Verification of Continuum Kinetics in NIMROD

CEMM Meeting, New Orleans, LA

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Electron, ion and hot particle DKEs in NIMROD

- Hazeltine's form for the first-order drift kinetic equation in energy, ε, and magnetic moment, μ, variables:

$$\frac{\partial f}{\partial t} + (\mathbf{v}_{||} + \mathbf{v}_D) \cdot \nabla f + \left(\mu \frac{\partial B}{\partial t} + e(\mathbf{v}_{||} + \mathbf{v}_D) \cdot \mathbf{E} \right) \frac{\partial f}{\partial \varepsilon} = C(f)$$

- Transforming to pitch-angle, $\xi = v_{||}/v$, and normalized speed, $s = v/v_0$, variables yields

$$\frac{\partial f}{\partial t} + (\mathbf{v}_{||} + \mathbf{v}_D) \cdot \left[\nabla f - \frac{1-\xi^2}{2\xi} \nabla \ln B \frac{\partial f}{\partial \xi} - \frac{s}{2} \nabla \ln T_0 \frac{\partial f}{\partial s} \right] - C(f) +$$
$$\frac{1-\xi^2}{2\xi} \left[-\xi^2 \frac{\mathbf{b}}{B} \cdot \frac{\partial \mathbf{B}}{\partial t} + \frac{q}{s^2 T_0} (\mathbf{v}_{||} + \mathbf{v}_D) \cdot \mathbf{E} + \xi^2 \frac{\mathbf{E} \times \mathbf{B}}{B^2} \cdot \nabla \ln B \right] \frac{\partial f}{\partial \xi} +$$
$$\frac{s}{2} \left[-(1-\xi^2) \frac{\mathbf{b}}{B} \cdot \frac{\partial \mathbf{B}}{\partial t} + \frac{q}{s^2 T_0} (\mathbf{v}_{||} + \mathbf{v}_D) \cdot \mathbf{E} + (1+\xi^2) \frac{\mathbf{E} \times \mathbf{B}}{B^2} \cdot \nabla \ln B \right] \frac{\partial f}{\partial s} = 0$$

where

$$\mathbf{v}_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{T_0 s^2}{q B^2} \left[(1+\xi^2)\, \mathbf{b} \times \nabla B + 2\xi^2 \mu_0 \mathbf{J}_\perp + (1-\xi^2) \mu_0 \mathbf{J}_{||} \right] + \frac{m v_0 s \xi}{q B^2} \mathbf{b} \times \frac{\partial \mathbf{B}}{\partial t}.$$

Continuum Electron and Ion DKE verification

- Quantitative agreement between NIMROD and NEO for
  (1) high aspect ratio circular equilibrium,
  (2) high-beta, DIII-D like equilibrium, and
  (3) NSTX equilibrium.
- Consistent bootstrap currents: NIMROD, NEO, DK4D, NCLASS and Sauter.
- Paper written and soon to be submitted.

Equations for NIMROD/NEO Benchmark

- Solve simplified DKEs:

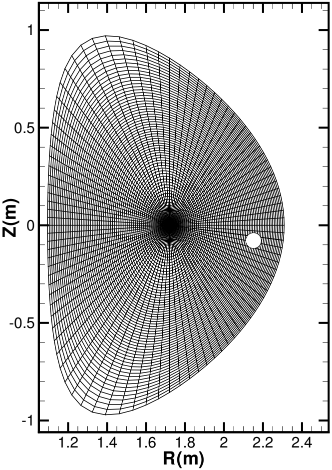
$$\partial_t f_1 + \mathbf{v}_{||} \cdot \nabla f_1 - \left(\mathbf{v}_{||} \cdot \nabla \ln B\right) \frac{1-\xi^2}{2\xi} \partial_\xi f_1 - C_{aa} - C_{ab} =$$
$$-\mathbf{v}_D \cdot \nabla f_0 + s v_D \cdot \nabla \ln v_0 \partial_s f_0 - \frac{e}{2\varepsilon_0 s} \mathbf{v}_{||} \cdot \left(\mathbf{E}^A - \nabla \phi_1\right) \partial_s f_0.$$

