CORE-EDGE INTEGRATION STUDIES IN NEGATIVE TRIANGULARITY IN TCV

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Introduction — Negative Triangularity (NT) configurations have demonstrated higher energy confinement compared to the conventional Positive Triangularity (PT) configurations. Experiments on TCV and DIII-D have shown that NT L-Mode plasmas can exhibit confinement comparable to H-mode, with β_N up to 2.8 (2 in steady-state) demonstrated in TCV. This suggests the potential for high-confinement L-Mode reactors that circumvent H-mode challenges, including ELMs, L-H and H-L transition power thresholds, as well as density control issues. In this contribution, we investigate power exhaust in Ohmic and high-power NT configurations to demonstrate the compatibility of NT plasmas with reactor relevant operation and core-edge integration.

Comparing intrinsic differences between NT and PT detachment — In Ohmic L-Mode TCV discharges, detachment in NT configurations is challenging [1], with the outer target harder to cool to sufficiently low electron temperature (<5 eV) using core density ramps, compared to PT. SOLPS-ITER simulations could reproduce this observation [2], and ascribe it to the unmatched divertor geometries, leading to a different neutral particles behavior in the Scrape-Off Layer (SOL) and resulting in different ionization sources and heat flux distribution in the two configurations. Increasing the divertor closure through the addition of divertor gas baffles [3] decreases the outer target temperature, but detachment remains more difficult to achieve than in PT [4]. In Lower Single-Null (LSN), changing only the upper triangularity (δ_u) from positive to negative, whilst matching the divertor geometries, still results in harder detachment. This is, at least partially, explained by the role of the SOL width (λ_q), which is smaller in NT than in L-Mode PT [6], in agreement with theoretical and numerical predictions [5]. Experimentally, it is found that λ_q is influenced by δ_u, while the lower triangularity (δ_l) has little impact on λ_q [6]. Furthermore, experiments with matched divertor geometries exhibit a typically lower divertor neutral pressure in NT than in PT, even with increased divertor closure [1,4]. Using extrinsic impurity seeding (N_2), NT detachment was achieved, at the expense of reduced core confinement, due to core impurity contamination, and still exhibiting higher difficulty to detach as compared to PT.

Towards high-performance, fully detached NT scenarios — These Ohmic studies have recently been extended to high-input power scenarios. The scenario is a 170kA LSN (some discharges were also performed with a snowflake divertor) with favourable ion grad-B drift, with negative δ_u and positive δ_l, to maintain compatibility with divertor baffles, Figure 1a, employing the Neutral Beam Heating (NBH) system of TCV, Figure 1c. High performance is achieved, with β_N up to 1.8 (H_{98} near 1), Figure 1d, at a relatively high density, Figure 1b, (Greenwald fraction of about 0.4, vs 0.55 for the PT H-Mode) sustained in steady-state conditions, for the duration of the NBH. The NT scenario achieves higher central ion and electron temperatures than its PT counterparts, Figures 1e, 1f. While the scenario remains in L-Mode for most of the explored heating power range, H-Mode transitions occur with the addition of ECRH power, likely linked to the marginality of the δ_u in preventing access to second stability for the shape considered.

Even without extrinsic impurity seeding, the divertor is relatively cold, as evidenced by the CIII front retreating from the outer target, a low outer target temperature (Te ~ 6 eV, measured by Langmuir Probes, Figure 1g) and a significant radiated power fraction, attributed in part to the high operationnal density. When N_2 seeding in the divertor is introduced, an X-Point Radiator forms, further cooling the divertor. This, however, leads to reduced plasma performance. Real-time β-control can recover performance by increasing the NBH power, and enabled the demonstration of fully detached, high-performance ($\beta_N = 1.6$) L-mode NT plasmas, comparable to ELMy H-mode, which suffers from reattachment during ELMs.

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Outlook — In future work, these high-power scenarios will be further characterized with various sets of baffles, and extended to higher input power, leveraging TCV's ECRH system, as well as TCV's second, higher-energy, neutral beam. The possibility to achieve high-performance scenarios with a fully detached divertor, featuring either a radiative mantel or an X-Point Radiator, with extrinsic impurity seeding (N2, Ne, Ar) will be assessed.

