R_X-Dependent Toroidal Rotation in the Edge of TCV

T. Stoltzfus-Dueck
Princeton University

A. Karpushov
O. Sauter
École Polytechnique Fédérale de Lausanne

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Outline

Background:

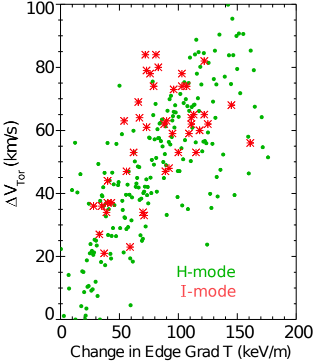
- Experimentally observed features of edge intrinsic rotation
  - "Edge" means pedestal-top out through SOL
- Theory: rotation due to drift orbits and turbulent diffusion
  - resulting formula for the edge rotation depends on R_X

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

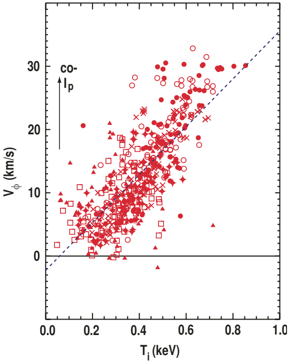
- Linear dependence of "pedestal-top" v_ϕ on R_X (✓)
- Rotation sign change for adequately outboard X-point (✓)
- Reasonable agreement between predicted and measured v_ϕ
  - USN edge rotation was about 5 km/s more counter than LSN

Please ask questions!

H-mode plasmas rotate without external torque, pedestal-top velocity appears proportional to temperature.



Rice et al PRL 2011, Fig. 5b



deGrassie et al NF 2009, Fig. 7

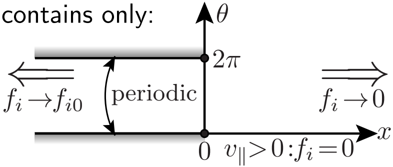
- Co-current, especially in the edge.
- $v_\phi/v_{\rm ti} \sim O(10^{\rm ths})$ at the pedestal top.
- Edge rotation proportional to T or ∇T?
- Spin-up at L–H transition.
- Roughly proportional to W/I_p.

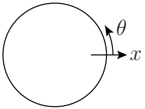
A simple kinetic transport theory predicts edge intrinsic rotation.

$$\partial_t f_i + v_\parallel \partial_\theta f_i - \delta v_\parallel^2 \partial_r f_i - \partial_r \left[D\left(r,\theta\right) \partial_r f_i \right] = 0$$

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 r
- Two-region geometry
  - Confined edge: periodic in θ
  - SOL: pure outflow to divertor legs



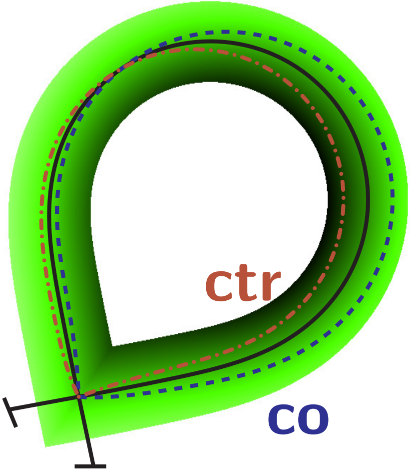


After some variable transforms, obtain steady-state equation

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

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

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



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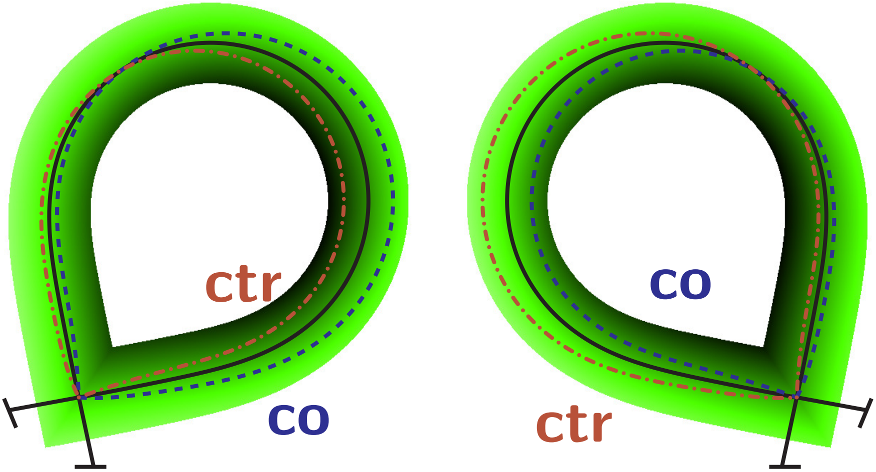

