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Torque balance analysis in real-time of rotating MHD for disruption prediction and avoidance in KSTAR

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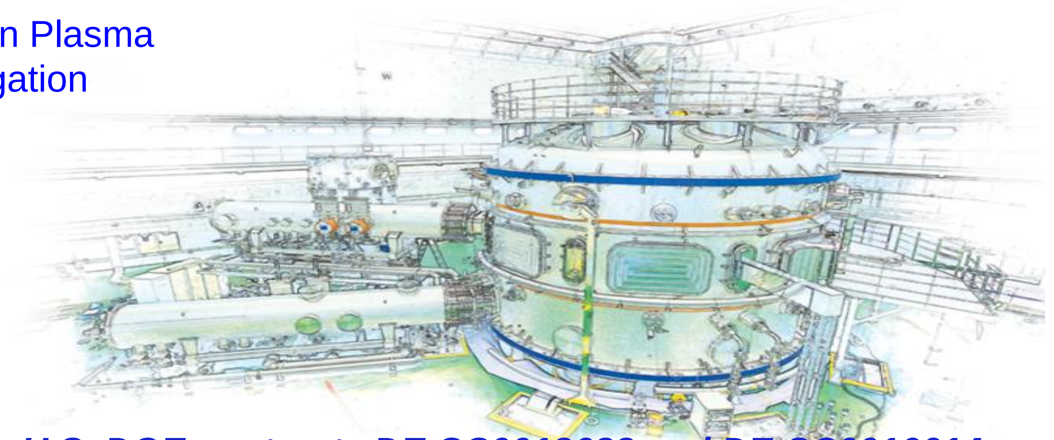
PPPL

Columbia University
in the City of New York

KSTAR



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Abstract

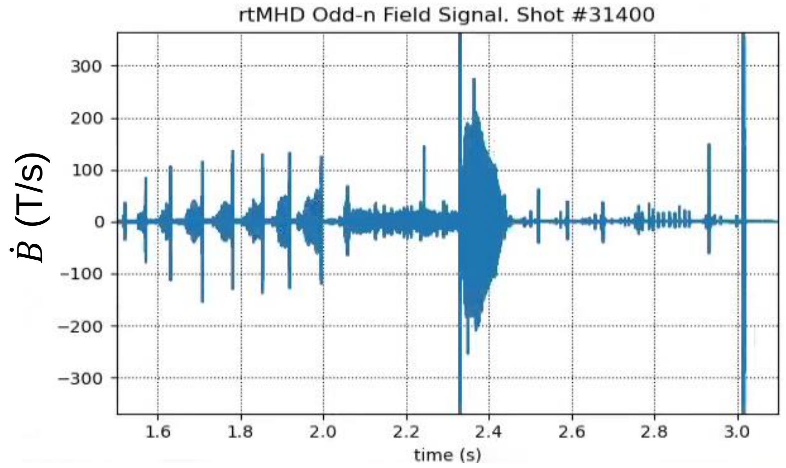
- Advanced tokamak reactors require a low disruptivity ceiling to reach commercial viability. The damaging impact of plasma disruptions on machine components can greatly reduced the lifetime of a device. A precursor to disruptions is the locking dynamic of rotating MHD events that are often neoclassical tearing modes (NTM). The drag of electromagnetic and fluid viscosity torques can cause the slowing down of NTM’s with a saturated island width and lock them to the wall reference frame. A balance of the driving torque from the NBI, and drag from perpendicular viscous diffusion drag and electromagnetic forces on the mode, as well as its inertia is used to model the mode rotation dynamics. Threshold rotation frequencies below which the mode rotation is expected to lead to a locking serve as a disruption forecaster. Mode identification is computed most accurately by Fourier analysis of a toroidal array of magnetic probes, or using simpler approaches generally more amenable to real-time calculation. From the rotation, the torque components are then calculated based on conditions for the expected drag torque ratios at the mode onset, changes in frequency, and Mirnov signal amplitudes. This technique is employed for offline and real-time analysis of KSTAR plasmas with potential to signal use of active mode control or disruption mitigation systems.

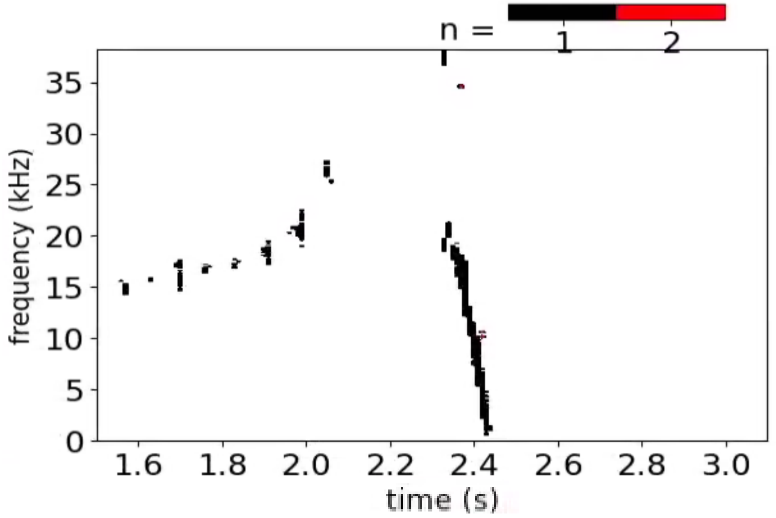
Successfully forecasting the locking of rotating MHD modes can be used to engage disruption avoidance and/or mitigation

- Motivation
  - The stress on or heating of device components caused by high performance plasma disruptions could render reactor scale tokamaks, like ITER, inoperable and in need of costly repair. Forecasting, avoiding, suppressing, and/or mitigating disruptions are then a crucial part of tokamak research and development.
  - Born-rotating MHD modes can slow down to the wall reference frame and drastically increase heat transport away from the core frequently leading to a plasma disruption
- Outline
  - Introduction to the Disruption Event Characterization and Forecasting (DECAF) code
  - Physics of the torque balance model used to develop a mode locking forecaster
  - Diagram of the real-time forecasting algorithm
  - Performance of the forecaster in predicting a mode locking and subsequent disruption
  - Triggering avoidance and mitigation strategies
  - Summary and next steps

The DECAF code offers a general physics-based approach to disruption forecasting and includes a mode locking forecaster

- A toroidal array of Mirnov probes picks up the field oscillations and signature of the mode.
- Spectral decomposition or a more straightforward zero-crossings analysis used to identify the mode number, amplitude, and rotation frequency
- Threshold conditions on these mode parameters are used to characterize the rotating MHD modes as precursor events to a plasma disruption
- The locking of modes along with other physics based and technical events are used to identify the causal chains that lead to plasma disruption. This is the basis for the development of the automated and device-general DECAF code.

