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The Combining Effect of the Inductive Electric Field and the Lower Hybrid Waves on the Impurity Ions Toroidal Rotation in the Lower Hybrid Current Drive Tokamak Plasmas

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1. INTRODUCTION

- The inductive electric field (IEF) used to drive plasma current and heat plasma in tokamaks has considerable effect on the plasma rotation even though it is not a source of total toroidal momentum in a quasi-neutral plasma [Pan&Wang'2007POP].
- The counter-current rotation driven by the LHW during the lower hybrid current drive (LHCD) was first reported by Alcator C-Mod team.
- The LHW counter-current momentum is coupled to the ions through collisional friction force against the resonant electrons.
- In the later studies, both the counter-current and co-current rotation changes were observed during LHCD.
- The loop voltage drops during LHCD. The counter-current rotation of the impurity ions induced by the IEF will decrease. The LHW will induce counter-current rotation for the impurity ions instead.
- The toroidal rotation velocity of the impurity ions should be determined by the combining effect of the IEF and LHW.

2. THEORETICAL MODEL (I)

The first order neoclassical flows

$$\mathbf{u}_j^s = u_{\theta,j}^s(\psi)\frac{\mathbf{B}}{<B_\theta>} + \frac{V_j^s B}{I}R^2\nabla\phi, V_1^s = -\frac{IT_s}{e_s B\psi'}\left(\frac{p_s'}{p_s} + \frac{e_s\Phi'}{T_s}\right), V_2^s = -\frac{IT_s}{e_s B\psi'}$$

Parallel and toroidal components of momentum equation

$$\partial_t\left(n_s m_s < \mathbf{u}_1^s\cdot\mathbf{B} >\right) = -<\mathbf{B}\cdot\nabla\cdot\mathbf{\Pi}_s^{CGL}> - <\mathbf{B}\cdot\nabla\cdot\mathbf{\Pi}_s^{NCGL}> + <\mathbf{B}\cdot\mathbf{F}_{s1}> + <\mathbf{B}\cdot\mathbf{F}_{sf,1}> + e_s n_s <\mathbf{B}\cdot\mathbf{E}^{(A)}>,$$

$$e_s n_s < \mathbf{u}_1^s\cdot\nabla r > \psi' = -<R^2\nabla\phi\cdot\mathbf{F}_{s1}> - <R^2\nabla\phi\cdot\mathbf{F}_{sf,1}> - e_s n_s <R^2\nabla\phi\cdot\mathbf{E}^{(A)}> + \partial_t <R^2\nabla\phi\cdot n_s m_s\mathbf{u}_1^s> + <R^2\nabla\phi\cdot\nabla\cdot\mathbf{\Pi}_s^{NCGL}>,$$

Equations to determine the poloidal rotations

$$\begin{bmatrix} -<\mathbf{B}\cdot\nabla\cdot\mathbf{\Pi}_s^{CGL}> \\ -<\mathbf{B}\cdot\nabla\cdot\mathbf{\Theta}_s^{CGL}> \end{bmatrix} + \begin{bmatrix} <\mathbf{F}_{s1}\cdot\mathbf{B}> \\ <\mathbf{F}_{s2}\cdot\mathbf{B}> \end{bmatrix} + \begin{bmatrix} <\mathbf{F}_{sf,1}\cdot\mathbf{B}> \\ 0 \end{bmatrix} + \begin{bmatrix} e_s n_s <\mathbf{E}^{(A)}\cdot\mathbf{B}> \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Before LHW injection, equation to determine the REF

$$<\sum_s R^2\nabla\phi\cdot n_s m_s\mathbf{u}_1^s> = 0$$

With LHW injection, equation to determine the REF [Wang'2011]

$$\partial_t\Gamma + \frac{1}{r}\frac{\partial}{\partial r}\left\{r\left[\left(-D\frac{\partial}{\partial r} - U\frac{r}{a}\right)\Gamma\right]\right\} = S, \Gamma = <\sum_s R^2\nabla\phi\cdot n_s m_s\mathbf{u}_1^s>, S = <R^2\nabla\phi\cdot\mathbf{F}^w>$$

