbf{x} \rangle_\varphi ,$$ -- Coordinate Transformation

$$F_{\alpha gc} = \sum_{j=1}^{N_\alpha} \delta(\mathbf{R} - \mathbf{R}_{\alpha j}) \delta(\mu - \mu_{\alpha j}) \delta(v_\parallel - v_{\parallel \alpha j})$$

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GK Equations in Toroidal Geometry (cont.)

- GK Poisson's equation - in laboratory coordinates [Lee JCP '87]

$$\nabla^2\phi + \frac{\tau}{\lambda_D^2}[\phi(\mathbf{x}) - \tilde{\phi}(\mathbf{x})] = -4\pi\rho_{gc}(\mathbf{x}) \quad \xrightarrow{(k_\perp\rho_i)^2 \ll 1} \quad \boxed{\frac{\rho_s^2}{\lambda_D^2}\nabla_\perp^2\phi(\mathbf{x}) = -4\pi\rho_{gc}(\mathbf{x})}$$

$$\tilde{\phi}(\mathbf{x}) \equiv < \int \bar{\phi}(\mathbf{R})F_i(\mathbf{R},\mu,v_\parallel)\delta(\mathbf{R}-\mathbf{x}+\rho)d\mathbf{R}d\mu dv_\parallel >_\varphi$$

$$\rho_{gc}(\mathbf{x}) = \sum_\alpha q_\alpha \langle \int F_{\alpha gc}(\mathbf{R})\delta(\mathbf{R}-\mathbf{x}+\rho)d\mathbf{R}dv_\parallel d\mu\rangle_\varphi$$

- GK Ampere's law -- in laboratory coordinates [Qin et al. PP '99]

$$\boxed{\nabla^2\mathbf{A} - \frac{1}{v_A^2}\cancel{\frac{\partial^2\mathbf{A}_\perp}{\partial t^2}} = -\frac{4\pi}{c}\mathbf{J}_{gc}} \qquad \omega^2/k^2v_A^2 \ll 1$$

$$\mathbf{J}_{gc}(\mathbf{x}) = \mathbf{J}_{\parallel gc}(\mathbf{x}) + \mathbf{J}^M_{\perp gc}(\mathbf{x}) + \mathbf{J}^d_{\perp gc}(\mathbf{x})$$

$$= \sum_\alpha q_\alpha \langle \int (\mathbf{v}_\parallel + \mathbf{v}_\perp + \mathbf{v}_d)F_{\alpha gc}(\mathbf{R})\delta(\mathbf{R}-\mathbf{x}+\rho)d\mathbf{R}dv_\parallel d\mu\rangle_\varphi$$

$$\mathbf{v}_d \equiv \frac{v_\parallel^2}{\Omega_{\alpha 0}}\hat{\mathbf{b}}_0 \times (\hat{\mathbf{b}}_0\cdot\nabla)\hat{\mathbf{b}}_0 + \frac{v_\perp^2}{2\Omega_{\alpha 0}}\hat{\mathbf{b}}_0 \times \nabla ln B_0$$

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GK Equations in Toroidal Geometry (cont.)

- Calculations of FLR effects for $k_\perp \rho_i \sim 1$ is only possible in the gyrocenter coordinates, but not in the laboratory coordinates

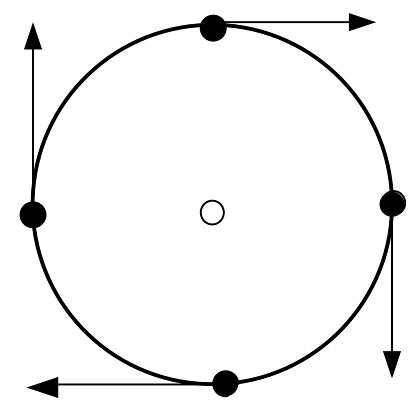
$$\begin{pmatrix} \bar{\phi} \\ \bar{\mathbf{A}} \end{pmatrix} (\mathbf{R}_{\alpha j}) = \langle \begin{pmatrix} \phi \\ \mathbf{A} \end{pmatrix} (\mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$\rho_{gc}(\mathbf{x}) = \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$\mathbf{J}_{\parallel gc}(\mathbf{x}) = \sum_\alpha q_\alpha \sum_{j=1}^{N} v_{\parallel \alpha j} \langle \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$\mathbf{J}^M_{\perp gc}(\mathbf{x}) = \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \mathbf{v}_{\perp \alpha j} \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$\mathbf{J}^d_{\perp gc}(\mathbf{x}) = \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \mathbf{v}_{d \alpha j} \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$



Coordinate Transformation

- Perpendicular current for $k_\perp \rho_i \ll 1$ [Qin et al. PP '00]

$$\mathbf{J}_{\perp gc} = \mathbf{J}^M_{\perp gc} + \mathbf{J}^d_{\perp gc} = \frac{c}{B_0} \sum_\alpha \left[\hat{\mathbf{b}}_0 \times \nabla p_{\alpha \perp} + (p_{\alpha \parallel} - p_{\alpha \perp})(\nabla \times \hat{\mathbf{b}}_0)_\perp \right]$$

- Pressure Balance: $p = p_{\alpha \parallel} = p_{\alpha \perp}$

$$\mathbf{J}_{\perp gc} = \frac{c}{B_0} \sum_\alpha \hat{\mathbf{b}}_0 \times \nabla p_\alpha$$

Reduced MHD Equations vs. Gyrokinetic-MHD Equations

- GK Three-field Equations for $k_\perp \rho_i \ll 1$ w/o geometric simplification [Lee and Qin PP '03]

$$\frac{d}{dt}\nabla_\perp^2\phi + \frac{v_A^2}{c}(\hat{\mathbf{b}}\cdot\nabla)\nabla^2 A_\parallel - \boxed{4\pi\frac{v_A^2}{c^2}\nabla_\perp\cdot\mathbf{J}^d_{\perp gc}} = 0$$

$$\frac{1}{c}\frac{\partial A_\parallel}{\partial t} + \mathbf{b}\cdot\nabla\phi = 0.$$

$$\frac{dp_\alpha}{dt} = 0$$

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} - \frac{c}{B}\nabla\bar{\phi}\times\hat{\mathbf{b}}_0\cdot\nabla$$

$$\mathbf{J}^d_{\perp gc} = \frac{c}{B_0}\sum_\alpha\left[p_\alpha(\nabla\times\hat{\mathbf{b}}_0)_\perp + p_\alpha\hat{\mathbf{b}}_0\times(\nabla lnB_0)\right]$$

- Reduced High-ß Three-Field MHD Equations [Strauss PF '78]

$$\frac{d\nabla_\perp^2\phi}{dt} + \frac{v_A^2}{c}(\hat{\mathbf{b}}\cdot\nabla)\nabla_\perp^2 A_\parallel - \boxed{\frac{2}{R_0}\frac{\partial p}{\partial y}} = 0$$

$$\frac{1}{c}\frac{\partial A_\parallel}{\partial t} + \mathbf{b}\cdot\nabla\phi = 0.$$

$$\frac{dp}{dt} = 0$$

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Magnetic Field Calculations

- For given zeroth-order field and density, parallel current and temperature profiles

$$\mathbf{J}_{\|gc}(\mathbf{x}) = \sum_{\alpha} q_\alpha \sum_{j=1}^{N} v_{\|\alpha j} \langle \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$\mathbf{J}^{M}_{\perp gc}(\mathbf{x}) = \sum_{\alpha} q_\alpha \sum_{j=1}^{N} \langle \mathbf{v}_{\perp \alpha j} \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$\mathbf{J}^{d}_{\perp gc}(\mathbf{x}) = \sum_{\alpha} q_\alpha \sum_{j=1}^{N} \mathbf{v}_{d\alpha j} \langle \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

- Ampere's law

$$\nabla^2 \mathbf{A} = -\frac{4\pi}{c} \mathbf{J}_{gc}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

- FLR effects are taken into accounted in gyrocenter-space

Fluctuation-Dissipation Theorem and Particle Simulation

- Plasma Waves and Finite-Size Particles [Langdon and Birdsall, PF **13**, 2115 (1970)]

$$V\frac{|\mathbf{E}(\mathbf{k})|^2}{8\pi} = \frac{T/2}{1+k^2\lambda_D^2/S^2} \rightarrow T/2\,,\quad V \text{ -- volume},\ \ S \text{ -- particle shape}$$

- Gyrokinetic Particle Simulation [Krommes et al., PF '86; Lee, JCP '87]

$$V\frac{|\mathbf{E}(\mathbf{k})|^2}{8\pi} = \frac{\lambda_D^2}{\rho_s^2}(T/2) \quad \text{for} \quad k\rho_i \ll 1$$

- Shear-Alfven Waves in Gyrokinetic Plasmas [Lee et al., PP '01]

$$V\frac{|\mathbf{E}(\mathbf{k})|^2}{8\pi} = \frac{\lambda_D^2}{\rho_s^2}\frac{T/2}{1+\omega_{pe}^2/c^2k^2}\quad , \qquad \text{cold electrons}$$

$$V\frac{|\mathbf{E}(\mathbf{k})|^2}{8\pi} = k^2\lambda_D^2\frac{T/2}{1+k^2\rho_s^2}\quad , \qquad \text{warm electrons}$$

- Compressional-Alfven Waves in Gyrokinetic Plasmas

$$\frac{A_\perp}{A_\parallel} \sim \frac{\omega^2}{k^2 v_A^2} \ll 1$$

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Perturbative Particle Simulation

- δf simulation schemes:

-- [Dimits and Lee, JCP '93; Parker and Lee, PF '93]

