NSTX-U *Supported by* U.S. DEPARTMENT OF ENERGY | Office of Science

1: About Disruptions
2: Disruption Detection and Halo Currents in NSTX

S.P. Gerhardt

Thanks to: M. G. Bell, R.E. Bell, A.H. Boozer, J. Breslau, E. Fredrickson, B. P. Le Blanc, R. Maingi, J. Manickam, J.E. Menard, D. Mueller, S. A. Sabbagh, H. Yuh and the NSTX Research Team

PPPL Research Seminar
7/15/2013
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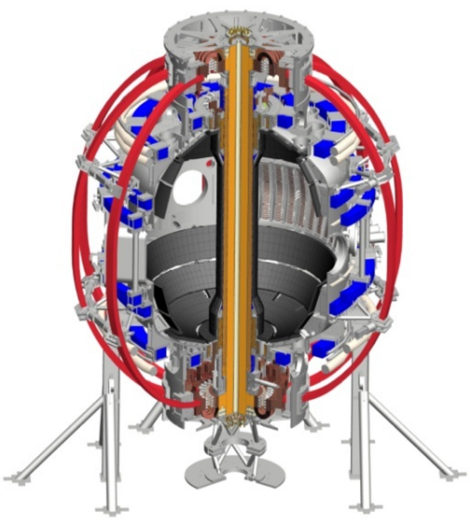

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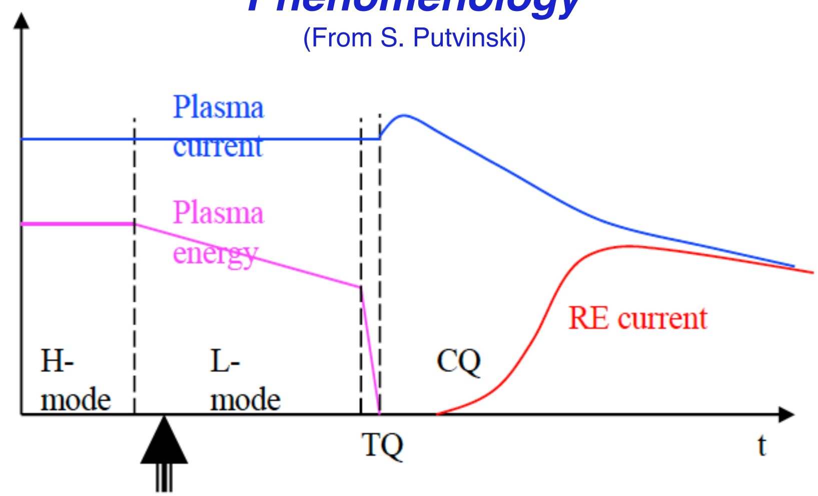
- Introduction:
  - What is a disruption?
  - What causes them?
  - What is “mitigation”?
- Some NSTX results:
  - Disruption detection
  - Halo current dynamics

Disruption: Catastrophic Loss of Thermal Confinement, Followed By a Rapid Decay of the Plasma Current

- Start with the pre-disruption, possibly high-performance, phase of discharge.
- Disruption process is initiated, often with some energy loss.
- Remaining stored energy is rapidly lost during the thermal quench.
  - Due to island overlap, large convective cells
  - Results in strong thermal loading of the PFCs.
- Current quench results from the high resistivity of the now cold plasma
  - Large flux changes can result in EM forces from eddy currents
- Electric field during the current quench can drive a runaway electron (RE) tail.
  - Avalanche Gain ~e^{Ip}: $G_{ITER}/G_{JET}=e^{15-4}=60000$.
  - Think of a huge electron beam welder.
- If, at any stage in the process, control of the plasma position is lost, then halo currents can flow.
  - Halo currents = currents that link plasma and PFCs, resulting in large forces.

Typical Disruption Phenomenology

(From S. Putvinski)



Typical chain of events during plasma disruption

Disruptions Pose a Significant Danger to the ITER Plant

	NSTX-U	JET	ITER
R	1	2.9	6.2
I_P [MA]	2	4	15
W_{mag} [MJ]	1	11	400
W_{Th} [MJ]	1	12	350
A_{div} [m]	0.5	1.6	3.5
Thermal Loading [$MJm^{-2}s^{-1/2}$]	15	67	540

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W=350 +400 MJ will melt about 1.1 ton of copper.

To melt 1 kG: 1000K * 385 J/K + 205000 J = 600 kJ
(Pointed out to me by G. Wurden)

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X 100!

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X 100!

Racing at Daytona/Talladega: $43\cdot 0.5\cdot 1500kg\cdot (89m/s)^2 = 250MJ$
Entire field, at 200 miles/hour, has ~250 MJ

Is especially bad if the heat is focused (Ex: Coolant channels near PFC surfaces, water leaks into tritium contaminated vessel)

- Conduction to divertor during TQ.
- RE beam strikes

Experimentalists Have Historically Broken Disruptions Into a Set of Physics Causes

- Ideal Beta Limit: Global kink instabilities, $\beta_N=\beta_T aB_T/I_P<2\text{-}8$
  - β_N limit depends on kinetic & magnetic profiles, passive conductors, control.
- Ideal Current Limit: Global kinks with edge-q less than ~2.2

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- Density Limit: Roughly speaking $f_{GW}=n_e/(I_P/\pi a^2)\sim 1$
  - H->L back-transitions and disruptions.
  - Similar phenomenology in many “cold edge” disruptions.
- Resistive Limits: Neoclassical tearing modes
  - Rotating magnetic islands grow due to positive feedback mechanism w/ the bootstrap current.
  - Soft β-limit for m/n=3/2, but can be disruptive for m/n=2/1 if the plasma rotation is sufficiently damped by the mode.
- Locked Mode: Error fields brake the plasma rotation, allowing a large m/n=2/1 magnetic island to form.
  - Often sets a low density limit, though effects can be important at high-β as well.

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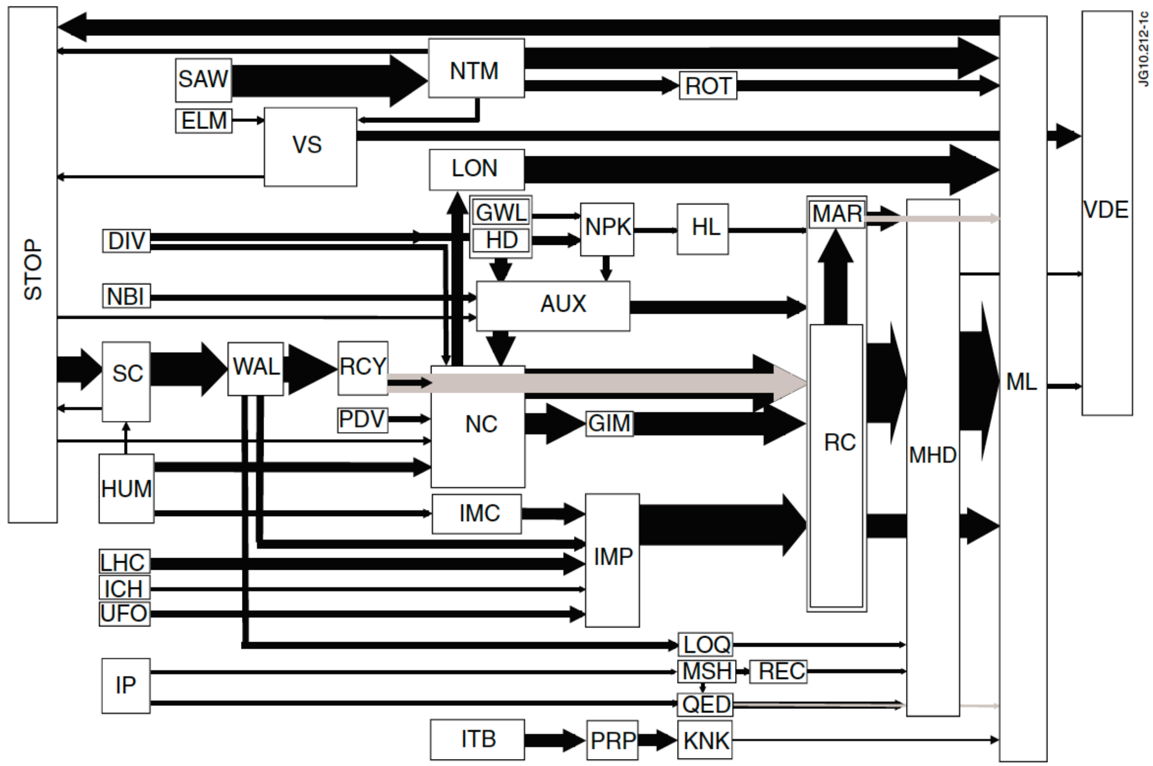
- VDE: Plasma drifts up or down in the confinement chamber, impacting the wall.
- UFOs: Macroscopic parts of divertor/FW enter the plasma, leading to radiative collapse.

While the Disruption is Ultimately Due to MHD, Many Factors Can Start the Chain of Events

Type of technical problem	Label
Impurity control problem	IMC
Influx of impurities	IMP
Density control problem	NC
Too much gas from gas injection module	GIM
No (effective) pumped divertor	DIV
Shape control problem	SC
Plasma too close to the wall	WAL
High recycling	RCY
Other real-time control problem	RTC
Emergency shut-down	STOP
Manual emergency stop by operator	SL
Wrong validated density for feedback	PDV
Magnetic signal(s) error	MAG
Reciprocating probe	PRO
Na influx by lithium beam diagnostic	LIB
Other diagnostic problem	DIA
Too little auxiliary power	AUX
Too little torque/rotation	ROT
Problem with neutral beam injection	NBI
Impurity release due to LHCD	LHC
Impurities from ICRH antennae	ICH
Problem with vertical stability control	VS
(Intentional) vertical kink	VSK
Temperature too high in VS amplifier	VST
Over-current in VS amplifier	VSI
Other failure of VS amplifier	VSA
Human error	HUM
Too fast a current ramp-up	IP
Other power supply problem	PS
Unidentified impurity influx (flying object)	UFO
Problems due to pellet injection	PEL
Impurity influx by laser ablation	ABL
No clear cause	NON

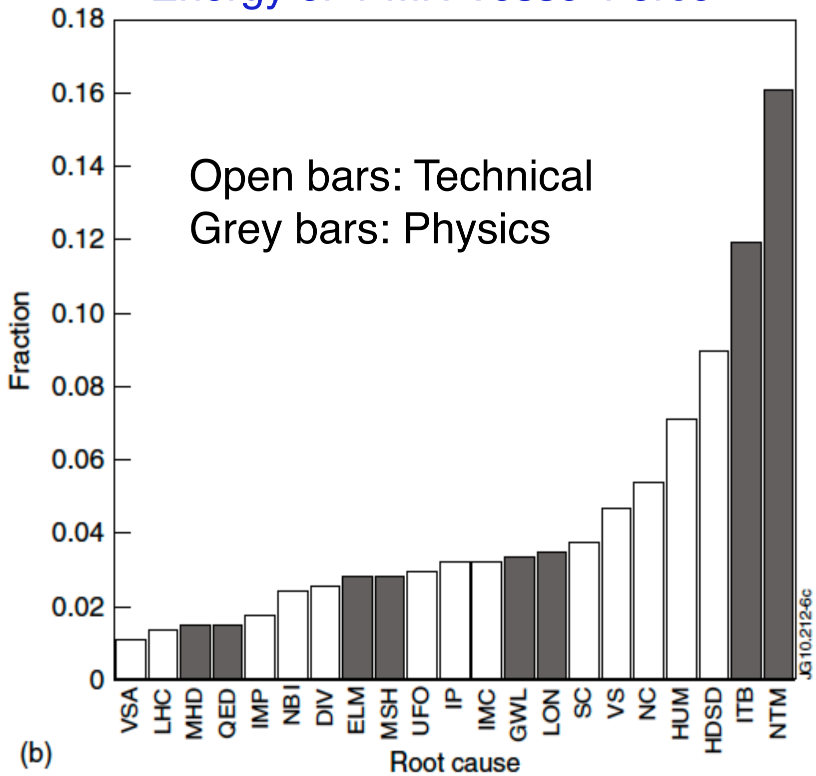


Type of physics problem	Label
General (rotating) $n = 1$ or 2 MHD	MHD
Mode lock	ML
Low q or $q_{95} \sim 2$	LOQ
Edge q close to rational (>2)	QED
Large sawtooth crash	SAW
Neo-classical tearing mode	NTM
Internal kink mode	KNK
Reconnection	REC
Radiative collapse ($P_{rad} > P_{in}$)	RC
MARFE	MAR
Greenwald limit (n_{GW})	GWL
High density operation (near n_{GW})	HD
Too low density (and low q)	LON
H-to-L back-transition	HL
Strong density peaking	NPK
Too strong internal transport barrier (ITB)	ITB
Strong pressure profile peaking	PRP
Negative central magnetic shear	MSH
Large edge localized mode (ELM)	ELM
Vertical displacement event	VDE

From P.C. de Vries, Nuclear Fusion **51**, 053018 (2011)

Root Disruption Causes Were From Both Plasma Physics and Technical Issues

Root Causes for Unintentional Disruptions with 1 MJ Plasma Energy or 1 MN Vessel Force



From P.C. de Vries, Nuclear Fusion **51**, 053018 (2011)

"The development of more robust operational scenarios has reduced the JET disruption rate over the last decade from about 15% to below 4%. A fraction of all disruptions was caused by very fast, precursorless unpredictable events. The occurrence of these disruptions may set a lower limit of 0.4% to the disruption rate of JET. *If one considers on top of that human error and all unforeseen failures of heating or control systems this lower limit may rise to 1.0% or 1.6%, respectively."*

HUM: Human Error
NC: Density Control
VS: Vertical Stability Control
SC: Shape Control
LON: Low Density

From P.C. de Vries, Nuclear Fusion **51**, 053018 (2011)

Much Research Now Focusing on "Mitigation"

- Goal: Trade disruption you can't tolerate for one you (maybe) can.
- Technologies are being developed to inject large amounts of medium/high Z material into the plasma (Carbon, Neon, Argon)
  - Very high-pressure gas injectors. Layered pellets. Shattered pellets.
- Why?
  - Impurities radiate the plasma thermal energy uniformly to the FW instead of allowing it to be conducted to the PFC surfaces.
  - Current quench rate can (in theory) be tailored.
  - Large enough number of injected electrons can potentially be used to collisionally suppress RE generation.
- Because RE suppression is a serious issue for ITER, large effort at DIII-D on magnetic control of RE beam.
- This is a US contribution to ITER.

