# Simulations of Low-q Disruptions in the Compact Toroidal Hybrid Experiment

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CTH
Compact Toroidal Hybrid

NIMROD
Non-Ideal MHD with Rotation
Open Discussion Project

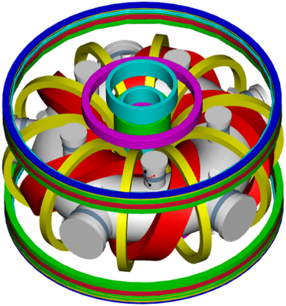
# Numerical simulations are used to investigate the MHD precursors to low-q disruptions in the Compact Toroidal Hybrid device (CTH).

- Experimental Observations
- Numerical Model
- Simulation Results
    - Disrupting $t_{vac} = 0.015$ Discharge
    - Non-Disrupting $t_{vac} = 0.075$ Discharge
- Conclusions

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

CTH Parameters

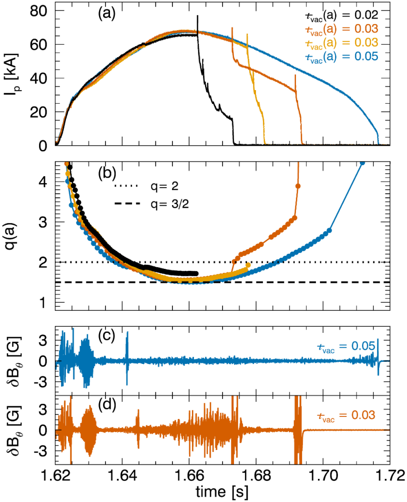
| | |
|---|---|
| Field Periods | 5 |
| Major Radius | 0.75m |
| Minor Radius | 0.20m |
| Magnetic Field | $\leq 0.7$ T |
| Plasma Current | $\leq$ 80kA |
| Number Density | $\leq 5 \times 10^{19}\text{m}^{-3}$ |
| Electron Temperature | $\leq$ 200 eV |



- The rotational transform is generated by a combination of external 3D helical coil currents and internal plasma currents.
    - The rotational transform, $\iota$, 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.

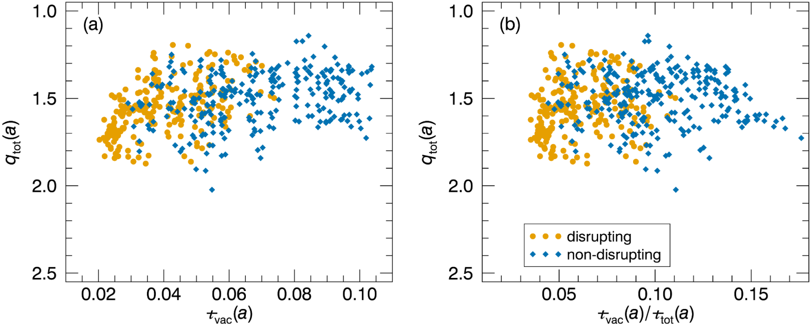
# Small amounts of externally applied rotational transform allows CTH to operate with $q(a) < 2$.

- External kink stability limits tokamak operation to $q(a) \geq 2$.
- Disruptions are observed in 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 $q(a) \approx 1.7$.



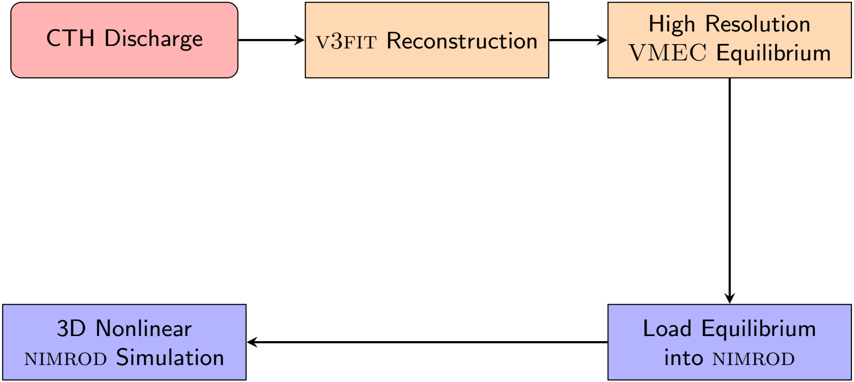
[M. D. Pandya et al., POP 22, 2015 ]

