A multi-machine analysis of non-axisymmetric and rotating halo currents

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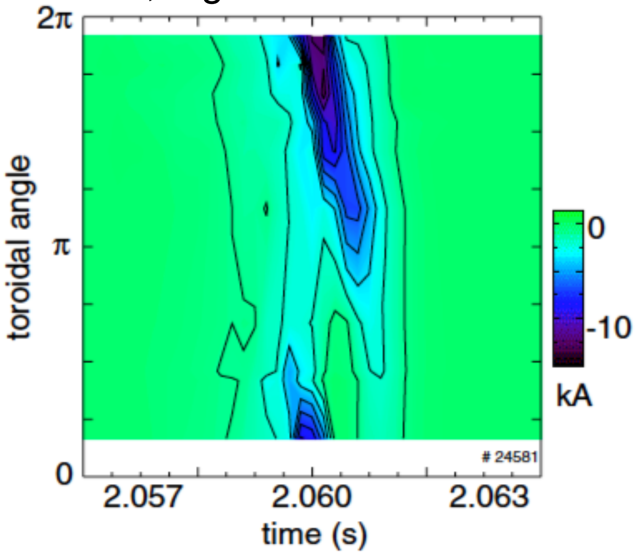
Poster Outline

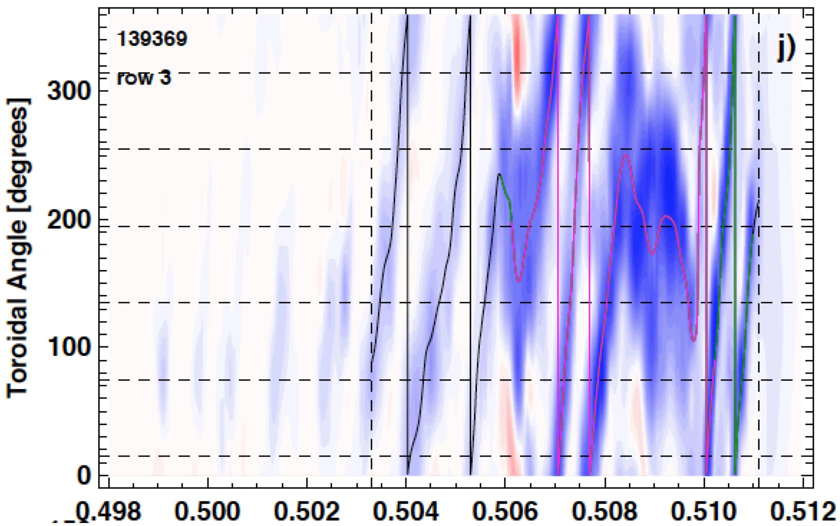
- Goal: Study halo current non-axisymmetry and rotation across many machines → use a common analytical framework
- Working to build a halo current database filled with “data units” from various machines (NSTX, DIII-D, AUG, C-Mod, etc.)
- Progress report:
  - Status of the ITPA halo current database
  - Analysis framework and representative examples
  - Preliminary statistical analysis
  - Future plans

Asymmetry and rotation observed in many machines

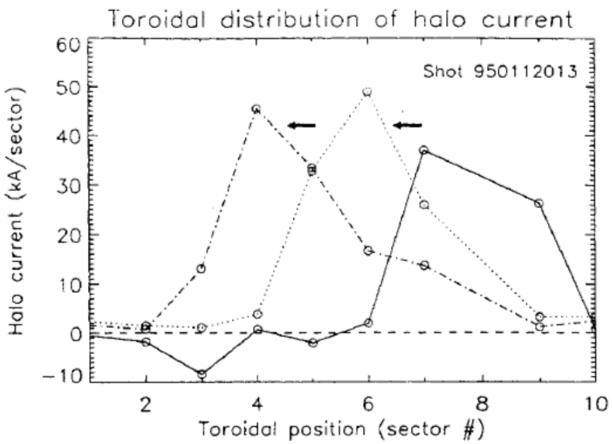
- Halo currents often exhibit non-axisymmetric structure → n=0 with an n=1 "lobe"
- Full or partial rotation of the n=1 lobe observed in NSTX, AUG, and C-Mod
- How do non-axisymmetry and rotation vary with machine, discharge parameters?
- What common physics drives the observed non-axisymmetry and rotation?

G. Pautasso, *Nucl. Fusion,* 2011, Fig. 15





S.P. Gerhardt, *Nucl. Fusion*, 2013

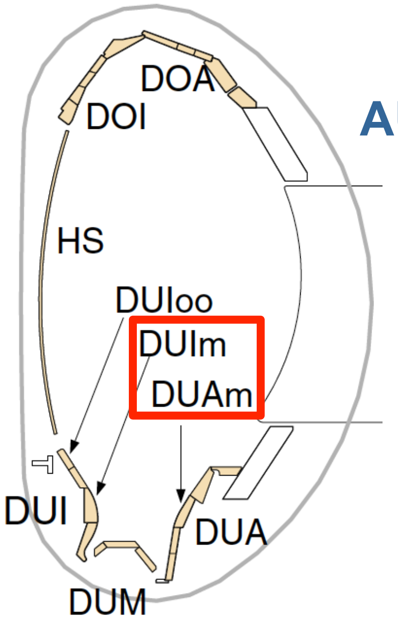


R. S. Granetz, *Nucl. Fusion*, 1996, Fig. 10

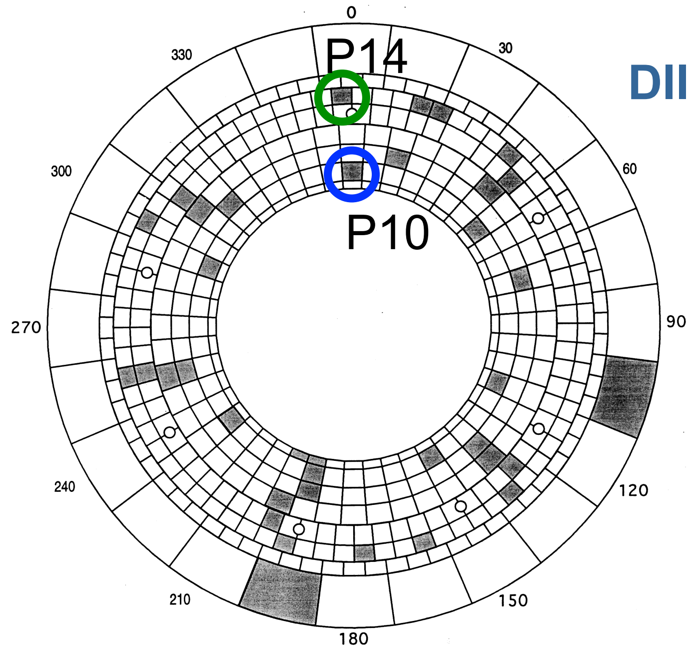
Status of the ITPA halo current database

- One "data unit" per shot (or per toroidal array per shot):
  - Equilibrium data (I_P, B_T, κ, Z_P, W_{MHD}, MGI, …)
  - Halo current data as a function of toroidal angle
  - At least four toroidal locations per sensor array
- Present contents of the database:
  - Recent NSTX shunt tile data: ~140 shots × 2 poloidal locations
  - Recent AUG shunt tile data: ~4 shots × 2 poloidal locations
  - DIII-D TAC shunt tile data: ~60 shots × 5 poloidal locations
  - C-Mod partial rogowski data: ~90 shots × 1 poloidal location
- Recent additions:
  - C-Mod shots fully integrated
  - Current quench timing now analyzed

