Automated Characterization of Rotating MHD Modes and Subsequent Locking in a Tokamak

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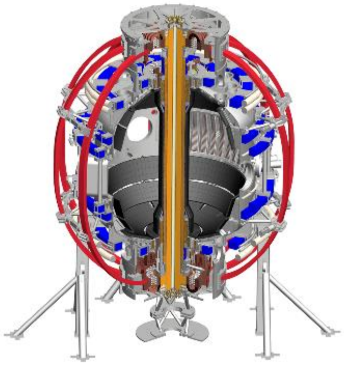
PPPL



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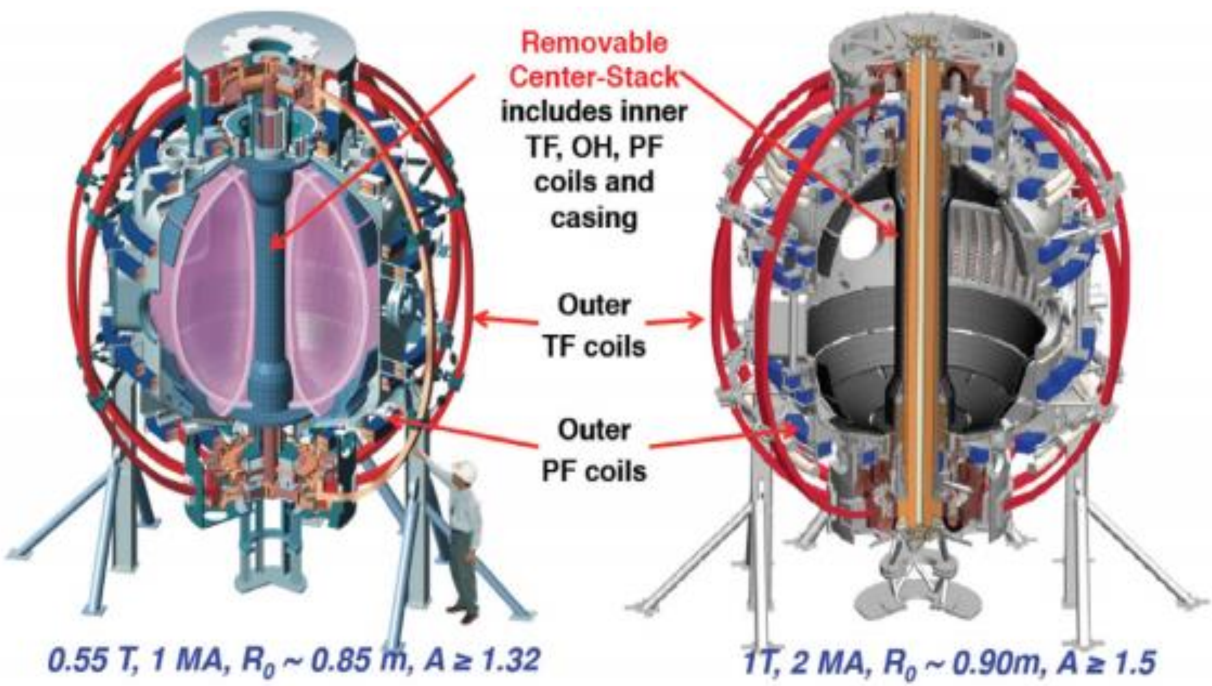
Characterization of rotating MHD instabilities will aid future forecasting and avoidance of disruptions

- Motivation
  - Disruption avoidance in tokamaks is highly desired to maintain steady plasma operation and to avoid potential damage to device components. This high priority research is being conducted at PPPL by analyzing data from NSTX and its upgrade, NSTX-U.
  - A key cause of disruptions is the physical event chain that comprises the appearance of rotating MHD modes, their slowing by resonant field drag mechanisms, and their subsequent locking. The present research aims to define algorithms to automatically find and characterize such physical event chains in the machine database. Characteristics such as identification of a mode locking time based on a loss of torque balance and bifurcation of the mode rotation frequency are examined to determine the reliability of such events in predicting disruptions.
- Goal
  - To detect such behavior as early as possible during a plasma discharge, and to further examine potential ways to forecast it. This capability could be used to provide a warning to use active mode control as a disruption avoidance mechanism, or to trigger a controlled plasma shutdown if desired.

Disruption prediction and avoidance is part of the research conducted at the National Spherical Torus Experiment

- Spherical tori (low aspect ratio tokamaks) offer a special advantage as a potential fusion reactor
  - Higher plasma pressure per magnetic pressure (β) than most tokamaks
- Plasmas generated in NSTX-U are not always stable. For example, error field can lead to unstable modes.