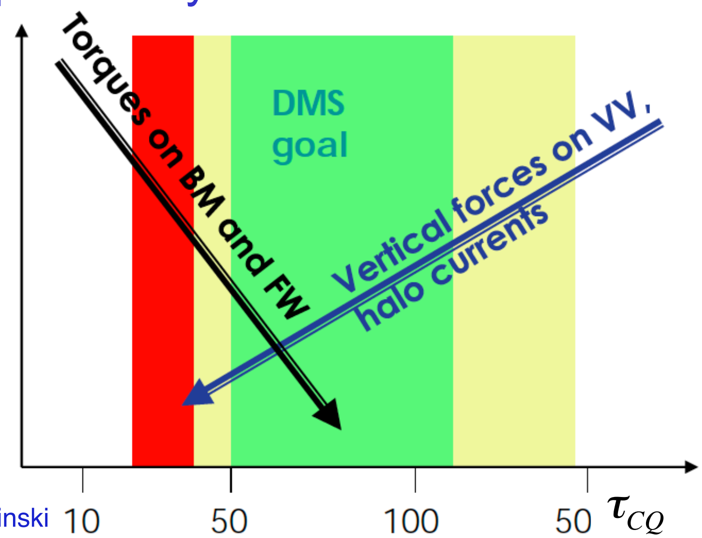
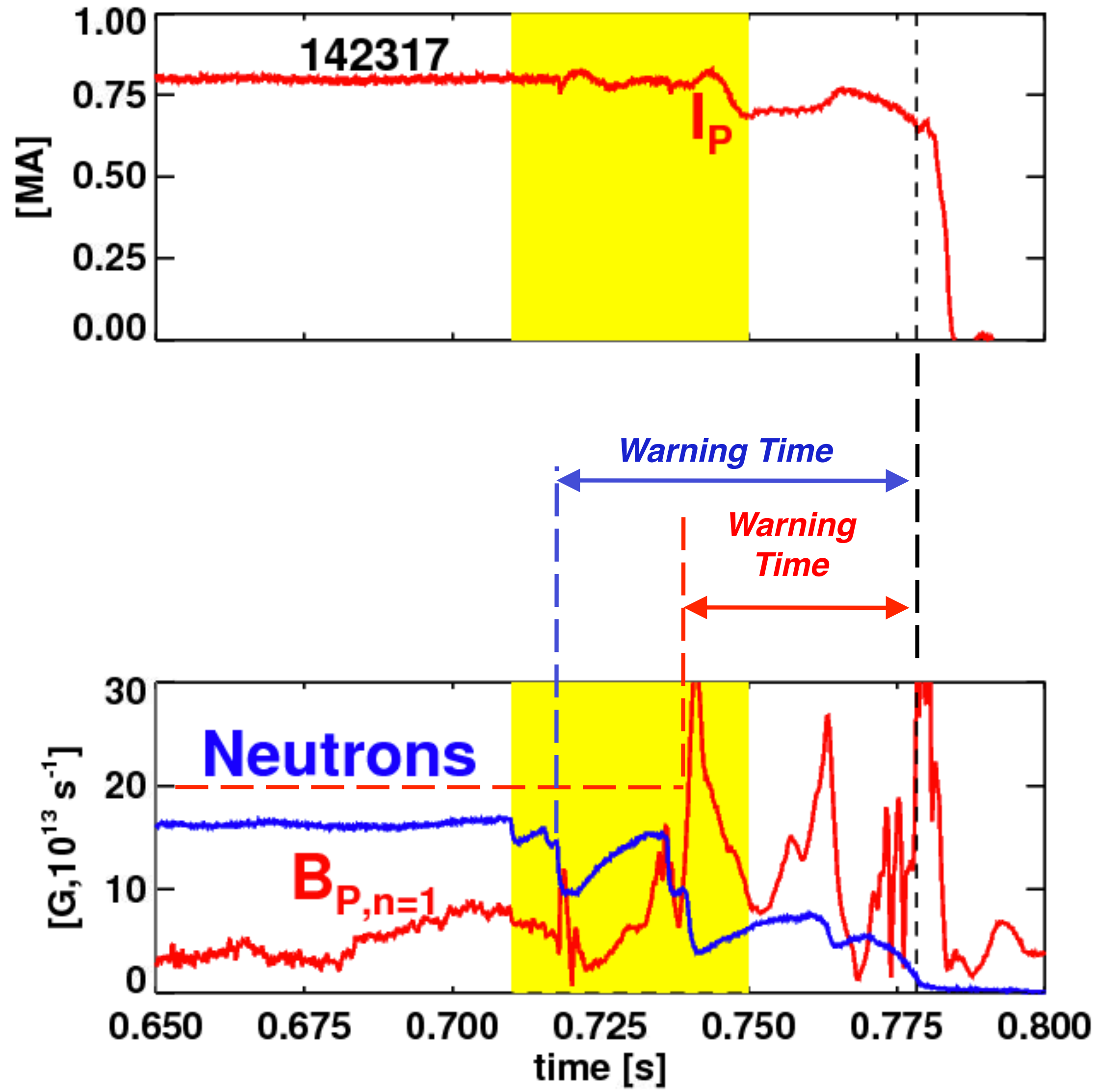


Figure from S. Putvinski

- Introduction: What is a disruption?
- Some NSTX results:
  - Disruption detection
    - Much effort spent on developing mitigation strategies, but need effective triggering systems.
    - Most present work on detection involves very sophisticated statistical analysis of prcesursor signals.
    - My contention: important to incorporate as much physics as possible in detection schemes.
    - No previous work on disruption detection in high-β ST configurations.
  - Halo current dynamics

Warning Times Defined With Respect to the Current Quench



<u>False Positive:</u>

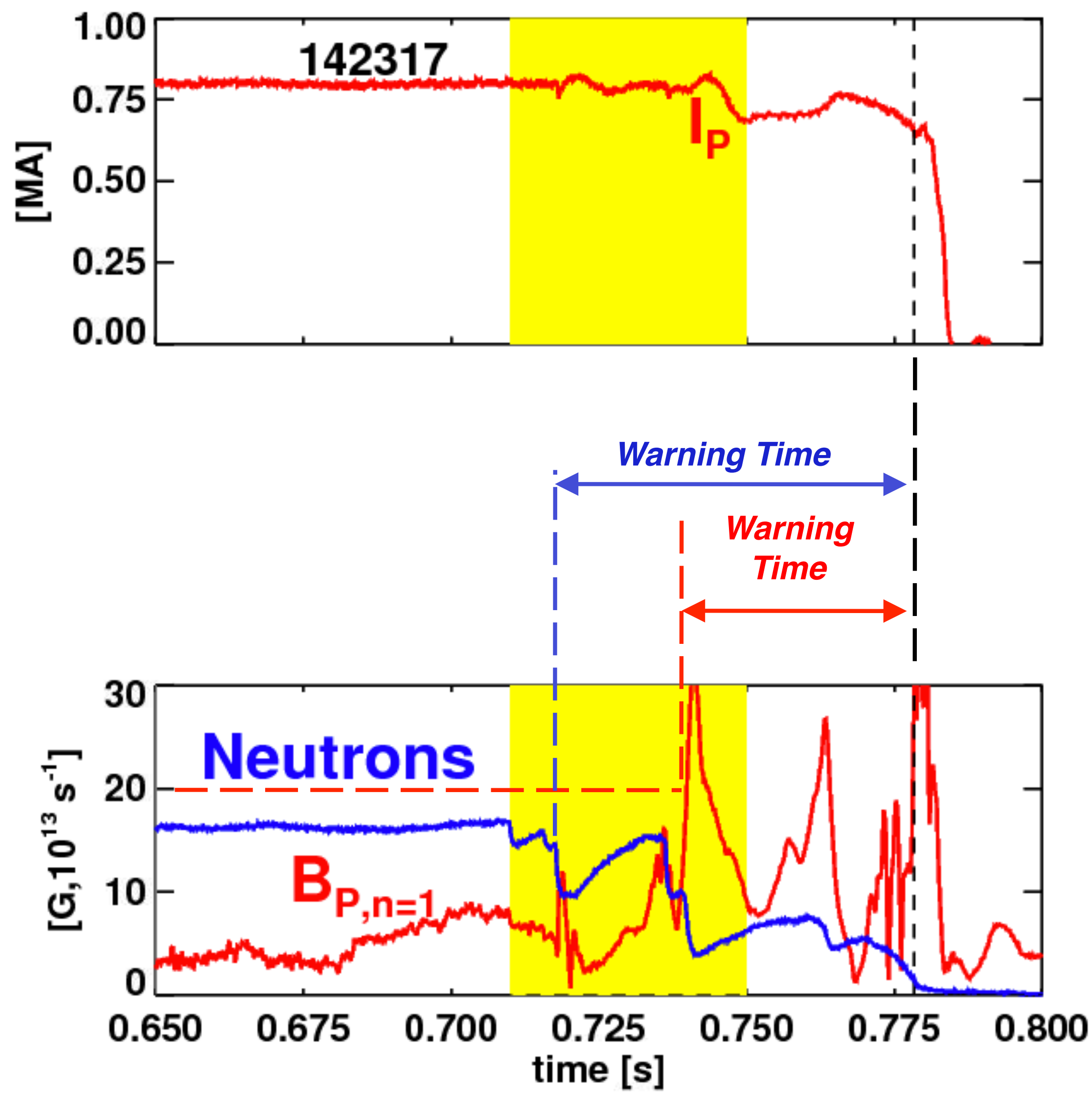
Warning more than 300 ms in advance of current quench.

<u>Late Warning:</u>

Warning later than 10 ms before the current quench.

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

Warning Times Defined With Respect to the Current Quench



Thermal quench leads the CQ by only a few ms, so not significantly different in timing, but much much easier to detect.

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

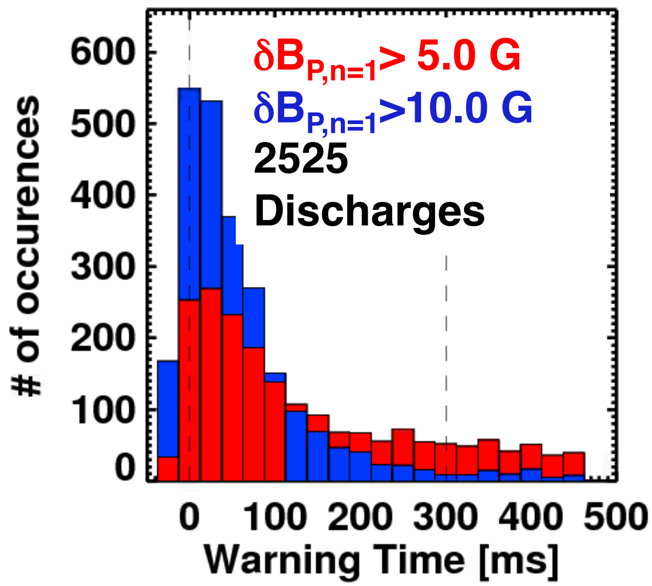
<u>Late Warning:</u>
Warning later than 10 ms before the current quench.

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

Individual Threshold Tests Form the Basis For Detection

- 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



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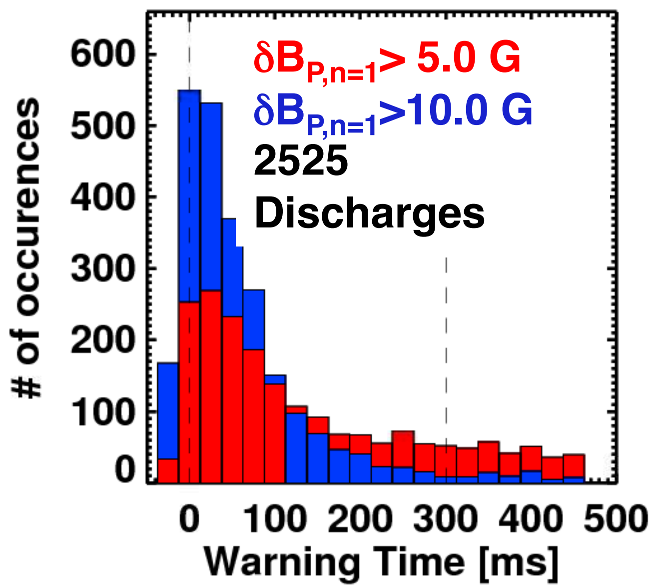
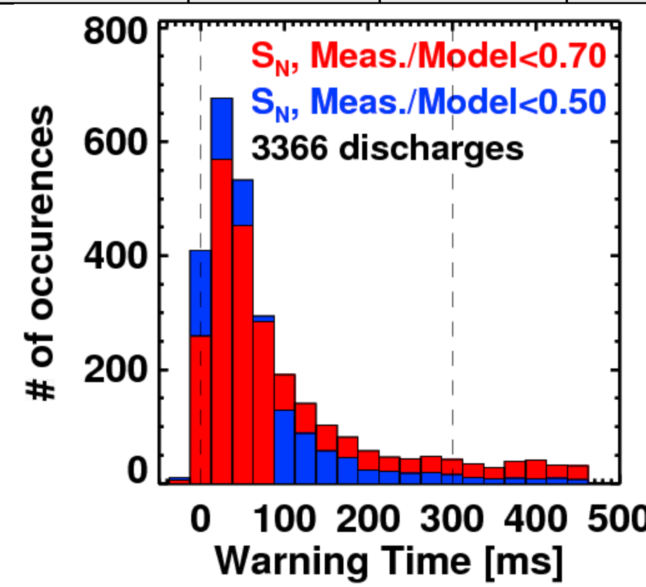


- Often a significant drop in neutron emission proceeding a disruption.
- Due to loss, not rapid slowing down.
- Estimate the neutron emission from a simple slowing down model.
  - T_e, Z_{eff}, n_e are inputs.

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



Low threshold levels lead to high false positive rates, few missed disruptions.

Developed a Method to Combine These Tests For Improved Prediction

- No one of these diagnostic tests was good enough to predict all disruptions.
  - Must combine the tests in some fashion.
- Algorithm summary:
  - Take a series of ~15 threshold tests like those previously described.
  - Foe each test, assign a number of “points” for various thresholds, for instance:

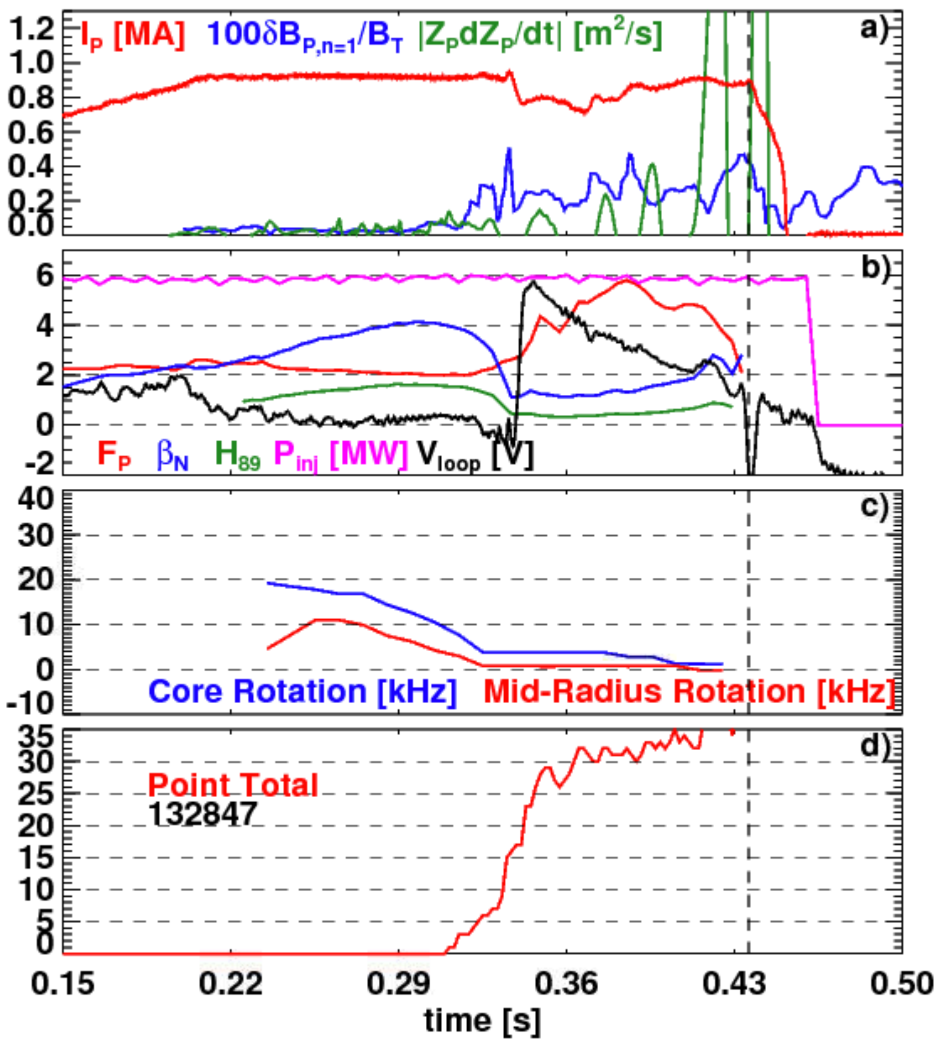
Table for 3-level detection (full table has 15 rows)

Test	1 pt -> 2% False Positive Rate	2 pt ->1% False Positive Rate	3 pts -> 0.5% False Positive Rate
n=1 B_P Perturbation [G]	16	22	27
Neutrons, Meas./Model	0.4	0.35	0.29
V_{loop}, Meas./Model	10	16	24

  - Evaluate tests at each time-slice, sum the points from threshold tests to form an “aggregate” point total (APT).
  - **Declare a disruption warning if the aggregate point total (APT) exceeds a chosen value**.

