Lower Hybrid Wave Current Drive Efficiency on the HT-7 Tokamak *

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Lower hybrid (LH) wave current drive efficiency on our HT-7 tokamak has been investigated based on the hot electrical conductivity theory. The interaction of the residual toroidal electric field with fast electrons has been included in the determination of current drive efficiency. The LH wave power scan was performed in the plasma parameter ranges of $I_{\rm p} = 50$–$156\,kA$, $\bar{n}_e = 0.5 \times 10^{19}$–$1.6 \times 10^{19}\,m^{-3}$, $P_{\rm LH} = 50$–$350\,kW$. *The current drive efficiency is derived to be about* 0.1×10^{19}–$0.4 \times 10^{19}\,Am^{-2}W^{-1}$ *on the HT-7 tokamak, which depends on the electron density and the LH wave phase velocity. At the electron density of about* $1.5 \times 10^{19}\,m^{-3}$, *with the LH wave parallel refraction index peaked at 1.8, the highest current drive efficiency was obtained. A more generally normalized method is introduced to analyse the experimental data, which combines all the data in one curve. The normalized parameters are independent of the plasma parameters.*

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Lower hybrid (LH) waves[1] are routinely used to drive currents in tokamak plasmas non-inductively, thus significantly extending the tokamak operation space to long-pulse, steady state discharges.[2,3] A more ambitious goal is the use of LH current drive to control the current density profile, so as to improve both the plasma stability and confinement properties. The current drive (CD) efficiency is an important physical quantity in evaluating the lower hybrid current drive (LHCD) experiments. In steady state operation of the LHCD experiment, the loop voltage is zero, and the current is sustained only by LH waves. The CD efficiency at zero loop voltage determines the amount of LH power to achieve the steady state operation. Investigation of key factors in obtaining high CD efficiency is required as database for reactor-grade machine. In order to understand and to improve the CD efficiency, parameter dependences of the CD efficiency have been widely investigated on the LH wave phase velocity, the electron density, the toroidal magnetic field, the effective ion charge $Z_{\rm eff}$, the electron temperature, and so on.[4−7]

HT-7 is an important machine, which is focused on the long pulse quasi-steady state operation with LH waves. The effects of plasma density and toroidal magnetic field on LHCD efficiency have been investigated on HT-7, based on the relative change of loop voltage.[6] However, synergy of the residual toroidal electric field and fast electron has an important impact on the LHCD efficiency, this will overestimate the fully non-inductive CD efficiency.

The experimental current drive efficiency is defined by $\eta = I_{\rm rf}\bar{n}_e R/P_{\rm LH}$, where $\bar{n}_e$ is line averaged density, $I_{\rm rf}$ is the current driven by LH wave, R is the major radius of the plasma, and $P_{\rm LH}$ is the injected LH wave power. When the loop voltage reaches zero, the plasma current is driven fully non-inductively and the CD efficiency is $\eta_0 = I_{\rm p}\bar{n}_e R/P_{\rm LH0}$. $P_{\rm LH0}$ is the required LH wave power to achieve zero loop voltage. The fully non-inductive CD efficiency η_0 can be well determined when the zero loop voltage is achieved. A large amount of LHCD discharges on the HT-7 tokamak, however, were operated at the non-zero loop voltage. The residual DC electric field accelerates the fast electrons, which can significantly enhance the CD efficiency. In this case, the CD efficiency η_0 can be obtained by including the effect of residual toroidal electric field on fast electrons, which is based on Fisch's hot electric conductivity theory.[8] In the presence of a dc electric field, the total plasma current density can be written as $J_{\rm tot} = J_{\rm OH} + J_{\rm rf} + \sigma_1 E + \sigma_2 E^2 + \cdots$, where $J_{\rm OH}$ is the ohmic (OH) current that results in the absence of rf power, $J_{\rm rf}$ is the rf current that results in the absence of a dc electric field, and $\sigma_1 E + \sigma_2 E^2 + \cdots$ are the additional currents when both rf and dc electric fields are present. While σ_1 is the hot electrical conductivity caused by the LH wave driven suprathermal electron.[9] Generally, the higher cross terms are negligible, i.e.

$$J_{\rm tot} = J_{\rm OH} + J_{\rm rf} + \sigma_1 E. \tag{1}$$

The LH wave driven non-inductive current can be obtained from the relative drop in loop voltage,

$$I_{\rm rf} = -\frac{\Delta V}{V_{\rm OH}} I_{\rm p}, \tag{2}$$

where $\Delta V = V_{\rm LH} - V_{\rm OH}$ is the loop voltage change between the LHCD phase and the ohmic phase.