Let $F = F_0 + \delta f \longrightarrow \frac{d\delta f}{dt} = -\frac{dF_0}{dt}$

Let $w \equiv \frac{\delta f}{F} \longrightarrow \delta f = \sum_{j=1}^{N} w_j \delta(\mathbf{R} - \mathbf{R}_j)\delta(\mu - \mu_j)\delta(v_\parallel - v_{\parallel j})$

Noise reduction: $|E|^2 \propto w^2$ [Hu and Krommes, PoP '94]

-- [Aydemir, PoP '94]

$$F = F_0 + \delta f \longrightarrow w \equiv \frac{\delta n}{n}$$

- Split-weight schemes: [Manuilskiy and Lee, PoP '00; Lee et al., PoP '01, Lewnadowski, PoP '03]

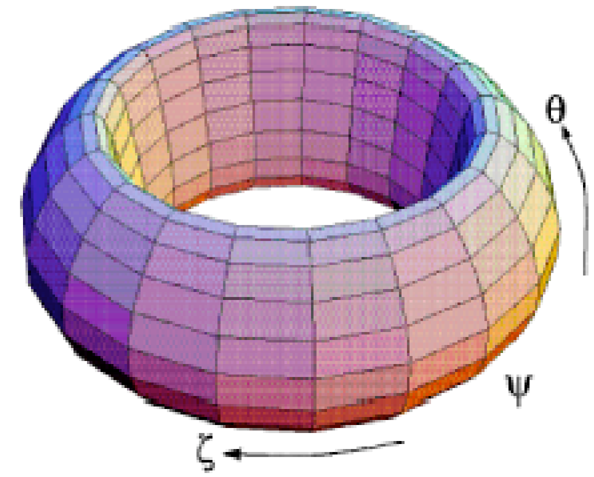
$$F = F_0 + \psi F_0 + \delta h \qquad \psi = \phi + \frac{1}{c}\int \frac{\partial A_\parallel}{\partial t} dx_{\parallel 0}$$

- Hybrid Scheme [Lin and Chen, PoP '01]

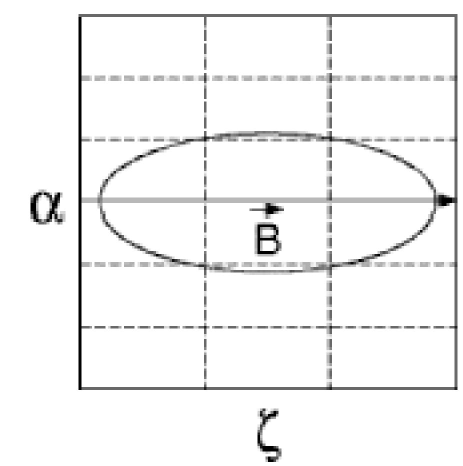
- Time step is determined by zeroth order transit time of the electrons along the field line.

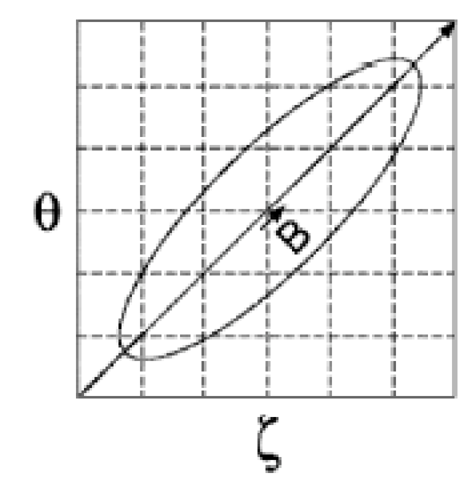
Global Gyrokinetic Toroidal Particle Simulation Code: GTC

[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, i-i and e-e
- Neoclassical Transport Code: GTC-neo [W. X. Wang, 2004]





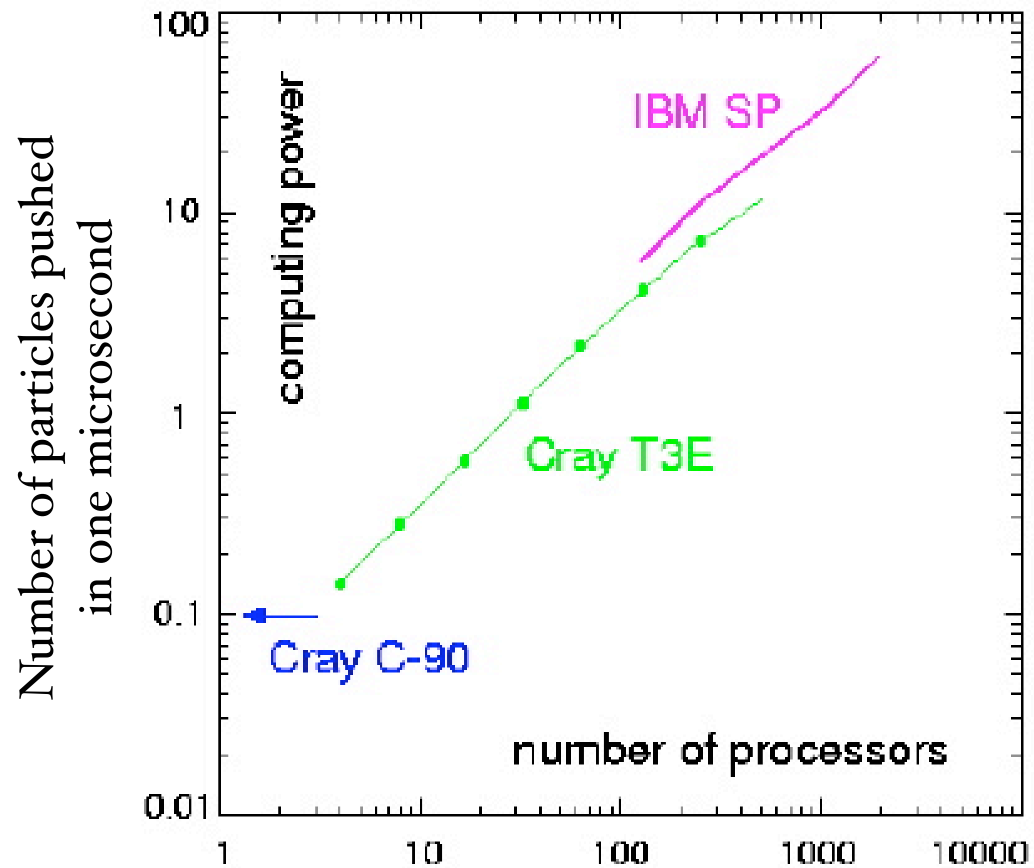
Global Turbulence Code (GTC)

PPPL Single Processor Performance (S. Ethier)

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 25% 10 (Ethier)
3.7 TeraFlop with 2048 processors using 5 billion particles

GTC Scalable to a Large Number of processors (Lin and Ethier)

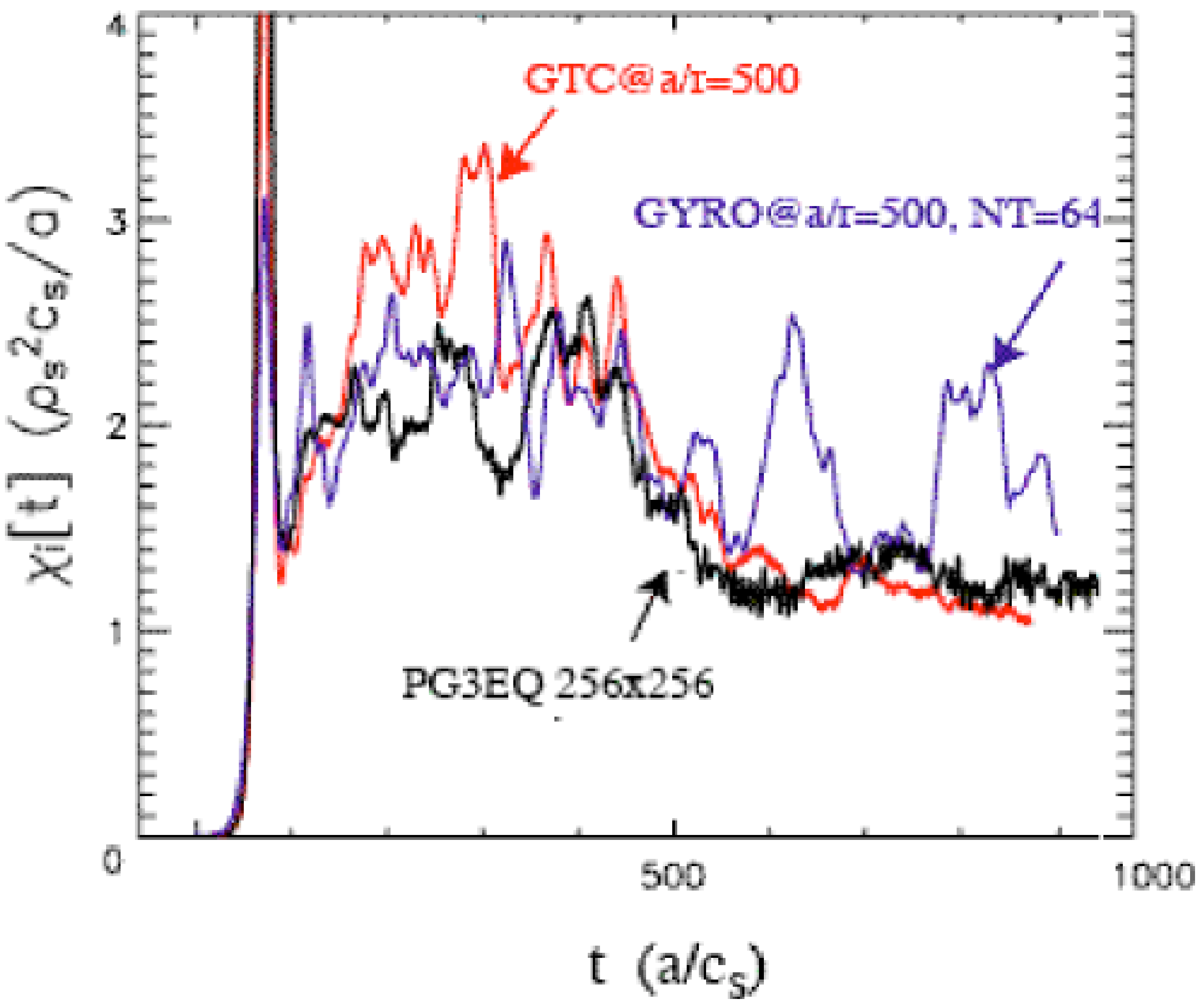


Y-axis: the number of particles (in milions) which move 1 step in 1 second

GTC size scaling studies (Lin et al. 2002 IAEA): 1 billion particles (8 particles/cell) for $a/\rho_s = 1000$ using 1024 processors on IBM-SP for 7000 time-steps took 72 wallclock hours to simulate 1 msec of discharge.

