GryfX: A GPU Gyrofluid Turbulence Code with Kinetic Zonal Flows and Advanced Nonlinear Closures

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Introduction to Gyrofluid (GF) Model

- Tokamak turbulence can be described by the gyrokinetic approximation:

$$\frac{\omega}{\Omega} \sim \frac{\rho_i}{L_{eq}} \sim k_\parallel \rho_i \sim \frac{e\Phi}{T_e} \sim \frac{\delta B}{B_0} \sim O(\epsilon); \quad k_\perp \rho_i \sim O(1)$$

- Gyrofluid model derived by taking moments of toroidal gyrokinetic equation (Beer and Hammett, 1996)

$$\frac{\partial}{\partial t} F + \nabla \cdot \left[F \left(v_\parallel \hat{\mathbf{b}} + \mathbf{v}_E + \mathbf{v}_d \right) \right] + \frac{\partial}{\partial v_\parallel} \left[F \left(-\frac{e}{m} \hat{\mathbf{b}} \cdot \nabla J_0 \Phi - \mu \hat{\mathbf{b}} \cdot \nabla B \; + \; v_\parallel (\hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}}) \cdot \mathbf{v}_E \right) \right] = C(F)$$

- Closures chosen to capture important kinetic effects, most notably Landau damping, toroidal ∇B and curvature drifts and associated phase mixing, and toroidal finite Larmor radius (FLR) effects

Moment definitions and normalizations

$$\delta n = \int \delta f \; d^3 v \qquad n_0 \delta u_\parallel = \int \delta f \; v_\parallel \; d^3 v$$

$$\delta p_\parallel = m \int \delta f \; v_\parallel^2 \; d^3 v \qquad \delta p_\perp = (m/2) \int \delta f \; v_\perp^2 \; d^3 v$$

$$\delta q_\parallel = -3 m v_t^2 n_0 \delta u_\parallel + m \int \delta f \; v_\parallel^3 \; d^3 v \qquad \delta q_\perp = -m v_t^2 n_0 \delta u_\parallel + (m/2) \int \delta f \; v_\parallel v_\perp^2 \; d^3 v$$

$$\delta r_{\parallel,\parallel} = m \int \delta f \; v_\parallel^4 \; d^3 v \qquad \delta r_{\parallel,\perp} = (m/2) \int \delta f \; v_\parallel^2 v_\perp^2 \; d^3 v$$

$$\delta r_{\perp,\perp} = (m/4) \int \delta f \; v_\perp^4 \; d^3 v \qquad \delta s_{\perp,\perp} = -2 m v_t^2 n_0 \delta u_\parallel + (m/4) \int \delta f \; v_\parallel v_\perp^4 \; d^3 v$$

$$\delta s_{\parallel,\parallel} = -15 m v_t^4 n_0 \delta u_\parallel + m \int \delta f \; v_\parallel^5 \; d^3 v \qquad \delta s_{\parallel,\perp} = -3 m v_t^2 n_0 \delta u_\parallel + (m/2) \int \delta f \; v_\parallel^3 v_\perp^2 \; d^3 v$$

$$\left(\frac{\delta n}{n_0}, \; \frac{\delta u_\parallel}{v_t}, \; \frac{\delta T_\parallel}{T_0}, \; \frac{\delta T_\perp}{T_0}, \; \frac{\delta q_\parallel}{n_0 T_0 v_t}, \; \frac{\delta q_\perp}{n_0 T_0 v_t}, \; \frac{e \delta \Phi}{T_0} \right) = \frac{\rho_i}{a} \left(\tilde{n}, \; \tilde{u}_\parallel, \; \tilde{T}_\parallel, \; \tilde{T}_\perp, \; \tilde{q}_\parallel, \; \tilde{q}_\perp, \; \tilde{\Phi} \right)$$

