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Linking Edge Flows to the Magnetic Geometry Asymmetry in Tokamaks

S. Rienäcker¹, L. Vermare¹, P. Hennequin¹, C. Honoré¹, S. Coda², B. Labit², L. Frassinetti³, B. Vincent², M. Agostini⁴, M. La Matina⁴, M. Ugoletti⁴, A. Balestri², P. Manas⁵, O. Panico^{1,5}, the TCV team^a, the WEST team^b, and the EUROfusion Tokamak Exploitation team^c

¹Laboratoire de Physique des Plasmas, CNRS, Sorbonne Université, École polytechnique, Institut Polytechnique de Paris, Palaiseau, France

²Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, Lausanne, Switzerland

³Division of Fusion Plasma Physics, KTH Royal Institute of Technology, Stockholm, Sweden

⁴Consorzio RFX, Padova, Italy

⁵CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

Introduction. Empirically, tokamak plasmas are sensitive to the magnetic geometry (or topology): The power threshold needed to trigger the L- to H-mode transition is significantly increased when the ion magnetic (or $B \times \nabla B$) drift is pointing *away from* as compared to *toward* the active X-point. The topologies thus referred to as *unfavorable* and *favorable*, respectively, also differ in other aspects, such as edge turbulence and flow characteristics.^{1,2} Notably, the $E_r \times B$ shear is more pronounced in favorable L-mode discharges on the AUG and WEST tokamaks compared to their unfavorable counterparts.³⁻⁵ We present first dedicated experiments aimed at characterizing the edge E_r profile on the TCV tokamak for favorable (Fav.) and unfavorable (Unfav.) magnetic configurations. They are part of a multi-device study which seeks to clarify the origin of the modified E_r structure with topology, and the possible link with the altered H-mode access. The results are confronted with those obtained on WEST, in particular with regard to the plasma current sensitivity.

Experimental Method. The *Tokamak à Configuration Variable* (TCV)^a is well suited for the present study given its highly flexible plasma geometry and freedom as to the B -field and plasma current orientations. Compared to the large aspect ratio, full tungsten wall and high ripple device WEST^b, TCV offers complementary characteristics as a smaller, carbon wall machine capable of high power density heating. On both devices, measurements of the edge perpendicular flow velocity are performed via Doppler backscattering (DBS), with two separate but comparable systems developed and operated by LPP.^{6,7} DBS detects the component of an incident microwave beam scattered back by density fluctuations from a region localized around the beam's turning point. The Doppler shift introduced by the moving scatterers gives access to

^aSee author list of H. Reimerdes et al 2022 Nucl. Fusion [62 042018](#)

^bSee author list of J. Bucalossi et al 2022 Nucl. Fusion [62 042007](#) and the [WEST team](#)

^cSee the author list of "Overview of the EUROfusion Tokamak Exploitation programme in support of ITER and DEMO" by E. Joffrin Nuclear Fusion 2024 [10.1088/1741-4326/ad2be4](#)

their perpendicular velocity v_{\perp} (in the lab frame) which is a measure of the mean plasma flow given by the $E \times B$ velocity (if the turbulence phase velocity can be neglected). Radial profiles of $v_{\perp} \sim E_r/B$ can thus be obtained by stepping the microwave probing frequencies, typically requiring 100 ms for a 20 point profile under stationary L-mode conditions.

Sensitivity of E_r to topology on TCV. The velocity profiles obtained on TCV for a pair of lower single-null (LSN) discharges with opposite $B \times \nabla B$ drift but otherwise matched parameters are displayed in Fig. 1 (a), along with the corresponding plasma equilibrium (b) and electron kinetic profiles obtained from Thomson Scattering (c-d).

