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

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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)

\[
\frac{\partial}{\partial t} F + \nabla \cdot \left[ F \left( v_\parallel \hat{b} + v_E + v_d \right) \right] + \frac{\partial}{\partial v_\parallel} \left[ F \left( -\frac{e}{m} \hat{b} \cdot \nabla J_0 \Phi - \mu \hat{b} \cdot \nabla B + v_\parallel (\hat{b} \cdot \nabla \hat{b}) \cdot v_E \right) \right] = C(F)
\]

Closures chosen to capture important kinetic effects, most notably Landau damping, toroidal \( \nabla B \) and curvature drifts and associated phase mixing, and toroidal finite Larmor radius (FLR) effects
Moment definitions and normalizations

\[ \delta n = \int \delta f \, d^3 v \]
\[ \delta p_\parallel = m \int \delta f \, v_\parallel^2 \, d^3 v \]
\[ \delta q_\parallel = -3 m v_t^2 n_0 \delta u_\parallel + m \int \delta f \, v_\parallel^3 \, d^3 v \]
\[ \delta r_{\parallel,\parallel} = m \int \delta f \, v_\parallel^4 \, d^3 v \]
\[ \delta r_{\perp,\parallel} = (m/4) \int \delta f \, v_\perp^4 \, d^3 v \]
\[ \delta s_{\parallel,\parallel} = -15 m v_t^4 n_0 \delta u_\parallel + m \int \delta f \, v_\parallel^5 \, d^3 v \]

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

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

where \( v_t = \sqrt{T_0/m} \)
Equations: 6 moment Gyrofluid Model

\[
\begin{align*}
\frac{\partial n}{\partial t} + v_\psi \cdot \nabla n + \left[ \frac{1}{2} \hat{\nabla}^2 v_\psi \right] \cdot \nabla T_\perp + B \nabla_\parallel \frac{u_\parallel}{B} &- \left( f' + \frac{t'}{2} \hat{\nabla}_\perp^2 \right) i\omega_\star \Psi \\
&+ \left( 2 + \frac{1}{2} \hat{\nabla}_\perp^2 \right) i\omega_d \Psi + i\omega_d \left( T_\parallel + T_\perp + 2n \right) = 0
\end{align*}
\]

\[
\begin{align*}
\frac{\partial u_\parallel}{\partial t} + v_\psi \cdot \nabla u_\parallel + \left[ \frac{1}{2} \hat{\nabla}^2 v_\psi \right] \cdot \nabla q_\perp + B \nabla_\parallel \frac{T_\parallel}{B} + B \nabla_\parallel \frac{n}{B} + \nabla_\parallel \Psi \\
&+ \left( T_\perp + n + \frac{1}{2} \hat{\nabla}_\perp^2 \Psi \right) \nabla_\parallel \ln B + i\omega_d \left( q_\parallel + q_\perp + 4u_\parallel \right) = 0
\end{align*}
\]

