The Curious Case of Toroidal Rotation

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on behalf of the
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MIT - Plasma Science and Fusion Center

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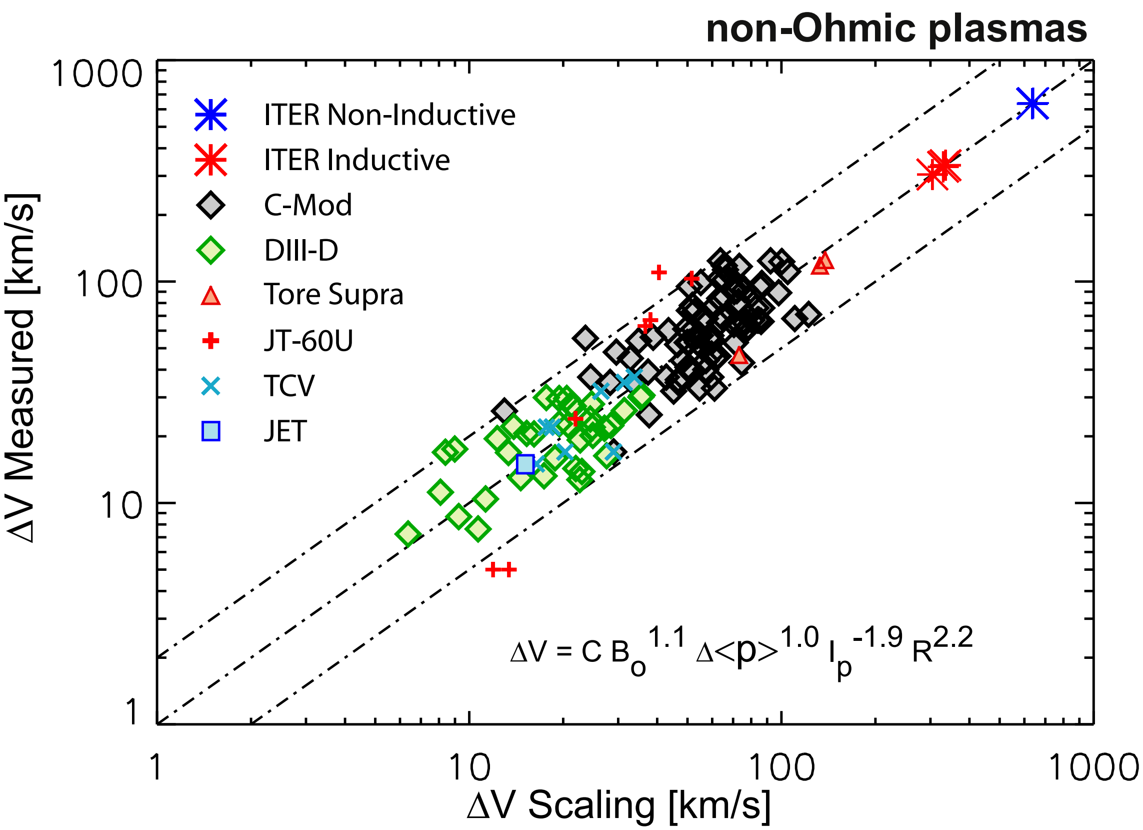
Alcator C-Mod

This talk and others available at: http://www.psfc.mit.edu/research/alcator/pubs/index.htm

Background

Although widely observed, what causes tokamak plasmas to <u>rotate without external momentum input</u> is not yet well understood

For ITER, if intrinsic rotation is not sufficient, then we need to develop torque sources for large, high field/density machines



[1]J.E. Rice, *et al*. Nucl. Fusion. **47** 1618 (2007)

- first multi-machine scaling attempts done by Rice, *et al*[1].
- plenty of unanswered questions and cases that do not conform to this empirical scaling
- **this was meant to be a beginning and not an end**

The Entire Community is Engaged

JET

identified importance of TF ripple[1], showed ELMy H-modes do not agree with scaling results[2]

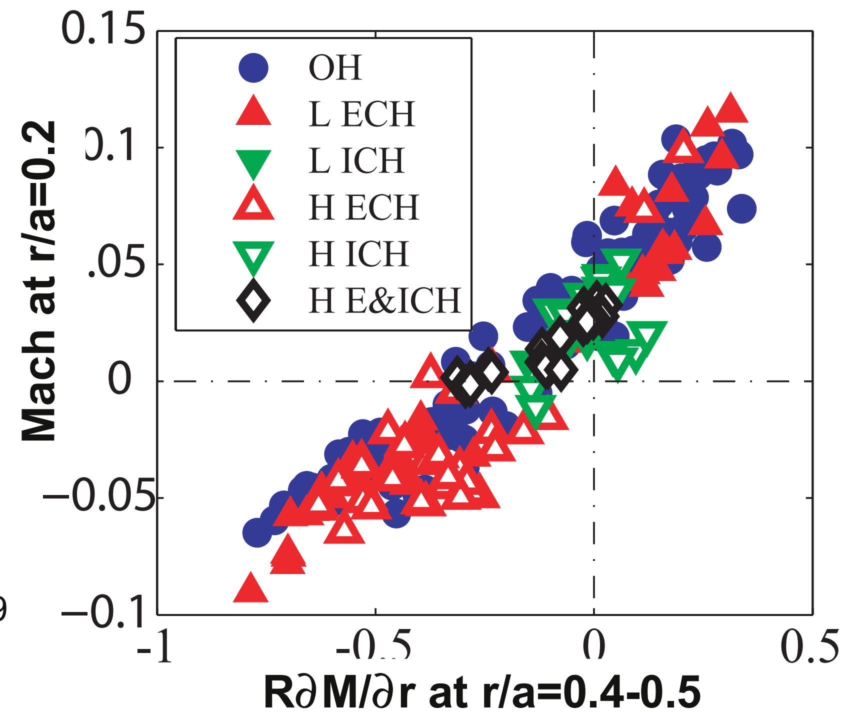
DIII-D

using mix of co/cntr beams to zero out v(r) to get at intrinsic torque, showed ∇p_e correlation, impact of core ECH[3]

ASDEX-U

improved core CXRS allowing "beam-blip" studies of v(r)

able to unify results for a wide variety plasmas[4] →



THEORY

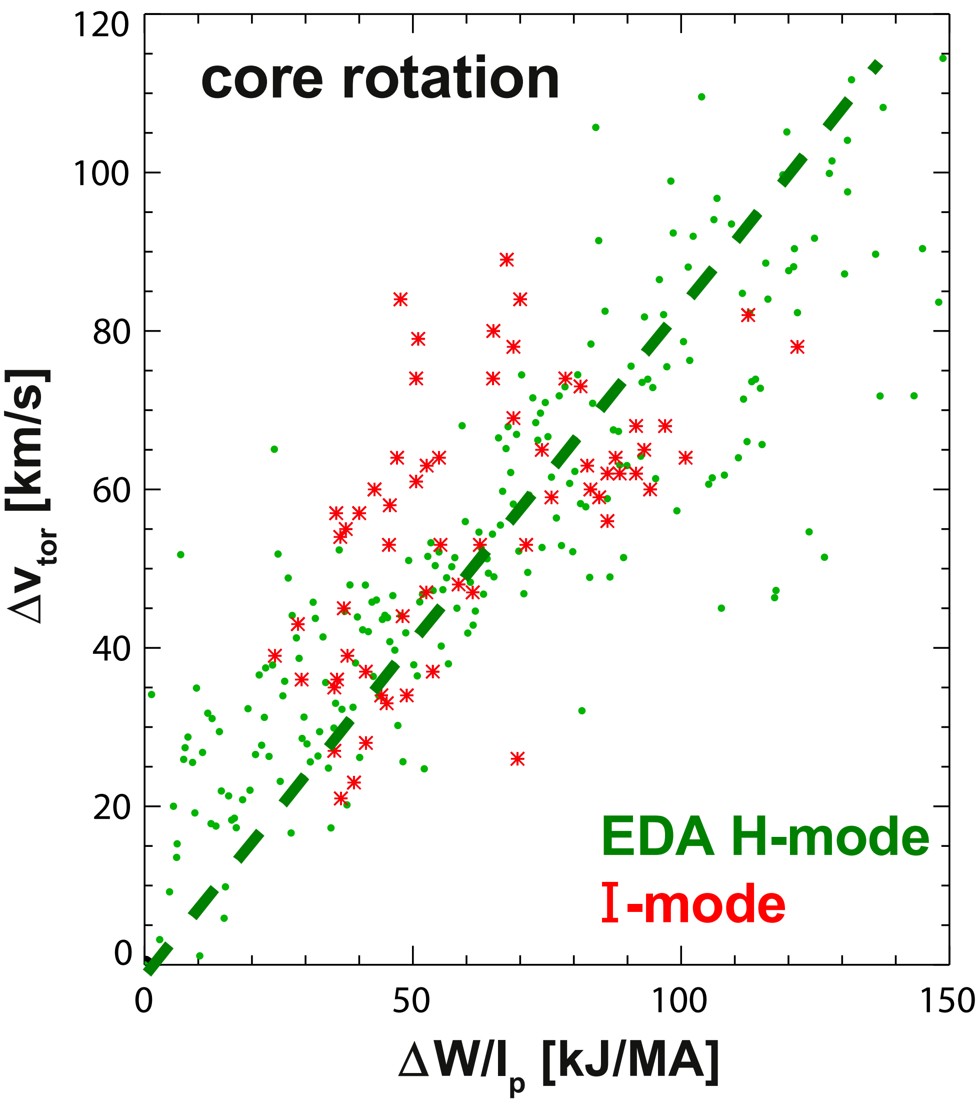
Reynolds stress, symmetry breaking, NTV, others

This list is by no means complete!

[1]M. Nave, *et al*. PRL **105** 105005 (2010), [2]M. Nave JET-PR(11)19
[3]W.M. Solomon, *et* al. Nucl. Fusion **51** 073010 (2011)
[4]C. Angioni, *et al*. PRL **107** 215003 (2011)