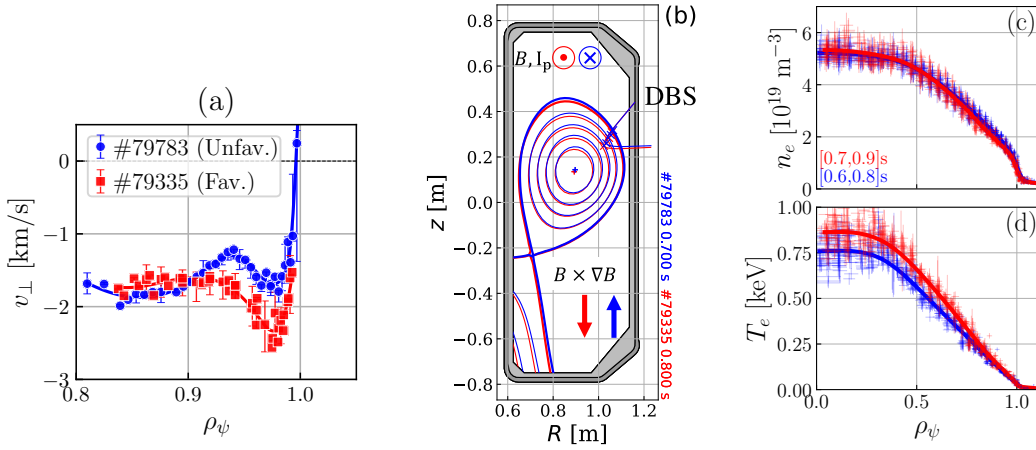


Figure 1: (a) Edge velocity profiles measured by DBS for a pair of Ohmic LSN Fav./Unfav. discharges with $I_p = \mp 210$ kA and $B_0 = \mp 1.44$ T. (b) Equilibrium reconstruction with representative ray traces indicating the DBS beam probing region (localized around the ray turning point, with probed wave number $k_{\perp} \approx [7, 9] \text{ cm}^{-1}$). Density (c) and electron temperature (d) profiles obtained from Thomson Scattering.

The deeper well observed in the Fav. case at similar edge kinetic profiles is consistent with the reported trends on WEST⁵ and AUG.^{3,4} It should be noted that the Fav./Unfav. difference in v_{\perp} is found to be sometimes less pronounced in other plasma conditions at TCV. In particular, as reported below, high values of I_p tend to reduce the asymmetry, but also other parameters like density appear to play a role in this respect and will be investigated in future work.

Plasma current scan. The edge $E_r \times B$ flow behavior is examined in Fav. compared to Unfav. topology through a shot-to-shot variation of the plasma current I_p , confronting WEST and TCV results. On WEST, a deepening of the E_r well had been observed with increased I_p in Ohmic plasmas.⁵ It was subsequently confirmed under stationary conditions instead of I_p ramps, with the results shown in Fig. 2. The findings highlighted a sensitivity of the flow structure to I_p that is significantly more pronounced in Unfav. USN compared to Fav. LSN discharges. They gave rise to an extensive numerical study on the role of I_p (or edge safety factor) in setting the E_r profile⁸ and also called for an experimental cross-device comparison. A similar Ohmic I_p scan was thus carried out on TCV, with the results presented in Fig. 3. The corresponding plasma parameters are summarized in Tab. 1.

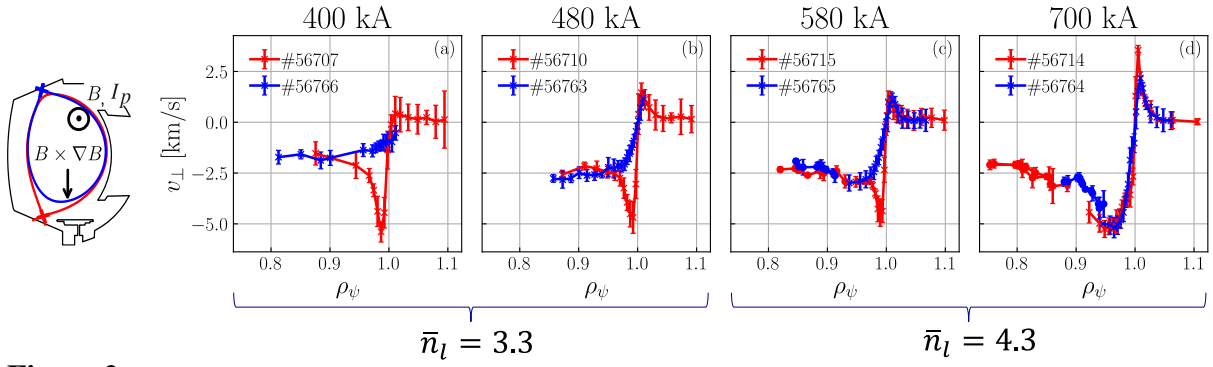


Figure 2: Variation of plasma current I_p in *unfavorable* USN versus *favorable* LSN stationary, Ohmic discharges on WEST. A clear deepening of the well with I_p is observed in the former case.

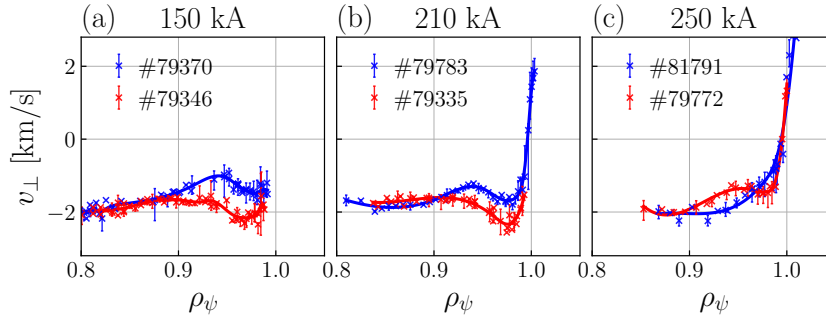


Figure 3: Plasma current scan replicated on TCV for *unfavorable* versus *favorable* LSN discharges during stationary, Ohmic phases. At high current, the velocity profiles inside the separatrix tend to be flatter, whereas from low to intermediate I_p they remain largely unchanged.

device	topology	I_p [kA]	q_{95}	\bar{n}_l/n_G	$\bar{n}_l [10^{19} \text{m}^{-3}]$	$B_0 [\text{T}]$
WEST	LSN Fav.	-(400 → 700)	5.8 → 3.3	0.50 → 0.37	3.2-4.4	-3.7
	USN Unfav.		4.7 → 2.8			
TCV	LSN Fav.	+(150 → 250)	5.0 → 3.0	0.44 → 0.26	3.6-4.2	+1.4
	LSN Unfav.					

