NIMROD Simulations of Low-q Discharges in the Compact Toroidal Hybrid Device

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AUBURN UNIVERSITY

CTH Compact Toroidal Hybrid

NIMROD Non-Ideal MHD with Rotation Open Discussion Project

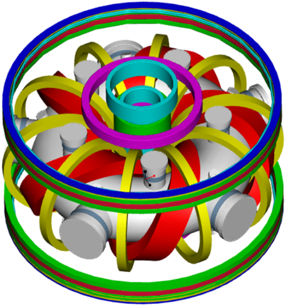
Outline: Resistive MHD simulations using NIMROD are used to investigate low-q disruptions in the Compact Toroidal Hybrid device (CTH).

1. Experimental Observations of Low-q Disruptions in CTH
2. Modeling CTH with NIMROD
3. Simulation Results
4. Conclusions and Future Work

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

CTH Parameters

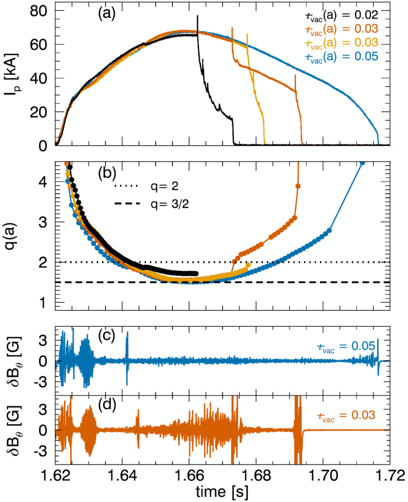
Field Periods	5
Major Radius	0.75m
Minor Radius	0.20m
Magnetic Field	≤ 0.7 T
Plasma Current	≤ 80kA
Number Density	$\leq 5 \times 10^{19}\text{m}^{-3}$
Electron Temperature	≤ 200 eV



- The rotational transform is generated by a combination of currents in external 3D helical coils and internal plasma currents.
  - The rotational transform, ι, is the inverse of the safety factor: $\iota = 1/q$.
- The fractional transform, f, quantifies the amount of 3D shaping.
  - $f = \iota_{vac}/\iota_{total}$
- CTH can operate with a fractional transform that ranges from $f = 4\%$ to $f = 100\%$ by adjusting the plasma current.

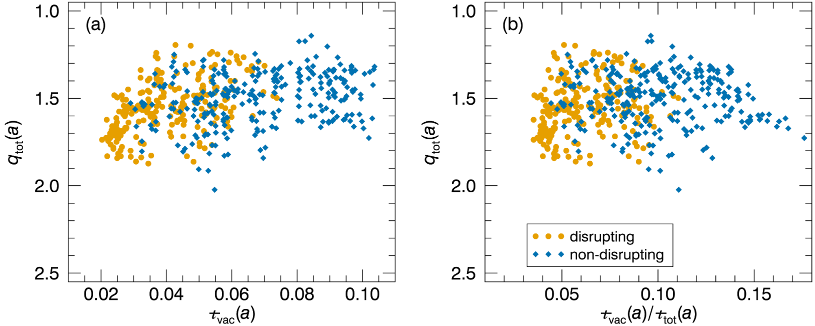
A small amount of vacuum rotational transform allows CTH to operate with $q(a) < 2$.

- 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]

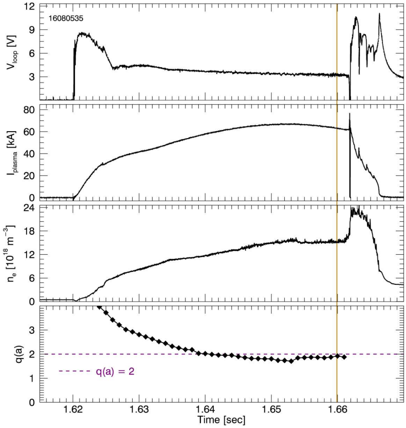
Low-q disruptions are suppressed at large vacuum transform.