# 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.

# Nonlinear simulations are initialized with V3FIT reconstructions of experimental discharges.


CTH Discharge

V3FIT Reconstruction

High Resolution VMEC Equilibrium

Load Equilibrium into NIMROD

3D Nonlinear NIMROD Simulation

# NIMROD evolves the nonlinear MHD equations in primitive form.

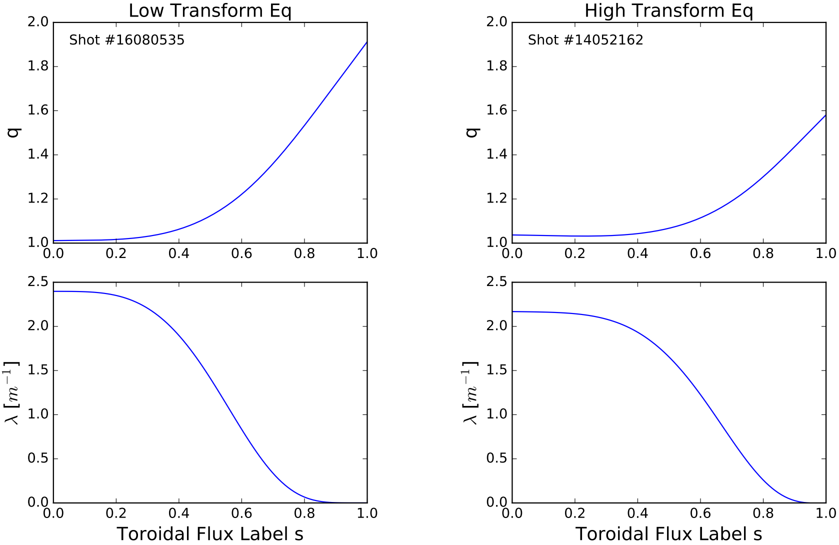
$$
\begin{aligned}
\frac{\partial \vec{B}}{\partial t} &= -\nabla \times \left[\eta \left(\vec{J} - \vec{J_S}\right) - \vec{V} \times \vec{B}\right] + k_{divb} \nabla \nabla \cdot \vec{B} \\
\frac{\partial n}{\partial t} &+ \nabla \cdot \left(n \vec{V}\right) = \nabla \cdot \left(D \nabla n - D_h \nabla \nabla^2 n\right) \\
\rho \left(\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V}\right) &= \vec{J} \times \vec{B} - \nabla P - \nabla \cdot \vec{\vec{\pi}} \\
\frac{3}{2} n \left(\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T\right) &= -P \nabla \cdot \vec{V} - \nabla \cdot \vec{q} + \eta J^2
\end{aligned}
$$

- 3D current source maintains the current profile against resistive decay.
- Magnetic divergence diffusivity enforces $\nabla \cdot \vec{B} \approx 0$.
- Artificial particle diffusivity smooths small scale density fluctuations.

# Transport effects are modeled using a collisional closure for a hydrogen plasma.

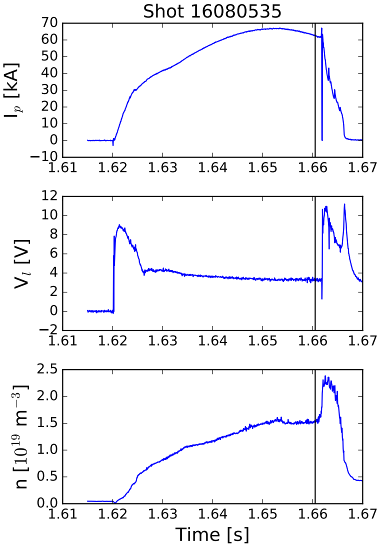
- Temperature dependent magnetic diffusivity:
  - $\frac{\eta}{\mu_0} = \frac{\eta_0}{\mu_0} T^{-\frac{3}{2}}$
  - $\frac{\eta_0}{\mu_0} = 1.23 \times 10^3 \frac{m^2}{s}$
- Thermal conduction is anisotropic with temperature dependent thermal diffusivities:
  - $\vec{q} = -n\chi_{\|} \nabla_{\|} T - n\chi_{\perp} \nabla_{\perp} T$
  - $\chi_{\|} = \chi_{\|0} T^{5/2}, \qquad \chi_{\|0} = 1.26 \times 10^3 \frac{m^2}{s}$
  - $\chi_{\perp} = \chi_{\perp 0} T^{-1/2}, \qquad \chi_{\perp 0} = 2.69 \frac{m^2}{s}$
- The viscous stress tensor is isotropic with a constant viscosity:
  - $\vec{\vec{\pi}} = -\nu_0 mn \left( \nabla \vec{V} + \nabla \vec{V}^T - \frac{2}{3} \vec{\vec{I}} \nabla \cdot \vec{V} \right), \quad \nu_0 = 1 \frac{m^2}{s}$