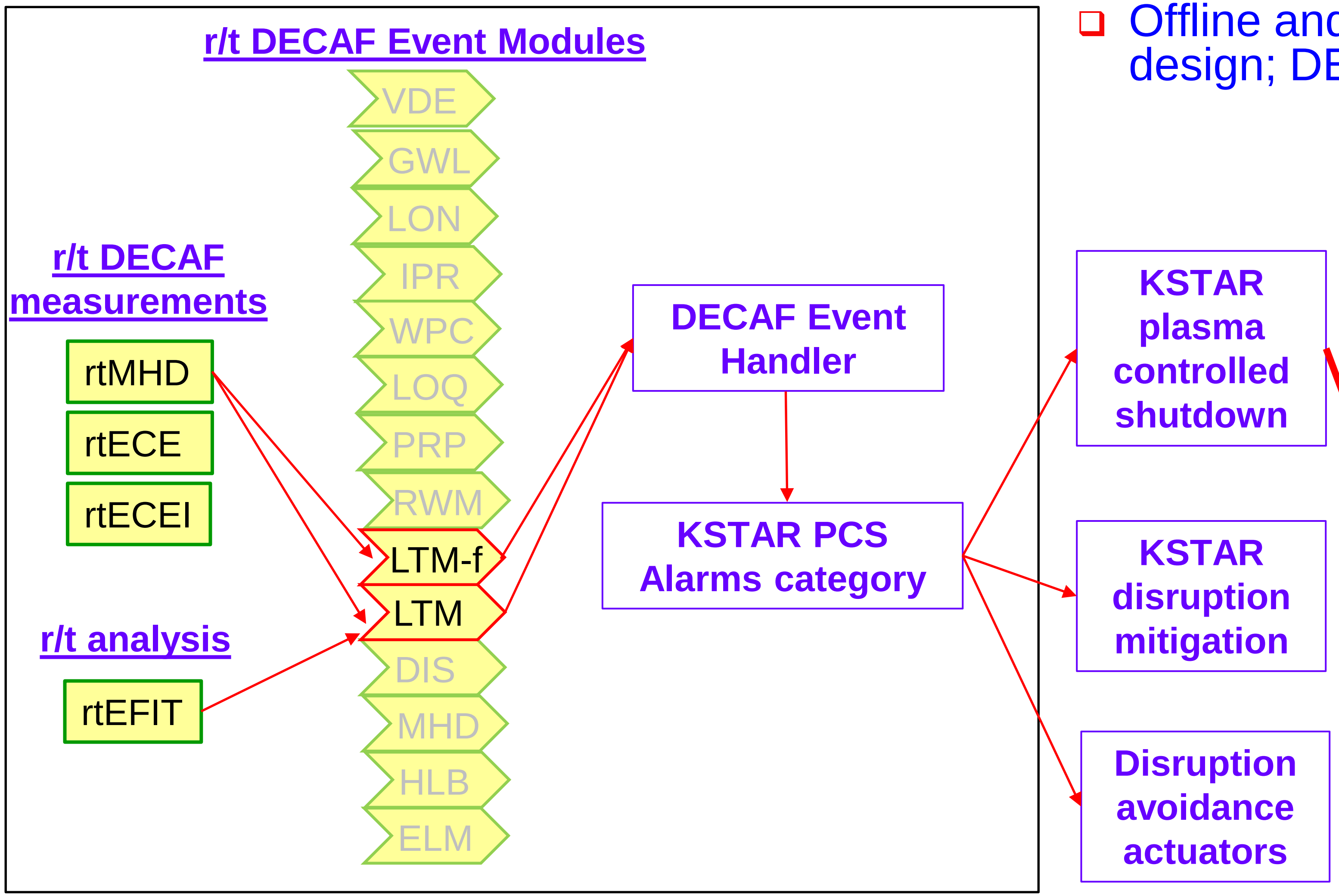




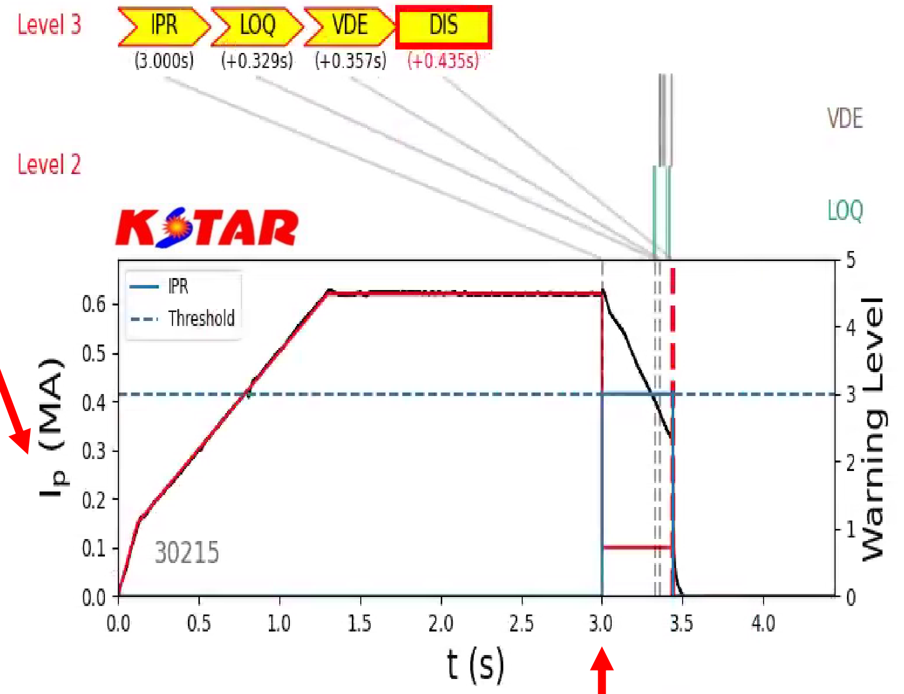
chain of events

Four real-time software elements were installed and tested for use in real-time disruption forecasting

KSTAR PCS



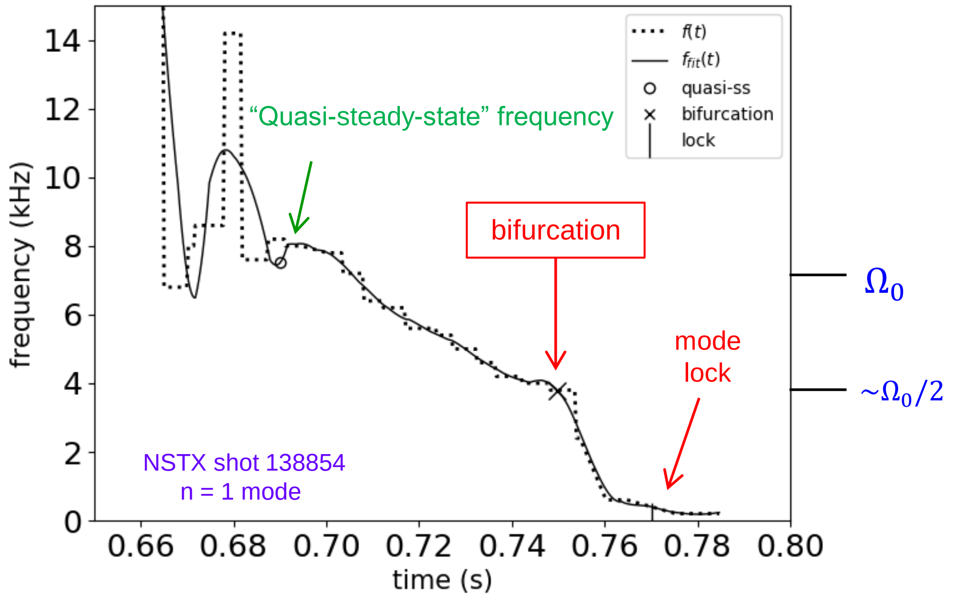
- Offline and real-time DECAF codes follow similar design; DECAF events added as modules

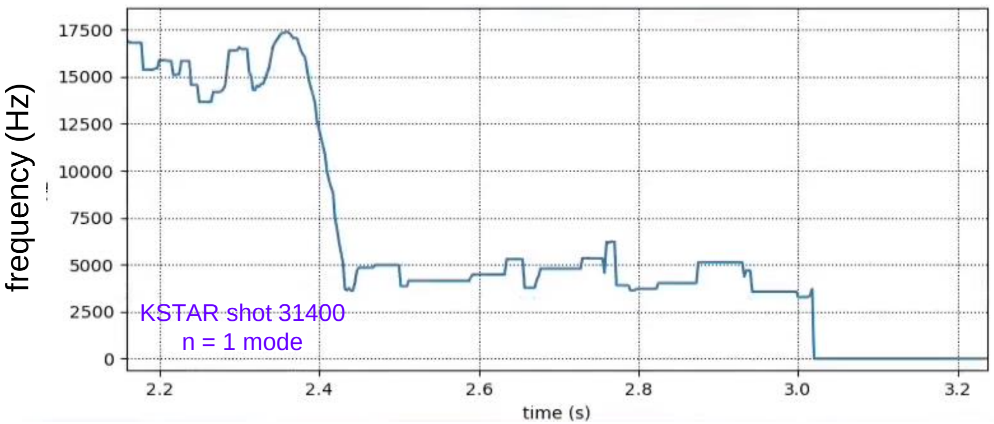


Controlled shutdown triggered (using pre-programmed “event”)

Rotating MHD modes create a friction in the plasma that leads to slowing of the modes and potential locking

- Natural frequency of mode rotation is reached due to a force balance of drag and driving auxiliary heating
- In the process of slowing down, the mode can lose force balance leading to a rotation frequency bifurcation that locks the mode to the wall reference frame, as is shown for an NSTX shot
- In KSTAR plasmas, however, because of the lower background error field, modes can remain in a slowly rotating state or speed back up again before locking.

