Update on giant sawtooth, importance of GS resolves, and improvements to PIC closures

E.D. Held, J. Jepson, T.G. Jenkins, S.E. Kruger

UtahStateUniversity

Outline

- Brief report on testing the accuracy of NIMROD equilibria with resolves of the Grad-Shafranov equation.
- Brief report on continuum kinetics applied to giant sawtooth problem.
- Improvements to NIMROD's delta-f PIC algorithm.
- Plans for continuum kinetics

Computation of vanishing contribution to ion distribution function.

- Test accuracy of NIMROD resolves of Grad-Shafranov equilibrium on vanishing neoclassical term predicted by Ramos for $\nu \sim \rho/L << 1$ (Phys. Plasmas 22, 070702 (2015)) :

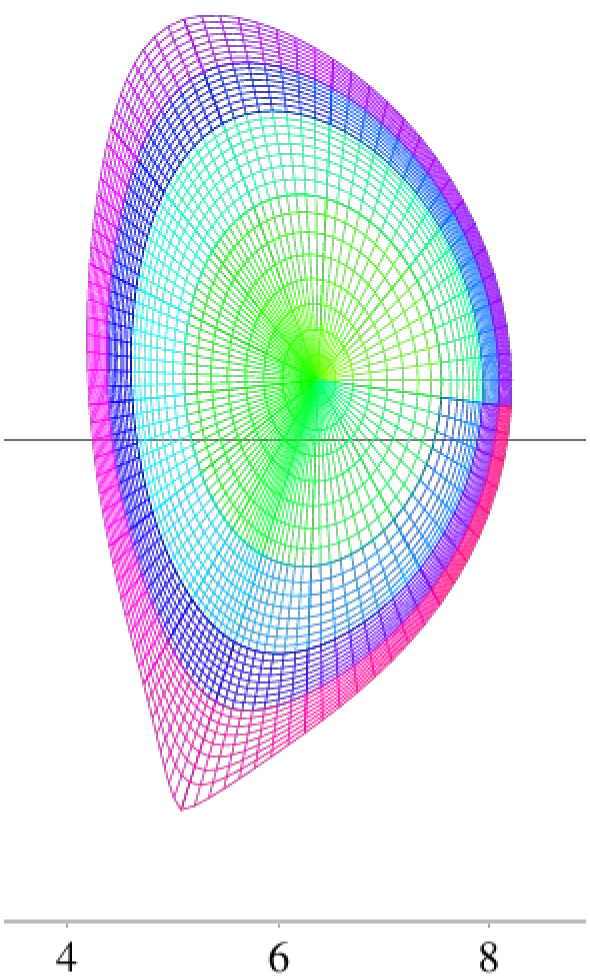
$$\Gamma\left(\psi\right) = 2\frac{d}{d\psi}\int dl\, B\cdot\nabla R^2 + \int \frac{dl}{B}\left[2\mathrm{b}\cdot\nabla\left(\nabla\psi\cdot\nabla\ln R^2\right) + \nabla\psi\cdot\nabla\left(b\cdot\nabla\ln B\right)\right]$$

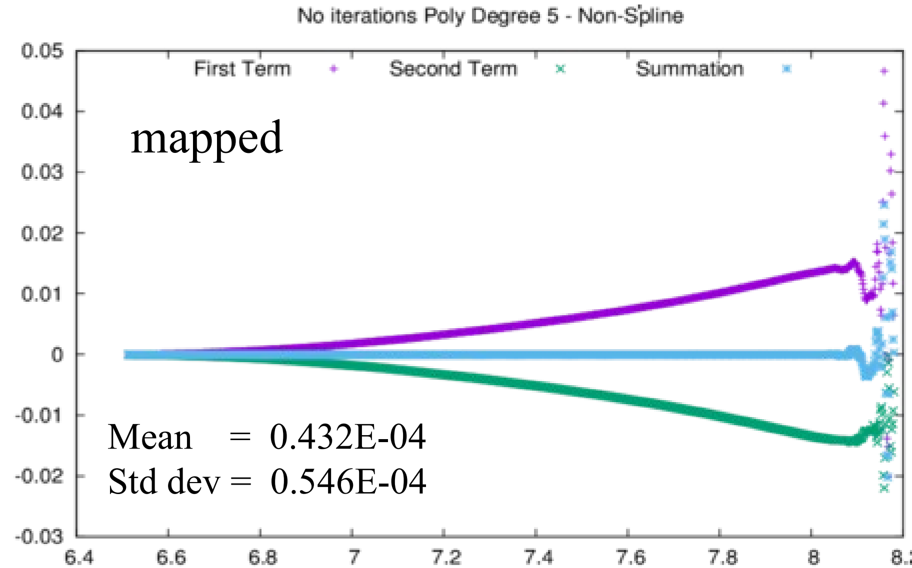
- Ramos writes, "Even though the result was masked by numerical noise, it was sufficiently suggestive of $\Gamma(\psi)$ being zero to motivate the search for the analytic proof that this geometrical function vanishes identically."