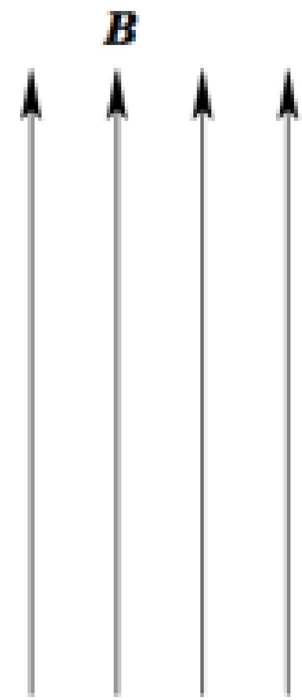
NSTX (1999 - 2011) **NSTX-U (2015 -)**



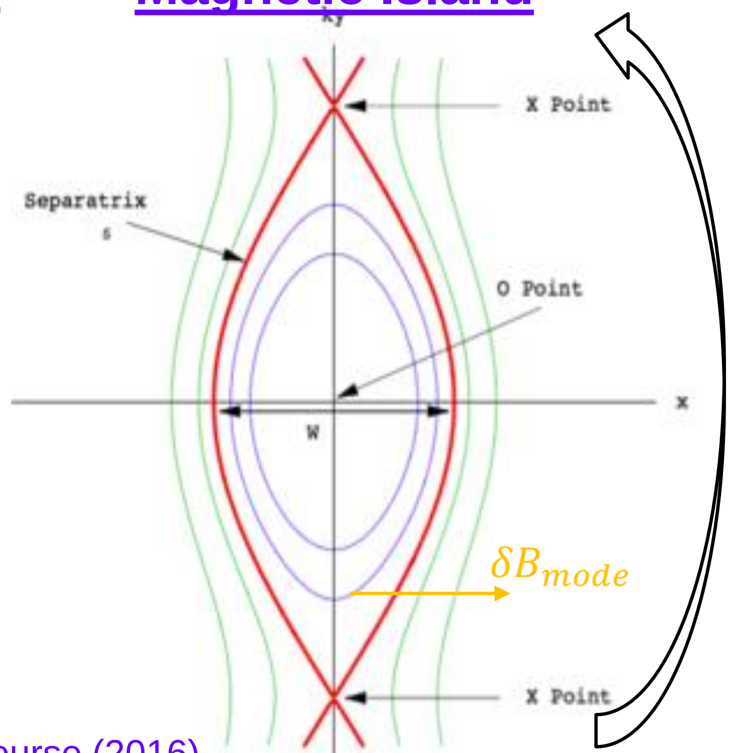
- The mode of interest for this project is the rotating MHD or kink/tearing mode (TM)

Plasma instabilities generate magnetic islands that can lead to a mode lock and subsequent disruption

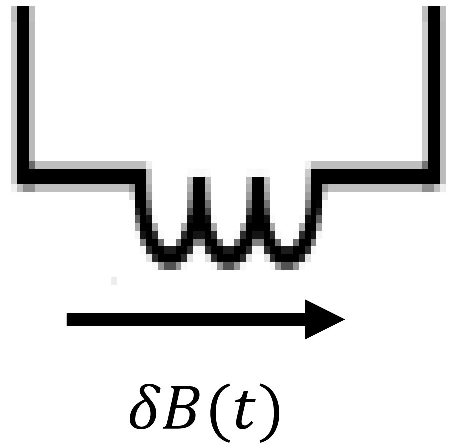
Nested Surfaces



Magnetic Island



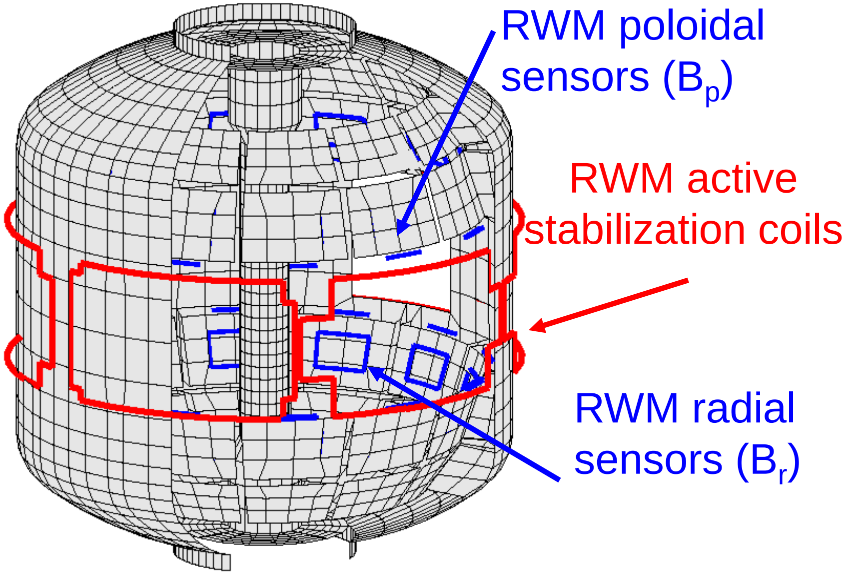
N.F. Loureiro, SULI Intro. Course (2016)