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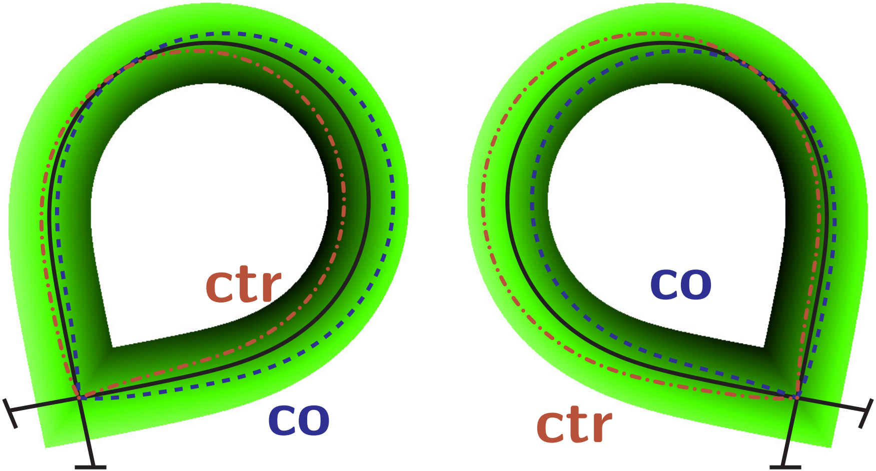
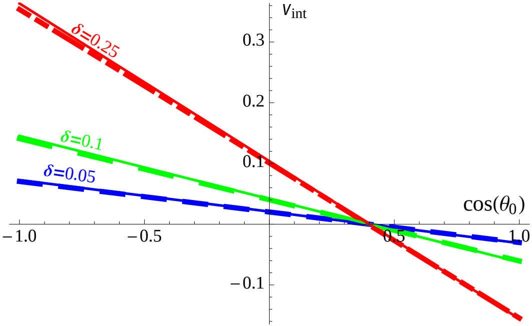


Edge rotation may become counter-current for outboard X-point!

Vanishing momentum transport sets pedestal-top intrinsic rotation.

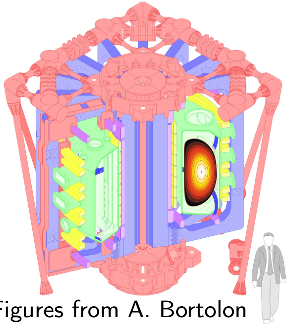
$$0 = \int_{-\infty}^{\infty} \left(v_{\rm int} + v_{\|}\right) \Gamma\left(v_{\|}\right) dv_{\|} = v_{\rm int}\Gamma^p + \Pi$$

$$v_{\rm int}^{\rm dim} = -\frac{\Pi}{\Gamma^p} v_{\rm ti}\big|_{\rm pt} \approx 1.04\left(\frac{1}{2}d_c - \cos\theta_0\right)\frac{q\rho_i|_{\rm pt}}{L_\phi} v_{\rm ti}\big|_{\rm pt} \propto \frac{T_i|_{\rm pt}}{B_\theta L_\phi}$$



- $D = D_0(1 + d_c \cos\theta)$
- $1/B_\theta \Rightarrow 1/I_p$
- X-point angle dependence
- Co-current for realistic parameters
- Rotation magnitude $O(v_{\rm ti}/10)$
- L-H spin-up due to $\Uparrow T_i|_{\rm pt}$, $\Downarrow L_\phi$

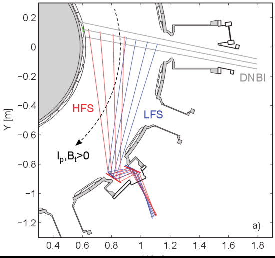
TCV is well-suited to investigate R_X-dependent edge rotation.

