NSTX-U

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# Characterization of Disruption Halo Currents in NSTX

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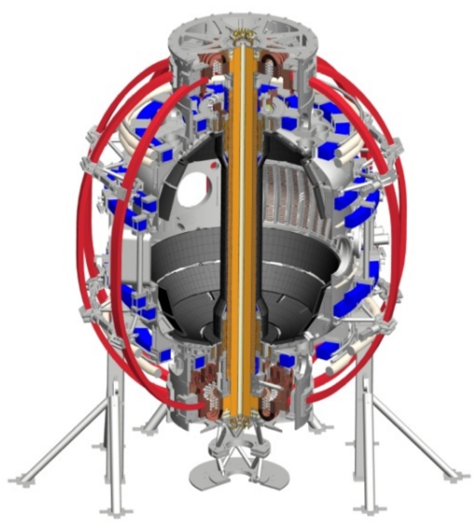

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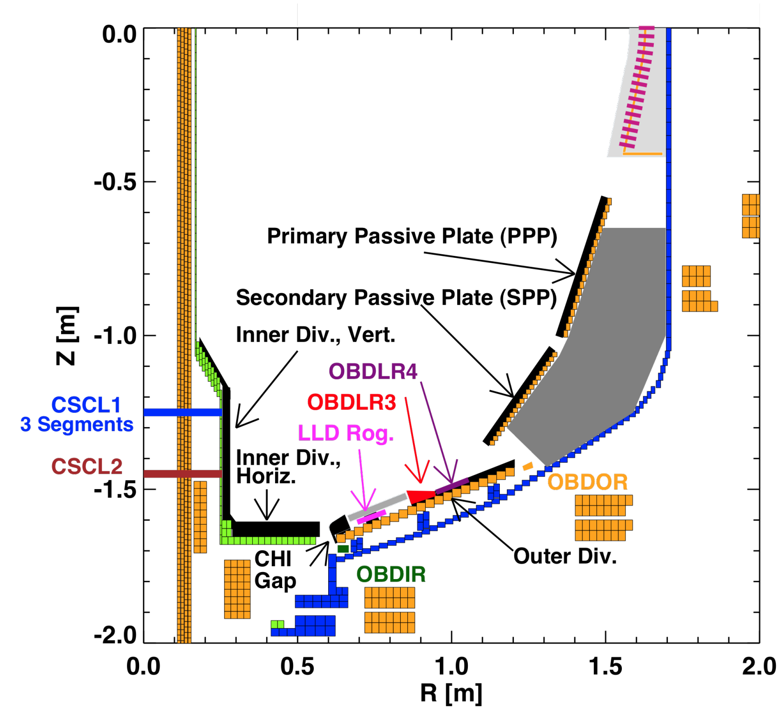
# Overview of 2010/2011 NSTX Halo Current Instrumentation (Color Coded)

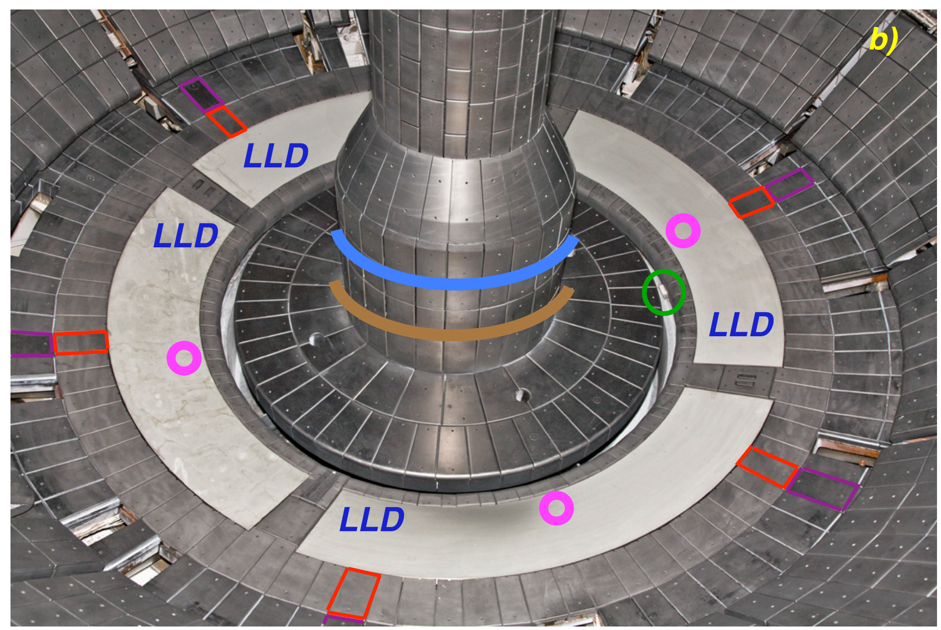
**Entrance Point Currents**

Row-3 Tiles (OBDLR3)
Row-4 Tiles (OBDLR4)
LLD Ground Rogowskis (they worked, but ground faults on LLD rendered measurements questionable)

**Structure Currents**

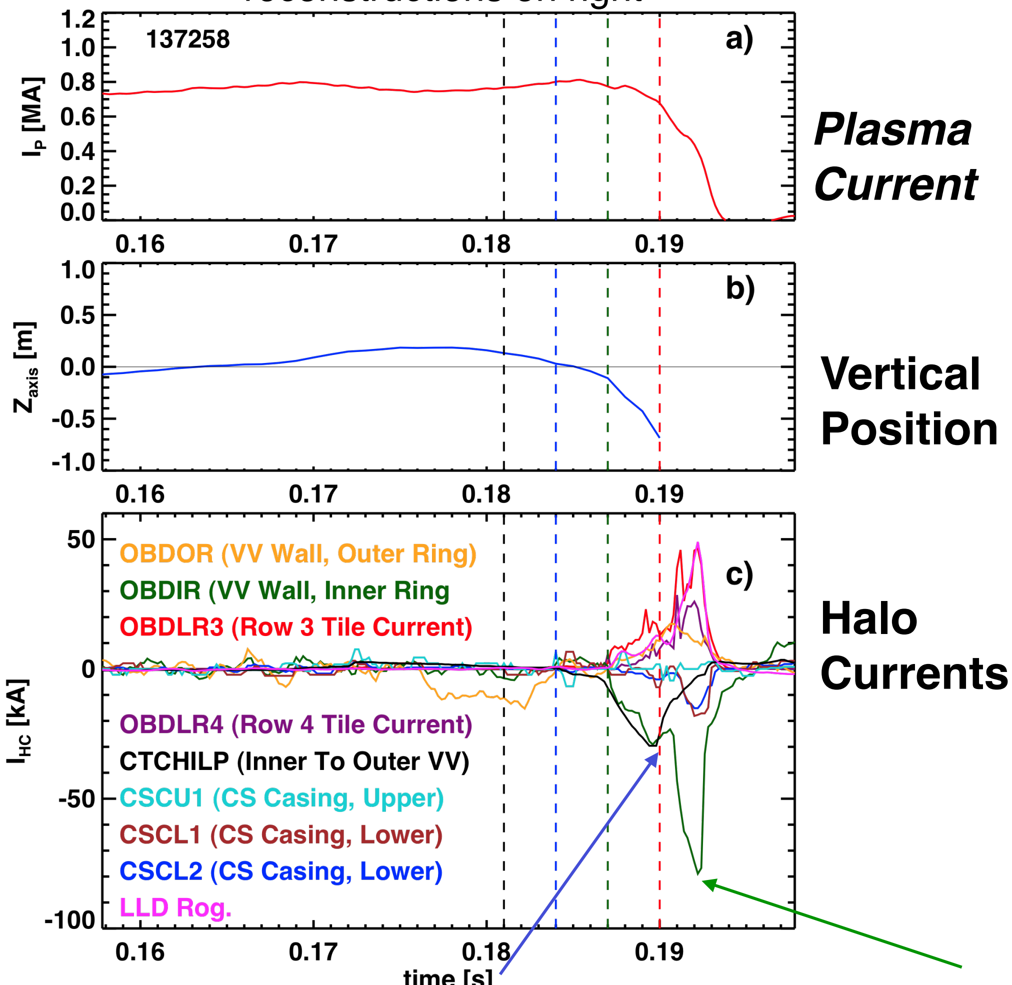
Inner Ring $B_T$ Detectors (OBDIR, one circled)
Outer Ring $B_T$ Detectors (OBDOR, not in picture)
CSC Rogowski, Lower #2 (CSCL2)
CSC Rogoswki, Lower #1 (CSCL1, Segmented)
CSC Rogowski, Upper #1 (CSCU1)
Current in Connections Bridging CHI Gap (CTCHILP)



