Giant Sawtooth Modeling with NIMROD

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in collaboration with

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Sawtooth basics

Normal/giant sawtooth modes

-Plasma has q(0) > 1, peaked current density on axis

-Ohmic heating introduced (e.g. 80 keV neutral beam)

-Preferential heating near axis (higher J) ➔ decreased core resistivity ($\sim T^{-3/2}$) ➔ further current peaking, dropping q(0)

-(1,1) internal kink instability triggered when q(0) < 1

-Energetic particle population (e.g. induced by RF heating) alters internal kink stability ➔ higher Te and stored energy

-Potential trigger for ELMs, NTMs, large wall heat load

DIII-D shot #96043

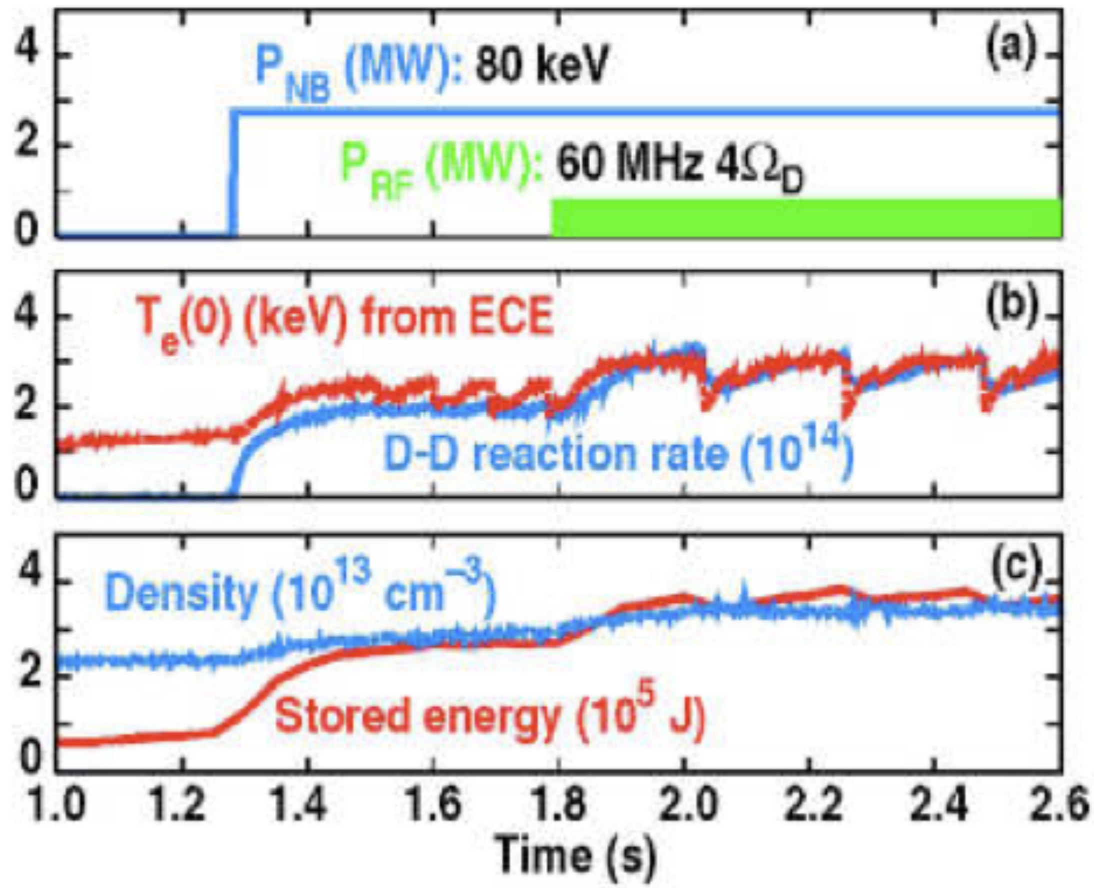


Figure from M. Choi et al., *Sawtooth control using beam ions accelerated by fast waves in the DIII-D tokamak*, Phys. Plasmas **14**, 112517 (2007).

