OPERATING BEYOND THE GREENWALD DENSITY LIMIT IN NEGATIVE TRIANGULARITY PLASMAS ON DIII-D TOKAMAK

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Negative triangularity (NT) L-mode discharges on DIII-D achieved high line-averaged densities that surpassed the Greenwald limit by ~80% with substantial neutral beam heating power. This demonstrates a viable path to sustained high-density operation beyond the Greenwald density, hence offering the prospect of high fusion power, in future fusion power plants.

To understand the underlying physics, a detailed analysis of turbulence, radiation patterns, and equilibrium profiles was conducted. These investigations reveal a synergistic interplay between turbulence and radiative condensation as a key determinant of the density limit in NT plasmas. Specifically, turbulence increases during the density ramp-up phase, leading to the formation of MARFE [1], a localized radiative instability at the high-field side. This MARFE then enhances turbulence which, in turn, limits further density growth.

This study identifies distinct power and turbulence dependencies for density limits in the core and edge regions, instead of a single uniform scaling. The maximum density scales differently with loss power (P_{SOL}): $n_e \propto P_{\mathrm{SOL}}^{0.27\pm0.03}$ at mid-radius versus $n_e \propto P_{\mathrm{SOL}}^{0.42\pm0.04}$ at the separatrix (Fig. 1). This indicates distinct limiting mechanisms in different regions. The edge density is strongly influenced by MARFE dynamics, as it increases before MARFE onset but saturates immediately, below the Greenwald limit, afterward. Conversely, the core density is primarily limited by turbulent transport, which readily exceeds the Greenwald limit and saturates only when density fluctuations surpass a critical level. The observed responses of core density to midplane turbulence post-MARFE ($n_e \propto \tilde{n}_{\mathrm{MP}}^{0.25}$, Fig. 2) and edge density to HFS turbulence pre-MARFE ($n_e \propto \tilde{n}_{\mathrm{HFS}}^{0.42}$, Fig. 3) aligned closely with the respective power scaling, providing further support for the proposed interpretation.

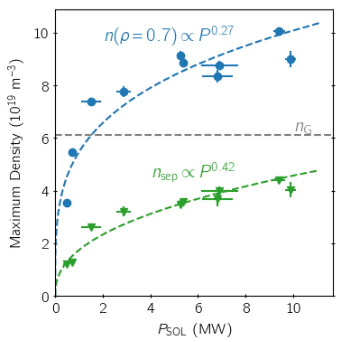

Fig. 1: Power scaling of maximum density at the separatrix (green) and core (blue).

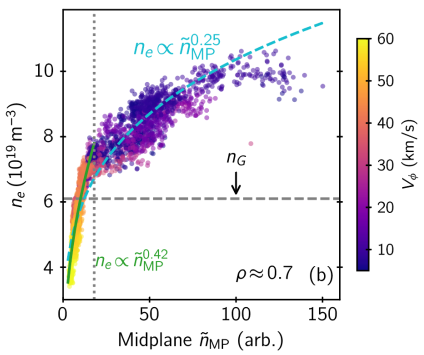

Fig. 2: Density at $\rho = 0.7$ plotted against mid-plane density turbulence. Density saturated at high turbulence.

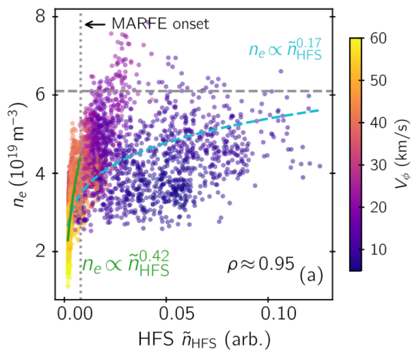

Fig. 3: Density at $\rho = 0.95$ plotted against HFS turbulence. Density saturated after MARFE.

As the density is raised in this study, substantial changes in equilibrium profiles are observed. Both electron and ion temperatures decrease, and the toroidal rotation profile flattens. The adiabaticity parameter ($\alpha_{\mathrm{adia}} = k_\parallel^2 v_{te}^2/\omega\nu_{ei}$) concurrently falls below unity near the $q = 3$ rational surface (Fig. 4), coinciding with discharge termination. The E_r profile collapses near the density limit (Fig. 5), indicating a weakened mean shear layer and allowing enhanced turbulent transport.

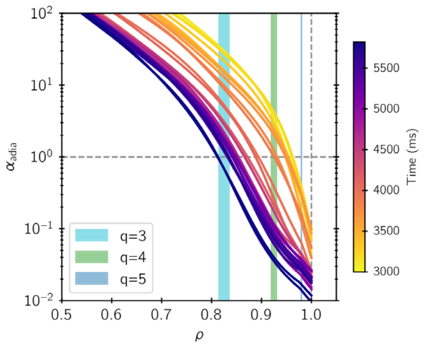

Figure 4: Time evolution of the radial profile of the adiabaticity parameter.

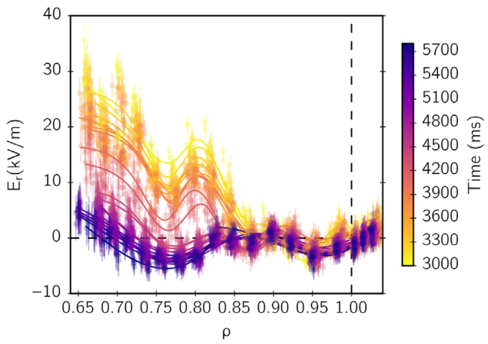

Figure 5: Time evolution of the E_r profile, which collapsed towards the density limit.

During the approach to the density limit, the edge plasma transitions from an initially attached divertor state to the formation of enhanced divertor radiation, ultimately developing into a MARFE. The MARFE, forming in the inner divertor and propagating along the high-field side (HFS) separatrix, significantly altered turbulence characteristics.

Beam emission spectroscopy measurements at the low-field side edge show increased normalized density fluctuation amplitude, changes in poloidal phase velocity, and variations in Reynolds stress and turbulent fluxes during the MARFE formation. Radial interferometer-polarimeter measurements show increased line-integrated density fluctuations across the midplane after the MARFE onset. These line-integrated density fluctuations also exhibit increased kurtosis ($K \approx 6$) and Hurst exponent ($H \approx 0.8$), as well as a $1/f$-type power-law spectrum, indicating avalanches in density fluctuations. Linear and nonlinear simulations using a 3-field fluid model within the BOUT++ framework have been conducted, and the results suggest that both resistive ballooning modes and drift-Alfven waves are important instabilities contributing to enhanced turbulent transport near the density limit.

Approaching the disruptive density limit, the toroidal rotation speed decreases towards zero, suggesting its potential role in maintaining high-density plasma stability. It is worth noting that neither temperature nor the shearing rate of the toroidal rotation converge to single values, indicating that the temperature or the flow shear alone does not determine the disruptive density limit in this experiment.

This research significantly advances our understanding of density limits in L-mode tokamak plasmas, potentially inspiring more compact and cost-effective designs of future fusion power plants. The results lead us to move beyond the traditional concept of a single, universal density limit, by revealing a more complex picture where distinct mechanisms govern the density limit in different regions of the tokamak plasma. The observed relationship between power, turbulence, and density suggests that higher heating power can enable operation significantly above the Greenwald limit. Realizing this in future reactors, however, will require advanced diagnostics and control systems for mitigating MARFEs and managing turbulence to achieve and sustain high-density operation.

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