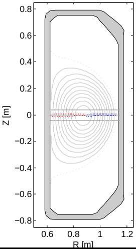


Figures from A. Bortolon

Parameter ranges for this experiment:

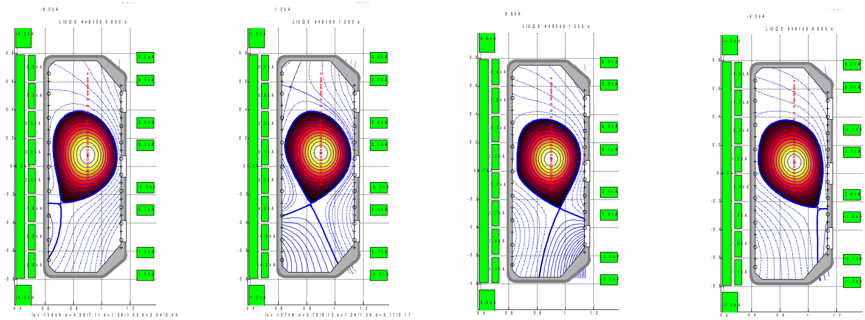
X-point major radius (R_X)	0.675–1.085m
Major radius (R_0)	0.88–0.89m
Minor radius (a)	0.22–0.23m
Edge safety factor (q_{eng})	3.6–4
Plasma current (I_p)	150–155kA
Electron density ($n_{e,\mathrm{avg}}$)	$1.4\text{–}2.2\times10^{19}\mathrm{m}^{-3}$
Elongation (κ)	1.35–1.45
Triangularity	-0.3 – +0.4





- Extreme geometric flexibility
- $n_{e,\mathrm{avg}}$ and I_p are feedback-controlled
- CXRS from carbon impurity
- DNBI torque negligible ($\sim1\%\tau_{\mathrm{int}}$)
- LFS & HFS toroidal viewing chords

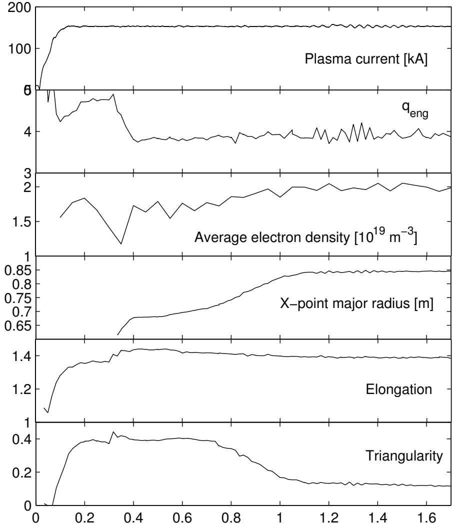
Theory-Expt Comparison: X-point scan of Ohmic L-modes.



$$v_{\text{int}} \approx .104\,(0.5d_c - \cos\theta_0)\,\frac{q}{L_\phi(\text{cm})}\,\frac{T_i|_{\text{pt}}(\text{eV})}{B_T(\text{T})}\,\text{km/s} \Leftrightarrow v_{\text{exp}} = \frac{1}{2}\left[v_{90,\text{LFS}} + v_{90,\text{HFS}}\right]$$

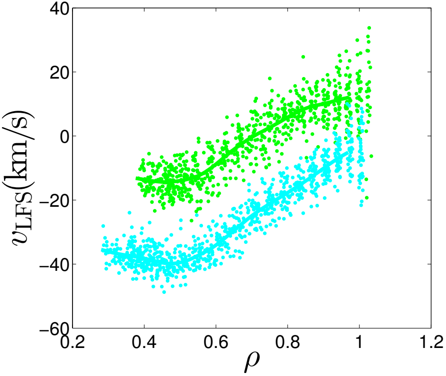
- Radial turb decay: $L_\phi \approx 1.0\,L_{Te}$
- In-out turb asymmetry: $d_c \approx 0.79$
- $\cos\theta_0 \doteq [2R_X - (R_{\text{out}} + R_{\text{in}})]/(R_{\text{out}} - R_{\text{in}})$
- $T_i|_{\text{pt}} = T_i(\rho = 0.9)$
- $v_{90} = v(\rho = 0.9)$ (km/s)
- both LSN & USN scanned

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)

Profiles with LFS and HFS X-points are similar, but shifted.



Comparison of raw and fitted velocity profile data for shots 48158 ($R_X \approx 71$cm, green) and 48407 ($R_X \approx 108.3$cm)

Theory-Experiment agreement is surprisingly good.

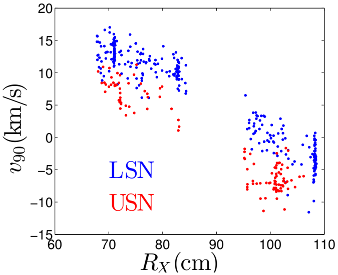
Roughly linear dep of v_{90} on R_X.

