Estimation of the ion toroidal rotation source due to momentum transfer from Lower Hybrid waves in Alcator C-Mod


Plasma Science and Fusion Center, MIT, Cambridge, USA

Abstract. Significant ion toroidal rotation (50 km/s) has been measured by X-Ray spectroscopy for impurities in Alcator C-Mod during lower hybrid (LH) RF power injection [1]. We investigate the relation between the computed toroidal momentum input from LH waves and the measured INITIAL change of ion toroidal rotation when the LH power is turned on. The relation may depend on the plasma current and magnetic configuration [2]. Because of the fast build up time of the electron quasilinear plateau (< 1 millisecond), the electron distribution function rapidly reaches steady state in which the electrons transfer momentum to the ions. The LH wave momentum input is computed from the self consistent steady state electron distribution function and a bounce-averaged quasilinear diffusion coefficient that are obtained by iterating a full wave code (TORLH) with a Fokker Plank code (CQL3D).

Keywords: Tokamaks, Lower hybrid wave, Rotation, Alcator-C Mod

PACS: 52.55.Fa,52.55.Wq,52.30.-q,52.35.Fp

INTRODUCTION

Lower Hybrid Current Drive (LHCD) is being investigated to drive non-inductive current to replace ohmic current and complement the bootstrap current in Advanced Tokamak (AT) steady state operation. The RF wave in the lower hybrid frequency regime (LH wave) transfers its momentum and energy to the plasma in a Tokamak by electron Landau damping. The toroidal asymmetric spectrum of the LH wave antenna system in Alcator C-Mod is designed to increase the number of non-thermal electrons with high parallel velocities in a range of several times the thermal velocity (about $3v_{te} - 10v_{te}$) along the counter-current toroidal direction. Here, $v_{te} = \sqrt{2T_e/m_e}$ is the electron thermal velocity.

Ion toroidal rotation shear is known to contribute to internal transport barrier formation by reducing the turbulence level, and the fast rotation inhibits the growth of 3-D asymmetric magneto-hydrodynamic unstable modes. Many researchers have investigated intrinsic toroidal rotation, both theoretically and experimentally, with no momentum source, as well as the rotation driven by a neutral beam momentum source. However, due to the complicated nature of turbulent momentum transport and boundary conditions at the edge, this research area still needs to be explored further.

In C-Mod, the non-negligible counter-current toroidal rotation induced by LH waves was observed by high-resolution spatially resolved X-ray spectroscopy for Helium-like Argon in 2008 [1], and the observed increase rate of toroidal momentum is in agreement
with the total wave momentum input based on a simple calculation [2]. In a recent measurement in 2011, the steady state rotation direction reversal is found when the plasma current is below about 400 kA [2]. However, even for the co-current steady flow, it seems that there exists a counter-current direction change right after LH is turned on. In this paper, the radial profile of the wave momentum source is compared with the experimentally measured ion toroidal rotation.

EVALUATION OF THE WAVE MOMENTUM SOURCE

Non-thermal electrons gain a toroidal momentum as well as energy from LH wave. However, the detailed mechanism by which ions gain toroidal momentum from the electrons is unclear. Collisions between electrons and ions could transfer most of the wave momentum, or LH wave could change the radial electric field associated with the rotation. The proper way to evaluate the ion rotation without inadvertently ignoring many mechanisms of momentum transfer is to use the momentum equation combining the electron (1) and ion (2) Fokker-Plank equations,

\[
\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \nabla f_e + \left( \frac{e}{m_e} \nabla \Phi + \Omega_e \mathbf{v} \times \hat{b} \right) \cdot \nabla_v f_e = C_{ee} \{ f_e \} + C_{ei} \{ f_e, f_i \} + \nabla_v \cdot \mathbf{D}_{ql} \cdot \nabla_v f_e, \tag{1}
\]

\[
\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \nabla f_i + \left( -\frac{Ze}{m_i} \nabla \Phi + \Omega_i \mathbf{v} \times \hat{b} \right) \cdot \nabla_v f_i = C_{ii} \{ f_i \} + C_{ie} \{ f_i, f_e \}. \tag{2}
\]

Here, \( f_e \) and \( f_i \) are the distribution functions of electrons and ions respectively, \( \Phi \) is the electrostatic potential, \( C_{ee}, C_{ei}, C_{ii}, \) and \( C_{ie} \) are the electron-electron, electron-ion, ion-ion, and ion-electron collision operators respectively, and \( \mathbf{D}_{ql} \) is the quasilinear diffusion tensor by LH wave. Since the collision operator conserves momentum and the electric field is canceled out, flux surface averaging of the toroidal component yields Eq. (3) below. Assuming ambipolarity, the ion toroidal rotation change on the LHS is determined by two terms, the off-diagonal stress tensor \( \Pi \) (viscosity) and the toroidal momentum source term (the last term on the RHS).

