Halo Currents, Disruption Detection, and a Few Comments on the Pre-Disruption Phase

S.P. Gerhardt

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PPPL Disruption Theory and Modeling Workshop
PPPL
7/17/2013

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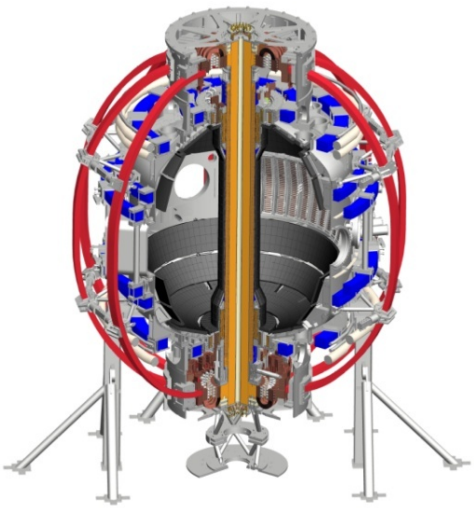

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Outline

- NSTX Halo Current Results
  - NSTX instrumentation and typical time evolution.
  - Time scales and peaking factors.
  - Some data on HC rotation dynamics.
- NSTX Disruption Predictor
  - Algorithm description.
  - Results and extrapolation.

If I have time

- Comments on the importance of the “pre-disruption” phase.

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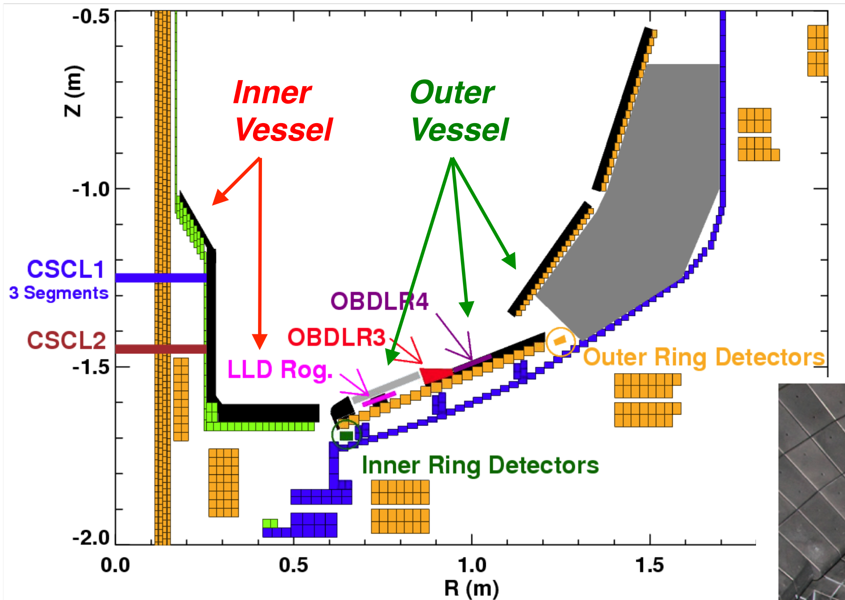
- NSTX Halo Current Results

- NSTX Disruption Predictor

If I have time

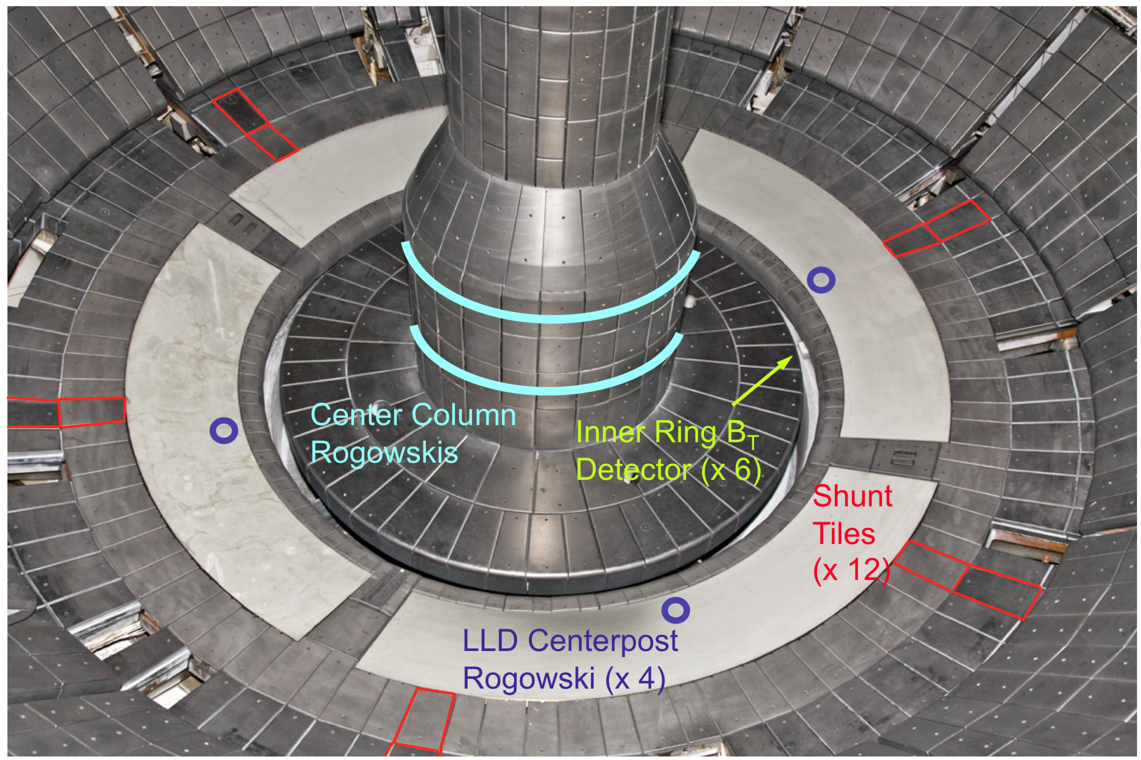
- Comments on the importance of the "pre-disruption" phase.

Quick Review of NSTX Halo Current Diagnostics



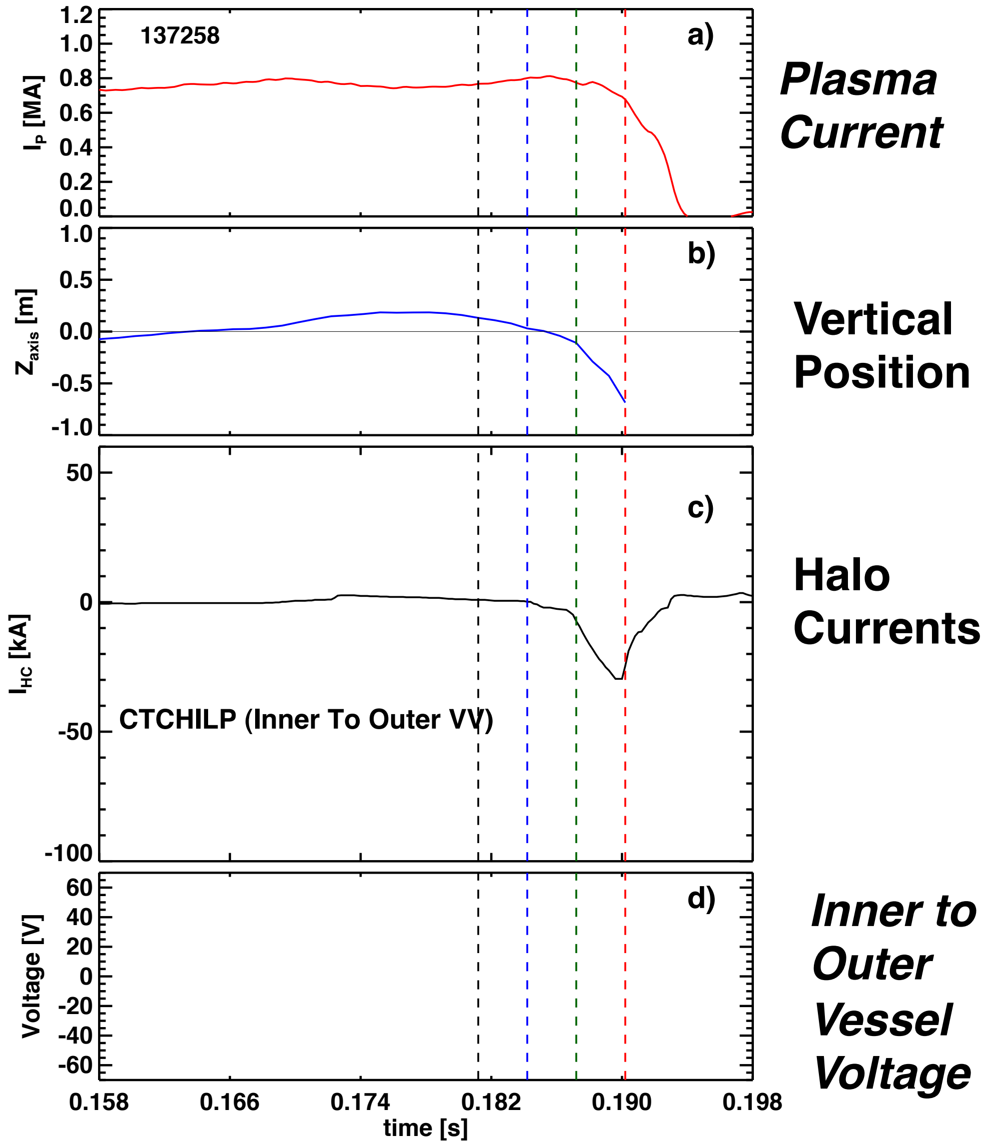
Different Detector Techniques:

- Partial and full Rogowskis on the CS
- Toroidal field sensors on the vessel wall
- Small rogowskis on LLD grounds
- Resistive shunts under tiles.

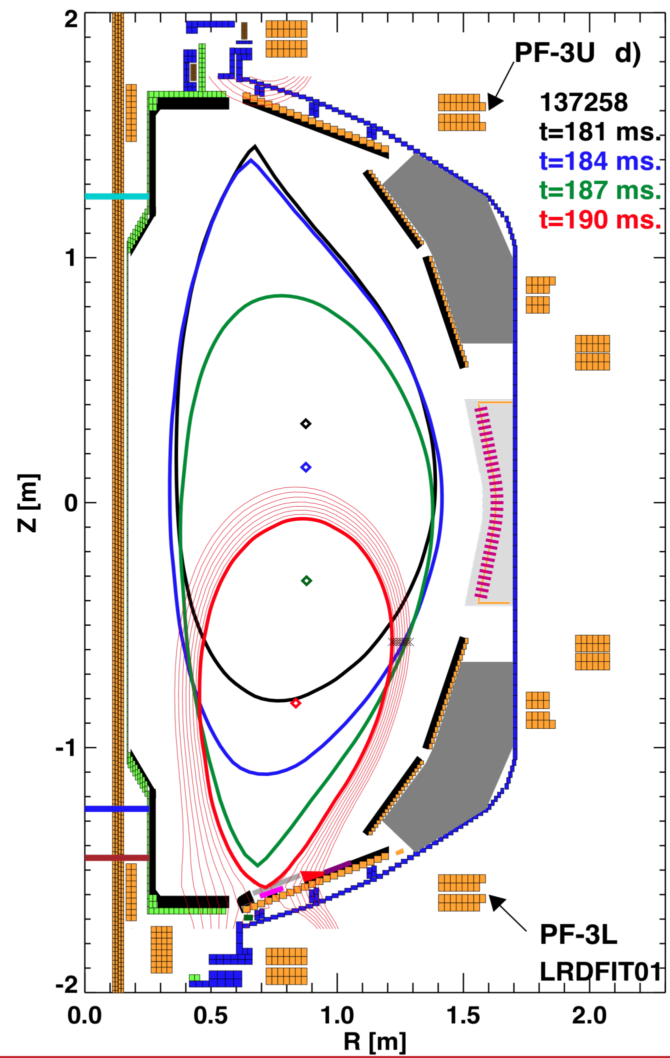


- NSTX has electrically isolated inner and outer vessels
- Center stack and horizontal inner target are electrically isolated from outer divertor and outer vessel.
- Connected by a long run of copper.

Example n=0 Current Dynamics for Downward VDE Landing on Outboard Divertor



Magnetics Constrained Grad-Shafranov Reconstruction for Times Proceeding Large Halo Currents



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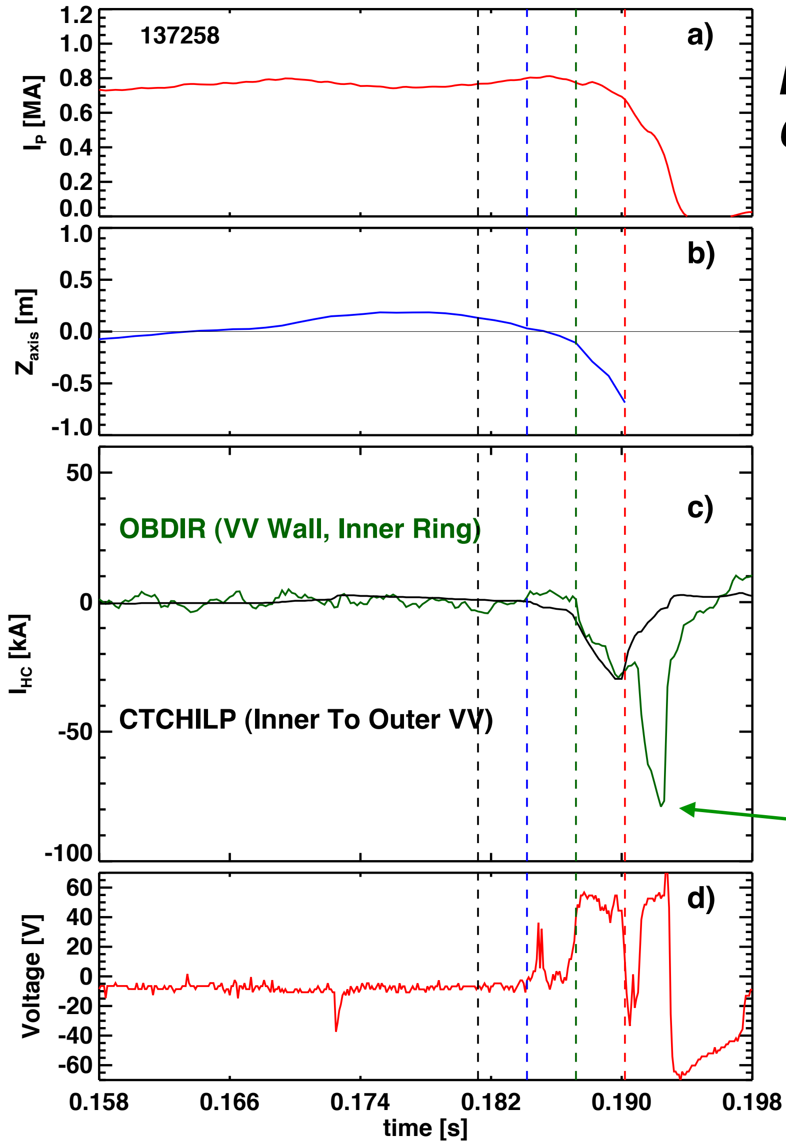

Plasma Current

Vertical Position

Halo Currents

Up to 90 kA flowing in vessel wall.

Inner to Outer Vessel Voltage

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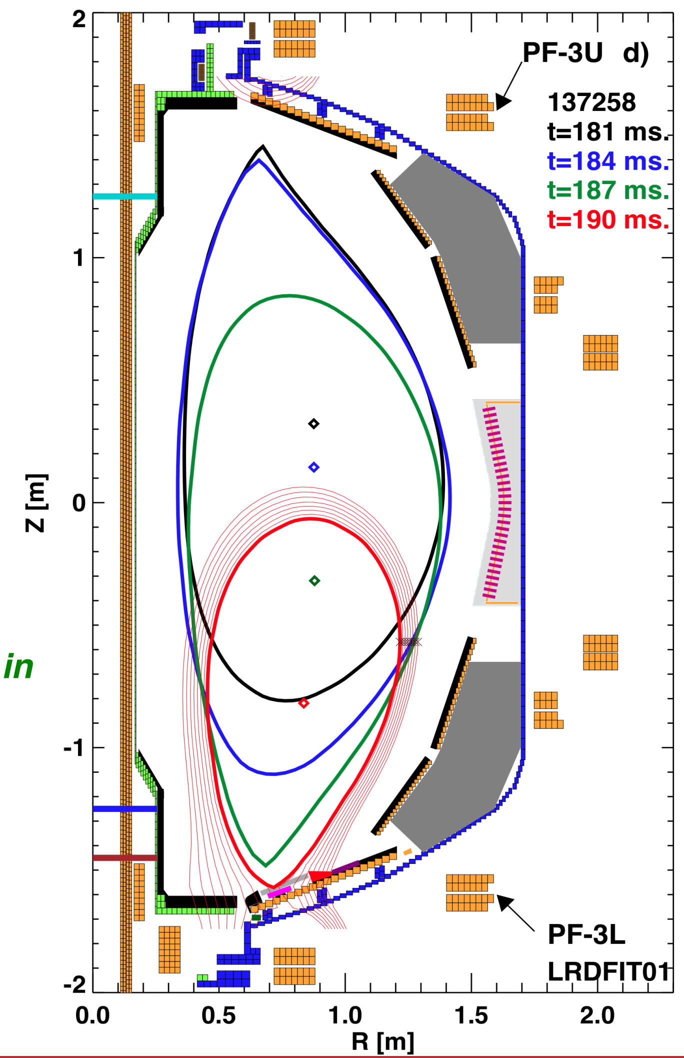

