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Plasma Rotation and RF Heating in DIII–D

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Abstract. In a variety of discharge conditions on DIII–D it is observed that rf electron heating reduces the toroidal rotation speed and core ion temperature. The rf heating can be with either fast wave or electron cyclotron heating and this effect is insensitive to the details of the launched toroidal wavenumber spectrum. To date all target discharges have rotation first established with co-directed neutral beam injection. A possible cause is enhanced ion momentum and thermal diffusivity due to electron heating effectively creating greater anomalous viscosity. Another is that a counter directed toroidal force is applied to the bulk plasma via rf driven radial current.

Stabilization of turbulent ion transport by sheared **E**×**B** flow has become a unifying theme in understanding transport barriers in tokamaks [1]. In DIII–D the largest constituent of the core radial electric field can typically come from the flow velocity, both toroidal and poloidal, resulting from neutral beam injection (NBI). It is observed in DIII–D that rf electron heating can reduce this NBI driven velocity, and the core ion temperature. This has been observed for both fast wave electron heating (FWEH) [2] and electron cyclotron heating (ECH) [3]. To date, all of these experiments have been done with NBI in the direction of the plasma current, that is co-injection. It is important to understand these effects for further insight into and potential control of transport barriers.

Analogous to ion thermal transport, a toroidal momentum equation should specify the toroidal velocity, V_ϕ. For steady state

$$M\vec{\nabla}\cdot\left[\chi_m\vec{\nabla}\left(nV_\phi\right)\right]+F_\phi+J_\rho B_p=0 \tag{1}$$

where we have neglected the (small) charge exchange momentum damping. 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, ρ a normalized radial coordinate, and χ_m the momentum diffusivity, measured to be of the order of the ion thermal diffusivity [4].

Equation (1) serves to catalog the various rf-heating induced mechanisms which could modify V_ϕ. First, resonantly heated particles can generate a nonambipolar radial current and a return current, J_ρ, which creates a force on the bulk. This force can be in the co or counter direction, depending upon the details. C.S. Chang has recently discussed this effect for ICRH [5], due to radial transport of resonant ions [6]. This apparently can explain the ICRH induced co-rotation observed in C-Mod [7]. The DIII–D

FWEH parameters are selected to minimize ion absorption, with typical operation at ≥ the 4th ion cyclotron harmonic, but absorption by fast beam injected ions has been observed [8]. For resonant electron heating the radial current should be much smaller, down by the ratio of the banana widths. However, there may be some indirect affect of ECH upon ions since fast ions have been measured in ECH experiments [9,10].

A related scenario is that an rf-induced force decreases V_ϕ which serves to reduce the shear **E**×**B** drift stabilization of turbulence and results in the enhanced ion thermal transport, reducing the core ion temperature.

A second possibility is that rf electron heating increases χ_m , increasing the viscous drag. A possible mechanism is that increased T_e/T_i, the electron to ion temperature ratio, destabilizes ion temperature gradient mode [11] turbulence and enhances ion thermal and presumably also momentum transport. Although the data qualitatively supports this mechanism detailed quantitative analysis is not definitive [12,3].

Other possibilities for changing V_ϕ are indicated by Eq. (1). The NBI drive, F_ϕ, might be reduced by the application of rf power in DIII–D. ICRH induced outward transport of beam ions before delivering full toroidal momentum decreases the core drive, as well as producing an rf induced counter force on the bulk. Magnetic modes in the core are known to degrade fast beam ion confinement and it is possible that strong core rf electron heating is leading to such modes, at levels difficult to detect. Finally, we note that an increase in density leads to reduced velocity, but assuming the transport codes accurately model the sources this is accounted for when transport coefficients are computed.

Experimental and theoretical efforts are underway on DIII–D to understand these effects. If enhanced transport is the cause, then reduced V_ϕ is indicated. If rf-induced forces are the cause, these might be used to advantage.