Sawtooth stability

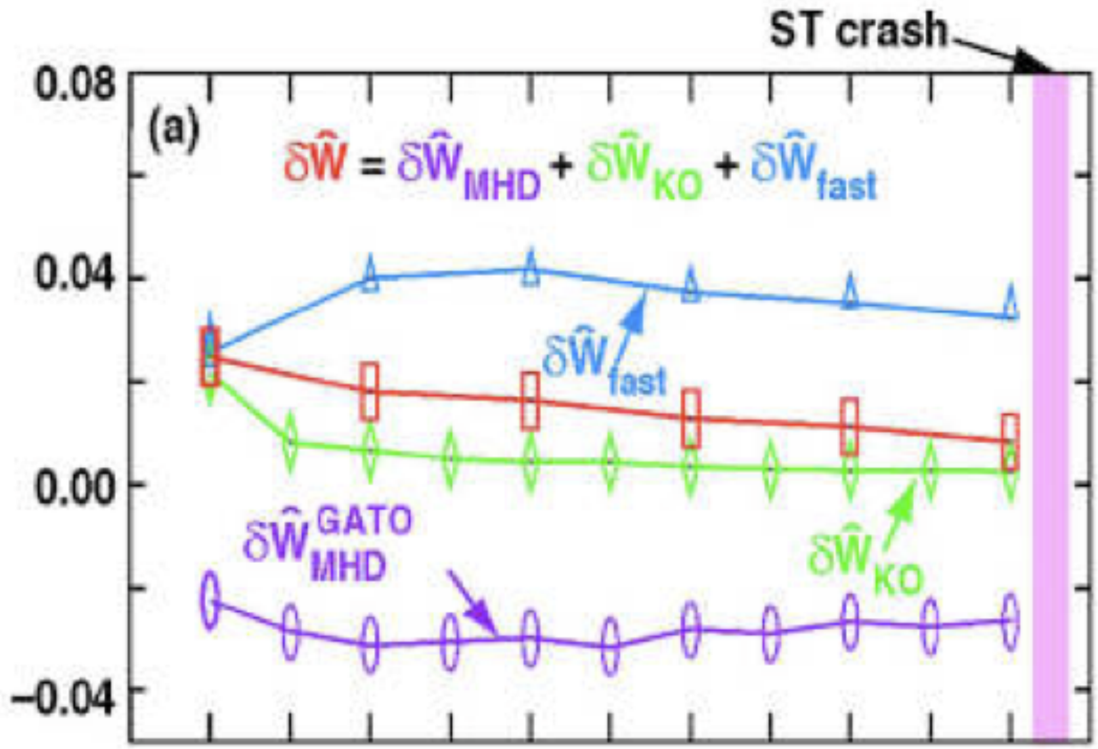


Figure from M. Choi et al., *Sawtooth control using beam ions accelerated by fast waves in the DIII-D tokamak*, Phys. Plasmas **14**, 112517 (2007).

Hot-particle effects

Bulk pressure tensor effects

Ideal MHD effects

Total stability parameter

- Does ideal MHD + hot-particle kinetics explain everything?
- Role of two-fluid effects?

Hot-particle sawtooth stabilization in NIMROD: computational approach

Momentum equation has an extra term:

$$\rho\frac{\partial\vec{V}}{\partial t}+\rho(\vec{V}\cdot\nabla)\vec{V}=\vec{J}\times\vec{B}-\nabla\cdot\overleftrightarrow{P}-\nabla\cdot\overleftrightarrow{P}_{hot}$$

