Disruption Detection and Halo Currents in NSTX

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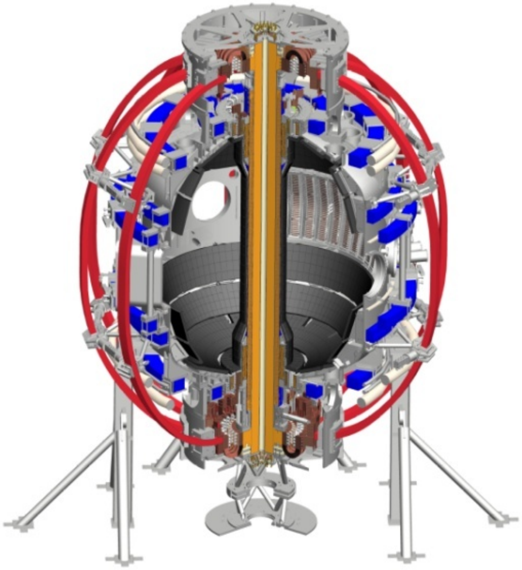

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This talk: Disruption Detection and Halo Currents

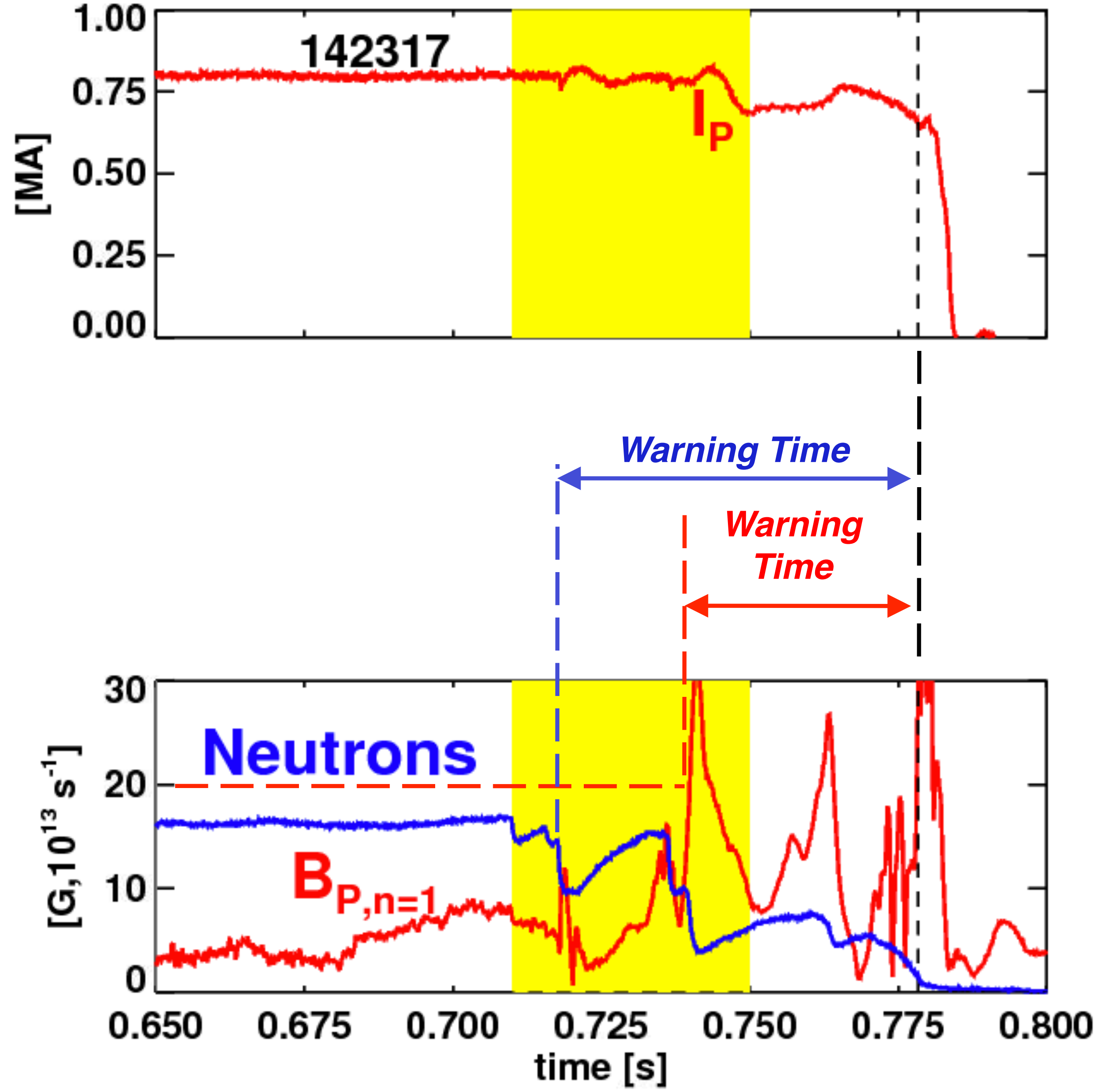
- NSTX research addresses many aspects of disruption avoidance.
  - See talks/papers by S. Sabbagh, J. Berkery, J. Menard, S.P. Gerhardt, J.-K. Park, A. Sontag,…

- Have initiated a program in mitigation physics.
  - See talks/paper by R. Raman

- This talk:
  - Disruption detection
  - Halo currents

- Try to provide a bit more detail than in IAEA FEC talk.

Warning Times Defined With Respect to the Current Quench



False Positive:

Warning more than 300 ms in advance of current quench.

Late Warning:

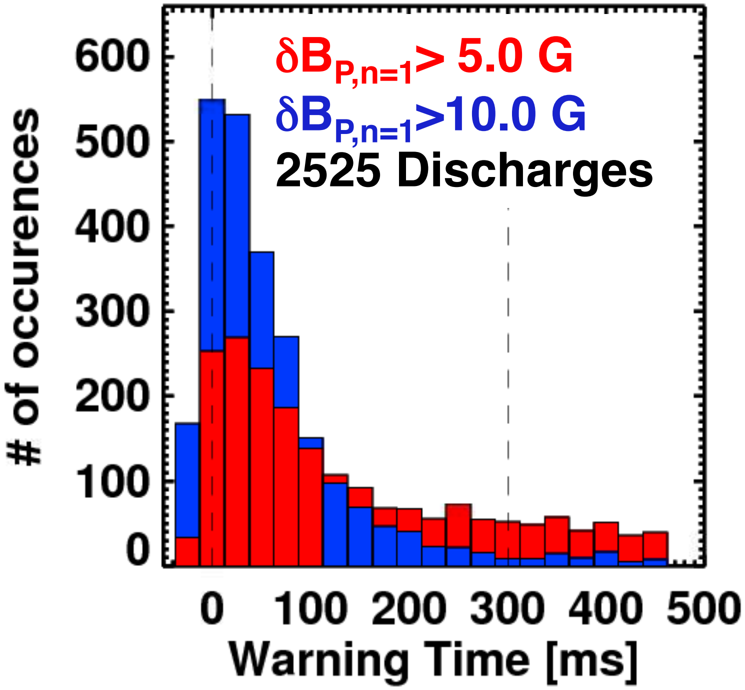
Warning later than 10 ms before the current quench.

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

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

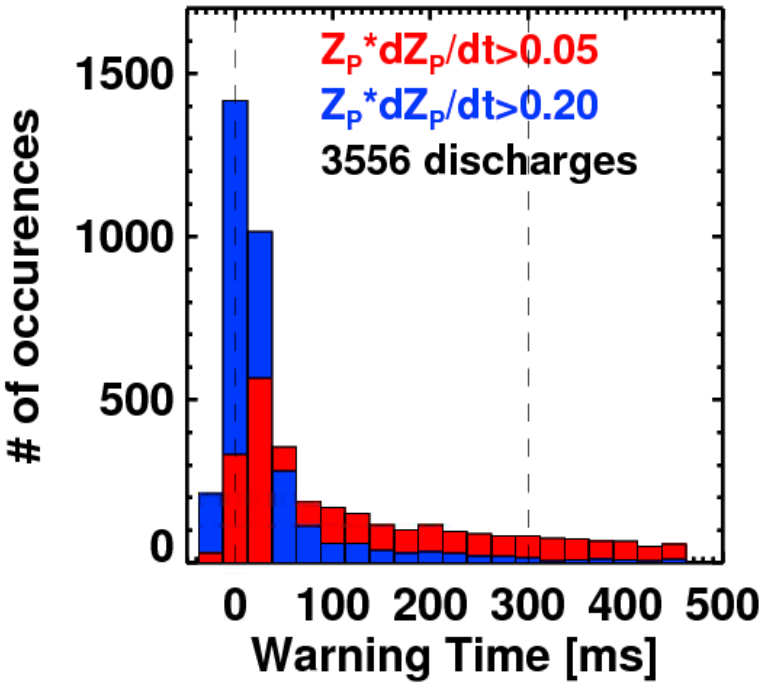
- n=1 perturbation inferred from array of 24 in-vessel poloidal field sensors
  - Useful for detecting resistive wall modes, locked modes