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

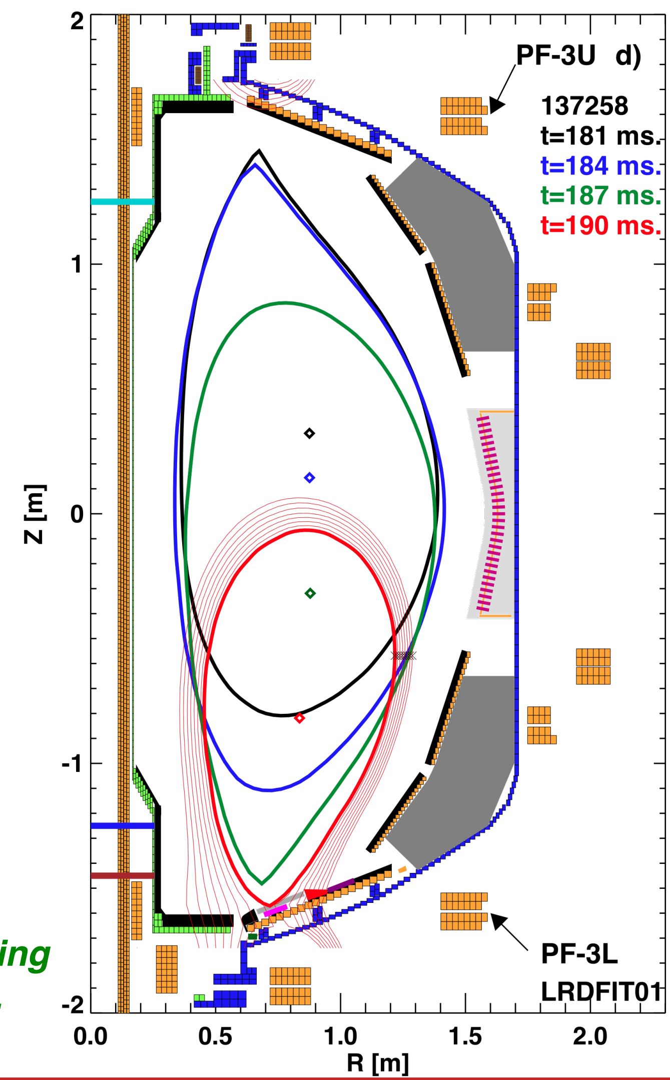
Dashed vertical lines correspond to times of reconstructions on right




*Increase in vessel currents, but drop in CHI bus work currents, at t=0.191! Why?*

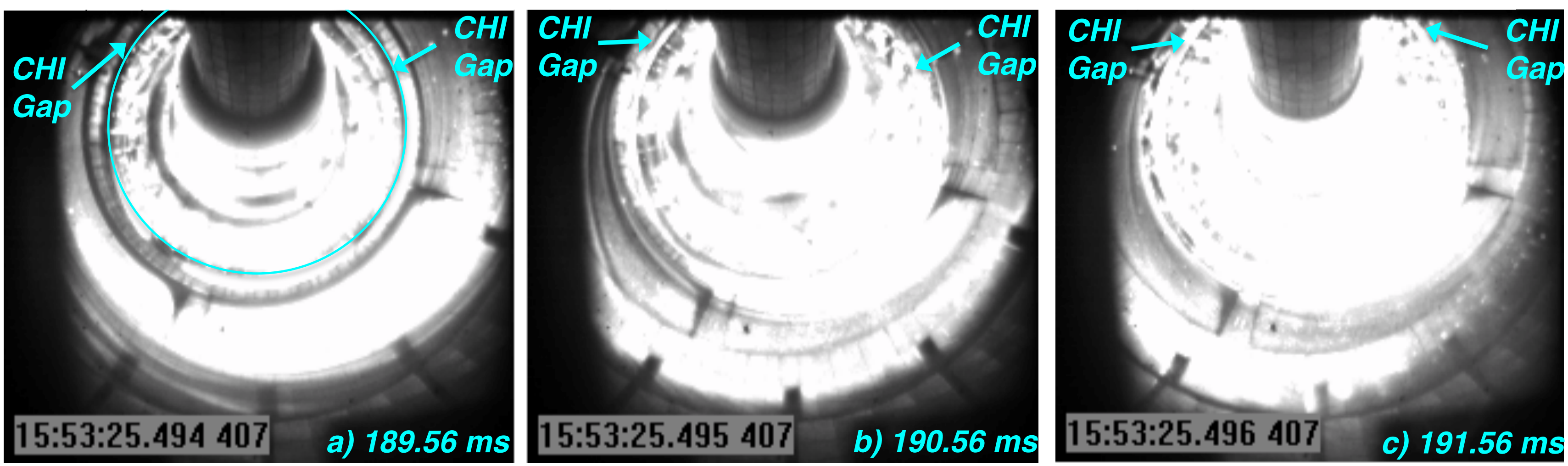
*Up to 90 kA flowing in vessel wall.*

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



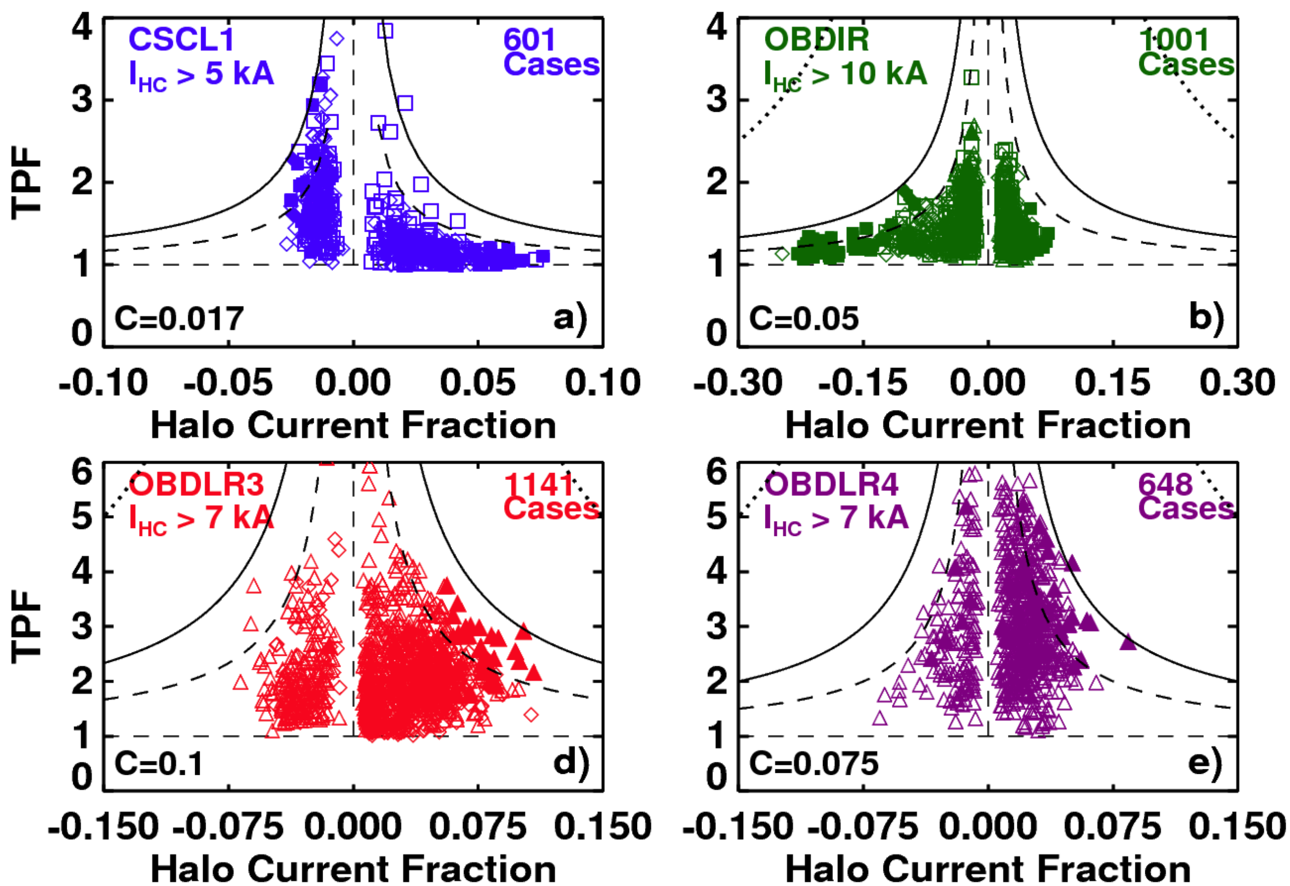
# Current Increase on Previous Slide Corresponds to “Arcing” Across the CHI Gap

- CHI gap is a toroidal insulator, used to provide electrical isolation (poloidal break) between inner and outer vessels.
  - Usually connected by a long (many meters) bus work connection.
- 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.
  - That connection is shorted out by the arc plasma



# Halo Current Fractions and Toroidal Peaking Factors Calculated for All Detector Arrays

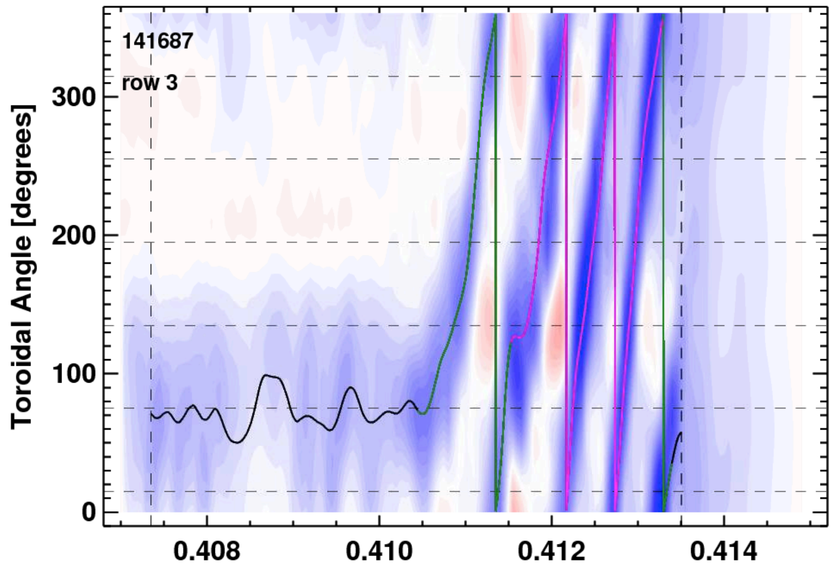
- Generally follow trend of reduced peaking at higher amplitude.
- These local halo current fractions should not be compared to “total” halo current fractions as often plotted for the ITER design basis.

