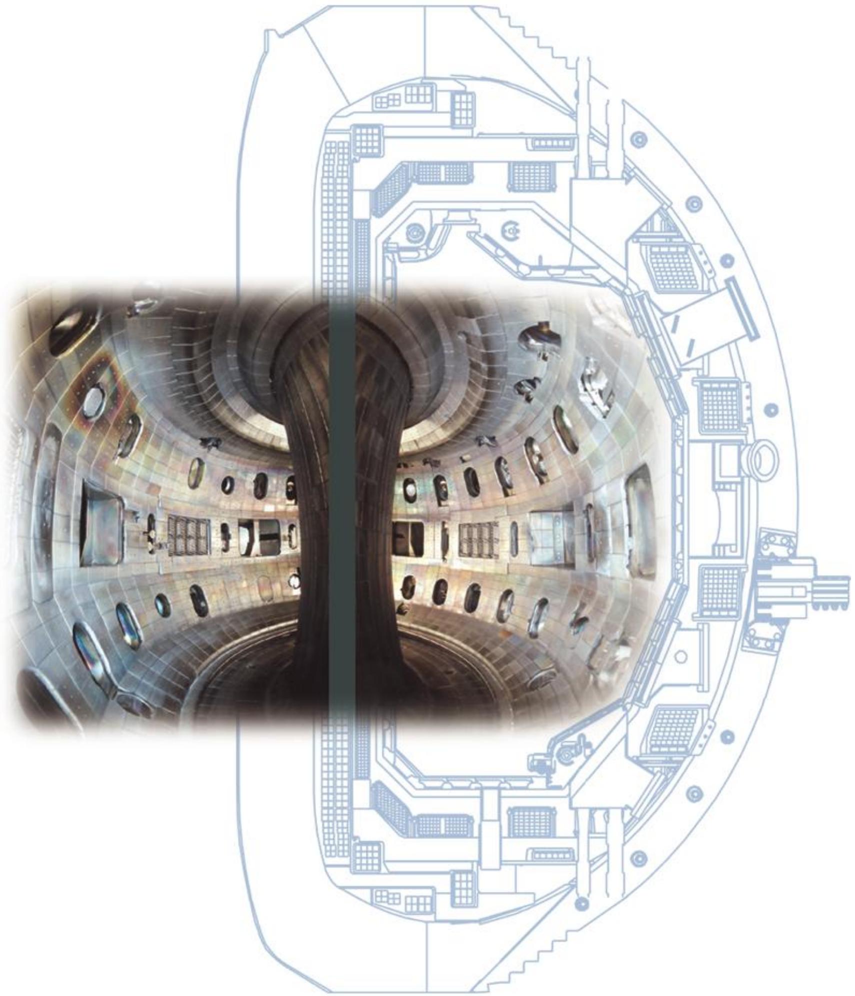
Impact of Torque and Rotation in High Fusion Performance Plasmas

by

W.M. Solomon[1]

K.H. Burrell[2], R.J. Buttery[2], J.S.deGrassie[2], E.J. Doyle[3], A.M. Garofalo[2], G.L. Jackson[2], T.C. Luce[2], C.C. Petty[2], P.A. Politzer[2], and F. Turco[4]

[1]Princeton Plasma Physics Laboratory
[2]General Atomics
[3]University of California, Los Angeles
[4]Columbia University



Presented at the

54th Annual Meeting of the APS Division of Plasma Physics Providence, RI October 29-November 2, 2012

DIII-D NATIONAL FUSION FACILITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

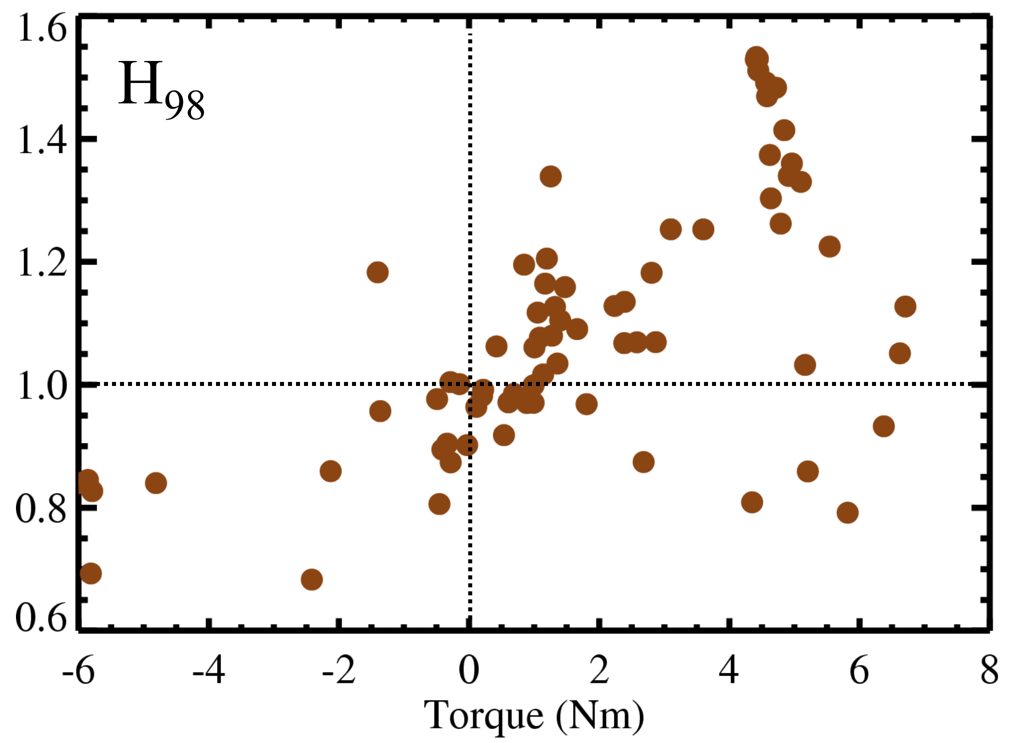
Motivation

- **High performance scenarios are typically characterized by rapid toroidal rotation, often driven by large external torque**
- **Due to the rapidly increasing moment of inertia with machine size compared with confinement time, it becomes more difficult to drive significant rotation in ITER and beyond**
  - Intrinsic drive on ITER may not be as large as originally projected [Solomon IAEA 2012]
- **Important to quantify impact of rotation on confinement, since the confinement quality (H-factor) directly affects the fusion gain**