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

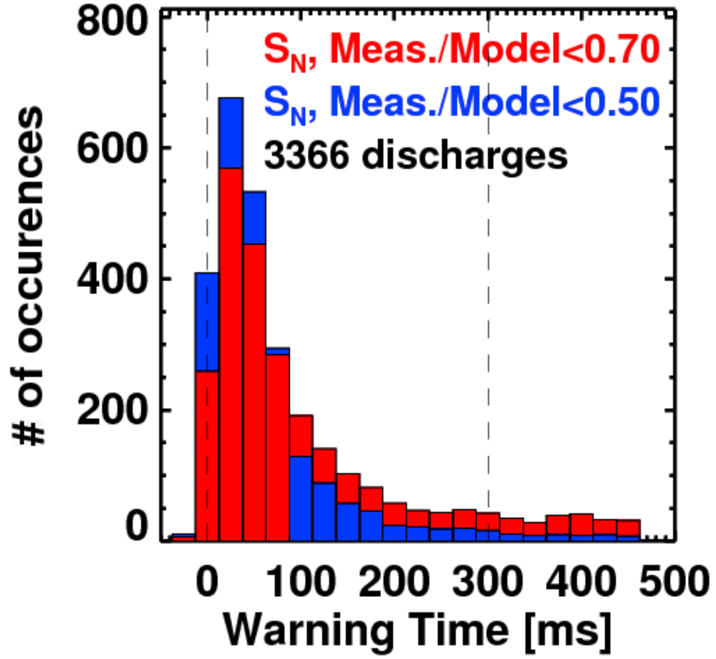
threshold	% Late Warning	% False Positive	% No Trigger
0.05	2	31	1
0.2	15	4	3



Comparison of Diagnostic Signal to Simple Models Can Provide Useful Indicators

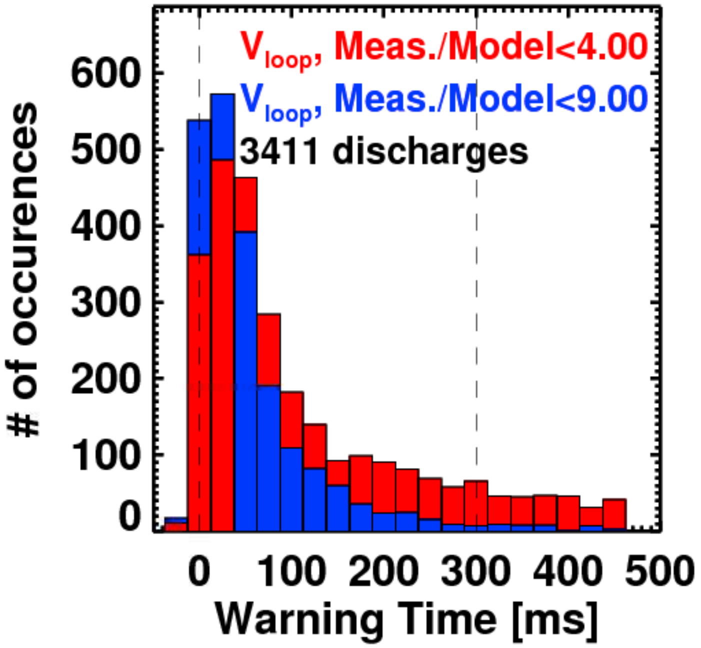
- Often a significant drop in neutron emission proceeding a disruption.
- Estimate the neutron emission from a simple slowing down model.
    - T_e, Z_{eff}, n_e are inputs.

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



Examined Many Threshold-Based Disruption Indicators

- Instantaneous Stability
  - Vertical motion indicators.
  - n=1 perturbed fields.
  - Low-frequency, large amplitude rotating MHD modes.
- MHD Equilibrium
  - $F_P=p_0/\langle p\rangle$, l_i, q_{95}, q^*
    - (β_N alone has no predictive value).
  - 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 ratio
  - Deviations between the current and the I_P request

Developed a Method to Combine These Tests For Improved Prediction

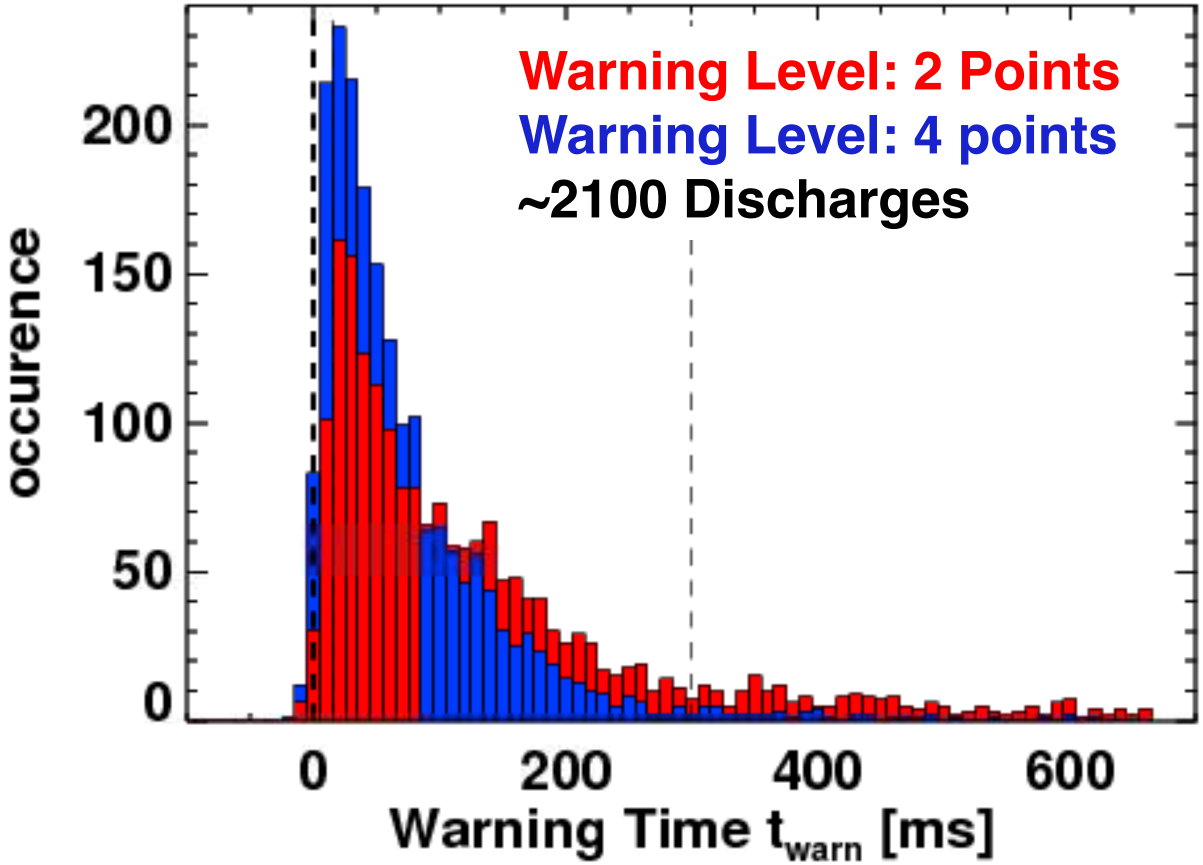
- No one of these diagnostic tests was good enough to predict all disruptions.
  - Must combine the tests in some fashion.
- Algorithm summary:
  - Note: Low threshold levels lead to high false positive rates, few missed disruptions.
  - Take a series of ~15 threshold tests like those previously described.
  - 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.
  - Declare a disruption warning if the aggregate total exceeds a chosen value.
  - May not yet be optimized.

