X-Point-Position-Dependent Intrinsic Rotation in the Edge of TCV

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Overview

A simple kinetic transport theory predicts strong linear dependence of edge intrinsic toroidal rotation on $\bar{R}_X \doteq (R_X - R_{\mathrm{mid}})/a$, with R_X the major-radial position of the X-point.

- "Edge" means $\rho_N \gtrsim 0.85$, both inside and outside the LCFS, where spatial variation is rapid.
- An analytic calculation yields a simple formula v_{Th} for the toroidal rotation at the core-edge boundary.

A series of Ohmic L-mode shots on TCV, scanning R_X, showed:

- Entire rotation profile shifts rather rigidly as R_X changes.
- Linear dependence of edge rotation on R_X (✓)
- Rotation sign change for adequately outboard X-point (✓)
- Reasonable quantitative agreement between predicted and measured rotation (✓)

Outline

- Theoretical background
  - Assumptions
  - Cartoon of model
  - Ingredients of analytical calculation
  - Resulting predictions
- Description of experiment
  - TCV features
  - Discharge geometry and evolution
- Results
  - Rotation profiles for different R_X
  - Qualitative and quantitative comparison with theory

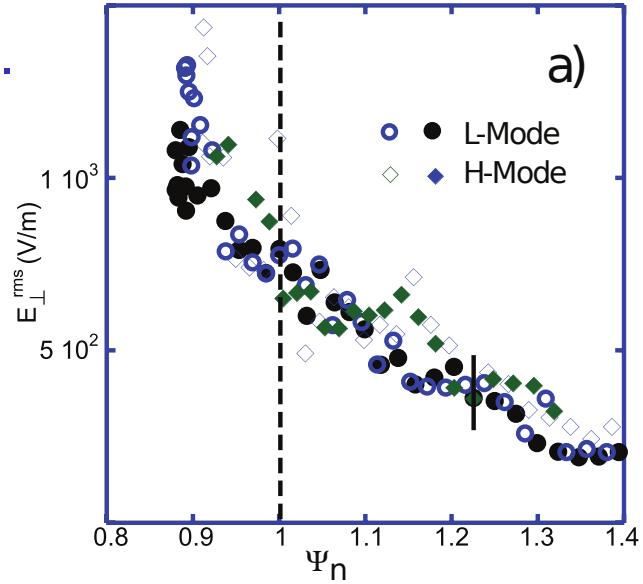
Assumption: In the outer edge and SOL, turbulent viscosity χ_ϕ^{turb} decreases with r.

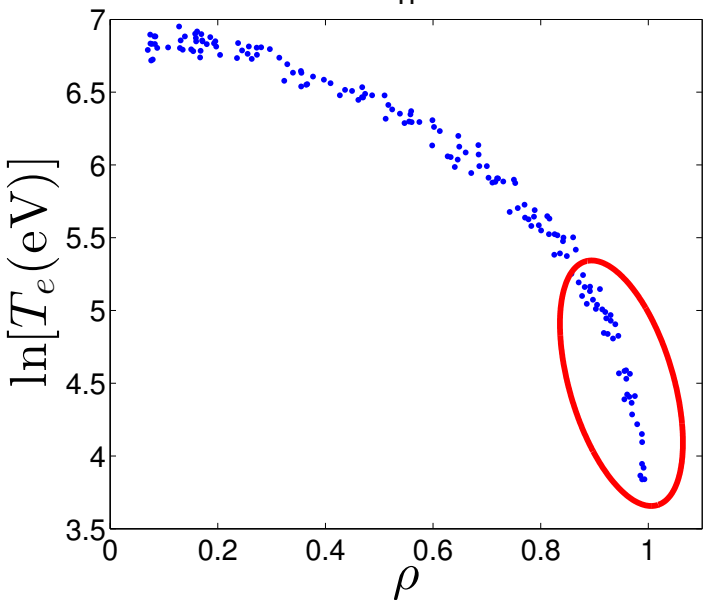
Focus:

- outer edge and SOL, $\rho_N \gtrsim 0.85$
  - region of steep gradients
- strongly turbulent viscosity
  - $\chi_\phi \sim \tilde{v}_{Er}^2 \tau_{ac} \sim \tilde{v}_{Er}^2 / k_\perp \tilde{v}_{Er} \sim c\tilde{\phi}/B$
  - $\tilde{\phi}$ is *unnormalized*, drops with T_e

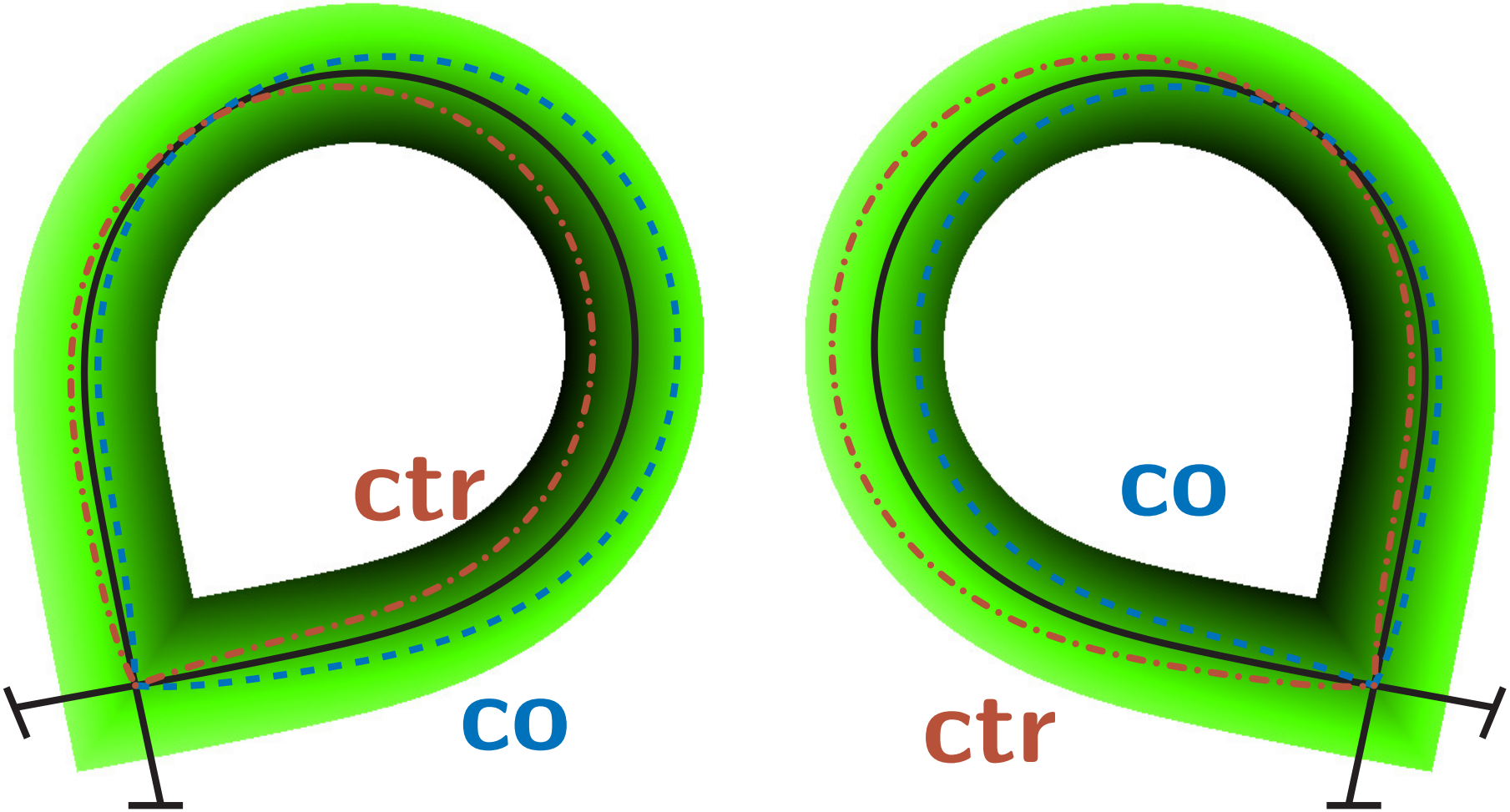
Probe measurements show $\tilde{\phi}$ decreases with r in the outer edge and SOL, e.g.:

- NSTX (Boedo PoP'14, upper, $\tilde{E}_\theta$)
- TCV (lower, T_e)
- C-mod (LaBombard NF'05)
- AUG (Endler NF'95, Horacek NF'10)
- JET (Silva RSI'04)
- W7-AS (Bleuel NJP'02)
- TEXT (Ritz PRL'90)
- Caltech (Zweben NF'85)





Theory: Orbit-averaged diffusivity is different for co- and counter-current ions.

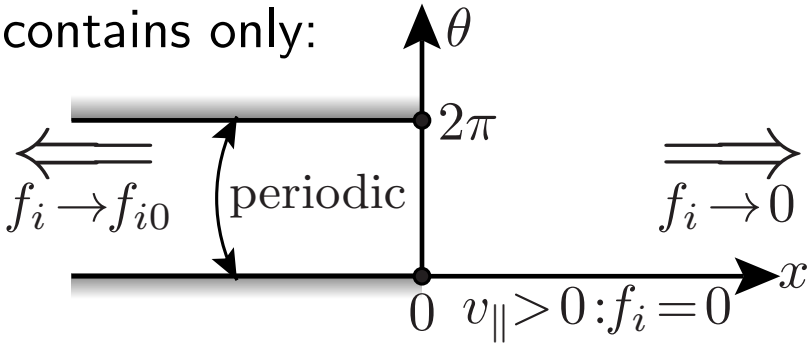


Edge rotation may become counter-current for outboard X-point!

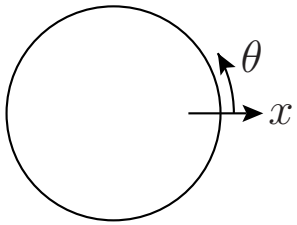
A simple kinetic transport theory models edge intrinsic rotation.

$$\partial_t f_i + v_\parallel \partial_\theta f_i - \delta v_\parallel^2 (\sin\theta)\, \partial_x f_i - \partial_x \left[\chi(x,\theta)\, \partial_x f_i\right] = 0$$

Extremely simple kinetic transport model contains only:



- Free flow along the magnetic field
- Radially-directed curvature drift
- Radial diffusion due to turbulence
  - Diffusivity stronger outboard, decays in x
- Two-region geometry
  - Confined edge: periodic in θ
  - SOL: pure outflow to divertor legs



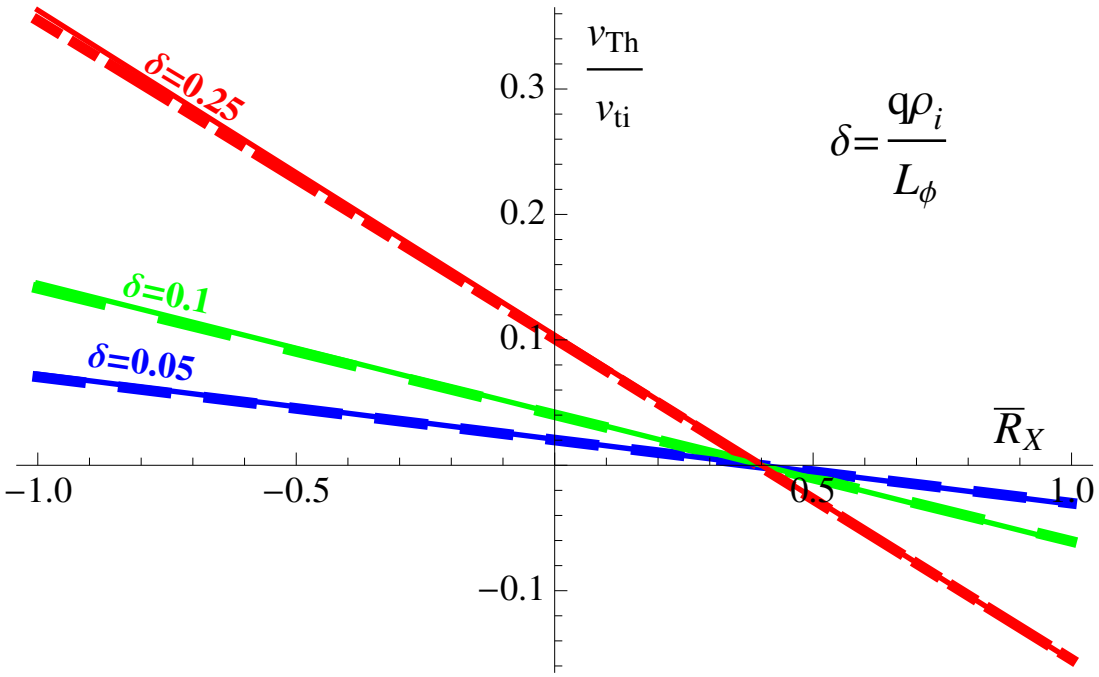
After some variable transforms, obtain steady-state equation

$$\partial_{\bar\theta} f_i = \chi_{\text{eff}}\left(v_\parallel\right) \partial_{\bar x}\left(e^{-\bar x} \partial_{\bar x} f_i\right),$$

in which χ_{eff} depends *on the sign* of $v_\parallel$.

Vanishing momentum flux sets intrinsic rotation at boundary with core.

$$0 = \int_{-\infty}^{\infty} \left(v_{\mathrm{Th}} + v_{\|}\right) \Gamma\left(v_{\|}\right) dv_{\|} = v_{\mathrm{Th}} \Gamma^{p} + \Pi$$



$$v_{\mathrm{Th}} = -\frac{\Pi}{\Gamma^{p}} v_{ti} \approx 1.04 \left(\frac{1}{2} d_c - \bar{R}_X\right) \frac{q\rho_i}{L_\phi} v_{ti} \propto \frac{T_i}{B_\theta L_\phi}$$

Reproduces known results: $\propto T_i$, $\propto 1/B_\theta \propto 1/I_p$, typically co-current

Predicts linear dependence on $\bar{R}_X \doteq (R_X - R_{\mathrm{mid}})/a \Rightarrow$can change sign!

