Progress Toward Steady State Tokamak Operation Exploiting the high bootstrap current fraction regime

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Recent DIII-D experiments have advanced the normalized fusion performance of the high bootstrap current fraction tokamak regime toward reactor-relevant steady state operation. The experiments, conducted by a joint team of researchers from the DIII-D and EAST tokamaks, developed a fully noninductive scenario that could be extended on EAST to a demonstration of long pulse steady-state tokamak operation. Fully noninductive plasmas with extremely high values of the poloidal beta, $\beta_p \geq 4$, have been sustained at $\beta_T \geq 2\%$ for long durations with excellent energy confinement quality ($H_{98,2} \geq 1.5$) and internal transport barriers (ITBs) generated at large minor radius ($\geq 0.6$) in all channels ($T_e, T_i, n_e, V_T f$). Large bootstrap fraction ($f_{BS} \sim 80\%$) has been obtained with high $\beta_p$. ITBs have been shown to be compatible with steady state operation. Because of the unusually large ITB radius, normalized pressure is not limited to low $\beta_N$ values by internal ITB-driven modes. $\beta_N$ up to $\sim 4.3$ has been obtained by optimizing the plasma-wall distance. The scenario is robust against several variations, including replacing some on-axis with off-axis neutral beam injection (NBI), adding electron cyclotron (EC) heating, and reducing the NBI torque by a factor of 2. This latter observation is particularly promising for extension of the scenario to EAST, where maximum power is obtained with balanced NBI injection, and to a reactor, expected to have low rotation. However, modeling of this regime has provided new challenges to state-of-the-art modeling capabilities: quasilinear models can dramatically underpredict the electron transport, and the Sauter bootstrap current can be insufficient. The analysis shows first-principle NEO is in good agreement with experiments for the bootstrap current calculation and ETG modes with a larger saturated amplitude or EM modes may provide the missing electron transport.

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