The Confinement Quality of H-mode Plasmas Is Generally Affected by Applied Torque

- **Confinement characterized by IPB98(y,2) H-mode (H98) scaling**
  - Includes parametric dependences on I_p, B_t, P, n, R, ε, κ
  - H_{98}=1 implies confinement is as expected from scaling

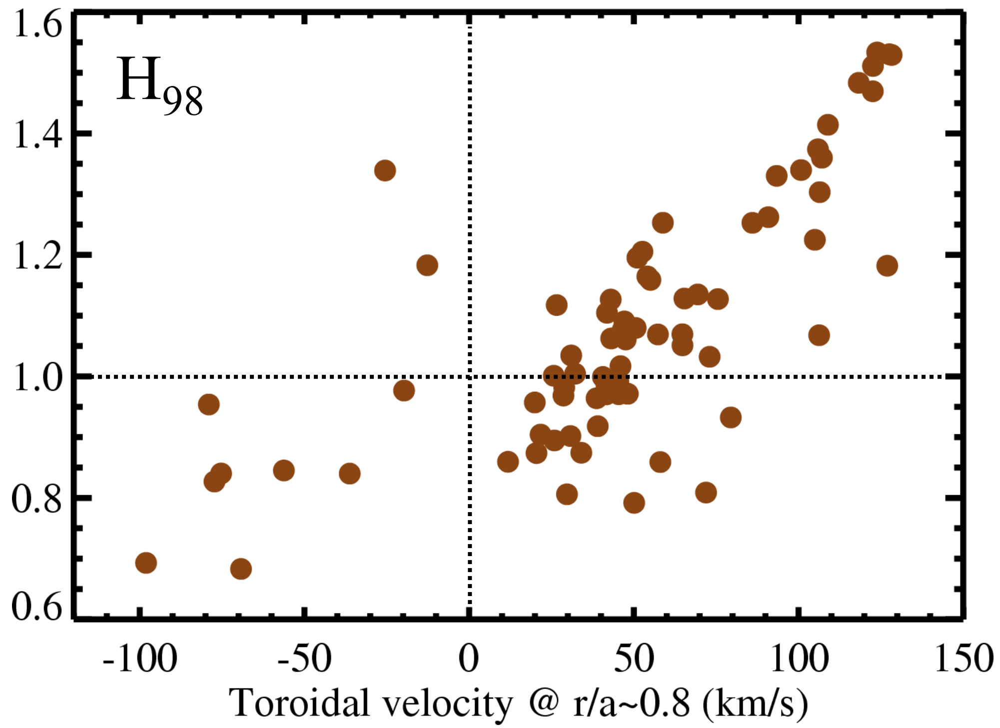
- **Data comes from wide variety of H-mode plasmas**
  - Standard type I ELMing
  - RMP ELM suppressed
  - ITER baseline (q_{95}~3.1, shape, beta…)
  - Advanced inductive
  - Quiescent H-mode



DIII-D NATIONAL FUSION FACILITY

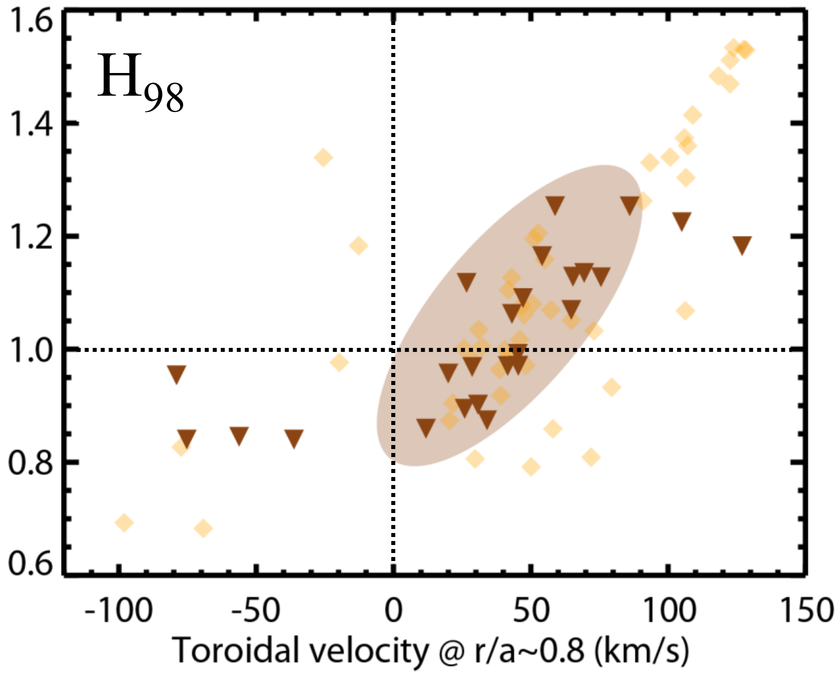
The Confinement Factor Shows Clear Dependence on Toroidal Rotation

