Plasma Shape and Safety Factor Optimization for Steady-State Tokamak Development in DIII-D


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Recent steady-state scenario development studies on DIII-D have focused on the optimization of plasma shape and safety factor profile. Steady-state tokamak operation requires all the plasma current be driven noninductively. The bulk of this must be provided by bootstrap current with the remainder provided by external sources such as electron cyclotron and neutral beam current drive. The bootstrap current fraction \( f_{BS} \) scales as \( q \beta_N \), where \( q \) is the safety factor and \( \beta_N \) is the normalized pressure. The work discussed here uses a high triangularity double-null (DN) magnetic divertor shape with \( q_{min} > 1.5 \). The shape is chosen to maximize the ideal-wall external kink stability and therefore the achievable \( \beta_N \). Elevated \( q_{min} \) is chosen because ideal MHD stability modelling suggests high \( q_{min} \) scenarios can have a high wall-stabilized \( \beta_N \)-limit, and higher \( q_{min} \) is expected to generate higher \( f_{BS} \). Systematic scans show that the baseline DN shape has a significant performance dependence on the shape parameter squareness (\( \zeta \)), which may be adjusted without affecting divertor coupling. Within the range of \( \zeta \) explored, the achievable \( \beta_N \) varied by \( \sim 30\% \), the energy confinement time (\( \tau_E \)) at fixed \( \beta_N \approx 2.4 \) varied by \( \sim 30\% \), and \( \tau_E \) at peak sustainable \( \beta_N \) varied by \( \sim 70\% \). These variations are attributable to greater pedestal pressure and external kink stability and lower core thermal transport at the lower end of the \( \zeta \) range. A small imbalance of the DN divertor optimizes the control of the line-averaged density through pumping with reductions up to 30%. Using these shape optimizations, the \( q_{min} > 1.5 \) scenario has achieved a noninductive fraction \( f_{NI} = I_{NI}/I_P \) near unity for over 1 second with \( 3.5 < \beta_N < 3.9 \), \( f_{BS} > 65\% \), and good confinement. Similar optimization of the \( q \)-profile is underway. In some cases as \( q_{min} \) is increased, \( \tau_E \) and maximum \( \beta_N \) are observed to decrease, so maximum \( f_{BS} \) may not correspond to the highest \( q_{min} \).

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