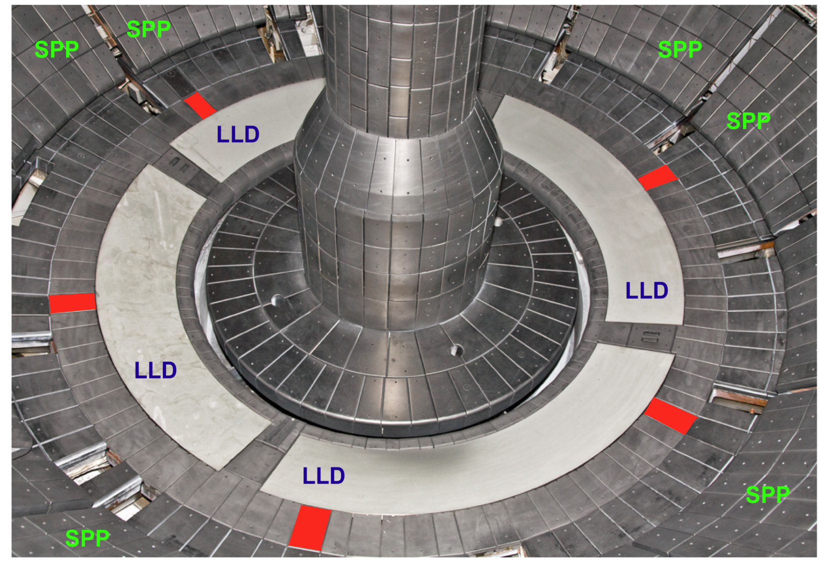


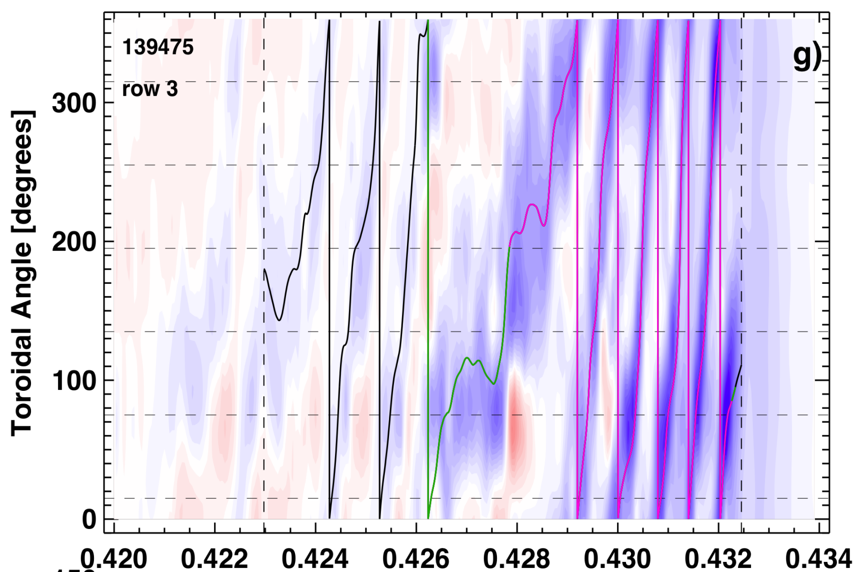

**But what about the detailed dynamics of the currents where they enter the divertor floor?**

***See rest of poster!***

# Halo Currents at Entrance Points Are Strongly Non-Axisymmetric

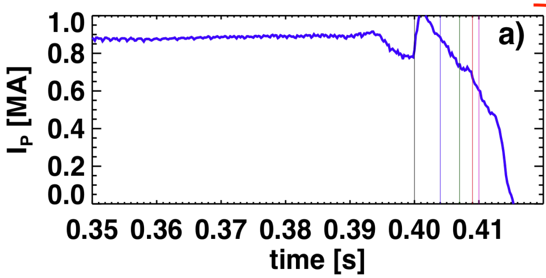


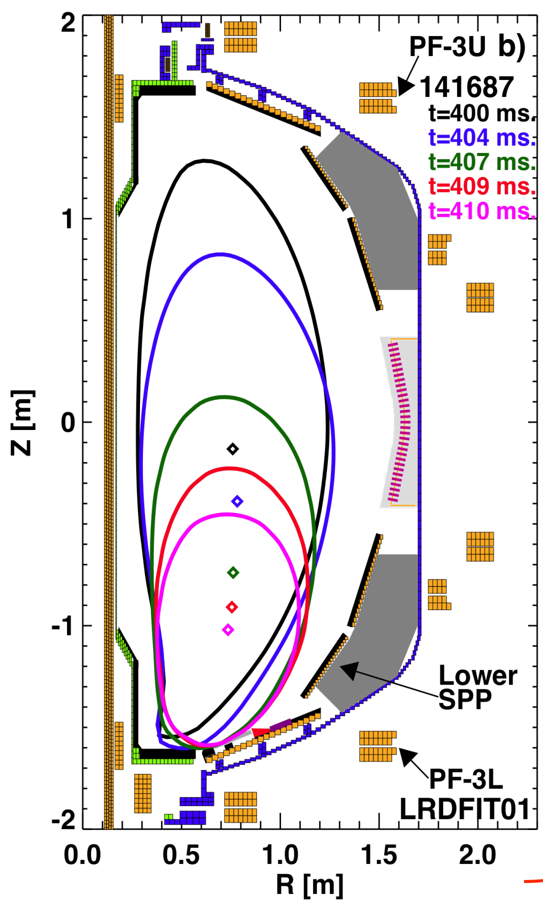




- Measurements from the array of instrumented tiles (OBDLR3)
  - Same poloidal angle
  - Distributed toroidally
- Infer strong toroidal asymmetry, often with significant rotation, at locations where currents enter the divertor floor.

# Rotation Dynamics of Example Landing on the Outboard Divertor Floor




Overall Equilibrium Evolution

a) Plasma current

b) Boundary evolution

Detailed Evolution:

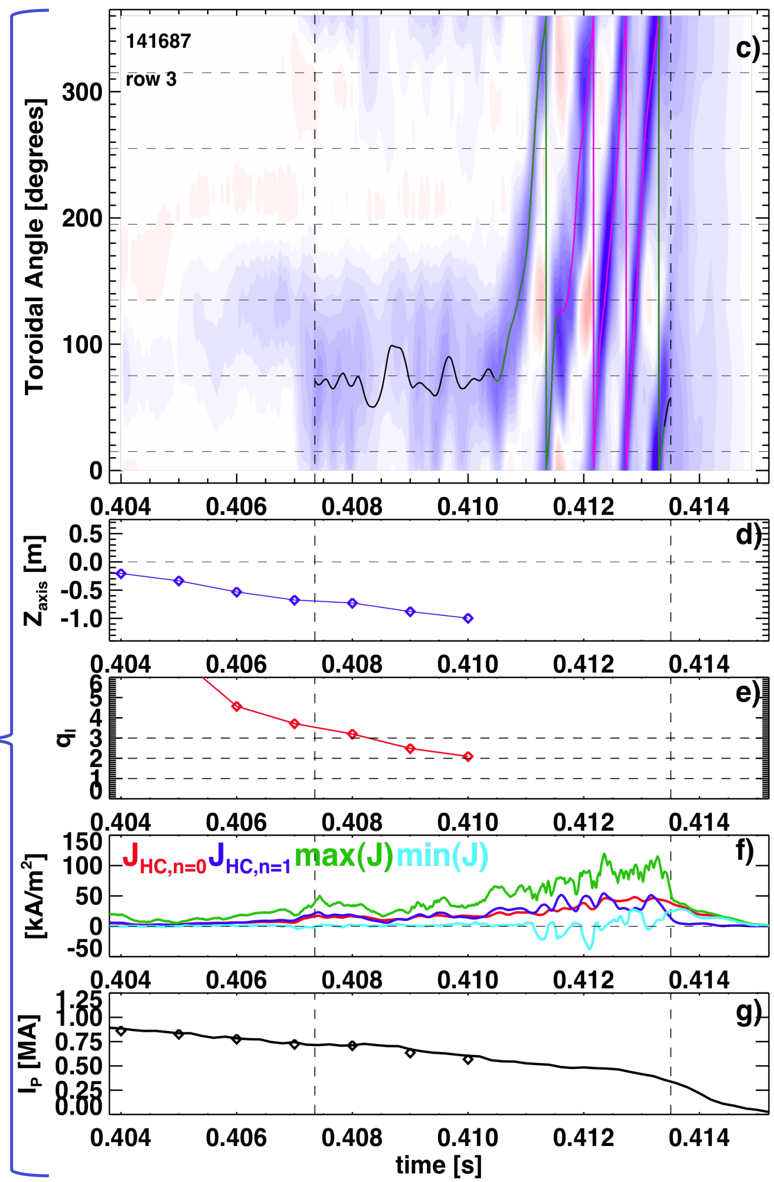
c) Halo current vs. angle and time

d) Axis location

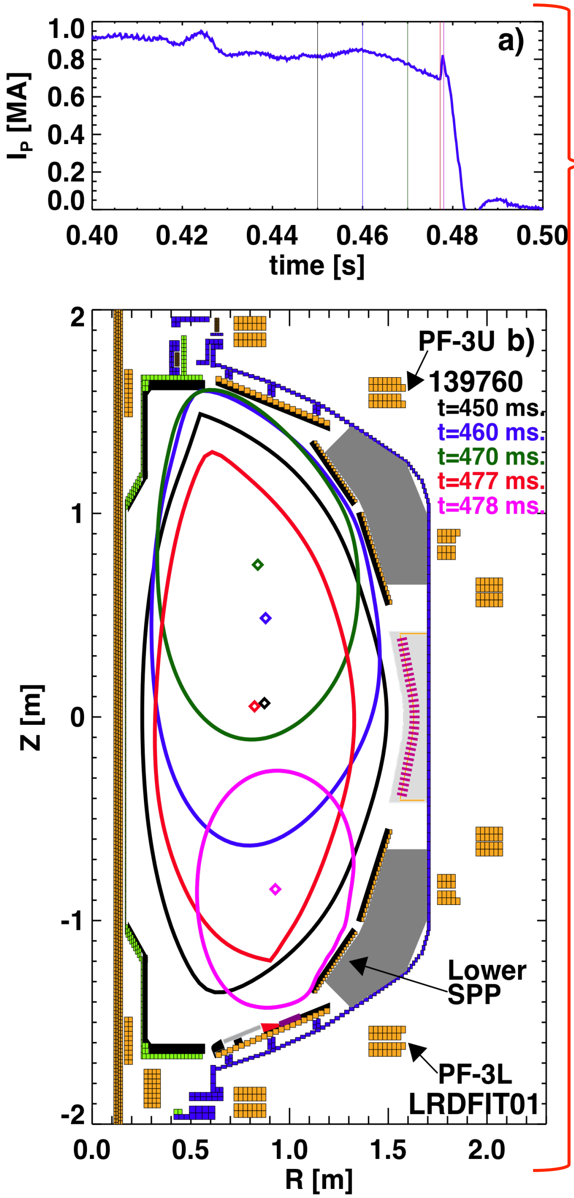
e) Edge q

f) Halo current magnitude

g) Plasma current

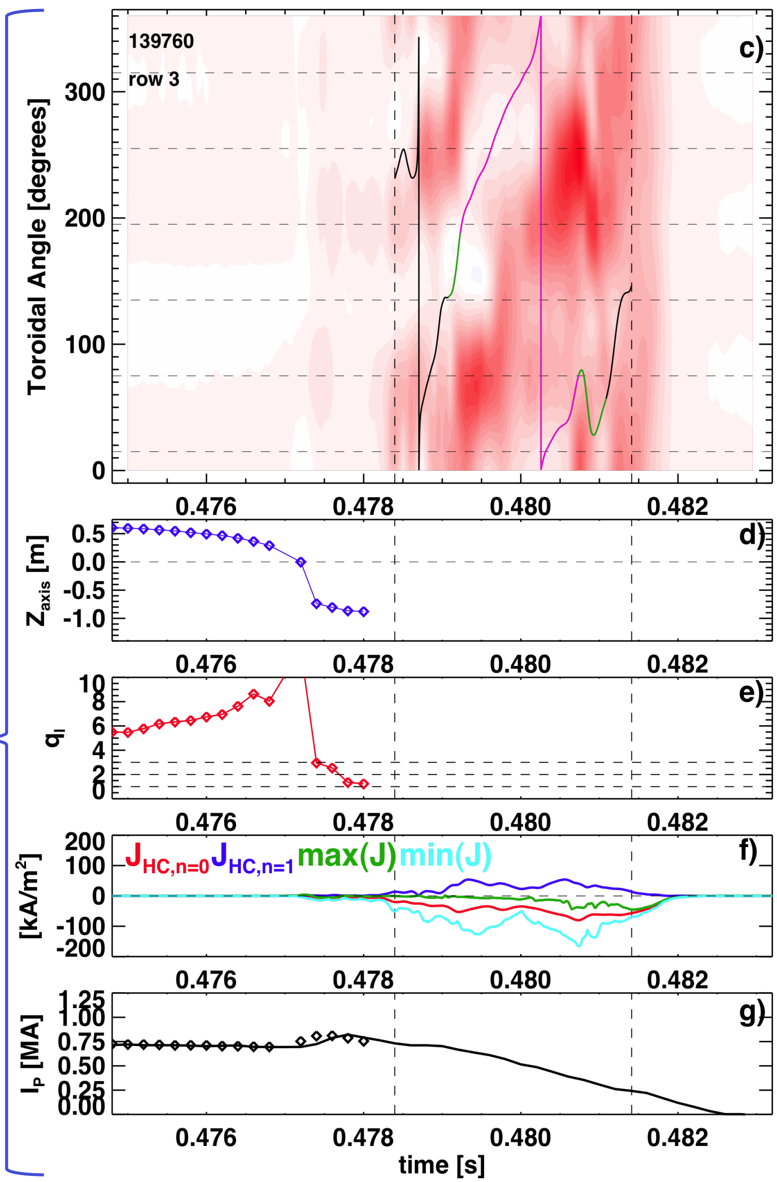


# Rotation Dynamics of Example Landing on the Secondary Passive Plates



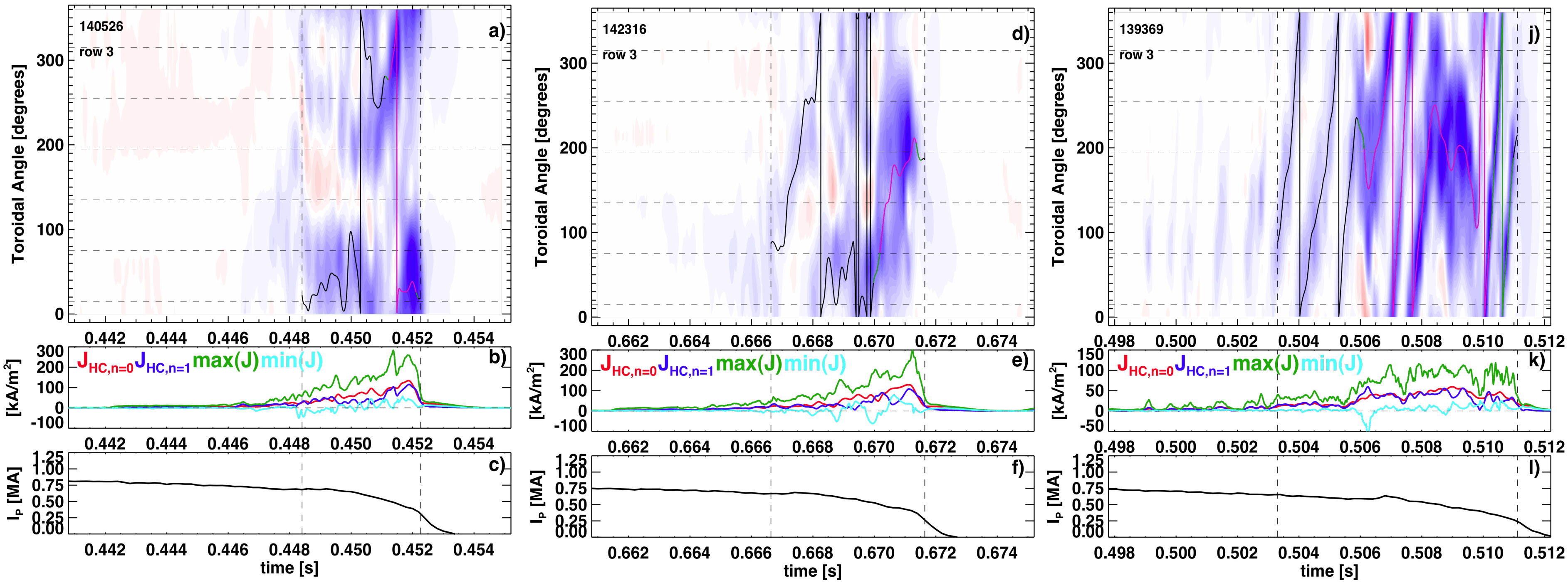

Overall Equilibrium Evolution
a) Plasma current
b) Boundary evolution

Detailed Evolution:
c) Halo current vs. angle and time
d) Axis location
e) Edge q
f) Halo current magnitude
g) Plasma current



# Further Examples of Halo Current Rotation Dynamics

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




<u>Key Observations</u>

Dominant structure is typically a toroidally-rotating lobe.

