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Gaining insight into $E \times B$ flow control in tokamaks

S Rienäcker, P. Hennequin, R Varennes, C Honoré, J P Gunn

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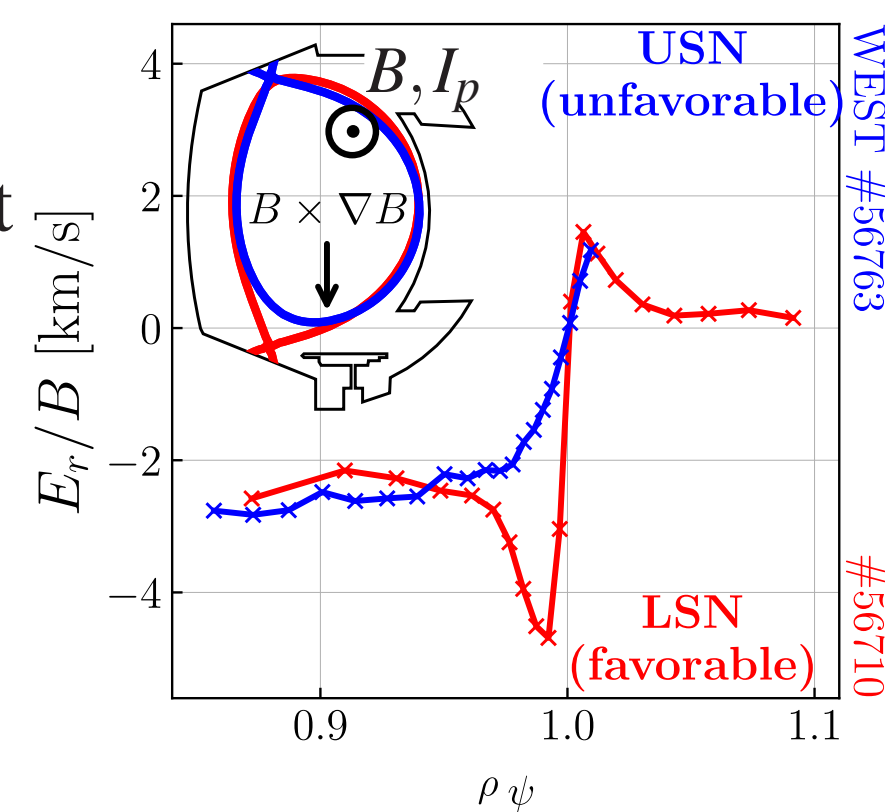
Motivations

- ▶ Sheared $E \times B$ flows: key players in turbulence regulation and confinement bifurcations.
- ▶ Tokamak plasmas generally exhibit an edge $E \times B$ shear layer, or radial electric field (E_r) “well”.

“Favorable” vs. “unfavorable” magnetic topology

Direction of ion ∇B drift (or $B \times \nabla B$) direction relative to X-point matters:

- ▶ Impact on L→H power threshold (lower when $B \times \nabla B$ towards X-point ⇒ “favorable”)
- ▶ Strong influence on edge E_r profile on WEST^[1], AUG^[2, 3]
- ▶ Underlying mechanism for this asymmetry unclear



Another parameter drawing attention: plasma current I_p

- ▶ Strong impact on the E_r well depth on WEST^[1] (Fig. 1)
- ▶ Sensitivity is more pronounced in USN (unfavorable $B \times \nabla B$) configuration
- ▶ Previously: similar observation on TORE SUPRA^[4], (Fig. 2)

