Link between edge radial electric field and confinement improvement in negative triangularity plasmas in TCV

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Introduction. Negative triangularity (NT) has emerged as a promising alternative to the conventional positive triangularity (PT) shape of tokamak plasmas. Owing to the suppression of large ELMs, combined with outstanding L-mode confinement, NT appears to be a suitable candidate for core-edge integration[1,2]. The improved L-mode confinement in NT relative to PT is commonly attributed to a stabilizing impact of NT-shaping on turbulence, as supported by experiments[3–6] and theory[7–12]. Experiments further emphasize the importance of the NT edge region[13,14] to the overall performance gain. Drawing on recent experiments [15] on the *Tokamak à Configuration Variable* (TCV)[a] and extending them, we investigate the radial electric field (E_r) and its associated $E_r \times B$ shear at the edge as a possible mechanism for reducing turbulent transport in NT relative to PT.

Experiment design. To test this hypothesis, the perpendicular velocity of density fluctuations $v_\perp$—a proxy for the $E_r \times B$ drift—is measured using a dual-channel Doppler backscattering (DBS) system [16], and compared in appropriately matched NT and PT L-mode plasmas. The plasma geometries of the main (reference) scenarios are shown Fig. 1. These upper single-null (USN) shapes have opposite signs of the bottom (non-X-point) triangularity, $\delta_{\mathrm{nX}} \approx \pm 0.33$, but are matched in the upper half-section. This minimizes possible geometry-induced biases in the DBS measurements (taken in the upper LFS region), while isolating the impact of *non-X-point* triangularity (as opposed to *overall* or *X-point* triangularity).

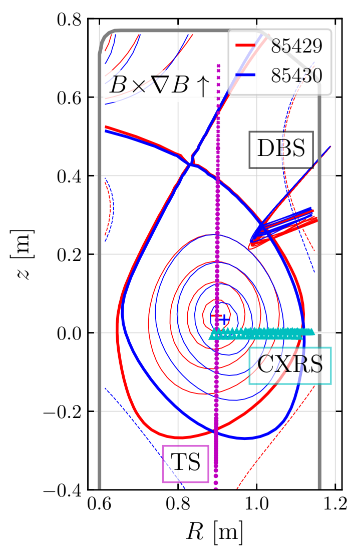

Figure 1: *NT/PT shapes of the reference scenario.*

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Comparison in matched USN geometry. The edge E_r profiles collected under various heating conditions in plasmas with the reference USN shapes of Fig. 1 are compiled in Fig. 2 (upper panels), alongside the electron pressure (p_e) inferred from Thomson Scattering (bottom panels). In all cases, the NT plasma

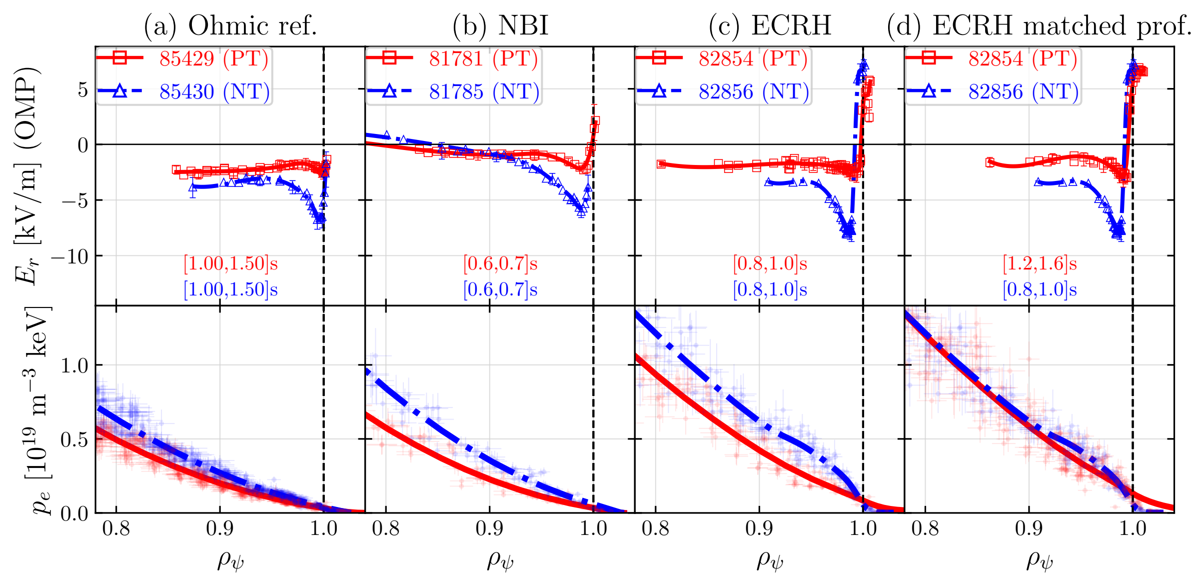

Figure 2: *(Upper panels) E_r profiles mapped to the outboard midplane and (bottom panels) electron pressure, for the USN shapes of Fig. 1 under different heating conditions: (a)* 195 kW *Ohmic only, (b)* 420 kW *co-current NBI, (c)* 580 kW *second-harmonic ECRH, and (d) also ECRH but with higher power in PT (*850 kW*) than NT (*580 kW*)—resulting in similar pressure profiles.*