Aggregate Total Increases Monotonically Towards the Disruption

Early Rotating Mode Lock



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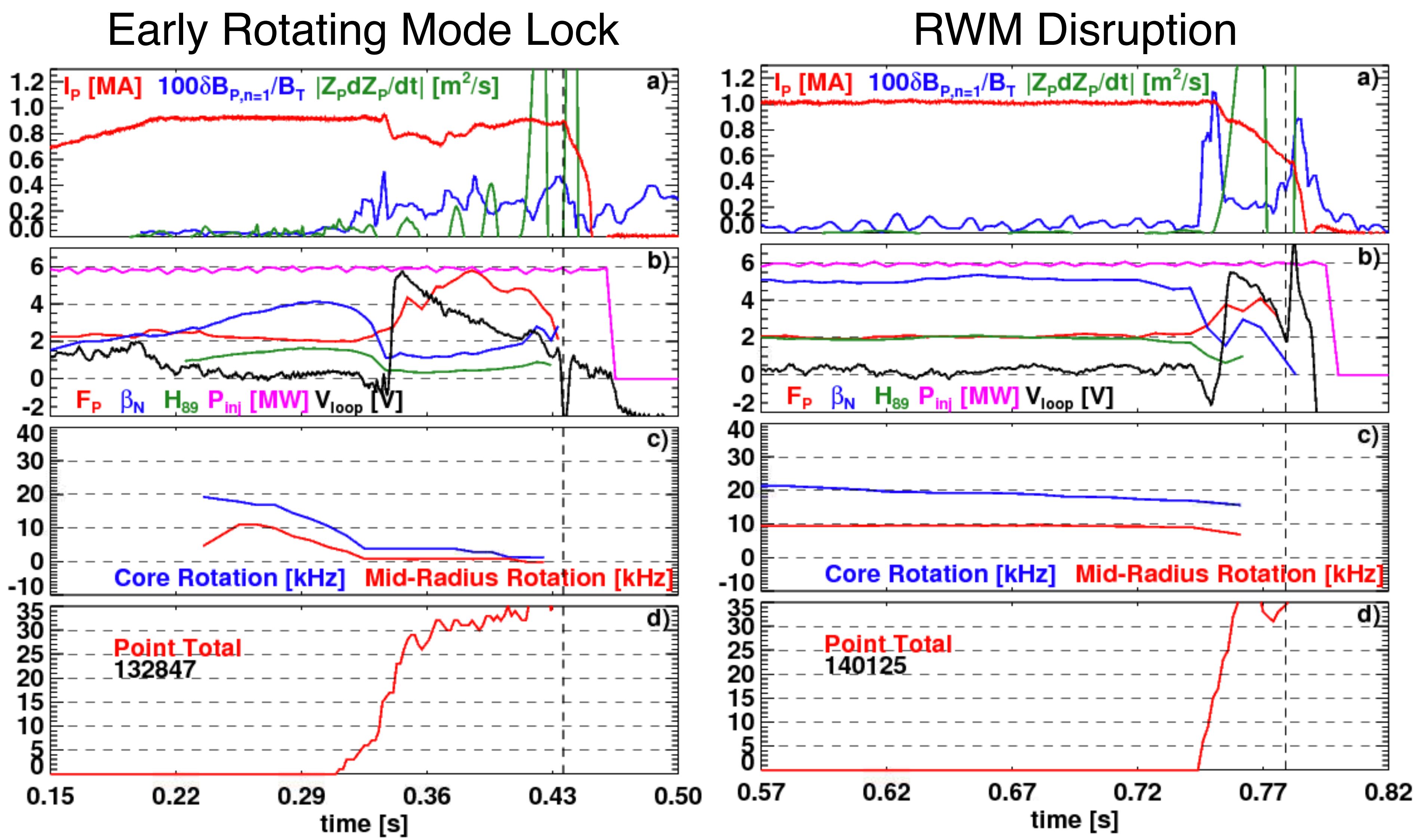
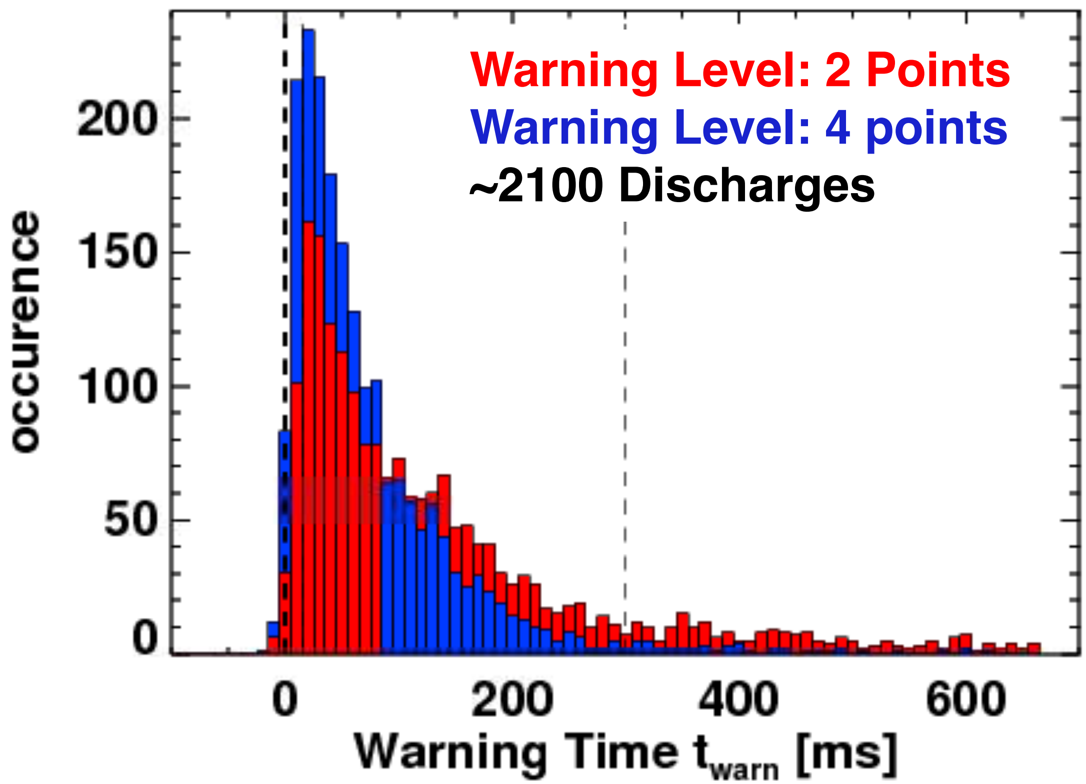


3-Level Warning Rule Can Predict Most Disruptions



Warning at APT= 2 Points

1.8% late warning

15% false positive

Sum: 16.8%

Warning at APT=4 Points

~2.8% late warning

~4.8% false positive

Sum: 7.6%

Actual algorithm has ~15 rows

Test	1 pt -> 2% False Positive Rate	2 pt ->1% False Positive Rate	3 pts -> 0.5% False Positive Rate
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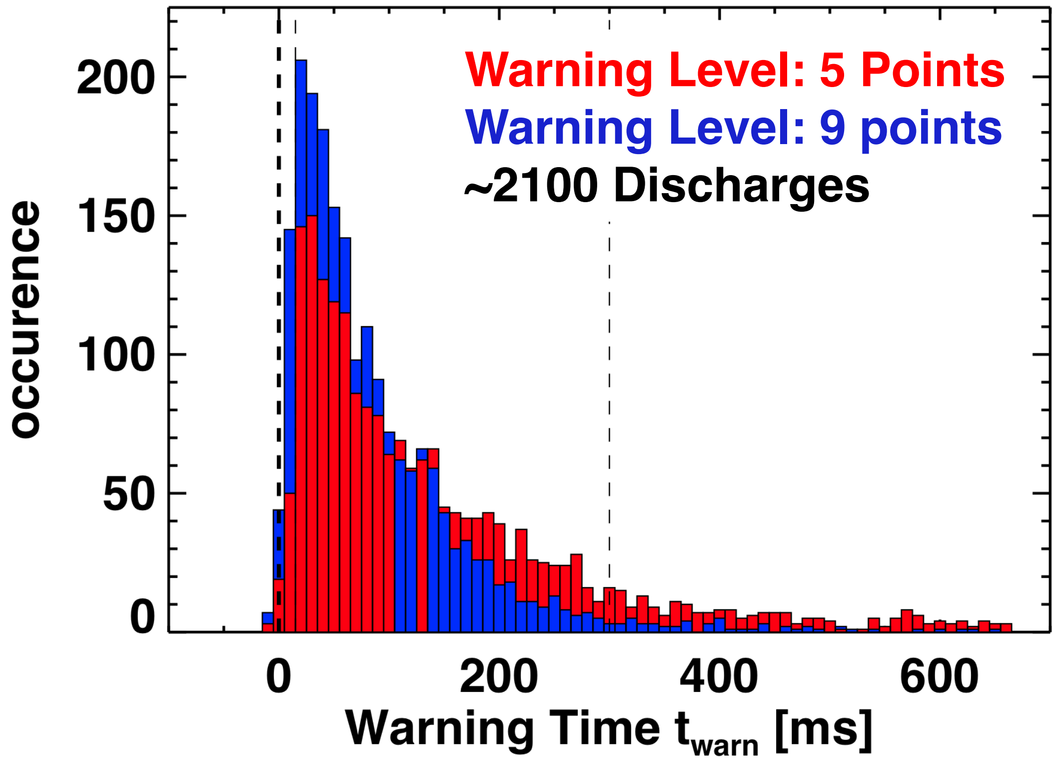
5-Level Warning Rule is Even a Bit Better



Warning at APT=5 Points

<1% late warning

~15% false positive

Sum: 16%

Warning at APT=9 Points

~2% late warning

~4% false positive

Sum: 6%

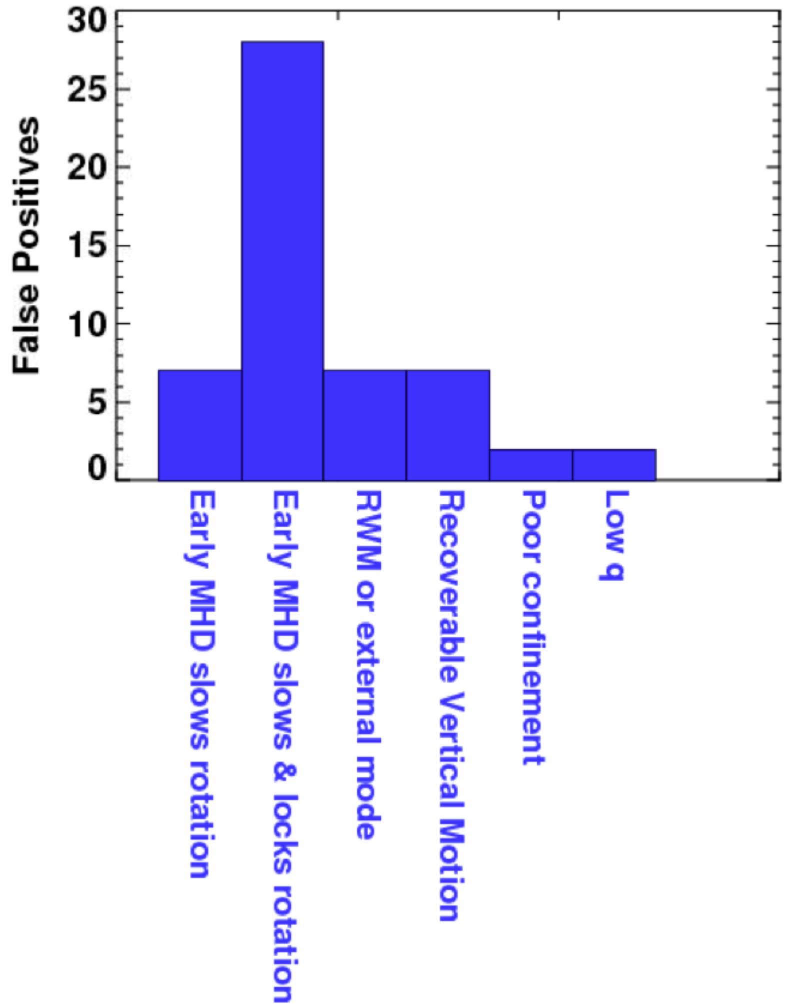
(False positive count dominated by near-disruptive MHD events)

Actual algorithm has ~15 rows

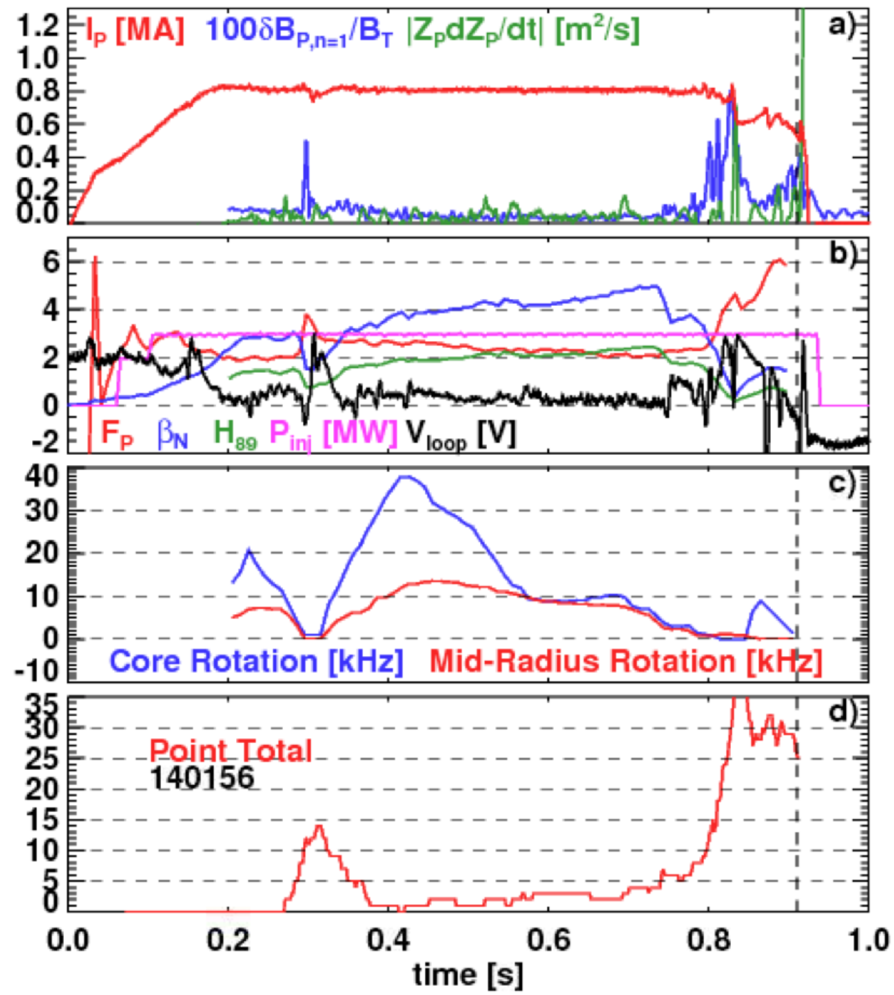
Test	1 pt -> 10% False Positive Rate	2 pt ->5% False Positive Rate	3 pts -> 2% False Positive Rate	4pts -> 1% False Positive Rate	5pts -> 0.5% False Positive Rate
n=1 B_P Perturbation [G]	8	10	16	22	27
Neutrons, Meas./Model	0.59	0.51	0.41	0.35	0.29
V_{loop}, Meas./Model	6	7.5	10	16	24