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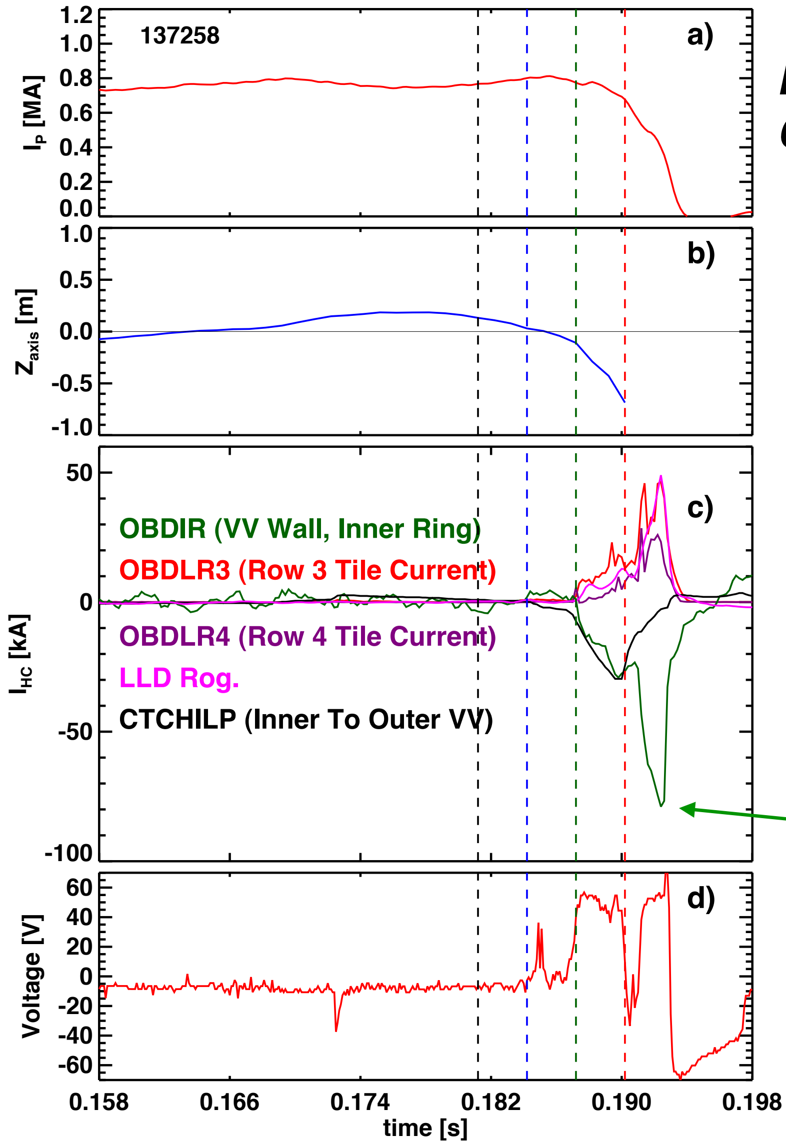

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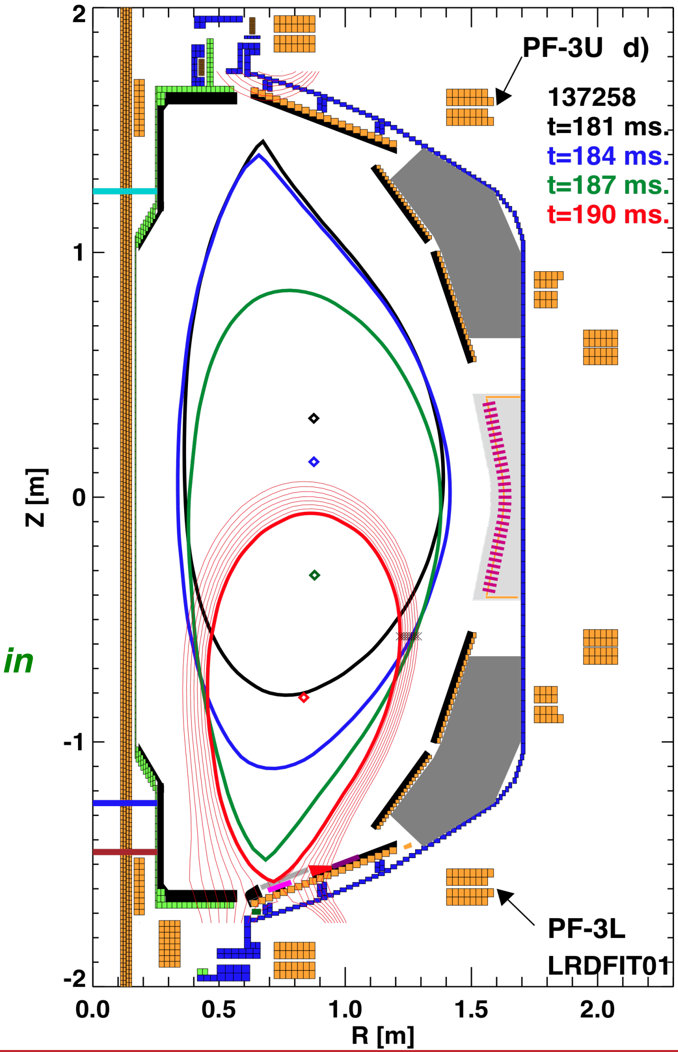

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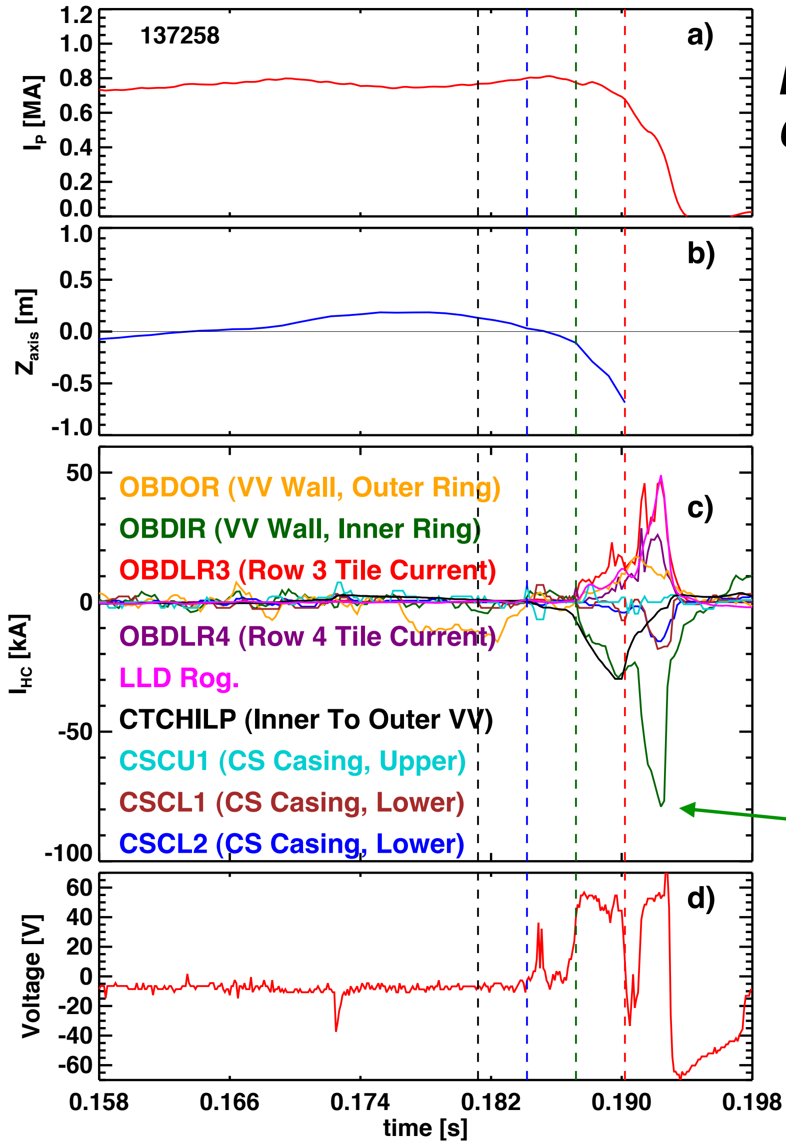

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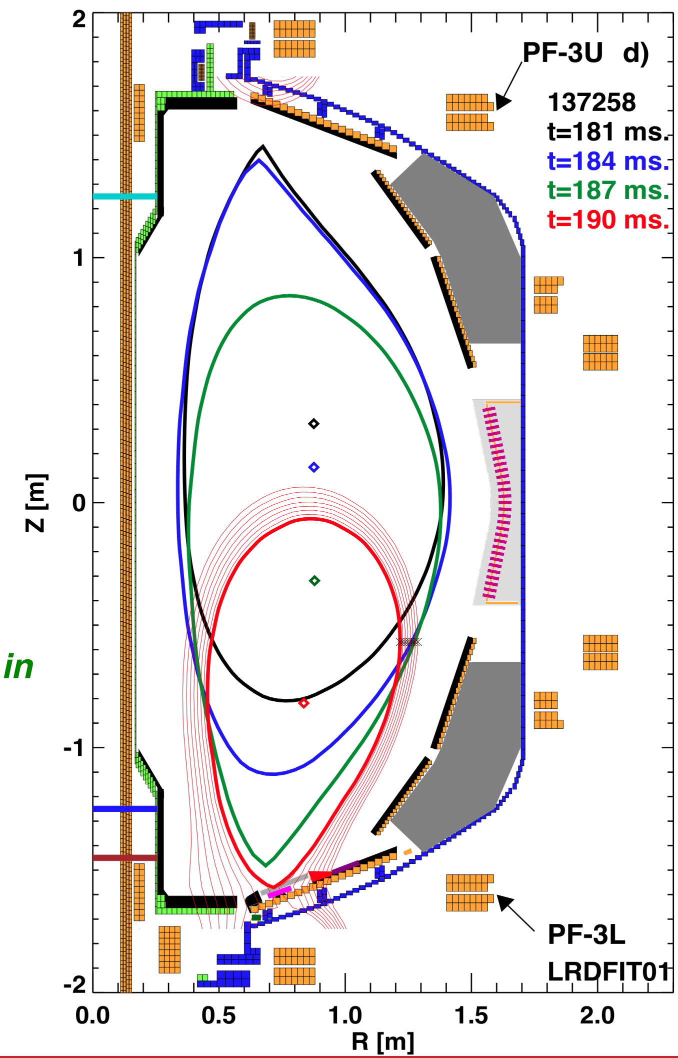
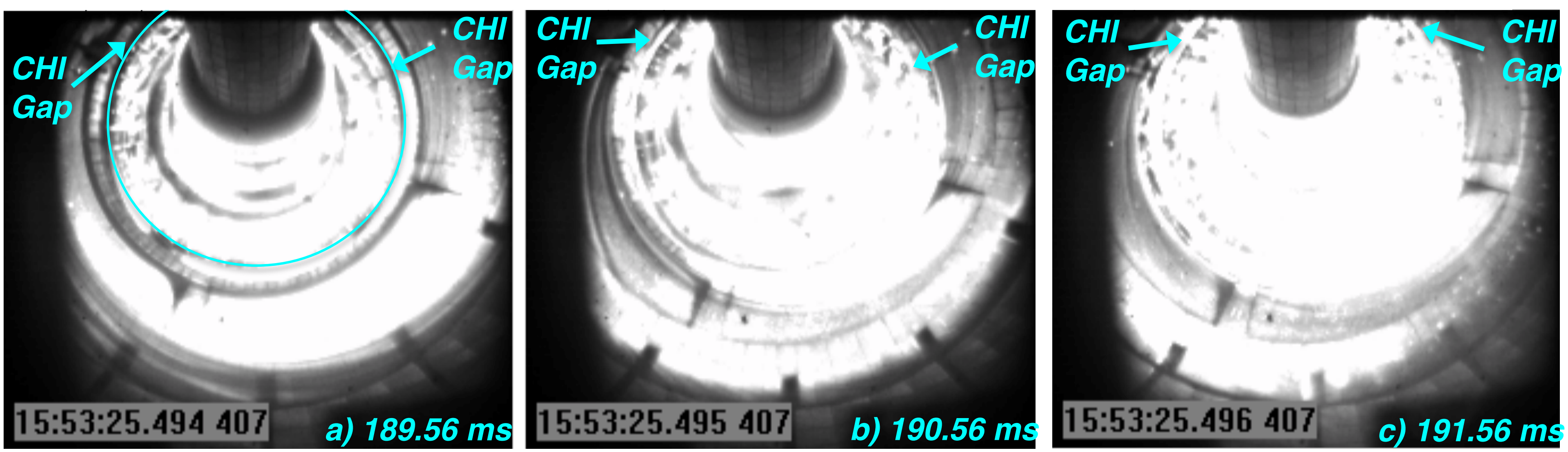
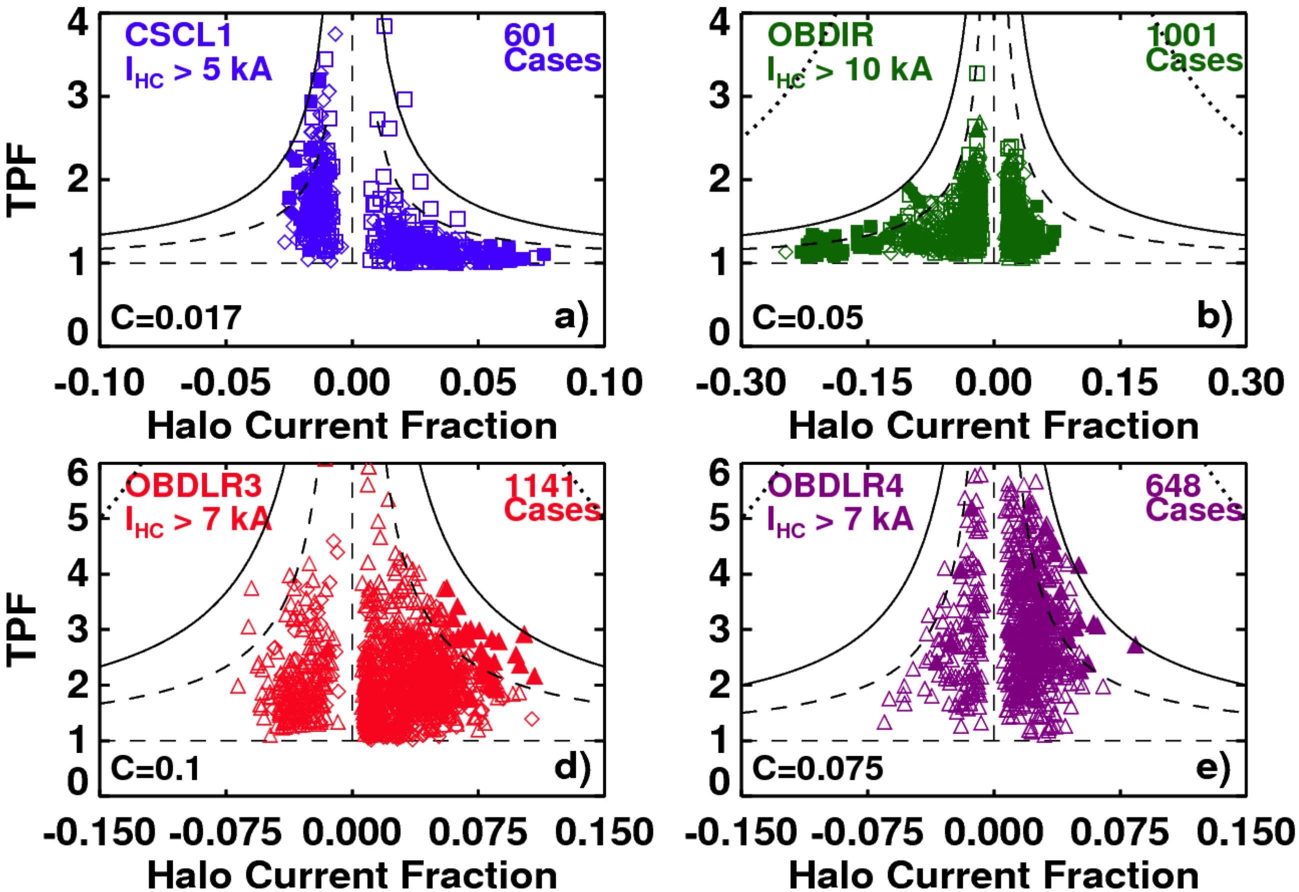


Current Increase on Previous Slide Corresponds to "Arcing" Across the CHI Gap

- Increase in vessel current corresponds to plasma forming in gap:
  - t=189.56 ms: gap is still dark
  - t=190.56 ms: gap begins to show light
  - t=191.56 ms: gap is completely full of plasma
- Once arc forms, there is a large drop in the currents in bus work connecting inner and outer vessels.
  - But large increase in current magnitude.
- Theory implication:
  - conducting paths may not be well known in advance.
  - Insulating structures may not insulate.



Your Measurement of Peaking Factor Depends on How Where You Measure the Halo Currents



3 Top Frames
HCF vs TPF in the wall.

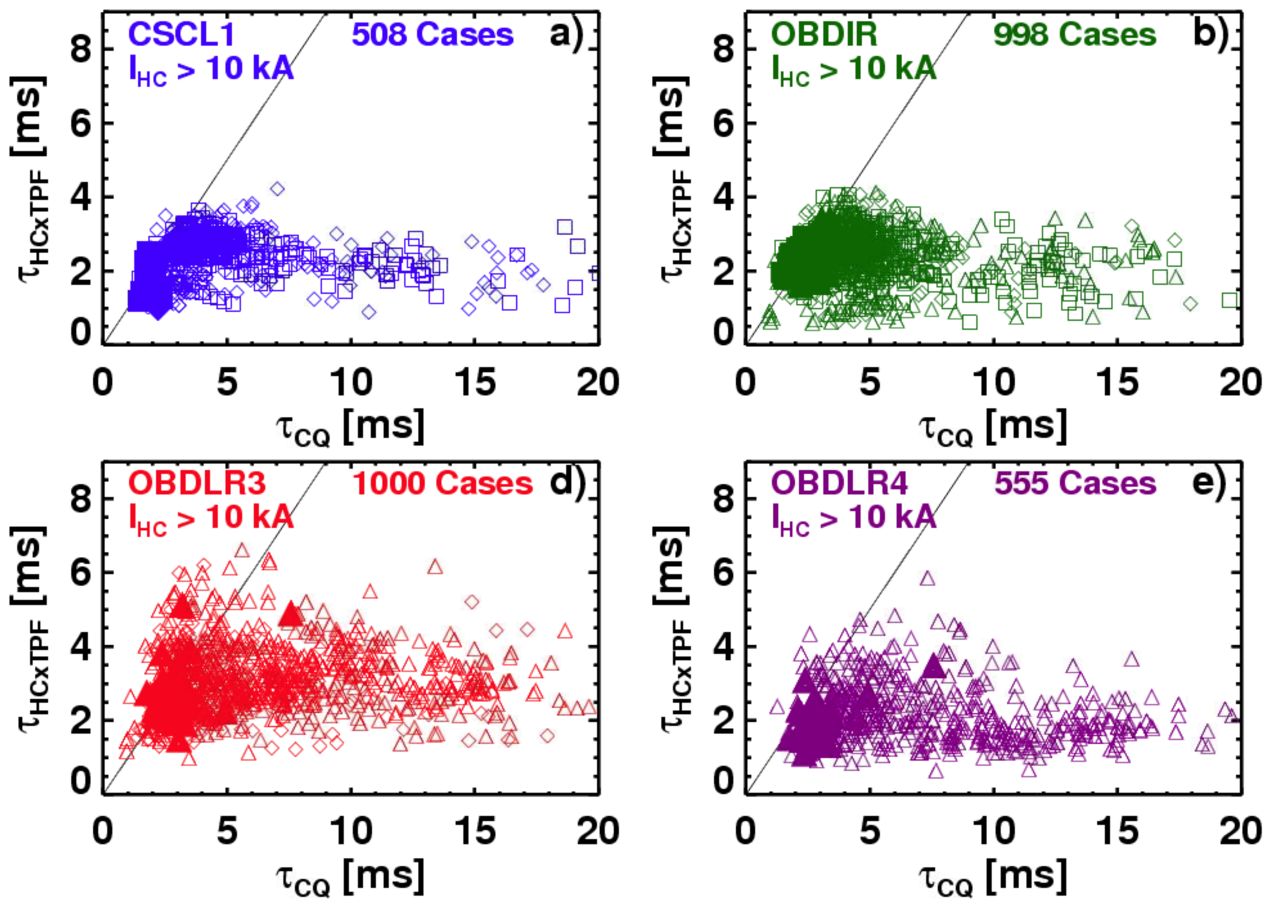
2 Bot. Frames
HCF vs. TPF in tiles where the halo currents enter.

