A multi-machine scaling of halo current rotation

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Motivation: The rotating halo current problem

- Substantial halo current rotation observed in a number of devices:
  - JET Noll 1996, Riccardo 2004 & 2009, Gerasimov 2014 & 2015
  - 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)

- The concern for ITER:
  - Forces are dynamically amplified if $N_{rot} > 2\text{-}3$
  - Critical mechanical resonances in the 3-8 Hz range [Schioler FED 2011]
  - Overall response is broader (10-20 Hz) [Bachmann FED 2011 & Lehnen]

- **Critical question:**
  - **Are halo currents in ITER likely to complete 2-3 full rotations at frequencies below 20 Hz?**

Key quantities: Rotation duration and frequency

- **Are halo currents in ITER likely to complete 2-3 full rotations at frequencies below 20 Hz?**

- Deconstruct N_{rot} into rotation duration and rotation frequency:

$$N_{\mathrm{rot}} = \langle f_{\mathrm{h}} \rangle \cdot t_{\mathrm{rot}} = \frac{\langle v_{\mathrm{h}} \rangle}{2\pi R} \cdot t_{\mathrm{rot}}$$

N_{rot} = number of rotations
$\langle f_{\mathrm{h}} \rangle$ = rotation frequency
t_{rot} = rotation duration
$\langle v_{\mathrm{h}} \rangle$ = rotation velocity (toroidal)
R = major radius

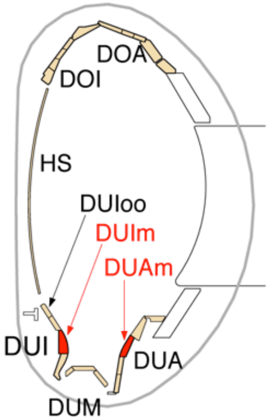
- Construct a new ITPA halo current rotation database to develop empirical scalings for $\langle f_{\mathrm{h}} \rangle$ and t_{rot}

Presentation outline

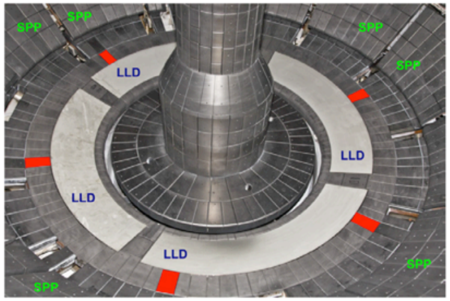
- The ITPA halo current rotation database
- Current quench analysis and scalings
- The halo current rotation analysis procedure
- Development of rotation scalings
  - Halo current rotation duration, t_{rot}
  - Halo current rotation frequency, $\langle f_{\mathrm{h}} \rangle$
- Projection to ITER
  - Projected ITER behavior is marginal w.r.t. ITER resonances
  - $N_{\mathrm{rot}} > 3$ at $\langle f_{\mathrm{h}} \rangle > 20$ Hz is likely
  - $N_{\mathrm{rot}} \sim 3$ at $\langle f_{\mathrm{h}} \rangle \sim 10$–$20$ Hz is possible

Halo current sensor arrays in the ITPA database

a AUG (2008-2015)

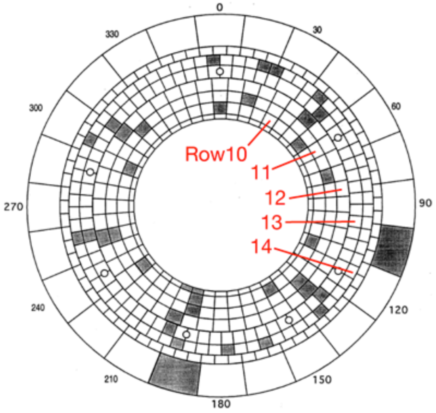


b NSTX (2010)

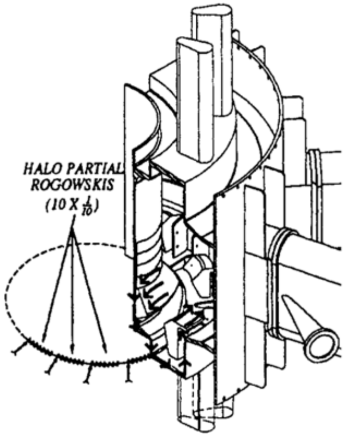


- The DIII-D, AUG, and NSTX sensors are shunt tile arrays
- The C-Mod sensors are partial toroidal rogowski coils
- In JET, poloidal field sensor arrays provide I_p asymmetry measurements

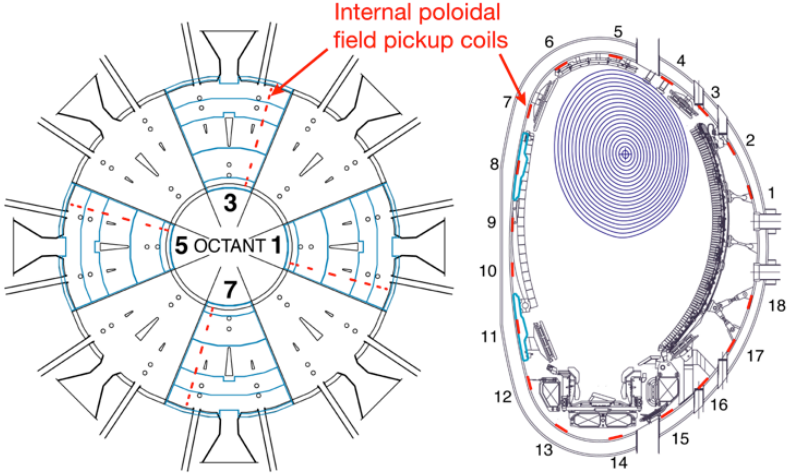
c DIII-D (1997)



d C-Mod (1995-1996)



e JET (2005-2015)



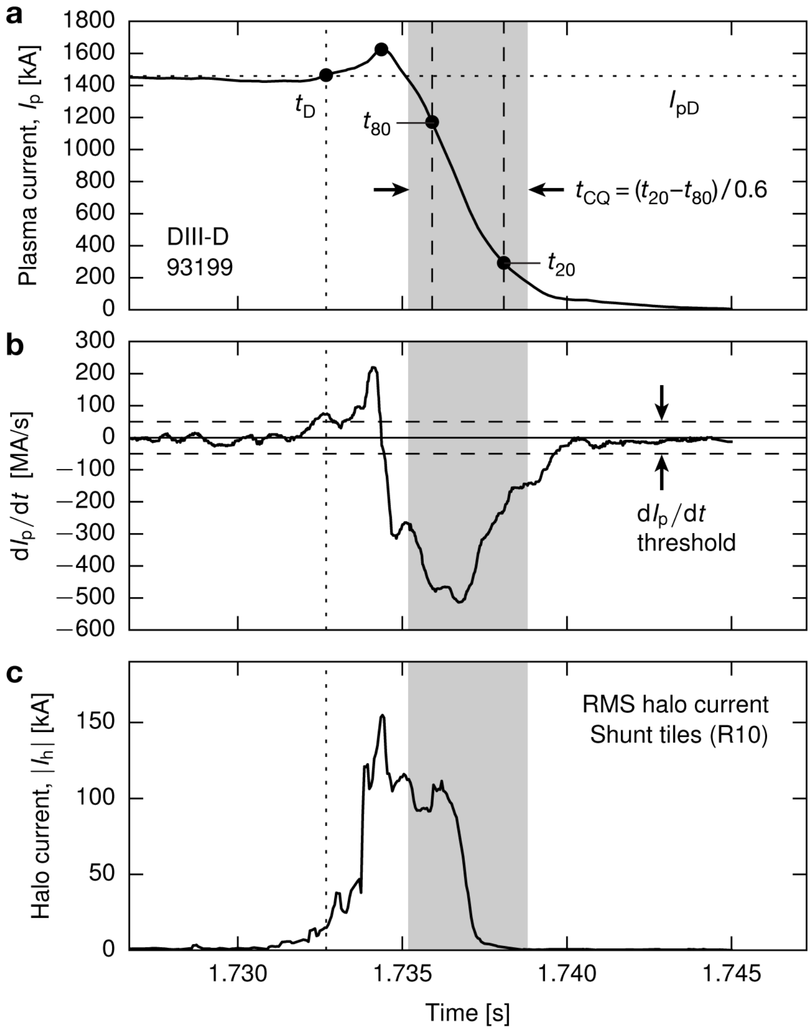
The ITPA halo current rotation database

- One ‘data unit’ per shot:
  - Halo current vs. toroidal angle (one or more sensor arrays)
  - At least four toroidal locations per sensor array
  - Auxiliary data (I_p, B_T, κ, Z_p, W_{MHD}, MGI, …)
- Contents of the database (~850 total shots):

