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Toroidal Rotation and Core Ion Confinement with RF Heating in DIII–D

J.S. deGrassie,[1] C.M. Greenfield,[1] D.R. Baker,[1] K.H. Burrell,[1] Y.R. Lin-Liu,[1] J. Lohr,[1] T.C. Luce,[1] C.C. Petty,[1] R. Prater,[1] G.M. Staebler,[1] W.W. Heidbrink,[2] B.W. Rice,[3] T.K. Mau,[4] and M. Porkolab[5]

[1]*General Atomics, P.O. Box 85608, San Diego, California 92186-5698*
[2]*University of California, Irvine, California*
[3]*Lawrence Livermore National Laboratory, Livermore, California*
[4]*University of California, San Diego, California*
[5]*Massachusetts Institute of Technology, Cambridge, Massachusetts*

Shear in the **E**×**B** flow velocity can stabilize turbulent transport [1], and so it is of interest to understand the physics behind electric field generation and modification in the tokamak. In DIII–D the core radial electric field in many regimes is generated by flow velocities driven by momentum input from neutral beam injection (NBI). In a variety of conditions it is observed that direct electron heating is accompanied by a reduction in the NBI driven toroidal rotation velocity, U_ϕ, and the ion temperature, T_i, primarily in the core, $\rho < 0.5$ (where ρ is a radial coordinate of the normalized toroidal flux). This electron heating can be done with either electron cyclotron heating (ECH) or fast wave electron heating (FWEH). Both can be accompanied by the reduction in U_ϕ and T_i [2–4]. Details of the parallel wavenumber ($k_{//}$) spectrum of the launched rf do not seem to be important in either case for the effect to exist. Reductions are observed for EC waves launched with nonzero $k_{//}$ for current drive or launched radially with $k_{//}$ =0; and for FWEH with waves directed either co or counter, using the DIII–D four strap antennas [5]. This universality indicates that increased electron temperature, T_e, is increasing ion momentum and thermal transport, at least in the parameter regimes of these experiments. It is also possible that nonambipolar transport of resonantly heated particles is playing a role. To date, the great majority of the DIII–D experiments have been conducted with the rf target discharges driven by co-injected NBI.

The commonality of this reduction in U_ϕ and T_i with direct electron heating is shown in Fig. 1. Data from four discharges are shown, the only difference being the details of rf electron heating. These particular discharges have co NBI applied early in the current ramp to create an inverted safety factor (*q*) profile in the core, the so-called negative central shear regime on DIII–D [3]. At the time of rf application the discharge is still evolving so it is important to compare to a discharge without any rf power, the (O) data case in Fig. 1. One discharge has 1.4 MW of ECH resonant near the magnetic axis (●), and another the same ECH power resonant off axis at $\rho \cong 0.35$ (✧). The 110 GHz EC wave is launched radially and heats at the second harmonic electron cyclotron resonance. The fourth discharge (—) has 1.7 MW of FWEH. FW damping is predominantly on electrons for this discharge in DIII–D.

The reduction in central rotation speed is shown in Fig. 1(a). It is strongest for the on axis ECH case with the largest rise in $T_e(0)$ [Fig. 1(c)], but it is also significant for the off-axis case with little change in $T_e(0)$. FWEH raises $T_e(0)$ more than off-axis ECH but is accompanied by a similar velocity reduction. The measured response in $T_i(0)$ is shown in Fig. 1(b). The velocity and ion temperature measurements are made with charge exchange recombination spectroscopy of the ambient carbon impurity in DIII–D [6]. T_e in Fig. 1(c) is measured with electron cyclotron emission radiometry [7], and also Thomson scattering.

There are conceivably numerous ways in which rf heating could affect the toroidal rotation of the discharge. In order to identify some straightforward mechanisms, consider a steady state one dimensional momentum transport equation for the main ions

$$\vec{\nabla} \cdot \left[\chi_m \vec{\nabla}\left(nMV_\phi\right)\right] + F_\phi + J_\rho B_p - f_\phi = 0 \qquad (1)$$

where the (small) charge exchange momentum damping has been neglected. Here, n is the bulk plasma ion density, M the ion mass, B_p the poloidal magnetic field, J_ρ a radial current density, F_ϕ the input NBI force density, f_ϕ the frictional force on the main ions from other species, and χ_m the momentum diffusivity. If χ_m increases with T_e, that is if the viscous drag is enhanced, then U_ϕ will be reduced. This could be due to an increase in the anomalous transport rate due to an increase in T_e/T_i, which is theoretically known to increase the growth rate of ion temperature gradient turbulence [8]. Or if a reduction in E_ρ reduces the **E**×**B** shearing rate then the shear stabilizing influence is reduced and transport could increase.