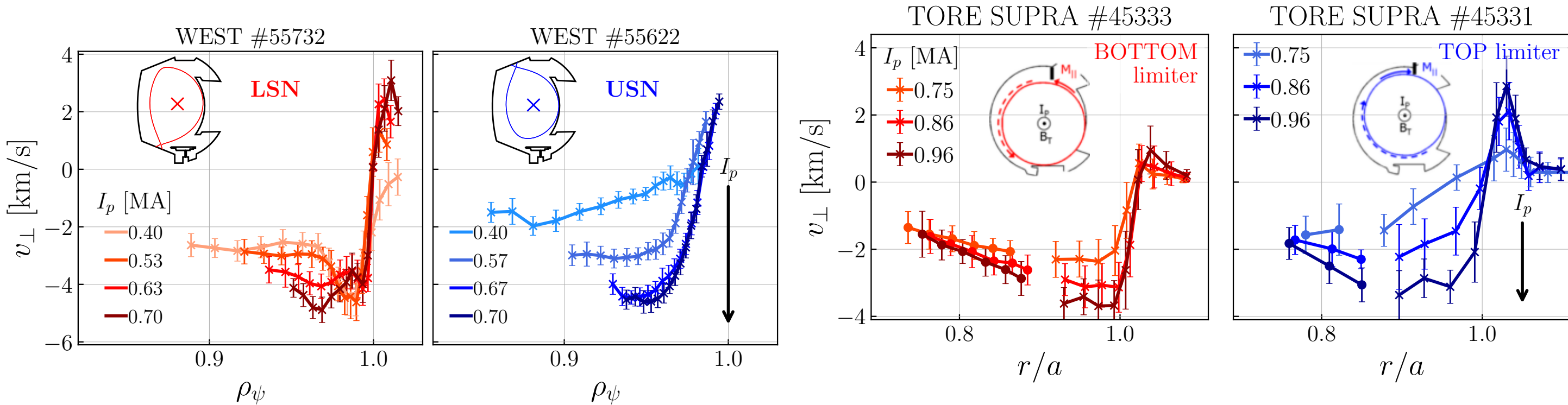


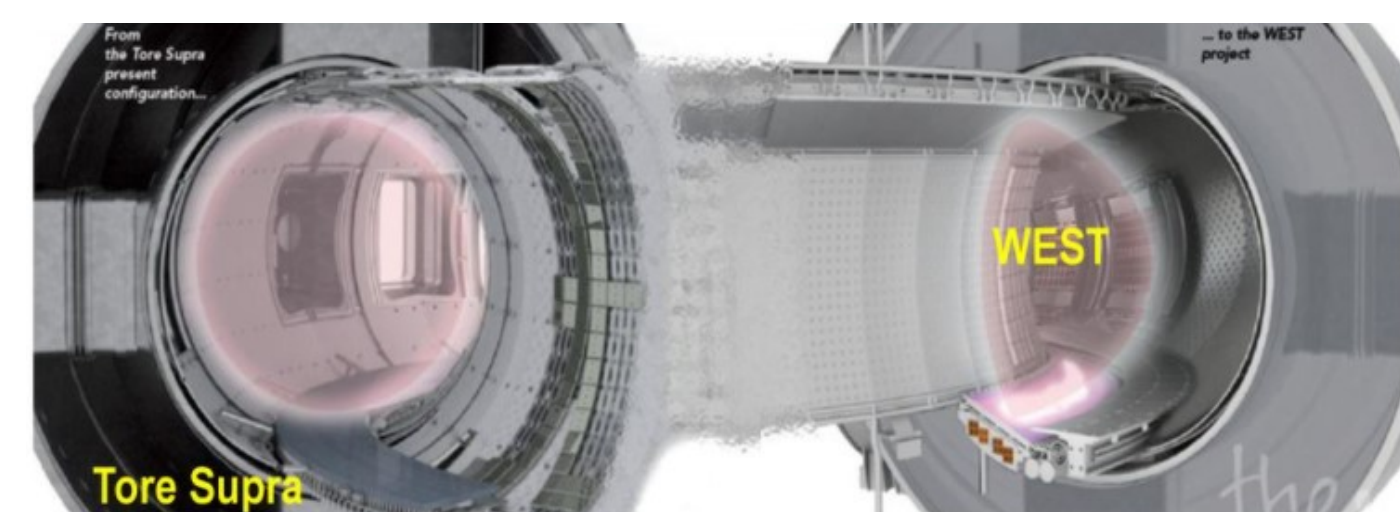
Figure 1: Current scan on WEST in LSN vs. USN. Figure 2: Current scan on TORE SUPRA using bottom vs. top limiter position.

Questions:

- ▶ What is the origin of the I_p sensitivity?
- ▶ Why is it different in the two configurations?
- ▶ How robust are the observations?

Experimental Setup

WEST tokamak (formerly TORE SUPRA)

