NSTX-U

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Disruptions in the High-β Spherical Torus NSTX

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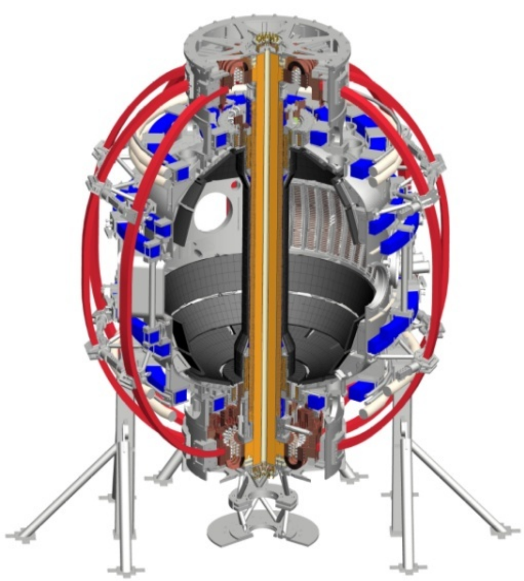
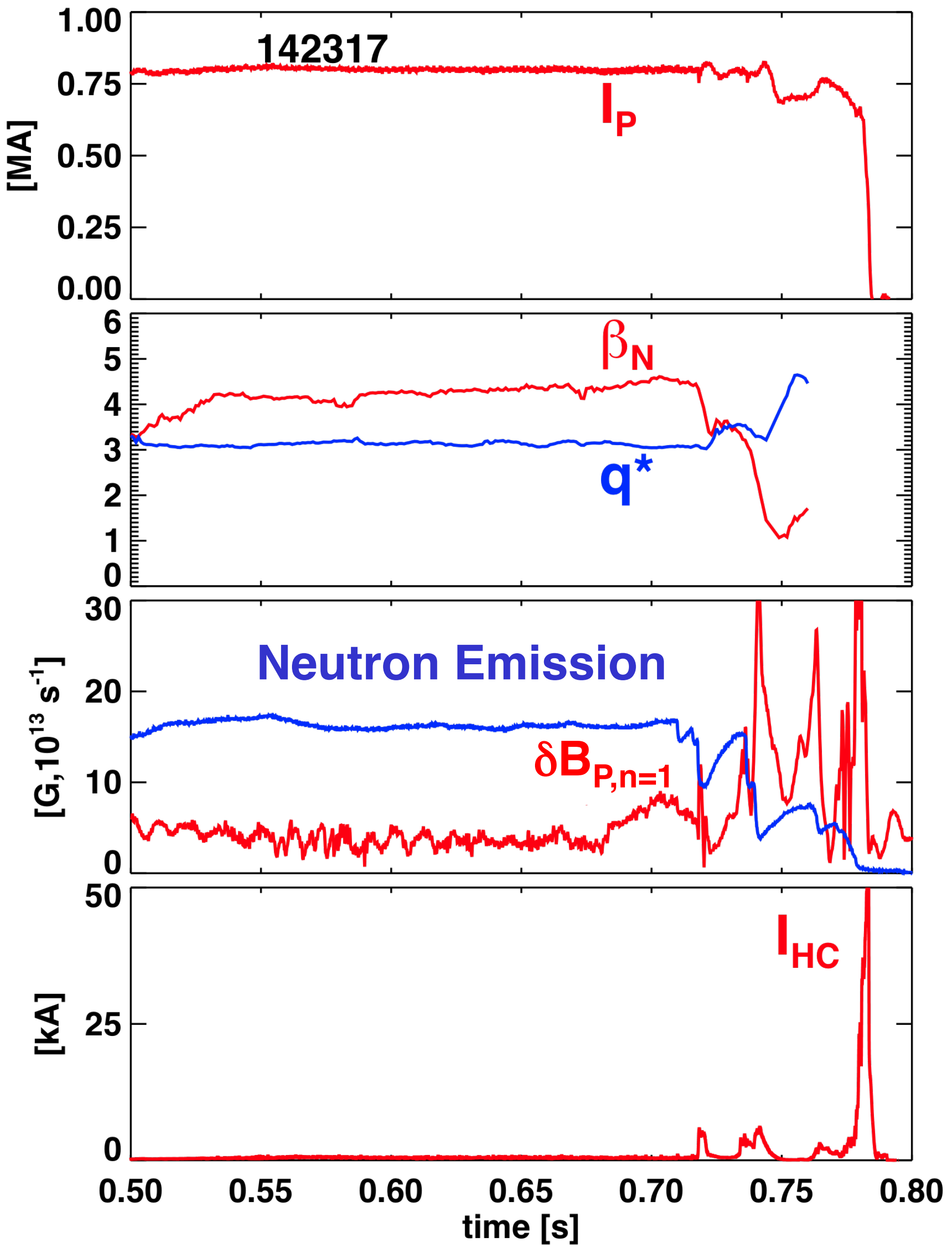


Disruptions Are a Critical Issue for the Tokamak/ST Line of Fusion Systems

- Phases and consequences:
  - Thermal quench can lead to excessive PFC thermal loading.
  - Current quench can lead to large eddy current forces/moments on in-vessel structures or the chamber itself.
  - Combined, the thermal and current quench phases can lead to the generation of potentially damaging runaway electron beams.
  - If vertical motion of the plasma column occurs, then large halo current loading of in-vessel structures can result.

- Strategies to address this problem include development of…
  - operations regimes and control techniques to avoid disruptions,
  - recovery techniques when the plasma has become unstable,
  - disruption detection, and rapid discharge shut-down methods once a disruption is deemed imminent,
  - improved understanding of disruption effects.

Outline
Talk Addresses Three Aspects of Disruptions



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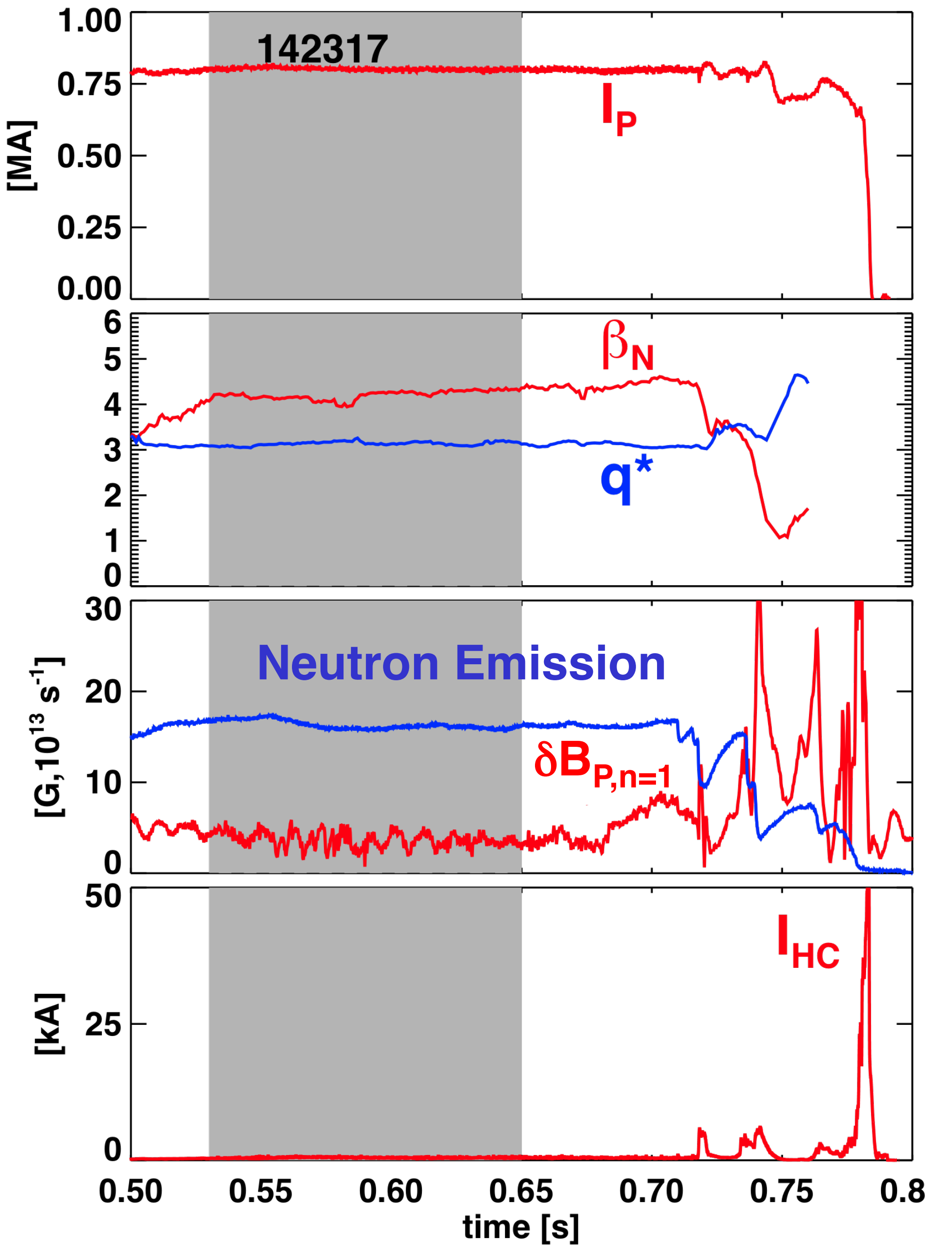

1: Conditions with minimal disruptivity

Determine desirable operating points for next step STs.

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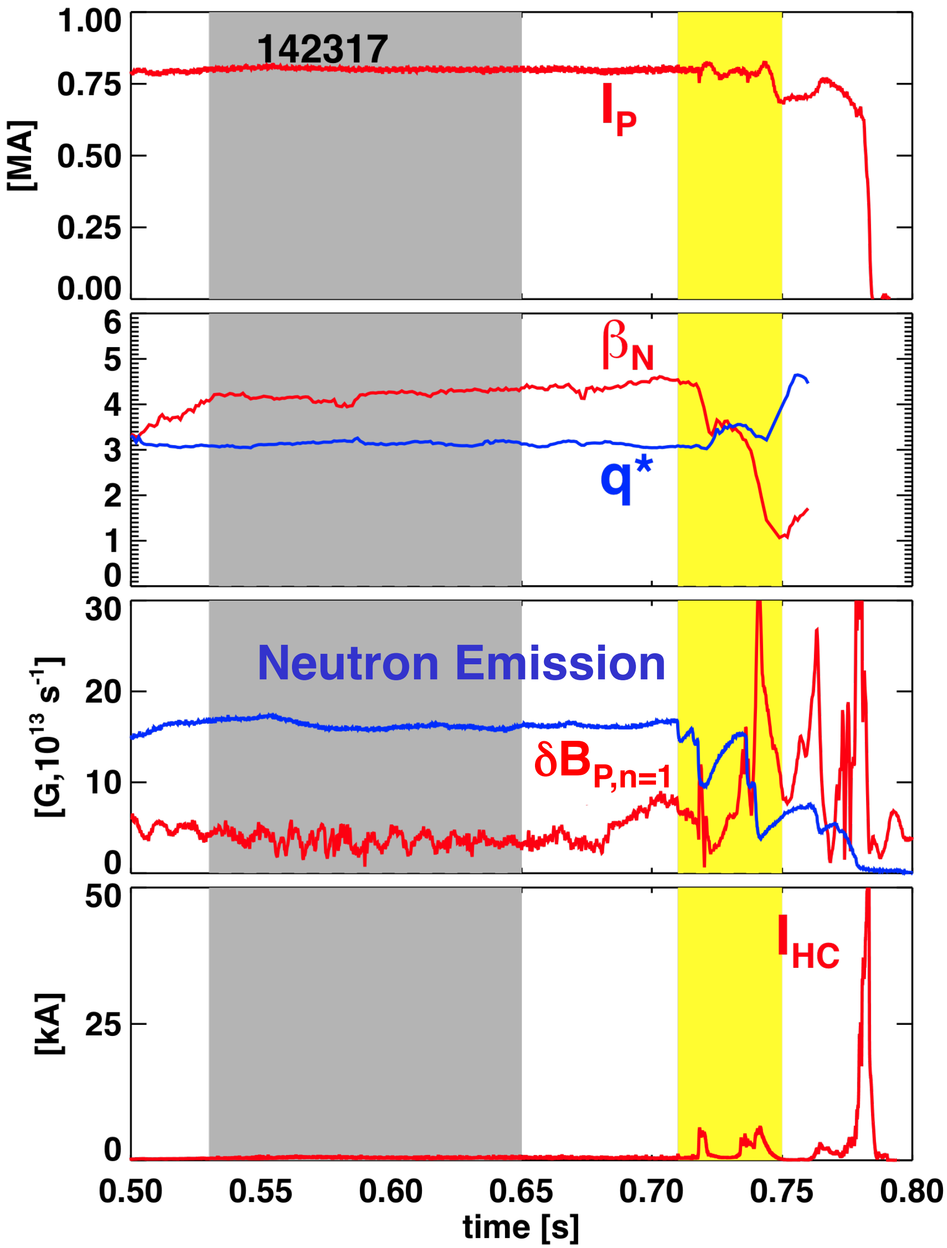

1: Conditions with minimal disruptivity

Determine desirable operating points for next step STs.

2: Disruption detection

Improve the basis for triggering mitigation systems.

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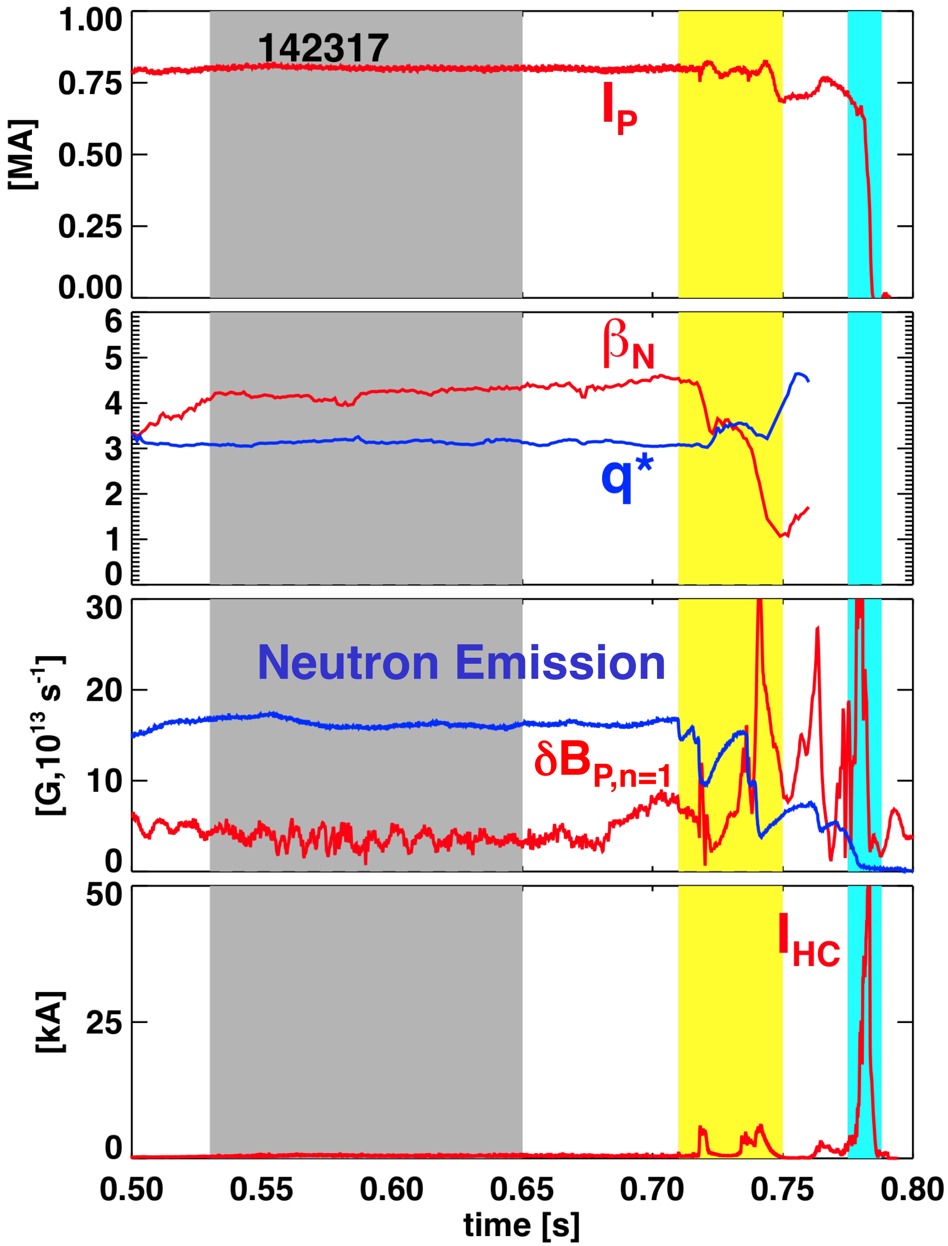

1: Conditions with minimal disruptivity

Determine desirable operating points for next step STs.

2: Disruption detection

Improve the basis for triggering mitigation systems.

3: Disruption halo currents.

Better understand the dynamics of, and mechanical loading from, these currents.

Outline
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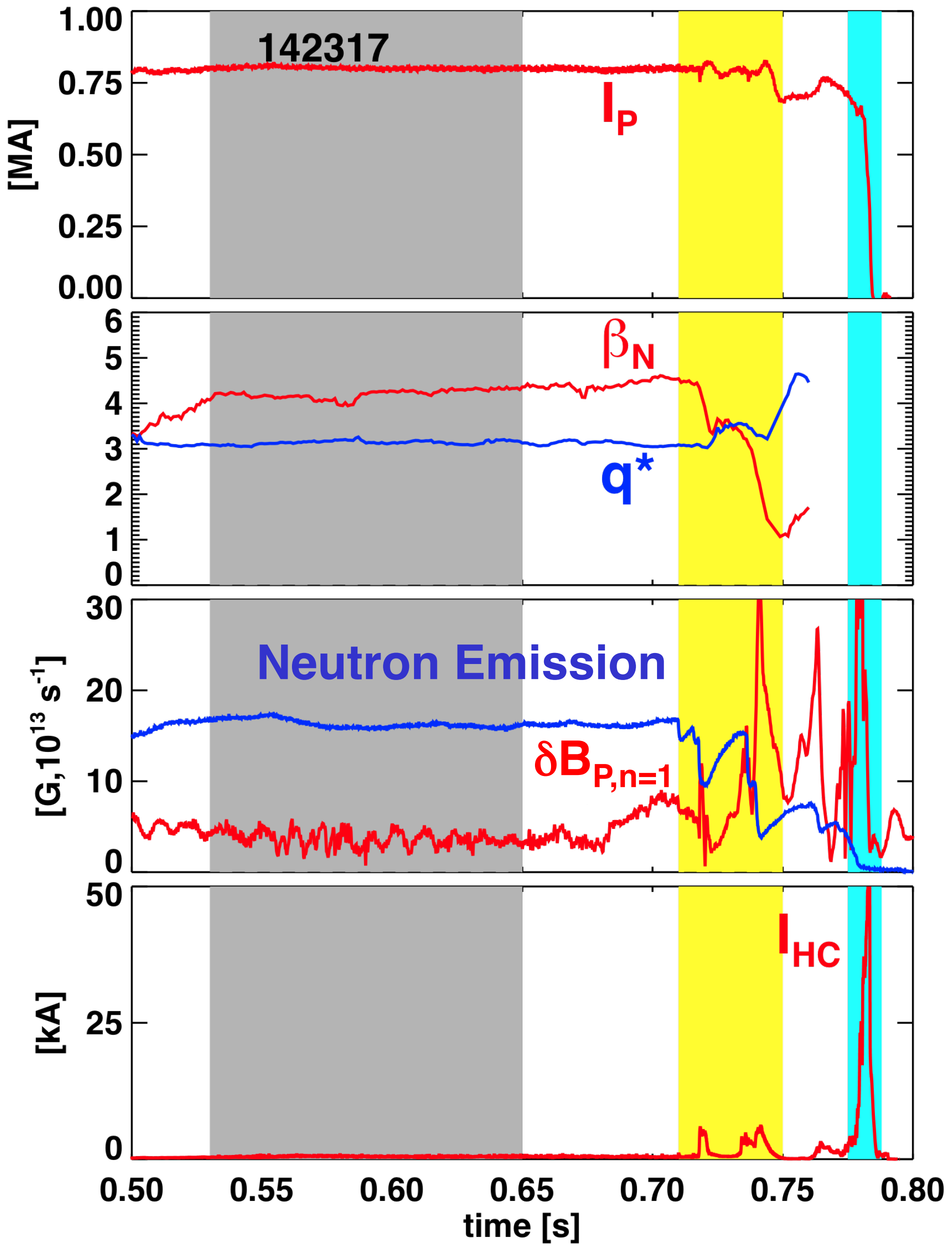
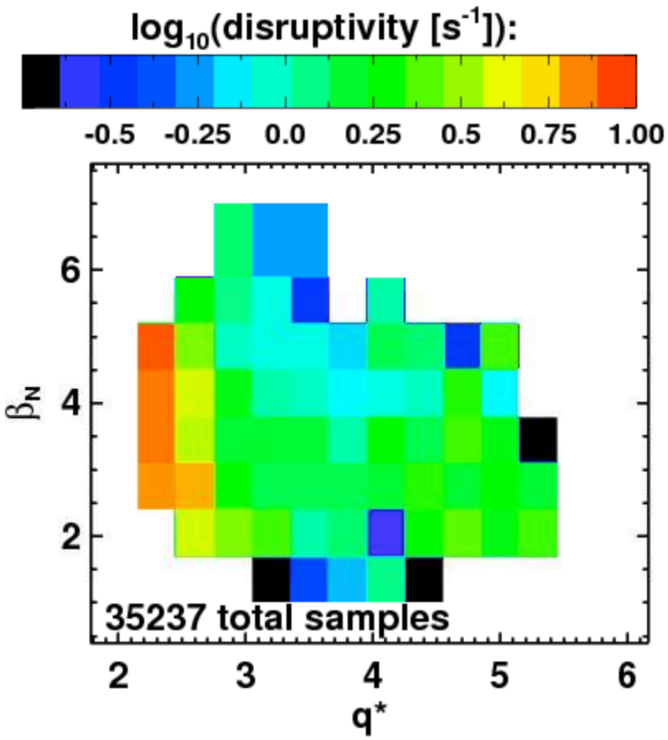


