Letter

Synergy effect of the Ohkawa current drive of electron cyclotron waves and the lower hybrid current drive: a new mechanism

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Abstract

A new synergy mechanism between the Ohkawa current drive (OKCD) of electron cyclotron (EC) waves and the lower hybrid current drive (LHCD) is discovered and discussed. The methodology to achieve this synergy effect is also introduced. Improvement of OKCD efficiency can be achieved by up to a factor of ~2.5 in the far off-axis radial region ($\rho > 0.6$) of tokamak plasma. By making EC wave heating of electrons have a parallel velocity in the co-$I_p$ direction and the lower hybrid wave heating of electrons have a parallel velocity in the counter-$I_p$ direction, the mechanism of this new synergy effect comes from the results of the electron trapping and detrapping processes. The OKCD makes the low-speed, barely-passing electrons be trapped (trapping process), the LHCD pulls some of the high-speed barely-trapped electrons out of the trapped region in velocity space (detrapping process) and accelerates the detrapped electrons to a higher speed.

Keywords: Ohkawa current drive, lower hybrid current drive, synergy effect, far off-axis current drive

(Some figures may appear in colour only in the online journal)

1. Introduction

The synergy effect of electron cyclotron (EC) waves and lower hybrid (LH) waves is of great interest in the area of non-inductive current drive in tokamaks. Although they have limited control capabilities, LH waves are believed to provide the highest current drive efficiency. EC waves have a lower efficiency compared to LH waves, but they can drive highly localized currents. The concept of synergy between the electron cyclotron current drive (ECCD) and lower hybrid current drive (LHCD) was firstly proposed by Fidone \textit{et al} [1]. Relevant experiments were carried out [2–7], but they could not conclude that there is a synergy effect. Numerical and analytical calculations [8–11] showed that current driven by the simultaneous use of the EC and LH waves, $I_{EC} + I_{LH}$, can be significantly larger than sum of currents driven by the two waves separately, $I_{EC} + I_{LH}$. Studies on Versator II [12] and TdeV [13] attempted to demonstrate the effect, but failed to produce a conclusive result. Experiments performed on the FTU indicated a possible improvement of ECCD efficiency with an LH driven electron tail [14]. Studies on Tore Supra demonstrated both in theory and experimentally that a strong synergy effect existed [15] and improved ECCD efficiency in plasmas sustained by LHCD. This synergy effect was found in the inner half region of the Tore Supra (normalized small radius $\rho < 0.4$). Negative synergy [16] was also found by simulation, the effect is dependent on the frequency and parallel refractive index of EC waves [17]. In recent experiments on the Experimental Advanced Superconducting
Tokamak (EAST), one EC and two LH waves with different frequencies are applied simultaneously [18], and a strong synergy effect among the three waves might exist [19]. All of these studies were concerned with making resonance regions of EC waves and LH waves overlap both in configuration space and in velocity space. However, what would happen if the resonance regions of the two kinds of waves do not overlap in velocity space, but only in configuration space?

The interaction mechanism of LH waves with electrons is Landau damping [20, 21]. LHCD induces electron detrapping rather than trapping, and possibly pulls some barely-trapped electrons out of the trapped region in velocity space. The Ohkawa current originates from selective electron trapping [21, 22], and it causes the resonant barely-passing electrons to become trapped and induces a net reverse parallel current. It is generally believed to be small, but reduces current drive efficiency greatly for the off-axis ECCD [23, 24], which originates from the Fisch–Boozer mechanism [25]. However, recent theoretical studies show that Ohkawa current drive (OKCD) of EC waves has a potential capability to drive an
effective localized current in the tokamaks with a large inverse aspect ratio \( \varepsilon \), or in a radial position where the local \( \varepsilon \) is large enough \([26, 27]\), so that a synergy effect between OKCD and LHCD can possibly exist. In this letter, we demonstrate theoretically that a strong synergy effect between OKCD and LHCD exists in a low \( \varepsilon \) tokamak.