3-Level Warning Rule Can Predict Most Disruptions



Warning at 2 Points

1.8% late warning

15% false positive

Sum: 16.8%

Warning at 4 Points

~2.8% late warning

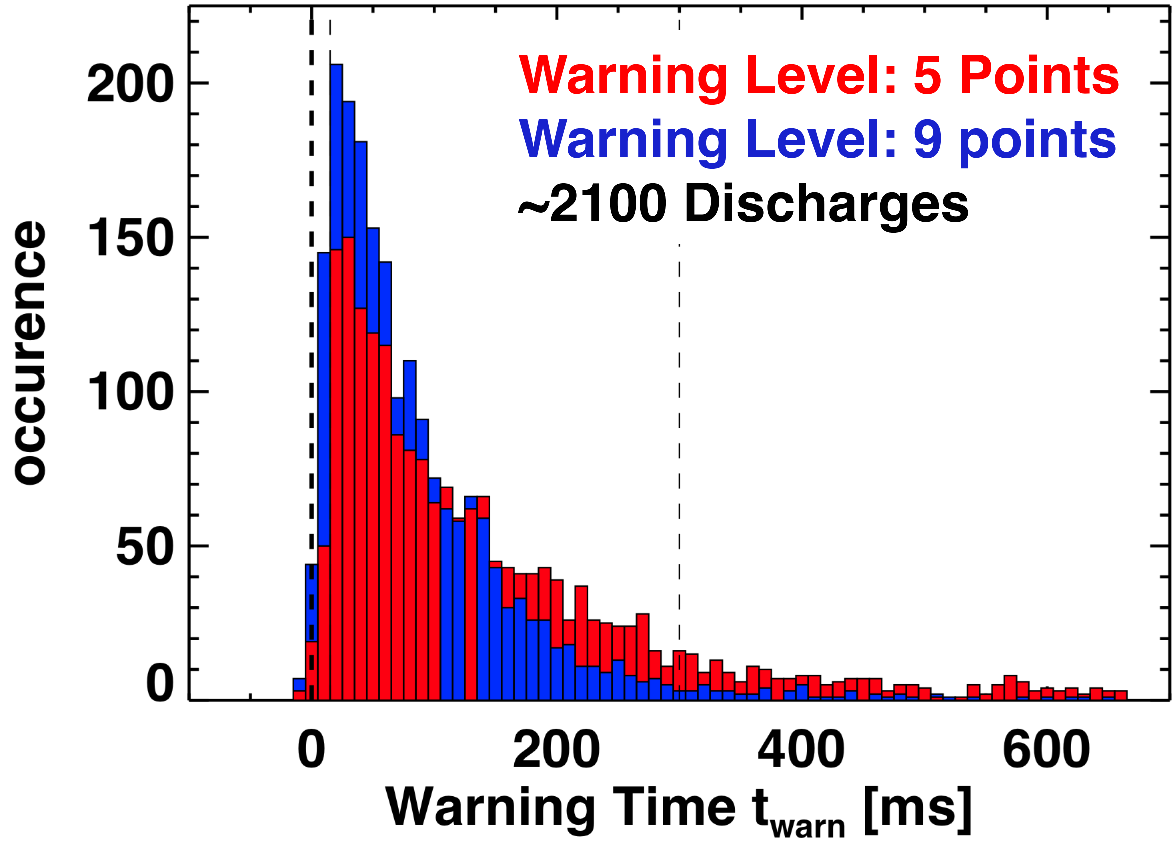
~4.8% false positive

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
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 5 Points

<1% late warning

~15% false positive

Sum: 16%

Warning at 9 Points

~2% late warning

~4% false positive

Sum: 6%

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

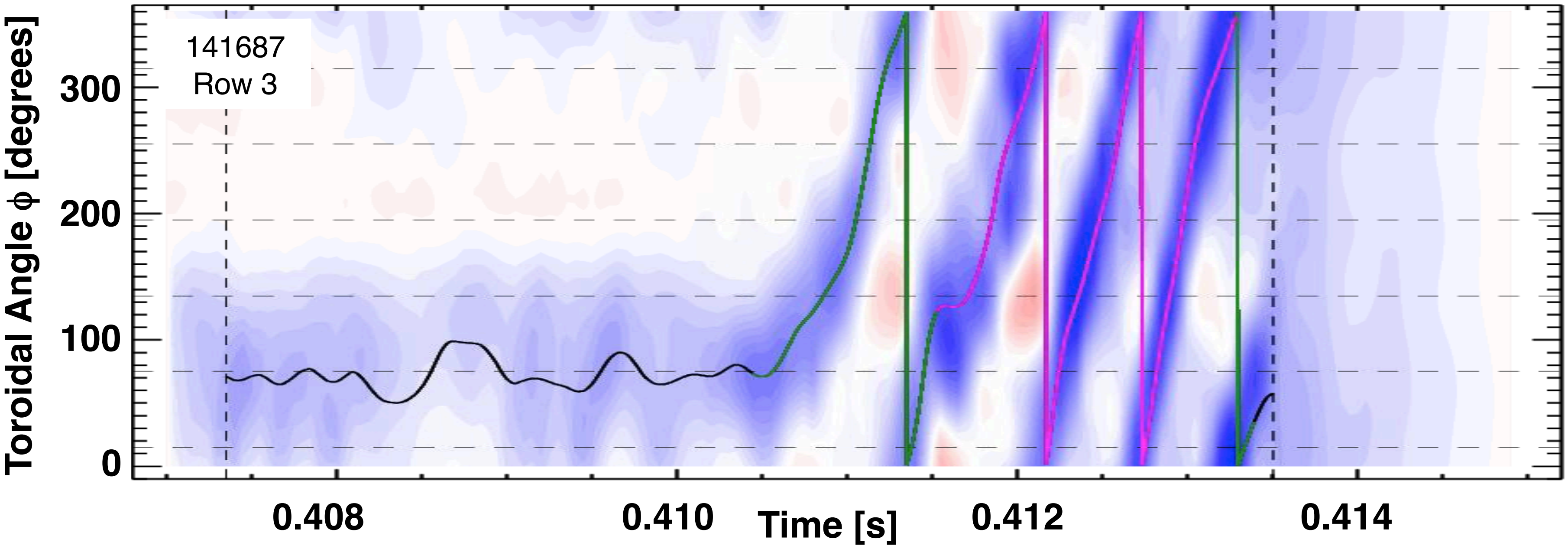
Actual algorithm has ~15 rows

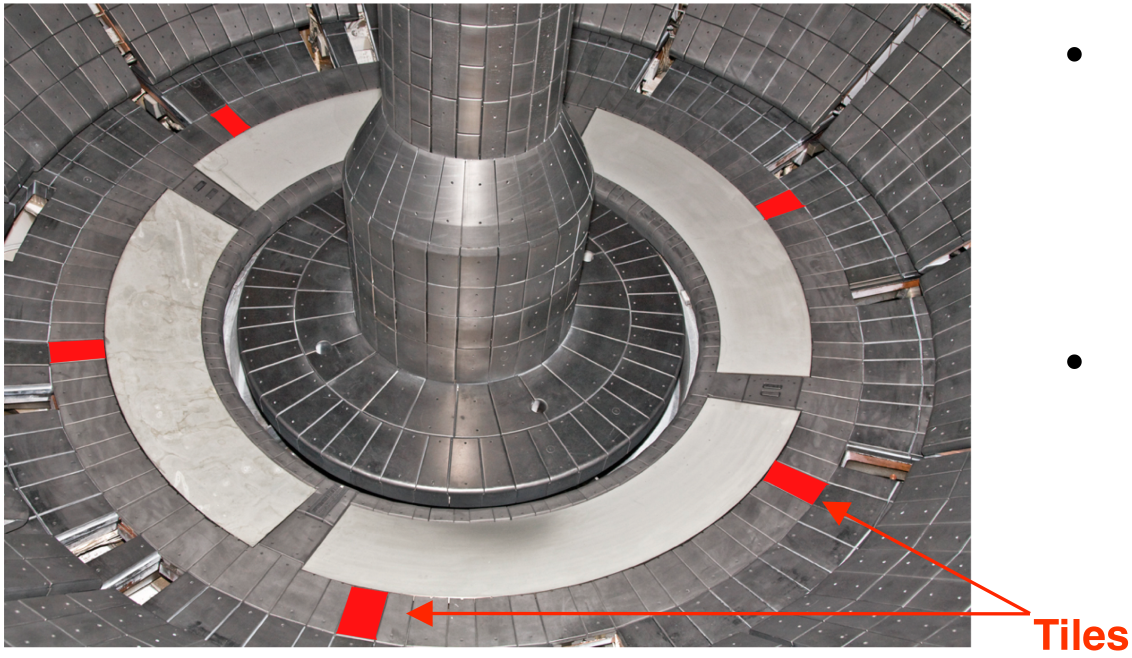
Test	1 pt -> 10% False Positive Rate	2 pt ->5% False Positive Rate	3 pts -> 2% False Positive Rate	4pts -> 1% False Positive Rate	5pts -> 0.5% False Positive Rate
n=1 B_P Perturbation [G]	8	10	16	22	27
Neutrons, Meas./Model	0.59	0.51	0.41	0.35	0.29
V_{loop}, Meas./Model	6	7.5	10	16	24

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.
    - Need excellent realtime diagnostics.
  - ITER will have only a few target scenarios, NSTX has *many, many* scenarios.
- IMHO, 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,…