- **Significant reduction in scatter when change from engineering to physics quantity**
- **Qualitatively similar plots for different radii**
- **Compare/contrast different regimes**



In Standard H-mode, Confinement Is Impacted by Rotation Mainly at Intermediate Rotation Levels

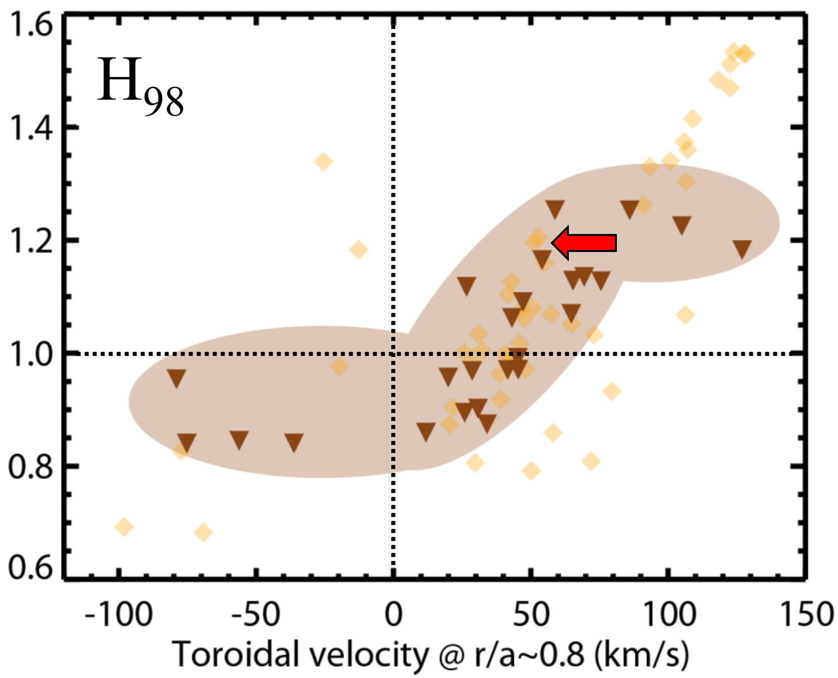
- **Significant enhancement in confinement as rotation spins up from 0 in co-I_p direction**

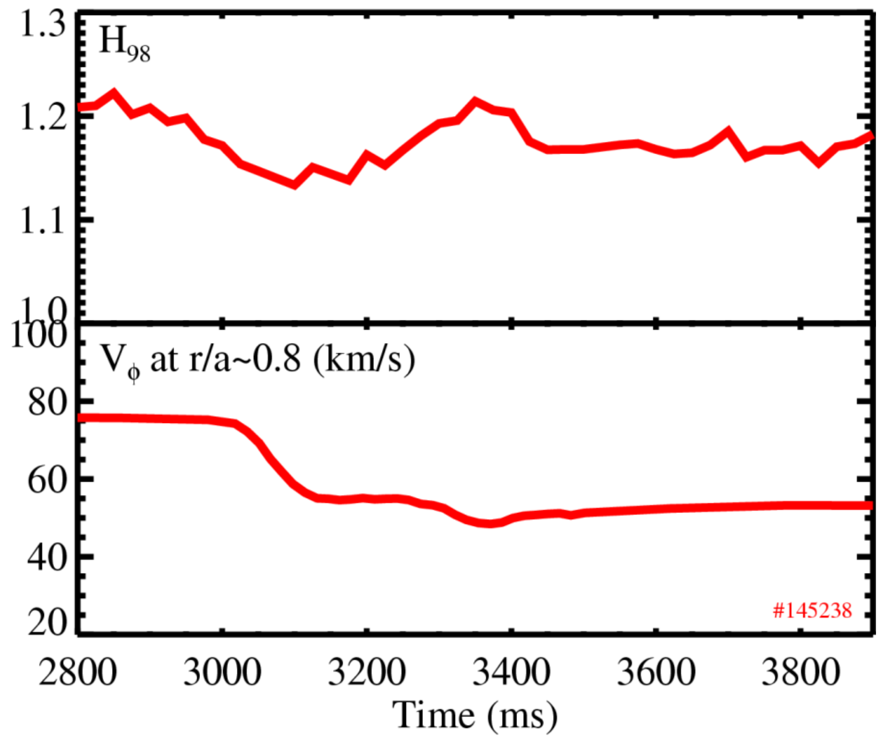


In Standard H-mode, Confinement Is Impacted by Rotation Mainly at Intermediate Rotation Levels

- **Significant enhancement in confinement as rotation spins up from 0 in co-I_p direction**

