100% Noninductive Operation at High Beta Using Off-axis ECCD[*]

EX-C

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The Advanced Tokamak (AT) program on DIII-D is aimed at developing the scientific basis for steady-state, high performance operation in future devices. The key element of the program is to demonstrate sustainment of 100% noninductive current for several seconds at high beta. Guided by integrated modeling, recent experiments using 2.5 MW of off-axis ECCD and ≤15 MW NBI with $q_{95} \approx 5$ have sustained ≈100% of the plasma current noninductively for 1 s at high beta ($\beta \approx 3.6\%$, $\beta_N \approx 3.4$, above the no-wall limit) with $q_{min} \geq 1.5$ and good confinement ($H_{89P} \approx 2.3$). Integrated modelings using both empirical and theory-based models are used to design experiments and to interpret their results. Modeling validates that a full noninductive discharge for >3 s (≥ current replacement time) can be achieved with a longer ECCD pulse and resistive wall mode feedback presently available. These experiments have achieved the parameters required for the ITER Q=5 steady-state scenarios, and the same modeling tools are already being applied to ITER simulations.

Based on previous experiments [1] with $q_{min} > 1.5$, $\beta_N = 2.9$, $f_{BS} \sim 50\%$, predictive modeling [2] indicates that increasing the neutral beam power would result in plasmas reaching a noninductive current fraction $f_{NI} \approx 100\%$ at higher β. Experiments have been carried out to test these predictions. Using 2.5 MW of off-axis (ρ = 0.4-0.5) ECCD and ≈15 MW NBI with $q_{95} = 5.0$, nearly 100% of the plasma current has been sustained for 0.5 s at high beta ($\beta \approx 3.6\%$, $\beta_N \approx 3.4$, slightly above the empirical no-wall limit, $4\ell_i$) with $q_{min} > 1.5$, as in Fig. 1. The makeup of the current profile in these discharges was analyzed using different codes including different bootstrap models. The experimental Ohmic current profile [Fig. 1(e)] is directly determined from internal loop voltage analysis (NVLOOP) using

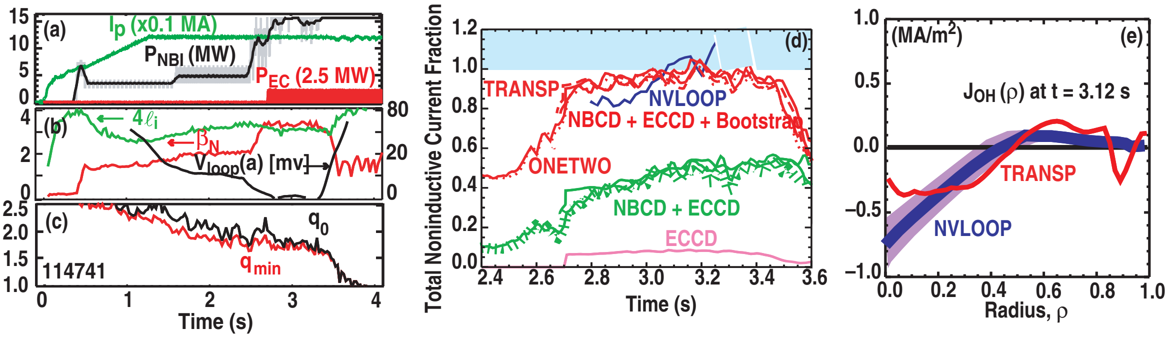

Fig. 1. A typical AT discharge with $f_{NI} \approx 100\%$, $\beta_N = 3.4$ and $\beta \approx 3.6\%$: Time histories of (a) plasma current I_p, neutral beam power P_{NBI}, EC power P_{EC}; (b) normalized beta β_N, approximate no-wall β limit $4\ell_i$, and loop voltage V_{loop}; (c) axial (q_0) and minimum (q_{min}) safety factor; (d) evolution of noninductive current fraction as determined from internal loop voltage analysis (NVLOOP) and from transport simulation using TRANSP and ONETWO with different bootstrap current and neutral beam current drive models; (d) the simulated Ohmic current profile agrees well with the experimental profile determined from an internal loop voltage analysis.

