Collisional Electrostatic and Collisionless Electromagnetic Simulations with the Global Gyrokinetic δf Particle-in-Cell Code ORB5

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1. Introduction

The global PIC gyrokinetic code ORB5 [1], based on δf-method, is upgraded with:

- Linearized intra- and inter-species Landau collision operators for ions and electrons [2]
- A novel background switching scheme in the frame of the δf PIC approach [2]
- A coarse graining procedure for avoiding the weight spreading [3]
- An electromagnetic solver [4]

Numerical results:

- Global neoclassical equilibria with self-consistent electric fields [2], [5] are obtained and used as starting point for carrying out simulations of electrostatic ITG microturbulence with collisional effects
- The crucial issue of numerical noise is addressed by showing that the coarse graining procedure makes it possible to run relevant collisional turbulent simulations
- Global collisionless electromagnetic simulations show the influence of β on heat transport

2. Two-Weight Scheme

- The gyro-averaged particle distribution function is split into a Maxwellian background f_0 and a perturbed part δf: $f = f_0 + \delta f$
- Marker distribution in gyrocenter phase space: $g(\vec{R}, v_\parallel, \mu, t)$
- In a collisional system, g is not constant along trajectories

$\Longrightarrow$ two marker weights required [6]:

$$w_r(t) = \frac{\delta f}{g}\bigg|_{\vec{R}_r(t), v_{\parallel,r}(t), \mu_r(t), t} \qquad p_r(t) = \frac{f_0}{g}\bigg|_{\vec{R}_r(t), v_{\parallel,r}(t), \mu_r(t), t}$$

3. PIC δf Collisional Model

- The collisionless marker motion in phase space is given by Hahm's gyrokinetic equations [7]
- Local Maxwellian (LM): $f_{LM} = \frac{n_0(\Psi)}{(2\pi T_0(\Psi)/m)^{3/2}} \exp\left[-\frac{mv_\parallel^2}{2T_0(\Psi)} - \frac{B\mu}{T_0(\Psi)}\right]$
- Canonical Maxwellian (CM): $f_{CM} = \frac{\mathcal{N}(\Psi_0)}{(2\pi\mathcal{T}(\Psi_0)/m)^{3/2}} \exp\left[-\frac{mv_\parallel^2}{2\mathcal{T}(\Psi_0)} - \frac{B\mu}{\mathcal{T}(\Psi_0)}\right]$
- Linearization of the e-e & i-i self-collision operators: $C[f, f] \approx C[\delta f_{LM}, f_{LM}] + C[f_{LM}, \delta f_{LM}]$
- Lorentz operator (pitch-angle scattering) for e-i collisions: $C_{ei}[\delta f_{LM,e}] \approx \nu_{ei}(v)\hat{L}^2 \delta f_{LM,e}$
- Gyrokinetic Fokker-Planck equation, δf model:

$$\frac{D\delta f_{CM}}{Dt} + C[f_{LM}, \delta f_{LM}] = -\frac{Df_{CM}}{Dt} - C[\delta f_{LM}, f_{LM}]$$
$$= -f_{CM}\left[\frac{d\ln\mathcal{N}}{d\Psi_0} + \frac{d\ln\mathcal{T}}{d\Psi_0}\left(\frac{v^2}{2v_{th}^2} - \frac{3}{2}\right)\right]\frac{d\Psi_0}{dt} + \frac{q\, f_{CM}}{\mathcal{T}(\Psi_0)}\langle\vec{E}\rangle \cdot \frac{d\vec{R}}{dt} - C[\delta f_{LM}, f_{LM}]$$