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

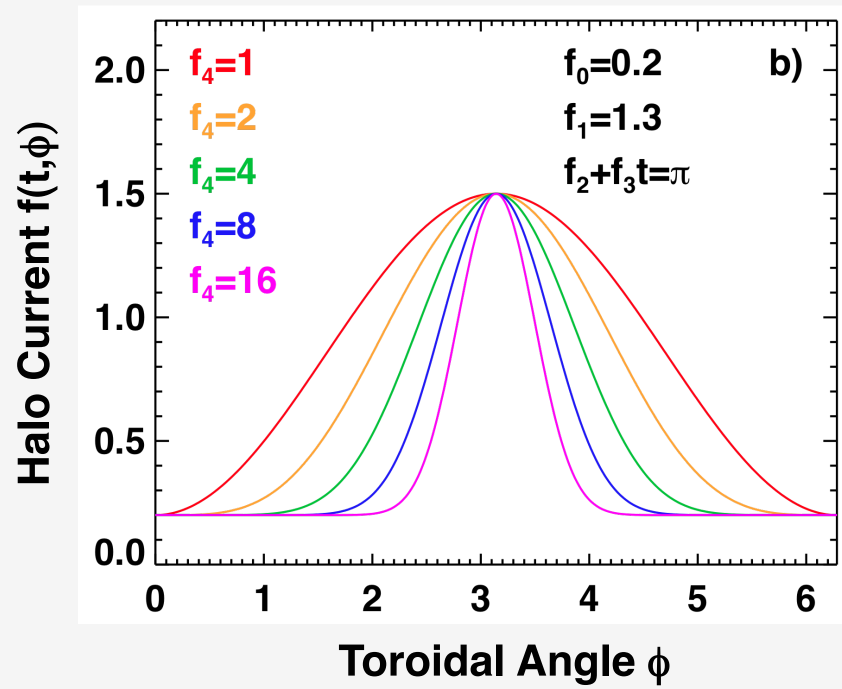
# Use a Model Fit Function To Better Resolve the Halo Current Dynamics

- 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 on next slide.

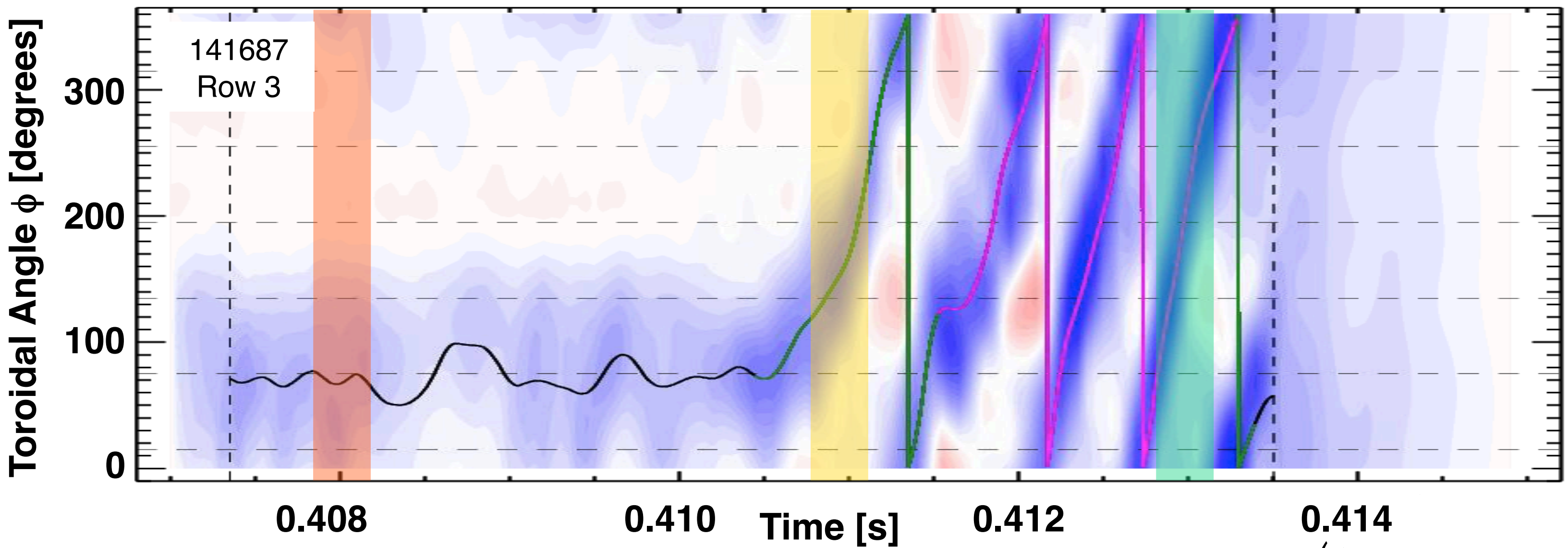
Model Function
"Windowed Cosine Power Fits"