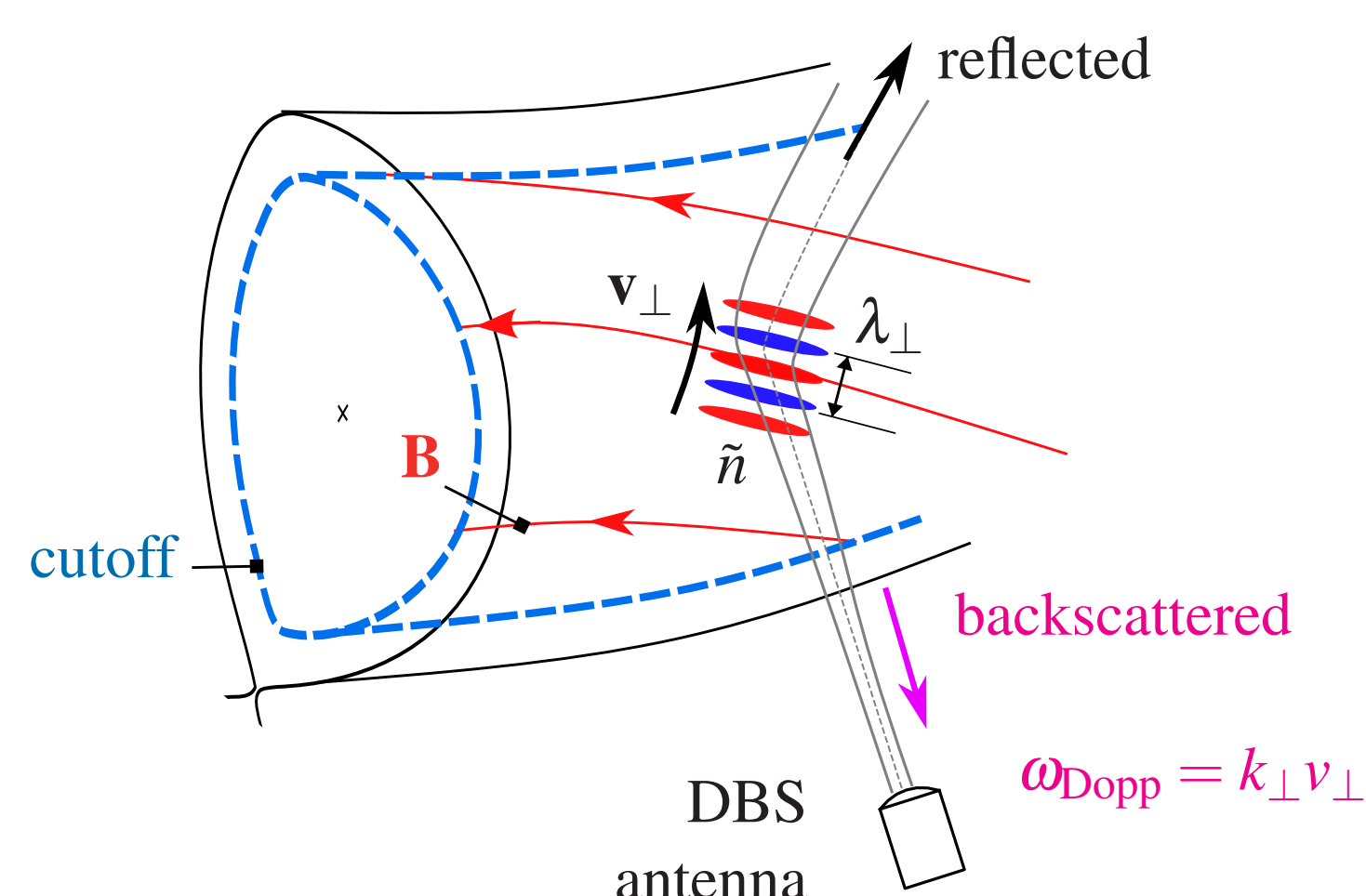


circular, limited → shaped, diverted

- ▶ WEST^[5]: $B_0 = 3.7$ T, $I_p \leq 1$ MA, $R_0 = 2.5$ m, $a = 0.5$ m
- ▶ Specificities:
 - ▷ high aspect ratio ($A \approx 5$)
 - ▷ strong ripple ($\delta \lesssim 2\%$)
 - ▷ up-down symmetric divertors
 - ▷ long pulse operation
 - ▷ full tungsten