Most False Positives are not "False"

Sources of False Positives



Example False Positive Due to Mode Lock

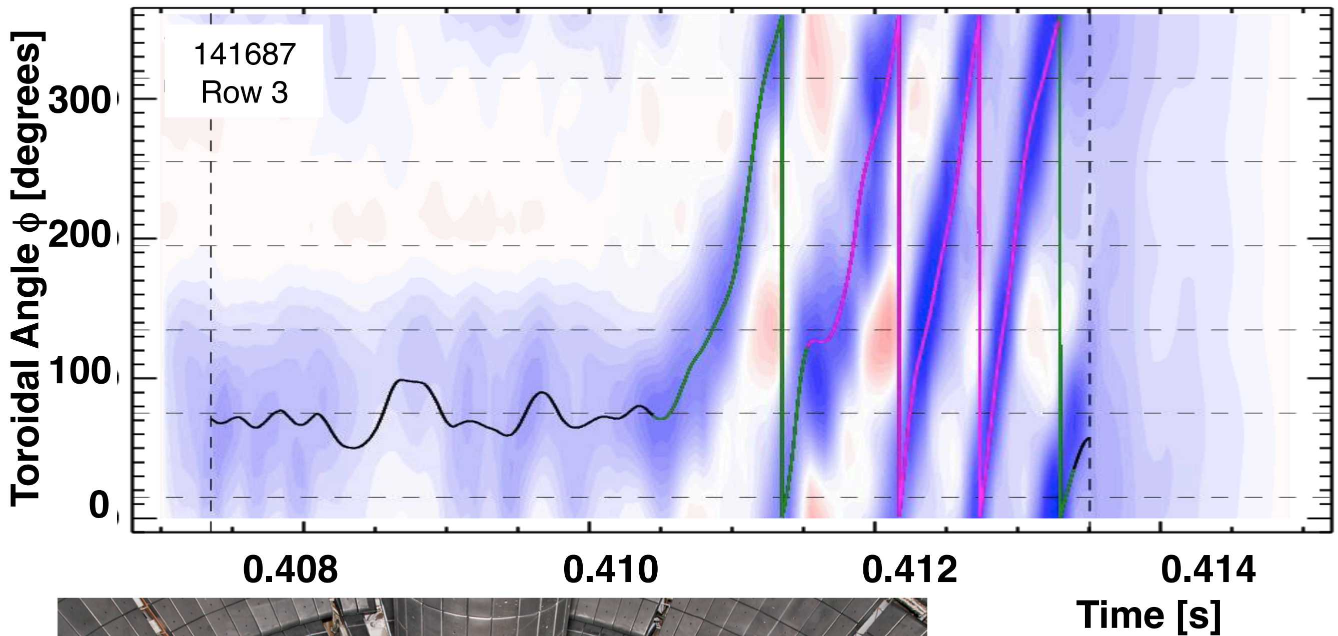


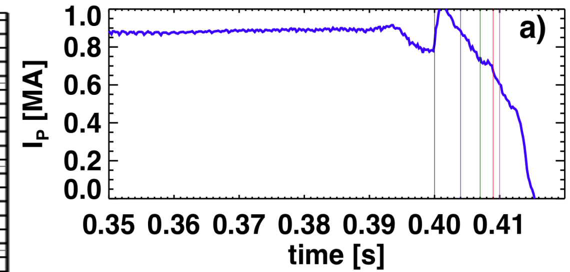
So What is the Utility of This?

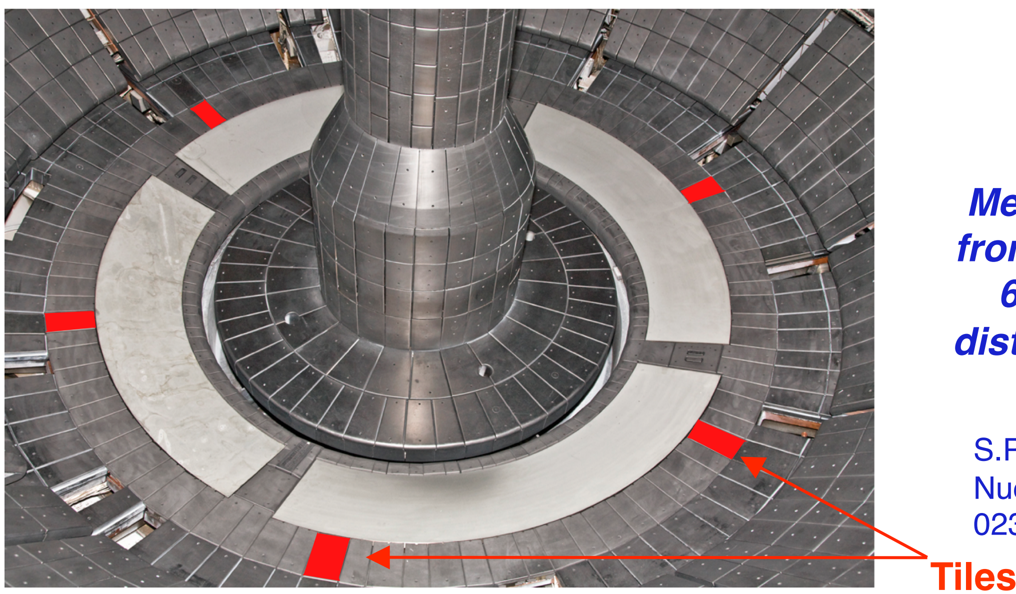
- Will form the basis for disruption detection for initial NSTX-Upgrade operations.
  - Present online diagnostics: n=1 poloidal field perturbation, vertical motion indicators, I_P deviations.
  - Still-evolving 5 year plan calls for realtime CHERS & MPTS, maybe others.
- Can it be used for ITER?
  - Possibly, but would need cross-machine checking (similar to a neural network).
    - Try to frame tests as a comparison to a control target (LoC) or physics-based model.
    - Best intitial comparison would be to another co-injected machine.
  - Need excellent realtime diagnostics.
  - ITER will have only a few target scenarios, NSTX has *many, many* scenarios.
- Should only be a last line of defense. Need development of:
  - Realtime forecasting of equilibrium, equilibrium actuator behavior.
    - GA has a realtime equilibrium code, TCV has a realtime transport/current drive code.
  - Realtime n=0 calculations (realtime ΔZ_{max}+disturbance spectrum?), realtime RWM assessments (model based RFA?), realtime NTM or RWM LoC assessments,…
- Method relies on their being a significant "pre-disruption phase"
  - Must have a gap between the LM/RWM onset and the start of the TQ & CQ.
  - If configuration is prone to disruptions w/o such a gap (think ITB), then that configuration may not be acceptable for tokamak operation

- Introduction: What is a disruption?
- Some NSTX results:
  - Disruption detection
  - Halo current dynamics: currents during a disruption that flow in both the plasma and the vessel at different places in their path.
    - Underlying spatial structure is often not stated.
    - Frequencies of rotating halo current asymmetries may match resonant frequencies of the ITER vessel or TBMs.
    - Measured dynamics seem to vary from device to device.

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

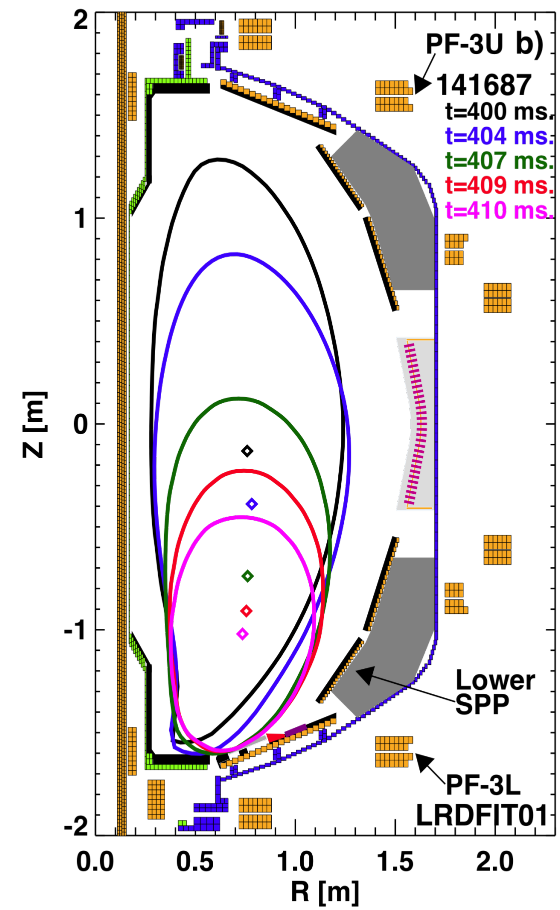






Measurements from an array of 6 toroidally distributed tiles.

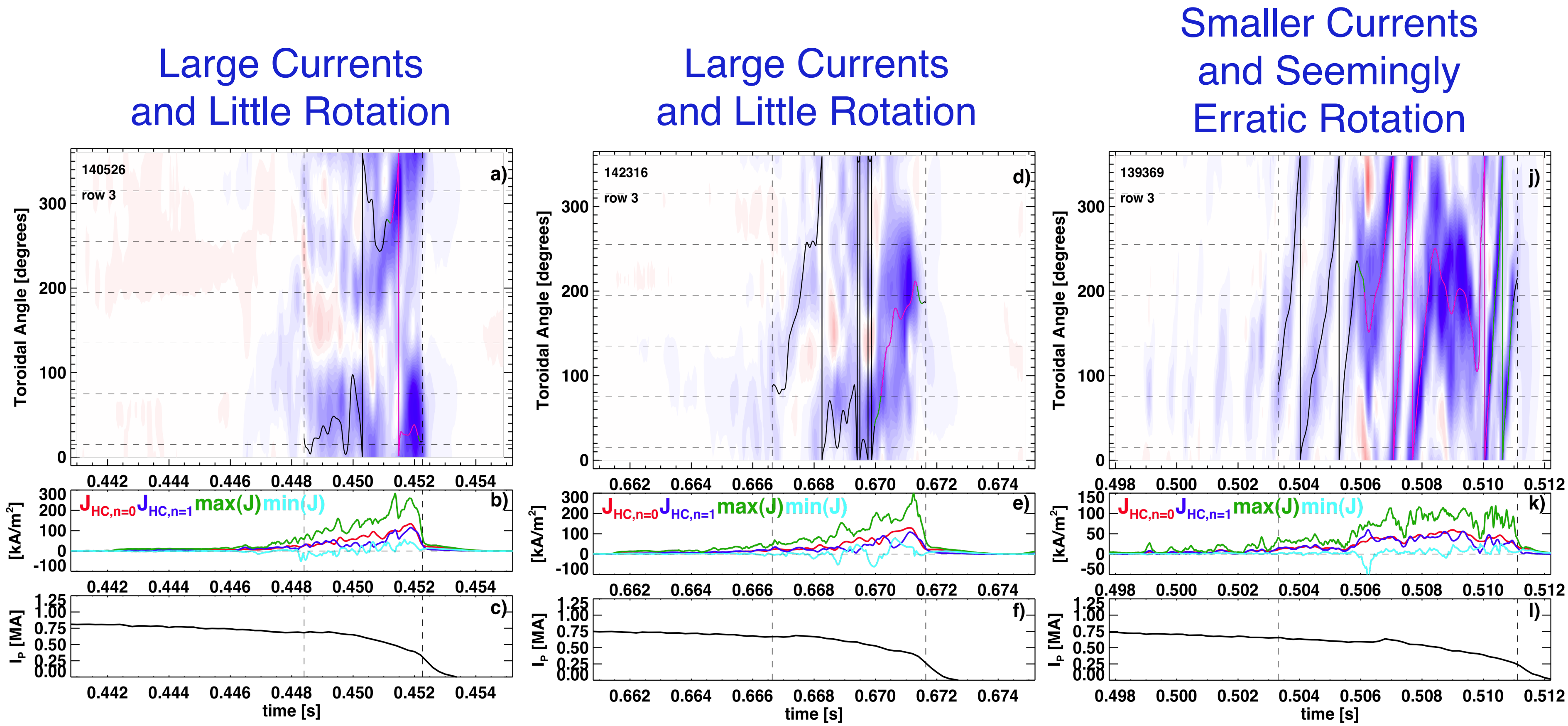
S.P. Gerhardt, et all., Nuclear Fusion **52** 023005 (2013)



Li I Camera Images Confirm Rotation of Structure Four Times

- Neutral lithium light most indicative of surface interactions

Further Examples of Halo Current Rotation Dynamics



Key Observations

Dominant structure is typically a toroidally-rotating lobe.

Rotation is typically in the counter-direction, except for short bursts.

S.P. Gerhardt, et all., Nuclear Fusion **52** 023005 (2013)

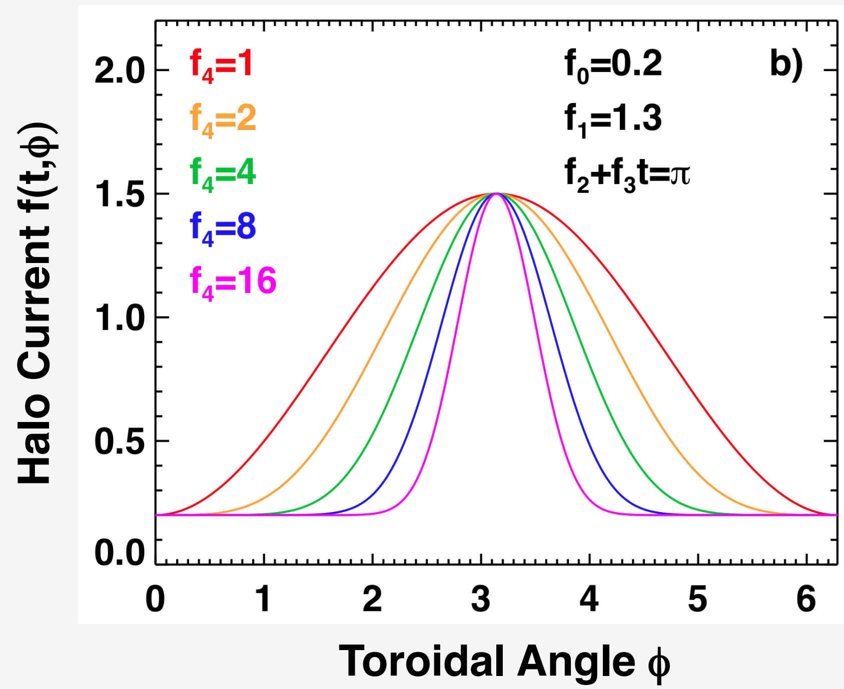
Use a Model Fit Function To Better Resolve the Halo Current Dynamics

- Observed structure is a toroidally localized lobe.
- Apply a fit function with
  - DC offset (f_0)
  - lobe of variable toroidal width (f_4) and amplitude (f_1)
  - Explicit rotation frequency (f_3)
- Divide data into δt~0.1 ms width windows, and fit data from all six tiles during each window.
  - Fitting windows allows the features to rotate over the tiles during periods of fits.

