MODELING GIANT SAWTOOTH MODES WITH PIC CLOSURES IN NIMROD: RECENT PROGRESS

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Sawtooth and giant sawtooth basics

- Plasma has $q(0) > 1$, peaked current density on axis
- Ohmic heating introduced (e.g. 80 keV neutral beam), leads to current peaking and decreased $q(0)$
- $(1,1)$ internal kink instability triggered when $q(0) < 1$
- Energetic particle population (e.g. induced by RF heating, or fusion reactions) alters stability of internal kink mode
- Higher temperatures and stored energies achievable even with $q(0) < 1$
- Terminates like a normal sawtooth crash, but with larger amplitude

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 sawtooth stabilization in NIMROD: PIC approach

Momentum equation has an extra term:

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

**Kinetic PIC:**

\( \vec{P}_{\text{hot}} \) represented by moments of PIC distribution, evolving according to drift-kinetic equation

\[ \vec{P} \rightarrow (1 - \beta_{\text{frac}})\vec{P} \]

\[ \vec{P}_{\text{hot}} = \beta_{\text{frac}} \vec{P} \]

comes from energetic particles, via \( T_i \) (energetic particles have low density and high temperature; \( n_{\text{hot}} \ll n \) but \( P_{\text{hot}} \sim P \))

Some fraction of fluid pressure removed; put back in as hot particles
Update from the summer meeting

• At the summer Boulder meeting, I showed results with unphysically large linear perturbation amplitudes that ensued when the PIC closure was used for hot particle modeling

  - Reason – phqty parameter (documented as “number of independent components in the pressure tensor”); setting phqty = 2 introduces a serious bug

  - phqty = 6 option has correct physics so we are using that at present
Other issues with the PIC closures are being addressed

- Eric and I have been also been looking at a number of other issues (in separate branches):
  - Hot particle rescaling of pressure only modifies ion temperature, but for single-fluid MHD this does not seem correct
  - Degeneracy at grid center leads to unphysical spike when particles are mapped to NIMROD grid (use bmxs parameter to modify – linear growth insensitive to this)
  - Some inconsistencies in weight equation, as it relates to background distribution function $f_{\text{hot}}^0$,
  - Verifying signs of terms which use psi from EFIT file (now a signed quantity)

Having both continuum and PIC closures, either of which can be used for a given problem, has been tremendously helpful in working out these issues.
Plot shows prior results with hot particles.

- Anisotropic stress tensor for hot particles couples to NIMROD’s momentum equation.
- With improved equilibria
  - revisit NIMROD’s continuum and $\delta f$-PIC predictions for slowing-down $f_0$ only.
  - add RF driven-tail to see if that fully stabilizes the ideal kink.
  - add anisotropic stress closure for thermal ions and two-fluid effects in more complete simulations.
Examples of $f_{\text{slow}}$.

\[ f_{\text{slow}} = A \exp(-\langle \psi \rangle / \psi_0) / (1 + s^3) \]

\[ f_0 = A \exp(-\langle \psi \rangle / \psi_0) / (1 + s^3) \]

\[ \langle \psi \rangle = P_\zeta / e - m \left( v_{\parallel} R \frac{B_0}{B} \right) \approx P_\zeta / e, \text{ trapped} \]

\[ \langle \psi \rangle \approx P_\zeta / e - v R_0 \text{sign} \left( \frac{v_{\parallel}}{v} \right) \sqrt{1 - \mu B_0 / E}, \text{ passing.} \]

\[ f_0(\psi, s) = A \rho_{\text{MHD}}(\psi) / (1 + s^3) \]
Results from $E_{\text{crit}} = 50$ keV and $E_{\text{inj}} = 80$ keV calculations.

- Growth rates relatively insensitive to pitch-angle anisotropy.
- Results in Choi et al. use $\delta \hat{W}_{\text{fast}} = C_f \varepsilon_1^{3/2} \beta_{\text{ph}} / s_1$ where $\beta_{\text{ph}}$ is isotropic, poloidal beta inside the $q=1$ surface.
Results from $E_{\text{crit}} = 28$ keV and $E_{\text{inj}} = 227$ keV calculations.

- Higher-energy particles = stronger stabilization.
- Difficult to ascertain γ’s from PIC calculations.
- Improve fidelity by addressing high-energy RF tail.
Comparison of growth rates for continuum and PIC.

- Compare $\beta_f = 0.3$ cases from previous slide: continuum(pink), 2e6 particles(green), 8e6 particles(blue).
Improve fidelity by incorporating RF tail in continuum calculations.

- Match energy dependence of ORBIT-RF simulations.
- Lowest-order energetic particle distribution $f_0 = f_{\text{slow}} + f_{\text{tail}}$.
Result from one low s resolution case.

- Continuing with higher resolution cases on Edison and Mira.
Goal: with hot particles, show that we can find a decreasing window of stability in the run-up to the giant sawtooth crash.
Conclusions

- Slowing-down-only growth rates insensitive to pitch-angle anisotropy in $f_0$.
- Continuum and PIC growth rates agree.
- Continuum simulations with RF tail underway for 6 equilibria in first giant sawtooth cycle.
- Remains to be seen if full stabilization requires anisotropic stress closure for thermal ions and/or two-fluid effects.