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

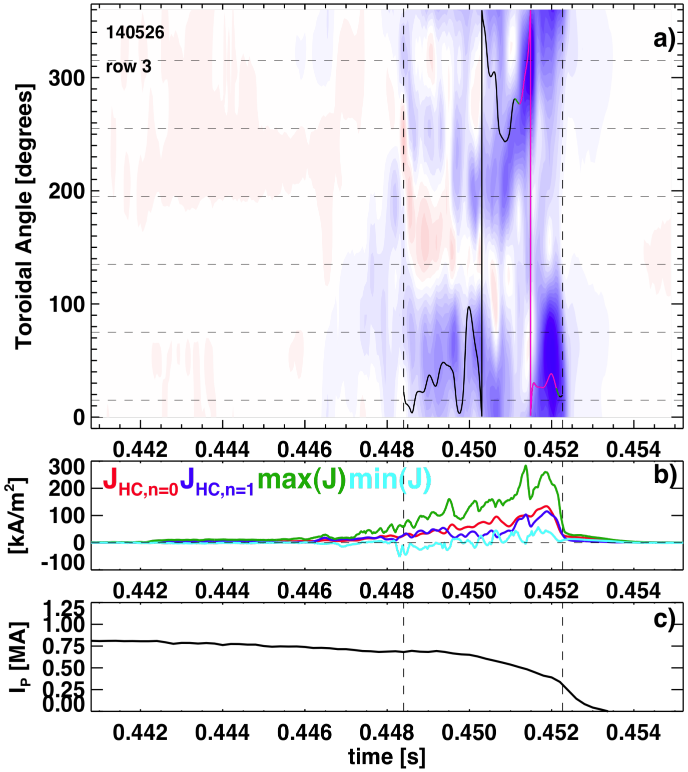




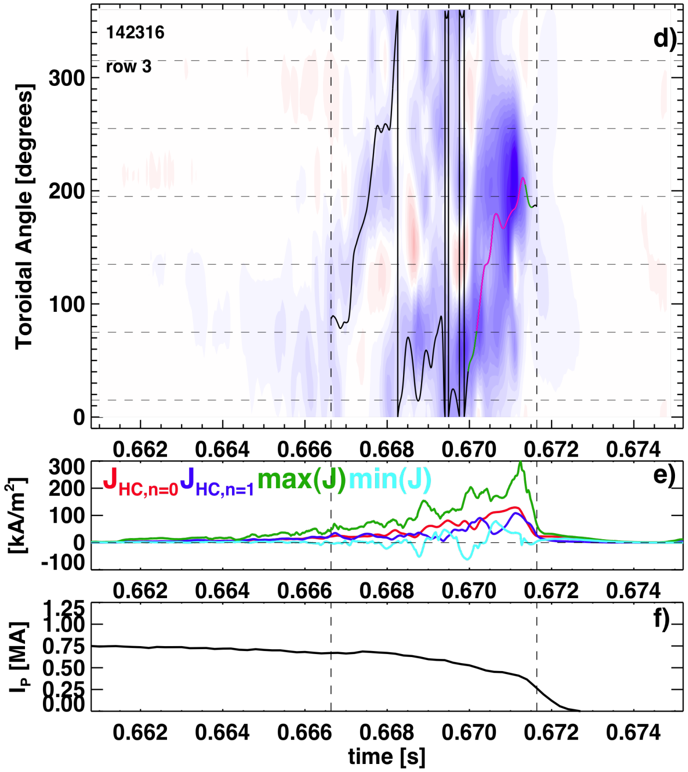
- Measurements from an array of instrumented tiles
  - Same poloidal angle
  - Distributed toroidally
- Infer strong toroidal asymmetry, often with significant rotation, at locations where currents enter the divertor floor.

Further Examples of Halo Current Rotation Dynamics

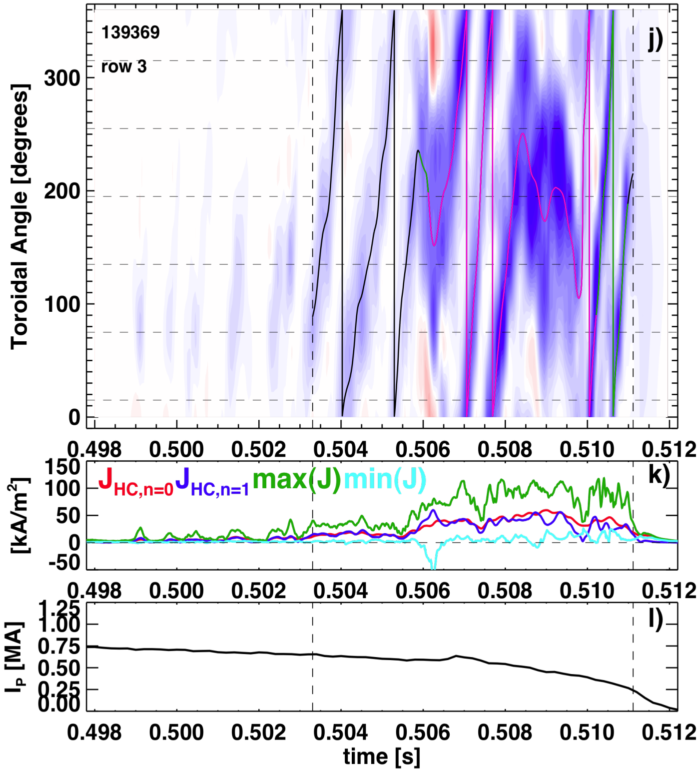
Large Currents and Little Rotation



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.

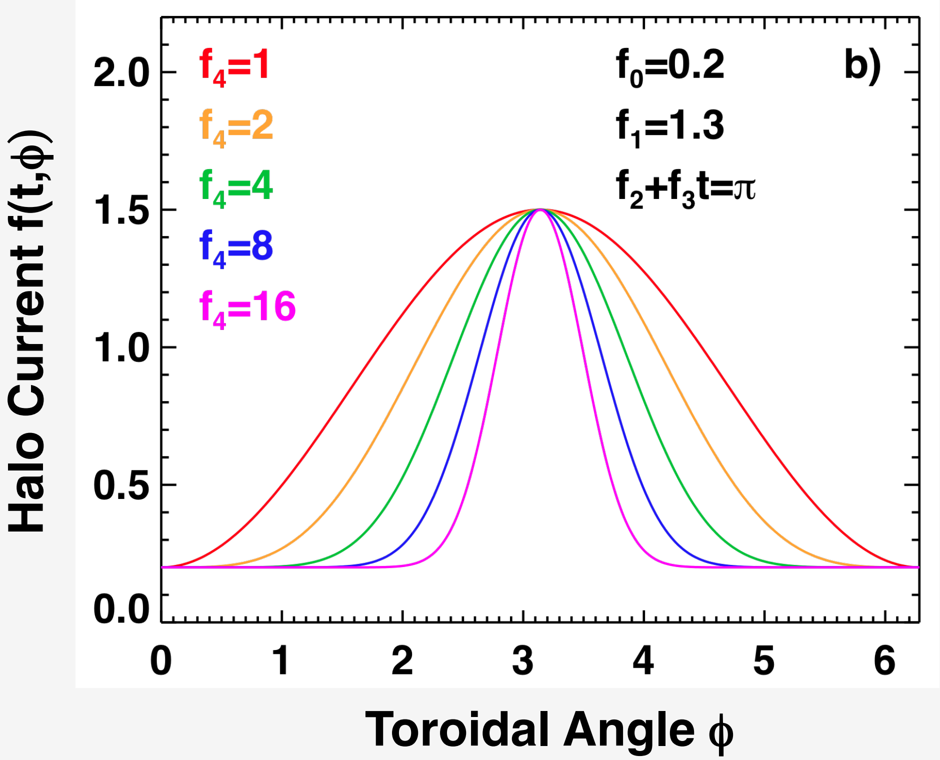
Use a Model Fit Function To Better Resolve the Halo Current Dynamics

- 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.
- Also did an "instantaneous" version of fit with no f_3 term, fits at each time sample.
  - These in red two slides forward.

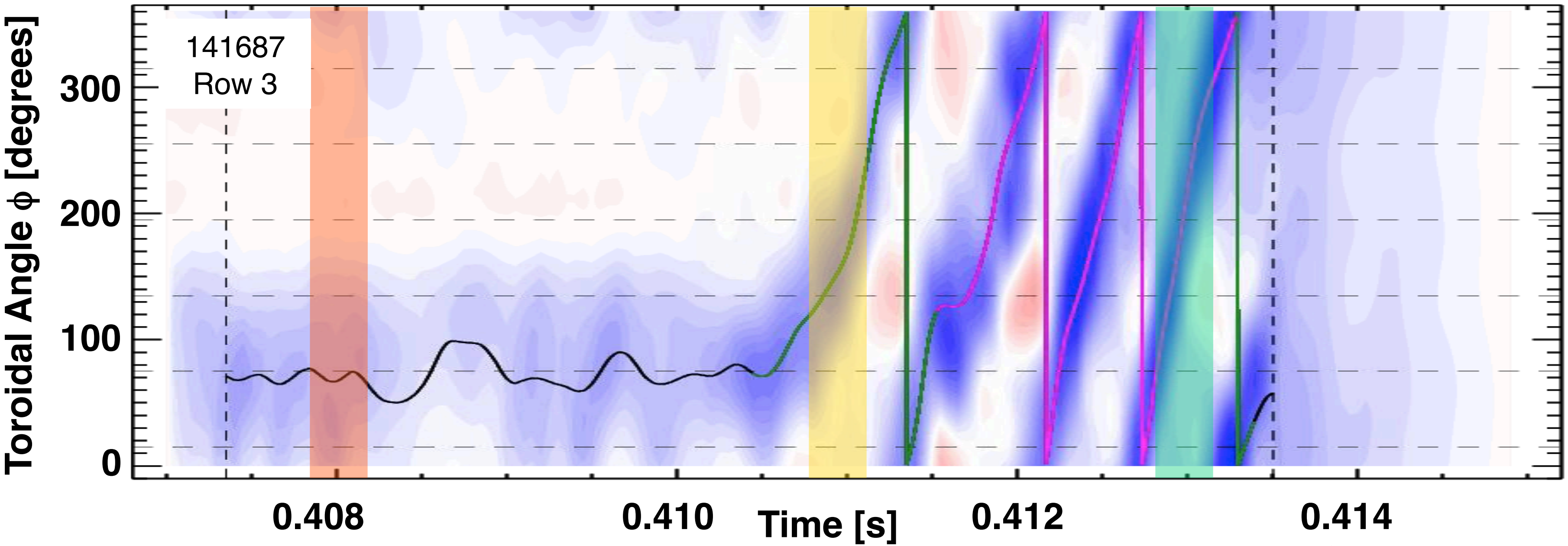
Model Function
"Windowed Cosine Power Fits"