- **Benefit of rotation shows signs of "saturating" above >50 km/s**

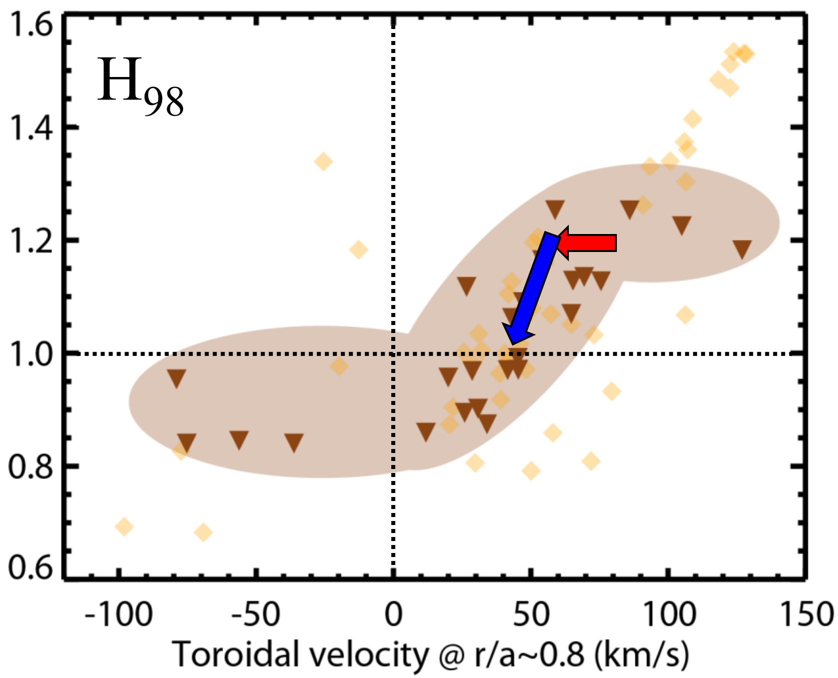


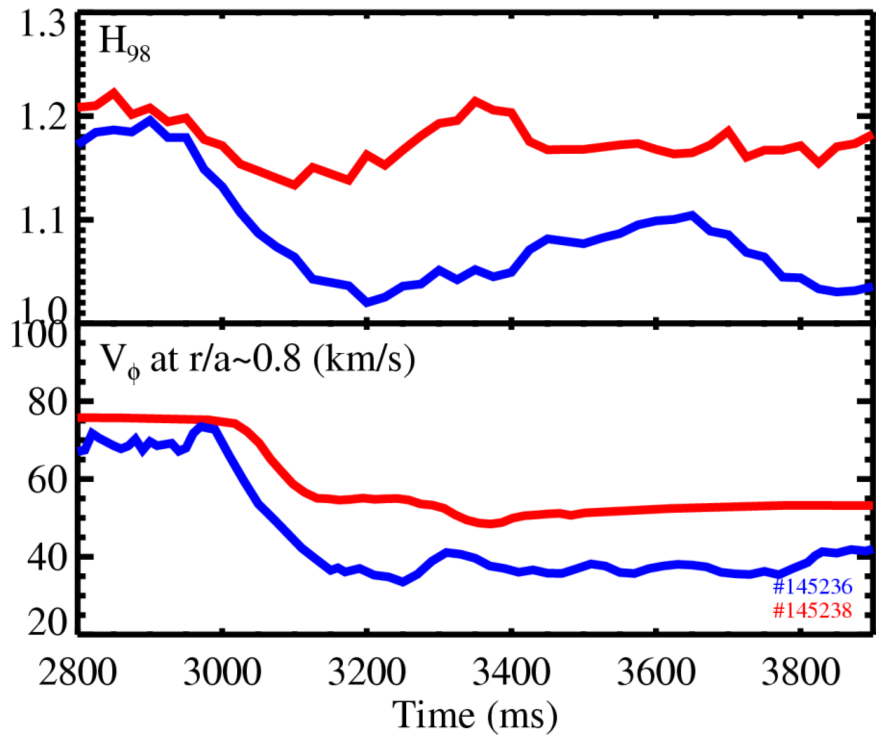


Standard H-mode Shows Confinement Is Impacted by Rotation Mostly at Intermediate Rotation Levels

- **Significant enhancement in confinement as rotation spins up from 0 in co-I_p direction**

- **Benefit of rotation shows signs of "saturating" above >50 km/s**

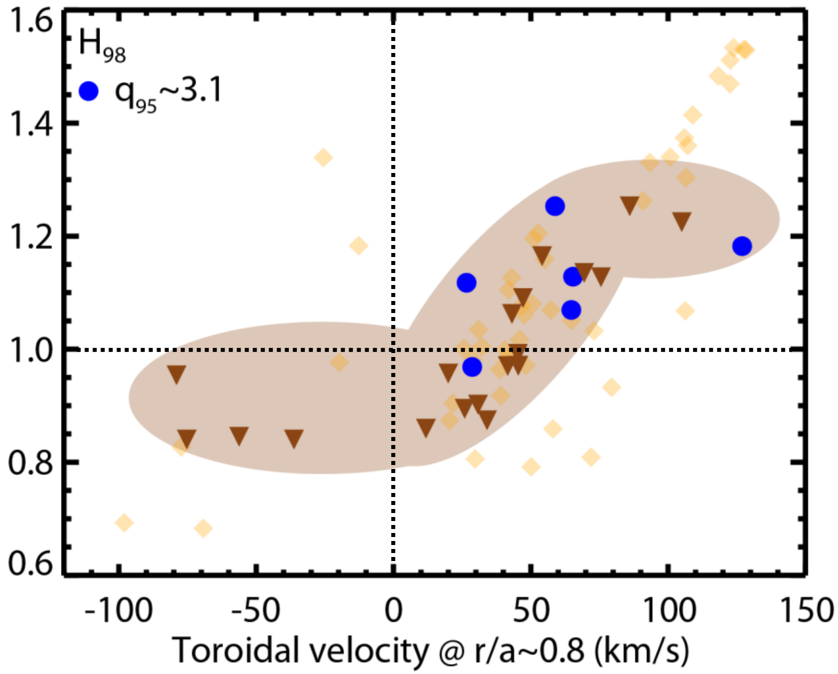




Standard H-mode Shows Confinement Is Impacted by Rotation Mostly at Intermediate Rotation Levels