C-Mod Has Found a Robust Δv Scaling

In EDA H-mode and I-mode, rotation (Δv) increases with $\Delta W/I_p$

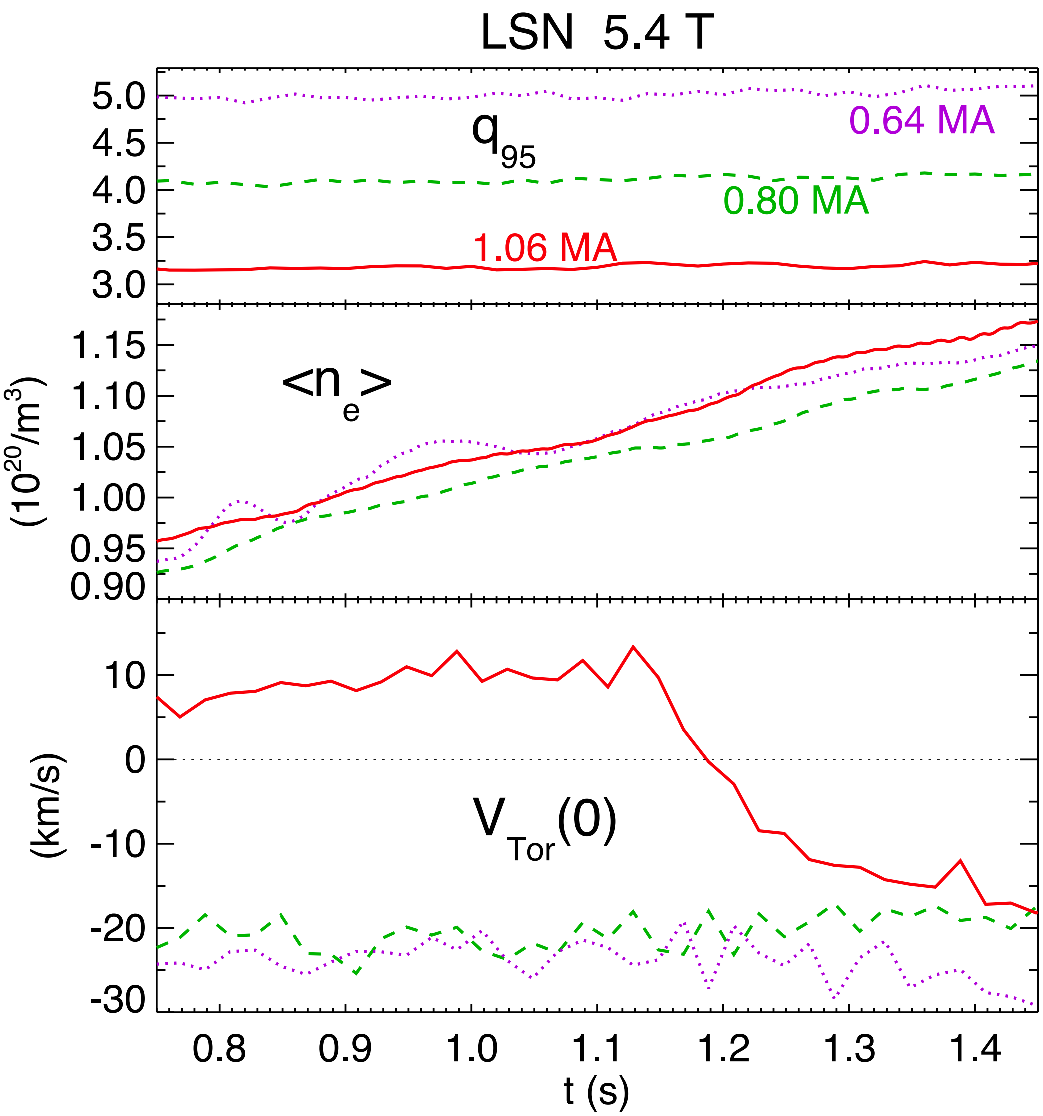


- momentum source is at the edge, transported inward
- recent results[1] show that $\Delta v \sim \Delta$ (pedestal ∇T_e)
- substantial scatter due to additional physics?

this scaling works for a wide range of C-Mod plasmas but there are noticeable exceptions

[1] J.E. Rice, *et al.* PRL **106** 215001 (2011)

C-Mod is Also Investigating Ohmic Rotation



[1]J.E. Rice, *et al.* Nucl. Fusion **51** 083005 (2011)
[2]see J.E. Rice presentation on 4/12

- In Ohmic plasmas, the direction of the core rotation has been shown to change spontaneously
- threshold shown to depend on n_e, I_p and B_t ($\sim n_e/q_{95}$)
- shown to be linked to the LOC/SOC boundary[2]

focus has been more on the direction of core rotation and not the peaked/hollow shape of the rotation profile

Outline

This talk explores cases when the toroidal rotation does not conform to expectations based on empirical scaling laws

- "occasional" counter-current rotation changes in EDA H-modes that use low-power LHRF
- sensitivity of core rotation and the rotation profile to small changes in n_e and I_p in ICRF-heated L/I-modes
- no consistent change in rotation when scanning the major radius of the D(H) resonance layer

These C-Mod results challenge "linearized" analysis techniques by demonstrating non-linear changes in the rotation profiles due to small changes in the background plasma

is there more than 1 player ($\Delta W/I_p$)? YES!

do we have a consistent story? NO!

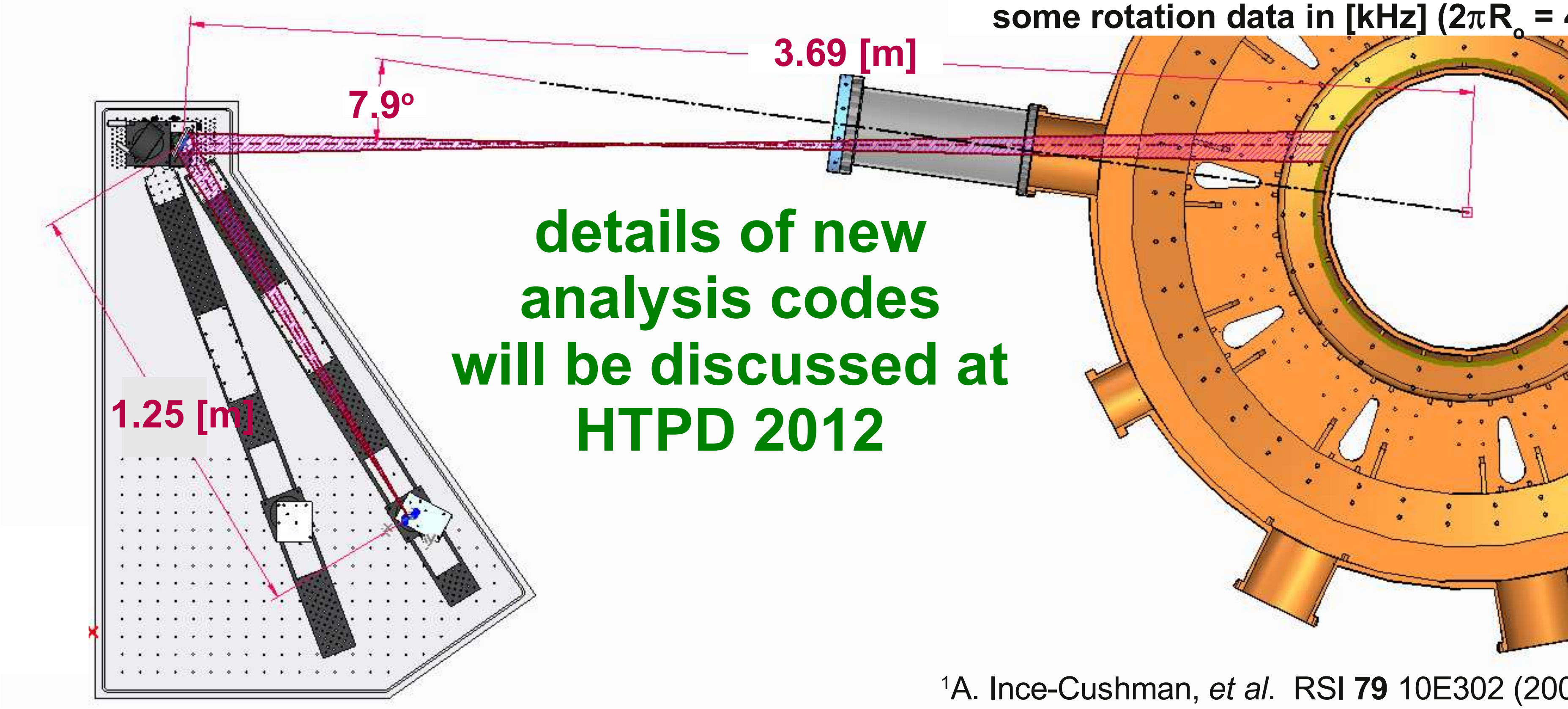
This talk presents a large amount of experimental data to facilitate discussions on the mechanisms behind intrinsic rotation

Flows Measured Passively with IXCS

Imaging X-Ray Crystal Spectroscopy (IXCS) is used to measure toroidal rotation profiles from Doppler shift of highly ionized argon[1]

- small toroidal angle enables toroidal rotation measurement, full poloidal fan allows for spatial resolution **[ITER PROTOTYPE]**
- profiles are line-averaged plotted w/r/t r_{TANG} as sqrt(ψ_n)

some rotation data in [kHz] ($2\pi R_o$ = 4.3)



details of new analysis codes will be discussed at HTPD 2012

[1]A. Ince-Cushman, *et al.* RSI **79** 10E302 (2008)

Local Rotation and Temperature Linked

IXCS enables comparison between local flow and ion temperature rather than line-averaged flow and ∇T_e profiles from Thomson

In a range of *ICRF-heated plasmas*, the <u>local</u> rotation speed is correlated to the <u>local</u> ion temperature

- <u>limited range</u> of target plasmas conditions

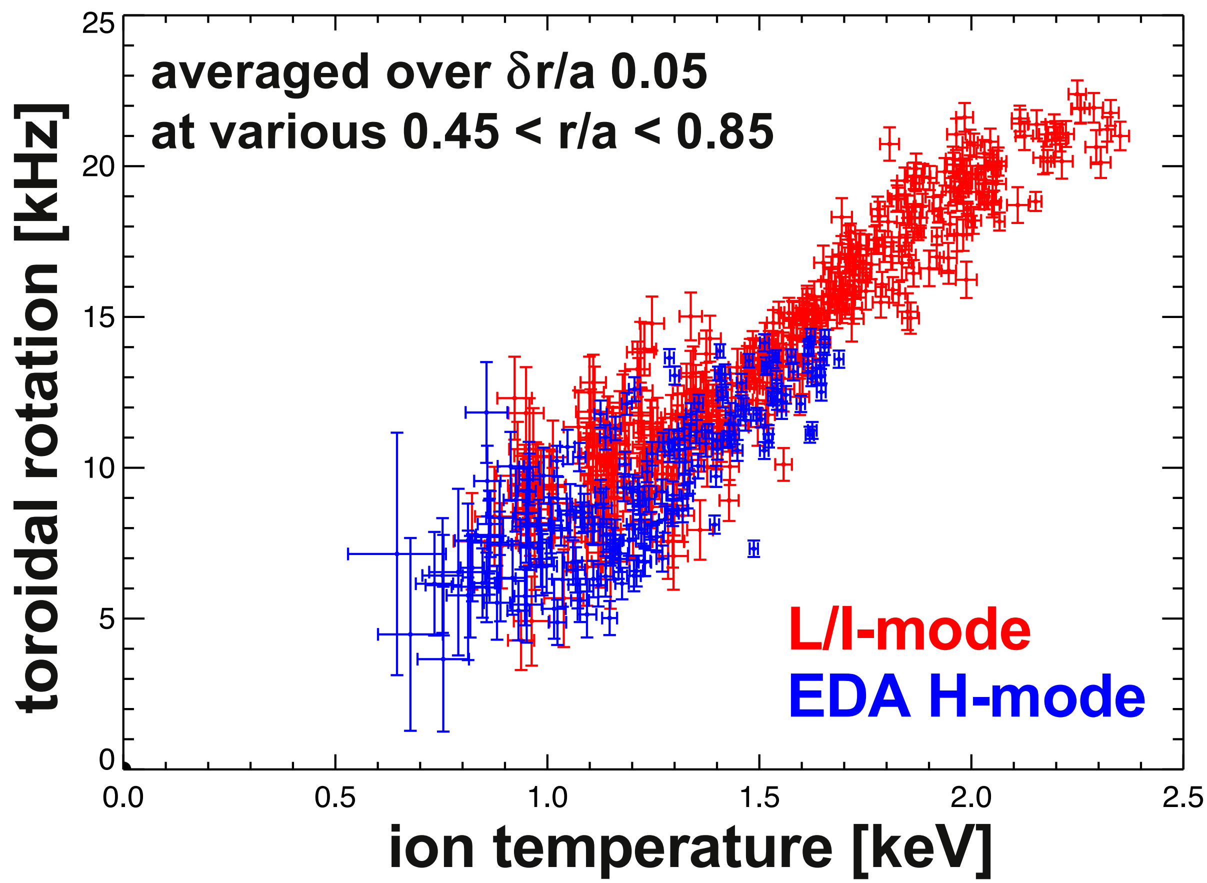
  I_p=1.1, 1.3 [MA]

  $1.5 < n_e(r) < 2.5\times10^{20}$ [m^{-3}]