\[
\frac{\partial}{\partial t} \left( \langle m_i \nabla V_i \hat{\phi} \rangle \right)_s = -\frac{1}{V} \frac{\partial}{\partial \psi} \langle V' \Pi \rangle + \langle \mathbf{J} \cdot \nabla \psi \rangle_s + \left\langle \int d^3 \mathbf{v} m_i \nabla \hat{\phi} \cdot \mathbf{D}_{ql} \cdot \nabla_v f_e \right\rangle_s. \tag{3}
\]

The wave momentum source term induces the initial change in rotation when the viscosity term is zero since it creates a steady intrinsic rotation before LH wave is launched. The flux surface averaged momentum source can be evaluated in (4) with a weighting factor (5) when calculating a power absorption due to the property of the dirac-delta function arising from the electron Landau damping in the quasilinear diffusion coefficient.

\[
\left\langle \int d^3 \mathbf{v} m_i \nabla \hat{\phi} \cdot \mathbf{D}_{ql} \cdot \nabla_v f_e \right\rangle_s = \frac{1}{\tau_s} \text{Re} \left\{ \sum_{m' \sum_{m}} \int \frac{d \ell}{B} e^{(m' - m) \theta} E^m_{m'} \text{Im} \{ \eta \} E^m_{||} \right\}, \tag{4}
\]

\[
\text{Im} \{ \eta \} = \frac{k_i}{\omega} R \langle \hat{e}_\parallel \cdot \hat{e}_\phi \rangle \text{Im} \{ X_{||} \} = \frac{n_i}{c} R \cos \Theta \text{Im} \{ X_{||} \}. \tag{5}
\]
FIGURE 1. (a) Poloidal cross section of parallel electric field simulated by TORLH and CQL3D for C-Mod shot 1080320017 (Lower single null divertor, $B_T = 6T$, $I_p = 850kA$, $T_e(0) = 3.5KeV$, $n_e(0) = 0.7 \times 10^{20}$, $n_\parallel = -1.9$, LH power = 850kW ) (b) Comparison between the simulated momentum source term (blue solid) by (4) and the initial counter-current direction increase rate of ion angular rotation by X-ray spectroscopy (yellow solid) on the LHS of (3) for the same shot 1080320017.

where flux surface averaging is $\langle \ldots \rangle_s \equiv \frac{1}{\tau_s} \oint_B \ldots d\ell$, and $E_m^\parallel$ is parallel electric field of poloidal mode number $m$. $\chi_\parallel\parallel$ is the contribution to the susceptibility from electron Landau damping that is used in the bounce-averaged power evaluation. The weighting factor for the angular momentum input from the power is $n_\parallel c R \cos \Theta$ where $n_\parallel$ is parallel refractive index, $R$ major radius, $\Theta$ an angle between toroidal direction and the magnetic field vector. This relation is in accordance with the rate of momentum injected by wave in (6) using the poyniting vector $[3]$,

$$\frac{\partial L_\Phi}{\partial t} = \int dA \cdot \frac{R}{\omega} \hat{\mathbf{k}} \cdot \hat{\mathbf{v}} \approx \int dA \langle W \rangle \frac{c}{R} R_0 n_\parallel c \text{Power.} \quad (6)$$

COMPARISON WITH MEASUREMENT

The computed wave momentum source in (4) by a full wave code, TORLH[4], and a Fokker Plank code, CQL3D[5], is compared with the measured radial profile of initial increase rate of toroidal angular momentum when LH wave is injected. Figure 1 shows a result of C-Mod case of counter-current steady flow when the current is 850 kA, and LH wave is damped by a nearly single pass due to $n_\parallel = -1.9$. In Fig. 1-(b), a total integrated wave momentum (i.e torque) of blue solid line by (4) is $4.19 \times 10^{-3} N \cdot m$, which is close to the value by (6), $3.60 \times 10^{-3} N \cdot m$, but is smaller than the total momentum increase by measurement from yellow solid line $1.02 \times 10^{-3} N \cdot m$.

Figure 2 shows a result of C-Mod case yielding a counter-current steady flow in a high plasma current 700 kA (a) and a co-current steady flow in a low current 370 kA (b). In these cases, LH wave is damped by multi passes due to low parallel refractive index of LH launcher, $n_\parallel = -1.6$.

For multi pass damping (Fig. 2-(a) and 2-(b)), since $n_\parallel$ in the core is upshifted by broad electric field spectrum, the simulated value by (4) is about two times bigger than the estimation with launched wave $n = -1.6$ by (6). For low plasma current in Fig. 2-(b),
the simulated value by (4) can be bigger than that of high plasma currents due to high cos Θ in (5). As shown in Fig. 2, the correlation of the profiles between the simulated momentum source and measured rotation change is very low even after 10 msec, so the momentum confinement time could be smaller than the spectroscopy resolution time (20 msec). Then, the transport analysis for the turbulent viscosity [6] should be included to explain even the measured initial changed of ion rotation induced by LH wave as well as its saturation level and direction.

ACKNOWLEDGMENTS

This work is supported by US DOE awards DE-FC02-99ER54512, and MIT Plasma Science and Fusion Center Theory Group parallel computational cluster.

REFERENCES

5. R.W.Harvey and M.G.McCoy, IAEA technical committee meeting(1992)