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

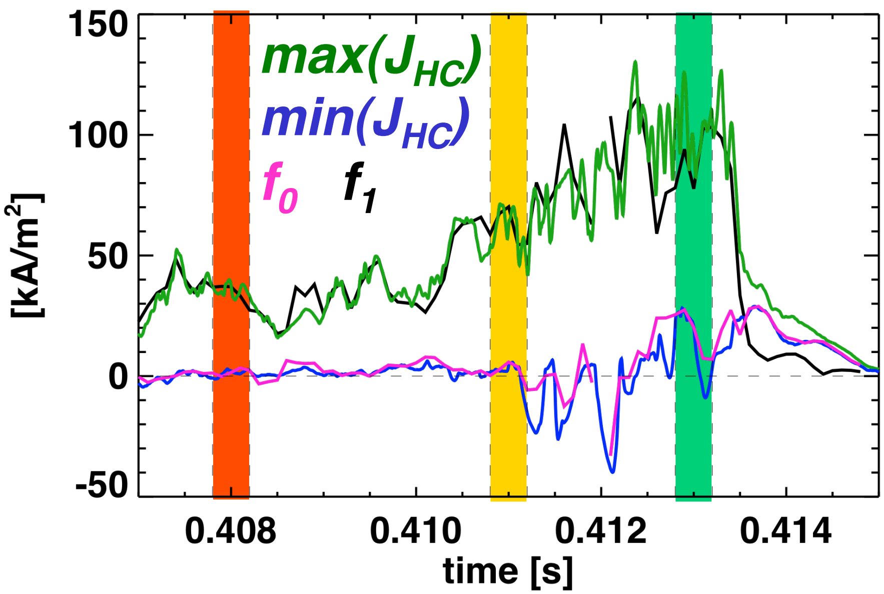
Example Curves

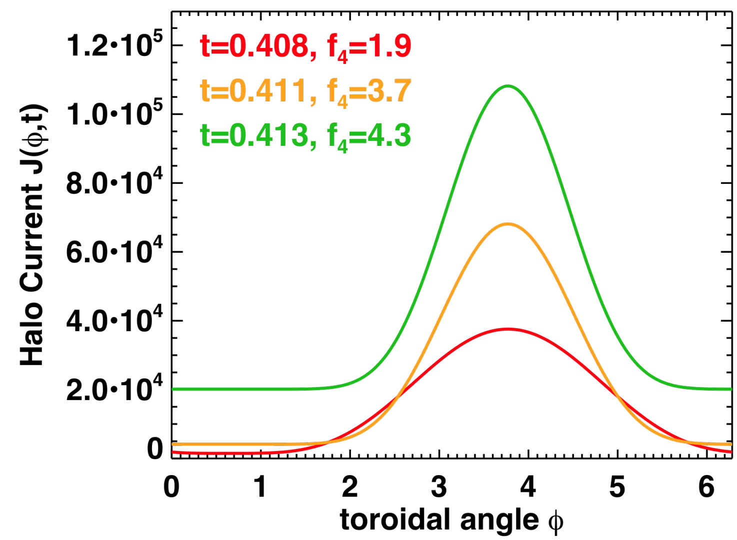


# Dominant Structure of the Halo Current is a Rotating Toroidally Localized Lobe of Current



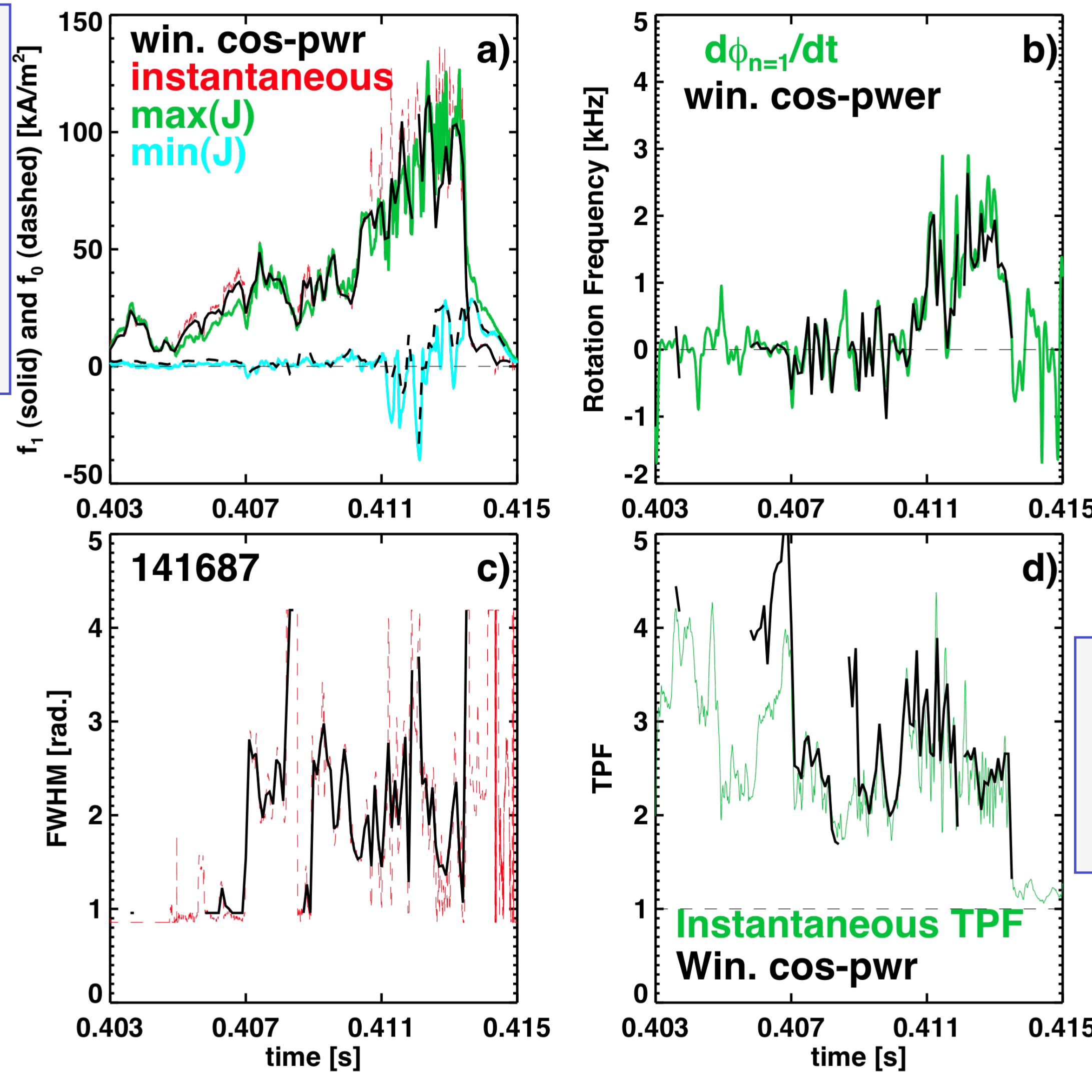

$$f(t,\phi) = f_0 + f_1 \cos^{2 f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$



# Fits Reveal Dynamics of the Halo Currents (Case With Steady Rotation in Slides 7 and 11)

**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

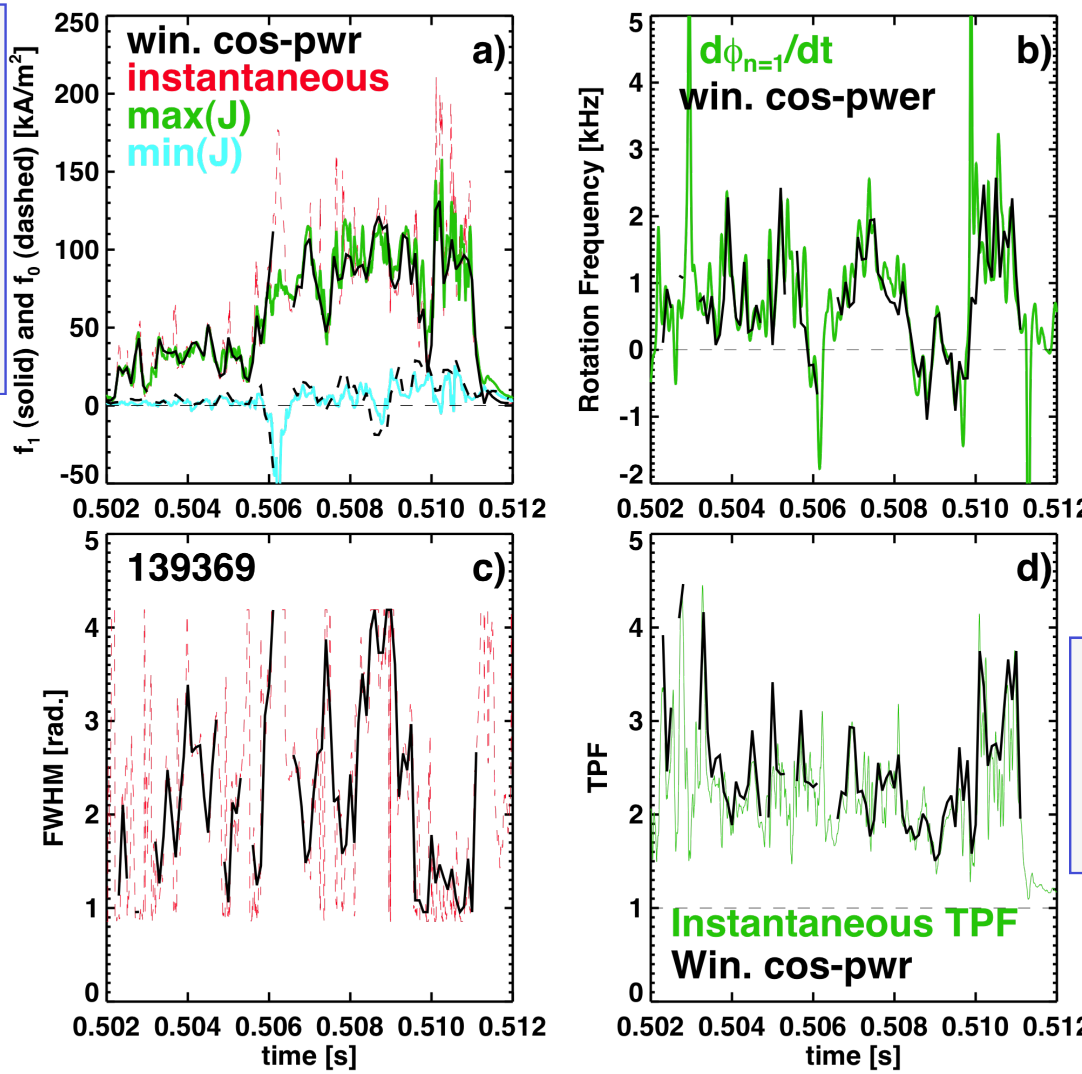
**Full Width at Half Maximum:**
Instantaneous cosine power fits
Windowed fits

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

# Fits Reveal Dynamics of the Halo Currents (Case With Erratic Rotation on Right of Slide 9)

**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:

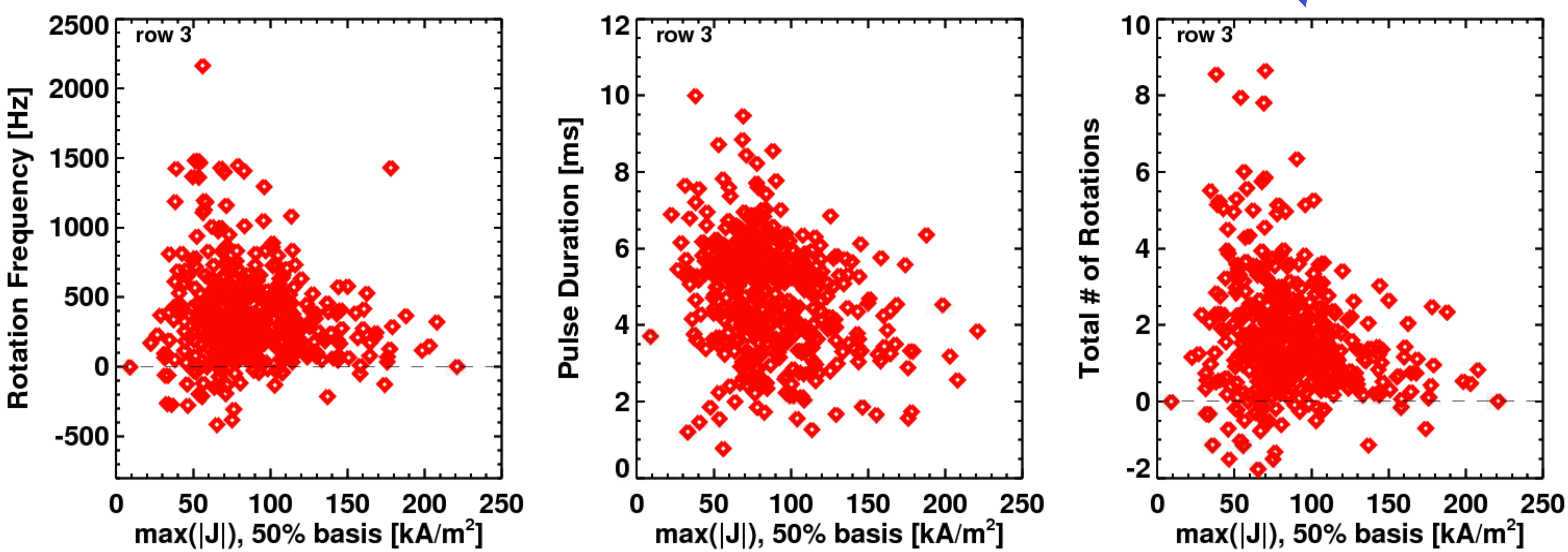
$$I_{HC}(\phi) = f_{n=0} + f_{n=1}\cos(\phi - \phi_{n=1})$$