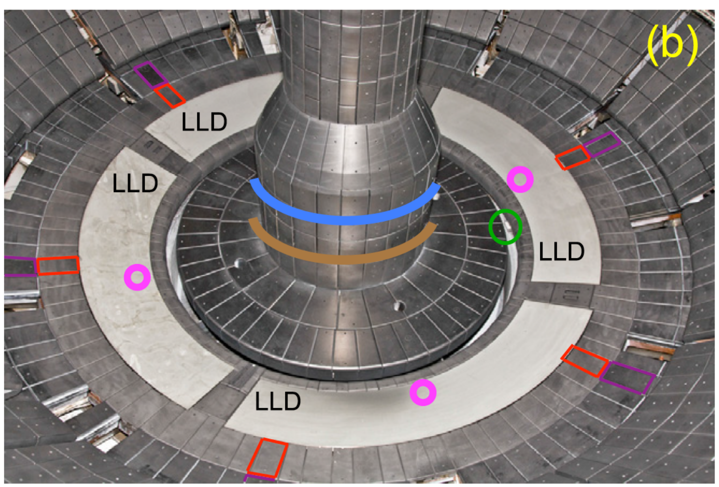
Various halo current sensor arrays



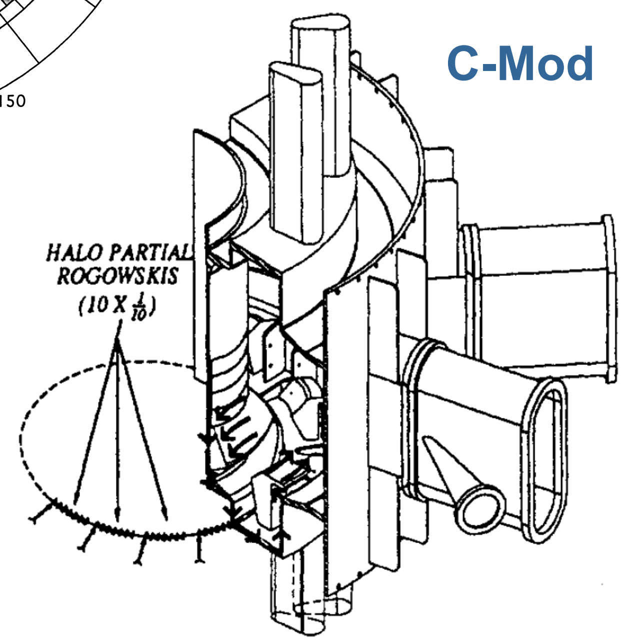
AUG



DIII-D

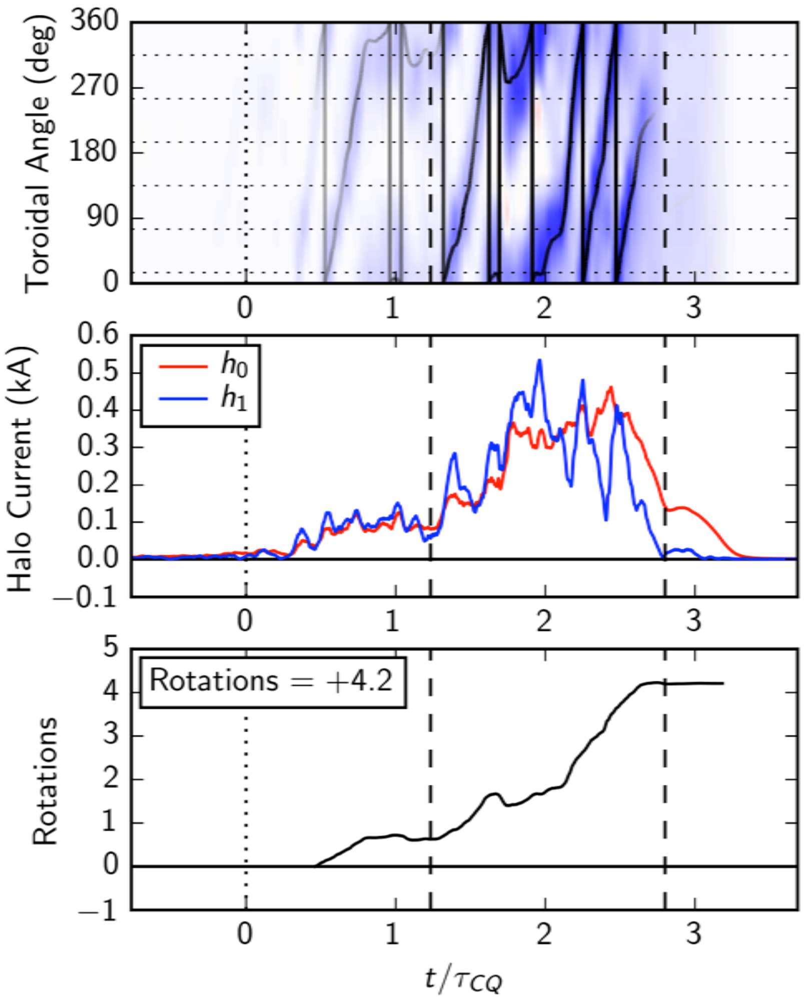


NSTX



C-Mod

Representative halo current analysis (NSTX)

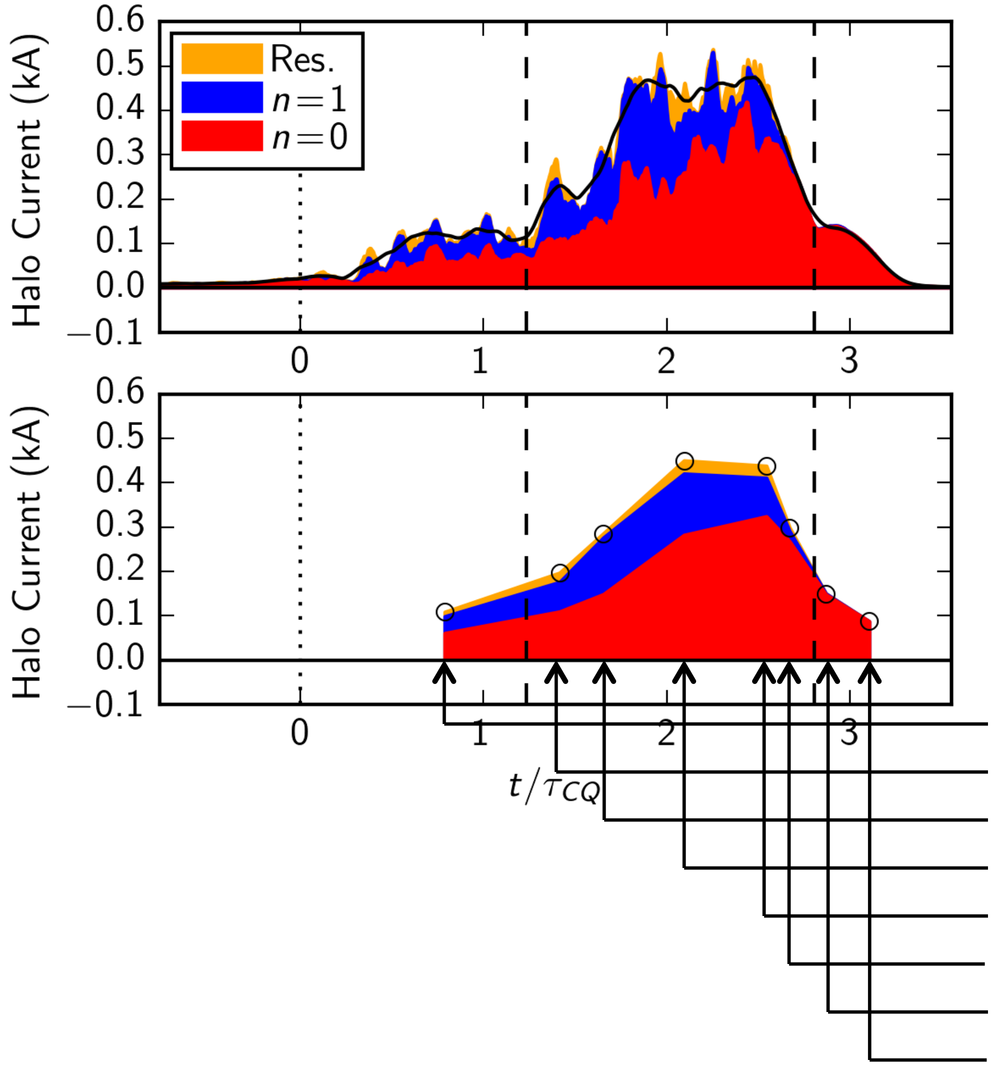


- Fit n=0,1 profile to each toroidal array at each time point:

$$I_h(\phi) = h_0 + h_1 \sin(\phi - h_2)$$

- Amplitude of each component tracked by h_0, h_1
- The n=1 phase is tracked by h_2
- Total rotation calculated by integrating h_2 in time
- Rotation is only "counted" when the n=1 contribution is at least 25% of the peak RMS HC value