2. THEORETICAL MODEL (II)

One-dimension model for current driven efficiency [Fisch&Boozer'80

$$\eta = \frac{J_N}{P_N} = \frac{J_{LH}/(en_e v_{Te})}{p_{LH}/(\nu_0 n_e m_e v_{Te}^2)} = \frac{8u^2}{5+Z_{eff}}, (u = \frac{\omega}{k_{//}v_{Te}})$$

The decrease of the loop voltage [Fisch'85,Giruzzi'97]

$$-\frac{\Delta V}{V_{ohm}} = \frac{I_{LH}/I_p + \alpha(Z_{eff})u^4 P_N}{1+\alpha(Z_{eff})u^4 P_N}, \ I_{LH} = 2\pi\int_0^a j_{LH} r dr, P_N = \frac{p_{LH}}{\nu_0 n_e m_e v_{Te}^2}, \alpha(z_{eff}) = \frac{1}{4(2/\pi)^{1/2}}\frac{Z_{eff}+0.72}{Z_{eff}+3}$$

3. Simulation Parameters

A model tokamak

$$B_{\phi 0} = 5.0T, a = 0.21m, R_0 = 0.67m, V_{ohm} = 1.0V$$

Momentum transport coefficients

$$D = 0.2m^2/s, U = 6.5m/s$$

Tracing impurity density fraction

$$f_{Ar} = n_{Ar}/n_e = 7.0\times10^{-6}$$

4. Simulation Results

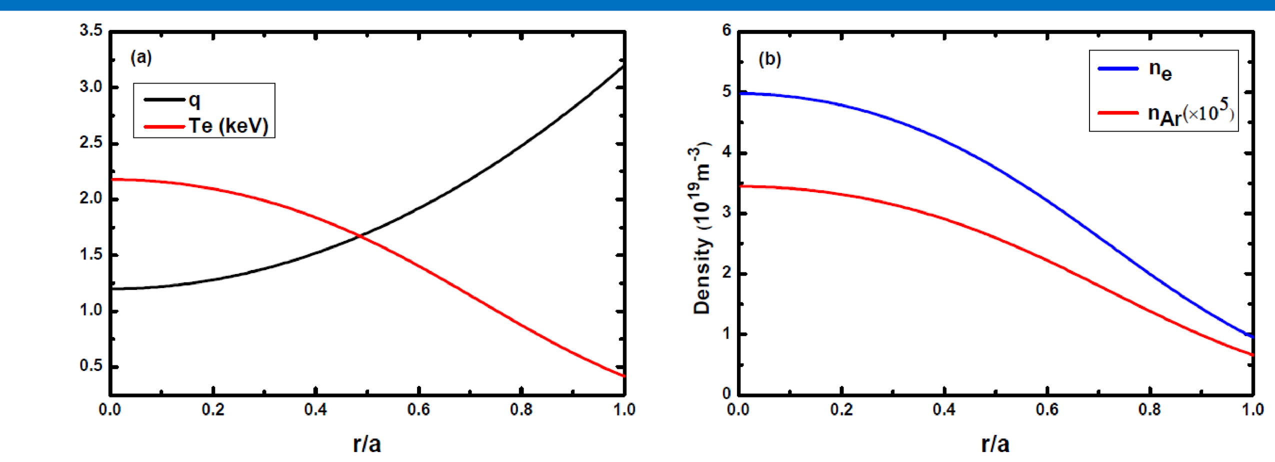

Figure 1. Profiles of (a) safety factor, electron temperature, (b) electron density, Ar^{17+} density.

