CURRENT PROFILE MODIFICATION WITH ELECTRON CYCLOTRON CURRENT DRIVE IN THE DIII–D TOKAMAK*

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Control of the plasma current profile is necessary to extend present high performance regimes achieved transiently on the DIII–D tokamak to steady state. Beyond the obvious need to maintain the total plasma current non-inductively, both the plasma stability and transport are dependent on the current profile. Electron cyclotron current drive (ECCD) is the leading candidate to fulfill this role on DIII–D due to the straightforward ability to control both the location and magnitude of the driven current under a wide variety of conditions. Recent experiments have clearly demonstrated the ability to affect the central current density and the plasma internal inductance in open loop tests with injected power >1 MW at 110 GHz. The central current driven by ECCD is up to 100 kA and total non-inductive current fractions (including neutral beam and bootstrap currents) over 75% have been achieved in 0.6 MA L–mode discharges. The current drive efficiency exhibits the predicted linear increase with electron temperature T_e and is similar to previous results from fast wave current drive [1].

The present ECCD system on DIII–D consists of two gyrotrons at 110 GHz. The first is a diode-type gyrotron rated at 900 kW for 2 s. The second is a triode-type gyrotron rated at 1 MW for 0.8 s. Both gyrotrons are limited in delivered energy by heating of the output window. Evacuated corrugated transmission line (31.75 mm diam.) delivers the power to the tokamak. Despite the long transmission line (~40 m), less than 5% is expected to be lost in the waveguide between the gyrotron and the tokamak. Two of the miter bends contain grooved mirrors to alter the linear polarization from the gyrotron to almost any desired polarization. The waves are launched into the tokamak from a copper mirror which can steer the beam poloidally. The toroidal angle is fixed in each launcher — one is set for co-current drive (ϕ = 24–31° depending on poloidal steering and waveguide position) and the other is set for purely radial launch. The experiments reported employ second harmonic absorption of the X–mode.

Power modulation techniques are employed to determine where the beam illuminates the resonance. Plasma response is measured by a 32-channel heterodyne radiometer measuring the electron temperature perturbation. Signal processing by Fourier analysis is used to

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increase the signal-to-noise ratio. The main absorption moves with the steering of the beam as expected. However, secondary peaks which appear for the farthest off-axis steering can be identified with second pass absorption of both X–mode and O–mode. (Due to low electron temperature and density in the outer half of the plasma and large $k_{||}$, the second harmonic X–mode first pass absorption is incomplete.) The slightly impure polarization limits the type of transport experiments which can be done at present, but does not significantly affect the current drive experiments.

Current drive experiments have clearly demonstrated modification of the central current density. The current drive is measured by the technique of taking spatial and temporal derivatives of the reconstructed poloidal flux ψ [2]. This is only feasible due to the excellent internal field measurements from the 35-channel motional Stark effect diagnostic. At any given value of enclosed toroidal flux (roughly minor radius), the time derivative of ψ gives $E_{||}$, while two spatial derivatives give the current density J. Assuming neoclassical resistivity [2], the ohmic current density $\sigma E_{||}$ can be subtracted from total J to give the non-inductive current J_{NI}. Both modeling and appropriate fiducial discharges have been used to separate the ECCD from the neutral beam current drive (NBCD) and bootstrap current. An example of central current drive is shown in Fig. 1. The discharge is developed to be a sawtooth-free L–mode plasma by the addition of early beam injection to maintain q(0) > 1. The top trace is ψ at the magnetic axis. On application of the EC power, $\partial\psi(0)/\partial t$ changes sign indicating that the central loop voltage has gone from positive to negative. This indicates the central non-inductive current drive is larger than the existing ohmic current; therefore, a back emf is generated. For reference a discharge without ECCD is shown. The central loop voltage remains positive throughout. Despite the long skin time, the ECCD is sufficient to modify the current density as indicated by q(0) [$\propto$ J(0)] in the second trace. The bottom trace shows that even the global quantities (here ℓ_i) change on the time scale of the ECCD pulse (~1 s). Because the current adds to the existing current, q(0) = 1 is achieved more rapidly as demonstrated by the earlier onset of sawteeth. Up to 200 kA of central ECCD has been observed in discharges like these. The efficiency of the central ECCD exhibits the expected temperature dependence and agrees with the current drive predicted by a linear model [3]. A more stringent test of this model will be the off-axis ECCD experiments now in progress.

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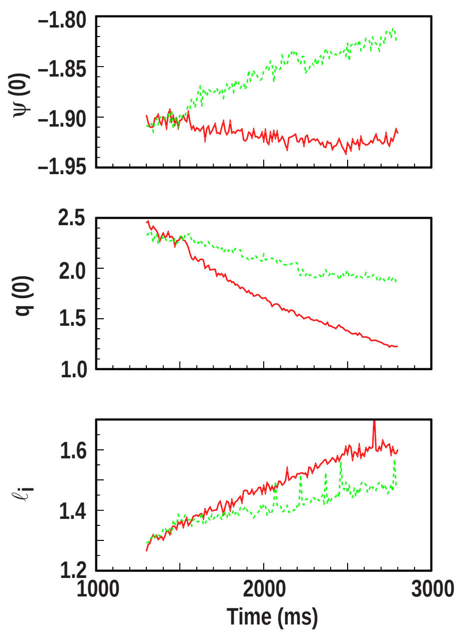

Fig. 1. Time histories of the poloidal flux at the magnetic axis $\psi(0)$, the safety factor at the axis q(0), and the internal inductance (ℓ_i) for a discharge with (solid line) and without (dashed line) ECCD. The single gyrotron delivers ~0.5 MW starting at 1500 ms.