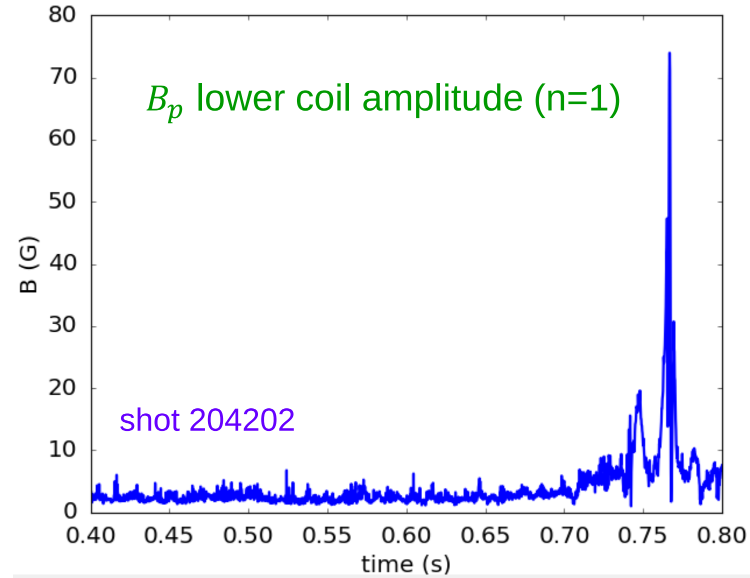


- Mode rotation can be picked up by "pick up" magnetic coils that toroidally wrap the tokamak.
- A mode can rotate both toroidally (n) and poloidally (m) the degree of which is determined by the rational surface on which it lies
  - "safety factor" q = m/n
- Mode rotation can slow down, lock in place, and disrupt the plasma

Toroidal pick up coils and locked mode magnetic sensors measure mode magnitude

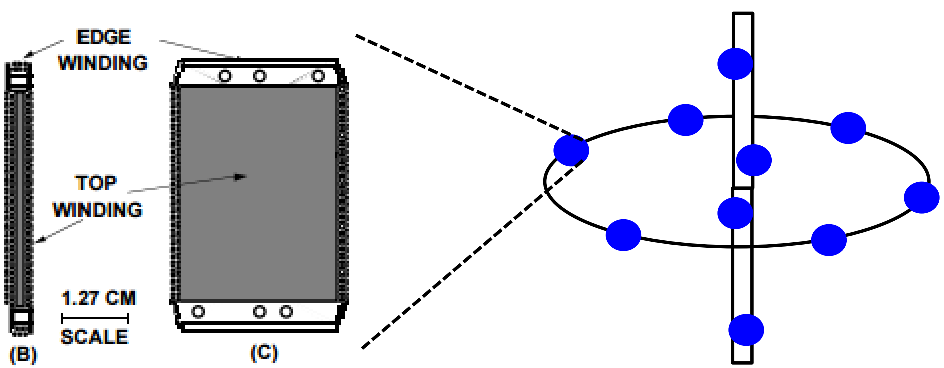
RWM (locked mode sensors) → **RWM sensor signal**