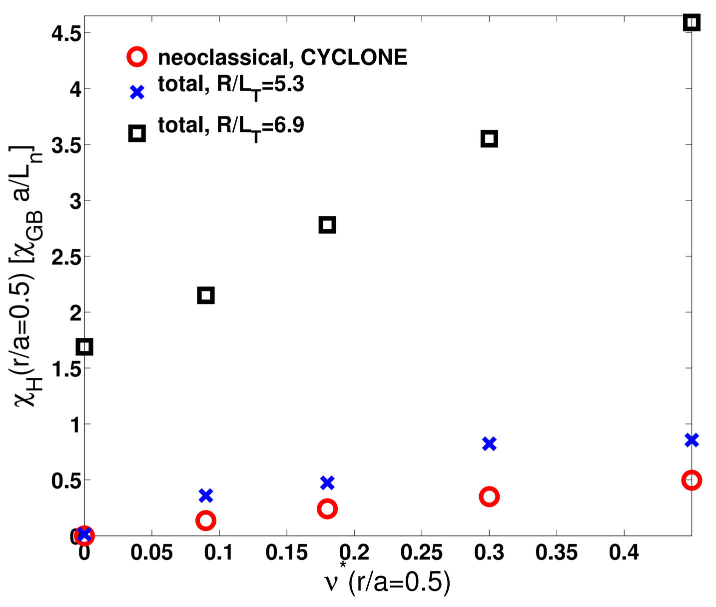
- Advection operator along collisionless guiding center trajectories:

$$\frac{D}{Dt} := \frac{\partial}{\partial t} + \frac{d\vec{R}}{dt}\cdot\frac{\partial}{\partial\vec{R}} + \frac{dv_\parallel}{dt}\cdot\frac{\partial}{\partial v_\parallel} = \frac{\partial}{\partial t} + \left(\vec{v}_\parallel + \vec{v}_{\nabla B} + \vec{v}_C + \frac{\langle\vec{E}\rangle \times \vec{B}}{B^2}\right)\cdot\frac{\partial}{\partial\vec{R}} + \frac{dv_\parallel}{dt}\cdot\frac{\partial}{\partial v_\parallel}$$

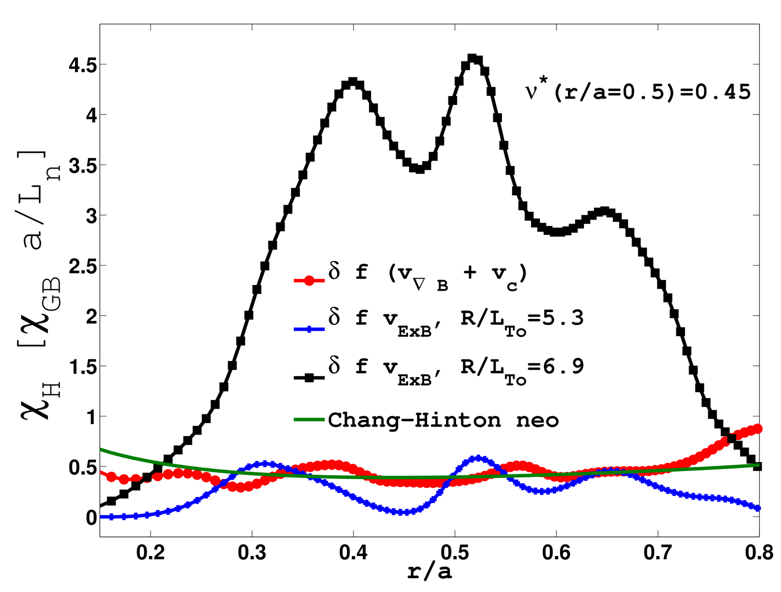
- Time splitting scheme: collisionless dynamics $\leftrightarrow$ collisional dynamics
- CM background for carrying out the collisionless dynamics: $f_0 = f_{CM}$
- LM background for carrying out the collisional dynamics: $f_0 = f_{LM}$
- Transformation between both representations CM and LM relying on the conservation of the total distribution: $f = f_{LM} + \delta f_{LM} = f_{CM} + \delta f_{CM} \Longrightarrow p_{LM} + w_{LM} = p_{CM} + w_{CM}$

