GA–A23687

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This is a preprint of a paper to be presented at the 14th Topical Conference on Applications of Radio Frequency Power to Plasmas, May 7–9, 2001, in Oxnard, California, and to be published in the *Proceedings.*

Work supported by
the U.S. Department of Energy
under Contracts DE-AC03-99ER54463 and DE-AC05-76OR00033

GA PROJECT 30033
JUNE 2001

Co-toroidal Plasma Rotation with Electron Cyclotron Power in DIII–D

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Abstract. RF electron heating and current drive in DIII-D are observed to typically reduce the core toroidal rotation velocity and core ion temperature when added to target discharges with rotation established by neutral beam heating. Two cases are noted here in which electron cyclotron heating and current drive are observed to increase co-toroidal rotation in different discharge regimes. In the first case electron cyclotron current drive (ECCD) is used to stabilize a 3/2 neoclassical tearing mode (NTM) and the stabilization is accompanied by an increase in rotation, ion temperature and plasma beta. In the second case electron cyclotron heating (ECH) added to a nominally Ohmic target discharge results in an increase in the co-toroidal rotation.

INTRODUCTION

Electron heating with rf power, either EC or Fast Wave, in DIII–D generally results in a decrease in the core toroidal rotation velocity and the core ion temperature, T_i [1,2]. These are invariably target discharges in which the toroidal rotation velocity, V_ϕ, has been established with neutral beam injection (NBI) and in which $T_i > T_e$, the electron temperature. The best explanation at this time is that an increase in T_e/T_i results in increased turbulent transport of ion momentum and energy [2].

In this paper we note two recent DIII–D cases in which the application of EC power has resulted in an increase in co-toroidal rotation (in the direction of the plasma current), as well as T_i. In the first, co-ECCD is used to stabilize a NTM [3] resulting in a restoration in confinement. Although perhaps an expected result, this serves to highlight the effect of internal MHD modes on plasma rotation. In the cases where V_ϕ is reduced by rf heating it is important to identify cases in which MHD activity is triggered by the heating or current drive. In the second example ECH is added to a "nominally" Ohmic discharge and an increase is measured in co-rotation, as well as in T_i. Short pulses of NBI must be used for the charge exchange recombination (CER) measurements of V_ϕ and T_i of the ambient carbon impurity, but comparison of times with and without ECH shows that these NBI "blips" are not affecting the measurements enough to mask the ECH result.

NTM STABILIZATION

NTMs have been stabilized on DIII–D with the application of localized co-ECCD, as predicted theoretically [3]. The EC current replaces bootstrap current "washed out" by the magnetic island, thereby reducing the island size. Figure 1 shows traces from two discharges, one with ECCD NTM stabilization (104328) and a comparison discharge without ECCD (104325). The mode amplitude is driven down to the noise level of the external loops used to measure the fluctuating magnetic field. With this stabilization the

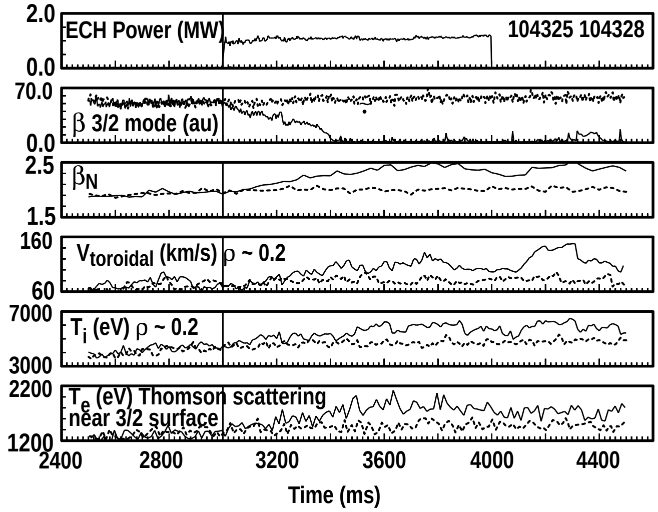

Figure 1. With co-ECCD quenching of the NTM mode htere is an increase in β_N, $V_{toroidal}$, T_i, and T_e. Shot 104328 has ECCD and 104325 is a comparison with no ECCD.

plasma stored energy increases, shown by the trace of β_N, where $\beta(\%) = \beta_N$ I(MA)/aB. These discharges are ELMing H–modes and have sawteeth.