C-Mod	Partial rogowskis	Moly	148	shots ×	1+ poloidal locations
NSTX	Shunt tiles	Carbon	141	shots ×	1+ poloidal locations
AUG-C	Shunt tiles	Carbon	158	shots ×	2+ poloidal locations
AUG-W	Shunt tiles	Tungsten	51	shots ×	2+ poloidal locations
DIII-D	Shunt tiles	Carbon	55	shots ×	4+ poloidal locations
JET-C	I_p asymmetry	Carbon	146	shots ×	4 toroidal octants
JET-ILW	I_p asymmetry	ITER-like	150	shots ×	4 toroidal octants

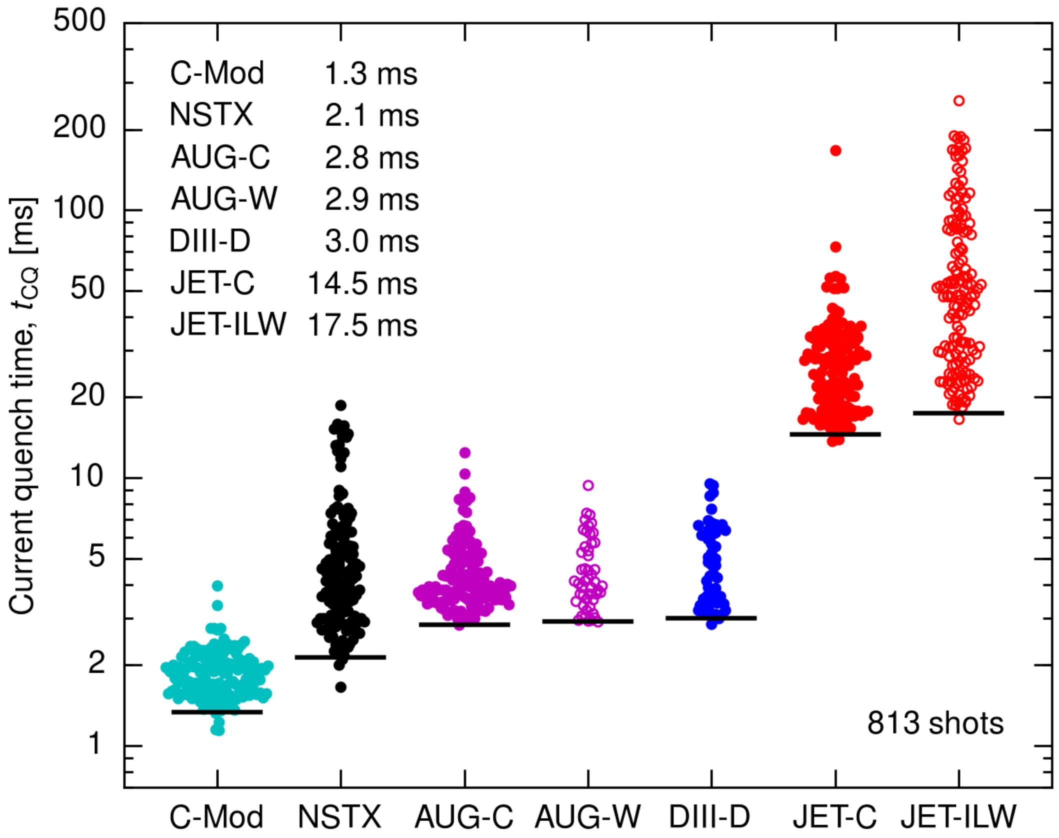
- All disruptions in the database are unmitigated

Analysis procedure: current quench



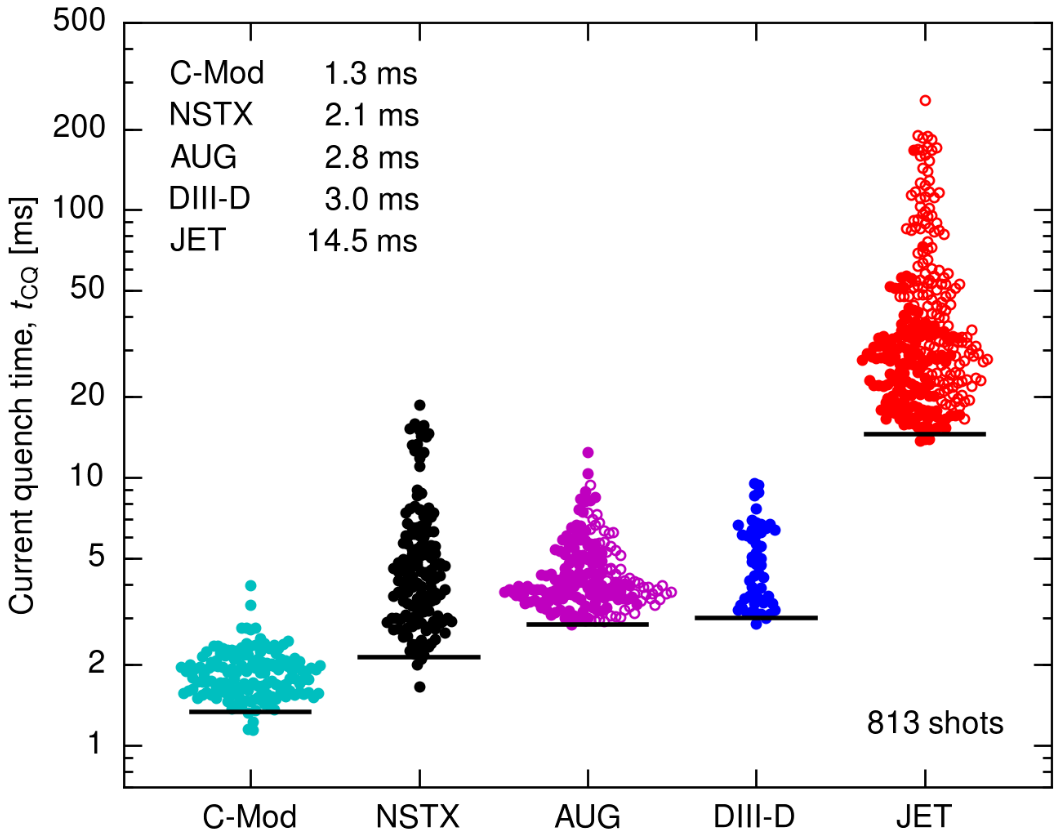
- Use standard $t_{CQ} = (t_{20} - t_{80}) /0.6$ current quench analysis
- Disruption time, t_D, determined with thresholds on dI_p/dt
- For JET, use Gerasimov algorithm for t_D → includes loop voltage
- t_{20} and t_{80} mark when I_p/I_{pD} is 80% and 20%, respectively
- The RMS halo current, $|I_h|$, is shown for a single shunt tile array (DIII-D Row 10)

Characteristic current quench timescales



- Denote the shot-specific current quench time as t_{CQ}
- Each device has a characteristic minimum current quench time, τ_{CQ}
- Define τ_{CQ} as the fastest quench time for each machine excepting outliers
- Conclude that CQ timing for asymmetric VDEs unaffected by wall material

Combine JET-C and JET-ILW data



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- Conclude that CQ timing for asymmetric VDEs unaffected by wall material
- Combine AUG-C, AUG-W and JET-C, JET-ILW

The Wesley τ_{CQ} ~ *L*/*R* current quench scaling

- Conjecture that the characteristic fast current quench time, τ_{CQ}, is set by the plasma *L*/*R* time:

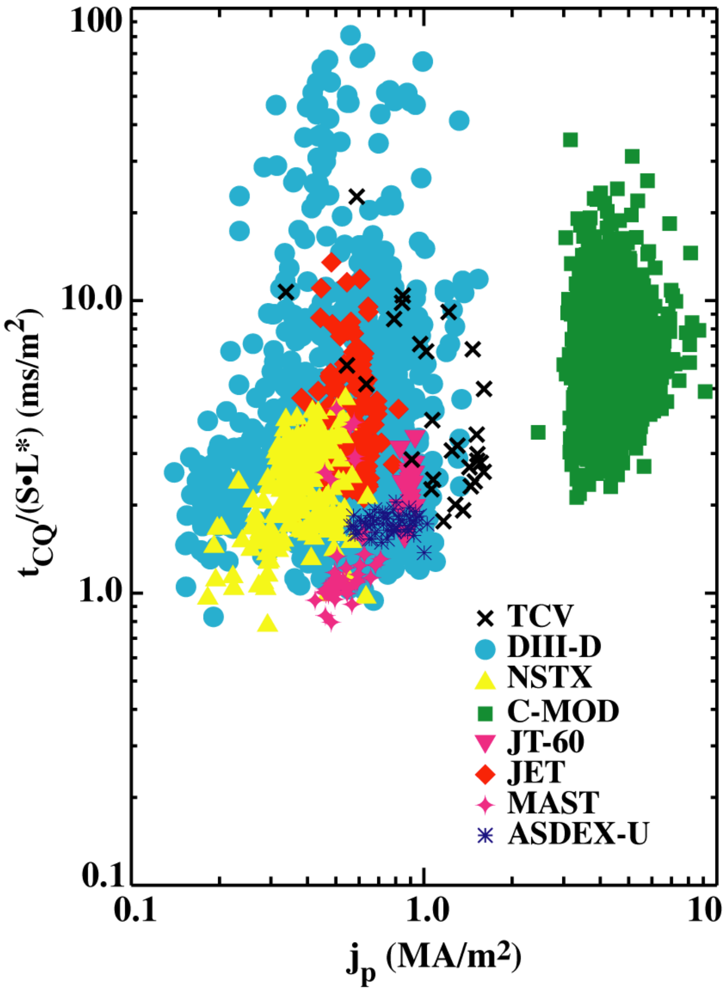
$$\mathcal{L} = \mu_0 R\,\ell, \quad \text{where} \quad \ell = \ln\left(\frac{8R}{a}\right) - 2 + \frac{\ell_i}{2}$$

$$\mathcal{R} = \eta\left(\frac{2\pi R}{S}\right), \quad \text{where} \quad S \simeq \pi\kappa a^2$$

$$\mathcal{L}/\mathcal{R} = \frac{\mu_0}{2\pi\eta}\left(S\cdot\ell\right) = C\left(\eta^{-1}\right)S\,\ell$$