4. Electrostatic Collisional Simulations [8]

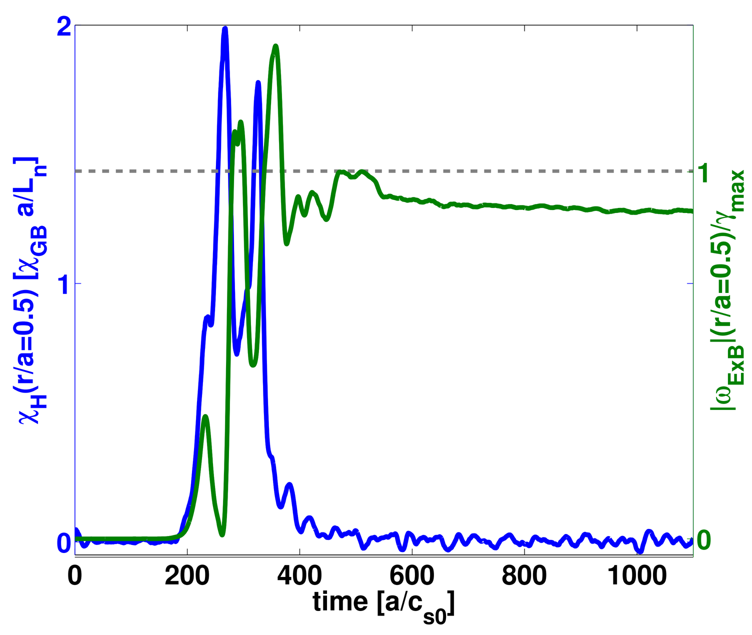
- Gradient-driven simulations, CYCLONE base case, adiabatic electrons. Two temperature gradients considered: $R_0/L_{T_0} = 5.3$ and $R_0/L_{T_0} = 6.9$. Total ion heat diffusivity in general increased by collisions
- Temperature profiles with wide gradients are used ($\Delta_T \sim 0.6a$), except for figures showing the time traces of the shearing rate (bursts more visible in a more local configuration, $\Delta_T \sim 0.3a$)



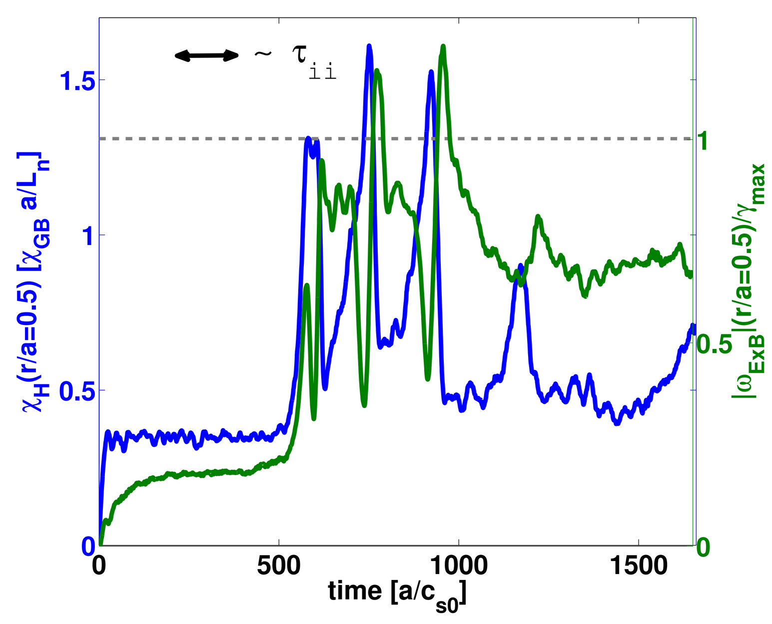
averaged diffusivity at $r = 0.5a$
$\chi_H(\nu^* \neq 0) \neq \chi_H(\nu^* = 0) + \chi_{H,\text{neo}}$



$R_0/L_{T_0} = 6.9$: $\chi_{H,\text{turb}} \gg \chi_{H,\text{neo}}$
$R_0/L_{T_0} = 5.3$: $\chi_{H,\text{turb}} \sim \chi_{H,\text{neo}}$



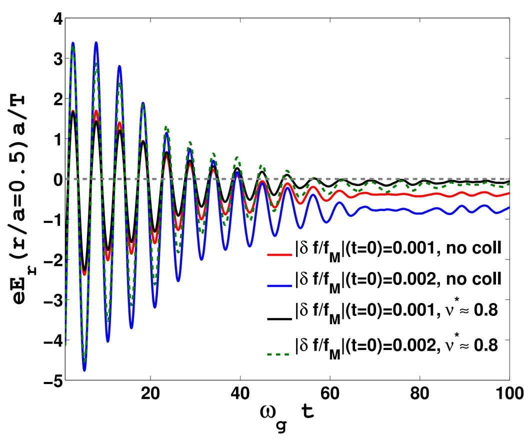
$\nu^*(r/a = 0.5) = 0$, $R_0/L_{T_0} = 5.3$
Dimits shift region, no transport