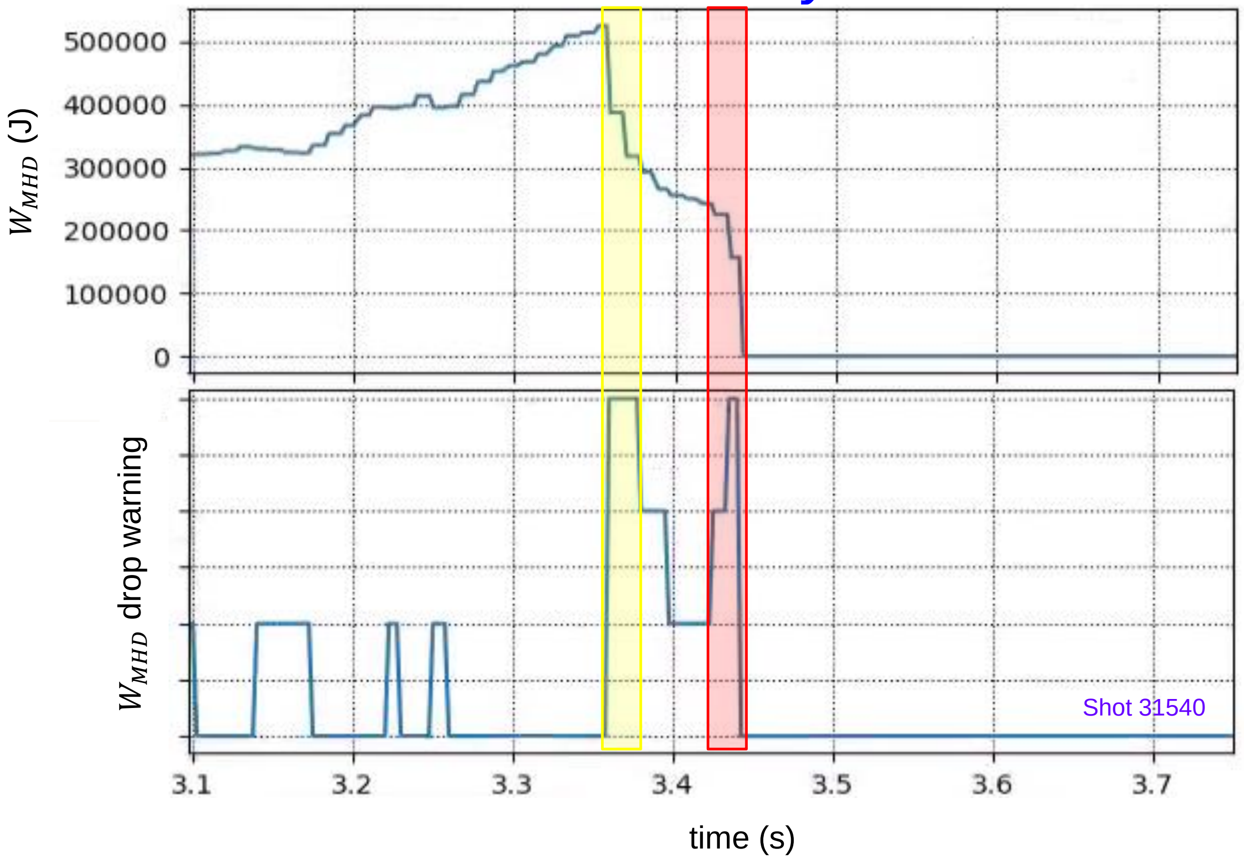


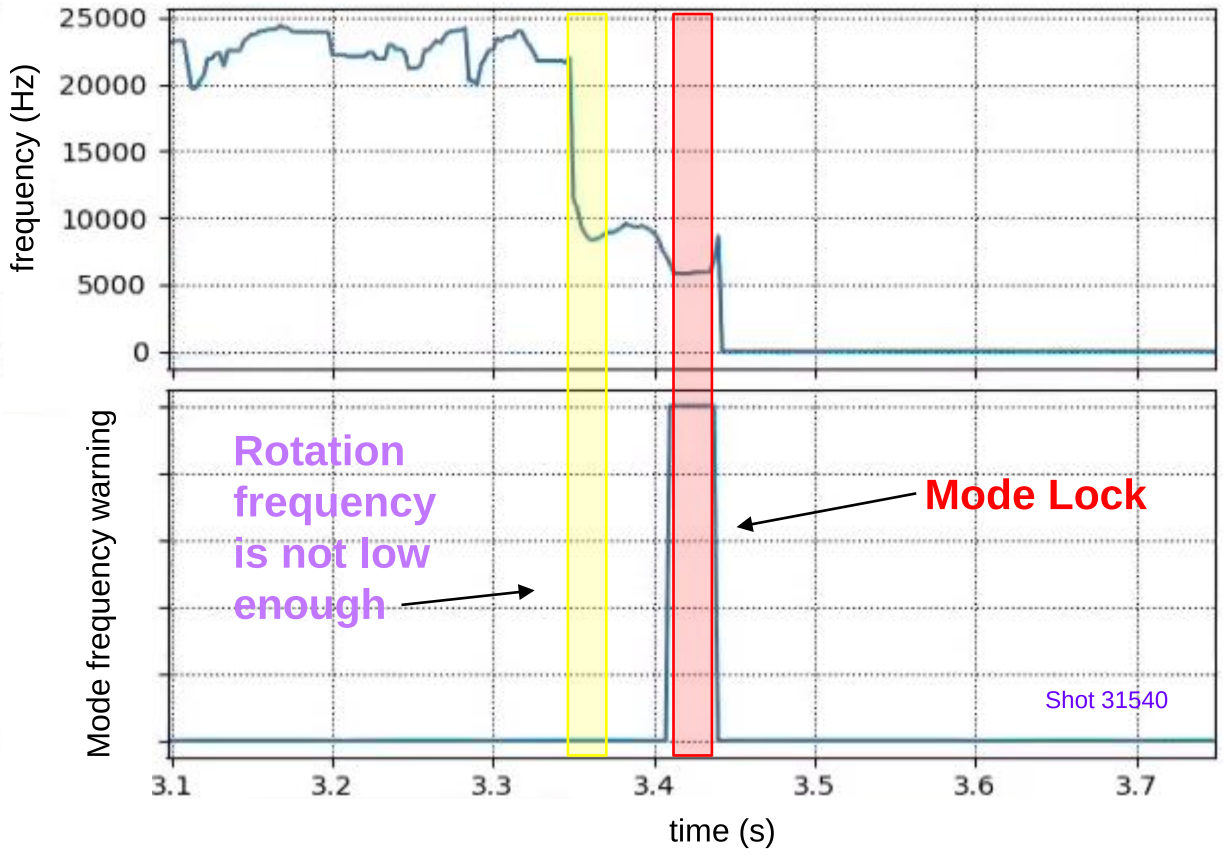


Characterization of the mode locking in KSTAR considers the mode rotation and drop in stored energy

- The Mirnov probes are not large enough to capture the magnetic signal of the more slowly rotating modes.