  I_p=0.7, 0.9 [MA]

  $1.5 < n_e(r) < 3.5\times10^{20}$ [m^{-3}]

- working to expand the dataset of **inverted** profiles to wider range of I_p, B_t, n_e



Rotation Changes Linked to LHRF

early work[1,2] showed only cntr-current changes in rotation in low density plasmas with lower-hybrid current drive (no ICRF)

- initial hypothesis was E_r change from fast-electron pinch
- possibly direct torque effect due to momentum in LH waves

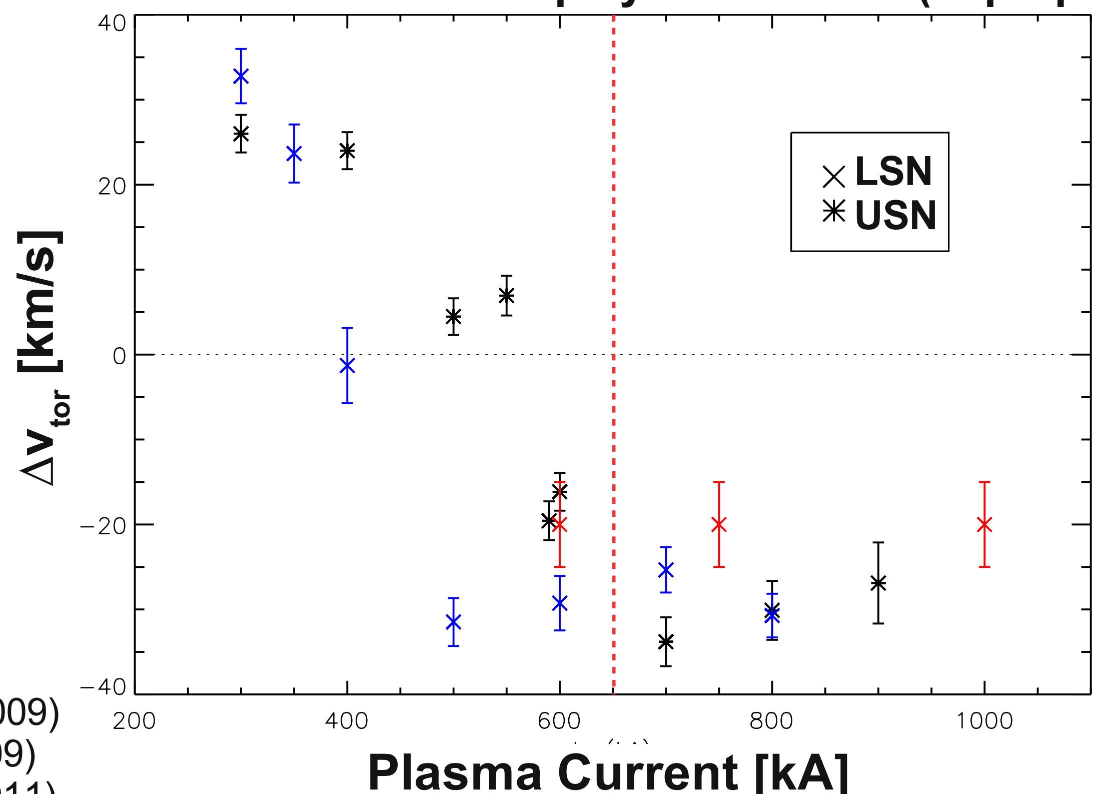
RECENT RESULTS

scan plasma current at fixed density and lower hybrid power

both co- and cntr-current rotation changes occur

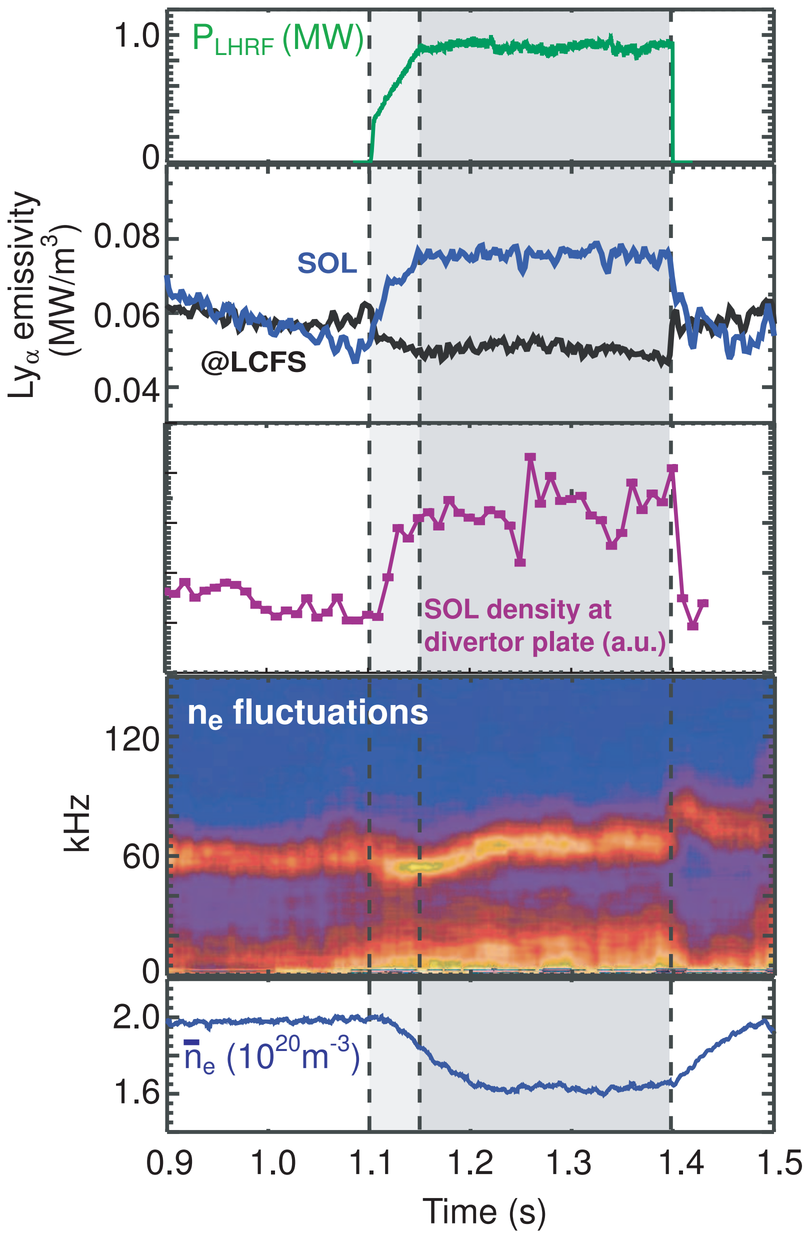
investigating link to the "rotation-reversal" physics[3]

from Y. Podpaly PhD Thesis (in prep.)



[1]A. Ince-Cushman, *et al*. PRL **102** 035002 (2009)
[2]J.E. Rice, *et al*. Nucl. Fusion **49** 025004 (2009)
[3]J.E. Rice, *et al*. Nucl. Fusion **51** 0830005 (2011)