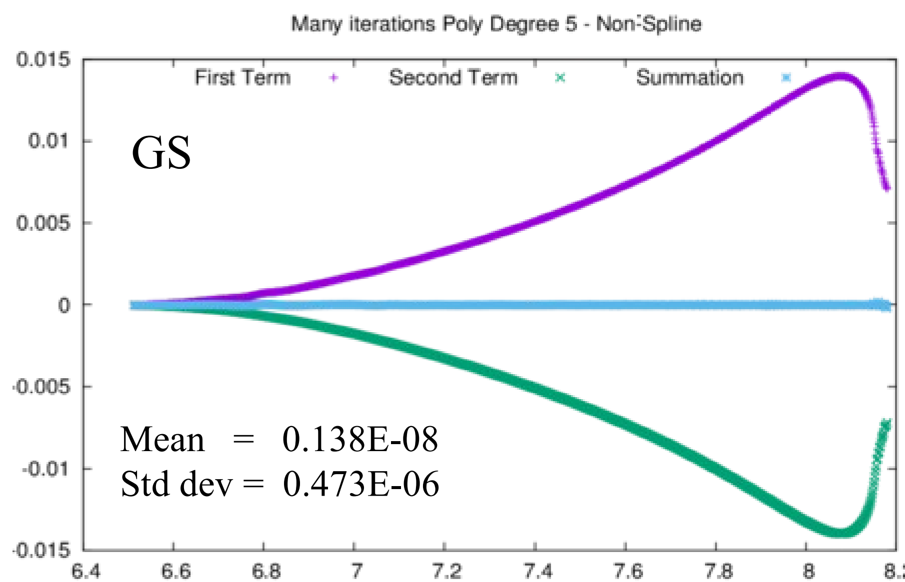
- Examine improvement to equilibria provided by GS resolves by testing the extent to which the two terms above cancel..

Results show importance of GS resolves.

- ITER equilibrium.

