Conclusion of the NIMROD Hot Particle Benchmark

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Review of Hot Particles in NIMROD

- NIMROD[a] fields use Lagrange type polynomial finite elements
- fields are separated into steady state and perturbation
  $\rightarrow A(\mathbf{x},t) = A_s(\mathbf{x}) + \delta A(\mathbf{x},t)$
- evolved momentum equation is

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

- $\delta \underline{\mathbf{p}}_h$ CGL-like form

$$\delta \underline{\mathbf{p}}_h = \begin{pmatrix} \delta p_\perp & 0 & 0 \\ 0 & \delta p_\perp & 0 \\ 0 & 0 & \delta p_\parallel \end{pmatrix} \qquad \begin{matrix} \delta p(\mathbf{x})_\perp \\ \delta p(\mathbf{x})_\parallel \end{matrix} = \int \begin{matrix} m\, v_\parallel^2 \\ \mu B \end{matrix} \; \delta f(\mathbf{x},\mathbf{v}) d^3 v$$

[a] C.R. Sovinec, et.al, "Nonlinear Magnetohydrodynamics Simulations using higher-order finite elements", *Jour. Comp. Phys.*, **195**, 2004

- use δf PIC[b] [c] to compute hot particle pressure $\delta\underline{\mathbf{p}}_h$

$$\dot{\delta f} = f_{eq}\left\{\frac{mg}{e\psi_0 B^3}\left[\left(v_\|^2+\frac{v_\perp^2}{2}\right)\delta\mathbf{B}\cdot\nabla B-\mu_0 v_\|\mathbf{J}\cdot\mathbf{E}\right]\right.$$
$$\left.+\frac{\delta\mathbf{v}\cdot\nabla\psi_p}{\psi_0}+\frac{3}{2}\frac{e\varepsilon^{1/2}}{\varepsilon^{3/2}+\varepsilon_0^{3/2}}\mathbf{v}_D\cdot\mathbf{E}\right\}$$

$\mathbf{v}_D$ curvature/∇B drift, $\delta\mathbf{v}$ mostly $\mathbf{E}\times\mathbf{B}$ drift

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[b] S. E. Parker and W. W. Lee, 'A fully nonlinear characteristic method for gyro-kinetic simulation', *Physics of Fluids B*, **5**, 1993

[c] G. Hu and J. A. Krommes, "Generalized weighting scheme for δf particle simulation method", *Physics of Plasmas*, **1**, 1994

Recent Algorithmic Improvements

- nonuniform loading in physical and velocity space
  - physical space loaded proportional to fluid pressure profile
  - velocity space loads slowing down distribution by inverting distribution

$$D(\varepsilon) = \frac{\int_0^{\varepsilon} f(\varepsilon')d\varepsilon'}{\int_0^{\varepsilon_{max}} f(\varepsilon')d\varepsilon'}$$

$D(\varepsilon)$ is a uniform random number where $D(0) = 0,\ D(\varepsilon_{max}) = 1$