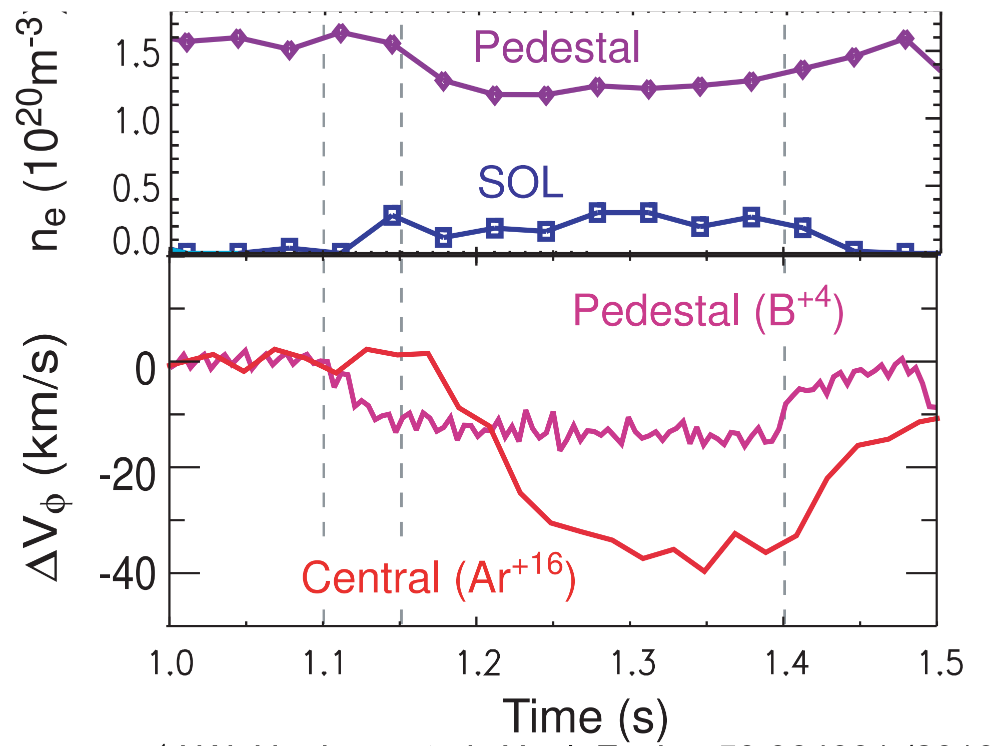
LHRF into H-modes Modifies Pedestal



initial results[1] showed drop in core density, increase in temperature

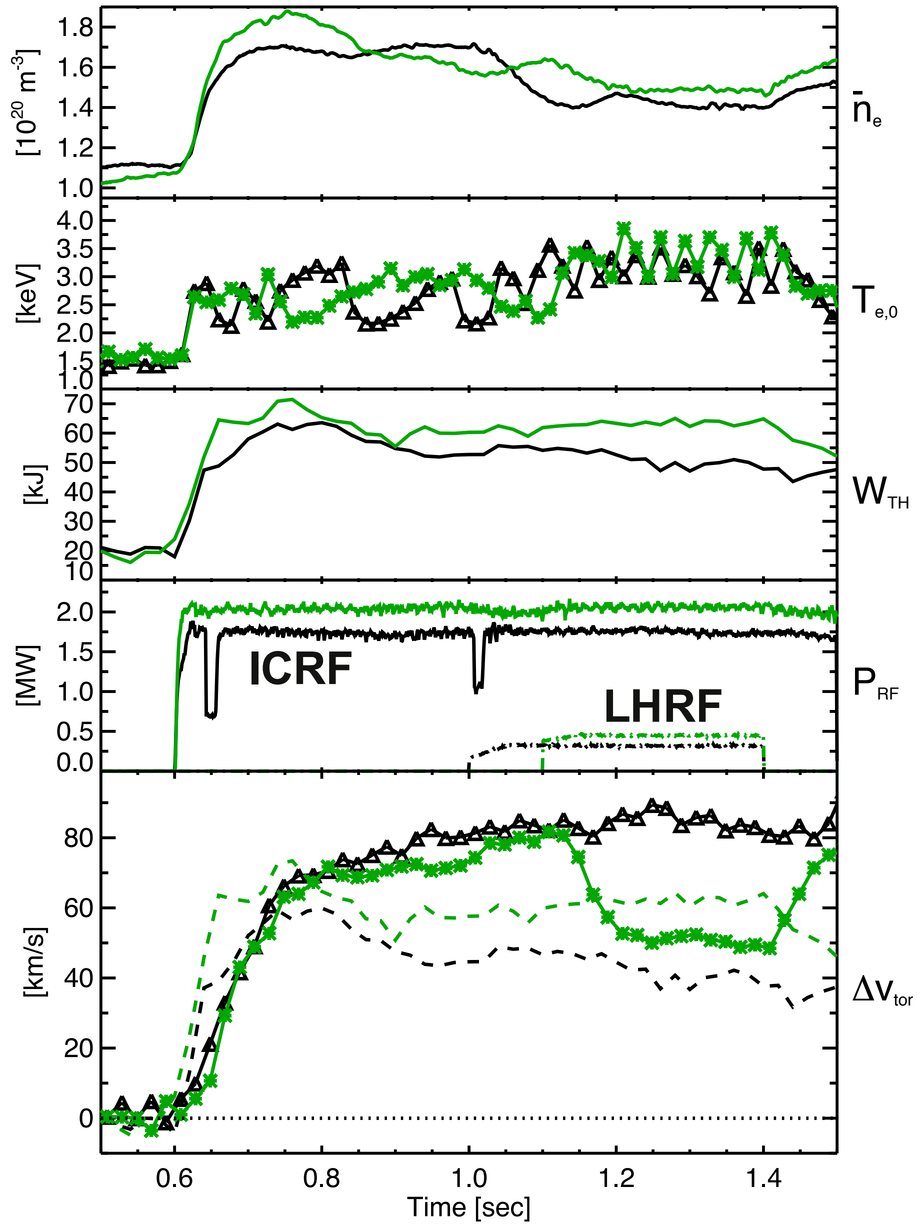
pedestal pressure ~ fixed

modification to neutral emission and <u>both core and edge rotation</u>



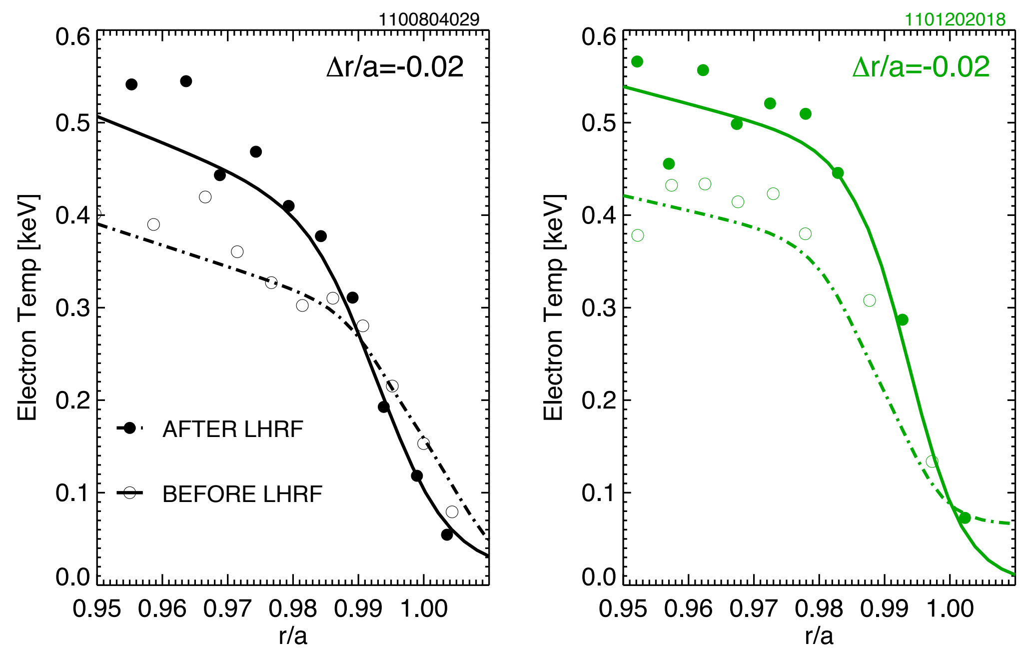
[1]J.W. Hughes, *et al.* Nucl. Fusion **50** 064001 (2010)

Rotation Change Not Always Seen



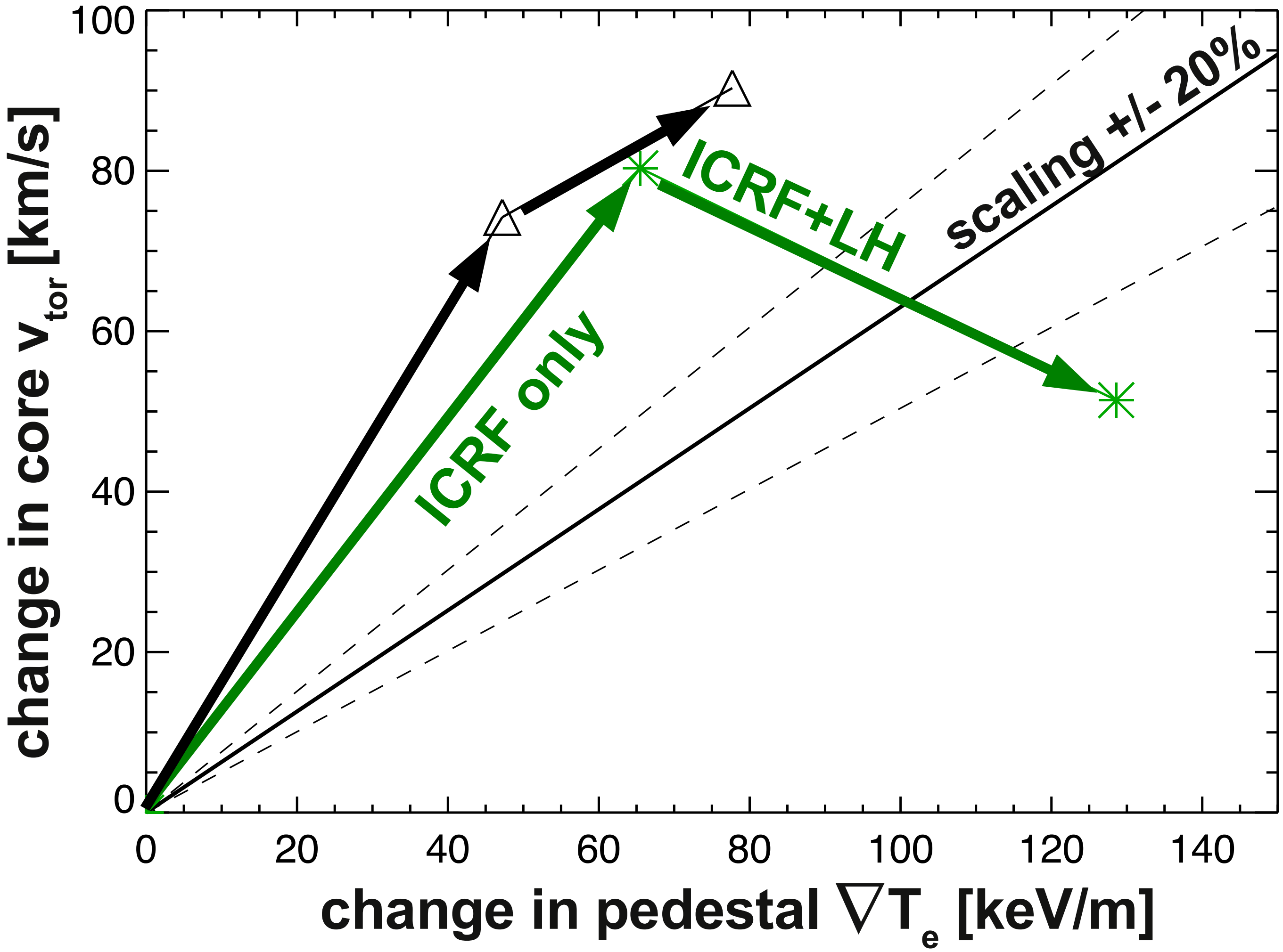
at reduced $n_{||}$ and P_{LHRF} the pedestal changes are still observed but the <u>rotation does not always occur</u>

- initial rotation changes from Ohmic to EDA H-mode exceed scaling
- LH waves do not propagate into the core, removing a direct torque source

