Status of the NIMROD Hot Particle Benchmark

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Review of Hot Particles in NIMROD

- modified momentum equation

$$\rho\left(\frac{\partial \mathbf{U}}{\partial t}+\mathbf{U}\cdot\nabla\mathbf{U}\right)=\mathbf{J}\times\mathbf{B}-\nabla\cdot\underline{\mathbf{p}}_b-\nabla\cdot\underline{\mathbf{p}}_h$$

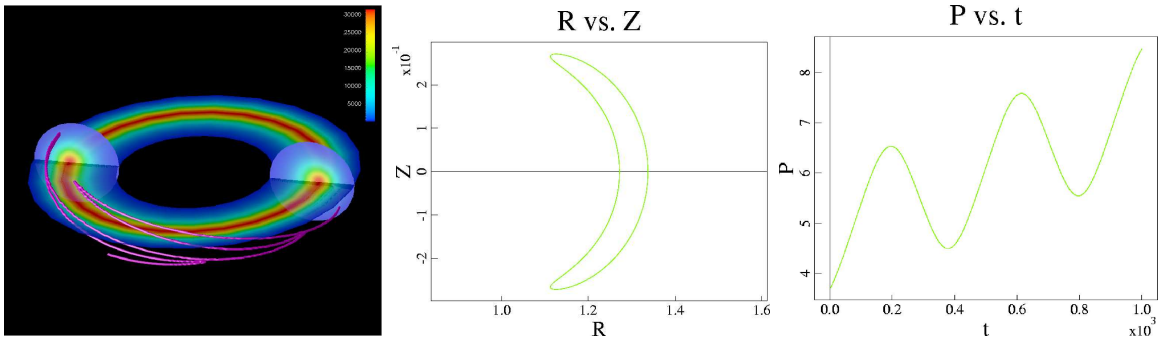
- hot particle pressure tensor is taken to be in the CGL-like form

$$\delta\underline{\mathbf{p}}_h=\begin{pmatrix}\delta p_\perp & 0 & 0\\ 0 & \delta p_\perp & 0\\ 0 & 0 & \delta p_\parallel\end{pmatrix}$$

where

$$\begin{pmatrix}\delta p(\mathbf{x})_\perp\\ \delta p(\mathbf{x})_\parallel\end{pmatrix}=\int\begin{pmatrix}m\,v_\parallel^2\\ \mu B\end{pmatrix}\delta f(\mathbf{x},\mathbf{v})d^3v$$

- check the equilibrium trajectories by integration of the characteristics along the equilibrium fields