where $v_t = \sqrt{T_0/m}$

Equations: 6 moment Gyrofluid Model

$$\frac{\partial n}{\partial t} + \mathbf{v}_\Psi \cdot \nabla n + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla T_\perp + B\nabla_\parallel \frac{u_\parallel}{B} - \left(f' + \frac{t'}{2}\hat{\nabla}_\perp^2\right) i\omega_\star \Psi$$
$$+ \left(2 + \frac{1}{2}\hat{\nabla}_\perp^2\right) i\omega_d \Psi + i\omega_d \left(T_\parallel + T_\perp + 2n\right) = 0$$
$$\frac{\partial u_\parallel}{\partial t} + \mathbf{v}_\Psi \cdot \nabla u_\parallel + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla q_\perp + B\nabla_\parallel \frac{T_\parallel}{B} + B\nabla_\parallel \frac{n}{B} + \nabla_\parallel \Psi$$
$$+ \left(T_\perp + n + \frac{1}{2}\hat{\nabla}_\perp^2 \Psi\right) \nabla_\parallel \ln B + i\omega_d \left(q_\parallel + q_\perp + 4u_\parallel\right) = 0$$
$$\frac{\partial T_\parallel}{\partial t} + \mathbf{v}_\Psi \cdot \nabla T_\parallel + B\nabla_\parallel \frac{q_\parallel + 2u_\parallel}{B} + 2\left(q_\perp + u_\parallel\right) \nabla_\parallel \ln B - t' i\omega_\star \Psi + 2i\omega_d \Psi$$
$$+ i\omega_d \left(6T_\parallel + 2n\right) + 2\left|\omega_d\right| \left(\nu_1 T_\parallel + \nu_2 T_\perp\right) = -\frac{2}{3}\nu_{ii} \left(T_\parallel - T_\perp\right)$$

Equations: 6 moment Gyrofluid model (continued)

$$\frac{\partial T_\perp}{\partial t} + \mathbf{v}_\Psi \cdot \nabla T_\perp + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla n + \left[\hat{\hat{\nabla}}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla T_\perp - B\nabla_\parallel \frac{u_\parallel}{B}$$

$$+ B^2 \nabla_\parallel \frac{q_\perp + u_\parallel}{B^2} - \left[\frac{f'}{2}\hat{\nabla}_\perp^2 + t'\left(1 + \hat{\hat{\nabla}}_\perp^2\right)\right] i\omega_\star \Psi + \left(1 + \frac{1}{2}\hat{\nabla}_\perp^2 + \hat{\hat{\nabla}}_\perp^2\right) i\omega_d \Psi$$

$$+ i\omega_d \left(4T_\perp + n\right) + 2\left|\omega_d\right| \left(\nu_3 T_\parallel + \nu_4 T_\perp\right) = \frac{1}{3}\nu_{ii}\left(T_\parallel - T_\perp\right)$$

$$\frac{\partial q_\parallel}{\partial t} + \mathbf{v}_\Psi \cdot \nabla q_\parallel + \left(3 + \beta_\parallel\right) \nabla_\parallel T_\parallel + \sqrt{2} D_\parallel \left|k_\parallel\right| q_\parallel + i\omega_d \left(-3q_\parallel - 3q_\perp + 6u_\parallel\right)$$

$$+ \left|\omega_d\right| \left(\nu_5 u_\parallel + \nu_6 q_\parallel + \nu_7 q_\perp\right) = -\nu_{ii} q_\parallel$$

$$\frac{\partial q_\perp}{\partial t} + \mathbf{v}_\Psi \cdot \nabla q_\perp + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla u_\parallel + \left[\hat{\hat{\nabla}}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla q_\perp + \nabla_\parallel \left(T_\perp + \frac{1}{2}\hat{\nabla}_\perp^2 \Psi\right)$$

$$+ \sqrt{2} D_\perp \left|k_\parallel\right| q_\perp + \left(T_\perp - T_\parallel + \hat{\hat{\nabla}}_\perp^2 \Psi - \frac{1}{2}\hat{\nabla}_\perp^2 \Psi\right) \nabla_\parallel \ln B$$

$$+ i\omega_d \left(-q_\parallel - q_\perp + u_\parallel\right) + \left|\omega_d\right| \left(\nu_8 u_\parallel + \nu_9 q_\parallel + \nu_{10} q_\perp\right) = -\nu_{ii} q_\perp$$

Quasineutrality and definitions

$$n_e = \frac{n}{1 + b/2} - \frac{bT_\perp}{2(1 + b/2)^2} + (\Gamma_0 - 1)\Phi$$

When electrons are assumed to adiabatic, which is the case for all results presented here, we have