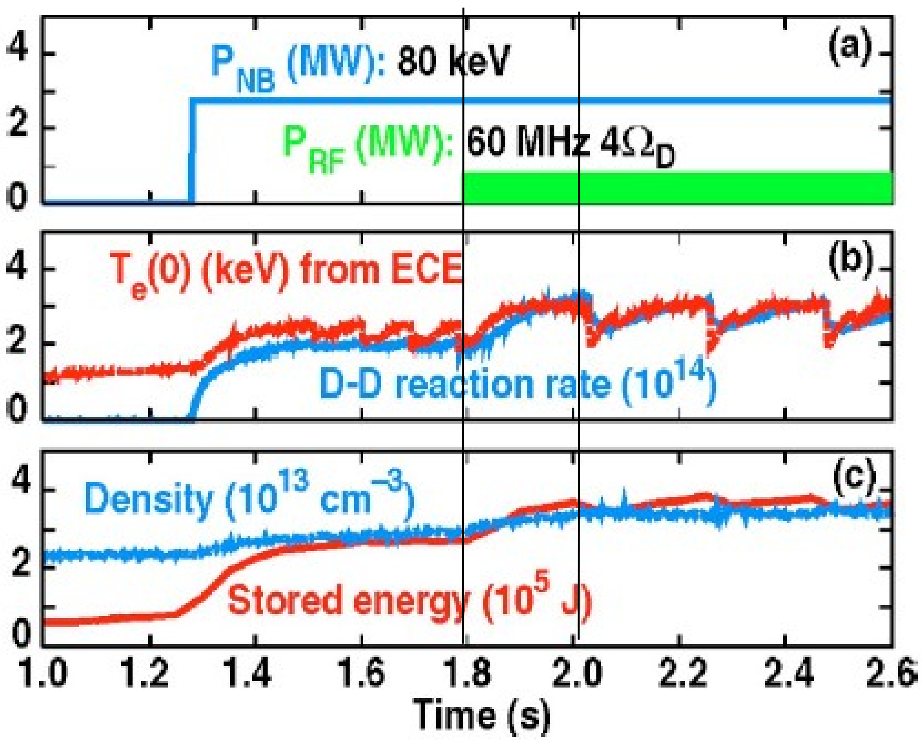


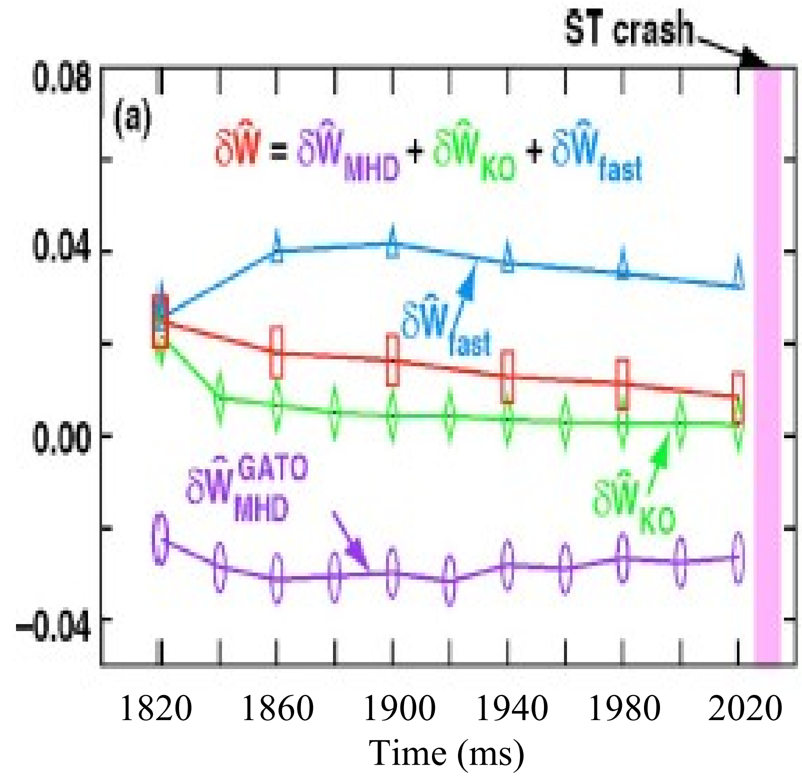




Background on giant sawooth problem

- RF-driven tail, slowing-down and thermal ions provide stabilizing effect on small sawteeth in DIII-D discharge #96043.
- Goal: use NIMROD to improve our understanding of this effect and the giant sawtooth cycle.