Recent PMP Code Comparisons and Controversies

(W. M. Nevins, 04)

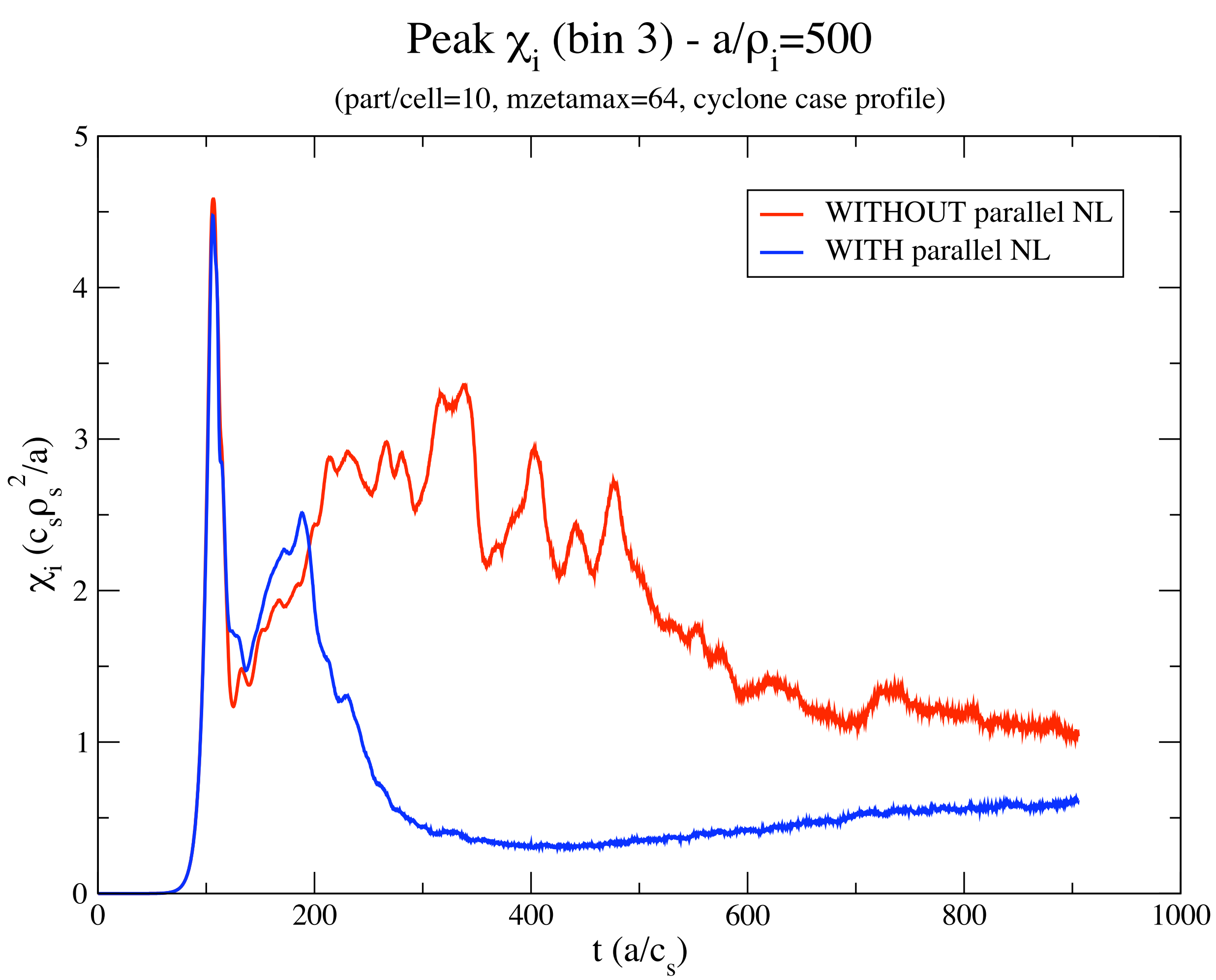


Code Comparisons:

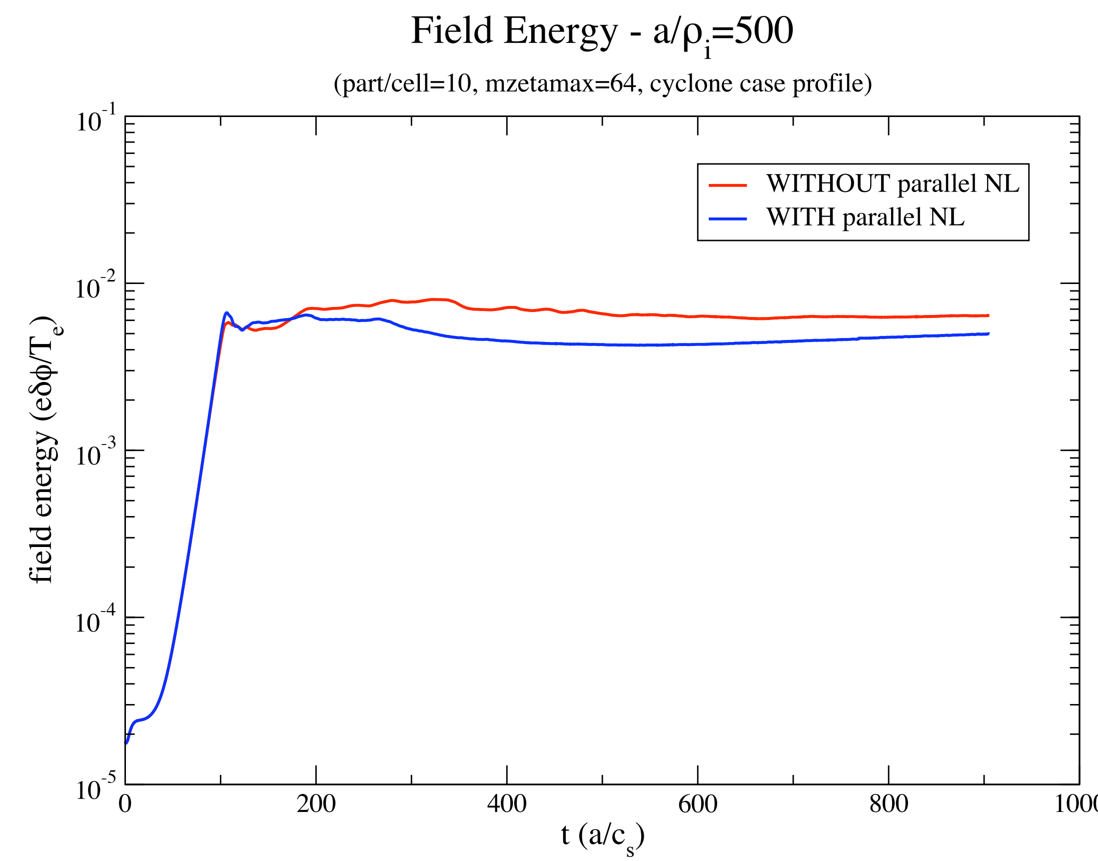
GTC - Particle Code

GYRO - Continuum Code

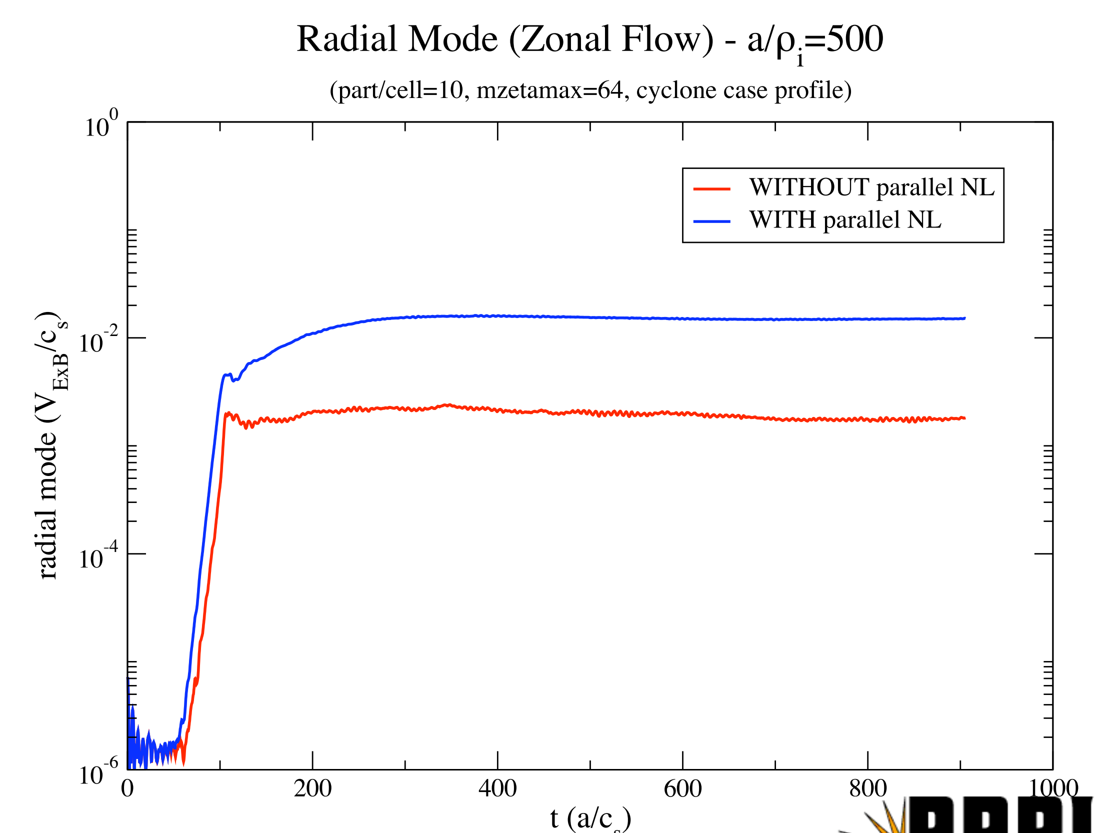
PG3EQ - Particle Code



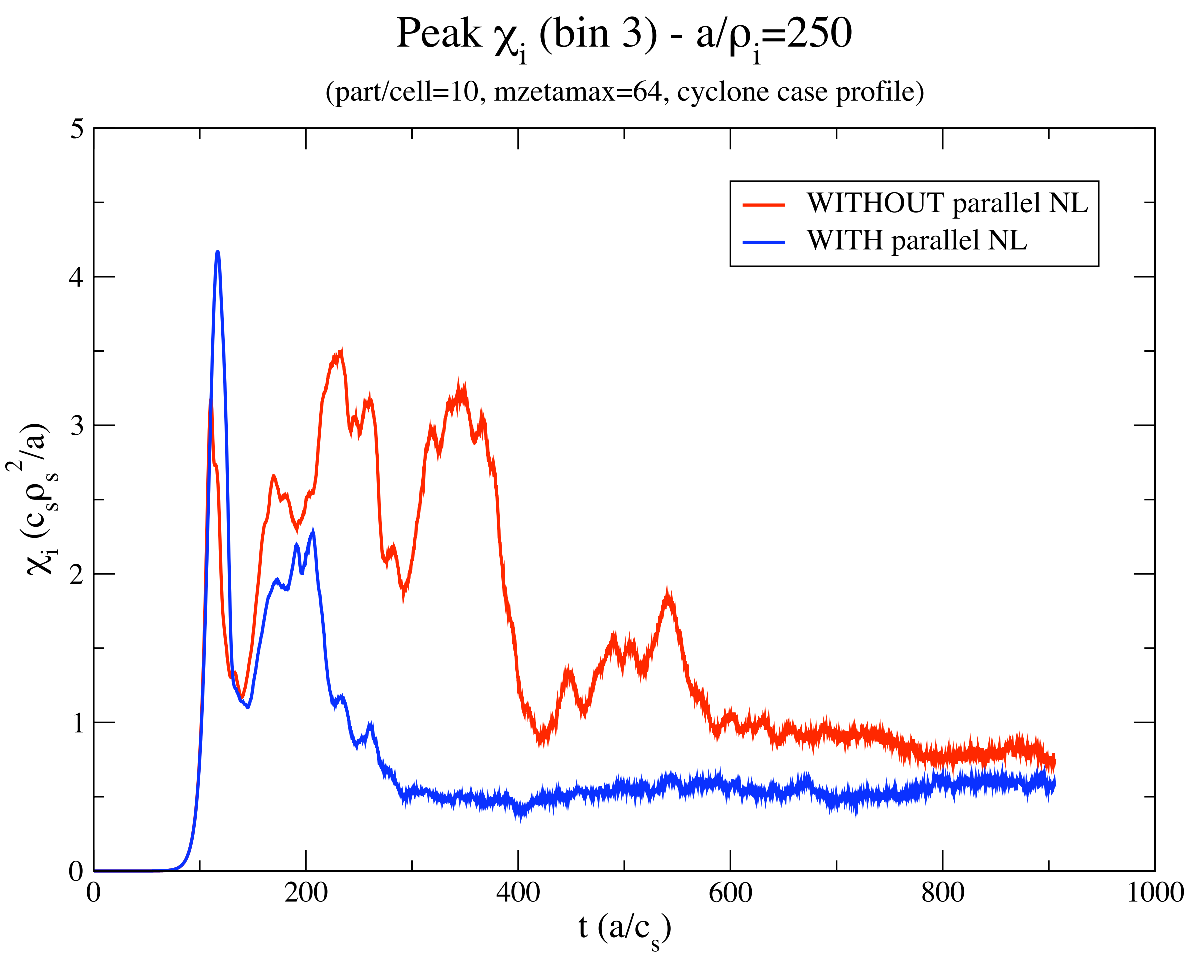
Peak χi (bin 3) - a/ρi=500
(part/cell=10, mzetamax=64, cyclone case profile)
WITHOUT parallel NL
WITH parallel NL
χi (csρs2/a)
t (a/cs)
0
1
2
3
4
5
0
200
400
600
800
1000



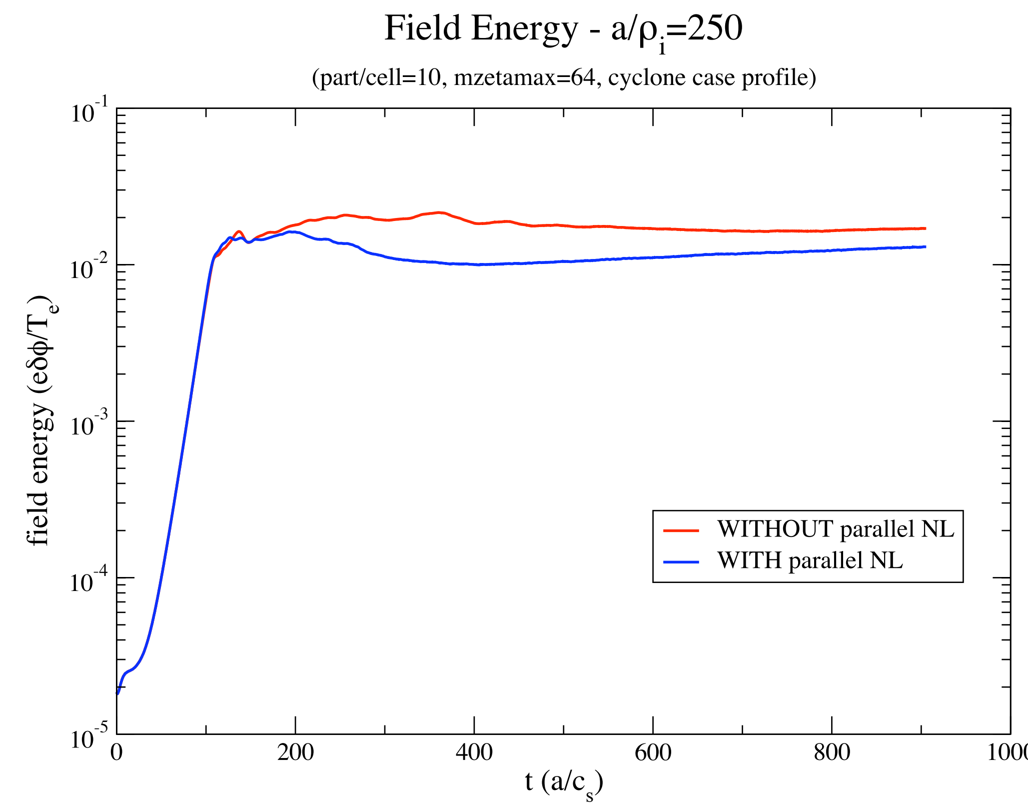
Field Energy - a/ρi=500
(part/cell=10, mzetamax=64, cyclone case profile)
WITHOUT parallel NL
WITH parallel NL
field energy (eδφ/Te)
t (a/cs)
10-1
10-2
10-3
10-4
10-5
0
200
400
600
800
1000