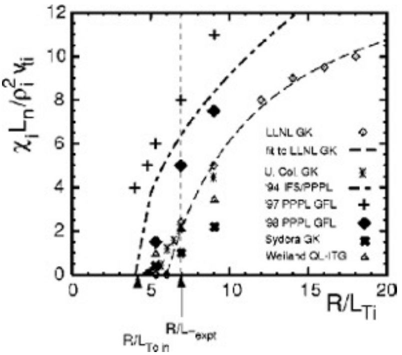
$$n_e = \frac{T_{i0}}{T_{e0}}(\Phi - \langle\Phi\rangle)$$

$$b = k_\perp^2 \rho_i^2, \qquad \Psi = \Gamma_0^{1/2}(b)\Phi, \qquad \mathbf{v}_\Psi = \frac{c}{B}\hat{\mathbf{b}} \times \Psi, \qquad \frac{1}{2}\hat{\nabla}_\perp^2 \Psi = b\frac{\partial \Gamma_0^{1/2}}{\partial b}\Phi,$$

$$\hat{\hat{\nabla}}_\perp^2 \Psi = b\frac{\partial^2}{\partial b^2}(b\Gamma_0^{1/2})\Phi, \qquad \nabla_\parallel = \hat{\mathbf{b}} \cdot \nabla, \qquad i\omega_* = \frac{-cT_0}{eBn_0}\nabla n_0 \cdot \hat{\mathbf{b}} \times \nabla,$$

$$i\omega_d = \frac{cT_0}{eB^2}\hat{\mathbf{b}} \times \nabla B \cdot \nabla, \qquad f' = \frac{a}{L_N}, \qquad t' = \frac{a}{L_T}$$

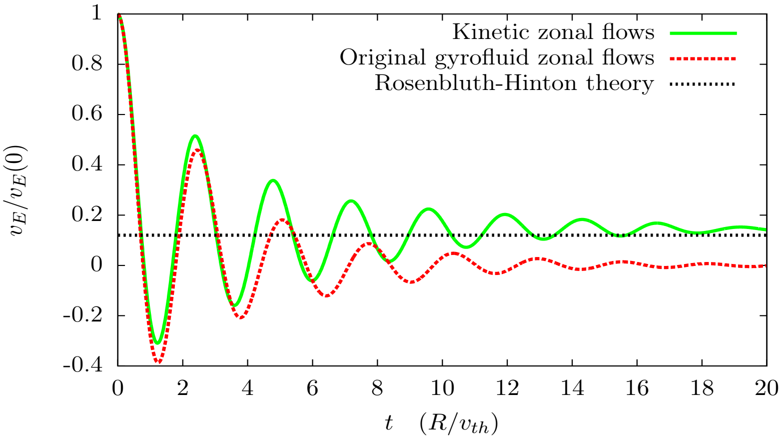
Need to improve original GF model



"Comparisons and physics basis of tokamak transport models and turbulence simulations", Dimits, et al. Phys. Plasmas, 2000.

- Original toroidal gyrofluid closures missing key physics: linearly undamped zonal flows and nonlinear FLR phase mixing (NLPM)
- Attempts made to correctly model zonal flows by modifying Landau damping closures (Beer, 1998)
- NLPM included in earlier slab-geometry gyrofluid model (Dorland, 1993), but not thought to be as important in toroidal geometry

Rosenbluth-Hinton residual flow



- Original gyrofluid model does not allow Rosenbluth-Hinton residual flow

Attempted Zonal Flow Closures (Varenna closure)

$$\sqrt{2}D_\parallel|k_\parallel|q_\parallel \rightarrow \sqrt{2}D_\parallel|k_\parallel|(q_\parallel - q_\parallel^{(0)})$$

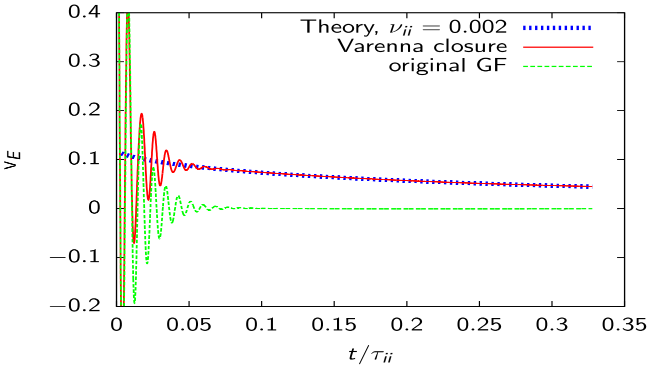
$$\sqrt{2}D_\perp|k_\parallel|q_\perp \rightarrow \sqrt{2}D_\perp|k_\parallel|(q_\perp - q_\perp^{(0)})$$

$$q_\parallel^{(0)} = 3ik_r\rho_i\frac{qB_0}{\varepsilon B}T_\parallel, \qquad q_\perp^{(0)} = ik_r\rho_i\frac{qB_0}{\varepsilon B}T_\perp$$