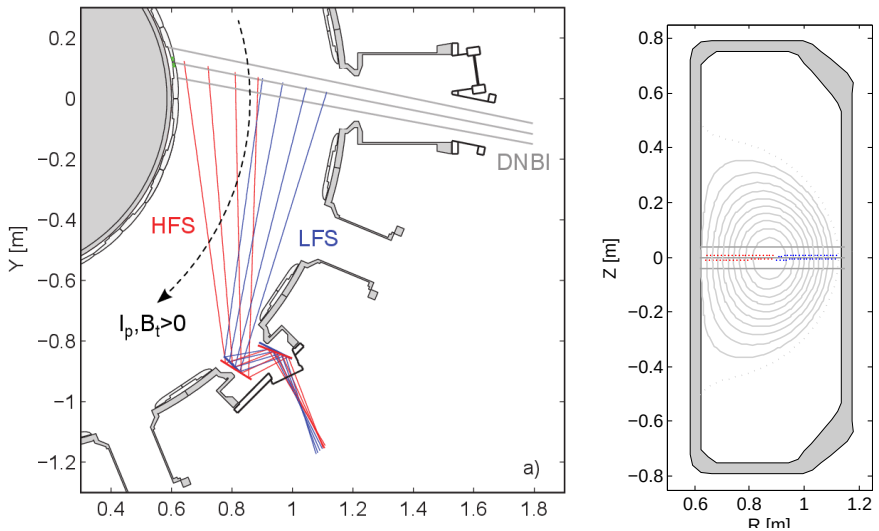
TCV is well-suited to investigate R_X-dependent edge rotation.

Extreme geometric flexibility:

- Vary R_X from inner to outer wall
- Both LSN and USN

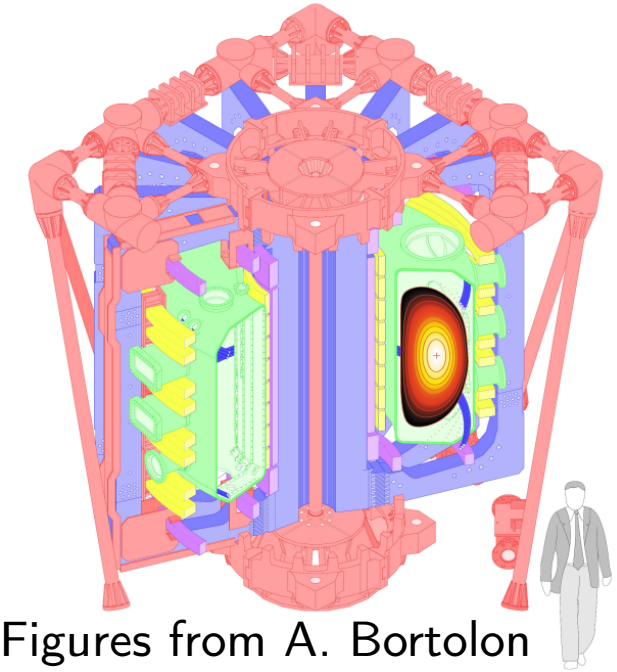
Diagnostic NBI for CXRS on C^{6+}:

- applies negligible torque ($\sim 1\% \tau_{\text{int}}$)
- LFS & HFS viewing chords



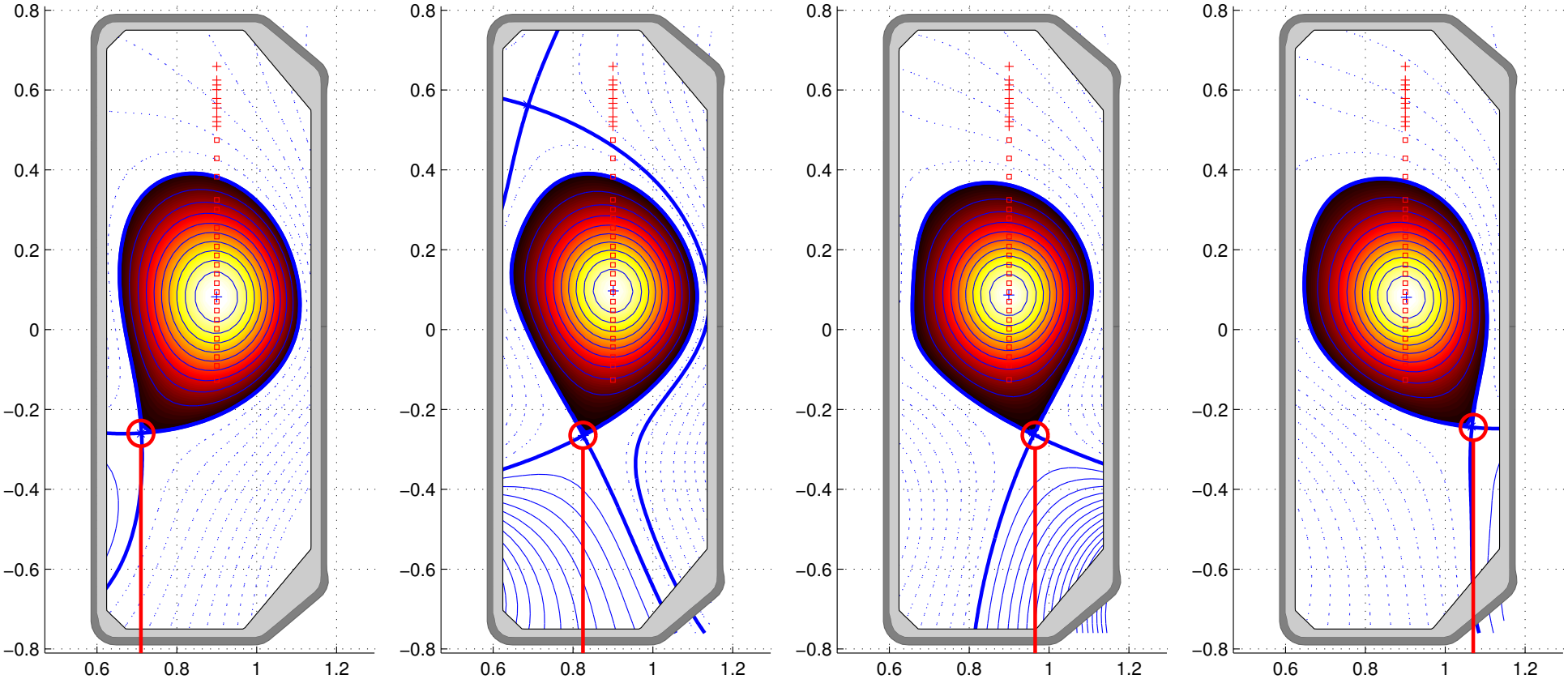
Parameter ranges for this experiment:

X-point major radius (R_X)	0.675–1.085m
Major radius (R_0)	0.88–0.89m
Minor radius (a)	0.22–0.23m
Edge safety factor (q_{eng})	3.6–4
Plasma current (I_p)	150–155kA
Electron density ($n_{e,\text{avg}}$)	$1.4–2.2 \times 10^{19} \text{m}^{-3}$
Elongation (κ)	1.35–1.45
Triangularity	-0.3 – +0.4



Figures from A. Bortolon

Discharges with R_X from inner to outer wall, USN and LSN.