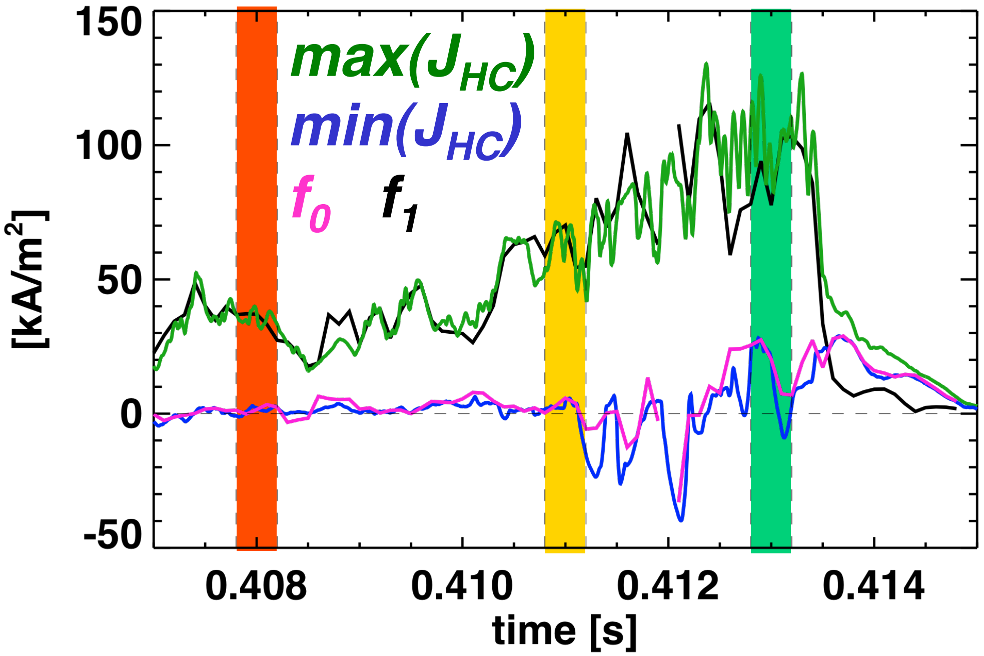
$$f(t,\phi) = f_0 + f_1 \cos^{2f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$

Example Curves

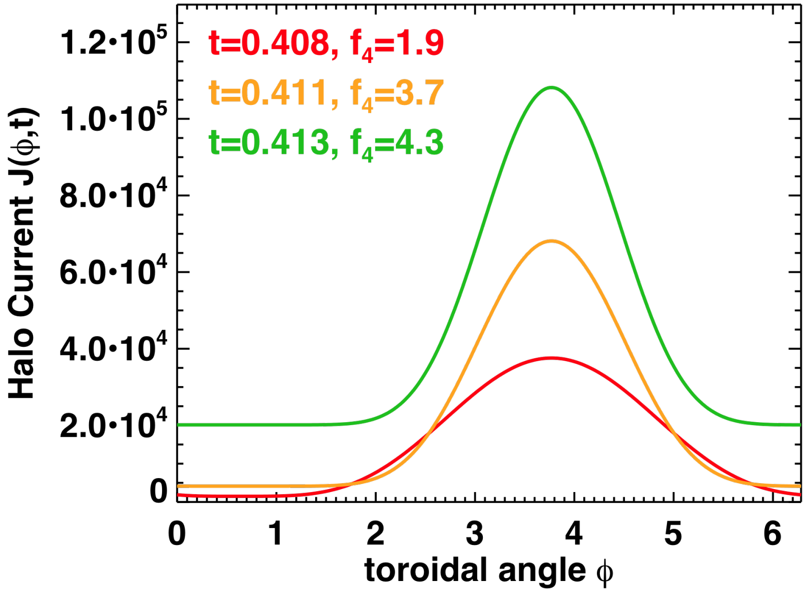


Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current





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



Fits Reveal Dynamics of the Halo Currents

Halo Current Amplitudes

Instantaneous cosine power fits (f_1)

Windowed fits (f_1: solid, f_0:dashed)

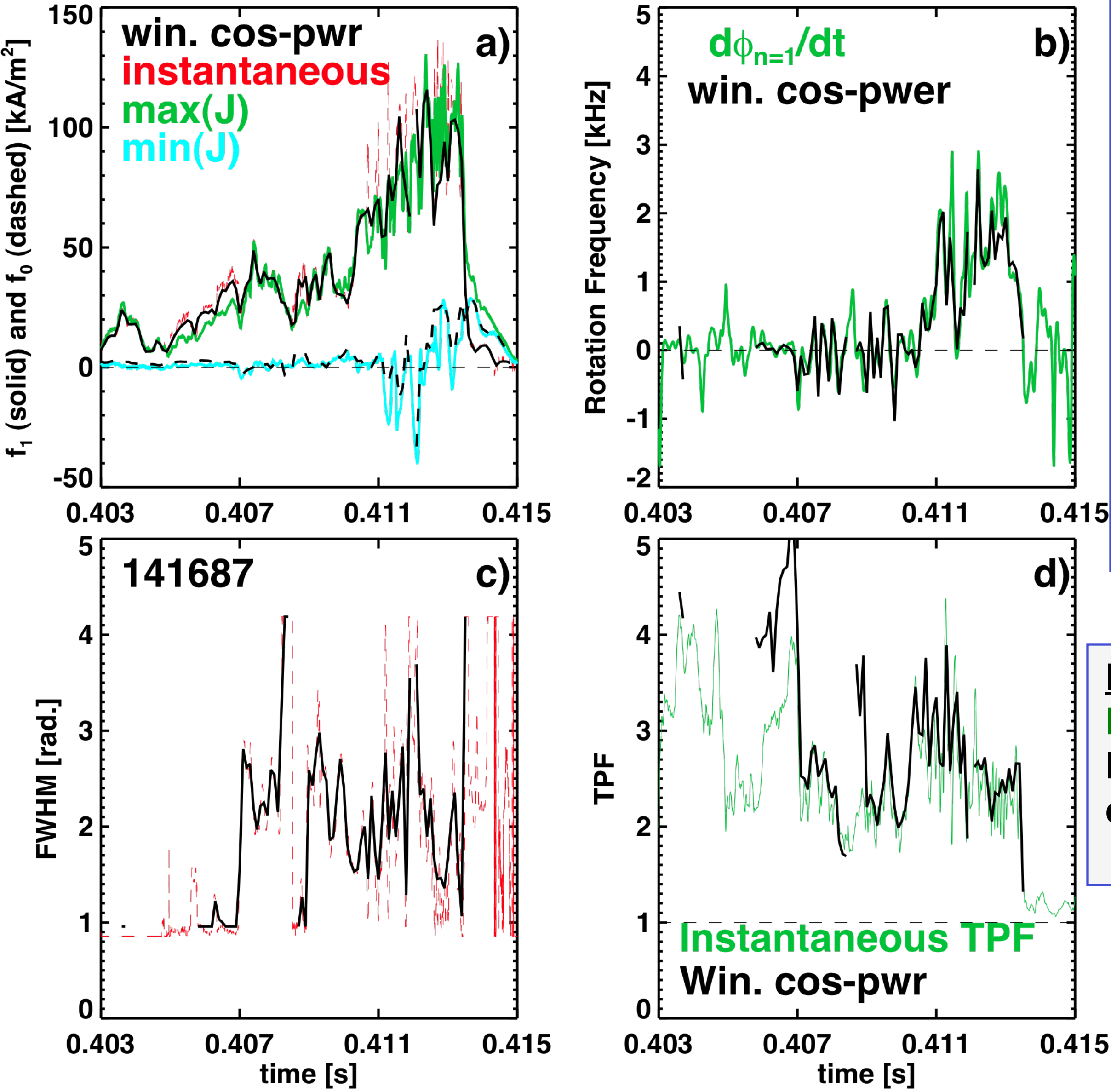
max(J_{HC})

min(J_{HC})

Full Width at Half Maximum:

Instantaneous cosine power fits

Windowed fits



Rotation Frequency

From differentiating phase of simple n=1 fits:

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

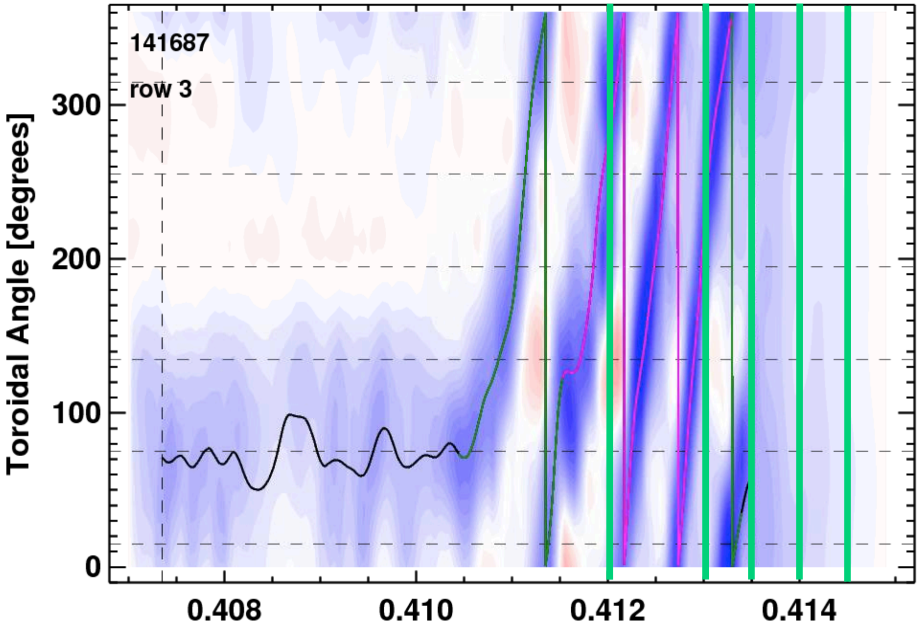
From "windowed cosine power" fits

Peaking Factor

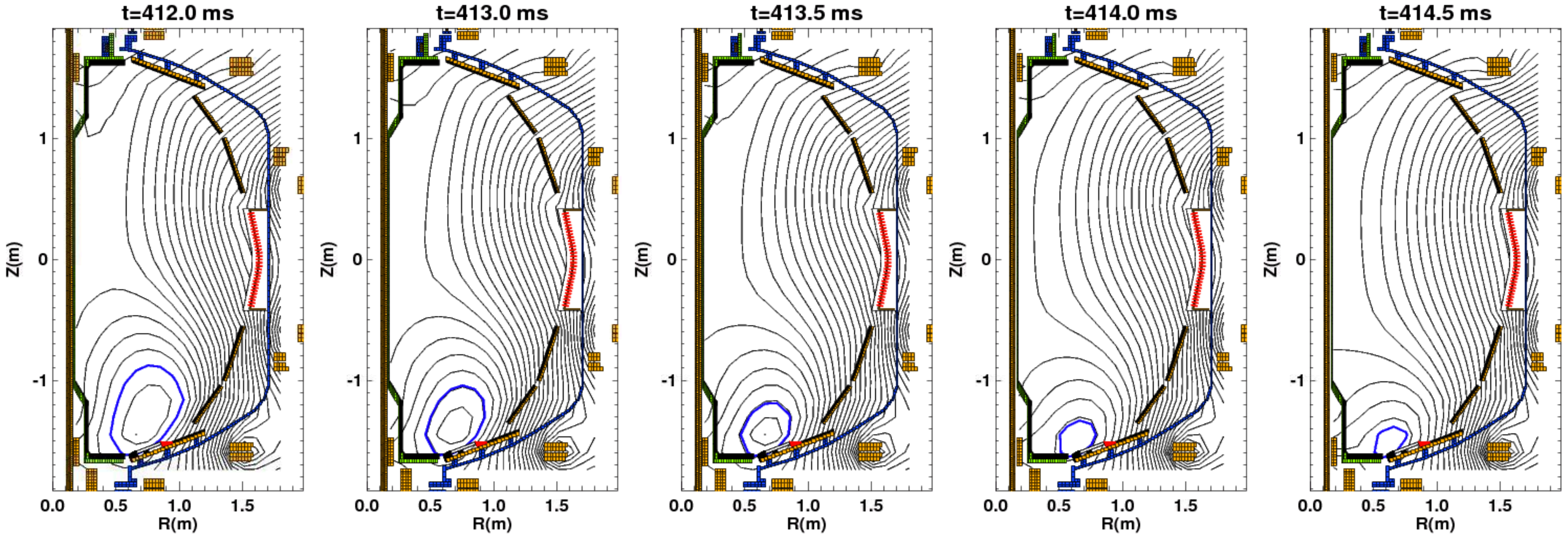
From raw data

From "windowed cosine power" fits

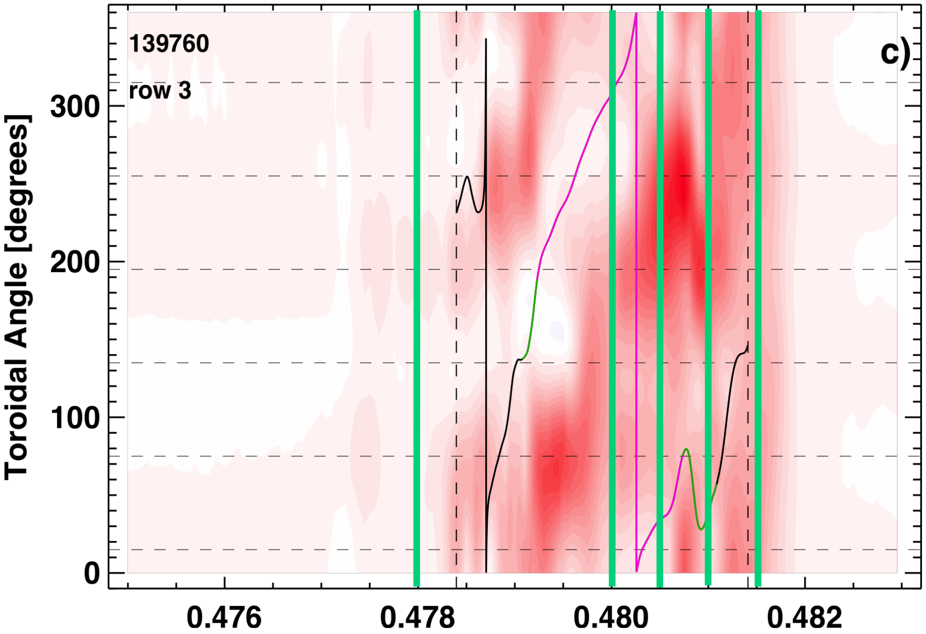
Halo Currents Become Symmeterized In the Final Phase of the Disruption: Example on OBD



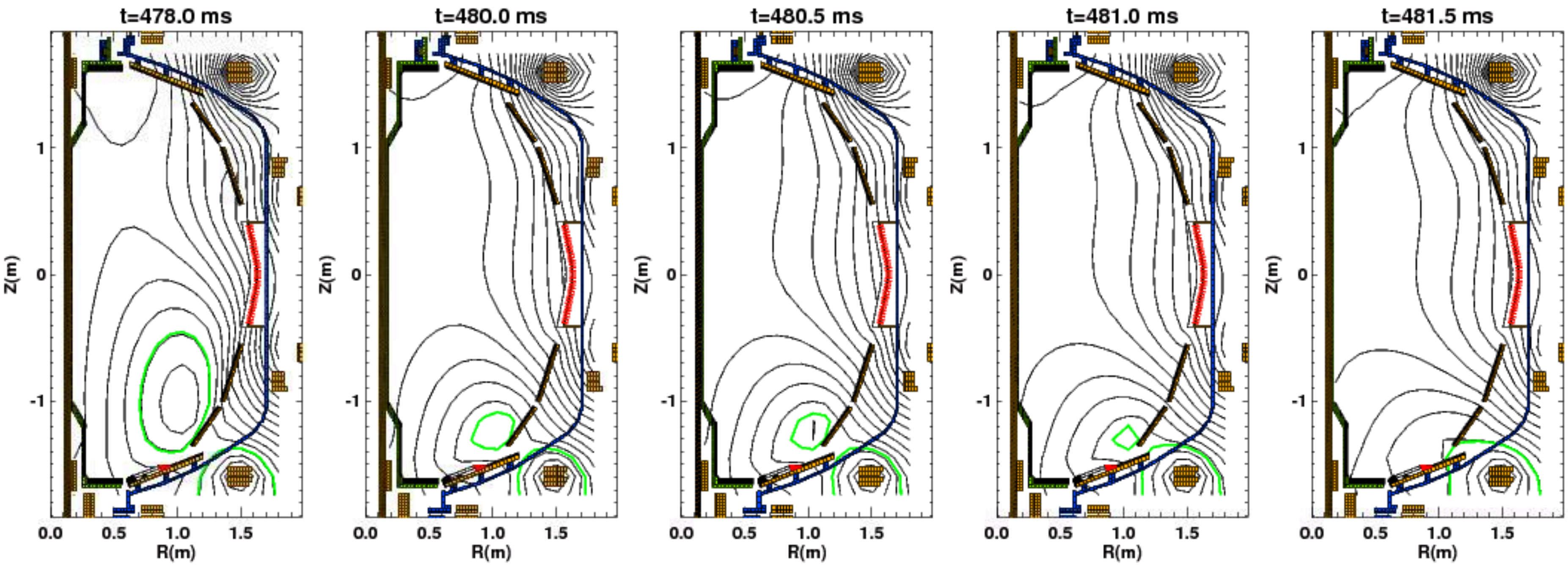
- Halo current contours are toroidally symmetric starting at ~0.4135 s
- Utilize a regularized toroidal filament model for the reconstruction.
    - Includes vessel eddy currents.
    - Does not satisfy $\nabla p = J \times B$
- Period of late axisymmetry corresponds to near or complete loss of closed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