FWEH and ECH raise T_e. This commonality is consistent with increased turbulent drag. However, discharges with an off-axis ECH resonance can show a significant V_ϕ and T_i reduction with little increase in T_e. Time traces from three discharges are shown in Fig. 1, one with no ECH (96010), one with ECH at $\rho = 0$ (96015), and one with ECH at $\rho = 0.5$ (96019). The EC wave is launched nearly perpendicular to the toroidal direction, and steered in the poloidal plane to vary the resonance location. V_ϕ and T_i are measured with charge exchange recombination spectroscopy (CER) of the ambient carbon impurity. A large rise in $T_e(0)$ is produced by on axis ECH, while there is a small amount for off-axis heating. Core heating in this discharge with off-axis resonance may be due to launching some non X–mode power which has lower first pass absorption and could reflect from the walls. $V_\phi(0)$ and $T_i(0)$ are reduced below those of the non-ECH control discharge, recovering to a common value after the ECH pulse. The NBI power is stepped up in the middle of the ECH pulse as shown in Fig. 1(e).

There is a small but reproducible rise in the electron density with ECH and the core CER amplitude, I_{cer}, increases, with little increase in carbon radiation from the edge. I_{cer} is proportional to the carbon density for constant beam deposition. Carbon density profiles indicate a modification to the carbon transport with strong central electron heating. Note that any change in n_e or I_{cer} produced by the NBI step is much smaller.

Profiles at t=1250 ms are shown in Fig. 2. The key point is that the relative change in V_ϕ and T_i is significant for shot 96019 with a small change in $T_e(\rho)$. If enhanced T_e is the cause, then there is a strong (“stiff”) dependence of the transport coefficients upon T_e, with some saturation feature. These are negative central shear (NCS) discharges with early beam injection to hold q on axis above 1 [3]. In experiments with the EC wave launched with a toroidal component to produce current drive, similar reductions for V_ϕ and T_i are obtained.

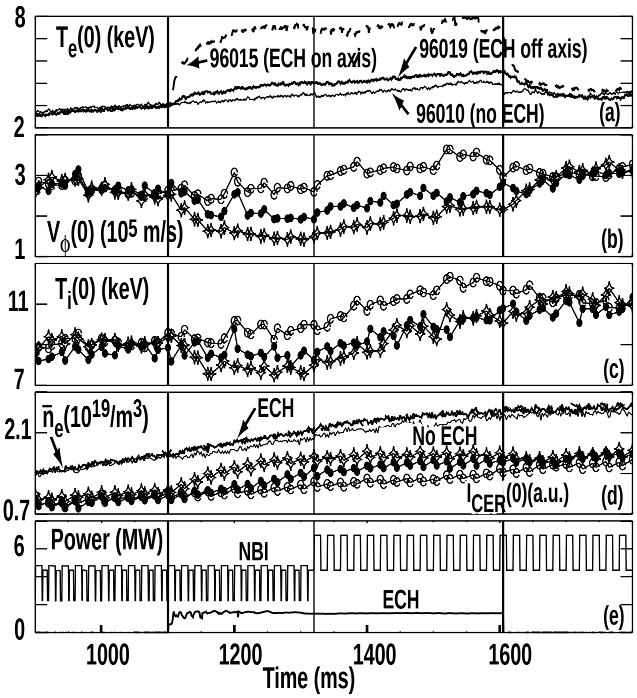

FIGURE 1. NCS L-mode discharges with different ECH resonance, $B_T = 2.0$ T, $I_p = 1.4$ MA, 96010 – no ECH (❍), 96015 – ECH on axis (☆), 96019 – ECH off axis (●).

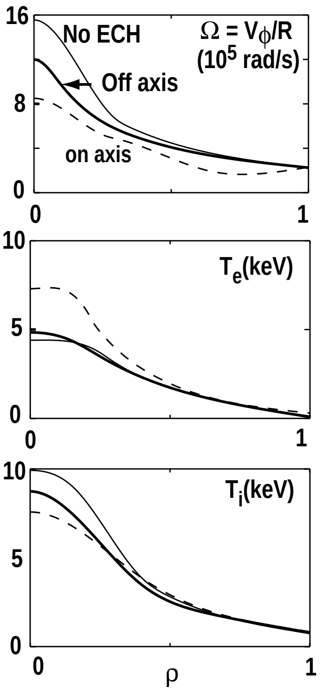

FIGURE 2. Profiles versus normalized toroidal flux for the discharges from Fig. 1.