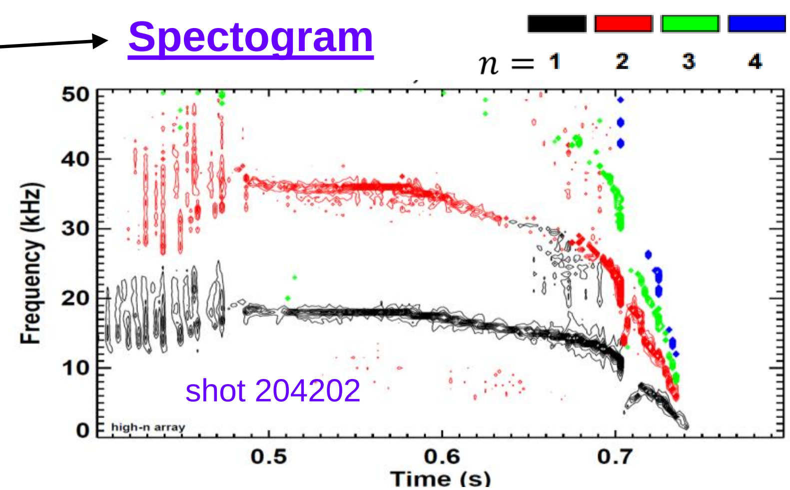




S. Sabbagh et al., Disruption Workshop 2016

Magnetic pickup / Mirnov coils → **Spectogram**

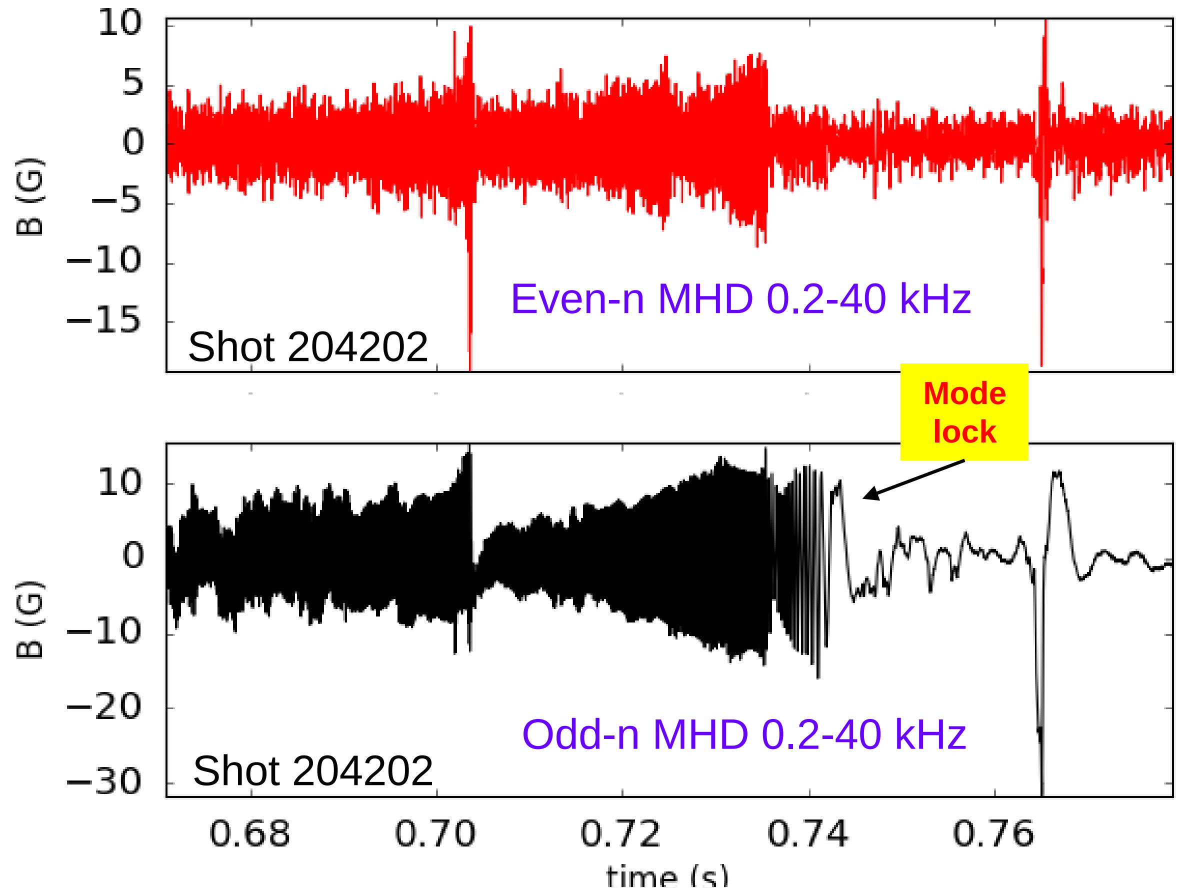




H.W. Kugel et al, NSTX High T Sensor System

Magnetic Diagnostics in NSTX-U allow for the separation of different parity modes

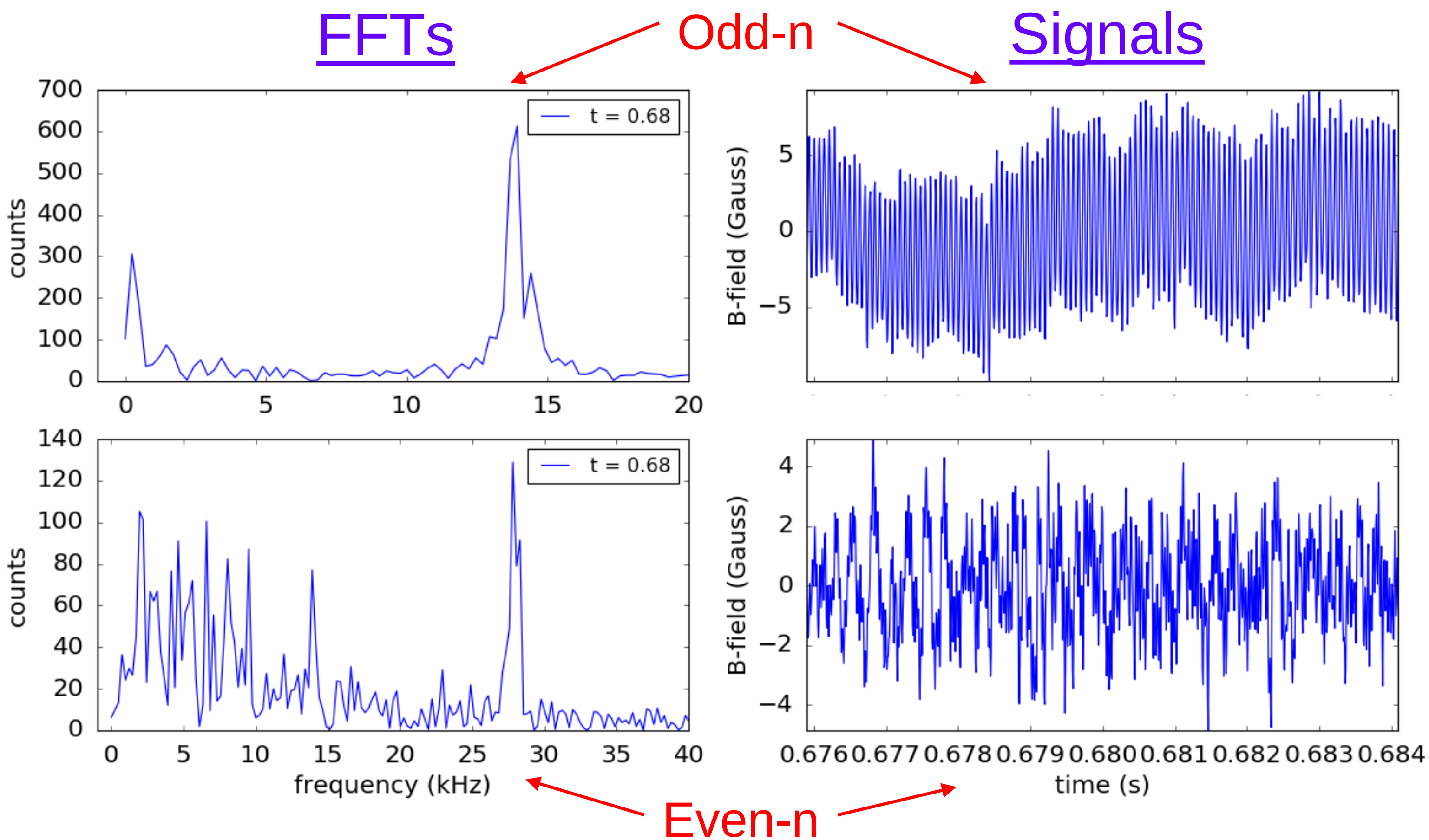
- The pick up coils can indicate the rotation of the mode by the changing magnitude
- The diagnostic measures modes in the 0.2 – 40 kHz range
- RWM poloidal detectors are also used to find lower frequency modes
  - Down to zero frequency