exhibits a remarkably deep negative E_r well compared to their PT counterpart (and more generally to typical PT L-mode plasmas [16]). With equal heating in NT and PT (a-c), the stronger edge $E_r \times B$ shear in NT is accompanied by a steeper edge p_e profile and—although not shown here—also a higher edge T_i [15]. Globally, the total thermal energy is about 25–30% higher in NT. Interestingly, the difference in E_r persists also when (d) using higher ECRH power in PT to match the NT density and temperature profiles. This suggests that the enhanced E_r well in NT does not merely reflect the edge $(\nabla p_i)/en_i$ behavior. It thus appears as a plausible *cause* for, or a contributor to the edge transport difference between NT and PT, rather than merely a consequence of it.

Extension to other scenarios. These findings are not unique to the specific USN shapes shown in Fig. 1. Similar comparisons were performed in other scenarios, covering various geometries (LSN, USN, limited). Likewise, they showed that the edge E_r is consistently more negative in NT. As an example, we consider a high-performance, fully-NT (DIII-D-like) shape and its flipped PT counterpart (Fig. 3 a) [15]. Both are subject to 850 kW of co-current NBI heating and remain in L-mode, partly because of the unfavorable $B\times\nabla B$ drift. Despite the unfavorable $B \times \nabla B$ drift—usually associated with a shallow E_r profile [17–20], the NT discharge exhibits a remarkably pronounced E_r well. Consistent with the results shown in Fig. 2, the NT case also

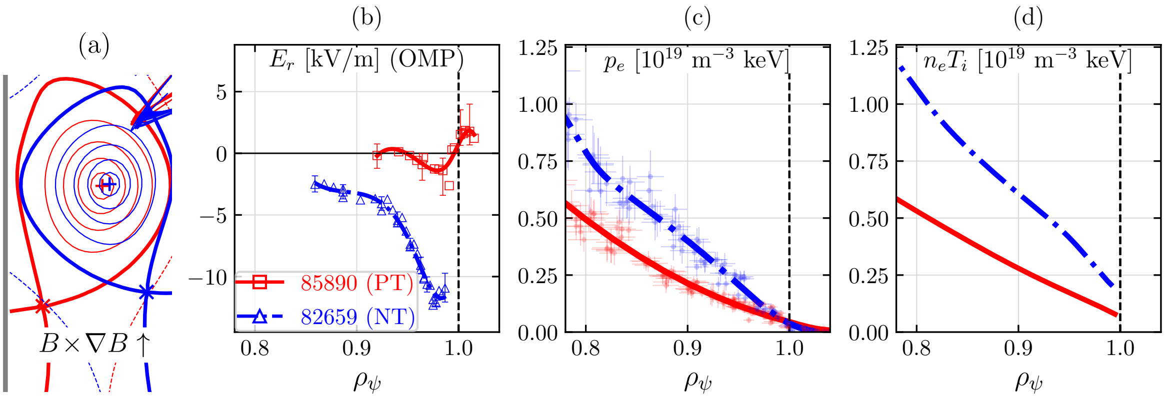

Figure 3: *Comparison between a high-performance, fully-shaped NT plasma to its flipped PT counterpart* [15]. *(a) Equilibria, (b) radial electric field profiles at the outboard midplane, (c) electron pressure and (d) ion pressure profiles.*

has significantly steeper electron and ion pressure profiles (c-d) than its PT counterpart. We note, however, that in some other NT/PT geometries, neither the edge $E_r \times B$ *shear* nor the confinement is significantly enhanced in NT. This may relate to the observation that, in TCV, negative *X-point triangularity* has a weak impact on confinement compared to negative *non-X-point* triangularity [21]—this will be investigated further.