# Simulations of a small transform disrupting discharge are compared against simulations of a large transform non-disrupting discharge.

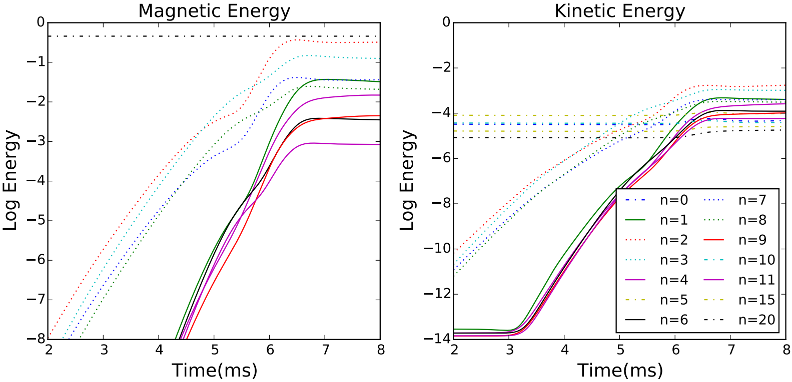


# A small $t_{vac}$ case is used to study the dynamics of a disrupting discharge.

- Simulations model a discharge with a $t_{vac} = 0.015$.
- Simulations are initialized with equilibrium reconstructions of the plasma 2ms before the disruption.
- Small $t_{vac}$ discharges are most likely to disrupt.
- Small $t_{vac}$ eases toroidal resolution requirements.

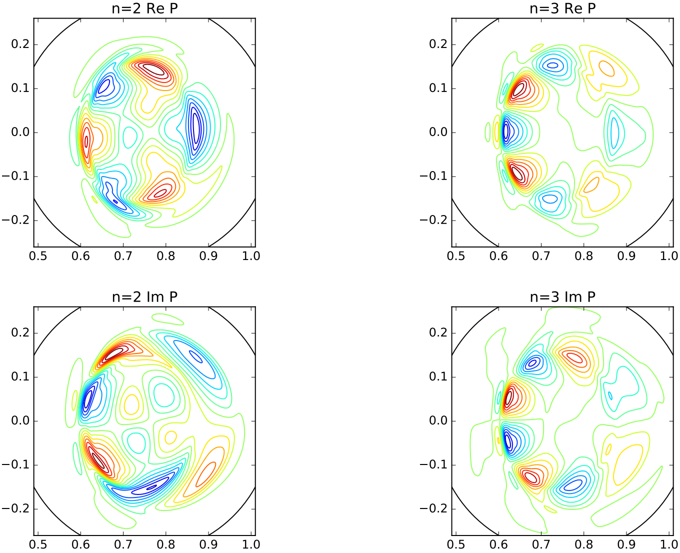


# Predominantly $n = 2$ and $n = 3$ modes are unstable and saturate at large amplitude.

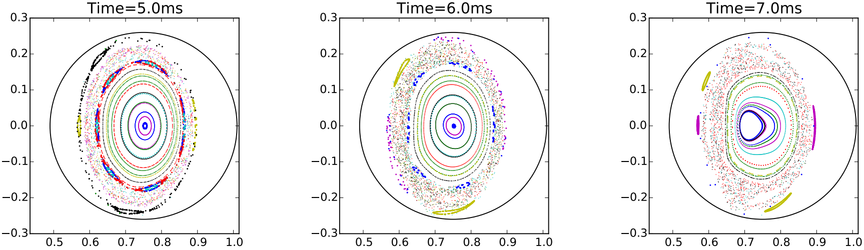


- Linear modes are composed of a family Fourier modes due to coupling with the stellarator equilibrium fields.

