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

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Abstract
Significant ion toroidal rotation (~50km/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 wave 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 the momentum to the ions. The LH wave momentum input is computed from the self consistent steady state cold electron distribution function and a bounce-averaged quasilinear diffusion coefficient that are obtained by iterating a full wave code (TORKLH) with a Fokker-Plank code (CQL3D).

I. Background

1. The quasilinear diffusion coefficient in velocity space describes electron landau damping of the LH wave in the electron Fokker-Plank equation. In the lowest order, the electron distribution function becomes steady state in very short time (~1 ms), thus we can balance the toroidal term with collision terms.

\[ f \frac{d}{dt} f = v_{\perp} (T_{\perp} f_{\perp} - T_{\parallel} f_{\parallel}) \]

2. A momentum equation is obtained by taking the first moment of both eqn (1) and (2) and summing them, ion mass is dominant over electron mass, the collision operator conserve momentum, and the electric field is canceled out.

\[ \frac{d}{dt} \left( \sum m_i v_i f_i \right) = \sum -v_i \cdot \nabla (m_i v_i f_i) \]

3. Flux surface averaging of the toroidal component of eqn (3) yields eqn. (4). Assuming ambipolarity, the ion toroidal rotation change in L.H.S is determined by two terms, the off-diagonal stress/viscosity and the toroidal momentum source.

\[ \frac{d}{dt} \int M f \, dv = \int \left( \sum -v_i \cdot \nabla (m_i v_i f_i) \right) \, dv \]

KEY QUESTIONS:
1. How big is the momentum source term?
2. What is the mechanism of momentum transfer from electron to ion?
3. What is the off-diagonal stress term? And how big is it (momentum confinement time?)

II. Experimental results

1. Ion toroidal rotation is measured by X-ray spectroscopy for He-like Argon impurity.

\[ \frac{d}{dt} \sum m_i v_i f_i \parallel = \int \sum \left( \sum -v_i \cdot \nabla (m_i v_i f_i) \right) \, dv \parallel \]

2. The parallel stress/viscosity is determined by: the initial ion toroidal rotation change due to pumping (eqn (5)) and the initial change of ion rotation by x-ray spectroscopy in the L.H.S of Eqn (4).

\[ \frac{d}{dt} \sum m_i v_i f_i \parallel = \frac{1}{2} \int \left( \sum m_i v_i^2 f_i \right) \, dv \parallel - \int \sum \left( \sum -v_i \cdot \nabla (m_i v_i f_i) \right) \, dv \parallel \]

III. Numerical results


\[ f_{eq} = \frac{1}{\sqrt{2\pi T_{\perp}}} \exp \left( -\frac{v_{\perp}^2}{2T_{\perp}} \right) \]

\[ f_{\parallel} = \frac{1}{\sqrt{2\pi T_{\parallel}}} \exp \left( -\frac{v_{\parallel}^2}{2T_{\parallel}} \right) \]

Electron distribution function

2. Quasilinear Diffusion Coeff. 

\[ D_{\parallel} = \frac{1}{2} \frac{m_i}{e} \frac{v_i^2 f_i}{T_{\perp}} \]

\[ D_{\perp} = \frac{1}{2} \frac{m_i}{e} \frac{v_i^2 f_i}{T_{\parallel}} \]

3. Torque by Eqn. (5) (Blue solid line): 6.15×10^2 Nm

4. Total momentum increase by measurement (Yellow solid line): 1.9×10^2 Nm

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6. For multi pass damping (case 2 and case 3), since \( n_{\parallel} \) is upshifted by broad electric field spectrum, the simulated value by (6) is much bigger than the estimation with launched wave \( n_{\parallel} \sim 1.6 \times 6 \times 10^2 \) Nm

IV. Conclusions

- Theoretically, the initial ion toroidal rotation change by LH wave can be estimated only by wave momentum source term

- Wave momentum source is evaluated by quasilinear diffusion term and the self-consistent steady state electron distribution function, and it is proportional to power and parallel wave refractive index.

- The time resolution of rotation measurement may be bigger than the spectroscopy resolution time (200ms) 

- Evaluation of the viscosity term [ref. 6] could explain the rotation radial profile as well as its saturation level and direction

References
2. R.Parker, this conference (A-21)