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

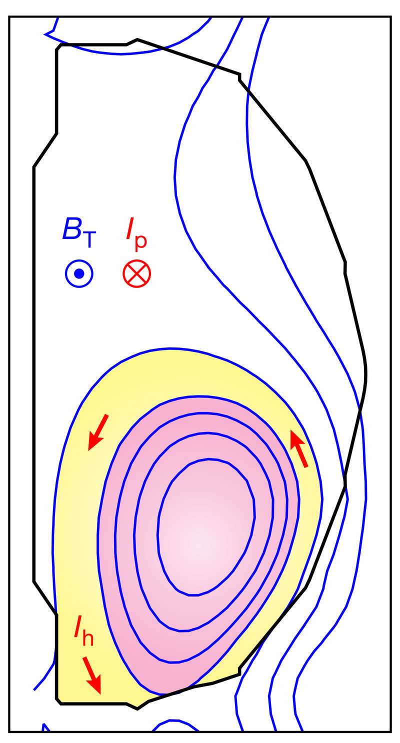
Clayton E. Myers[1], S. P. Gerhardt[1], N. W. Eidietis[2], R. S. Granetz[3], G. Pautasso[4], and the ITPA Working Group on Non-Axisymmetric Halo Currents

[1] Princeton Plasma Physics Laboratory, [2] General Atomics, [3] MIT Plasma Science and Fusion Center, [4] Max-Planck-Institüt für Plasmaphysik

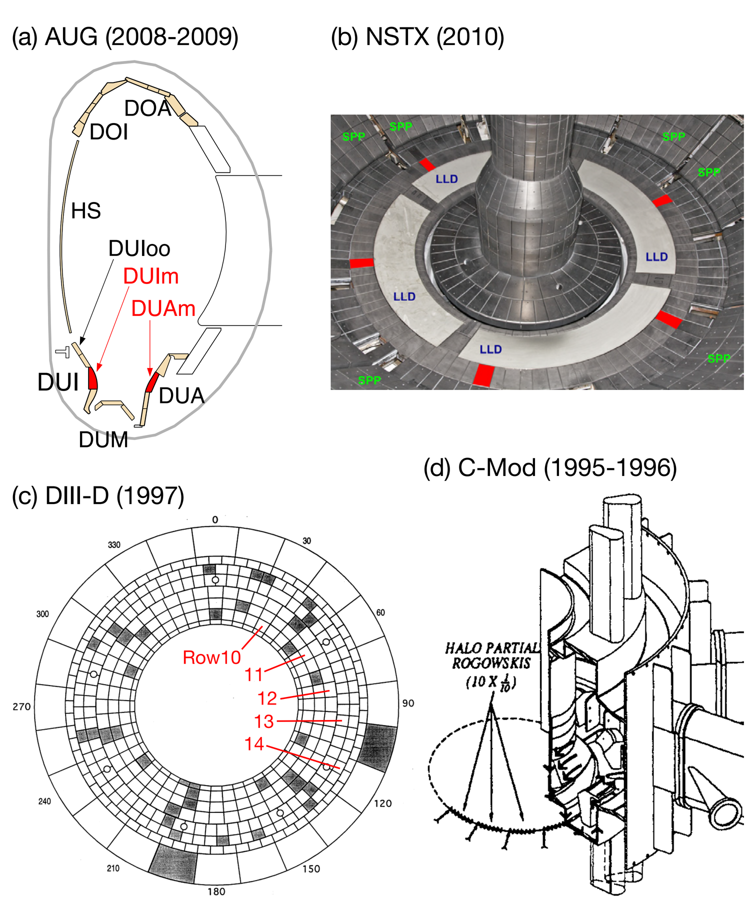
Halo current rotation & the ITPA halo current database