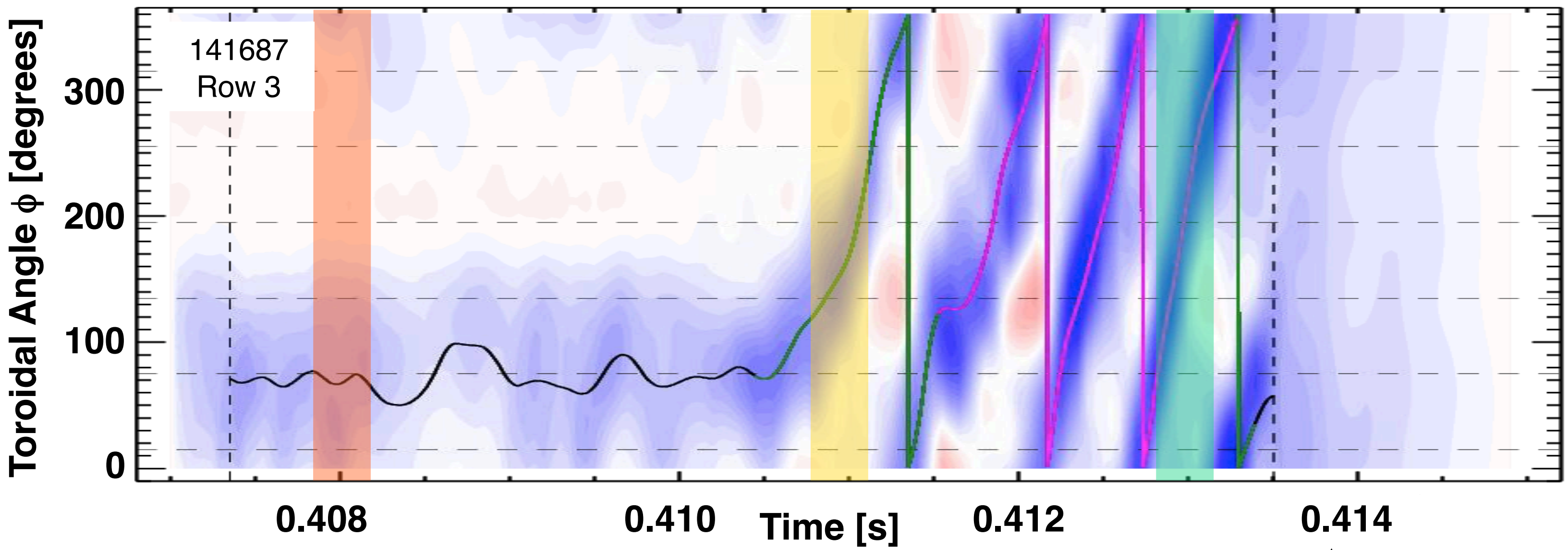
Model Function
"Windowed Cosine Power Fits"

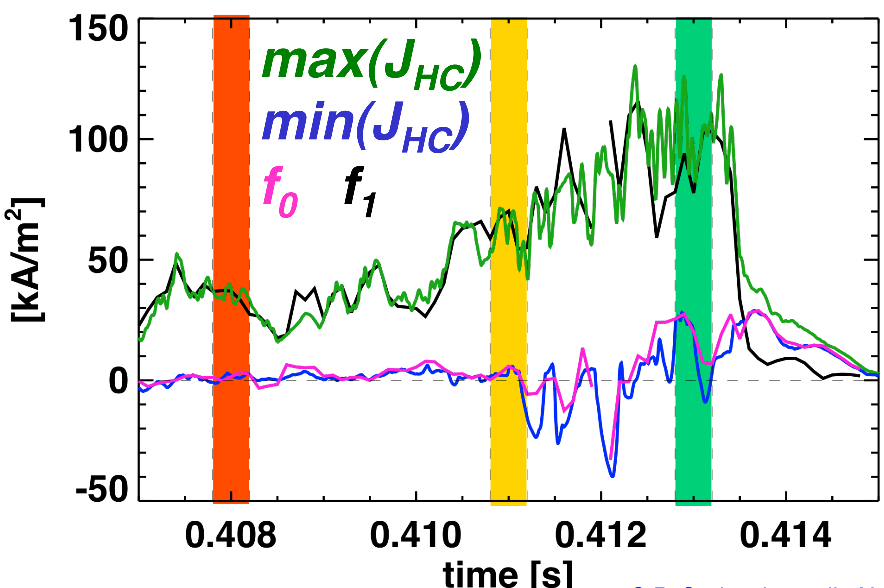
$$f(t,\phi) = f_0 + f_1 \cos^{2f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$

Example Curves

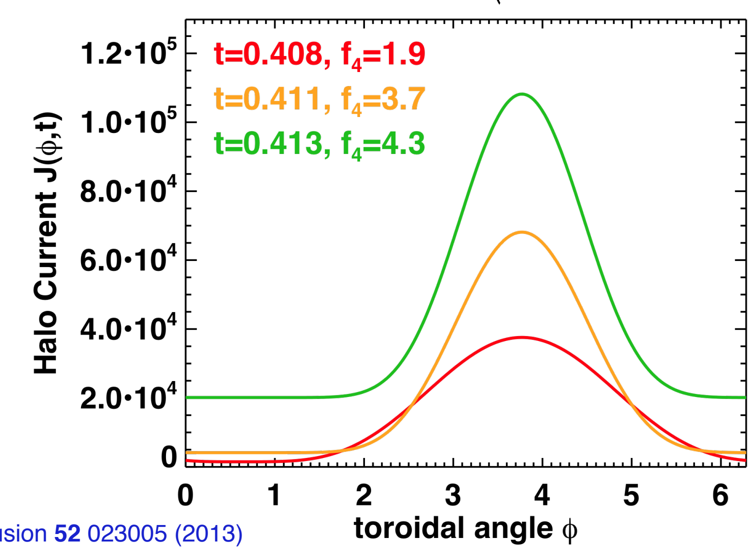


Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current





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



S.P. Gerhardt, et all., Nuclear Fusion **52** 023005 (2013)

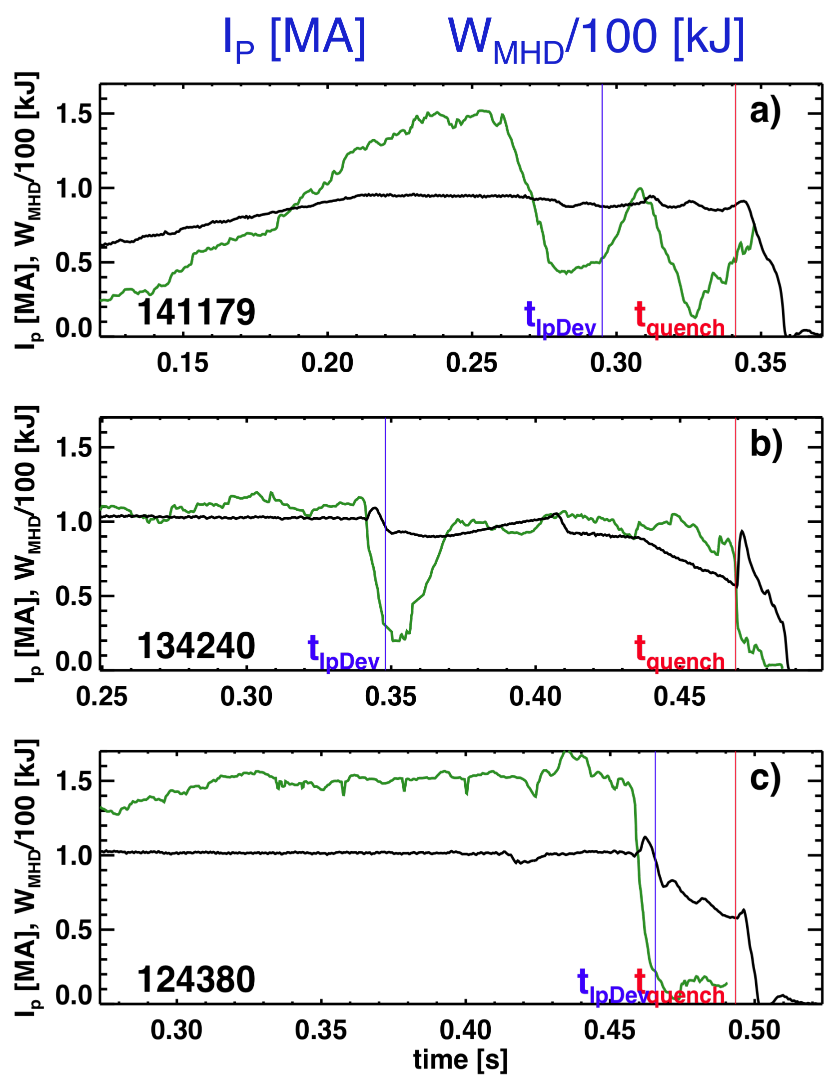
Summary

- Disruptions are bad.
- Disruptions in the high-β ST appear to be detectable.
  - Many individual signals can provide a useful indicator of disruption imminence, but none alone can form the basis for a detection algorithm.
  - Simple combination of diagnostic tests can predict nearly all disruptions.
- Basic structure of the halo current in NSTX is a rotating, toroidally localized lobe.
  - The lobe can make up to 8 total toroidal revolutions, though the rotation can be quite erratic.
  - Variation between shots, and within a single shot.

The End

Detection is Less Effective if Defined With Respect to the Initiation of the Disruption Process

- Disruption process initiated by some locked mode, RWM,…
  - Confinement loss follows.
  - Lots of loop voltage applied by PCS.
  - Position control can fail
  - Thermal quench is delayed by some duration.
  - Rely on that phase for detection.
- Exercise: Recompute warning statistics with respect to the first I_P negative deviation.
  - Use this as a surrogate for the initiating event in the disruption



S.P. Gerhardt, et al., Nuclear Fusion **53**, 043020 (2013)

Detection is Less Effective if Defined With Respect to the Initiation of the Disruption Process

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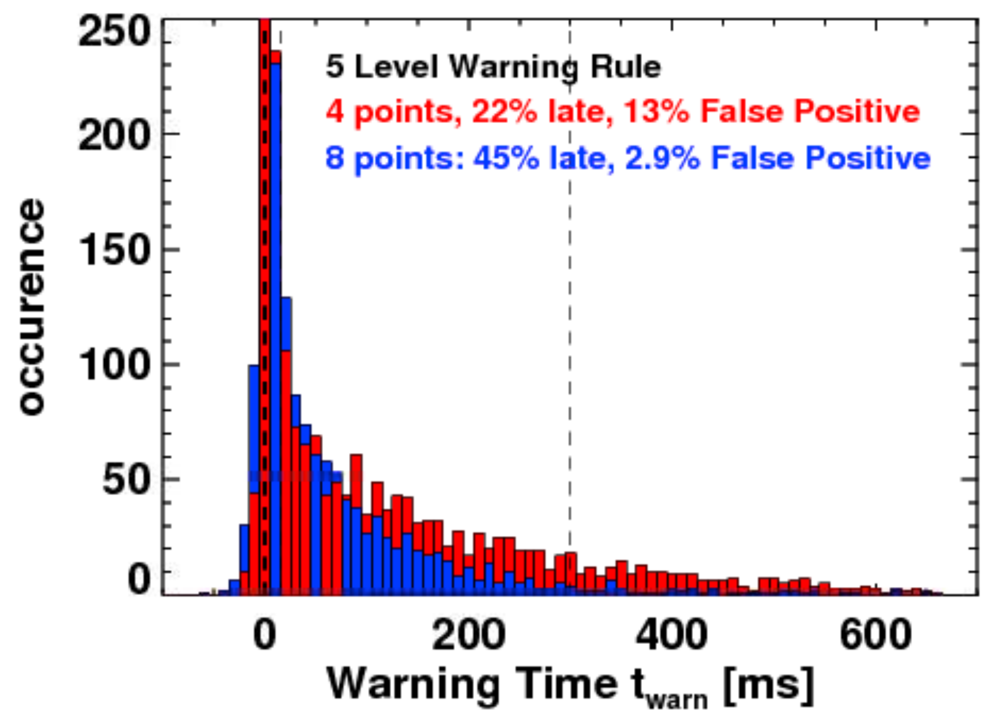
  - Confinement loss follows.
  - Lots of loop voltage applied by PCS.
  - Position control can fail
  - Thermal quench is delayed by some duration.
  - Rely on that phase for detection.
- Exercise: Recompute warning statistics with respect to the first I_P negative deviation.
  - Use this as a surrogate for the initiating event in the disruption process.
- Result: Very poor prediction efficiency.
  - Interesting question: are disruption dynamics different if there is no solenoid to provide "stabilizing" loop voltage.

Warning at APT=4 Points
<22% late warning, ~13% false positive
Sum: 35%

Warning at APT=8 Points
~45% late warning, ~3% false positive
Sum: 48%



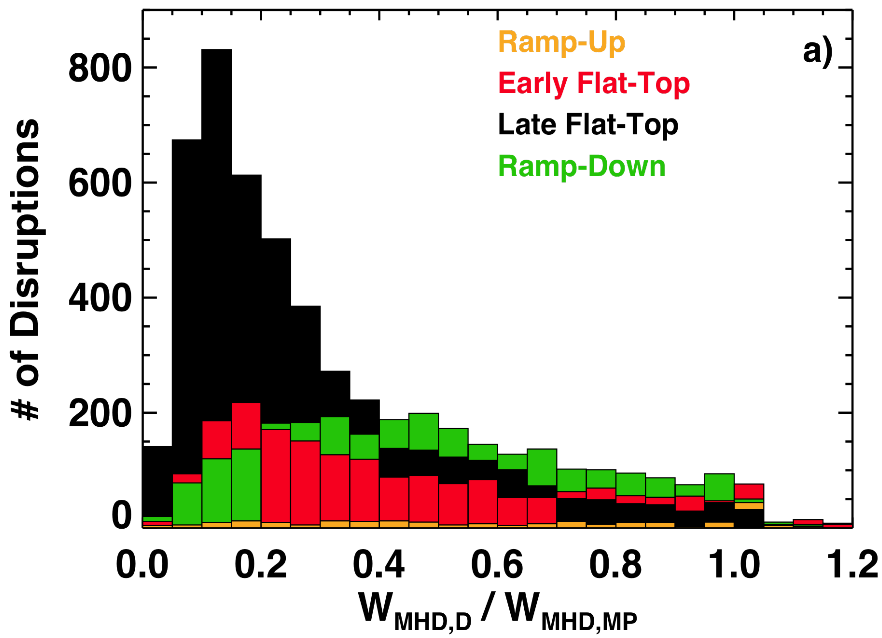
S.P. Gerhardt, et al., Nuclear Fusion **53**, 063021 (2013)

Understanding the Pre-Disruption Phase is Key: Energy Loss

Period after modes have locked, H->L transition, but before the thermal quench

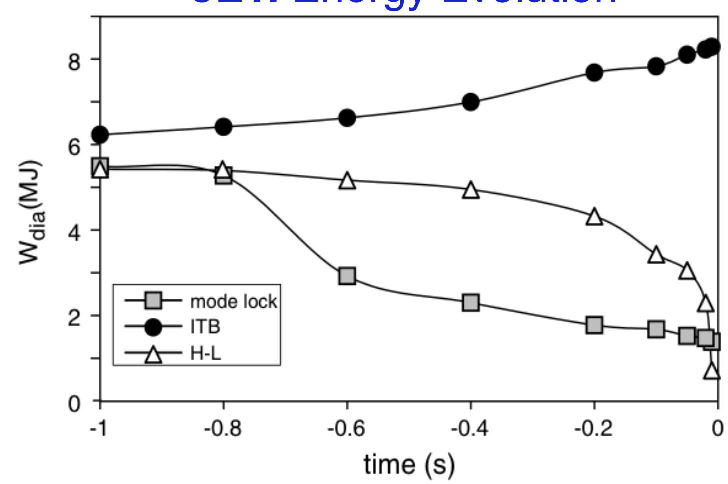
This phase determines the energy at the thermal quench

NSTX Data: Large Fractional Stored Energy Drops Are Typical, Especially in the Later Flat-Top

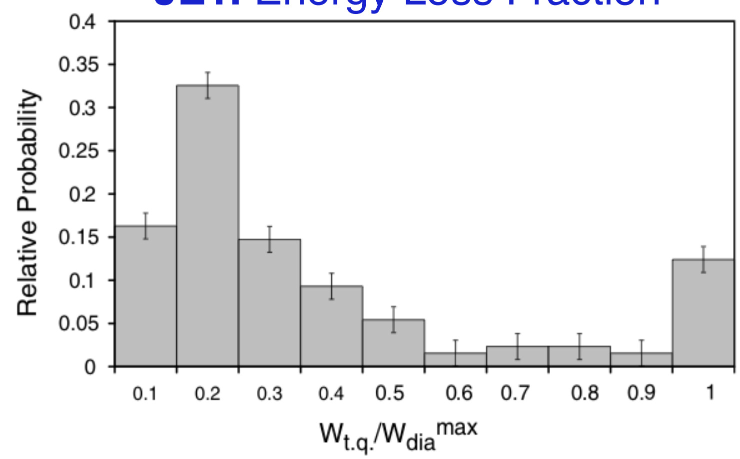


S.P. Gerhardt, et al., Nuclear Fusion **53**, 043020 (2013)