- The frequency of disruptions decreases with increasing vacuum transform.
  - Disruptions always occur when $\iota_{vac} \lesssim 0.03$
  - Disruptions are completely suppressed for $\iota_{vac} \gtrsim 0.07$.
- Here $q_{tot}\,(a)$ is the value of the edge safety factor at peak plasma current.

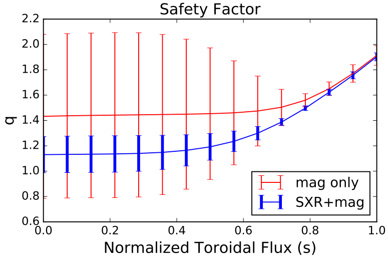
Modeling CTH with NIMROD: Nonlinear simulations are initialized with V3FIT reconstructions of experimental discharges.

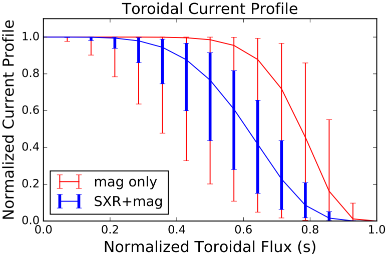
- Simulations are initialized with V3FIT reconstructions of CTH discharges.
- In the results presented here we model CTH discharge 16080535.
- This is a low-q discharge with $\iota_{vac} = 0.015$ that disrupted around $t = 1.662$s.
- The simulations are initialized with reconstructions of the equilibrium 2ms before the disruption.
- This discharge has a strong soft X-ray signal which aids in the reconstruction of the internal current profile.



Equilibrium reconstructions incorporate soft X-ray measurements to constrain the internal safety factor profile.

- The reconstructed safety factor profile calculated using only the magnetic diagnostics is only accurate in the edge ($s \gtrsim 0.8$).
  - s is the normalized toroidal flux.
- Reconstructions that incorporate soft X-ray measurements provide a better estimate of the internal q profile.
  - We assume that the soft X-ray emissivity is a flux function.
  - This constrains the shape of internal flux surfaces.
- See X. Ma's poster, CP10.00031, for more information on the incorporation of soft X-ray measurements into CTH reconstructions.





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

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

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

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

$$\vec{\vec{\pi}} = \rho \nu \left(\nabla \vec{V} + \nabla \vec{V}^{\intercal} - \frac{2}{3} \vec{\vec{\mathrm{I}}} \nabla \cdot V \right)$$

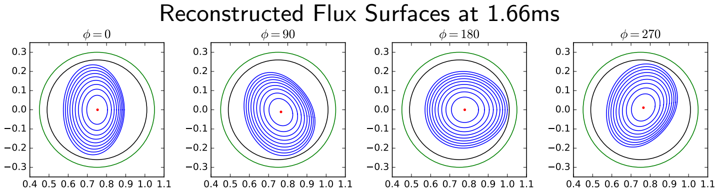
$$\vec{q} = -n \chi_{\parallel} \hat{b}\hat{b} \cdot \nabla T - n \chi_{\perp} \left(\vec{\vec{\mathrm{I}}} - \hat{b}\hat{b} \right) \cdot \nabla T$$

- Magnetic divergence diffusion is used to control $\nabla \cdot \vec{B}$ errors.
- Artificial particle diffusivities smooth out small scale density fluctuations.

The nonlinear evolution of the current and pressure profiles depends on the transport coefficients.