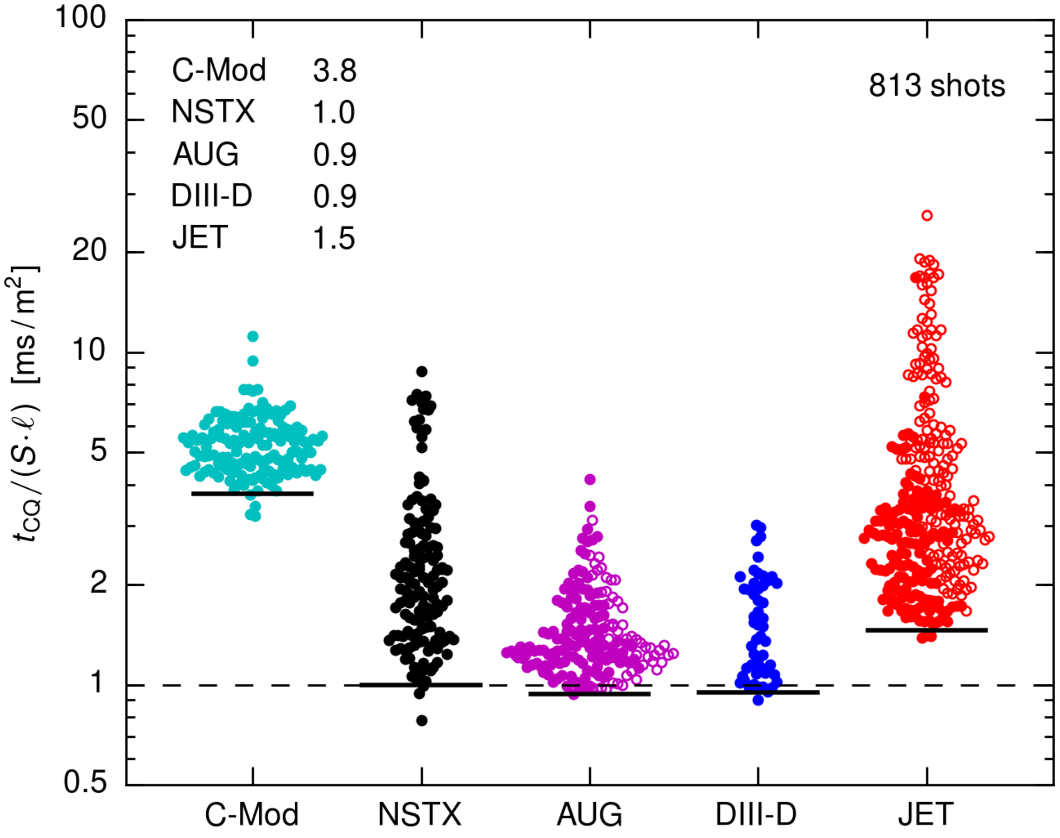
- From the Wesley dataset, *C* ~ 1 [see right]
- Note that C-Mod does not fit the scaling:
  - Higher current density leads to ohmic reheating during the CQ [Granetz]
- Assuming $\ell_i = 0.5$, the 'Wesley time' is given by:

$$\tau_{CQ}\left(R, a, \kappa, \eta\right) = C\left(\eta^{-1}\right)\cdot S\left(a, \kappa\right)\cdot \ell\left(R, a\right)$$



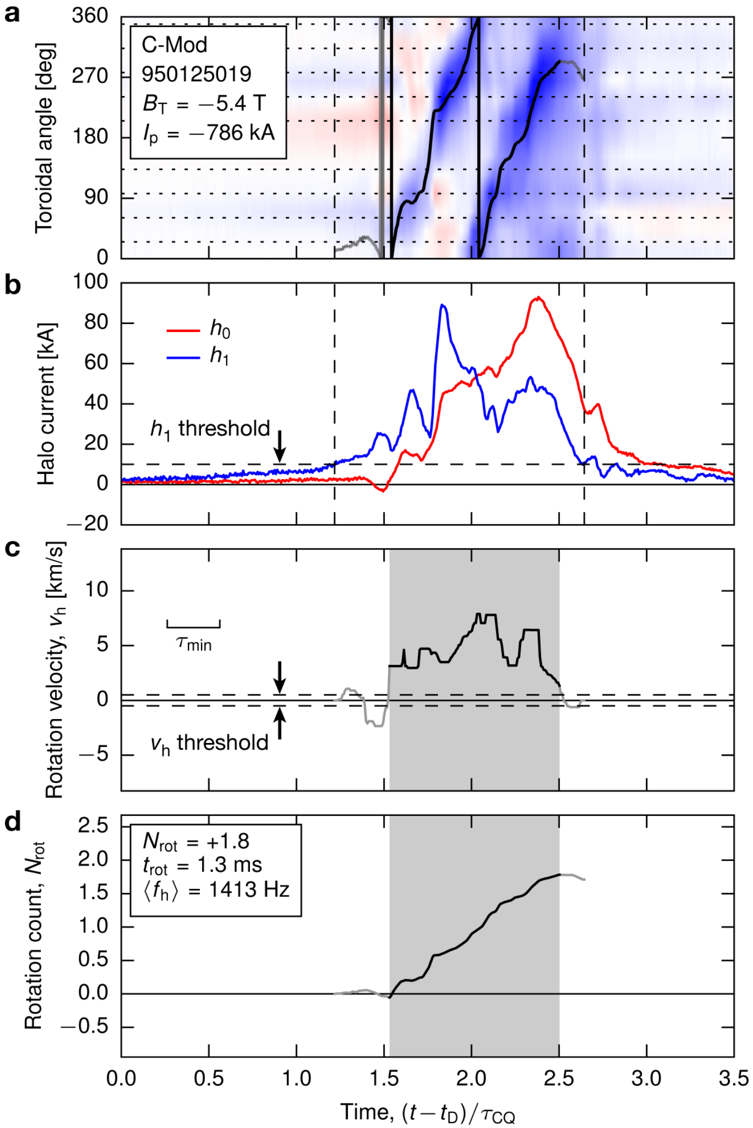
Wesley et al., IAEA FEC 2006, IT/P1-21

Comparison to the Wesley $\tau_{CQ} \sim L/R$ scaling



- NSTX, AUG, and DIII-D normalize to $C \sim 1$, in agreement with Wesley
- As expected, C-Mod does not fit the scaling ($C = 3.8$)
- JET has modestly larger normalization ($C = 1.5$)
- Assume that ITER will lie between JET and C-Mod:
  → $\tau_{CQ} \sim$ 50–130 ms

