Offline Torque Balance Analysis of Rotating MHD for Real-Time Application

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J.D.Riquezes[1], S.A. Sabbagh[1], J.W. Berkery[1], Y.S. Park[1], J.M. Bialek[1], V. Klevarova[1], Y. Jiang[1], J. Butt[1], J.G. Bak[2], M.D. Boyer[3], K. Erickson[3]

[1]Dept. of Applied Physics and Applied Mathematics, Columbia U., New York, NY, USA

[2]Korea Institute for Fusion Energy, Daejeon, Republic of Korea

[3]Princeton Plasma Physics Laboratory, Princeton, NJ, USA

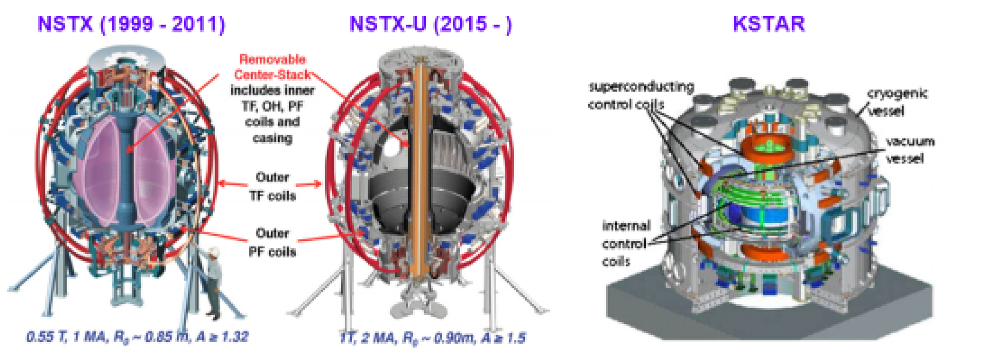
Abstract

Reactor scale tokamak devices require a low disruptivity ceiling for full performance operation. An approach has been developed to automatically establish disruption event chains based on the relevant precursors. An important precursor to disruptions is the presence of rotating neoclassical tearing modes (NTM). Through coupling, NTM's with a saturated island width can slow down the plasma rotation and lock it to the wall reference frame. A balance of the driving torque from the NBI, the perpendicular viscous diffusion drag, the electromagnetic drag of the mode, and its inertia is used to model the rotation dynamics. Threshold rotation frequencies are derived from this model below which the plasma rotation is expected to lead to a mode lock, serving as a forecaster. A zero-crossings analysis of a toroidal array of Mirnov probes is used to calculate the rotation frequency of the mode. From the rotation, the torque components are then calculated based on conditions for the expected drag torque ratios at the mode onset, increases in frequency, and Mirnov signal amplitudes. The approach was validated by comparisons of the viscous diffusion time with energy confinement time, and NBI torque with NBI total power and plasma density. This technique is prepared for real-time analysis of KSTAR plasmas with possible use in engaging active control systems. Results are compared between real-time and offline implementations to establish the feasibility of the forecaster.

An algorithm has been created to automatically identify aspects of MHD activity supporting disruption prediction

- Motivation
  - Identify rotating MHD instabilities in a tokamak plasma
  - Develop a forecaster of locked modes (LTM)
  - Create a portable code to be used generally on several tokamaks
- Outline
  - Mode rotation frequency calculation
  - Plasma moment of inertia calculation
  - Torque balance model
  - Parameter calculation
  - KSTAR Shot List Results

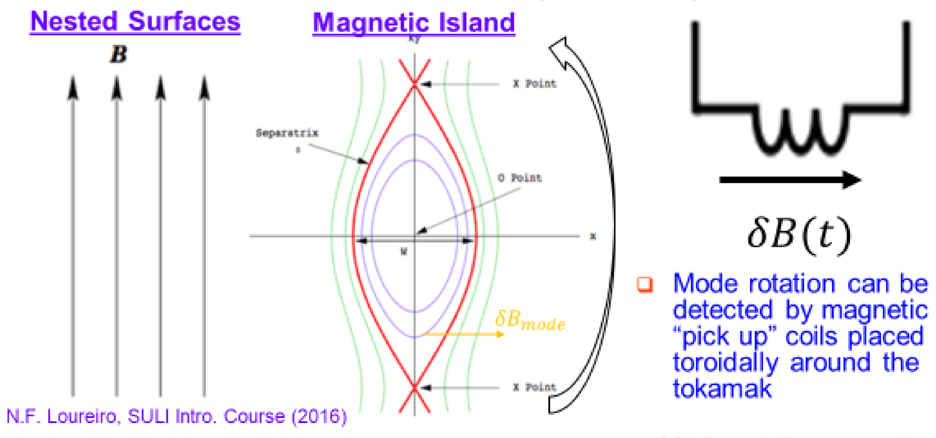
Disruption prediction and avoidance is part of the research conducted at NSTX and KSTAR