Accompanying this increase in β there is an increase in the core toroidal velocity and the core ion temperature. The magnetic island induced degradation in confinement is reduced, or eliminated, by the ECCD suppression. There is EC electron heating and the lower trace shows the measurement of T_e at the resonant surface by Thomson scattering. The ECCD must be placed at the right spot relative to the m=3/n=2 q surface for suppression [3].

The measured radial profiles of T_e, T_i, electron density n_e, and angular toroidal rotation velocity V_ϕ/R, are shown in Fig. 2 for both discharges in Fig. 1. The horizontal axis is the normalized toroidal flux, ρ, a measure of the minor radius. Each of these profiles shows an increase in the core with NTM stabilization. The 3/2 surface corresponds approximately to ρ = 0.55.

Transport analysis with the ONETWO transport code indicates a decrease of about a factor of 2 in the ion thermal diffusivity in the core with NTM stabilization. Of course, with a magnetic island present there is not a true diffusivity in all liklihood, yet this analysis does serve to give a comparison and to compute the NBI heating source and verify that there is not a significant source difference.

CO-ROTATION ACCOMPANYING ECH IN OHMIC DISCHARGES

A series of experiments has been done to investigate the possibility of a heat pinch [4] by using off-axis ECH and looking for anomalous electron heating near the axis. For the discharges considered here the heating location is at the second electron cyclotron harmonic (110 GHz), near ρ = 0.3, on the high field side and above the midplane. The EC waves are launched from the low field side with minimal $k_{||}$ in order to limit the absorption width due to Doppler shifts.

The key traces from one discharge in this experiment are shown in Fig. 3. The plasma current and magnetic field are constant over this time at 1.2 MA and 1.65 T, respectively. The upper traces show the time of application of ECH and 4 NBI blips for CER measurements. With ECH there is a rise in T_e, and a slight increase in the line

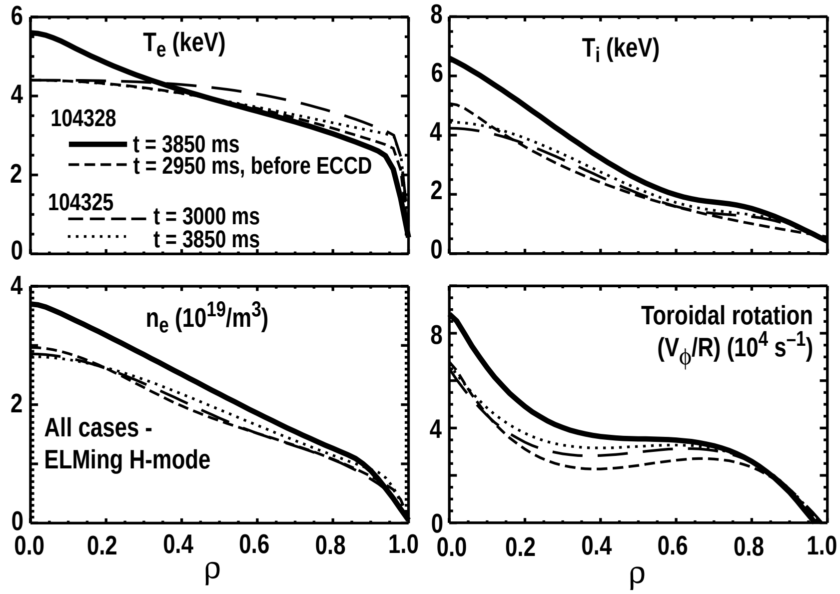

Figure 2. Kinetic profiles show increases with NTM stabilization.

averaged electon density. The lower two boxes show the CER analyzed carbon toroidal velocity and ion temperature. Comparing the blip times during ECH with the one before indicates that there is an increase in both V_ϕ and T_i. For all of these time slices this discharge has sawteeth.