- Can complement a rotation threshold with a fractional change in stored energy threshold to better identify a mode locking in KSTAR





Torque balance model can reproduce the key mode dynamics approaching a locking state

- A straightforward torque balance equation can be derived to find the toroidal rotational speed values at which the plasma is in a steady state

- Components in the model include:
  - 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}

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

- Dragging torque components are defined with respect to the mode rotation by making simplifying assumptions
  - Can assume a "no-slip" or "slip" condition of the plasma past the X-points in island chain
    - $T_{mode,no-slip} = -\frac{k_1}{\Omega}$ $T_{mode,slip} = -\frac{k_2\Omega}{1+k_3\Omega^2}$, where the coefficients k_i are associated with the mode amplitude or island width.
  - Establish a characteristic perpendicular viscous diffusion time for the viscous drag
    - $T_{2D} = -\frac{(I\Omega)}{\tau_{2D}}$
  - Ignore variations in moment of inertia $I = I_{avg}$

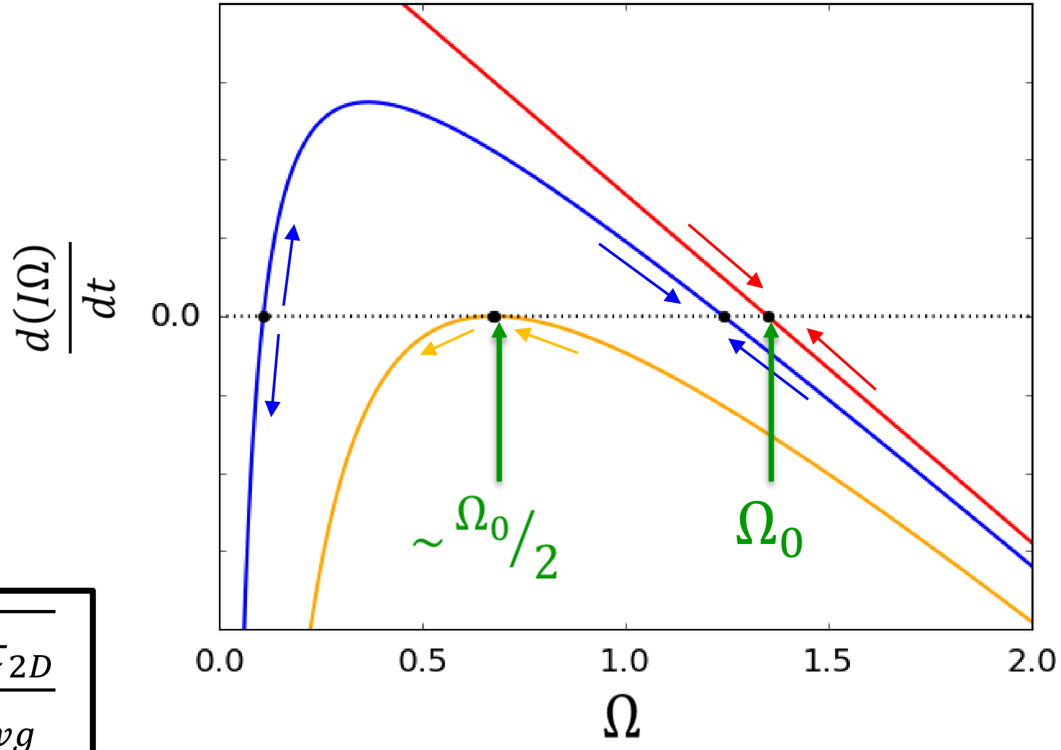
The inflection frequency can be used as a forecasted rotation threshold below which a mode locking is expected

- For steady state solutions: $\left(\frac{d(I\Omega)}{dt} = 0\right)$
- $k_1 = 0$: "red curve"
  - No mode present
- $k_1 < \frac{{T_{aux}}^2 \tau_{2D}}{4 I_{avg}}$: "blue curve"
  - Two steady state solutions
- $k_1 = \frac{{T_{aux}}^2 \tau_{2D}}{4 I_{avg}}$" : "orange curve"
  - One steady state solution $(\sim \frac{\Omega_0}{2})$
  - Bifurcation and Inflection

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

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

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



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

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

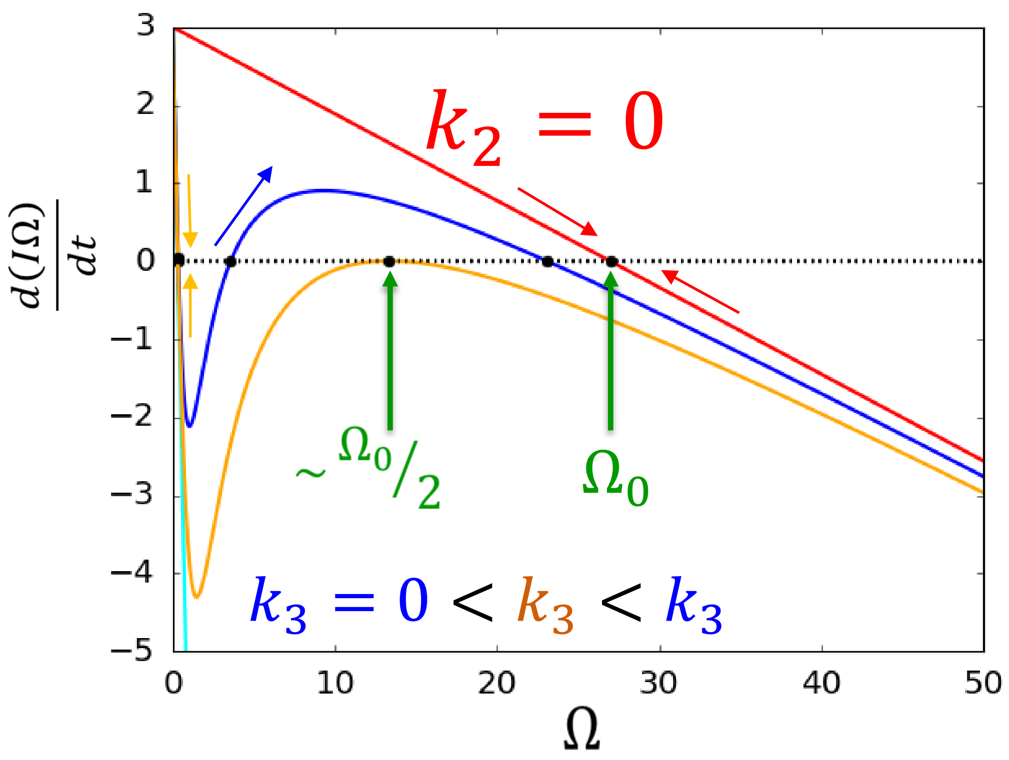
- A possible model of the drag for both a “slip” and a “no slip” condition is:

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

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

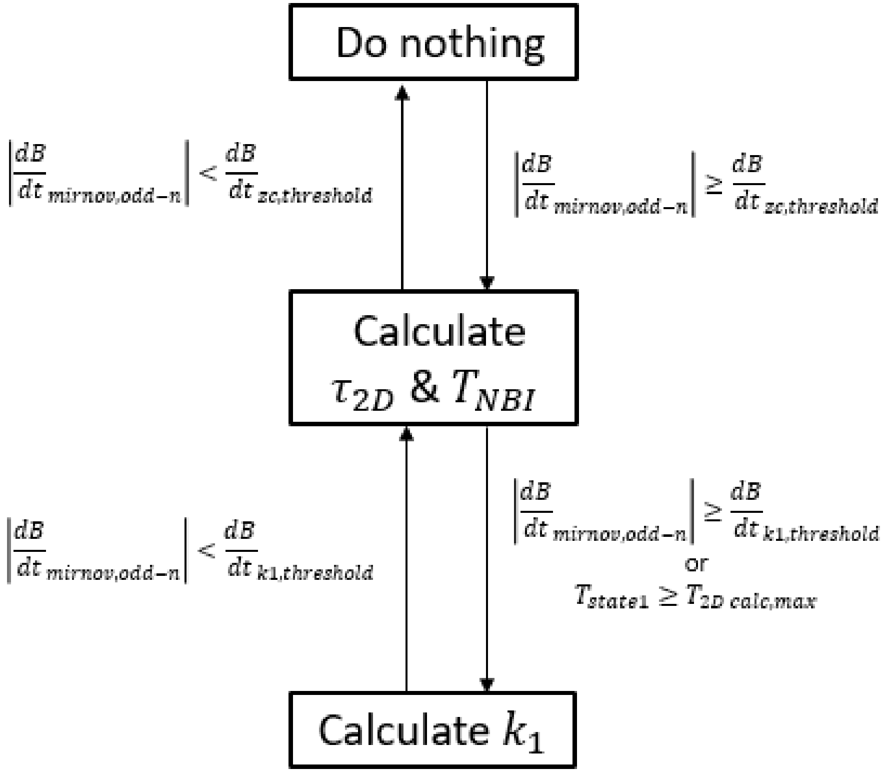
$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_2 \Omega}{1 + k_3 \Omega^2} - \frac{(I\Omega)}{\tau_{2D}}$$