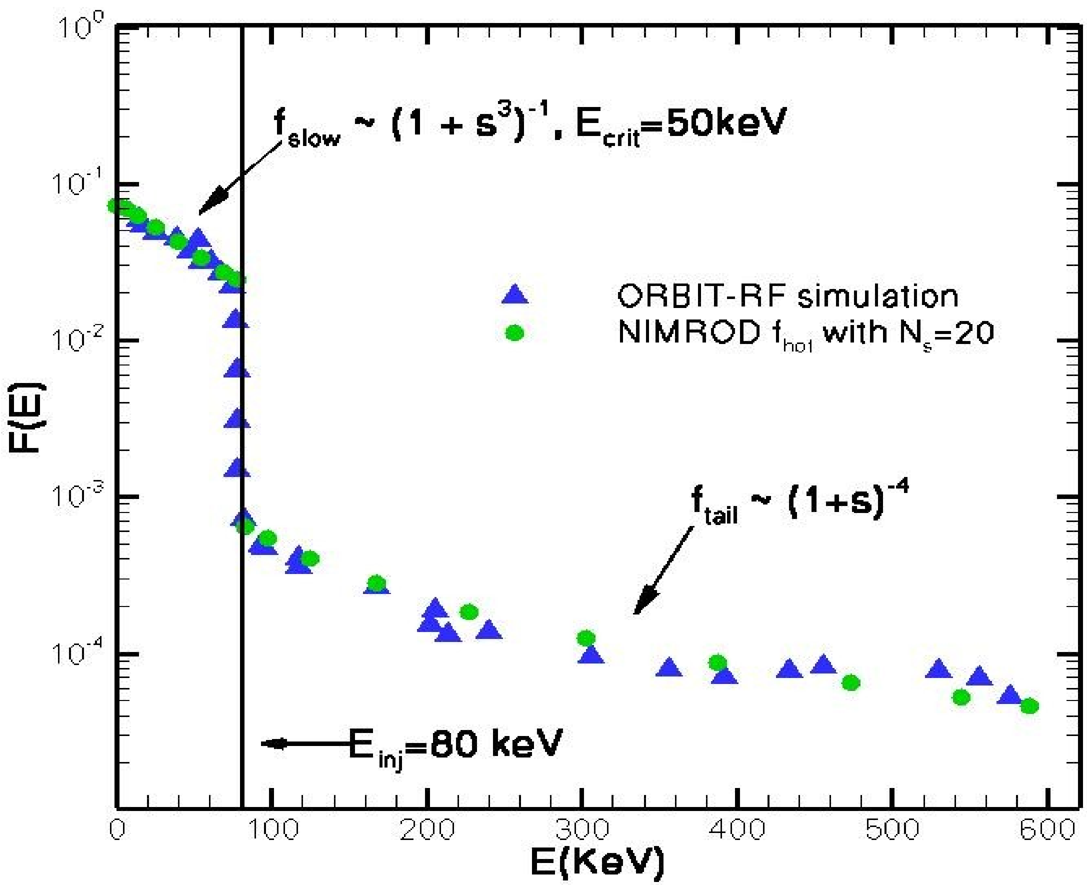




(Choi et al. POP, 2007).

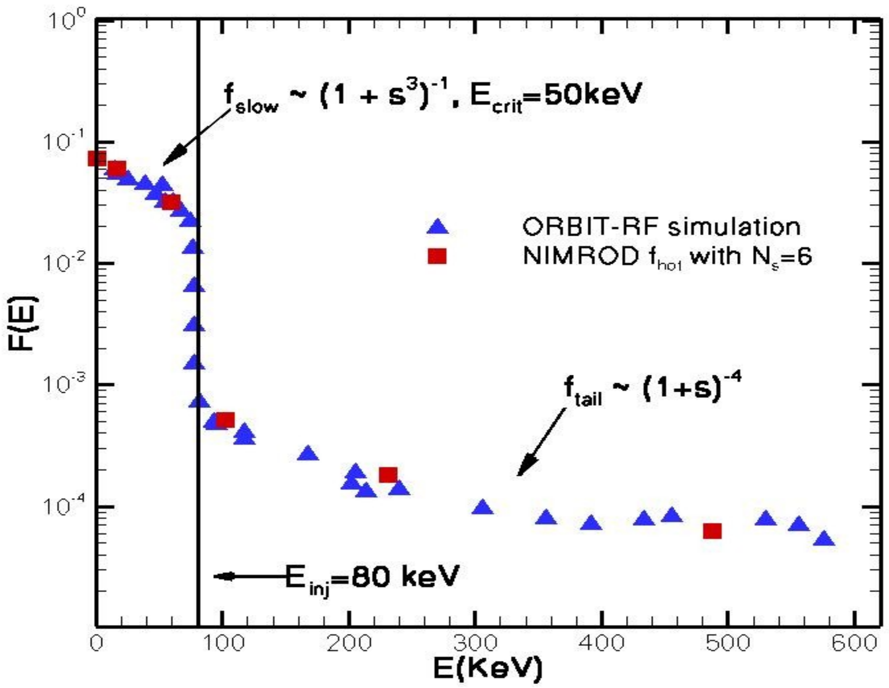
NIMROD's continuum kinetics applied to giant sawtooth.

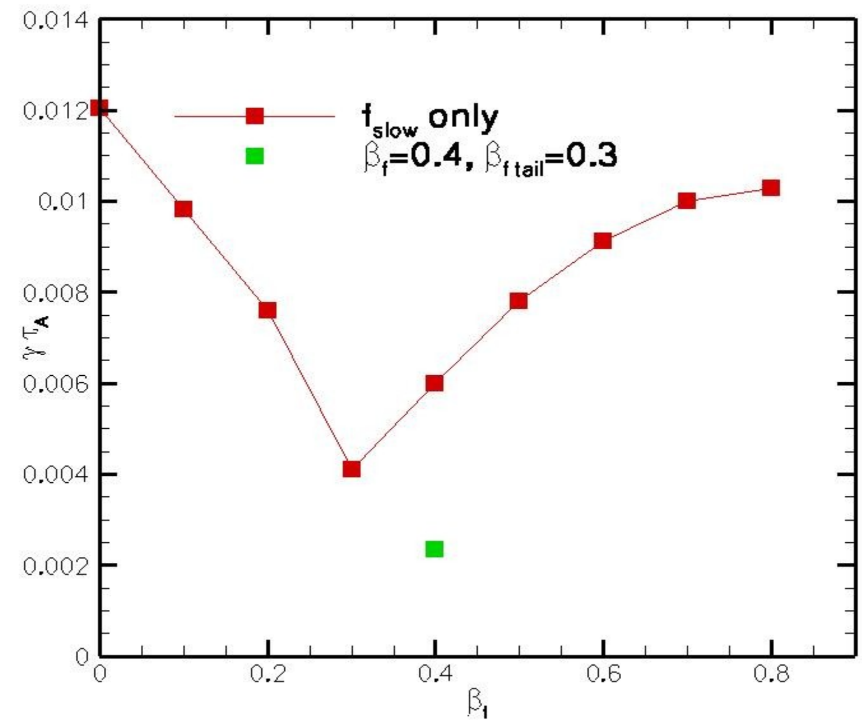
- Match energy dependence of slowing-down and RF tail ions.
- Use as lowest-order solution to energetic ion drift kinetic equation.
- Growth rates at t=1900ms insensitive to pitch-angle dependence.