1: Conditions with minimal disruptivity

Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX

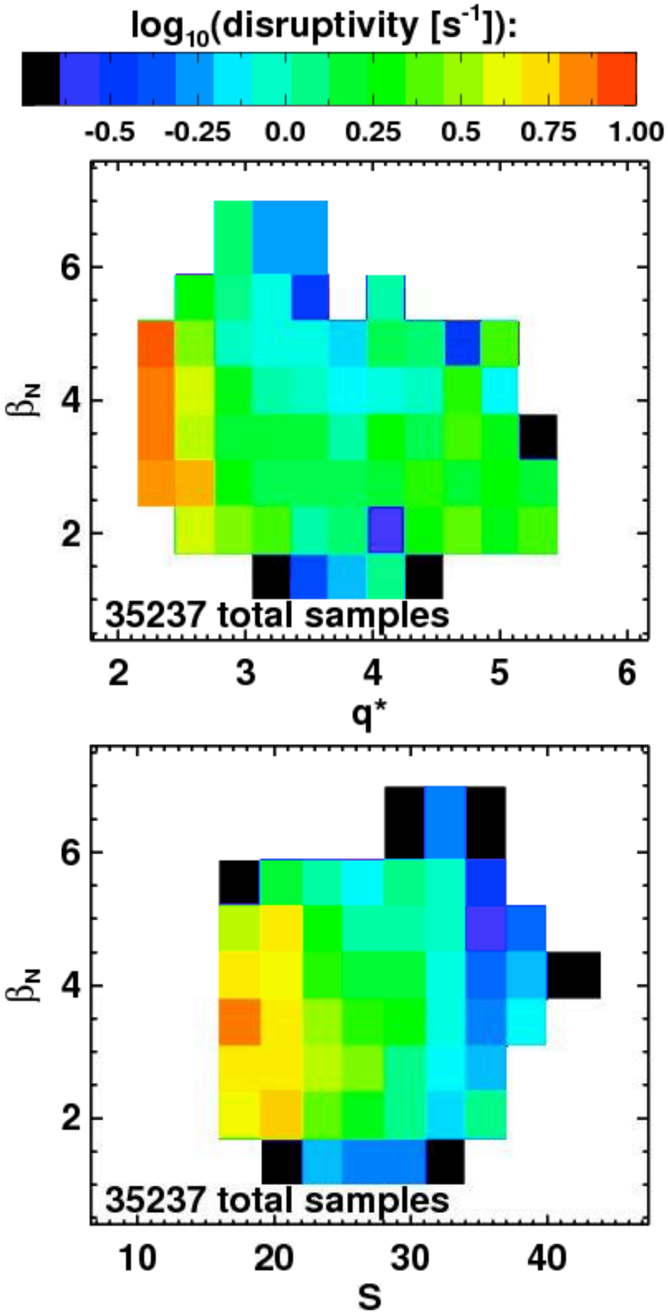


Definition of Disruptivity:
Select a Portion of Operating Space For Analysis
Disruptivity = # of Disruptions / Discharge Time

Sample all NSTX H-mode discharges since 2007, every 33.3 ms, for these studies

$$q^* = \varepsilon \pi a B_T \left(1+\kappa^2\right) / \mu_0 I_P$$

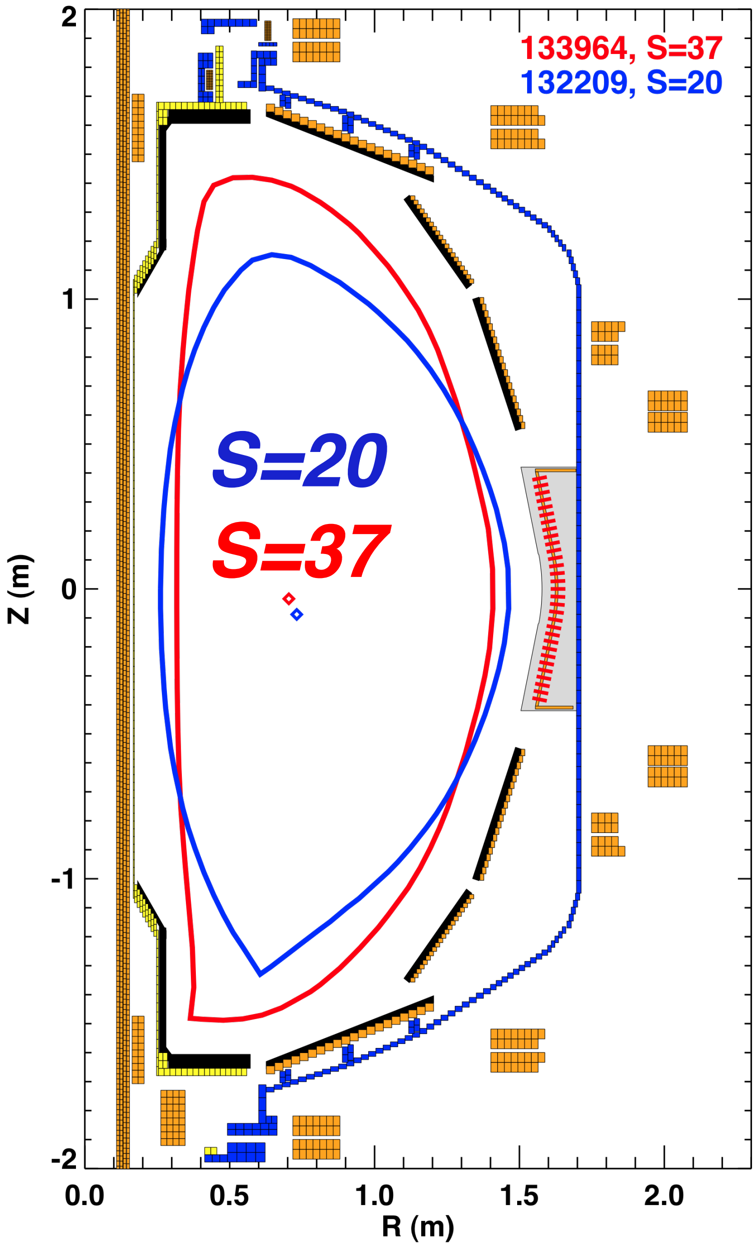
Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX



$$q^* = \varepsilon\pi a B_T\left(1+\kappa^2\right)/\mu_0 I_P$$

$$S = q_{95} I_P / a B_T \propto$$

$$\varepsilon\left(1+\kappa^2\right) f\left(\kappa,\delta,\varepsilon,\ldots\right)$$



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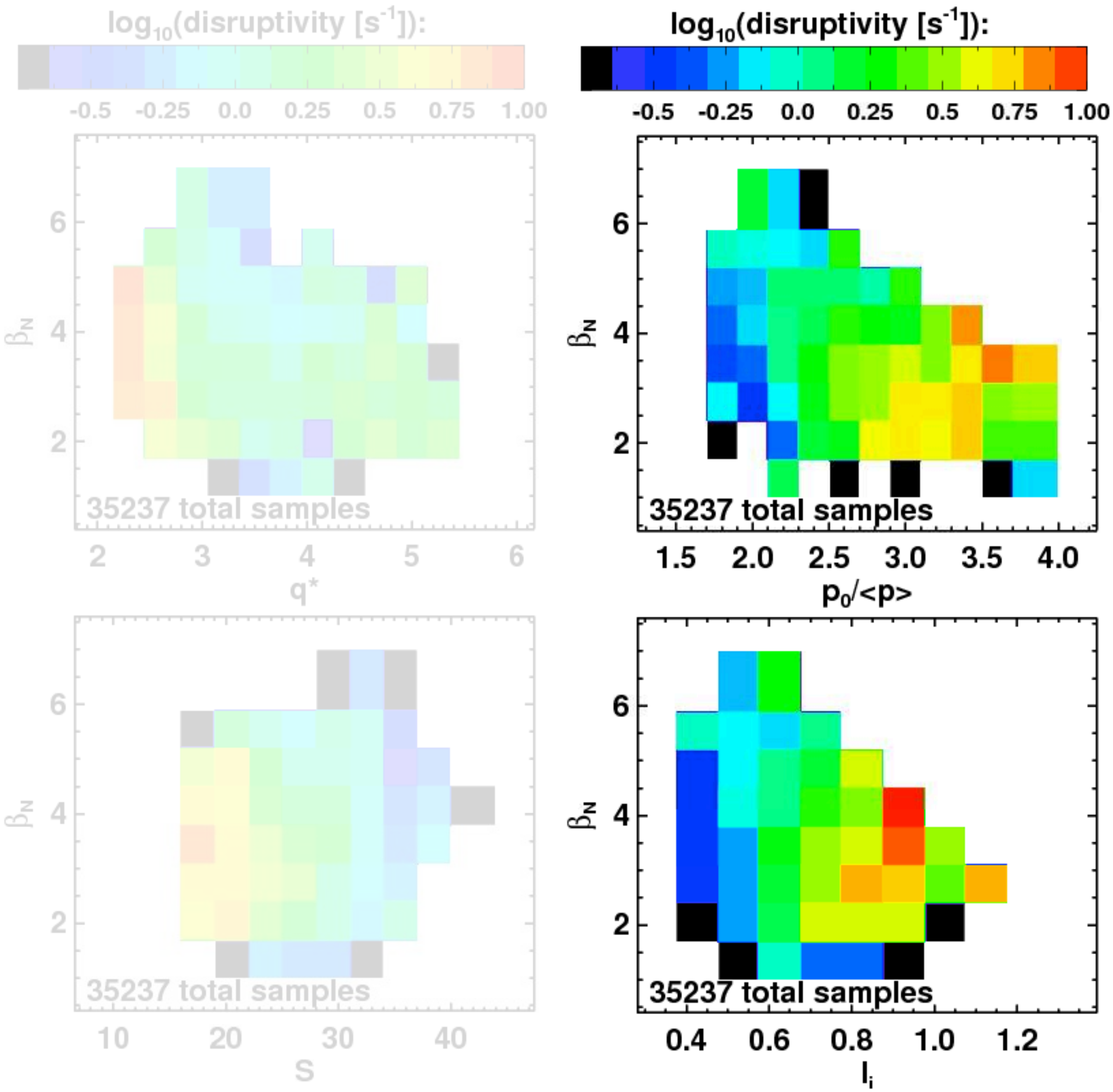

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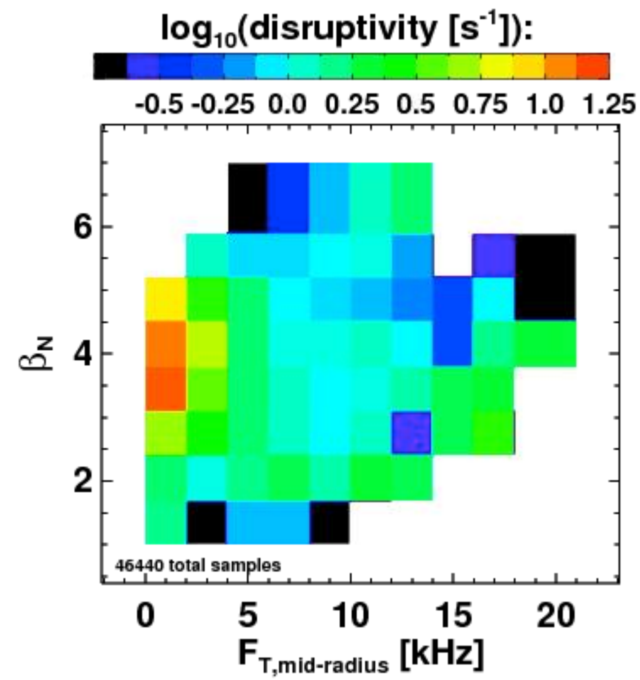


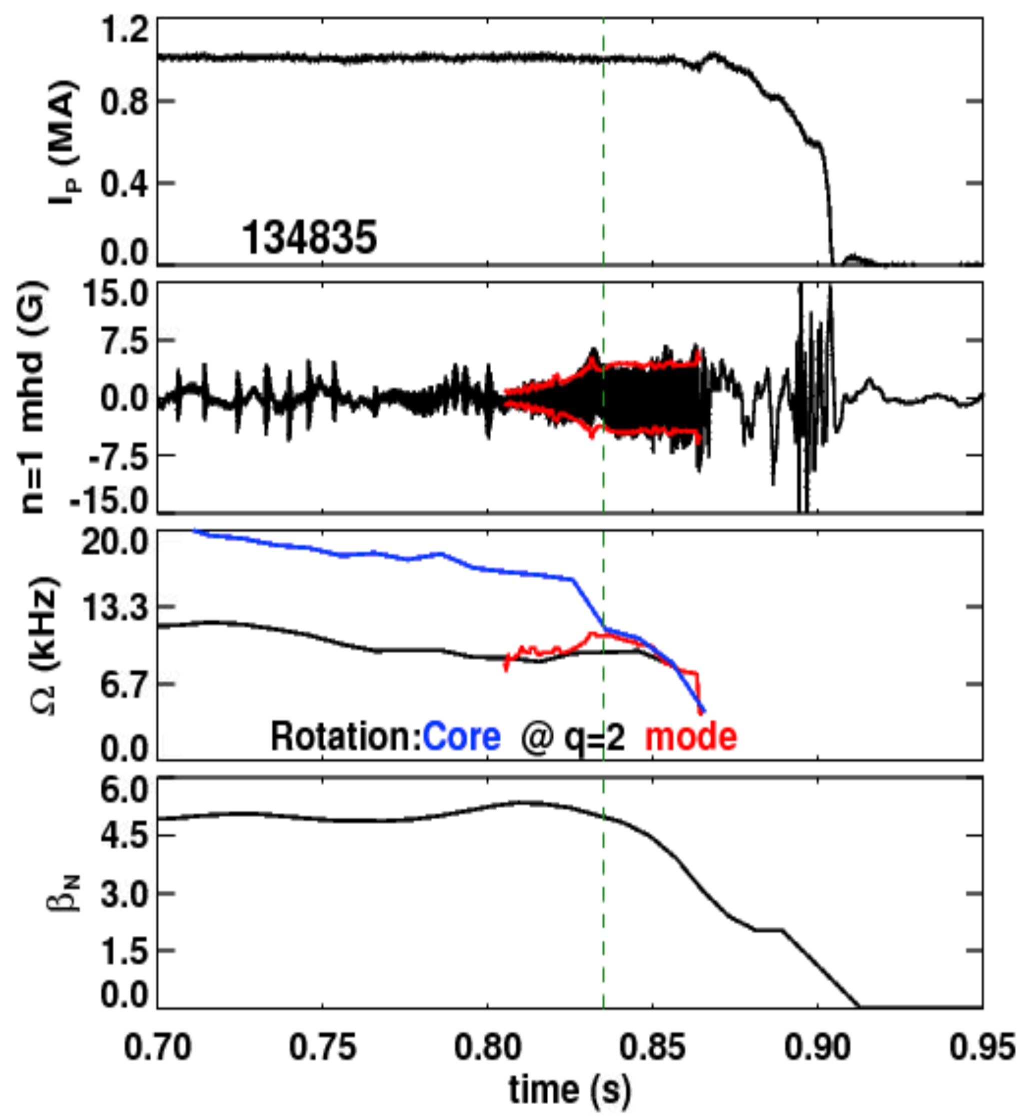
Relationship between stability and rotation at high-β_N can non-monotonic:

- due to resonances in the kinetic RWM stabilization effects.

See Berkery, et al., EX/P8-07

When Global Stability Limits are Avoided, Rotating Core n=1 Modes Often Limit Performance

- Mode onset at t~800 msec.
  - Locks at t~860 ms, followed by disruption
- Initial rotation is with the q=2 surface.
  - First the core rotation is damped
  - Then the total rotation is reduced.
- Analysis of soft X-ray data shows a coupled eigenfunction:
  - m/n=1/1 core kink
  - m/n=2/1 magnetic island
- Similar, but not identical, to "long-lived mode" on MAST.



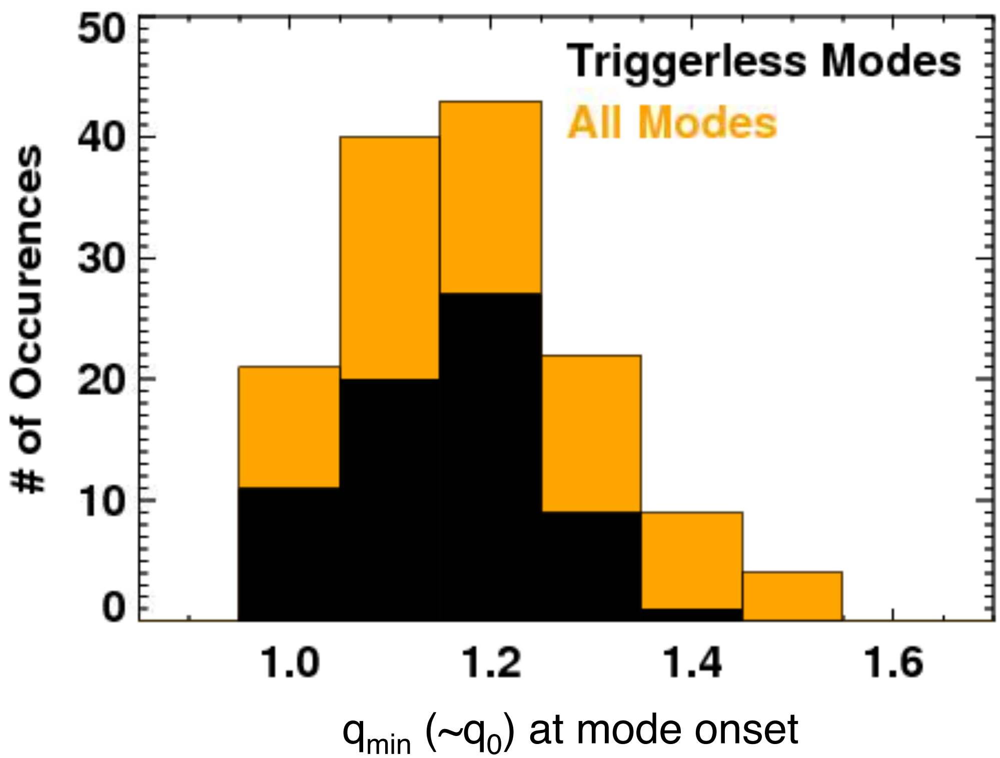
Maintaining Elevated q_{min} Helps Avoid Core n=1 Kink/ Tearing Modes

Experiment

Database of 139 H-mode discharges
MSE constrained reconstructions

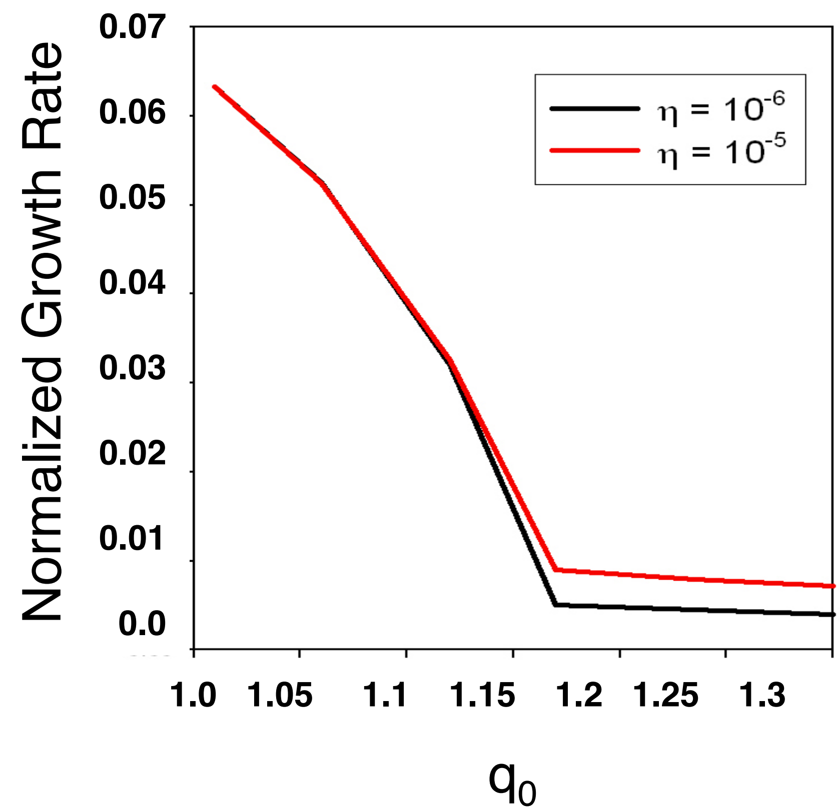
68 discharges with no observable trigger
q_{min} at onset typically <1.25