Analysis procedure: halo current rotation

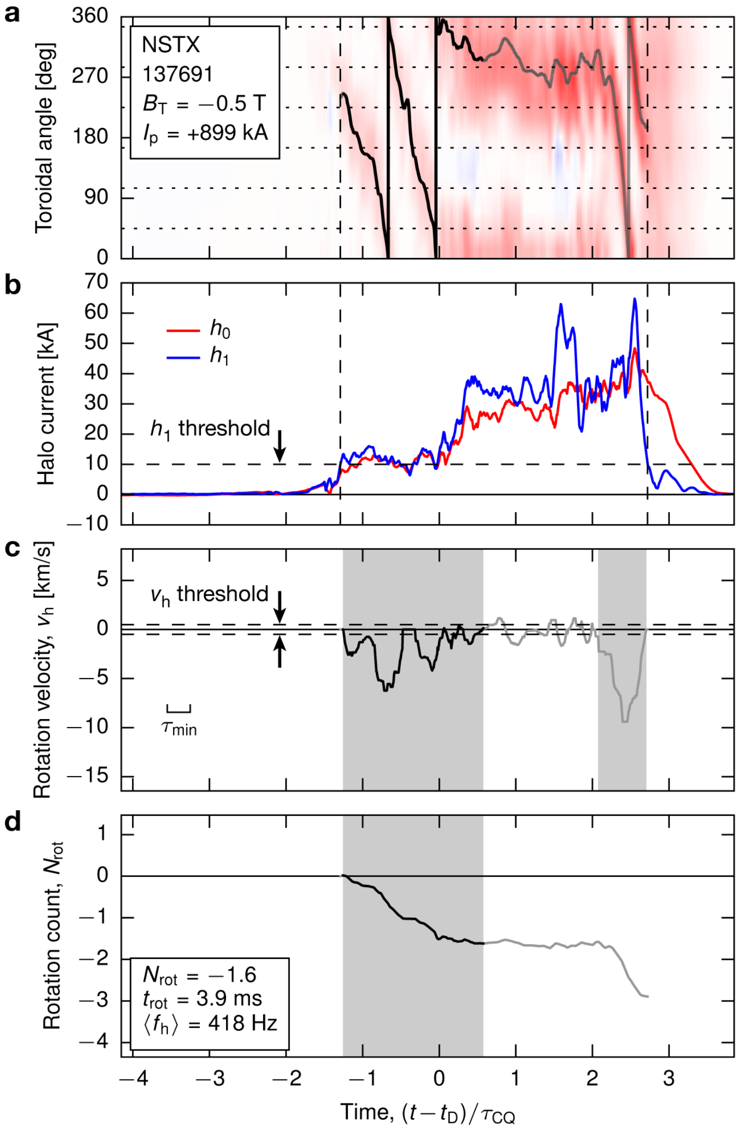


- Fit $n = 0,1$ profile to each toroidal array at each time point:

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

- Identify ‘asymmetry interval’ using h_1 > 10 kA threshold
- Identify ‘rotation interval’ using $|v_h|$ > 0.5 km/s threshold
- Enforce minimum dwell time, $\tau_{min} > 0.3\,\tau_{CQ}$
- Record N_{rot}, t_{rot}, $\langle f_h \rangle = N_{rot} / t_{rot}$

Account for rotation locking or reversal



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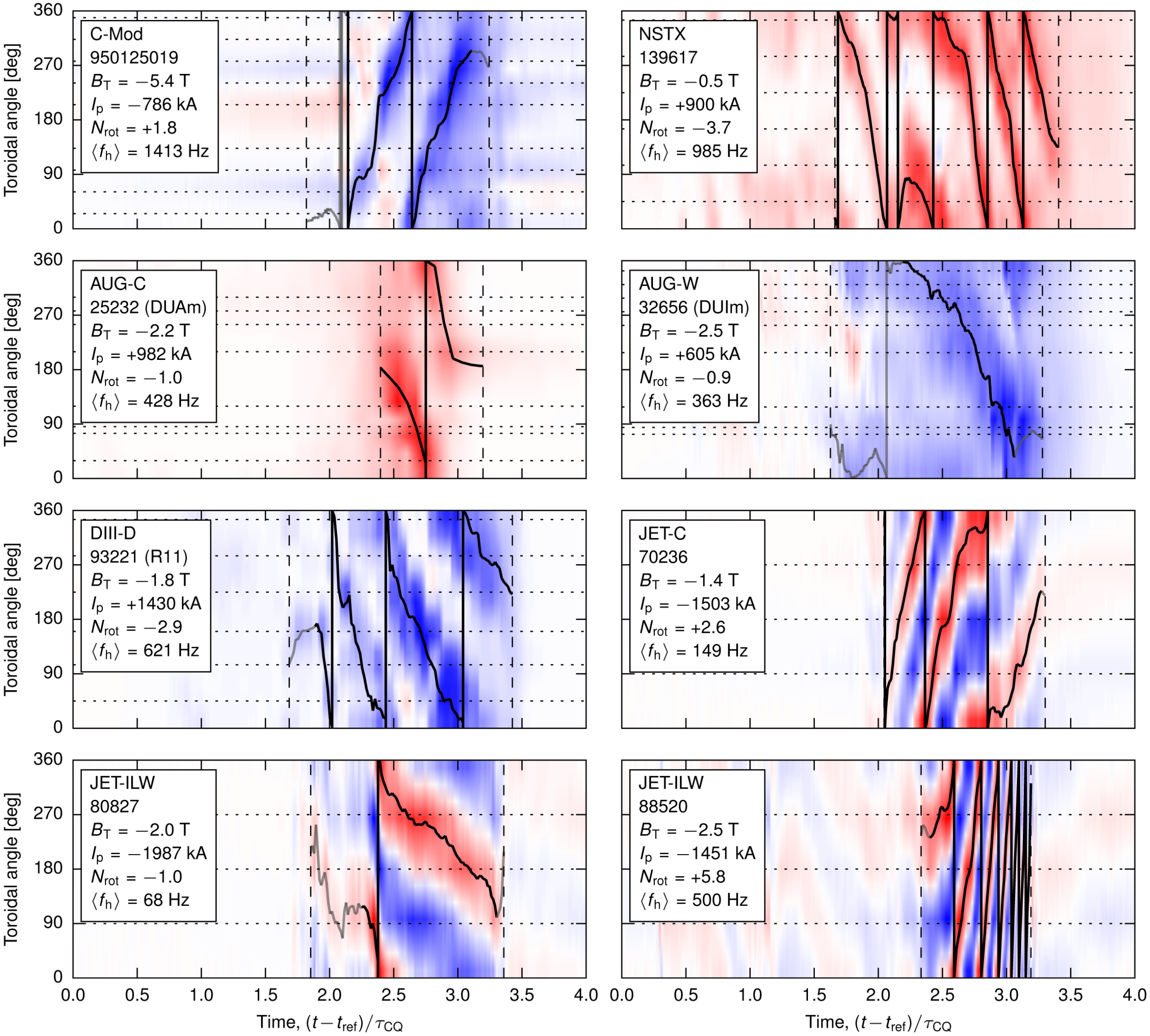
- Identify 'asymmetry interval' using $h_1 > 10$ kA threshold
- Identify 'rotation interval' using $|v_h| > 0.5$ km/s threshold
- Enforce minimum dwell time, $\tau_{min} > 0.3\ \tau_{CQ}$
- Record N_{rot}, t_{rot}, $\langle f_h \rangle = N_{rot} / t_{rot}$
- In cases with multiple rotation intervals, select the longest