- Theory implication: Codes should compare their TPF output to the correct measurements (likely the TPF at the entrance points).
  - Paths in the wall determined by Ls and Rs of the available paths.

Halo Current Duration is Often Much Shorter Than the Current Quench

$$\tau_{CQ} = \frac{5}{3}\left(t_{20} - t_{80}\right)$$

$$\tau_{HCF \times TPF} = \frac{\int (HCF \times TPF)\,dt}{\max(HCF \times TPF)}$$



- Halo current impulse duration is typically 1-3 ms.
  - Typically shorter than the current quench time.
  - Exception: Driven VDEs often show halo currents before I_P begins to quench.

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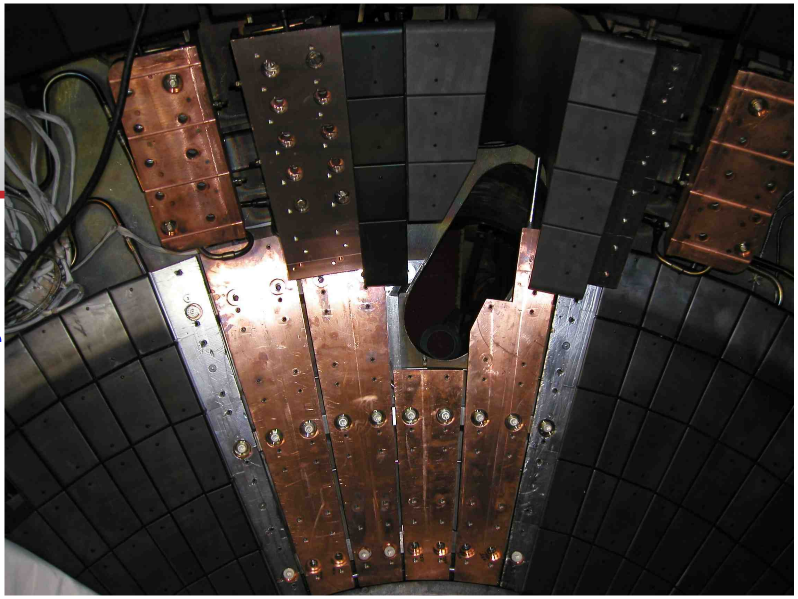
What are the Relevant Time-Scales in NSTX?



- Current Quench Time: 2-15 ms
- Halo Current Time: 1.5-4 ms
- VDE time: 10-30 ms

} ***Experimental Observations***

- Time-scale for halo currents to grow: ~0.5-1 ms
- Alfven Time (n_e=5x10^{19} m^{-3}): τ_A=1 μs
- Lundquist numbers:
  - Plasma during quench: 10^5
  - High-performance phase: 10^7

$$\eta_{\parallel} = \frac{1.03\times 10^{-4}}{2} Z\ln(\Lambda) T_e^{-3/2}$$

$$S = \frac{\mu_0 L V_A}{\eta}$$

$$\text{Halo: } \tau_h \equiv \frac{\mu_0}{\eta_{hp}} a\Delta_h; \ \text{Wall: } \tau_w \equiv \frac{\mu_0}{\eta_w} a\Delta_w; \ \text{Plasma: } \tau_p \equiv \frac{\mu_0}{\eta_p} a^2.$$

If Z_{eff}=2, T_e=10 eV, a=40cm, Δ_h=4 cm

η=4x10^{-5} Ωm
τ_h=0.5 ms

Primary metal component of the divertor are radial running copper slats

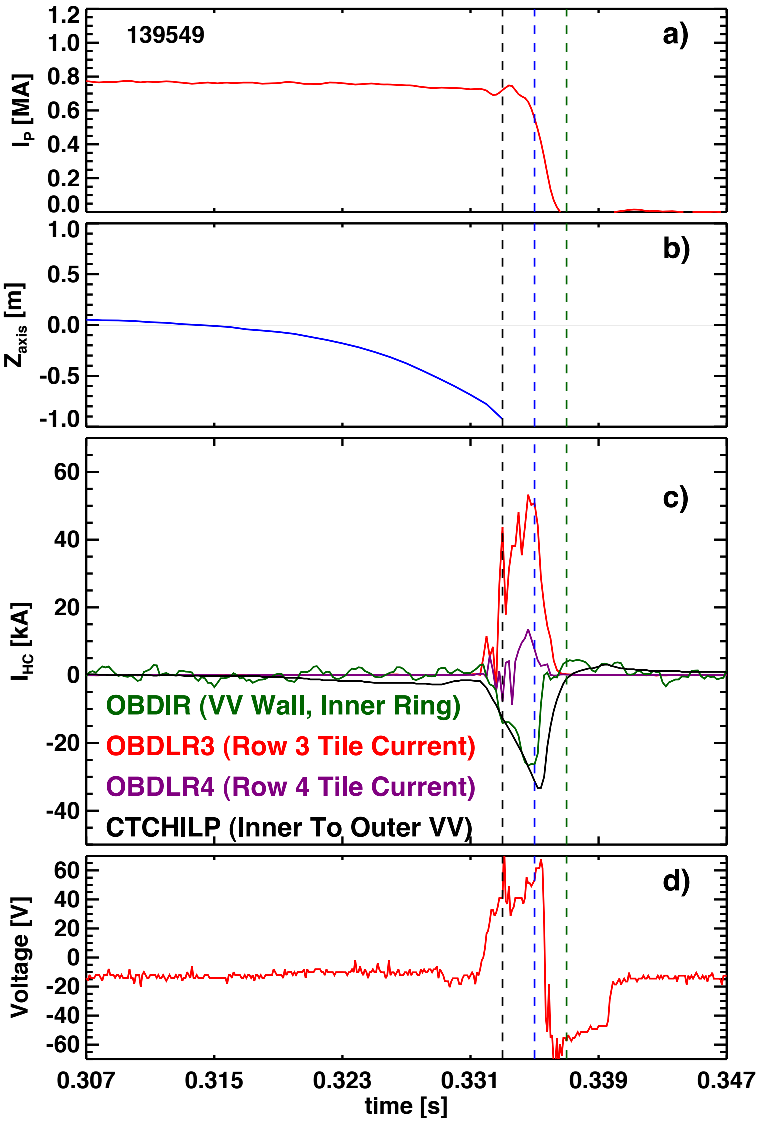
Δ_w=1 cm, a=0.4 m
η=17 nΩm = 1.7x10^{-8} Ωm
$\tau_{w,Cu}$=0.3 s
$\tau_{w,SS}$=7 ms

If Z_{eff}=2, T_e=25 eV, a=40cm

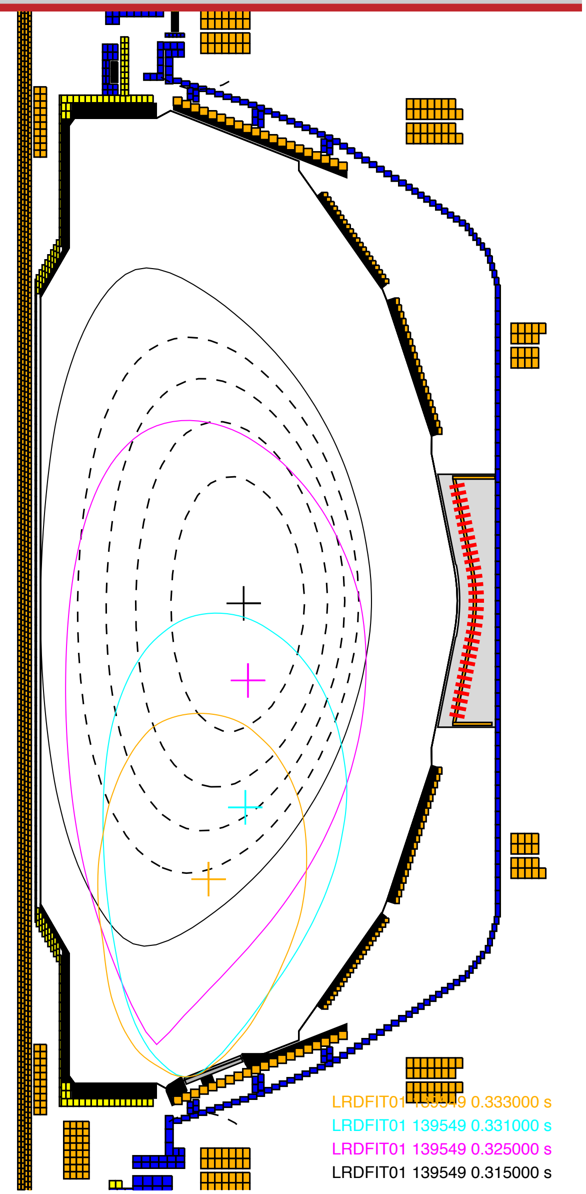
η=10^{-5} Ωm
τ_p=21 ms

So, satisfies $\tau_A \lll\lll \tau_h \ll \tau_P \ll \tau_{w,Cu}$

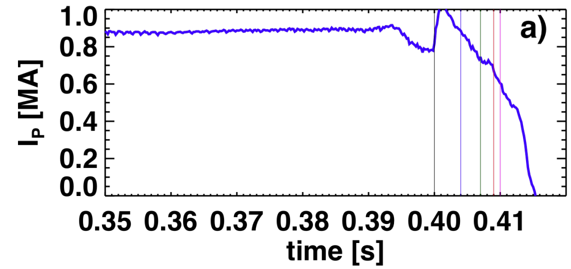
For Fast VDEs, Halo Currents Can Lead the Current Quench
Example: Deliberate VDE w/ Downward Push

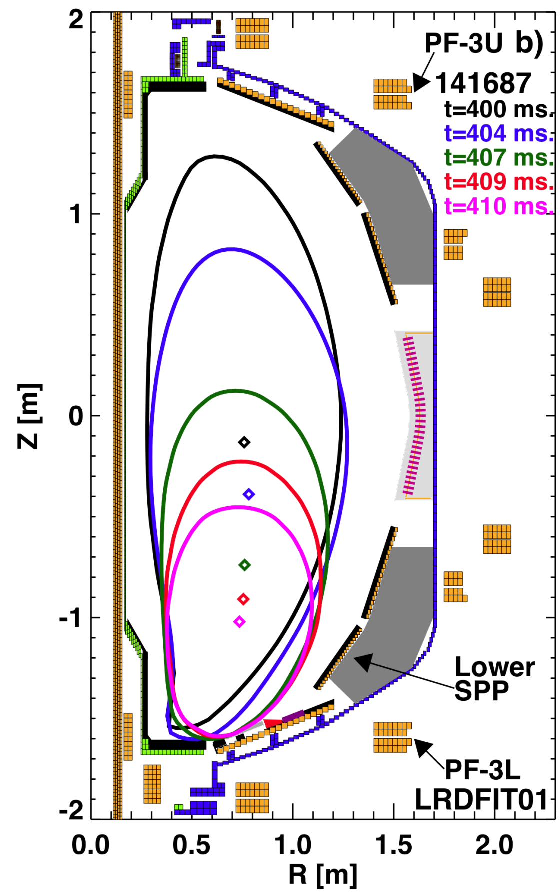


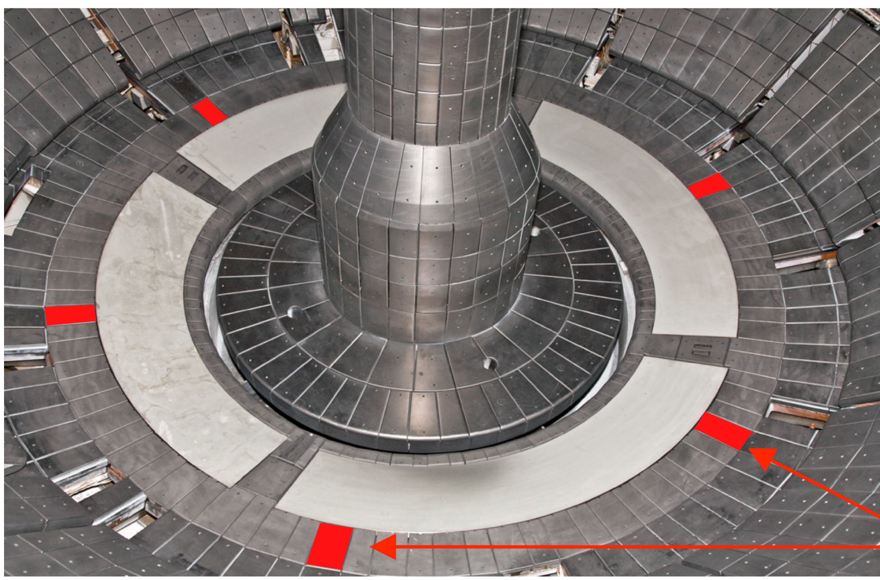
shot	139549
time	0.333000
chi**2	88.806
Rout(m)	0.722
Zout(m)	-0.978
a(m)	0.347
elong	1.739
utri	0.040
ltri	0.179
indent	0.000
V (m**3)	2.836
A (m**2)	0.639
W (MJ)	0.000
betaT(%)	0.000
betaP	0.000
betaN	0.000
In	4.971
Li	0.403
error(e-4)	0.000
q1	1.382
q95	1.360
dsep(m)	0.000
Rm(m)	0.000
Zm(m)	0.000
Rc(m)	0.000
Zc(m)	0.000
betaPd	0.000
betaTd	0.000
Wdia(MJ)	0.000
Ipmeas(MA)	0.697
BT(0)(T)	-0.408
Ipfit(MA)	0.704
Rmidin(m)	0.375
Rmidout(m)	1.069
gapin(m)	0.190
gapout(m)	0.315
gaptop(m)	1.966
gapbot(m)	0.013
Zts(m)	0.000
Rvsin(m)	0.000
Zvsin(m)	0.000
Rvsout(m)	0.000
Zvsout(m)	0.000
Rsep1(m)	0.000
Zsep1(m)	0.000
Rsep2(m)	*************
Zsep2(m)	*************
psib(Vs/R)	0.005
elongm	1.731
qm	0.000
nev1(e19)	0.000
nev2(e19)	0.000
nev3(e19)	0.000
ner0(e19)	0.000
n/nc	0.000
dRsep	0.000
qmin	1.352
rhoqmin	0.000



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







Measurements from an array of 6 toroidally distributed tiles.

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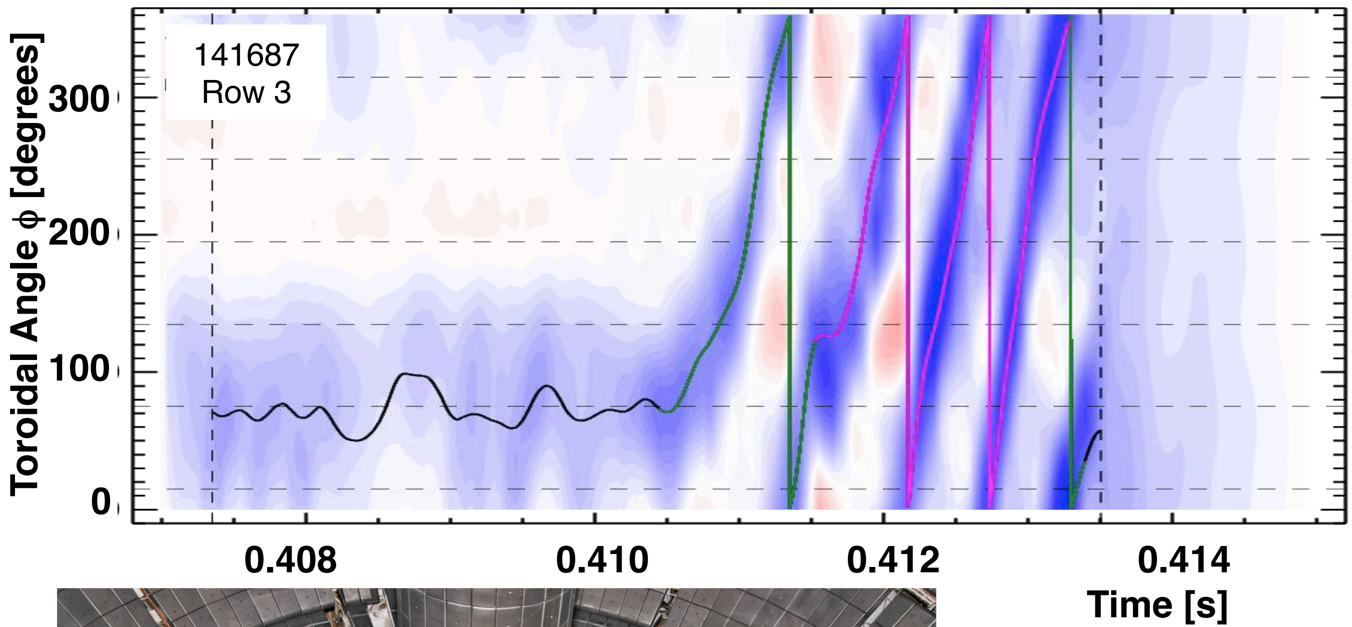

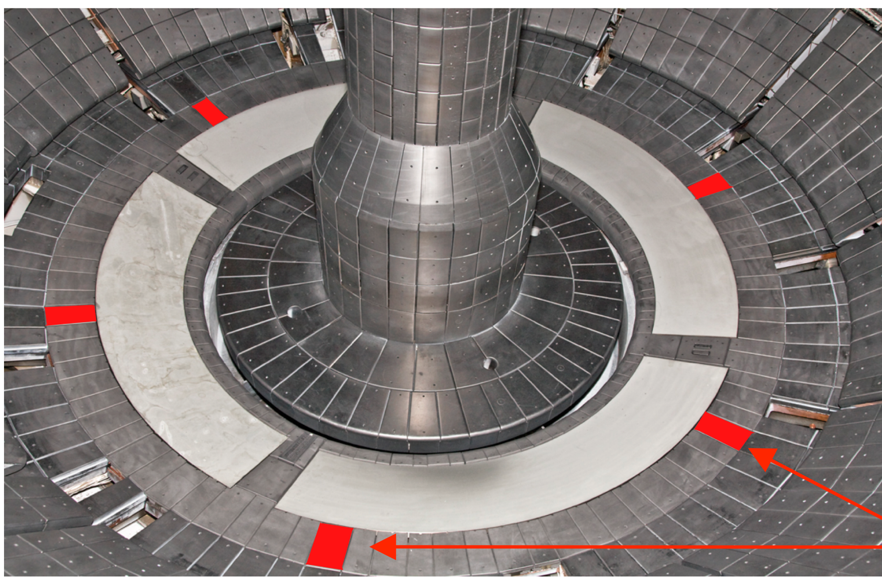

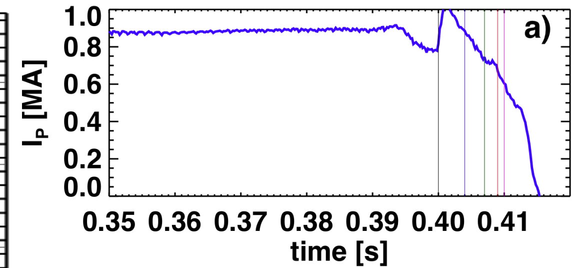

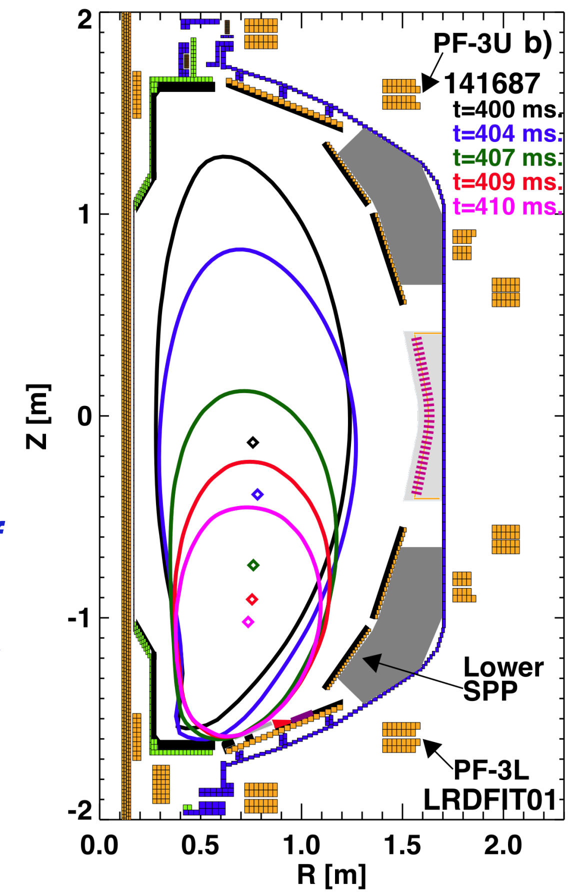

Tiles

Measurements from an array of 6 toroidally distributed tiles.

