Plasma Rotation in Electron Cyclotron Heated H-modes in DIII-D[*]

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H-modes driven by electron cyclotron heating (ECH) in DIII-D have nonzero toroidal rotation with essentially no auxiliary momentum input. The striking feature is the sheared rotation profile, counter-I_p directed in the core and co-directed outside, in contrast with Ohmic H-modes in DIII-D, having rotation everywhere co-directed, as seen in other devices, such as C-Mod [1]. To our knowledge these are the first such measurements for ECH H-mode conditions.

In tokamak discharges the details of the plasma flow velocity, U, are understood to be crucial in the areas of MHD stability and confinement. The magnitude of U promotes stability of the resistive wall mode [2], while shear in U can suppress turbulent transport [3], both impacting the design of a burning plasma experiment (BPX). The design margin of a BPX must now be set conservatively because there is uncertainty in extrapolating present flow velocities to this new regime, especially since there is foreseen little unbalanced auxiliary momentum input, Γ. Yet it is known presently that Γ is not required to obtain toroidal rotation, $\omega_\phi = U_\phi/R$, [1,4,5]. It is important to understand the physics behind this effect, and to develop predictive capabilities.

Profiles of ω_ϕ for an ECH H-mode and a comparison Ohmic H-mode are shown in Fig. 1(a). The core rotation with ECH is counter-I_p for $\rho < 0.6$, where ρ is the toroidal flux coordinate. In Fig. 1(b,c) we plot the T_e and T_I profiles for the time slices of Fig. 1(a). The ECH H-mode case has T_e/T_i clearly above 1 in the core. The profile of ECH power deposition is also plotted, indicating that the region of transition from co- to counter-rotation corresponds with the deposition region, or perhaps equivalently the region of elevated T_e/T_i.

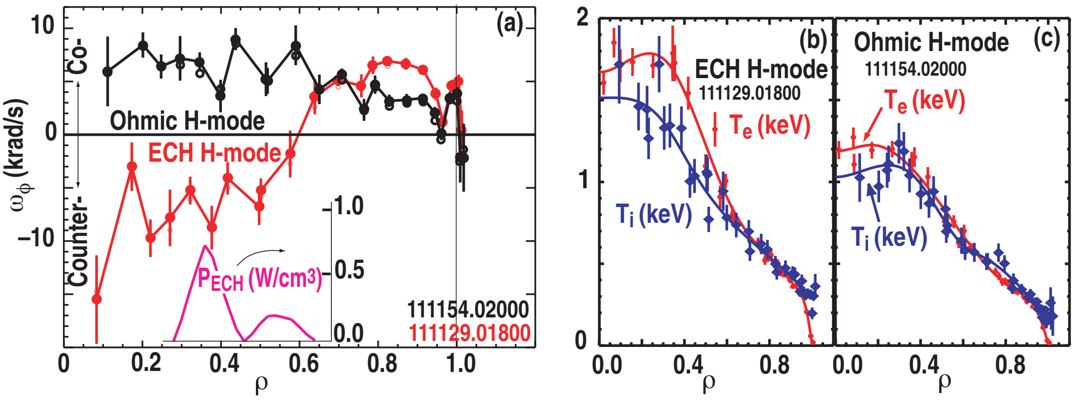

Fig. 1. (a) Toroidal rotation profiles, $\omega_\phi = U_\phi/R$, in ECH (red) and Ohmic (black) H-mode discharges. $B_T = 1.75$ T, $I_p = 1.3$ MA (ECH), 1.5 MA (Ohmic), $q_{95} = 3.5, 3.2$, $\bar{n}_e = 5.0, 5.7\times10^{19}/m^3$, respectively. (b,c) Electron and ion temperature profiles for these cases.

The ion velocity and temperature measurements are made with charge exchange spectroscopy (CER) on the intrinsic fully stripped C ions which have acquired an electron through CE with a neutral beam injected (NBI) D neutral. The NB does inject toroidal torque and we must verify that our measurement technique does not perturb the target ECH plasma. We find

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that only the first 2 ms of NBI can be used to determine the rotation velocity. In order to build up a time sequence of profiles, the time of NBI start is moved from shot to shot.