Rotating halo current examples from each machine



C-Mod

NSTX

AUG-C

AUG-W

DIII-D

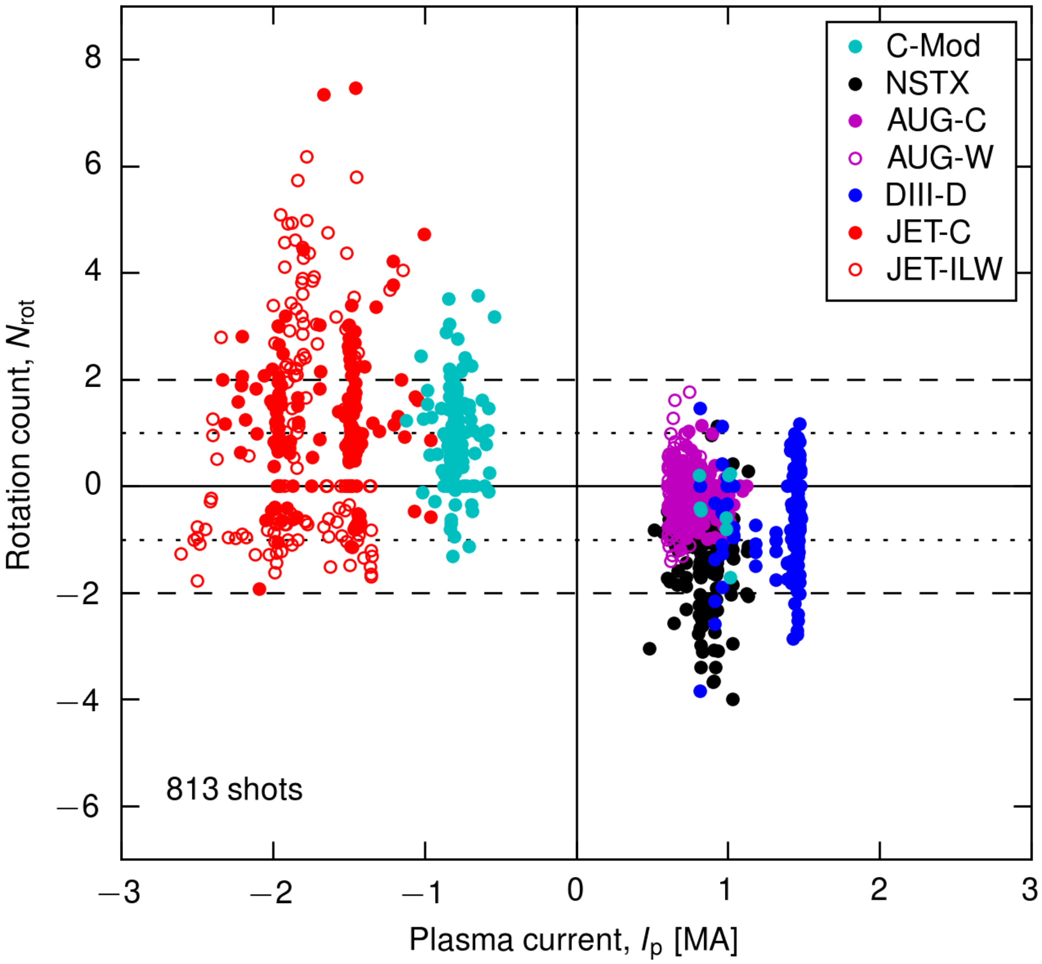
JET-C

JET-ILW

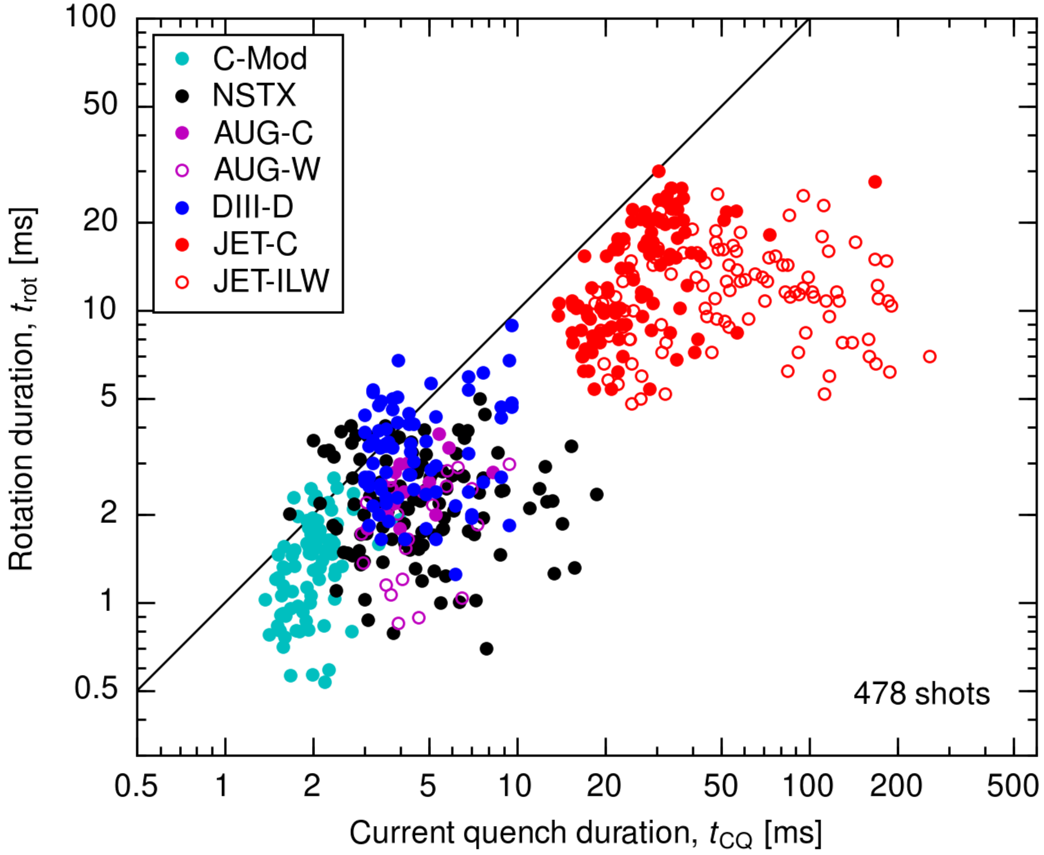
JET-ILW

The rotation is predominantly counter-I_p

- Many discharges with low rotation dither incoherently
- All discharges with $|N_{rot}| > 2$ rotate counter-I_p
- This effect is independent of the polarity of B_T
  - There are reversed B_T points from both DIII-D and C-Mod in the database
- The worst JET-ILW cases are no worse than the worst JET-C cases



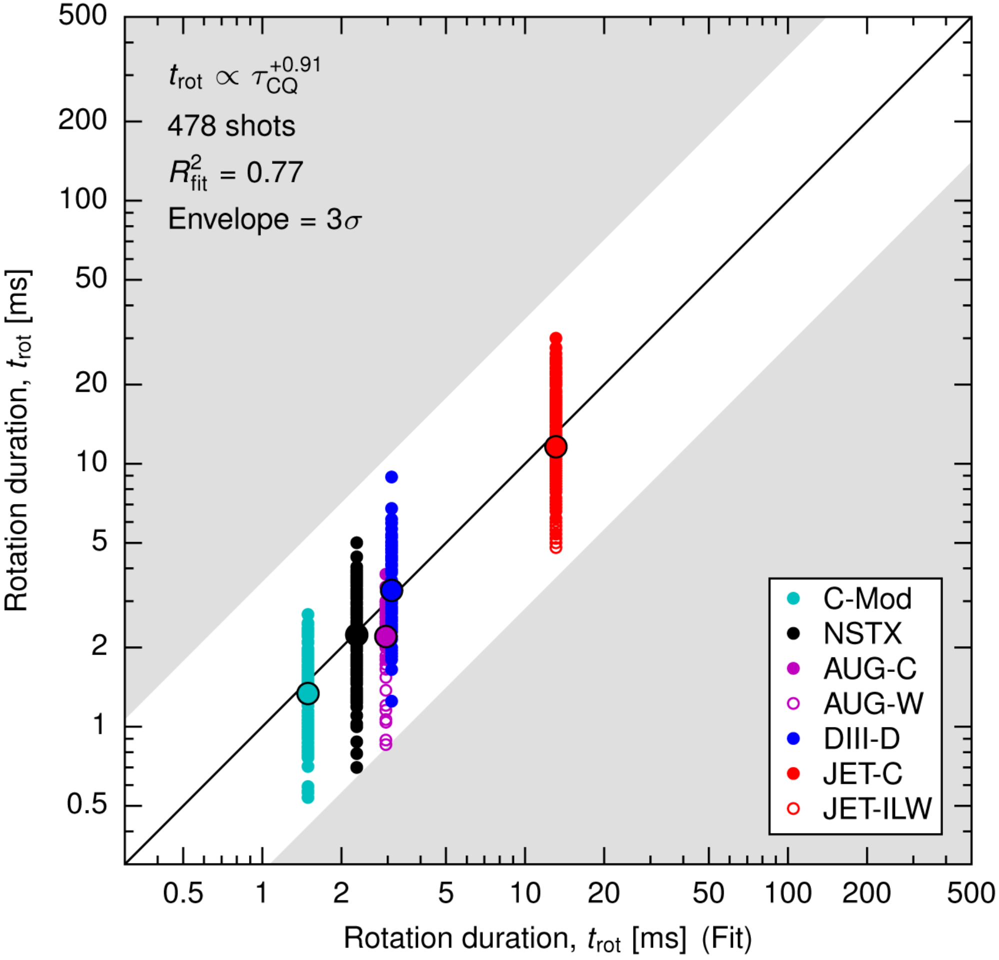
The rotation duration, t_{rot}, correlates with τ_{CQ} not t_{CQ}



- Down-select to include only shots with $|N_{rot}| > 0.75$
- One might expect that t_{rot} scales with shot-specific t_{CQ}
- Instead, t_{rot} scales from device to device rather than shot-to-shot
- The minimum quench time, τ_{CQ}, captures the device-to-device scaling
- Use τ_{CQ} in t_{rot} regression

