Conf-950704--6

GA–A22088

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This is a preprint of a paper presented at the 22nd EPS Conference on Controlled Fusion and Plasma Physics, July 3–7, 1995, Bournemouth, United Kingdom, and to be printed in the *Proceedings.*

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Work supported by
U.S. Department of Energy Contracts
DE–AC03–89ER51114 and DE–AC05–84OR21400

GENERAL ATOMICS PROJECT 3466
JULY 1995



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# First Results on Fast Wave Current Drive in Advanced Tokamak Discharges in DIII–D

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## Abstract

Initial experiments have been performed on the DIII–D tokamak on coupling, direct electron heating, and current drive by fast waves in advanced tokamak discharges. These experiments showed efficient central heating and current drive in agreement with theory in magnitude and profile. Extrapolating these results to temperature characteristic of a power plant (25 keV) gives current drive efficiency of about 0.3 MA/m$^2$.

## Introduction

An objective of the Advanced Tokamak (AT) program on DIII–D [1] is to develop discharges with improved confinement and improved beta limit, per unit plasma current. Success may lead to fusion reactors with higher performance and lower cost. This approach also leads to higher fraction of the plasma current driven by the bootstrap effect, so that fully noninductive steady state discharges may be obtained economically even if current drive efficiencies do not improve beyond those now theoretically projected for power plant conditions.

Two particularly promising approaches to the AT program are the high $\ell_i$ and the Reverse Central Shear (RCS) discharges. Discharges in DIII–D have been shown to have confinement and beta limits which are proportional to $\ell_i$, presumably due to increased magnetic shear in the plasma core. Confinement up to 1.7 times the DIII–D/JET H–mode scaling was obtained in high $\ell_i$ H–mode discharges [2]. Likewise, RCS discharges [3] have demonstrated equilibria with very high beta [$\beta(0) = 44\%$], and discharges in which the minimum safety factor $q_{\rm min}$ is above 2.0 have greatly reduced MHD activity and improved confinement [4].

The high $\ell_i$ and RCS discharges have been obtained in DIII–D by transient means, such as ramping the plasma current or the elongation, or by applying neutral beam heating during the current rise to generate hollow current profiles. It is the goal of the current drive program on DIII–D to generate the means to sustain these discharges for the 10 sec duration of the toroidal field.

## Fast Wave Current Drive

Fast wave current drive (FWCD) has been applied in L–mode discharges in DIII–D to generate an understanding of the physics [5–7] and to develop the technology. Extensive experiments have been performed with the 2 MW, 60 MHz, system, which

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uses a four-strap antenna. The straps can be phased for electron heating $(0, \pi, 0, \pi)$, which has a launched $n_{\parallel}$ (parallel index of refraction) of about 10, or for current drive $(0, \pi/2, \pi, 3\pi/2)$ with an $n_{\parallel}$ of about 5. More recently, two new systems with frequency range 60 to 120 MHz and power of 2 MW each were added. The higher frequency is expected to have stronger damping and higher current drive efficiency in the high electron temperature plasmas expected in the AT program.

Experiments under a wide range of conditions over several years have shown that FWCD is an effective tool for driving current [8]. Full current drive was attained with 1 MW of current drive power in discharges in which the plasma current was ramped down shortly before the rf power was applied. This generated a discharge with high $\ell_i$, with improved confinement and high electron temperature relative to its final plasma current of 0.16 MA [8].

This experiment and others with partial current drive in discharges with fixed current have shown that fast wave current drive and heating can be effective even under conditions where the single pass damping is weak, as low as 5%. Comparisons of experimental results with results from the CURRAY ray tracing code show that the current drive efficiency can be understood if a power loss of about 4% per pass is arbitrarily added [8]. Figure 1 (circular data points) shows that the measured efficiency plotted as a function of electron temperature matches well with the code results. The origin of the 4% loss per pass is not understood, but it is not believed due to collisional damping. These experiments were performed with a low toroidal field, near 1 T, which helps to improve the single pass damping (which is proportional to $B^{-3}$) and minimizes the ion cyclotron damping.

Studies of wave propagation using an array of rf probes on the inner and outer walls of DIII–D show that the directionality of the antenna and the launched spectrum of parallel wavenumber are in reasonable agreement with theory [9]. Measurements shown in Fig. 2 of the parallel wavenumber detected on the inside wall across from the antenna show that the sign of $k_{\parallel}$ is as expected from the launch conditions (co-, counter-current drive, and 0 phasing), but the upshift in $k_{\parallel}$ is a little smaller than that expected from the ratio of the major radii of the antenna and the location of the detectors.