Characterization of Rotating MHD Mode

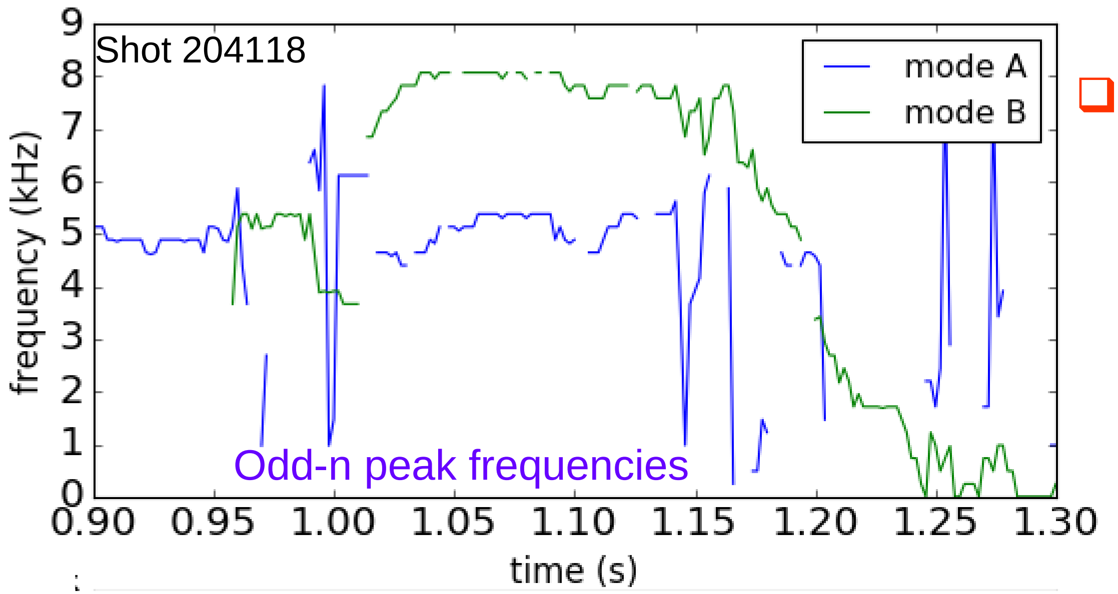
Fast Fourier transforms used to find mode peak frequency within a time interval

- Calculated the rotational frequency of the modes present in the plasma from the magnetic diagnostics results using FFTs



Approaches to determine mode rotational frequency with respect to time, $f(t)$

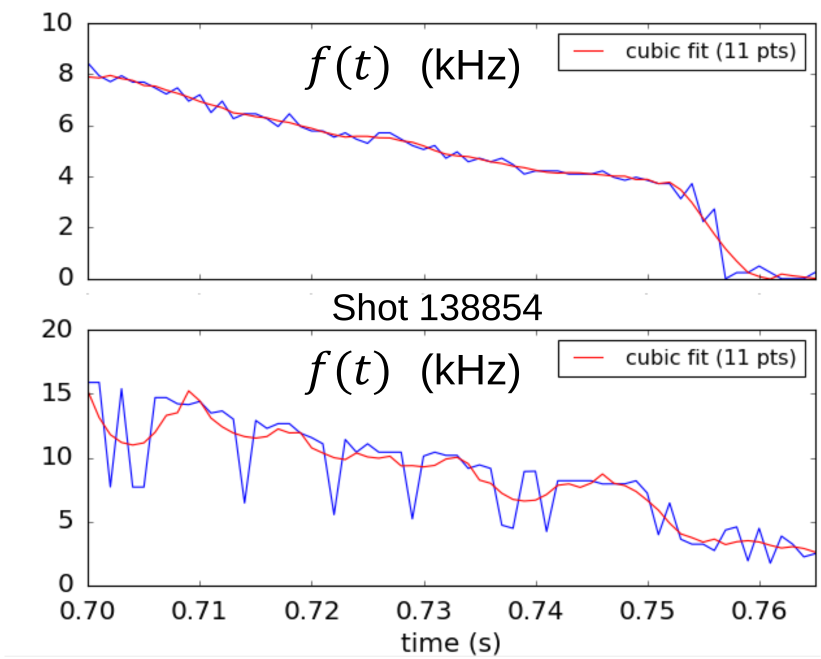
- Two methods used for finding the peak frequency from FFTs
  - Simple method: Find maximum value
  - Gauss Fit: Find the full bandwith of the mode and fit a Gaussian
- The algorithm can be causal or acausal (centered)
- Can also find two active modes