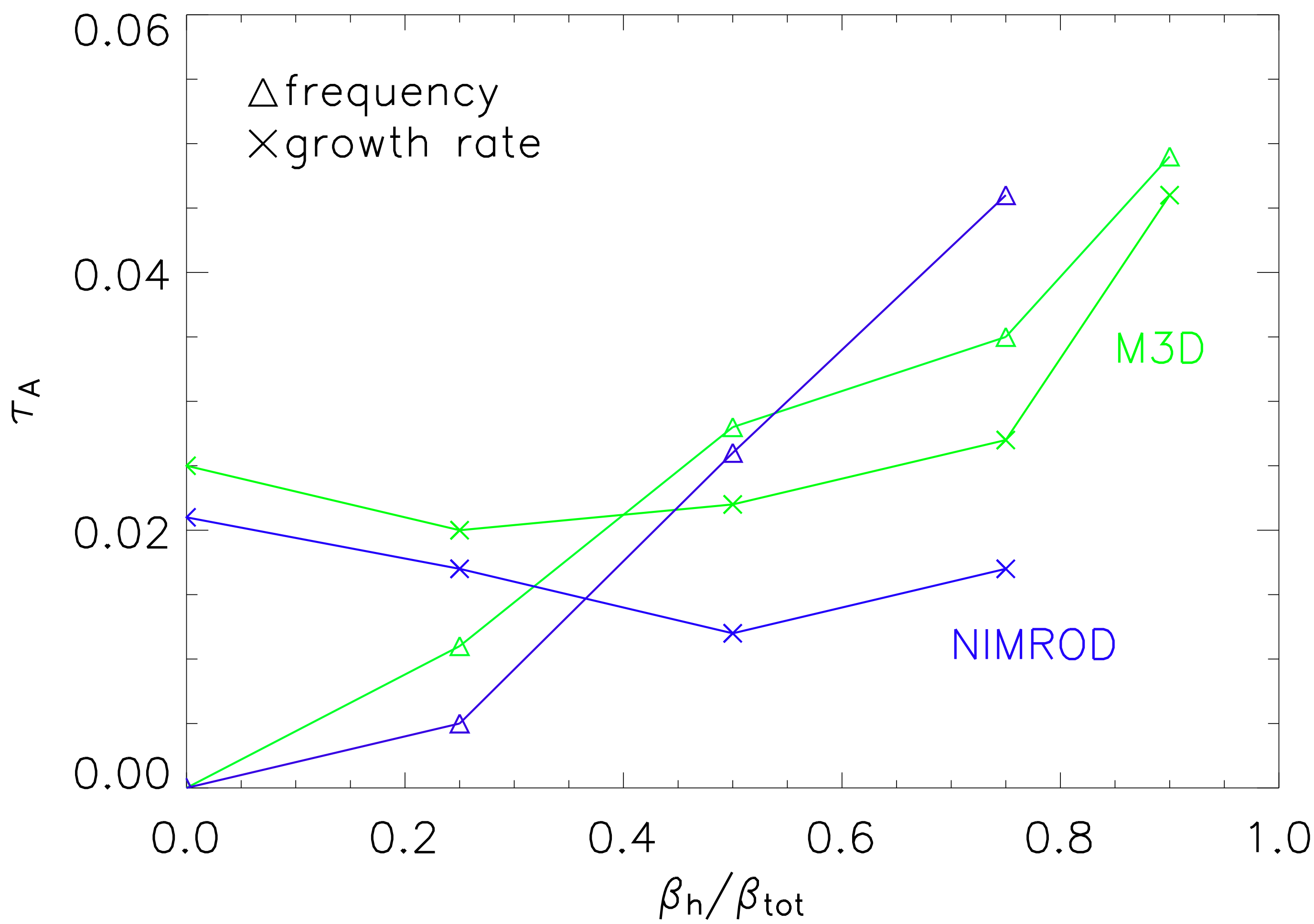
- implement integration by parts of weak form of gradient of hot particle pressure tensor

$$-\int d\mathbf{x}\mathbf{A}^* \cdot \nabla \cdot \underline{\mathbf{p}}_h = \int d\mathbf{x} \left(\nabla \mathbf{A}^*\right)^T : \underline{\mathbf{p}}_h$$