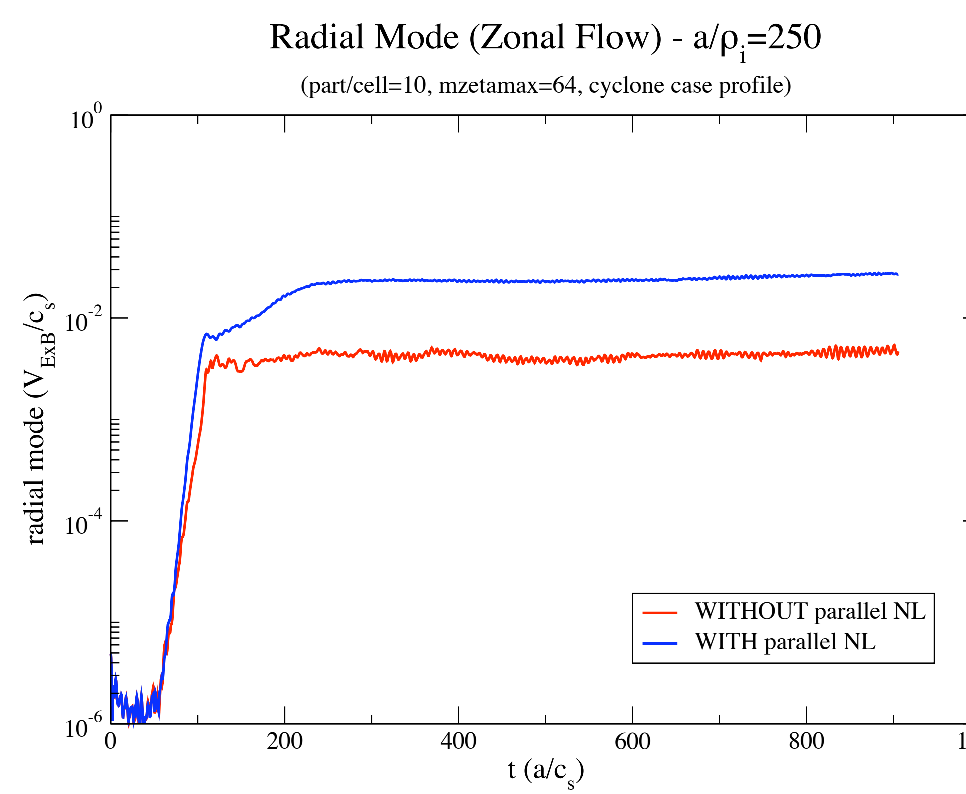


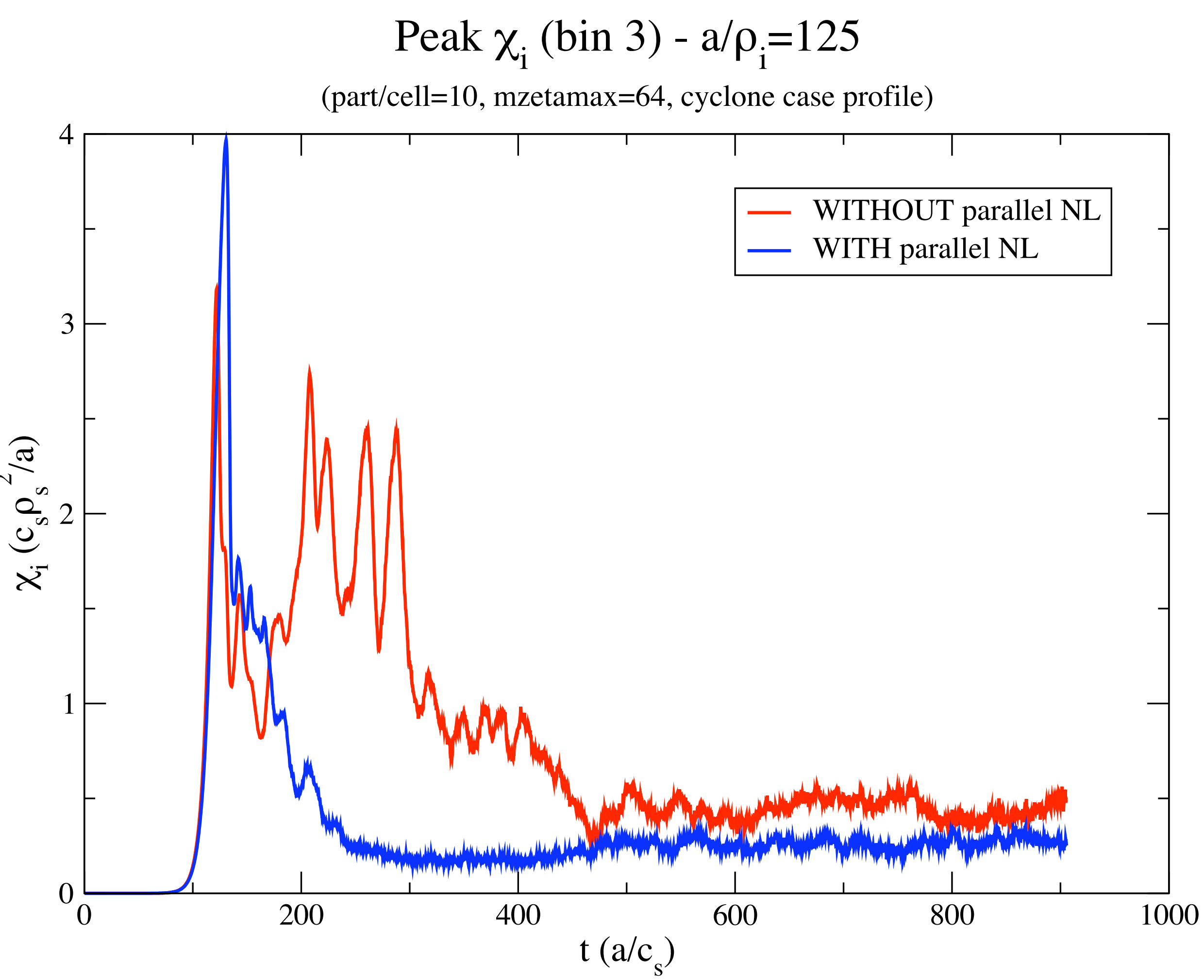
Radial Mode (Zonal Flow) - a/ρi=500
(part/cell=10, mzetamax=64, cyclone case profile)
WITHOUT parallel NL
WITH parallel NL
radial mode (VExB/cs)
t (a/cs)
100
10-2
10-4
10-6
0
200
400
600
800
1000

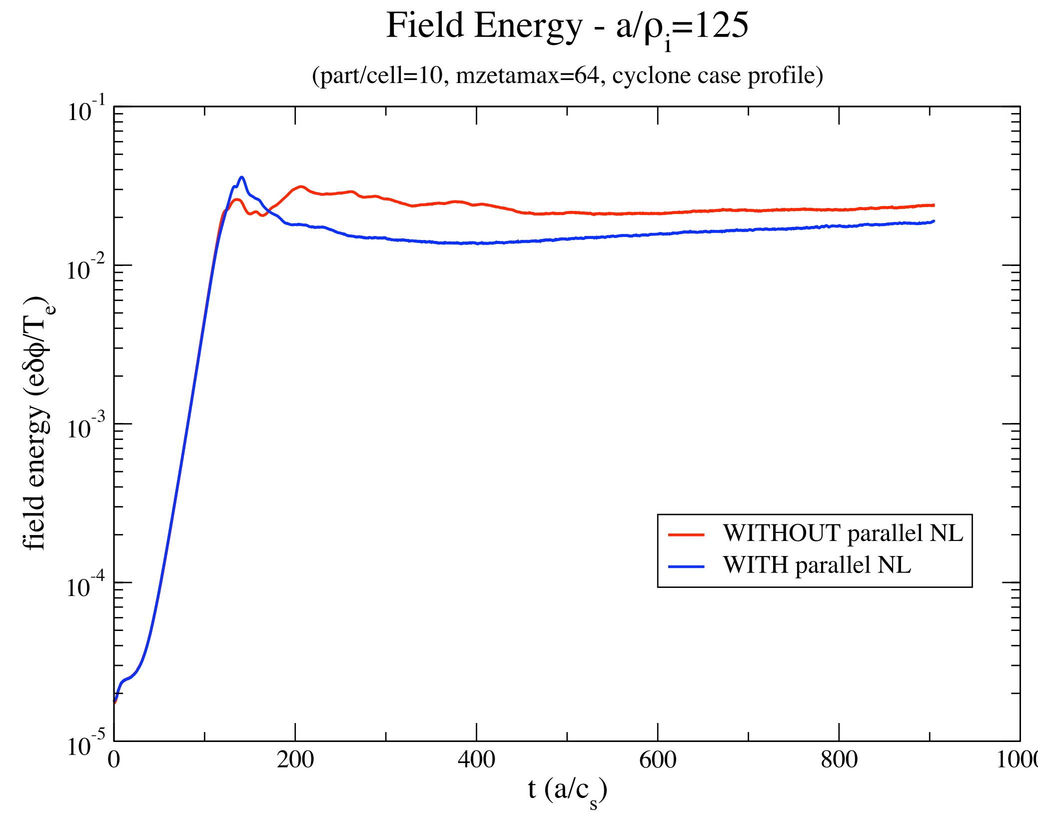


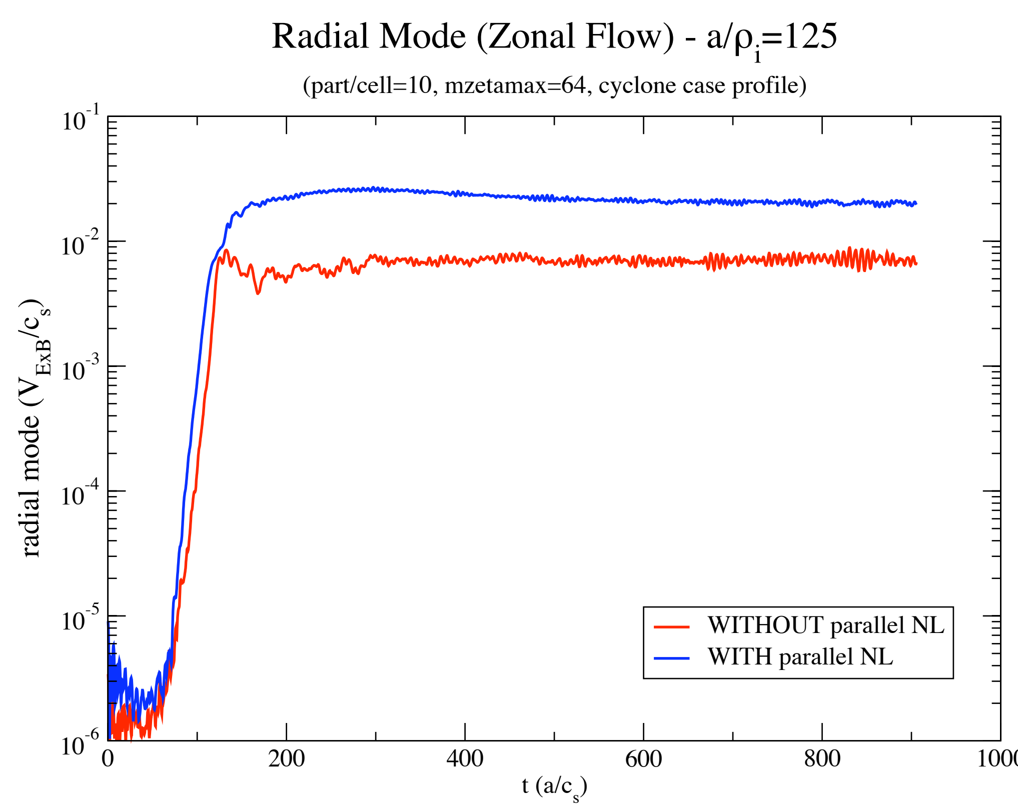
[Lee, Ethier et al., invited talk, APS/DPP2004]