Statistical link with confinement. In view of statistically capturing the link between edge E_r behavior and confinement improvement in NT, we compute the NT/PT difference in E_r at the minimum of the well ($E_r^{\min}$)—as a crude proxy for the $E_r \times B$ shear difference at the edge. This $E_r^{\min}$ difference is plotted in Fig. 4 over relative confinement improvement, according to

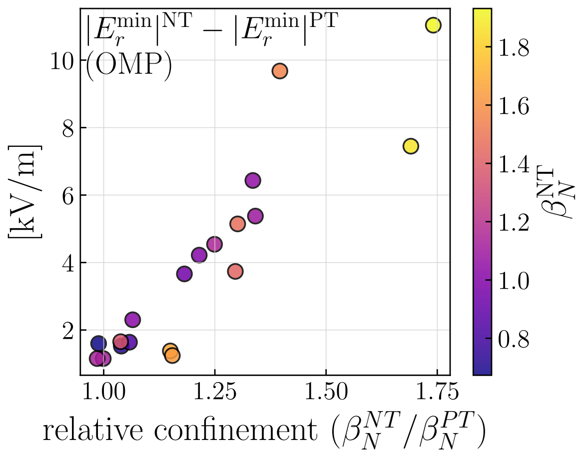

Figure 4: *Difference (NT−PT) in* $|E_r^{min}|$ *as a function of the NT/PT ratio of normalized* β.

the normalized beta (β_N). The data cover various comparable NT/PT pairs (L-mode only), across different shapes (LSN, USN, limited) and under various heating or density conditions. A detailed assessment of the correlation is difficult, given the currently limited number of comparable NT/PT pairs with both E_r and T_i data. However, we note that larger $E_r^{\min}$ differences coincide with significant confinement improvement, indicating a tight connection between edge

$E_r \times B$ shear enhancement and reduced transport in NT.

Conclusions. Over a wide range of scenarios, NT plasmas in TCV show a deeper edge E_r well than corresponding PT plasmas. $E_r \times B$ shear differences are associated with steeper edge pressure profiles (at equal heating) along with higher total energy content. Thus, $E_r \times B$ shear regulation of turbulent transport at the edge is a plausible candidate to explain the L-mode confinement gain in NT over PT, alongside other proposed mechanisms, such as geometry-induced direct stabilization of ion-scale instabilities [7,11,13,22]. To clarify the origin and role of the differing edge E_r behavior in NT and PT, edge transport simulations of TCV plasmas using the `GENE-X` code are underway [23], complementing similar efforts using other turbulence codes [24,25].

Acknowledgements. *This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). This work has benefited from a grant managed by the Agence Nationale de la Recherche (ANR), as part of the program "Investissements d'Avenir" under the reference (ANR-18-EURE-0014). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them. This work was supported in part by the Swiss National Science Foundation. This work was supported in part by the US Department of Energy under Award DE-FC02-04ER54698.*

[1] Kathreen E. Thome et al. *Plasma Physics and Controlled Fusion* (2024).

[2] O. Février et al. Submitted for publication to *Nuclear Fusion* (2026).

[3] M. Fontana et al. *Nuclear Fusion* (2017).

[4] Zhouji Huang, Stefano Coda, et al. *Plasma Physics and Controlled Fusion* (2018).

[5] Max E. Austin et al. *Physical review letters* (2019).

[6] A. Marinoni et al. *Physics of Plasmas* (2019).

[7] Alessandro Marinoni et al. *Plasma Physics and Controlled Fusion* (2009).

[8] G. Merlo et al. *Plasma Physics and Controlled Fusion* (2021).

[9] Giovanni Di Giannatale et al. *Plasma Physics and Controlled Fusion* (2024).

[10] A. Balestri et al. *Plasma Physics and Controlled Fusion* (2024).

[11] Xavier Garbet et al. *Nuclear Fusion* (2024).

[12] P. Ulbl et al. *Nuclear Fusion* (2025).

[13] A. Balestri et al. *Plasma Physics and Controlled Fusion* (2024).

[14] A. O. Nelson et al. *Plasma Physics and Controlled Fusion* (2024).

[15] S. Rienäcker et al. *Nuclear Fusion* (2025).

[16] Sascha Rienäcker et al. *Plasma Physics and Controlled Fusion* (2025).

[17] L. Vermare et al. *Nuclear Fusion* (2022).

[18] U. Plank et al. *Physics of Plasmas* (2023).

[19] S. Rienäcker et al. *29th Joint EU-US Transport Task Force Meeting, Budapest, Hungary*. Oral contribution. 2025.

[20] S. Rienäcker et al. (2026). Paper in preparation.

[21] S. Coda et al. *49th EPS Conference on Plasma Physics*.

[22] Gabriele Merlo et al. *Physics of Plasmas* (2023).

[23] B. J. Frei and P. Ulbl. Private communication. 2025.

[24] Marina Bécoulet et al. *Plasma Physics and Controlled Fusion* (2026).

[25] L. De Gianni et al. *13th Festival de Théorie, Aix-en-Provence, France*. Oral contribution. 2025.