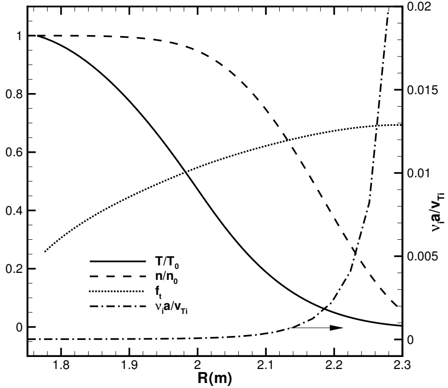
Using $g_1 = f_1 - (e\phi_1/T_0) f_0$ and assuming steady-state yields (Belli and Candy, 51 PPCF 2009):

$$\mathbf{v}_{||} \cdot \nabla g_1 - \mathbf{v}_{||} \cdot \nabla \ln B \frac{1-\xi^2}{2\xi} \partial_\xi g_1 - C_{aa} - C_{ab} =$$
$$-\mathbf{v}_D \cdot \nabla f_0 + s v_D \cdot \nabla \ln v_0 \partial_s f_0 - \frac{e}{2\varepsilon_0 s} \mathbf{v}_{||} \cdot \mathbf{E}^A \partial_s f_0.$$

High-β Equilibrium

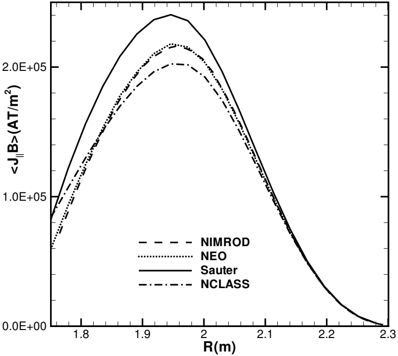
- T on axis 7.5 KeV.

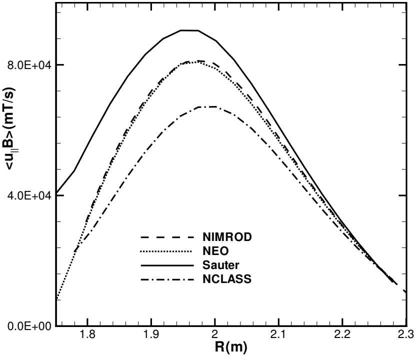




Bootstrap Currents and Parallel Ion Flows

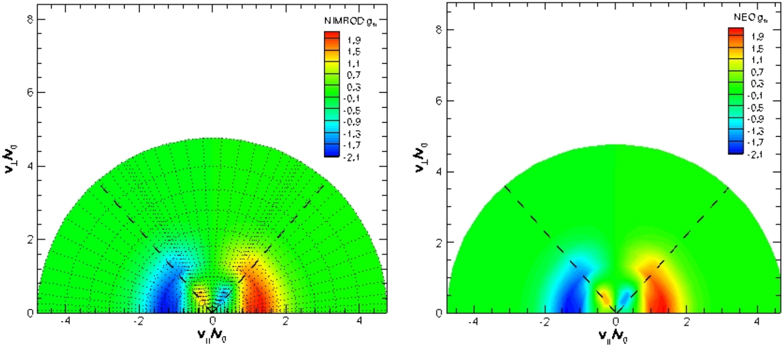
$$\langle J_{\|} B\rangle = \sum_b q_b \langle B \int d\mathbf{v} v_{\|} g_{1b}\rangle, \ \langle V_{\| i} B\rangle = \langle (B/n) \int d\mathbf{v} v_{\|} g_{1i}\rangle.$$





Ion Distribution Functions

- g_{1i} shown near outboard midplane: R=2.16, Z=-0.071.



