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Evidence for Anomalous Effects on the Current Evolution in Tokamak Operating Scenarios*

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In advanced tokamak (AT) modes of operation [1], the desired current density profile is fully sustained using a combination of external, noninductive current drive sources along with the internally driven bootstrap current density (J_{BS}). These AT modes impose significant demands in establishing a self-consistent pressure profile to properly align J_{BS} along with external sources to achieve the desired current density profile for optimal stability. Alternatives to the usual picture of AT discharges are those that form when anomalous effects alter the plasma current and pressure profiles, and/or those discharges that achieve stationarity through self-organizing mechanisms, so that the desired AT characteristics are maintained without external current-profile control. Two regimes that exhibit this behavior are those with evolution of the safety factor (q) to a stationary profile with $q(0)>1$ and those with a deeply hollow current channel. Operating scenarios with high fusion performance at low current and where the inductively-driven current density achieves a stationary configuration with either no or small sawteeth, may extend the pulse length and increase the neutron fluence per pulse on ITER and future burning plasmas. Hollow current profile discharges exhibit high confinement and a strong "box-like" internal transport barrier (ITB). In assessing the effects on the q profiles due to anomalous conductivity, we use a combination of time-dependent analysis of experimental data to compare and contrast with modeling of the discharge evolution. Determination of the underlying physical processes leading to these anomalous effects is important for scaling of current experiments to potential application in future burning plasma devices.

Experiments worldwide have discovered inductively-driven operating configurations with moderately high performance where the stationary q profile remains above unity. These stationary conditions have been observed [as evidenced by the motional Stark effect (MSE) data] on several experiments in two distinctly different operating regimes, the hybrid mode [2,3] and quiescent double barriers (QDB) mode [4], the latter of which can be described as a quiescent H-mode (QH-mode) with an ITB. In both cases, we present evidence for the presence of anomalous current diffusion in the stationary phase that alters the q profile evolution in the DIII-D experiment. We compare the AT current profile evolution that is well described by neoclassical conductivity with the hybrid and QDB stationary conditions where anomalous affects help determine the minimum of q, q_{min}. We use CORSICA modeling of discharges to compare and contrast with the experimental observations.

In hybrid scenarios, while the usual feedback control of density and power are employed, a key ingredient is the ability to passively sustain a stationary current density profile with safety factor above 1.0 everywhere and, therefore, with no sawteeth over several current diffusion time scales. The lack of sawteeth with $q>1$ in turn minimizes the seed-island drive and the excitation of a deleterious $m=2/n=1$ neoclassical tearing mode (NTM). This permits operation with higher performance and β_N closer to the no-wall limit. The hybrid stationarity is seen to be closely linked to the presence of an $n=2$ or $n=3$ NTM. As shown in Fig. 1, we compare the anomalously stationary hybrid discharges with the modeled evolution and assess the influence of beam diffusion. Experimental and theoretical efforts are underway to find the mechanism by which these NTMs sustain $q(0)>1$ indefinitely.

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In a manner similar to the hybrid mode, QDB operation in DIII-D also requires precise establishment of discharge conditions. In this case, strong shaping with active control of the density profile via divertor pumping is required. To date, we achieve the QDB in DIII-D by operation with counter-NBI and excitation of the edge harmonic oscillation (EHO). The EHO, consistent with peeling-ballooning mode stability drive for an external kink, provides the edge density transport required for particle control. In these discharges, we also observe quasi-stationary q profile evolution where we have maintained q_{min} significantly higher than 1.0, e.g. $q_{min} \sim 1.5$, by incorporating off-axis current drive. Again, evolution with nearly constant values of core safety factor indicates anomalous effects are important. We demonstrate the presence of the anomalous stationarity of the current profile in QDB scenarios through CORSICA discharge simulations that include a hyper-resistivity model, an effective anomalous electron viscosity [5,6].

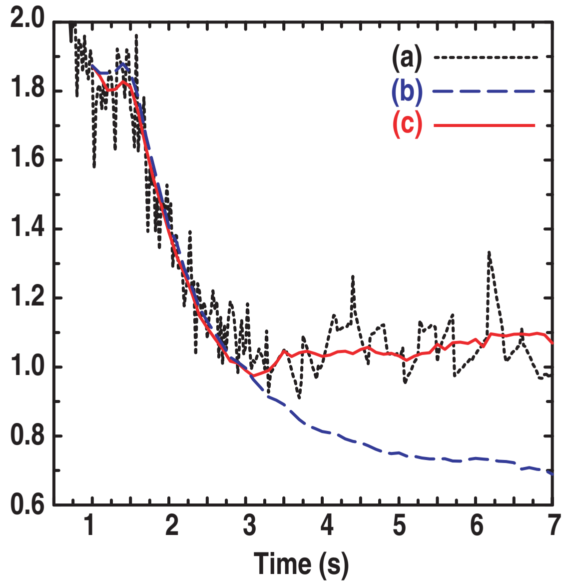

Fig. 1. $q(0)$ evolution for DIII-D hybrid shot 104276 indicating anomalous effects: (a) MSE-constrained EFIT and Ohm's law evolution using measured kinetic profiles with (b) neoclassical conductivity and (c) neoclassical plus conductivity limit model.

High-confinement "current-hole" plasmas have been generated and sustained in the DIII-D tokamak. In such discharges, the current profile is observed to be organized by a combination of the slowing down of inductively-driven flux diffusion, formation of an internal transport barrier, and the resulting strong bootstrap current in the middle of the plasma. In a self-organizing manner, the strongly reversed shear also causes strong diffusion of fast-ions thus suppressing the usual neutral beam current drive in the core and enhancing the current drive outside the barrier. The current profile in the presence of a strongly hollow current profile is difficult to obtain through equilibrium fits due to fast-ion redistribution in these plasmas. However, robust MSE-constrained equilibrium fits for DIII-D current-hole discharges have been obtained. We compare the kinetic fits obtained using different models for the neutral beam dynamics. We show the profiles of these current components obtained from the TRANSP code that are consistent with the current and pressure profiles obtained from the experimental data.

In summary, we present analyses of three distinct modes of operation on DIII-D that appear to require some level of self-organization and/or anomalous current or fast ion diffusion effects: hybrid modes generated from H-mode-like conditions, QDB operation with and ITB formed from counter-NBI into a QH-mode plasma, and high confinement hollow-current profile discharges. We examine the role of these anomalous current evolution effects to explore details of the current profile formation and maintenance. Modeling results of the ramp-up phase of hybrid discharges in DIII-D will be presented. By contrasting measurements with the neoclassical evolution we infer the location and amount of anomalous current diffusion required to maintain these discharges. A hyper-resistive model is applied to provide at least a heuristic understanding of the current evolution observed in QDB modes. Additional data to explore these characteristics will be obtained in operation using the new balanced-NBI capabilities on DIII-D and an associated upgrade to the MSE diagnostic. The effect of changing the mix of co- and counter-NBI to the neutral beam current drive and the current evolution in the hybrid and QH/QDB discharges will be assessed.

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