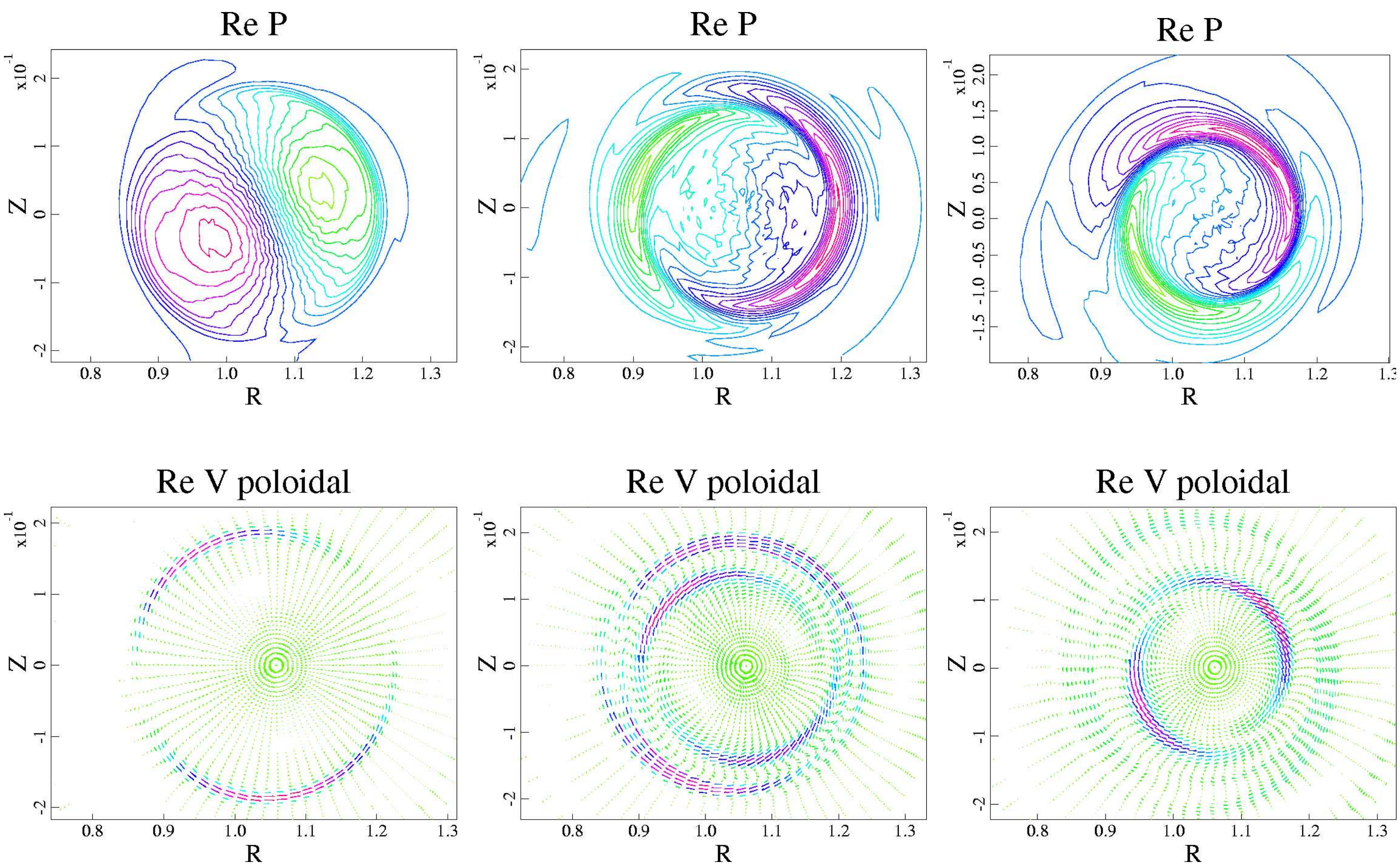
- both, particularly latter, greatly reduce particle noise
- reduce particle quantities to single precision - improves performance $\sim 30\%$
- results shown run on local cluster (Athlon 1.4GHz) 8 processors, 100Mb ethernet