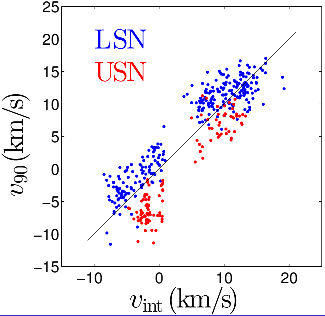
- Sign change for large R_X.

Simple formula for $v_{\rm int}$ matches v_{90} well.

- Reasonable fitting parameters:
  $d_c \approx 0.79,\ L_\phi / L_{Te} \approx 1.0$

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





Recall:

$v_{\rm int} \doteq .104\,(d_c/2 - \cos\theta_0)\,\frac{q}{L_\phi(\rm cm)}\,\frac{T_i|_{\rm pt}(\rm eV)}{B_T(\rm T)}\,\rm km/s$

v_{90}: LFS/HFS-averaged cubic spline fit

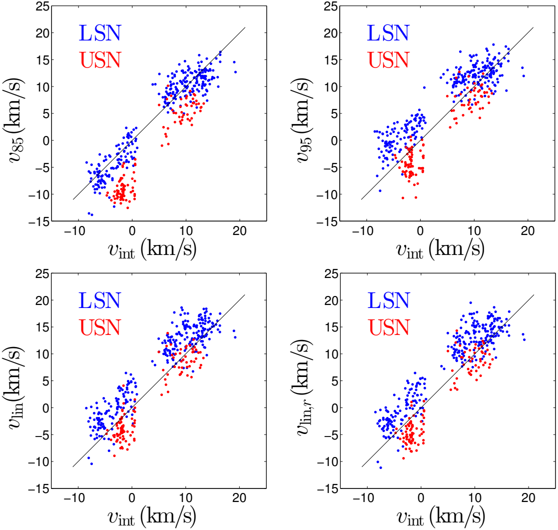
$\cos\theta_0 \doteq [2R_X - (R_{\rm out} + R_{\rm in})]/(R_{\rm out} - R_{\rm in})$

The basic trend holds for alternate edge velocities.

LFS/HFS-avgd v vs v_{int} for:

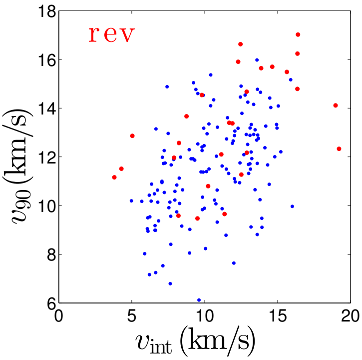
Cubic spline-fitted profiles:
UL: $v_{85} = v(\rho = 0.85)$
UR: $v_{95} = v(\rho = 0.95)$

Linearly-fitted profiles, $v_0 + 0.9v'$, using raw data from $0.6 \leq \rho \leq 0.9$:
DL: v_{lin}: points weighted with σ^{-2}
DR: $v_{\text{lin},r}$: "robust fit" routine



Core rotation reversal has 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



v_{90}(km/s) versus $v_{\rm int}$(km/s), core reversal in red.
(Only LSN/HFS plotted, since ∼no core rotation reversals in other quadrants.)

Summary

- Simple theory for intrinsic rotation due to interaction of:
  - spatial variation of turbulence
  - passing-ion radial orbit excursions
- Predicted rotation depends strongly on R_X
- Performed series of Ohmic L-modes on TCV, scanning R_X
- Experiment and theory appear fairly consistent
  - v_ϕ depends about linearly on R_X.
  - v_ϕ goes counter-current for large R_X.
  - Simple v_{int} formula seems to capture most variation of v_{90}.
  - Basic results hold for various choices for experimental v.
  - Edge v_ϕ appears insensitive to core rotation reversal.
- USN rotation shows modest counter-current shift, compared to LSN.

Comments/Questions?

Some edge parameters are important for intrinsic rotation.