71 discharges with ELM or EPM trigger
q_{min} up to 1.5 at onset



Theory

Linear Growth Rate vs. q_0
Representative NSTX H-Mode Equilibria for Triggerless Onset Mode
(from M3D-C1, Breslau NF 2011)



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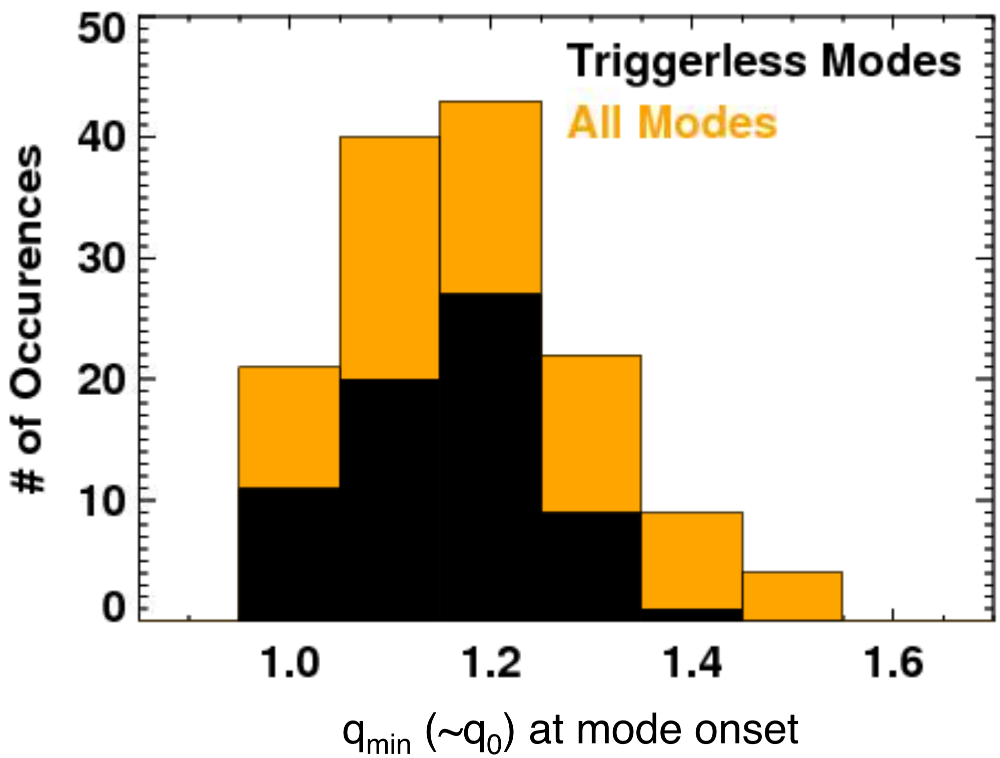


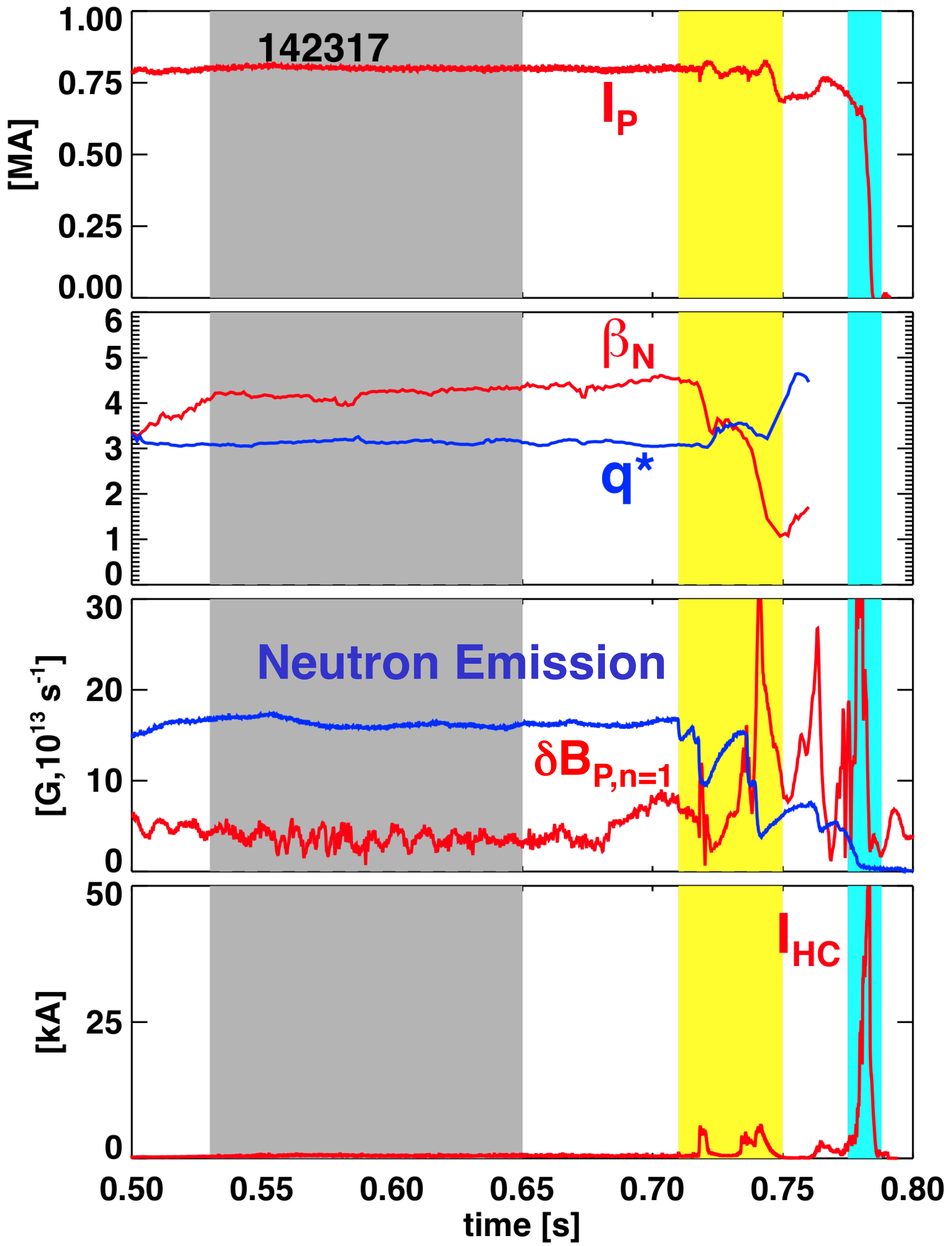
Summary (1)

Disruptions are best avoided in NSTX when

- Plasma is strongly shaped
- q* maintained above ~2.7
- Pressure and current profiles are broad.
- Rotation is maintained
- q_{min} is kept elevated

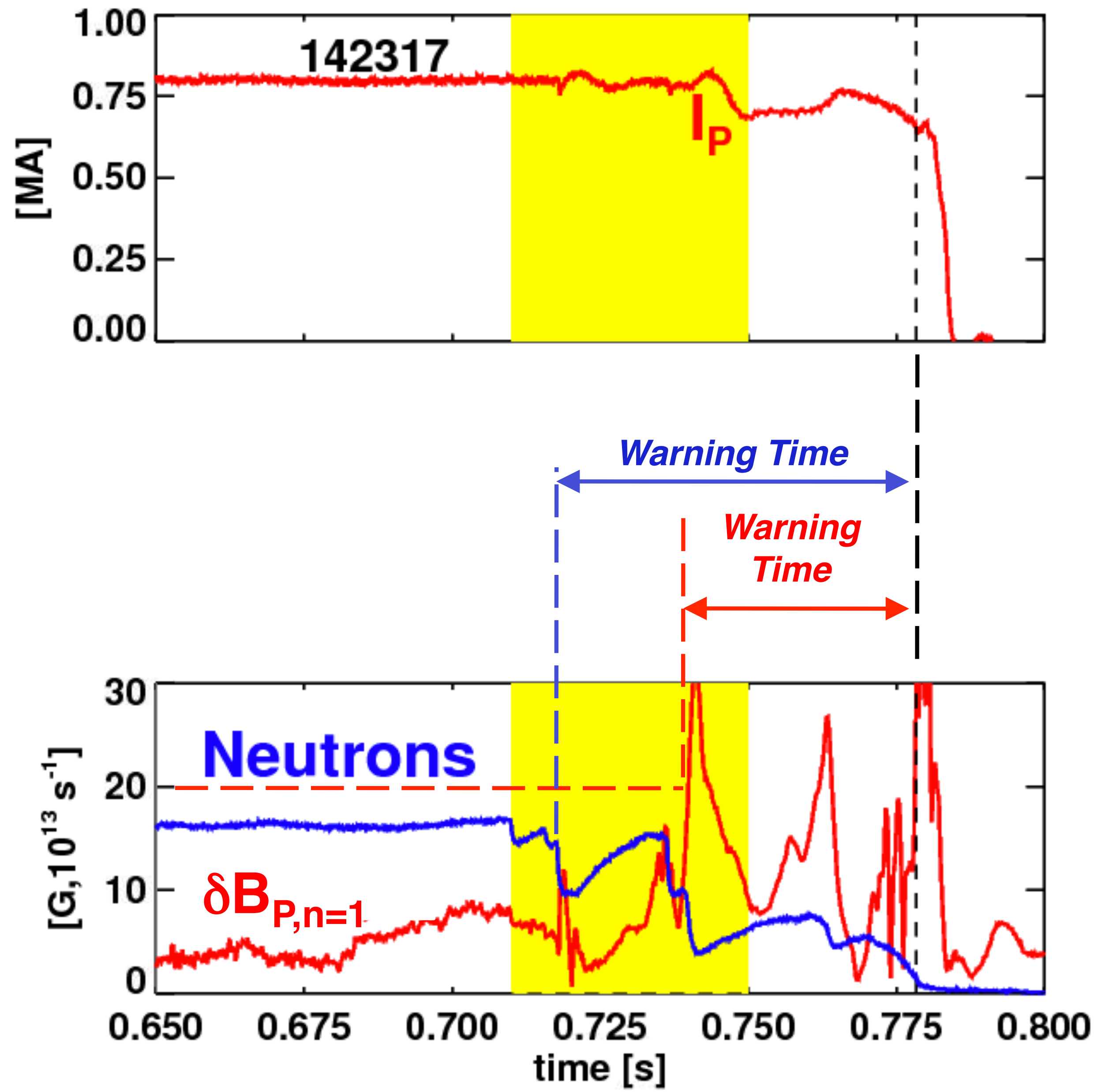
These conditions do not eliminate need for active control, but rather provide situations when control is likely to be most successful.

Talk Addresses Three Aspects of Disruptions



2: Disruption detection

Warning Times Defined With Respect to the Current Quench



<u>False Positive:</u>
Warning more than 300 ms in advance of current quench.

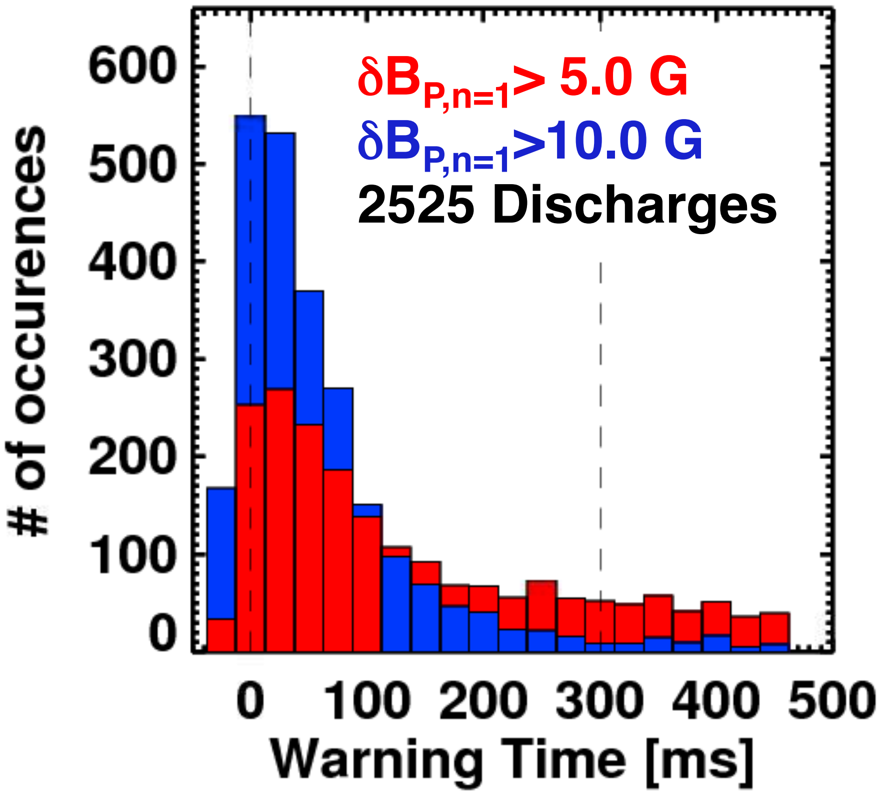
<u>Late Warning:</u>
Warning later than 10 ms before the current quench.

$$\frac{R_{ITER}}{R_{NSTX}} \cdot 10ms = 72ms$$

Single Threshold Tests Form a Basis For Disruption Prediction

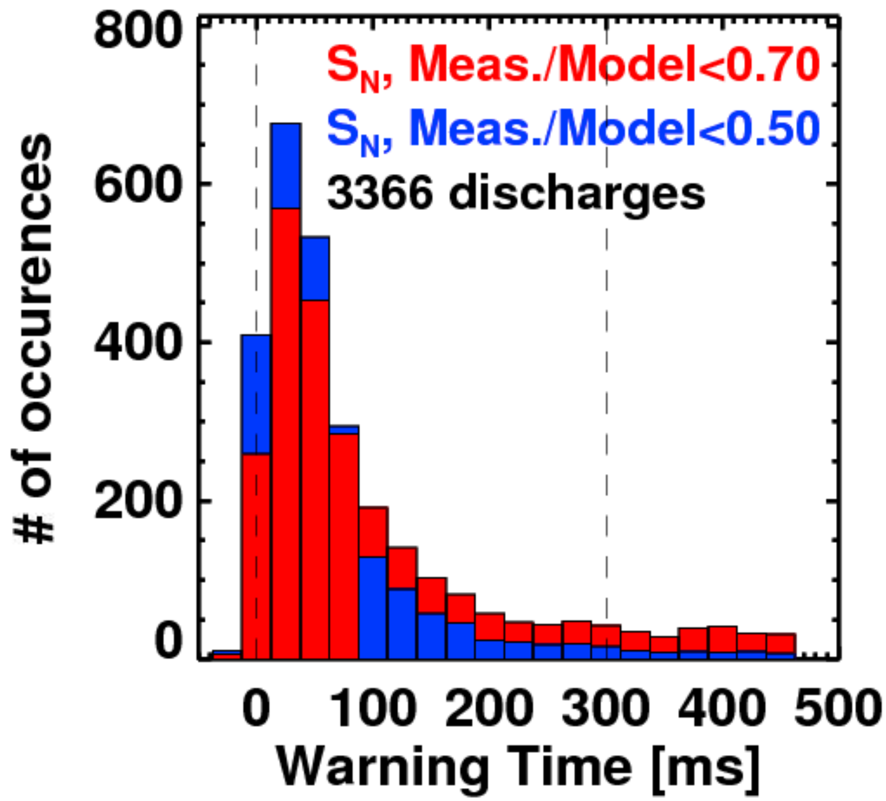
Instability Detection

- n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes



Model Comparison

- Often a significant drop in neutron emission proceeding a disruption.
- Estimate the neutron emission from a simple slowing down model.
  - T_e, Z_{eff}, n_e are inputs.



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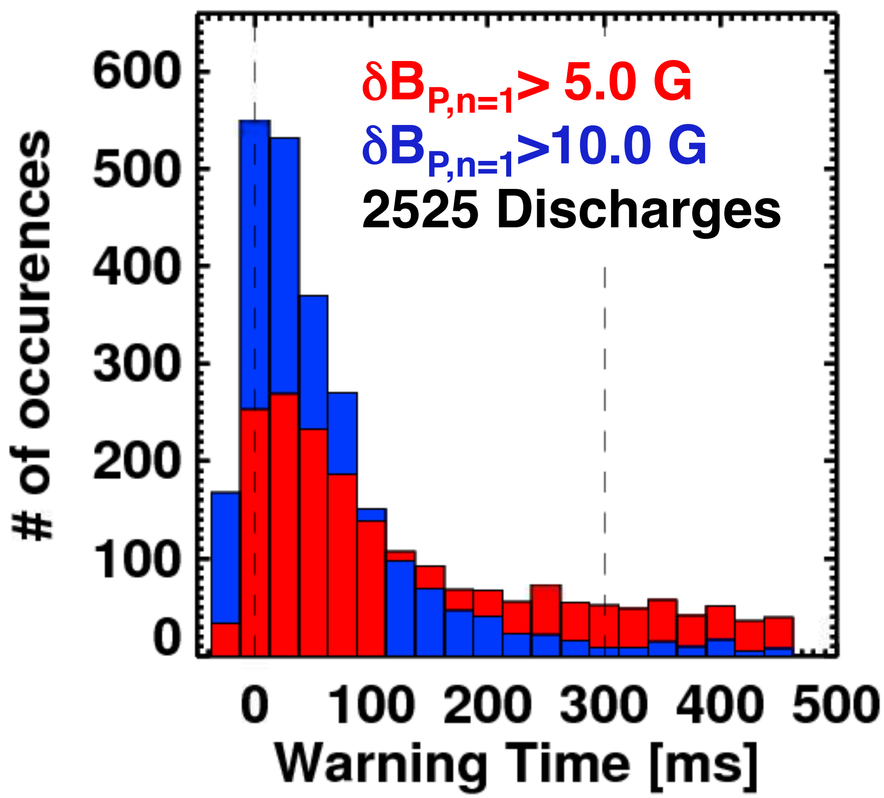


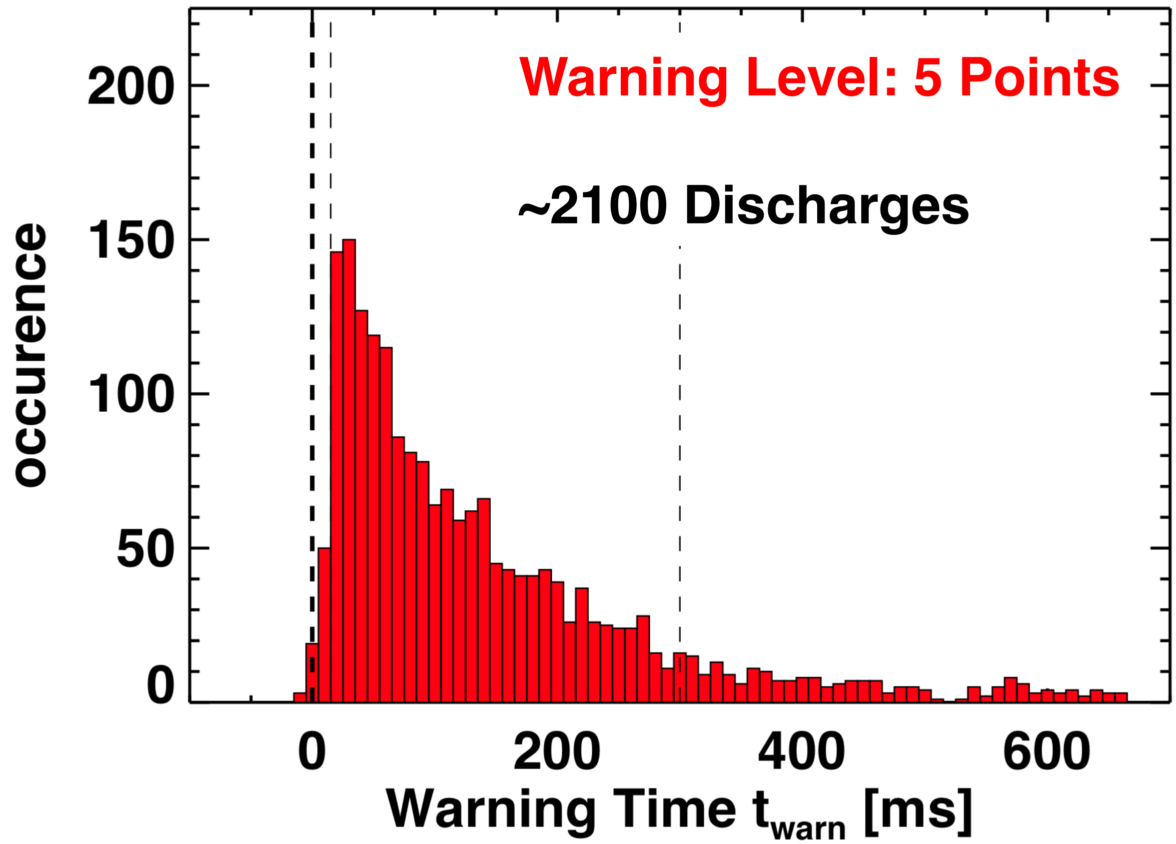
Examined Many Threshold-Based Disruption Indicators

- MHD Equilibrium and Stability
  - Vertical motion indicators
  - n=1 perturbed fields
  - $F_P=p_0/\langle p\rangle$, l_i, q_{95}, q^*
  - Boundary-wall gaps
- Transport indicators for comparisons to simple models
  - Neutron rate
  - Stored energy
  - Loop voltage
- Other
  - Line-average density transients
  - Rotation and rotation shear
  - Radiated power / Input Power
  - Deviations of I_P from request

Developed a Method to Combine These Tests For Improved Prediction

- No one of these diagnostic tests could serve as a stand alone disruption indicator.
  - Must combine the tests in some fashion.
- Common way to combine data is to use neural nets.
  - Here explore an alternative system.
- Algorithm summary:
  - Take a series of ~15 threshold tests like those previously described.
  - For each test, assign a number of “points” for various thresholds, for instance:
    - 1 point if the n=1 amplitude exceeds 10 G,
    - 2 points for 15 G
    - 3 points for 20 G
  - Evaluate tests at each time-slice, then sum the points from threshold tests to form an “aggregate” point total.
  - Declare a disruption warning if the aggregate total exceeds a chosen value.
  - May not yet be optimized.

