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Electron Cyclotron Current Drive and Current Profile Control in the DIII–D Tokamak*

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Recent work in many tokamaks has indicated that optimization of the current profile is a key element needed to sustain modes of improved confinement and stability. Generation of localized current through application of electron cyclotron (EC) waves offers a means of accomplishing this. In addition to profile control, electron cyclotron current drive (ECCD) is useful for sustaining the bulk current in a steady state manner and for instability suppression. ECCD is particularly well suited for control of the current profile because the location of the driven current can be regulated by external means, through steering of the incident EC waves and setting the magnitude of the toroidal magnetic field. Under most conditions the location of the driven current is insensitive to the plasma parameters. Central ECCD has been studied in a number of tokamaks and found to have characteristics commensurate with theory as expressed through ray tracing and Fokker-Planck computer codes. The present experiments on DIII–D explore central current drive and are the first to test off-axis ECCD. These experiments are unique in using internal measurements of the magnetic field to determine the magnitude and profile of driven current.

ECH System

The EC waves are generated by two 110 GHz gyrotrons capable of combined power of 1.7 MW for 1 s pulses. The transmission lines are windowless evacuated corrugated waveguides of relatively small diameter, 31.75 mm, which have operated with excellent reliability in extensive operation. Two pairs of mirrors have been used as wave launchers, one of which has a toroidal angular component of 19 deg, used for current drive, while the other has nearly radial injection. The launch location is in the upper outboard side as illustrated in Fig. 1. The mirrors can be rotated about a horizontal axis between discharges to steer the beam in the poloidal direction.

Each gyrotron contains a mode converter followed by a set of relay mirrors which produce a “flattened Gaussian” distribution at the gyrotron window in order to spread the thermal load on the window. Two external mirrors are designed to transform the waves into a Gaussian distribution of the correct diameter and constant phase at the input to the waveguide in order to couple the power to the HE_{11} waveguide mode. In the initial implementation the mirror surfaces were calculated from a model of the internal mode converter and the relay mirrors, but very significant improvements in the coupling efficiency have been made by using *ad hoc* determinations of the phase fronts. These determinations are made by imaging the heating (proportional to the square of the local wave amplitude) of a resistive screen placed in the beam from a gyrotron. By combining such measurements at several distances

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from the gyrotron the phase fronts can be reconstructed, and from these empirical phase fronts the correct mirror surfaces can be determined. In combination with staff from MIT and Gycom, using separate computational models, new mirrors designed using this process have improved the coupling to the waveguide from just over 60% with the theoretical mirrors to greater than 80% for each gyrotron system. Further improvements are expected as this process becomes more sophisticated.

The 110 GHz power corresponds to the second harmonic of the electron cyclotron frequency in DIII–D. A wave incident at the edge of the plasma can be decomposed into two normal modes when it enters the plasma, the ordinary mode (O–mode) and the extraordinary mode (X–mode), which differ in polarization. Since the O–mode is weakly damped near the second harmonic resonance while the X–mode is strongly damped, it is desirable to have the incident wave polarized so that it couples purely to the X–mode. The wave polarization is performed in the waveguide by grooved mirrors in two consecutive mitre bends [1]. With this system, nearly any elliptical polarization can be obtained by adjusting the inclination of the grooved mirrors. The desired polarization for coupling to the X–mode is calculated for the actual equilibrium and wave angles in use.

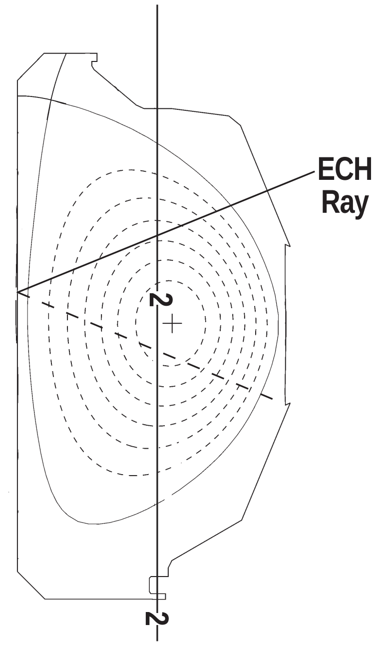

Fig. 1. Plasma magnetic equilibrium for discharge #96225. The ray shown is the center of a narrow EC beam launched radially, neglecting refraction. The toroidal field is 1.97 T and the plasma current is 0.6 MA.