Representative halo current analysis (NSTX)



$$\mathrm{RMS}\{I_h\}^2 = \frac{1}{N_\phi}\sum_i I_h^2(\phi_i)$$

$$= h_0^2 + \frac{1}{2}h_1^2 + \text{Residual}$$

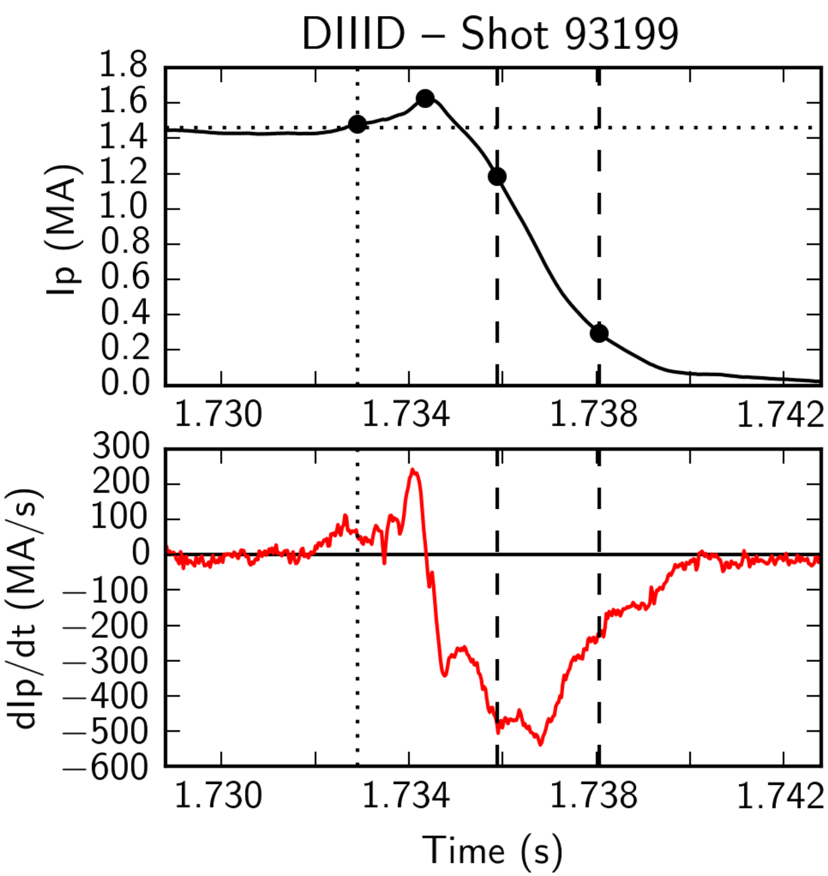
$$n=1 \text{ fraction} \equiv \frac{h_1^2/2}{\mathrm{RMS}\{I_h\}^2}$$

- Interval 1: 10–25%
- Interval 2: 25–50%
- Interval 3: 50–75%
- Interval 4: 75–100%
- Interval 5: 100–75%
- Interval 6: 75–50%
- Interval 7: 50–25%
- Interval 8: 25–10%

$$\frac{\mathrm{RMS}\{I_h\}}{\max\{\mathrm{RMS}\{I_h\}\}}$$

Current quench timing analysis

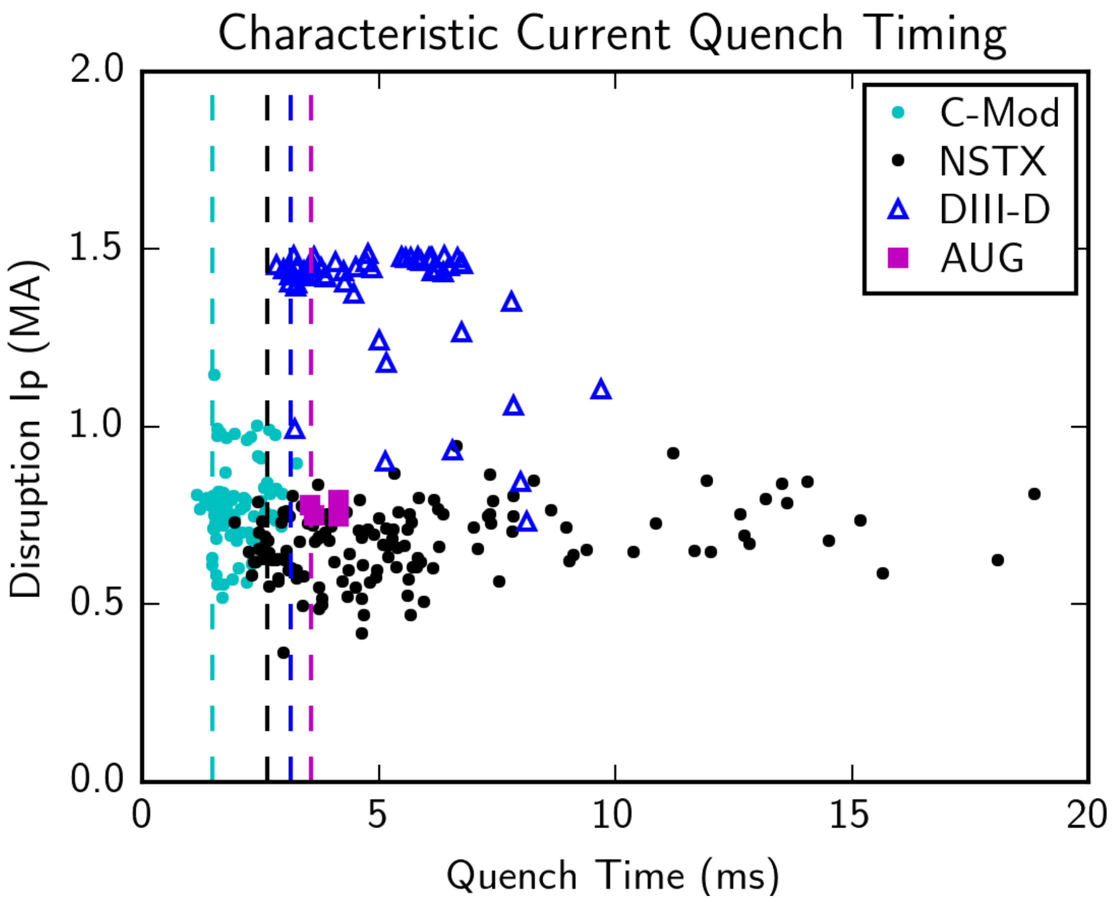
Use traditional $t_{20} - t_{80}$ current quench analysis:



Determine characteristic "fast" quench time for each machine from the database ensemble of shots:

Machine	Characteristic Fast Quench Time
C-Mod	1.5 ms
NSTX	2.7 ms
DIII-D	3.2 ms
AUG	3.6 ms