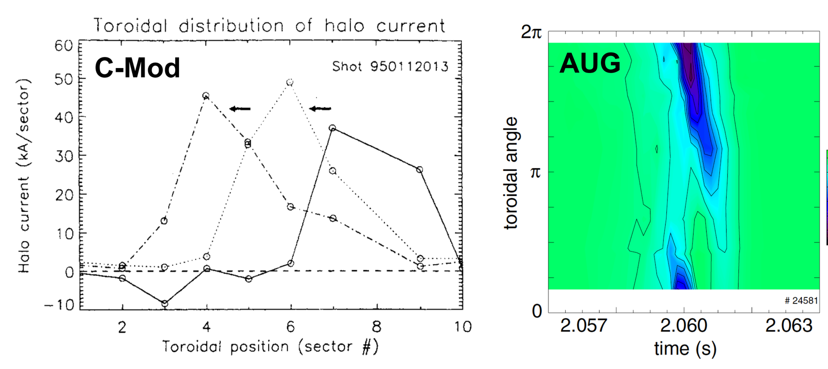
Halo currents are driven in the conducting structures of a tokamak when a disrupting plasma contacts the first wall → plasma + vessel circuit

Vessel forces are amplified when halo currents are toroidally non-axisymmetric and rotating → Will this be a problem for ITER?



Adapted from Manickam et al. *Phys. Plasmas* **19**, 082013 (2012)





Evidence for halo current rotation in many devices:
- JET: Noll 1996, Riccardo 2004, Gerasimov 2014
- C-Mod: Granetz et al. Nucl. Fusion **36**, 545 (1996)
- DIII-D: Evans et al. *J. Nucl. Mater.* **241-243**, 606 (1997)
- AUG: Pautasso et al. *Nucl. Fusion* **51**, 043010 (2011)
- NSTX: Gerhardt *Nucl. Fusion* **53**, 023005 (2013)

ITER considerations:
- Dynamic amplification requires 2+ complete rotations
- The most critical resonances are in the 3-8 Hz range
- [Schioler et al. *Fusion Eng. Des.* **81**, 1963 (2011)]

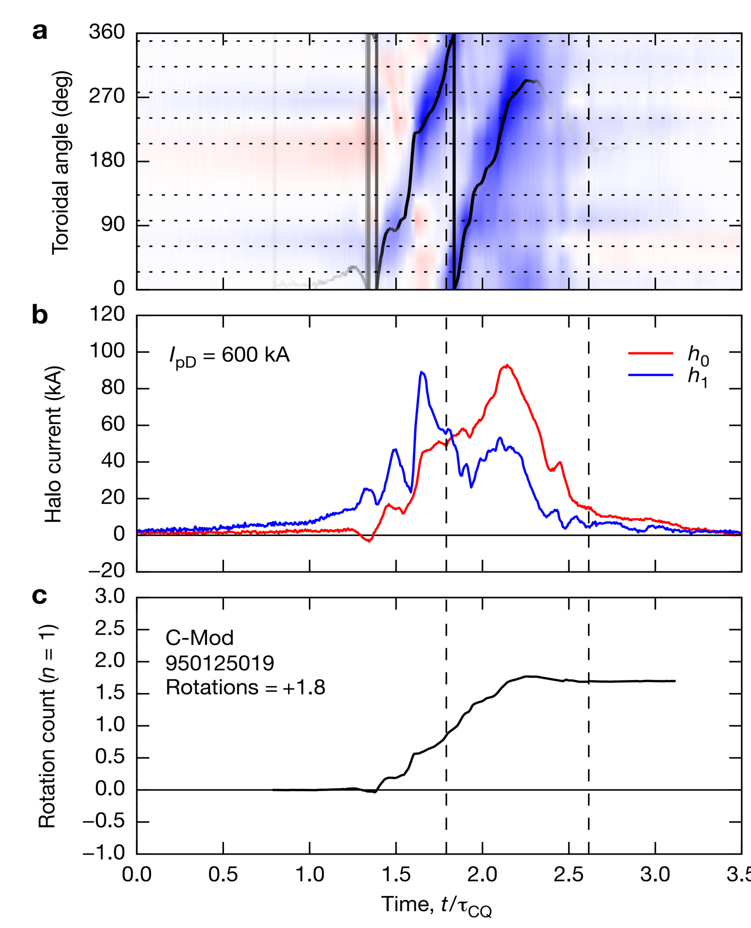
ITPA halo current database:
- C-Mod = 100+ shots @ 1 poloidal loc. (seg. rogowski)
- DIII-D = ~60 shots @ 5 poloidal locs. (shunt tiles)
- AUG = 100+ shots @ 2+ poloidal locs. (shunt tiles)
- NSTX = 140+ shots @ 1+ poloidal locs. (shunt tiles)