# The dominant $n = 2$ and $n = 3$ poloidal structures are consistent with experimental observations.



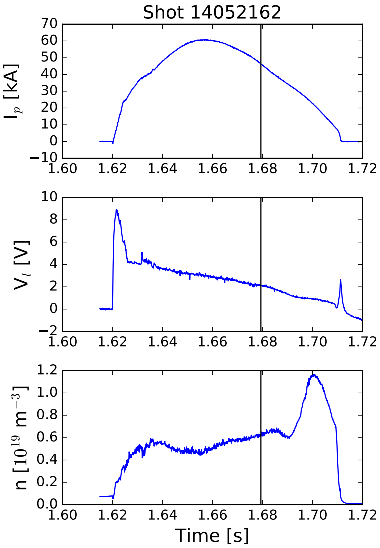
# The interaction between the unstable modes and symmetry preserving islands leads to a large region of stochastic field.



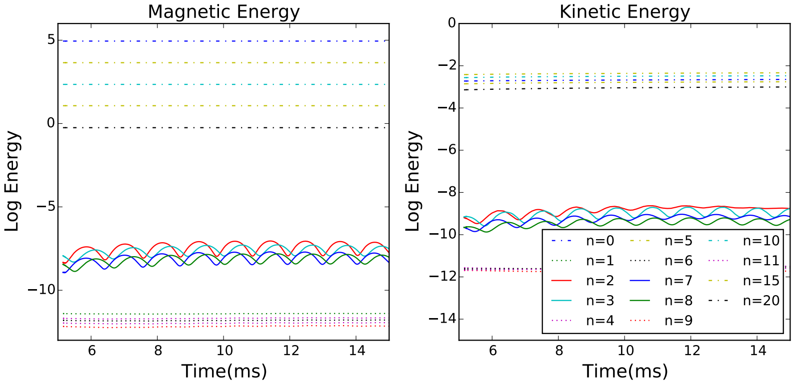
- Symmetry preserving islands are observed early in time.
    - 6/5, 7/5, 8/5, and 9/5 islands are observed
- Islands degrade as the unstable modes grow.
- Thermal energy is lost when the innermost island chain is destroyed.

# A large $t_{vac}$ discharge is used to study the dynamics of a non-disrupting discharge.

- This non-disrupting discharge has $t_{vac} = 0.075$.
- Disruptions are not observed in CTH discharges with $t_{vac} \gtrsim 0.07$.
- Simulations are initialized with reconstructions at conditions when $q\left(a\right) \approx 1.7$.
- In the experiment disruption occur most frequently when $q\left(a\right) \approx 1.7$.

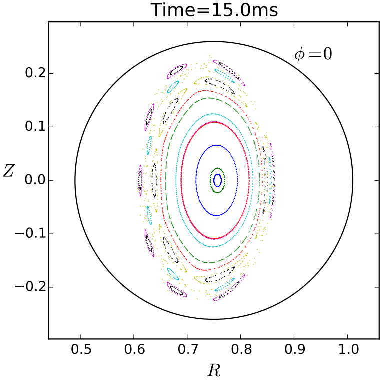


# The linearly unstable modes saturate at very small amplitude.



# Symmetry preserving islands persist throughout the simulation

- The 6/5, 7/5, and 8/5 island chains are seen in the figure.
- Good nested flux surfaces are present in the core.
- Thermal energy increases throughout the simulation.



# Simulations suggest that low-q disruptions are triggered by an interaction between symmetry preserving islands and symmetry breaking instabilities.

- Symmetry preserving islands form at the $q = 6/5$, $7/5$, $8/5$, and $9/5$ rational surfaces.
- At small vacuum transform the $4/3$ and $3/2$ modes are unstable and grow to large amplitude.
    - The $4/3$ and $3/2$ modes interact with the symmetry preserving islands.
    - The destruction of the islands creates a large volume of stochastic field.
    - Thermal energy is lost when the inner most island chain is destroyed.
- At large vacuum transform the $4/3$ and $3/2$ modes saturate at small amplitude.
    - Symmetry preserving islands persist throughout the simulation.