Other possibilities for modifying U_ϕ are suggested by Eq. (1). Radial nonambipolar current could result from resonant rf heating, creating a return current, J_ρ, in the bulk and applying a toroidal force to the bulk, which can be co or counter depending upon the details. C.S. Chang recently discussed this effect for ICRH [9]. The DIII–D FWEH parameters are selected to minimize ion absorption by operating at high ion cyclotron harmonic number, but some power absorption by fast beam injected ions has been observed in certain conditions [10]. Radial current from resonant electron heating should be much smaller, and it may be negligible. However, it is noted that fast ions generated by some mechanism have been reported in some ECH experiments [11,12]. For ICRH the bulk radial current J_ρ is driven by an opposite radial current of resonantly heated particles, so one must also include the mechanical momentum transfer from this resonant population via collisions, f_ϕ. Depending upon the details of the orbits, f_ϕ can largely cancel $J_\rho B_p$ [13].

Another possibility is that the NBI drive, F_ϕ, is in some way reduced by rf electron heating. Outward transport of beam ions before delivering the full momentum to the bulk would reduce F_ϕ. Magnetic modes in the core are known to degrade fast ion confinement and it is possible that strong core electron heating is leading to such modes at levels difficult to detect.

Detailed transport analyses of such rf heated discharges on DIII–D are in progress to test the theoretical consistency of the modified transport explanation [3,14]. Shown in Fig. 2 are the momentum and thermal ion diffusivity profiles for the reference and ECH discharges from Fig. 1, at t = 1450 ms (experimental data analysis done with TRANSP). Both ECH discharges show an increase in χ_m and χ_i throughout most of the interior, although the absolute levels are still small near the axis. Thus, U_ϕ and T_i are reduced near the axis largely because of increases in diffusivity farther out and the commensurate decrease in gradients (electron transport analyses are ongoing, and are described in [3,14]).

It is becoming generally understood that shear in the **E**×**B** velocity can reduce, or even eliminate, turbulent transport [1]. If the local shearing rate, $\omega_{E\times B}$, is greater than the local maximum modal growth