Common analytical framework

Fit model function to assess the $n = 0$ and $n = 1$ components of the halo currents:

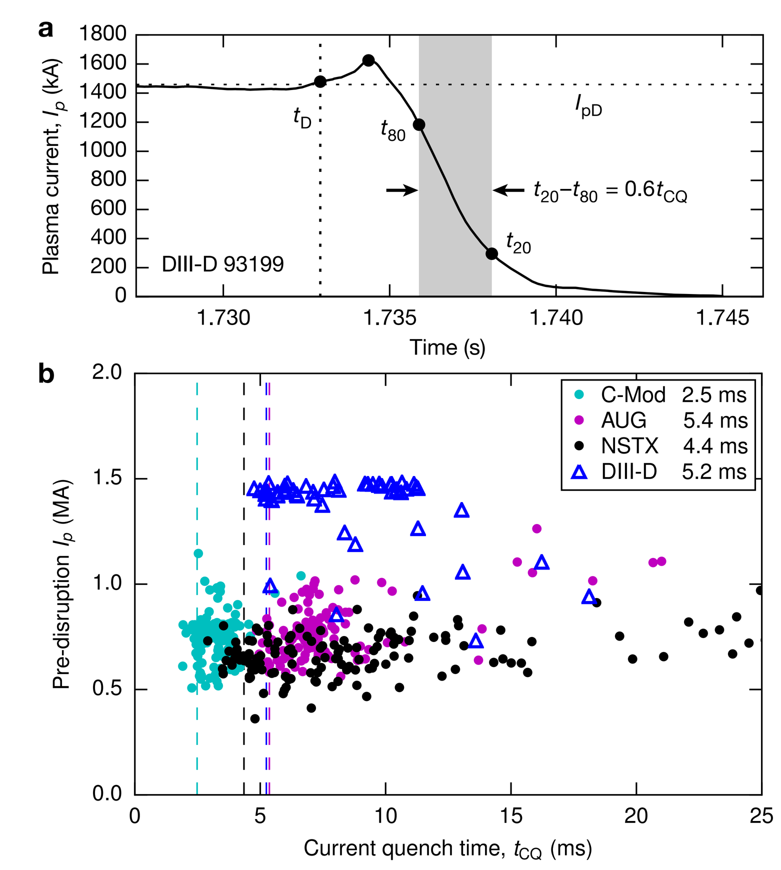
$$I_h(t) = h_0 + h_1 \sin(\phi - h_2)$$

Integrate the phase (h_2) to track rotation