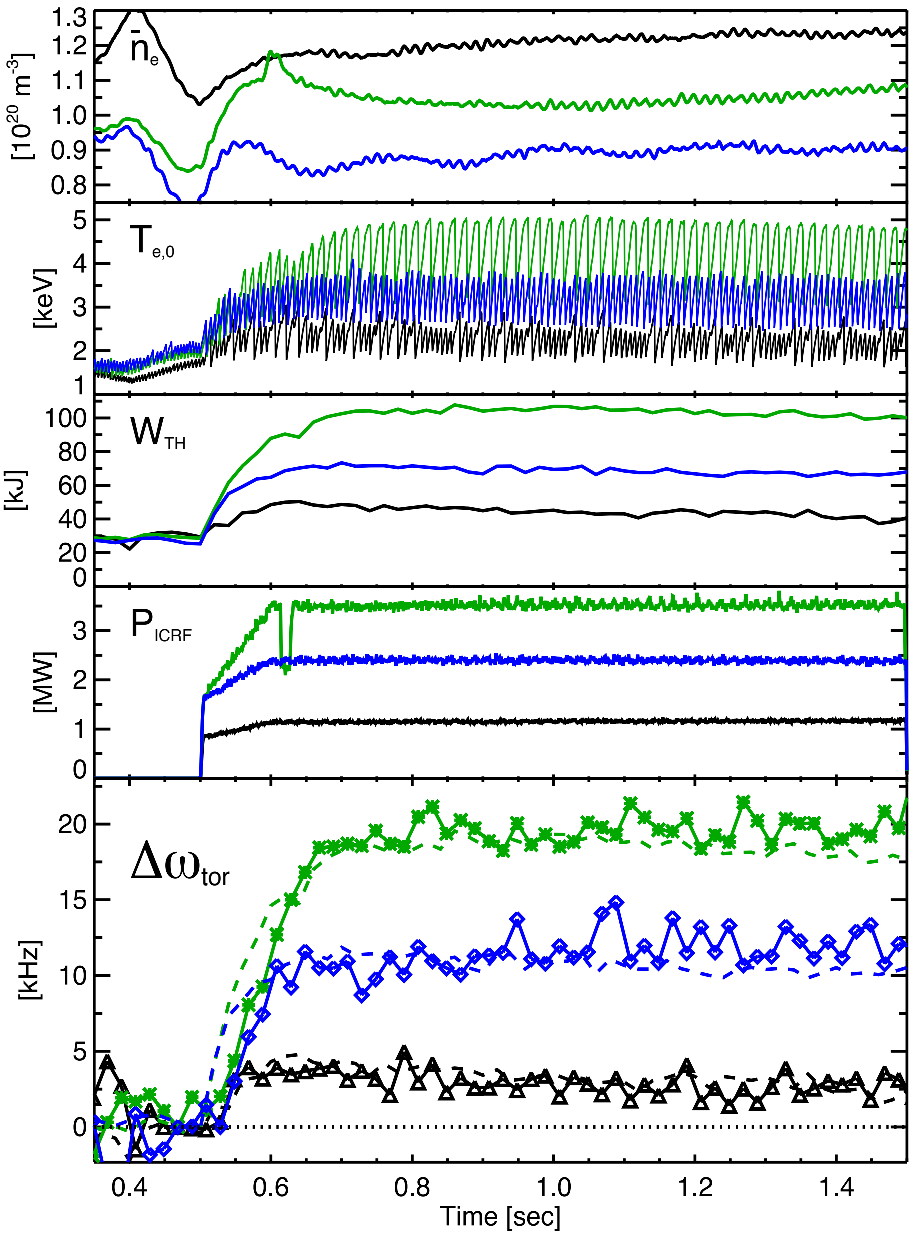


v_{tor} Changes Orthogonal to Scaling

drop in rotation after an increase in ∇T_e contradicts empirical predictions

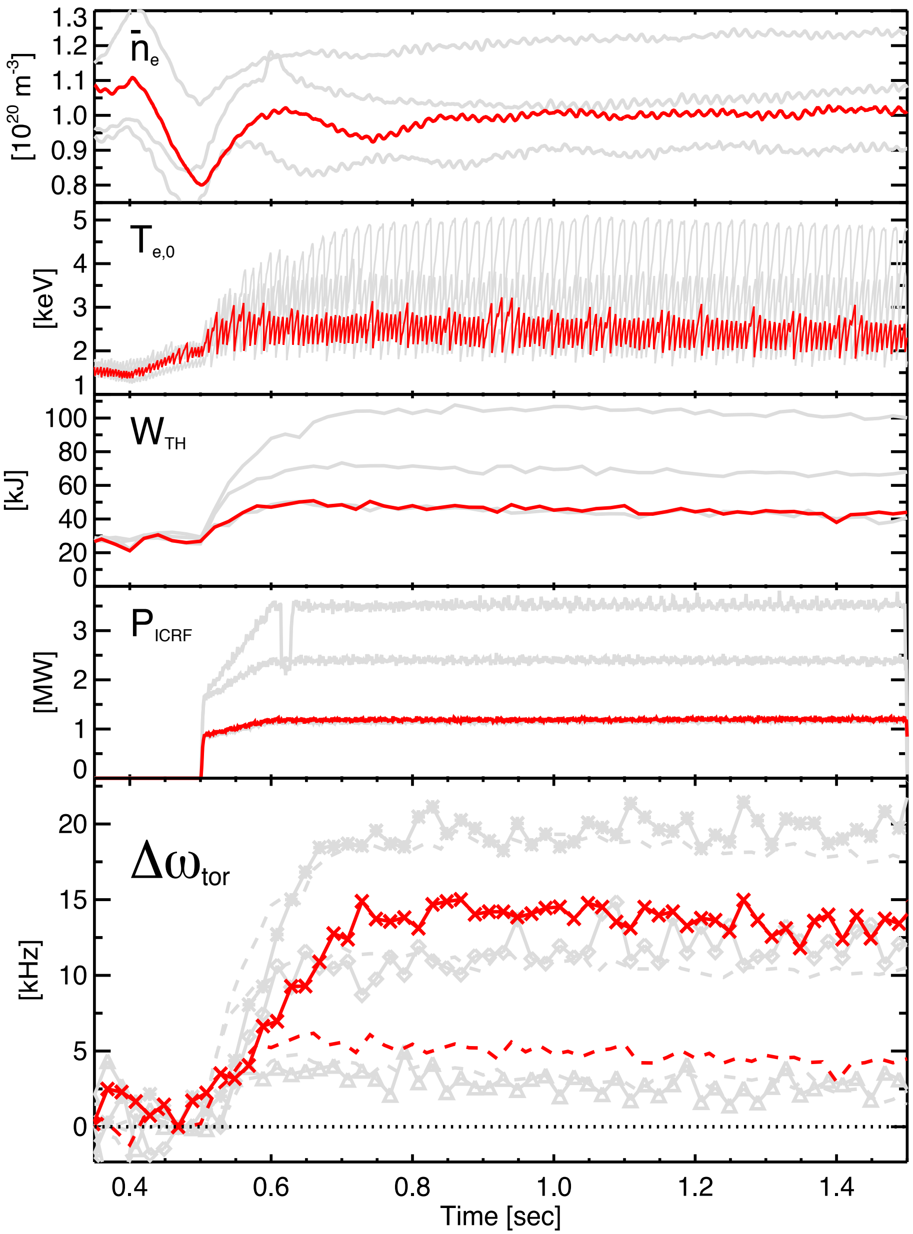


The $\Delta W/I_p$ Scaling Works Well...



- scan ICRF power (**1.2**, **2.3** and **3.5** [MW]) at fixed I_p=0.8 [MA] and B_t=5.4 [T] in an USN L-mode
- for a range of line-averaged n_e from 0.9-1.2x10^{20} [m^{-3}] the measured core $\Delta\omega_{tor}$ (symbols) follows the $\Delta W/I_p$ scaling (**- - - -**)

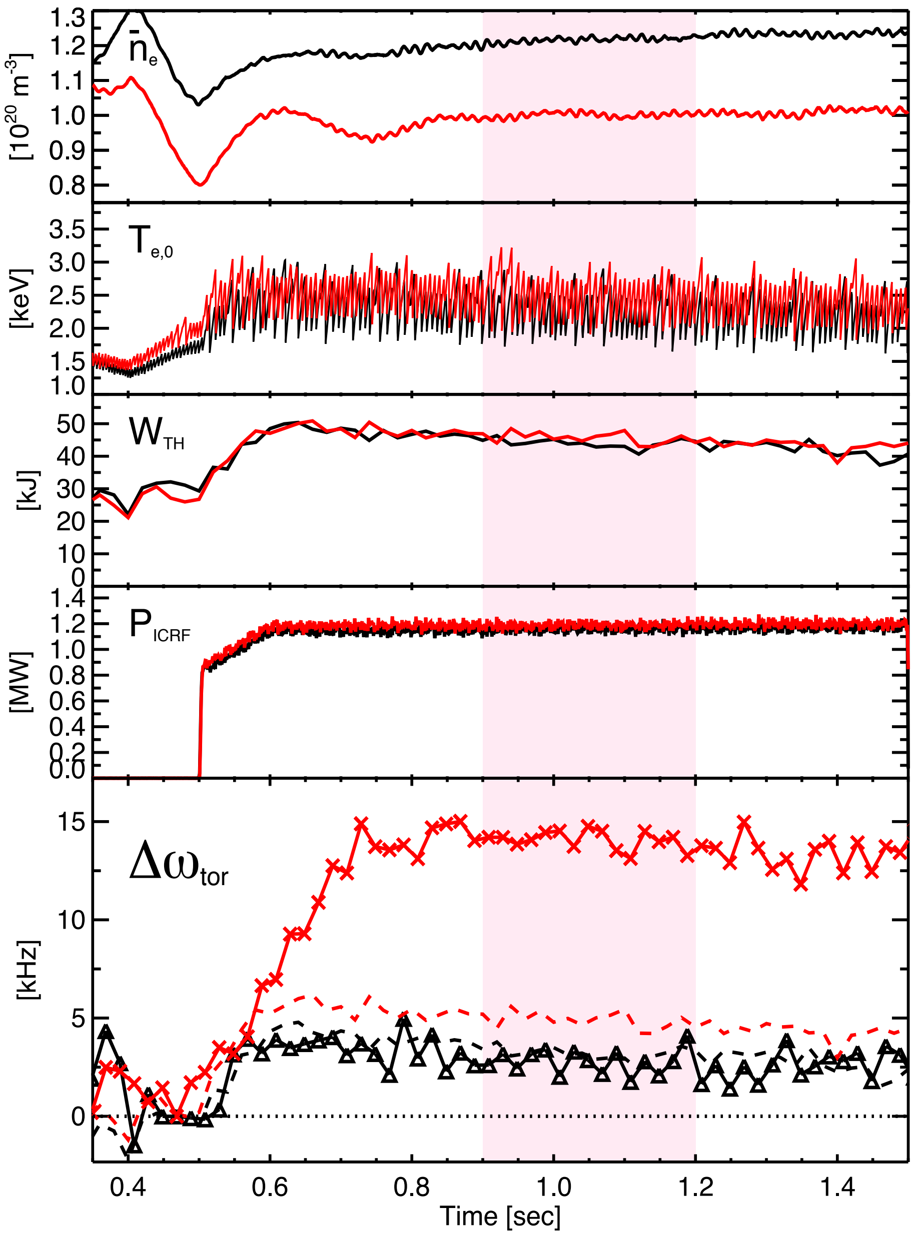
...Except When it Doesn't



dropping $\bar{n}_e$ by ~17% leads to >10 kHz (~50 km/s) change in core rotation

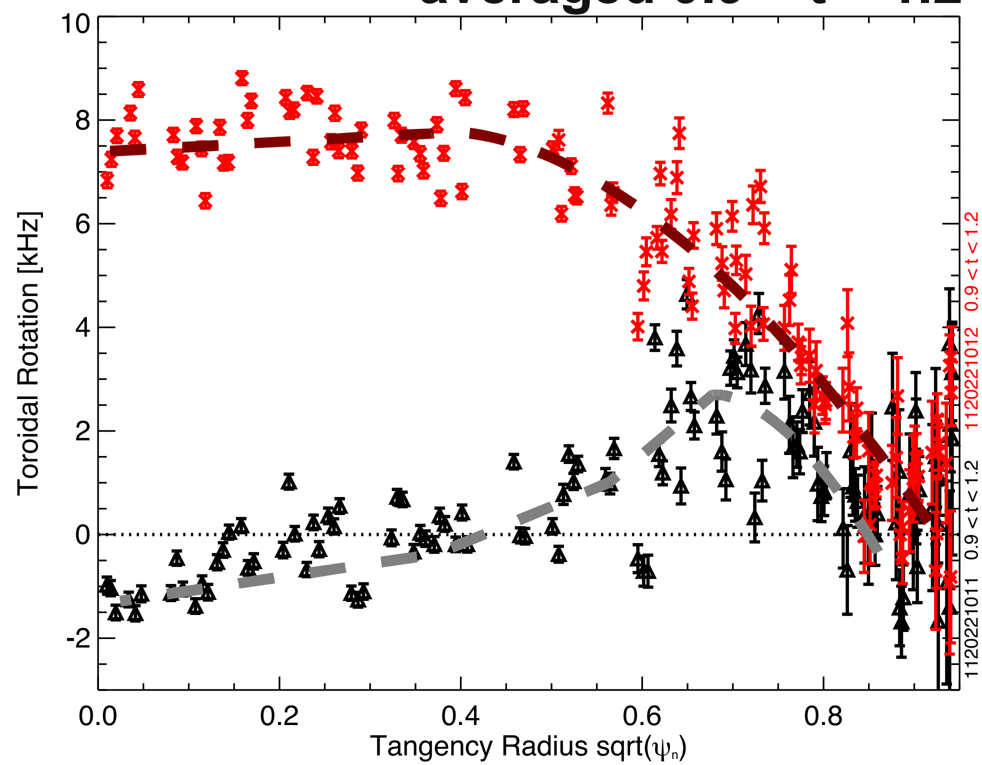
- for P_{ICRF} = **1.2** [MW] at line-averaged n_e of 1.0×10^{20} [m^{-3}] measured core $\Delta\omega_{tor}$ (symbols) exceeds the $\Delta W/I_p$ scaling (- - - -)
- rotation increase even exceeds case with twice as much ICRF heating power