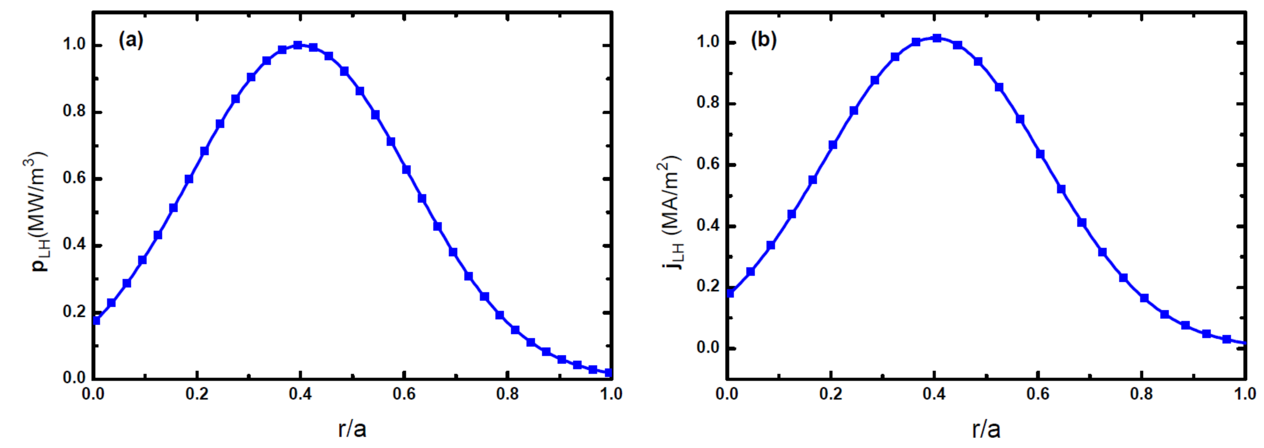

Figure 2. Profiles of (a) LHW power deposition density, and (b) current density driven by the LHW. The total input power of LHW is 0.25 MW and the total plasma current due to LHCD is 60 kA.

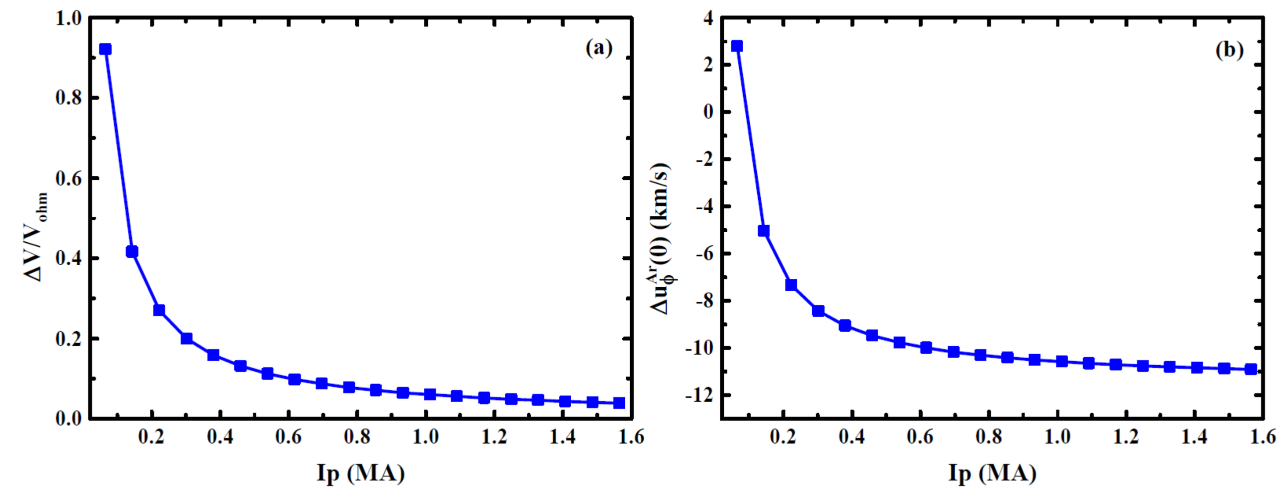

Figure 3. (a) The changes of the loop voltage due to the LHW injection; (b) the changes of the toroidal rotation velocity for the Ar^{17+} impurity ions at the magnetic axis during the LHW injection. The total input power of LHW is 0.25 MW and the total plasma current due to LHCD is 60 kA.