JET: Energy Evolution



JET: Energy Loss Fraction

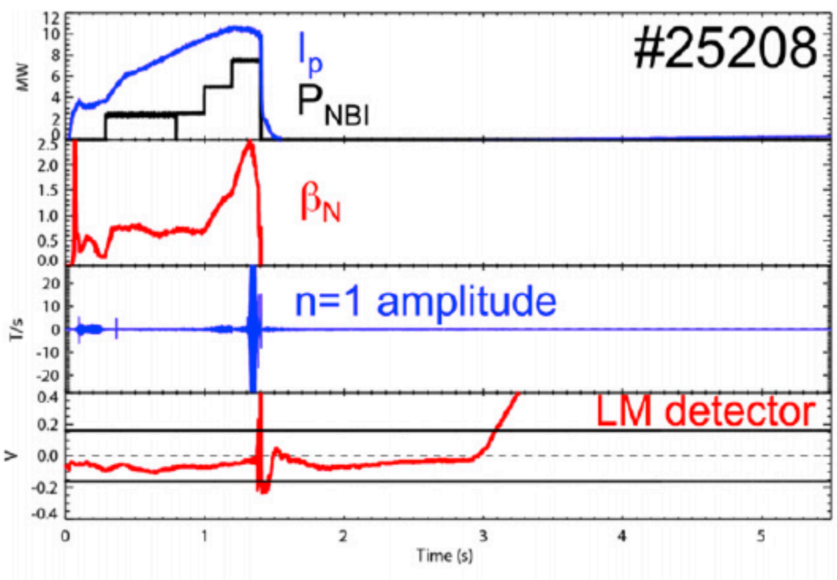


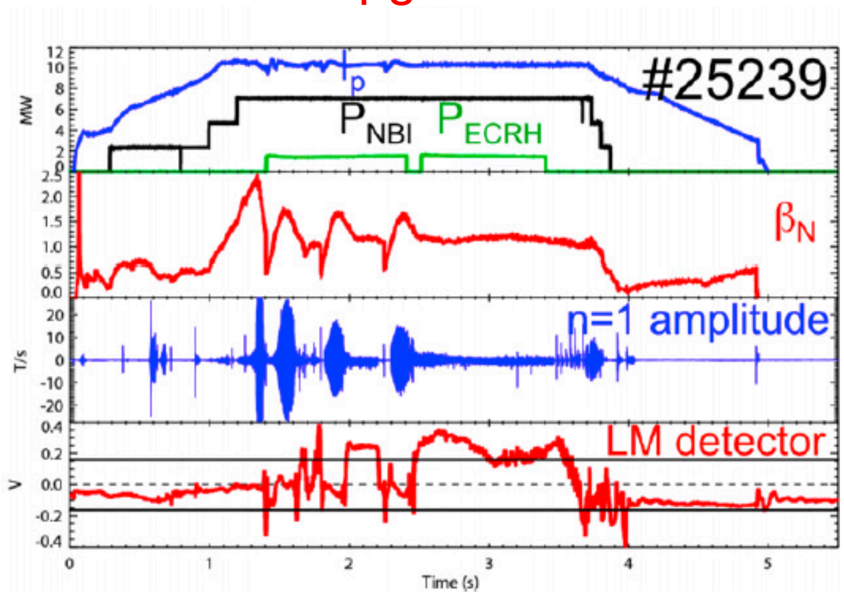
V. Riccardo, et al., Nuclear Fusion **45**, 1427 (2005)

Understanding the Pre-Disruption Phase is Key Actuation (I)

Period after modes have locked, H->L transition, but before the thermal quench

This phase is the last opportunity for “actuation”:
ECH applied to high-β 2/1 island in ASDEX-Upgrade





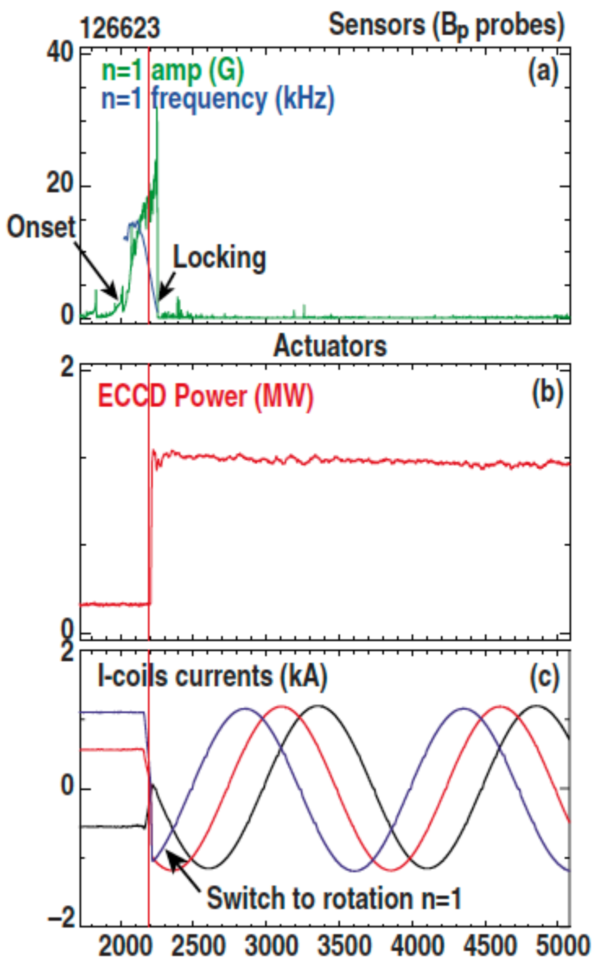
Roughly similar results for density-limit disruptions in ASDEX-Upgrade and FTU.
However, subtle differences in details of where the ECH was deposited for maximum effect.

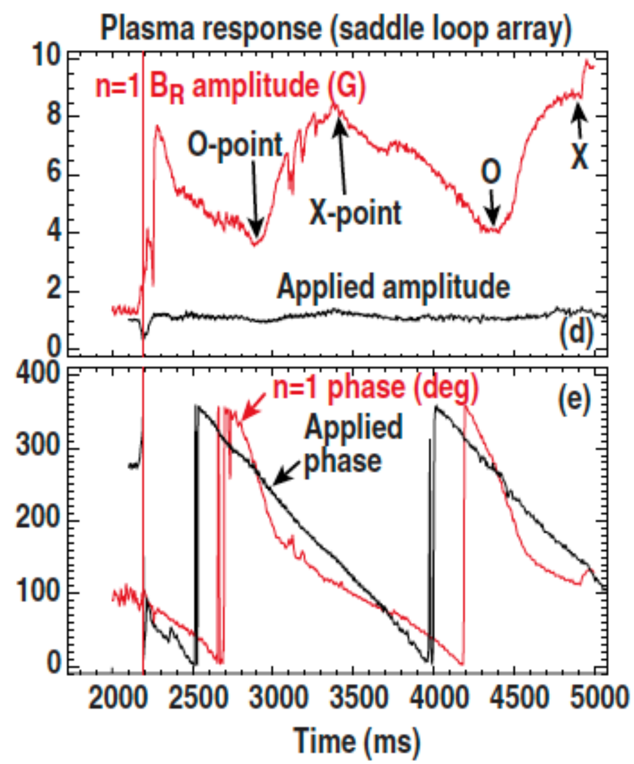
B. Esposito, et al., Nuclear Fusion **51**, 083051 (2011)

Understanding the Pre-Disruption Phase is Key Actuation (II)

Period after modes have locked, H->L transition, but before the thermal quench

This phase is the last opportunity for “actuation”:
ECH + RMP applied to high-β 2/1 island in DIII-D





F. Volpe, et al., Phys. Plasmas **16**, 102502 (2009)

Understanding the Pre-Disruption Phase is Key Detection

Period after modes have locked, H->L transition, but before the thermal quench

Typical Signals in Recent ANN & Similar Disruption Studies (often normalized, sometimes with time derivatives):

Z_P [4,5,8]
I_P [1,2,4,5,6,8]
q_{95} [1,3,4,5,6,7]
Mode Lock [1,3,4,5,6,7,8]
P_{rad} [1,4,5,8,9] or $P_{rad,frac}$ [3]
P_{net} or P_{in} [1,4,5,6,7,8]
n_e [1,2,4,5,6,8] or f_{GW} [3,7]
L_i [1,3,4,5,6,7]
W_{MHD} or W_{dia} [1,2,4,6,8]
β_P [1,4,5,6,7] or β_T [2] or β_N [2,3]
H [3]
$\langle T_e \rangle$ [2]
S_N [2]
S_N/W_{dia} [2]
S_P (shape) [2], δ [2]

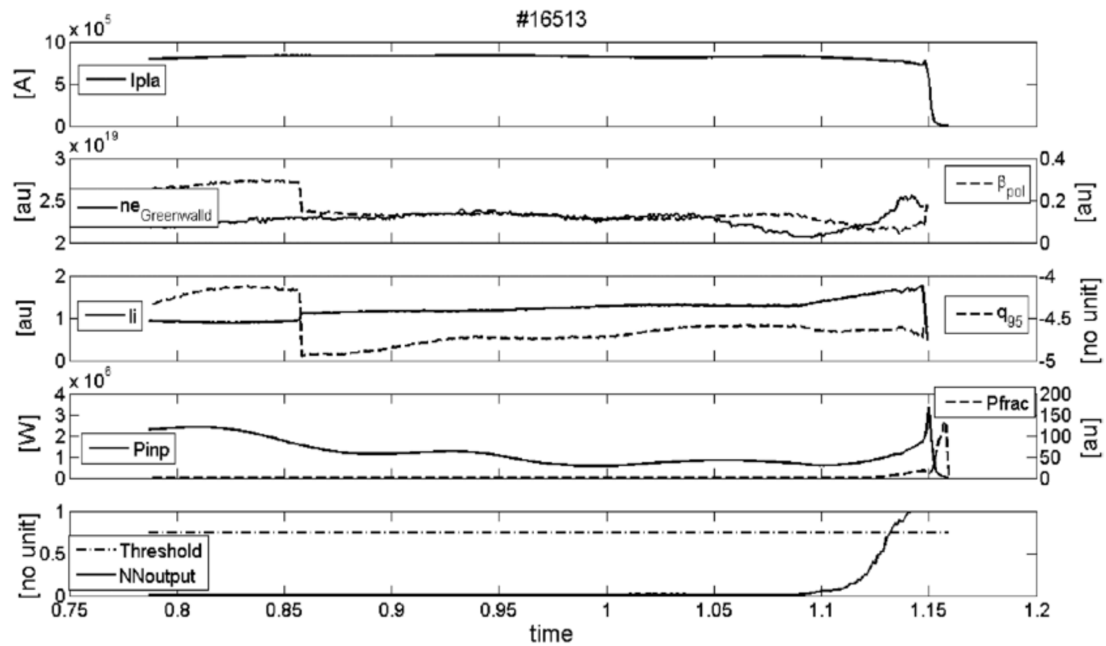


Figure 2. Some plasma parameters, and the corresponding alarm function for the pulse #16513.

From Ref. 7

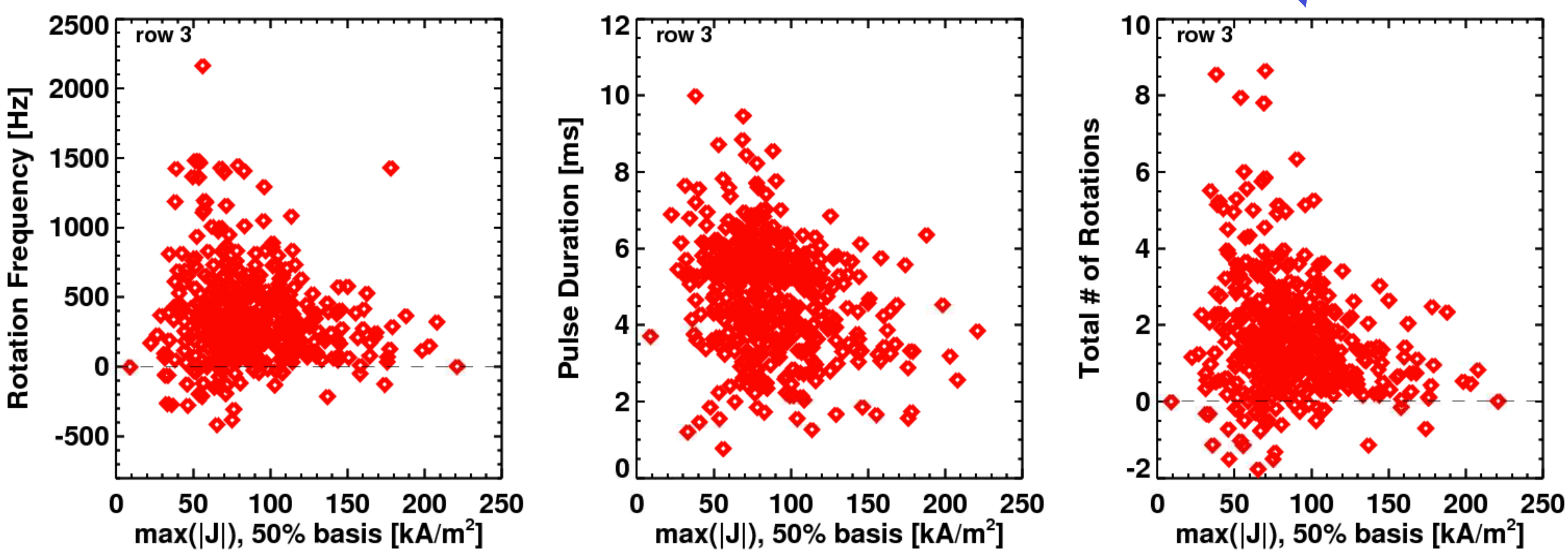
[1] B. Cannas, et al, Nuclear Fusion **44**, 68 (2004)
[2] R. Yoshino, Nuclear Fusion **45**, 1232 (2005).
[3] C.G. Windsor, et al, Nuclear Fusion **45**, 337 (2005)
[4] B. Cannas, et al. Nuclear Fusion **46**, 699 (2006)
[5] B. Cannas, et al, Nuclear Fusion **47**, 1559 (2007)
[6] A. Murari, et al., Nuclear Fusion **49**, 055028 (2009)
[7] B. Cannas, et al, Nuclear Fusion **50**, 075004 (2010)
[8] A. Murari, et al., Nuclear Fusion **53**, 033006 (2013)

Understanding the Pre-Disruption Phase is Key: Theory Aspects

- What physics determines the duration of this phase?
  - Time for growth of multiple islands? How big before the TQ?
  - Ratio of volume in isolated islands vs. good surfaces vs. stochastic regions? What sets the transport/confinement?
- What actuators are best used during this phase?
  - How far into this phase will any given actuator be effective?
  - For ECH, which rational surface or mode to target?
    - Can it be the sub-dominant mode in a coupled mode situation?
    - How to align the locked modes with the ECH (RMP as in DIII-D)? Refraction?
- How does the physics and actuator response change with n_e & q_{95}?
- Are there scenarios prone to not having this phase?
  - Yes: ITB/high-β disruption…any others? Does this disqualify them?
- Will the very large stored energy losses in an ITER or DEMO truncate this phase due to impurity generation effects?
- What about the ST?
  - Unlikely to have a solenoid, will not have ECH.
    - EBW is hard enough during the stationary phase…
  - Available actuators are the NBs, outer PF induction, maybe 3D fields.