In order to test the effect of the polarizers on high power waves in the waveguide, a polarimeter was developed by H. Ikezi [2]. The polarimeter samples the power in the waveguide through a mitre bend with a partially transmitting mirror. The polarimeter uses a spinning birefringent plate to determine the polarization as a function of time. This device was able to uncover some errors in the initial implementation of the polarizers and small birefringence in some of the waveguide elements.

Experimental Results

The heat deposition profile can be estimated by modulating the heating and looking for the profile of response in the electron temperature (as indicated by the intensity of second harmonic emission). This response, along with knowledge of the density profile and the differential volume of the plasma, can be used to calculate the power density as a function of normalized minor radius. In general, the effect of transport is to make the plasma response broader in minor radius than the heating profile, and the lower the modulation frequency the larger the effect. In DIII–D modulation at 100 Hz allows some broadening, but higher frequencies suffer from low signal-to-noise ratio.

The geometry of Fig. 1 is useful for testing the effect of polarization. The wave is incident nearly normally on the plasma, and the power propagates into the plasma where the X–mode component is fully absorbed near the resonance at a normalized minor radius of 0.4. The

O–mode component is calculated to be only 5% absorbed there and the remaining power propagates through the plasma to the inner wall. Specular reflection there sends the wave back nearer the center of the plasma at minor radius 0.2, where absorption is higher, calculated to be about 20%, due to the higher temperature and density. The remaining unabsorbed power in the O–mode ray is probably scattered at the vessel walls, with the possibility of some mode conversion, and it is absorbed partly by the plasma and partly by the walls.

The importance of optimizing the wave polarization can be seen directly in the plasma heating for the geometry of Fig. 1. Figure 2 shows power density profiles for three polarizations of the incident waves. It is clear that setting the polarizers to apply nearly pure X–mode (calculated) produces the largest response near the first pass intersection of the ray and the resonance. For pure O–mode polarization, on the other hand, the response at 0.4 is very small but the the response at 0.2 is much larger. For a calculated equal mix of modes, the response is mixed. Hence, for maximum effectiveness it is important to excite a pure X–mode at the plasma edge, not only because the heating profile is closer to the desired profile, but also because the fraction of the incident power appearing in the plasma is larger.

Initial experiments on current drive with central aiming of the antennas and oblique launch showed that large noninductive currents, with the ECCD component in excess of 100 kA, could be obtained [3]. The current drive figure of merit, η, exhibits the expected linear dependence on the electron temperature, and it reaches 3×10^{18} A/Wm^2 at 7 keV. This value is about 65% of the η found for fast wave current drive at similar power levels in DIII–D [4]. This difference may be due to non-thermal effects caused by the local back-EMF induced to conserve the magnetic flux when current drive is initiated. For the ECCD cases considered here the driven current density exceeds the equilibrium current density, so the net local electric field is negative. Previous experiments in DIII–D have shown that modest electric fields, 0.2 V/turn, can have effects of this order of magnitude on the ECCD, and that the effect increases approximately like the square of T_e/n_e [5]. Modeling with a Fokker-Planck code is underway.

Off-axis ECCD is accomplished by aiming the oblique steering mirrors and adusting the toroidal field so that the intersection of the rays with the second harmonic resonance occurs near the desired minor radius. Off-axis driven currents are measured in the same way as central currents [3]. When the EC deposition is placed at a normalized minor radius of 0.4, the total noninductive current rises by of order 50 kA with a profile peaked near that minor radius. Most of this change can be attributed to ECCD, rather than neutral beam current drive