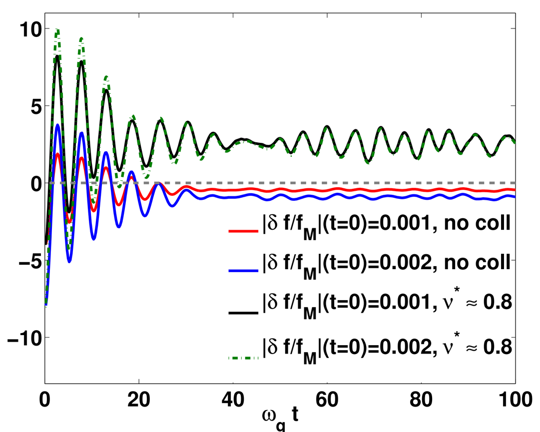
$\nu^*(r/a = 0.5) = 0.3$, $R_0/L_{T_0} = 5.3$
Collisional bursts of heat transport

5. RH test, effects of gradients

- Collisionless simulations: the residual value of the zonal flow is proportional to the initial amplitude of the perturbation
- Collisional simulations: the zonal flow converges towards the neoclassical equilibrium, regardless of the initial electric field amplitude



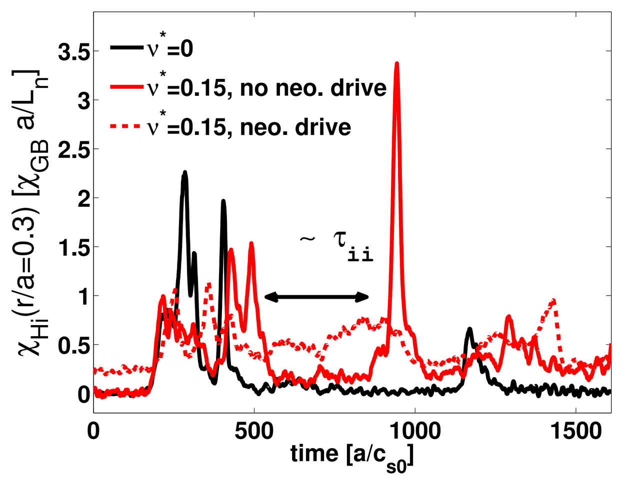
no gradients

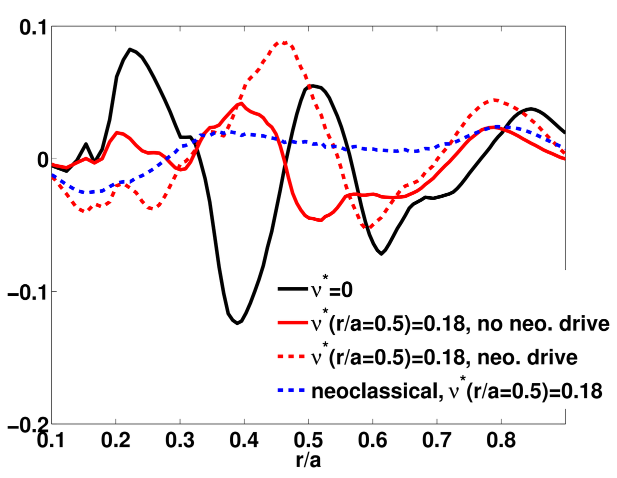


CYCLONE gradients

6. Suppressing the Neoclassical Electric Field

- Simulations where the neoclassical drive dynamics $(\vec{v}_{\nabla B} + \vec{v}_C) \cdot \partial f_{LM}/\partial\vec{R}$ is removed are compared to turbulent simulations started from a neoclassical equilibrium. $R_0/L_{T_0} = 5.3$