M. Ono et al, Nucl. Fusion 55 (2015) 073007 Y. S. Bae et al, Fusion Sci. & Tech. (2014)

- Spherical tori (low aspect ratio, higher β) and superconducting tokamaks (high aspect ratio, long pulse) both offer a special advantage as potential fusion reactors
- Differences in vacuum error field amplitudes has an effect of mode dynamics/severity.

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

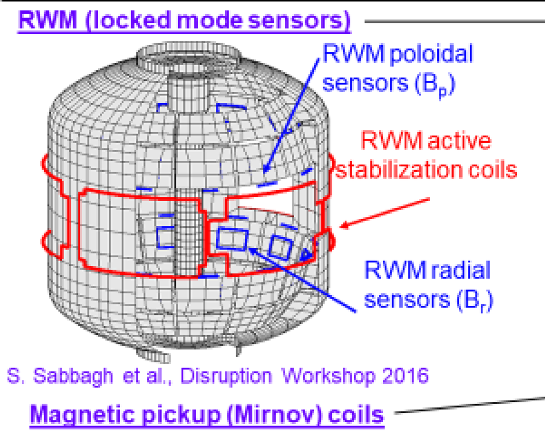


N.F. Loureiro, SULI Intro. Course (2016)

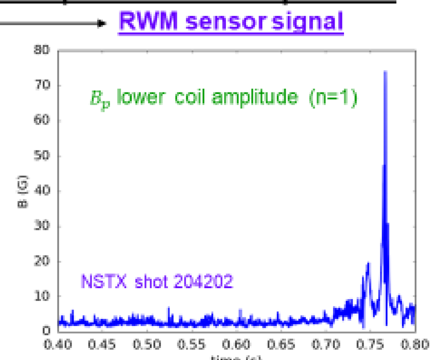
- Mode rotation can be detected by magnetic "pick up" coils placed toroidally around the tokamak
- Mode rotation can slow down, lock in place, and disrupt the plasma
- A mode can rotate both toroidally (n) and poloidally (m) the degree of which is determined by the rational surface on which it lies
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

Toroidal pick up coils and locked mode magnetic sensors can measure mode amplitude and phase

RWM (locked mode sensors)

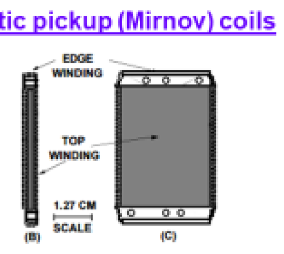


RWM sensor signal

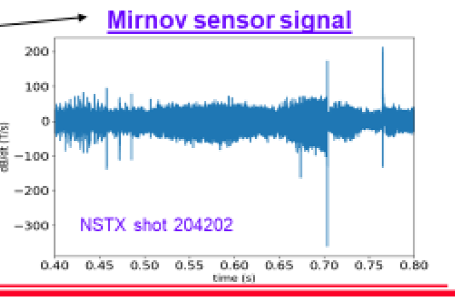


S. Sabbagh et al., Disruption Workshop 2016

Magnetic pickup (Mirnov) coils



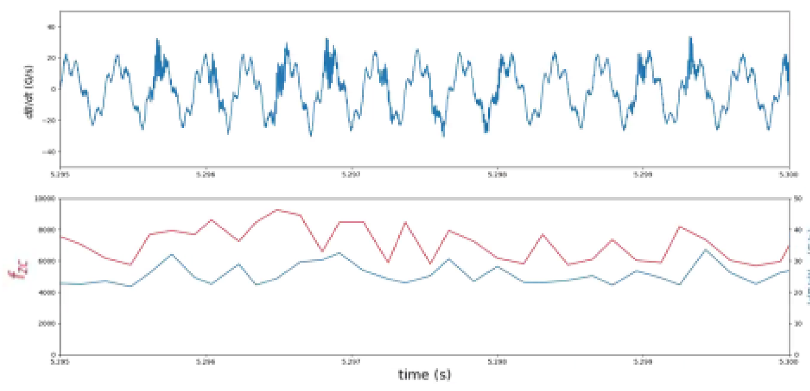
Mirnov sensor signal



Zero-crossings analysis used to calculate the odd-n mode rotation frequency

- Diametrically opposed Mirnov probes are subtracted and halved to calculate the field signal for odd-n rotating mode