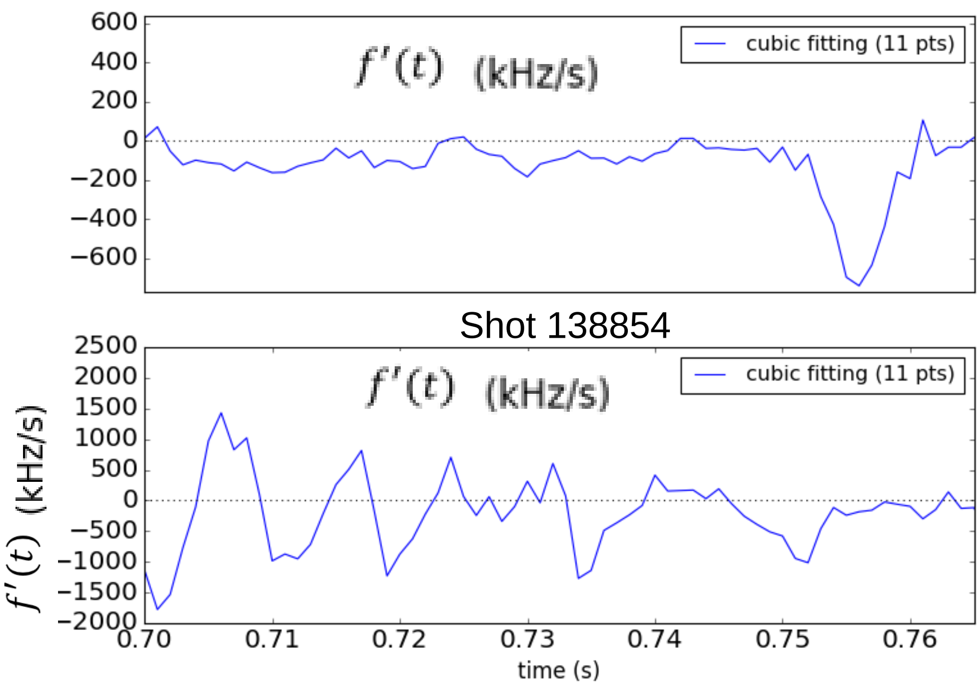


- (finds 2nd mode if it's larger than 20% of 1st mode)

$f(t)$ and $f'(t)$ are both useful for the characterization of rotating MHD modes and their locking

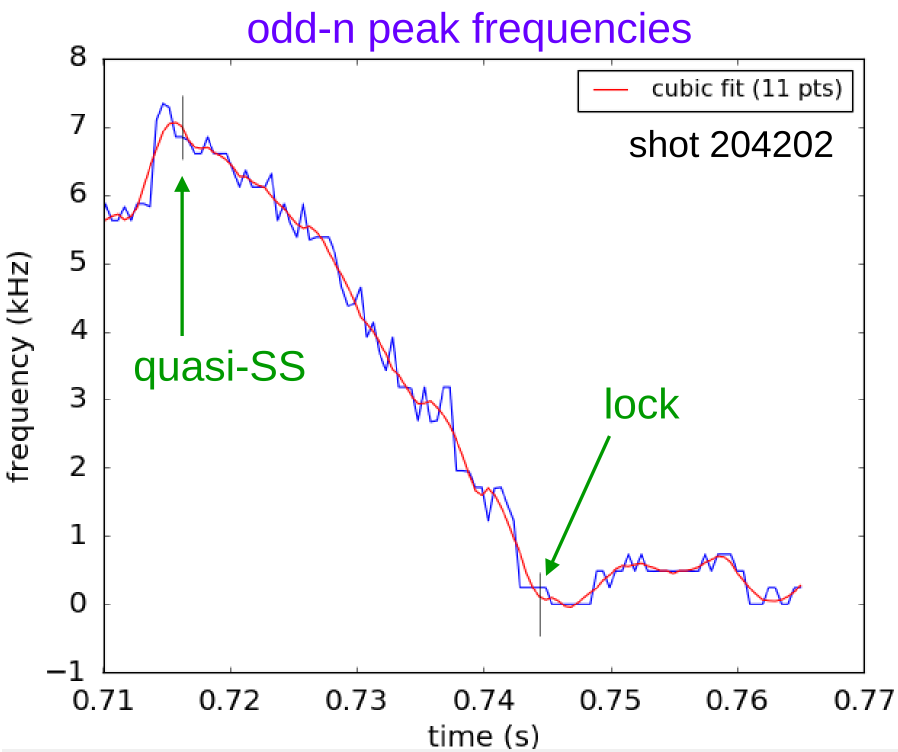
- Used a cubic fitting approach to smooth out $f(t)$ and reduce the noise. And then directly calculated $f'(t)$ analytically
- Better to look at the derivative of the frequency, $f'(t)$, than looking at the frequency of the mode, $f(t)$, to find the steady state regions