The coefficients in the torque components are determined in different regimes of mode rotation/amplitude

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

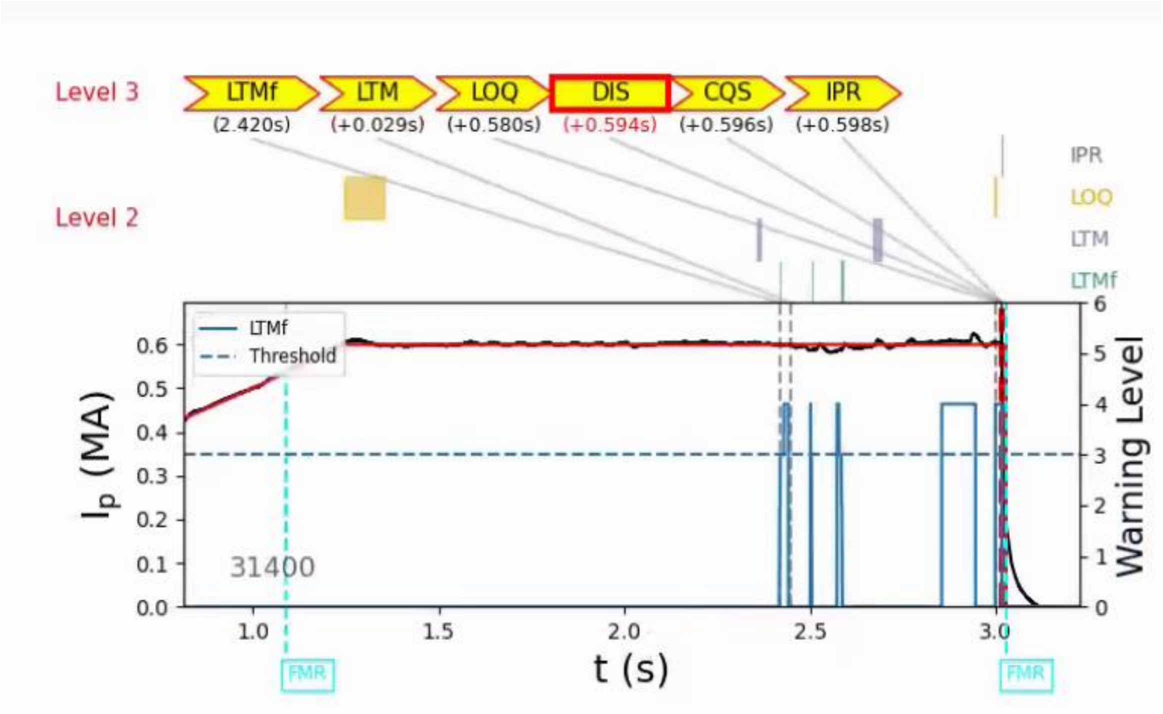
- While the mode is highly rotating the viscous drag is larger than the EM drag. The characteristic perpendicular viscous diffusion time τ_{2D} is calculated and driving torque T_{aux} can be calculated in this regime
- T_{aux} is set to a value that makes $\tau_{2D} \sim \tau_E$.
  - Energy confinement time is estimated as $\tau_E = \frac{W_{tot}}{P_{NBI}}$
- k_1 is then calculated using the average value of the previously calculated τ_{2D}
- Moment of inertia is calculated from line average density measurements and assumed constant throughout mode dynamics
- This computational approach is used in both offline and real-time DECAF analysis



Real-time forecaster of locked modes shows good performance in forecasting mode locking and subsequent disruptions

- Succesfully forecasted ~50 shot with mode locking that disrupted in KSTAR 2022 run. Actuation windows of up to 2 seconds for KSTAR plasmas.