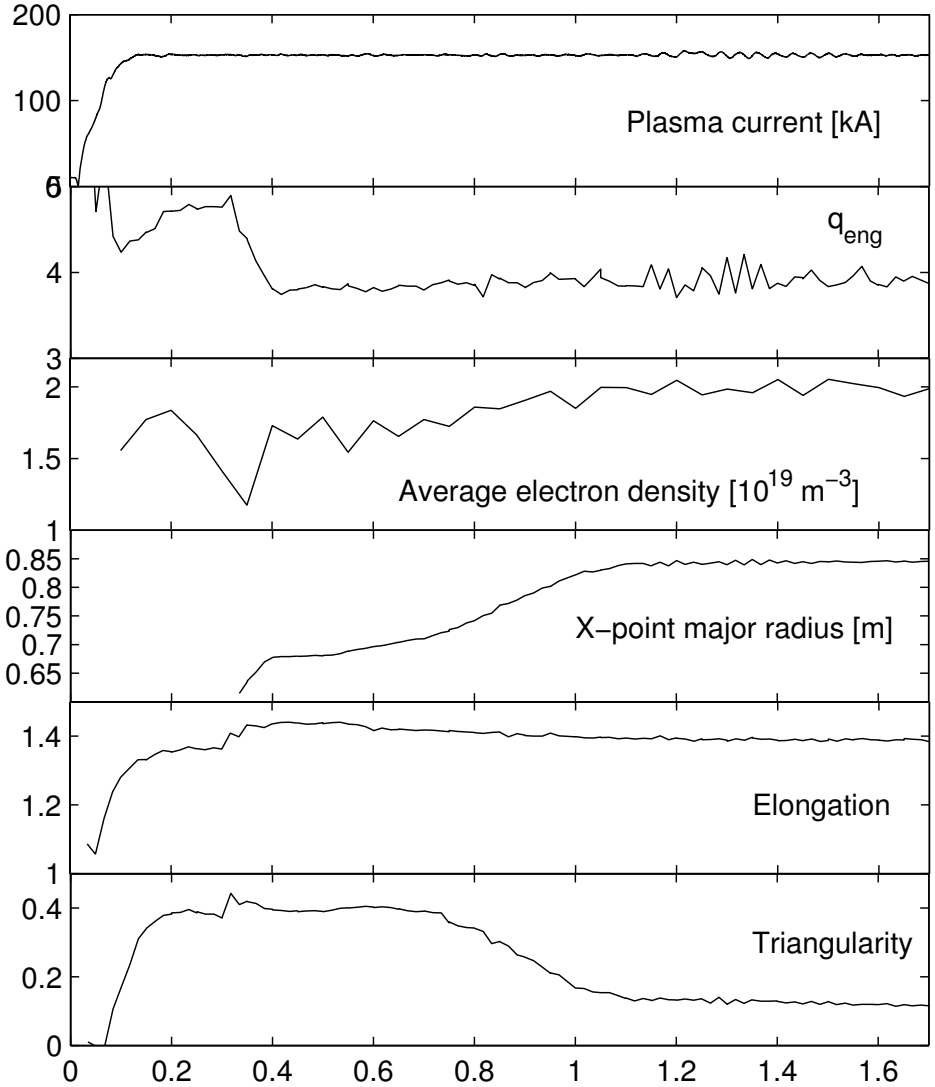
$R_X = 71\text{cm}$, $\bar{R}_X = -0.75$,

$R_X = 83\text{cm}$, $\bar{R}_X = -0.21$,

$R_X = 96\text{cm}$, $\bar{R}_X = +0.35$,

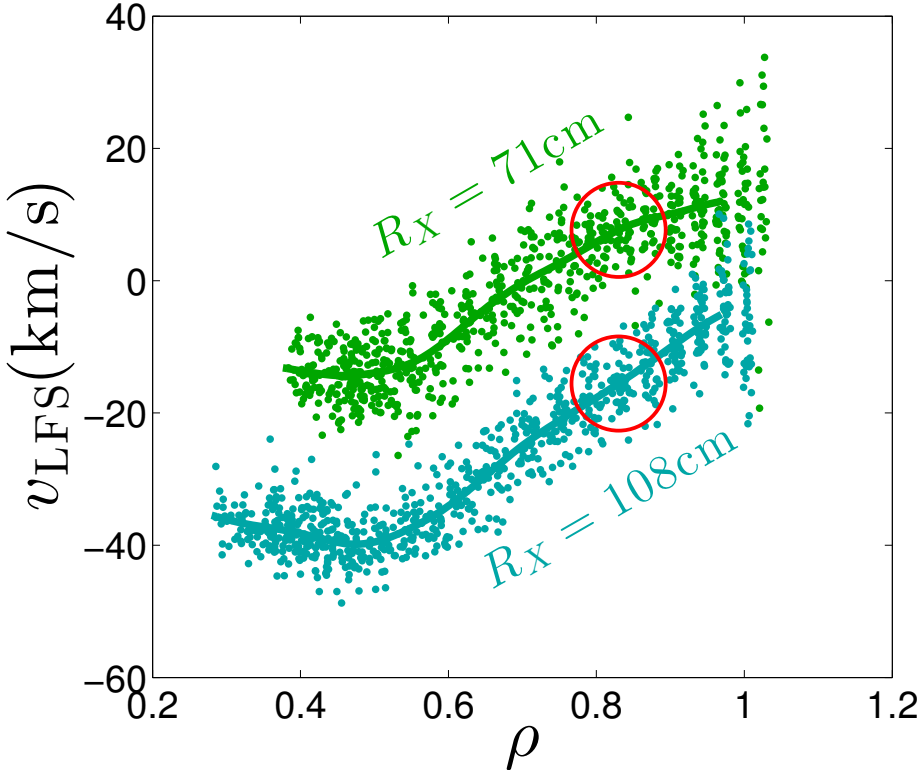
$R_X = 107\text{cm}$ $\bar{R}_X = +0.83$

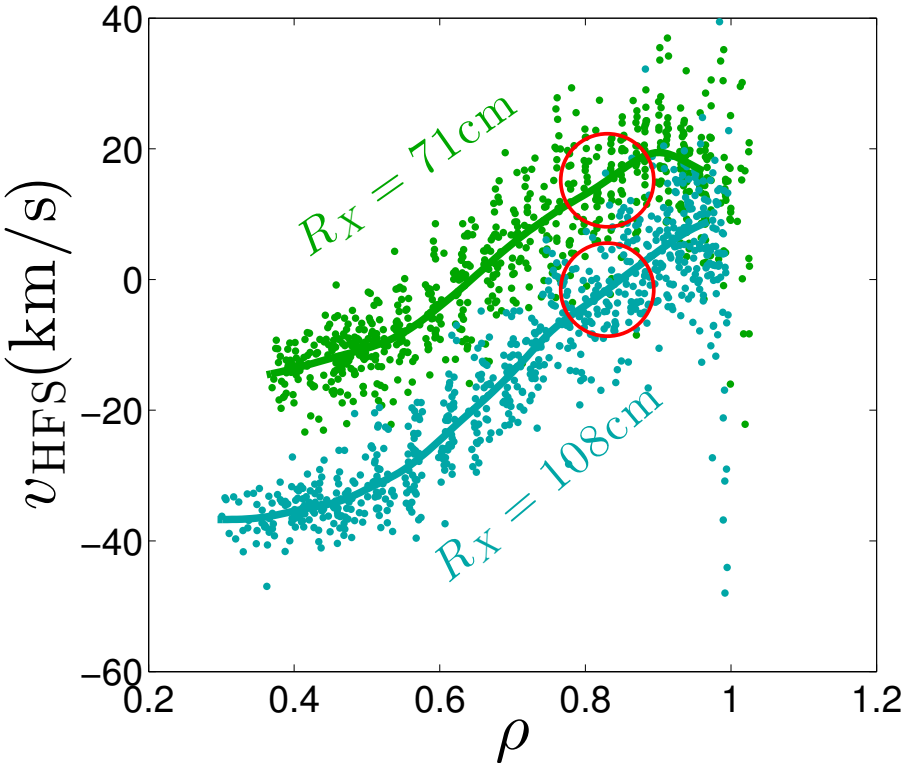
Example discharge with X-point position sweep



- All shots Ohmic L-modes
- Included static and swept R_X
  - Data taken in both swept & stationary phases
- pulsed DNBI (20ms on/40 off)
  - integration time short compared to profile evolution
  - measurements for $t \geq 0.4$s
- $n_{e,\mathrm{avg}}$, I_p are feedback-controlled

Changing $\bar{R}_X$ indeed shifts the boundary rotation, shifting the whole rotation profile with it.