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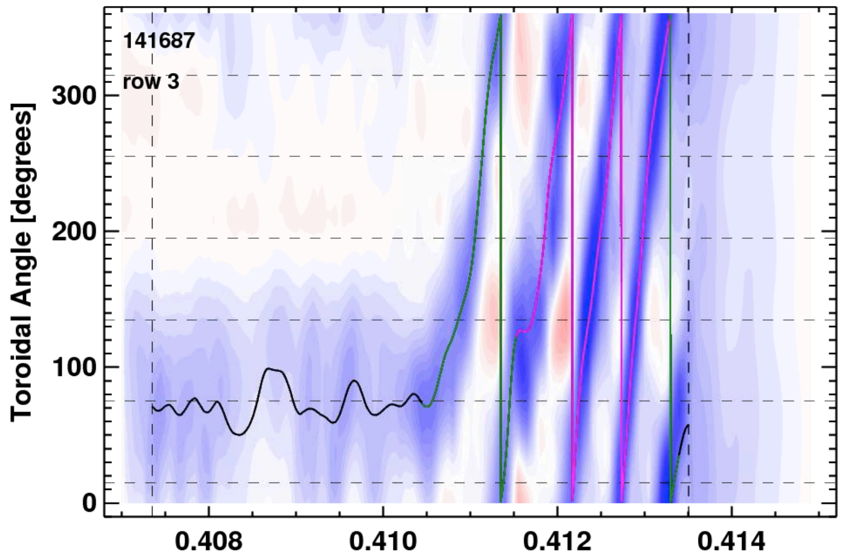
Li I Camera Images Confirm Rotation of Structure Four Times

- Neutral lithium light most indicative of surface interactions

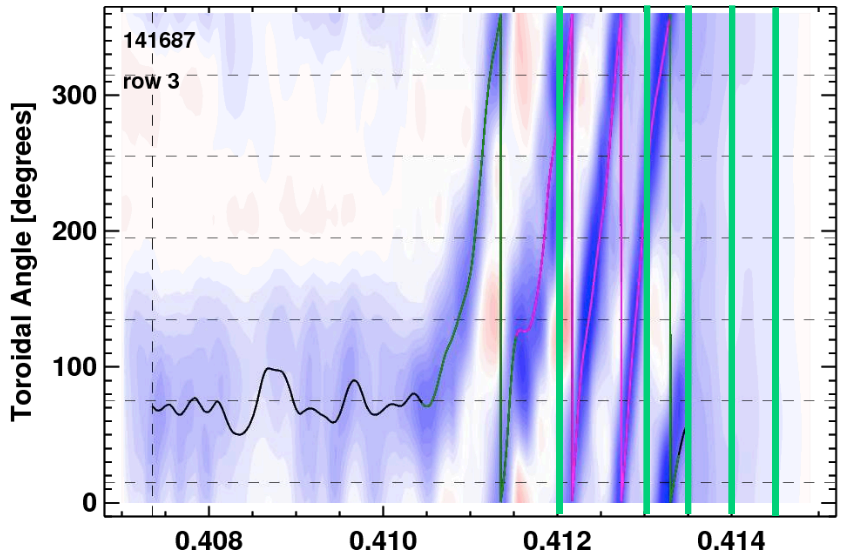
More information on the rotation dynamics to be presented in talk by T. Hender

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

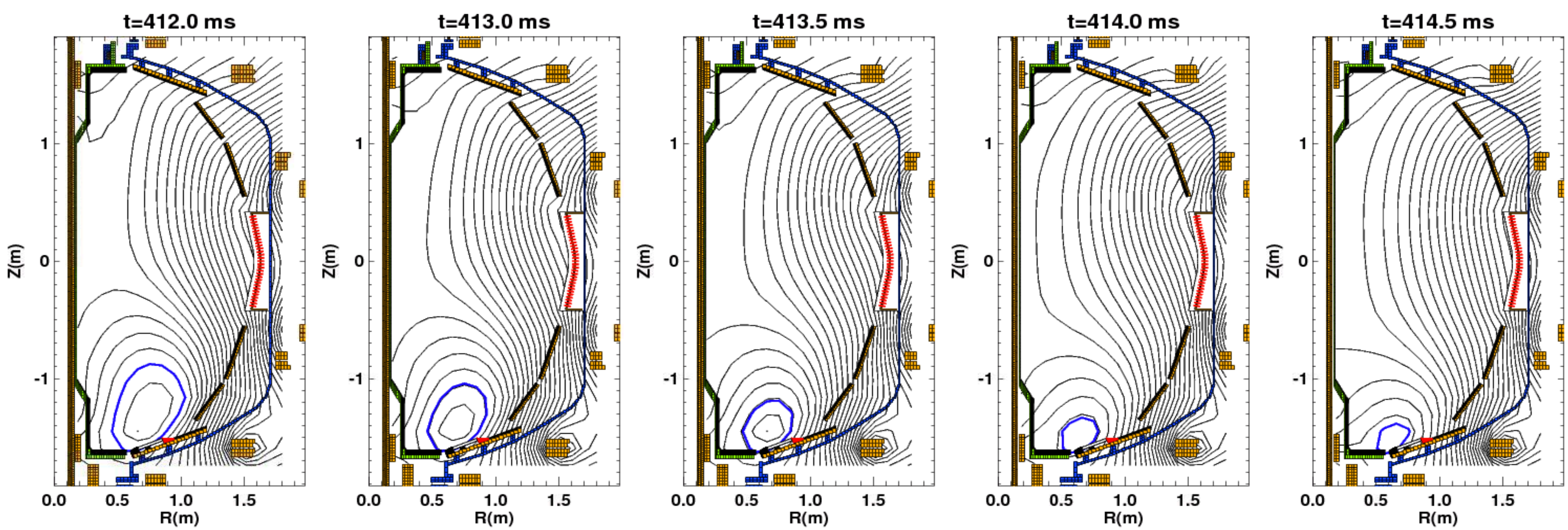


- Halo current contours are toroidally symmetric starting at ~0.4135 s

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



Outline

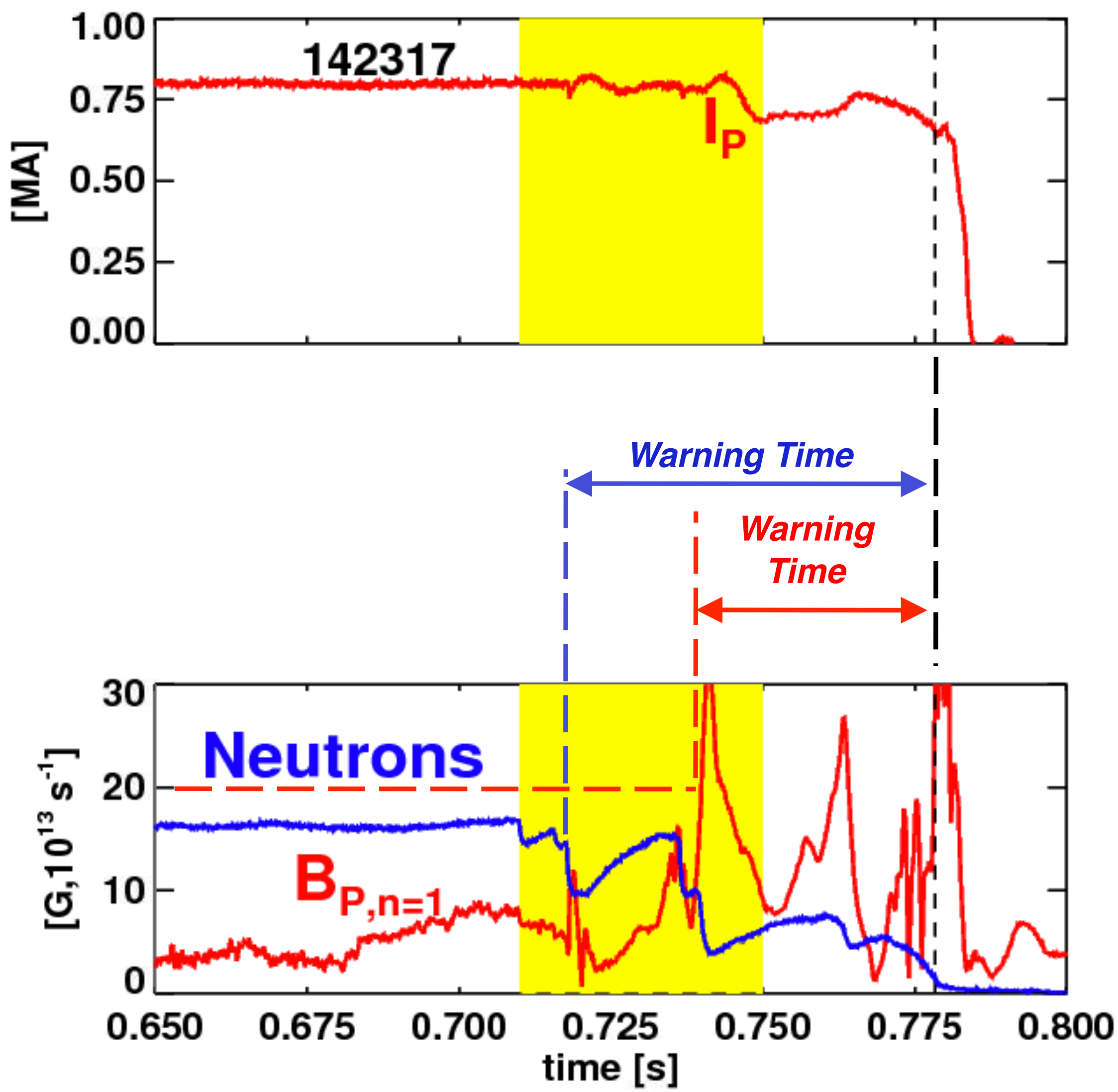
- NSTX Halo Current Results

- NSTX Disruption Predictor

If I have time

- Comments on the importance of the "pre-disruption" phase.

Warning Times Defined With Respect to the Current Quench



False Positive:

Warning more than 300 ms in advance of current quench.

Late Warning:

Warning later than 10 ms before the current quench.

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

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

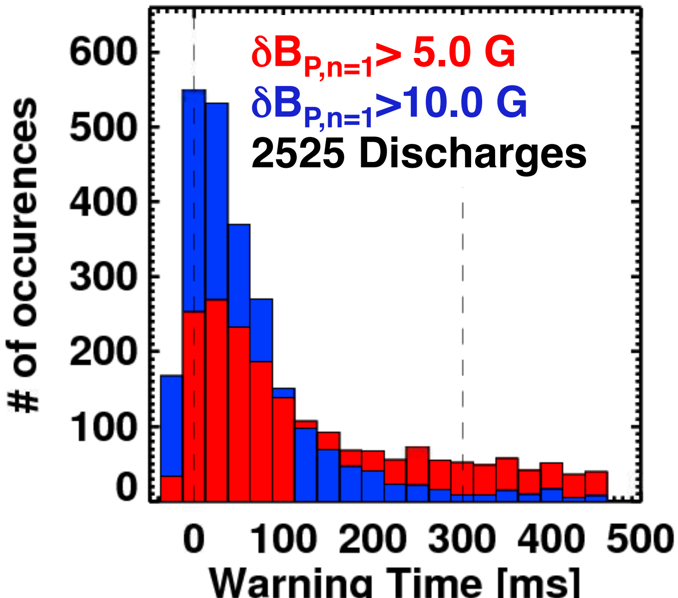
Individual Threshold Tests Form the Basis For Detection

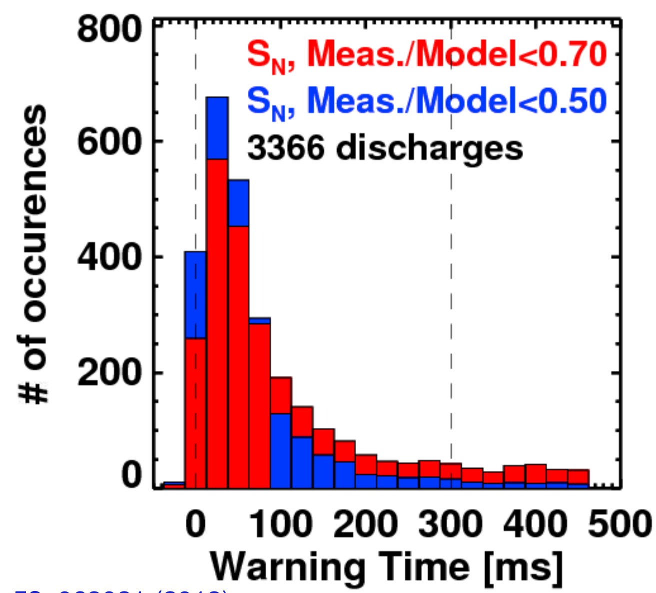
- n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes

- 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
5 G	4	35	0
10 G	13	5	2

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





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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:
  - Note: Low threshold levels lead to high false positive rates, few missed disruptions.
  - 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**.

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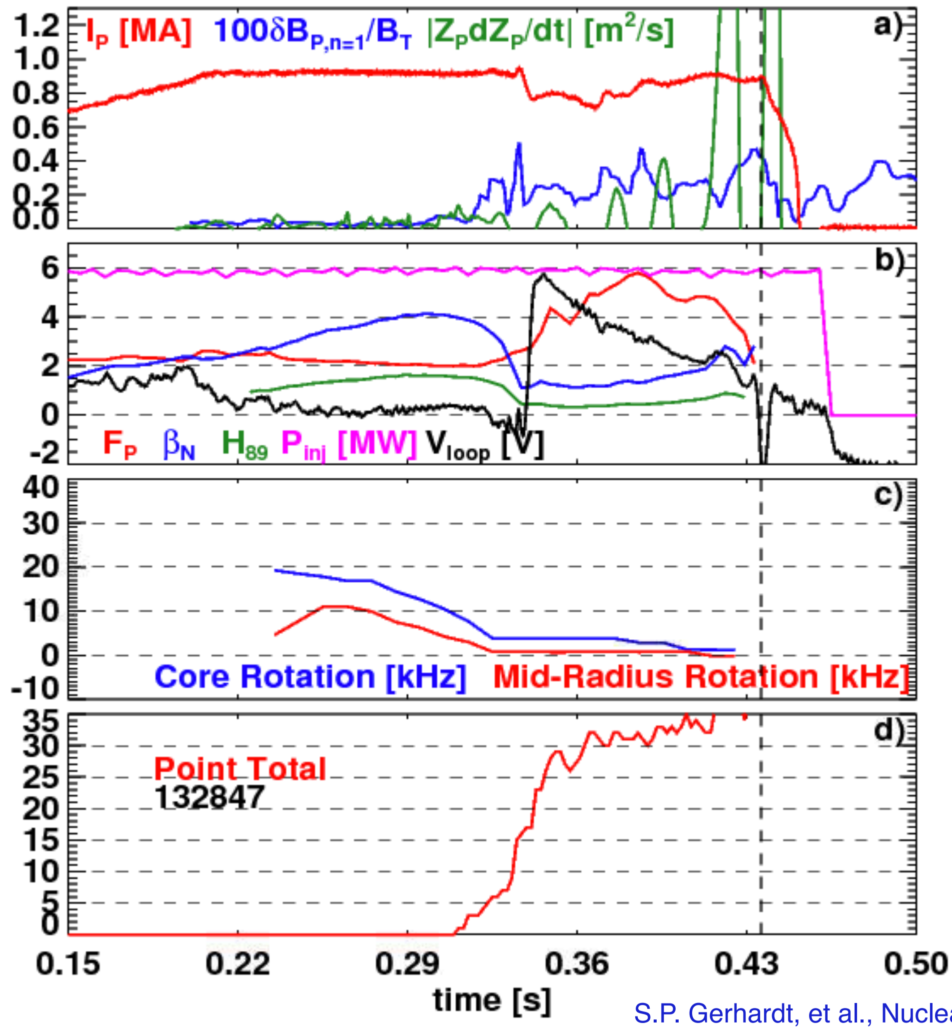
Examined Many Threshold-Based Disruption Indicators Leading or Trailing The Start of the Disruption Process

- 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)