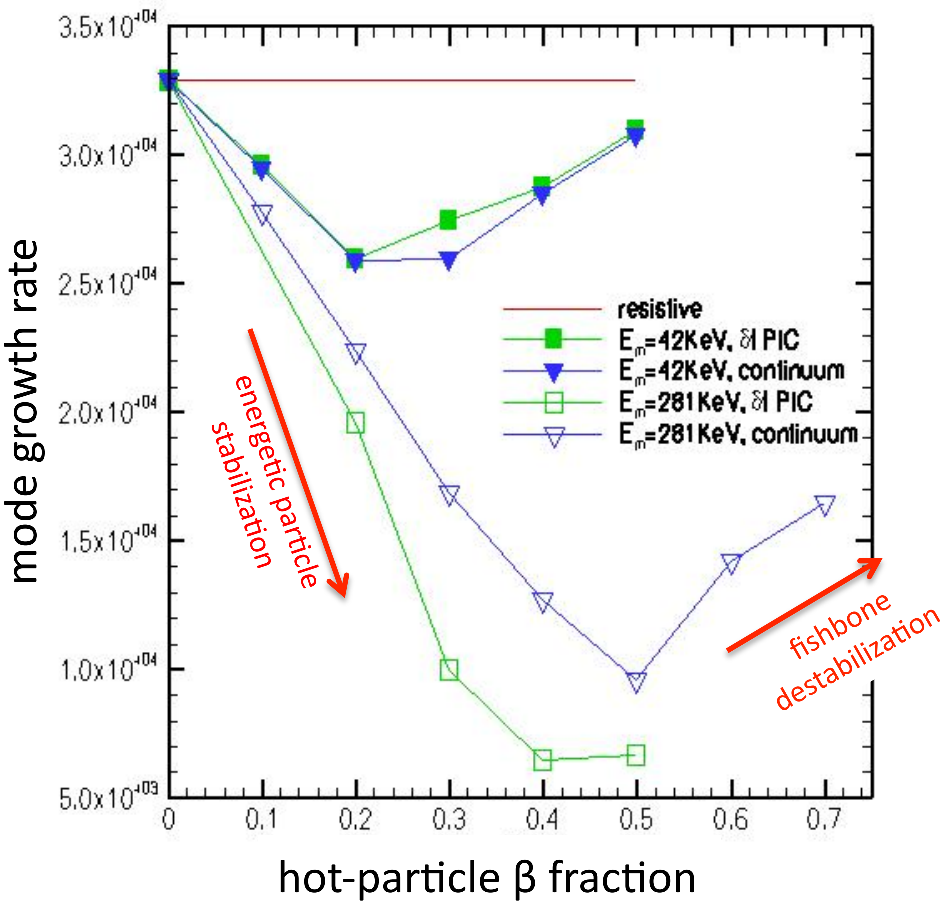
Continuum kinetic:

$\overleftrightarrow{P}_{hot}$ represented by moments of Eric's solution to drift-kinetic equation

Kinetic PIC:

$\overleftrightarrow{P}_{hot}$ represented by moments of evolving PIC distribution

Revisiting Dalton's linear sawtooth runs



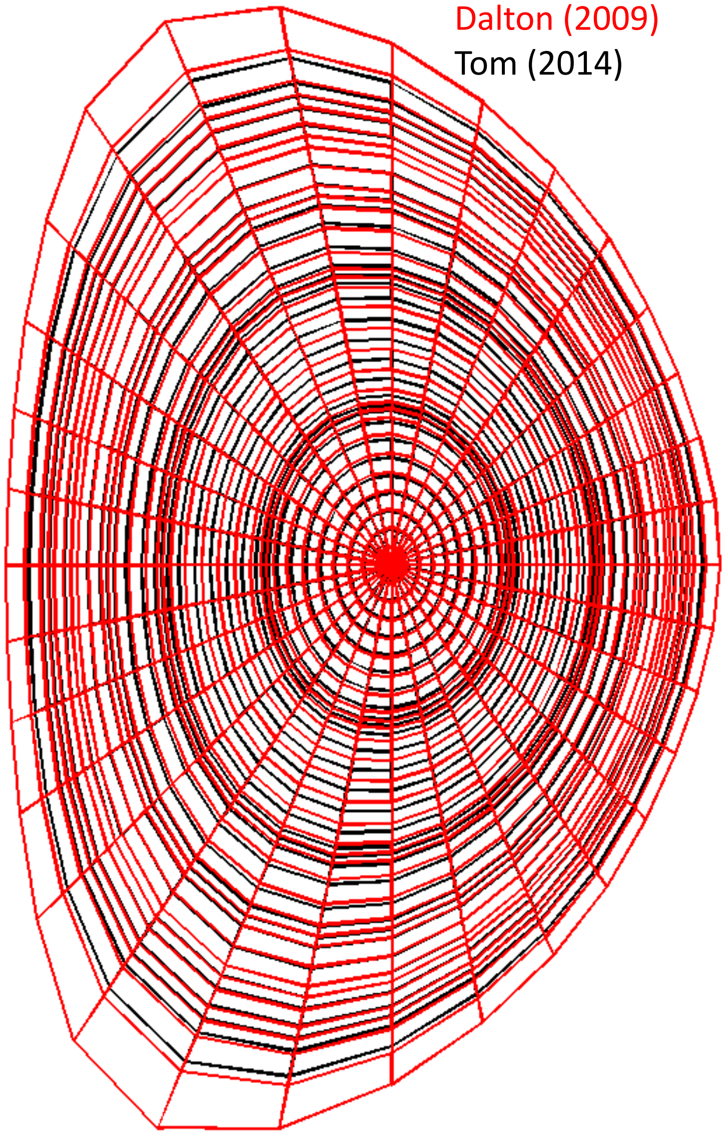
E_m = peak energy of slowing-down distribution function

