PATHWAYS TO IMPROVED CORE-EDGE INTEGRATION FOR NEGATIVE TRIANGULARITY SCENARIOS IN THE DIII-D TOKAMAK

[1]F. SCOTTI, [1]N. LI, [1]A.G. MCLEAN, [1]M.G. BURKE, [1]M. ZHAO, [2]K. THOME, [2]D. ELDON, [2]A. HYATT, [2]H.Q. WANG, [2]X. MA, [3]A. MARINONI, [4]J. LORE, [4]M. SHAFER, [5]C. PAZ-SOLDAN, [5]A.O. NELSON, [6]L. SCHMITZ, [6]R. HONG, [7]F. KHABANOV, [8]O. SAUTER

[1]Lawrence Livermore National Laboratory, Livermore, US, [2]General Atomics, San Diego, US
[3]University of California, San Diego, US, [4]Oak Ridge National Laboratory, ORNL, US
[5]Columbia University, New York, US, [6]University of California, Los Angeles, US
[7]University of Wisconsin, Madison, US, [8]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
Email: scotti1@llnl.gov

Novel experimental measurements and fluid modeling of the divertor and scrape-off layer (SOL) of Negative Triangularity (NT) plasmas in the DIII-D tokamak enable the extrapolation of the optimal path to accessing dissipative divertor conditions in proposed upgrades on DIII-D and future NT devices while maintaining a high-performance core plasma. For the first time in NT, they provide: - the scaling of SOL heat flux widths (λ_q), - the parametric dependence of upstream separatrix densities $n_{e\text{-}sep}$ needed for detachment, - the explanation for the confinement degradation with divertor detachment observed in NT plasmas in DIII-D and - the sustainability of high density operation [1]. NT scenarios are promising candidates for a fusion power plant due to the energy confinement comparable to H-mode, the intrinsic elimination of ELMs, the absence of an L-H power threshold, and short impurity confinement times. Characterizing the dependence of λ_q and the requirements to access dissipative divertor conditions is necessary to extrapolate the compatibility of NT scenarios in future tokamaks with the engineering limits due to plasma-facing components (PFCs). A narrowing of λ_q from L-mode values is measured with an inverse dependence on plasma current (I_p), driving a parametric dependence of detachment access similar to positive triangularity (PT) ($n_{e\text{-}sep}$ at detachment increasing linearly with I_p and with the square root of power). Quantitative characterization of NT SOL and divertor plasmas, together with the improved understanding of the triangularity dependence of core confinement and ELM avoidance, facilitate the design of a new proposed divertor for NT shapes in DIII-D to improve core-edge compatibility and provide particle exhaust.

SOL heat flux widths in NT are reduced up to a factor of 2 compared to multi-machine L-mode scalings, consistent with reduced edge turbulence and the formation of a narrow edge transport barrier, which results in an electron temperature T_e pedestal [2]. A database of λ_q values across NT (strong NT with average triangularity δ~–0.5, reduced NT δ~0/–0.2) and other ELMy and ELM-free regimes was assembled from DIII-D discharges. A reduction by a factor of 2 is observed when comparing λ_q in NT discharges to L-mode measurements in DIII-D and multi-machine L-mode scalings (Figure 1-left) [3]. NT SOL widths remain larger than H-mode multi-machine scalings [4] (Figure 1-right), while following their parametric dependence on I_p. SOL heat flux widths in NT agree with multi-machine cross-regime scalings, where SOL widths correlate to edge plasma pressure [5]. BOUT++ two-fluid turbulence non-linear simulations reproduce the experimentally measured λ_q with strong NT, and capture the narrowing of λ_q with ion B×∇B drift direction away from the X-point, due to the reduced fluctuation entrainment driven by ballooning instabilities from inside the separatrix to the SOL. The radial turbulence transport in the SOL for strong NT is stronger than that in PT no-ELM regimes but lower than that in PT small ELM regimes, leading to a broader λ_q compared to PT no-ELM regimes but a narrower λ_q compared to PT small ELM regimes.

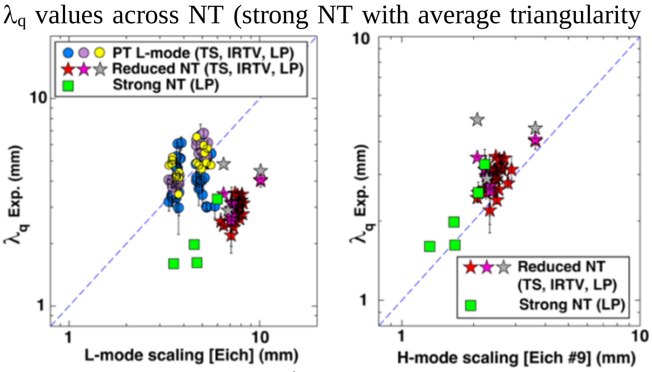

Figure 1 Left: Experimental λ_q for L-mode and NT discharges as a function of L-mode scaling [3]. Right: Experimental λ_q in NT as a function of H-mode scaling [4]. NT heat fluxes remain intermediate between those typical of L and H-mode discharges. λ_q is measured from IR thermography (IRTV), Langmuir probes (LP) at the outer strike point (OSP) and upstream Thomson scattering (TS).