\[
\begin{align*}
\frac{\partial T_\parallel}{\partial t} + v_\psi \cdot \nabla T_\parallel + B \nabla_\parallel \frac{q_\parallel + 2u_\parallel}{B} &+ 2 \left( q_\perp + u_\parallel \right) \nabla_\parallel \ln B - t' i\omega_\star \Psi + 2i\omega_d \Psi \\
&+ i\omega_d \left( 6 T_\parallel + 2n \right) + 2 |\omega_d| \left( \nu_1 T_\parallel + \nu_2 T_\perp \right) = -\frac{2}{3} \nu_{ii} \left( T_\parallel - T_\perp \right)
\end{align*}
\]
\[ \frac{\partial T_\perp}{\partial t} + \mathbf{v}_\Psi \cdot \nabla T_\perp + \left[ \frac{1}{2} \hat{\nabla}_\perp^2 \mathbf{v}_\Psi \right] \cdot \nabla n + \left[ \hat{\nabla}_\perp^2 \mathbf{v}_\Psi \right] \cdot \nabla T_\perp - B \nabla_\parallel \frac{u_\parallel}{B} \\
+ B^2 \nabla_\parallel \frac{q_\perp + u_\parallel}{B^2} - \left[ \frac{f'}{2} \hat{\nabla}_\perp^2 + t' \left( 1 + \hat{\nabla}_\perp^2 \right) \right] i\omega_\star \psi + \left( 1 + \frac{1}{2} \hat{\nabla}_\perp^2 + \hat{\nabla}_\perp^2 \right) i\omega_d \psi \\
+ i\omega_d \left( 4 T_\perp + n \right) + 2 |\omega_d| \left( \nu_3 T_\parallel + \nu_4 T_\perp \right) = \frac{1}{3} \nu_{ii} \left( T_\parallel - T_\perp \right) \\
\frac{\partial q_\parallel}{\partial t} + \mathbf{v}_\Psi \cdot \nabla q_\parallel + \left( 3 + \beta_\parallel \right) \nabla_\parallel T_\parallel + \sqrt{2} D_\parallel \left| k_\parallel \right| q_\parallel + i\omega_d \left( -3 q_\parallel - 3 q_\perp + 6 u_\parallel \right) \\
+ |\omega_d| \left( \nu_5 u_\parallel + \nu_6 q_\parallel + \nu_7 q_\perp \right) = -\nu_{ii} q_\parallel \\
\frac{\partial q_\perp}{\partial t} + \mathbf{v}_\Psi \cdot \nabla q_\perp + \left[ \frac{1}{2} \hat{\nabla}_\perp^2 \mathbf{v}_\Psi \right] \cdot \nabla u_\parallel + \left[ \hat{\nabla}_\perp^2 \mathbf{v}_\Psi \right] \cdot \nabla q_\perp + \nabla_\parallel \left( T_\perp + \frac{1}{2} \hat{\nabla}_\perp^2 \psi \right) \\
+ \sqrt{2} D_\perp \left| k_\parallel \right| q_\perp + \left( T_\perp - T_\parallel + \hat{\nabla}_\perp^2 \psi - \frac{1}{2} \hat{\nabla}_\perp^2 \psi \right) \nabla_\parallel \ln B \\
+ i\omega_d \left( -q_\parallel - q_\perp + u_\parallel \right) + |\omega_d| \left( \nu_8 u_\parallel + \nu_9 q_\parallel + \nu_{10} q_\perp \right) = -\nu_{ii} q_\perp \]
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

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

\[ b = k_\perp^2 \rho_i^2, \quad \Psi = \Gamma_0^{1/2}(b)\Phi, \quad v_\Psi = \frac{c}{B} \hat{b} \times \Psi, \quad \frac{1}{2} \hat{\nabla}_\perp^2 \Psi = b \frac{\partial \Gamma_0^{1/2}}{\partial b} \Phi, \]

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

\[ i\omega_d = \frac{cT_0}{eB^2} \hat{b} \times \nabla B \cdot \nabla, \quad f' = \frac{a}{L_N}, \quad t' = \frac{a}{L_T} \]
Need to improve original GF model

- 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

Original gyrofluid model does not allow Rosenbluth-Hinton residual flow
Attempted Zonal Flow Closures (Varenna closure)

\[ \sqrt{2}D_{||} |k_{||}| q_{||} \to \sqrt{2}D_{||} |k_{||}| (q_{||} - q_{||}^{(0)}) \]

\[ \sqrt{2}D_{\perp} |k_{||}| q_{\perp} \to \sqrt{2}D_{\perp} |k_{||}| (q_{\perp} - q_{\perp}^{(0)}) \]

\[ q_{||}^{(0)} = 3ik_{r}\rho_{i}\frac{qB_{0}}{\varepsilon B} T_{||}, \quad q_{\perp}^{(0)} = ik_{r}\rho_{i}\frac{qB_{0}}{\varepsilon B} T_{\perp} \]