From "windowed cosine power" fits

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

# # of Rotations is Observed to Scale Inversely with Halo Current Magnitude

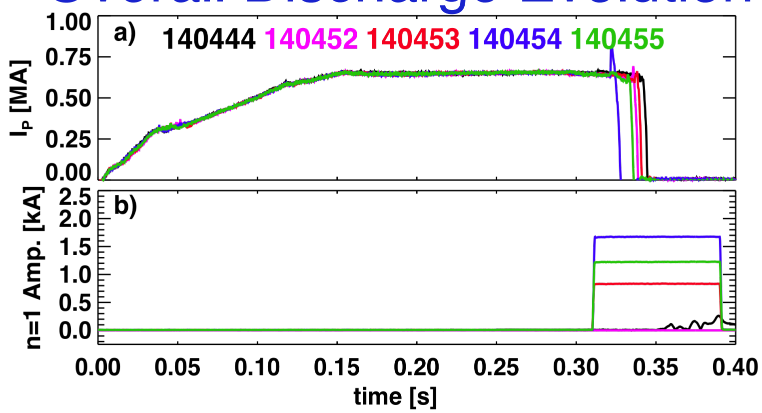
- Compute the rotation dynamics during time when n=1 halo current is >25% of its maximum.
- Compare to the time average of the maximum halo current magnitude.
  - Rotation frequency usually lower at high amplitude.
  - Pulse duration usually lower at high amplitude
  - *Total # of rotations drops at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



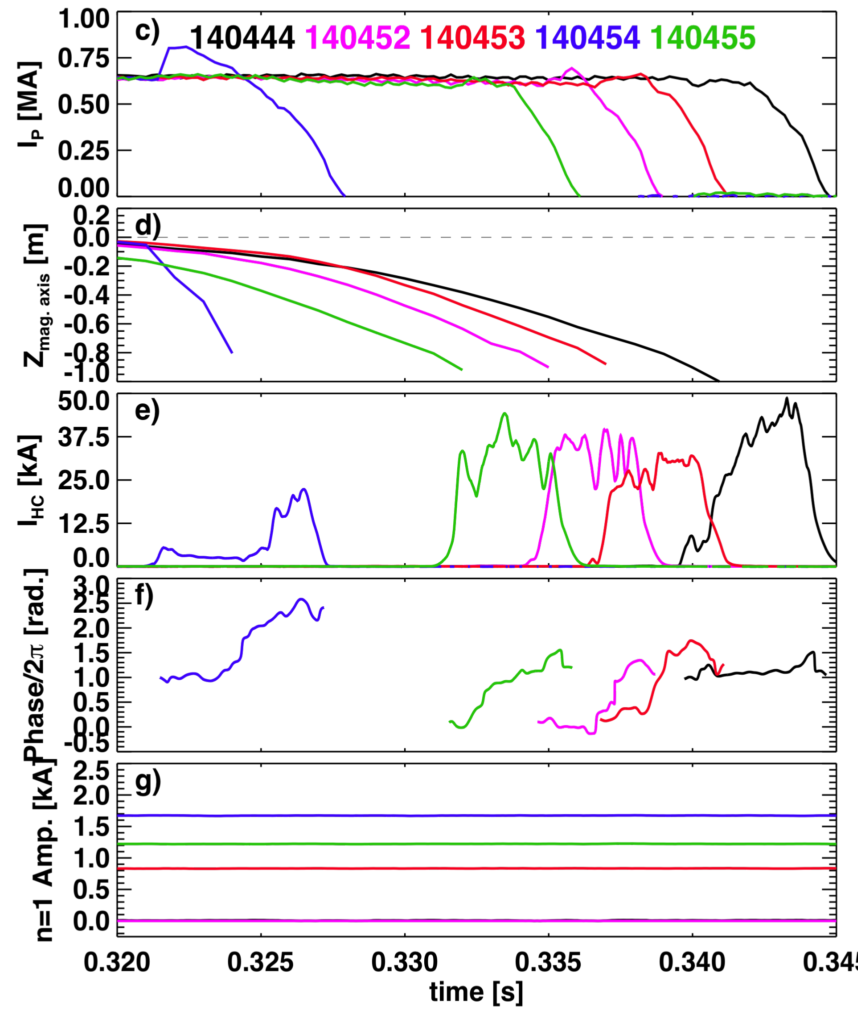
# n=1 Fields Did Not Modify HC Rotation During Deliberate VDEs