Neoclassical theory [6] has been used to compute the bulk D^+ velocity given the measured kinetic profiles and the C^{+5} velocity. The result is shown in Fig. 2 for the same cases. Smooth spline profiles are fit to the measured ω_ϕ profiles for C. The computed D velocity is more in the co-direction, but the shift is not enough to remove the feature of the counter-rotation in the core with ECH H-mode. The large qualitative difference between the two cases remains for the bulk ion ω_ϕ, as well as the spatial gradient.

One theory that explicitly predicts a toroidal rotation profile in the absence of external torque is that of Claassen et al. [7], although the theory is applicable only to the collisional regime, which does not describe this experiment. Nevertheless we have applied this theory to these data and find the prediction for rotation near the edge is correct in order of magnitude, but the spatial transition from co- to counter- rotation in ECH H-mode cannot be described.

In this experiment the rotation profiles evolve in time and those shown in Fig. 1 are the maximum in magnitude for these conditions. There is a long ELM-free period after the H-mode transition with ECH, accompanied by a density rise and evolving conditions, as shown in Fig. 3(a). Here, the time of the first NBI pulse has been moved to t = 2600 ms to measure rotation at that time. The core counter-rotation increases after the H-mode transition to a maximum at t = 1800 ms, then decreases until being essentially zero at t = 2600 ms, after the start of ELM bursts and a clamping of the density rise. This is shown in Fig. 3(b) where we plot the averaged rotation of the inner four core CER channels, located as shown in Fig. 1(a). Each point here is obtained from a separate shot with the first NBI pulse moved to that time. By t = 2600 ms ray tracing computations show that the ECH power is cut-off from the core by the rise in density. Throughout the density rise the core T_e/T_i is decreasing from a value of ~2, at t = 1600 ms, to 1 by the onset of ELMs. It is not yet known which of these evolving parameters is most important in abating the counter-rotation in the core. The T_e/T_I ratio could be a key factor, since we note that in the Compact Helical System core counter-rotation is induced by the addition of ECH to create a hot electron regime, even in the presence of co-NBI torque [8].

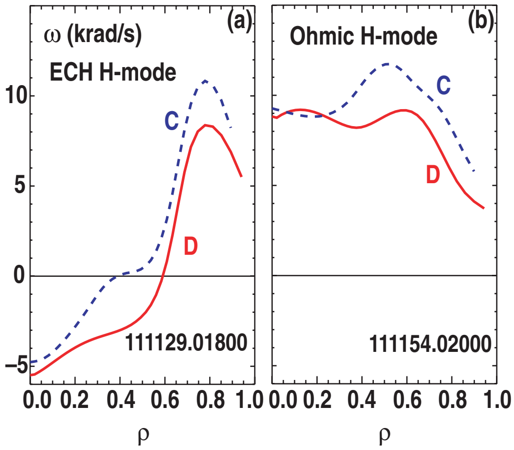

Fig. 2. Measured C and neoclassically computed D profiles. (a) ECH H-mode (b) Ohmic H-mode for comparison.

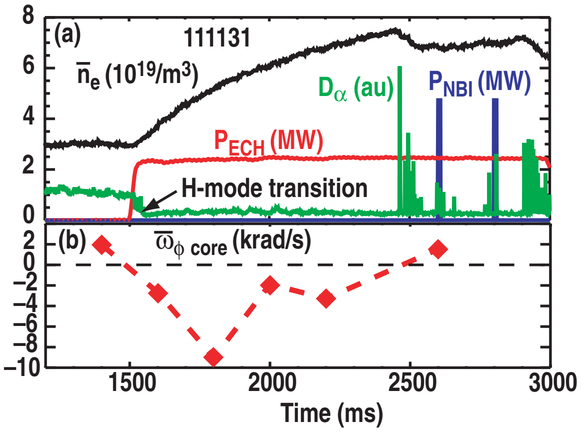

Fig. 3. ECH H-mode (a) ECH and NBI power, line averaged density and D_α. (b) Rotation vs time for average of inner four CER channels.

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