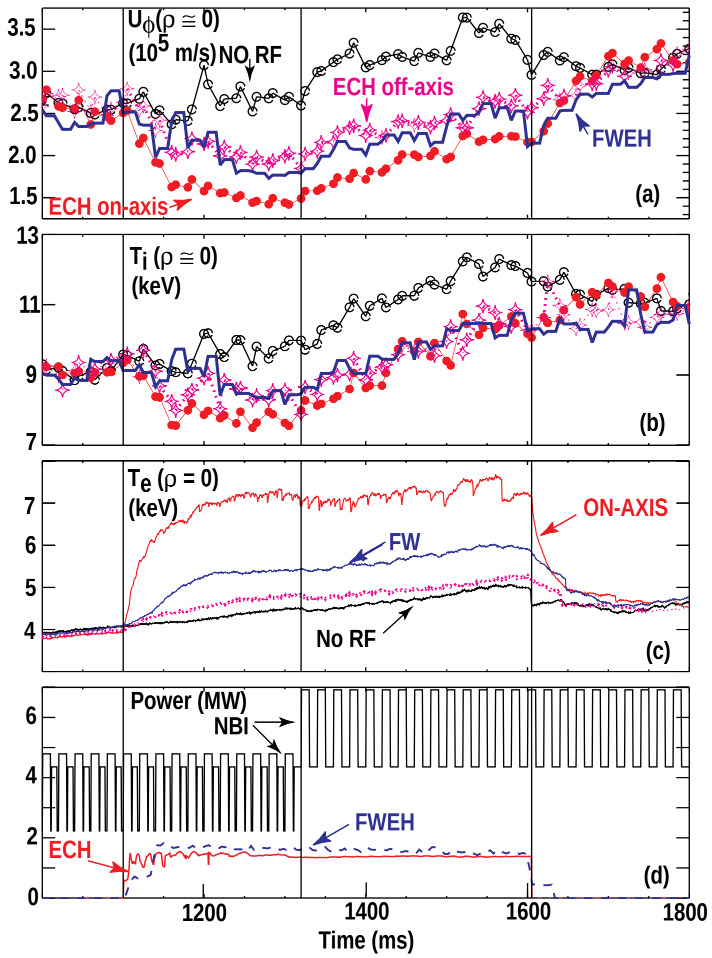

Fig. 1. (a) Toroidal velocity reduction with rf heating in three discharges; 96015 central ECH, 96013 off-axis ECH, 96002 FWEH (central electron heating), compared to 96010 with no rf heating. (b) and (c) central ion and electron temperatures for these discharges, and (d) auxiliary heating power; NBI common to all of these discharges. [I_p = 1.5 MA, B_T = 2.0 T, $\bar{n}_e$ ~ $2\times10^{19}/m^{-3}$ (evolving)]. FW power consists of 0.6 MW at 60 MHz ($k_{//}R_{ant} \cong 14$), and 1.1 MW at 83 MHz ($k_{//}R_{ant} \cong 18$).

rate, γ_{max}, then one expects a reduction of turbulent transport at that location. For these discharges $\omega_{E\times B}$ is calculated from the experimental profiles [15] and $\gamma_{max}(k)$ is calculated using a gyrokinetic stability code with non-circular, finite aspect ratio equilibria and full electromagnetic dynamics [16]. Results are shown in Fig. 3. In the region of k space typical of ion temperature gradient type modes, $k < 10\ cm^{-1}$, there is little change in the location of the stability boundary, where $\omega_{E\times B} > \gamma_{max}$, with or without ECH. However, there is a qualitative agreement in that a reduction in ω_{EXB} accompanies ECH, thereby removing some of the shear stabilizing influence, although not falling below γ_{max} in the interior. (We note that for this series of discharges the carbon level was abnormally high for DIII–D, with core Z_{eff} ~ 3, assuming carbon impurity. The carbon profiles are thus affecting the calculations of γ_{max}, contributing to the relatively small change in γ_{max}.)

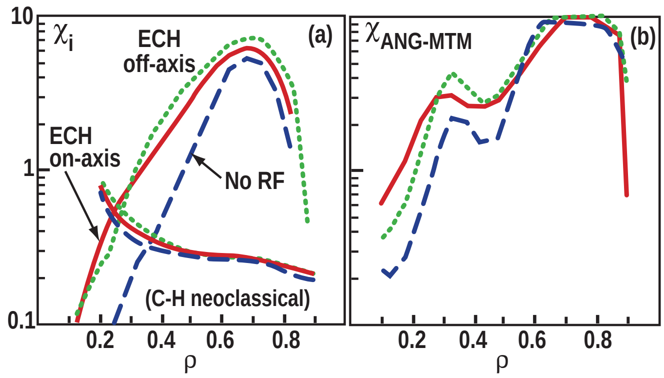

Fig. 2. Thermal (a) and angular momentum (b) diffusivities computed with TRANSP for the ECH discharges from Fig. 1, at t = 1450 ms.

In such NCS target discharges without sawteeth the central ion thermal confinement is good, with χ_i below standard neoclassical predictions (Fig. 2). One might suspect that such good confinement is conducive to this rf slowing effect in that a small incremental increase in transport would be more readily manifested. However, reduction in U_ϕ and T_i have also been observed with FW heating in non-NCS, sawtoothing discharges [4]. This particular series of experiments was carried out to investigate fast ion stabilization of sawteeth and it was concluded that the main resonance was with energetic D beam ions at the 4th harmonic [17]. Yet the data show no good correlation of the reduction in U_ϕ with an enhancement in the measured D-D neutron rate, the latter used as a measure of the amount of rf ion absorption by D ions. This indicates that even in this ion absorption experiment the mechanism of nonambipolar radial transport of fast ions is not the primary cause of slowing in the toroidal rotation, as it is assumed that the strength of this current (and thus the size of the reduction) would be proportional to the amount of rf power absorbed by the resonant ions.