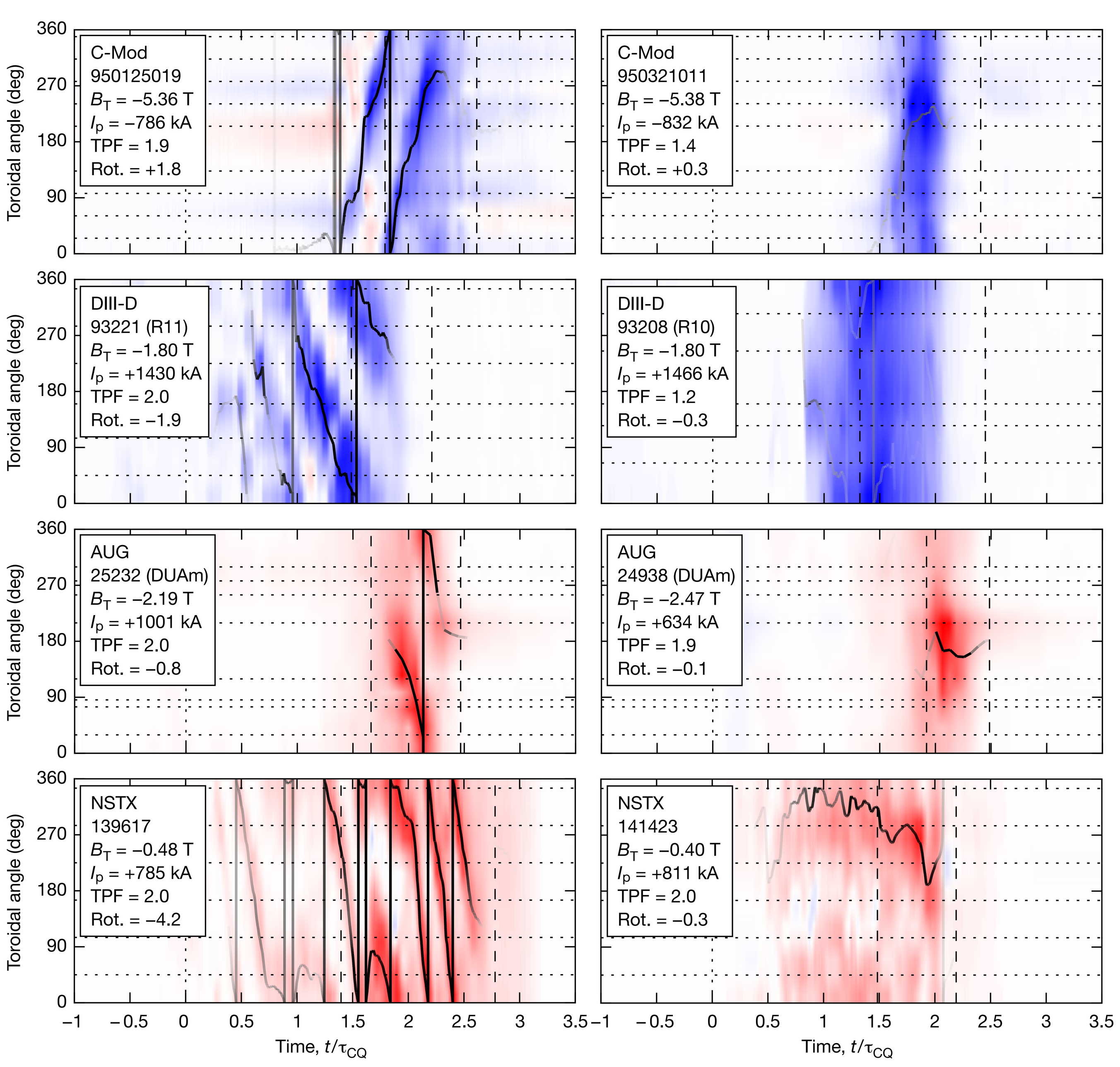


Apply standard disruption timing analysis to find current quench time, $t_{CQ} = 5/3(t_{20} - t_{80})$

Normalize to measured characteristic 'fast' current quench time for each device, τ_{CQ}