Influence of SOL$\Longrightarrow$nonlocal, steep gradients, strong turbulence, very anisotropic

Lengths: $\frac{L_\perp}{a}, \frac{a}{qR} \ll 1,\ k_\parallel \sim \frac{1}{qR},\ \frac{k_\parallel}{k_\perp} \lesssim k_\parallel L_\perp \lll 1$

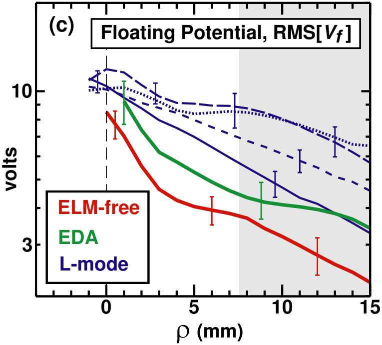
Rates: $\frac{D_{\mathrm{tur}}}{L_\perp^2} \sim \frac{v_{\mathrm{ti}}|_{\mathrm{sep}}}{qR} \lll \omega \sim \frac{v_{\mathrm{ti}}}{L_\perp}$

$D_{\mathrm{tur}} \sim \tilde{v}_{Er}^2 \tau_{\mathrm{ac}} \sim \tilde{v}_{Er}^2 / k_\perp \tilde{v}_{Er} \sim c\tilde{\phi}/B$
decreases in r near LCFS, on scale $L_\phi \sim L_\perp$

$\Delta v_\parallel|_{\mathrm{turb}} : \left(\frac{\Delta v_\parallel|_{\mathrm{turb}}}{v_{\mathrm{ti}}|_{\mathrm{pt}}}\right)^2 \sim \frac{k_\parallel}{k_\perp}\left(\frac{T_e}{T_i|_{\mathrm{pt}}} \frac{e\tilde{\phi}}{T_e} \frac{1}{k_\perp \rho_i|_{\mathrm{sep}}}\right) \ll 1$

Wide passing-ion orbits: $\delta \doteq \frac{q\rho_i|_{\mathrm{pt}}}{L_\phi} \sim O(1)$

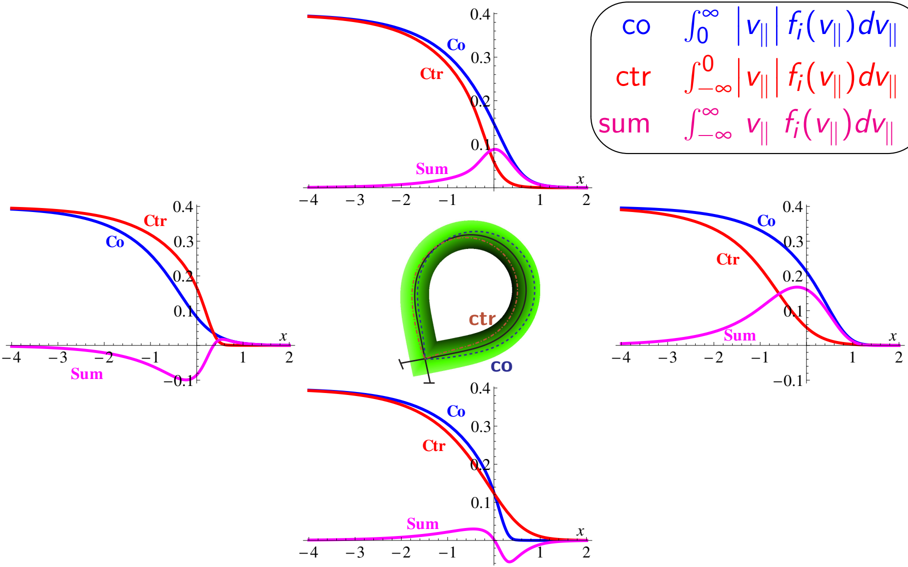
Absolute Fluctuation Levels



LaBombard et al NF 2005, Fig. 8.

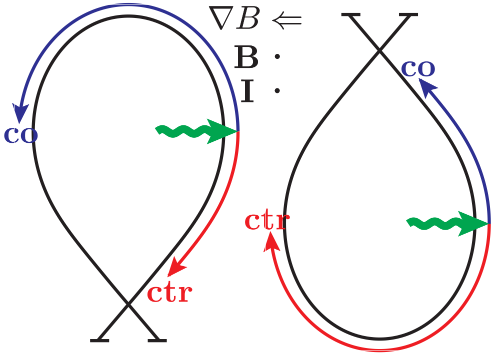
Profiles show interaction of transport with orbit shifts.