Shape of ω_{tor} Profile Changes with n_e

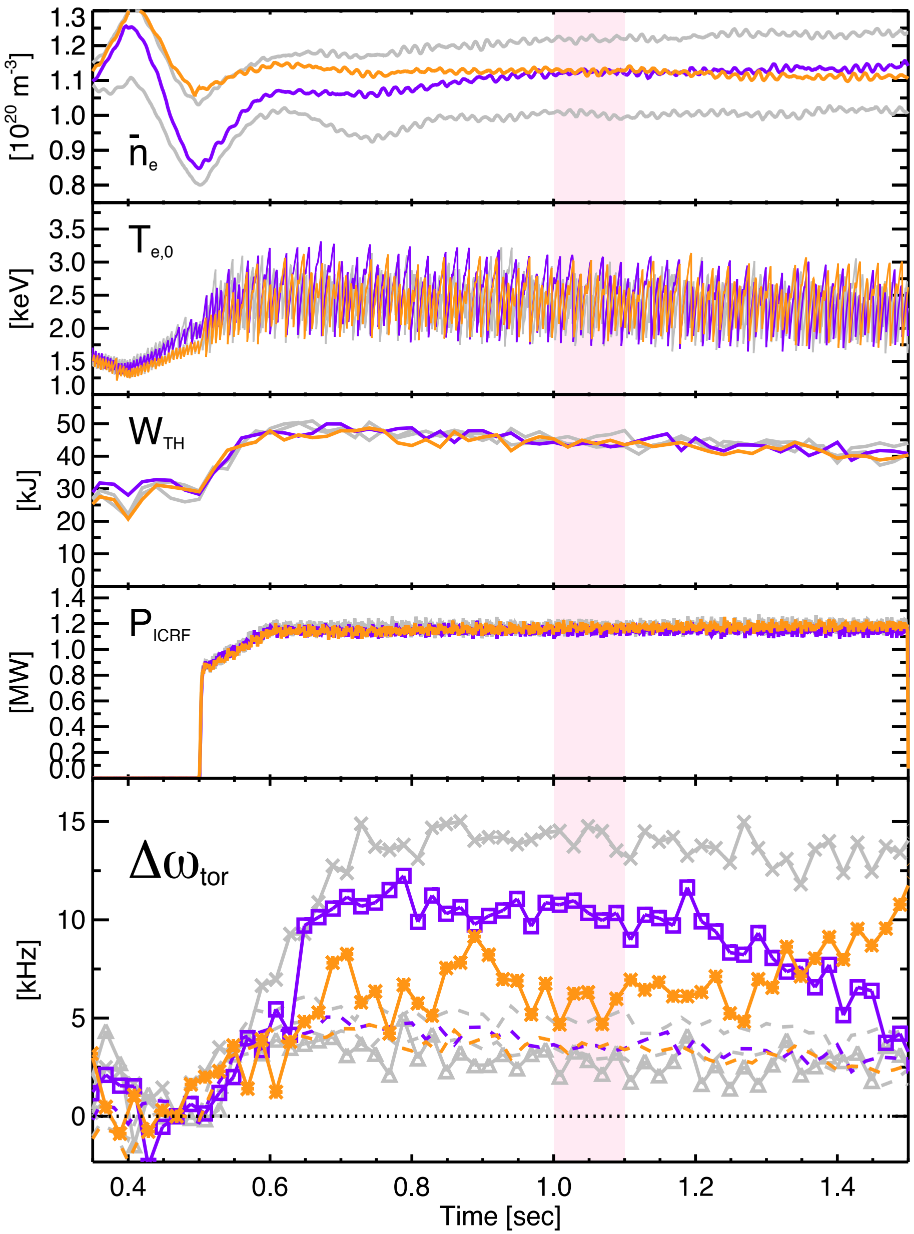


- hollow rotation profile for slightly higher density plasma
- sign of $d\omega_{tor}/dr$ changes at $\rho \sim 0.6$
- connects to the ASDEX-U results

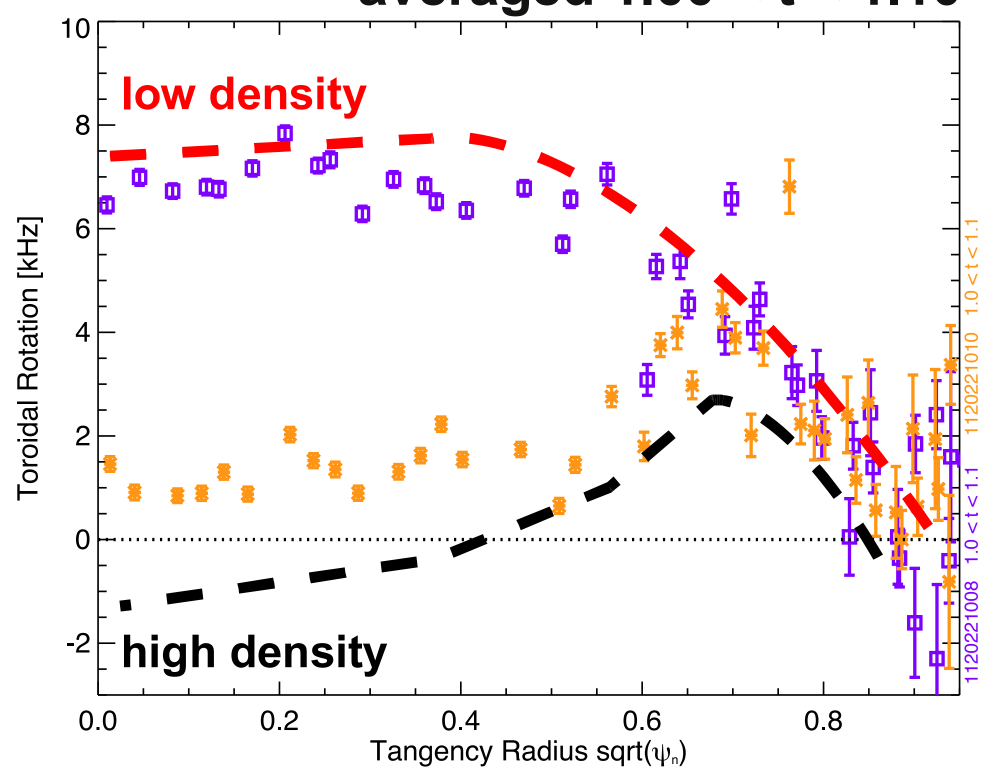
averaged 0.9 < t < 1.2



Intermediate n_e Move Between Limits



- slow change (> τ_E ~22 ms) indicates that transitions is likely NOT a bifurcation
- ω_{tor} peaking versus line-averaged density



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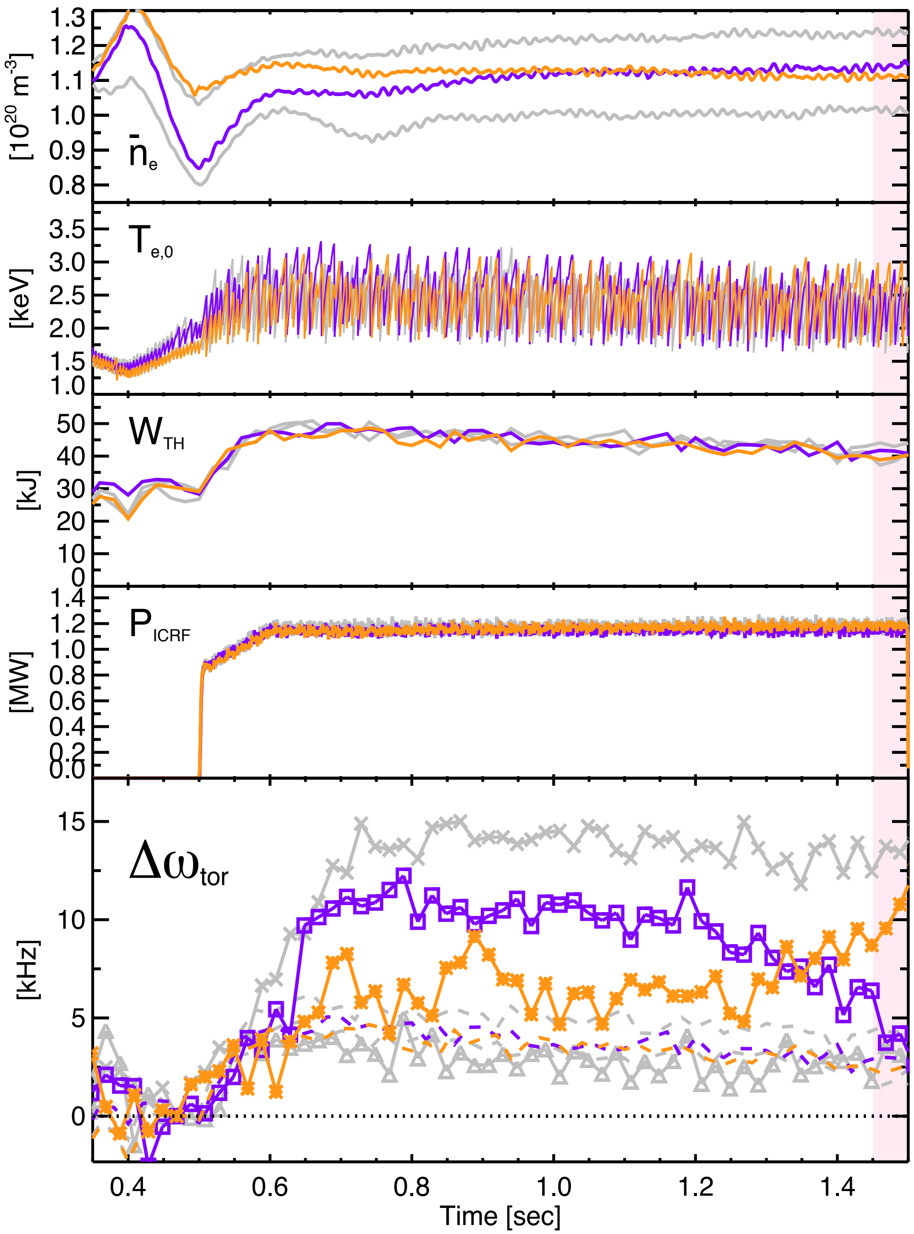