- GF modified by Beer et al to allow linearly undamped R-H residual flows; published in Varenna Proceedings, 1998
- $q_\parallel^{(0)}$ and $q_\perp^{(0)}$ are Pfirsch-Schluter heat flows
- New model damps to non-zero equilibrium solution

Beer and Hammett, invited talk, published in Proc. of the Joint Varenna-Lausanne Int. Workshop on Theory of Fusion Plasmas (August 1998), p.19 (Varenna, Italy 1998).

Problems with Varenna zonal flow closures



- Agreement with Rosenbluth-Hinton theory only good for a small range of low k_x
- Residual still has some damping even without collisions
- Collisional damping of zonal flows not modeled well
- For more exotic geometries, theory of residuals becomes very complicated (Catto & Xiao)

Even better: Fully kinetic zonal flows

- Evolve $k_y = 0$ modes with gyrokinetic model (GS2), and all other modes with original gyrofluid model $\rightarrow$ Spectral representation makes this trivial for linear terms
- Essentially running GS2 with `Ny=1` linearly with nonlinear source term from GryfX
- All nonlinear terms calculated in gyrofluid model; in gyrokinetic equation, $\mathcal{N}_{gk}$ must be reconstructed from the $k_y = 0$ component of the nonlinear terms of the gyrofluid moments:

$$\hat{\mathcal{N}}_{gk} = \mathcal{N}_n + \frac{v_\parallel}{v_t}\mathcal{N}_{u_\parallel} + \frac{1}{2}\left(\frac{v_\parallel^2}{v_t^2} - 1\right)\mathcal{N}_{T_\parallel} + \frac{1}{2}\left(\frac{v_\perp^2}{v_t^2} - 2\right)\mathcal{N}_{T_\perp} + \frac{1}{2}\left(\frac{v_\parallel^3}{3v_t^3} - \frac{v_\parallel}{v_t}\right)\mathcal{N}_{q_\parallel} + \frac{v_\parallel}{v_t}\left(\frac{v_\perp^2}{2v_t^2} - 1\right)\mathcal{N}_{q_\perp}$$

- Consistent with moment definitions, such that $\mathcal{N}_n = \int \hat{\mathcal{N}}_{gk}\ d^3v,\ \mathcal{N}_{u_\parallel} = \int \hat{\mathcal{N}}_{gk}\ v_\parallel\ d^3v$, etc

Hybrid gyrofluid-gyrokinetic algorithm

GPU (GF)

CPU (GK)

calculate $\mathcal{N}_{m_i}[t]_{\text{all } k}$

calculate $\mathcal{L}_{m_i}[t]_{k_y \neq 0}$

estimate $m_i(t + \Delta t/2)_{k_y \neq 0}$, $\Phi(t + \Delta t/2)_{k_y \neq 0}$

copy GPU→CPU

$\mathcal{N}_{m_i}[t]_{k_y = 0}$

advance $g_{k_y=0}$, $\Phi_{k_y=0}$ $t \rightarrow t + \Delta t/2$

calculate $m_i(t + \Delta t/2)_{k_y=0}$

copy CPU→GPU

$m_i(t + \Delta t/2)_{k_y=0}$, $\Phi(t + \Delta t/2)_{k_y=0}$

calculate $\mathcal{N}_{m_i}[t + \Delta t/2]_{\text{all } k}$

calculate $\mathcal{L}_{m_i}[t + \Delta t/2]_{k_y \neq 0}$

calculate $m_i(t + \Delta t)_{k_y \neq 0}$, $\Phi(t + \Delta t)_{k_y \neq 0}$

copy GPU→CPU

$\mathcal{N}_{m_i}[t + \Delta t/2]_{k_y=0}$

advance $g_{k_y=0}$, $\Phi_{k_y=0}$ $t + \Delta t/2 \rightarrow t + \Delta t$

calculate $m_i(t + \Delta t)_{k_y=0}$

copy CPU→GPU

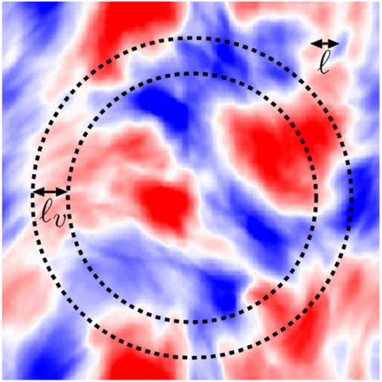
$m_i(t + \Delta t)_{k_y=0}$, $\Phi(t + \Delta t)_{k_y=0}$