Characteristic current quench timescales



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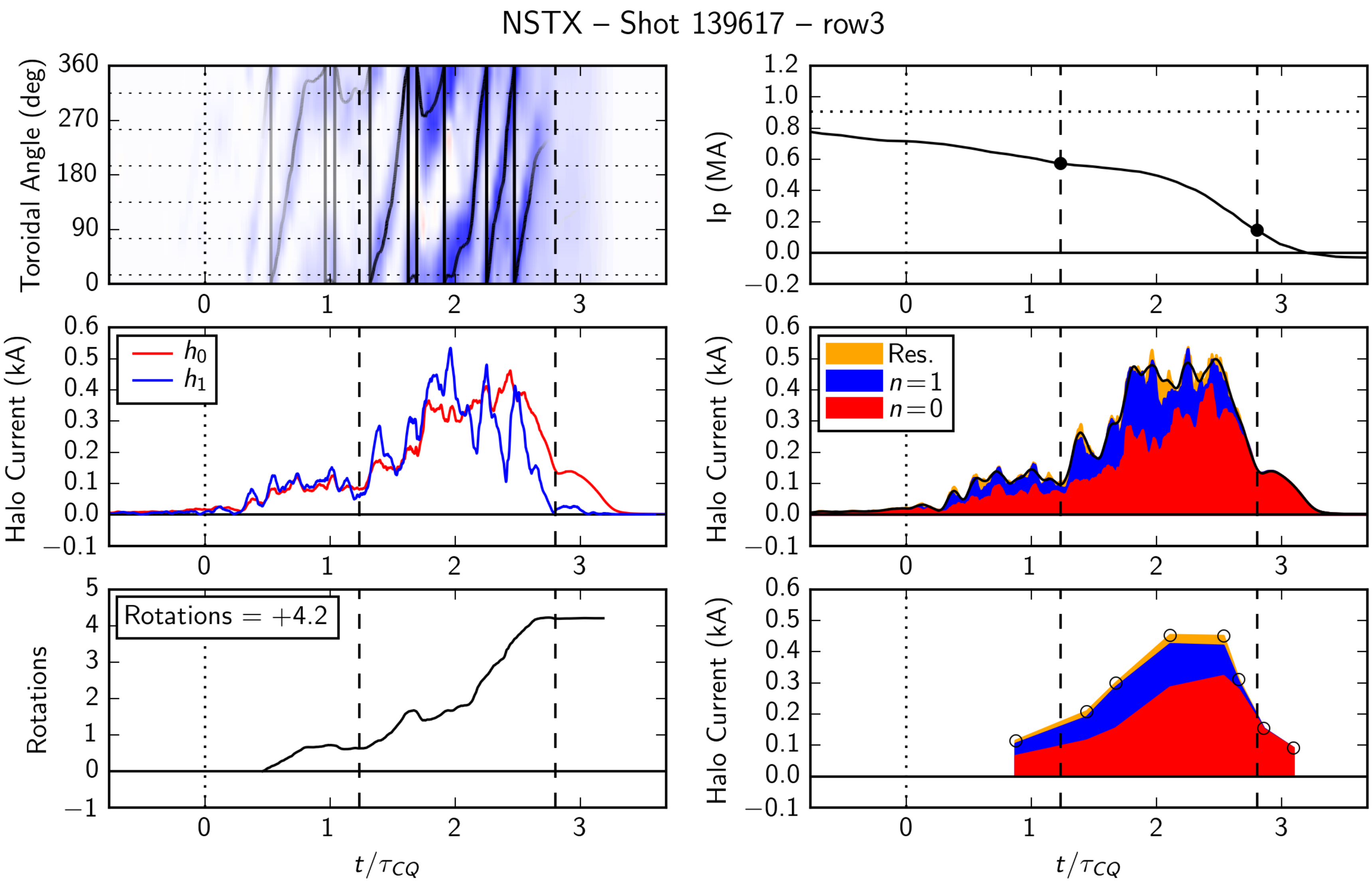
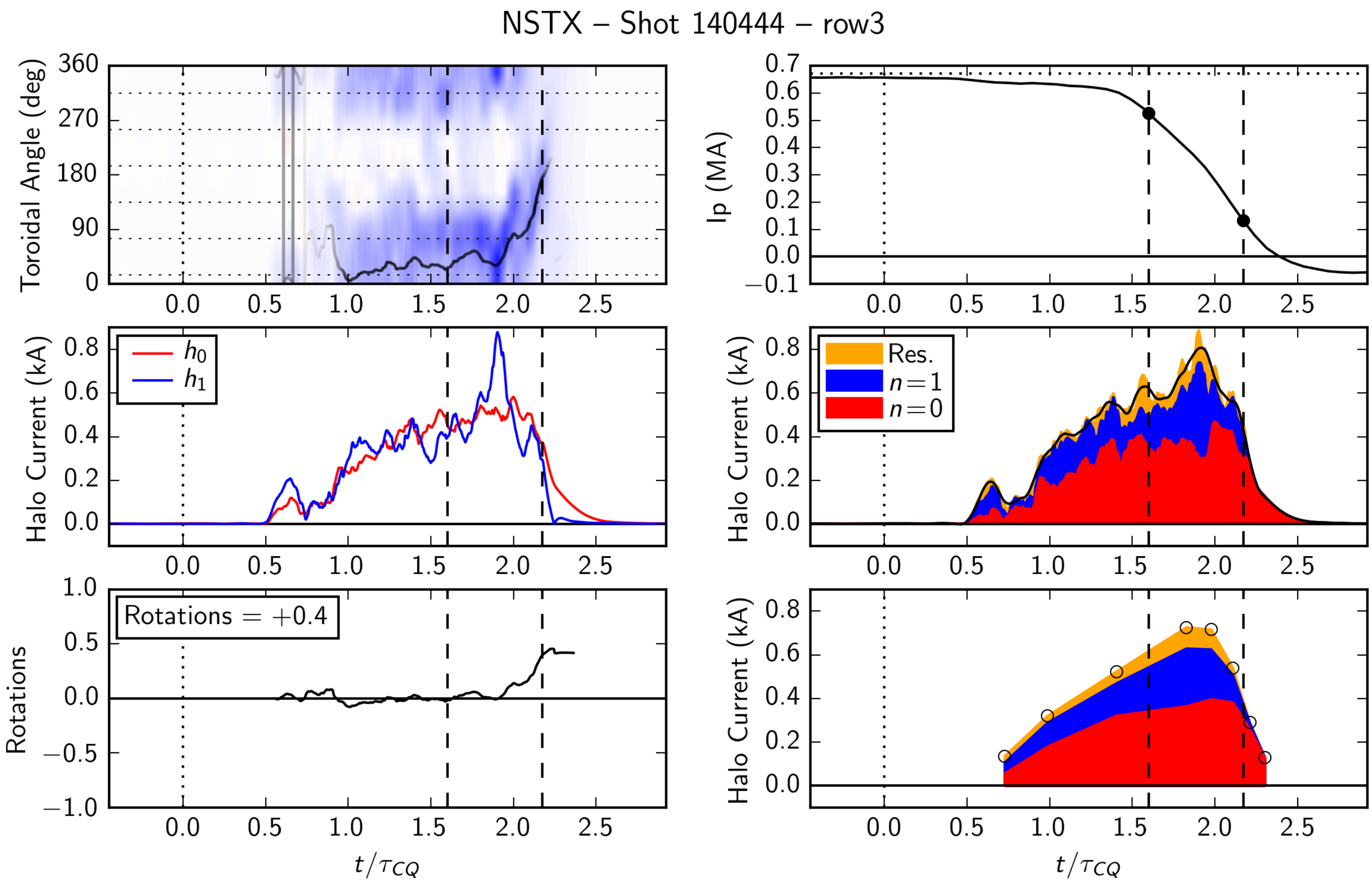
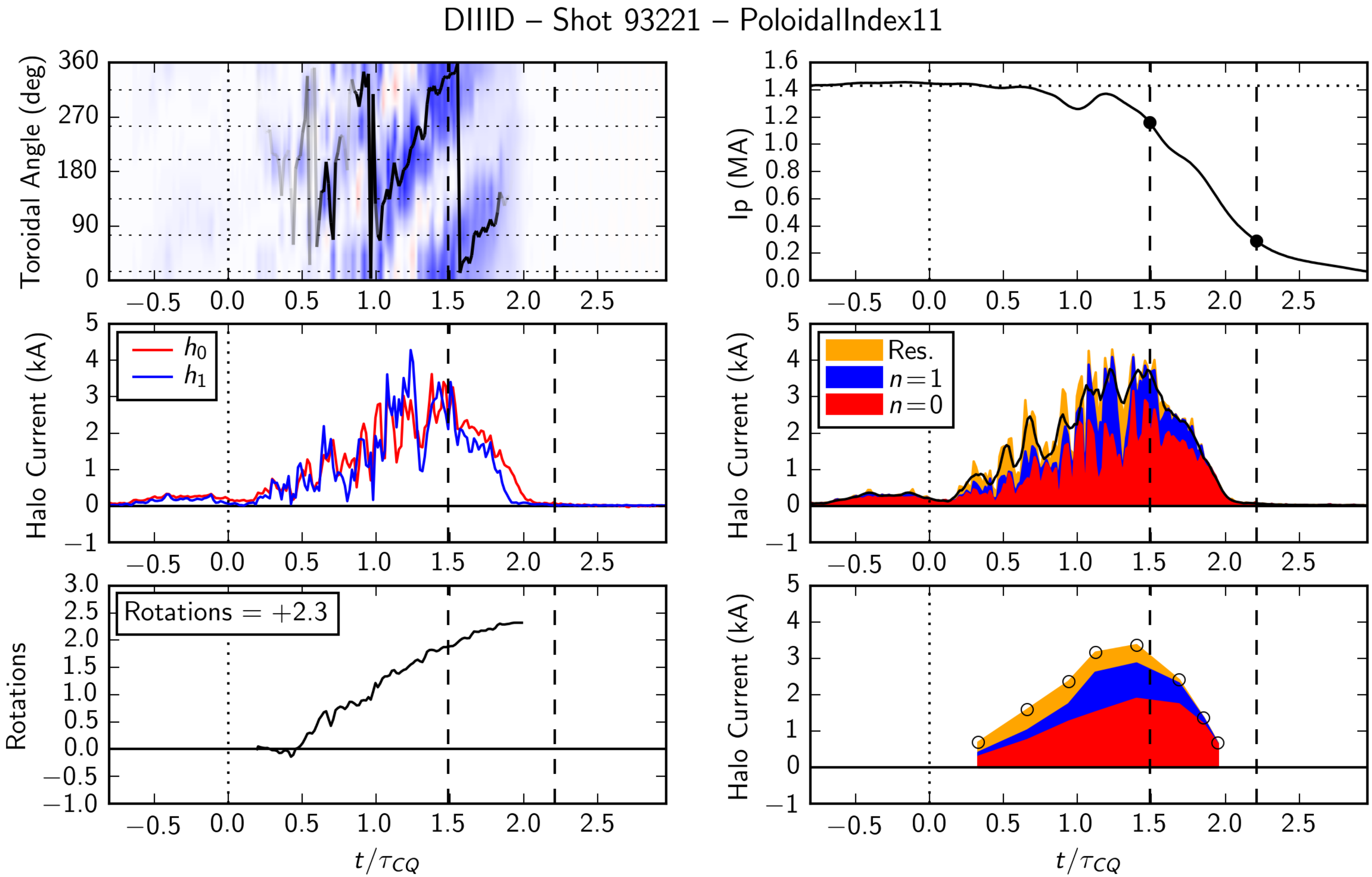
Representative NSTX Example (rotating)