Warning Level Increases Monotonically Towards the Disruption

Early Rotating Mode Lock



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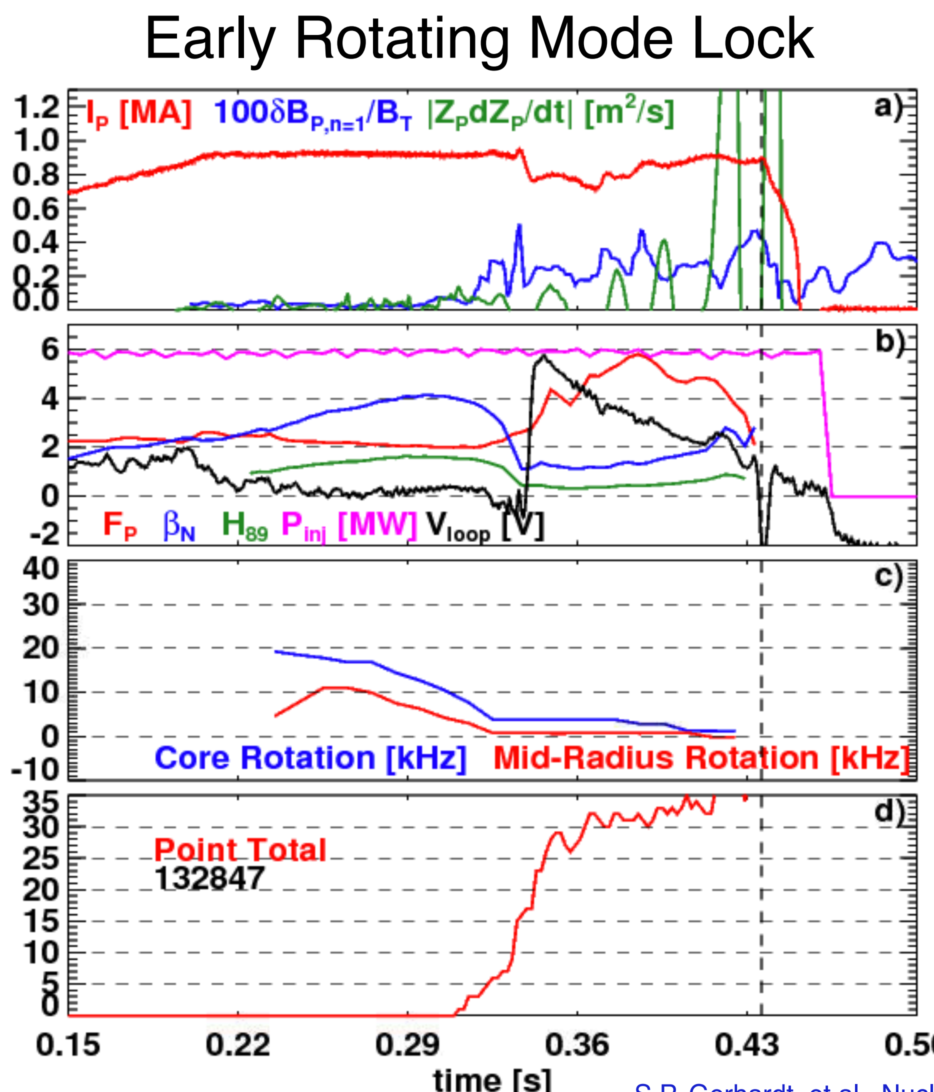

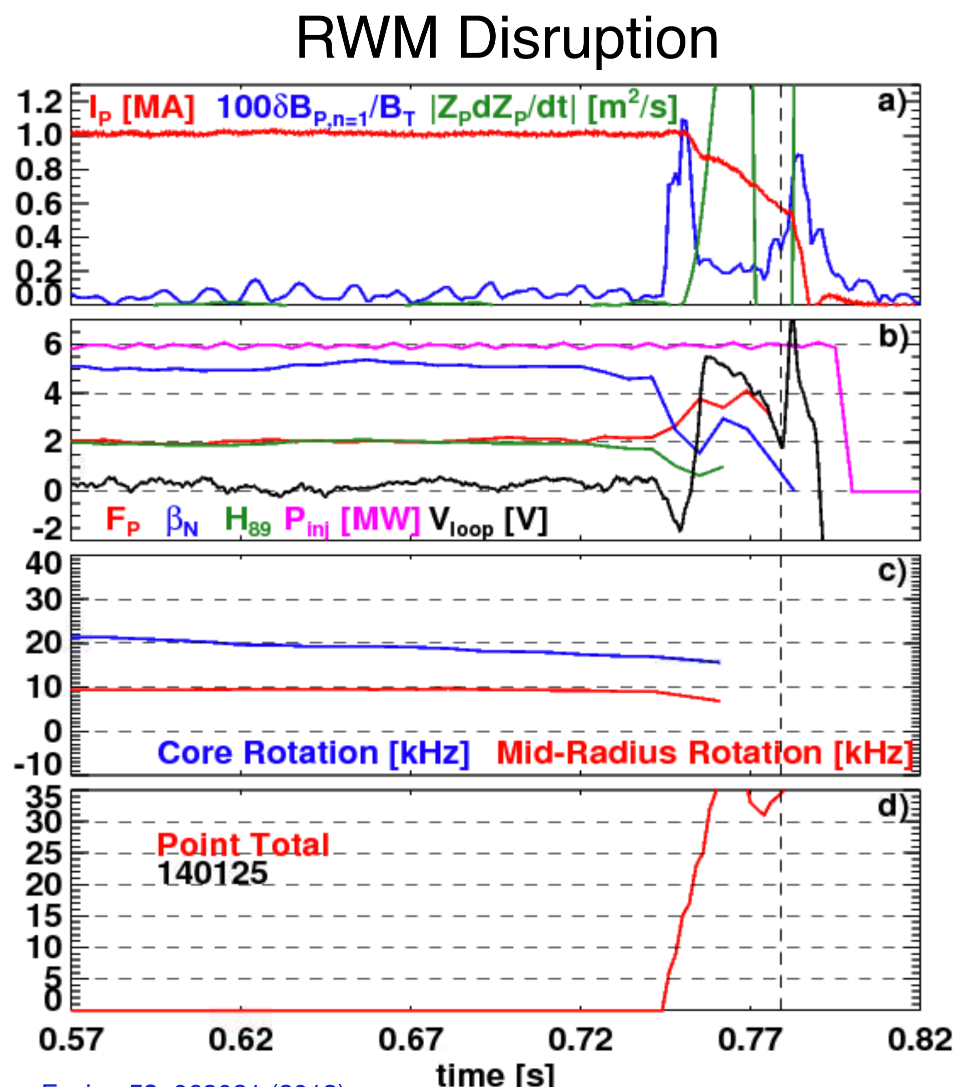

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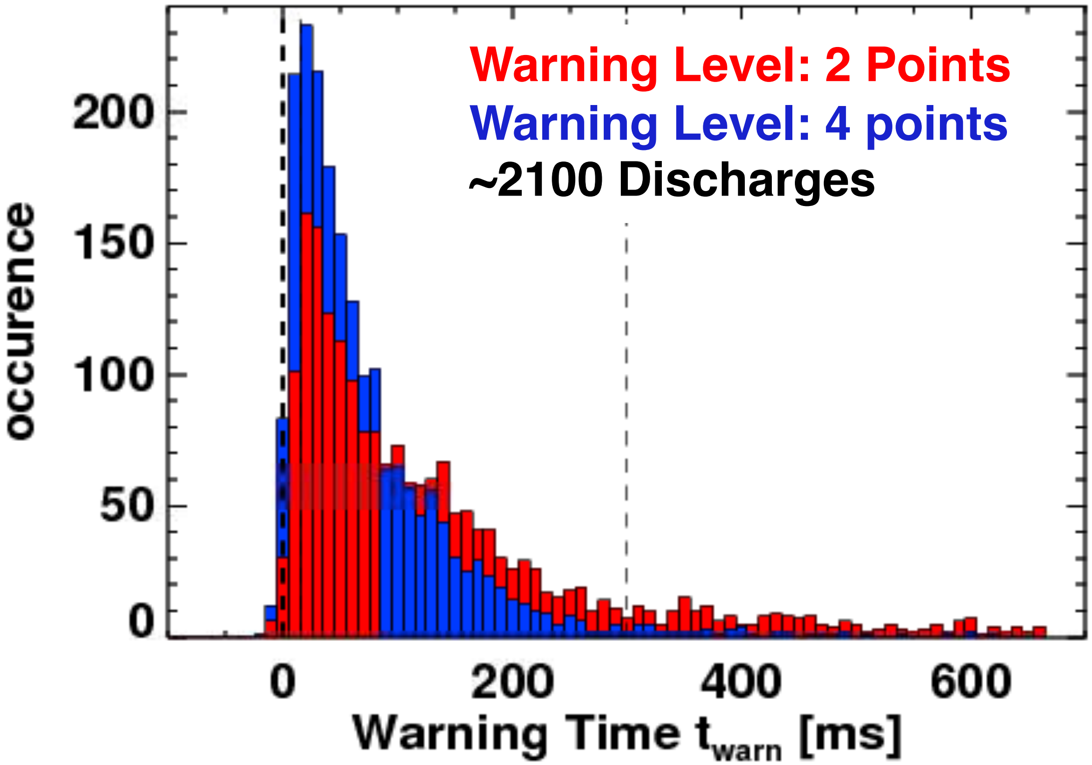
3-Level Warning Rule Can Predict Most Disruptions



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%

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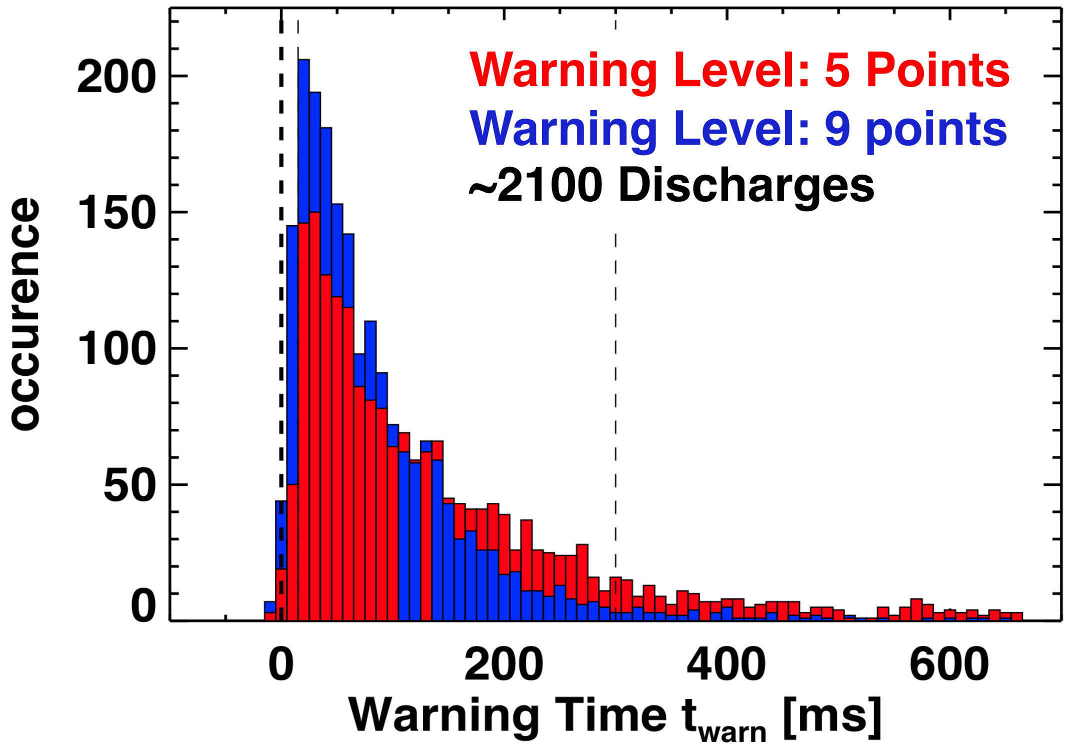
Actual algorithm has ~15 rows

Test	1 pt -> 2% False Positive Rate	2 pt ->1% False Positive Rate	3 pts -> 0.5% False Positive Rate
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

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

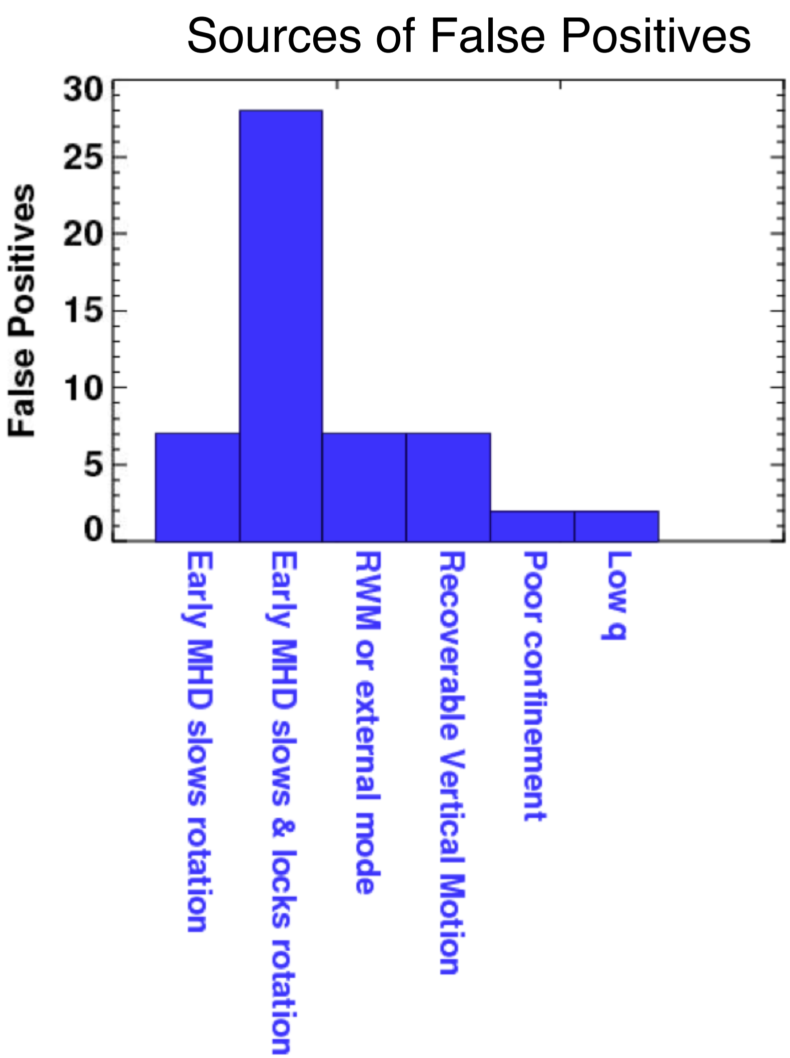
Sum: 6%

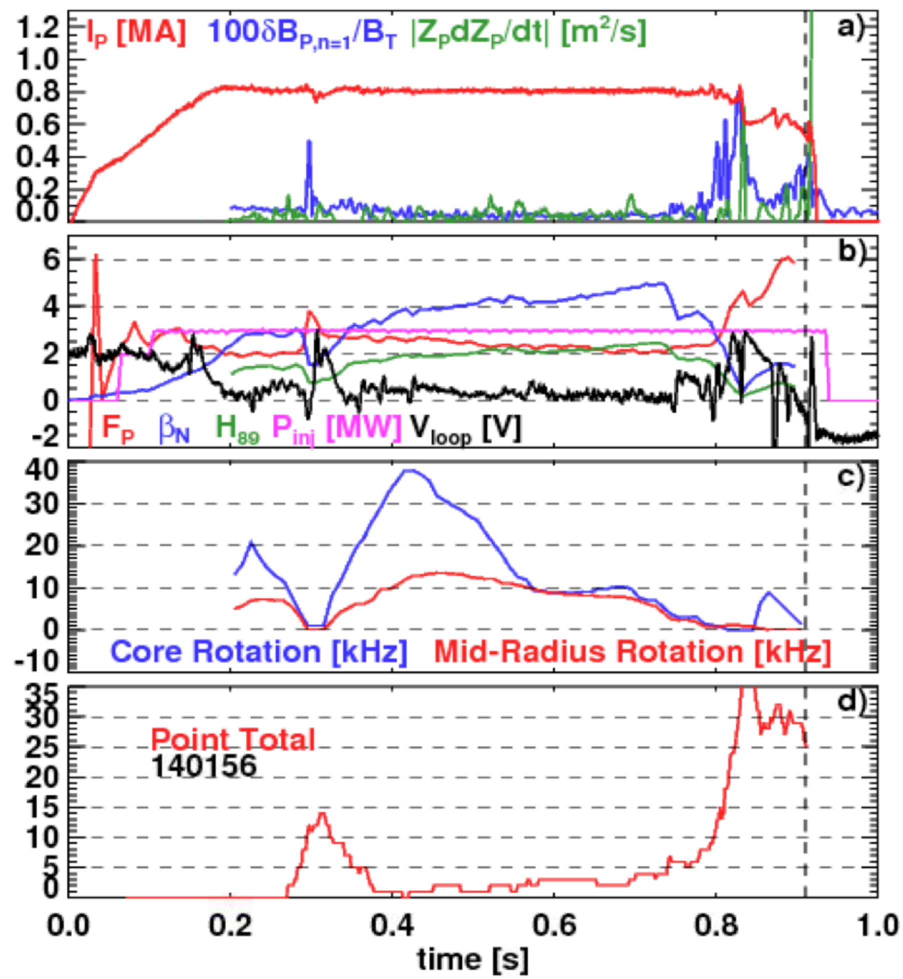
(False positive count dominated by near-disruptive MHD events)

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

Sources of False Positives





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Theory & Extrapolation Issues

- Key objection is (clearly) that the coefficients are based on a database of NSTX data.
- However, many of these test assess loss-of-control (LoC)
  - Test on n=1 B_P perturbation: loss of RWM (or LM) control.
  - Test on I_P deviations: loss of I_P control.
  - Test on dZ_P/dt, or $Z_P dZ_P/dt$: loss of vertical position control.
  - Test on H_{89}: loss of β-control.
- Replace these with first-principle control estimates
  - Example: vertical control
    - Realtime calculations/estimates of Δz_{max} (maximum controllable displacement)
    - Realtime measurements/estimates of the disturbance spectrum.
    - Model based control of the vertical position.
  - NSTX Example: State-Space RWM controller
    - Use this to generate LoC warnings (future work).
- Potential simplifying fact: ITER will have only a few target scenarios, NSTX has *many, many* scenarios.

Outline

- NSTX Halo Current Results

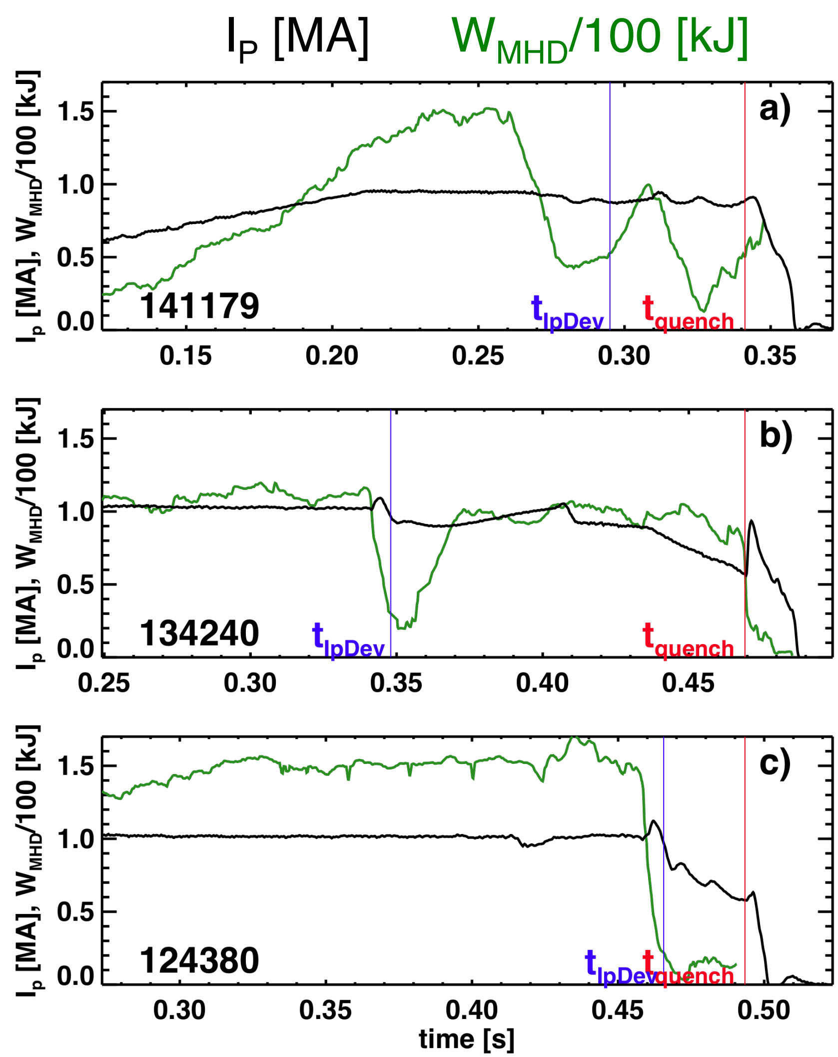
- NSTX Disruption Predictor

If I have time

- Comments on the importance of the “pre-disruption” phase.