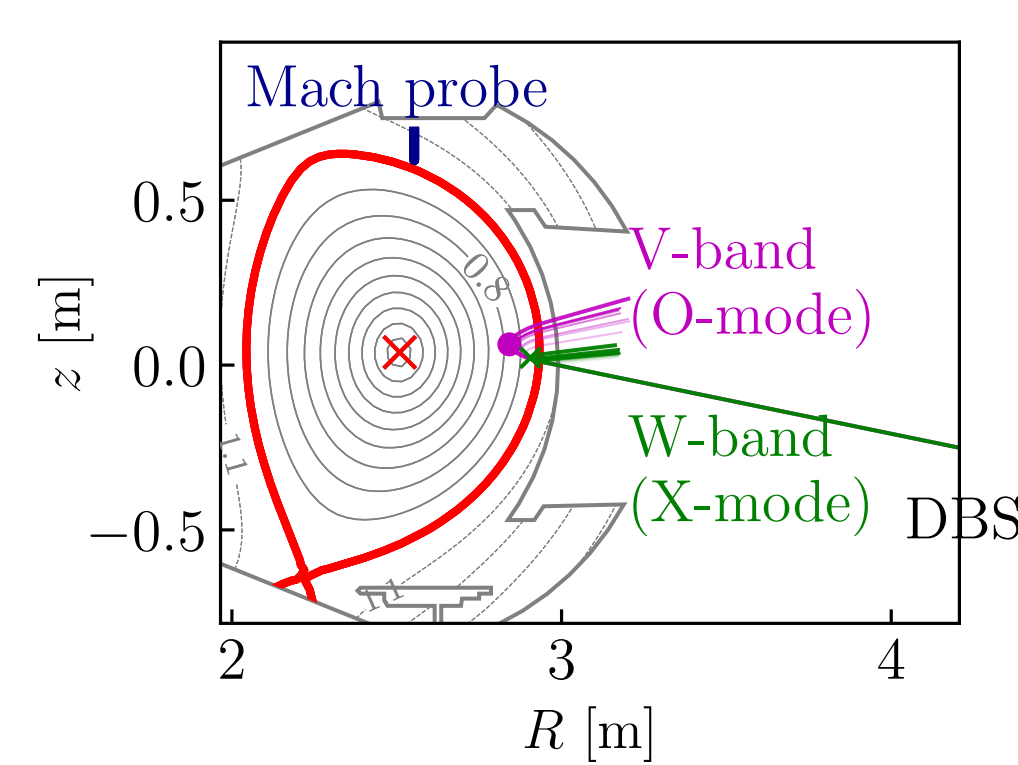
Access to E_r profile using Doppler backscattering (DBS)

- ▶ DBS: microwave scattering technique
- ▶ Detects wave scattered back by density fluctuations (\tilde{n}) close to radial cutoff
- ▶ \tilde{n} 's propagation velocity v_\perp determined from Doppler shift
- ▶ v_\perp dominated by global flow $v_\perp \approx E_r/B$



DBS system on WEST^[6]