ZF velocity space resolution requirements/questions

- Preliminary simulation results with low velocity space resolution (`ngauss=3, negrid=6`) give same heat fluxes as higher resolution (`ngauss=8, negrid=16`)
- `ntheta=32` so really just reducing v-space resolution for passing particles
- How much (non-trapped) velocity space resolution is necessary to capture zonal flow dynamics?
- What is the velocity space structure of the zonal flows in a full GS2 simulation?
- We only have 6 gyrofluid moments ($\sim$ 6 grid points) for non-zonal modes... would having too much velocity space resolution for zonal modes ever become problematic/overdetermined?

Nonlinear FLR Phase Mixing

- Spread in gyro-averaged $\mathbf{E}\times\mathbf{B}$ velocities leads to phase mixing in perpendicular direction (analogous to Landau damping in parallel direction)
- Entropy cascade in $k_\perp$ and $v_\perp$
- Damping proportional to $k_\perp^2 |\mathbf{v}_E \cdot \mathbf{k}_\perp|$



1-D model of NLPM

- Consider a static zonal flow potential $\Phi = \Phi_{ZF}(x)$ in sheared slab geometry
- Neglecting equilibrium and parallel gradients, the GK equation is

$$\frac{\partial F_1}{\partial t} + J_0\left(\frac{k_x v_\perp}{\Omega}\right) v_E \frac{\partial F_1}{\partial y} = 0$$

- Consider initial perturbation $F_1(t=0) = e^{ik_y y} F_M(v)$, so the solution is

$$F_1(t) = F_M e^{ik_y [y - J_0(k_x v_\perp/\Omega) v_E t]}$$

1-D model of NLPM

- Expanding J_0 for small $k_\perp$, we can integrate analytically to see that all moments of F_1 decay in time:

$$n_{1kin}(t) = \int d^3v F_1 \simeq n_0 e^{ik_y(y-v_E t)} \frac{1}{1 - ik_y b v_E t/2}$$

$$p_{\perp kin}(t) = \int d^3v \frac{mv_\perp^2}{2n_0 v_t^2} F_1 \simeq n_0 e^{ik_y(y-v_E t)} \frac{1}{(1 - ik_y b v_E t/2)^2}$$

$$T_{\perp kin}(t) = p_{\perp kin} - n_{kin} \simeq n_0 e^{ik_y(y-v_E t)} \frac{ik_y b v_E t/2}{(1 - ik_y b v_E t/2)^2}$$

$$r_{\perp,\perp kin}(t) = \int d^3v \frac{mv_\perp^2}{4n_0 v_t^4} F_1 \simeq n_0 e^{ik_y(y-v_E t)} \frac{2}{(1 - ik_y b v_E t/2)^3}$$

where here $b = k_x^2 v_t^2/\Omega^2$.

1-D model of NLPM

- Working backwards, we find that these expressions are exact solutions of the following set of equations:

$$\frac{\partial n}{\partial t} + \left(1 - \frac{b}{2}\right) v_E \cdot \nabla n - \frac{b}{2} v_E \cdot \nabla T_\perp = 0$$

$$\frac{\partial T_\perp}{\partial t} + \left(1 - \frac{3b}{2}\right) v_E \cdot \nabla T_\perp - \frac{b}{2} v_E \cdot \nabla n$$
$$- \frac{b}{2} v_E \cdot \nabla \left(r_{\perp,\perp} - 2n - 4T_\perp\right) = 0$$

- Match low-b limit of original gyrofluid nonlinear terms with exception of last term
- For this test problem, an exact solution for $r_{\perp,\perp}$ can be expressed as

$$r_{\perp,\perp} = \frac{4(n + T_\perp)}{1 - ik_y b v_E t/2} - \frac{2n}{(1 - ik_y b v_E t/2)^2}$$