Compound Threshold Tests Can Predict Most Disruptions.



Tuned To Minimize Late Warnings

<1% late warning

~15% false positive

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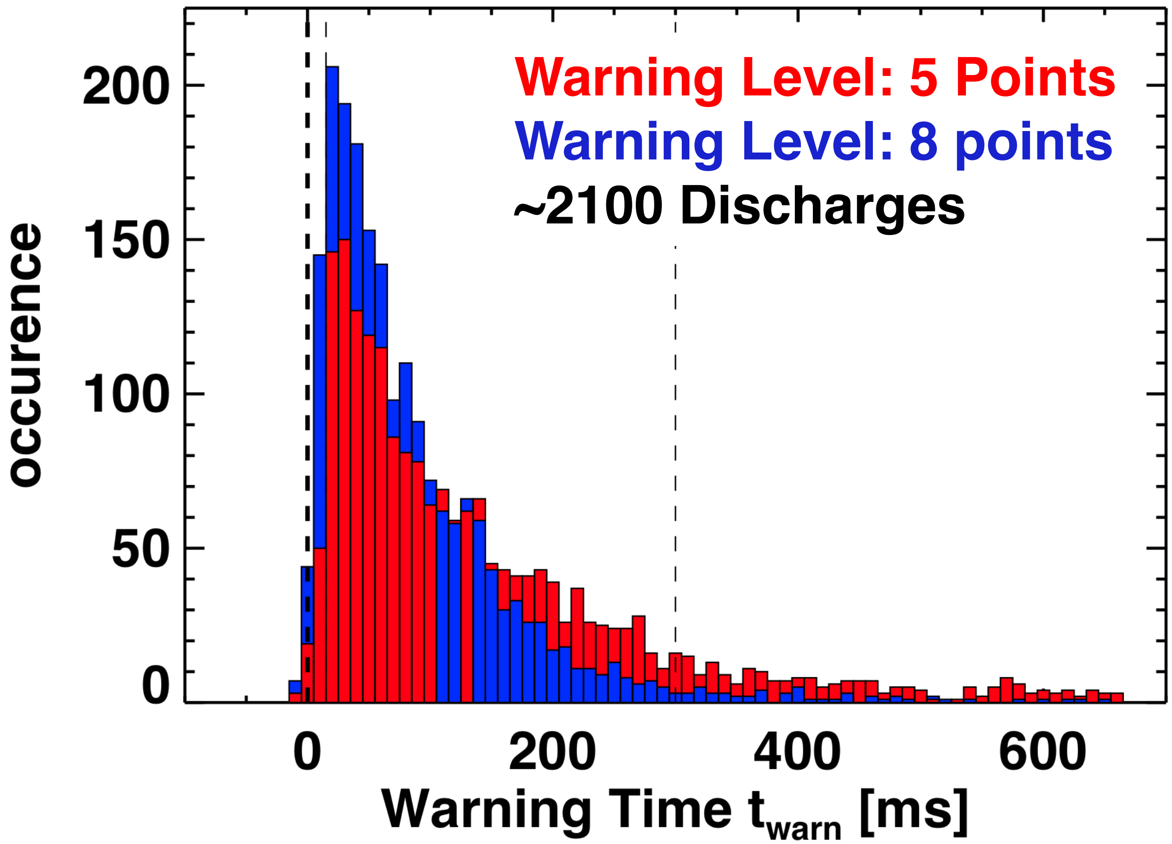

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Tuned To Minimize Late Warnings + False Positives

~2% late warning

~4% false positive

(False positive count dominated by near-disruptive MHD events)

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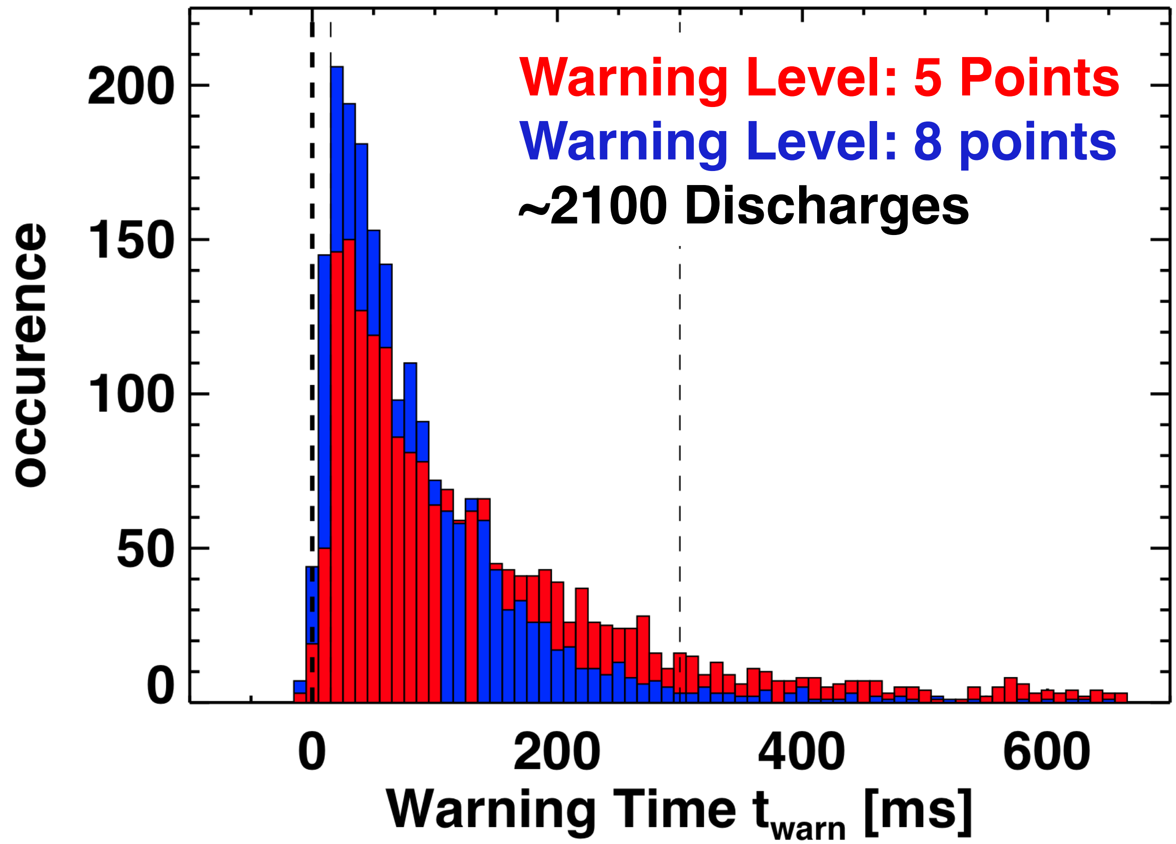

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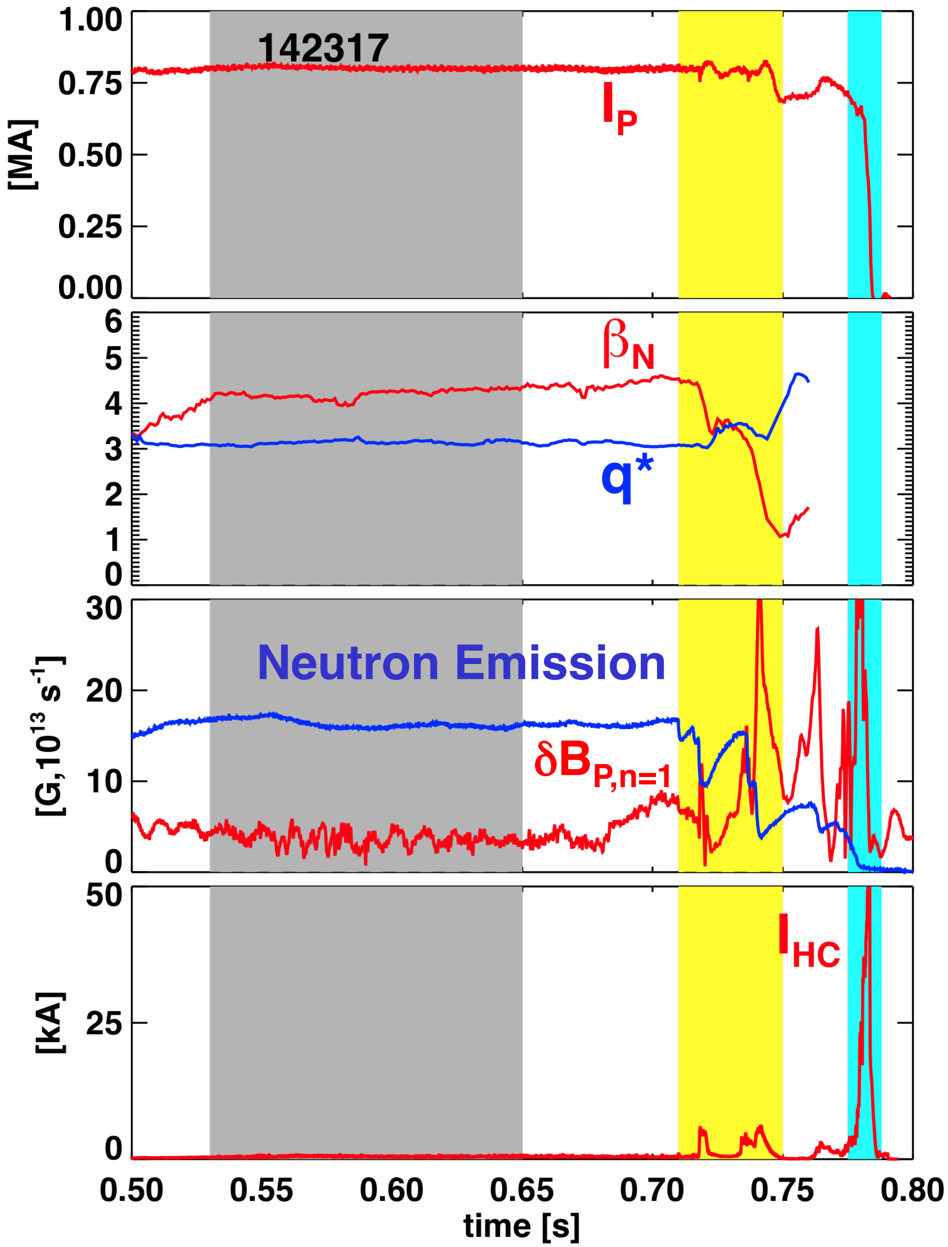
Summary (2)

The vast majority of NSTX disruptions have detectable precursors.

Both raw diagnostic data and comparisons to simple models can contribute to prediction.

A simple combination of disruption tests can produce high-fidelity prediction.

Talk Addresses Three Aspects of Disruptions



3: Disruption halo currents.

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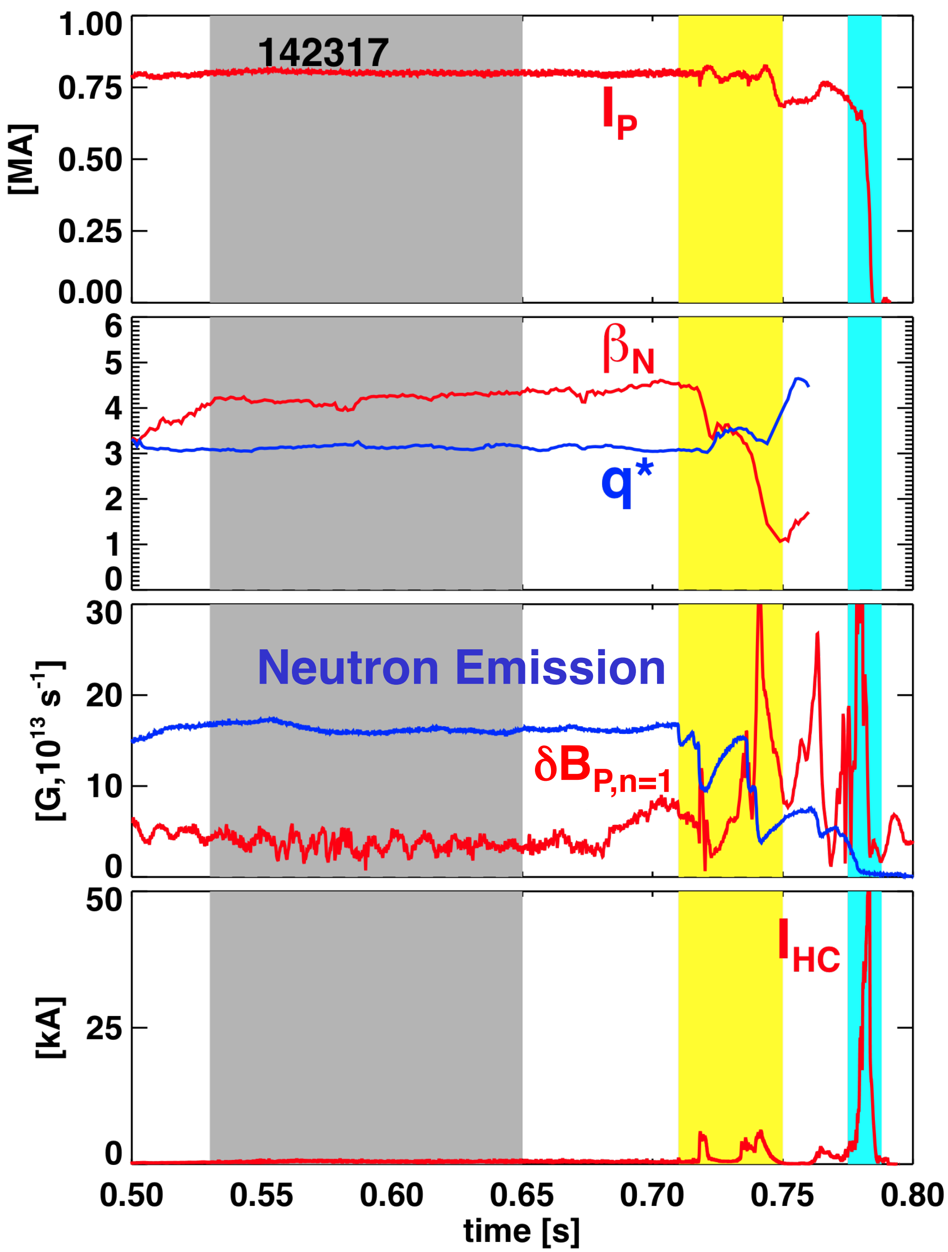


Halo currents:

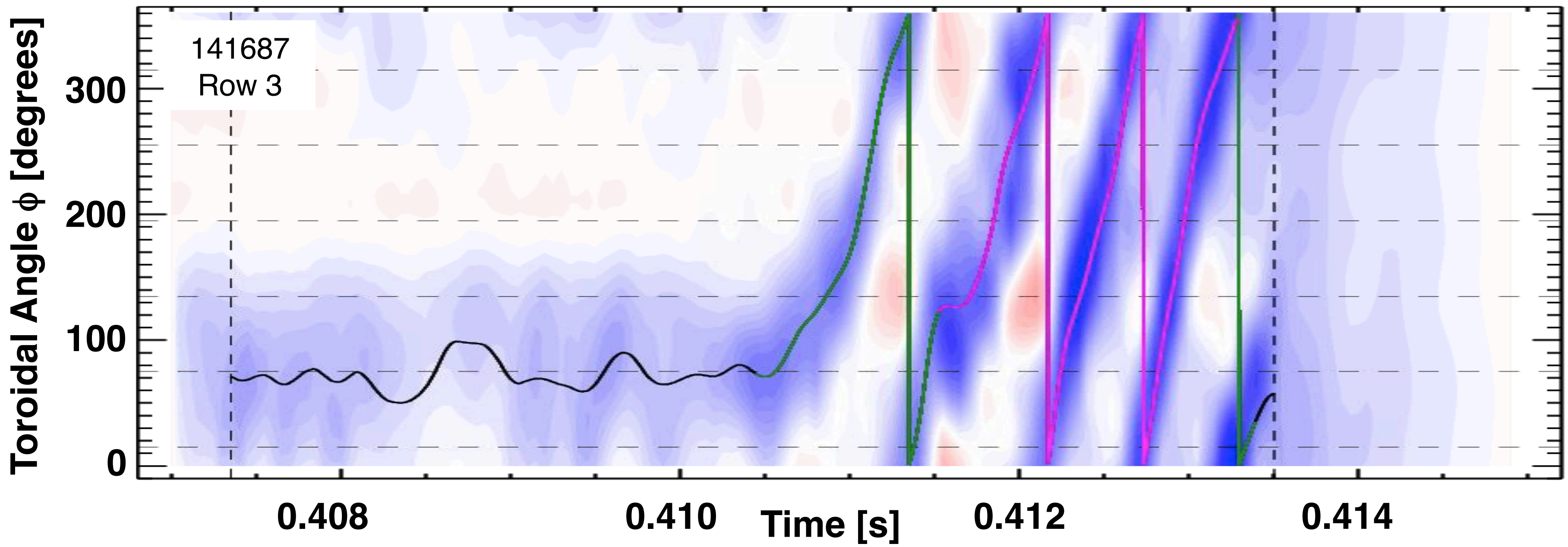
- When vertical position control is lost, the plasma can come in contact with the divertor or first wall.
- Currents then flow between the plasma and the vessel, PFCs, or divertor structures, leading to mechanical loading of structures.

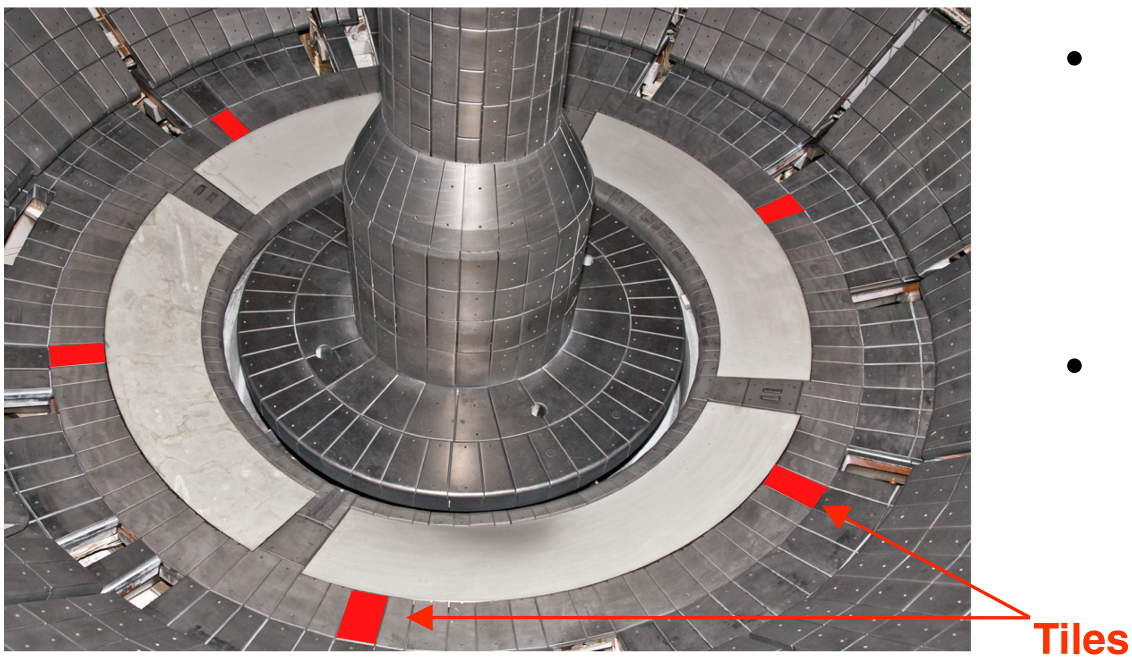
Currents can be toroidally asymmetric:

- When toroidally localized, forces are concentrated.
- Those asymmetries can rotate toroidally, potentially in mechanical resonance with in-vessel structures.

3: Disruption halo currents.

