EFFECTIVE EDGE TRANSPORT BARRIERS SUPPORTED BY INTRINSIC ROTATION SHEAR IN DIII-D NEGATIVE TRIANGULARITY PLASMAS

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It is demonstrated for the first time that DIII-D plasmas with strongly negative triangularity (NT) shaping ($\delta_{Ave} \leq$ -0.35) exhibit a narrow edge transport barrier (width ~2ρ_s with ρ_s the ion sound Larmor radius) that forms due to strongly sheared counter-I_p intrinsic edge rotation (in the absence of external neutral beam torque input). This barrier forms without bifurcation, with the edge pressure gradient remaining well below the peeling-ballooning threshold, hence avoiding the conventional ELMing H-mode. Maintaining effective edge transport barriers without triggering ELMs [1] is a novel achievement in NT plasmas that eases core-edge integration issues by avoiding large transient and steady-state divertor peak heat loads. Plasmas with strong NT in DIII-D have demonstrated high normalized beta ($\beta_n \geq 2.5$) simultaneously with H-mode-like energy confinement ($H_{98} \geq 1$) at high Greenwald fraction ~1. The narrow edge barrier significantly contributes to achieving these global parameters, allowing significantly enhanced electron and ion edge temperature in contrast to weak NT or positive triangularity (PT) L-modes [1,2]. The decoupling of barrier physics from peeling-ballooning pedestal pressure limits, and the robust absence of ELMs are crucial strengths of the NT approach that warrant further exploration of NT as a reactor concept. The limited density pedestal height may also simplify plasma fueling in future reactor-relevant devices with NT shaping as NT pedestals will remain more transparent to neutrals.

The crucial physics ingredient for barrier formation in these plasmas, localized counter-current intrinsic edge rotation, is shown to be a consequence of NT shaping, due to the expected symmetry-breaking between the turbulent loss of co- and counter-I_p passing ions [3]. Fig. 1(a-c) demonstrate that plasmas with strong NT exhibit a localized, large edge density gradient, enhanced $\boldsymbol{E}\times\boldsymbol{B}$ shear, and a reduced density fluctuation level just inside the last closed flux surface (LCFS), compared to a weak NT (δ_{Ave} ~ -0.12) comparison case. The difference in $v_{E\times B}$ (and $\boldsymbol{E}\times\boldsymbol{B}$ shear) is largely due to strong counter-current toroidal rotation and rotation shear [fig. 1(d)] at strong NT (as opposed to weak co-current rotation with weak NT). In weak NT and PT plasmas, intrinsic co-rotation reduces the edge $\boldsymbol{E}\times\boldsymbol{B}$ drift and shear resulting from the ion pressure gradient, whereas with strong NT the counter-I_p intrinsic rotation

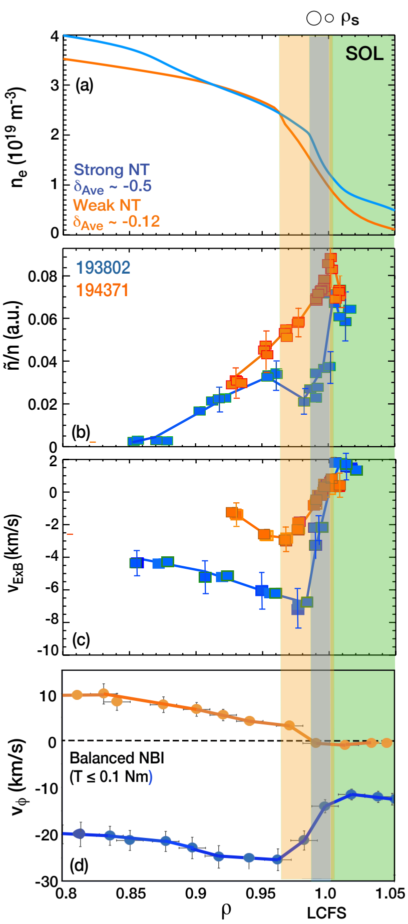


Fig. 1: (a) Electron density profile from high resolution profile reflectometry for plasmas with strong (δ_{Ave} ~ - 0.5; orange line) and weak (δ_{Ave} ~ - 0.12; blue line) negative triangularity; (b) measured density fluctuation level from Doppler Backscattering (DBS; $k_\theta\rho_s$ ~0.4-0.8); (c) edge $\boldsymbol{E}\times\boldsymbol{B}$ *velocity extracted from DBS data; (d) edge intrinsic toroidal rotation profile from impurity CER data. The width of the transport barrier for both cases is indicated by orange (194371) and blue-grey (193802) shading. The approximate size of the ion sound Larmor radius at the bottom and top pedestal is indicated on top of the figure.*

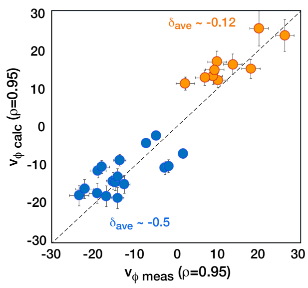


Fig. 2: Comparison of measured and calculated intrinsic edge rotation at moderate (δ_{Ave} ~ -0.12) and strongly (δ_{Ave} ~ -0.5) negative triangularity, demonstrating edge rotation reversal that leads to increased edge ***E***×***B*** *shear at strong NT (δ_{Ave} ~ -0.5) as shown in fig.1(c).*

enhances the edge E_r well and ***E***×***B*** shear. The experimentally observed direction and magnitude of intrinsic edge rotation is well described by analytical theory [3] (see fig. 2). This theory is based on the fact that co-I_p and counter-I_p directed passing ions have different radial orbit excursions due to differences in their magnetic drift in strong NT, versus weak NT or PT configurations. As a result, ions orbiting in co-current direction sample plasma regions with higher edge turbulence intensity near the LCFS with strong NT, and sample regions with weaker turbulence in weak NT or in PT plasmas. This leads to enhanced radial edge loss of co-current-directed ions in NT plasmas (hence resulting in net counter-I_p intrinsic edge rotation). Fig. 2 demonstrates that the measured intrinsic toroidal edge rotation agrees well with the theoretically predicted scaling for strong and weak NT.