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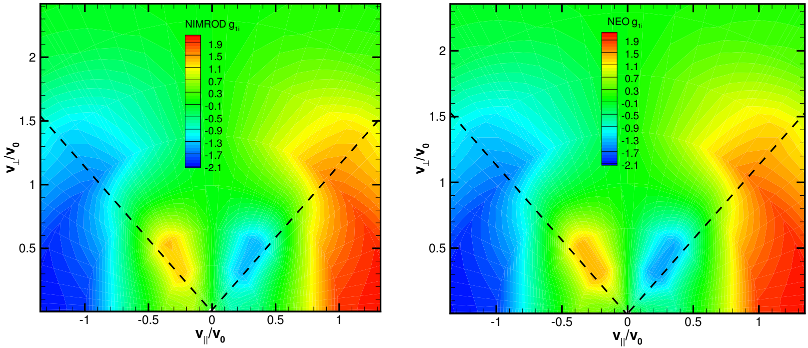
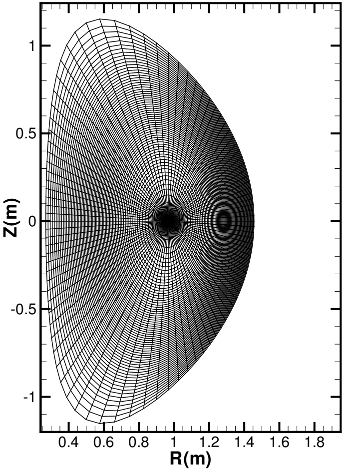
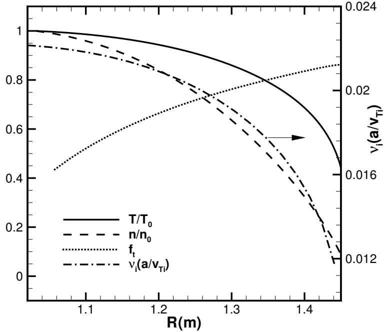


NSTX Benchmark

- NSTX equilibrium provided by Brendan Lyons (Phys. Plasmas 19, 082515 (2012)).





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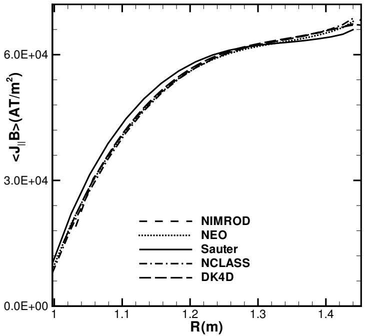

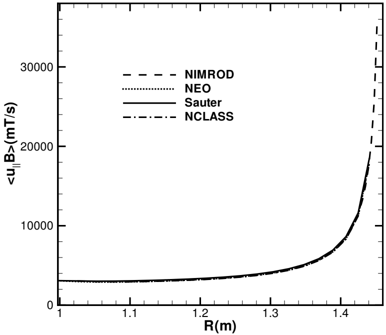

Verification of Continuum Drift Kinetic Equation Solvers in NIMROD.

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Abstract

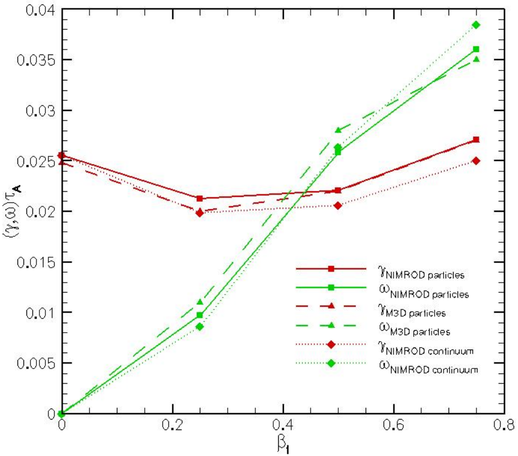
Verification of continuum solutions to the electron and ion drift kinetic equations (DKEs) in NIMROD[1] is demonstrated through comparison with several established neoclassical transport codes, most notably NEO[2]. The DKE solutions use NIMROD's spatial representation, 2D finite-elements in the poloidal plane and a 1D Fourier expansion in toroidal angle. For 2D velocity space, a novel 1D expansion in finite elements is applied for the pitch angle dependence and a collocation grid is used for the normalized speed coordinate. The full, linearized Coulomb collision operator is kept and shown to be important for obtaining quantitative results. Bootstrap currents, parallel ion flows, and radial particle and heat fluxes show quantitative agreement between NIMROD and NEO for a variety of tokamak equilibria. In addition, velocity space distribution function contours for ions and electrons show nearly identical detailed structure and agree quantitatively. A Θ-centered, implicit time discretization and a block-preconditioned, iterative linear algebra solver provide efficient electron and ion DKE solutions that ultimately will be used to obtain closures