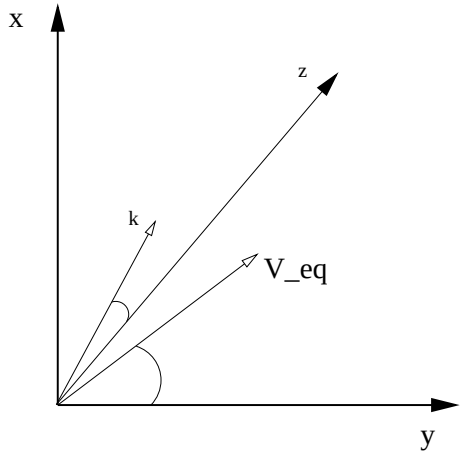


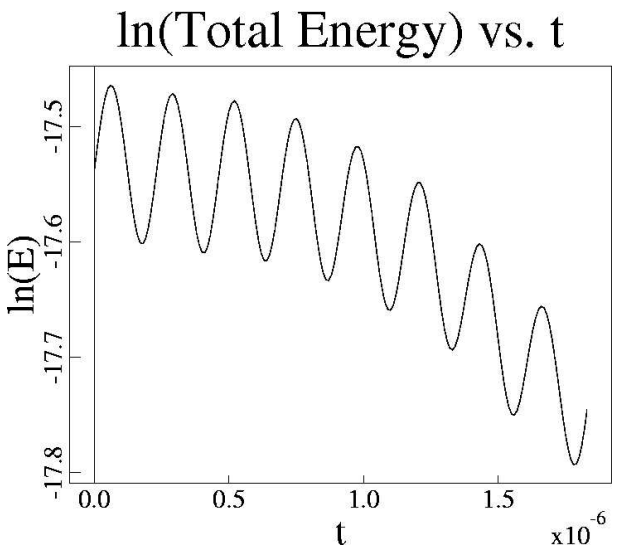
Outline

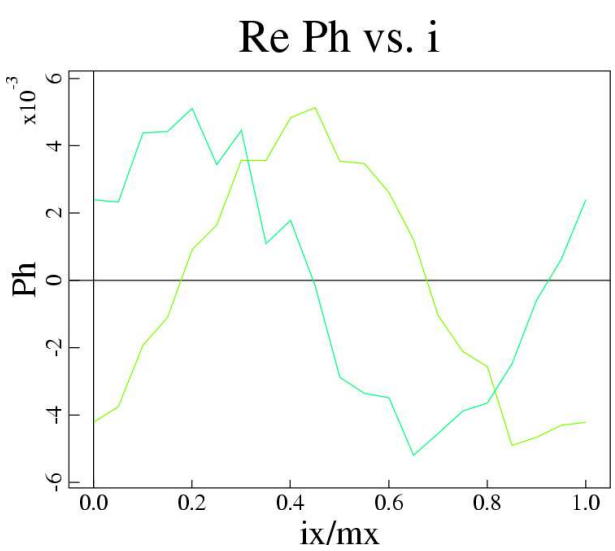
- implemented equilibrium anisotropic pressure $\Delta p = p_{\|} - p_{\perp}$ term
- growth rate and real frequency found to be sensitive to $\nabla \cdot \mathbf{B}$ errors
- trapped hot particle precession observed to suppresses $\delta \mathbf{J}$
- hot particle (1,1) eigenmode (fishbone) global in stucture than ideal (1,1) mode
- observed hot particle Landau damping of compressional Alfven wave
- compressional alfven mode and landau damping with hot particles also very sensitive to particle noise and $\nabla \cdot \mathbf{B}$ errors

Landau Damping of Compressional Alfven Eigenmode

- test problem - Landau damping of compressional Alfven mode in a box[1]
- compressional Alfven eigenmode damped by hot particles with $v_{\|} \simeq \omega / k_{\|}$
- $v_A = 1.5e5$, $v_{hmax} = 5e5$







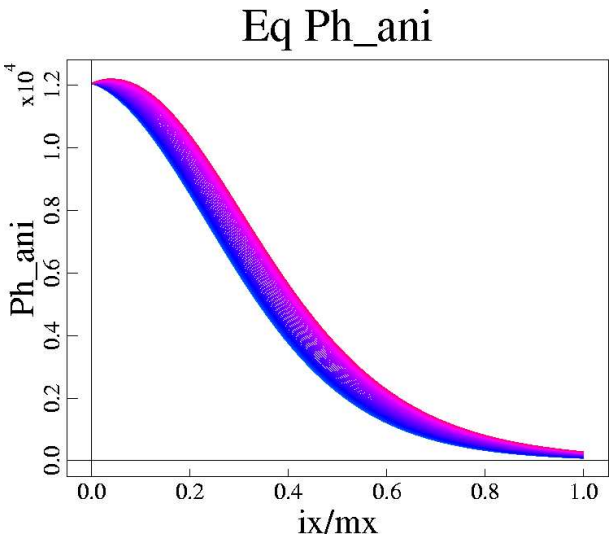
- $\nabla \cdot \mathbf{B}$ error results in program termination
- limited test of hot particle functionality

[1] E.V.Belova, et al, "Hybrid Simulations of teh Effects of Energetic Particles on Low Frequency MHD Waves", JCP, 1997

Recent Developments

- implemented equilibrium anisotropic pressure $\Delta p = p_{\|} - p_{\perp}$ term