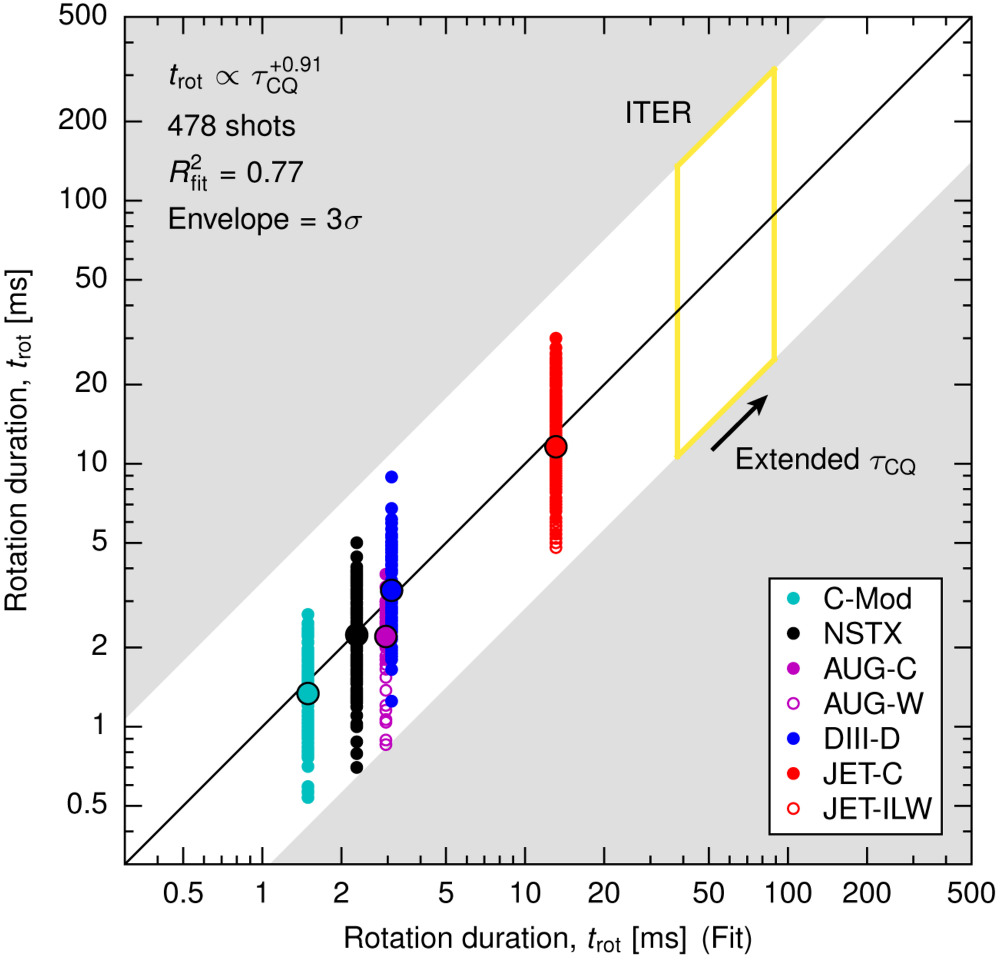
Empirical scaling of the rotation duration, t_{rot}

- Down-select to include only shots with $|N_{\mathrm{rot}}| > 0.75$
- Carry out regression using one machine-specific parameter:
  - → τ_{CQ}
- Additional parameters do not improve the regression:
  - → R, a, I_p, B_T, t_{CQ}
- Hidden variables not available in the database may explain intra-machine variability

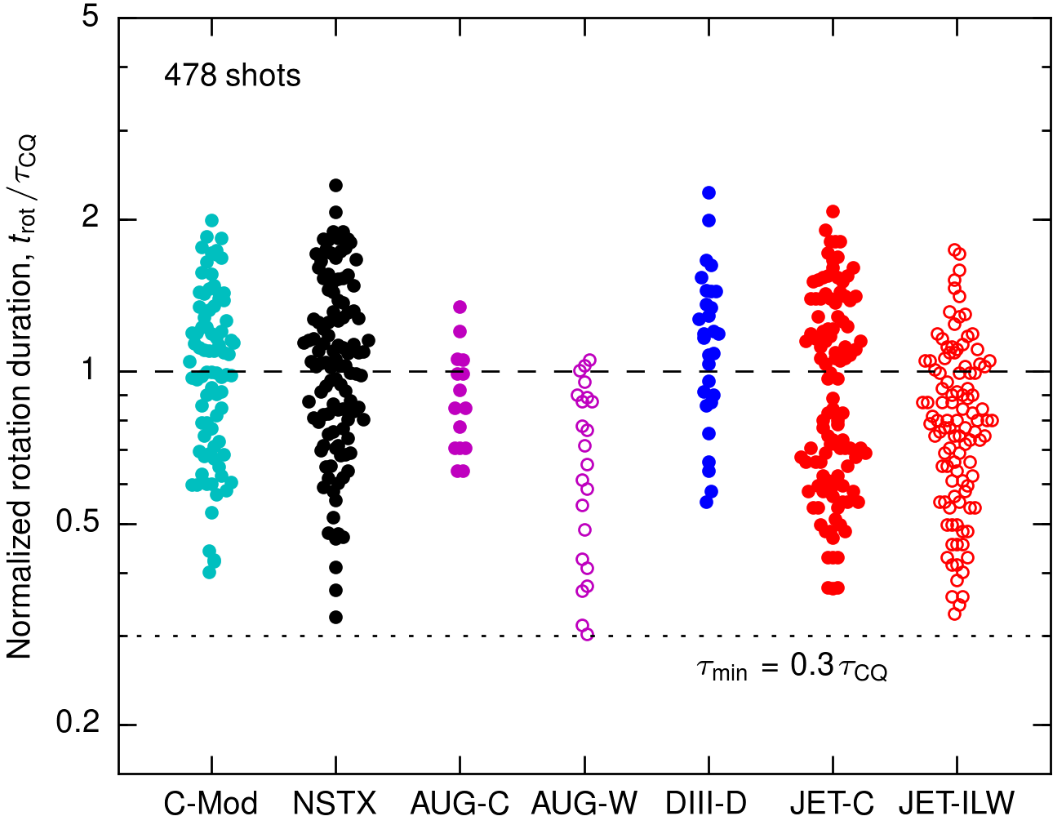


Project the rotation duration scaling to ITER

- Down-select to include only shots with $|N_{\mathrm{rot}}| > 0.75$
- Carry out regression using one machine-specific parameter:
  → τ_{CQ}
- Additional parameters do not improve the regression:
  → R, a, I_p, B_T, t_{CQ}
- Hidden variables not available in the database may explain intra-machine variability
- Projecting to ITER gives upper bound of t_{rot} = 135–320 ms