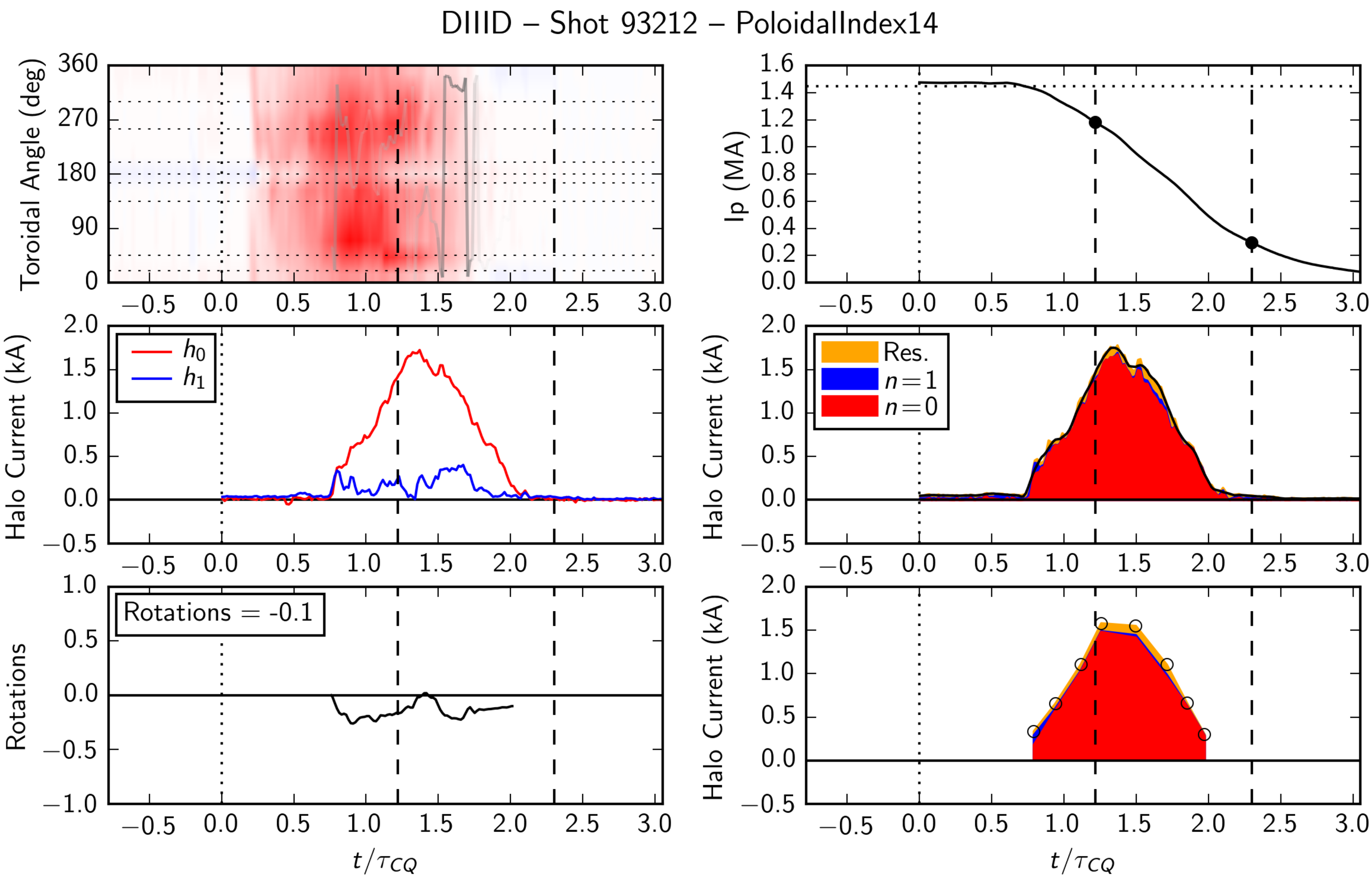
Representative NSTX Example (locked)



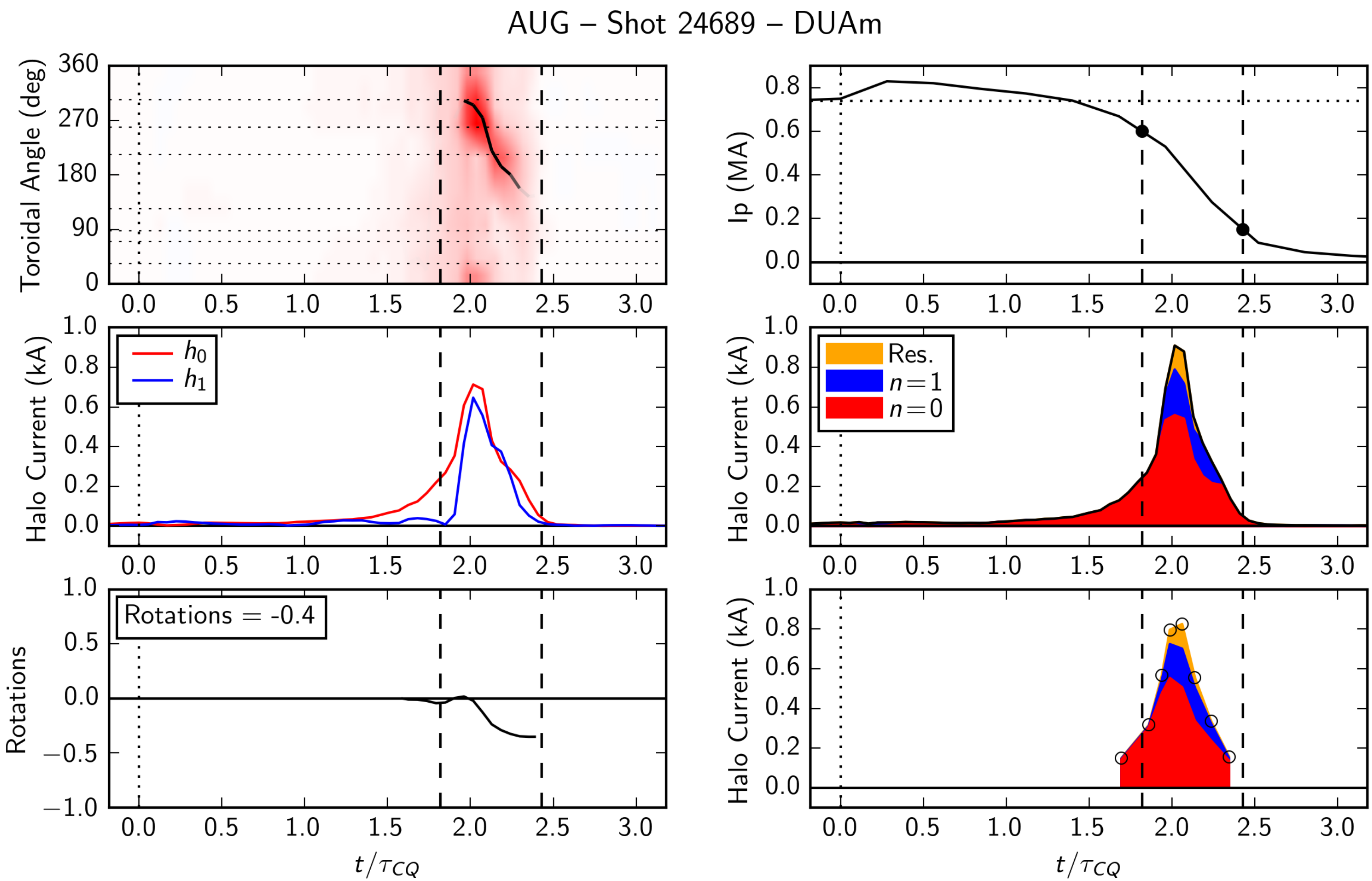
Representative DIII-D Example (rotating)



