100% noninductive operation at high beta using Off-axis ECCD in DIII-D

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Abstract. The Advanced Tokamak (AT) program on DIII-D is to develop the scientific basis for steady state, high-performance operation in future devices. We report on experiments attempting to demonstrate sustainment of 100% noninductive current for several seconds at high beta, using up to 2.5 MW of off-axis electron cyclotron current drive (ECCD) and up to 15 MW of neutral beam injection (NBI) with $q_{95} \approx 5$. A 100% noninductive condition was achieved both globally and locally across the plasma with $\beta_T = 3.6\%$, $\beta_N = 3.5$, and $H_{89} = 2.4$. However, the duration of this phase was limited by the pressure profile evolution, leading to MHD instabilities after about 0.7 s. In a separate discharge, a nearly (~90%) noninductive, stationary condition was maintained for one current relaxation time (1.8 s), only limited by the duration of the hardware system. These experiments have achieved normalized fusion performance $\beta_N H_{89}/q_{95}^2 \approx 0.3$ with bootstrap current fraction $f_{BS} \approx 60\%$, consistent with requirements for the ITER $Q=5$ steady-state scenarios. The modeling tools that were successfully employed to devise experiments in DIII-D are applied to ITER, indicating full noninductive operation is plausible for an ITER steady state scenario with $Q \approx 5$.