Changing $\bar{R}_X$ shifts the boundary rotation value, ∼rigidly shifting the entire rotation profile with it.

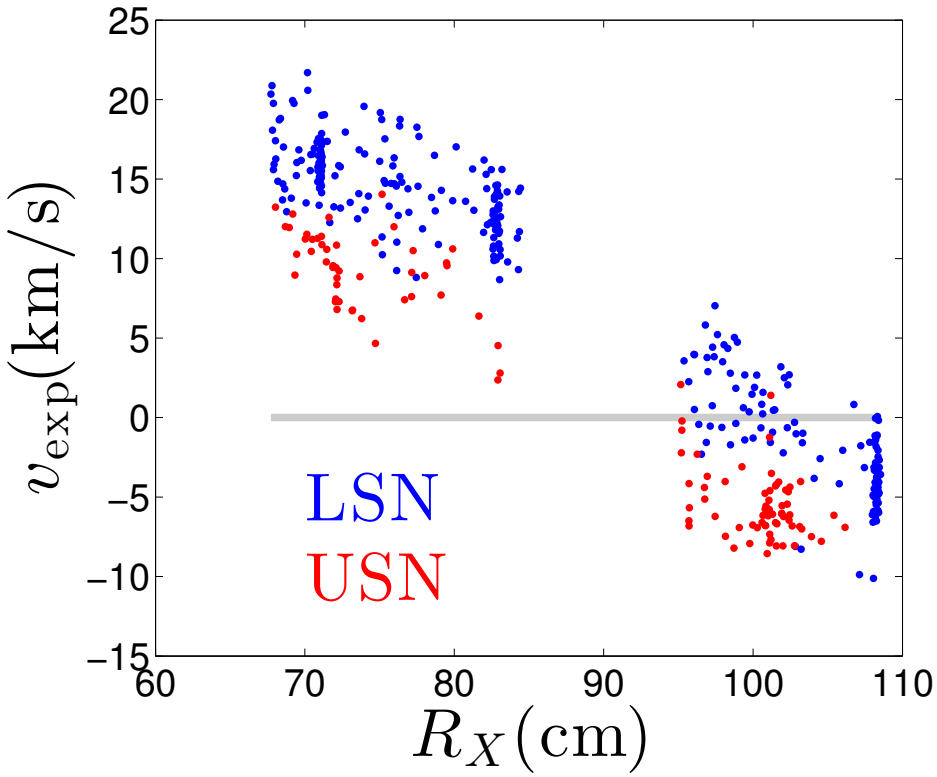
Experimentally measured edge rotation was compared with theoretical predictions.

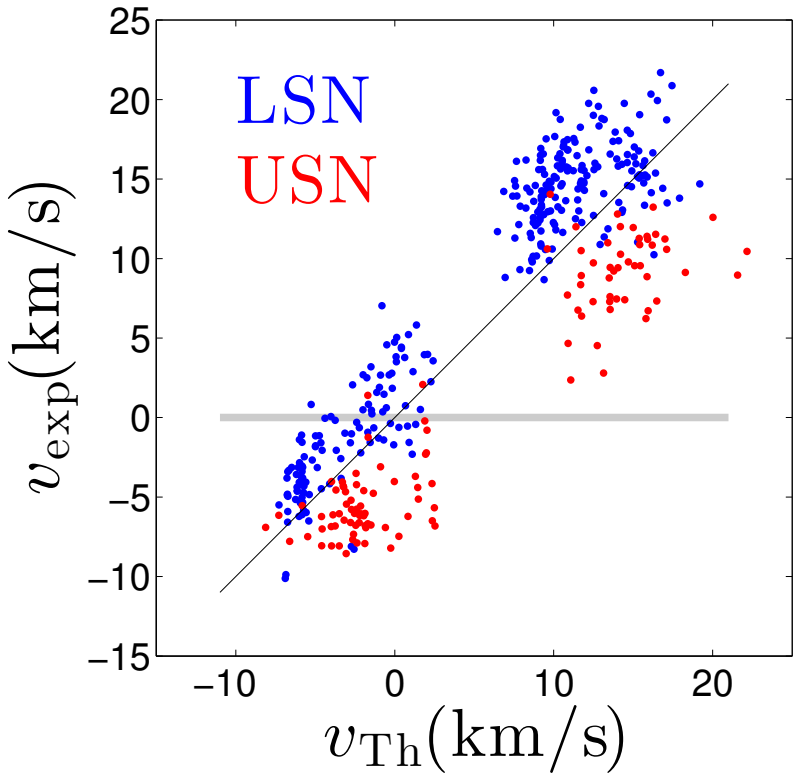
$$v_{\mathrm{Th}} = .104\left(0.5 d_c - \bar{R}_X\right)\frac{q}{L_\phi(\mathrm{cm})}\frac{T_i(\mathrm{eV})}{B_T(\mathrm{T})}\mathrm{km/s}$$

$$v_{\mathrm{exp}} = \frac{1}{2}\left[v_{\phi,\mathrm{LFS}} + v_{\phi,\mathrm{HFS}}\right] + \Delta_{\mathrm{C}\to\mathrm{D}}$$

- $D \propto (1 + d_c \cos\theta)$
  - d_c taken constant
- $\bar{R}_X \doteq (R_X - R_{\mathrm{mid}})/a$
- $q \to q_{\mathrm{eng}} \propto a^2 \kappa B_T / R_0 I_p$
- L_ϕ: length scale for radial decay of turbulent fluctuations $\langle\tilde{\phi}^2\rangle^{1/2}$
  - taken constant
- T_i, v_ϕ: measurements at $\rho_{\mathrm{pol}} = 0.83$
- $\Delta_{C\to D} \approx v_{\phi D} - v_{\phi C} \approx 5\mathrm{km/s}$
  - evaluated with NEOART
  - varies little with radius or X-point position
- For comparison, filtered out:
  - strong MHD
  - wall gaps < 7mm
  - large CXRS-estimated error, both raw data and fitted profiles

Theory-Experiment agreement is surprisingly good.





Roughly linear dep of v_{exp} on R_X.

- Sign change for large R_X.