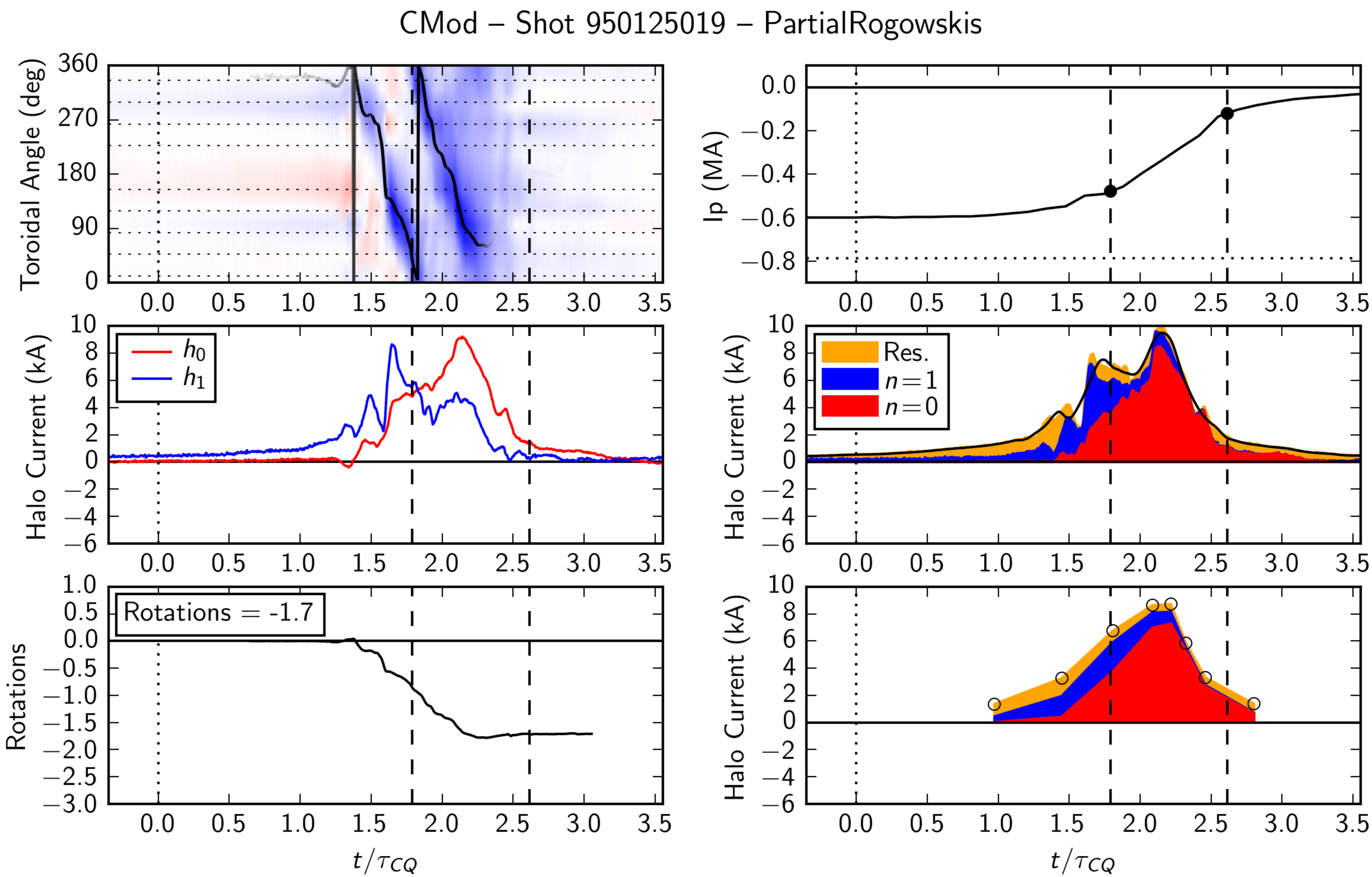
Representative DIII-D Example (locked)