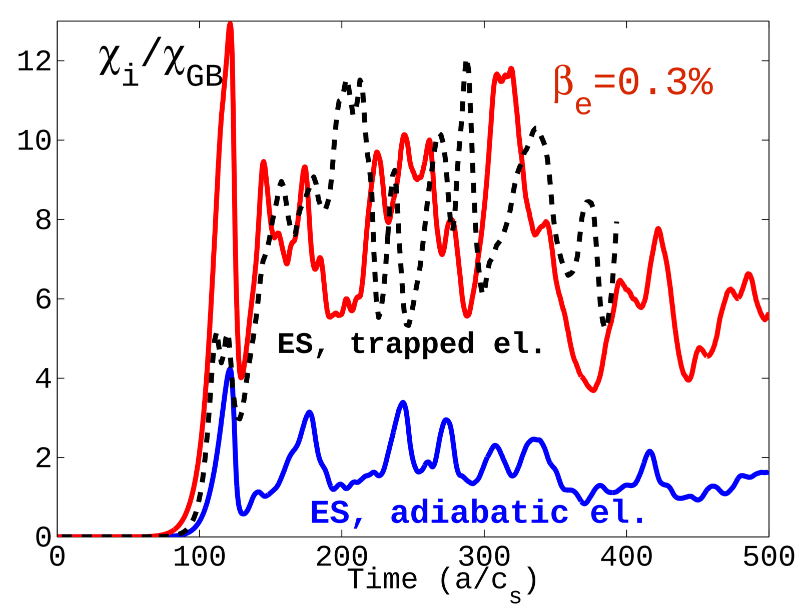


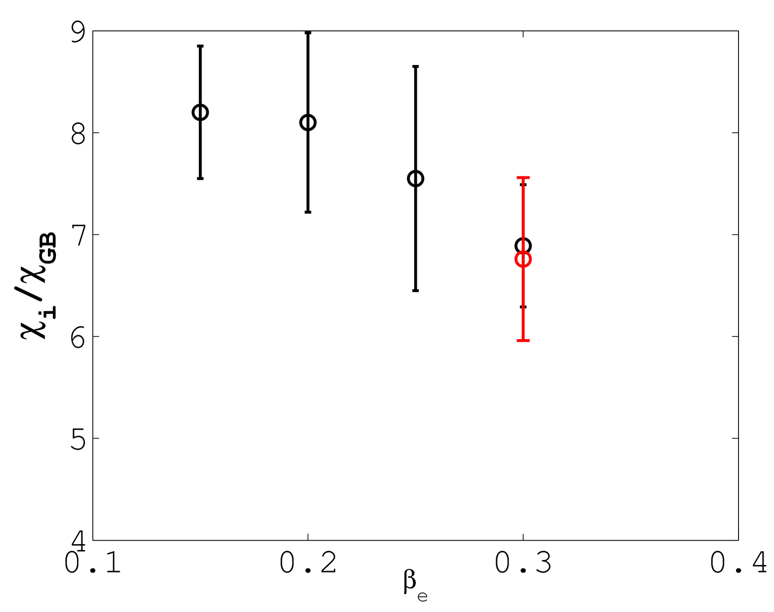


- Suppressing the neoclassical drive and the related shearing rate could increase the transport

7. Electromagnetic Collisionless Simulations [9]

- CYCLONE base case, $\rho^* = 1/184$, $m_i/m_e = 1000$
- Left: Time evolution of the ion thermal diffusivity for an electromagnetic $\beta_e = 0.3\%$ simulation (red), and electrostatic simulation with kinetic trapped and adiabatic passing electrons (black, dashed) and with all electrons adiabatic (blue)
- Right: ion thermal diffusivity as a function of β_e, sources applied. The red point: different initial conditions (white noise). χ_i averaged over radius and time (moving average)





- $A_\parallel^2$ and ϕ^2 spectra reach a maximum for the same value of toroidal mode number and show an identical power-law decay behavior for high n. The same result is present in gyrofluid simulations. At low n, gyrofluid spectrum values are significantly higher than the global gyrokinetic ones
- The code ORB5 has been proved to scale up to 32k cores on a BlueGene/P architecture for CYCLONE
- Linear benchmarks have been performed with the GYGLES code

8. Conclusions

- Non-negligible collisional effects on turbulence
- Kinetic electrons increase ITG heat diffusivity
- Future work: Collisional TEM simulations

References :

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