Electron Cyclotron Heating and Core Intrinsic Rotation Reversal in DIII-D

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Abstract. The effect of electron cyclotron heating (ECH) on the intrinsic rotation profile in DIII-D is shown experimentally. Former DIII-D experiments have shown that ECH tends to cause an interior reduction in the normally co-Ip directed intrinsic rotation profile, and this core rotation can be fully reversed to the opposite direction. This effect is due to a turbulent rearrangement of the interior rotation profile. Here, we show results that there is more than one mechanism causing this. We compare two low density L-mode discharges where the only operational difference is the location of the ECH deposition. At low ECH power, comparable to the Ohmic power, the primary change is in the q-profile accompanied by a reversal of the core intrinsic rotation direction for the more off-axis deposition. The change in the shear of the q-profile fits well with a recent theoretical prediction for this rotation reversal. At higher ECH power, the primary change is in the core electron temperature, Te, accompanied by a hollowing of the rotation profile near the magnetic axis. This effect appears to be due to the change in electron collisionality, consistent with another theoretical, gyrokinetic prediction. The variety of phenomena that could allow ECH to modify the intrinsic rotation profile give some expectation that regions of large velocity shear in the interior could be generated, with the possibility of triggering internal transport barriers.

INTRODUCTION AND OVERVIEW

Electron cyclotron heating (ECH) is a well developed auxiliary heating tool in modern tokamaks, used to provide localized electron heating and current drive, and will be used on ITER for heating, q-profile control, and neoclassical tearing mode suppression. In DIII-D, ECH-generated H-modes have been used to study so-called intrinsic rotation, where the tokamak is observed to rotate toroidally with no auxiliary injected torque [1-3]. One odd experimental observation regarding toroidal rotation profiles is that there can be a "spontaneous" reversal of the direction of rotation in the core during a slow sweep of the plasma density or the plasma current magnitude. This was first reported for L-mode conditions inTCV [4] and subsequently also investigated in C-Mod for both L- and H-mode discharges [5]. The rotation closer to the outboard edge of the plasma remains in the same direction while the core direction undergoes a rapid reversal. Several theoretical explanations have been put forward for these reversals, including the details of the dominant plasma core turbulence [6,7], the neoclassically predicted reversal of poloidal velocity direction with collisionality regime [8], and an effect due to turbulence coupled to the shear in the q-profile [9].

Reversal of core rotation relative to the edge increases the shear in the profile which could lead to enhanced energy confinement through the ExB shear effect. For this reason we are interested in understanding this phenomenon and investigating how to control it. Here, we show two matched DIII-D discharge conditions where the primary difference is the deposition location of the ECH power, with one case showing a dramatically reversed rotation profile from the other. The best explanation appears to be the q-shear effect [9]. With higher ECH power in these same conditions there is a less pronounced reversal and minimal difference in q-shear, indicating the dominant turbulence effect is responsible in this condition [7].

EFFECT OF ECH DEPOSITION ON INTRINSIC ROTATION PROFILE

In Fig. 1 we show time traces from two low density ECH L-mode discharges in DIII-D, both having the same programmed step up in ECH power as shown in Fig. 1(c). The NBI blips [Fig. 1(b)] are used for ion temperature and velocity measurements of the minority carbon constituent in these deuterium bulk ion plasmas. At the highest ECH power an H-mode transition occurs, indicated by the secular rise in density [Fig. 1(a)]. In the time traces in Fig. 1 the blue have the more central ECH deposition than the red, as indicated in Fig. 2.

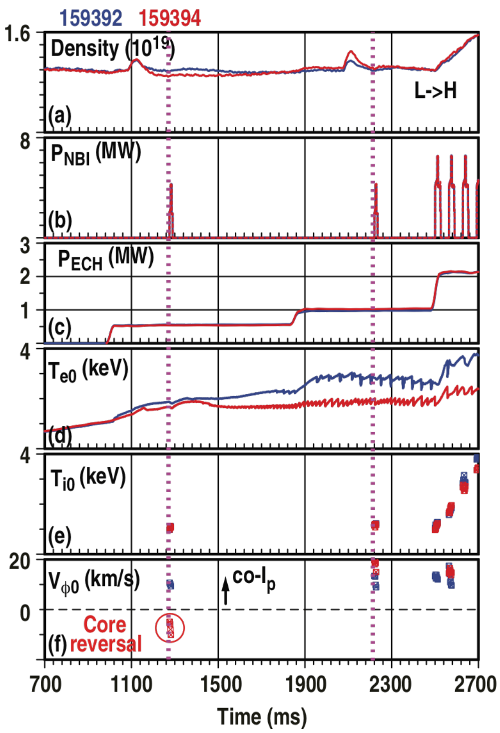

FIGURE 1. Time traces of two discharges with differing ECH deposition locations. (a) line averaged electron density (b) NBI blip power (c) ECH power steps (d) Core electron temperature (e) core ion temperature (f) core toroidal velocity.