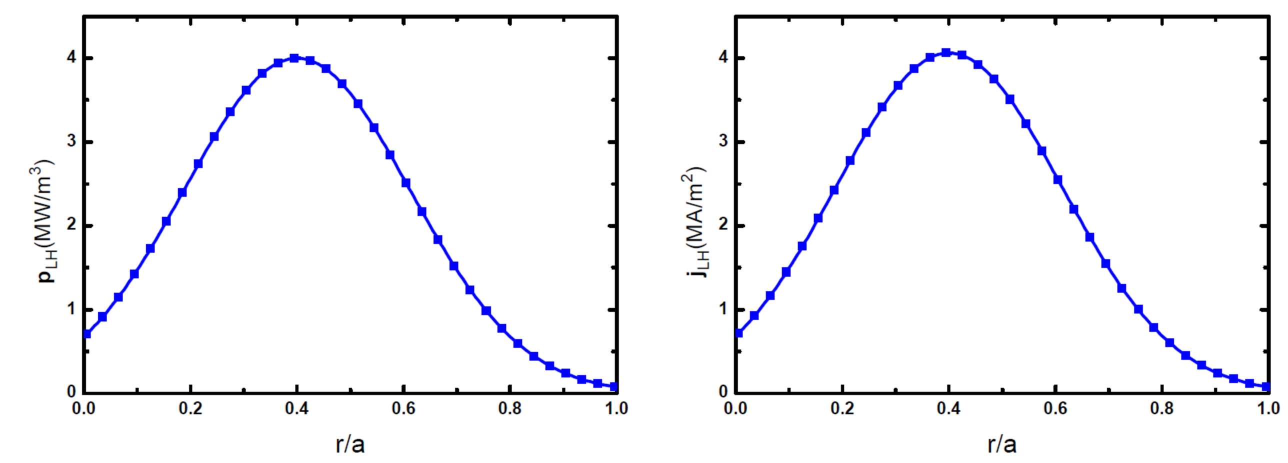

Figure 4. Profiles of (a) LHW power deposition density, and (b) current density driven by the LHW. The total input power of LHW is 1.0 MW and the total plasma current due to LHCD is 240 kA.

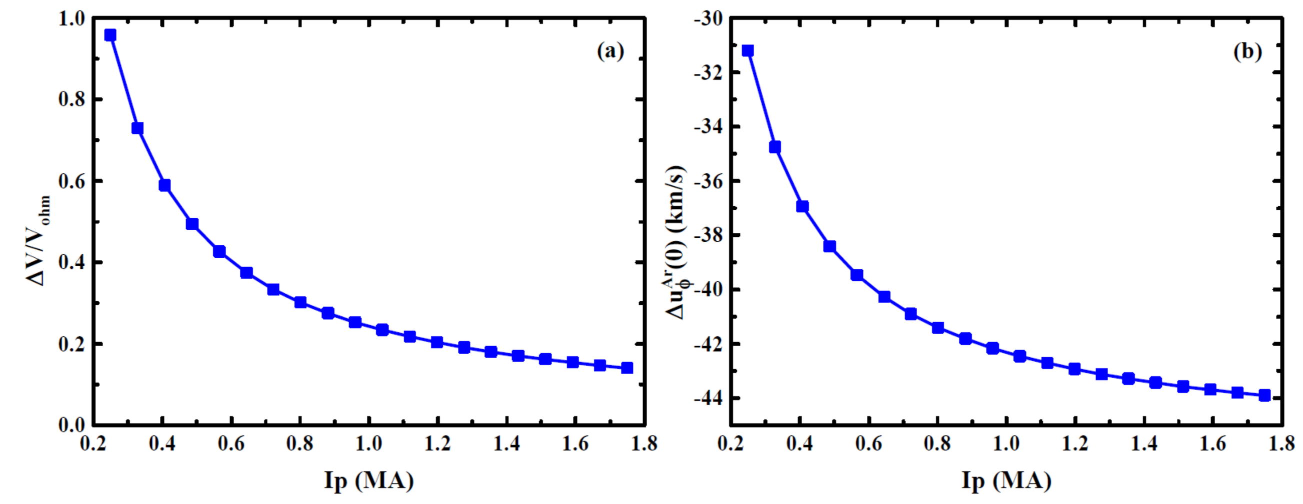

Figure 5. (a) The changes of the loop voltage due to the LHW injection; (b) the changes of the toroidal rotation velocity for the Ar^{17+} impurity ions at the magnetic axis during the LHW injection. The total input power of LHW is 1.0 MW and the total plasma current due to LHCD is 240 kA.

5. CONCLUSIONS

- The IEF decreases due to the drop of the loop voltage during LHCD. With the same LHW input power, the effect of the IEF is negligible for the high plasma current case and can not be neglected for the low plasma current case.
- The resulting toroidal rotation velocity of the impurity ions should be determined by including the combining effect of the IEF and the LHW.

Acknowledgements

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