Also shown is the beginning of a beam pulse after the ECH has been turned off, around t=3000 ms. However the same CER blip is not the first NBI pulse at this time as it was for the preceeding 4 blips. At this later time there has been greater NBI torque

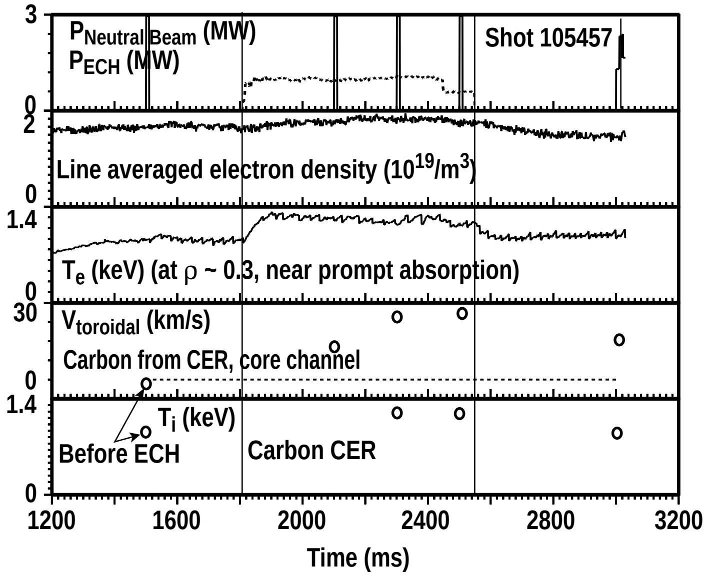

Figure 3. Core $V_{toroidal}$ enhanced with ECH, as well as core T_i. NBI blips are used for CER ion kinetic measurements but do not dominate the toroidal rotation.

applied by the time of the CER measurements. Nevertheless, V_ϕ and T_i are still somewhat below the values during ECH. So there is a development of co-rotation, and possibly small improvement in ion thermal confinement accompanying the application of ECH. The effect may in some way be related to C-MOD observations of co-rotation enhancement with rf heating [5].

Full angular rotation profiles are shown in Fig. 4 for the five time slices shown in Fig. 3. Before ECH there is a small counter rotation in the core, with co in the outer region. With ECH a significant co-rotation develops in the core. In the later time (t=3025 ms) a qualitative difference can be seen in the rotation profile showing some evidence of co-induced rotation from the co NBI pulse. Note that it is not known from these data whether the toroidal rotation goes sharply to zero at the outer edge or not since there was no measurement on this outer surface. These rotation rates are roughly a factor of 3 to 10 lower than what is measured in typical steady NBI heated discharges in DIII–D. In addition to a core enhancement of V_ϕ and of course T_e, due to the ECH, the n_e profiles also show a core enhancement during the ECH pulse.

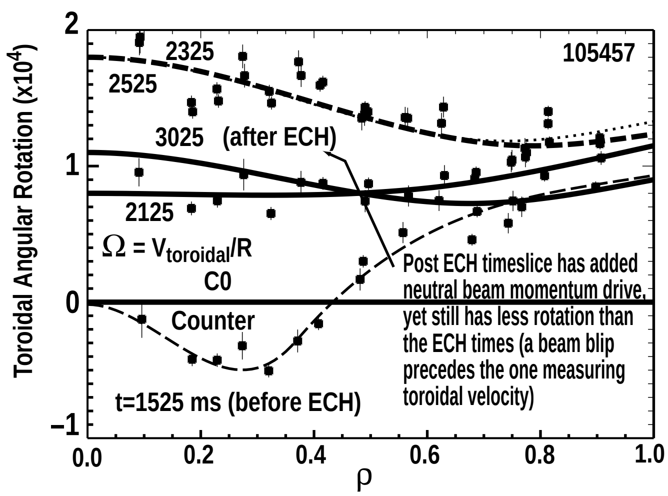

Figure 4. Toroidal rotation profiles from CER at the 5 NBI times indicated in Fig. 3; essentially an Ohmic target discharge, sawteeth at all times.

ACKNOWLEDGMENT

Work supported by U.S. Department of Energy under Contracts DE-AC03-99ER54463 and DE-AC05-76OR00033.

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