Mirnov signal & Mode frequency/amplitude



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

- A straightforward 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 can depend 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

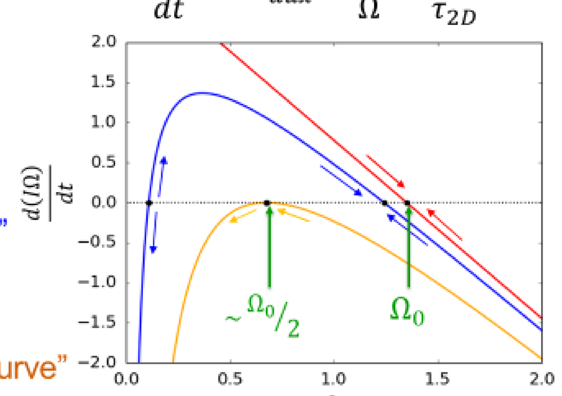
The model using a "no slip" condition has no steady state solutions at a large enough island width ($\boldsymbol{k_1}$)

- For steady state

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

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

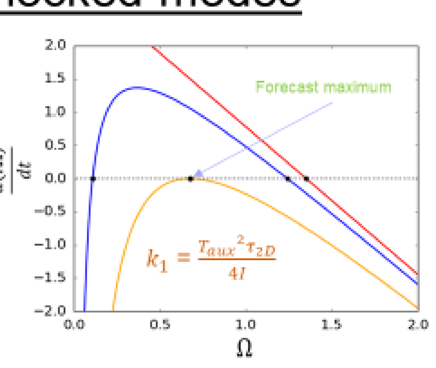
- $k_1 = 0$: "red curve"
  - No mode present
- $k_1 < \frac{{T_{aux}}^2\tau_{2D}}{4I}$: "blue curve"
  - Two steady state solution
- $k_1 = \frac{{T_{aux}}^2\tau_{2D}}{4I}$: "orange curve"
  - One steady state solution $(\sim\frac{\Omega_0}{2})$



- Bifurcation
- At close to half the steady state natural rotation frequency (Ω_0)

Inflection frequency calculation serves as a forecaster of subsequent locked modes

- Once the frequency is below the inflection point the model predicts the mode will lock barring any change in parameters



$$\frac{\partial}{\partial\Omega}\left(\frac{I_{avg}d\Omega}{dt} = T_{aux} - \frac{k_1}{\Omega} - \frac{(I_{avg}\Omega)}{\tau_{2D}}\right)$$

$$0 = \frac{k_1}{I_{avg}{\Omega_{inf}}^2} - \frac{1}{\tau_{2D}}$$

$$\Omega_{inf} = \sqrt{\frac{k_1\tau_{2D}}{I_{avg}}}$$

Torque balance model automated parameter calculation

- Based on the model while the mode is highly rotating the viscous drag is larger than the EM drag. The characteristic perpendicular viscous diffusion time τ_{2D} is calculated
  - Early in mode activity
  - At higher rotation
  - With low field amplitude (small k_1)
  - For a window similar to τ_E

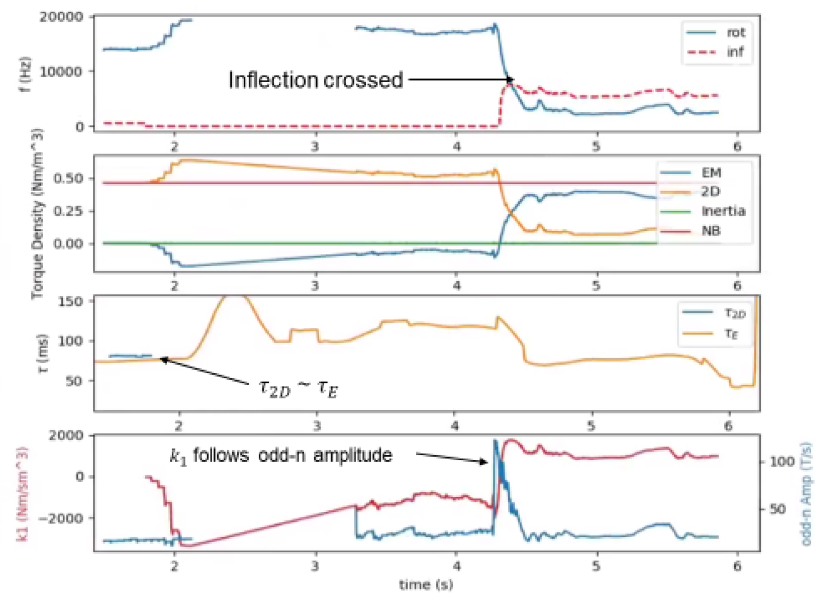
$$\tau_{2D} = \frac{I\Omega}{T_{aux} - I\frac{d\Omega}{dt} - \frac{k_1}{\Omega}}$$