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

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 $N_y=1$ linearly with nonlinear source term from GryfX
- All nonlinear terms calculated in gyrofluid model; in gyrokinetic equation, $N_{gk}$ must be reconstructed from the $k_y = 0$ component of the nonlinear terms of the gyrofluid moments:

$$\hat{N}_{gk} = N_n + \frac{v_{\|}}{v_t} N_{u_{\|}} + \frac{1}{2} \left( \frac{v_{\|}^2}{v_t^2} - 1 \right) N_{T_{\|}} + \frac{1}{2} \left( \frac{v_{\perp}^2}{v_t^2} - 2 \right) N_{T_{\perp}}$$

$$+ \frac{1}{2} \left( \frac{v_{\|}^3}{3v_t^3} - \frac{v_{\|}}{v_t} \right) N_{q_{\|}} + \frac{v_{\|}}{v_t} \left( \frac{v_{\perp}^2}{2v_t^2} - 1 \right) N_{q_{\perp}}$$

- Consistent with moment definitions, such that $N_n = \int \hat{N}_{gk} \ d^3v$, $N_{u_{\|}} = \int \hat{N}_{gk} \ v_{\|} \ d^3v$, etc
Hybrid gyrofluid-gyrokinetic algorithm

**GPU (GF)**

- calculate $N_{m_i}[t]_{all \ k}$
- calculate $L_{m_i}[t]_{k_y \neq 0}$
- estimate $m_i(t + \Delta t/2)_{k_y \neq 0}$, $\Phi(t + \Delta t/2)_{k_y \neq 0}$

**CPU (GK)**

- 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

- copy GPU→CPU

- calculate $N_{m_i}[t+\Delta t/2]_{all \ k}$
- calculate $L_{m_i}[t+\Delta t/2]_{k_y \neq 0}$
- calculate $m_i(t + \Delta t)_{k_y \neq 0}$, $\Phi(t + \Delta t)_{k_y \neq 0}$

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

- $t + \Delta t/2 \rightarrow t + \Delta t$

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

- copy CPU→GPU

- copy GPU→CPU

- $m_i(t + \Delta t)_{k_y=0}$, $\Phi(t + \Delta t)_{k_y=0}$
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 (∼ 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 $\nu_\perp$
- Damping proportional to $k_\perp^2 |\mathbf{v}_E \cdot \mathbf{k}_\perp|$
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

$$F_1(t) = F_M e^{ik_y [y - J_0 (k_x v_\perp / \Omega) v_E t]}$$
Expanding $J_0$ for small $k_\perp$, we can integrate analytically to see that all moments of $F_1$ decay in time:

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

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

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

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

where here $b = k^2 x v_t^2 / \Omega^2$. 
1-D model of NLPM

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

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

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

- 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

\[
r_{\perp,\perp} = \frac{4(n + T_\perp)}{1 - i k_y b v_E t/2} - \frac{2n}{(1 - i k_y b v_E t/2)^2}
\]

- Can extend to higher \(b\) by taking \((1 - b/2)v_E \rightarrow v_\Psi\), \((-b/2)v_E \rightarrow \frac{1}{2} \hat{\nabla}_\perp^2 v_\Psi\)
We want to recover this damping behavior with our closures, so we break the $r_{\perp,\perp}$ closure into Maxwellian and dissipative pieces

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

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

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

Find $\mu$’s by minimizing difference between fluid and kinetic density responses for $b = 0.1$
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

\[ |\mathbf{v} \cdot \nabla| M \simeq |k_x| (v_x M - (v_x M)_0) + |k_y| (v_y M - (v_y M)_0) \]

where in equilibrium, \( \frac{\partial}{\partial x} (v_x M)_0 = -\frac{\partial}{\partial y} (v_y M)_0 \), so that \( \nabla \cdot (\mathbf{v} M)_0 \rightarrow 0 \)
Nonlinear FLR Phase Mixing

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

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

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

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

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

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

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

- 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