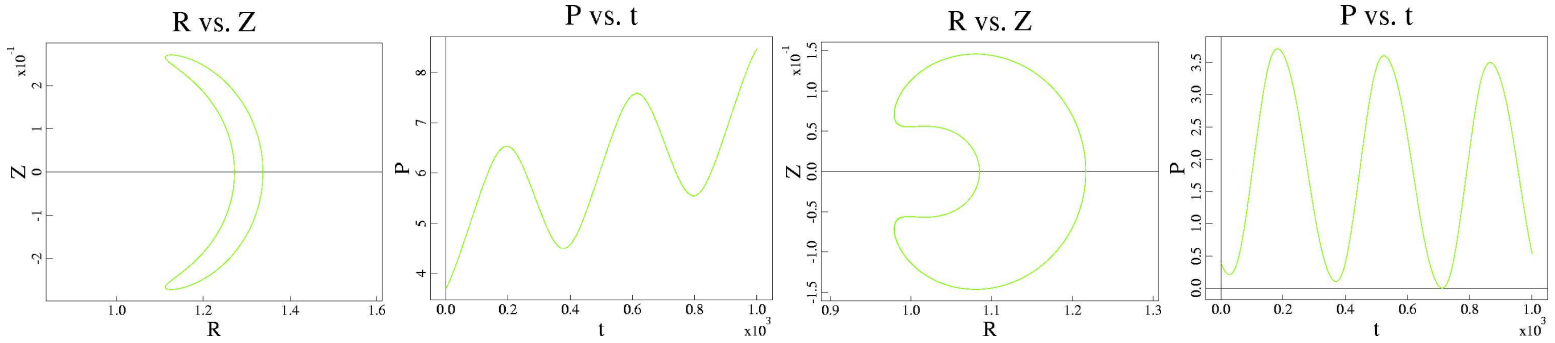
$$\nabla \cdot \underline{\mathbf{\Delta p}} = \Delta p \nabla \cdot (\delta\hat{b}\hat{b}_0 + \hat{b}_0\delta\hat{b})$$



$\frac{\beta_h}{\beta}$	$\omega\tau_A$	$\gamma\tau_A$	$\nabla \cdot \mathbf{B}$
0	0	.0274	$> .1$
.01	0	.0251	$> 1.$
.02	0	.0272	$> 1.$
.05	0	.0292	$> 1.$
.1	0	.0321	.6
.6	.0087	.0472	4.
.7	.010	.0463	5.5
.7	.011	.0471	3.7

- note peak off axis
- dip in γ at higher β_h attributed to noise
- note difference in growth rate for differing values of $\nabla \cdot \mathbf{B}$
- low value of ω a result of noise (in Δp_h)
- no significant stabilization observed

- particle orbits look good



- stabilization should occur due to conservation of third adiabatic invariant[2]
- should manifest as a trapped particle precessional current
- evidence is dubious