- Offline and real-time analysis in close forecasting agreement



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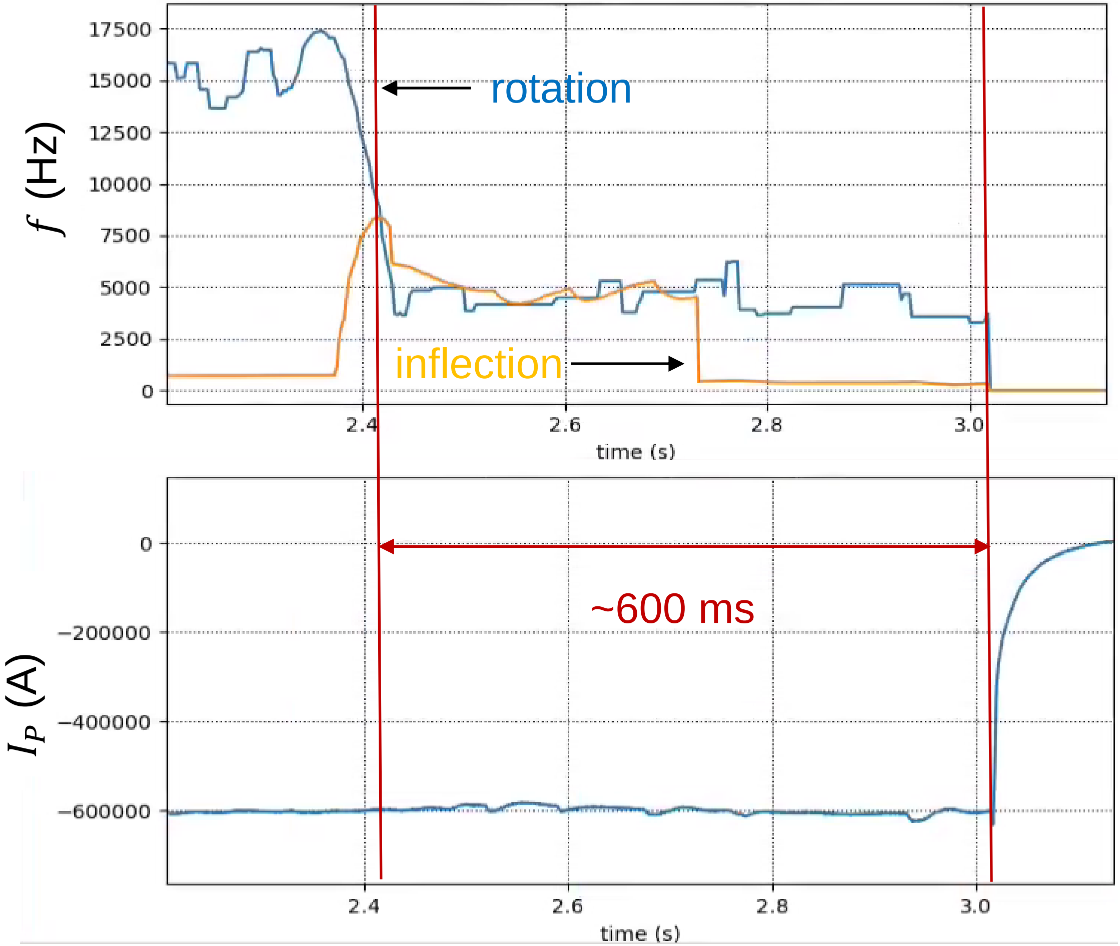
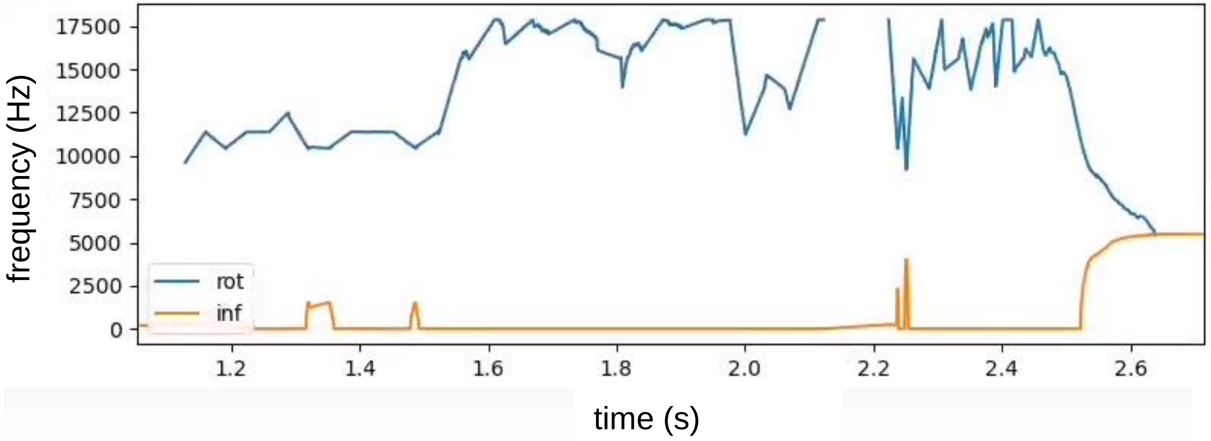
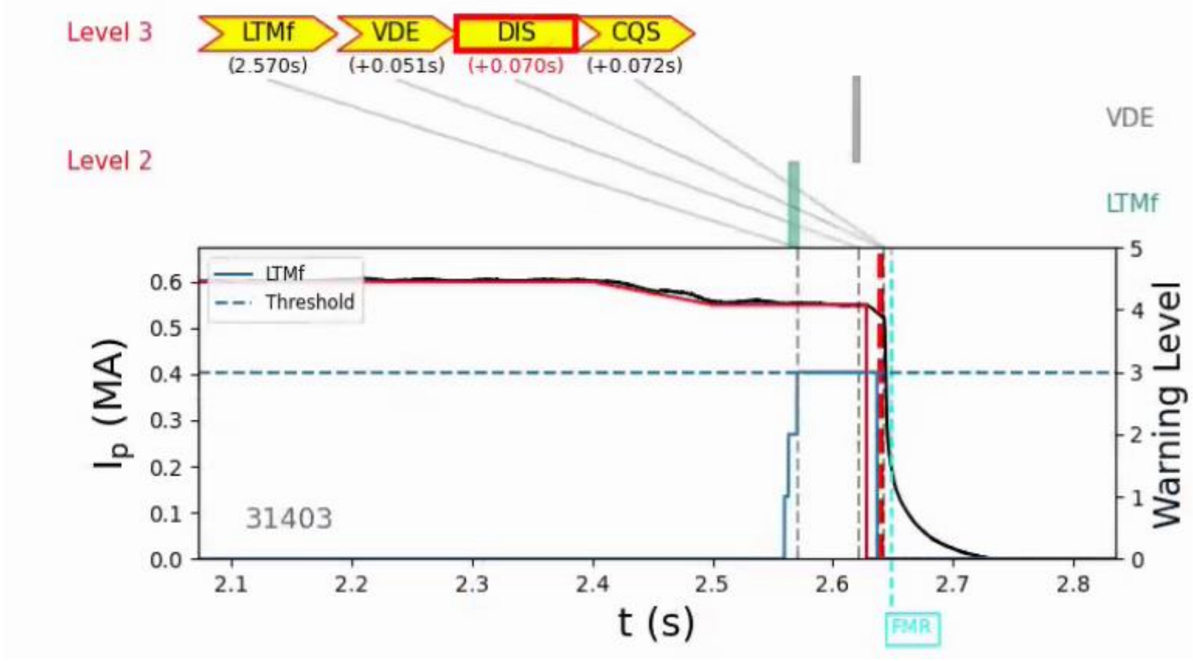
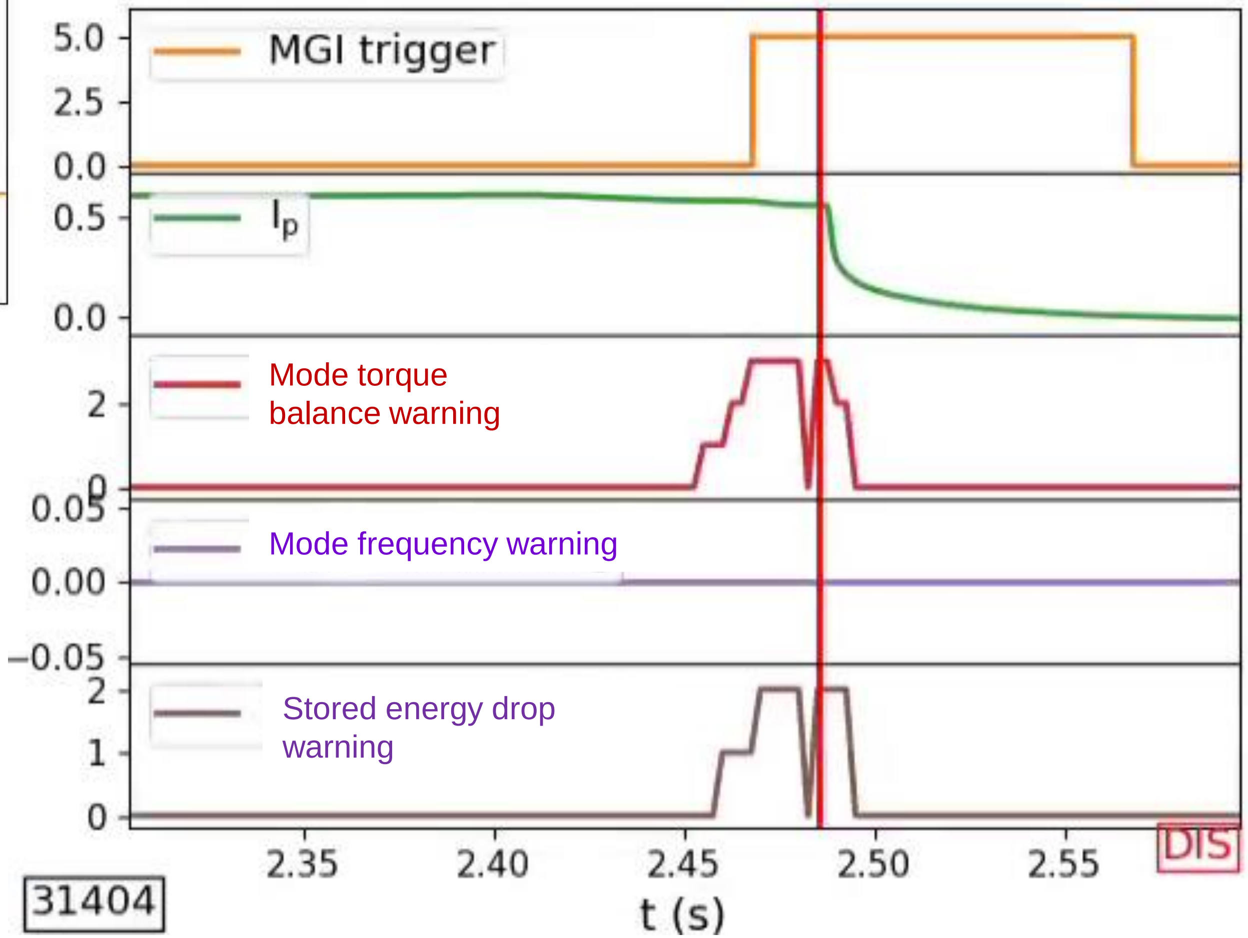


Real-time forecaster can trigger a massive gas injection as a disruption mitigation strategy