Continuum Hot Particle DKE verification

- Ideal kink benchmark with NIMROD (continuum and δf-PIC) and M3D (δf-PIC) done.
- Verification and validation of NIMROD's continuum and δf-PIC hot particle algorithms for giant sawteeth (GS) in DIII-D in progress.
- Verification and validation of NIMROD's continuum hot particle algorithm with GYRO, GTC and TAEFL for reversed shear Alfven eigenmodes (RSAE) in DIII-D in progress.

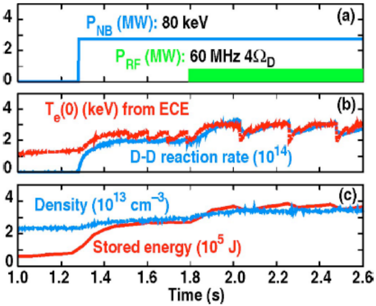
Agreement on Ideal Kink Benchmark

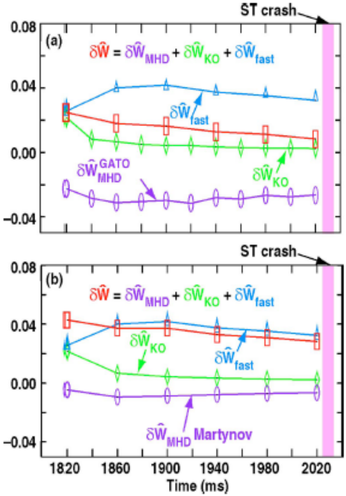
- Ideal kink benchmark with NIMROD (continuum and δf-PIC) and M3D (δf-PIC).



Sawteeth stabilized by fast ions in shot #96043

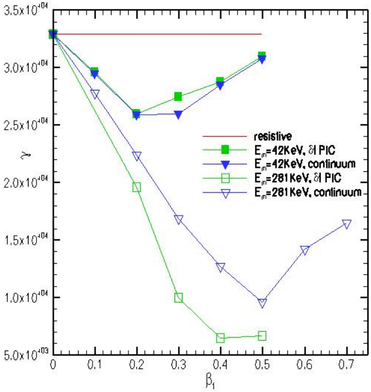
- Toroidal precession of high-energy tail stabilizes small sawteeth but results in giant sawteeth (Choi et al. POP, 2007).





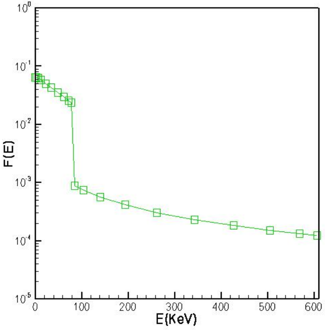
NIMROD results for GS

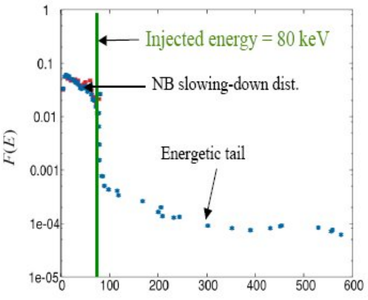
- Continuum and δf-PIC growth rates for slowing-down f_0 in the same ballpark.
- Thermal ions and RF-driven high energy tail in beam distribution important for stabilization.