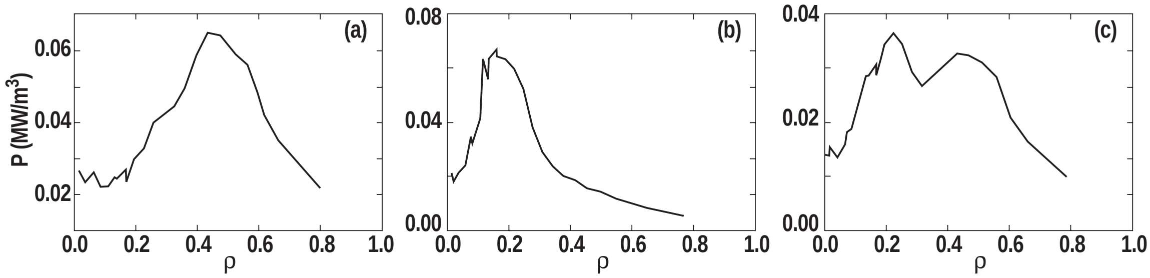

Fig. 2. Measured profiles of response characterized as MW/m^3 to 0.59 MW of ECH power modulated at 100 Hz using the CPI gyrotron. The geometry is as shown in Fig. 1. The EC waves polarized as (a) X–mode (#96225), (b) O–mode (#96226), and (c) 44% X–mode and 56% O–mode (#96227). The volume integrated power is 0.53 MW, 0.29 MW, and 0.39 MW respectively.

or bootstrap current, but the detailed breakdown of the noninductive current into its components is in progress.

The effect of central co-ECCD is to peak the current profile (as described in Ref. 3), while off-axis co-ECCD broadens the current profile. This can be seen in Fig. 3 in which discharges with no ECCD, central co-ECCD, and off-axis co-ECCD are compared. For central CD, the central safety factor $q(0)$ drops more rapidly than without ECCD [Fig. 3(a)], and the global parameter describing the current profile, the internal inductance, increases [Fig. 3(b)]. Changes are small on the time scale of the ECH pulse due to the long inductive times characteristic of these high temperature plasmas. The central loop voltage, the time derivative of the central flux shown in Fig. 3(c), changes sign when the central ECCD is applied, giving a negative loop voltage. Off-axis ECCD causes the central safety factor to increase as shown in Fig. 3(a), as expected due to the slow broadening of the current-regulated discharge on the resistive time scale. Similarly, the internal inductance decreases. The central loop voltages for the NBI-only and off-axis ECCD cases are the same to within the precision of the measurement. These results for off-axis CD qualitatively support the more detailed determinations of the profiles of driven current which are being made using the standard reconstruction techniques previously applied to central ECCD [3].

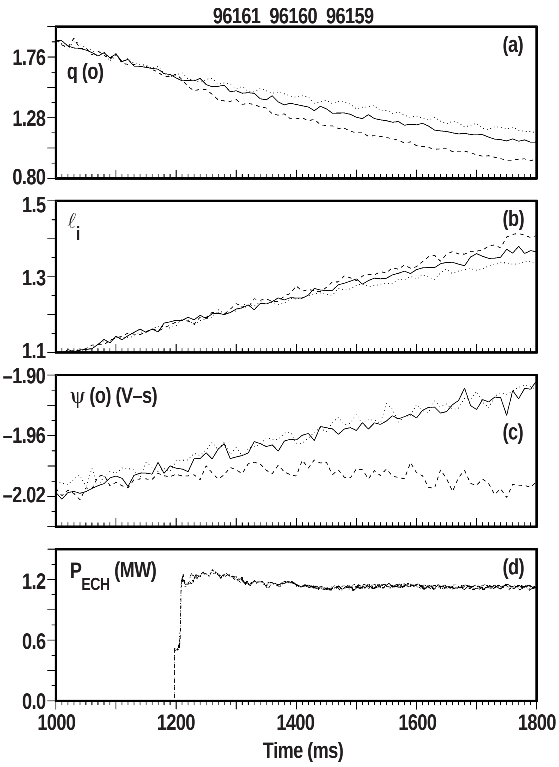

Fig. 3. The central safety factor q(0), the internal inductance l_i, the poloidal flux at the plasma center, and the applied ECH power, for three discharges. In #96161 there is no ECH power, in #96160 (dashed line) there is central co-ECCD (1.03 MW), and in #96159 (dotted line) there is co-ECCD (1.07 MW) applied at a normalized minor radius near 0.4. The toroidal field is 1.97 T, the line-averaged electron density is 1.7×10^{19} m^{-3}, and the plasma current is 1.0 MA. In all three cases the neutral beam power is 2.5 MW.

In summary, central and off-axis current drive have the expected effects on the discharge parameters. Detailed calculations of the magnitude and profile of the driven current are underway. Accurate coupling to the X–mode is beneficial to overall power efficiency as well as control of the deposition profile, and it can be accomplished through control of the incident polarization.

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