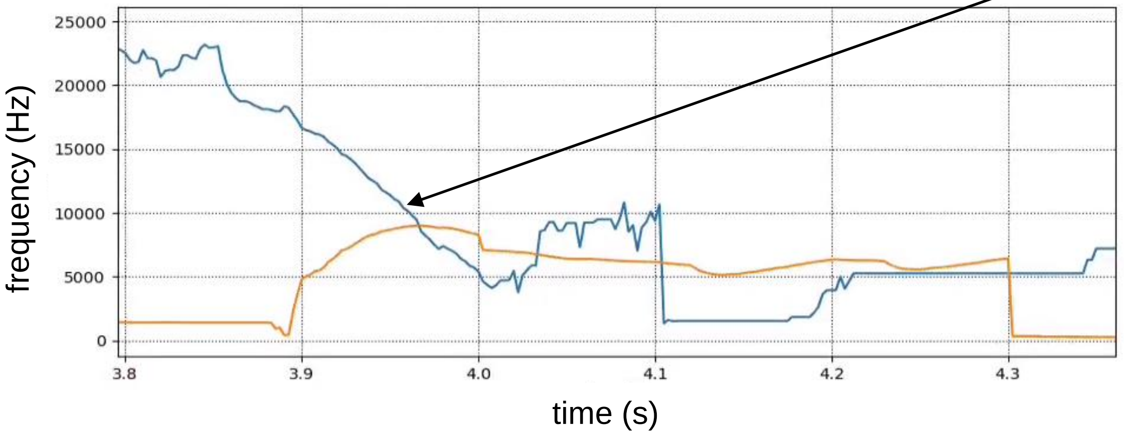


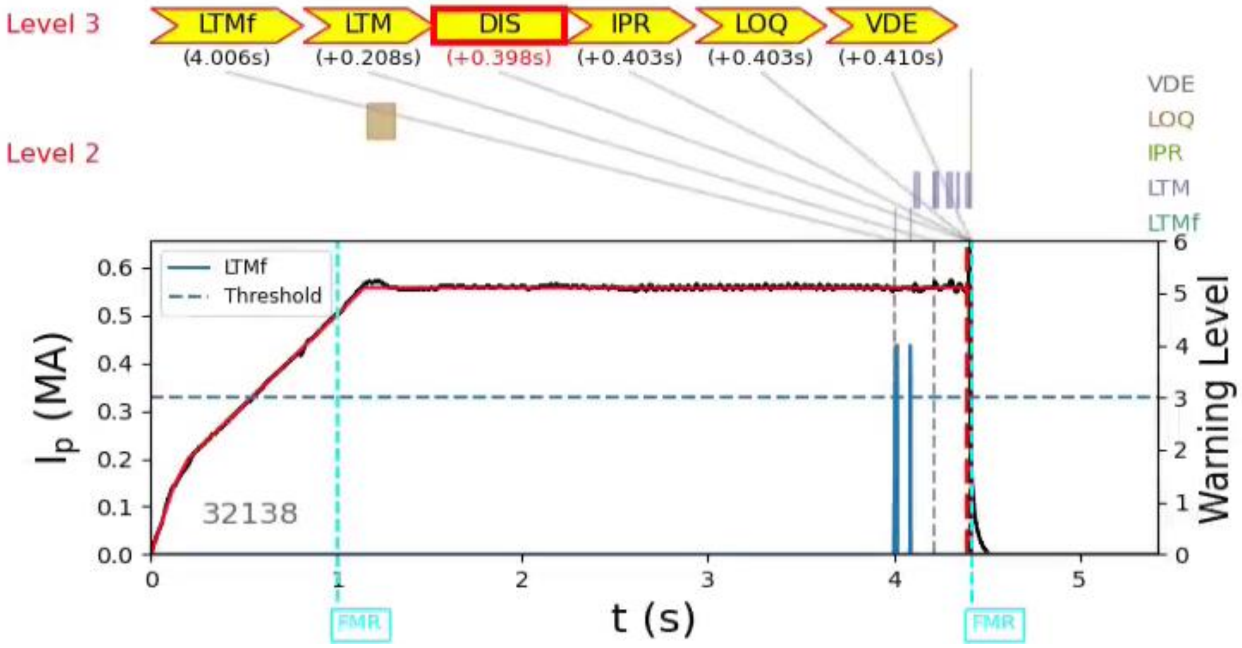


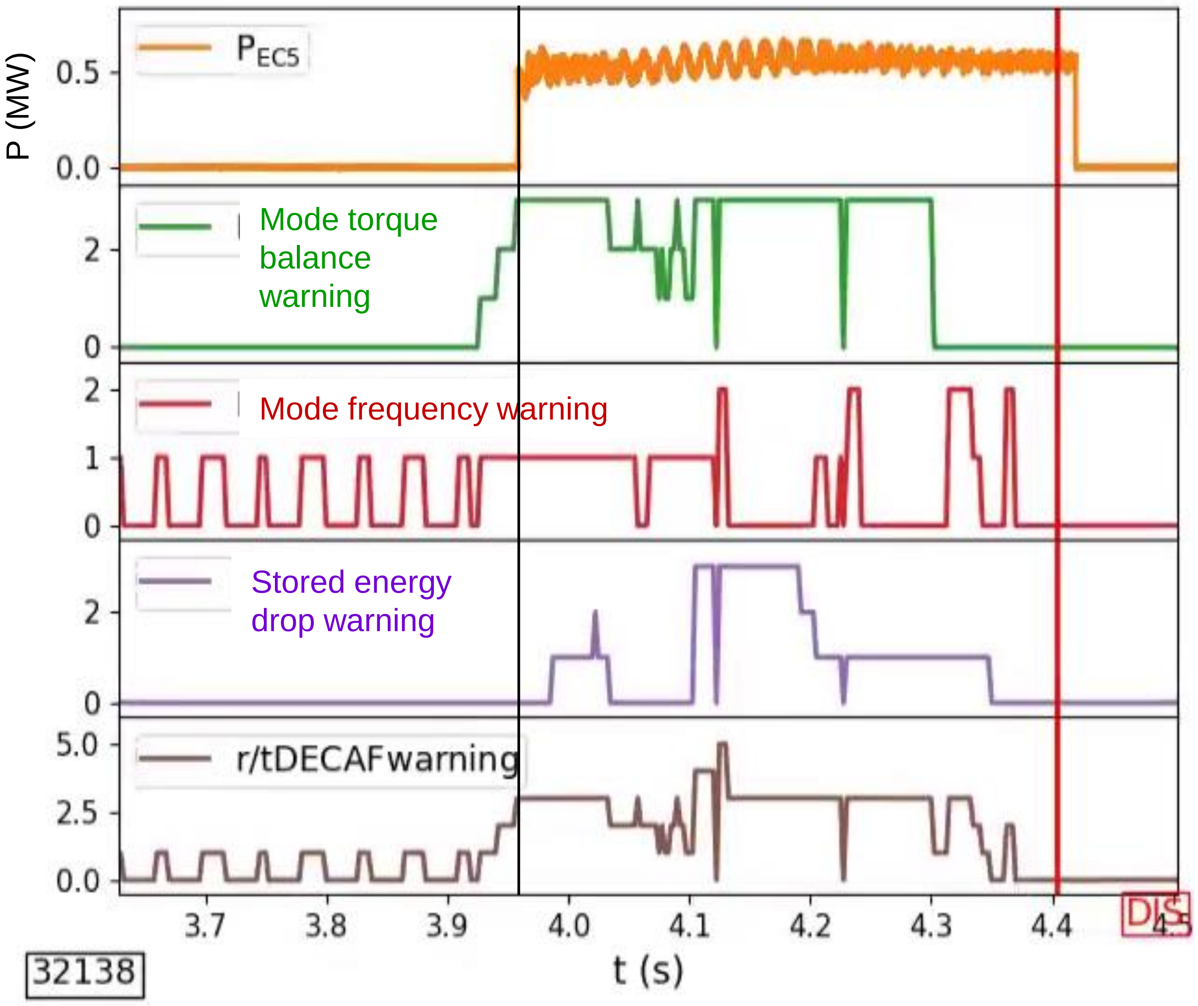


Triggered ECCD actuation of the rotating MHD mode leading to a 400 ms window before the plasma disruption