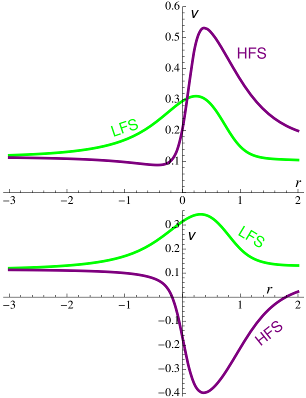
co	$\int_0^\infty \left\lvert v_\parallel \right\rvert f_i(v_\parallel) dv_\parallel$
ctr	$\int_{-\infty}^0 \left\lvert v_\parallel \right\rvert f_i(v_\parallel) dv_\parallel$
sum	$\int_{-\infty}^\infty v_\parallel \; f_i(v_\parallel) dv_\parallel$



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

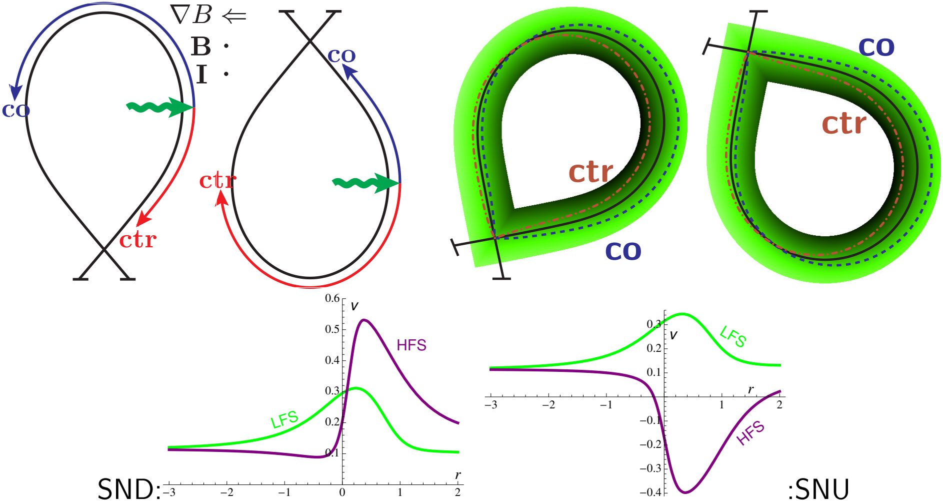
Although transport-driven toroidally-asymmetric flows exist in the theoretical calculation, they do not drive rotation at the boundary with the core plasma.



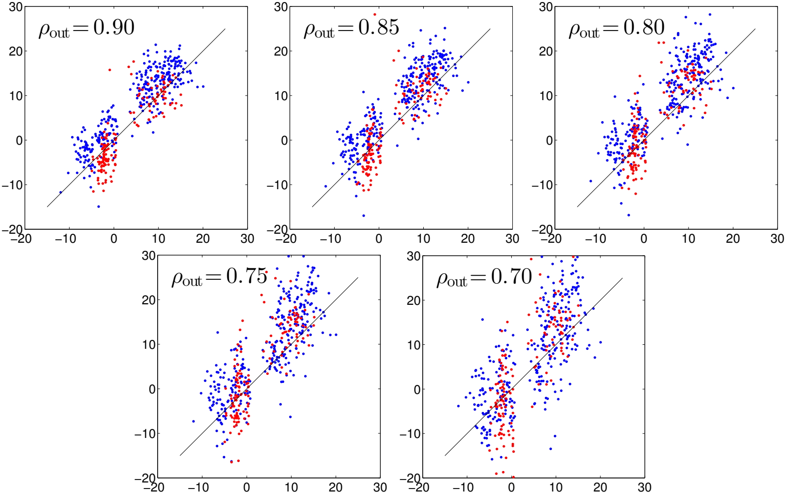


Favorable/unfavorable ∇B comparison can clarify physics.

Reverses transport-driven flows but not orbit-driven flows.

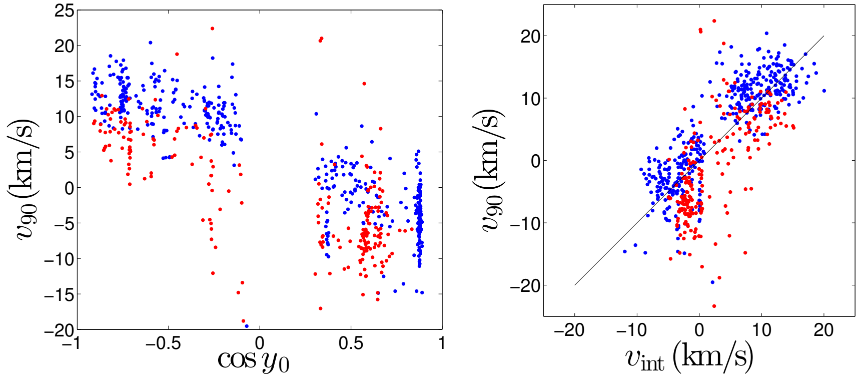


Some LSN/USN difference may be a simple edge layer.