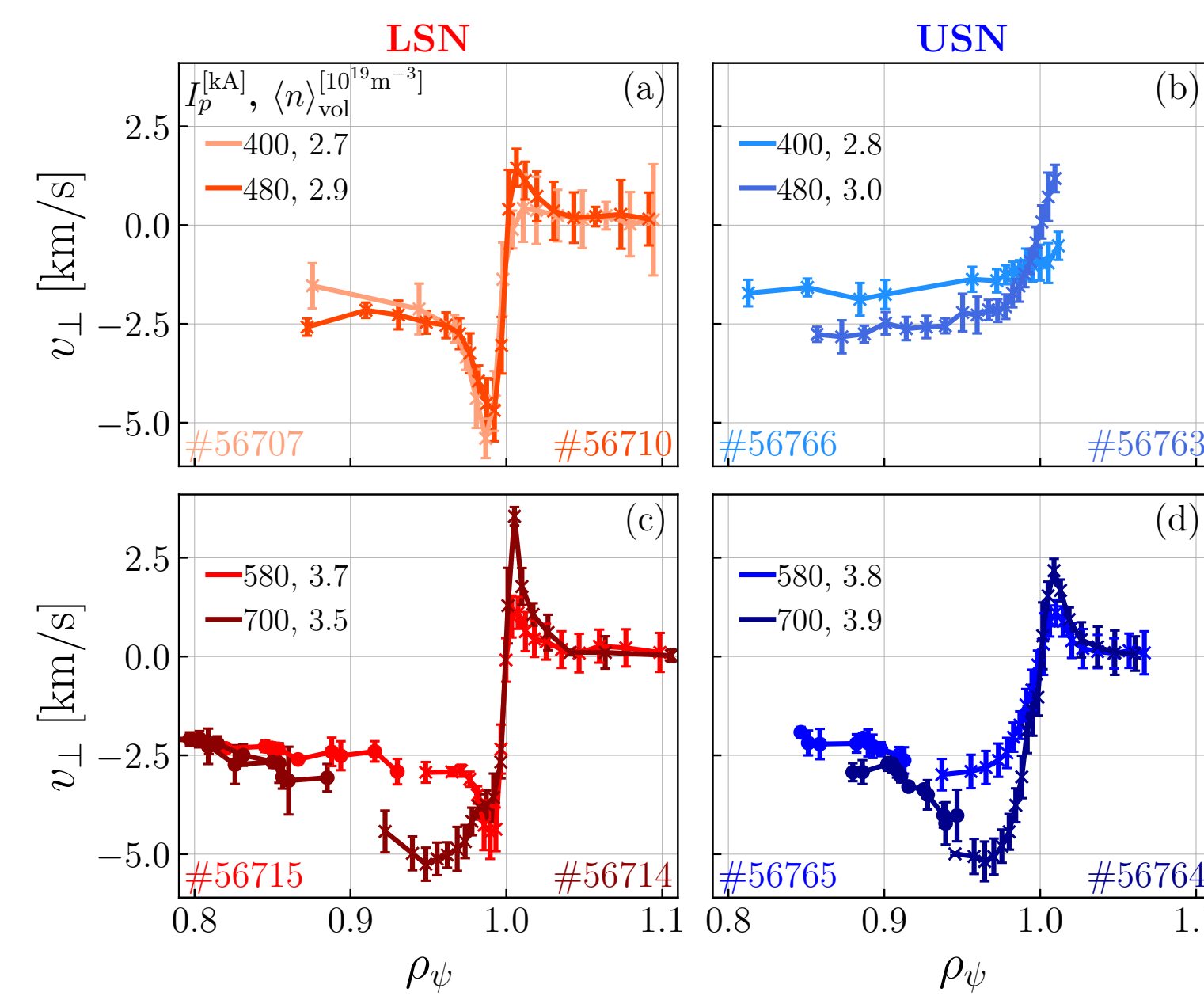
- ▶ 2 independent channels (V- and W-band) polarized in O- and X-mode, resp.
- ▶ W-band covers edge to SOL region: $0.8 \lesssim \rho_\psi \lesssim 1.1$
- ▶ Selected wave number range is $5 \lesssim k_\perp [\text{cm}^{-1}] \lesssim 10$
- ▶ Continuous acquisition throughout discharge (~ 10 s)
- ▶ Typical time resolution for a v_\perp profile: ~ 0.2 s



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Robustness of E_r Sensitivity to I_p in LSN/USN



Matched Ohmic LSN/USN series

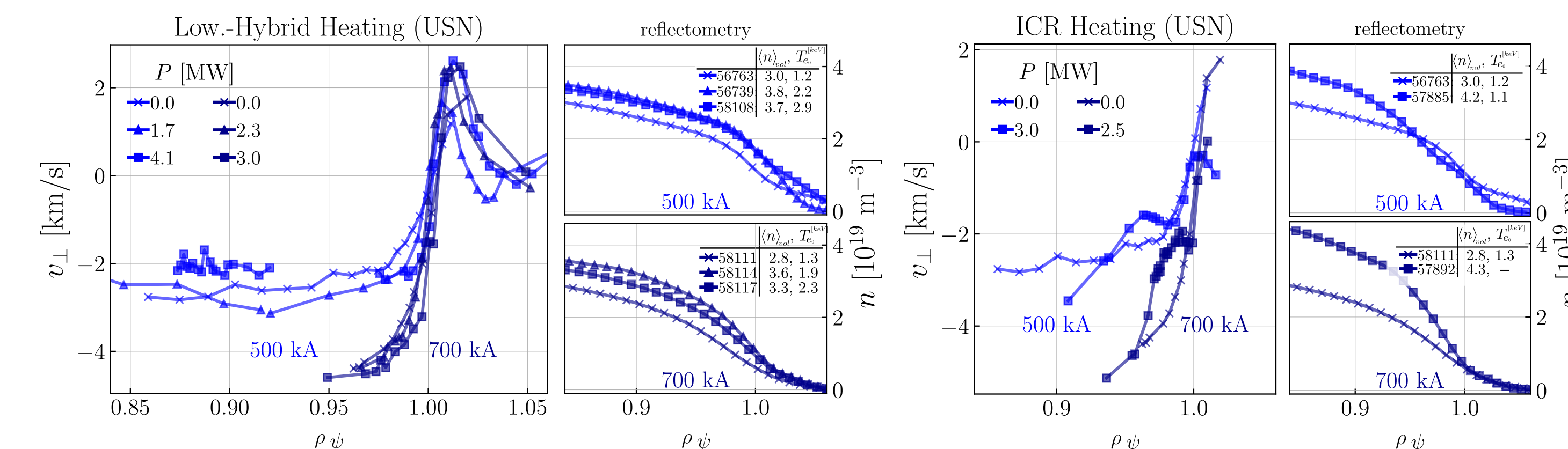
Stationary plasmas at different I_p

Table 1: Discharge parameters

X config.	I_p [kA]	$(n)_{vol}$ [10^{19}m^{-3}]	B_0 [T]	q_{95}	τ_{E95} [s]
LSN	400-700	2.7-3.7	3.76	5.8-3.3	0.29-0.33
USN	400-700	2.8-3.9	3.68	4.7-2.8	0.26-0.31