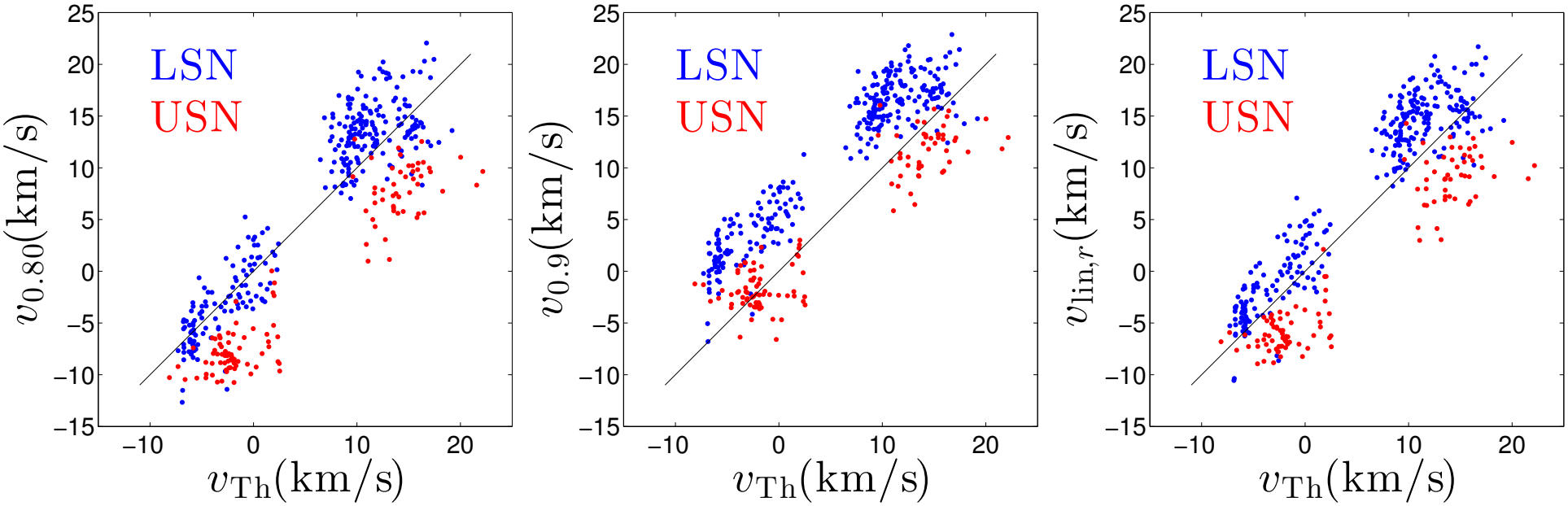
USN$\sim$ 5km/s more counter-current than LSN.

Simple formula v_{Th} matches v_{exp} well.

- Reasonable fitting parameters: $d_c \approx 0.93$, $L_\phi \approx 4.2$cm

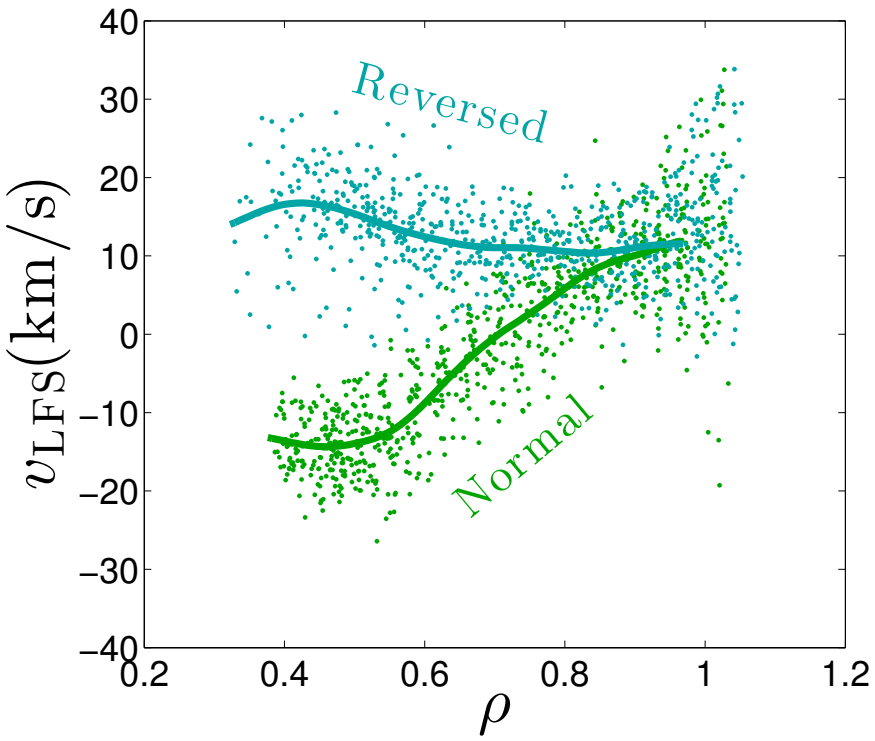
Some mid-range R_X inaccessible due to machine constraints

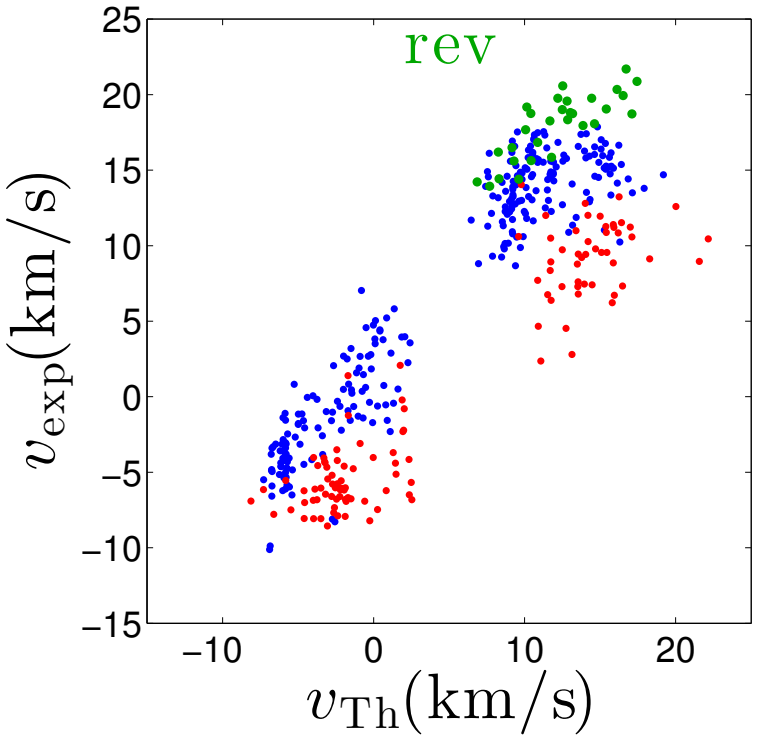
The basic trend holds for alternate edge velocities.



Core rotation reversal seems to have little effect on edge rotation.