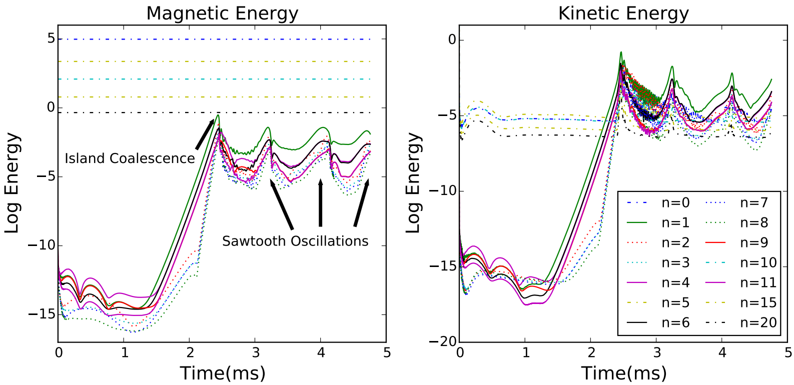
- The resistivity and parallel thermal diffusivity are calculated using the Braginskii model for deuterium plasma.
  - We use a temperature dependent Spitzer resistivity: $\eta = \eta_0 T^{-3/2}$.
    - $S = 1.1 \times 10^5$
  - Temperature dependent parallel thermal diffusivity: $\chi_{\|} = \chi_{\|0} T^{5/2}$.
    - The electron parallel thermal diffusivity is used since $\chi_{e\|} \gg \chi_{i\|}$.
- Uniform viscosity and uniform perpendicular thermal diffusivity are used for numerical convenience.
  - The perpendicular thermal diffusivity is $\chi_\perp = 2\mathrm{m}^2/\mathrm{s}$.
  - The isotropic viscosity is $\nu = 10\mathrm{m}^2/\mathrm{s}$.
    - $\mathrm{Pr_m} \approx 20$
- A loop voltage is applied to maintain the current throughout the simulation.

Simulations use a circular mesh to represent the limited domain.



- CTH plasmas are limited by a collection of partial circular limiters.
  - The radius of the limiters varies from 24.5 cm to 27 cm.
  - The limiters are located at different toroidal and poloidal locations.
  - The limiters subtend an angle between 30° to 120° in the poloidal direction.
- NIMROD uses a spectral element mesh to represent the poloidal plane and a Fourier series to represent the toroidal direction.
  - The code requires an symmetric computational domain.
- We use a circular mesh with a 26cm radius to approximate the combined effect of all the limiters.
  - Previous modeling efforts used a circular mesh with a 30cm radius.

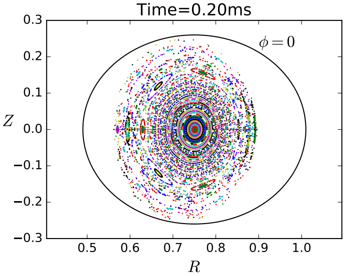
Simulation Results: Nonlinear simulations exhibit a variety of different types of MHD activity.

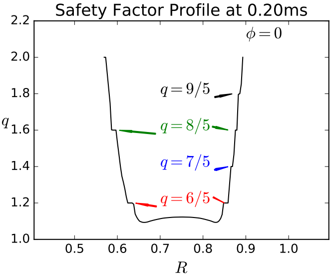


- The first 2 ms of the simulation are quiescent.
- A 5/5 island chain coalesces into an 1/1 island around t=2.5 ms.
- Sawtooth observations are observed after the island coalescence.
- The figure shows 14 Fourier modes for clarity. The simulations use 43 Fourier modes to resolve the toroidal direction.

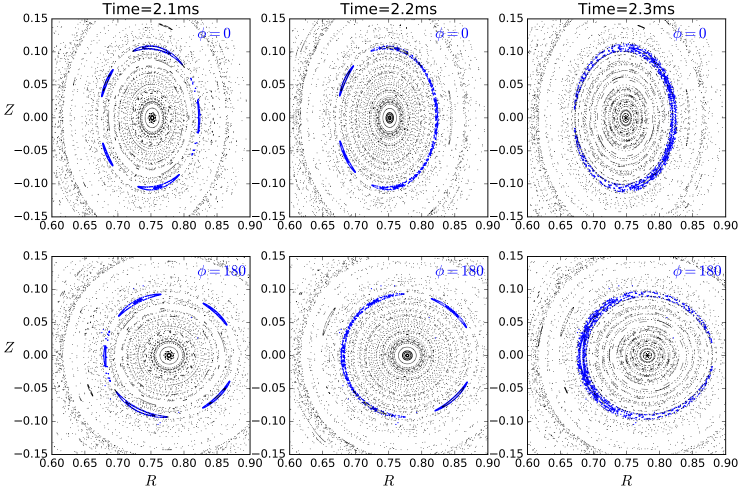
Islands with $n = 5$ toroidal periodicity are easily excited early in the simulation.