•From Dalton's logbook, have begun to sort out the details of what he was doing and why.

•Initially, looking at linear scans in more detail to understand the basic sawtooth physics and the PIC algorithms.

•Basic sanity check - can we reproduce some basic results Dalton got, e.g. linear MHD mode growth with and without hot particles?

Despite a five year time gap, we can reproduce Dalton's linear MHD results pretty well

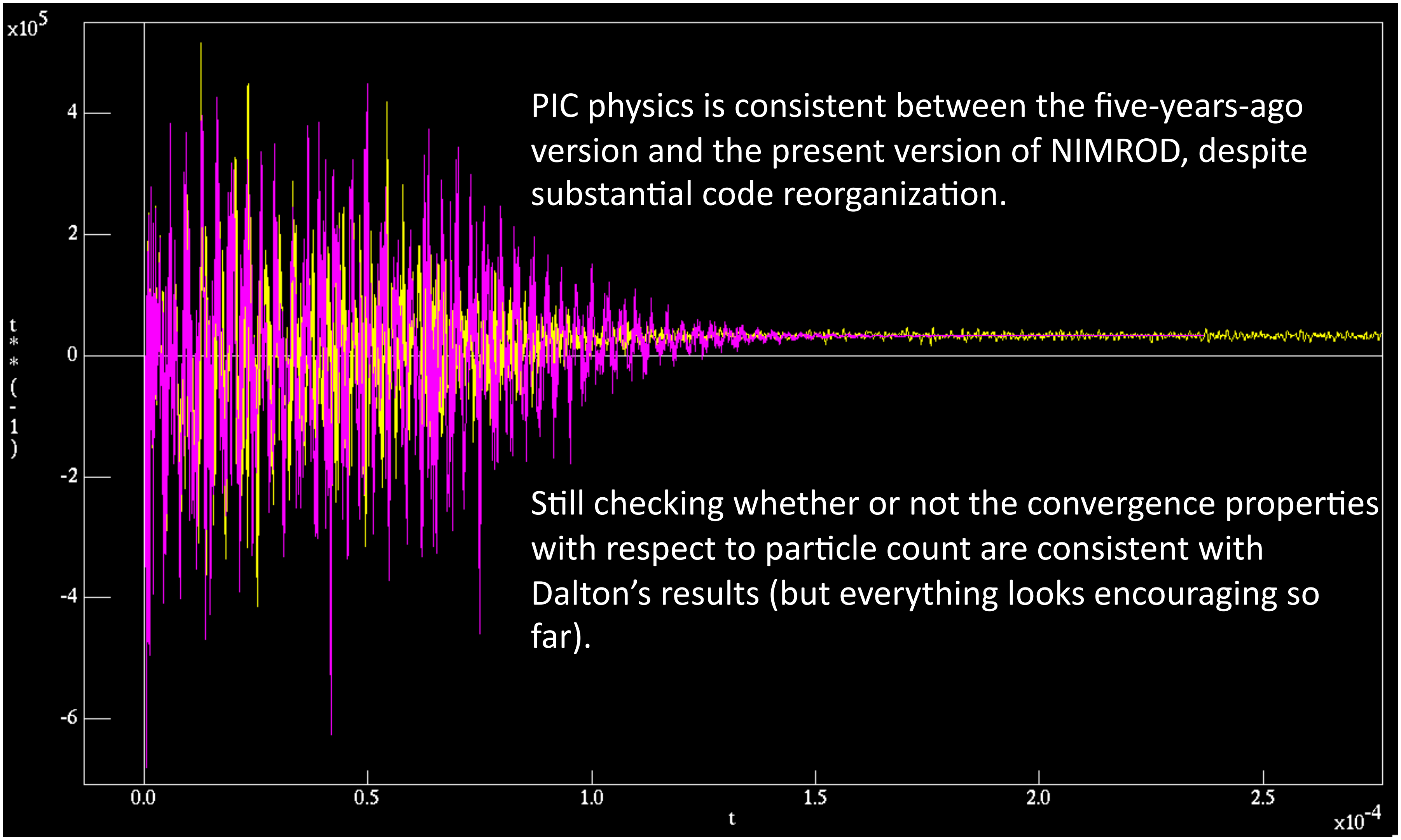


•Old input files now generate a slightly different grid (conducting wall boundary); slight alterations regenerate the old grid and yield reasonably comparable growth rates (γ_D = 3.341 x 10^4 s^{-1}, γ_T = 3.277 x 10^4 s^{-1}) for linear n = 1 growth (no hot particles). Run appears to be converged with respect to grid refinement.