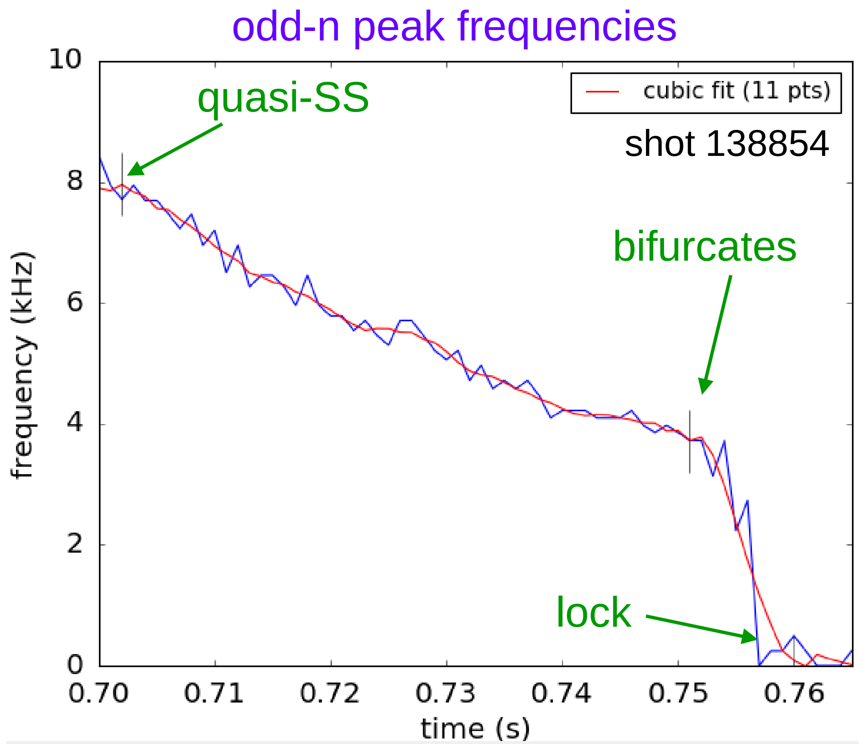




The characterization algorithm shows that the expected bifurcation event can be found

- To determine the bifurcation, an algorithm was written that finds a region of quasi-steady state first, then the deviation (bifurcation), and finally the locking based on a smooth fit
  - Approaches: Method 1 uses percentages, Method 2 uses std. deviation





MHD Instability Bifurcation Models

Plasma rotation evolution can be modeled with rate of change of angular momentum

- Angular speed is a plasma parameter that is relevant to describing the steady state and stability conditions (Ω rad/s)
- A simple torque balance equation can be derived to find the toroidal rotational speed values at which the plasma is in a steady state
- Bifurcation model includes:
  - Torque from auxiliary power: T_{aux}
  - Torque from drag due to plasma viscosity: T_{2D}
  - Torque from electromagnetic (EM) drag of the mode: T_{mode}

$$\frac{d(I\Omega)}{dt} = T_{aux} + T_{2D} + T_{mode}$$

Torque components for bifurcation model

- The drive torque T_{aux} comes from neutral beam injection
- The drag torque that comes from plasma viscosity is expected to be negative and proportional to the angular speed of the plasma (like friction):

$$T_{2D} = -\frac{(I\Omega)}{\tau_{2D}}$$

- The EM drag torque is more complicated and depends on whether the plasma slips with respect to the magnetic flux

- "No slip":

$$T_{mode} = -\frac{k_1}{\Omega}$$

- "Slips":

$$T_{mode} = -k_1\Omega$$

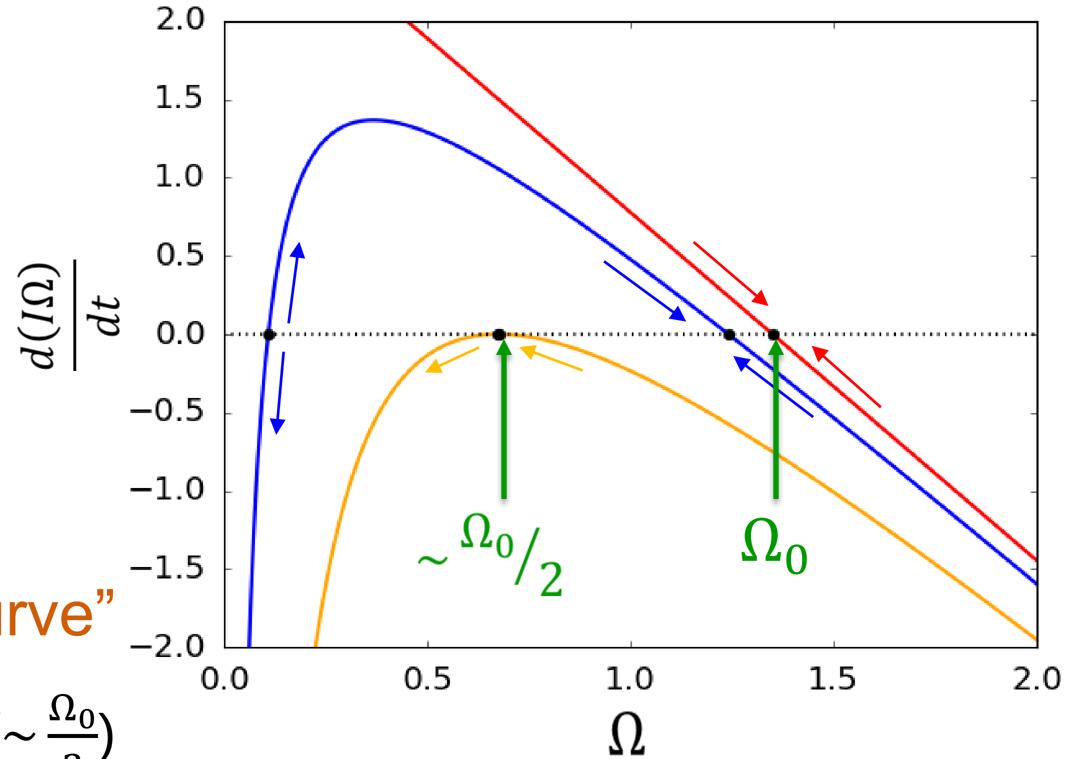
- k_1 is proportional to the island width of TM

