GA–A22571

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This is a preprint of a paper presented at the 12th Topical Conference on Radio Frequency Power in Plasmas, April 1–3, 1997, Savannah, Georgia, and to be printed in the *Proceedings.*

Work supported by
U.S. Department of Energy
Contract DE-AC03-89ER51114

GENERAL ATOMICS PROJECT 3466
APRIL 1997

Reduction of Toroidal Rotation by Fast Wave Power in DIII–D

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Abstract. The application of fast wave power in DIII–D has proven effective for both electron heating and current drive Since the last RF Conference FW power has been applied to advanced confinement regimes in DIII–D; negative central shear (NCS), VH- and H–modes, high β_p, and high-ℓ_i. Typically these regimes show enhanced confinement of toroidal momentum exhibited by increased toroidal rotation velocity. Indeed, layers of large shear in toroidal velocity are associated with transport barriers. A rather common occurrence in these experiments is that the toroidal rotation velocity is decreased when the FW power is turned on, to lowest order independent of whether the antennas are phased for co or counter current drive. At present all the data is for co-injected beams. The central toroidal rotation can be reduced to 1/2 of the non-FW level. Here we describe the effect in NCS discharges with co-beam injection.

Fast wave current drive (FWCD) at high harmonics of the ion cyclotron frequency has been demonstrated on DIII–D [1,2], and a description of the DIII–D FW systems can be found in the references [1,3,4]. Recently, record levels of FW current, and efficiency have been achieved [2].

A major focus of the DIII–D program is the development of advanced tokamak scenarios, and the concomitant study the physics of discharges with enhanced confinement and transport barriers. In so-called NCS discharges, characterized by $dq/d\rho \leq 0$ in the central region, FWCD has been used to delay or advance the onset time of sawteeth, with counter- or co-current drive phasing respectively, as the central q value relaxes downward to unity [2] (here q = safety factor, ρ = minor radius coordinate). Additionally, FWCD has now been applied to a large variety of neutral beam (NB) heated discharge classes on DIII–D.

In essentially all of these conditions with FW power added to NB heated discharges, there is some level of reduction of the toroidal rotation of the discharge, as measured by charge exchange recombination spectroscopy (CER). A similar observation has been made on JET in minority ion heating mode [5]. The magnitude of the DIII–D core rotation, and the fractional reduction with FW, is largest for the NCS discharges which exhibit an internal transport barrier and values of the central ion thermal diffusivity below the so-called neoclassical value. This FW rotation slowing has also been observed in ELMing H–mode, high β_p H–mode, kappa-ramped L–mode (with some enhanced confinement), and possibly standard L–mode. To date, all of these cases have NB injection in the co-current direction.

Consider the NCS discharge shown in Fig. 1(a). To establish the NCS target conditions NB power is injected during plasma current ramp-up, which increases the electron temperature T_e, delays current penetration, and creates a transiently hollow current profile and inverted q profile [6]. Toroidal rotation u_ϕ and ion temperature T_i are measured with CER emission from ambient carbon in the discharge. CER data channels view toroidally and vertically. A core barrier is evidenced by the increase in u_ϕ and T_i at $t \cong 860$ msec. Considerable evidence indicates that this barrier results from a self consistent increase in the shear of $E \times B$ flow which reduces the turbulence driving the anomalous transport [7].

FW power is applied at $t = 1100$ msec with three systems each phased for counter current drive; 0.8 MW at 60 MHz from one system and 1.6 MW (combined) at 83 MHz from the other two. The primary deuterium ion cyclotron resonances in the core ($\rho \le 0.35$) are $n = 4$ for 60 MHz and $n = 5$, 6 for 83 MHz, where $\omega = n\Omega_D$ ($B_{T0} = 2.1$ T). Central electron heating accompanies the FW power while u_ϕ and T_i are reduced in the core (small ρ). This FW power should produce about 250 kA of central, counter FWCD, from the efficiency scaling developed from detailed analyses of the large data set on DIII–D [2], although relaxation of the current profile would not occur on this timescale. Later in the discharge, $t = 1320$ msec, the NB power is increased and u_ϕ and T_i recover to, or exceed, the pre-FW levels. Figure 1(b) shows measured rotation profiles.

Transport analyses of these three regimes with the ONETWO code reveals that the core ion thermal conductivity χ_i is small, at or below the usual neo-classical benchmark. The computed value at $\rho = 0.1$ is 0.2, 0.6, and 0.3 m^2/sec corresponding to the three increasing times in Fig. 1(b). The angular momentum diffusivity follows the same pattern.

One possible explanation for this effect is that the increase in electron temperature caused by the FW increases the turbulence which had been suppressed [7]. An increase in T_e/T_i increases the growth rate. For the three timeslices, the core χ_i is monotonic in T_e/T_i. Extensive analyses are ongoing to calculate the growth, and $E \times B$ shear stabilization rates in such NCS + FW discharges.

Other possible mechanisms are being investigated. Slowing occurs for both co- and counter launched FW power, as shown for two companion shots in Fig. 2. This apparently eliminates direct rf mechanisms which move trapped particles radially due to a wave-particle resonance linear in n_ϕ, the toroidal mode number [8]. There can be a diffusivity scaling as $(n_\phi)^2$. For the heated electrons the direction of diffusive charge transport from high to low electron density would tend to increase co rotation rather than retard it [9].