•When hot particles are added, parameters in old input file need to be renormalized to match new code conventions (energy in J, not keV).

$$f_0 = \frac{P_0 \exp\left(\frac{4 v_{\|} R B_\phi}{\Omega \psi_0} - \frac{4\psi}{\psi_0} \right)}{\varepsilon^{3/2} + \varepsilon_{crit}^{3/2}}$$

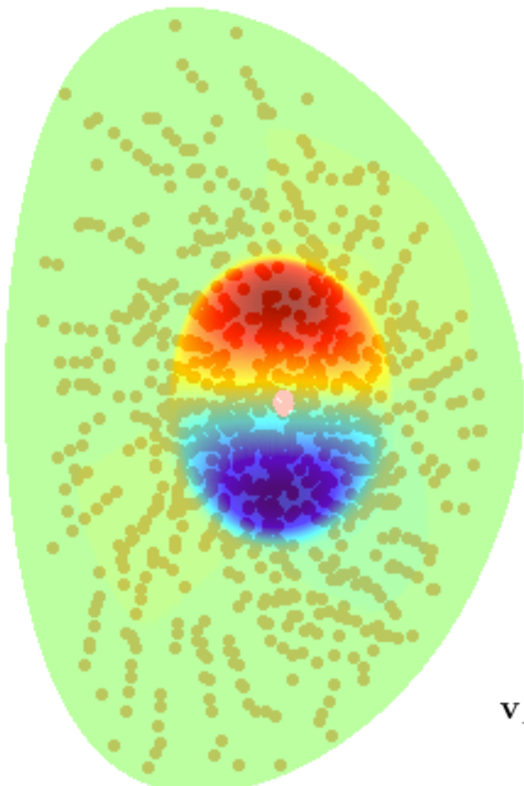
Linear MHD growth rates with hot particles (n = 1) also match Dalton's old results



PIC physics is consistent between the five-years-ago version and the present version of NIMROD, despite substantial code reorganization.

Still checking whether or not the convergence properties with respect to particle count are consistent with Dalton's results (but everything looks encouraging so far).