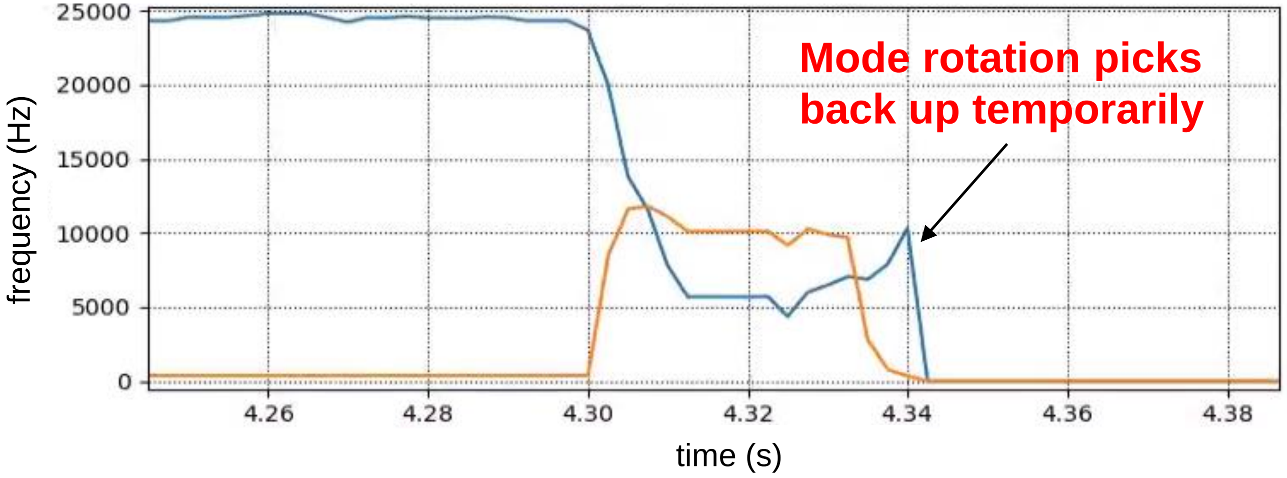
Actuation trigger

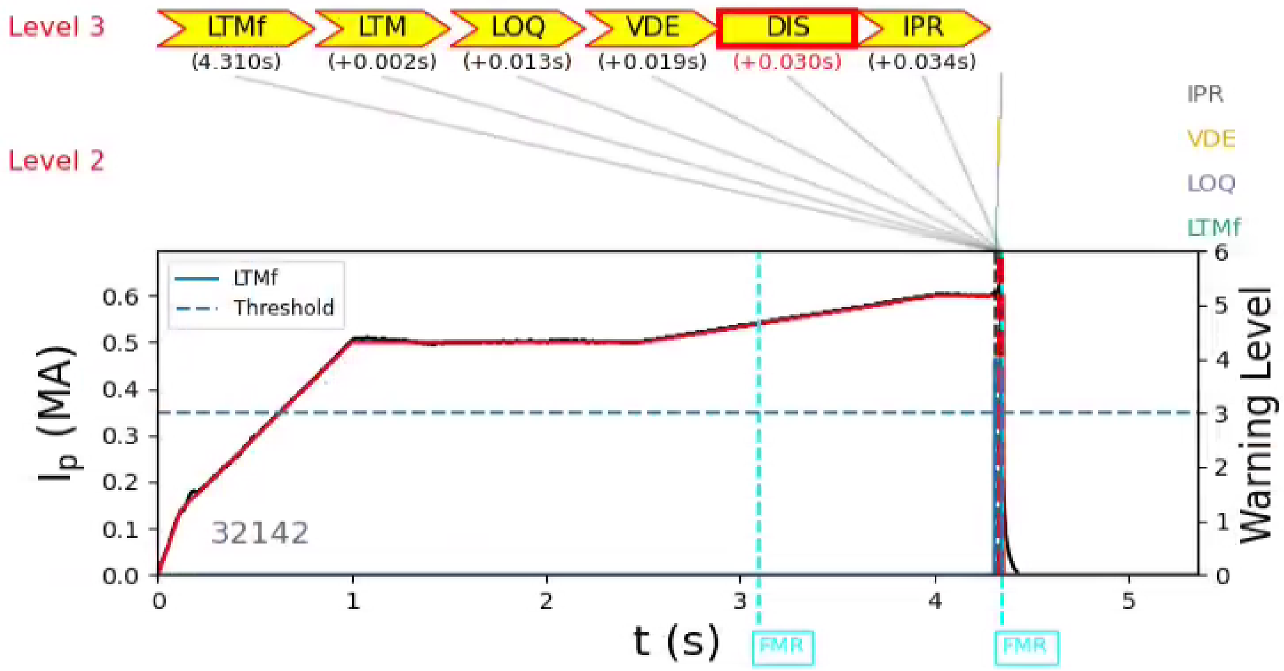


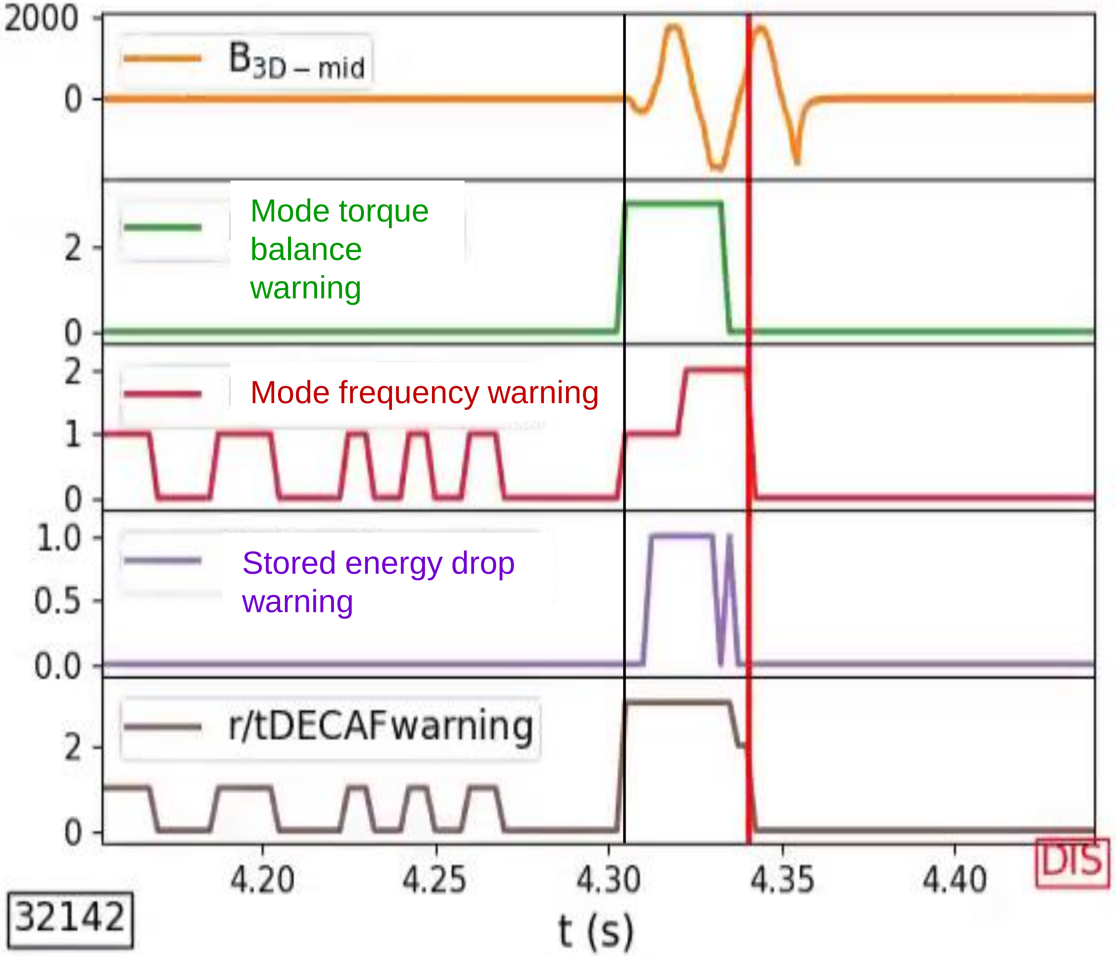




Successfully triggered an n=1 toroidally rotating field that temporarily recovered the mode rotation before locking







The LTM forecaster and broader DECAF code is a promising tool for the purposes of disruption prediction, avoidance, and mitigation

Summary

- Developed an algorithm to characterize and forecast the locking of rotating MHD modes as part of the general DECAF code.
- Implemented the forecaster in the KSTAR PCS showing high accuracy in predicting disruptions caused by mode locks
- Successfully triggered various avoidance and mitigation strategies (ECCD, 3D n=1 applied fields, and MGI)

Next Steps

- Optimize the actuation strategies for successful avoidance
- Use the real-time calculated spectrogram to improve the mode lock forecaster and characterization
- Add more real-time precursor events in KSTAR to better forecast disruptions