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Observation of Self-Generated Flows in Tokamak Plasmas with Lower-Hybrid-Driven Current

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In Alcator C-Mod discharges lower hybrid waves have been shown to induce a countercurrent change in toroidal rotation of up to 60 km/s in the central region of the plasma ($r/a \sim <0.4$). This modification of the toroidal rotation profile develops on a time scale comparable to the current redistribution time (~ 100 ms) but longer than the energy and momentum confinement times (~ 20 ms). A comparison of the co- and countercurrent injected waves indicates that current drive (as opposed to heating) is responsible for the rotation profile modifications. Furthermore, the changes in central rotation velocity induced by lower hybrid current drive (LHCD) are well correlated with changes in normalized internal inductance. The application of LHCD has been shown to generate sheared rotation profiles and a negative increment in the radial electric field profile consistent with a fast electron pinch.

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The beneficial effects of rotation on toroidal plasmas have been well documented. Strong rotation can help stabilize destructive magneto-hydrodynamic instabilities (i.e., resistive wall modes [1,2]) while gradients in rotation can improve confinement by suppressing turbulence [3,4]. In many experiments the rotation profiles associated with improved performance are generated through the use of neutral beam injection. This approach may prove impractical in the large, high density plasmas envisioned for next generation devices such as ITER [5,6]. As a result, there is a need to develop alternative methods for driving plasma rotation. Significant self-generated flows have been observed on a number of tokamaks [7] suggesting that it may be possible to reap the benefits of rotation without the use of neutral beams.

Self-generated flows associated with lower hybrid current drive (LHCD) have been observed in both *L*-mode and *H*-mode discharges on Alcator C-Mod when lower hybrid waves are launched such as to drive positive current. These changes to the toroidal rotation profile are core localized ($r/a \sim <0.4$) and always in the countercurrent direction. When the waves are launched against the inductive toroidal electric field, very little current is driven and no effect on the rotation profile is observed. This result indicates that it is the LHCD (as opposed to heating) that is responsible for the countercurrent change in toroidal rotation. In discharges with sufficient LHCD, a region of enhanced velocity shear forms concurrently with a negative increment in the radial electric field profile.

The results presented in this Letter were obtained on Alcator C-Mod [8], a compact tokamak (major radius $R = 0.67$ m, typical minor radius = 0.21 m) that operates at the high magnetic fields ($B_t > 5$ T) and high densities

($n_e \sim 10^{20}$ m $^{-3}$) envisaged for burning plasma reactors such as ITER and DEMO [9]. In the experiments described here, the lower hybrid waves were injected by an 88 wave guide launcher capable of delivering up to 1.2 MW of power at 4.6 GHz with an n_{\parallel} range of 1.5–4 in either direction [10]. (Here n_{\parallel} is the refractive index of the injected LH waves parallel to the magnetic field.) The impurity rotation and temperature profiles presented are based on the Doppler shifts and broadening of line emission from trace amounts of highly ionized argon, measured by a high resolution imaging x-ray crystal spectrometer [11]. The electron temperature and density profiles were measured using a Thompson scattering diagnostic while the line averaged density measurements are based on interferometry [8].

Shown in Fig. 1 is the temporal evolution of selected parameters for an *L*-mode discharge in which the injection of lower hybrid waves caused a strong countercurrent change in the toroidal rotation profile (solid lines). 600 kW of lower hybrid power (with $n_{\parallel} = 1.6$) are coupled to the plasma at $t = 0.8$ s. Immediately following the application of LH power, the central toroidal rotation began to evolve on a time scale considerably longer than the energy and momentum confinement times (~ 20 ms) but comparable to the current redistribution time [10] [$\tau_{CR} = 1.4\kappa a^2 T_e^{1.5}(\text{keV})/Z_{\text{eff}} \sim 150$ ms]. The ability to sustain LHCD for many current redistribution times makes it possible to study the induced rotation in plasmas with fully relaxed current density profiles.