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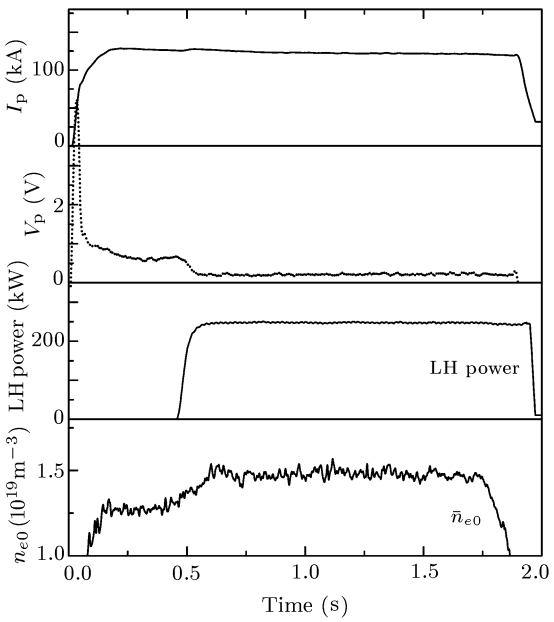


Fig. 1. A typical LHCD discharge (#70818) with 250 kW LH wave power. When the power was injected, it causes the loop voltage to drop approximately 60% so that the total current is constant.

Combined Eq. (1) with Eq. (2), we obtain the relation between $-\dfrac{\Delta V}{V_{\rm OH}}$ and normalized LH power $P_{\rm norm}$ as follows,

$$-\frac{\Delta V}{V_{\rm OH}} = \frac{(\eta_0+\eta_1)P_{\rm norm}}{1+\eta_1 P_{\rm norm}}, \tag{3}$$

where $P_{\rm norm} = P_{\rm LH}/\bar{n}_e I_{\rm p} R$, which is the inverse of the current drive efficiency when the loop voltage is zero; η_0 is the CD efficiency at zero loop voltage, η_1 is the CD efficiency caused by fast electron hot electrical conductivity and defined as $\eta_1 = \sigma_1/(P_{\rm norm}\sigma_{\rm sp})$, $\sigma_{\rm sp}$ is the Spitzer conductivity. Determination of the purely non-inductive CD efficiency η_0 and the CD efficiency η_1 is based on LH power scan experiment. From the discharges with various LH powers at constant plasma current and density, we obtain $-\dfrac{\Delta V}{V_{\rm OH}}$ as a function of the LH power $P_{\rm norm}$. The CD efficiency can be determined by a simple two-parameter (η_0, η_1) least-square fit, even if the data at $-\dfrac{\Delta V}{V_{\rm OH}} = 1$ is absent.