Table 1: Comparison of main plasma parameters throughout the I_p scans on the two devices.

Between the low and intermediate I_p , Fig. 3 (a-b), the v_{\perp} profiles do not evolve significantly. At the highest I_p , Fig. 3 (c), the wells tend to flatten out, especially in the Unfav. case. In Fav., the well remains visible albeit shallower and shifted up. The overall trend on TCV appears qualitatively different from the one observed on WEST, if not even reversed: the well deepens with I_p in Unfav. topology on WEST, while it becomes shallower on TCV. However, caution is required: First, the density profiles evolve along the I_p scan on TCV, resulting in higher edge density with increasing I_p . Thus, the effects of I_p and density on E_r could potentially mix. Second, the experimental conditions are not exactly the same: On WEST, the comparison is between LSN and USN discharges, as opposed to a fixed LSN shape on TCV.

Evolution towards the L-H transition. The Fav./Unfav. asymmetry in terms of E_r was further investigated on TCV through power ramps to explore regimes closer to the L-H transition. A co-current injected neutral beam ramp was programmed as shown in Fig. 4 (a), and

repeated for the two topologies by keeping the sign of I_p fixed and reversing only the B -field. The results for $I_p = -150$ kA are shown in Fig. 4 (b). A largely consistent trend was found for a similar power ramp at $I_p = -210$ kA (not shown). It is observed that the E_r well deepens in

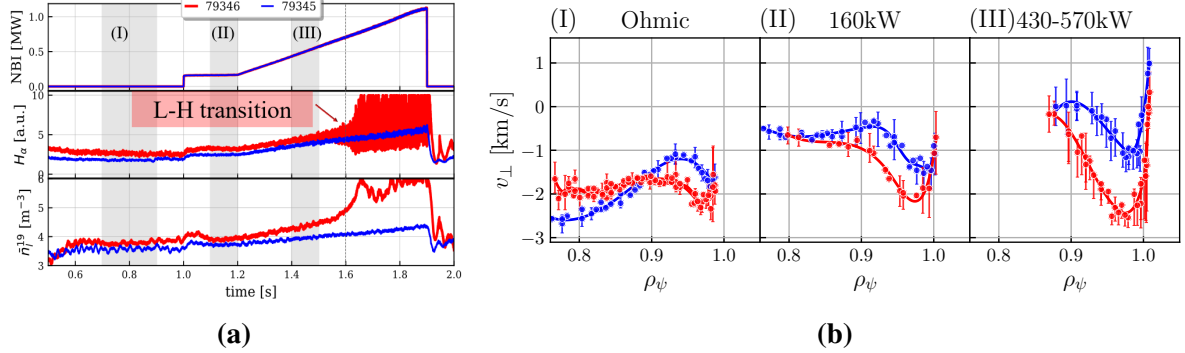


Figure 4: (a) From top to bottom: Traces of neutral beam injected (NBI) power, vertically detected $H\alpha$ line signal and line averaged density along the heating ramp. The shaded areas indicate the three time windows investigated, where the last one (III) is close to the L-H transition triggered around 1.6 s for the Fav. case. (b) Evolution of the E_r well showing a marked increase of the inner shear in Fav. approaching the L-H transition.

the Fav. $B \times \nabla B$ case as the power is ramped up, while the depth does not evolve in the unfavorable. At the same time, the inner part of the profiles are shifted up, probably as a consequence of the co- I_p torque. This results in a significant steepening of the inner shear layer in the Fav. compared to the Unfav. case. It is followed by an L-H transition (around 1.6 s at 700-750 kW), while the Unfav. case remains in L-mode throughout the ramp. These observations are compatible with the inner velocity shear being important in triggering the L-H transition⁹, which could explain the reduced power threshold in Fav. topology.

Summary. The edge $E_r \times B$ flow has been characterized on TCV for a series of discharges in favorable and unfavorable magnetic topologies. The asymmetry in E_r previously observed on AUG and WEST is recovered, with a shallower well when $B \times \nabla B$ is in the unfavorable direction for H-mode access. On TCV, the E_r structure is found to vary with the plasma current only towards high values (regardless of topology). The well is shallower at high current, in qualitative contrast to results from WEST. The evolution of E_r approaching the L-H transition reveals a marked increase of the inner shear in Fav. configuration, suggesting a link with the facilitated H-mode access compared to unfavorable.

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