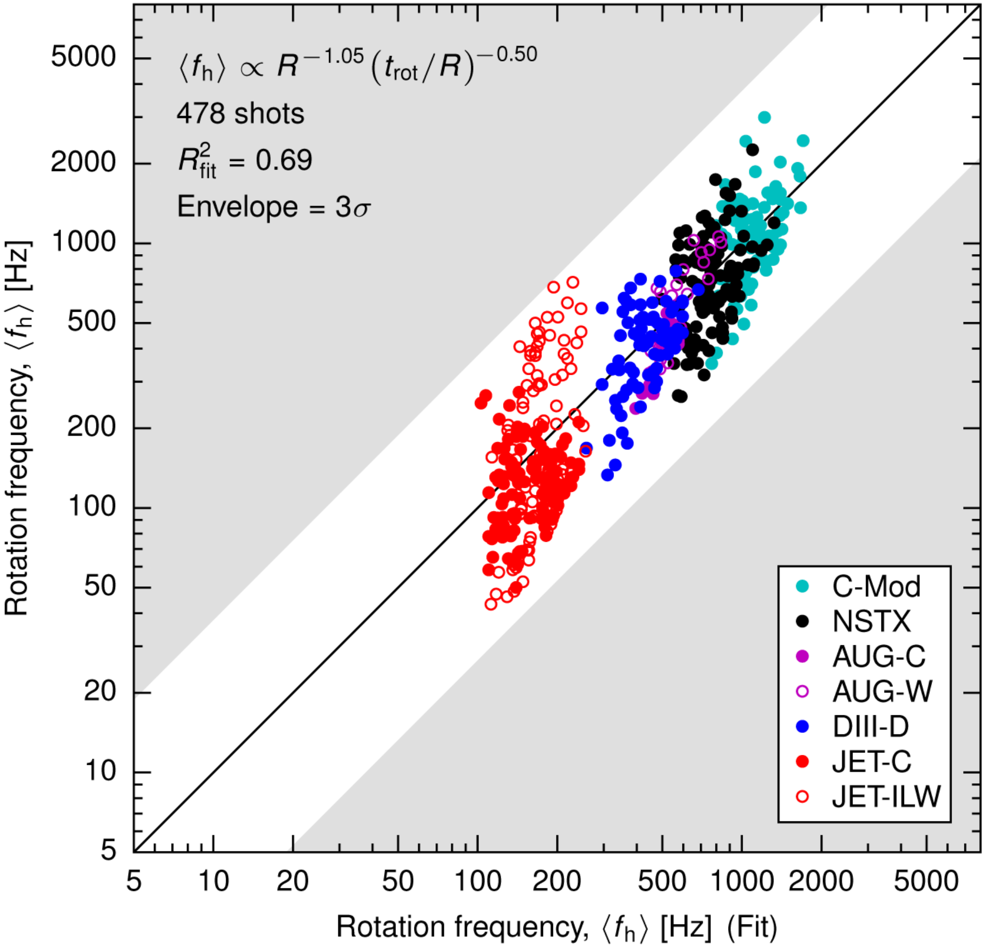


The normalized rotation duration is remarkably consistent



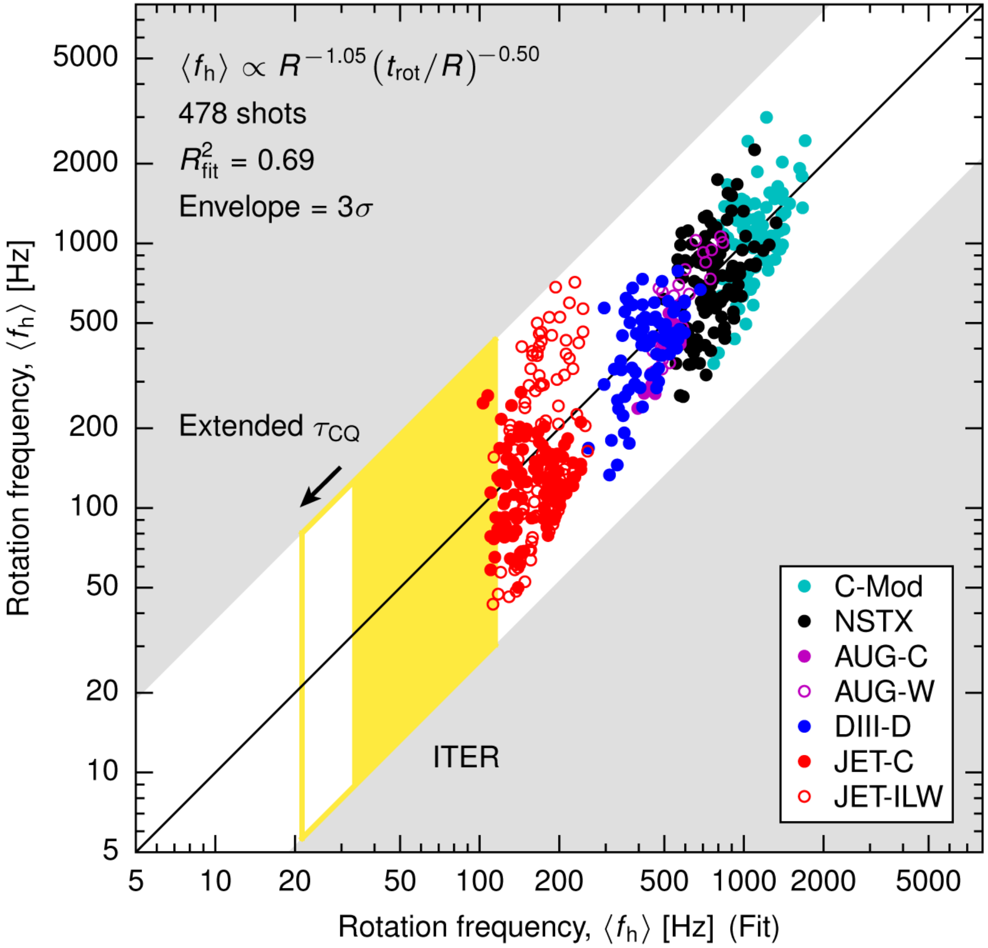
- As regression indicates, t_{rot} is roughly prop. to τ_{CQ}
- Most data points fall with a factor of two of τ_{CQ}
- Metal wall machines have comparable or even *shorter* rotation durations than their carbon counterparts
- Unable to determine what role the wall time might play since all wall times in the database are ~10 ms

Empirical scaling of the rotation frequency, $\langle f_h \rangle$



- Define the average rotation frequency as $\langle f_h \rangle = N_{rot} / t_{rot}$
- Carry out regression using two parameters:
  - → R, t_{rot}
- Additional parameters do not improve the regression:
  - → a, I_p, B_T, t_{CQ}
- Hidden variables not available in the database may explain intra-machine variability

Project the rotation frequency scaling to ITER



- Define the average rotation frequency as $\langle f_h \rangle = N_{rot} / t_{rot}$
- Carry out regression using two parameters:
  → R, t_{rot}
- Additional parameters do not improve the regression:
  → a, I_p, B_T, t_{CQ}
- Hidden variables not available in the database may explain intra-machine variability
- Projecting to ITER indicates that halo current rotation below 20 Hz is probable

Further analysis of the rotation scalings

Decomposition of the various rotation scalings:

$$t_{\mathrm{rot}} \propto \tau_{\mathrm{CQ}}^{+0.91} \qquad \langle f_{\mathrm{h}} \rangle \propto R^{-1.05} \left(t_{\mathrm{rot}} / R \right)^{-0.50}$$

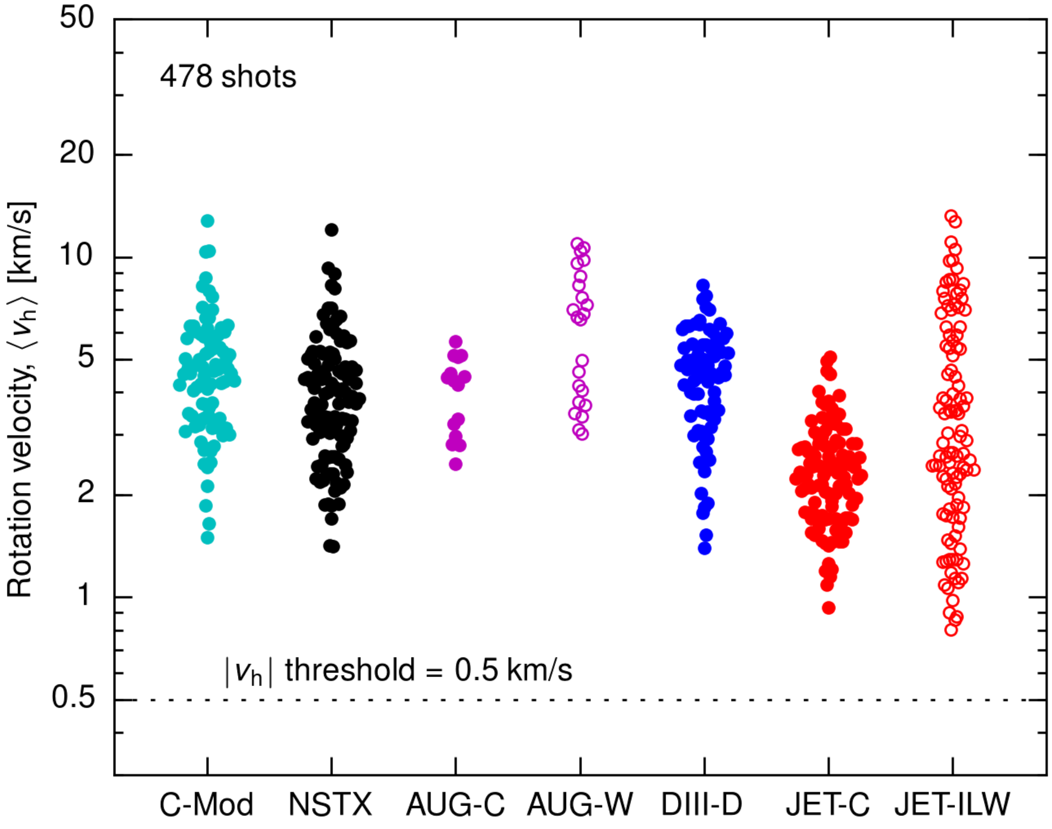
$$\langle v_{\mathrm{h}} \rangle = 2\pi R \cdot \langle f_{\mathrm{h}} \rangle \propto R^{-0.05} \left(t_{\mathrm{rot}} / R \right)^{-0.50} \sim \left(\tau_{\mathrm{CQ}} / R \right)^{-0.5}$$

$$N_{\mathrm{rot}} = \langle f_{\mathrm{h}} \rangle \cdot t_{\mathrm{rot}} \propto R^{-0.05} \left(t_{\mathrm{rot}} / R \right)^{+0.50} \sim R^{-0.1} \left(\tau_{\mathrm{CQ}} / R \right)^{+0.5}$$

The quantity τ_{CQ}/R grows weakly with machine size:

Machine	R [m]	$S \cdot \ell$ [m^2]	$C(\eta^{-1})$ [ms $\cdot$ m^{-2}]	τ_{CQ} [ms]	τ_{CQ}/R [ms $\cdot$ m^{-1}]	$\langle v_{\mathrm{h}} \rangle$ [km $\cdot$ s^{-1}]
C-Mod	0.68	0.35	3.8	1.3	2.0	4.8
NSTX	0.85	2.1	1.0	2.1	2.5	4.3
AUG	1.65	3.0	0.9	2.8	1.7	4.6
DIII-D	1.67	3.2	0.9	3.0	1.8	4.5
JET	2.96	9.9	1.5	14.5	4.9	3.0
ITER	6.20	33	1.5–4	50–130	8–20	1.6–2.5