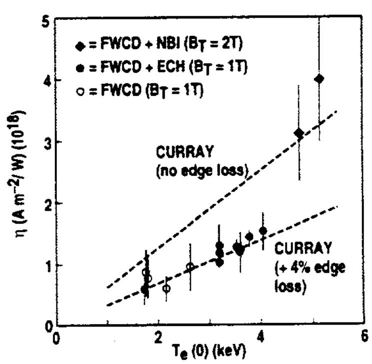


*Fig. 1: Measured FWCD efficiency as a function of electron temperature. The diamond-shaped points are taken in 2 T discharges with reversed central shear and neutral beam preheating.*

## FWCD in Reversed Central Shear Discharges

The initial work in AT discharges was done under conditions of reversed central shear, which was generated by applying 3.7 MW of neutral beam heating during the current ramp phase of the discharge to generate a hollow current profile with $q_{\min}$ above 2.0 for a period of nearly 3 sec. This RCS

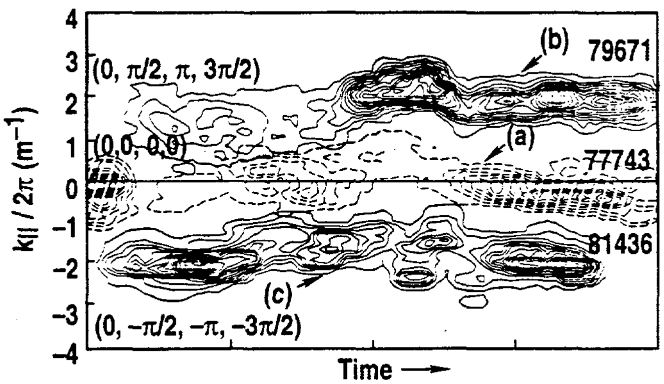


*Fig. 2: Parallel wavenumber measured on the inner wall, as a function of time for three discharges, with fast wave antenna phasing of (a)* $(0, 0, 0, 0)$, *(b)* $(0, \pi/2, \pi, 3\pi/2)$, *and (c)* $(0, -\pi/2, -\pi, -3\pi/2$.

configuration was selected for initial experiments because it has high central electron temperature which leads to high CD efficiency, it lacks sawteeth, which interfere with central current drive [10] as well as with the method of measuring the profile of driven current [11], and it has steady boundary conditions, which facilitates coupling of fast waves to the plasma. The experiment was done in deuterium plasmas at 2 T, for which the lowest frequency applied, 60 MHz, corresponds to the 4th harmonic of the ion cyclotron resonance at the center of the plasma. The hydrogen fraction was kept to a minimum (below the measurement threshold of 1% to 2% measured at the edge) to minimize ion absorption at the second harmonic. The plasma configuration was double null divertor with plasma current of 1.4 MA.

The current profile is deduced [11] from a time series of magnetic reconstructions. The reconstructions, using the EFIT code, are constrained by data from the motional Stark effect and other diagnostics measuring the electron and ion temperature profiles, the density profile, and the $Z_{eff}$ profile. A radial derivative of the flux gives the profile of the total current density and a time derivative gives the profile of electric field. Since the local electric field is known, the inductive current density can be subtracted from the total current density using neoclassical resistivity. By comparing co-current drive and counter-current drive discharges, the neutral beam driven current and the bootstrap current, which are independent of the phasing of the fast wave antenna, can be subtracted. This leaves the profile of currents driven by the fast wave power.

Profiles of FWCD determined in this manner are in excellent agreement with theory. This is shown in Fig. 3, in which the experiment is compared with calculations using the CURRAY code (without the artificial 4% loss per pass), the FASTCD code [12] which assumes stochastic rays, and the RANT3D/PICES full wave code [13]. The codes and the experiment are in striking agreement. It should be noted that none of the codes have any free parameters, and that the agreement is excellent both in profile and magnitude.

The current drive efficiency for these discharges is larger than that in discharges with normal current profiles. This is shown in Fig. 1 (diamond points). It is conjectured that the difference is due to the higher temperature in the boundary in the RCS discharges due to the additional beam heating, and that the 4% loss per bounce of the rays does not apply. (Avoidance of the 4% loss is not due to stronger damping at the higher central temperature of the RCS discharges, since these discharges are also at higher toroidal field, which greatly weakens the damping.) Extrapolation of the efficiency linearly with temperature to the 25 kV temperature of a power plant, after correcting for $Z_{eff}$, gives a respectable $\eta = 0.31 \times 10^{20}$ MA/MW m$^2$.

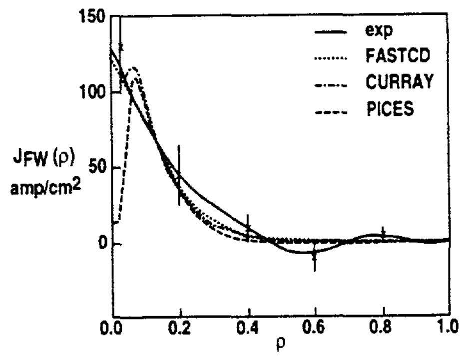


*Fig. 3: Radial profile of experimentally determined current density, with calculated profiles from three different computer codes.* $I_p = 1.4$ *MA,* $T_e(0) = 4.5$ *keV,* $n_e(0) = 2.9 \times 10^{19}$ $m^{-3}$, $B_t = 2.1$ *T,* $P_{NBI} = 3.5$ *MW,* $P_{FW} = 1.4$ *MW. The FW driven current is 0.135 MA.*

## Acknowledgments

This is a report of work supported by U.S. DOE Contracts DE-AC03-89ER51114 and DE-AC05-84OR21400 and in part by an appointment to the U.S. DOE Fusion Energy Postdoctoral Research Program at General Atomics administered by the Oak Ridge Institute for Science and Education.

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