- Can extend to higher b by taking $(1 - b/2)\mathbf{v}_E \rightarrow \mathbf{v}_\Psi$, $(-b/2)\mathbf{v}_E \rightarrow \frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi$

1-D model of NLPM

- We want to recover this damping behavior with our closures, so we break the $r_{\perp,\perp}$ closure into Maxwellian and dissipative pieces

$$r_{\perp,\perp} = 2n + 4T_\perp + \frac{\left|[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi] \cdot \nabla\right|}{[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi] \cdot \nabla} [\mu_1(n + T_\perp) + \mu_2 n]$$

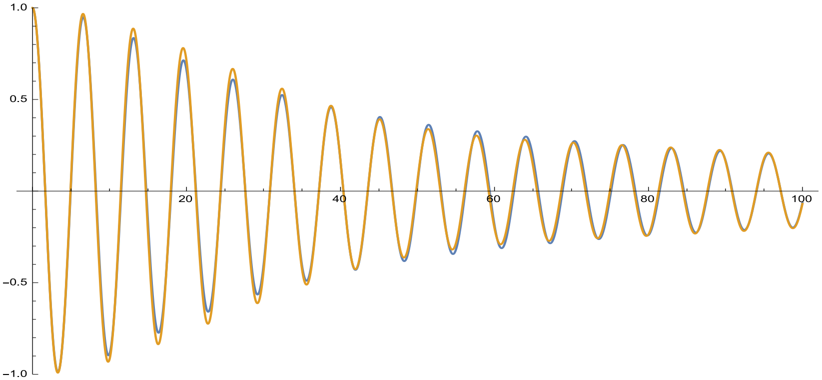
- The closure coefficients contain a dissipative and non-dissipative piece, to try to capture the phase shift

$$\mu = \mu_r + \mu_i \frac{\left|[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi] \cdot \nabla\right|}{[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi] \cdot \nabla} = (\mu_r,\ \mu_i)$$

- Find μ's by minimizing difference between fluid and kinetic density responses for $b = 0.1$

1-D model of NLPM

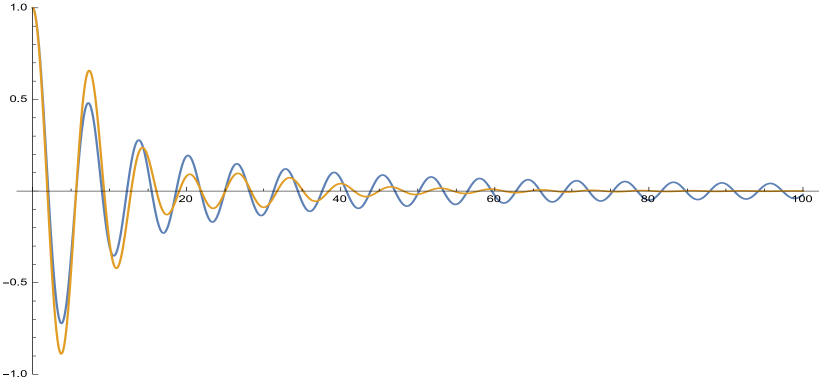
- Good agreement for density response for $b = 0.1$.



GryfX in yellow, Kinetic in blue

1-D model of NLPM

- Not as good for larger b... here $b = 0.5$.



GryfX in yellow, Kinetic in blue

Extending NLPM model to 3-D

- In general 3-D geometry, we currently approximate

$$|\mathbf{v} \cdot \nabla| \, M \simeq D_{PM} \left(|v_x| \left| \frac{\partial}{\partial x} \right| M + |v_y| \left| \frac{\partial}{\partial y} \right| M \right)$$

- This misses interference terms in the original absolute value
- Adjustable scalar parameter D_{PM} included to account for this, with $D_{PM} \lesssim 1$
- Is there a better way to evaluate these terms? Greg suggested

$$|\mathbf{v} \cdot \nabla| \, M \simeq |k_x| \left(v_x M - (v_x M)_0 \right) + |k_y| \left(v_y M - (v_y M)_0 \right)$$

where in equilibrium, $\frac{\partial}{\partial x}(v_x M)_0 = -\frac{\partial}{\partial y}(v_y M)_0$, so that $\nabla \cdot (\mathbf{v} M)_0 \to 0$