Peak χi (bin 3) - a/ρi=125
(part/cell=10, mzetamax=64, cyclone case profile)
WITHOUT parallel NL
WITH parallel NL
χi (csρs2/a)
t (a/cs)
0
1
2
3
4
0
200
400
600
800
1000


Field Energy - a/ρi=125
(part/cell=10, mzetamax=64, cyclone case profile)
field energy (eδφ/Te)
t (a/cs)
WITHOUT parallel NL
WITH parallel NL
10-1
10-2
10-3
10-4
10-5
0
200
400
600
800
1000


Radial Mode (Zonal Flow) - a/ρi=125
(part/cell=10, mzetamax=64, cyclone case profile)
radial mode (VExB/cs)
t (a/cs)
WITHOUT parallel NL
WITH parallel NL
10-1
10-2
10-3
10-4
10-5
10-6
0
200
400
600
800
1000

Entropy Production - ITG modes

- δf-formulation: $F_i = F_{0i} + \delta f_i$, ν is the collison freqeuncy, and Q_{ix} is the radial ion enrgy flux

$$\frac{\partial}{\partial t}\langle \int \frac{\delta f_i^2}{F_{0i}} dv_\parallel + \tau\phi^2 + \tau|\nabla_\perp \phi|^2\rangle + \langle \tau \frac{\partial \phi}{\partial x_\parallel} \int v_\parallel \frac{\delta f_i^2}{F_{0i}} dv_\parallel + 2\tau\nu \int \frac{dv_\parallel}{F_{0i}} \left(\frac{\partial \delta f_i}{\partial(v_\parallel / v_{ti})} + \frac{v_\parallel}{v_{ti}} \delta f_i \right)^2 \rangle = \kappa_{Ti} \langle Q_{ix} \rangle$$

$$\tau \equiv T_e/T_i, \quad \kappa_{Ti} \equiv -d\ln T_{0i}/dx, \quad \langle \ldots \rangle \equiv \frac{1}{V}\int d\mathbf{x},$$

- Let $w \equiv \delta f_i / F_{0i}$, $E_\parallel \equiv -\partial\phi/\partial x_\parallel$, $\partial \delta f_i / \partial(v_\parallel / v_{ti}) \approx -\beta \delta f_i$, $\beta \ll 1$, N is the particle number,

$$\frac{\partial}{\partial t} \sum_{j=1}^{N} \frac{w_j^2}{1-w_j} + \tau \frac{\partial}{\partial t}\langle \phi^2 + |\nabla_\perp \phi|^2 \rangle + \sum_{j=1}^{N} \left[-\tau E_{\parallel j} v_{\parallel j} + 2\nu\tau(1-\beta)^2 (\frac{v_{\parallel j}}{v_{ti}})^2 \right] \frac{w_j^2}{1-w_j} = \kappa_{Ti}\langle Q_{ix} \rangle$$

- Energy balance:

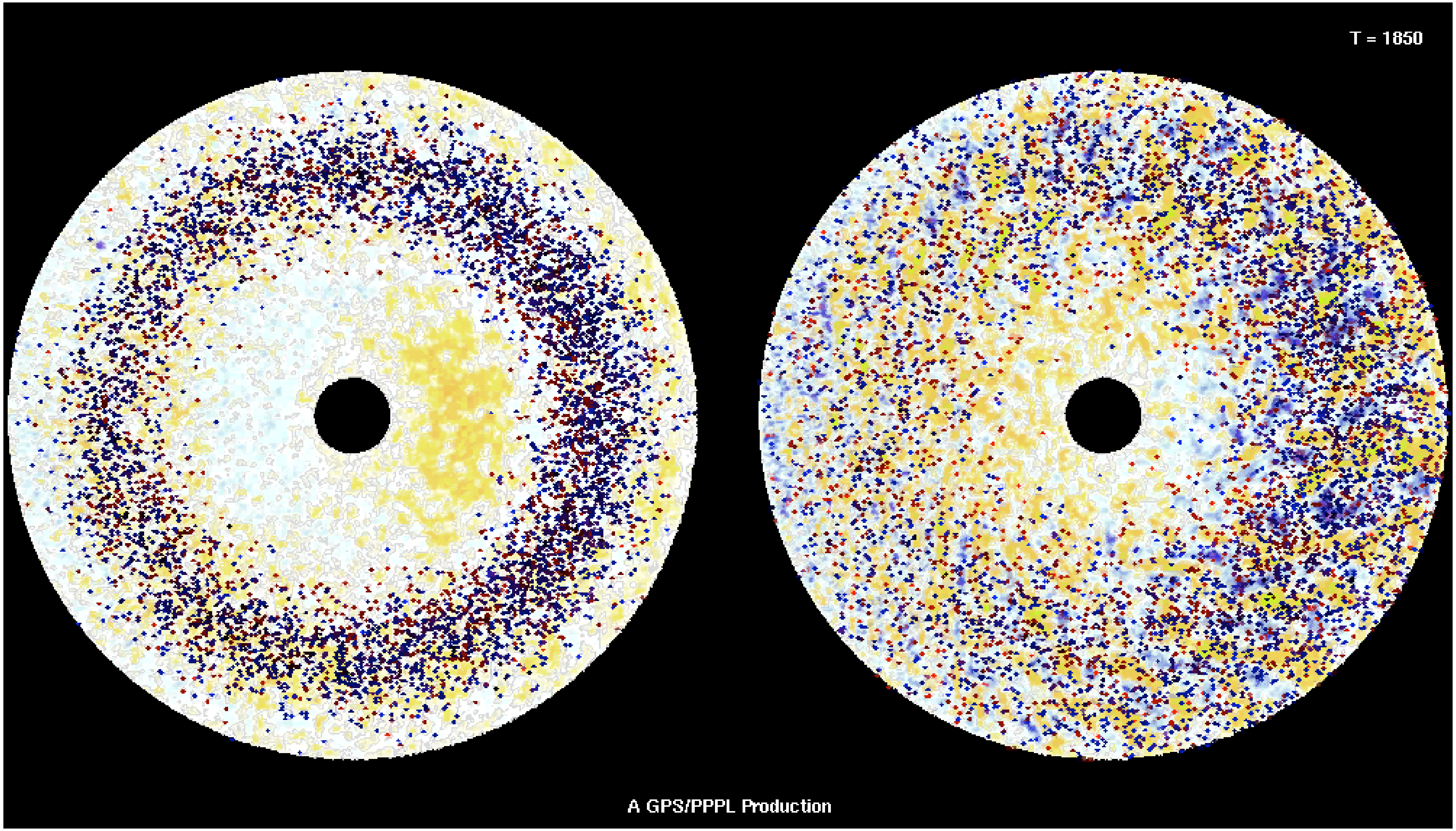
$$\sum_{j=1}^{N} E_{\parallel j} v_{\parallel j} w_j = \frac{1}{2}\frac{\partial}{\partial t} \sum_{j=1}^{N} v_{\parallel j}^2 w_j \approx \frac{1}{2}\frac{\partial}{\partial t} \sum_{j=1}^{N} \alpha v_{ti}^2 w_j, \quad \alpha \approx 1 \quad or \quad \alpha \ll 1$$

- In the steady state $(\partial/\partial t \langle \phi^2 + |\nabla\phi|^2 \rangle = 0)$, with $w \ll 1$:

$$\frac{\partial}{\partial t} \sum_{j=1}^{N} (1 - \frac{\alpha}{4}) w_j^2 + 2\nu\tau(1-\beta^2)\alpha \sum_{j=1}^{N} w_j^2 = \kappa_{Ti}\langle Q_{ix} \rangle$$

Velocity-Space nonlinearity reduces ion energy flux, but collisons enhance it.

Particle Diffusion due to Toroidal ITG Modes



With | Without

Parallel Velocity-Space Nonlinearity

GyroBohm? | Bohm?

