Simulations of Low-q Disruptions in CTH

E.C. Howell and the CTH Team

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The Compact Toroidal Hybrid device (CTH) is stellarator-tokamak hybrid designed to study the effects of 3D shaping on MHD instabilities.

<table>
<thead>
<tr>
<th>CTH Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Periods</td>
<td>5</td>
</tr>
<tr>
<td>Major Radius</td>
<td>0.75m</td>
</tr>
<tr>
<td>Minor Radius</td>
<td>0.20m</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>≤ 0.7 T</td>
</tr>
<tr>
<td>Plasma Current</td>
<td>≤ 80kA</td>
</tr>
<tr>
<td>Number Density</td>
<td>≤ 5 \times 10^{19} \text{m}^{-3}</td>
</tr>
<tr>
<td>Electron Temperature</td>
<td>≤ 200 eV</td>
</tr>
</tbody>
</table>

- The rotational transform is generated by a combination of currents in external 3D helical coils and internal plasma currents.
  - The rotational transform, $\tau$, is the inverse of the safety factor: $\tau = 1/q$.
- The fractional transform, $f$, quantifies the amount of 3D shaping.
  - $f = \tau_{\text{vac}}/\tau_{\text{total}}$
- CTH can operate with a fractional transform that ranges from $f = 4\%$ to $f = 100\%$ by adjusting the plasma current.
A small amount of vacuum rotational transform allows CTH to operate with \( q(a) < 2 \).

- External kink stability typically limits tokamak operation to \( q(a) \geq 2 \).
- Strong \( m/n = 2/1 \) mode activity is not observed in CTH when \( q(a) \) passes through 2.
- Disruptions are observed in these low-q discharges after peak plasma current.
  - 3/2 mode activity is observed in both disrupting and non-disrupting discharges.
  - 4/3 mode activity is only observed in disrupting discharges.
  - 1/1 activity is observed in both cases.
- Disruptions occur when the edge safety factor passes through \( q(a) \approx 1.7 \).

[M. D. Pandya et al., POP 22, 2015]
Low-q disruptions are suppressed at large vacuum transform.

- The frequency of disruptions decreases with increasing vacuum transform.
  - Disruptions always occur when $t_{\text{vac}} \lesssim 0.03$
  - Disruptions are completely suppressed for $t_{\text{vac}} \gtrsim 0.07$.

- Here $q_{\text{tot}}(a)$ is the value of the edge safety factor at peak plasma current.
NIMROD is being used to model low-q disruptions in CTH.

- Simulations model a discharge with a small vacuum transform, $t_{\text{vac}} = 0.015$, and strong soft X-ray signals.
- Soft X-ray signals help constrain the reconstructed internal current profile.
- Low $t_{\text{vac}}$ eases toroidal resolution requirements.
- Low $t_{\text{vac}}$ discharges are most likely to disrupt.
- Simulations are initialized 2ms before the disruption.
Nonlinear simulations are initialized with \texttt{v3FIT} reconstructions of experimental discharges.

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NIMROD Simulations of Low-q Discharges in CTH
Previous simulations exhibited a variety of MHD activity but did not disrupt.

- A loop voltage is applied to sustain the net toroidal current.
- The safety factor decreased due to a steeping of the current profile.
- A chain of 5/5 islands is destabilized when $q_0$ drops below 1.
- Simulations use 86 Fourier modes.
A 3D current source is added to sustain the current profile.

\[
\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left[ \eta \left( \vec{J} - \vec{J}_S \right) - \vec{V} \times \vec{B} \right] + k_{\text{divb}} \nabla \nabla \cdot \vec{B}
\]

\[
\frac{\partial n}{\partial t} + \nabla \cdot \left( n \vec{V} \right) = \nabla \cdot \left( D \nabla n - D_h \nabla^2 n \right)
\]

\[
\rho \left( \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} \right) = \vec{J} \times \vec{B} - \nabla P - \nabla \cdot \vec{q}
\]

\[
\frac{3}{2} n \left( \frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T \right) = -P \nabla \cdot \vec{V} - \nabla \cdot \vec{q} + \eta J^2
\]

- 3D Equilibrium current is subtracted from the total current in Ohm’s law.
- This prevents the equilibrium current from resistively decaying.
- No loop voltage is applied.
MHD activity is observed when the $n = 2$ and $n = 3$ Fourier modes grow large in amplitude.

- A small current spike occurs around 6.5ms.
- The thermal energy decreases following the current spike.
The dominant $n = 2$ and $n = 3$ poloidal structures are consistent with experimental observations.
MHD activity coincides with the destruction of the symmetry-preserving islands.

- Symmetry preserving islands are observed early in time.
  - 6/5, 7/5, 8/5, and 9/5 islands
- Islands degrade as the n=2 and n=3 Fourier modes grow.
- MHD event occurs when the 6/5 island chain is destroyed.
- The 3D current source helps a lot.
- Simulations reproduce behavior consistent with the experiment.
  - 3/2 and 4/3 structures are observed.
  - Current spike followed by loss in thermal energy.
- Compare a disrupting discharge with a similar non-disrupting discharge
- Most low-q CTH discharges have weak soft X-ray signals.
  - CTH needs to operate at low density to go to high current.
- Not clear where to initialize a non-disrupting case.
Current goal is to add both toroidal and poloidal flow.

The Grad-Shafranov equation with flow depends of 5 flux functions:

$$\nabla \cdot \left[ \left( 1 - \frac{\Phi(\psi)^2}{\rho} \right) \frac{\nabla \psi}{r^2} \right] = -\mu_0 \rho H'(\psi) + \frac{1}{\gamma - 1} \mu_0 \rho^\gamma S'(\psi)$$

$$- \frac{B_\phi}{r} F'(\psi) - r \mu_0 \rho V_\phi \Omega'(\psi) - \sqrt{\mu_0} \vec{V} \cdot \vec{B} \Phi'(\psi)$$

$$H(\psi) = \frac{\Phi(\psi)^2 B^2}{2\mu_0 \rho^2} - \frac{r^2 \Omega(\psi)^2}{2} + \frac{\gamma}{\gamma - 1} \rho^{\gamma - 1} S(\psi)$$

We are starting with the simpler case of no poloidal flow ($\Phi = 0$).