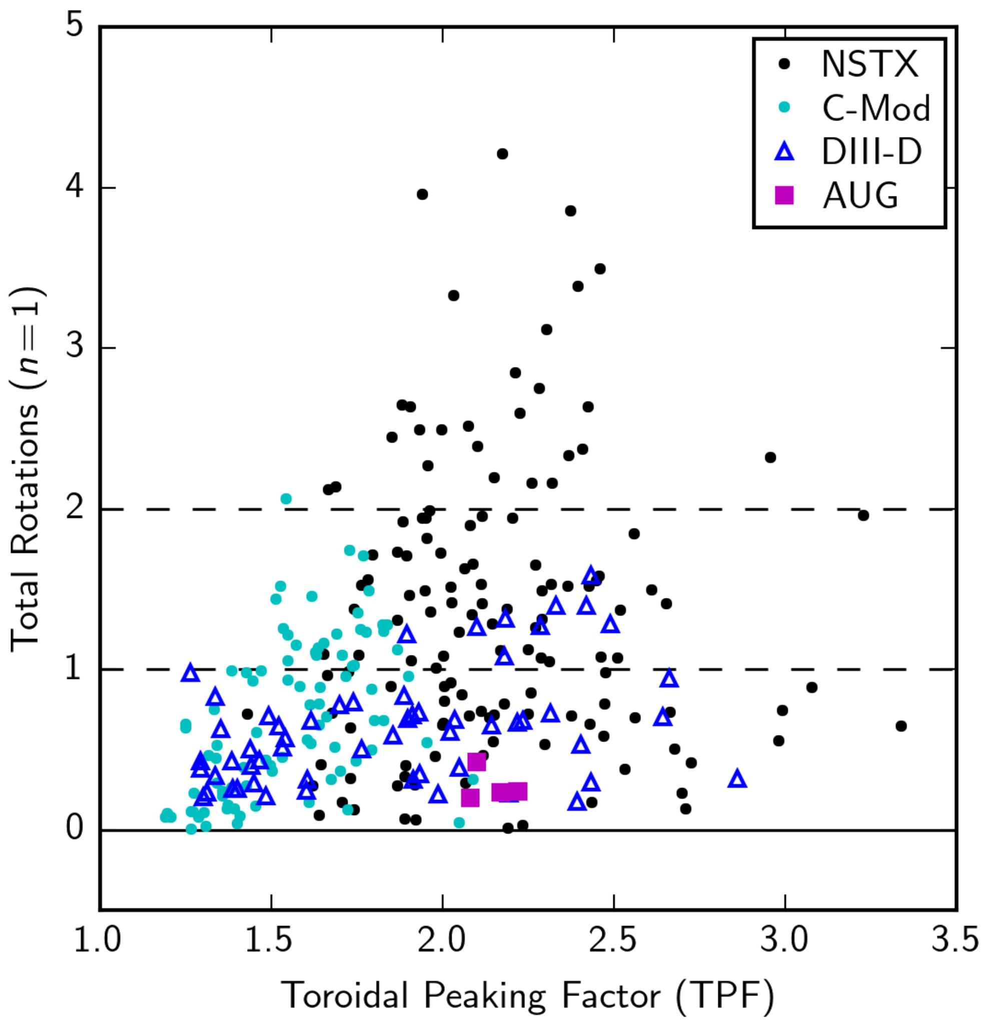
Representative AUG Example



Representative C-Mod Example



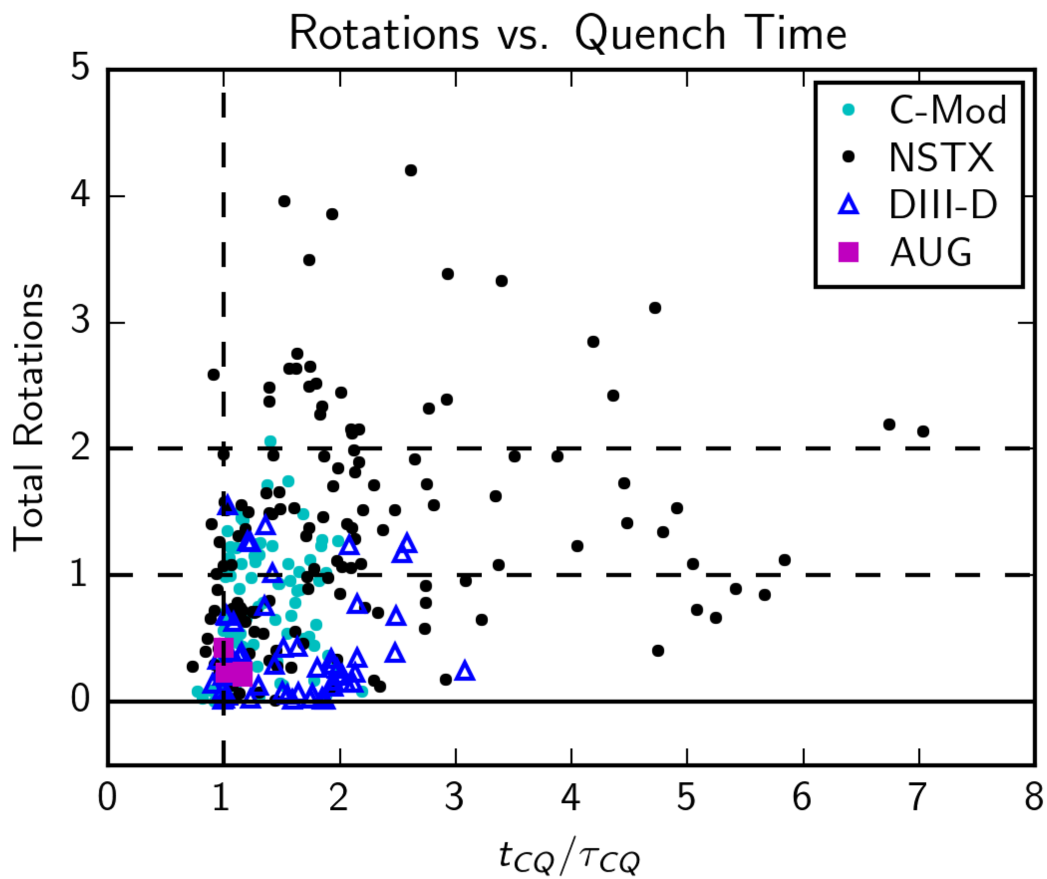
Combined non-axisymmetry and rotation



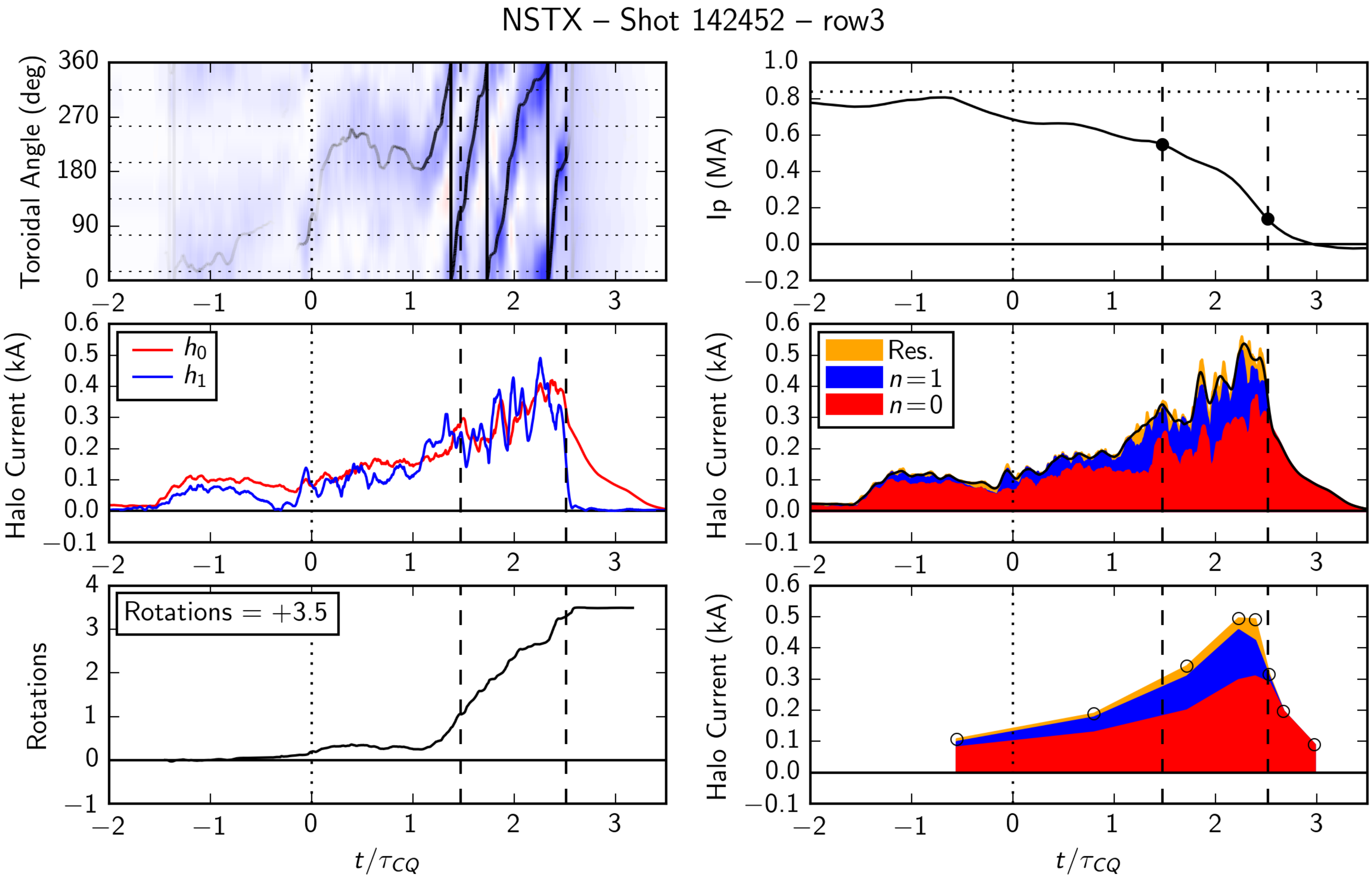
- Average the TPF around peak I_{HC}
- Weighted sum of all sensor arrays for a given discharge
- NSTX:
  - Consistently peaked
  - Highest observed rotation
- C-Mod and DIII-D:
  - Cluster of quasi-axisymmetric points for both machines
  - Many non-axisymmetric points
  - DIII-D more peaked
- AUG:
  - High peaking but low rotation
  - Does this hold with more shots?

High rotation observed even for fast CQ times

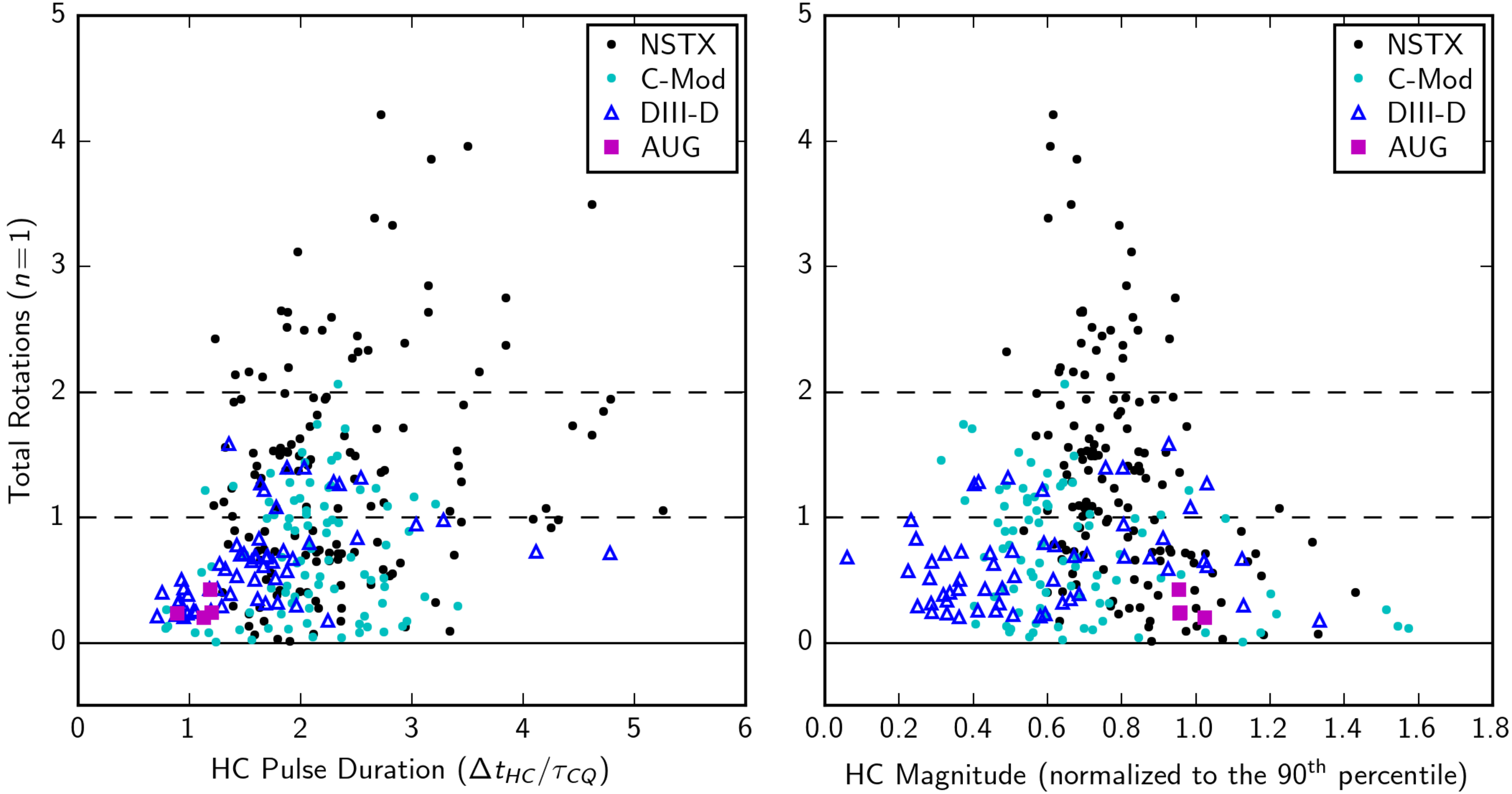
- Use CQ data to look for trends
- Do slow CQs drive more rotation?
- Seemingly less correlation than expected
- High rotation in NSTX even for fast CQs
- Does CQ timing capture the “right” details?