- 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

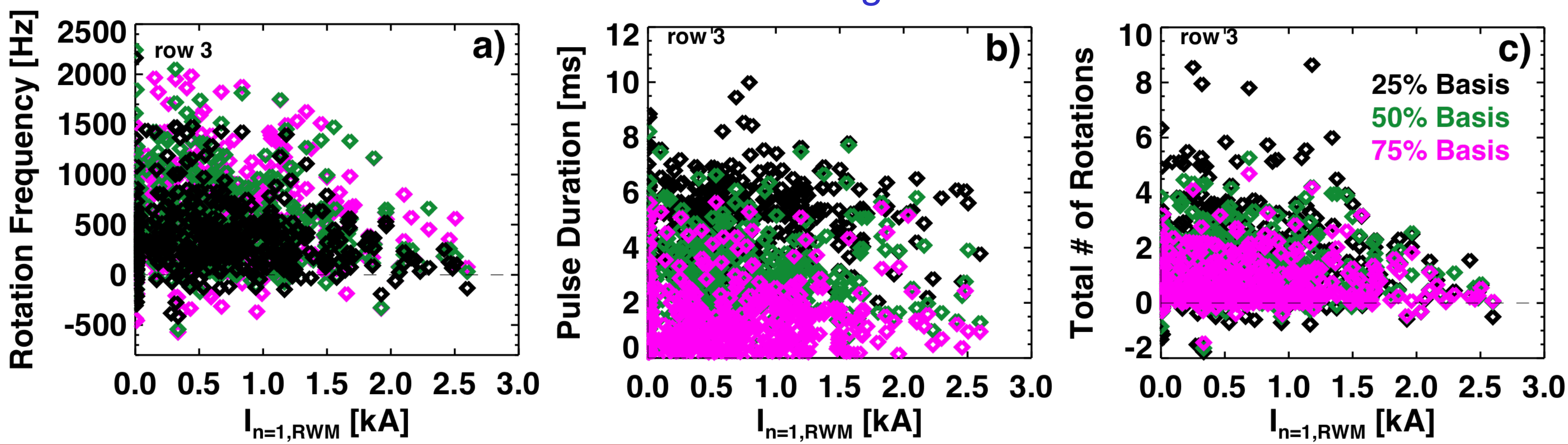



## Dynamics of the Disrupting Phase

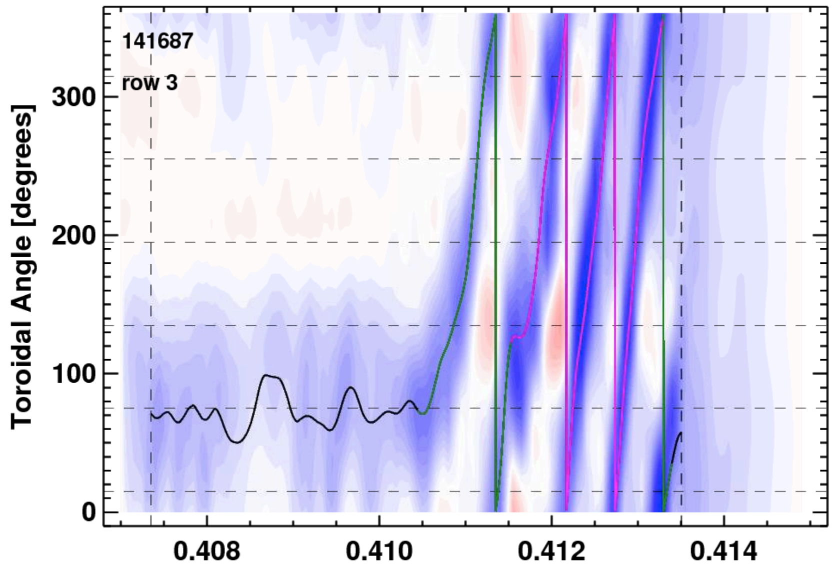


# Statistical Analysis Shows Less Rotation in Cases With Strong n=1 Fields

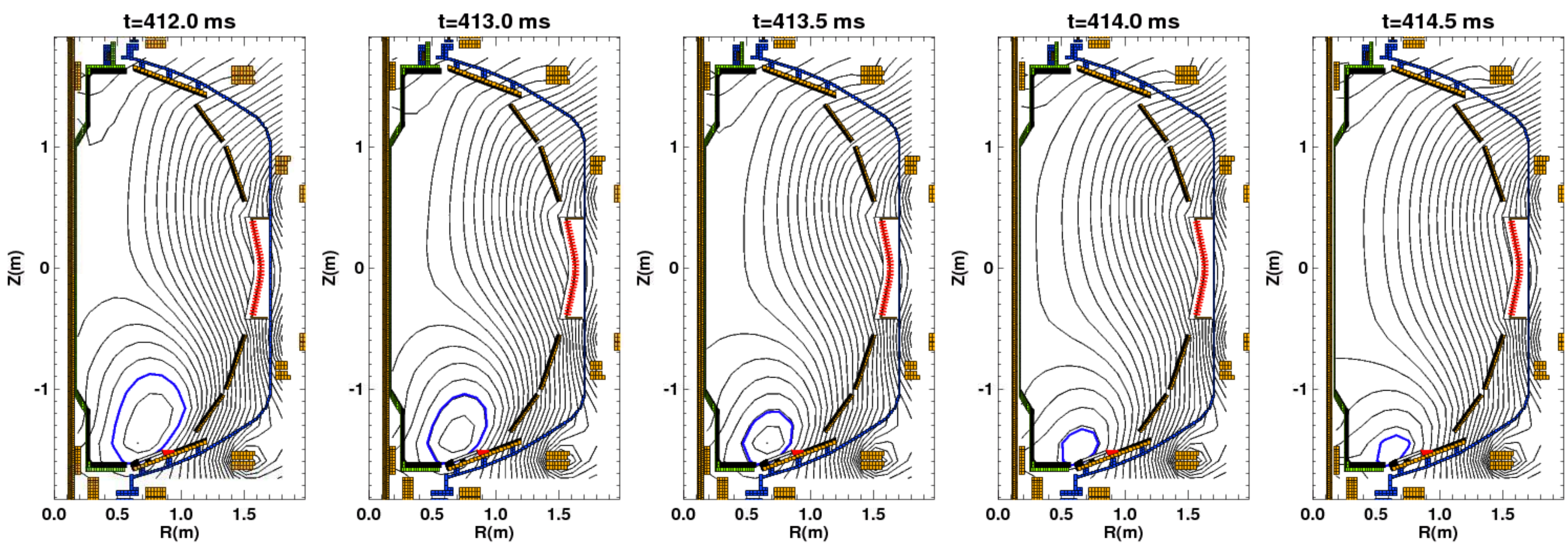
- Large n=1 fields are often applied by the RWM control system during a disruption. Due to:
  - Actual 3D distortions of the plasma
  - Toroidal & non-axisymmetric eddy currents leading to incorrectly identified "modes".
    - On-line doesn't have $v_{loop}$ sensor compensationsas in the off-line analysis.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



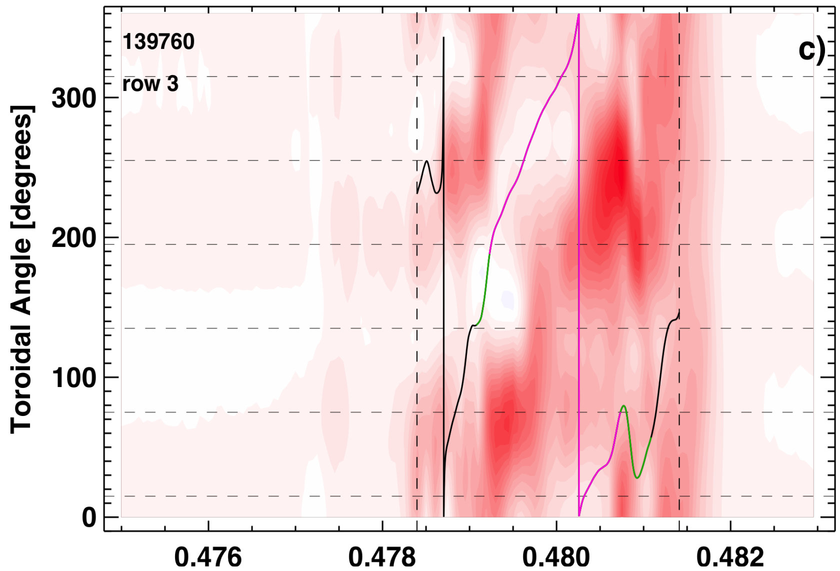
# Halo Currents Become Symmeterized In the Final Phase of the Disruption: Example on OBD



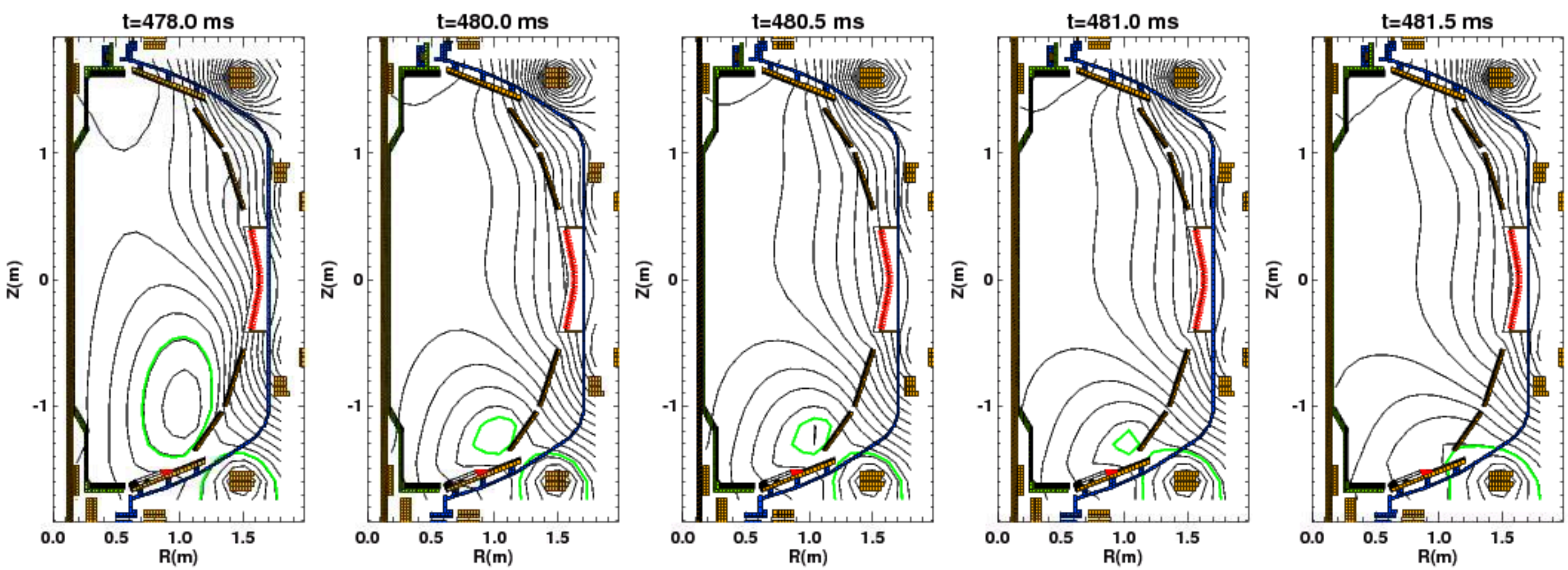

- Halo current contours are toroidally symmetric starting at ~0.4135 s
- Utilize a regularized toroidal filament model for the reconstruction.
  - Includes vessel eddy currents.
  - Does not satisfy $\nabla p = J \times B$
- Period of late axisymmetry corresponds to near or complete loss of closed surface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



# Summary

- Currents can "arc" across gaps in PFCs and structural elements.
  - The actual halo current path may not be knowable in advance.
- The dominant structure of the halo currents is a rotating, toroidally localized lobe of current.
  - Can be significantly more peaked than a simple n=1 variation.
- Up to eight total revolutions of the toroidal asymmetry have been observed.
  - # of revolutions tends to be small for the cases with largest currents.
- Story with regard to n=1 fields is mixed:
  - In large $J_{HC}$ VDEs, applied n=1 fields to not impact the toroidal rotation.
  - In a large database, there were no observed cases with both many toroidal revolutions and large n=1 fields.

# NSTX Disruption References


- S.P. Gerhardt, et al. "*Characterization of the Plasma Current Quench During Disruptions in the National Spherical Torus Experiment*", Nuclear Fusion **49**, 025005.

- S.P. Gerhardt, et al. "*Characterization of Disruption Halo Currents in the National Spherical Torus Experiment*", Nuclear Fusion **52**, 063005

- S.P. Gerhardt, et al. "*Dynamics of the Disruption Halo Current Toroidal Asymmetry in NSTX*", submitted to Nuclear Fusion.

- S.P. Gerhardt, et al. "*Disruptions, Disruptivity, and Safer Operating Windows in the High-$\beta$ Spherical Torus NSTX*", submitted to Nuclear Fusion.

- S.P. Gerhardt, et al. "*Disruptions in the High-$\beta$ Spherical Torus NSTX*", IAEA-FEC 2012, EX/9-3