v_{lin}(km/s) versus v_{int}(km/s) using CXRS raw data from $0.5 \leq \rho \leq \rho_{out}$ for ρ_{out} =0.90, 0.85, 0.80 (top, L to R) and 0.75, 0.70 (bottom L and R). $(\overline{v_{lin} - v_{int}}|_{SND} - \overline{v_{lin} - v_{int}}|_{SNU})$(km/s) is 4.15, 3.36, 2.78, 2.17, 1.87, respectively.

Even unfiltered results clearly show rotation reversal.



Almost all CXRS measurements plotted, but omitted:

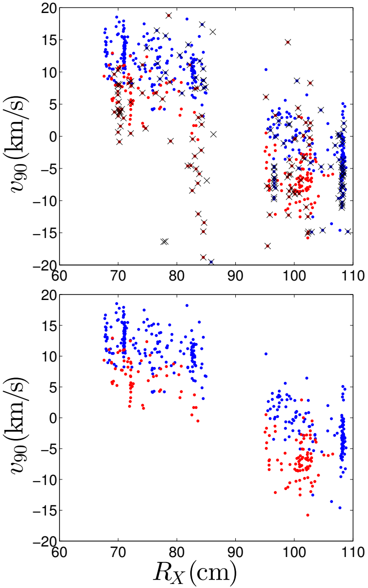
- Some limited periods
- The single reversed-B_T shot (49759)

Data filtering isolates the physics of interest.

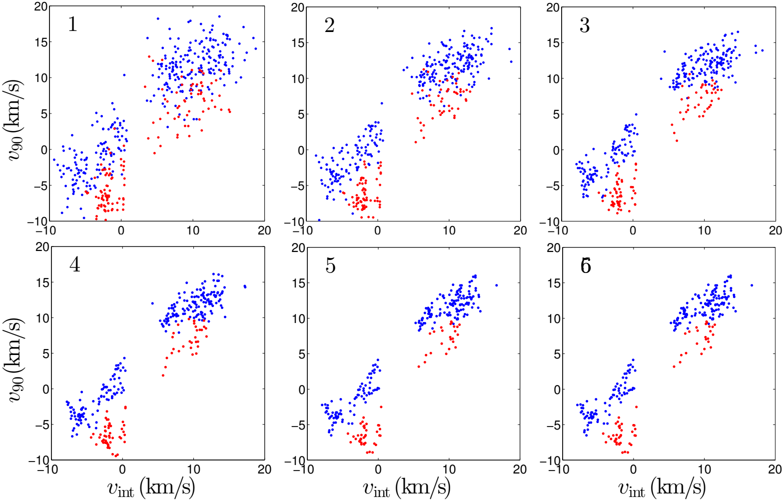
Filtered out:

- Reversed B_T (only one shot)
- Active MHD modes
  - Counter-current shift & scatter
- Small wall gaps (<7mm)
  - Change boundary condition
- Large self-reported CXRS error:
  - Raw: $v_{\mathrm{err}}^{L} \doteq N_p^{-1} \sum_{0.6 \le \rho \le 0.9}^{\mathrm{LFS}} \sigma_{\mathrm{CXRS}}^{\mathrm{raw}}$,
    $v_{\mathrm{err}}^{N} \doteq v_{\mathrm{err}}^{L} / \overline{v_{\mathrm{err}}^{L}} + v_{\mathrm{err}}^{H} / \overline{v_{\mathrm{err}}^{H}} > 3.1$
  - Fit:
    $v_{\mathrm{err}}^{f,L} \doteq N_p^{-1} \sum_{0.875 \le \rho \le 0.925}^{\mathrm{LFS}} \sigma_{\mathrm{CXRS}}^{\mathrm{fit}}$,
    $v_{\mathrm{err}}^{f} \doteq (v_{\mathrm{err}}^{f,L} + v_{\mathrm{err}}^{f,H})/2 > 9.9\mathrm{km/s}$

$\sigma_{\mathrm{filt}} \approx 4.39 \mathrm{km/s}, \quad \sigma_{\mathrm{unfilt}} \approx 6.30 \mathrm{km/s}$



Smoothing over 2–3 CXRS times reduces noise.