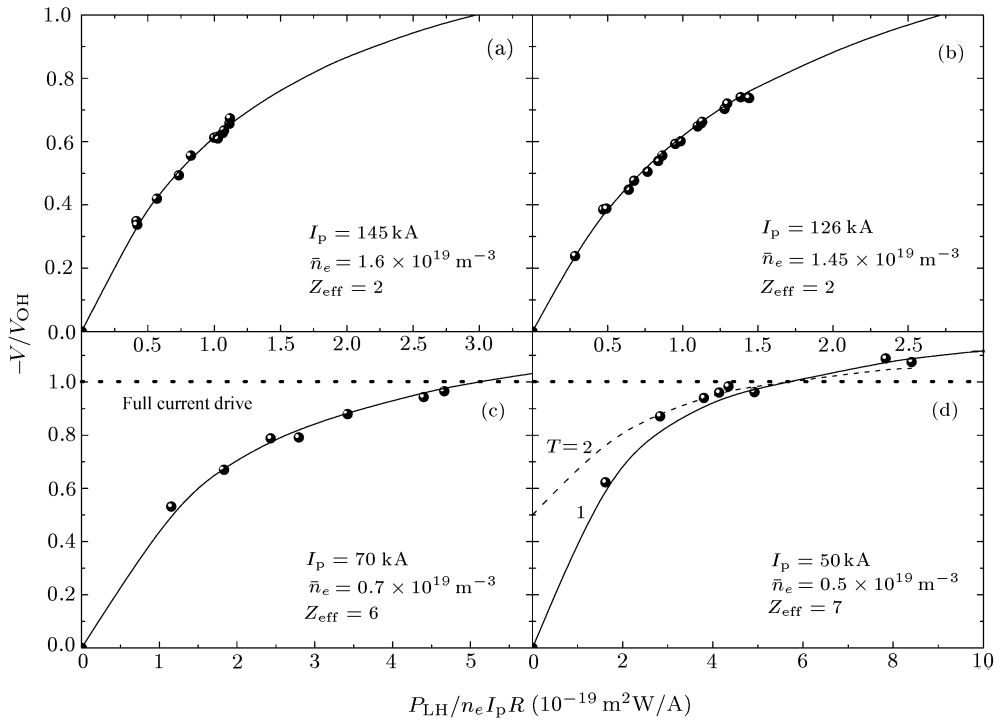


Fig. 2. Characteristics of $-\Delta V/V_{\rm OH}$ versus normalized LH power $P_{\rm norm}$ with different plasma parameters. The fitting results for different plasmas are: (a) $\eta_0 = 0.342 \pm 0.061 \times 10^{19}$Am^{-2}W^{-1}, $\eta_1 = 0.713 \pm 0.026 \times 10^{19}$Am^{-2}W^{-1}; (b) $\eta_0 = 0.364 \pm 0.007 \times 10^{19}$Am^{-2}W^{-1}, $\eta_1 = 0.652 \pm 0.019 \times 10^{19}$Am^{-2}W^{-1}; (c) $\eta_0 = 0.196 \pm 0.015 \times 10^{19}$Am^{-2}W^{-1}, $\eta_1 = 0.388 \pm 0.027 \times 10^{19}$Am^{-2}W^{-1}; (d) $\eta_0 = 0.183 \pm 0.012 \times 10^{19}$Am^{-2}W^{-1}, $\eta_1 = 0.615 \pm 0.071 \times 10^{19}$Am^{-2}W^{-1}. In (d), the Spitzer resistance ratio of $T = 2$ between OH phase and LHCD phase is used to fit the data at high LH power.

In the present work, the experiments of LH power scan were repeated at different plasma currents and electron densities. The accessibility condition was fulfilled in those LHCD discharges. The toroidal magnetic field B_T was kept at 1.87 Tesla. The plasma current is feedback controlled at constant value during the LHCD pulse. The loop voltage drops to the value required to keep the sum of LH driven current $I_{\rm rf}$ and

inductively current $I_{\rm OH}$ unchanged. The possible contribution of the bootstrap current was estimated to be small and was neglected.[10] Figure 1 shows a typical LHCD discharge (#70818) with 250 kW of LH wave power. The loop voltage was dropped approximately by 60%. The physical quantities discussed here have been averaged over a time interval during a stationary state. At the stationary phase, plasma inductance is constant and does not have effect on the loop voltage. There are no visible MHD activities during LHCD discharges.

Figure 2 shows $-\dfrac{\Delta V}{V_{\rm OH}}$ as a function of normalized LH power $P_{\rm norm}$ at different plasma parameters. The injected LH wave parallel refractive index is peaked at $N_{\parallel} = 2.35$. The dots represent the experimental data and the curves denote the fitting of Eq. (3). The relation between $I_{\rm rf}$ and $P_{\rm LH}$ is nonlinear in the presence of a residual dc electric field. The drop of loop voltage is first characterized by a steep linear variation with $P_{\rm norm}$, which results from the well-known synergy between the LH wave and the ohmic electric field. The electric field moves electrons from lower to higher velocities, making their interaction with the wave field stronger and the current drive more efficient.[11] Here $-\Delta V/V_{\rm OH}$ varies progressively to saturation as the power increased further, because of the diminishing effect of the electric field as more current is driven by the LH wave. While $-\dfrac{\Delta V}{V_{\rm OH}} = 1$ indicates the full non-inductively CD operation. The CD efficiency at zero loop voltage η_0 is in the range of 0.1×10^{19}–$0.4 \times 10^{19}\,{\rm A m^{-2} W^{-1}}$, depending on the plasma densities. The LH power for zero loop voltage operation can be extrapolated from the fitting curves. They are about 820, 610, 305, and 167 kW for plasmas shown in Fig. 2, respectively.

At high densities, the experimental data are well fitted by Eq. (3). At the lower density of $0.5 \times 10^{19}{\rm m^{-3}}$, however, $-\dfrac{\Delta V}{V_{\rm OH}}$ versus $P_{\rm norm}$ deviates from Eq. (3). The assumption of the constant Spitzer conductivity between the OH phase and the LHCD phase is no longer invalid. We define the ratio of the Spitzer resistance between the OH and LHCD phases as $T = R_{\rm sp}/R_{\rm LH}$. At lower LH power, the experimental data are consistent with the fitting curve at $T = 1$. As the power increases, they fall on the fitting curve at $T = 2$, which is presented by a dashed line in Fig. 2(d).