Nonlinear FLR Phase Mixing

- Following a similar procedure for the remaining equations, the final gyrofluid nonlinear terms become

$$\mathcal{N}_n = \mathbf{v}_\Psi \cdot \nabla n + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla T_\perp$$

$$\mathcal{N}_{u_\parallel} = \mathbf{v}_\Psi \cdot \nabla u_\parallel + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla q_\perp$$

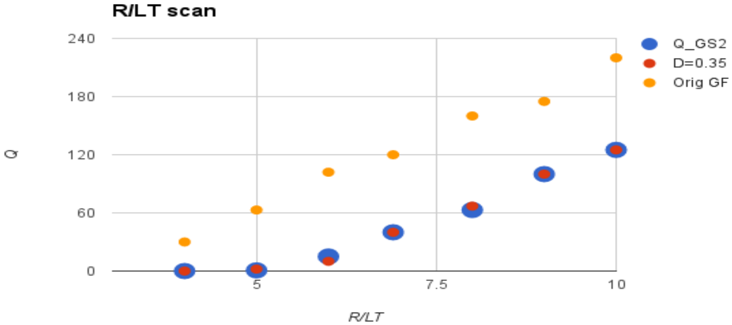
$$\mathcal{N}_{T_\parallel} = \mathbf{v}_\Psi \cdot \nabla T_\parallel + \left|\left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla\right| \mu_3 T_\parallel$$

$$\mathcal{N}_{T_\perp} = \mathbf{v}_\Psi \cdot \nabla T_\perp + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla n + \left[\hat{\hat{\nabla}}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla T_\perp + \left|\left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla\right| (\mu_1 T_\perp + (\mu_1 + \mu_2) n)$$

$$\mathcal{N}_{q_\parallel} = \mathbf{v}_\Psi \cdot \nabla q_\parallel + \left|\left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla\right| \mu_3 q_\parallel$$

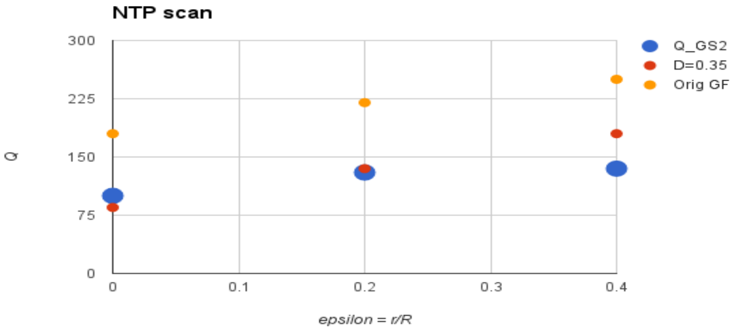
$$\mathcal{N}_{q_\perp} = \mathbf{v}_\Psi \cdot \nabla q_\perp + \left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla u_\parallel + \left[\hat{\hat{\nabla}}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla q_\perp + \left|\left[\frac{1}{2}\hat{\nabla}_\perp^2 \mathbf{v}_\Psi\right] \cdot \nabla\right| (\mu_1 q_\perp + (\mu_1 + \mu_2) u_\parallel)$$

R/L_T scan with NLPM



- Including NLPM and kinetic ZF brings GryfX heat flux predictions into good agreement with GK (GS2)
- $D_{PM} = 0.35$ for all these simulations, `ngauss=3, negrid=6`

NTP scan with NLPM



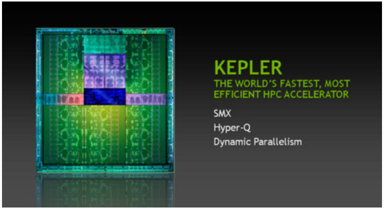
- Too much NLPM for $\epsilon = 0$, too little for $\epsilon = 0.4$
- D_{PM} could scale with ZF amplitude?
- Or find better way of evaluating $|\mathbf{v}_E \cdot \nabla|$

Why do we need Gyrofluid Codes?