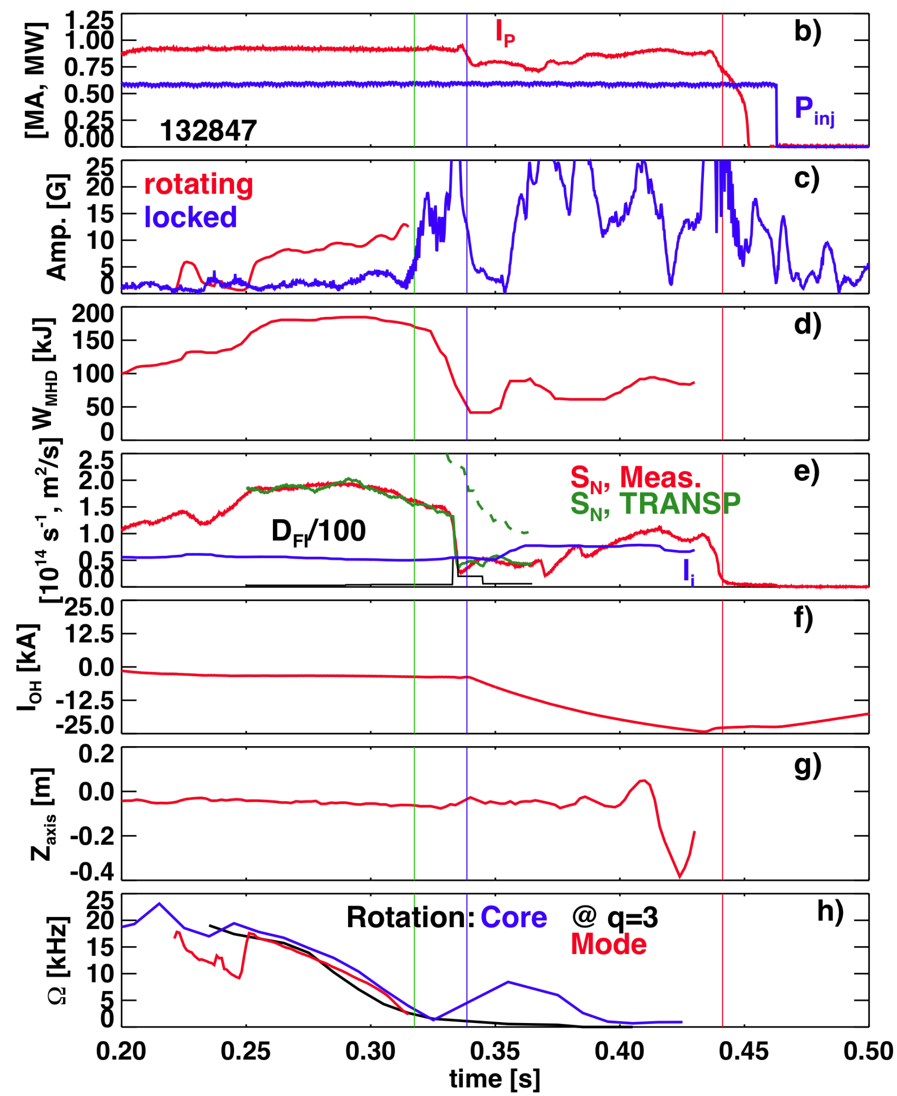
of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- Compute the rotation dynamics during time when n=1 halo current is >25% of its maximum.
- Compare to the time average of the maximum halo current magnitude.
  - Rotation frequency usually lower at high amplitude.
  - Pulse duration usually lower at high amplitude
  - *Total # of rotations drops at high amplitude*



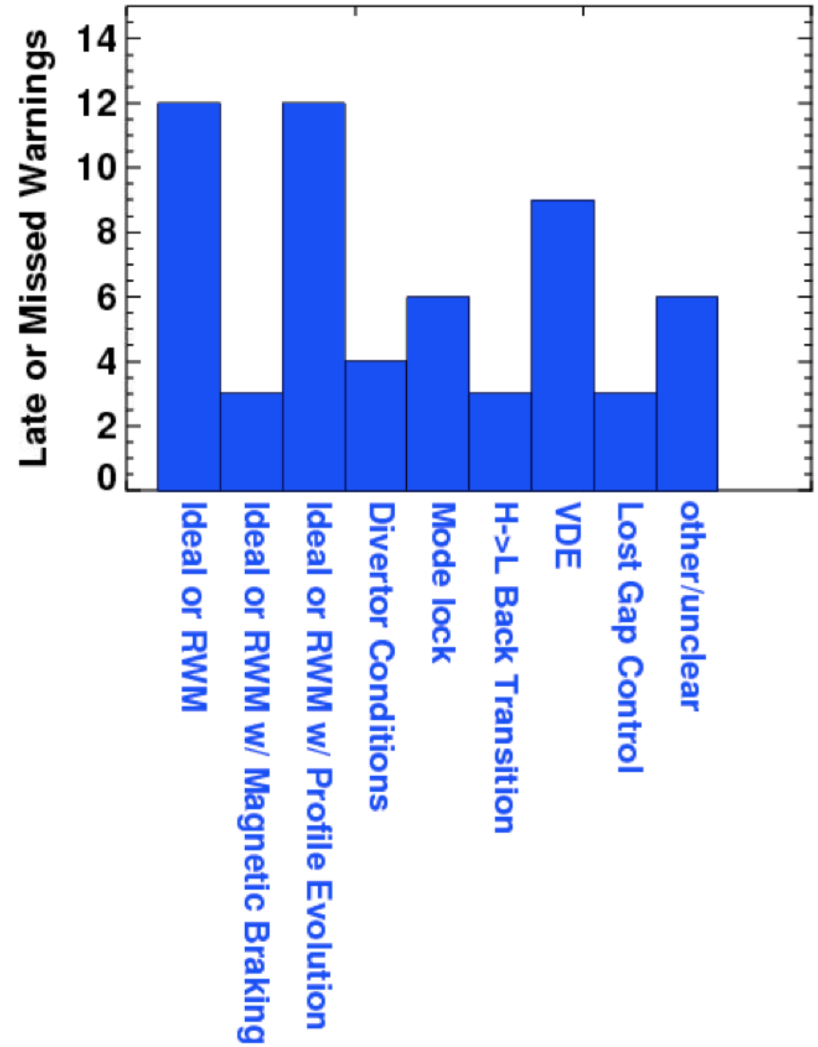
Neutron Emission Collapses Are Due to MHD-Driven Loss, Not Rapid Slowing Down

- This example: mode lock just after flat-top
- Strong collapse in S_N following the locked mode growth
- 50 m^2/s spike of anomalous diffusion required to achieve the observed neutron emission drop.



RWMs and Ideal Modes Dominate Late/Missed Warnings

- ~1/2 of the RWM disruptions are proceeded by gradual rise in pressure peaking (~100 ms timescale) or magnetic braking.
  - Other half are fast disruptions, hard to detect in advance.
- Disruptions due to mode lock, VDEs, & gap control problems could be eliminated, at the expense of higher false positive rates.



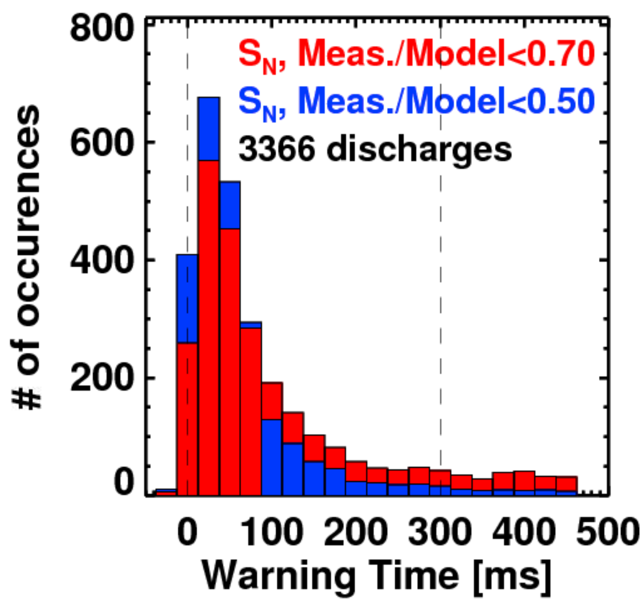
Examined Many Threshold-Based Disruption Indicators Leading or Trailing The Start of the Disruption Process

- Instantaneous Stability
  - Vertical motion indicators. (Trailing)
  - n=1 perturbed fields. (Trailing)
  - Low-frequency, large amplitude rotating MHD modes. (Trailing)
- MHD Equilibrium
  - $F_P=p_0/\langle p \rangle$, l_i (Trailing)
  - q_{95}, q^* (Leading)
    - (β_N alone has no predictive value).
  - Boundary-wall gaps (Leading)
- Transport indicators for comparisons to simple models
  - Neutron rate (Trailing)
  - Stored energy (Trailing)
  - Loop voltage (Trailing)
- Other
  - Line-average density transients (Trailing)
  - Rotation and rotation shear (Leading)
  - Radiated power ratio (Leading)
  - Deviations between the current and the I_P request (Trailing)

Comparison of Diagnostic Signal to Simple Models Can Provide Useful Indicators

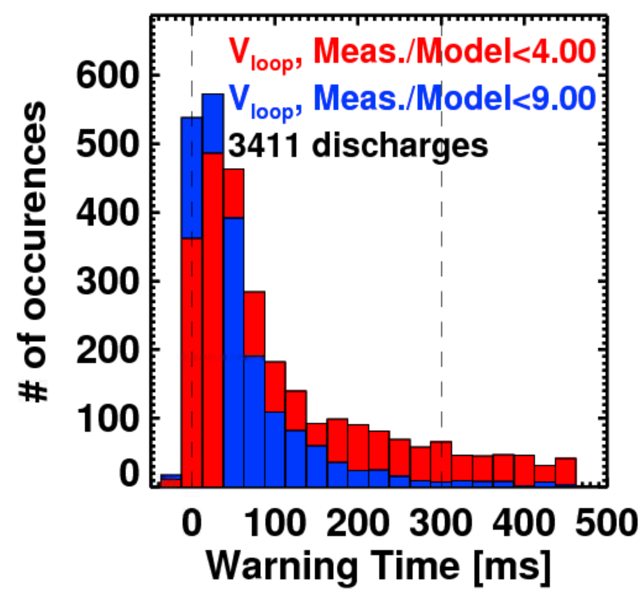
- Often a significant drop in neutron emission proceeding a disruption.
- Estimate the neutron emission from a simple slowing down model.
    - T_e, Z_{eff}, n_e are inputs.

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.

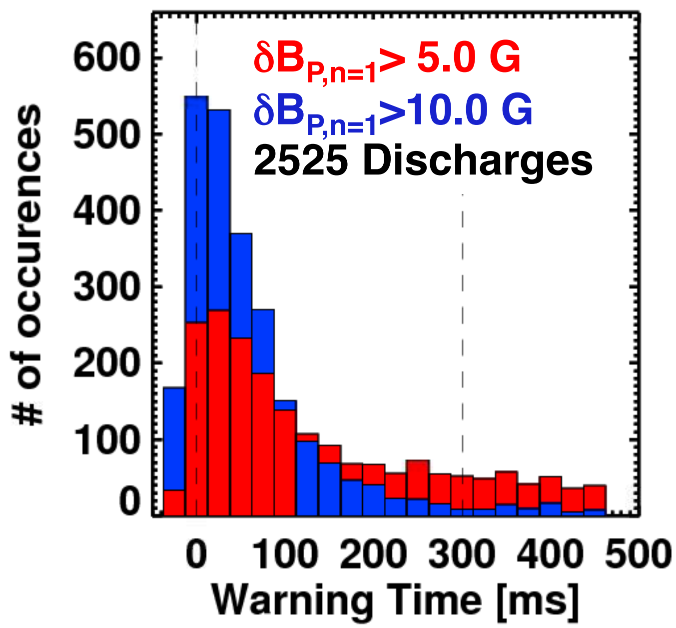
threshold	# Late Warning	% False Positive	# No Trigger
4	2	18	11
9	5	2	37



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

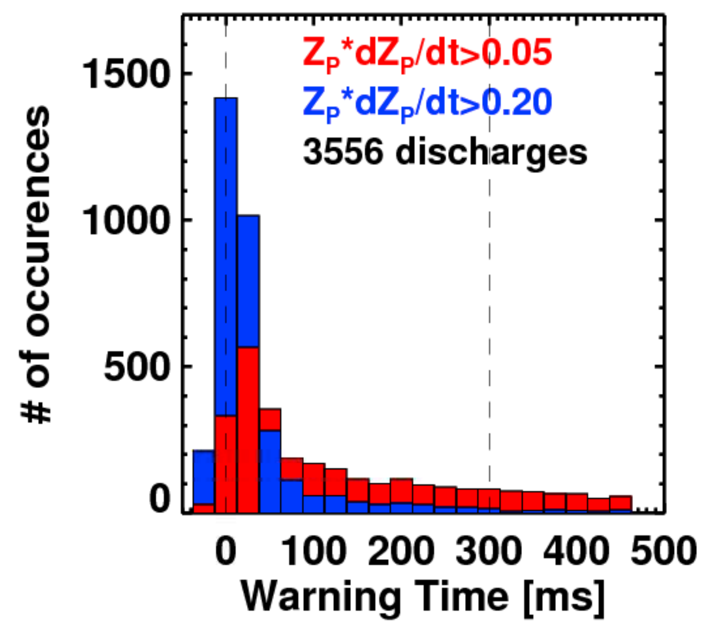
- n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes

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



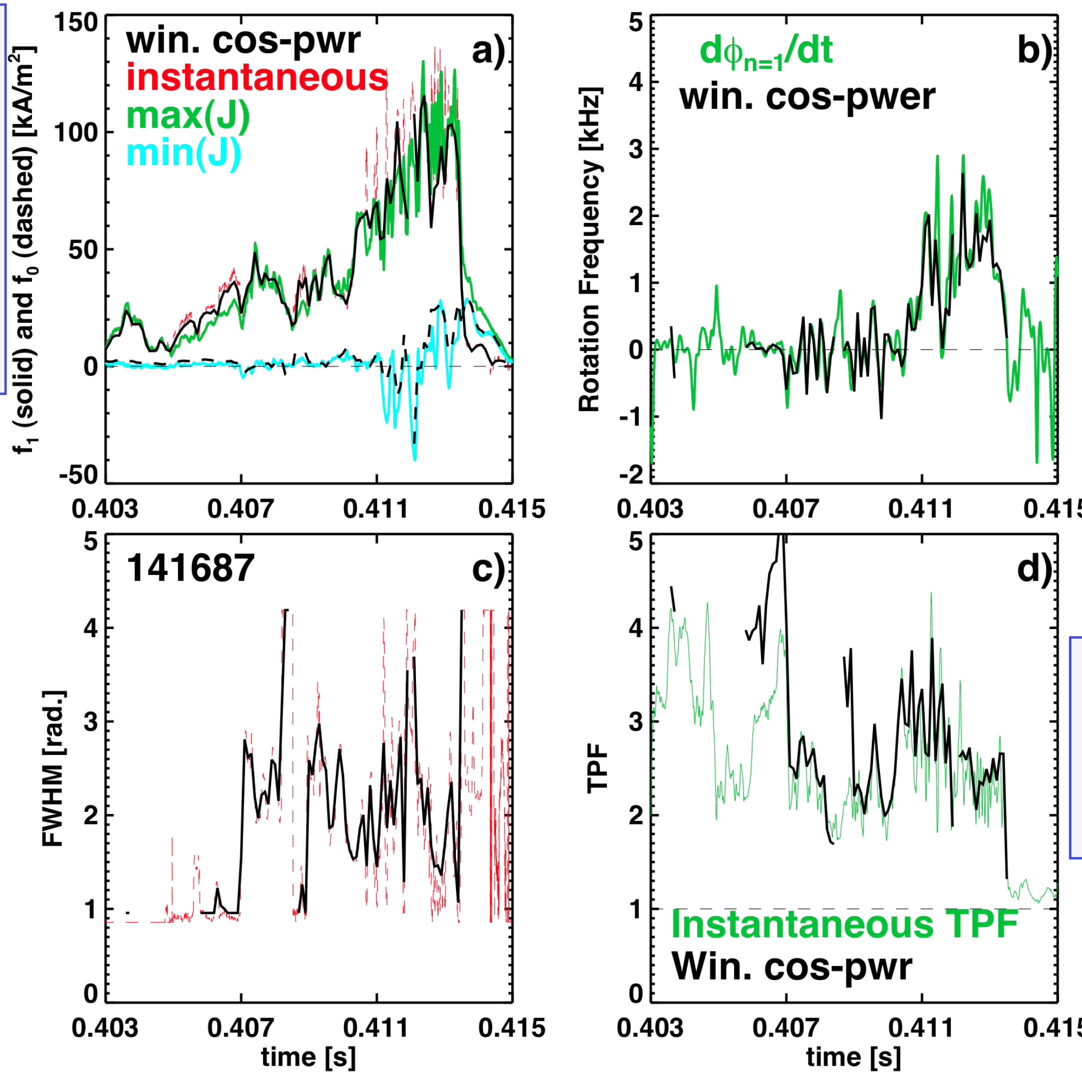
- Estimate $Z_P \cdot {}^{dZ_P}\!/_{dt}$ from two toroidal loops on outboard side of plasma, above and below midplane.
  - Z_P from fluxes
  - dZ_P/dt from voltages