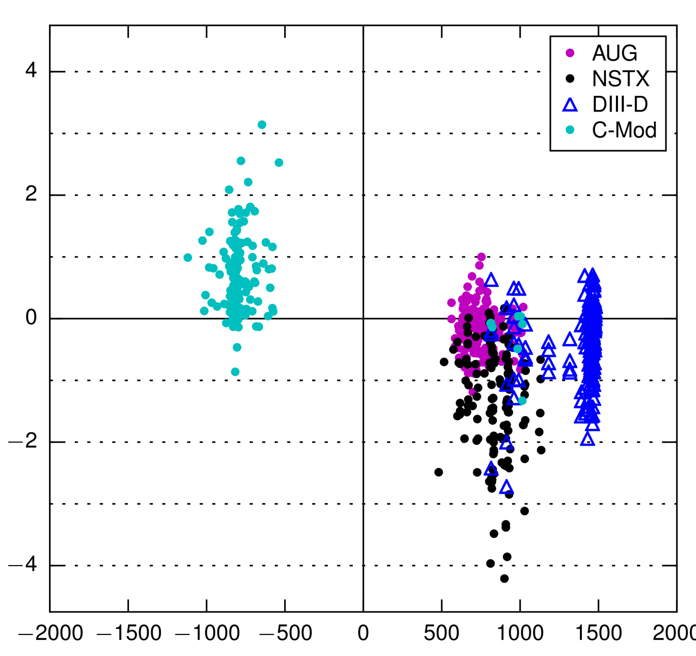
Database-wide phenomenology and trends

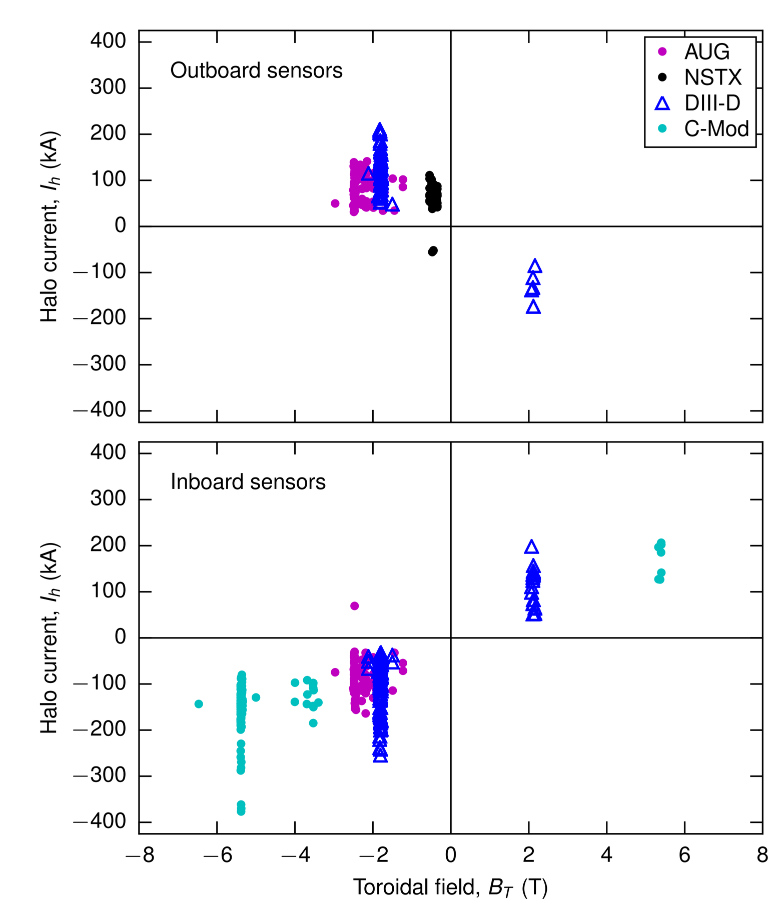


Both rotating and locked/symmetric cases are observed in each machine (left).

Blue halo currents are entering the wall and red halo currents are exiting the wall. The C-Mod and DIII-D sensors plotted here are inboard, while the AUG and NSTX sensors are outboard.

Thus, all halo currents are flowing poloidally from outboard to inboard, which is paramagnetic with respect to the negative B_T.