Data Management and Visualization
[Klasky, Ethier in collaboration with Beck, Ma]

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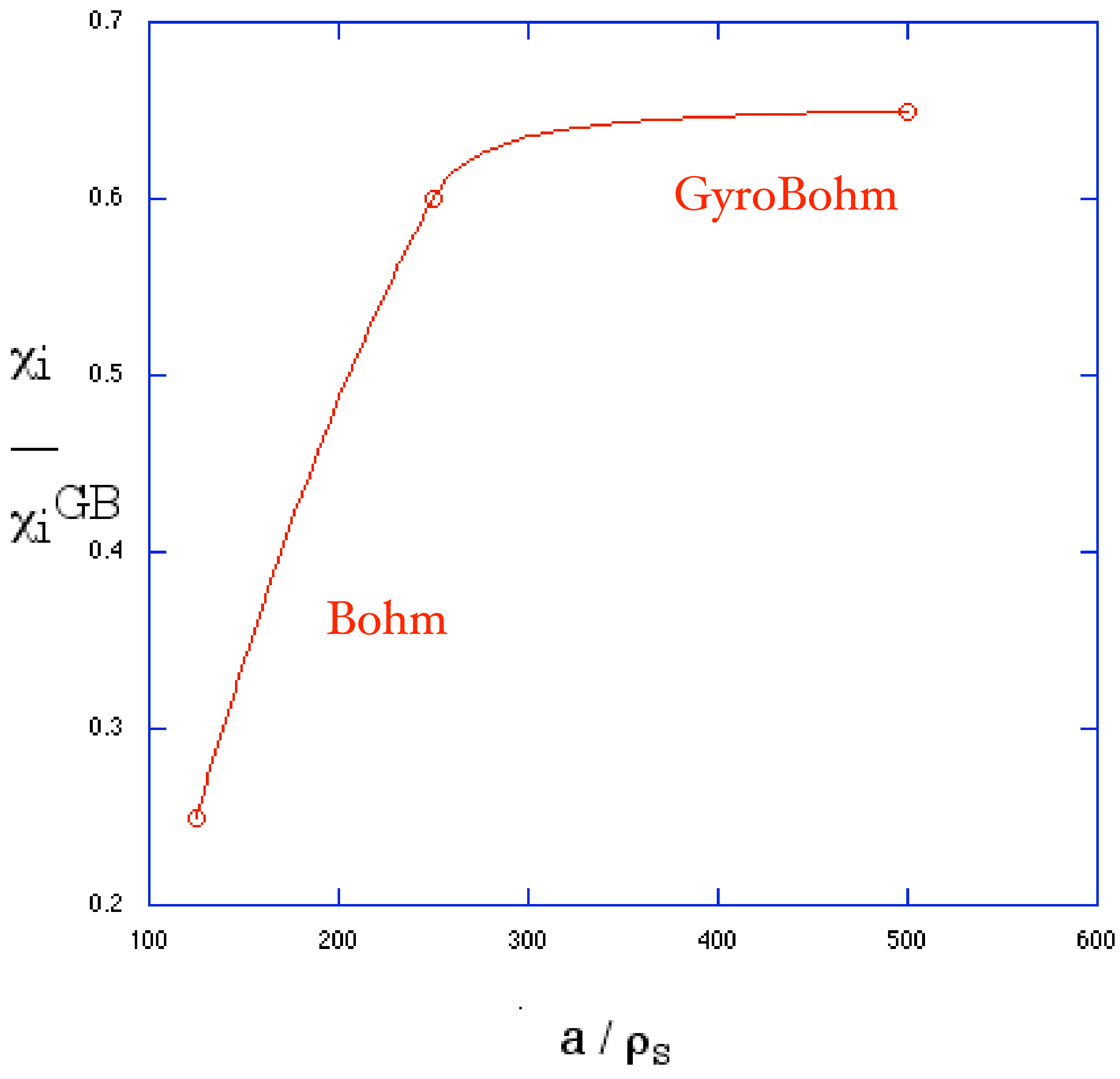
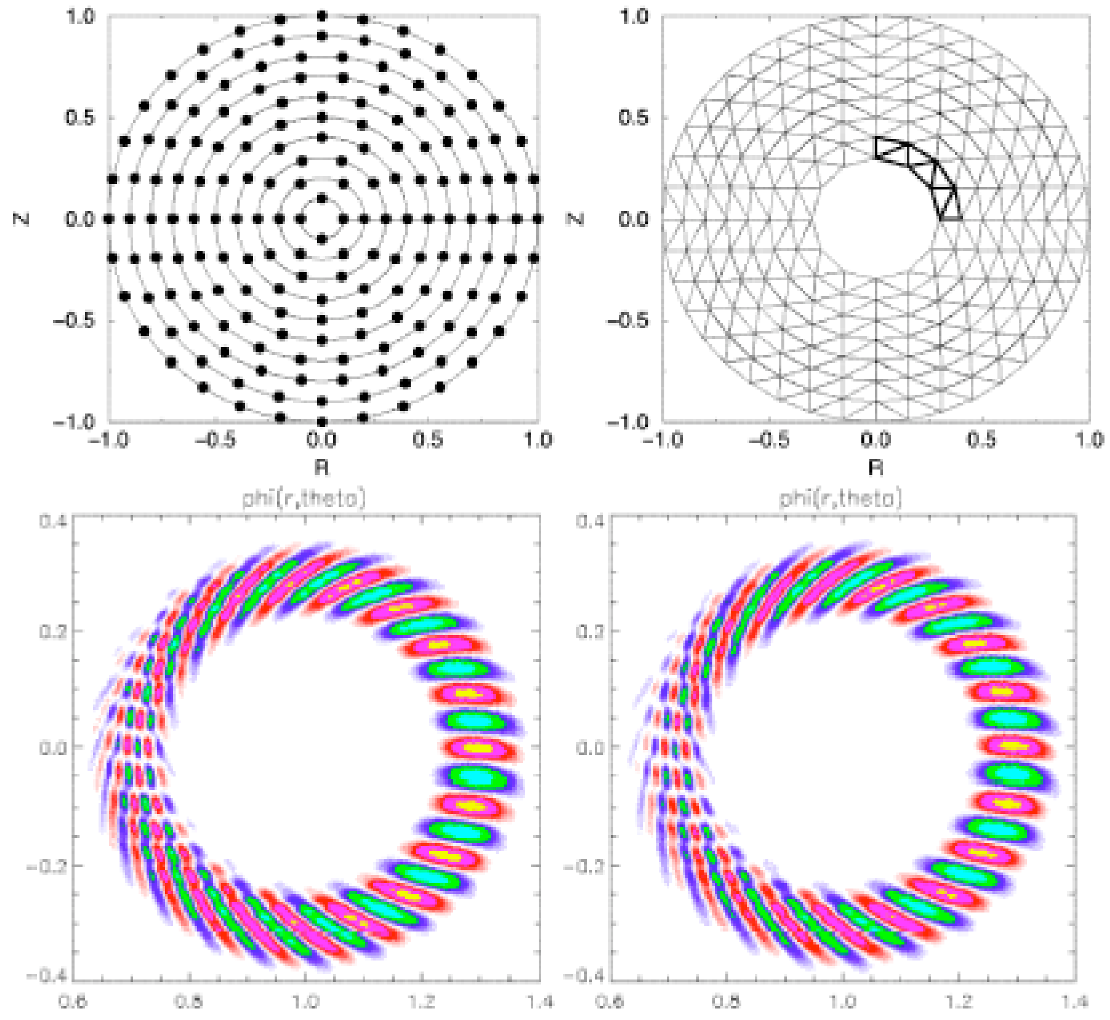
Transition from Bohm to GyroBohm similar to Lin, Ethier, Hahm and Tang, PRL '02?



Code Development - Finite Element Poisson Solver via PETSc

Old GTC solver vs. New GTC solver

[Nishimura et al., submitted to JCP]



Collaboration with SciDAC-TOPS: D. E. Keyes and M. Adams

Split-weight Scheme for Toroidal Plasmas

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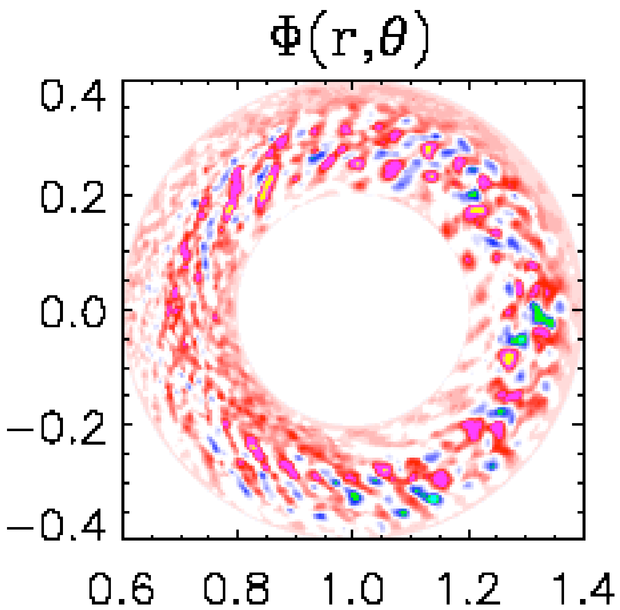
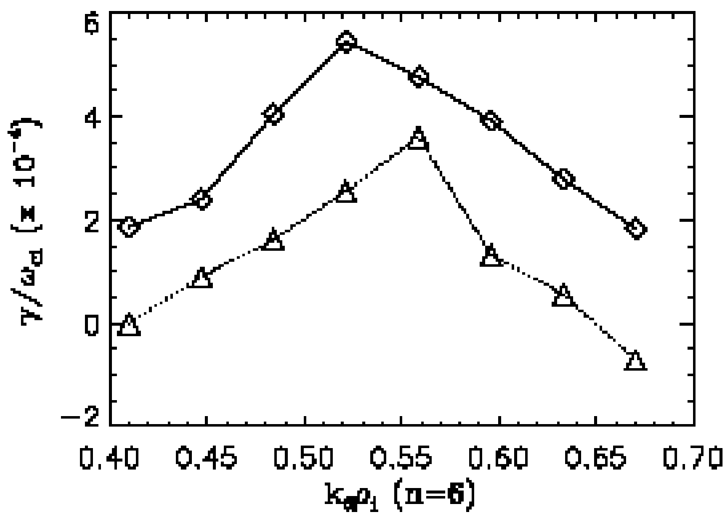
[J.L.V. Lewandowski, poster EP1.054]