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



Fits Reveal Dynamics of the Halo Currents

Halo Current Amplitudes
Instantaneous cosine power fits (f_1)
Windowed fits (f_1: solid, f_0:dashed)
max(J_{HC})
min(J_{HC})



Rotation Frequency
From differentiating phase of simple n=1 fits:

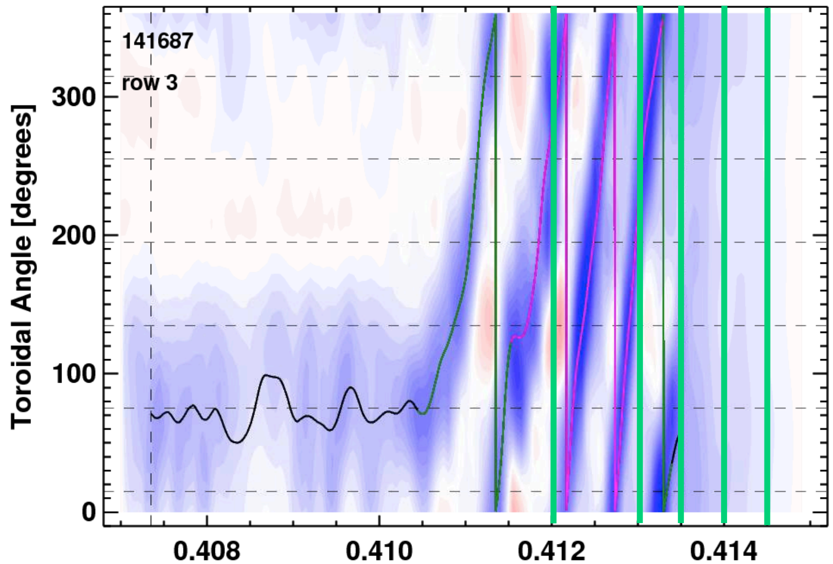
$$I_{HC}(\phi) = f_{n=0} + f_{n=1}\cos(\phi - \phi_{n=1})$$

From "windowed cosine power" fits

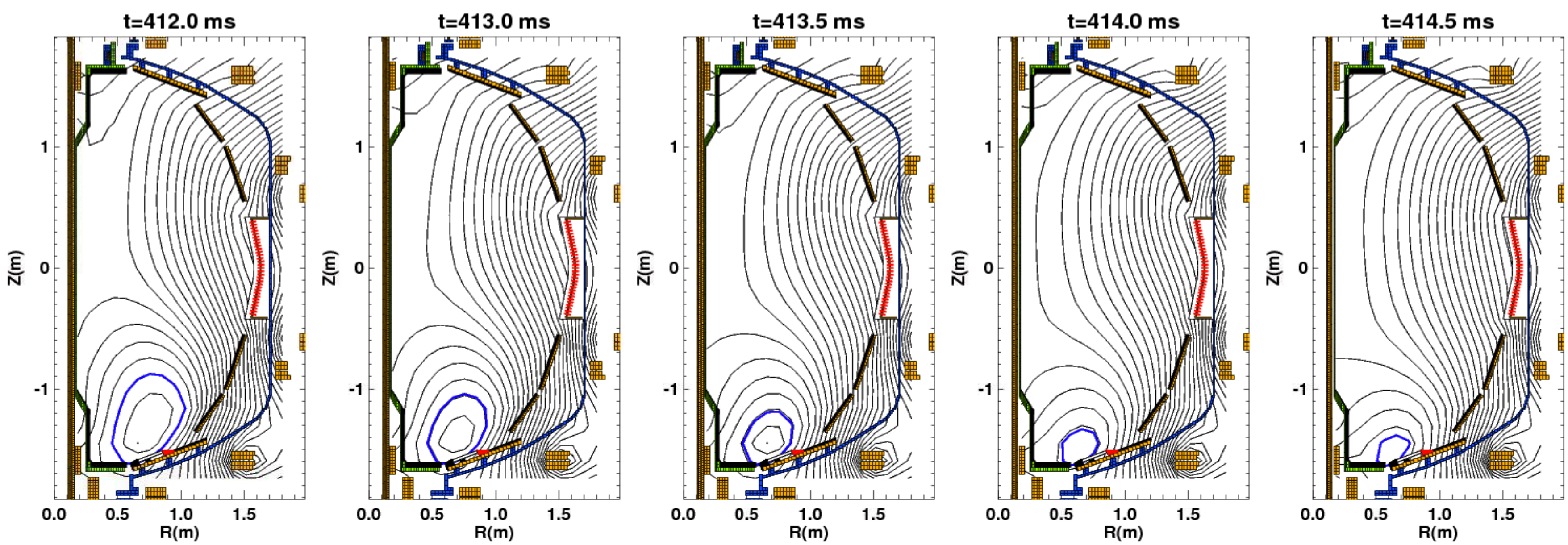
Full Width at Half Maximum:
Instantaneous cosine power fits
Windowed fits

Peaking Factor
From raw data
From "windowed cosine power" fits

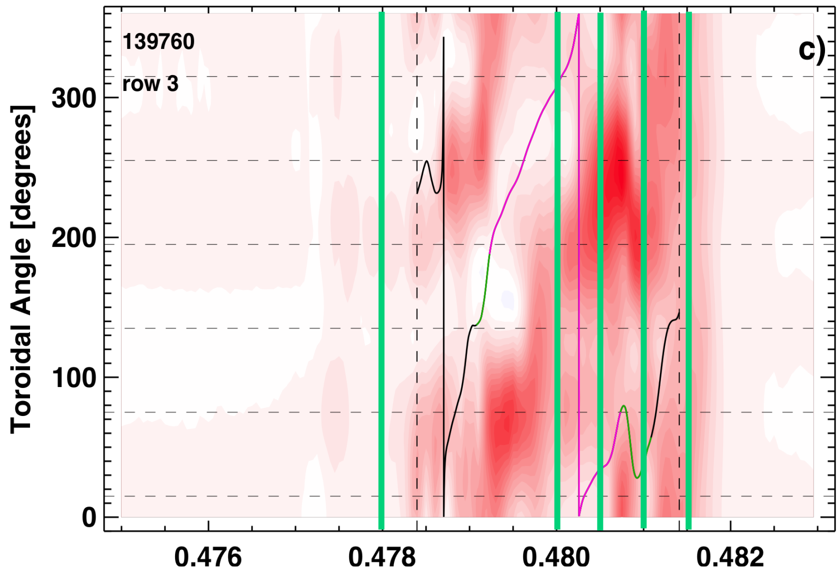
Halo Currents Become Symmeterized In the Final Phase of the Disruption: Example on OBD



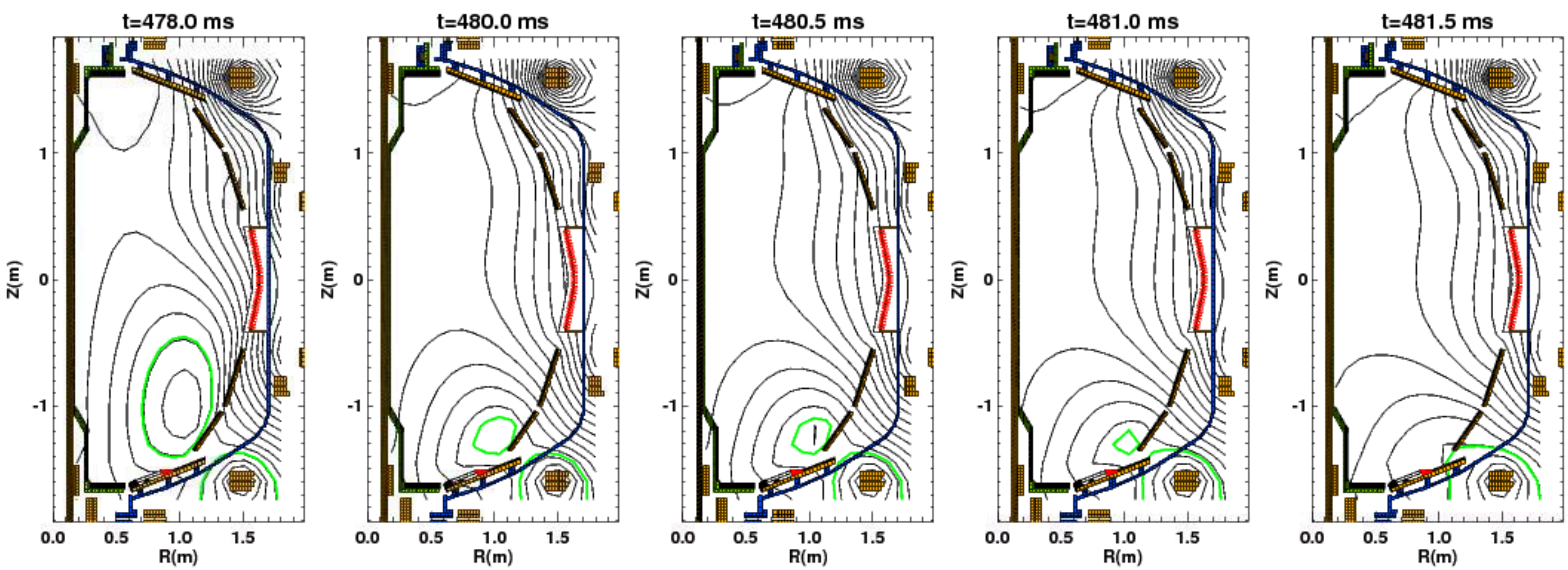
- Halo current contours are toroidally symmetric starting at ~0.4135 s
- Utilize a regularized toroidal filament model for the reconstruction.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late axisymmetry corresponds to near or complete loss of closed surface geometry



Halo Currents Become Symmeterized In the Final Phase of the Disruption: Example on Secondary Passive Plate

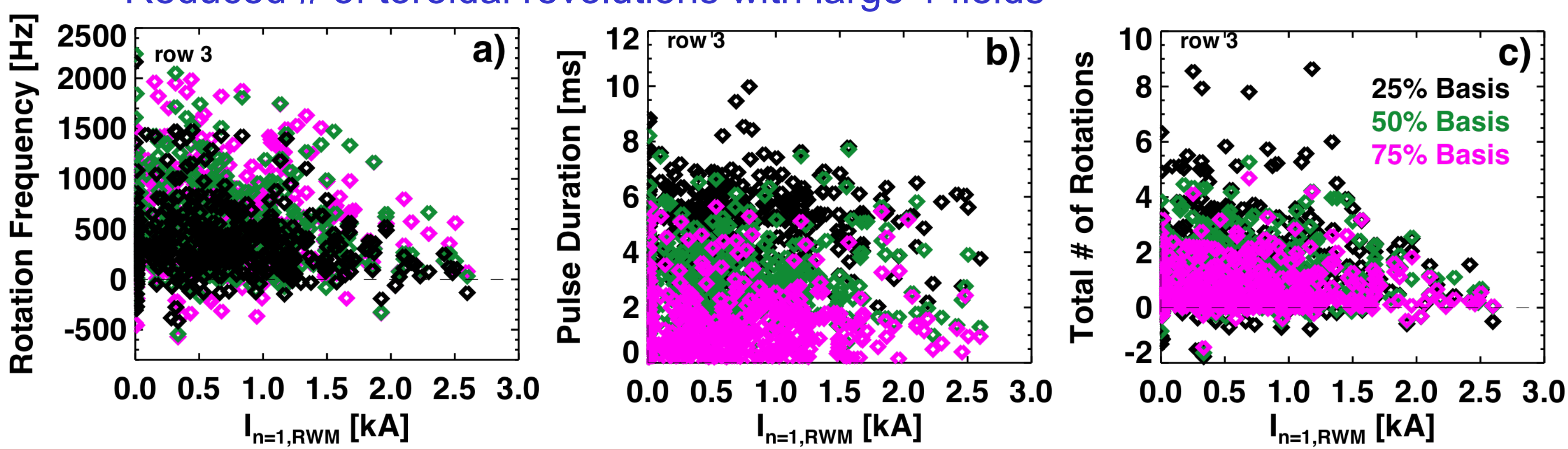


- Halo current contours are toroidally symmetric starting at ~0.481 s
- Utilize a regularized toroidal filament model for the reconstruction.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late axisymmetry corresponds to near or complete loss of closed surface geometry



Statistical Analysis Shows Less Rotation in Cases With Strong n=1 Fields

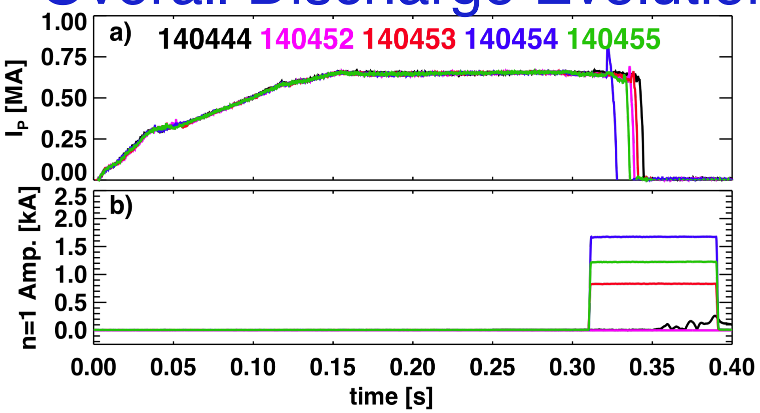
- Large n=1 fields are often applied by the RWM control system during a disruption. Due to:
  - Actual 3D distortions of the plasma
  - Toroidal & non-axisymmetric eddy currents leading to incorrectly identified "modes".
    - On-line doesn't have v_{loop} sensor compensationsas in the off-line analysis.
- Result of database study:
  - Rotation frequency tends to be smaller when the n=1 field is higher.
  - No effect on the pulse duration
  - Reduced # of toroidal revolutions with large 1 fields



n=1 Fields Did Not Modify HC Rotation During Deliberate VDEs

- Deliberate VDE are prone to ***very large halo currents, few toroidal revolutions***.
  - Shots with no n=1 fields (140444 and 140452) shows zero and a single rotation.
- Shots with large n=1 applied field showed between 0 and 1.5 asymmetry revolutions.
  - 140453: 0.8 kA n=1, ~1.25 revolutions.
  - 140454: 1.6 kA n=1, *~1.5 revolutions, with an apparent locked mode!*
  - 140455: 1.2 kA n=1, ~1.5 revolutions.

Overall Discharge Evolution



Dynamics of the Disrupting Phase