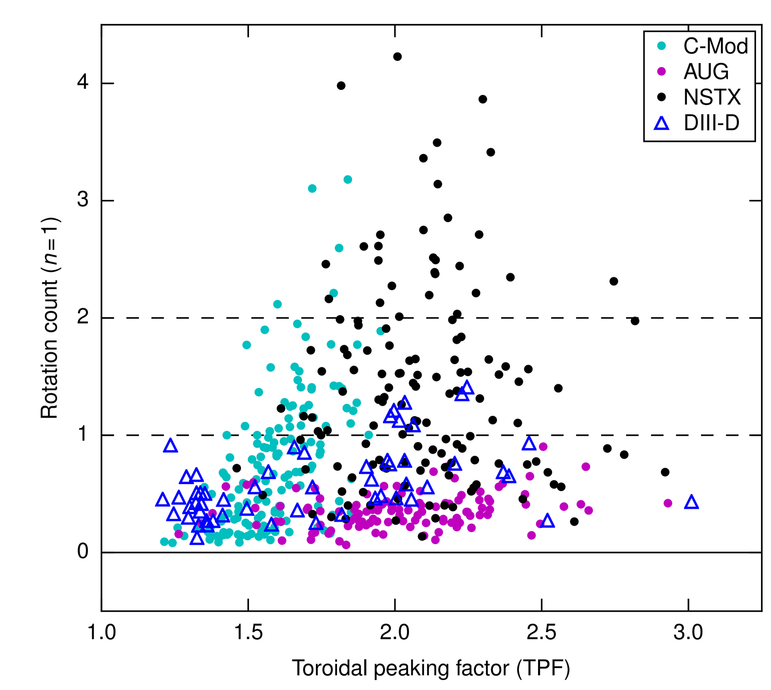


Database-wide halo current polarity shows that the poloidal direction of the halo currents is paramagnetic w.r.t. B_T (above).

Database-wide rotation data shows the rotation is predominantly counter-I_p (left).

Database-wide comparison of halo current rotation vs. non-axisymmetry (TPF) shows no strong correlation.

Minimal rotation in quasi-symmetric cases → h_1 threshold on integrated rotation



1. Polarity = paramagnetic w.r.t. B_T
2. Rotation = predominately counter-I_p
3. No strong correlation between non-axisymmetry and rotation

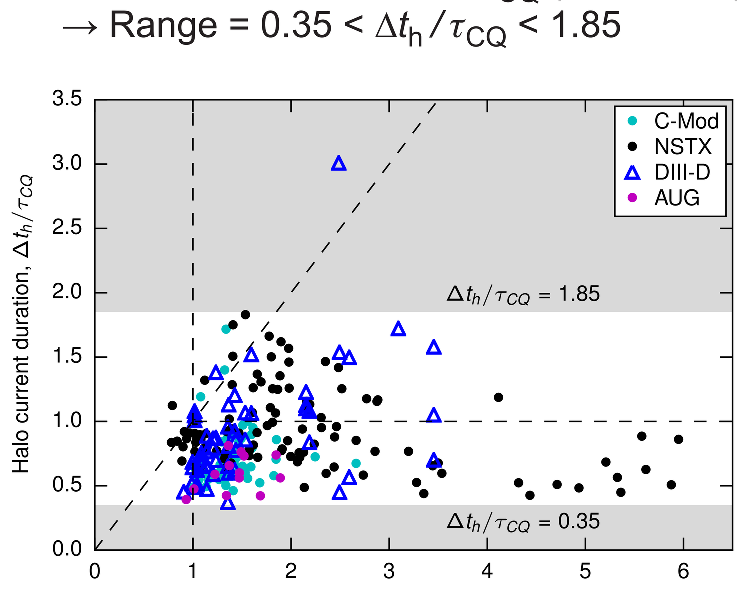
Halo current rotation and duration scalings

