THE CRITICAL ROLE OF SHEAR FLOW COLLAPSE IN NEAR GREENWALD DENSITY LIMIT OPERATION ON THE HL-2A TOKAMAK

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Although Greenwald himself emphasized the critical role of turbulent transport in density limits as early as 2002 [1], it was not until recent work by researchers like Singh and Diamond [2] that theoretical models for density limits in large high-temperature tokamak plasmas gradually emerged. They believes that zonal flows collapse and the turbulence level increases when the density exceeds the critical density. As a result, the local edge particle and heat diffusivities increase. Internationally, there have been few studies examining density limit physics from the perspective of turbulence-shear flow competition, either theoretically or experimentally. In this research, we conduct experimental investigations on the behavior of the turbulence-shear flow system in the edge region under high-density operation to elucidate the physical mechanisms underlying density limits.

This study demonstrates the simultaneous achievement of active detachment control and high-density plasma operation on the HL-2A tokamak, while providing new insights into the critical role of turbulence and transport mechanisms in this operational regime. A total of 40 discharges with comparable high-density detached configurations were analyzed, characterized by L-mode operation in a single lower divertor configuration with line-averaged densities ranging from $0.63n_{GW}$ to $0.91n_{GW}$ (where n_{GW} represents the Greenwald density limit).

For detailed analysis, shot #39070 was selected as the representative case, with shot #39069 serving as a comparative reference. Both discharges shared nearly identical operational parameters: plasma current ($I_p = 160$ kA), toroidal magnetic field ($B_t = 1.36$ T), and auxiliary heating power (390 kW neutral beam injection). As consecutive discharges, they are presumed to have comparable wall conditioning states. Active detachment was achieved through controlled nitrogen injection from the divertor target into the divertor chamber.

The recovery process of radial density profile redistribution has been systematically investigated. A distinct bifurcation pattern emerges between core and edge regions: continuous electron density accumulation persists within the core region ($\rho < 0.7$), while relative density stabilization characterizes the edge domain ($\rho > 0.7$). This core density amplification drives significant profile steepening through radial density redistribution mechanisms.

Following detachment recovery, temporal evolution of the density gradient reveals progressive development of a saddle-shaped profile morphology, with the inflection minimum localized at $\rho \approx 0.7$. Such structural evolution implies strong localized electron accumulation, which fundamentally modifies the radial electric field (E_r) configuration through space charge effects.

The enhanced E_r field induces consequential plasma dynamics, generating sustained poloidal rotation (V_θ) in the $\rho \approx 0.7$ transition region. This self-consistent $E_r \times B$ torque mechanism establishes a transport barrier, effectively maintaining the observed high-density confinement state through velocity shear stabilization.

The temporal evolution of radial toroidal velocity profiles (V_φ) has been systematically examined. A characteristic toroidal flow reversal is observed at $\rho \sim 0.7$, demonstrating the formation of a significant toroidal velocity shear layer at this critical radial position. This shear structure plays a crucial role in facilitating enhanced confinement of the high-density core plasma through shear-induced stabilization mechanisms.

Furthermore, the shear layer maintains remarkable stability throughout the density redistribution phase, persisting until the eventual disruption triggered as the plasma approaches the Greenwald density limit. This critical transition occurs when the established shear configuration becomes insufficient to sustain the accumulated free energy in the core region, leading to an abrupt collapse of toroidal rotation within the shear layer.

The turbulence characteristics within the shear layer - a critical radial domain exhibiting density profile redistribution and toroidal velocity reversal - have been systematically investigated. Figure 1 presents the time-frequency spectrum derived from Beam Emission Spectroscopy (BES) measurements at normalized radial coordinate $\rho = 0.714$. This analysis reveals the first experimental observation of a novel turbulence mode oscillating at 18.6 kHz. Notably, this mode emerges abruptly following plasma detachment events and demonstrates strict spatial localization within the shear layer boundaries. Detailed experimental characterization identifies the 18.6 kHz mode as: (1) Highly localized in radial extent; (2) Low poloidal mode number structure; (3) Predominantly electrostatic in nature. This mode serves as a distinct signature and dominant mode of shear and shear-induced profile redistribution, edge turbulence inhibition and compatible operation under close Greenwald density limit on the HL-2A tokamak.

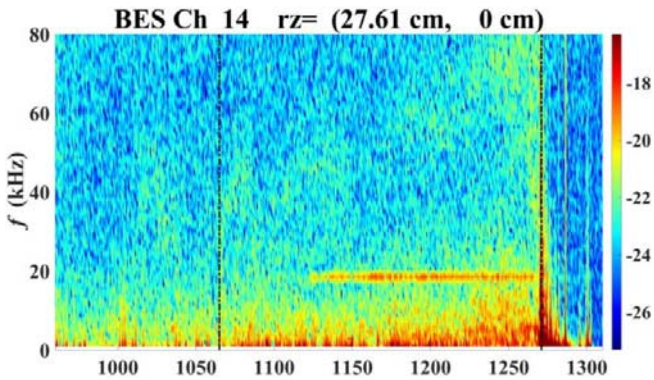

Figure 1. Power spectrum of BES signal at location $\rho = 0.714$.

The breakdown of plasma compatibility is systematically examined as the density approaches the Greenwald limit. Through integrated diagnostic analysis, the temporal evolution reveals a precise sequence of physical processes:

(1) Pre-1263ms: Continuous density ramp establishes a steep gradient (∇n), enhancing free energy sources for instabilities.
(2) t=1263ms: Onset of turbulence amplification and intensified edge particle transport.
(3) t=1264ms: Initiation of linear density decay.
(4) t=1266ms: Concurrent suppression of 18.6kHz modes and commencement of toroidal rotation damping.
(5) t=1268ms: Saturation of edge probe signals, indicative of particle fluxes exceeding diagnostic thresholds.
(6) t=1270ms: Disruption onset coinciding with complete rotation collapse.

Our experimental findings demonstrate shear layer degradation phenomena as plasma density approaches the Greenwald density limit, while revealing the existence of a critical shear threshold governing disruption onset. This investigation highlights the pivotal role of turbulence-shear dynamic competition in disruption mechanisms.

ACKNOWLEDGEMENTS

The author (Y.Yu) would like to acknowledge the HL-2A/HL-3 team. This work is supported by the National Key Research and Development Program of China under Grant No. 2022YFE03100002, and the National Natural Science Foundation of China under Grant No. 12435015.

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