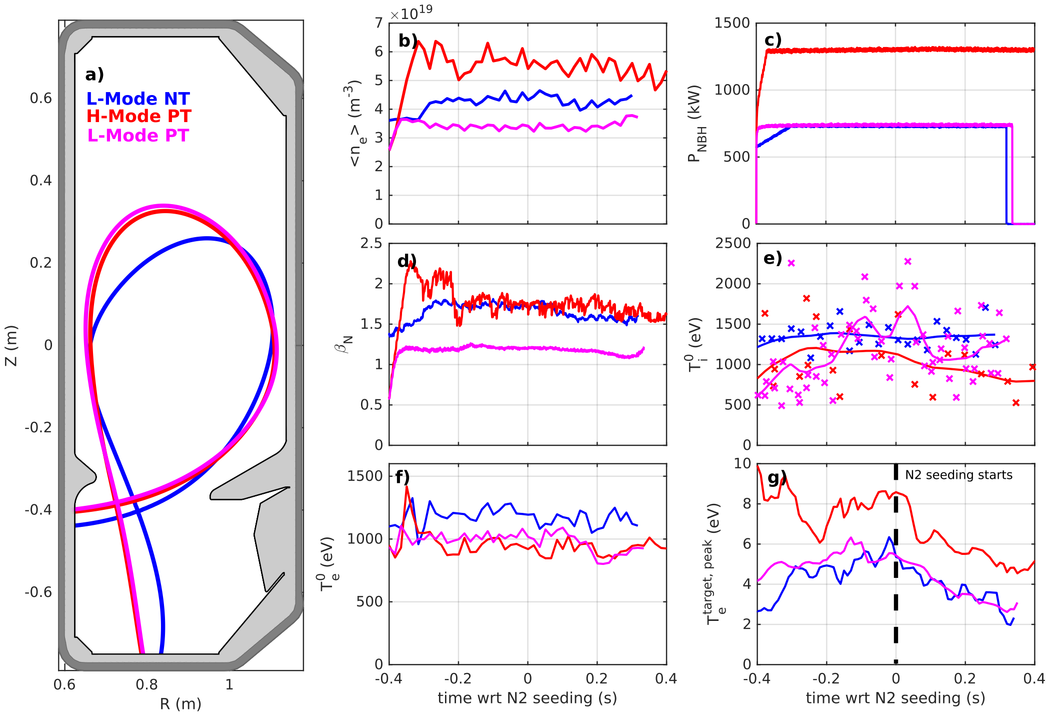

Figure 1 – (a) Shape of the NT (blue) and PT (red: H-Mode, magenta: L-Mode) high-input power scenarios. (b) line-averaged density $<n_e>$, (c) injected NBH power, (d) β_N, central ion (e) and electron (f) temperatures, outer target peak temperature (g), as a function of the time with respect of N_2-seeding start.

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REFERENCES

[1] CODA S., *et al*, "Enhanced confinement in diverted negative-triangularity L-mode plasmas in TCV", Plasma Phys. Control. Fusion **64** (2022) 014004

[2] FEVRIER O., *et al*, "Comparison of detachment in Ohmic plasmas with positive and negative triangularity", Plasma Phys. Control. Fusion **66** (2024) 065005

[3] TONELLO E., *et al*, « Modelling of power exhaust in TCV positive and negative triangularity L-mode plasmas", Plasma Phys. Control. Fusion **66** (2024) 065006

[4] REIMERDES H., *et al*, "Initial TCV operation with a baffled divertor", Nucl. Fusion **61** (2021) 024002

[5] DURR-LEGOUPIL-NICOUD G., *et al*, in preparation (2025)

[6] LIM K., *et al*, "Effect of triangularity on plasma turbulence and the SOL-width scaling in L-mode diverted tokamak configurations", Plasma Phys. Control. Fusion **65** (2023) 085006

[7] MORGAN R., *et al*, in preparation (2025)

[8] FAITSCH M., *et al*, "Dependence of the L-Mode scrape-off layer power fall-off length on the upper triangularity in TCV", Plasma Phys. Control. Fusion **60** (2018) 045010