The model using a "no slip" condition has no steady state solutions at a large enough island width (k_1)

- For steady state solutions: $\left(\frac{d(I\Omega)}{dt} = 0\right)$

- $k_1 = 0$: "red curve"
  - No mode present
- $k_1 < \frac{{T_{aux}}^2 \tau_{2D}}{4I}$: "blue curve"
  - Two steady state solution
- $k_1 = \frac{{T_{aux}}^2 \tau_{2D}}{4I}$" : "orange curve"
  - One steady state solution ($\sim\frac{\Omega_0}{2}$)
  - Bifurcation
    - At close to half the steady state natural rotation frequency (Ω_0)

$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_1}{\Omega} - \frac{(I\Omega)}{\tau_{2D}}$$



Model that allows for slipping shows how a mode can pick back up after bifurcation

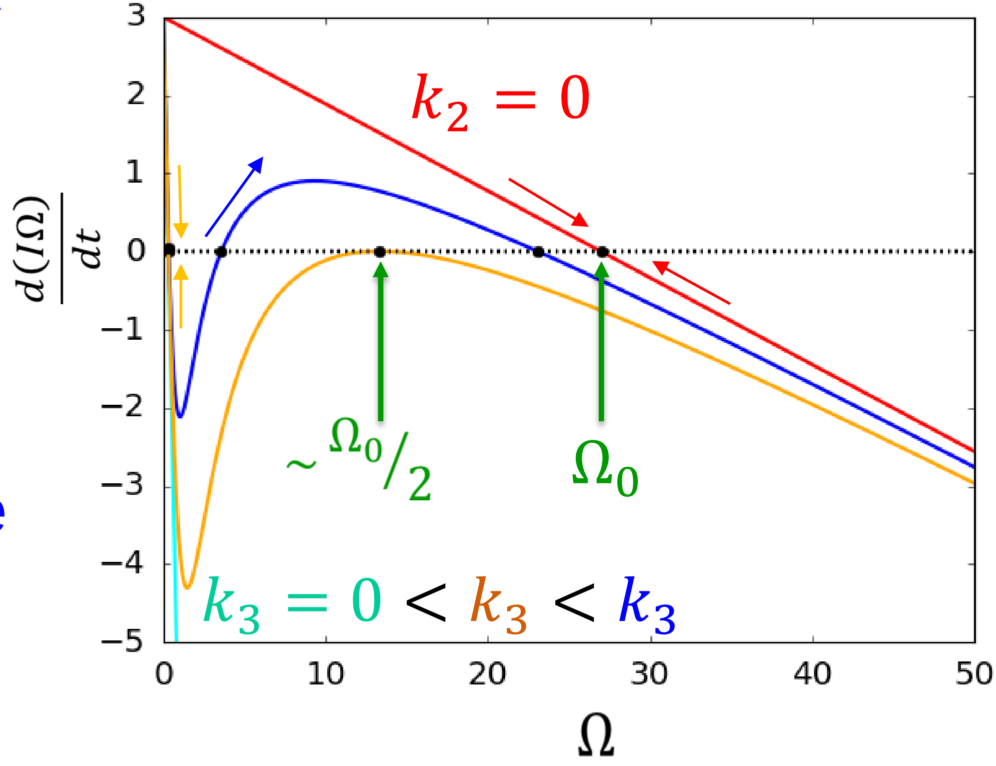
- A possible model of the drag for both a "slip" and a "no slip" condition is:

$$T_{mode} = \frac{k_2 \Omega}{1 + k_3 \Omega^2}$$

R. Fitzpatrick et al., Nucl. Fusion 33 (1993) 1049

- At very low angular speed the mode reaches a stable steady state that gives the plasma a possibility to regain angular speed

$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_2 \Omega}{1 + k_3 \Omega^2} - \frac{(I\Omega)}{\tau_{2D}}$$



A successful characterization of rotating MHD modes and their locking will add to the disruption forecasting goal

- Conclusions
  - Developed of a simple automated algorithm that can be used to characterize rotating MHD modes and the bifurcation of their rotating frequency. The algorithm can account for the presence of two modes, has different approaches to finding the peak frequencies
- Future Work
  - Run the algorithm on the NSTX and NSTX-U shots database to determine the accuracy of the code (% of false positives) and improve it based on the feedback
  - If an accuracy margin is achieved it could then be incorporated into the Disruption Event Characterization And Forecasting (DECAF) code and aid the forecasting and avoidance efforts
- Acknowledgments

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