Hot-particle formulation: kinetic-PIC



Begin with Eric's drift-kinetic equation

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

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

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

in pitch angle and normalized speed coordinates

$$\xi = v_{||}/v \qquad s = v/v_0$$

and with drift velocity

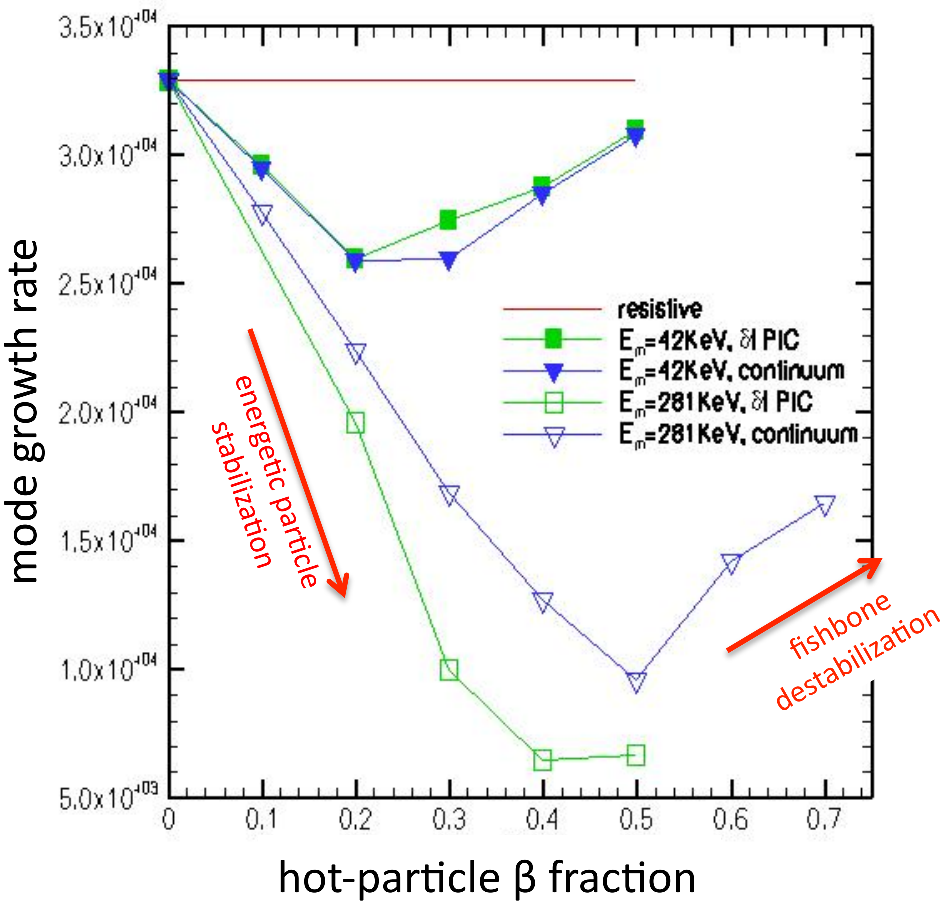
$$\mathbf{v}_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{T_0 s^2}{q B^2} \left[\left(1+\xi^2\right) \mathbf{b} \times \nabla B + 2\xi^2 \mu_0 \mathbf{J}_\perp + (1-\xi^2) \mu_0 \mathbf{J}_{||} \right] + \frac{m v_0 s \xi}{q B^2} \mathbf{b} \times \frac{\partial \mathbf{B}}{\partial t}$$

Most general case – let f = f_0 + δf, and formulate a weight equation for δf-PIC.

How to calculate derivatives of f_0 on RHS of weight equation?

- -Analytically (Dalton/Charlson)
- -Numerically (using Eric's new continuum closure datastructures)

Sensible benchmarking



E_m = peak energy of slowing-down distribution function

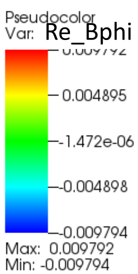
- Some concerns about whether the equilibria used in this benchmark are the same for PIC and continuum cases.