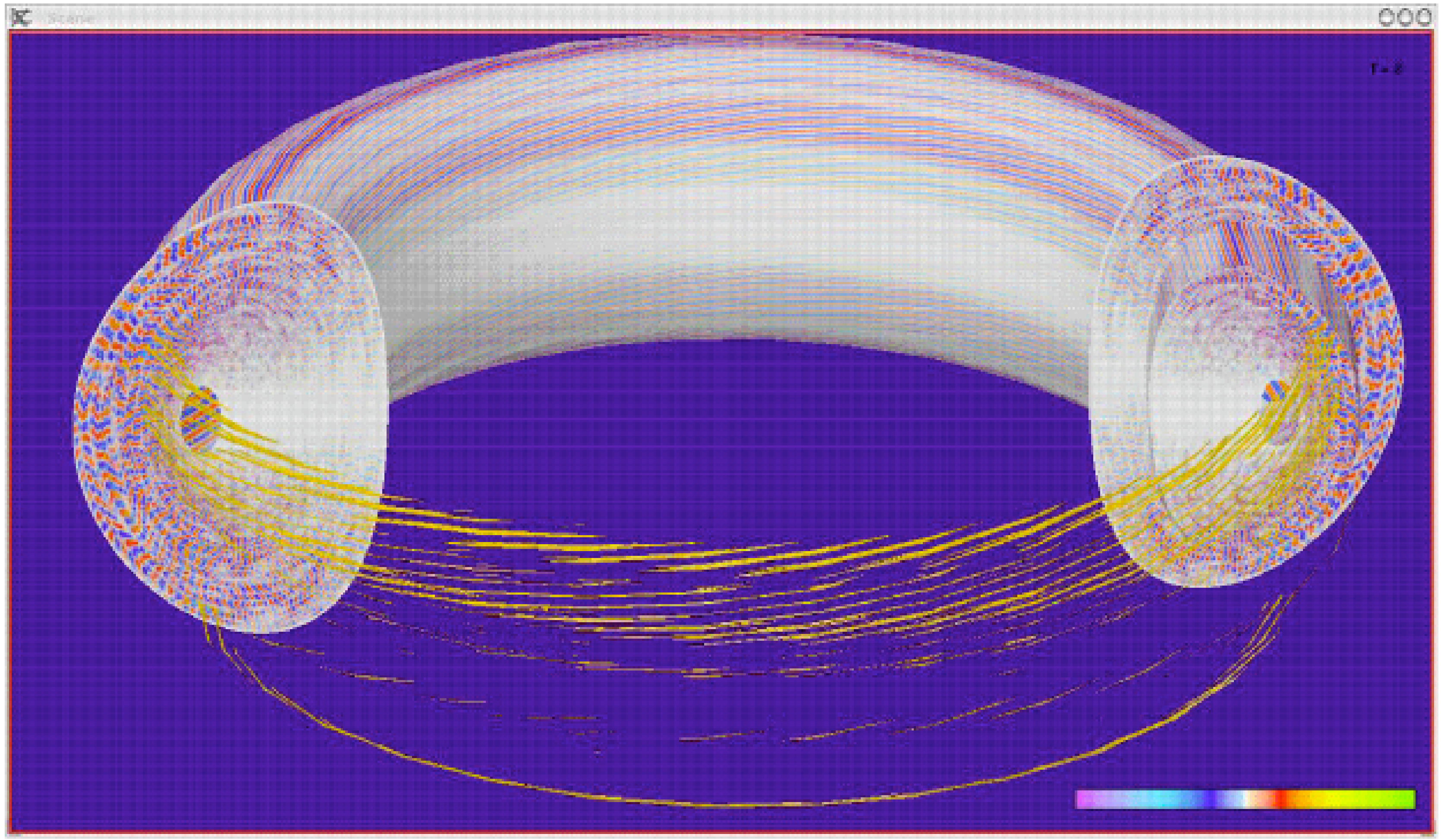


Parameters: $R_0/L_n = 2.22$, $R_0/L_{T_i} = R_0/L_{T_e} = 6.92$, $r/a = 0.5$.

- Split-weight scheme resolves non-adiabatic electron response only (allows for turbulent & collisional friction between trapped and untrapped electrons)
- Extension from sheared-slab 1D to toroidal geometry completed.
- Global finite element Poisson solver used to invert $\mathbf{L}\partial_t\Phi = S$ (32 to 64 different stiffness matrices $\mathbf{L}$)
- Numerical method is stable for large time step $\Delta t = 5 - 10\omega_{ci}^{-1}$

Code Development - Shaped Plasmas

[Wang, Klasky and Ethier]



Core-Edge Simulations via GTC

- Basic requirements for the validity of gyrokinetic Vlasov-Maxwell equations are:

$$\rho/L_B \sim o(\epsilon),$$

$$\partial F/\partial\phi = 0,$$

$$d\mu_B/dt = 0.$$

- GTC already has Lorentz collision operators for e-i, and momentum and energy conserving collision operators for like species.

- The core uses the δf scheme of

$$\frac{D\delta f}{DT} = -\frac{DF_0}{Dt}.$$

- The edge uses the δf scheme of

$$\delta f = F - F_0.$$

- Core-edge simulation inside the separatrix using GTC with electrons and multi-species ions is feasible.

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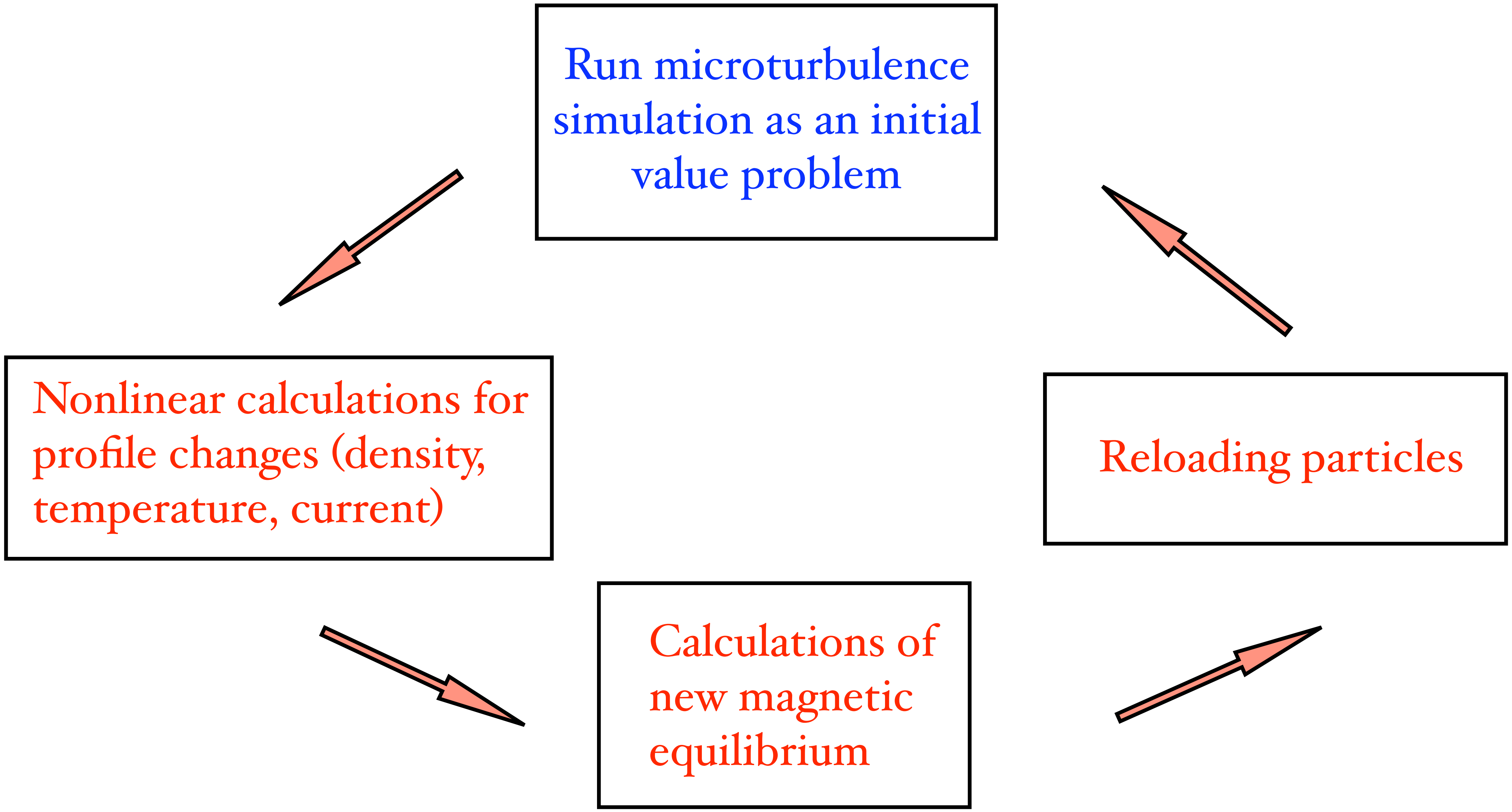
Turbulence Simulation in Transport Time Scale



Conclusions

- Gyrokinetic Particle Simulation is a vital tool for fusion research

- Gyrokinetic formalism is most suitable for tokamak and stellarator physics when FLR effects, inertial effects and linear and nonlinear wave-particle interactions are important

- Gyrokinetic PIC toroidal simulation is an international effort:
  GTC, GEM, PG3EQ, GT3D (JAERI), ORB5(CRPP)

- Team coding: version control, developer's manual, OO (with V. Decyk)

- Strong candidate for Integrated Fusion Simulation Project

Related GTC papers:
J. Lewandowski et al.-- Kinetic electrons using split-weight scheme [EP1.054]
Y. Nishimura et al. -- Alfven physics using hybrid scheme [CP1.048]
W. X. Wang et al. -- Global simulation of shaped plasmas [CP1.047]
Z. Lin et al., -- Global ETG modes [NI1.003]
S. Ethier et al.-- GTC performance on MPP platforms [HP1.014]
T. S. Hahm et al., -- Turbulence Spreading [EP1.063]
T. G. Jenkins et al. -- Parallel velocity space nonlinearity in in slab [CP1.053]

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