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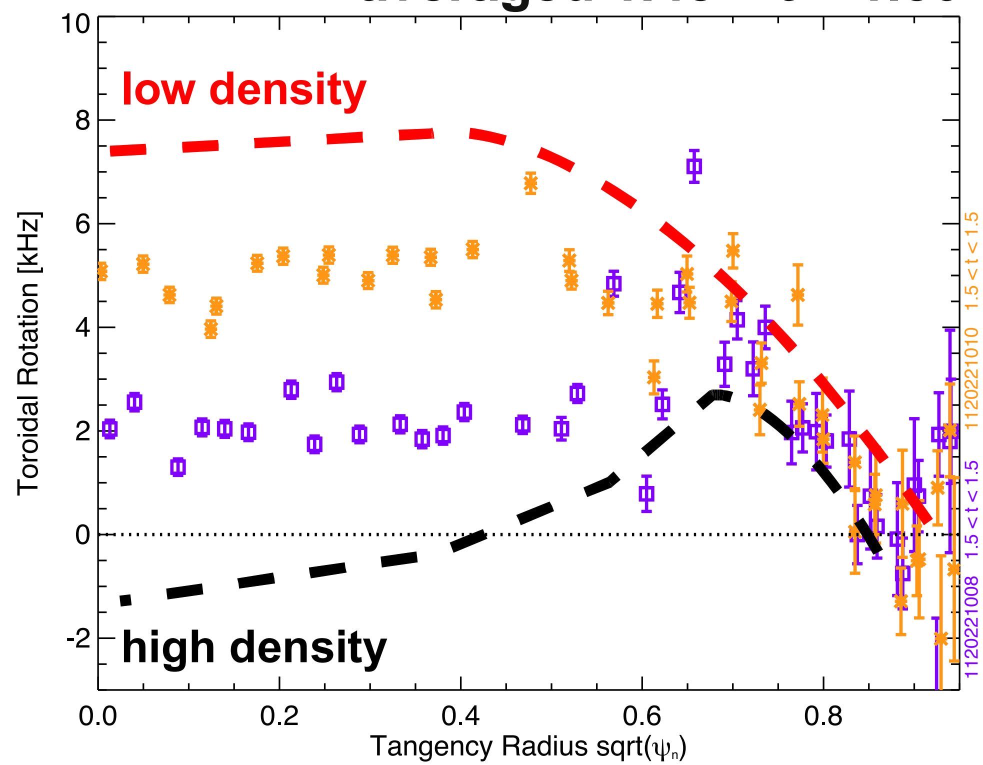
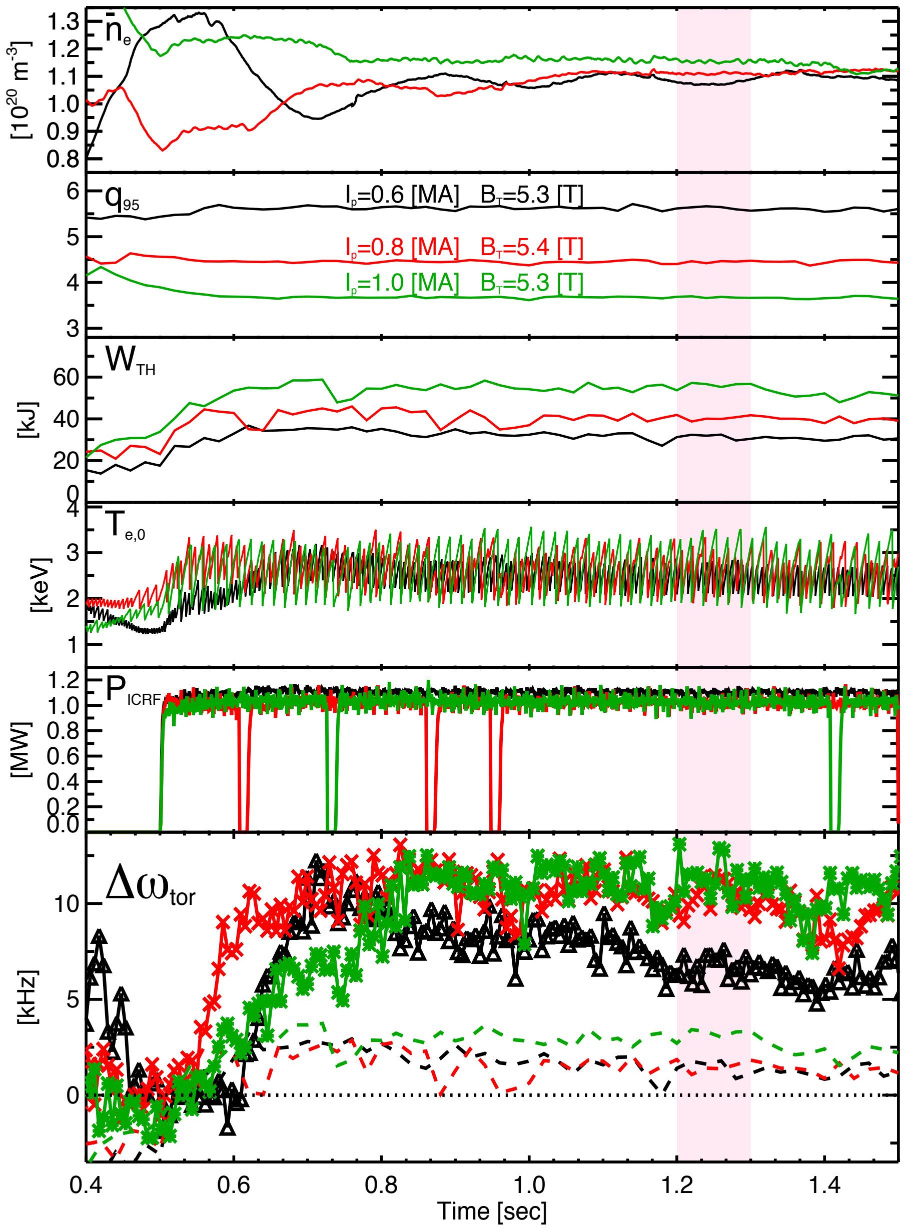
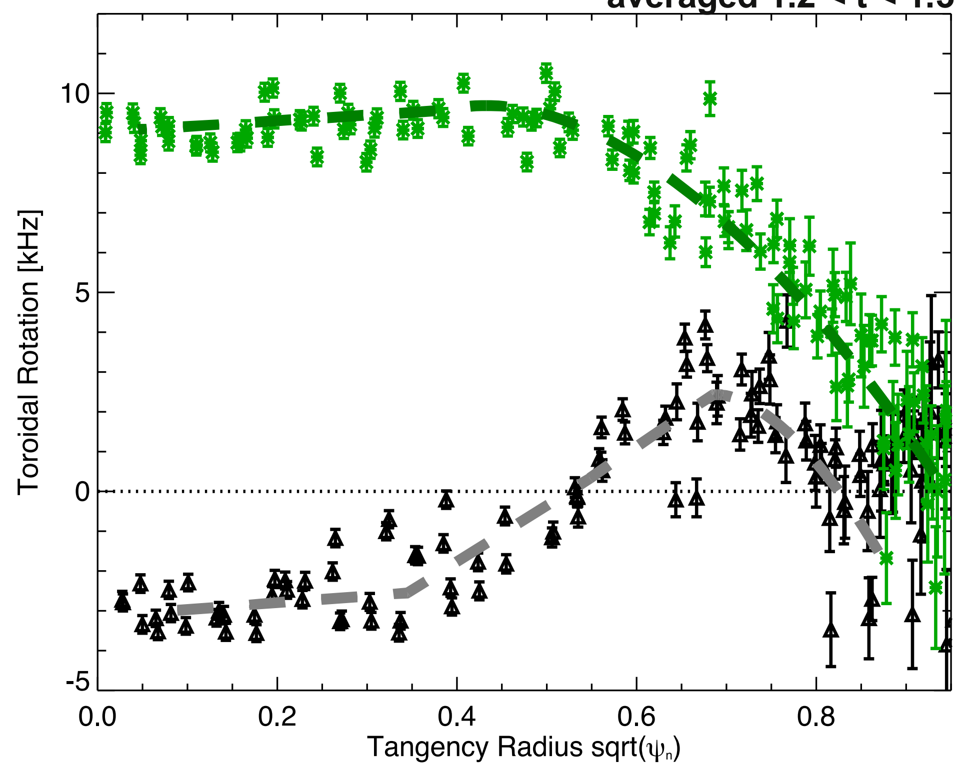


Shape of ω_{tor} Profile Changes with I_p



- at fixed n_e, B_t and P_{RF} the plasma current is scanned: **0.6** **0.8** to **1.0** [MA]
- at **low current** Δv is reduced, but all are still well above $\Delta W/I_p$ scaling
- ω_{tor} profile shows sign change in *dv/dr*

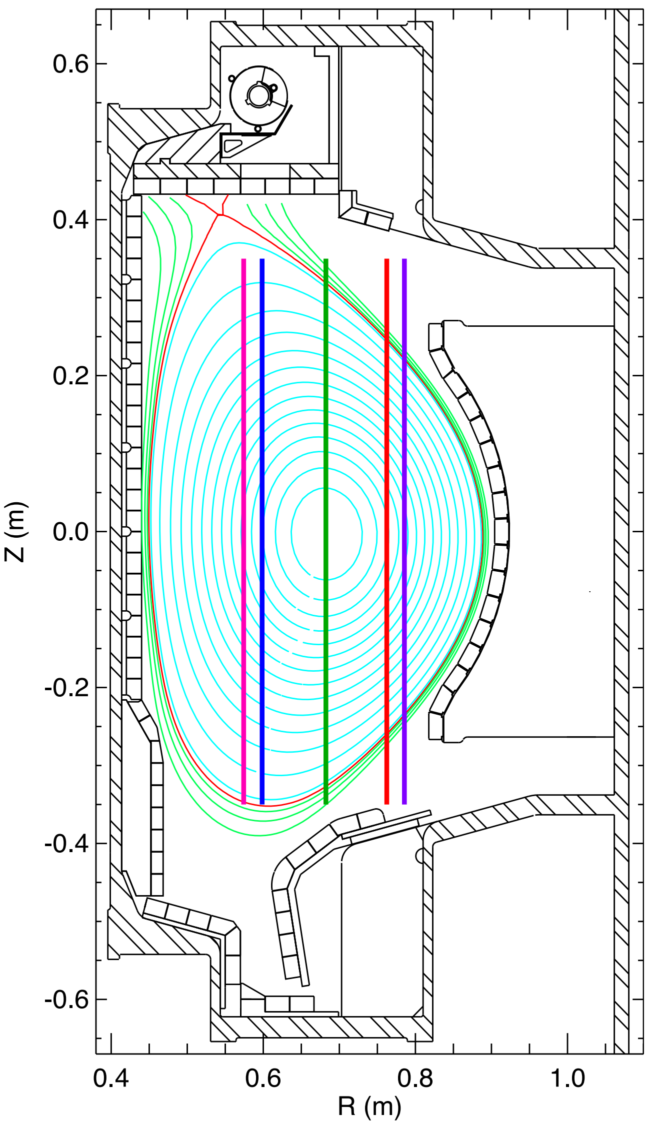


Understanding ω_{tor} Profile Sensitivity Critical

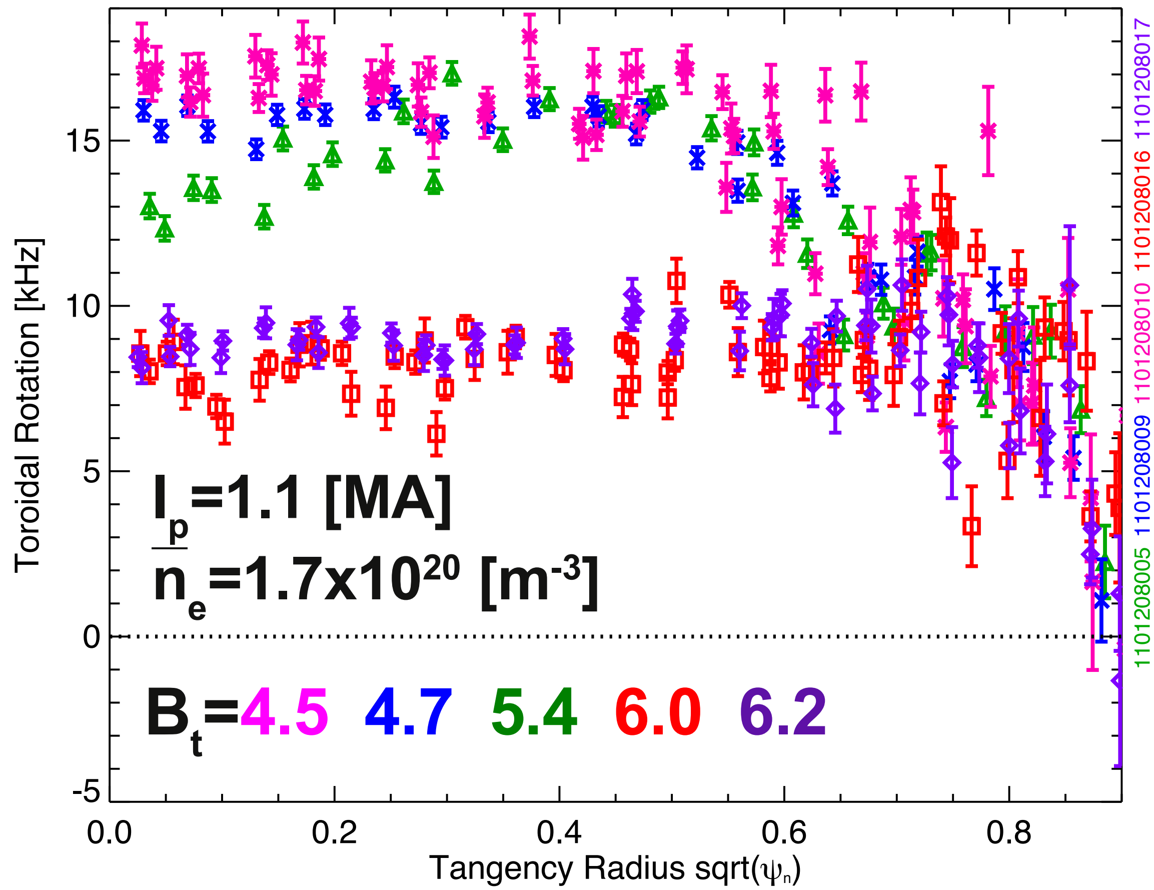
- **predicting the flow "regime" important for ITER's needs**
  - will ITER see "low" or "high" flow?
  - at what *r/a* will ITER's *dv/dr* change sign?
  - do power-law scalings capture correct physical framework?
- **is there a connection to TEM/ITG transition as discussed for Ohmic plasmas in the LOC/SOC changeover?**
- **warning for "linearized" analysis techniques of these plasmas**
  - using "beam-blips" assumes linear *dv/dt* for back-extrapolation
  - Fourier-based momentum transport techniques assume that one can Taylor expand about the DC point
- **FUTURE: move results to non-dimensional analysis studies**
  - C-Mod, AUG already looking at correlations to, R/L_n, ν_*, T_e/T_i
  - work with theory/simulation to predict qualitative features