- **Significant enhancement in rotation as spin up from 0 in co-Ip direction**

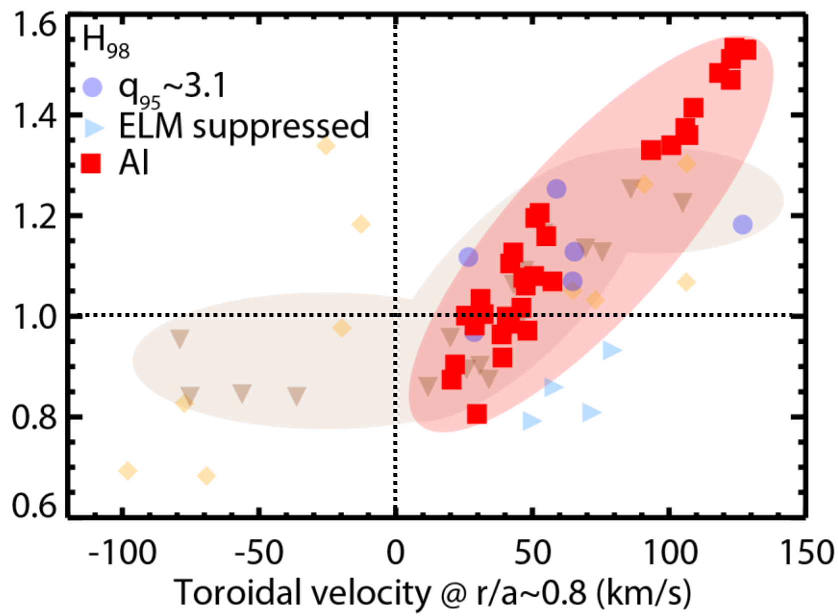
- **Benefit of rotation shows signs of "saturating" above >50 km/s**



- **ITER baseline with q_{95}~3.1 performs similarly to other H-modes**

Confinement of Advanced Inductive Plasmas Is Affected by Rotation Over a Larger Range than Standard H-mode

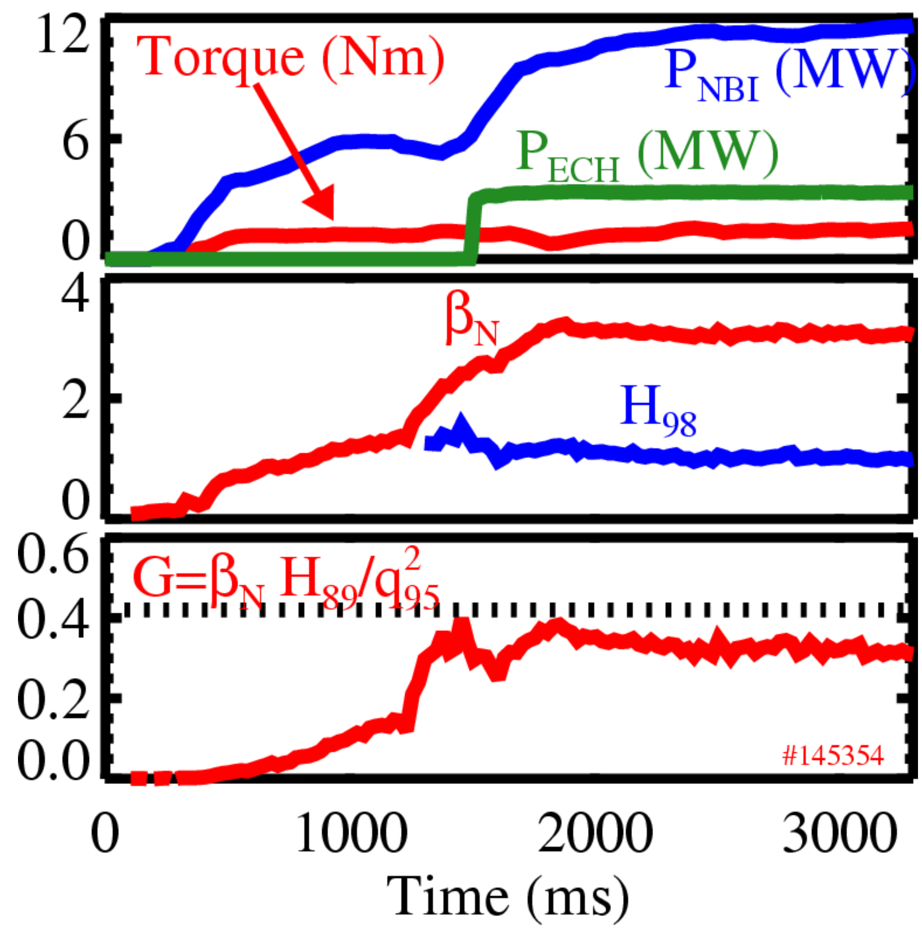
- **H_{98} increases from approx 1.0 to above 1.5 as rotation increased from balanced NBI to all co-NBI**
- **Continued enhancement of confinement with rotation in AI regime may be a property of the flat q-profile**
  - Stiffness mitigation by rotation more effective at low magnetic shear [Mantica PRL 2011]



WM Solomon/APS/Nov2012

Despite Reduced Confinement, High Performance Advanced Inductive Plasmas Obtained at Low Rotation