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 process.



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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  - 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

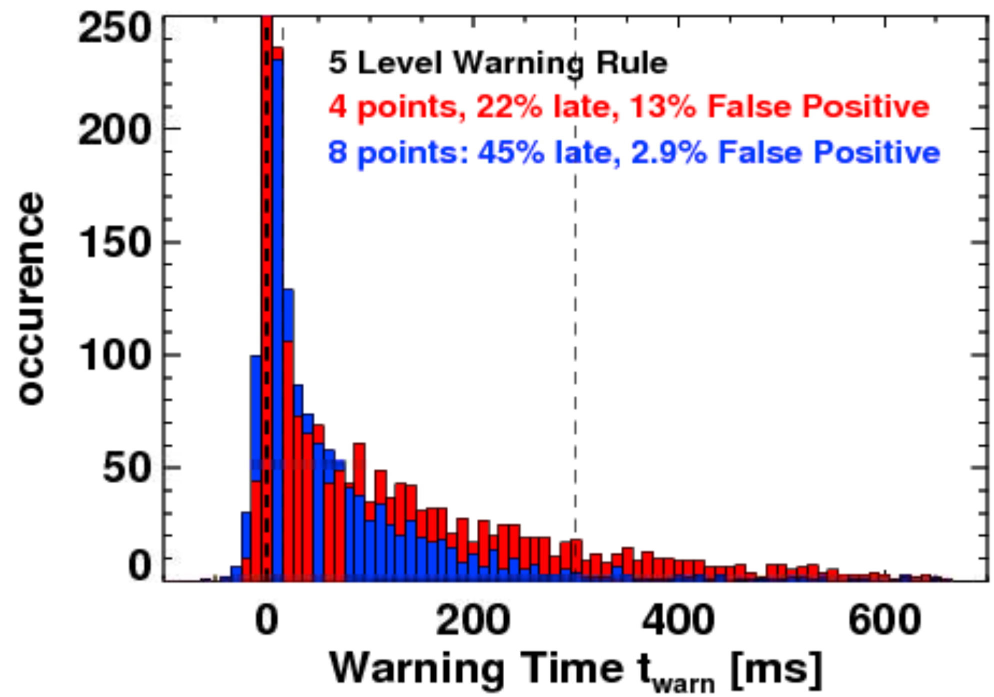
<22% late warning, ~13% false positive

Sum: 35%

Warning at APT=8 Points

~45% late warning, ~3% false positive

Sum: 48%



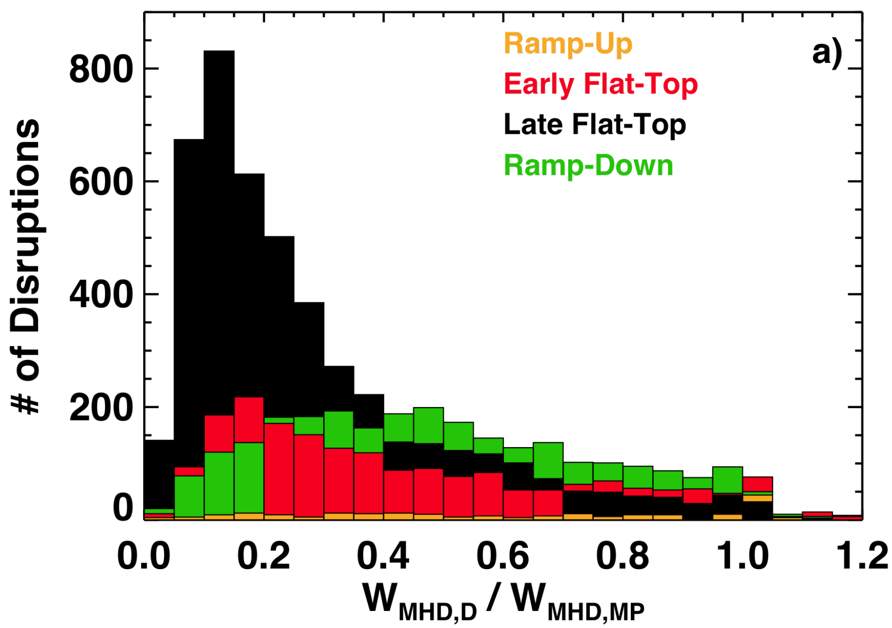
S.P. Gerhardt, et al., Nuclear Fusion **53**, 063021 (2013)

Understanding the Pre-Disruption Phase is Key: Energy Loss

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

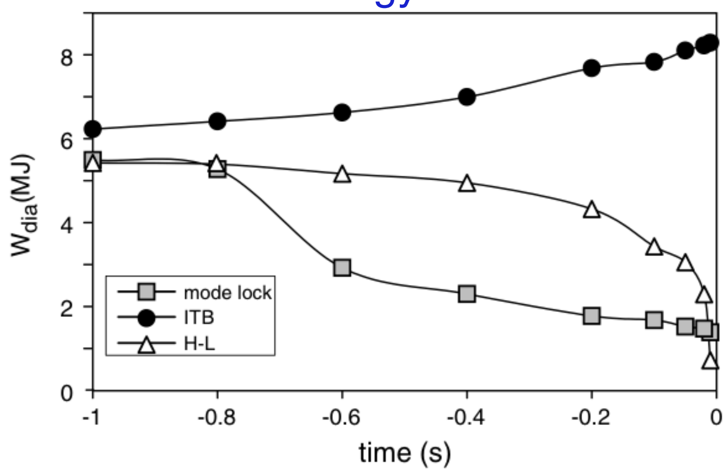
This phase determines the energy at the thermal quench

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

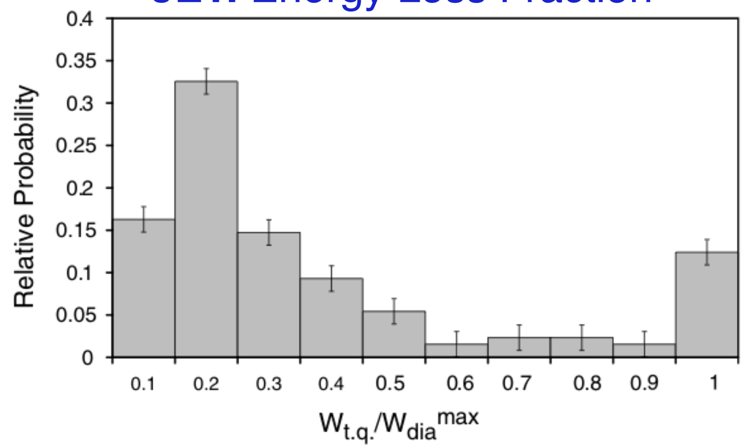


S.P. Gerhardt, et al., Nuclear Fusion **53**, 043020 (2013)

JET: Energy Evolution



JET: Energy Loss Fraction



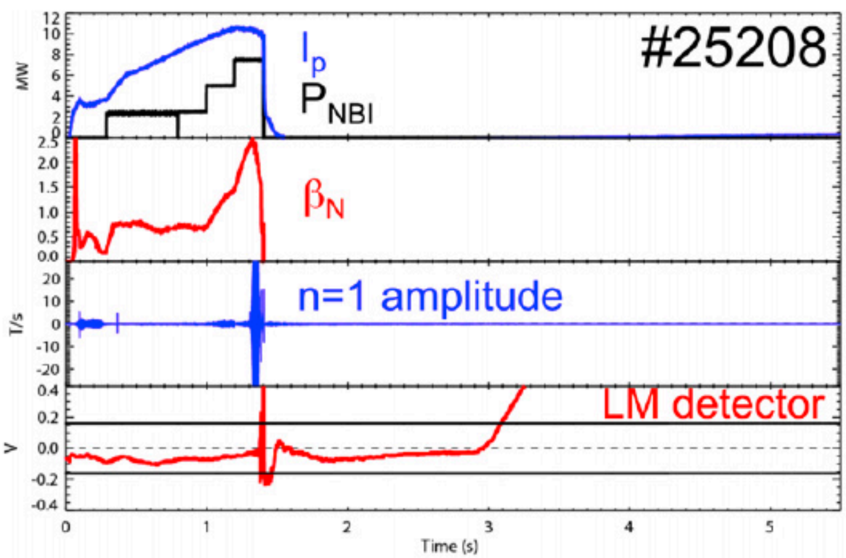
V. Riccardo, et al., Nuclear Fusion **45**, 1427 (2005)

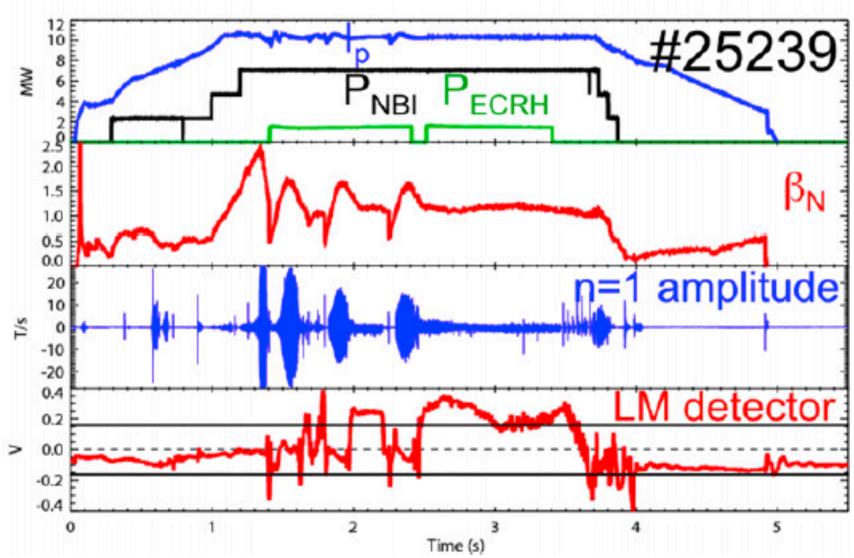
Understanding the Pre-Disruption Phase is Key: Actuation and MGI

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

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





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.

Also: presence of large modes may impact mitigation dynamics (M. Lehnen talk)

Also highly relevant: Work on DIII-D by F. Volpe and students, N. Eidietis,…

Understanding the Pre-Disruption Phase is Key: Detection

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

Signals in Recent ANN & Similar Disruption Studies Similar to NSTX Study (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]
$<T_e>$ [2]
S_N [2]
S_N/W_{dia} [2]
S_P (shape) [2], δ [2]

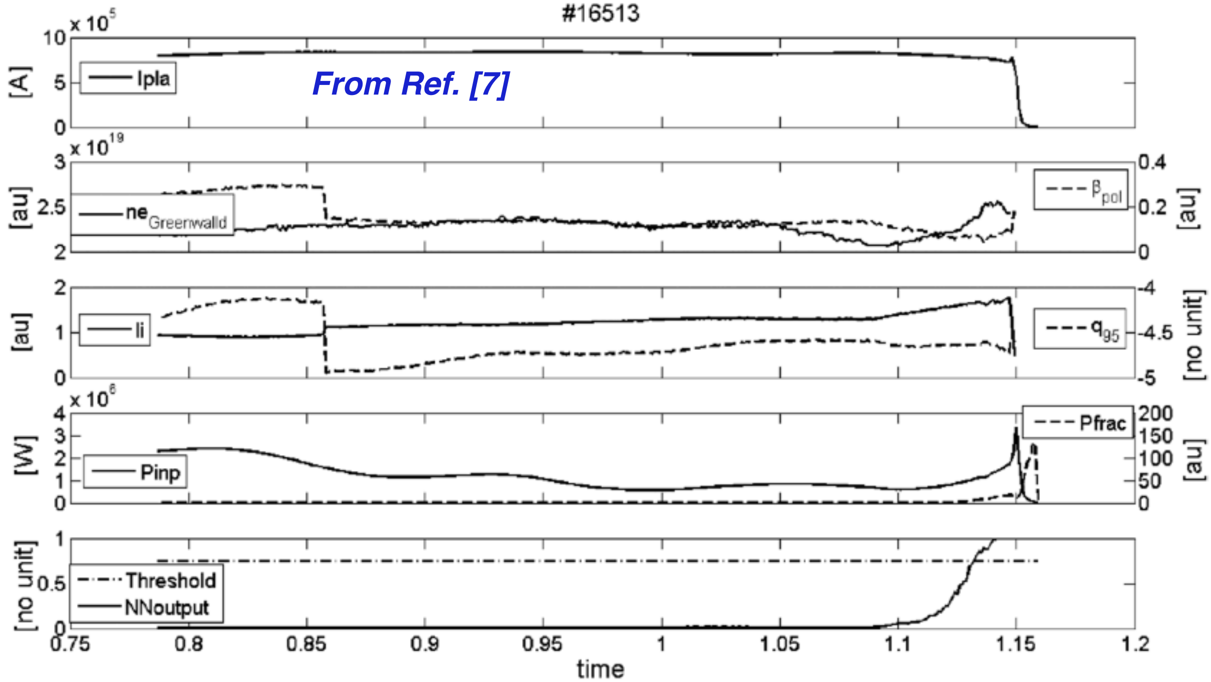


Figure 2. Some plasma parameters, and the corresponding alarm function for the pulse #16513.

[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.

Summary

- Halo currents:
  - Halo currents are observed jump “insulating” breaks.
  - Peaking factors at the location of current entrance appears to be meaningfully larger than in the vessel wall.
  - Typical pattern at the entrance point in NSTX is a toroidally localized lobe, which is often rotating.

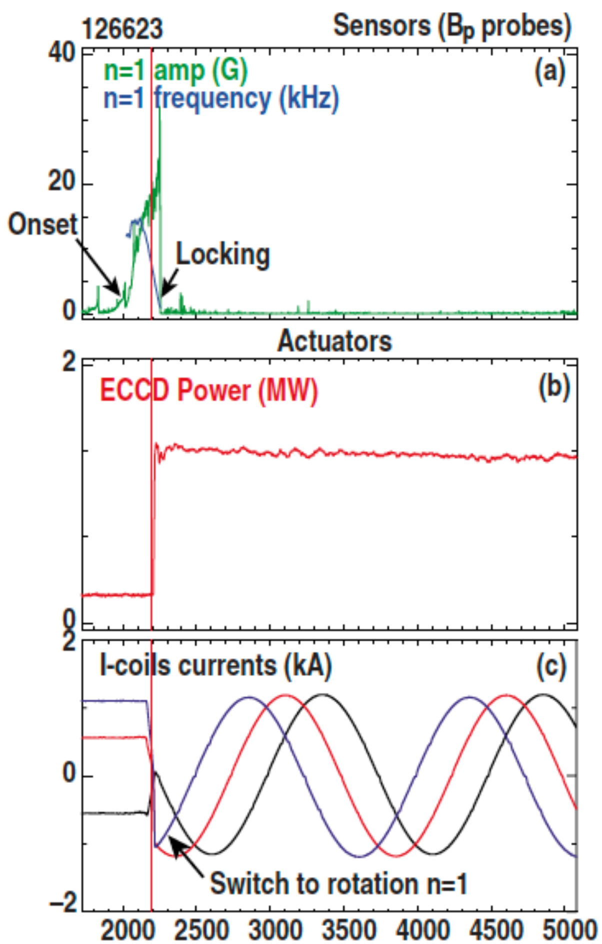
- Disruption Detection:
  - Technique in NSTX is based on summing the outputs of multiple individual threshold tests.
  - Works fairly well (~6% total failure rate).
    - However, relies on there being a meaningful “pre-disruption” phase.