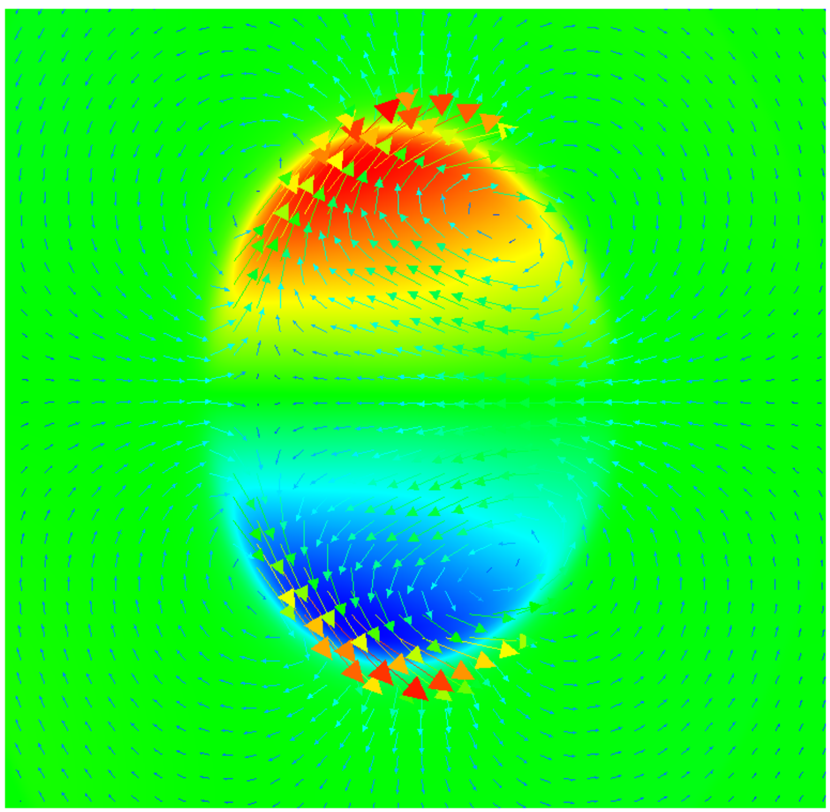
- Will also be meeting with Alan Turnbull this week to ensure that we understand assumptions underlying the DIII-D EFIT equilibrium on which these cases are based.

2-fluid and nonlinear computations

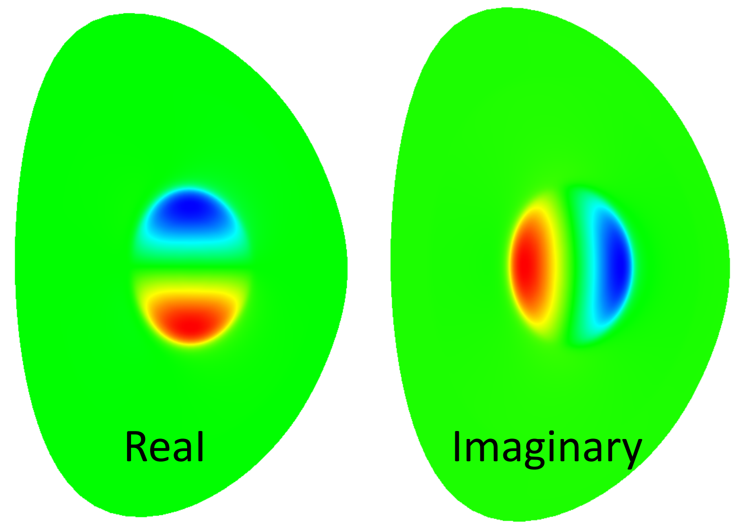
•Initial testing of nonlinear and two-fluid capabilities is being carried out (working with Eric, Jake, Carl) – no notable results yet.

New HDF5 interface – visualization with VisIt





Perturbed magnetic field (Br, Bz vectors)



Perturbed T_e

Relevant CEMM milestones

	Year 4	Year 5
Sawtooth	•Apply continuum closure models for energetic and thermal ions to the Giant Sawtooth problem (Tech-X).	•Continue linear modeling of sawtooth stabilization in DIII-D shot 96043 (Tech-X). •Demonstrate nonlinear evolution of sawtooth with continuum kinetic closures and extended MHD Ohm's law (Tech-X/USU).
Model development - continuum kinetic (with Eric Held)	•Improve parallel scaling of kinetic closures (USU).	•Demonstrate applicability by applying to a 3D coupled problem (USU/Tech-X)
Model development - kinetic PIC	•Begin new particle parallelization development for NIMROD (Tech-X).	•Complete, test, and apply the new particle parallelization in NIMROD (Tech-X).

Plan of action going forward

- Continue exploring the extent to which Dalton's runs characterize the MHD and 2-fluid(?) behavior of linear sawtooth onset – fill in the gaps
- Exercise different combinations of physics components – MHD, 2-fluid, parallel closure, particles (all of them important for this work at some level)
- Near-term goal – ensure self-consistency between PIC and continuum approaches, in collaboration with Eric. Get experience using particle capabilities and continuum kinetic capabilities.
- Longer-term goals – gaining physics/computational insights with NIMROD
  -code performance improvements for development milestone
  -examine the effect of more general hot-particle distribution functions
- Eventual milestone – DIII-D shot 96043 modeling