Depth of the well sensitive to I_p , and more pronounced in USN. (Consistent with earlier I_p scans)

Heated L-mode series (USN only)



- ▶ Trend not blurred by moderate heating: I_p -sensitivity in USN appears robust.
- ▶ But observations are preliminary: missing comparison with LSN, so no firm conclusion on LSN/USN asymmetry towards higher P_{aux} .

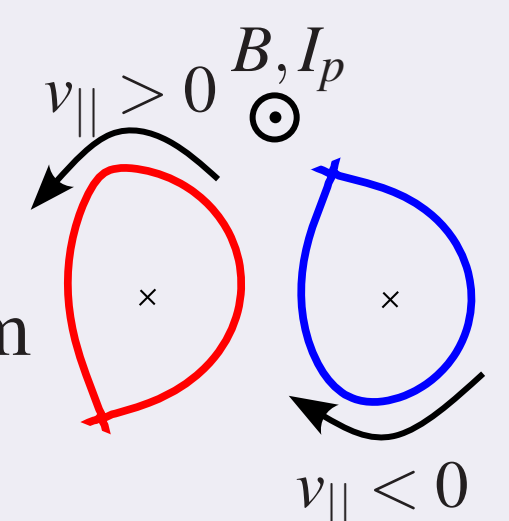
Further observations

- ▶ Parallel SOL flows at the top are co-current in both configurations (smaller $|v_\parallel|$ in USN), but preliminary comparison does not reveal significant trend with I_p .

Discussion

I. LSN / USN asymmetry – possible mechanisms:

1. Topology-dependent SOL v_\parallel flows affecting core rotation
 - ▷ Motivated by asymmetric flow patterns observed on Alcator C-Mod^[7]
 - ▷ Asymmetry in SOL flows on TORE SUPRA^[4] using top/bottom contact point
 - ▷ But: no asymmetry in edge v_ϕ on AUG^[3], at odds with this hypothesis
2. Shear-induced Reynolds stress caused by tilted eddies^[8]
 - ▷ Based on that argument, promising models were applied to: TORE SUPRA^[9], WEST^[10] and AUG^[11]
3. Ion orbit losses (IOL)^[12, 13]
 - ▷ Thermal IOL appear subdominant according to preliminary evaluation for WEST USN Ohmic plasmas^[15]
 - But recent modelling also suggests:
 - ▷ Measurable impact of IOL on E_r and toroidal momentum in L-mode^[17]
 - ▷ IOL sensitive to X-point topology (and shaping^[18]), but mechanism and magnitude unclear yet^[16, 17]



II. E_r sensitivity to I_p

- ▶ Observed in circular, limited (TORE SUPRA) and shaped, diverted (WEST) geometry: **X-point not an essential ingredient**
- ▶ Safety factor $q \propto I_p^{-1}$ role: involved in various transport processes (neoclassical & turbulent, flow damping, ...)
- ▶ Gyrokinetic study on the impact of q in circular geometry^[19, 20, 21]:
 - ▷ E_r deeper at low q in GYSELA, consistent with experiment but weaker.
 - ▷ Turbulence (and GAM) intensity grow with q , while larger and more stationary Zonal Flows at lower q . Possible explanation from collisional flow damping.

Conclusions and Outlook

1. Experiments on WEST confirm a strong influence of I_p on edge $E \times B$ flows and highlight the **asymmetric response to I_p** depending on X-point configuration.
2. Strong I_p sensitivity in USN appears robust to moderate auxiliary heating.

Next, to address why magnetic topology affects I_p sensitivity:

- ▶ SOLEDGE2D-EIRENE fluid boundary simulations^[22] in LSN/USN
- ▶ Extend multi-machine comparison: WEST, AUG, TCV
- ▶ On TCV: study effect of triangularity on E_r asymmetry
- ▶ On WEST: explore LSN/USN asymmetry in higher power scenarios