- These islands are non-symmetry breaking.
  - They have the same symmetry as CTH.
- The islands saturate at small amplitude and have a minimal effect on the dynamics.
- The islands grow and decay as the safety factor profile evolves due to a steepening of the current profile.
- A 5/5 island chain appears when the safety factor drops below 1.

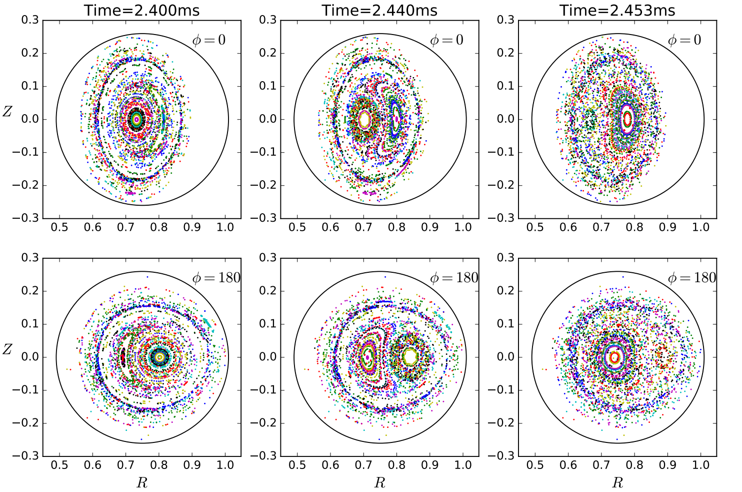




The 5/5 island chain coalesces into 1/1 island.

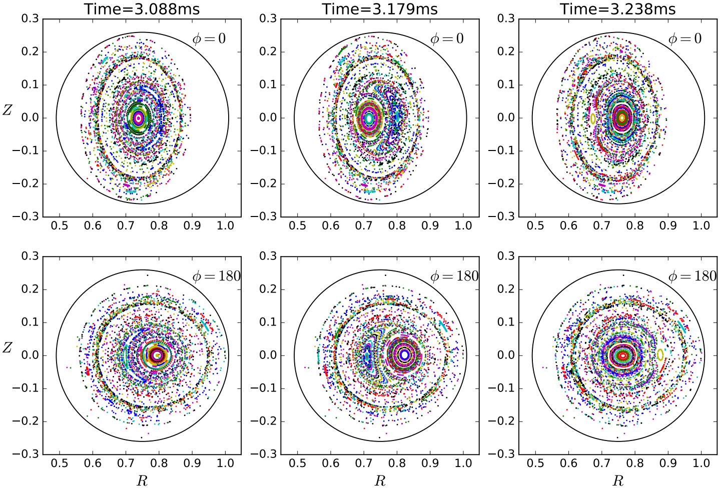


The 1/1 island grows to large amplitude and severely degrades confinement.



- A large volume of stochastic field is observed as the island grows to large amplitude.

Repeated sawtooth oscillations are observed late in time.



- Field line degradation is limited to the core.
- Sawtooth oscillations have be studied in CTH both experimentally (see poster CP10.00030) and numerically (N.A. Roberds POP 23, 2016).

Efforts to model low-q CTH discharges are progressing.

- Reconstructions that incorporate soft X-ray measurements provide more accurate initial conditions for the simulations.
- The 3/2 and 4/3 modes believed to be responsible for the low-q disruptions in the experiment are not yet observed in simulations.
- The $n = 2$ and $n = 3$ Fourier mode energies grow early in the simulation; however, these modes saturate at small amplitude.
  - These modes initially have little energy and are stabilized before they have time to grow to a significant amplitude.
  - We hypothesize that these modes are stabilized by changes in the current and pressure profiles.
  - In the simulations these profiles evolve due to the transport effects in the resistive MHD model.
- We are exploring several remedies to address the above issue.
  - Remedy 1: Initialize simulations with reconstructions of the discharge at peak plasma current, and then model the entire current decay.
  - Remedy 2: Initialize the simulation with larger $n = 2$ and $n = 3$ perturbations.