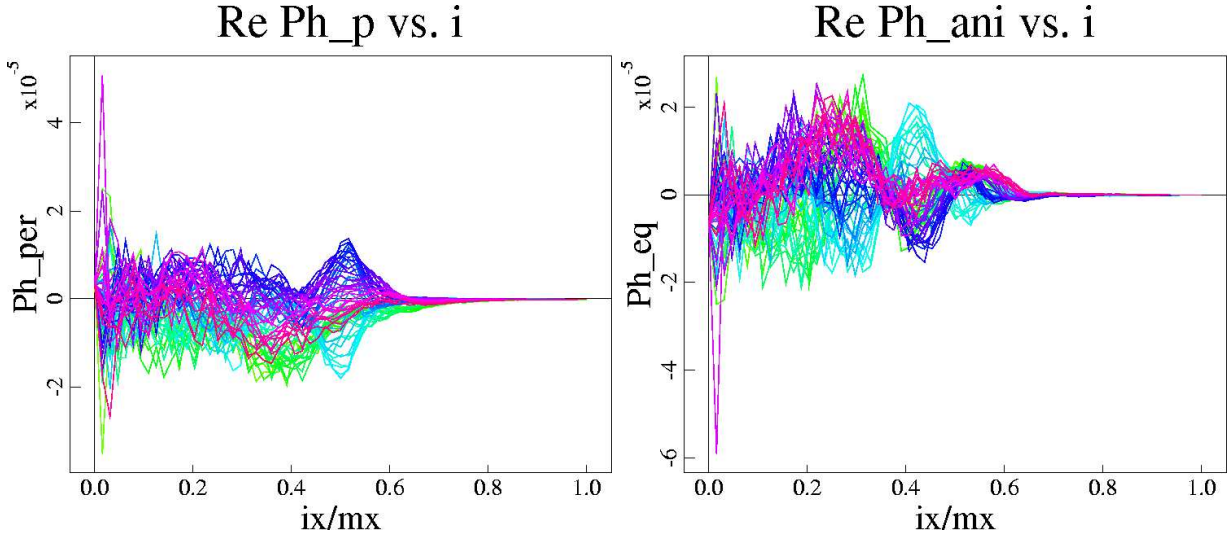
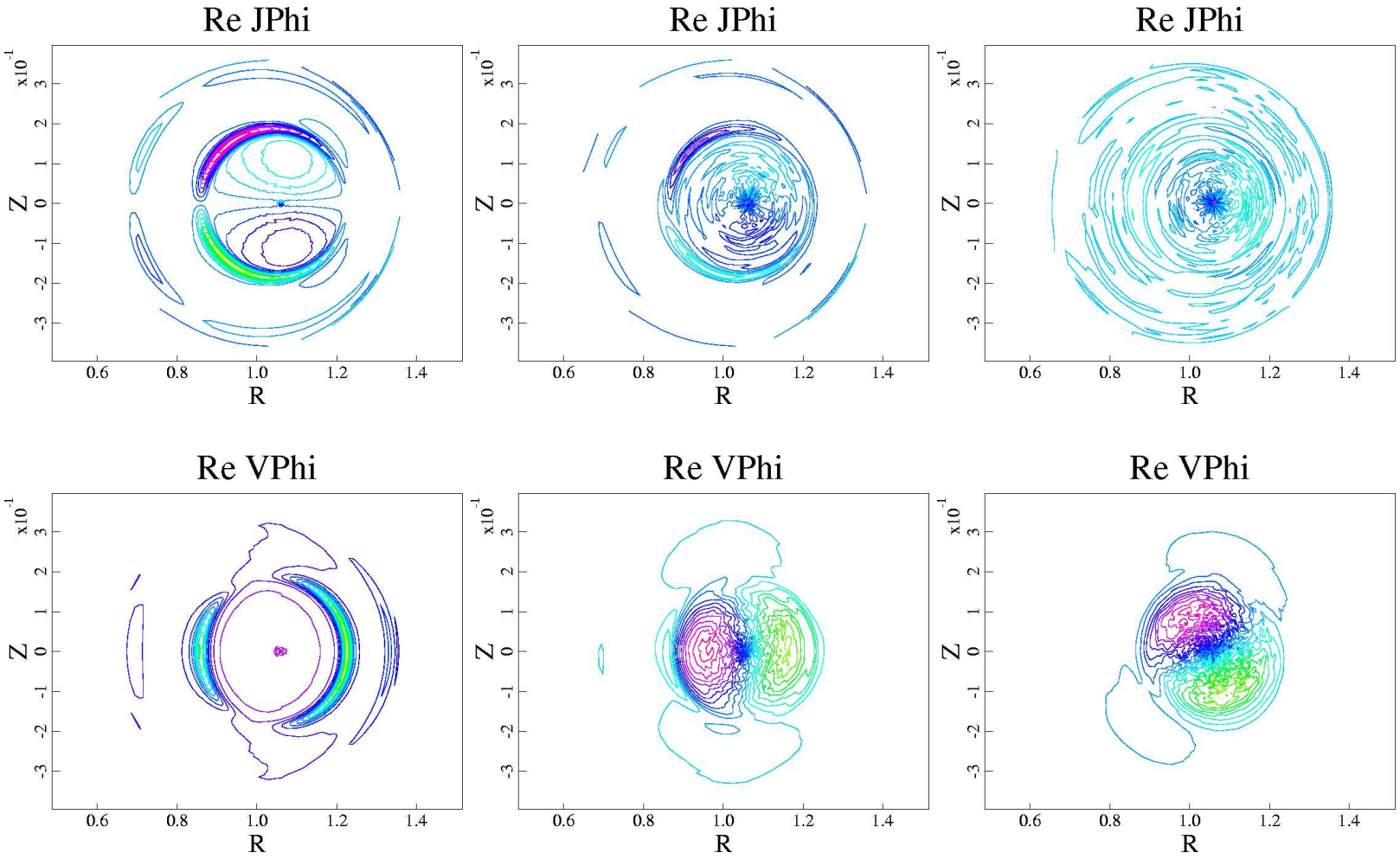


Figure 1: $\frac{\beta_h}{\beta} = .01$

[2]F. Porcelli, "Fast Particle Stabilisation", Plasma Physics and Controlled Fusion", 1991

Hot Particles Change Eigenmode Structure



- figures show eigenmodes for ideal, only $\nabla p_{h\perp}$, full $\nabla \underline{\mathbf{p}}_h$
- with any hot particle effect, $\delta J_p = 0$
- Δp_h necessary for real frequency i.e. fishbone branch

Summary

- hot particle Landau damping of compressional Alfven wave works
- complex frequency and eigenmode of hot particle observed
- need to reduce the noise and $\nabla \cdot \mathbf{B}$ error
  - adjust velocity loading
  - explicit ϕ grid for particles
  - try $\mathbf{J}_h$ coupling
  - higher order elements
- implement more diagnostics - $\mathbf{J}_h$, $< \omega_D >$
- pursue filtering
- study time advance and stability