$(1,1)$ Benchmark

- 64×64 poly_degree=1, dt=5e-8, $\tau_A = 1.e6$

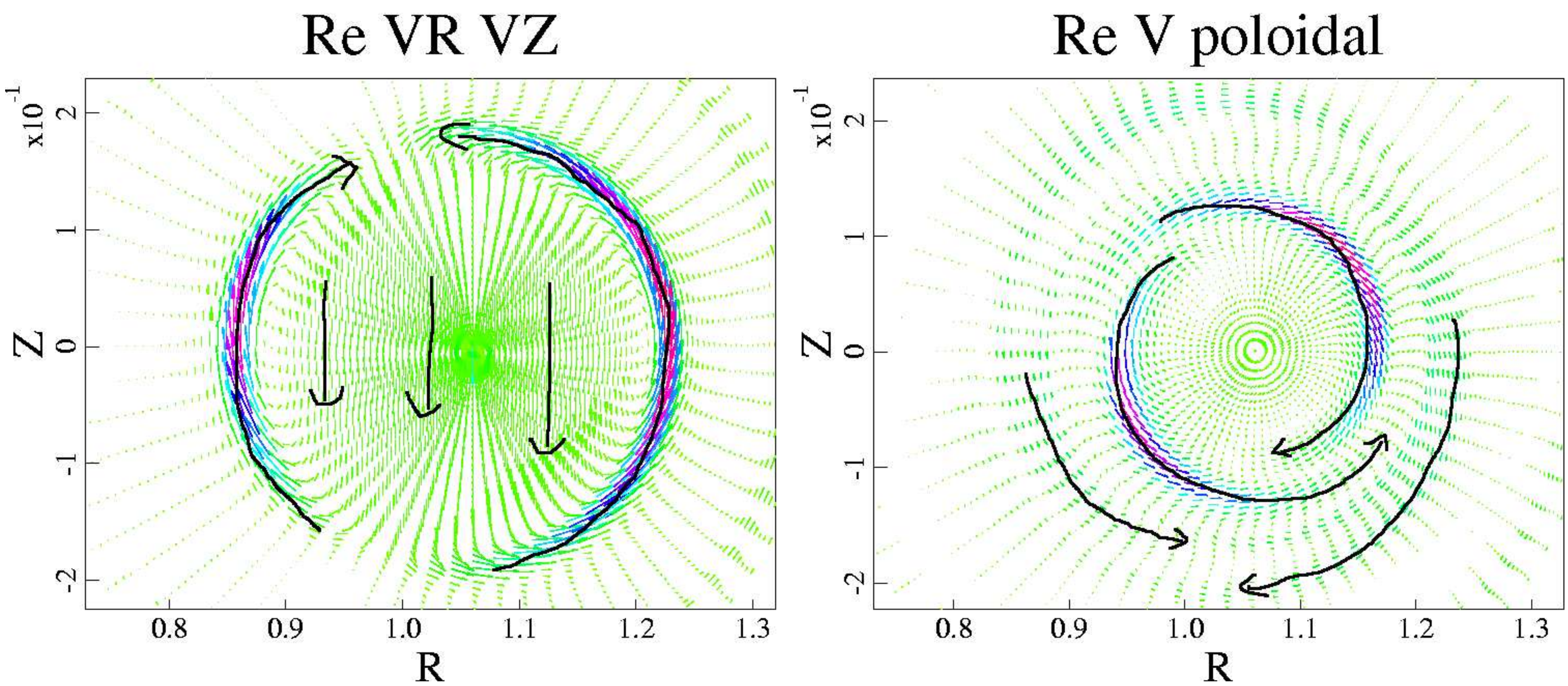


some eigenmodes



- n=1 component of fluid pressure and poloidal flow for $\beta_h/\beta_{tot} = [.25, .5, .75]$

Marked Change in flow



- ideal kink characterized by rigid shift of $q < 1$ core with return flow along narrow layer
- fishbone more complex, ‘overlapping’ flow

Remaining tasks towards Physics Applications

- implement higher order poly_degree for particles gather/scatter
- improve timestep - orbit averaging, implicit PIC?
- test alternative hot particle coupling to MHD ($\mathbf{J}_h$ coupling)
- algorithm improvements - take advantage of shared memory architecture
- fill transition of kink to fishbone
- timings and scaling
- lost particle recycling
- seek out applicable hot particle-MHD problems - sawteeth?