Modification of the toroidal rotation profile by LHCD has been observed over a range of electron densities, plasma currents, magnetic fields, and lower hybrid powers. Although the magnitude of the effect depends on these

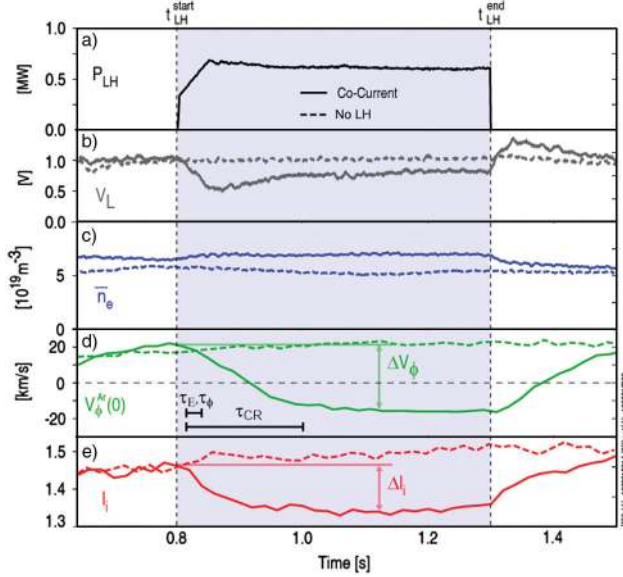


FIG. 1 (color). Time histories of (a) lower hybrid power, (b) loop voltage, (c) line averaged density, (d) central argon toroidal rotation velocity and (e) the normalized internal inductance ℓ_i for discharges with LHCD (solid lines) and without LHCD (dashed lines). Both discharges had the same magnetic field (5.4 T) and plasma current (800 kA).

parameters, in every instance the change in toroidal rotation is in the countercurrent direction. In discharges initially rotating in the cocurrent direction (as in Fig. 1) the application of LHCD can cause the rotation to change sign. While the precise mechanism by which the lower hybrid waves affect the rotation profile remains uncertain, rotation inversions such as these can not be explained solely by changes in viscous damping (an increase or decrease in viscous damping would change the magnitude of the flow but not its sign).

Also of interest is the change in normalized internal inductance, ℓ_i (a measure of the peakedness of the current density profile [12], given by the ratio of the volume averaged to surface averaged poloidal magnetic energy). Current profile measurements were not available for these discharges, but information about the current profile can be inferred from quantities such as ℓ_i and changes in loop voltage. The decrease in ℓ_i between 0.8 and 1.3 s indicates that the current density profile is broadening due to the off-axis current being provided by the lower hybrid waves.

The quantity $\Delta\ell_i$ shown in Fig. 1 is defined as the change in the internal inductance relative to the start time of the LHCD pulse (ΔV is defined similarly). The clear correlation between $\Delta V_\phi(t)$ and $\Delta\ell_i(t)$ during the LHCD phase in Fig. 1 is seen in all LHCD discharges and provides further evidence of the relationship between LHCD and rotation profile modification. Figure 2 shows trajectories in the $-\Delta V_\phi$ vs $-\Delta\ell_i$ plane for identical target discharges with varying n_{\parallel} values of the launched LH waves. The trajectories in Fig. 2 all start at the origin [since

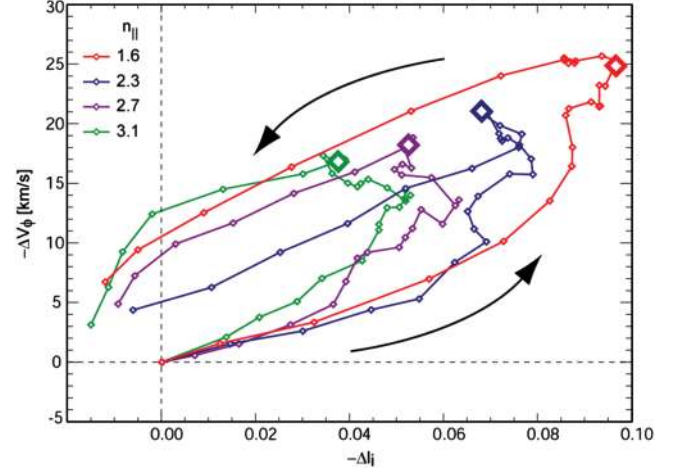


FIG. 2 (color). Trajectories in the $-\Delta V_\phi$ vs $-\Delta\ell_i$ plane for discharges with LHCD at varying n_{\parallel} . Each diamond represents the average value over a 20 ms time period. The LH power in all four discharges was ~ 400 kW.