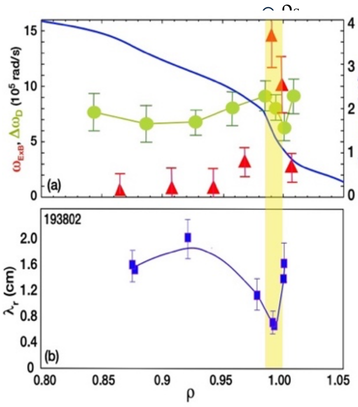
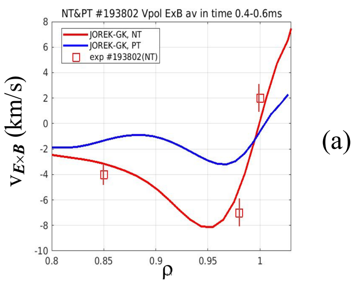


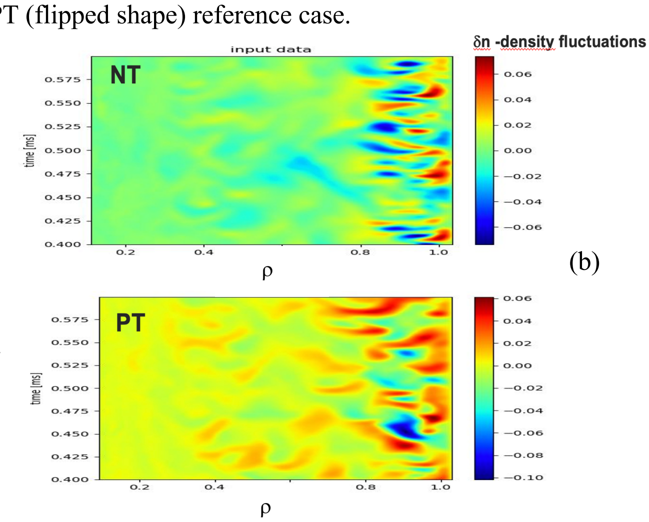
Fig. 3: (a) ***E***×***B*** *shearing rate $\omega_{E\times B}$, (red), lab-frame turbulence décor-relation rate $\Delta\omega_D$ (green), and electron density (blue) vs. normalized minor radius for a plasma with strong NT, demonstrating that $\omega_{E\times B}$ is exceeding or similar to $\Delta\omega_D$ in an extremely narrow edge transport barrier layer; (b) radial density turbulence correlation length from DBS for six reference radii.*

Narrow (~2ρ_s wide) edge barriers are confirmed via high resolution profile reflectometry [fig.1(a)] and independently via measured turbulence/shear flow properties: the ***E***×***B*** shearing rate $\omega_{E\times B}$ only exceeds the lab-frame turbulence decorrelation rate $\Delta\omega_D$ within the radially narrow barrier layer [fig. 3(a)], satisfying the criterion for local shear decorrelation and quench of turbulence [4]. The radial correlation length of density fluctuations, measured by using eight different DBS channels, exhibits a clear minimum within the edge transport barrier [fig. 3(b)] and increases significantly inboard of the barrier. Strong NT plasmas also show a locally reduced density fluctuation skewness S ~ 0 at ρ =0.98, in the outer shear layer (as opposed to S ~ 0.4 in the weak NT comparison shot; data not shown here), indicating local reduction or interruption of turbulent streamers at strong NT. Reduced transport avalanching has also been confirmed by a locally reduced Hurst exponent within the edge barrier (ρ ~0.98) at strong NT.

Global, full-f JOREK-GK gyrokinetic simulations confirm these experimental findings. Fig. 4(a), from a JOREK-GK simulation based on the equilibrium of shot 193802 (strong NT), shows a significantly enhanced well in the edge ***E***×***B*** velocity and stronger ***E***×***B*** shear, compared to a PT reference case (in flipped shape/equilibrium). These simulations also confirm reduced density fluctuation levels and radial turbulence correlation length within the edge barrier in NT shape vs. the PT reference [fig. 4(b)], in agreement with experimental results [fig. 3(b)]. Furthermore, the global simulations also confirm that intrinsic counter-current rotation increases the E_r well depth and ***E***×***B*** flow shear in NT plasmas, compared to a PT (flipped shape) reference case.



(a)



(b)

Fig. 4: (a) Edge ***E***×***B*** *velocity from global gyrokinetic simulations of shot 193802 (strong NT, red) and a PT reference case (blue), demonstrating increased* ***E***×***B*** *shear in the NT case (exp. data are shown as squares); (b) time evolution of fluctuating density across the edge shear layer from the same gyrokinetic simulations, showing reduced radial streamer extent/correlation with NT.*

In summary, we have presented evidence of a narrow but effective edge transport barrier (without H-mode bifurcation) in plasmas with strong NT shaping, that decouples barrier physics from peeling-ballooning pedestal pressure limits, enables ELM-free operation with reduced pedestal density and pressure, and significantly contributes to the enhanced global confinement properties observed in NT plasmas.

ACKNOWLEDGEMENTS

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