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a time series of motional Stark effect (MSE)-constrained equilibrium reconstruction with neoclassical resistivity. Transport codes (ONETWO and TRANSP) calculate the Ohmic current by subtracting the calculated noninductive currents (electron cyclotron and neutral beam CD and bootstrap current) from the total current calculated from the reconstructed plasma equilibrium. While all of the required current is driven noninductively, alignment of driven current and total current is incomplete. Near the magnetic axis, the neutral beam drive actually overdrives the local current density, resulting in negative Ohmic current

Close coupling between modeling and experiment is a key to understand complex interactions associated with profile evolution and their integration into self-consistent high performance scenario in future experiments. A simulation in ONETWO using the retuned GLF23 [3] model was carried out for a ≈90% noninductive fraction case to predict the evolution toward a stationary state. The T_e, T_i, and toroidal momentum equations are solved with self-consistent "source and sink" calculations by time stepping from initial profiles over several confinement times. Figure 2 shows the resulting profiles that are in good agreement with experimental profiles. Simulation using GLF23 modeling of more recent shots with elevated NB power request shows that the predictive toroidal rotation is higher by about 50% than the experiment. Possible explanation for the discrepancy is a drag term due to the magnetic error fields and/or RWM effects missing in the toroidal momentum equation. Simulation also shows confinement improvement by using more negative central shear configuration rather than nearly monotonic q-profiles that occurred in the present experiments. This motivates efforts to improve RWM feedback and magnetic shear in the coming experiments. Experiments with fast wave current drive in these AT discharges are also planned to control the central magnetic shear.

These experiments have direct relevance to development of the ITER Q=5 steady-state scenario. These experiments have achieved a fusion performance figure of merit. $H_{89}\beta_N/q_{95}^2 \approx 0.3$ with bootstrap current fraction, $f_{BS} \approx 50\%$ that are required for the ITER Q=5 steady-state scenario. The same modeling tools are already being applied to ITER simulations. Special numerical techniques were developed to accelerate convergence to steady state conditions. Simulation of the DIII-D case shown by dashed curve in Fig. 2 indicates a small drop in the central safety factor due to the fully penetrated Ohmic current with little change in other profiles. The unique steady-state solution capability is particularly useful to predict steady-state performance of burning plasma experiments, since time-dependent stepping to steady state using a stiff transport model requires prohibitive computer time.

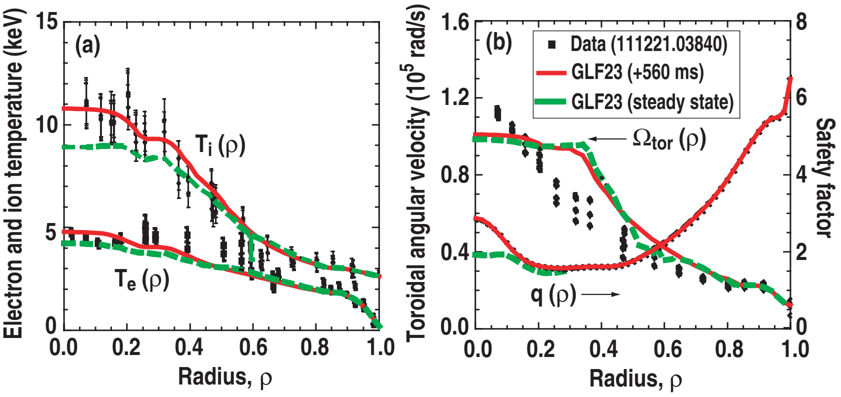

Fig. 2. Theory-based (GLF23) model predictions and experimental measurements of profiles of (a) electron and ion temperature and (b) angular rotation velocity and safety factor for the previously reported ≈90% noninductive AT discharge. Solid curves are predicted profiles with time-dependent calculations at 0.56 s after starting with the initial experimental profiles, and dashed curves are steady-state calculations including the poloidal magnetic field equation.

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