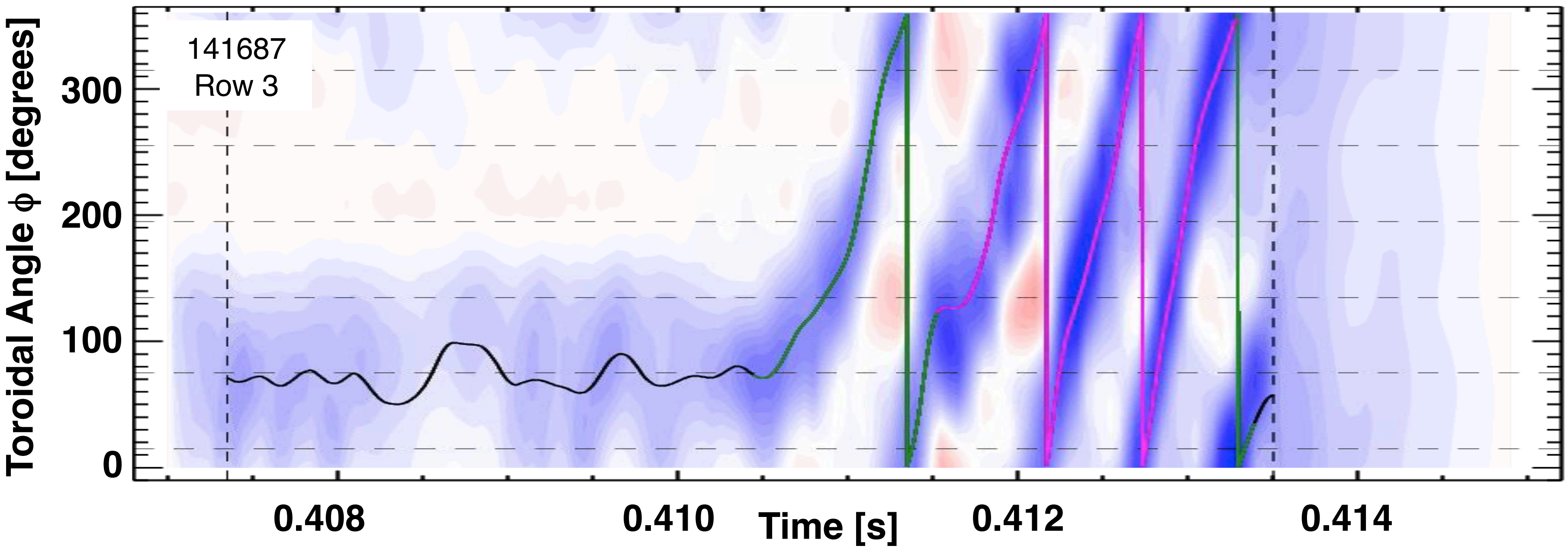
Strongly Non-Axisymmetric Halo Currents Detected in the NSTX Lower Divertor

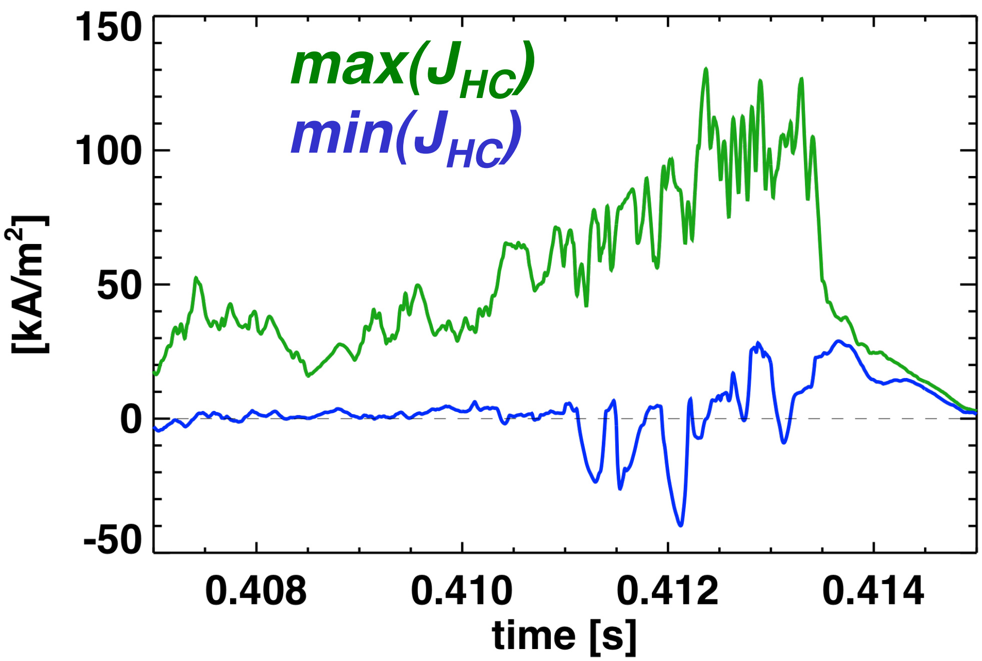




- Measurements from an array of instrumented tiles
  - Same poloidal angle
  - Distributed toroidally
- Infer strong toroidal asymmetry, often with significant rotation, at locations where currents enter the divertor floor.

Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current





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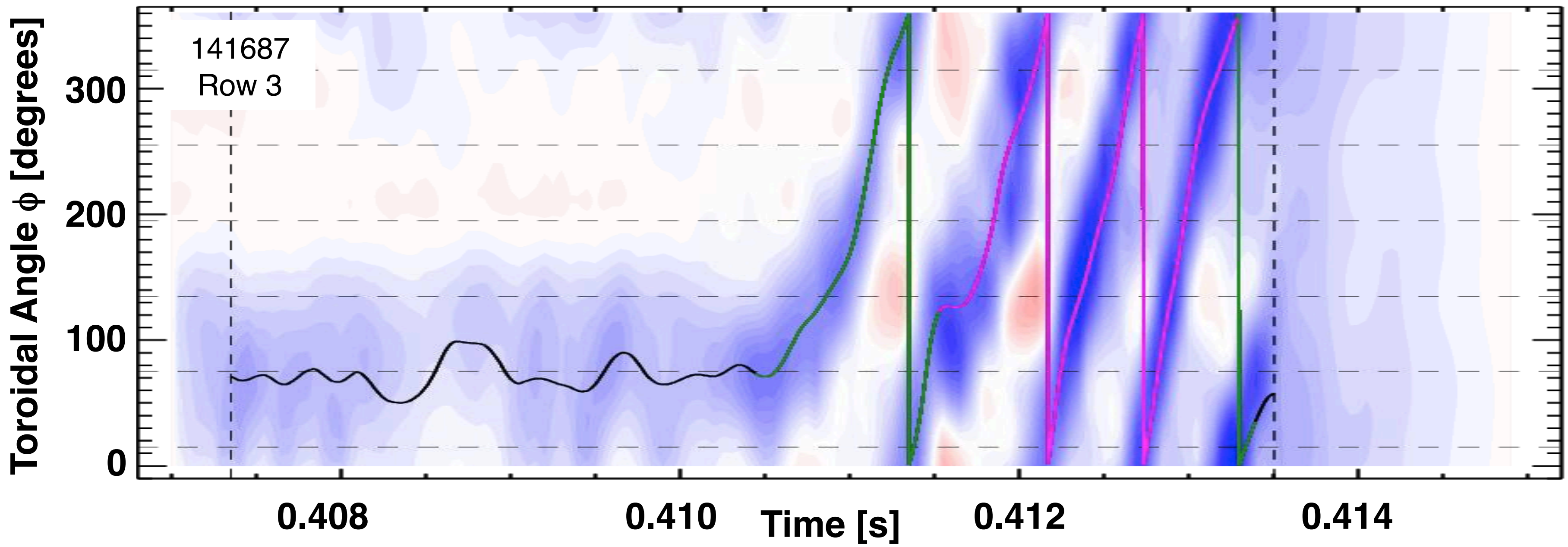

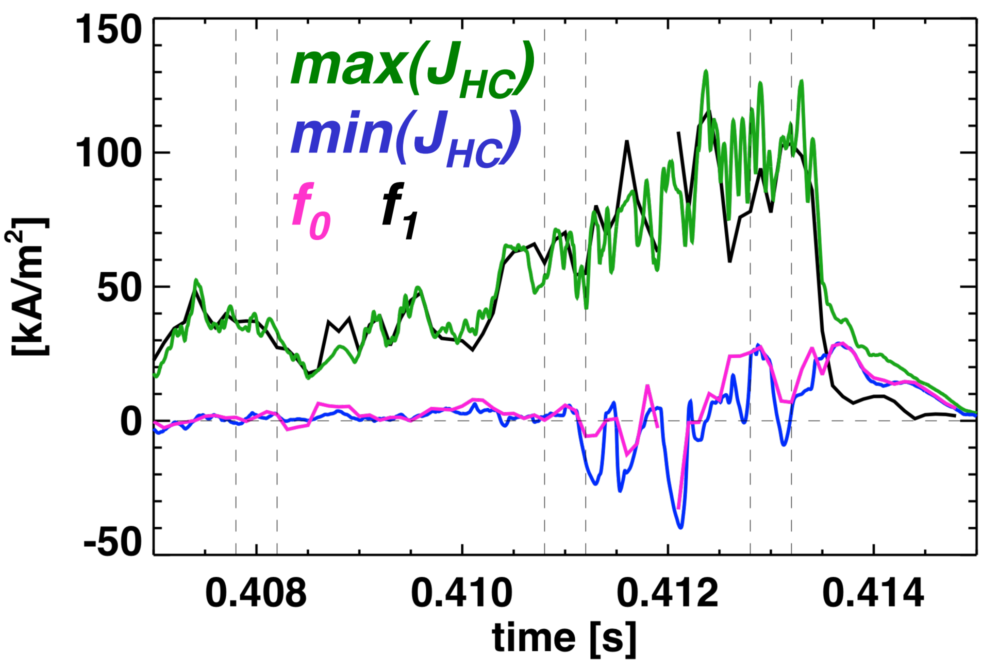

$$f(t,\phi) = f_0 + f_1 \cos^{2f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$

Fits applied during small time windows of width 0.1 ms

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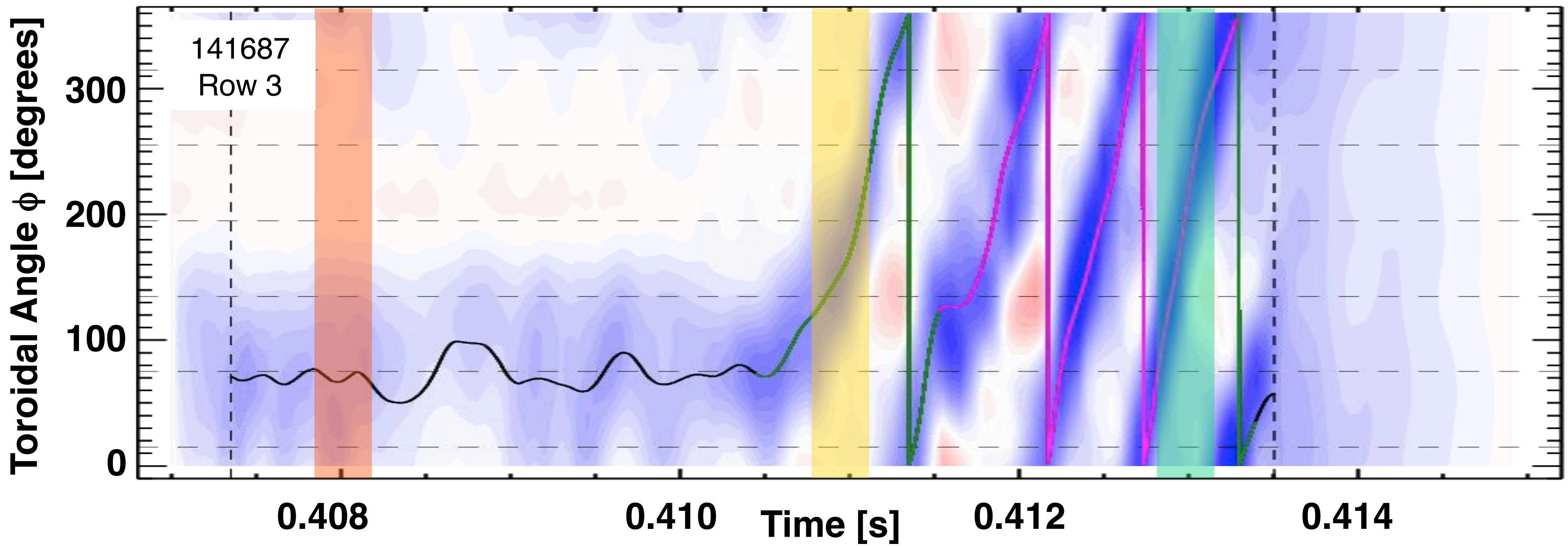

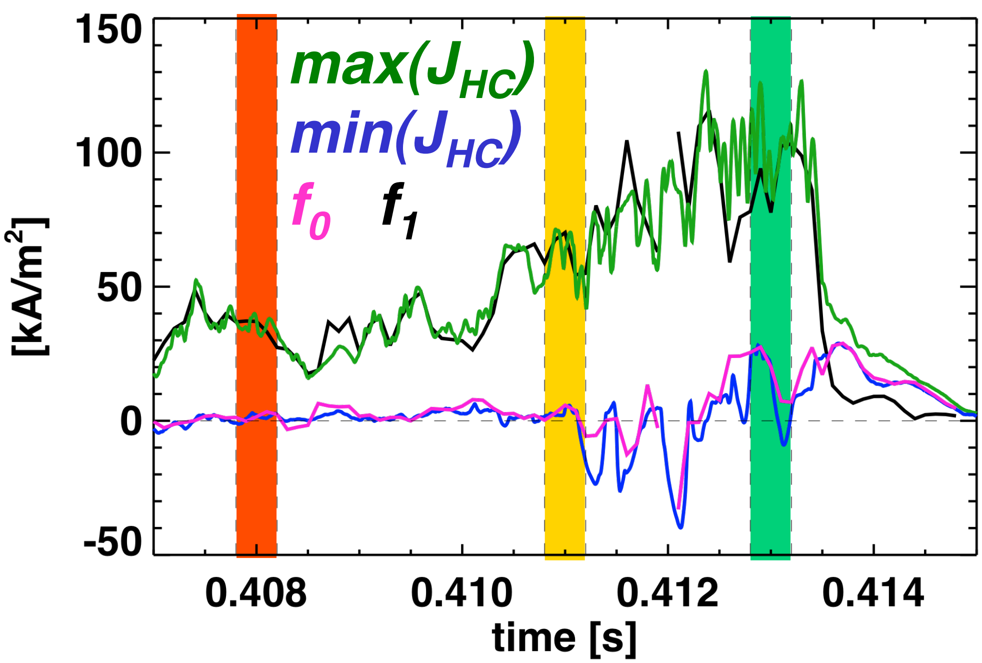

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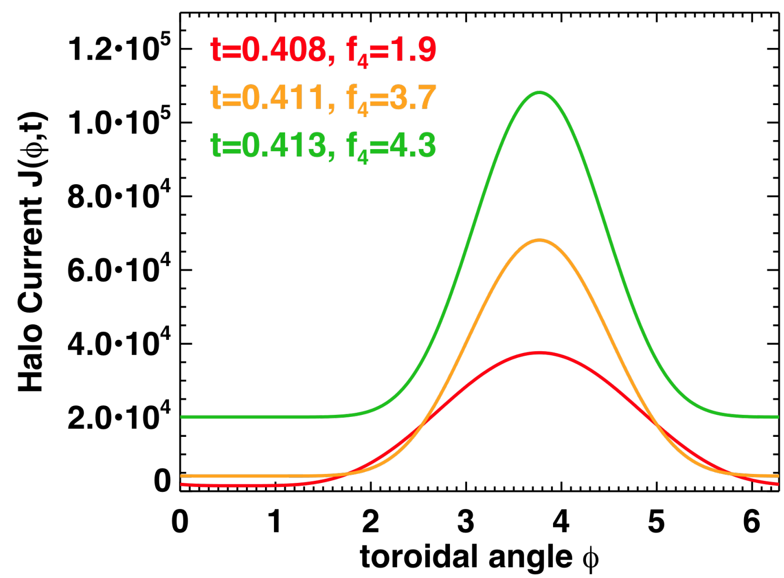
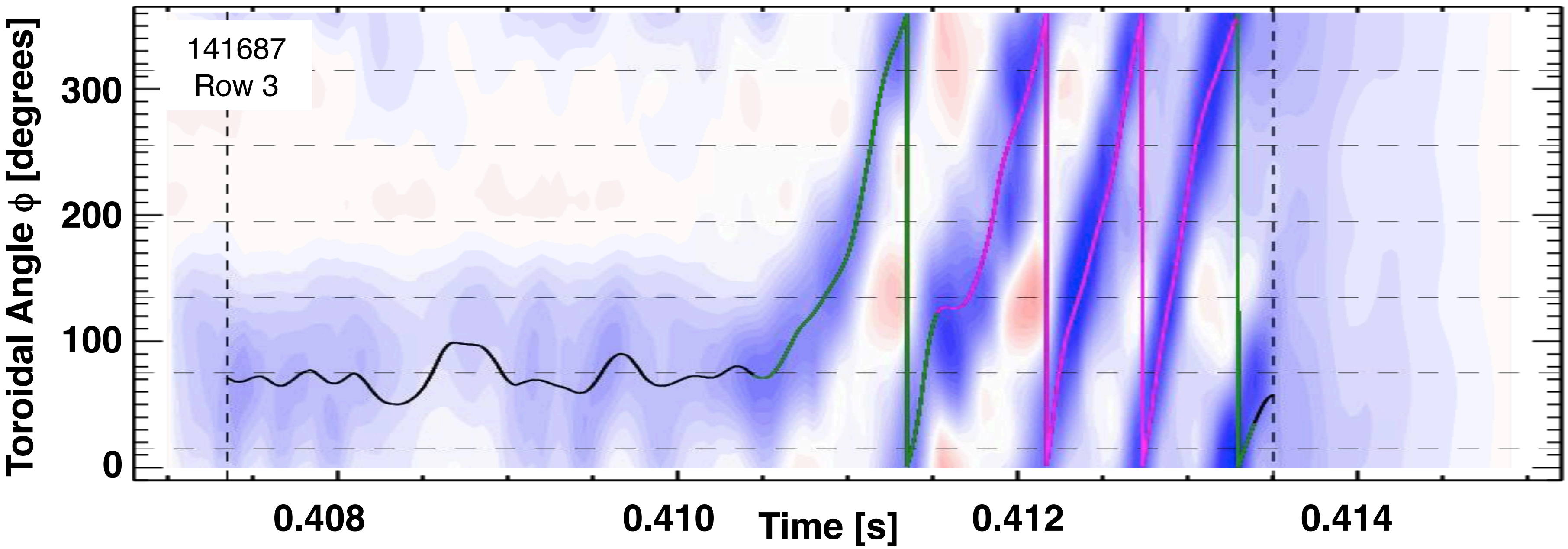


Halo Currents Become Symmeterized In the Final Phase of the Disruption



- Tendency is seen to some extent for virtually all halo current occurrences
- Utilize a regularized filament model for the reconstruction.
  - Find currents in a grid of toroidal filaments that provides best fit to magnetics measurements.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late halo current axisymmetry corresponds to near or complete loss of closed surface geometry