High-energy tail Implemented in NIMROD for GS

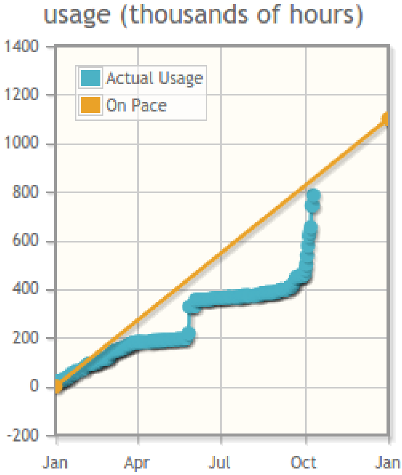
- Continuum linear simulations with high-energy tail matching Orbit-RF calculations in progress.
- Good scaling to 20,000 procs but significant compute time needed.





GS calculations need significant compute time

- Step function in June was GS calculations with 20,000 cores.
- (4 hours used) * (2 for MCF) * (20,000 cores) * (0.6 for regular queue) = 100,000 MPP hours.

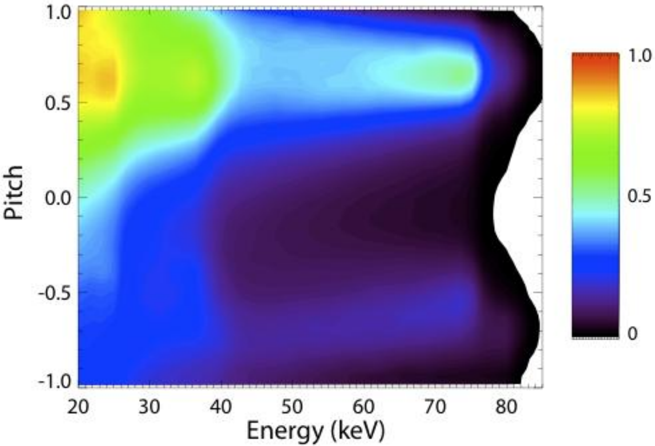


Verify hot particles in NIMROD on RSAE case

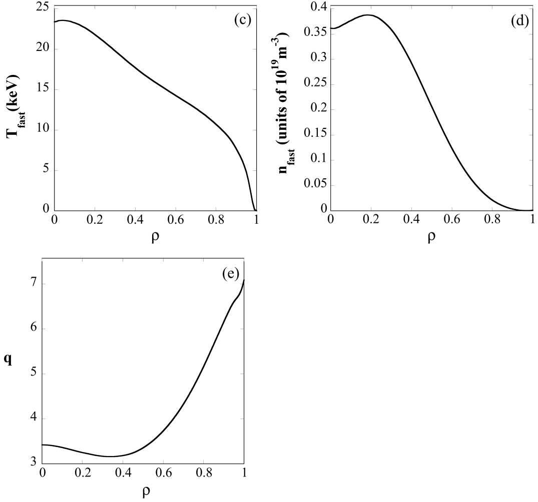
- From "Verification and validation of linear gyrokinetic simulation of Alfven eigenmodes in the DIII-D tokamak," Spong, *et al.*, Phys. Plasmas 19, 082511 (2012)

"Fully self-consistent simulation of energetic particle turbulence and transport in burning plasmas must incorporate three new physics elements: kinetic effects of thermal particles at the thermal ion gyro-radius (micro scale), nonlinear interactions of many meso scale (energetic particle gyro-radius) shear Alfvén waves induced by the kinetic effects at the micro scale, and meso-micro couplings of the micro-turbulence and shear Alfvén wave turbulence. The large dynamical ranges of spatial-temporal processes further require global simulation codes to be efficient in utilizing massively parallel computers. Therefore, the studies of energetic particle physics in the burning plasma regime require a new approach using gyrokinetic turbulence simulation. In this paper, we document progress in the verification and validation of the simulation of Alfvén eigenmodes using the advanced tokamak regime of the DIII-D experiment as a reference case."