The present DIII–D data on rf slowing in co rotating target discharges are best organized by T_i/T_e, whether using ECH or FW heating. This is shown in Fig. 4 where we plot $(U_{\phi o}/U_{\phi oref})$ versus $[(T_{io}/T_{eo})/(T_{io}/T_{eo})_{ref}]$. Here, ref indicates comparison at a specific time to an otherwise identical discharge without rf heating, or in some cases to the time in a discharge just before rf is applied. This database has 38 shots with multiple timeslices from a variety of experiments. The ECH data come from experiments with both radial ($k_{//}=0$) and current drive launch and with varying deposition location, from $\rho \cong 0$ to $\rho \cong 0.5$, and with two

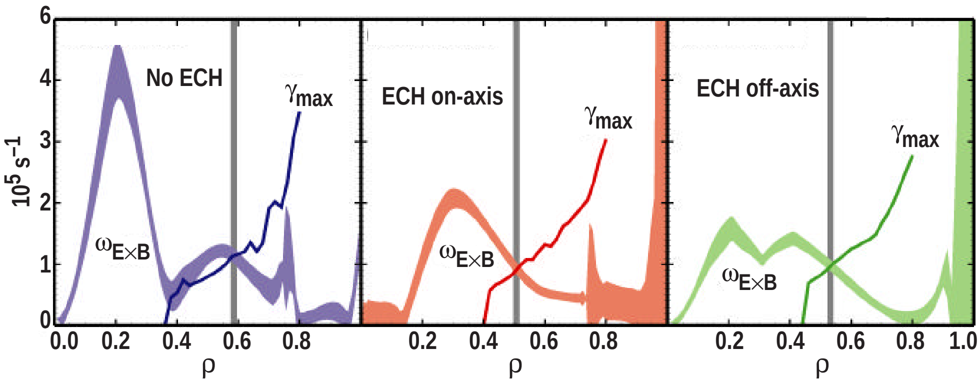

Fig. 3. Maximum theoretical long wavelength ($k_y < 10\ cm^{-1}$) growth rate compared with the experimentally computed $\omega_{E\times B}$ shearing rate for the ECH and reference discharges.

power levels. The FW data from the experiment on sawteeth have been averaged over the sawtooth period, which was as long as 200 ms for some cases. Most of the FW points are with $k_{//}$ in the direction of plasma current, and most are with 60 MHz, although some cases also have 83 MHz power. Some data are with FWEH induced slowing in an ECH experimental series (Fig. 1) and with ECH induced slowing in the sawtooth stabilization experiment, and also simultaneous heating methods in the latter. The cluster of points around (1,1), indicating small change, are largely due to comparisons between an rf and reference discharge at a time before rf is turned on, and are a measure of the discharge to discharge variance in these parameters. The correlation is better with T_i/T_e than with either T_e or T_i alone.

Although the ITG turbulence calculations have not yet shown a quantitative causality for an increase in core ion transport, the good correlation in Fig. 4 gives support for the enhanced transport model due to decreased T_i/T_e, at least in the momentum channel. Additionally, the data for FW heating with a fast ion resonance do not clearly indicate a $J_\rho B_\rho$ effect, as there is poor correlation of the slowing with rf power absorbed by the ions.

To summarize, the DIII–D data at present indicate enhanced transport as the cause of the observed rf induced toroidal slowing in co-rotating target discharges, although there is not a definitive connection to the ion turbulence theoretical calculations as yet. Future DIII–D experiments will seek to eliminate, or support, some of the other mechanisms indicated by Eq. (1). It is important to expand the DIII–D data set with counter-rotating target discharges in order to better separate the effect of enhanced viscosity from that of a counter torque. Some preliminary data from such counter targets also indicate an enhanced transport (drag) due to electron heating.

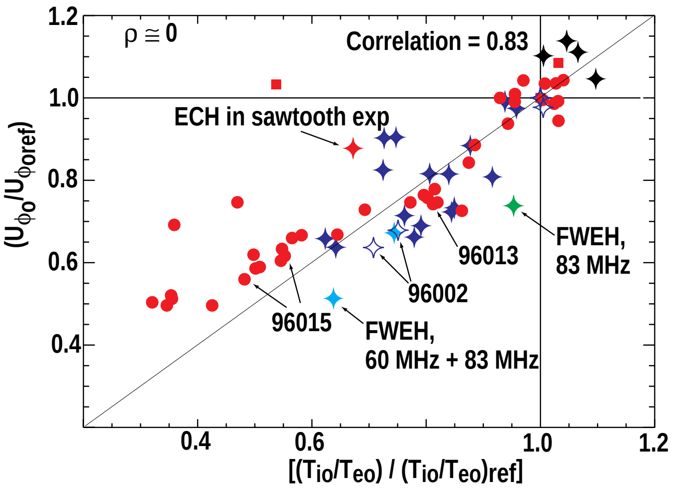

Fig. 4. Decrease in toroidal rotation versus decrease in T_i/T_e, at $\rho \cong 0$. Ratios are taken against a comparison case with no rf.

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