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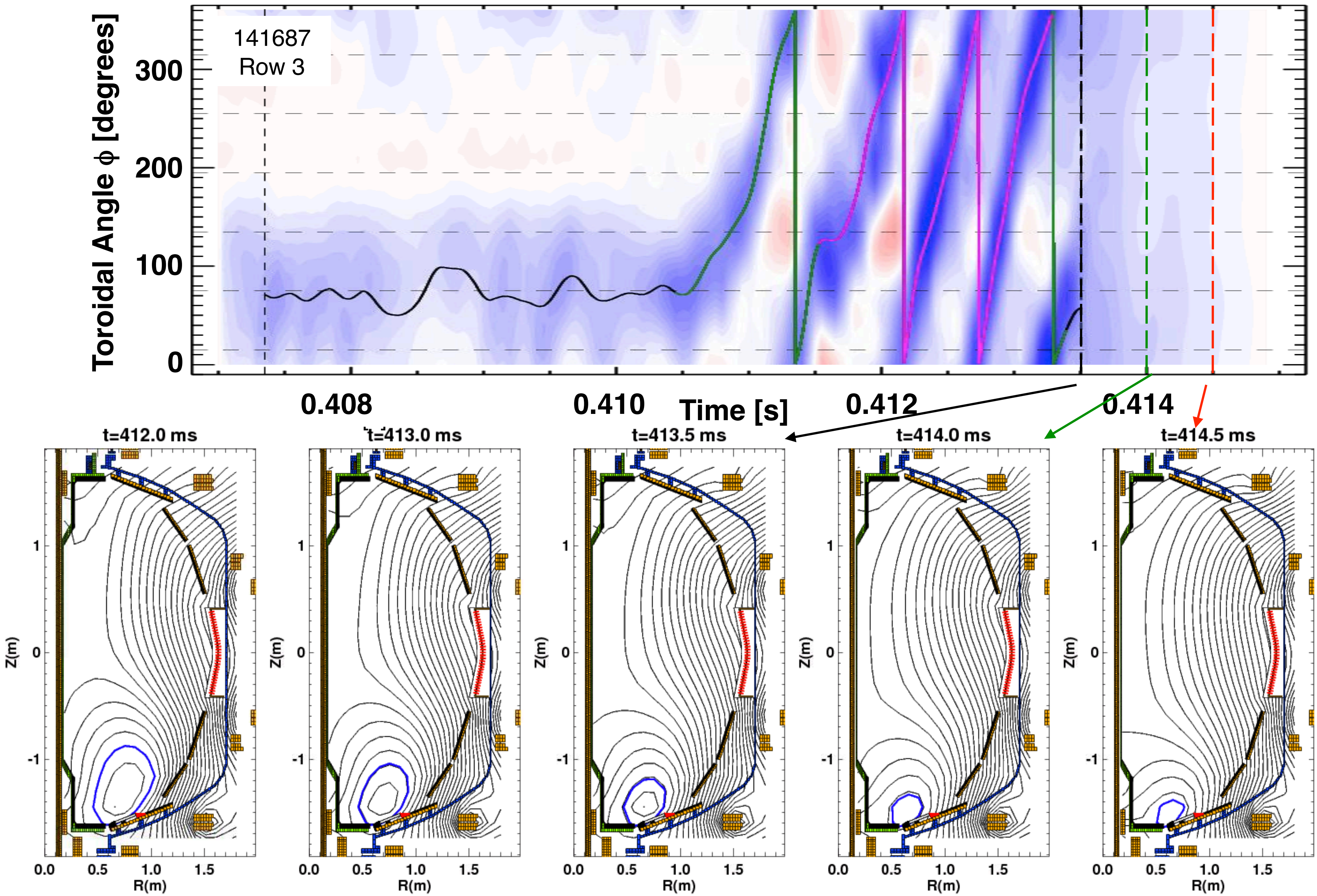
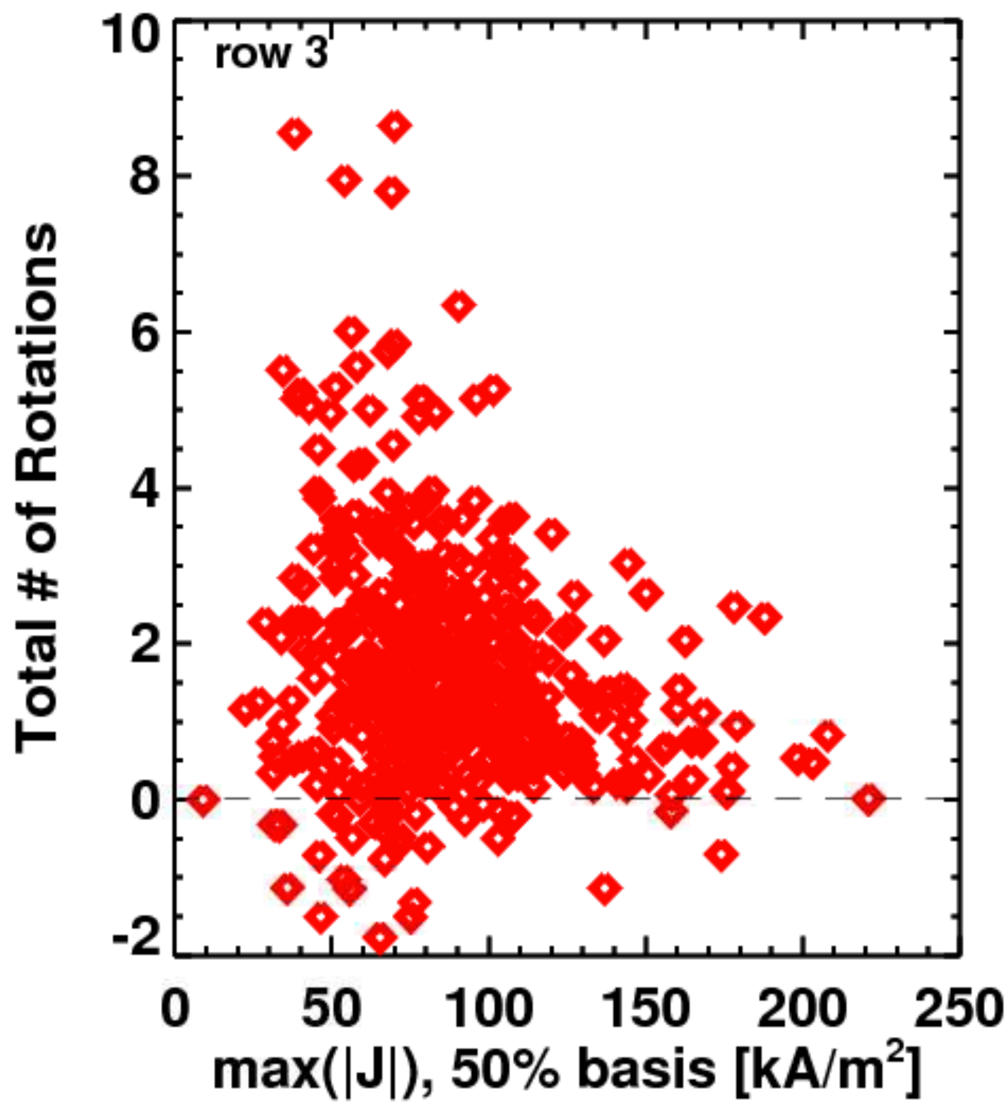


of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- Compute the rotation dynamics during time when the halo current is >25% of its maximum.
- Compare to the time average of the maximum halo current magnitude.



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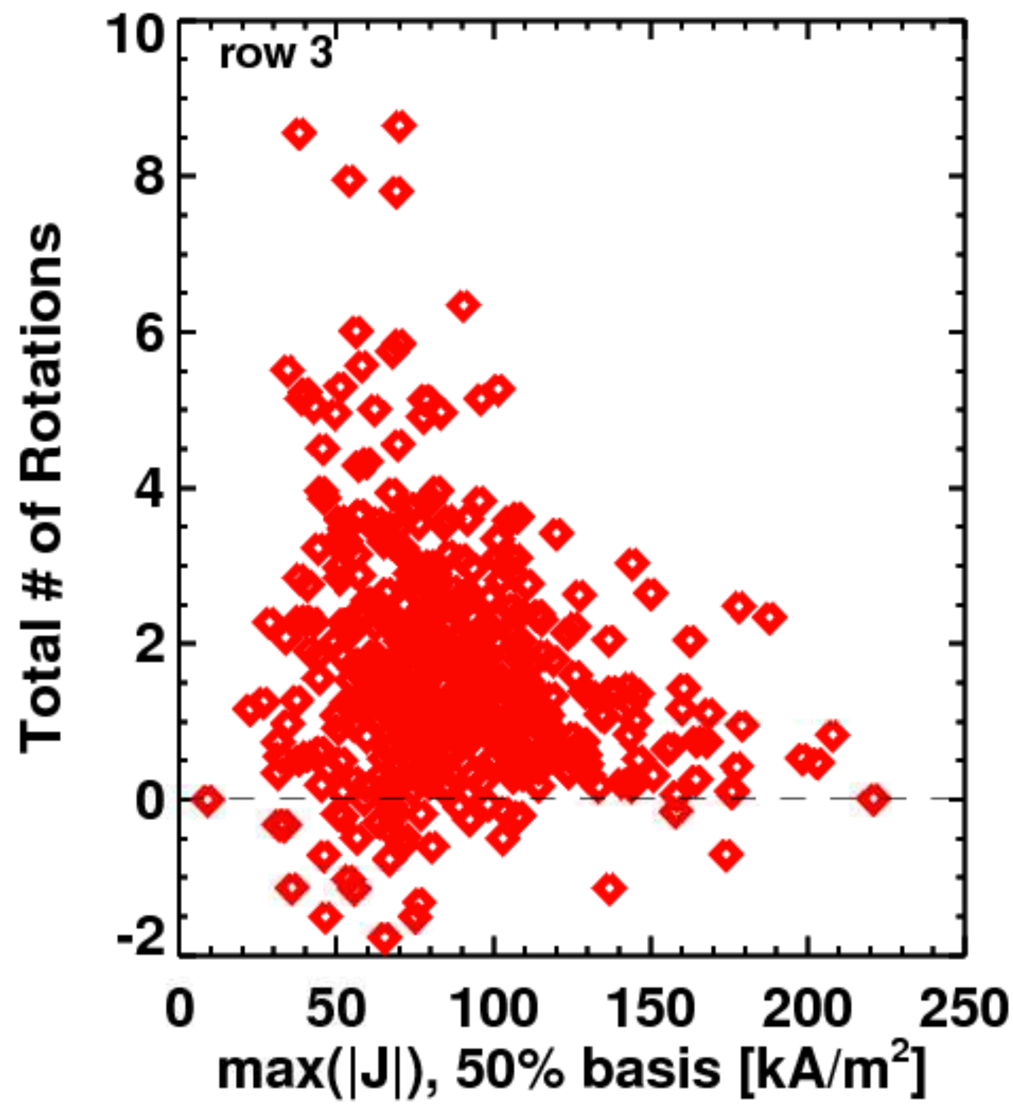


Summary (3)

- Dominant halo current pattern is a toroidally localized lobe of current.
- Up to 8 toroidal revolutions have been observed.
- # of revolutions scales inversely with halo current magnitude.

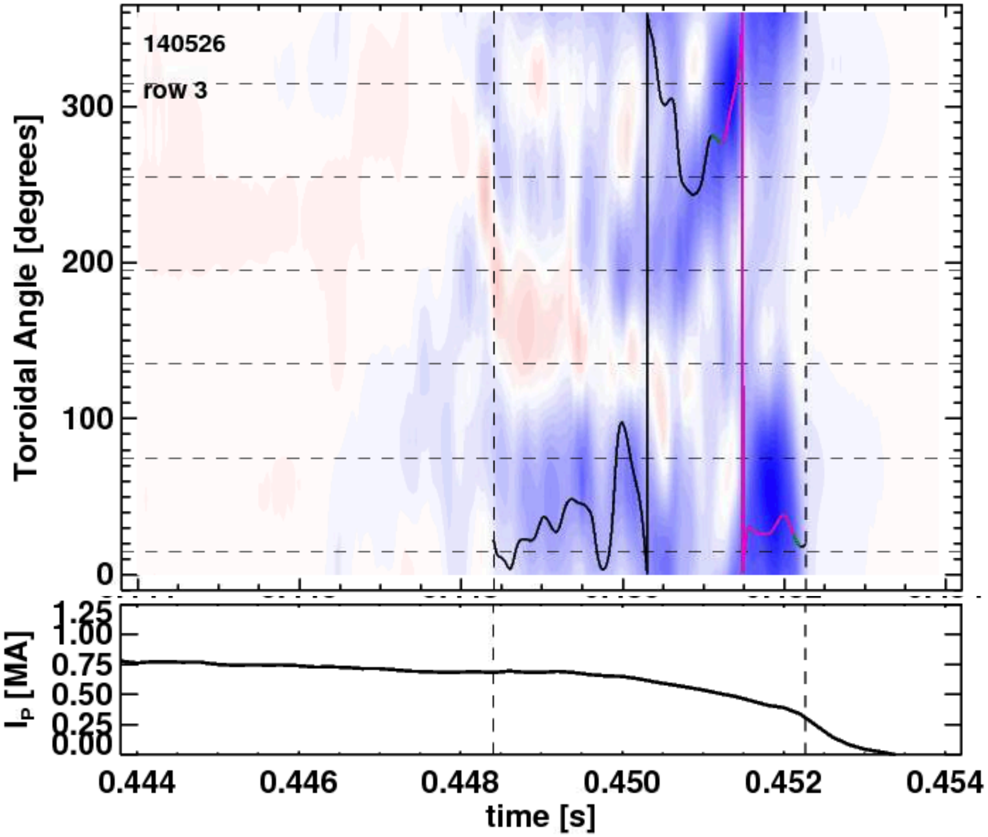
Summary

- Recipe for minimal disruptions includes strong shaping, broad profiles, maintained rotation, and sufficiently elevated q_{min}.
  - Sustaining these optimal scenario characteristics is a critical topic for NSTX-Upgrade research. [Menard FTP/3-4]
- Disruptions in NSTX are generally detectable, and a simple means of combining single threshold tests can predict most disruptions.
  - Encouraging for the detectability and mitigatability of disruptions in next-step ST devices.
- The dominant halo current pattern is a toroidally localized lobe, which has been observed to make up to 8 toroidal transits.
  - Lower loading in cases with many revolutions may, if confirmed in additional devices, alleviate the problem of HC rotation to some extent.

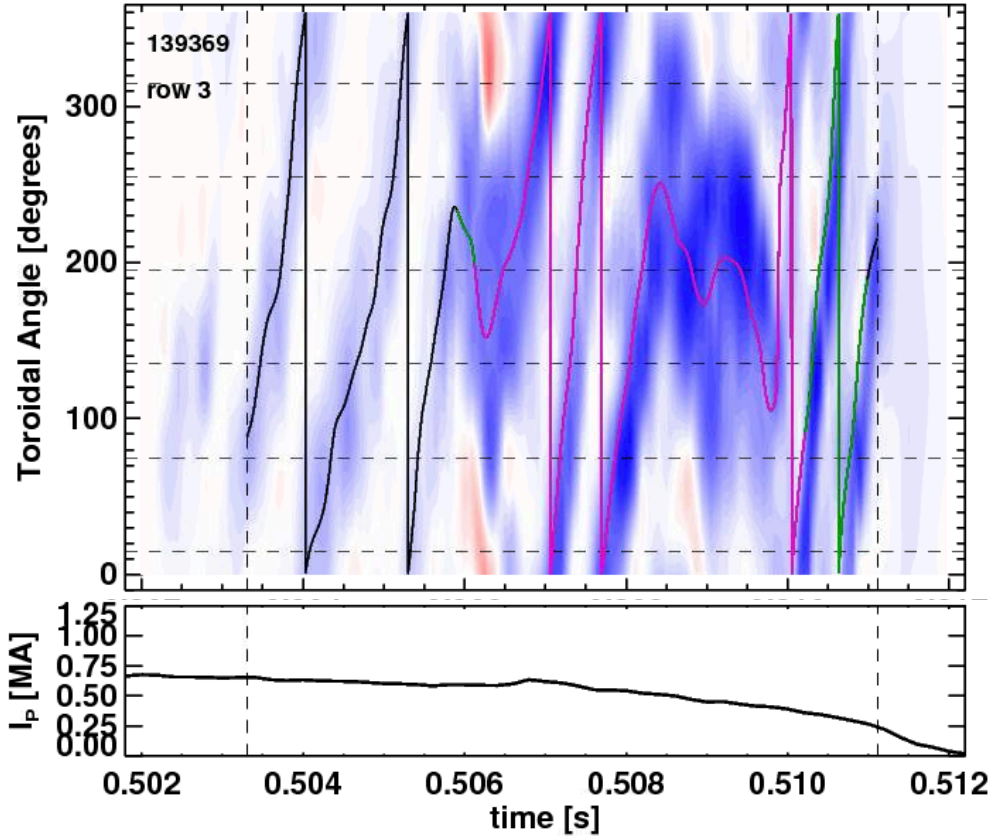
Backup

Halo Current Patterns Can Be Highly Variable in Space and Time

Large Halo Currents: max(I_{HC})~300 kA, Little Rotation



Reduced Currents: max(I_{HC}~150 kA), Seemingly Erratic Rotation



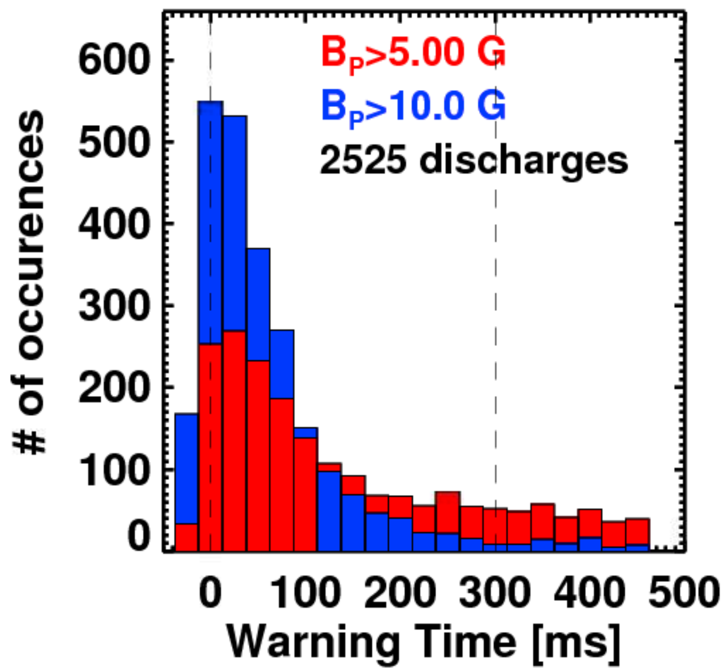
Observations

- Structure best described as a single lobe of current.
- Rotation, when it occurs, is typically in the counter-direction, except for short bursts.

Monitoring of n=1 and n=0 Perturbations Provides Foundation for Disruption Warning

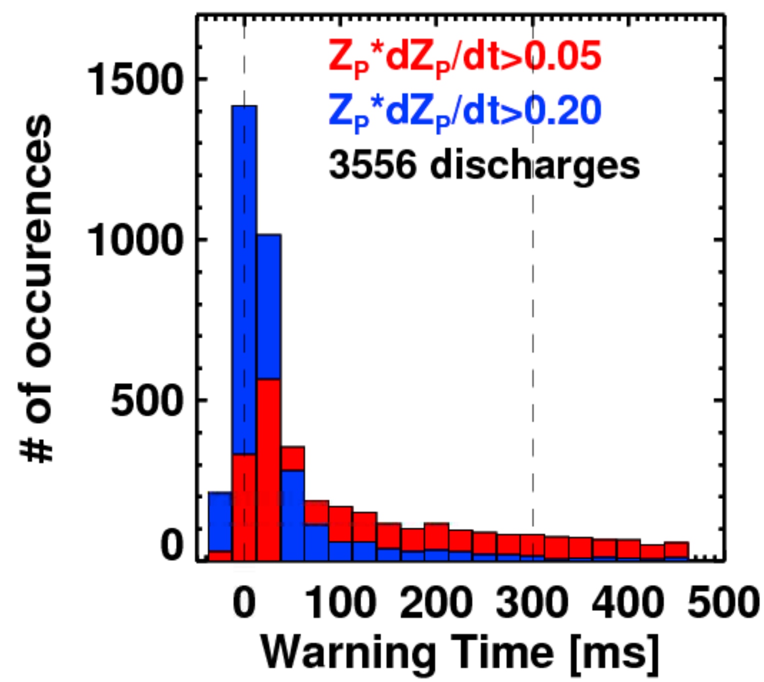
- n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes

threshold	% Late Warning	% False Positive	% No Trigger
5 G	4	35	0
10 G	13	5	2



- Estimate $Z_P \cdot \frac{dZ_P}{dt}$ from two toroidal loops on outboard side of plasma, above and below midplane.
  - Z_P from fluxes
  - dZ_P/dt from voltages

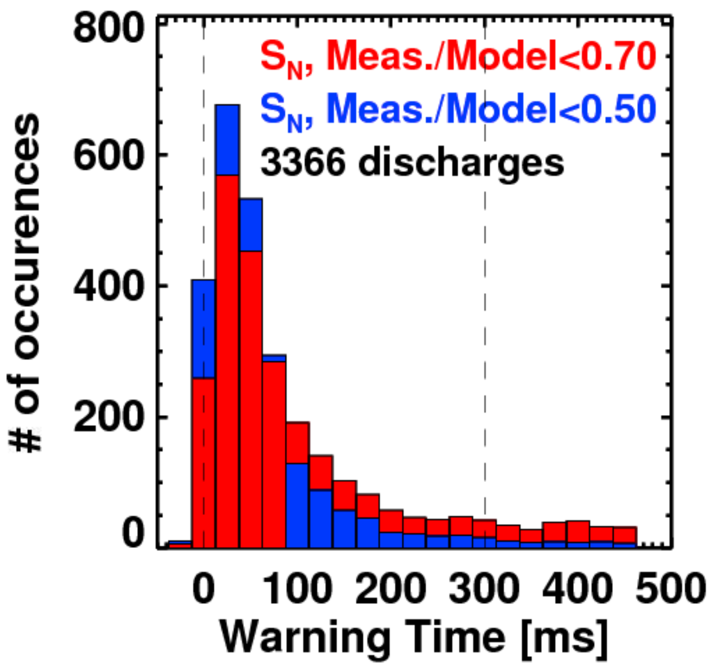
threshold	% Late Warning	% False Positive	% No Trigger
0.05	2	31	1
0.2	15	4	3



Comparison of Diagnostic Signal to Simple Models Can Provide Useful Indicators

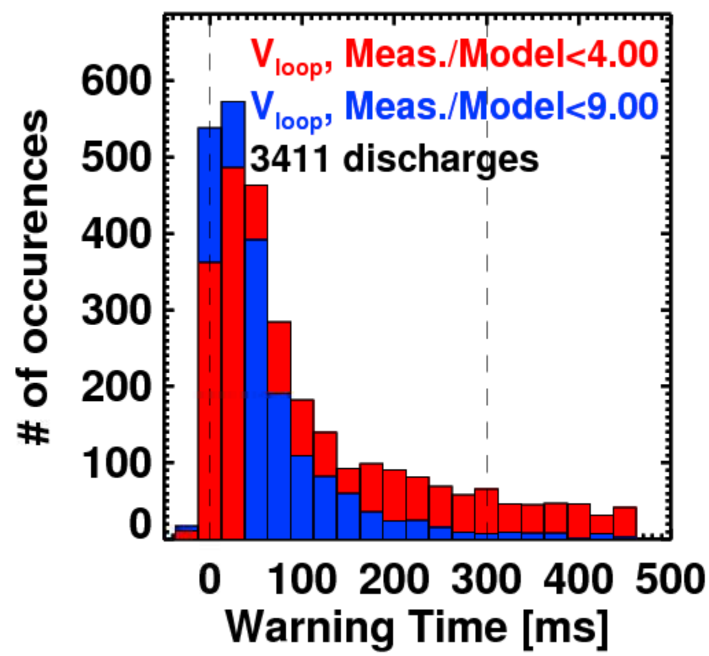
- Often a significant drop in neutron emission proceeding a disruption.
- Estimate the neutron emission from a simple slowing down model.
  - T_e, Z_{eff}, n_e are inputs.