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

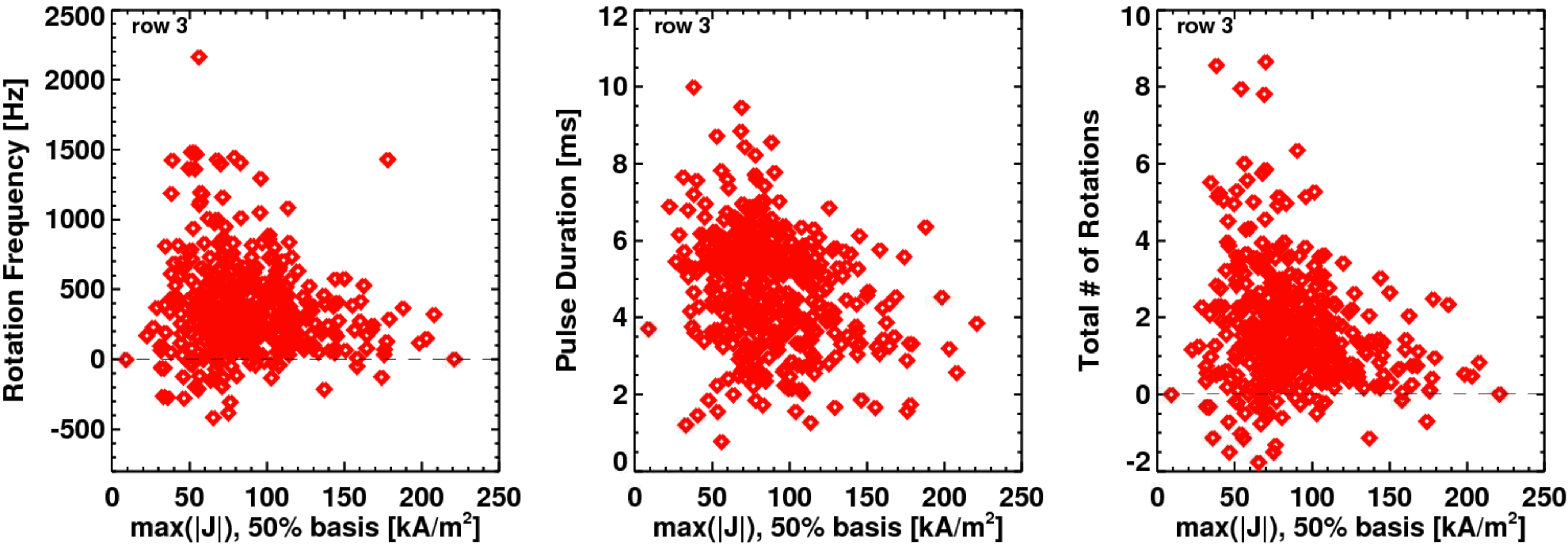


- Halo current contours are toroidally symmetric starting at ~0.481 s
- Utilize a regularized toroidal filament model for the reconstruction.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late axisymmetry corresponds to near or complete loss of closed surface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



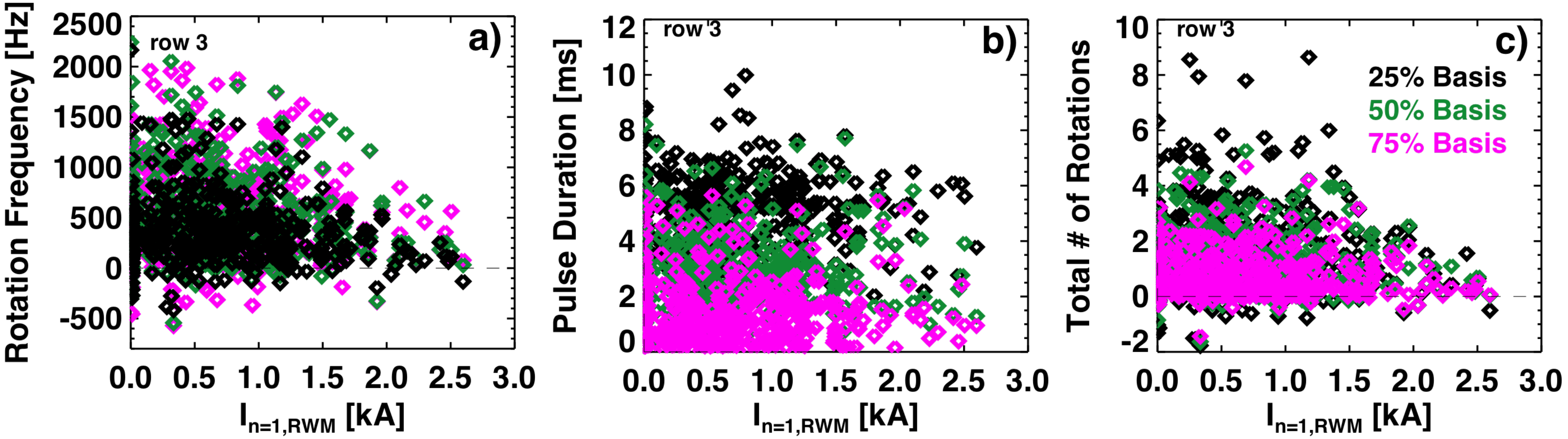
of Rotations is Observed to Scale Inversely with Halo Current Magnitude

- 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*



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

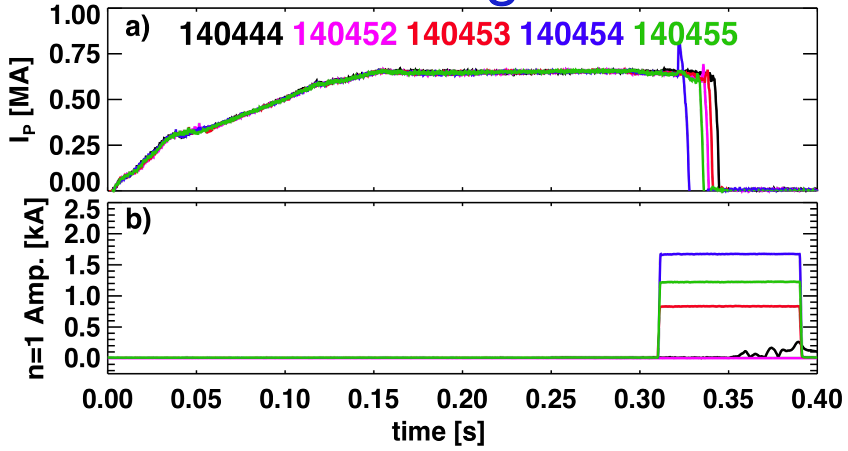
- Large n=1 fields are often applied by the RWM control system during a disruption. Due to:
  - Actual 3D distortions of the plasma
  - Toroidal & non-axisymmetric eddy currents leading to incorrectly identified “modes”.
    - On-line doesn’t have v_{loop} sensor compensationsas in the off-line analysis.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



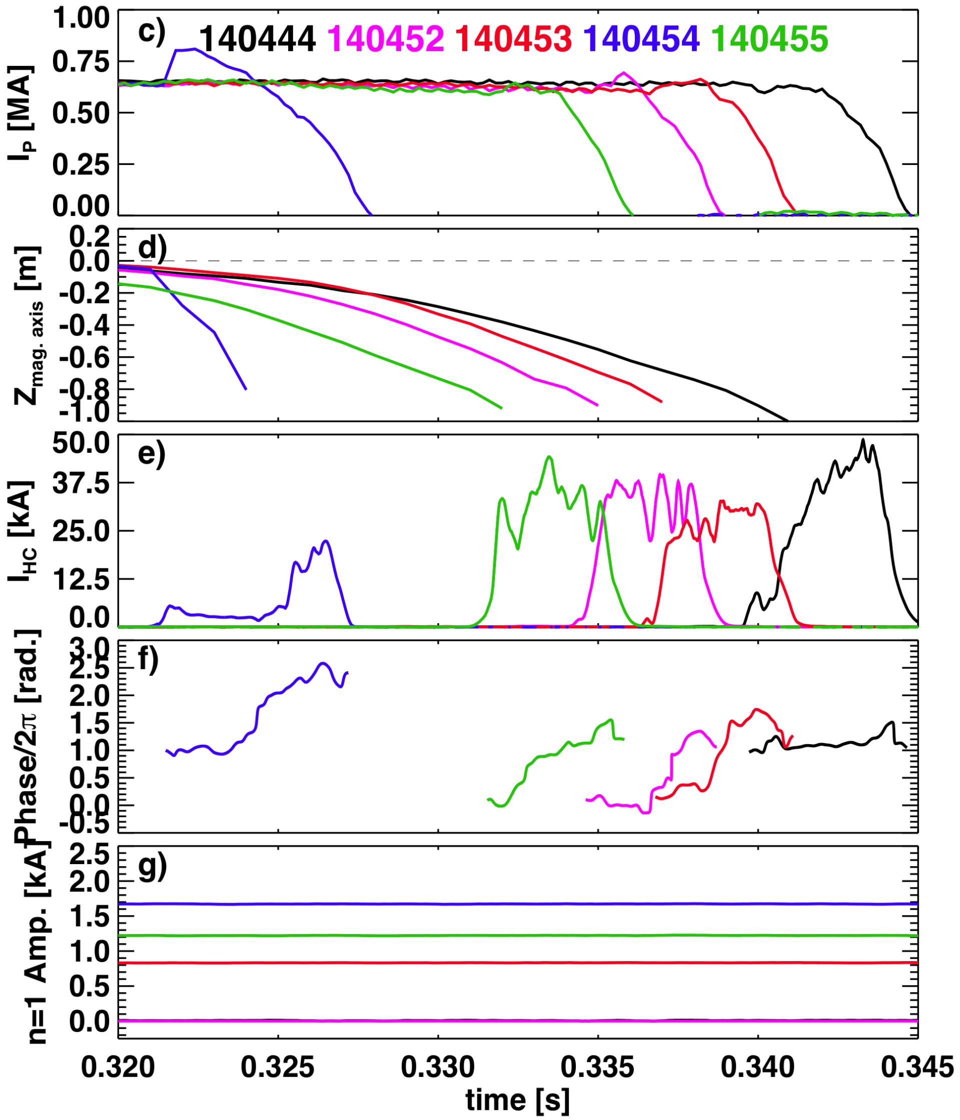
n=1 Fields Did Not Modify HC Rotation During Deliberate VDEs

- 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.