The rotation velocity is also remarkably consistent



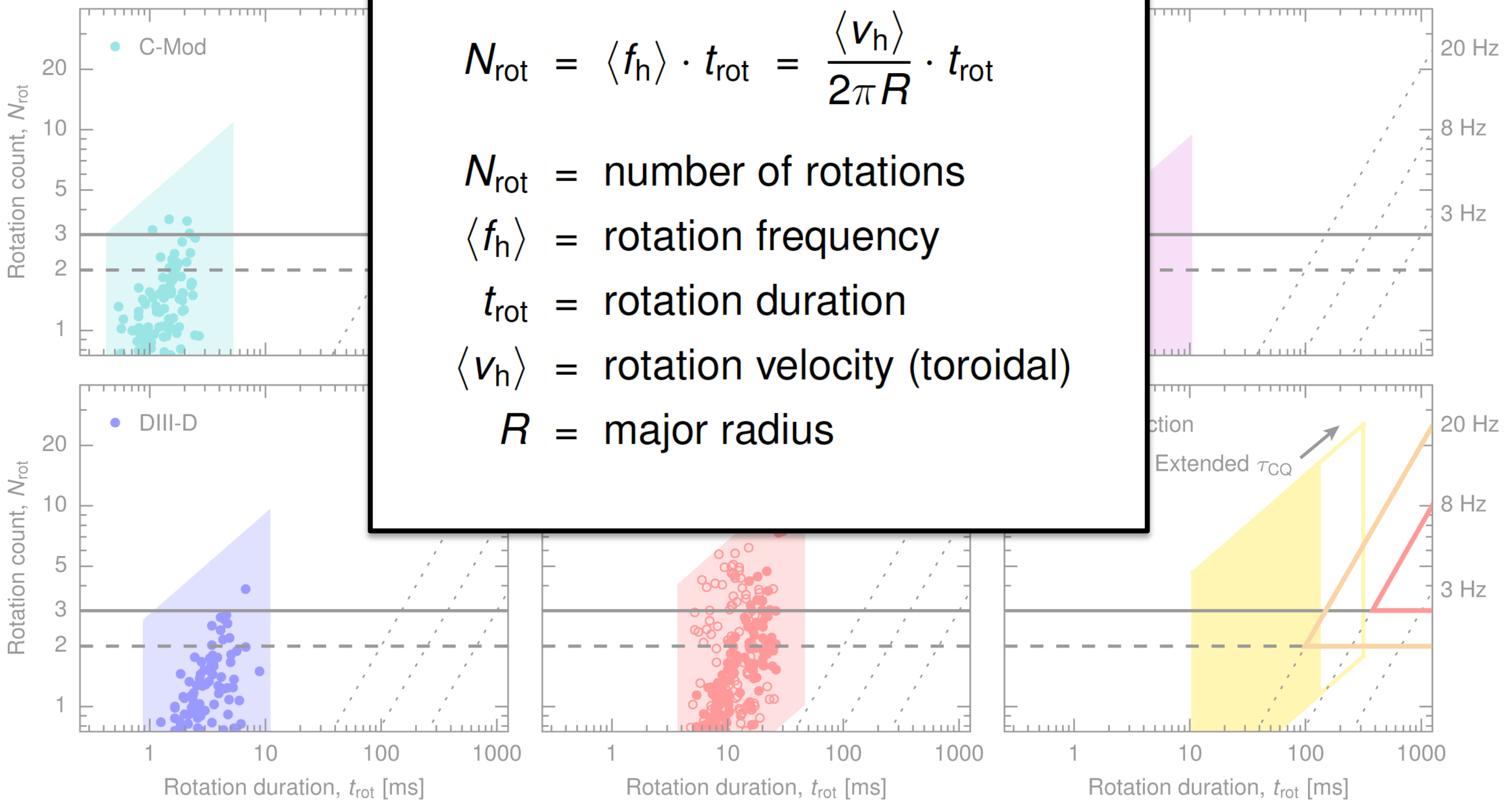
- As regression indicates, the rotation velocity should be relatively consistent
- All data points fall within a 0.7–17 km/s envelope
- Metal machines span the carbon space and add some faster points
- Any theory that explains halo current rotation must explain velocity invariance w.r.t. B_T, I_p, etc.

Projection to ITER → marginal w.r.t. damaging rotation

- ITER projections:
  - N_{rot} > 3 likely at f_{h} > 20 Hz
  - N_{rot} ~ 3 possible at f 10–20 Hz
- Cannot rule out possibility of damaging rotation in ITER
- Scaling of τ is important

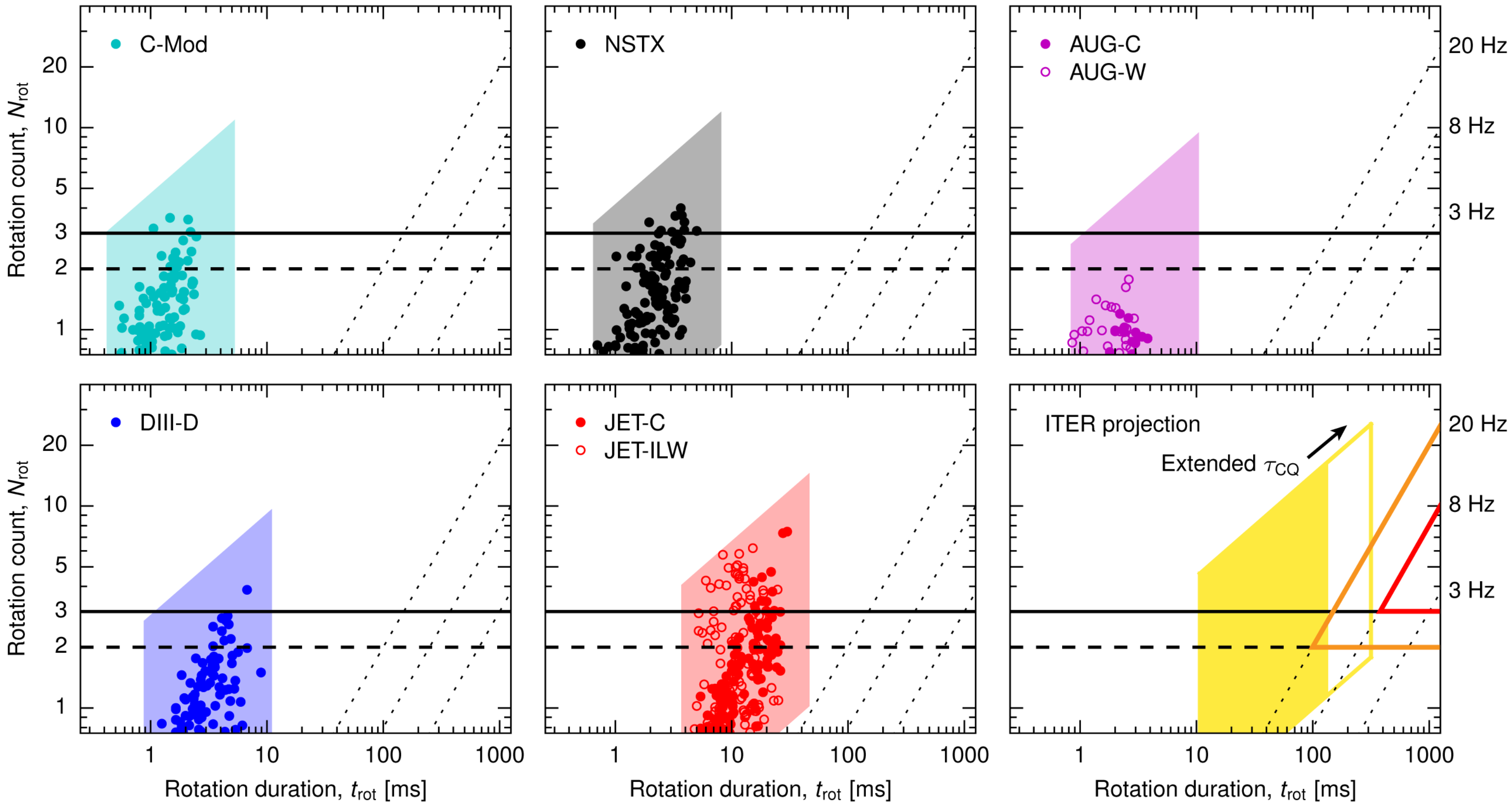
$$N_{\mathrm{rot}} = \langle f_{\mathrm{h}} \rangle \cdot t_{\mathrm{rot}} = \frac{\langle v_{\mathrm{h}} \rangle}{2\pi R} \cdot t_{\mathrm{rot}}$$

N_{rot} = number of rotations
$\langle f_{\mathrm{h}} \rangle$ = rotation frequency
t_{rot} = rotation duration
$\langle v_{\mathrm{h}} \rangle$ = rotation velocity (toroidal)
R = major radius



Projection to ITER → marginal w.r.t. damaging rotation

- ITER projections:
  - $N_{\mathrm{rot}} > 3$ likely at $f_h > 20$ Hz
  - $N_{\mathrm{rot}} \sim 3$ possible at f_h 10–20 Hz
- Cannot rule out possibility of damaging rotation in ITER
- Scaling of τ_{CQ} is important



Summary and future plans

- Empirical scalings for the rotation duration and frequency:
  - Duration scales with minimum current quench time
  - Frequency scales with major radius (to first order)
  - Range of rotation velocities largely consistent across devices

    → Requires physical mechanism independent of most parameters

- Projection to ITER:
  - $N_{\mathrm{rot}} > 3$ likely above 20 Hz and possible down to 10 Hz
  - Therefore cannot rule out the possibility of damaging rotation in ITER
  - The scaling of τ_{CQ} to ITER is key
- Path forward:
  - In final stages of preparing *Nucl. Fusion* manuscript
  - Will issue ITPA WG-6 report and then recommend closing the WG