A harmonic cyclotron resonance interaction between the FW and the D ions is being examined. For lower harmonic resonances, theoretical calculations have predicted an rf driven ion diffusivity comparable to neoclassical ion transport

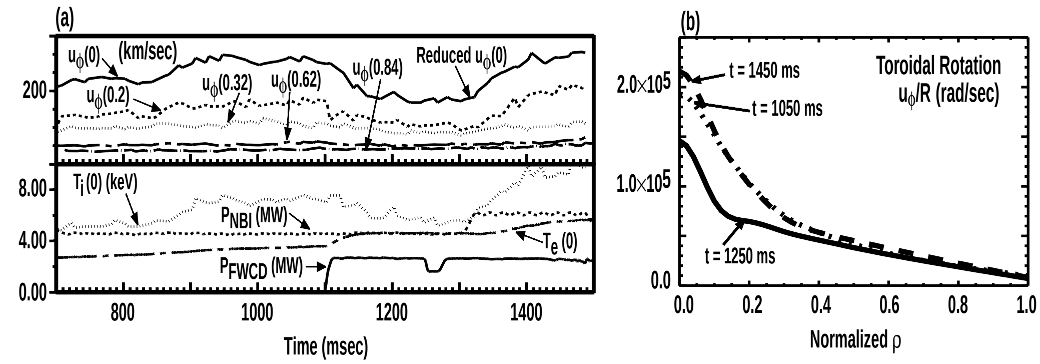

FIGURE 1. (a) FW slowing of core toroidal velocity $u_\phi(\rho)$ in DIII–D NCS discharge. (b) Profiles of u_ϕ / R at $t = 1050$, 1250, and 1450 msec.

[8,10,11]. More systematic data are required. The present data set reveals no strong signatures in FW rotation slowing as B_T is varied. FW frequency has not yet been varied. Also, $k_\perp \rho_i$ is not large, <1, assuming $k_\perp \sim k_{\text{Alfvén}}$ The resonant ion real and velocity space diffusivities are coupled via canonical angular momentum considerations. There may be some small excess in measured versus predicted neutron emission during FW [2], and we are calculating what upper bound this will place upon the incremental spatial diffusivity.

Edge effects also seem unlikely to cause slowing. A small density increase accompanies the FW power and there is an increase in the carbon influx from the edge. However a computation of Z_{eff} from carbon in the core (dominant impurity) shows little change. Z_{eff} in the outer region increases by about 50%. This limits a drag due to carbon in the core and an edge drag should slow the periphery, which is not observed experimentally. Two other external means are observed to reduce u_ϕ in DIII-D, application of external error fields for the specific purpose of slowing the rotation [12], and heavy nitrogen gas puffing into H–mode discharges for radiative divertor experiments. Both of these drive a qualitatively different response in the reduction of $u_\phi(\rho)$, namely slowing across the entire minor radius. Finally, recent results from JT60 show that the internal transport barrier in NCS survives neon and hydrogen gas puffing sufficiently large to create a radiative divertor [13].

Although the effect of T_e / T_i upon the turbulent driven transport may be applicable in explaining the FW slowing in NCS discharges, this may not be the only mechanism. A relatively smaller reduction in u_ϕ is observed in discharges without a core transport barrier. For example, in an ELMing H–mode discharge the increase in central electron temperature is very small, due to the much larger electron density, and u_ϕ is still reduced. Further, the slowing extends across the plasma, possibly due to interaction with the edge H–mode barrier.

Further experiments on DIII–D will address the effect of FW power on toroidal rotation and ion thermal transport. The emergent understanding of the role of rotational shear in transport makes this an important effect to understand. The definitive test of the role of T_e on core transport in NCS discharges will be done with the

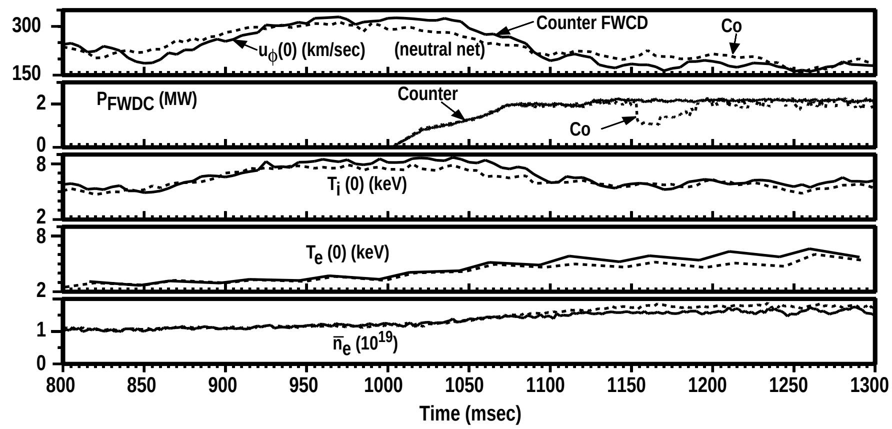

FIGURE 2. u_ϕ in the core reduced for co and counter phasing.

new DIII–D electron cyclotron heating system [14]. Another key experiment is the effect of FW in counter NBI discharges.

This is a report of work sponsored by the U.S. Department of Energy under Contract DE-AC03-89ER51114.

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