Progress on Modeling Giant Sawtooth Modes with NIMROD

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NIMROD team meeting
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Dalton’s NERSC data – a rather extensive digital curation project

• With help from Carl, we now have access to Dalton’s old NERSC data that was stored in HPSS.

• 1200 directories, 60k files, 740 GB –
  - DEBS
  - MRX
  - ELM studies (Dylan?)
  - SAIC stuff
  - NIMROD
  - other enigmatic acronyms

  Data going all the way back to 1989...

• Fortunately, most files are timestamped (either with original last-modified dates or with the date they were HPSS-archived), so finding the giant sawtooth runs has not been terribly difficult. Also, can look at nimrun.summary to find when batch scripts were generated, and get approximate timeframe.

• General approach:
  - Correlate timestamps on files to timing of presentations/talks/etc.
  - Look for groups of runs that are the same
  - Try to deduce what Dalton was thinking at the time, and why particular lines of inquiry were not pursued.

• A very convenient NERSC utility, with some limitations:
  http://my.nersc.gov/filebrowser.php
Facilitates file transfer to local machines, both from Hopper/Edison/etc., and HPSS

Log in at [http://my.nersc.gov/filebrowser.php](http://my.nersc.gov/filebrowser.php)
DIII-D equilibrium files are in HPSS

DIII-D shot #96043

• 40 EFIT files (from Alan Turnbull) from within the orange box

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).
“Best practices” for NERSC HPSS storage have introduced some complications

NERSC filebrowser utility does not work for large files, so it’s easier to get the nimrod.in files for directories that were archived as-is (not tar-ed). (About 25% of sawtooth runs – can move these files directly to my laptop with point-and-click.)

Directories in a tarball require more complicated workflow to even look at nimrod.in.
Large groups of similar datasets are usually pretty easy to explain

- From nimrod.in:
  - \( \text{vhmx}=2e6 \)
  - \( \text{mass0}=3.3435e-27 \),

Let \( E = \frac{1}{2} \times \text{mass0} \times \text{vhmx}^2 = 6.68e-15 \) J = 41.75 keV;
this is the top green plot.

- Run growth.py script to get growth rate of mode – agrees.

<table>
<thead>
<tr>
<th>Npart</th>
<th>( \beta )frac</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
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</thead>
<tbody>
<tr>
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<td>004bt</td>
<td>004bo</td>
<td>004bl</td>
<td>004bq</td>
<td>004bi</td>
<td></td>
</tr>
<tr>
<td>2 million</td>
<td>004bu</td>
<td>004bp</td>
<td>004bm</td>
<td>004br</td>
<td>004bj</td>
<td></td>
</tr>
<tr>
<td>4 million</td>
<td></td>
<td></td>
<td>004bn</td>
<td>004bs</td>
<td>004bk</td>
<td></td>
</tr>
</tbody>
</table>

convergence in particle number

scan in beta fraction
Other times it is not clear what went wrong

• What’s the growth rate?

• Several runs in a row, with varying betafrac – the approach was evidently abandoned (bad particle parameters? bugs that have since been fixed? Not immediately obvious.)

• Possible exercise: rerun some of the two-fluid cases that did not run for Dalton; see if bug fixes since that time have improved anything.
## Relevant CEMM sawtooth milestones

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

**Related physics/computation issues**

- Energetic particle kink stabilization, fishbone destabilization as β fraction increased

- Stabilization (3\textsuperscript{rd} adiabatic invariant – toroidal precession of energetic trapped particles modifies MHD) requires
  \[ \omega_{pd}/\gamma_R >> 1 \]
  (growth slow compared to precession)
  but for these cases,
  \[ \omega_{pd}/\gamma_R = 1.5 \text{ (42 keV)} \]
  \[ \omega_{pd}/\gamma_R = 10 \text{ (281 keV)} \]

Can we run at high enough energies and Lundquist numbers to achieve full stabilization? (particle population in phase space)

How much does the form of the hot-particle distribution function matter?

\[ E_m = \text{peak energy of slowing-down distribution function} \]
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

• Different combinations of physics components – MHD, 2-fluid, parallel closure, particles (all of them important for this work at some level)

• Near-term goal – understand/supplement MHD/2-fluid results so that they can be published
  - Goal – submit to Physics of Plasmas by this coming spring

• Longer-term goals – gaining physics/computational insights with NIMROD
  - get experience using particle capabilities and continuum kinetic capabilities
  - assess/begin code performance improvements for development milestone
  - examine the effect of more general hot-particle distribution functions

• Milestone – DIII-D shot 96043 modeling
Extra slides
Sawtooth basics

*Normal sawtooth mode*

- Plasma has $q(0) > 1$, peaked current density on axis
- Ohmic heating introduced (e.g. 80 keV neutral beam)
- Plasma near axis preferentially heated (higher J) $\Rightarrow$ decreased core resistivity ($\sim T^{-3/2}$) $\Rightarrow$ further current peaking, decreased $q(0)$
- (1,1) internal kink instability triggered when $q(0) < 1$, which rearranges magnetic flux and flattens temperature profile
- Cycle repeats

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).
Giant sawtooth basics

**Giant sawtooth mode**

- 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
- Potential trigger for ELMs, NTMs, large heat transfer to vessel wall

“slow leak” description
“soft \( \beta \) limit”

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).