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Toroidal Rotation in ECH H-modes in DIII-D

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Abstract. In ECH H-mode discharges with essentially no toroidal momentum input, counter toroidal rotation is measured in the interior, $\rho < 0.5$, while co rotation is measured outside this region. This is contrasted with Ohmic H-modes where the rotation is everywhere in the co direction. A simple parameterization is suggested to facilitate comparison between machines.

INTRODUCTION

Toroidal rotation exists in tokamak discharges with essentially no deliberately injected external torque, in ion cyclotron radiofrequency (ICRF)-heated discharges [1-3], and Ohmically-heated discharges [4]. Understanding the generation of this rotation is important because of the role of toroidal rotation in the stabilization of resistive wall modes [5] and the sheared E×B flow stabilization of microturbulence [6].

H-modes in DIII-D driven by electron cyclotron heating (ECH) also have nonzero toroidal rotation. The rotation in the interior region is in the counter direction, while in the outer region, $\rho > 0.6$, it is in the co direction. Co and counter are relative to the direction of plasma current, I_p, and ρ is the normalized toroidal flux coordinate. This is in contrast to rotation profiles measured in DIII-D for Ohmic H-mode discharges, which are in the co direction for all ρ.

The injection of short neutral beam (NB) pulses, or blips, is required to measure the velocity and temperature of the intrinsic carbon ion impurity in DIII-D using charge exchange recombination (CER) spectroscopy [7]. These blips do inject toroidal torque into the discharge. We find that using only the first 2 ms of the initial blip does give a good measure of the unperturbed velocity profile, as well as temperature profile. The toroidal velocity, U_ϕ, increases in the beam direction (co) during the 10 ms blips utilized in this experiment and the resultant toroidal momentum appears to have a very long confinement time relative to the energy confinement time of the discharge.

An effect of the long time momentum confinement in the NB blip format is that the toroidal velocity "stacks" up in DIII–D from blip to blip, even if the time interval is 200 or 400 ms. This was not known in a previous ECH experiment on the electron heat pinch in which NB blip velocity measurements were also used to infer the effect of

ECH [8]. Co core velocity was measured in that experiment, but this is now understood to be likely driven by a single NB blip 600 ms before this measurement. That experiment used L-mode discharges, rather than the H-modes considered here.

ECH AND OHMIC H-MODES

A comparison was made between ECH and Ohmic H-modes using the same CER measurement technique. For the ECH case, power from four gyrotrons was launched from the outboard side along the vacuum rays shown in Fig. 1, at 110 GHz [9]. The intersection with the vertical line indicates the second harmonic resonance. Gyrotrons 1-3 were launched radially ($k_\phi = 0$), while gyrotron 4 launched at a nonzero toroidal wavenumber. The nominal power from each was 500 kW. Raytracing with the TORAY-GA code indicates that the total EC driven current is less than 10 kA. For the ECH H-mode, I_p = 1.3 MA, B_T = -1.75 T, with line-averaged target electron density $\bar{n}_e = 3\times10^{19}/\mathrm{m}^3$. For the Ohmic H-mode case I_p was increased to 1.5 MA, with no ECH power applied.

Profiles of toroidal rotation frequency, ω, are shown in Fig. 2, for both H-mode cases. In Ohmic H-mode the rotation is in the co direction everywhere, while for the ECH H-mode it is in the counter direction in the interior coincident with the region of ECH power deposition, as indicated in Fig 2. We did not have the opportunity to vary the deposition profile, so it is not yet known if there is a causal relation here. The lines shown merely connect the points to guide the eye.

The electron and ion temperature profiles, T_e and T_i, accompanying these rotation profiles are shown in Fig. 3. The higher temperature trace in each plot goes with the ECH H-mode (dashed curves). The density profiles for each are relatively flat, with a density within the edge pedestal of approx. $6\times10^{19}/\mathrm{m}^3$. T_e is measured with Thomson scattering and T_i with the CER. The smooth curves are spline fits to the data points.