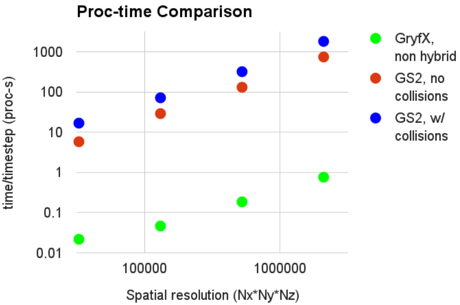
- Transport optimization: Use models coupled to TRINITY transport solver to evaluate transport properties of tokamak design configurations
- To evaluate a configuration, need to vary $T(a), n(a), Q, S, \Pi$ independently. With 3 points in each direction, $3^5 = 243$ TRINITY runs required.
- Configuration parameters to vary include current profile, elongation, triangularity, β, etc. 128 configurations would be a start.
- A single TRINITY + GS2 simulation requires O(1M) CPU hours, so entire scan would take $\sim$ 32,000 M CPU hours
- Need to find multiple orders of magnitude of acceleration to make this project possible $\rightarrow$ **gyrofluid, GPUs**

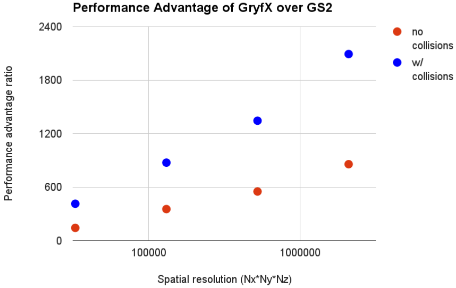
Introducing GryfX: A GPU-based Gyrofluid Turbulence Code with Kinetic Zonal Flows and Advanced Nonlinear Closures

- Gyrofluid vs Gyrokinetic: 6 moments vs 256 grid points in velocity space $\sim$ 40X speedup
- Gyrofluid model requires less memory $\rightarrow$ Able to fit efficiently on GPU
- GPU can achieve 20-30X speedup over CPU
- Total acceleration $>$ **1,200 X**



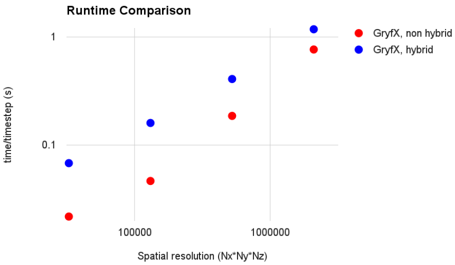
GryfX (non-hybrid) vs GS2 performance comparison

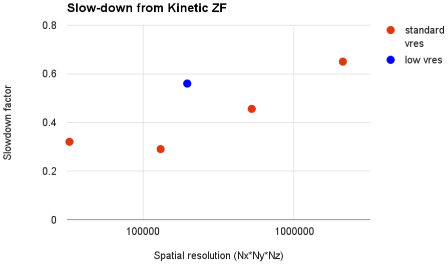




- Total speedup of more than 2,000X over GS2 for large grid

Cost of kinetic ZF minimized by GPU-CPU concurrency





- GF runs on GPU while GK runs on 16 CPUs: most supercomputer configurations allocate multiple CPUs for each GPU, so additional computation on CPU is essentially free
- Slows down by factor of 1-2, but this is an acceptable trade-off to get zonal flow physics right
- With 'low' velocity space resolution, converged nonlinear simulations in ~ 1 hour (on 1 node $=$ GPU $+$ 16 procs)

TRINITY + GryfX on Titan, for example

For full design scan:

- GS2 + TRINITY $\sim$ 32,000 M CPU hours
- GryfX (hybrid) + TRINITY $\sim$ 400 M CPU hours
- GryfX (non-hybrid) + TRINITY $\sim$ 25 M CPU hours (*only if charged as 1 GPU-hour = 1 CPU-hour*)
- Titan (ORNL) has 18,688 nodes, each with 1 GPU and 16 CPUs $\rightarrow$ 7M CPU hours per day $\rightarrow$ 450K GryfX runs per day
- Full tokamak design study could be completed in a month: each node is always running **its own** GryfX calculation, so that hundreds of configurations can be evaluated **simultaneously**
- Would take years to do this with GS2

Future Work

- Keep improving gyrofluid NLPM closures
- Use kinetic zonal flows to guide improvements to gyrofluid zonal flow closures
- Implement gyrofluid electron equations (Beer or Snyder)
- Use GryfX for more efficient study of experimental results
- If accurate enough, GryfX can directly aid gyrokinetic simulations (resolution/convergence, pre-conditions, etc)
- DEMO design project: TRINITY + GryfX
    - Scan large parameter space efficiently
    - Find ideal design configurations