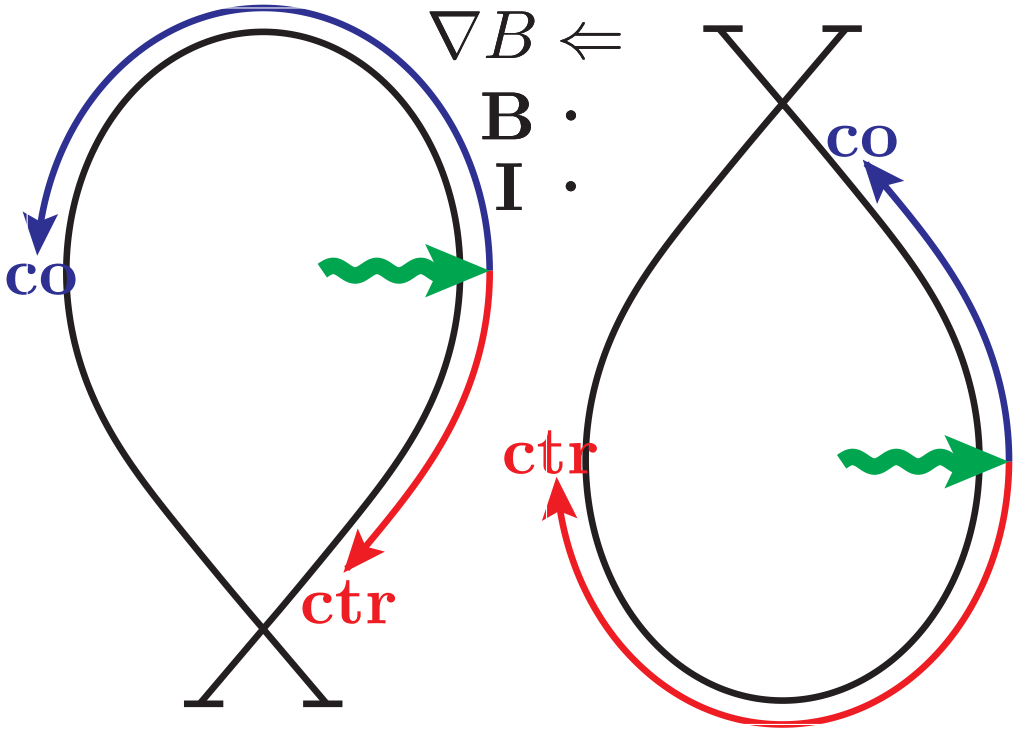
Spontaneous core rotation reversal well-known on TCV (Bortolon et al PRL 2006)
Accidentally triggered reversal in shots 48152–48153, due to larger I_p

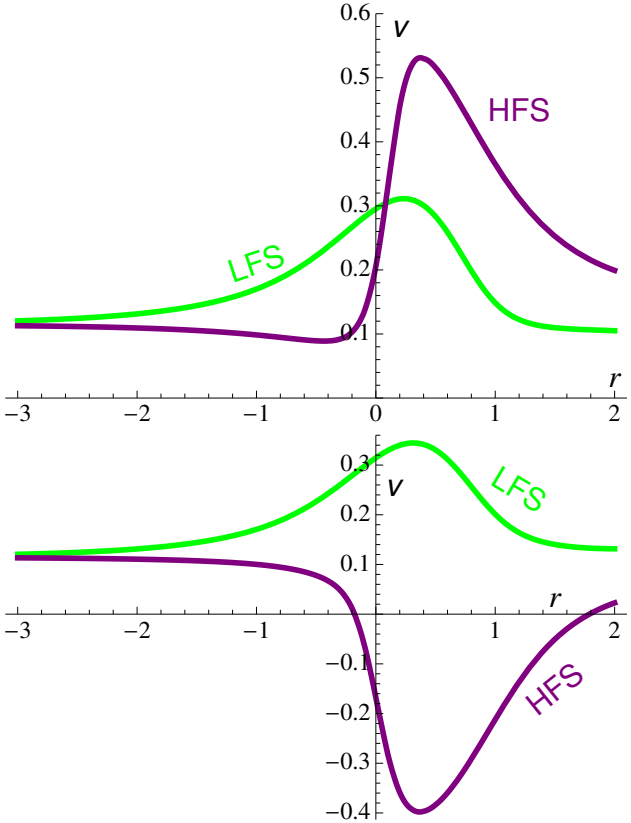




Can transport-driven SOL flows drive rotation in the confined plasma?

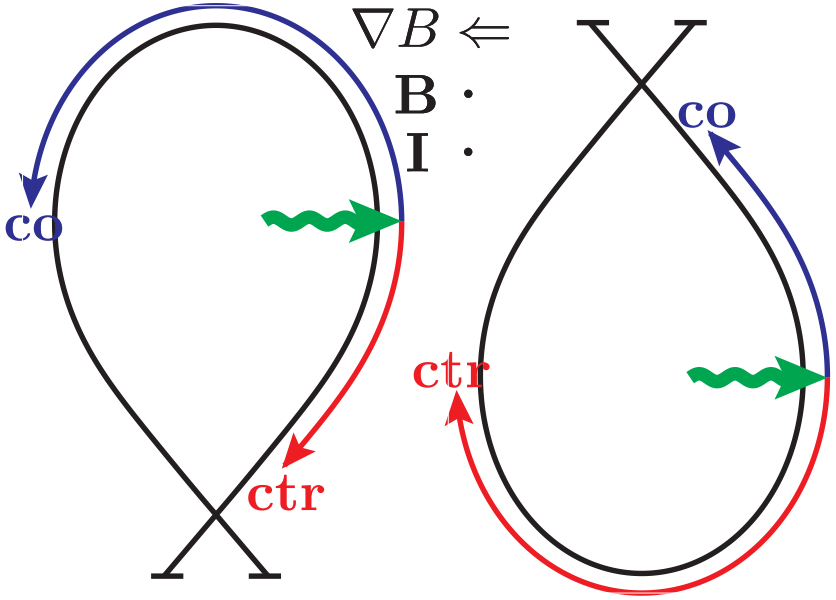
Intrinsic rotation velocity is determined by vanishing momentum flux. Although transport-driven toroidally-asymmetric flows exist in the theoretical calculation, they do not drive rotation at the boundary with the core plasma.

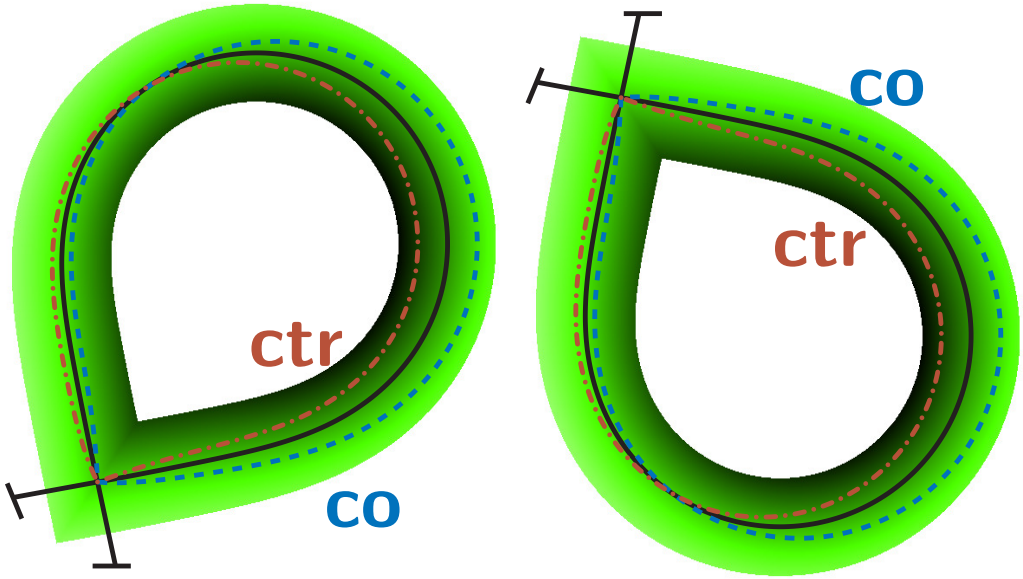


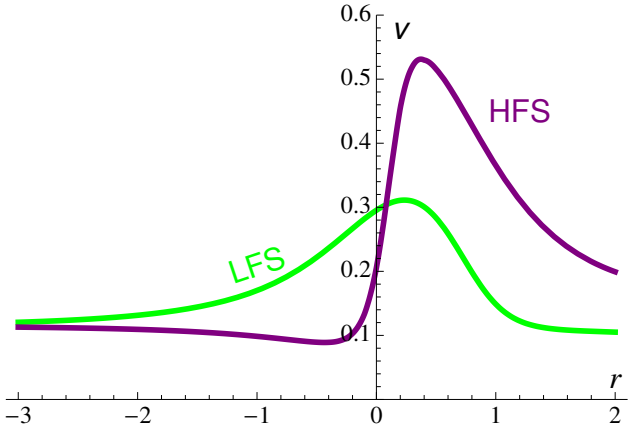


Favorable/unfavorable ∇B comparison can clarify physics.