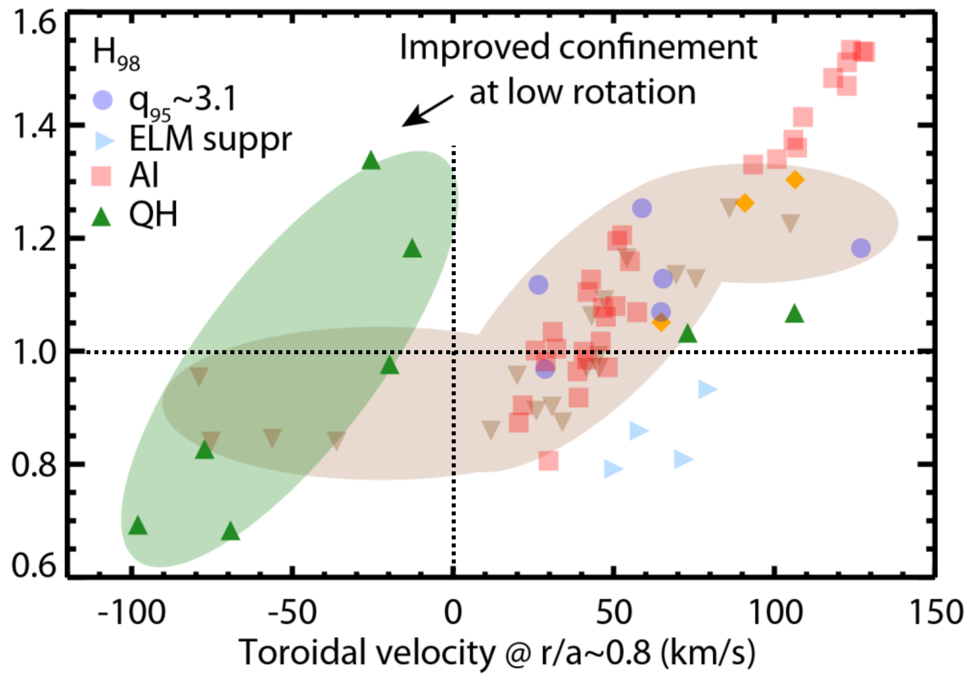
- **Torque ~1 Nm on DIII-D expected to drive similar rotation as ITER beams**
- **β_N~3.1, H_{98}~1, q_{95}~4 sustained for maximum duration of counter NBI**
- **Normalized fusion performance, $G=\beta_N H_{89}/q_{95}^2$ ~ 0.32-0.35**
  - Approaching ITER Q=10 target (G~0.42)



WM Solomon/APS/Nov2012

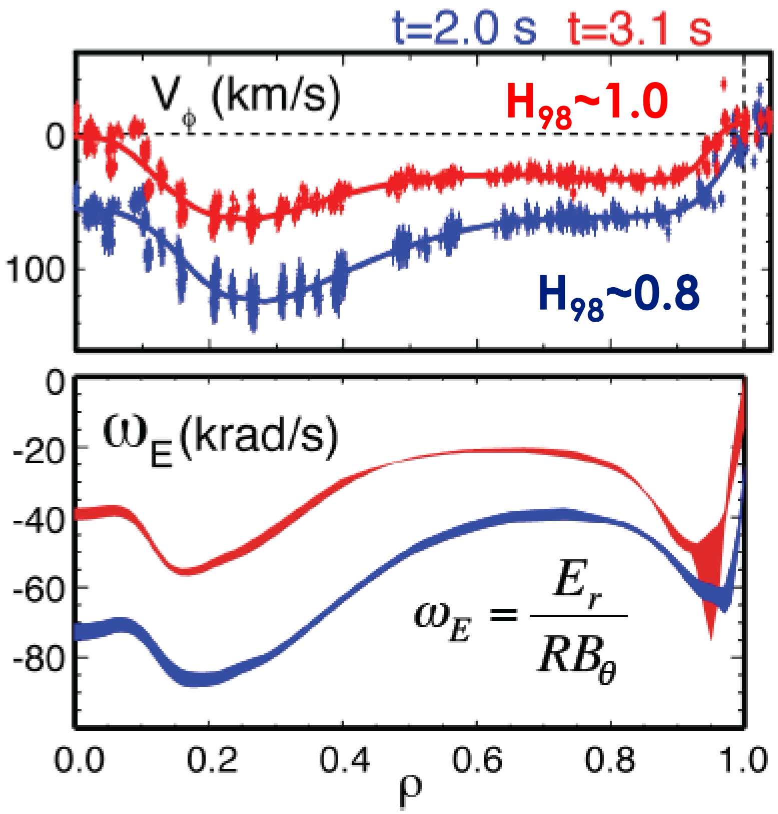
QH-mode Shows Surprising Improvement in Confinement at Low Rotation

- **QH-mode plasmas appear to continue the downward trend in confinement versus rotation**
  - Interestingly QH-mode confinement appears to be shifted toward the left, giving high confinement at low rotation



WM Solomon/APS/Nov2012

Edge ExB Shearing Rate Actually Increases At Reduced Rotation and Torque in QH-mode

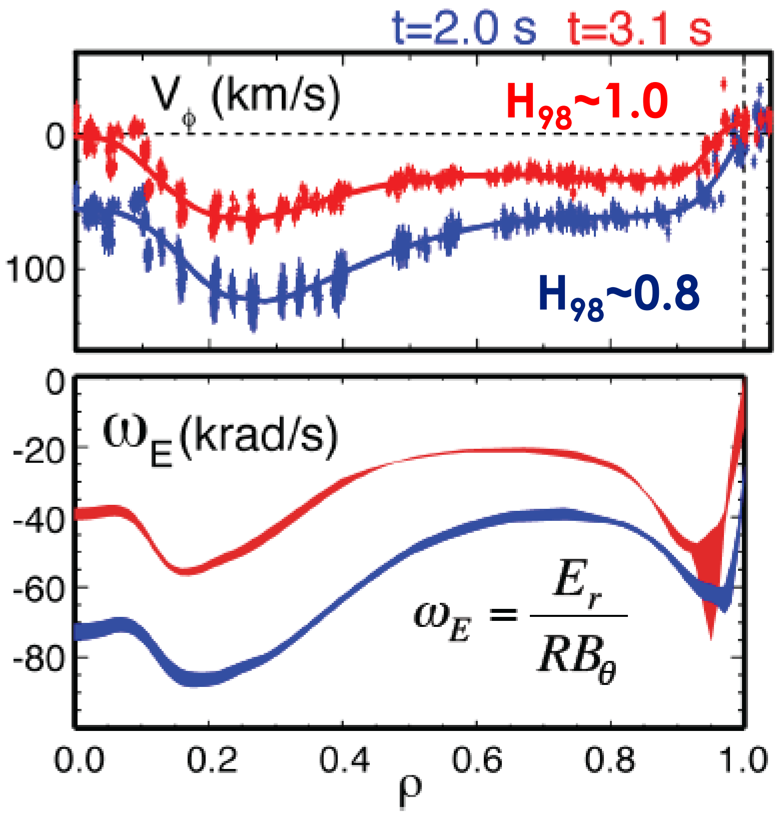


$$\omega_E = \frac{E_r}{RB_\theta}$$

$$\omega_{ExB} = \frac{(RB_\theta)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$

