Lower hybrid waves launched uni-directionally into tokamak plasmas impart momentum to the electrons. This momentum can be transferred to the ions, leading to substantial counter current rotation. Observations of LH-induced counter rotation have been previously reported [1], and the initial rate of increase has been found to be consistent with the calculated rate of wave momentum injection [2]. However, in recent experiments in Alcator C-Mod it has been found that application of LH waves to relatively low current (Ip ~ 0.4-0.6 MA) plasmas can result in a co-current change of rotation, which implies a different mechanism than that described above. This appears to be linked to the so-called intrinsic rotation commonly observed in Alcator C-Mod and other tokamaks [3]. In addition to the change in direction at low current, some dependence on the magnetic configuration (USL vs. LSN) has been observed.


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EM waves propagating in plasmas carry momentum

When EM waves damp, momentum is transferred to electrons or ions, depending on wave and damping mechanism.

Rate of momentum density injected by wave:\(^1\):

\[
\dot{p} = \frac{1}{\omega} \nabla \cdot [\vec{v}_g \vec{k}W]
\]

Total rate at which toroidal momentum is injected:

\[
\dot{P}_\varphi = \int dA \cdot \frac{1}{\omega} \vec{s} \vec{k} \cdot \hat{\varphi} = \frac{n_\varphi}{c} \int dA \langle W \rangle v_{gn} = \frac{n_\varphi}{c} \text{Power}
\]

For LH waves, fast current-carrying electrons lose momentum to ions:

\[
\dot{P} = 2\pi R \int dA \int dv \frac{m_e v f(v)}{\tau(v)}
\]

Orbit effects complicate the mechanism for transferring torque

Trapped electrons can absorb wave momentum and pinch inward to preserve canonical angular momentum.

Passing electrons lose momentum to both trapped electrons and ions, as well as passing ions.

An net inward pinch of either species can create an electric field. Radial force balance requires ion rotation:

\[
E_r \approx n_\varphi B_\theta - n_\var_\theta B_\varphi + \frac{1}{Z_i e n_i} \frac{dp}{dr}.
\]

In Alcator C-Mod, LH-induced toroidal momentum is observed, generally in counter-current direction as expected. However, situation is complicated when intrinsic momentum (prior to LH) is strongly counter current.
Examples of discharges with substantial LH-induced counter rotation

Discharge in right panel has stronger current drive, current profile modification.

MHD activity occurs at $t = 1.04$ s in this discharge, affecting profile evolution.
Wave-induced momentum is mainly localized to core

Toroidal rotation profiles are measured with an imaging x-ray spectrometer viewing lines of Ar17+. Chordal profiles have been inverted to give radial profiles.

LH-induced momentum change is localized to the core, r/a ~ 0.5. Changes further out are small and seem to evolve more slowly.

The torque applied by the wave can be estimated from the initial slope of the velocity when LH is applied, if it is assumed that the “intrinsic” rotation does not change over the first ~ 50 ms of the LH pulse.
The steady-state central rotation decrease due to LH momentum injection scales roughly as $P_{RF}/n$ ....
.....and correlates with $-\Delta I_i$, inversely with $n_{\phi 0}$
The torque applied by waves agrees with that calculated from ray-tracing, F-P simulation*

The torque is broadly distributed in the simulation.

Total torque:

**Applied (Waves)**  **Simulation***

3.6x10^{-3} N·m  4.2x10^{-3} N·m

**Measured (from dL/dt to r/a ~ 0.5)**

0.6x10^{-3} N·m

*See Poster by J-P. Lee*
At low plasma current, the effect of LH momentum injection is more complex.

Notice initial change in ctr direction.
Core rotation prior to LH pulse decreases with current and reverses at low $i_p$ during LH.

The initial change in rotation is negative although final may be positive.
The apparent reversal of LH-injected momentum appears to be related to a recently discovered reversal in “intrinsic” rotation*

An abrupt change in “intrinsic” rotation is observed in Alcator C-Mod at a critical density $n_{\text{crit}} \sim I_p$

*J. E. Rice, et.al., submitted to PRL, Nuclear Fusion
The critical density is related to the LOC to SOC transition, and therefore to turbulence modification.

The critical density appears to be linked to the density at which the transition from “linear” to “saturated” confinement occurs.

*J. E. Rice, et.al., submitted for publication*
A working hypothesis is that low current results are consistent with LH momentum injection in counter direction, taking account of a change in transport.

Initially, lower hybrid waves inject counter momentum as in the case of high current plasmas.

However, current drive from the LH waves modifies the equilibrium raising \( q(0) \) and possibly reversing the shear.

The equilibrium changes modify the “intrinsic” rotation through modification of the turbulence.

Example of a discharge in which LHCD modifies shear.
Summary

RF waves carry momentum, dissipation can be used to affect rotation.

Rotation changes observed in C-mod are consistent with injection of wave momentum.

“Intrinsic rotation” has to be taken into account in determining final rotational state of the plasma.