threshold	% Late Warning	% False Positive	% No Trigger
0.7	1	18	14
0.4	2	4	27



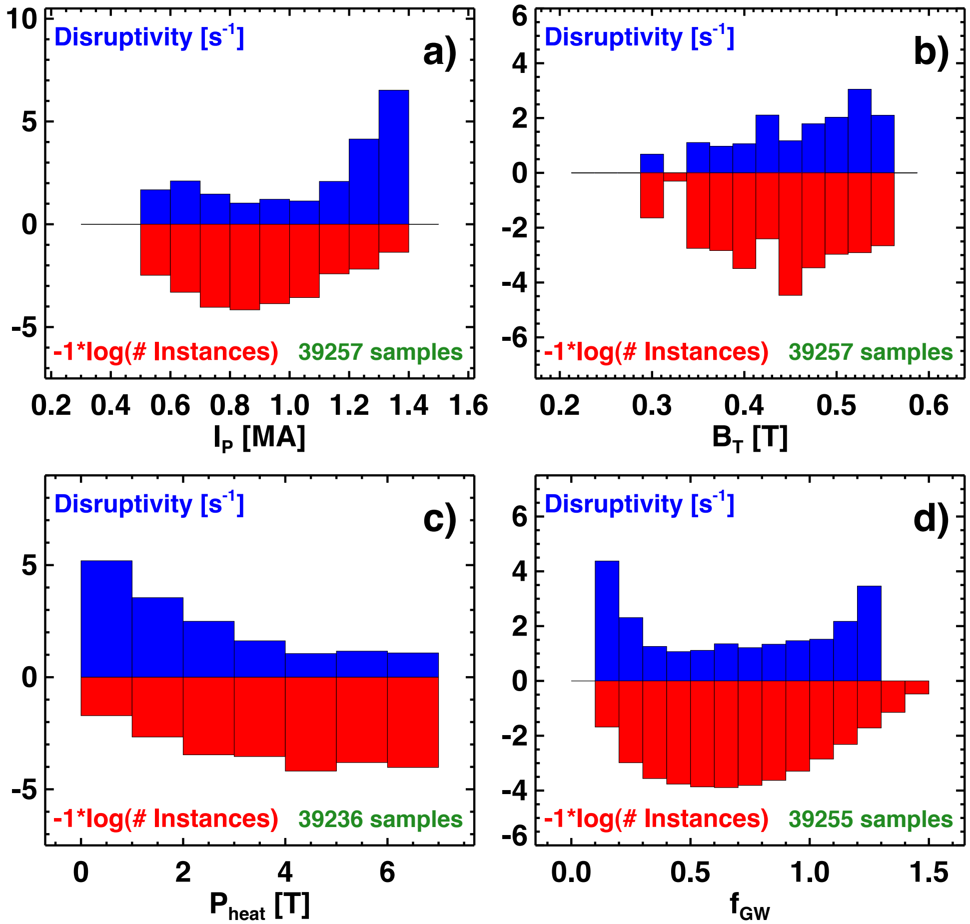
- Often an increase in loop voltage proceeding the disruption. Process:
  - Estimate T_e from ITER-98$_{y,2}$ scaling and measured n_e, B_T, I_P, P_{inj},…
  - Use these to calculate expected bootstrap and beam driven currents.
  - Use these to calculate inductive current and then loop voltage.

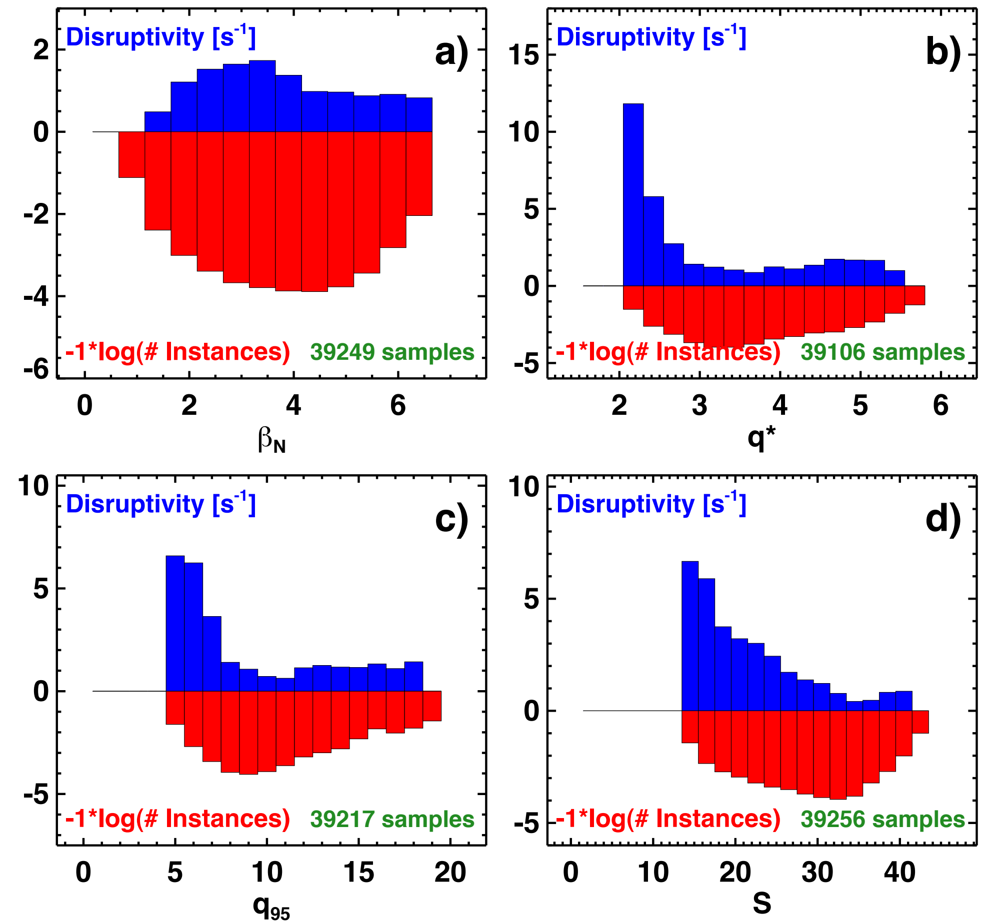
threshold	% Late Warning	% False Positive	% No Trigger
4	2	18	11
9	5	2	37



1D Disruptivity vs. Engineering and Equilibrium Parameters

- Figures show disruptivity (top, blue), and sample distribution (bottom, red)





Key results

Rapid increase in disruptivity at higher current

Rapid decrease in disruptivity at higher power

Key results

Some decrease in disruptivity at higher β_N

Rapid decrease in disruptivity at higher q or shaping

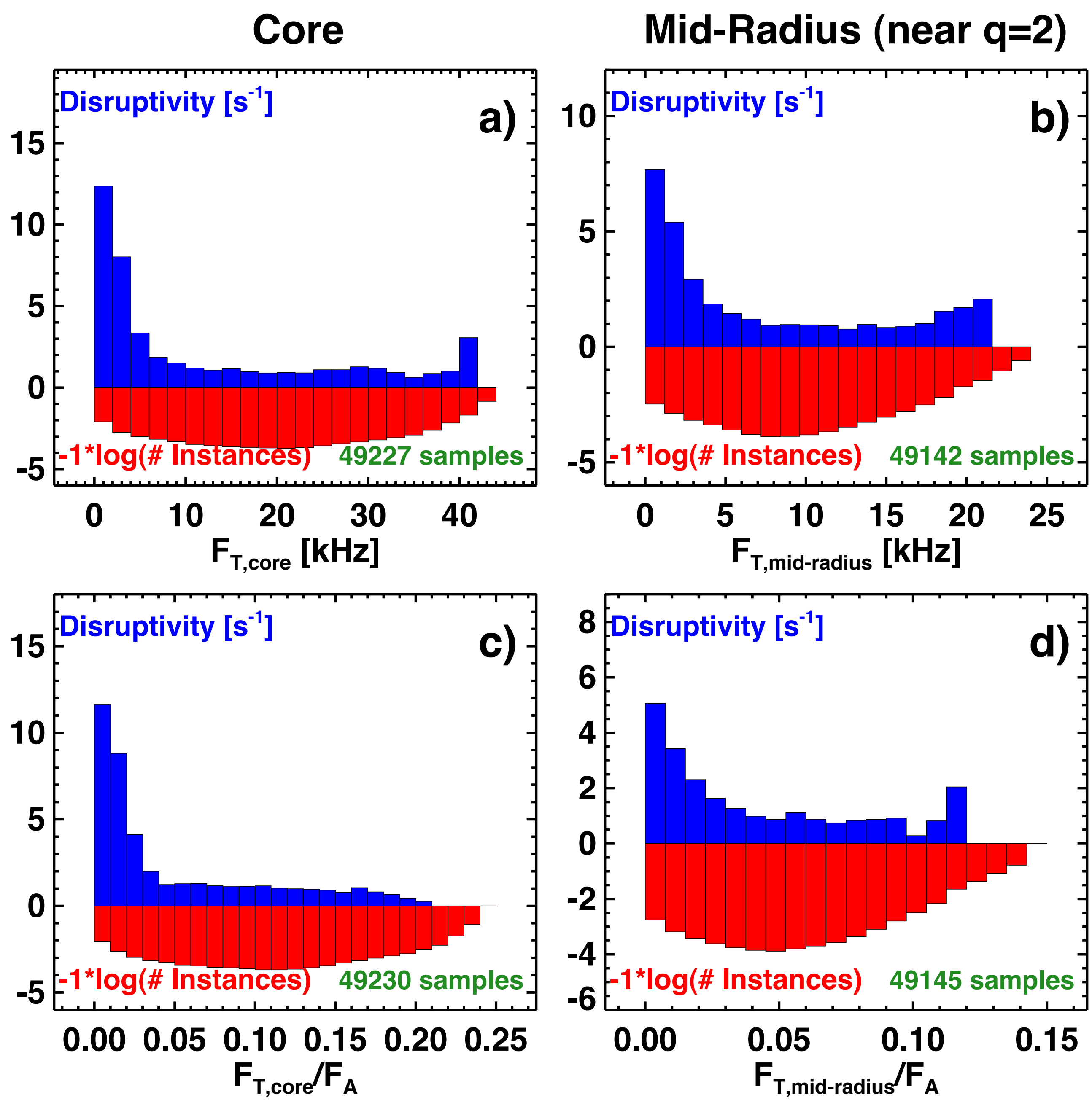
Sustained Rotation Helps to Avoid Disruptions

Absolute Frequency

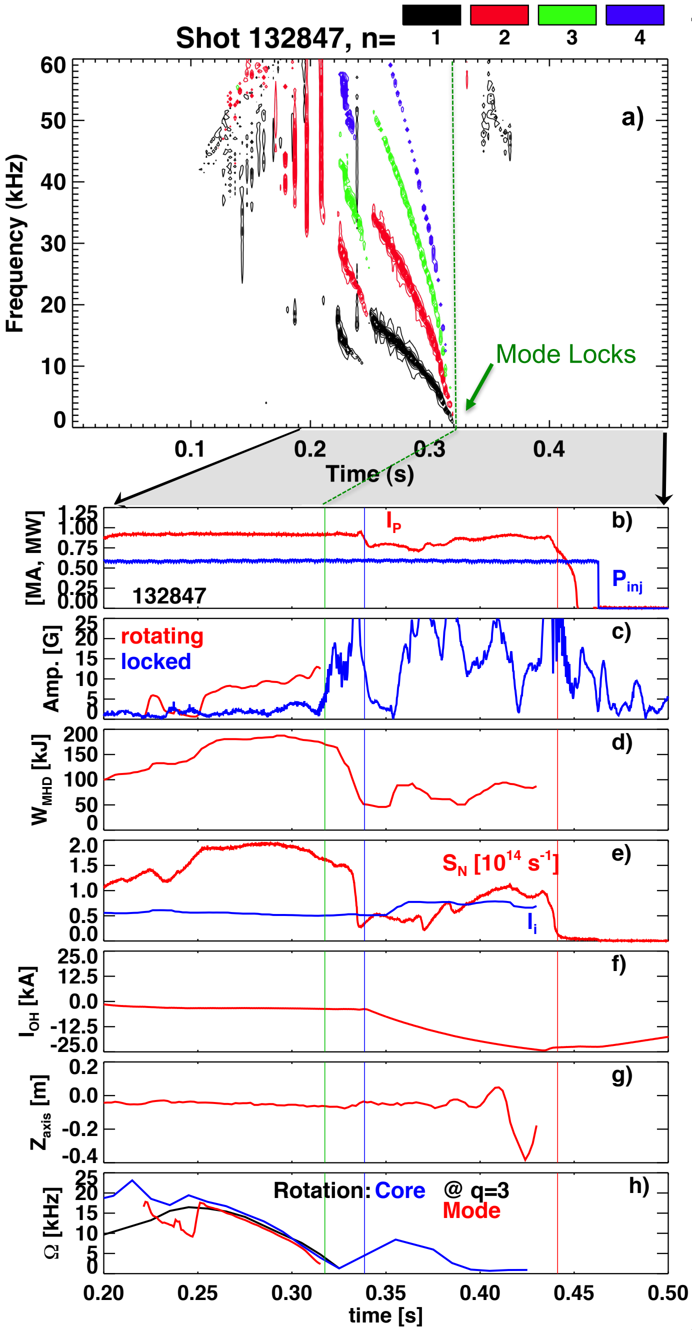
Normalized Frequency

$$V_A = |B_0| / \sqrt{2\mu_0 \bar{n}_e m_P}$$

$$F_A = V_A / 2\pi R_0$$



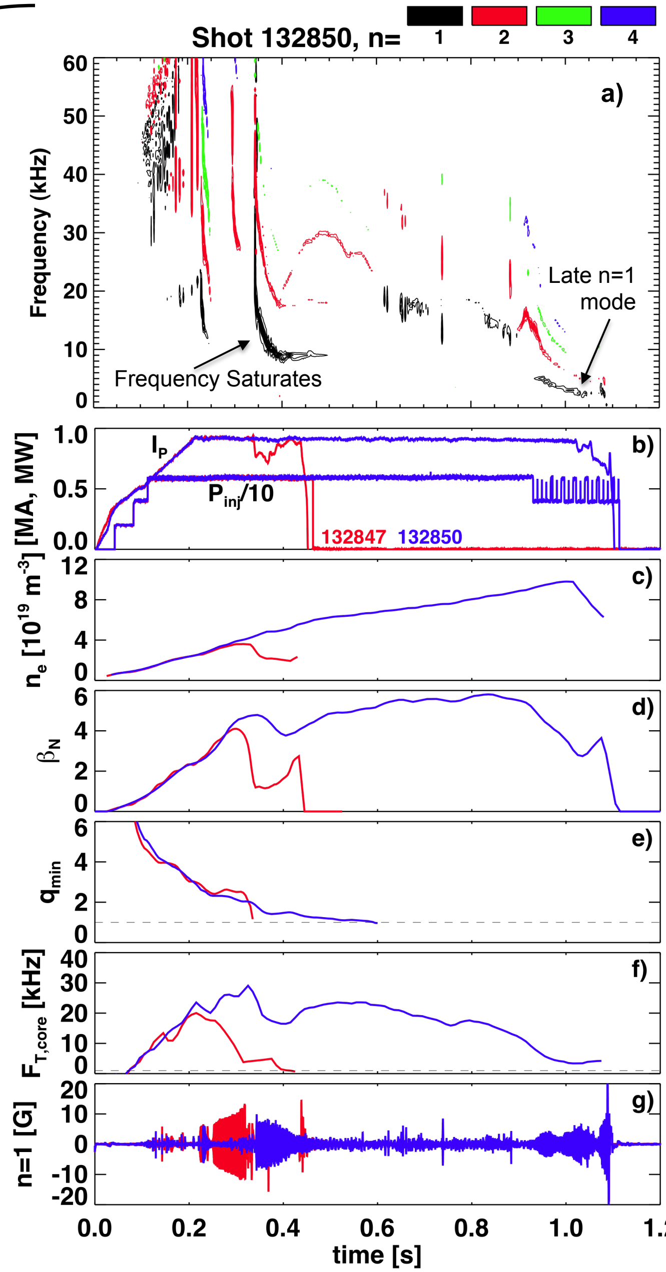
Small Changes in Early Gas Fuelling Have a Profound Impact on Early Disruptions



Discharge where incorrect fueling leads to the q=3 surface locking as soon as it enters the plasma (132847).

Fuelling was modified in 132850, resulting in longer pulse (comparison of 132847 and 132850).

Stability not from avoiding the early mode, but rather preventing it from slowing the plasma too much.

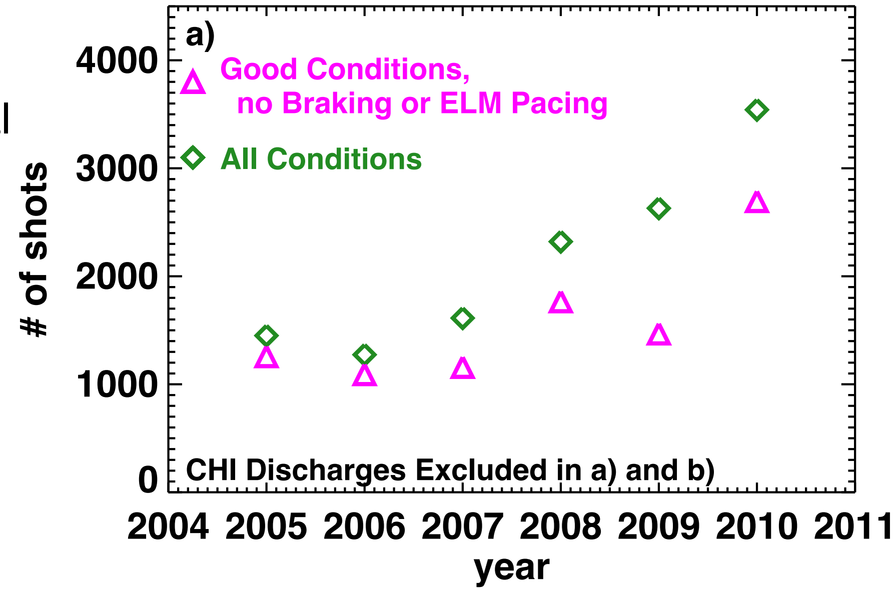


Break Disruption Rate Statistics into Four Times During the Discharge

Total # of Shots

Generally increased in later campaigns due to operational benefits of lithium PFC conditioning

Drop in # of good conditions in 2009 related to need to clean up residual lithium carbide from previous run campaign.



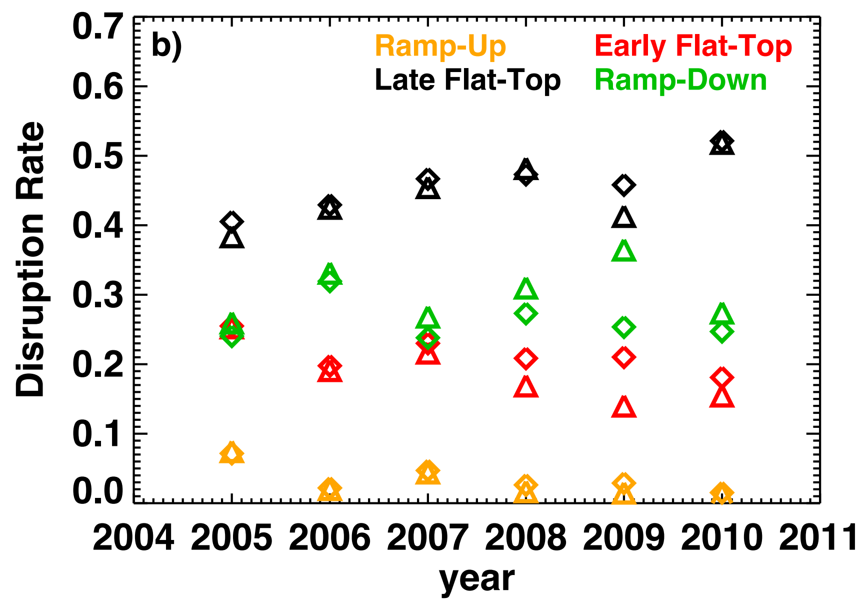
Disruption Rate

Ramp-Up:
Disruptions before start of flat-top were always uncommon.