v_{90}(km/s) versus $v_{\rm int}$(km/s),smoothed over 1,2,3 (Top, L to R), or 4,5,6 (Bottom, L to R) CXRS times. 2 or 3 CXRS times may be optimal?

leading to a deceptively simple transport model,

$$\partial_t f_i + v_\parallel \partial_\theta f_i - \delta v_\parallel^2 (\sin\theta)\, \partial_r f_i - D(\theta)\, \partial_r \left(e^{-r} \partial_r f_i\right) = 0$$

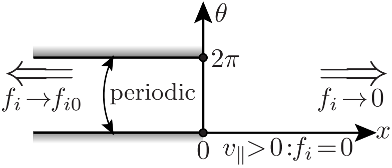
Gyrokinetic equation⇒average over turbulence⇒ $\frac{\rho_i}{L_\perp}, \frac{L_\perp}{a}, \frac{1}{q}, \frac{a}{R_0}, \frac{v_E}{v_{\mathrm{ti}} B_\theta / B_0} \ll 1$

- Turbulent $D \Longrightarrow$ purely diffusive turbulence, "null hypothesis"
  - arbitrary θ dependence, except $D(\theta) > 0$
  - exponentially decreasing radially
  - not necessarily order-unity
- No $\parallel$ acceleration of ions: allows $v_\parallel$-by-$v_\parallel$ solve
  - Collisionless: good for superthermal ions
  - No $\mu \nabla B$ force: passing-ion approximation
- Axisymmetric, radially-thin simple-circular geometry
- $\mathbf{E} \times \mathbf{B}$ flows below poloidal sound speed: $cE_r / B_\theta v_{\mathrm{ti}} \ll 1$

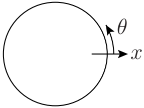
Normalizations: $v_\parallel$:$v_{\mathrm{ti}}|_{\mathrm{pt}}$, r:L_ϕ, t:$aB_0/B_\theta v_{\mathrm{ti}}|_{\mathrm{pt}}$, f_i:$n_i|_{\mathrm{pt}}/v_{\mathrm{ti}}|_{\mathrm{pt}}$, D:$L_\phi^2 B_\theta v_{\mathrm{ti}}|_{\mathrm{pt}}/aB_0$

which captures the radially-global nature of the problem.

$$\partial_t f_i + v_\parallel \partial_\theta f_i - \delta v_\parallel^2 (\sin\theta)\, \partial_r f_i - D(\theta)\, \partial_r \left(e^{-r} \partial_r f_i \right) = 0$$



- Solve for $f_i \sim F_0$
  - necessary since $v_\parallel / qR \sim D_{\mathrm{tur}} / L_\perp^2$
  - resulting f_i not symmetric in $v_\parallel$ or θ
- Pedestal-SOL formulation in boundary conditions
- Radial variation of turbulent diffusivity
- $\delta \doteq q\rho_i|_{\mathrm{pt}} / L_\phi$ a free parameter (may ≈ 1 in experiment)



- Invariant to rigid toroidal rotation v_{rig}
- Trivial conservation of a simplified toroidal momentum:

$$p_\phi \doteq \int dv_\parallel \left(v_\parallel + v_{\mathrm{rig}} \right) f_i$$

The mechanism is robust, but other terms likely matter too.

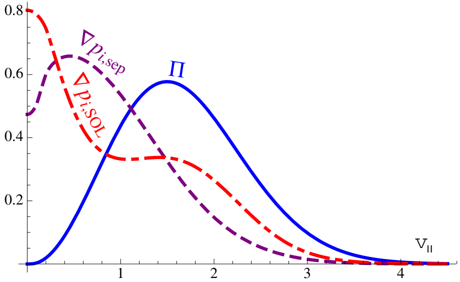
Recall the simplifying assumptions including:

- neglect of the $\mathbf{E} \times \mathbf{B}$ drift and its divergence,
- simple circular geometry,
- simplified, "deeply-passing" particle orbits,
- collisionless,
- purely-diffusive transport.

Relaxing these assumptions may:

- modify the given mechanism,
- contribute additional rotation drive terms.

Why should D_{tur} be proportional to $\tilde{\phi}$, instead of fitted χ_i?



Momentum flux from core dominated by higher-$V_{\parallel}$ ions:

- enter SOL mostly due to drift-orbit excursions
- relatively uncorrelated with blobs and other fluctuations

SOL profile gradients dominated by lower-$V_{\parallel}$ ions:

- enter SOL mostly due to transport
- highly correlated with blobs and other fluctuations