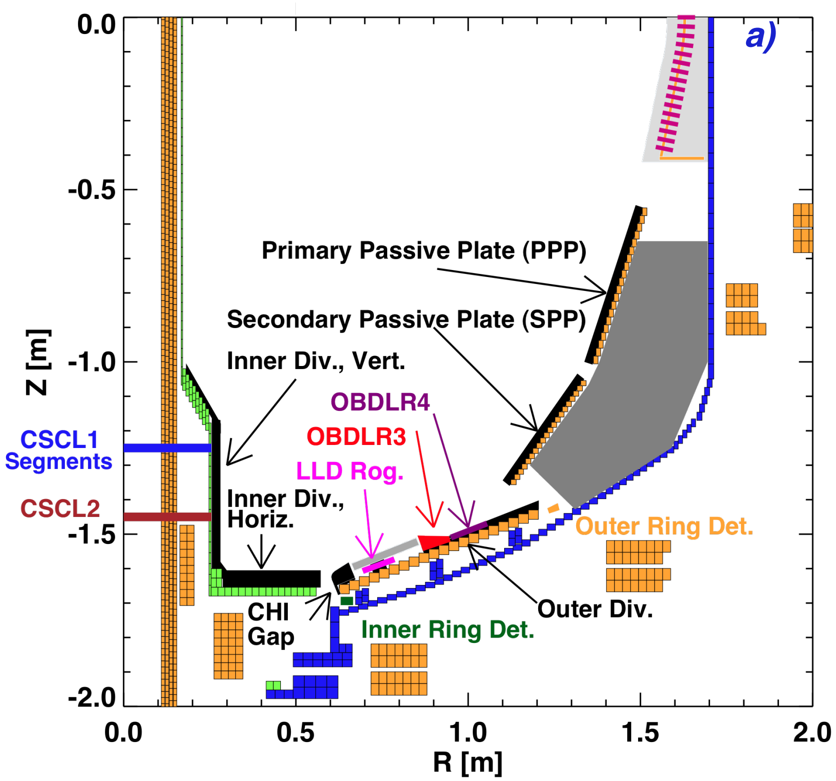
Overall Discharge Evolution

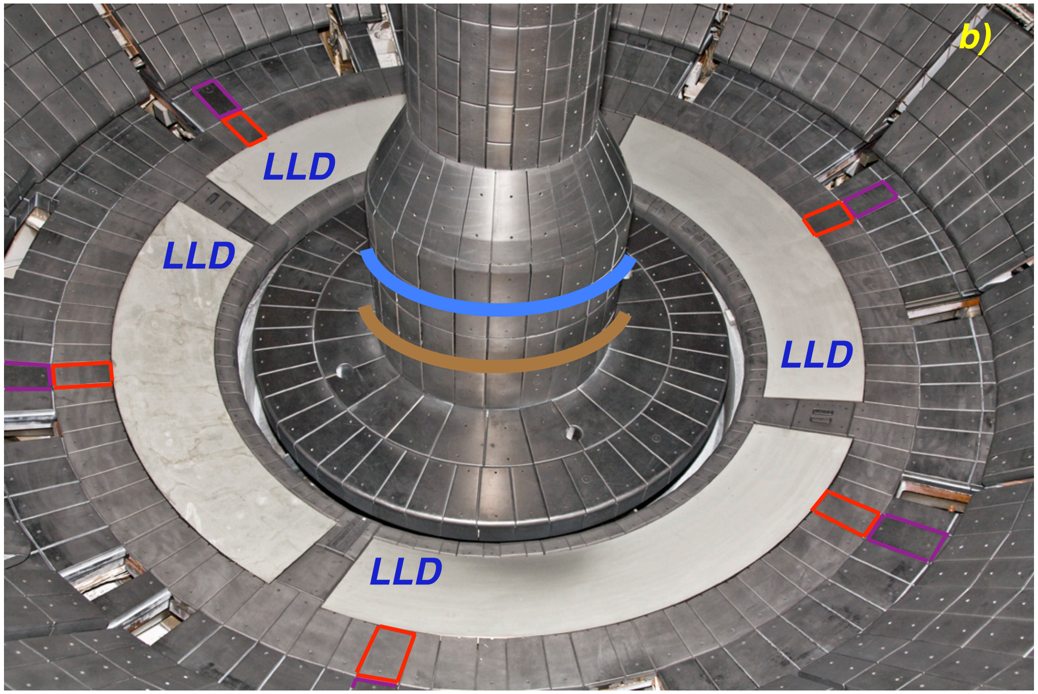


Dynamics of the Disrupting Phase



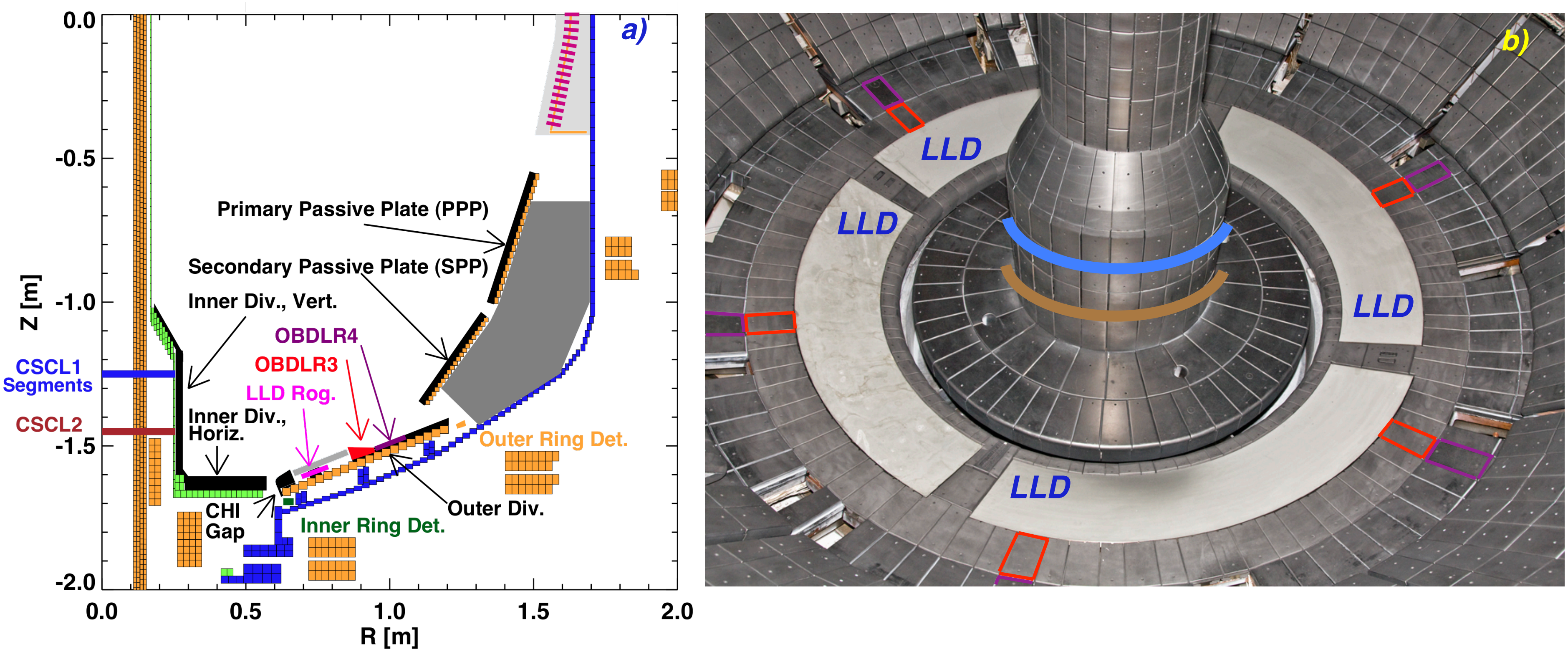
NSTX Cannot Measure the Total Halo Current…





- Can measure the currents flowing into part of the outboard divertor.
  - But not the entire divertor.
- Can measure the currents flowing in the vessel wall (OBDIR or OBDOR) at two locations.
  - But this will miss some currents flowing along divertor plates.

NSTX Cannot Measure the Total Halo Current…
…But ITPA Database Calls for the "Total Halo Current"



- Can sum the signals in two rows of tiles to capture most of the halo current.
  - Will still underestimate the HCF.
- Can create an IDDB entry about halo current density at divertor floor.
  - Normalized to poloidal arc length?
- Can separate vessel wall current and HC entrance point measurements in IDDB.
  - TPFs likely different at these locations anyway. (See Pomphrey 1998, Menard 2012).
- In any case, present NSTX data in IDDB suffers from this problem.
  - The NSTX HCF should be compared to that from other devices with great care.

The End