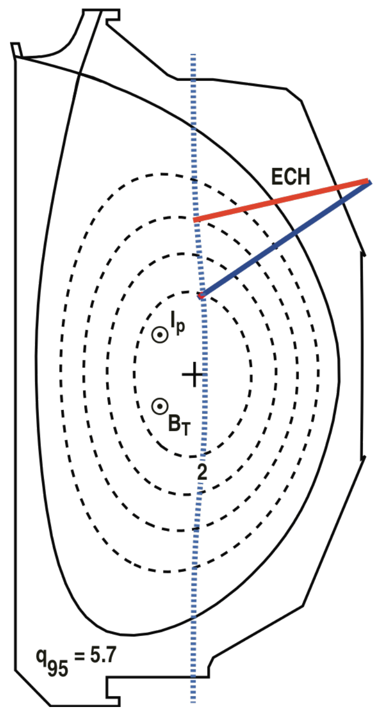

FIGURE 2. ECH power ray traces; absorption on the near vertical 2^{nd} harmonic surface. The surfaces are constant ρ. The color code is the same as in Fig. 1.

First, consider the time of the first NBI blip in Fig. 1 with the ECH power at only ~ 500KW, comparable to the Ohmic heating power. The electron density and the ion temperature profiles from the two shots at this time are nearly coincident, while the more central ECH deposition (blue) has a higher core electron temperature of ~ 15%. In this region Te/Ti ~2. In contrast, the rotation profiles are dramatically different, as shown in Fig. 3, where for off-axis ECH we see a depressed rotation going to the counter direction in the core, while the edge rotation is enhanced in the co-Ip direction. The calculated collisionality profiles for electrons and for ions in both deposition conditions are virtually identical also.

The significantly different profile is for the q shear as shown in Fig. 4. The relatively small difference in the conductivity profiles is enough to cause this difference in the q profiles. The dashed blue and red lines indicate the ECH power deposition profiles (a.u.). The horizontal dashed green line is the critical value of shear, 0.3, from reference [9], above which there is a transition from co- to counter-directed residual torque stress from collisionless trapped electron mode (CTEM) turbulence. It appears that in the core region near ρ ~ 0.3 that a negative turbulent torque would be possible, and it is inside of this location that the intrinsic rotation is negative. Turbulent stress rearranges the internal momentum profile and apart from an edge source or sink cannot create momentum per se. So, the remainder of the rotation profile would be in response to a core rearrangement. The balance of the ECH effect on Te, which can determine whether the turbulence is electron or ion directed, and the related effect on the current profile together determine the resultant direction of this internal turbulent torque [9]. The example shown here may be a subtle region in parameter space to see this effect in the one of two shots, at the same q95, constant density, and only a small difference in Te between these two deposition locations.

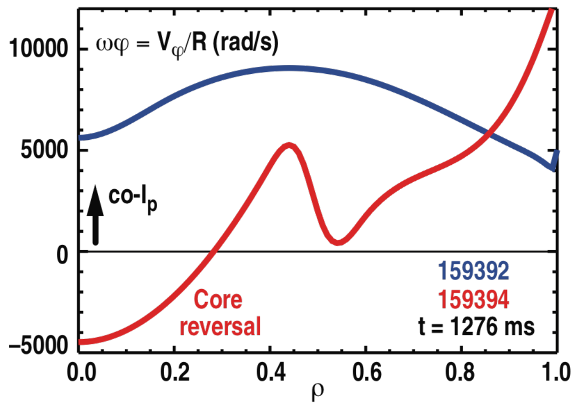

FIGURE 3. Toroidal rotation profiles for the low power time, with reversal in the off-axis deposition ECH discharge.

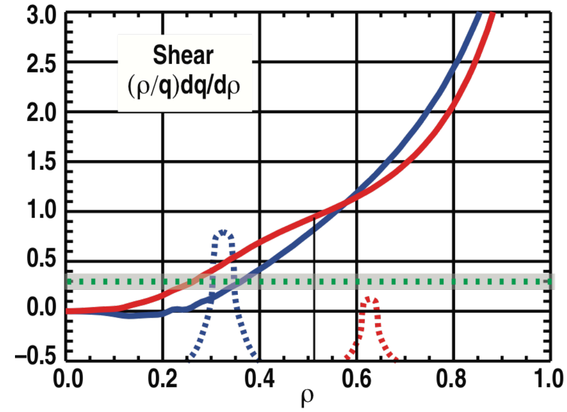

FIGURE 4. Normalized q-profile shear with the deposition locations indicated (au). The horizontal dashed line is at a critical value in the shear from ref [9].

It is not just the carbon rotation profile that is reversed in the core, but also that of the main deuterium ion. In recent years a main ion charge-exchange recombination (CER) system for the hydrogenic ions has been developed in DIII-D [10]. Measurements in these two shots shows deuterium rotation profiles similar to these carbon profiles, but with slightly more co-Ip directed rotation.