$\Delta V_\phi(t_{\text{LH}}^{\text{Start}}) = \Delta\ell_i(t_{\text{LH}}^{\text{Start}}) = 0$ by definition] and progress in a counterclockwise pattern indicating that ΔV_ϕ tends to lag behind $\Delta\ell_i$. There is also a clear trend in n_{\parallel} , with smaller n_{\parallel} giving larger excursions in ΔV_ϕ and $\Delta\ell_i$. The relationship between n_{\parallel} and $\Delta\ell_i$ is a competition between two main effects: the shape of the current density profile and current drive efficiency. Waves with large n_{\parallel} tend to drive current off-axis and therefore one might expect $|\Delta\ell_i|$ to increase with n_{\parallel} . At fixed power, however, LHCD efficiency is proportional to $1/n_{\parallel}^2$ suggesting larger excursion in $\Delta\ell_i$ for smaller n_{\parallel} [13]. The larger excursions in $\Delta\ell_i$ for low n_{\parallel} shown in Fig. 2, indicates that the current drive efficiency effect is stronger than the current density profile effect.

The correlation between changes in central toroidal rotation and normalized internal inductance is observed in a wide variety of plasmas. This is illustrated in Fig. 3 in which ΔV_ϕ and $\Delta\ell_i$ data are plotted for discharges with varying magnetic field, plasma current, density, magnetic topology, confinement regime, lower hybrid power and launched n_{\parallel} .

The modification of the toroidal rotation profile produced by LHCD tends to be core localized, with the largest changes occurring in the range $0 < r/a < 0.4$. The sawtooth averaged radial profiles of n_e , V_ϕ , T_e , T_i and E_r both before and during the application of LHCD are shown in Fig. 4. The radial electric field, E_r , was calculated by measuring all terms in the radial force balance equation, with the dominant contribution coming from the toroidal rotation term. The change in the radial electric field profile indicates that there is a nonambipolar radial current charging the plasma negatively with respect to its pre-LH state.

A possible explanation of this negative charging of the core is a resonant trapped electron pinch [14,15]. This

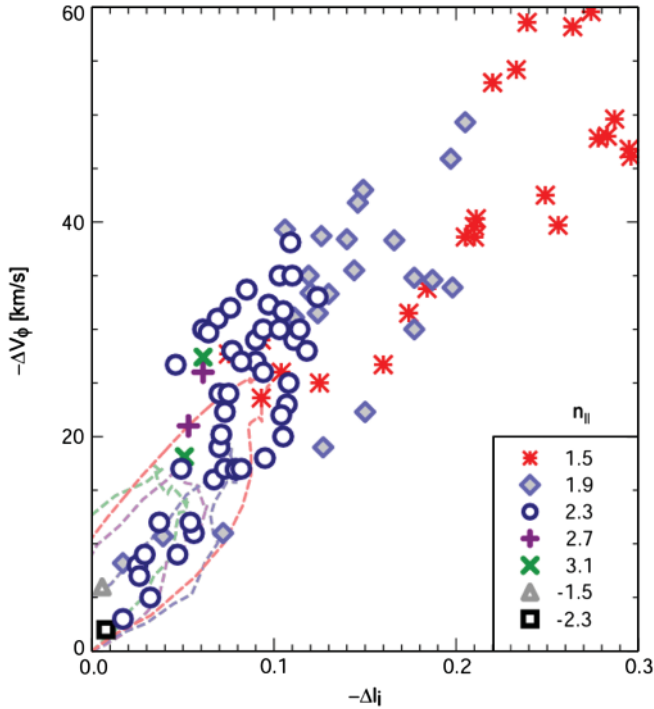


FIG. 3 (color). LH induced changes in central toroidal rotation and normalized internal inductance for a wide variety of plasmas (Each point represents a single discharge). The trajectories from Fig. 2 (dashed lines) are included for comparison.