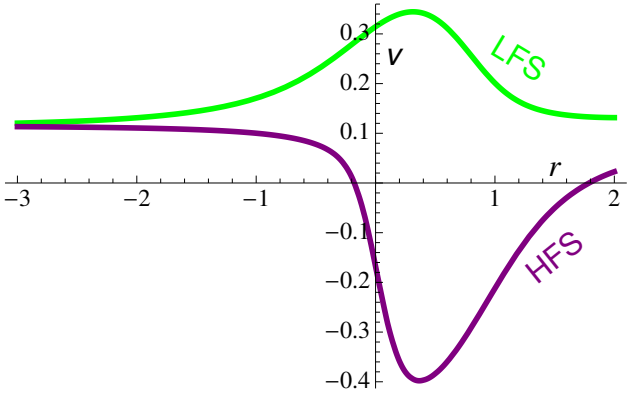
Reverses transport-driven flows but not orbit shifts and their flows.





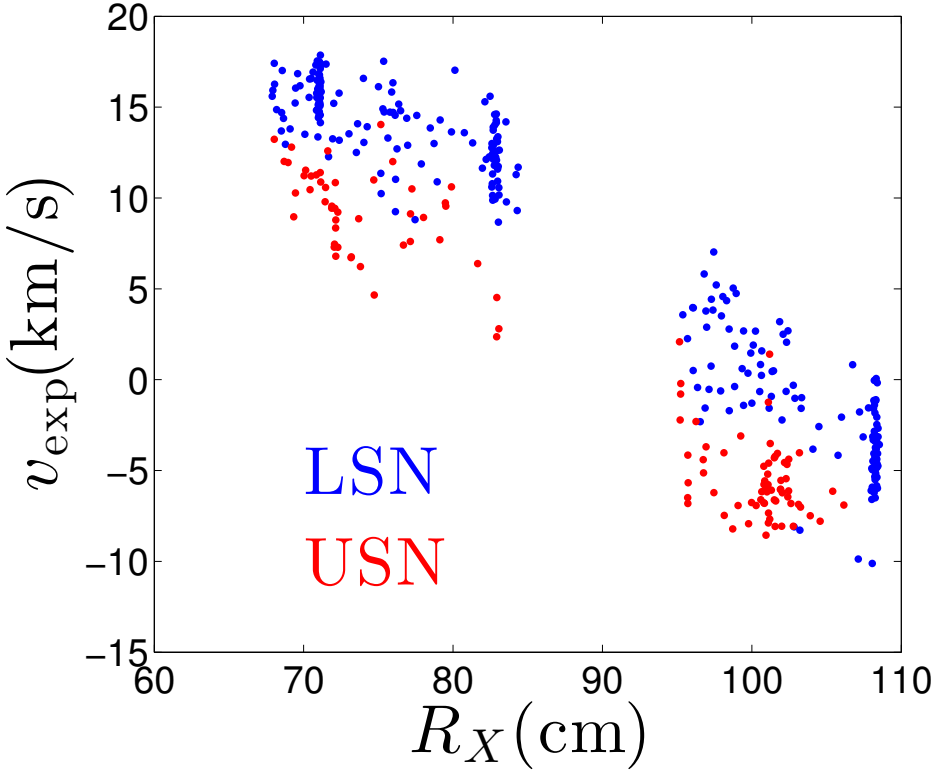


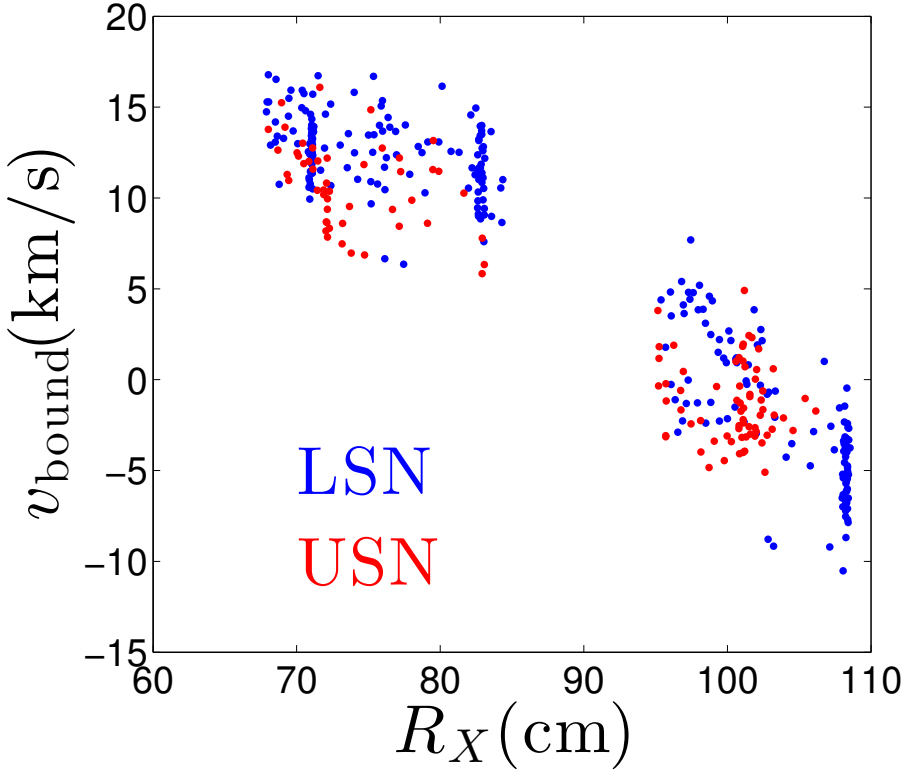
SND:



:SNU

Rotation data consistent with dominant drive by orbit shifts.





Dominant variation of rotation unaffected by LSN→USN.

Apparent $\sim$ 5km/s counter-I_p shift for USN shots may be an artifact due to:

- Core rotation reversal shots, were SND only
- Differing positions of the core-edge boundary, in presence of core counter-current peaking

Topic for future comparison with XGC simulations and DIII-D measurements.

Summary

- Simple theory for intrinsic rotation due to interaction of:
  - spatial variation of turbulence
  - different radial orbit excursions for co- and counter-current passing ions
- Predicted rotation depends strongly on R_X
- Performed series of Ohmic L-mode shots on TCV, scanning R_X
  - Change of R_X shifts entire rotation profile, fairly rigidly
- Experiment and theory appear fairly consistent
  - v_{exp} depends about linearly on R_X.
  - v_{exp} goes counter-current for large R_X.
  - Simple v_{Th} formula seems to capture most variation of v_{exp}.
  - Basic results hold for various alternate experimental v.
  - v_{exp} appears fairly insensitive to core rotation reversal.
- USN rotation shows modest counter-current shift, compared to LSN.