Dependence of the CD efficiency η_0 on the line averaged electron density is shown in Fig. 3, by neglecting the effect on plasma current. Plasma current only has a weaker effect on the CD efficiency via the plasma temperature, which increases with the plasma current.[7,12] At the line averaged density of about $\bar{n}_e = 1.5 \times 10^{19}\,{\rm m^{-3}}$, the highest CD efficiency η_0 is obtained.

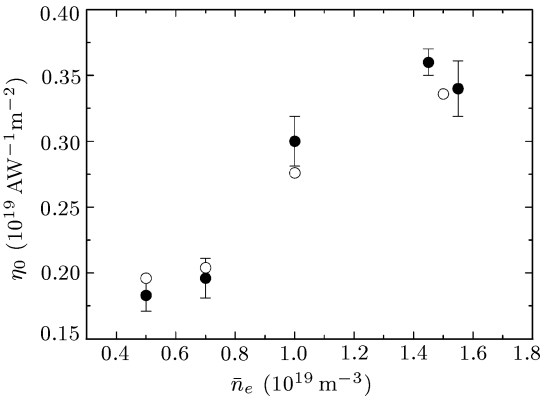


Fig. 3. Dependence of the CD efficiency η_0 on the line averaged electron density. The LH parallel refraction index $N_{\parallel 0}$ is 2.35. The effect from plasma current is neglected. The dots are derived from Eq. (3), while the open circles are derived from Eq. (4).

The theoretical value of the CD efficiency was given by $\eta_{cd} = \dfrac{1240}{\ln \Lambda (5 + Z_{\rm eff}) \langle N_{\parallel}^2 \rangle}$.[13] It depends only on the Coulomb logarithm $\ln \Lambda$, the effective ion charge number $Z_{\rm eff}$ and the LH wave parallel refraction index in plasma $N_{\parallel}$. In most LHCD experiments of different machines, correlations between the CD efficiency and the plasma density have been observed, while the theory prediction is independent of density. Generally, $Z_{\rm eff}$ is reversely proportional to the density. The density dependence of the CD efficiency from experimental observation may be linked to its dependence on $Z_{\rm eff}$.

By introducing a new normalized parameter $P'_{\rm norm}/(5 + Z_{\rm eff})$, Eq. (3) can be rewritten as

$$-\frac{\Delta V}{V_{\rm OH}} = \frac{(\eta'_0 + \eta'_1) P'_{\rm norm}}{1 + \eta'_1 P'_{\rm norm}}, \qquad (4)$$

which has the same form as Eq. (3), where η'_0 and η'_1 are $\eta_0(5 + Z_{\rm eff})$ and $\eta_1(5 + Z_{\rm eff})$, respectively. The parameters η'_0 and η'_1 are independent of the plasma parameters. In this case, the experimental data with different plasma parameters can in principle be fitted by a single curve when the values of the LH wave parallel refraction index $N_{\parallel}$ are the same. On the HT-7 tokamak, the dependence of $Z_{\rm eff}$ on the density has been obtained under different wall conditions.[14] In the higher electron density region above $1.4 \times 10^{19}{\rm m^{-3}}$, $Z_{\rm eff}$ is about 2, while in the lower density region below $0.8 \times 10^{19}{\rm m^{-3}}$, $Z_{\rm eff}$ is above 6. The experimental data and the fitting result with new normalized parameter are shown in Fig. 4. The fitting result is remarkable. With the new normalized parameter $P'_{\rm norm}$, all the experimental data in the density range of 0.5×10^{19}–$1.6 \times 10^{19}{\rm m^{-3}}$ are well presented by the same fitting curve. This proves that the new normalized parameters can reveal more general LHCD properties including the parameter dependence.