NCS discharges with $q_{min}(\rho) > 1$ are typically characterized by low thermal and momentum transport of the core ions. In such rf target discharges, with the absence of sawteeth, the rf reduction of V_ϕ and T_i described above stands out clearly. However, the rf slowing effect also exists in non-NCS discharges with sawteeth. Here, we present data from an experiment on ICRH sawtooth stabilization where the physical mechanism believed responsible for the increase of the sawtooth period is the on-axis 4th harmonic absorption of the FW power by fast, beam injected D ions, as evidenced by enhanced neutron production [13]. Figure 3 shows two discharges, one with steady FW power at 60 MHz and the other with low duty cycle FW power, used as a “no FW” comparison. The higher power case shows the increased sawtooth period in electron temperature, a reduction in $V_\phi(0)$, and no clear reduction in $T_i(0)$ [14] (although in some discharges a T_i reduction is seen). The core ion temperature clearly shows the sawteeth in the partially stabilized discharge. The line averaged density is the same for both discharges, $\sim 3\times 10^{19}/\mathrm{m}^3$. The “Rdd enhancement” trace is the ratio of the measured neutron production rate to a simplified theoretical approximation [13]. The enhanced value in the full power discharge indicates evidence for a fast ion tail due to FW absorption. Calculations with the CURRAY code predict the FW power absorption divides between (D beam ions: electrons: thermal hydrogen) roughly as (4:3:3) for these parameters [13].

FW heating in these discharges raised T_e in addition to power absorption by fast ions so it is difficult to separate a T_e/T_i effect from a J_ρ effect. Also analyses are complicated by the modulation due to sawteeth. Nevertheless, a good correlation is obtained between the fractional reduction of V_ϕ and $(T_e/T_i)^{-1}$, with the data averaged over sawteeth. This is for a data set of 25 timeslices from 17 discharges on FW

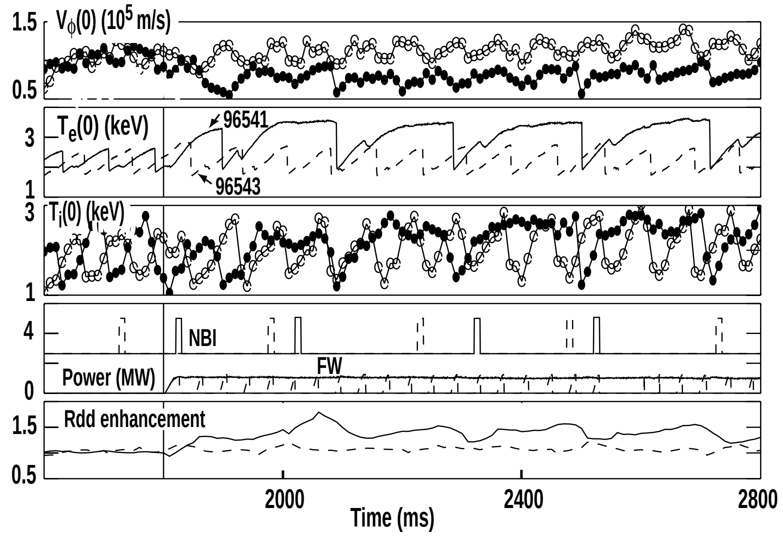

FIGURE 3. Sawtoothing L–mode discharges with and "without" FW heating for sawtooth stabilization. B_T =1.88 T, I_p =1.2 MA. 96541 with FW (●), 96543 minimal FW (❍).

sawtooth stabilization. However, estimating J_ρ [15] from the fast ion power absorption prediction from CURRAY produces a momentum change which is less than, but not negligible compared locally with F_ϕ.

Future experiments on DIII–D will continue to investigate the rf induced changes in V_ϕ and T_i. It is important to do the experiments with counter NBI target discharges to distinguish between a counter torque and enhanced transport.

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