Reduced Rotation for LFS Heating

scan of D(H) res. layer with shot-to-shot changes in B_t at P_{RF}=3 MW

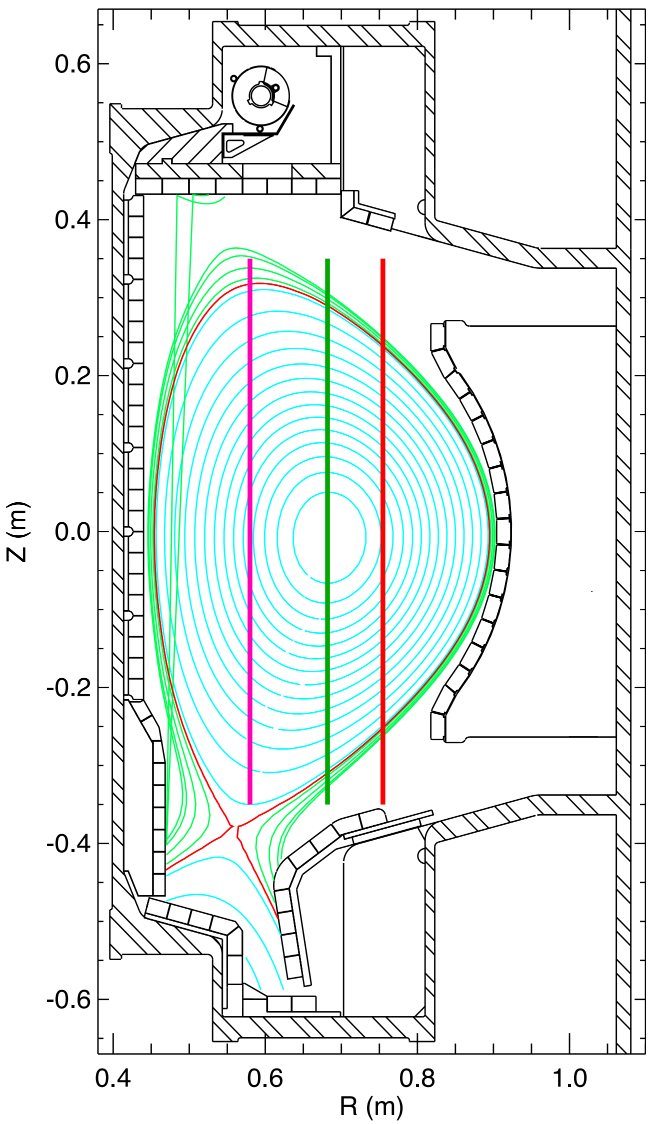


- rotation profile w/ LFS heating different than with on-axis or HFS heating
- is this torque due to fast-ion loss?

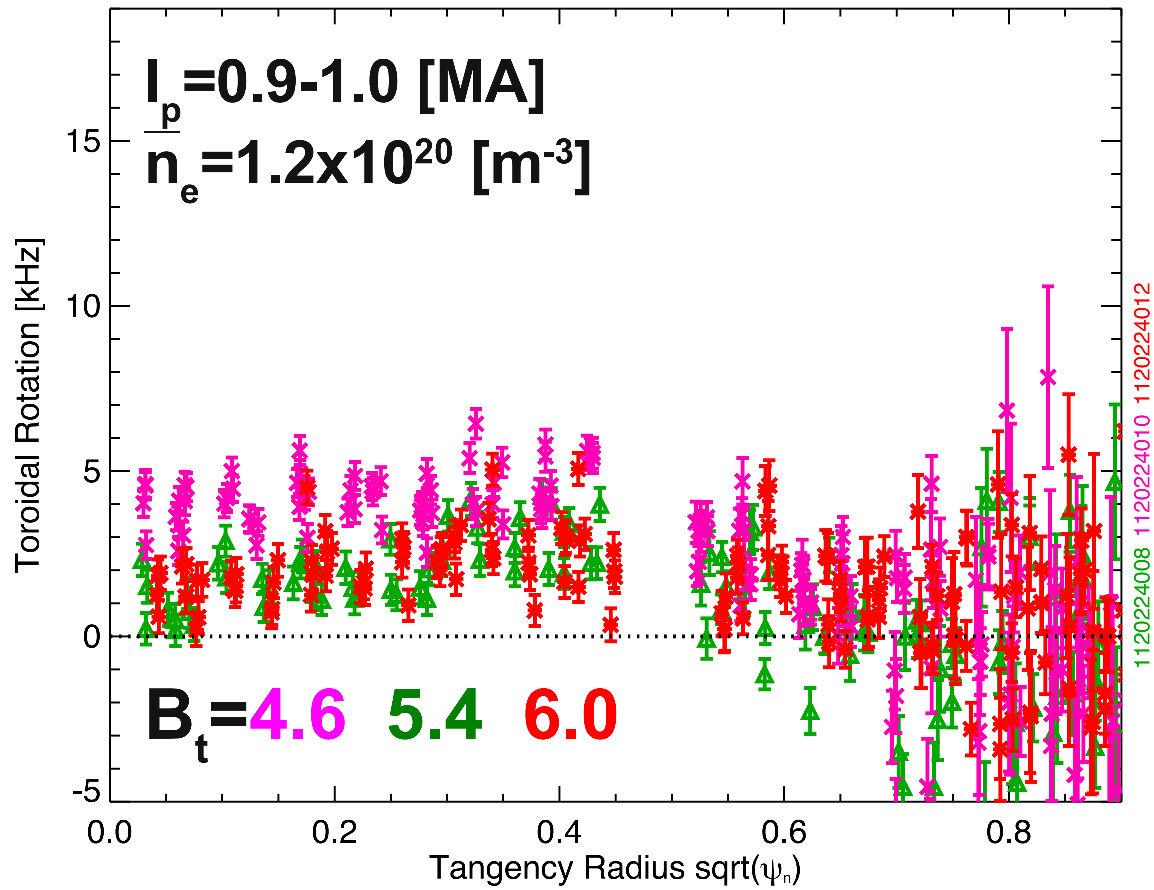


Rotation Independent of D(H) Layer

scan of D(H) res. layer with shot-to-shot changes in B_t at P_{RF}~3 MW



- rotation reduced relative to higher n_e, I_p shots (far below ΔW/Ip scaling)
- suggests link to parameter "sensitivity" physics



Summary

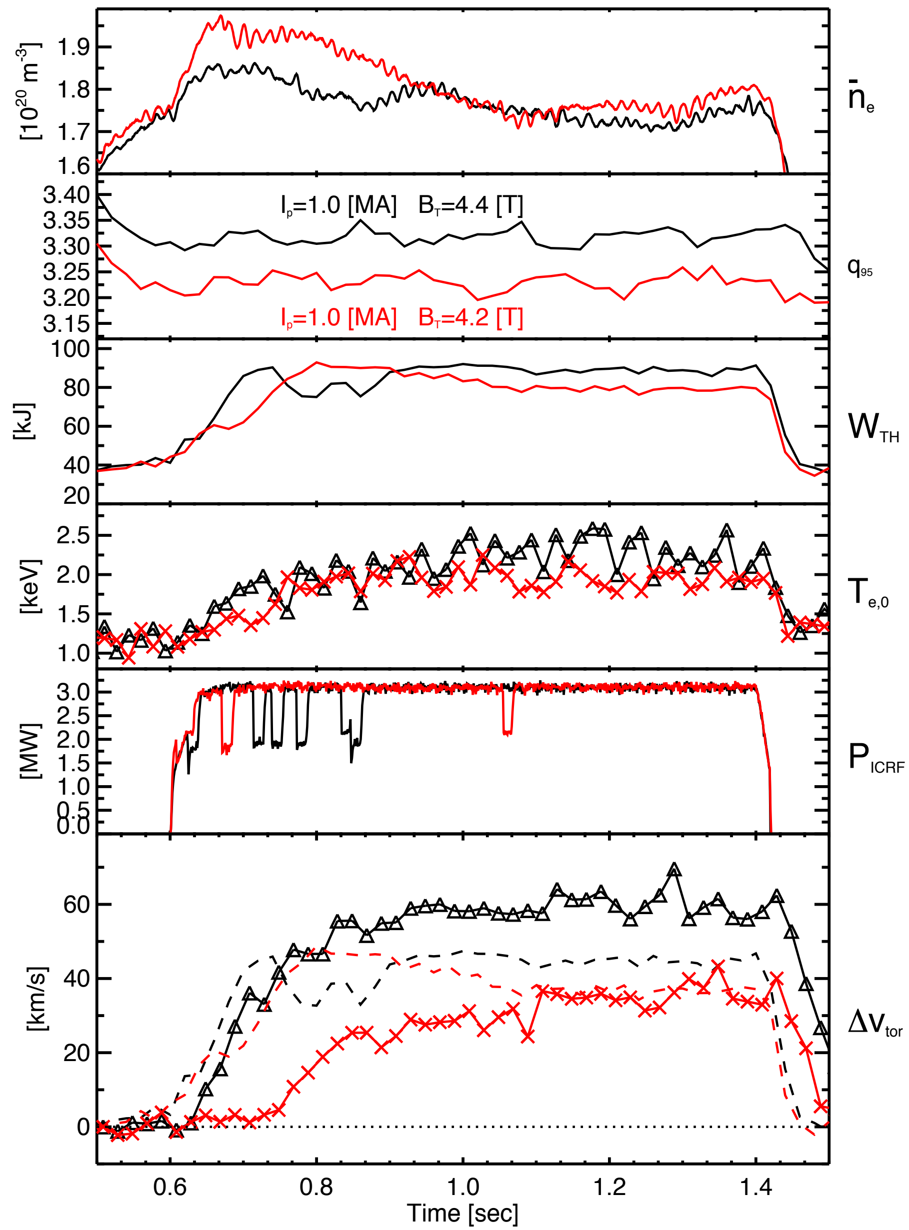
Alcator C-Mod is continuing investigations into the origins of intrinsic rotation in tokamak plasmas by studying the "outliers"

- core rotation changes in EDA H-modes using LHRF challenges existing empirical scaling that suggest $\Delta v \sim \Delta(\text{pedestal } \nabla T_e)$
  - counter-current Δv not always observed
  - impact of LHRF on neutral density a possible mechanism
- rotation profiles are demonstrated to be sensitive to small changes in n_e, I_p in ICRF-heated L/I-mode plasmas
  - possibly linked to the "rotation-reversals" physics observed in Ohmic plasmas
- changes in rotation when scanning the D(H) resonance layer do not appear to support torque due to fast-ion loss

work with the theory community to get verifiable/falsifiable predictions of rotation profiles for a plasmas shown here

BACKUP SLIDES

Shape of v_{tor} Profile Changes with B_t



- scan field from **4.4** to **4.2** [T] at fixed n_e and I_p, using HFS heating
- higher field shot has larger region of rotation increase from $0.45 < \rho < 0.65$