- T_{aux} is set to a value that makes $\tau_{2D} \sim \tau_E$.
  - Energy confinement time is calculated as $\tau_E = \frac{W_{tot}}{P_{NBI}}$
- k_1 is then calculated using the average value of the previously calculated τ_{2D}

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

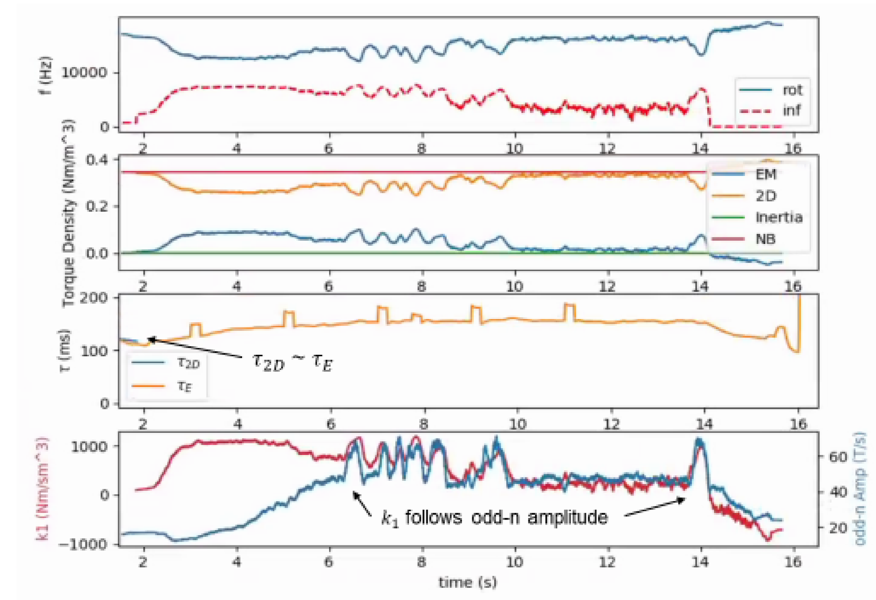
- Moment of inertia is calculated from line average density measurements and assumed constant throughout mode dynamics

Disrupting Shot



KSTAR shot 25829

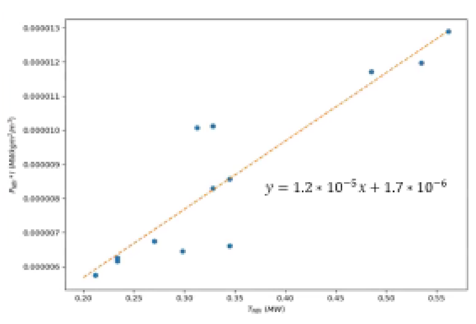
Non-disrupting Shot



KSTAR shot 23874

KSTAR Shot List Analysis Results

- A select set of 13 shots including disrupting and non-disrupting cases from the 2020 KSTAR run where analyzed
- From 13 shots there were 5 false positives for which the rotation went below the inflection frequency.
- If half of the inflection frequency is used as a threshold then all shots are correctly assessed
  - Inflection frequency is too conservative a condition and using a fraction of it as a threshold would be preferred



- The calculated NBI torque shows a proportionality with the NBI power and moment of inertia (i.e. density).
  - Can be used to crosscheck the calculated NBI torque values

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

- Conclusions
  - Developed a simple automated algorithm that can be used to forecast the locking of rotating MHD modes based on a torque balance model of its rotating frequency.
- Future Work
  - Run the algorithm on a larger set of shots and different machines to determine its accuracy (% of false positives) and improve it based on the feedback.
  - Further generalize the algorithm to allow for a broader set of MHD dynamics (i.e. mode slipping, mode coupling)
  - Incorporate latest version into the KSTAR PCS to aid forecasting and avoidance efforts. Potentially activate SPI disruption mitigation systems
- Acknowledgments

  - This work was made possible by funding from the Department of Energy. Supported by US DOE grant DE-SC0020415.