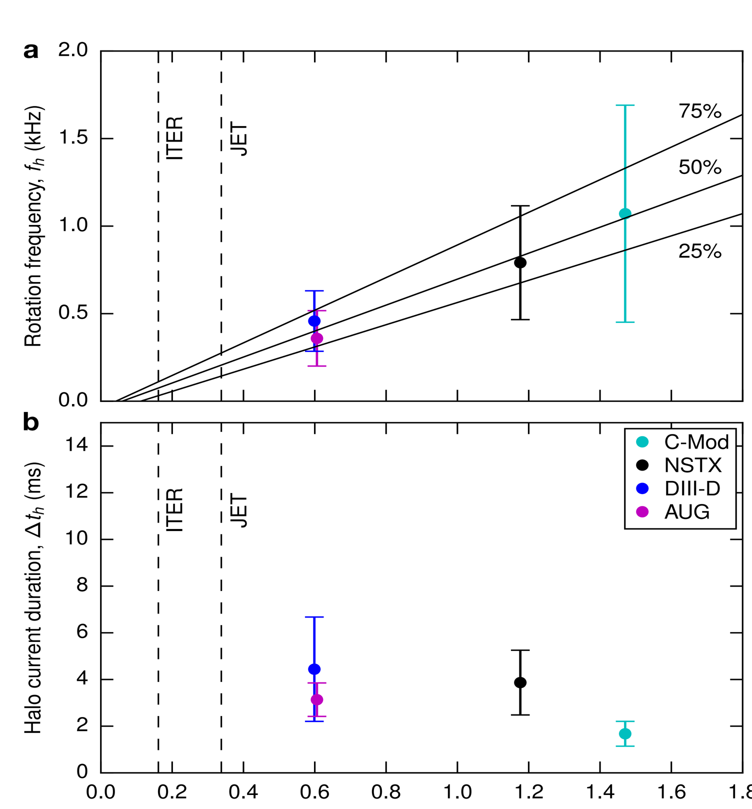
Only consider shots with > 0.75 rotations

The halo current rotation frequency scales linearly with inverse major radius (see right)
- → Consistent rotation velocity, $v_h \sim 5$ km/s
- → Projected ITER frequency, 30-110 Hz

The halo current duration, Δt_h, does not scale obviously with major radius

The halo current duration is bracketed by the characteristic current quench time, τ_{CQ} (see below)
- → Range = $0.35 < \Delta t_h / \tau_{CQ} < 1.85$





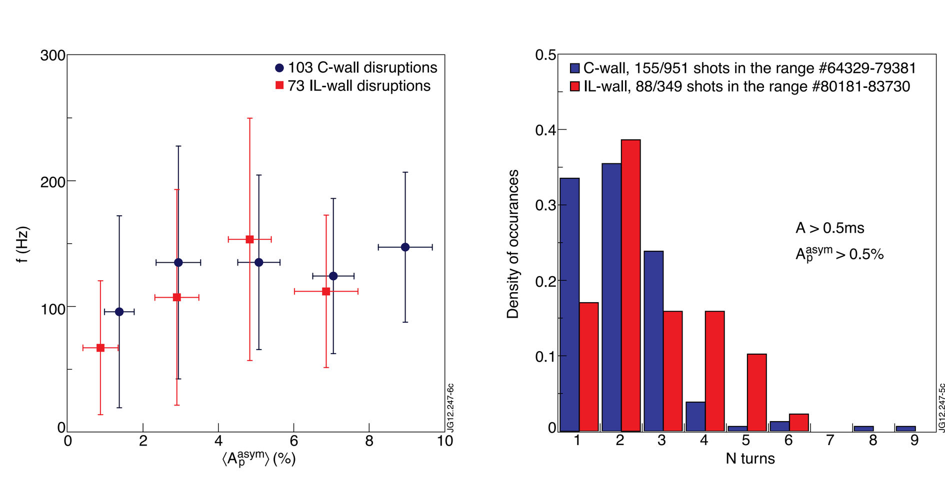
1. Consistent rotation velocity, $v_h \sim 5$ km/s
2. Projected ITER rot. frequency, $f_h \sim 30$-110 Hz
3. Halo current duration bracketed by the characteristic CQ time, $0.35 < \Delta t_h / \tau_{CQ} < 1.85$