In both of these types of discharge the toroidal rotation profile evolves with time. For the ECH H-mode there is a relatively long ELM-free period during which the

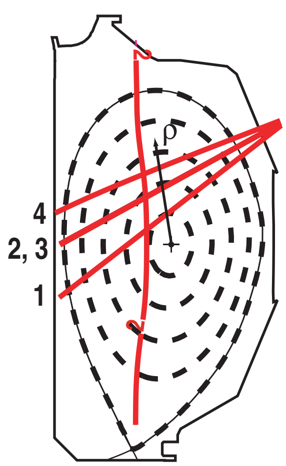

Figure 1. Vacuum rays for EC power launched with four gyrotrons in DIII-D.

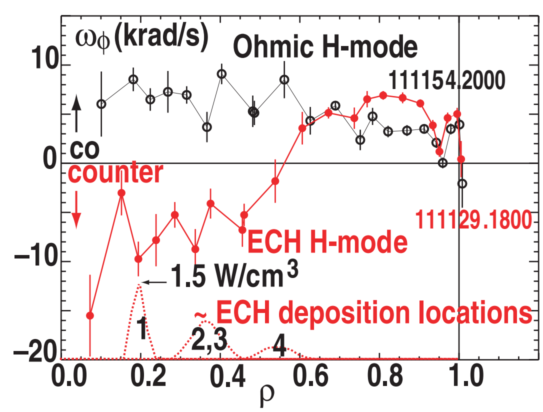

Figure 2. Toroidal rotation profiles for Ohmic (open circles t = 2000 ms) and ECH H-mode discharges (t = 1800 ms). The ECH power deposition profile is shown.

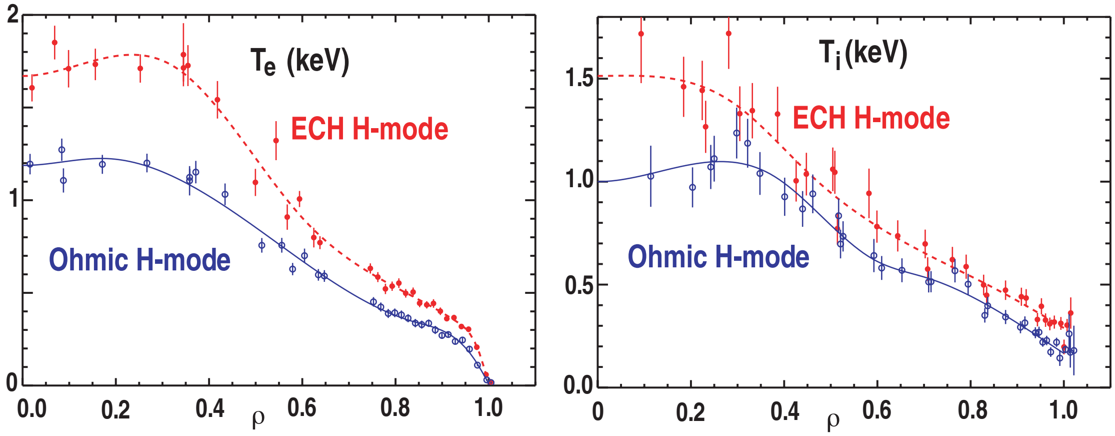

Figure 3. (a) Electron temperature, T_e, for the ECH and Ohmic H-mode discharges at the time of the rotation profiles shown in Fig. 2. (b) Ion temperature, T_i.

density rises until the ECH power is cut-off from depositing at the nominal locations indicated in Fig. 2. This is confirmed by cut-off in electron cyclotron emission from the plasma at a nearby frequency, and by ray tracing with TORAY-GA. Once there is no longer ECH power being deposited in the core, the density rise ceases, ELMs begin and the counter rotation in the core has died away. Also with the density rise T_e and T_i become equal, unlike the profiles shown in Fig. 3. It is not clear which of these phenomena, if any, are responsible for the loss of counter rotation in the core. For the Ohmic H-mode, ELMs begin relatively soon after the H-mode transition and the density rises, albeit less than in the ECH H-mode.