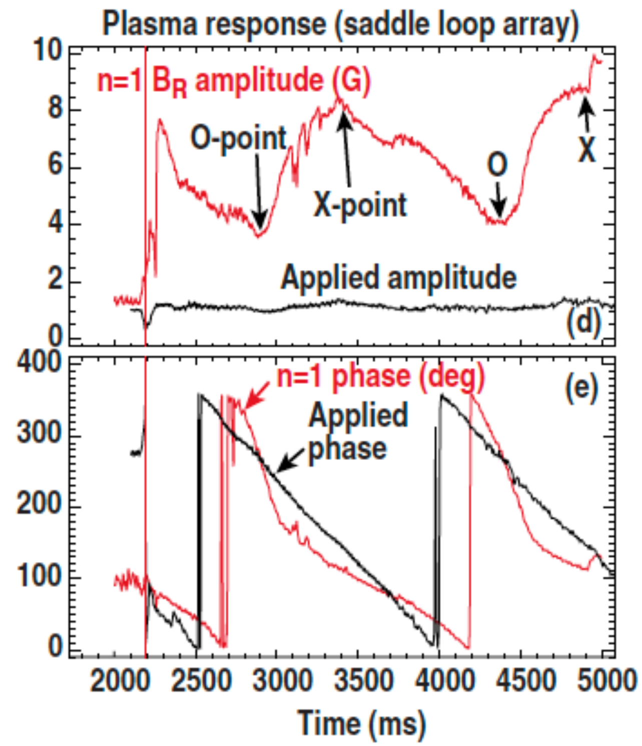
Backup

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

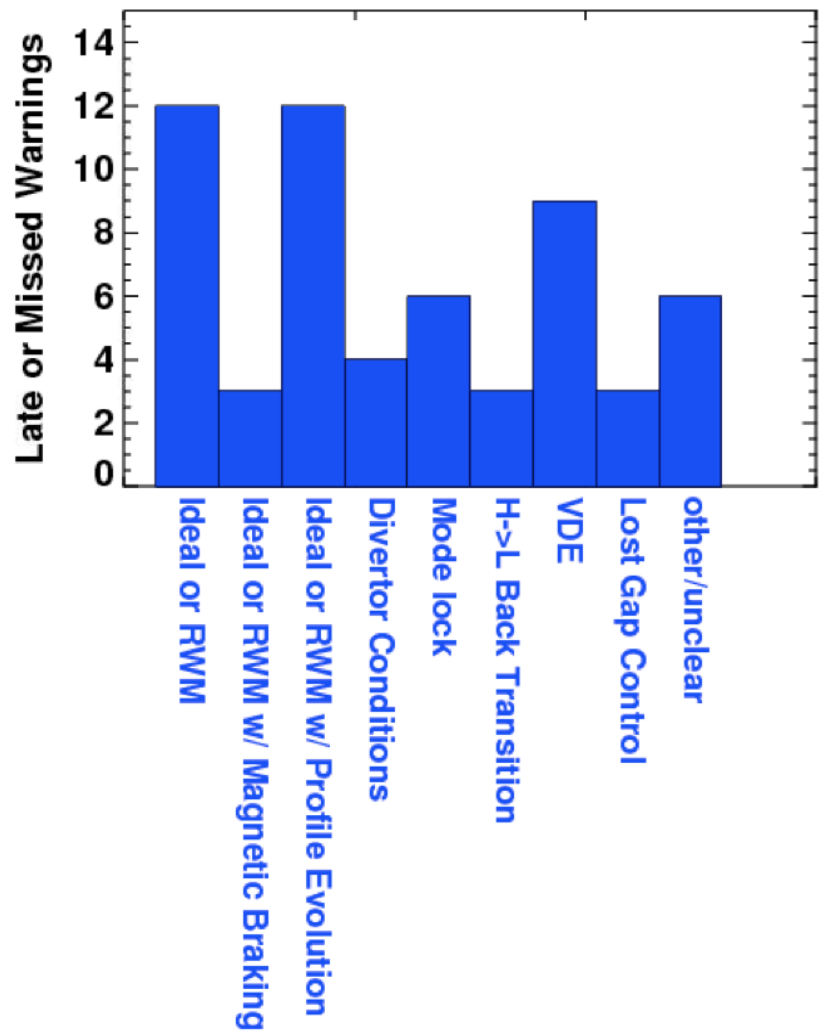




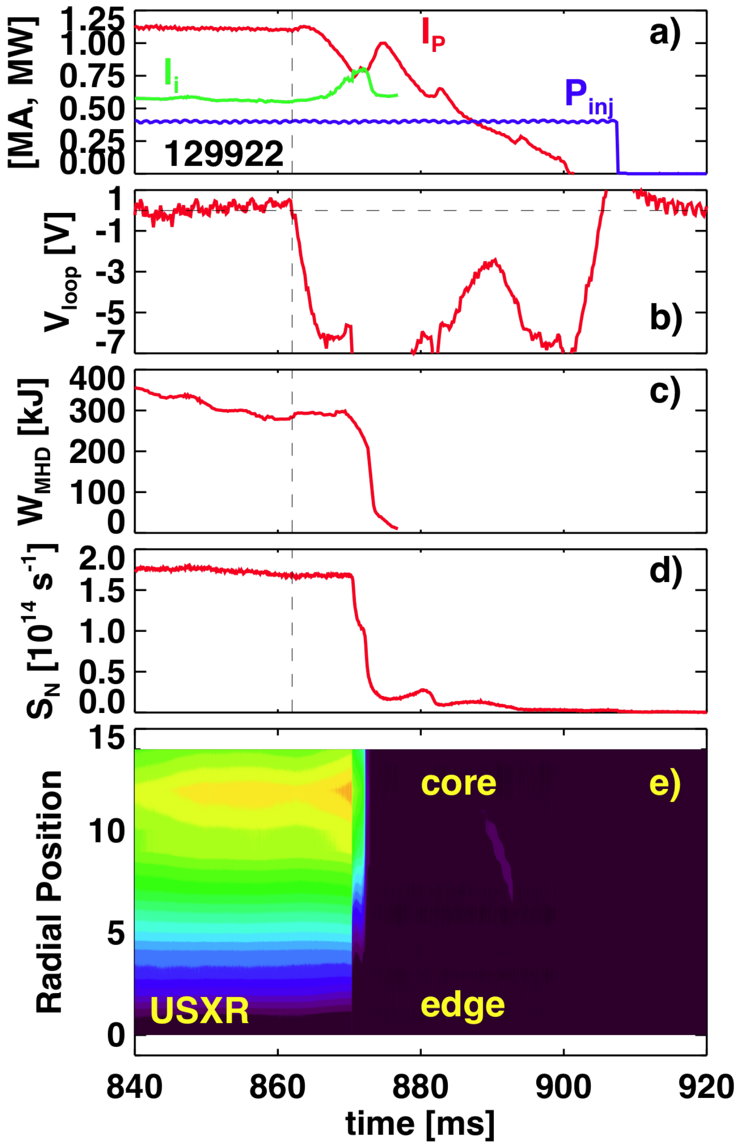
F. Volpe, et al., Phys. Plasmas **16**, 102502 (2009)

RWMs and Ideal Modes Dominate Late/Missed Warnings

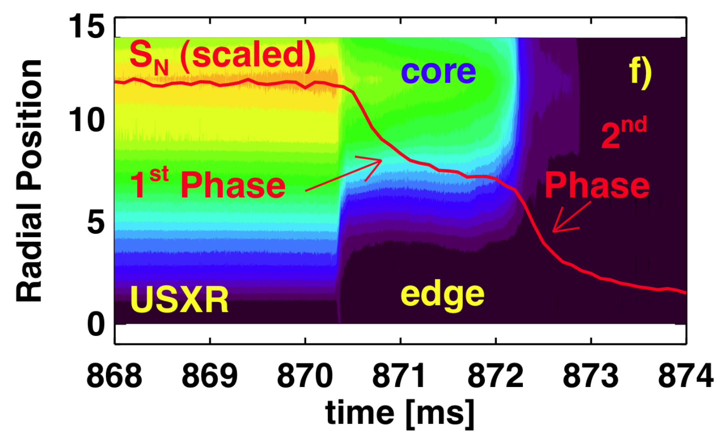
- ~1/2 of the RWM disruptions are proceeded by gradual rise in pressure peaking (~100 ms timescale) or magnetic braking.
  - Other half are fast disruptions, hard to detect in advance.
- Disruptions due to mode lock, VDEs, & gap control problems could be eliminated, at the expense of higher false positive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



Largest Stored Energy Disruptions in NSTX All Come from Loop Voltage Reversal

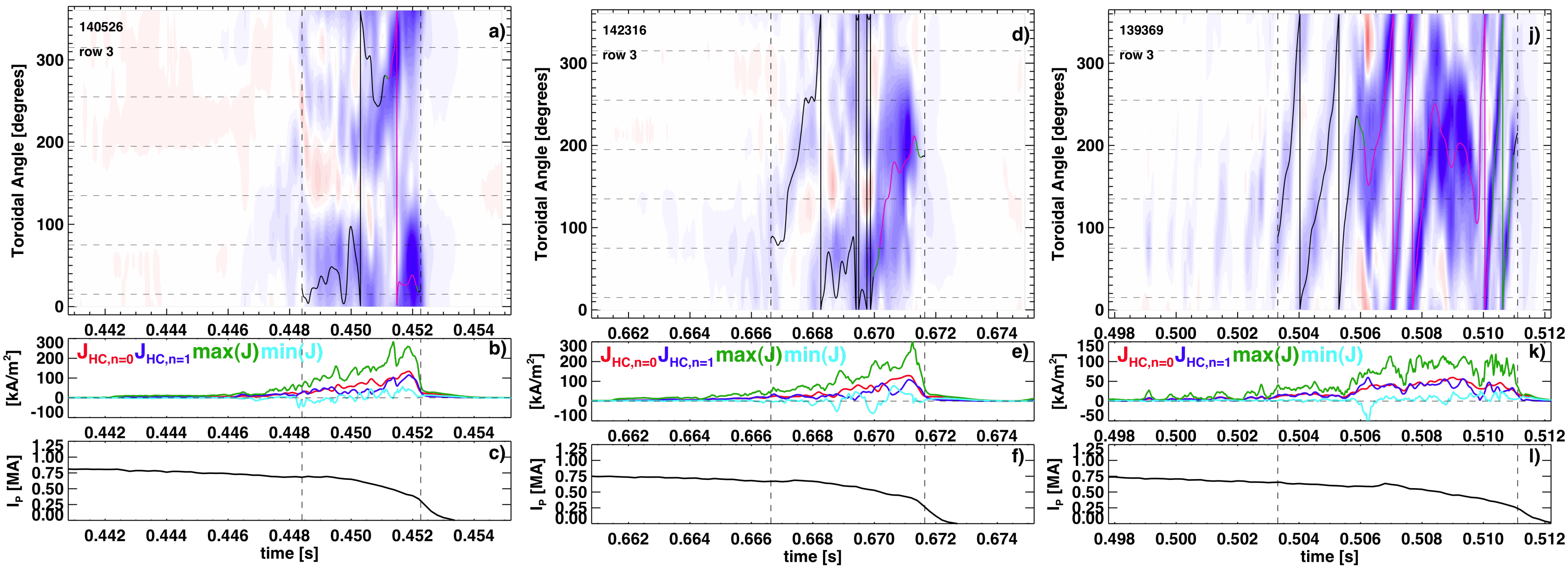


- 1100-1200 kA pulses, high highest energy, and use flux the fastest.
- Software simply reversed the loop voltage when the OH current limit was reached.
  - Disruption follows nearly immediately.
  - 21 of 22 largest energy disruptions, and all but with with W_{dis} > 275 kJ.



Further Examples of Halo Current Rotation Dynamics

Large Currents and Little Rotation	Large Currents and Little Rotation	Smaller Currents and Seemingly Erratic Rotation



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)

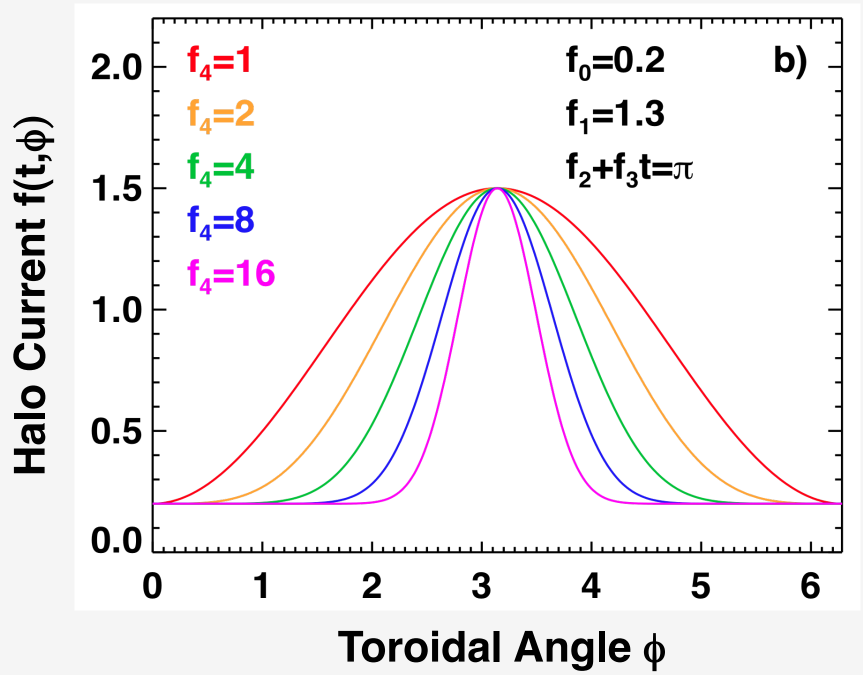
Use a Model Fit Function To Better Resolve the Halo Current Dynamics

- 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 $\delta t \sim 0.1$ 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.

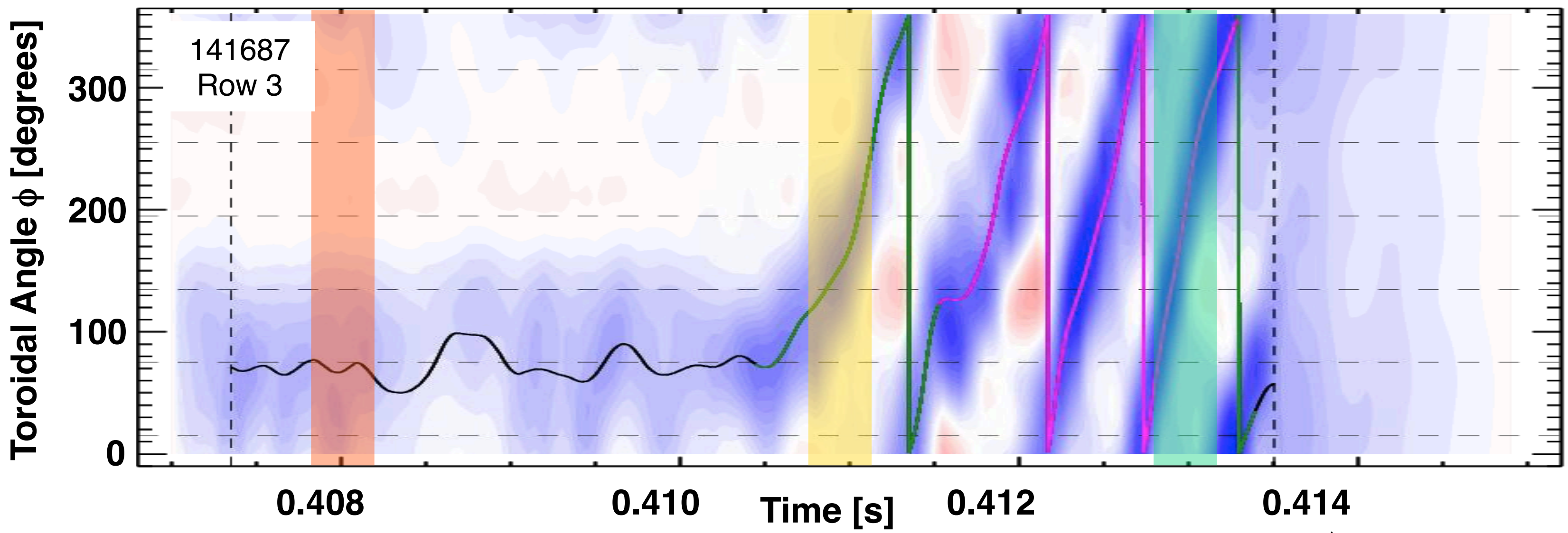
Model Function
"Windowed Cosine Power Fits"

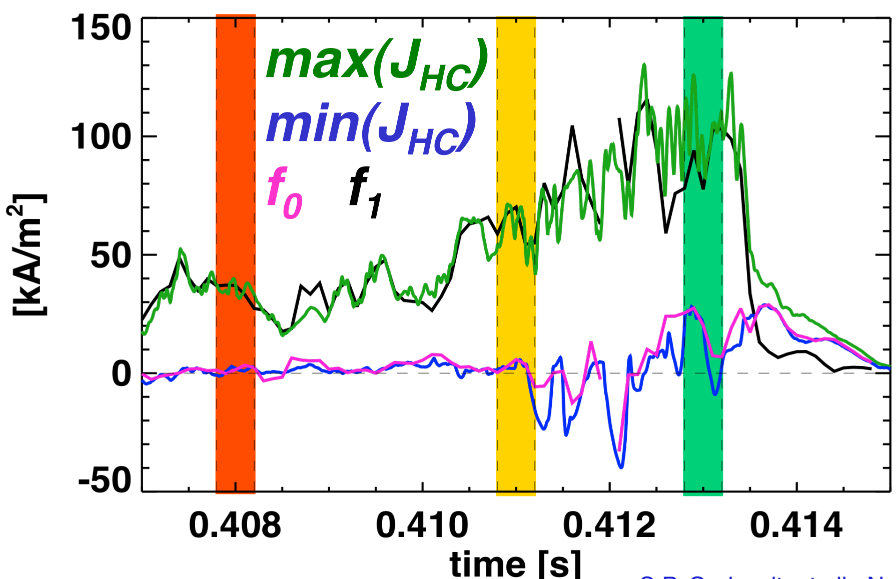
$$f(t,\phi) = f_0 + f_1 \cos^{2f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$

Example Curves

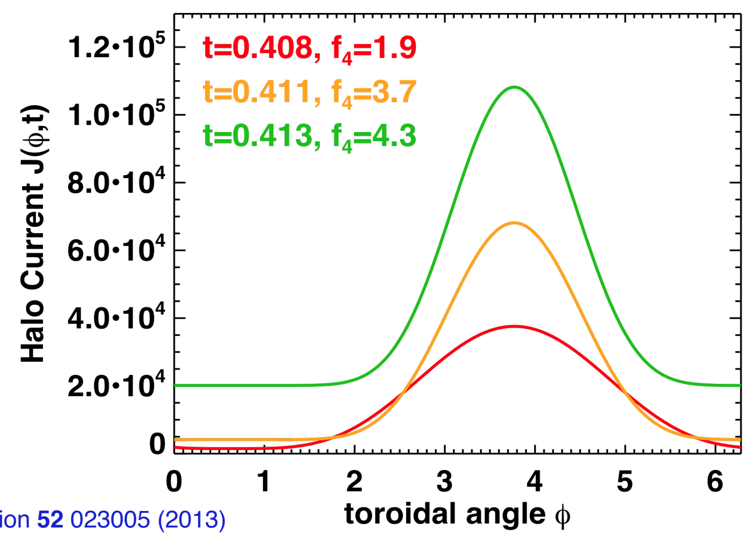


Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current





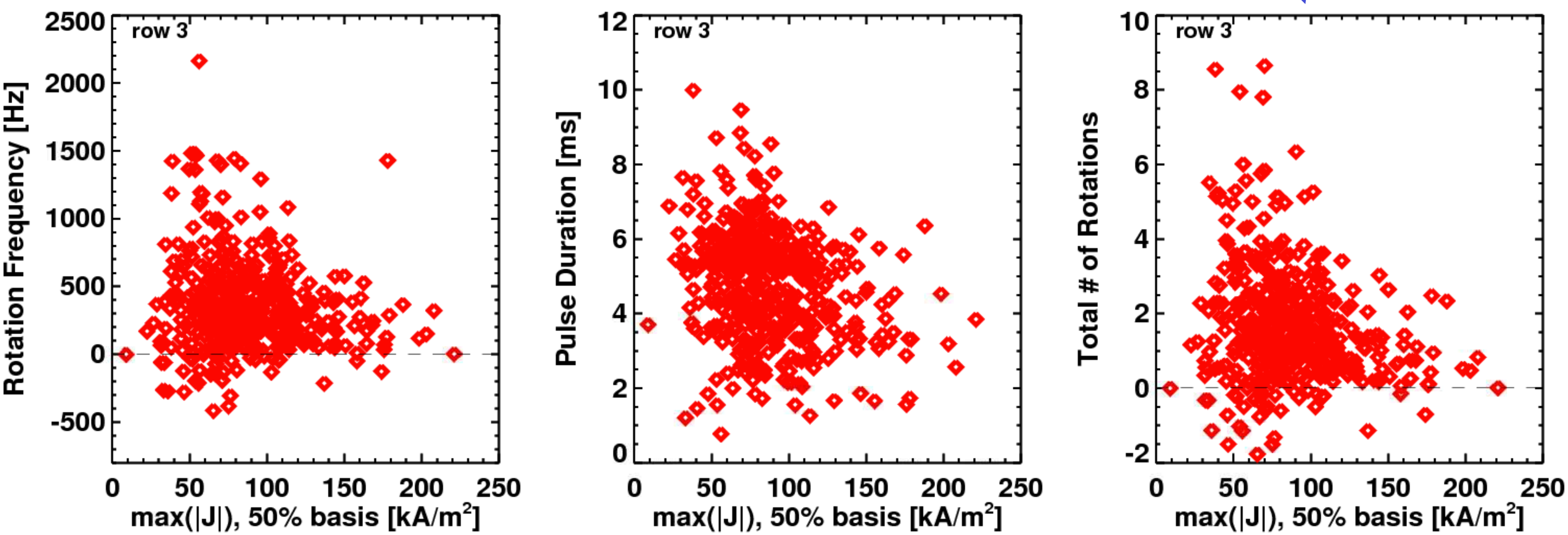
$$f(t,\phi) = f_0 + f_1 \cos^{2f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$