Projection to JET and ITER

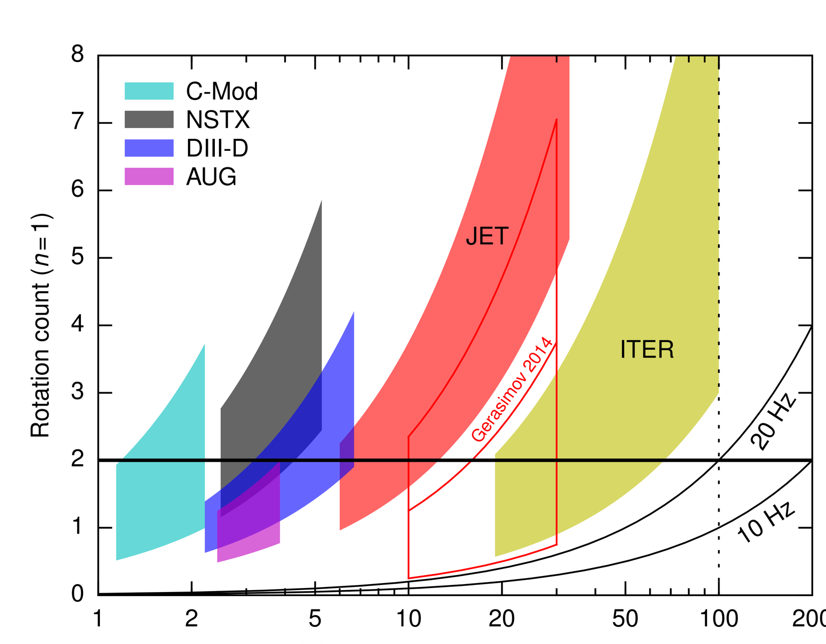
Use the rotation frequency scaling ($f_h \sim 1/R_0$) and the halo current duration bracket ($0.35 < \Delta t_h / \tau_{CQ} < 1.85$) to project to JET and ITER (see right).

The Wesley L/R (S•ℓ) scaling [IAEA FEC 2006 IT/P1-21] is used to project τ_{CQ} to ITER and JET (see table below).

Machine	R_0 [m]	a_0 [m]	κ	S [m^2]	ℓ	Meas. τ_{CQ} [ms]	$\tau_{CQ}/(S \cdot \ell_i)$	$0.35\,\tau_{CQ}$ [ms]	$1.85\,\tau_{CQ}$ [ms]
C-Mod	0.68	0.22	1.60	0.24	1.71	2.49	6.00	0.87	4.61
NSTX	0.85	0.68	2.65	3.85	0.80	4.48	1.45	1.57	8.29
AUG	1.65	0.65	1.80	2.39	1.51	5.33	1.48	1.87	9.86
DIII-D	1.67	0.67	1.80	2.54	1.49	5.24	1.38	1.83	9.69
JET	2.96	1.25	1.80	8.83	1.44	{18}	{1.4}	{6}	{33}
ITER	6.20	2.00	1.80	22.61	1.71	{54}	{1.4}	{19}	{100}



Gerasimov et al. *Nucl. Fusion* **54**, 073009 (2014)



1. Comparisons to JET results [Gerasimov 2014] show similar halo current durations at slightly slower frequencies
2. Project that ITER will exhibit substantial halo current rotation for $f_h > 20$ Hz
3. If the upper bound of 100 ms on the halo current duration holds, then ITER will avoid 2+ rotations at 3-8 Hz