pinch is the result of the canonical angular momentum absorbed by resonant trapped electrons while interacting with lower hybrid waves. Since the trapped resonant particles cannot on average carry toroidal mechanical angular momentum, the added momentum can only be realized by a change in the electron vector potential, and so they are forced to drift radially inwards. This mechanism can be thought of as a “Ware pinch”-like effect operating on resonant trapped electrons. The Ware pinch is automatically ambipolar because it is based on the $E \times B$ drift associated with the toroidal electric field and the poloidal magnetic field [16]. In the LHCD case, however, the fast electrons experience an enhanced electric field (due to their resonant interaction with the LH waves) and therefore experience a faster drift than the ions. This in turn, gives rise to a nonambipolar inward radial drift of electrons, and therefore negative charging of the core. A pinch of resonant electrons is consistent with the observation that no change in radial electric field is seen when LHCD is applied in the countercurrent direction. In this situation, virtually no fast electrons are produced because the LHCD is countered by the opposing Ohmic electric field (fast electrons were monitored with a hard x-ray camera [17]).

Regardless of the details of the electron pinch mechanism, as the plasma charges up negatively, the radial electric field is modified so as to oppose this charge separation. This negative increment in the radial electric field in turn drives countercurrent toroidal rotation via radial pres-

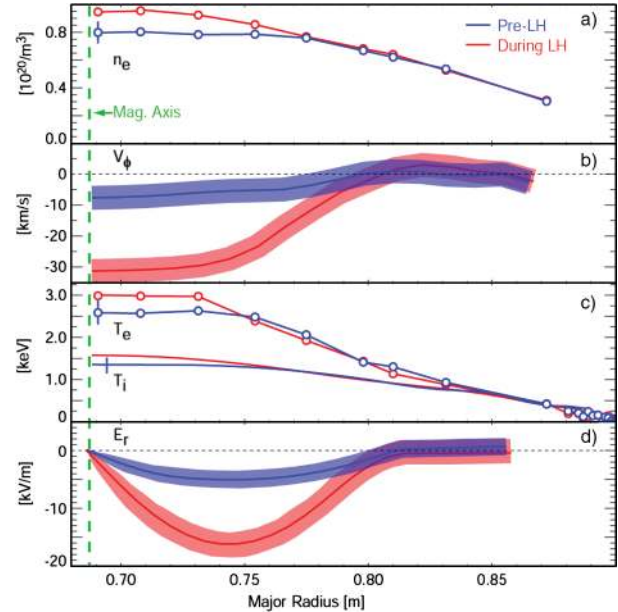


FIG. 4 (color). Profiles of (a) electron density, (b) impurity toroidal velocity, (c) electron and impurity temperature and (d) inferred radial electric field before and during the application of 600 kW of LHCD ($n_{||} = 2.3$).

sure balance. In steady state, the negative charging due to the electron pinch is balanced by a return current produced by the altered radial electric field.

The measurements described in this Letter represent the first observation of a LH induced electron pinch. They are not, however, the first observations of a wave induced particle pinch. In experiments on JET, the application of ICRF (ion cyclotron range of frequency) waves was shown to induce both an ion pinch and flow drive [18,19]. The similarities between the C-Mod and JET experiments suggest that it may be possible to induce resonant particle pinches with other wave heating and current drive methods.

In summary, lower hybrid waves have been shown to induce strong modifications to toroidal rotation profiles in Alcator C-Mod discharges. These modifications evolve on a time scale comparable to the current redistribution time and are well correlated with changes in normalized internal inductance, suggesting that LHCD (as opposed to heating) is their cause. In some discharges the application of LHCD created sheared rotation profiles and significant modification of the electric field profile. This phenomenon could prove to be an important consideration in the development of advanced scenarios on next generation tokamaks due to the coupling of rotation and current density profiles.

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