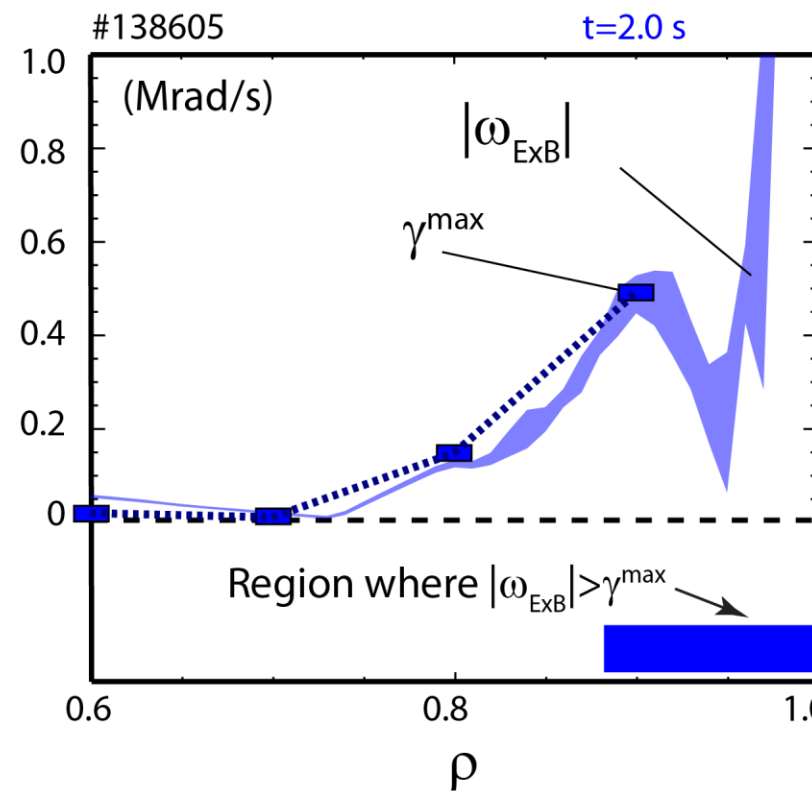
[Garofalo NF 2011]

Edge ExB Shearing Rate Actually Increases At Reduced Rotation and Torque in QH-mode



$$\omega_{ExB} = \frac{(RB_\theta)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$