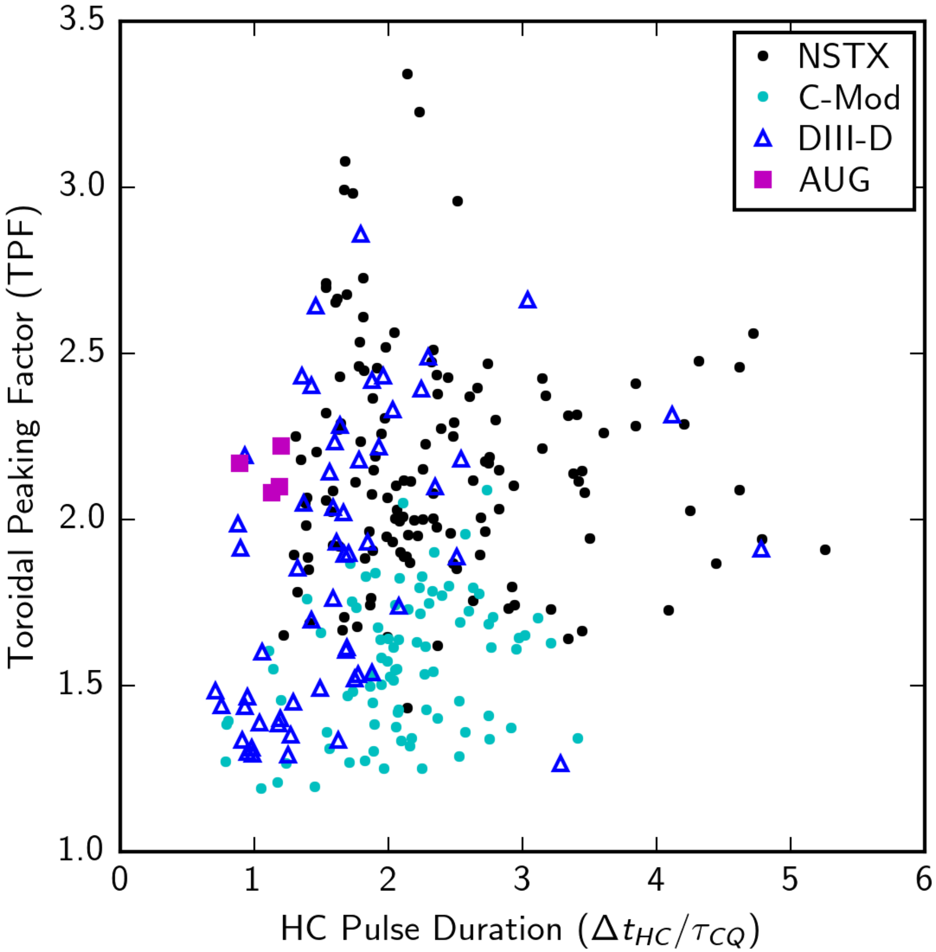
Halo current “foot” develops before main CQ

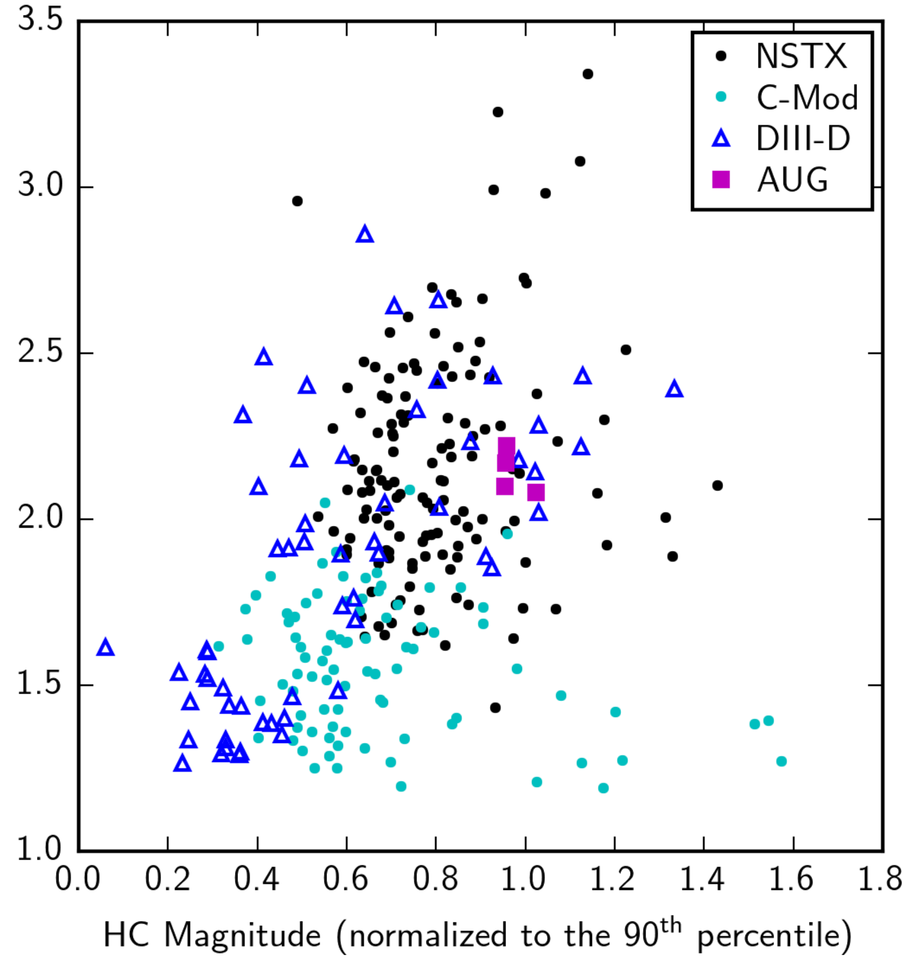


Rotation *correlates* with HC pulse duration and *anti-correlates* with HC magnitude



Non-axisymmetry *correlates* with HC magnitude





Summary

- Toroidally resolved halo current data obtained for four machines
- Common analysis procedure applied to all machines
- General findings:
  - At least some fraction of disruptions produce non-axisymmetric halo currents in all four machines
  - Significant rotation of the n=1 "lobe" observed in a non-negligible fraction of disruptions in NSTX, DIII-D, and C-Mod
- Preliminary trends:
  - Rotation loosely *correlates* with the HC pulse duration and *anti-correlates* with the HC magnitude
  - Non-axisymmetry loosely *correlates* with HC magnitude
  - May be able to trade HC rotation for HC magnitude at the risk of increased non-axisymmetry

Future plans

- Detailed analysis of rotation w.r.t. the pre-CQ I_{HC} "foot"
- Analysis w.r.t. the equilibrium data:
  - Equilibrium data (I_P, B_T, κ, Z_P, W_{MHD}, MGI, …)
  - Current quench times, edge safety factor, vertical position, etc.
- Fold in the new contributions:
  - More shots from AUG → coming soon
  - Contributions from JET? → difficult to compare
- Continue to work toward satisfying the ITPA WG specification doc:
  - "Windowed cosine power fits" rather than just simple n=0/n=1
  - Analyze locked vs. rotating cases independently
  - Comparison with proposed scaling laws