Next we consider the time of the second NBI blip in Fig. 1, where the only operational difference is a doubling of the ECH power to ~ 1MW. Again, the density and Ti profiles are essentially identical, and here the differences in the shear profiles seen in Fig. 4 are reduced by a factor of 3 or more in the interior, $\rho < 0.6$. The rotation profiles are also similar, except near the magnetic axis where it is now the core ECH deposition shot that shows a large reduction in the rotation, as shown in Fig. 5. Now the major difference is in the Te profiles where core deposition shows a significantly larger Te than the off-axis deposition, as shown in Fig. 6. This Te profile indicates an internal barrier, although it may be due to the localized deposition as shown in Fig. 4. Near the magnetic axis Te/Ti ~ 3 for this highest Te. Consequently the electron collisionality is over a factor of 2 smaller for the shot with the rotation depression and we postulate that effects other than shear are at work here, such as described in [7].

At this, more typical, higher ECH power level the difference in the shear profiles is small and the dominant effect is electron heating, that is, high Te/Ti. There is little or no ECH density pump-out seen here, presumably because the density is low to begin, and thus modification of the density profile is not a factor.

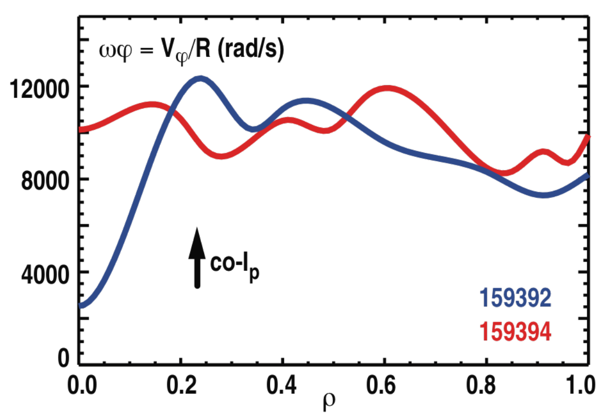

FIGURE 5. Toroidal rotation profiles for the higher power time, with a reduction in the near-axis rotation for the more on-axis deposition ECH discharge.

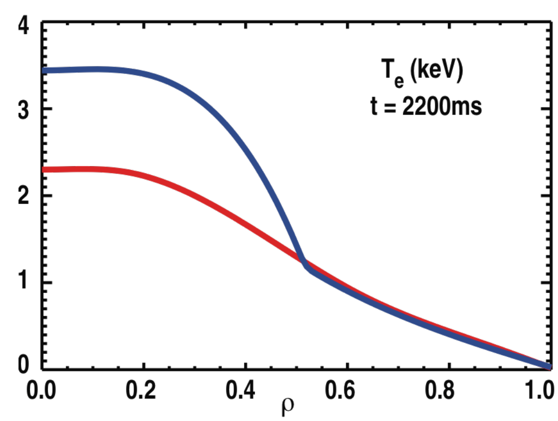

FIGURE 6. Te profiles at this higher power time.

DISCUSSION

ECH has a number of effects in the tokamak beyond basic localized electron heating. It is known to, in some regimes, increase the effective transport in all channels, notably for uni-directional NBI torque input to reduce the magnitude of the toroidal rotation profile [11]. Here, we see the capability of ECH to "tailor" the intrinsic rotation profile in a localized manner likely resulting from the highly localized power deposition. We have shown that there are multiple physical phenomena that lead to this modification. Presumably the most typical is the always present strong electron heating leading to elevated Te/Ti and the accompanying turbulence enhancement [2]. However, we have also encountered an effect due to a change in the magnetic shear profile with low ECH power wherein the change in shear is dominant over that of heating. While attaining this condition is subtle for ECH, it could perhaps be more readily applied directly by using electron cyclotron current drive (ECCD). If the shear in the rotation profile can be used to enhance energy confinement, this may have practical value. Experiments utilizing ECCD clearly need to be performed.

One of the dramatic experimental aspects of core rotation reversals is the "spontaneity" of the phenomenon when it is studied by slowly changing a parameter in time, such as density [6]. At a critical density the rotation in the core reverses, on a rapid time scale compared to the changing parameter in a shot. It would seem that there is some trigger or feedback effect beyond the slow changing of a density profile, or even a q-profile. Here, we suggest that for a reversal due to a change in q shear the feedback mechanism might be the current redistribution due to the ion velocity profile change itself. Consider Fig. 4 and inducing a reversal by going from the red (larger core shear) to the blue (smaller core shear) condition. To decrease the shear near r = 0.3 more plasma current density is needed in this region. If this change in the shear profile tends to cause more co-Ip ion velocity near this location (red to blue in Fig. 3), then this flow could increase the current density more in the direction to enhance the shear further, and so on, leading to the reversal bifurcation.

Further experiments are needed to investigate the ability to control the interior shear in toroidal rotation with localized q shear modification using ECCD. The benefit would be a local reduction in radial energy transport via ExB shear.

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