- **ExB shear rate exceeds growth rate at edge of plasma**

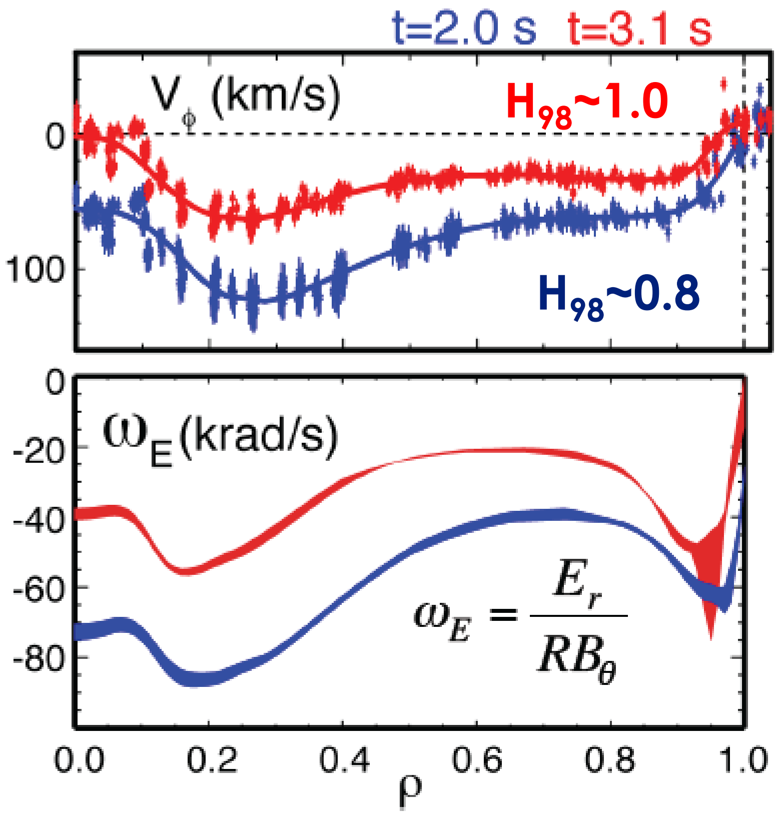


WM Solomon/APS/Nov2012

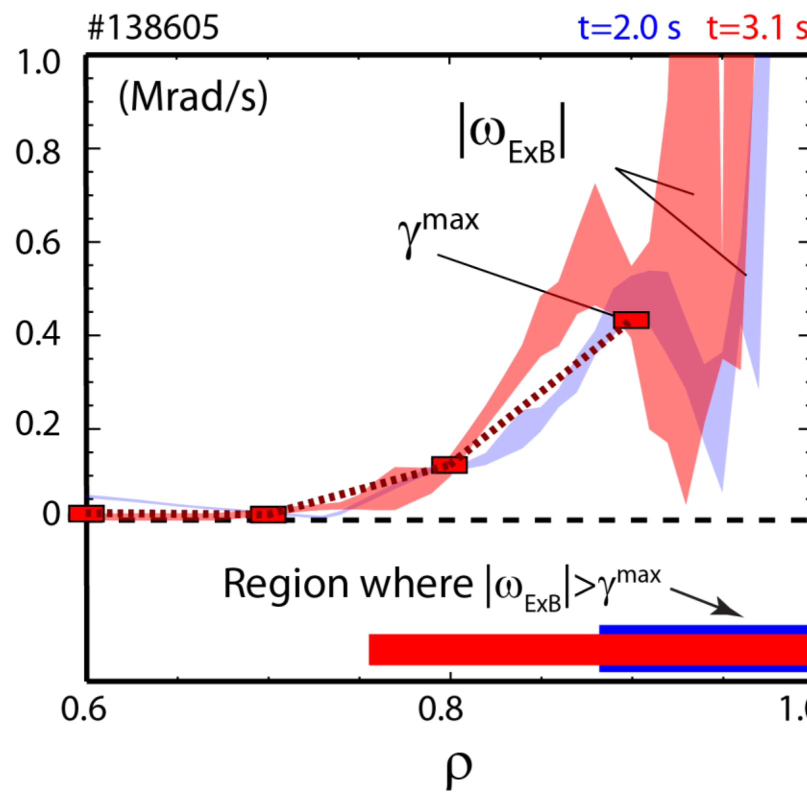
[Garofalo NF 2011]

Edge ExB Shearing Rate Actually Increases At Reduced Rotation and Torque in QH-mode

- **ExB shear rate exceeds growth rate at edge of plasma**
- **Region extends radially inward at low rotation**



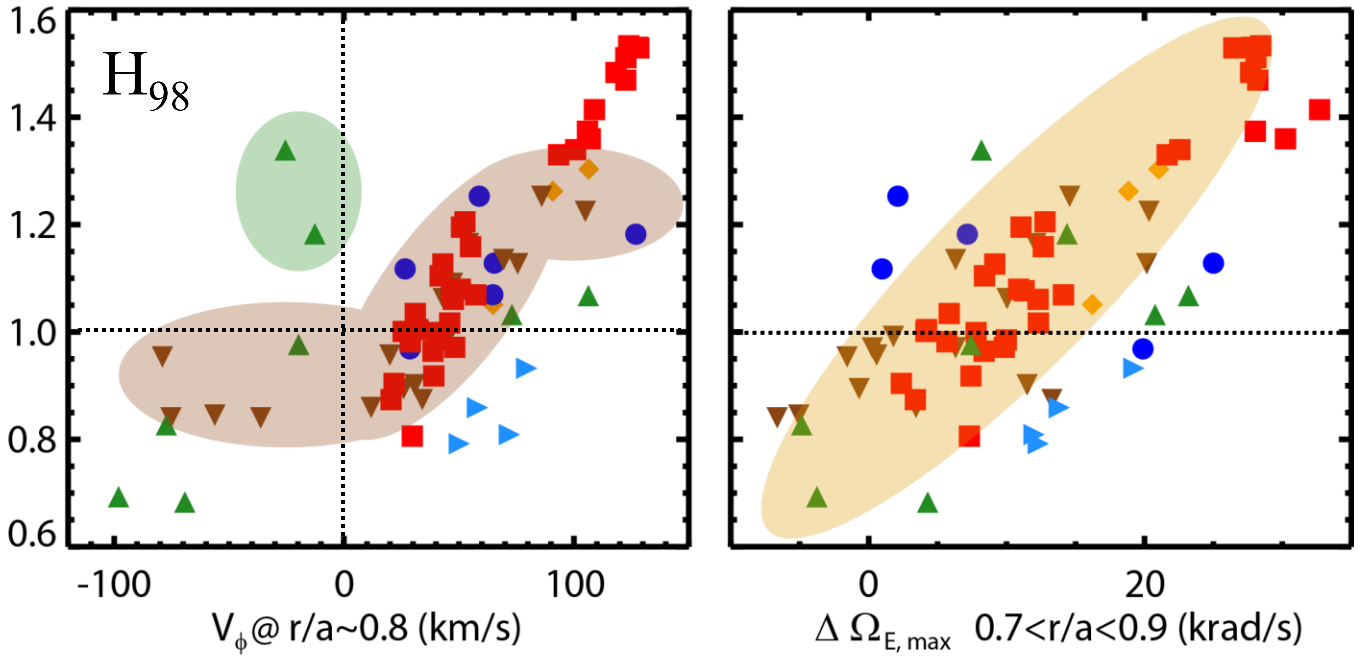
$$\omega_{ExB} = \frac{(RB_\theta)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$



[Garofalo NF 2011]

Is it Rotation or Rotation Shear That Affects Confinement?

- **Certain "anomalies" seen when plotting H_{98} versus rotation**
  - Saturation in confinement improvement at high rotation in H-mode
  - QH-mode with high confinement at low rotation
- **Such features are not observed when plotting against maximum ExB shearing rate → may suggest a better controlling variable**



Summary

- **Confinement quality (as described by H_{98}) is strongly affected by NBI torque and attained rotation in DIII-D discharges**
- **Effect is most pronounced and seen over widest range in rotation in advanced inductive plasmas**
- **QH-mode shows enhanced confinement at low rotation**
  - Associated with increased ExB shear
- **Enhanced confinement appears associated with increased levels of ExB shear**