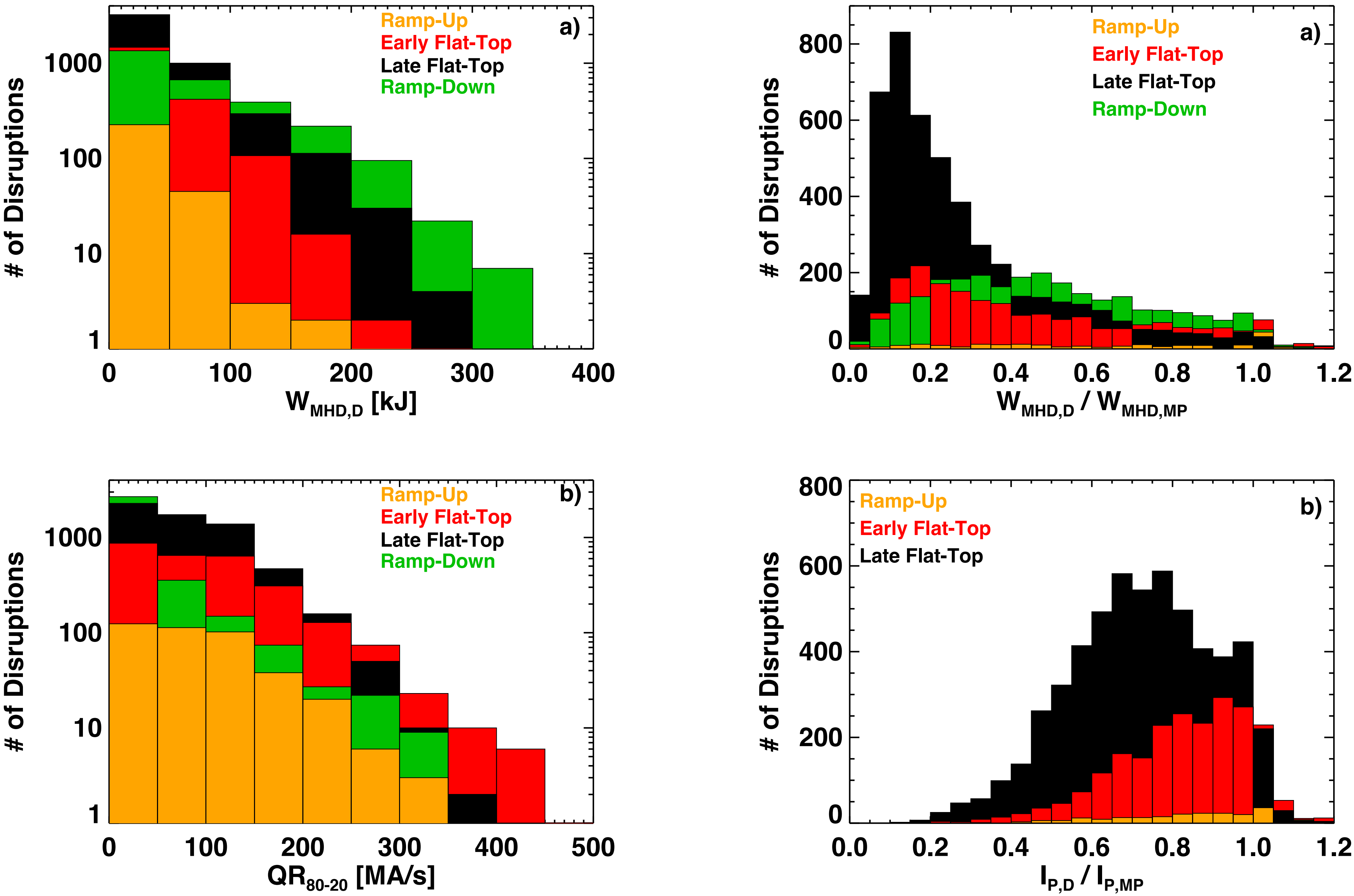
Early Flat-top:
Disruptions within 250 ms after the start of flat-top
Often coincide with MHD modes forming as rational surfaces enter the plasma locking to the wall

Late Flat Top:
RWMs, Locked Modes, H->L back transitions

Ramp-Down:
Includes deliberately ramped down cases, and instances where the solenoid current was reached and the PS software reversed the loop voltage.



Large Losses of Stored Energy and Plasma Current Commonly Proceed NSTX Disruptions

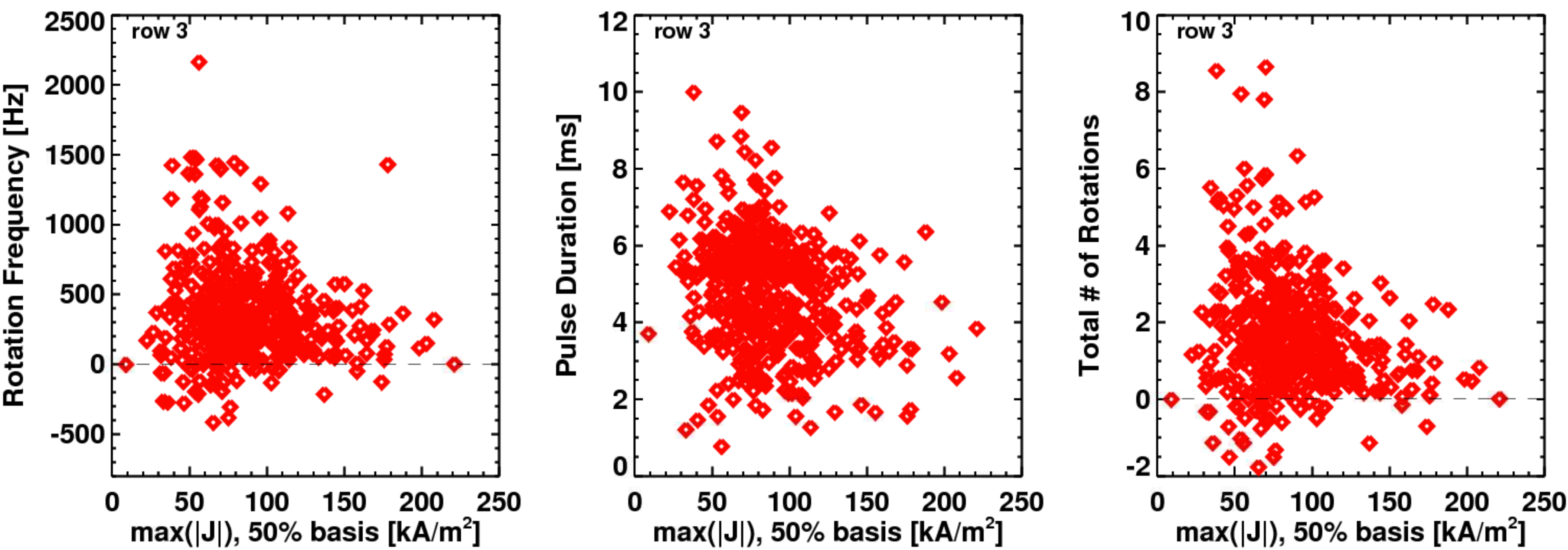


of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- Compute the rotation dynamics during time when the halo current is >25% of its maximum.
- Compare to the time average of the maximum halo current magnitude.

Summary (3)

- Dominant halo current pattern is a toroidally localized lobe of current.
- Up to 8 toroidal revolutions have been observed.
- # of revolutions scales inversely with halo current magnitude.



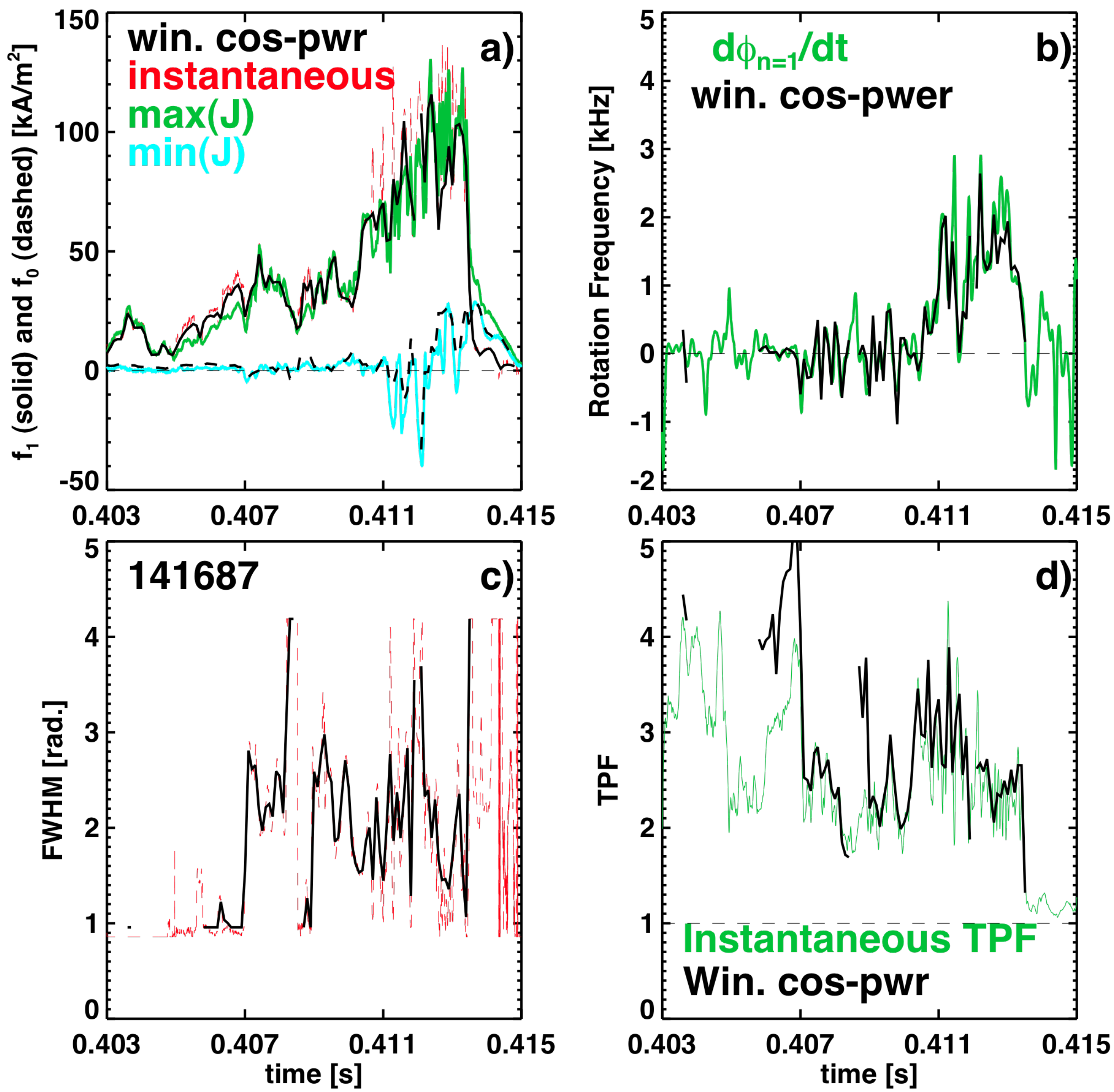
Fits Reveal Dynamics of the Halo Currents (Case With Steady Rotation)

Halo Current Amplitudes

From instantaneous cosine power fits (f_1)
From windowed fits (f_1: solid, f_0:dashed)
$max(J_{HC})$
$min(J_{HC})$

Full Width at Half Maximum:

From instantaneous cosine power fits
From windowed fits



Rotation Frequency

From "windowed cosine power" fits

From differentiating phase of simple n=1 fits:

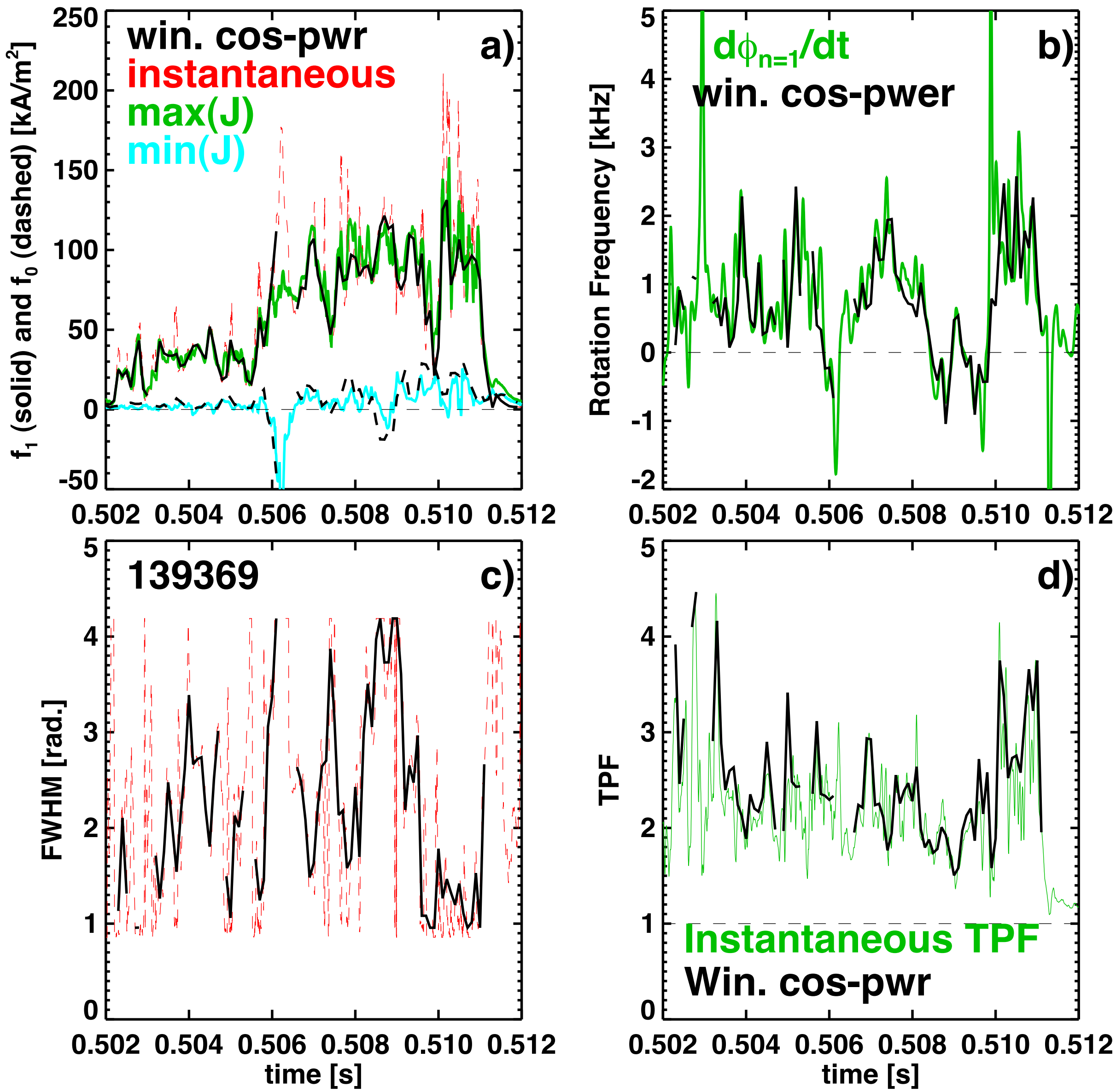
$$I_{HC} = f_{n=1} + f_{n=1}\cos(\phi - \phi_{n=1})$$

Peaking Factor

From "windowed cosine power" fits

From raw data

Fits Reveal Dynamics of the Halo Currents (Case With Erratic Rotation)



Halo Current Amplitudes

From instantaneous cosine power fits (f_1)
From windowed fits (f_1: solid, f_0:dashed)
$max(J_{HC})$
$min(J_{HC})$

Rotation Frequency

From "windowed cosine power" fits

From differentiating phase of simple n=1 fits:

$$I_{HC} = f_{n=1} + f_{n=1}\cos(\phi - \phi_{n=1})$$

Full Width at Half Maximum:

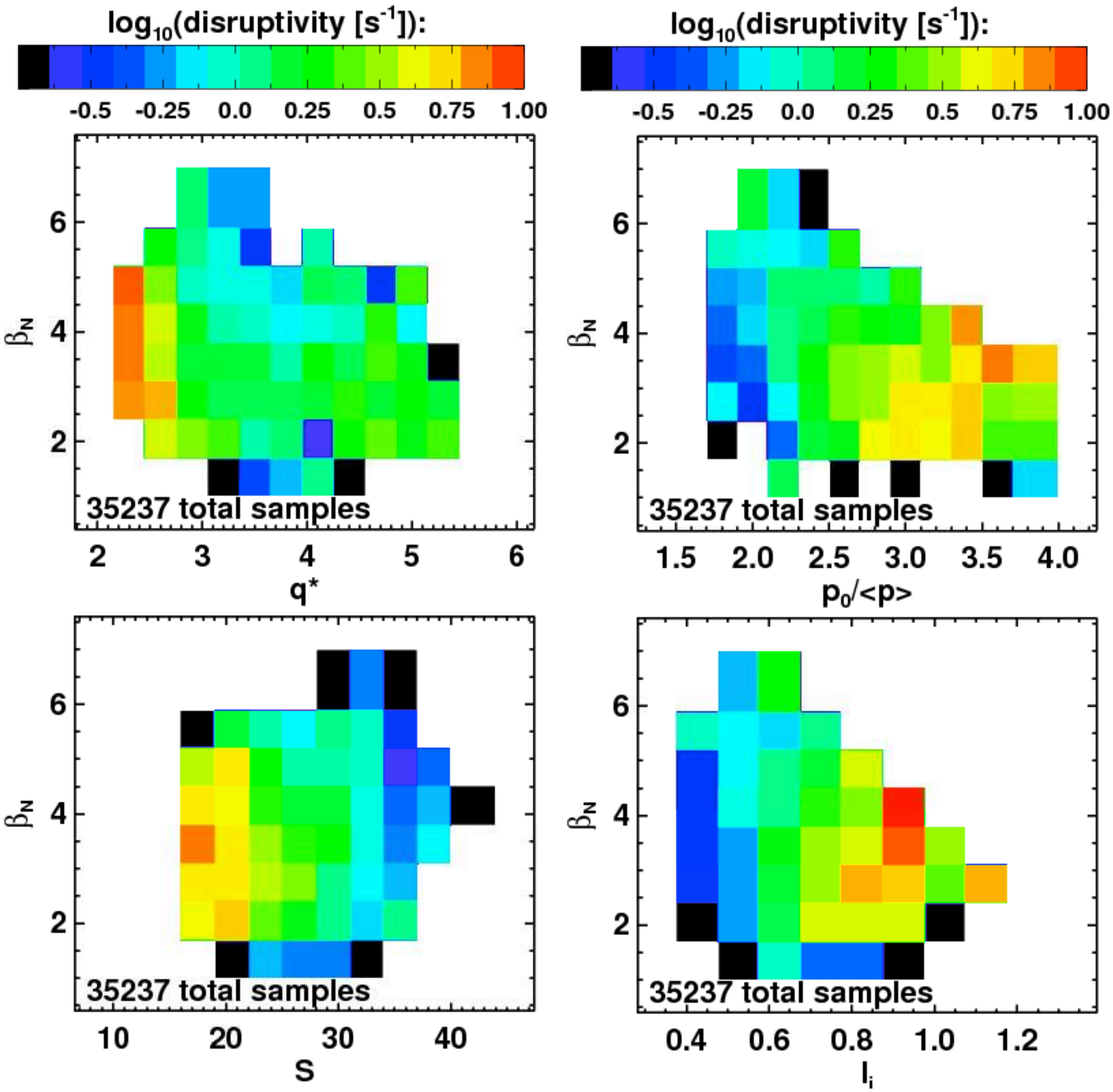
From instantaneous cosine power fits
From windowed fits

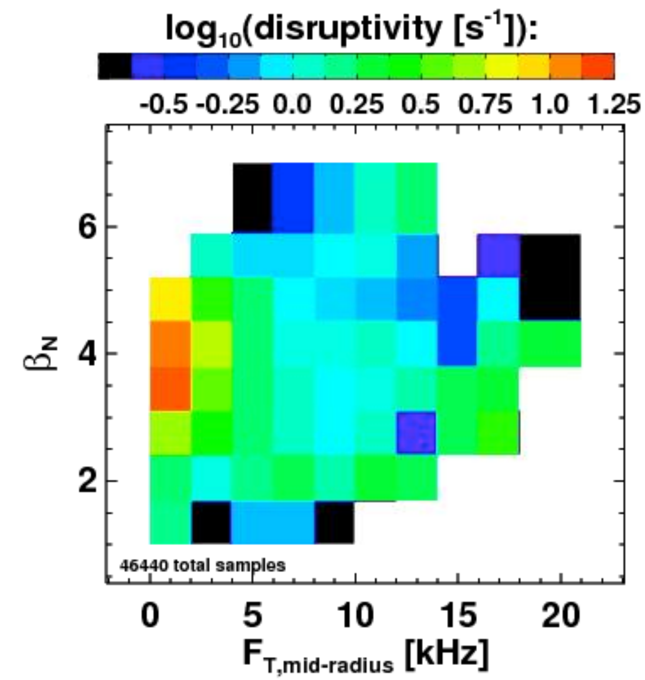
Peaking Factor

From "windowed cosine power" fits

From raw data

Global Kink Stability: Strong Shaping, Broad Profiles, and Rotation are Key For Avoiding Disruptions in NSTX





Relationship between stability and rotation at high-β_N can non-monotonic:

- due to resonances in the kinetic RWM stabilization effects.

See Berkery, et al., EX/P8-07