High densities (Greenwald density fraction f_{Gw}~1.3 with ion B×∇B drift into the divertor) were required for detachment in strong NT shapes in DIII-D due to the reduced edge radial transport compared to L-mode, the short midplane-to-target parallel connection lengths $L_{//}$, and the strong effect of cross-field drifts. Dissipative divertor conditions were achieved in NT discharges at different δ, injected power (0-10MW), I_p (0.6-1.0MA), and toroidal field directions. Parametric dependencies of $n_{e\text{-}sep}$ needed to access the detachment in NT on I_p and power flowing into the SOL (P_{SOL}) determined via regression analysis, remained similar to PT with a linear dependence on I_p ($I_p^{0.8}$) and sublinear dependence on power ($P_{SOL}^{0.4}$), consistent with expectations from the two-point model.

Impurity seeding was observed to reduce the density needed to detach by up to 30%, at the expense of core dilution. Interpretive edge fluid simulations (UEDGE, SOLPS-ITER) with the inclusion of cross-field drifts, matched to experimental conditions, were able to capture the high densities required to access dissipative divertor conditions in NT, the reduction in $n_{e\text{-}sep}$ needed to detach in unfavorable ion $B\times\nabla B$ direction, the degradation of the X-point T_e approaching detachment of the outer divertor leg and the stronger role of drifts on in/out particle asymmetries due to the larger X-point major radius in NT shapes. The role of leg length and radial transport were isolated in the simulations, highlighting how NT geometry and the reduction in λ_q are responsible for the high density needed for detachment in NT (Figure 2). The success in qualitatively reproducing experimental observations of access to detachment in NT plasmas with fluid codes increases the confidence in future studies for the optimization of NT divertors.

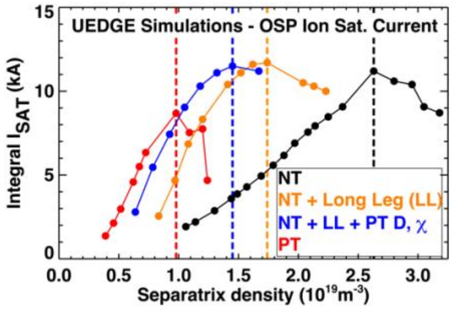

Figure 2 OSP ion saturation current (I_{SAT}) in density scans in UEDGE for: NT (black), NT with longer divertor leg (orange), NT with long leg and PT radial transport (blue) and PT (red). Dashed lines indicate $n_{e\text{-}sep}$ at detachment. Radial transport and geometry are responsible for higher $n_{e\text{-}sep}$ needed in NT.

The high density needed to detach was not intrinsic to the quiescent NT edge, as shapes with reduced average δ (positive lower δ and negative upper δ) were able to detach at lower $n_{e\text{-}sep}$, while maintaining an ELM-free NT edge. Systematic experimental detachment scans were performed in discharges with normalized plasma pressure β_N~2, scanning average δ from -0.5 to 0, while keeping the non-X-point δ of -0.4. At reduced NT, detachment was obtained at lower density compared to strong NT (f_{Gw}~0.9 vs 1.3), but with similar parametric dependencies, highlighting the role of longer $L_{//}$ and wider λ_q. Confinement degradation at deeper detachment levels (H-mode confinement factor $H_{98,y2}$~1.3 in attached conditions, $H_{98,y2}$~1.0 at detachment onset, $H_{98,y2}$~0.8 with deeper detachment) was, however, observed in all NT shapes, often associated with radiation instabilities starting at the high field side X-point and with the loss of the T_e pedestal [6]. A better isolation of X-point from recycling surfaces could help improve core-edge integration in NT regimes.

A new closed and pumped divertor has been designed for NT plasmas in DIII-D to improve core-edge compatibility using fluid and fluid-kinetic edge transport simulations. New NT shapes were developed in DIII-D experiments that are optimized for the proposed divertor with intermediate NT (δ~-0.3) with longer $L_{//}$ (x2.5) and poloidal leg length (2x) compared to stronger NT shapes (δ~-0.5). The intermediate NT enables access to the existing cryopump while remaining in the NT ELM-free operation space with a minimal impact on core confinement (maximized at strong NT). Closed divertor PFCs with private flux region pumping were optimized to reduce detachment onset density and improve particle control. From SOLPS-ITER and UEDGE simulations, the new divertor and plasma shapes are expected to reduce $n_{e\text{-}sep}$ at detachment up to a factor of 2 compared to strong NT shapes, improve divertor neutral compression (Figure 3), and enable particle exhaust. Simulations show higher T_e at the X-point before the onset of detachment in the new geometry, indicating reduced confinement degradation approaching detachment.

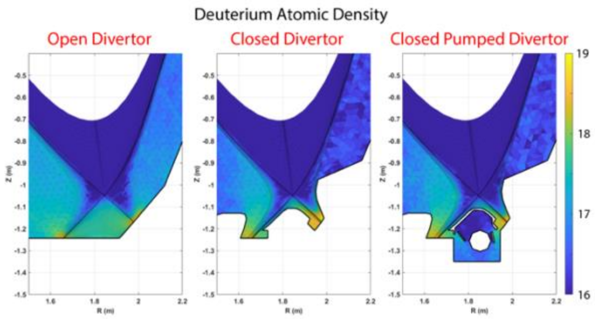

Figure 3 Effect of closure and pumping on 2D neutral density profiles in the proposed DIII-D NT divertor in SOLPS-ITER simulations. A reduction of a factor of 3 in midplane neutral density is obtained with divertor baffling.

This paper presents new experiments and modeling of divertor and SOL plasmas to establish the physics basis of NT scenarios and their potential for core-edge integration. The improved physics understanding is used to propose the next step for NT studies in DIII-D via the design of a closed pumped divertor at intermediate NT.

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