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Dynamics of transport barriers formation in HL-3 experiment and gyro-kinetic simulations

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The understanding of transport characteristics in L- and H-mode plasma is fundamental to advancing fusion research. In experiment and simulation, transport barriers are often created through plasma self-organization when sufficient heating power is applied, often involving complex interactions between plasma flows, magnetic field configurations, and turbulence mechanisms. In the outer plasma region, the Edge Transport Barrier (ETB) give rise to the high-confinement mode (H-mode), which create a "pedestal" in pressure profiles and dramatically improve energy confinement. Internal Transport Barriers (ITBs) which formed in the inner plasma region can further improve the performance by reducing heat and particle losses across multiple radial zones. Both the barrier types are crucial for achieving the plasma conditions needed for economical fusion energy.

Plasmas are initialized from L-mode, characterized by anomalous transport mechanisms that lead to strong profile constraints. L-mode is often referred to as profile stiffness or profile resilience. This stiffness implies that the plasma temperature and density profiles resist changes, limiting the achievable gradients despite variations in heating power or other external parameters. When ITBs are generated in L-mode plasmas, the behavior represents a significant deviation from typical L-mode, where turbulent transport is greatly reduced in localized regions within the plasma core. The formation of ITBs is generally associated with the suppression of turbulence through mechanisms like shear flow stabilization and changes in the radial electric field. For instance, the E×B shear can decorrelate turbulent eddies, reducing transport and allowing for the formation of sharp profile gradients. It is also related to the magnetic field configuration, heating method/power, etc.

Aiming at a deeper understanding of transport barriers in L-mode plasmas, we performed 13 discharges with the HL-3 tokamak between April 2024 and June 2025. These experiments employed both constant current and current ramp-up scenarios with varied heating configurations, combining Electron Cyclotron Heating (ECH) and Neutral Beam Injection (NBI) with total heating power ranging from 2.5 to 3.0 MW. In shot #6521, the core in temperature reached approximately 2.0 keV with clear evidence of internal transport barrier formation visible in the radial temperature profiles near 700ms. Energy confinement characteristics showed promising results, with the best stored energy achieved reaching approximately 300 kJ in shot #13373. Various heating schemes demonstrated differential impacts on plasma parameters, with some discharges exhibiting sawtooth oscillations indicative of specific magnetic field configurations. Shot #12192 notably demonstrated the complex relationship between increased NBI power and plasma confinement properties, highlighting the nonlinear nature of energy transport mechanisms in these regimes.

Safety factor profiles were successfully measured for current ramp-up experiments, particularly in shots #13374 and #13375, using Motional Stark Effect (MSE) diagnostics with equilibrium reconstruction performed via OMFIT. The time evolution of these profiles revealed initial q_0 values of approximately 2.6 at t=234ms, decreasing to about 1.5 by t=1408ms. While a key experimental goal was to establish reversed magnetic shear configuration, all measured q-profiles maintained positive shear. This outcome suggests that the implemented current ramp-up rate (initial rise to 300 kA in 100ms, followed by slow ramp to 600 kA by 1200ms) may have been insufficient to prevent current diffusion before the desired reversed q-profile could be established. Sawtooth oscillations observed in constant current discharges (#13371, #13372, #13373) provided further evidence of central safety factor values (q_0) below unity at the magnetic axis.

Temperature measurements across the discharge series revealed consistent Te/Ti temperature ratio regime characteristics, with core electron temperatures typically reaching 1.5-2.0 keV while ion temperatures generally remained lower at 0.75-1.0 keV, maintaining Te/Ti ratios consistently above unity. The application of ECH during current ramp-up phases effectively raised electron temperatures to approximately 1.5 keV, while NBI effects on ion temperature varied depending on power levels.

This experimental campaign provides valuable insights into ITB formation mechanisms in tokamak plasmas with unity electron/ion temperature ratio, while identifying specific challenges in achieving advanced magnetic configurations. For the next step, transport analysis using TRANSP or TASK code will help to better understand current penetration dynamics, and the gyrokinetic simulations using GKNET code can further investigate the formation mechanism based on the shear flow dynamics.

References

[1] Fujita, T., et al. (1997). PRL 78(12): 2377.
[2] Wolf, R. (2002). PPCF 45(1): R1.
[3] Yu, D., et al. (2016). NF 56(5): 056003.
[4] Ida, K. and T. Fujita (2018). PPCF 60(3): 033001.