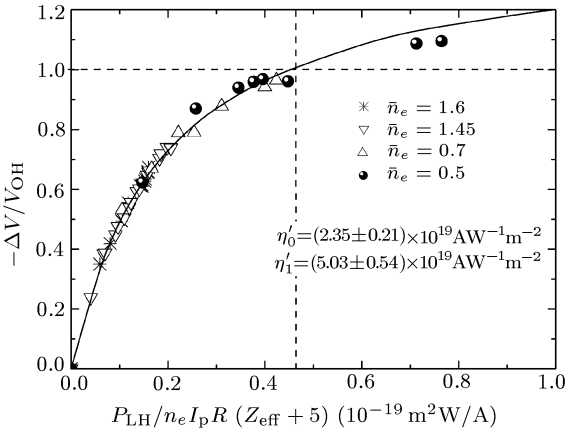


Fig. 4. Characteristics of $-\Delta V/V_{\rm OH}$ versus normalized parameter $P'_{\rm norm}$. The solid curve is the fitting of Eq. (4) with $\eta'_0 = (2.35 \pm 0.21) \times 10^{19}{\rm AW}^{-1}{\rm m}^{-2}$ and $\eta'_1 = 5.03 \pm 0.53 \times 10^{19}{\rm AW}^{-1}{\rm m}^{-2}$.

The CD efficiencies η_0 and η_1 with different electron densities can be determined by the parameters η'_0 and η'_1 via the relation between $Z_{\rm eff}$ and electron density $\bar{n}_e$. According to the definition, the CD efficiencies at different densities can be derived and are shown in Fig. 3 by open circles. The results are consistent with those from Eq. (3) within uncertainty of 8%. The CD efficiency η_0 derived from Eq. (4) increases monotonically with density, while the CD efficiency η_0 from the experimental observation has a maximum, at density of $1.5 \times 10^{19}{\rm m}^{-3}$. The possible explaination is that the efficiency is improved due to both the decreasing $Z_{\rm eff}$ and the stronger absorption of LH wave power with the increasing electron density in the lower density region. In the higher density region, however, the variation of $Z_{\rm eff}$ is very small. The fast electrons carrying plasma current suffer collision with bulk electrons more frequently, so that they are slowed down more easily, which causes a decrease of the CD efficiency η_0.

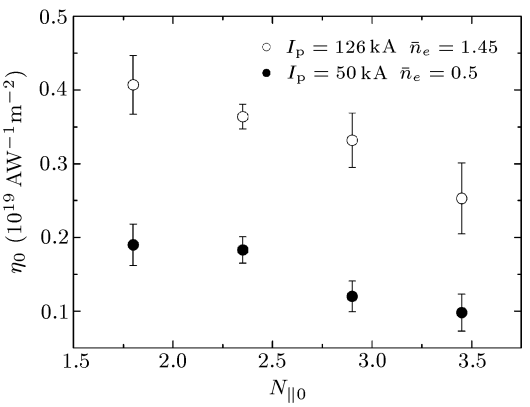


Fig. 5. Dependence of the CD efficiency η_0 on the LH wave parallel refraction index $N_{\|0}$. The density is in units of 10^{19} m^{-3}.

Another key factor that affects the CD efficiency is the launched wave spectrum. Many experiments have indicated higher CD efficiency at low and narrow $N_{\|}$.[4,5] Experiments of LH phase scan with $\Delta\Phi = -90°$, $0°$, $90°$, $180°$ at two different plasma parameters were performed. They correspond to the parallel refractive index $N_{\|0}$ peaked at 1.8, 2.35, 2.9, 3.45, respectively. The CD efficiency η_0 with different $N_{\|0}$ has been presented in Fig. 5. The lower $N_{\|0}$ has higher CD efficiency, and it decreases monotonically with increasing $N_{\|0}$.

In conclusion, the LHCD efficiency η_0 by considering the interaction between the residual electronic field and the fast electrons has been investigated at different line averaged densities and at different values of the LH parallel refractive index $N_{\|0}$. The experimental results are consistent with the theoretical prediction except in the high-density region. There is a favoured density region (near 1.5×10^{19} m^{-3} at $N_{\|0} = 2.35$) in which the CD efficiency is highest. By defining new normalized parameter $P'_{\rm norm} = P_{\rm norm}\Big/(5 + Z_{\rm eff})$, $-\dfrac{\Delta V}{V_{\rm OH}}$ as a function of $P'_{\rm norm}$ becomes more general, and independent of the plasma parameters. The experimental results based on the new model are consistent with the results of the previous models.

There is a caveat to bear in mind in using the formula $-\dfrac{\Delta V}{V_{\rm OH}} = \dfrac{(\eta_0 + \eta_1)P_{\rm norm}}{1 + \eta_1 P_{\rm norm}}$ to fit the experimental data. It has the assumption that the Spitzer conductivity between OH phase and LHCD phase is unchanged. This assumption is suitable in the high-density region or for lower LH power. At lower density and high power, the experimental results will deviate from the fitting formula, and the ratio of Spitzer resistance between OH and LHCD phases should be introduced.

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