The rotation profiles shown in Fig. 2 were taken at the measurement times of maximum rotation magnitude near the magnetic axis for each case. The relative timing of these profiles with the density rise is shown in Fig. 4, for the ECH H-mode and the Ohmic H-mode. The first 2 ms of the first NB blip in each shot was used for the rotation measurement. For the Ohmic H-mode case the NB blip generated a short ELM-free period. Clearly it is necessary to do more experiments in steady conditions to find the cause of the counter core rotation with ECH power.

COMPARISON PARAMETER

It is useful to have some parameter with which to compare toroidal rotation between devices in discharges with little or no toroidal momentum input. For the toroidal velocity we propose scaling by a characteristic electric field divided by the poloidal magnetic field that is, define $\Delta \equiv U_\phi/(E_\rho/B_\theta)$. This characteristic electric field has a magnitude determined by the radial pressure gradient, which is taken simply to be the total energy density on axis divided by the minor radius. (The sign of the velocity will not be given by this scaling.) Thus Δ can be written as

$$[\omega/(3/2)(T_i+T_e)]_0 = \Delta\, q_{95}/a^2 B_\phi \qquad (1)$$

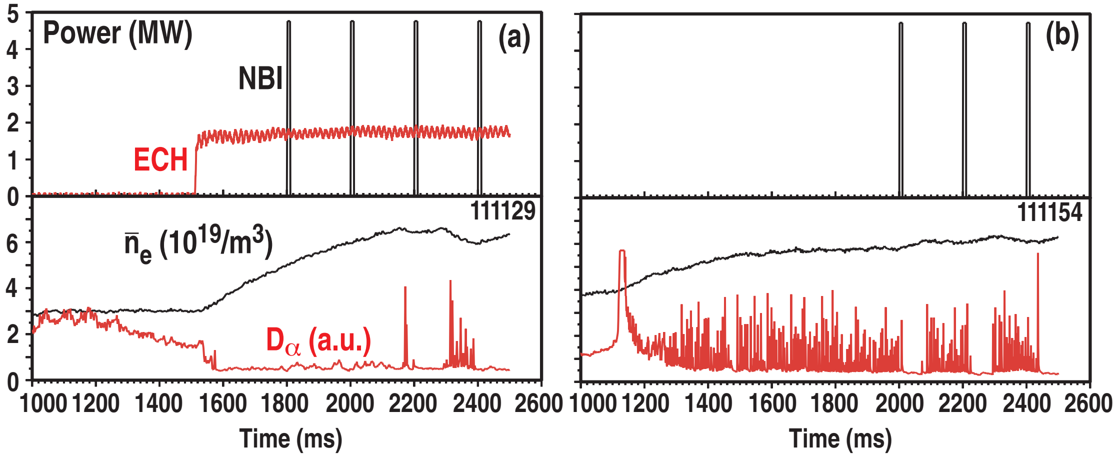

Figure 4. Density evolution in (a) ECH H-mode (1800 ms) and (b) Ohmic H-mode (2000 ms) discharges.

where we have cast this relation in terms which are readily scalable between devices. Here q_{95} is the safety factor at the 95% poloidal flux surface, a the minor radius, and B_ϕ the toroidal field on axis. For a simple circular approximation, Eq. (1) shows that $\Delta \sim (a/R_0)\Omega_\theta(L/W)_0$, where Ω_θ is the poloidal gyrofrequency and L and W are the angular momentum and thermal energy densities on axis, respectively. This scaling is consistent with that found on C-Mod [4], that $U_\phi \sim$ (total stored energy)/I_p. We have not yet tested this scaling in DIII-D.

For this Ohmic H-mode in DIII-D, Δ=0.5, while for a C-Mod example $\Delta\sim$ 0.8 [4]. A JET ICRH example has $\Delta\sim$1 [3], while for the ECH H-mode described here Δ= 0.4 (but negative). We note that for standard NB driven ELMing H-modes in DIII-D this same parameterization yields $\Delta\sim$ 1.5–2 [10].

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