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

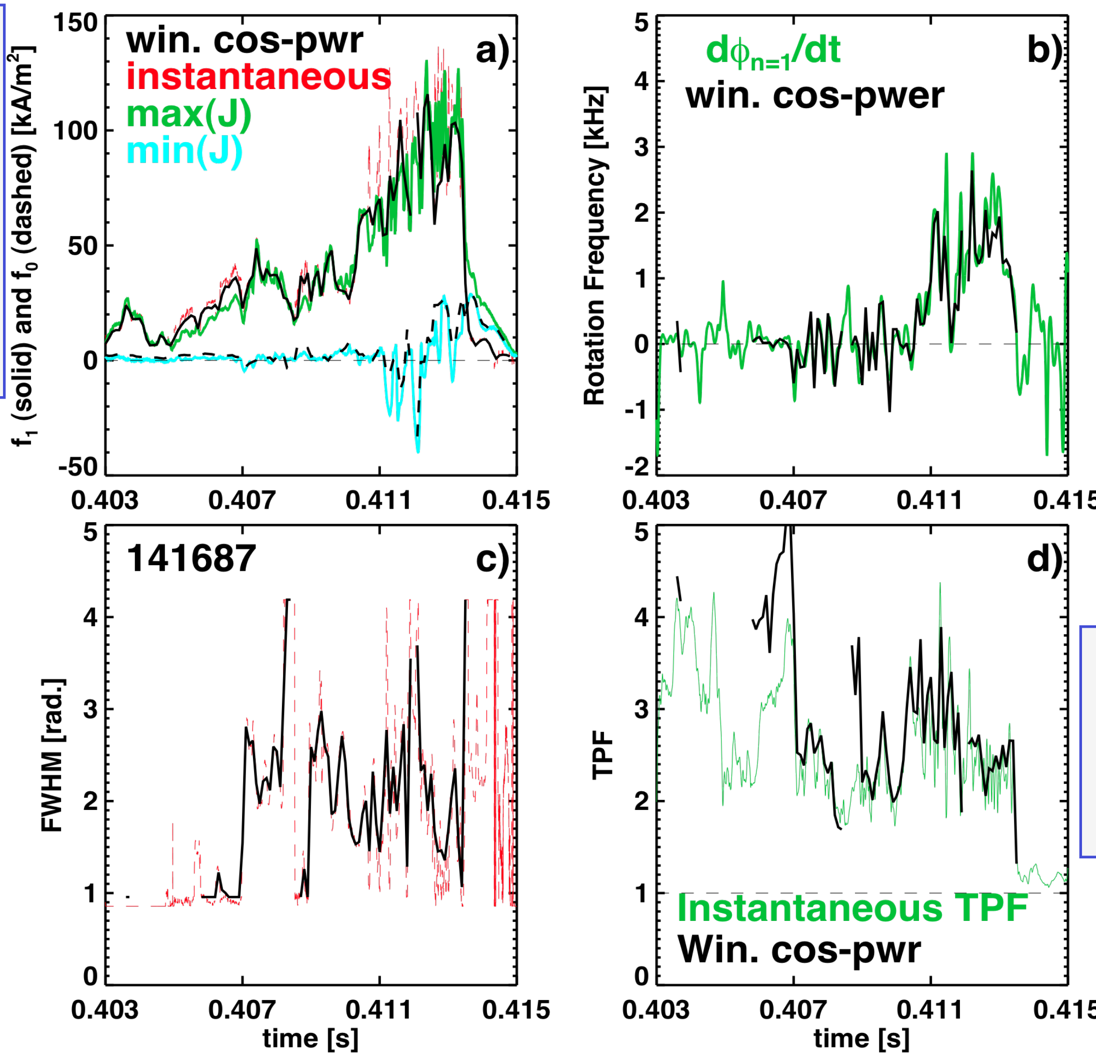
of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- 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*



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:

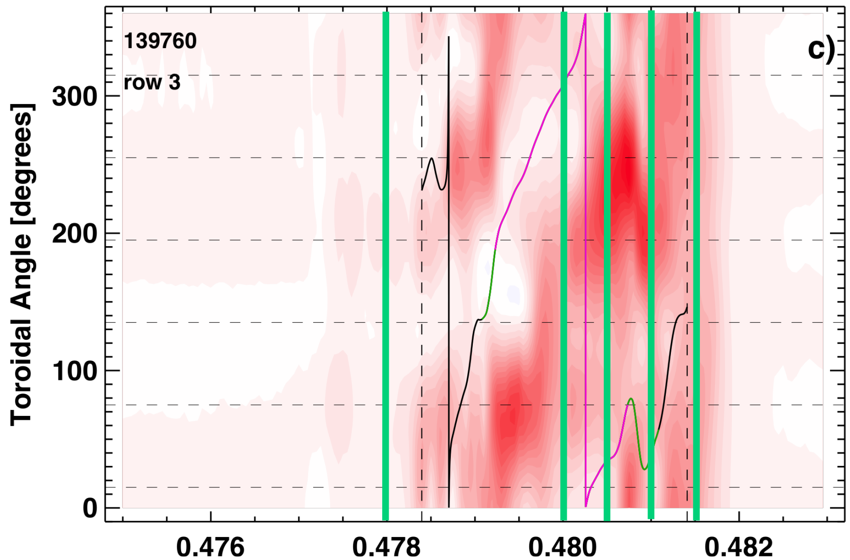
$$I_{HC}(\phi) = f_{n=0} + f_{n=1}\cos(\phi - \phi_{n=1})$$

From "windowed cosine power" fits

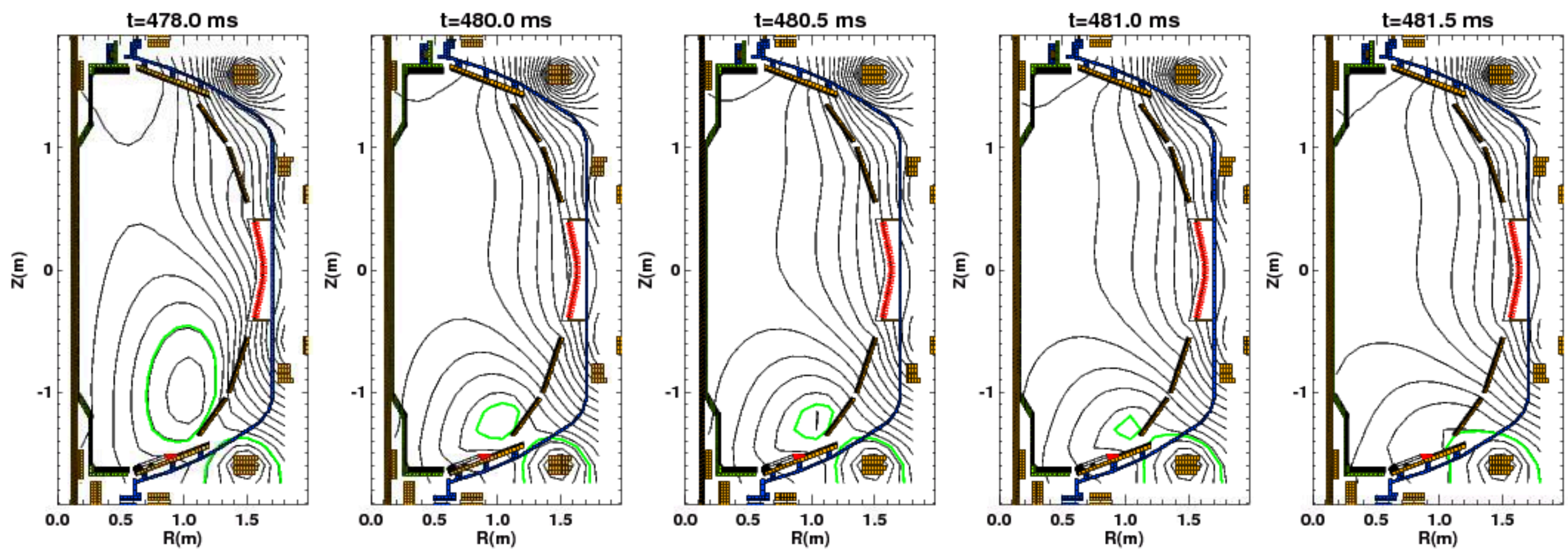
Full Width at Half Maximum:
Instantaneous cosine power fits
Windowed fits

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

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

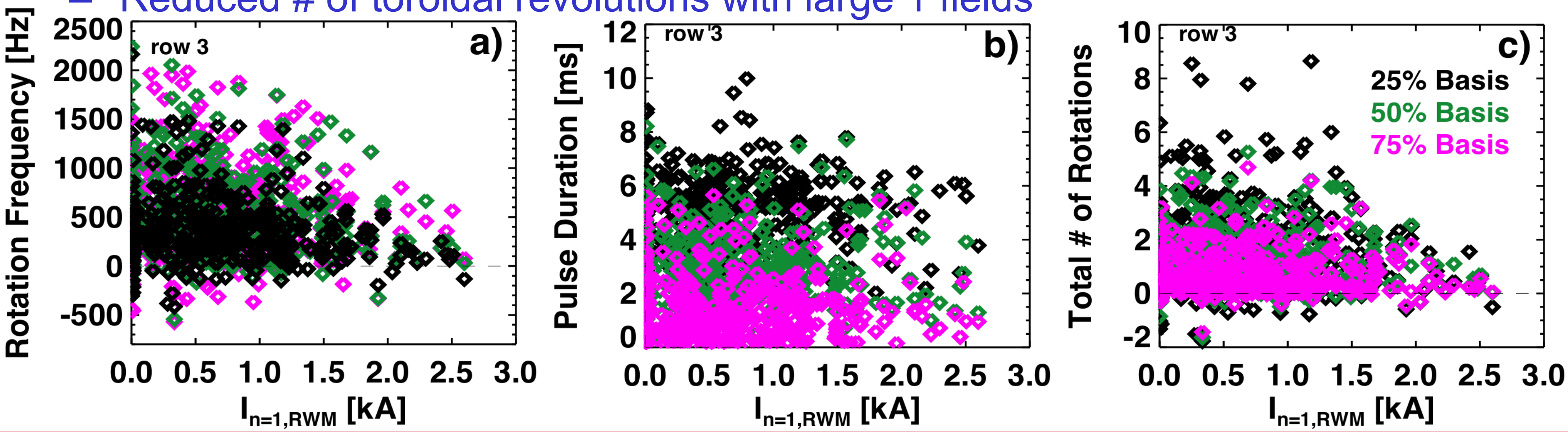


- Halo current contours are toroidally symmetric starting at ~0.481 s
- Utilize a regularized toroidal filament model for the reconstruction.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late axisymmetry corresponds to near or complete loss of closed surface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



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

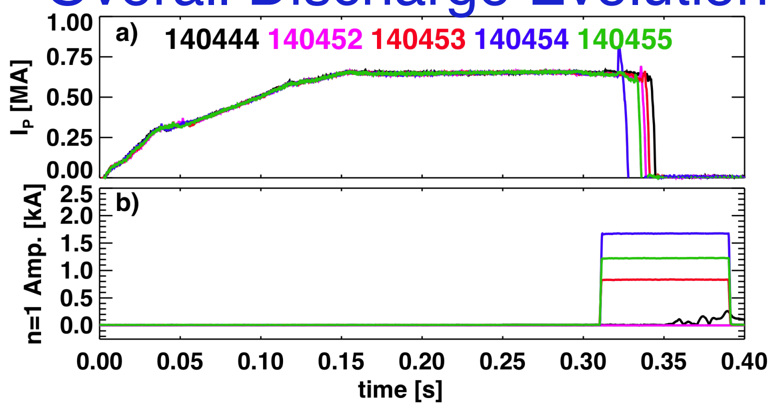
- Large n=1 fields are often applied by the RWM control system during a disruption. Due to:
  - Actual 3D distortions of the plasma
  - Toroidal & non-axisymmetric eddy currents leading to incorrectly identified “modes”.
    - On-line doesn’t have v_{loop} sensor compensationsas in the off-line analysis.
- 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



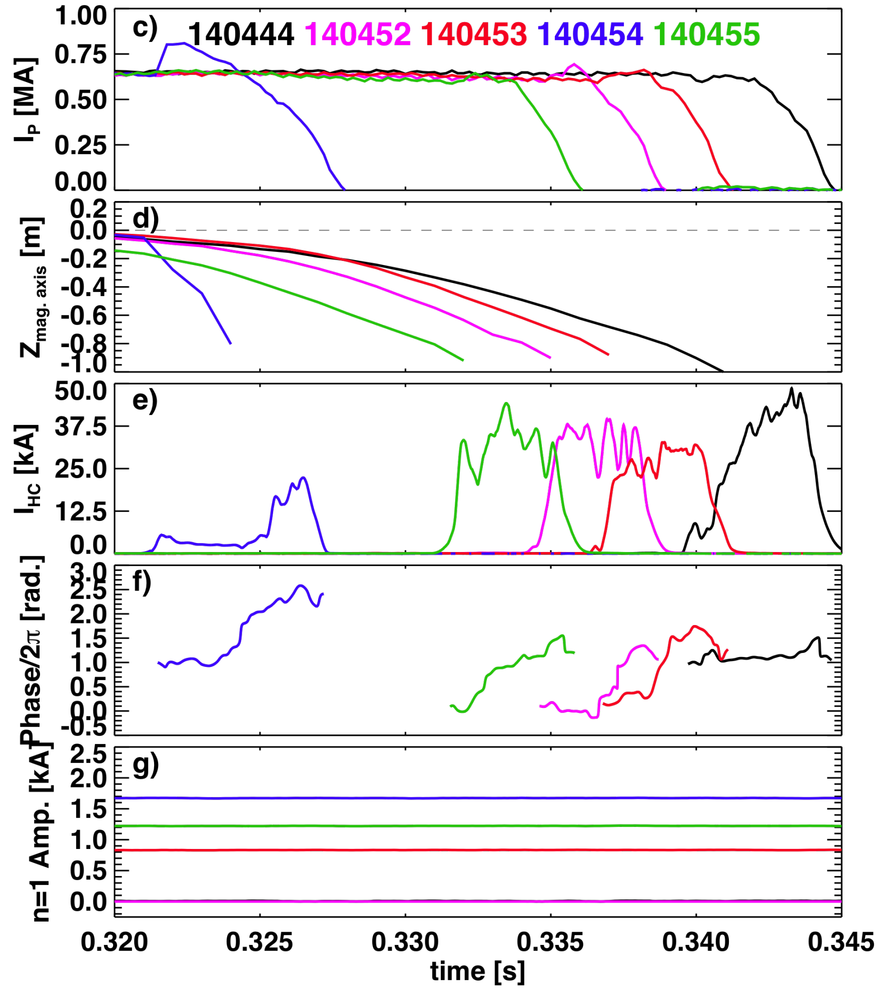
n=1 Fields Did Not Modify HC Rotation During Deliberate VDEs

- 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.

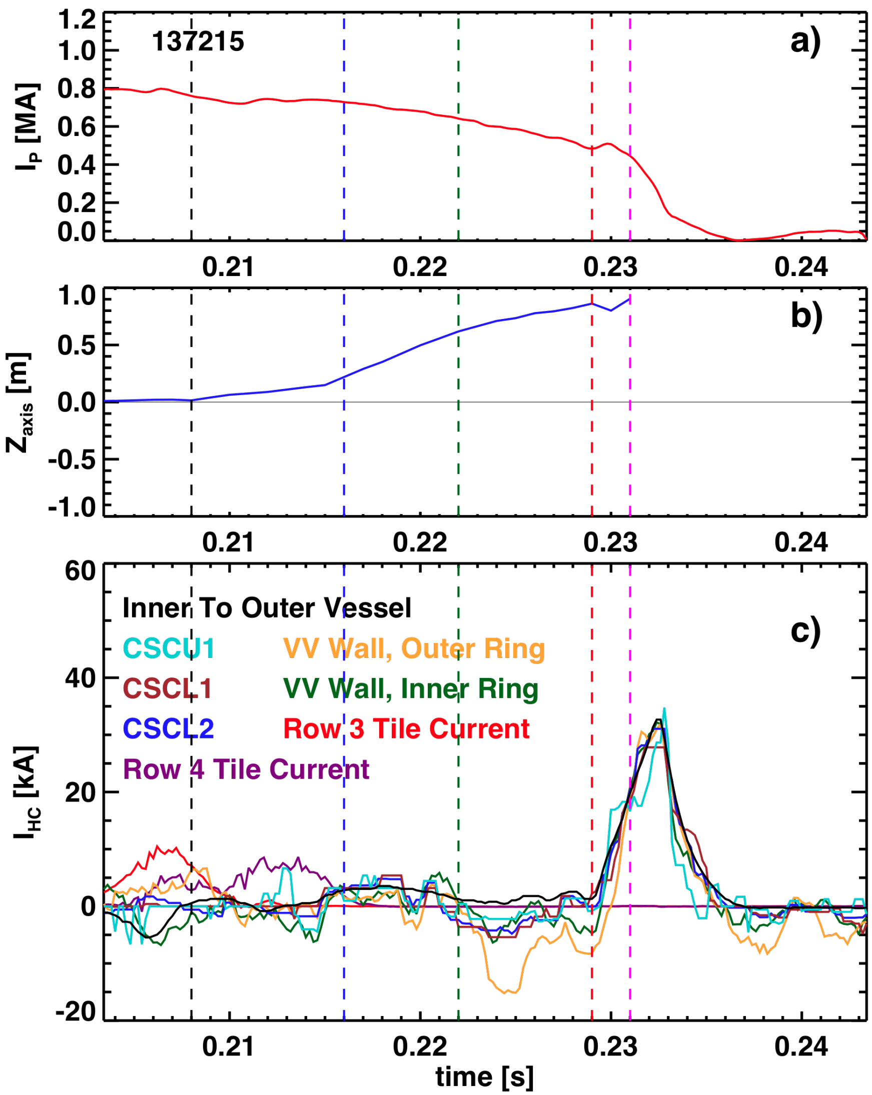
Overall Discharge Evolution



Dynamics of the Disrupting Phase



Upward VDEs Yield Odd Halo Current Pattern



Upward VDE results in currents in the bottom of NSTX

Halo extends to the upper inner horizontal target, where it can only return current through a circuitous router.