Growth rate results.

- Low resolution cases (3 speed grid points) show stabilizing/destabilizing effect for slowing-down-only distribution in a hot particle β scan (red).
- RF tail provides further stabilization (green).





Is PIC compatible with NIMROD philosophy?

- PIC: Solution of the Boltzmann equation
  - Eulerian in real space, Lagrangian in velocity space
  - Fundamentally explicit
    - Has value in few ops/time step
  - Convergence in number of particles is slow, error $\sim N^{-1/2}$
    - Solutions are noisy
- NIMROD:
  - Heavily implicit
    - Many ops/time step
  - High-order finite elements
    - Convergence is fast when solutions are smooth
- Why use PIC in NIMROD?
  - Good at capturing fluid-particle resonances with small amount of velocity space resolution.

Previous efforts: Use different grids

- G-Y Fu, Parker, etc. (M3D)
  - Use uniform cartesian grid for particles
  - Interopolate fluid quantities from cartesian grid to non-uniform fluid grid

- Kim, Parker, Sovinec (NIMROD)
  - Use linear finite elements for particles in poloidal plane. Fourier modes for toroidal.
  - Bilinear FE grid used on top of NIMROD high-order grid
    - Never had Fourier parallelization working
    - Benchmarked with G-Y Fu's code (and NIMROD's continuum kinetics) for linear kink mode
- New development:
  - Use NIMROD's HO-FE for particle push (advance particles) and weight advance.
  - Retain linear elements for deposition
    - Cannot easily put noisy data within NIMROD cell with pd>1
    - Mass matrix inversion projects this onto NIMROD's solution space.

Implementation details

- Implementation uses map_mod routine originally developed for nimfl and integral closure
  - Use single rblock to advance particles in global domain.
  - Toroidal parallelization comes along for free.
  - Scalability limited, but sufficient for planned usage: Double check continuum, tracer particles, etc.
- Problem: High-order FE evals are expensive
- Solutions:
  - Take all quantities to be evaluated at point and place into single vector
  - Cache certain data at field eval step in push to allow usage at the deposition step to optimize over current implementation
  - Certain other optimizations made possible by cleaning up coding

Implementation details

- Single vector includes B,J,E:

```
rb(ibl)%partvar%fs(1:3,:,:,:)=rb(ibl)%be%fs,
rb(ibl)%partvar%fs(4:6,:,:,:)=rb(ibl)%ja%fs,
rb(ibl)%partvar%fs(7:9,:,:,:)=rb(ibl)%eef%fs
```

- Evaluation of fields:

```
equilibrium:  CALL get_field(xyp,rb_cel(1)%partvar_eq,outfld,bigr,1._r8)
perturbed:    CALL get_field(xyp,,rb_cel(1)%partvar, outfld)
```

Does lagr_quad_eval that has nice type vectoriziation: only 1 lagr_1D for each direction instead of 3 for each direction:

```
CALL lagr_1D(pd,x-ix,alx,dalx,dmode)
CALL lagr_1D(pd,y-iy,aly,daly,dmode)
 laq%f=(laq%fs(:,ix  ,iy  ,:)*alx(0)+laq%fs(:,ix+1,iy  ,:)*alx(1))*aly(0)
+ (laq%fs(:,ix  ,iy+1,:)*alx(0) +laq%fs(:,ix+1,iy+1,:)*alx(1))*aly(1)
```

Plans for continuum kinetics

- Continuum energetic ions
  - quantitative verification with NIMROD's delta-f PIC (higher-order fields in push and weight advance may help)
  - explore anisotropic pressure versus current coupling
  - finish RSAE benchmark and giant sawtooth

- Continuum electrons
  - finish implementation of Ramos form for electron DKE (requires rewrite of acceleration term)
  - anisotropic conduction test problems using kinetic parallel heat flow closure in island geometry
  - applications with 3D fields: NTMs, RMPs
  - implement relativistic electron DKE

- Continuum ions
  - neoclassical toroidal viscosity studies
  - implement Ramos from for ion DKE (considerably messier than electron version)