- RSAE's driven by 4.6 MW of deuterium neutrals injected at 75-81 keV.
- Verification uses Maxwellian fast particles although TRANSP-NUBEAM predicts anisotropic distribution.

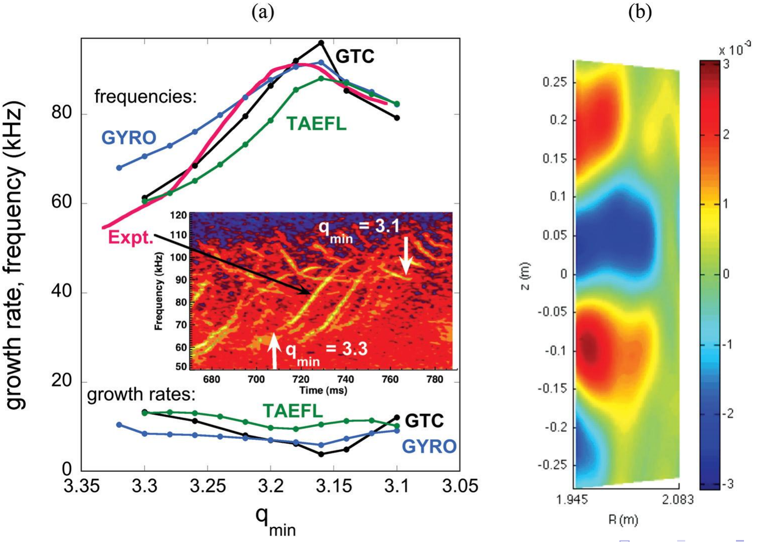


Hot particle Maxwellian used in benchmark

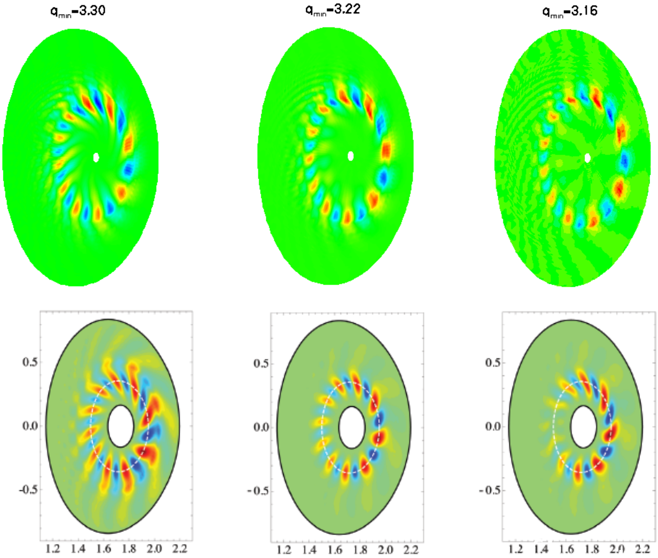


Growth and rotation rates change with q_{min}

- TAE real frequency changes as minimum in q decreases.



NIMROD/GYRO Eigenmode Comparisons



Future Work on Fast Particle Benchmarks

- Write fast particle verification paper that includes ideal kink benchmark (NIMROD continuum, NIMROD δf-PIC, and M3D δf-PIC) and RSAE results (verification with GTC, GYRO and TAEFL and validation with DIII-D).

- Collaborate with Tech-X and Wisconsin on Giant Sawteeth problem with continuum hot particles.

Theory work related to CEMM

- Jeong-Young Ji has two papers in preparation:
- "Electron Parallel Closures for Arbitrary Collisionality" provides fitted kernel functions for evaluating integral electron closures.
- "Electron Heat Transport in a Stochastic Magnetic Field" uses the electron parallel heat flow closure to estimate radial heat transport in the presence of magnetic field line fluctuations.