2. Simulation details

GENRAY \([28–30]\)/CQL3D \([31, 32]\) codes and EAST H-mode discharge \#013606 at the time of 7.104 s are used in the simulation. EAST is a medium sized tokamak with a major radius \( R_p = 1.85 \) m, minor radius \( a = 0.465 \) m, \( \varepsilon = aR_p \sim 0.25 \). The configuration of EAST, the electron density, the electron temperature, and the safety factor profiles are shown in figure 1. The equilibrium magnetic field is from EFIT \([33]\) reconstruction with plasma current \( I_p = 0.8 \) MA, the kinetic profiles are from an integrated modelling code. The central electron temperature in this discharge \( T_e0 = 7.28 \) keV, the central electron density \( n_e0 = 2.5 \times 10^{19} \) m\(^{-3}\), the central magnetic field \( B_{T0} = -2.2 \) T, and the effective ion charge \( Z_{\text{eff}} = 1.5 \). One of the LHCD systems in EAST operates with a frequency of 2.45 GHz, launched from low field side (LFS) mid-plane with the power spectra peaked at \( N_{||0} = 2.1 \) and initial spectral width \( \Delta N_{||0} = 0.26 \) \([34]\), and the EC wave is assumed with a frequency of 105 GHz (X2-mode) in order to generate an effective OKCD in the outer half region of EAST. As is shown in figure 1(a), the poloidal incident angle \( \beta \) of EC defined in the GENRAY code is measured from \( Z = \) constant plane and is positive above the mid-plane of the equilibrium and negative below it. The toroidal incident angle \( \alpha \) is measured from the \( R \)-vector through the EC source. For the purpose of making the current direction of the OKCD the same as the direction of LHCD, the toroidal launch angle of the EC wave is fixed at \( \alpha = 160^\circ \), which corresponds to the initial parallel refractive index of \(-0.342\). In other words, the EC wave propagates in the opposite toroidal direction against the LH wave. The LH wave heats electrons with a parallel velocity in the counter-\( I_p \) direction, whereas the EC wave heats electrons with a parallel velocity in the co-\( I_p \) direction. The radial power deposition of the EC wave is varied by changing \( \beta \) to make the EC and the LH powers overlap at the same radial location. The EC wave is launched from the LFS mid-plane at \( R = 2.45 \) m.

The GENRAY ray-tracing code is used to obtain wave parameters and power damping of the two waves. The Gaussian beam with 49 rays is used to describe the propagation of the EC wave. The LH antennas have five poloidal rows of waveguides, each of them launched with a narrow rectangular-like power spectrum \( P(N_{||0}) \). These waveguides are symmetrically distributed around the LFS mid-plane, the total size of the launcher has 0.776 m in height, each row of waveguides is simulated by ten rays, so that 50 rays in total are used in the GENRAY code, and the total launched power is \( 5 \times P(N_{||0}) \times \Delta N_{||0} \), which is equal to the total launched power \( P_{\text{LH}} \) of the LH wave. Summing up all the contributions from the GENRAY code to the quasi-linear diffusion coefficient, the
calculations are performed with the CQL3D Fokker–Planck quasi-linear code.

3. Simulation results and analysis

Figure 2 shows ray trajectories, calculated by the GENRAY code, of the EC and LH waves versus poloidal distance $s$, where $s$ is the arc length of the ray trajectories projected in a specific poloidal plane. As shown in figure 2(d), the two waves propagate along different toroidal directions, heating the passing electrons of different directions along the magnetic field lines of tokamak, respectively. Figures 2 and 3 show that the EC wave is absorbed in a single-pass before the power is absorbed completely, whereas the LH wave is in a strongly multi-pass regime, propagating a very long distance and undergoing significant upshifting before damping. The LH wave travels through the EC power deposition area several times during its propagation and deposits the wave power in the area.

Because the $\alpha$ is fixed for an effective OKCD, the desired EC driving current radial location $\rho_{EC}$ is varied by changing $\beta$. As is shown in figure 3(b) and will be shown in figure 7, the driven current of the EC is dominated by the Ohkawa mechanism. This is because the EC heats the resonant electrons in the positive direction of parallel velocity (figure 7), generating a positive current (figure 3(b)). The power deposition and the driven current profiles of the two waves are shown in figure 3. The power of the two waves is deposited in the radial range of $\rho = 0.70$–0.85 simultaneously. Following [10, 15], the synergy effect is quantified by the synergy factor $F_{syn} = \Delta I/I_{EC}$, where $\Delta I = I_{LH+EC} - I_{EC}, I_{LH+EC}$ is the current driven by the simultaneous use of the two waves, $I_{LH}$ and $I_{EC}$ are total driven current by the single LH and the single EC, respectively. Figure 3(b) shows radial driven current profiles for this case. The black solid line represents the profile of contribution of the two waves simultaneously. The green dash–dotted and blue dotted lines express profiles of the LH alone and the EC alone, respectively, and the red solid line indicates the synergy driven current profile, which is defined as $j_{EC+LH}(\rho) = j_{EC}(\rho) + j_{LH}(\rho)$. In this case, the power of both of the two waves is set as 1.0 MW. $I_{LH+EC} = 376.3$ kA, while $I_{EC} = 21.9$ kA and $I_{LH} = 338.0$ kA. The synergy factor $F_{syn}$ for this case is 1.75, which gives a moderate synergy effect. Scanning the $N_{||0}$ from 2.2 to 2.5 with an interval of 0.1, figure 4 shows that there is a positive synergy effect except $N_{||0} = 1.9$, which results in a negative synergy effect $F_{syn} = 0.84$, while a larger $N_{||0}$ results in a weaker synergy effect.

It has been shown that the choice of the number of rays for the simulation of the LH wave propagation had a significant influence on the final result [35]. If the launched rays of the two waves are doubled, $I_{EC} (21.9$ kA) is almost unchanged, and $I_{LH} (341.1$ kA) and $I_{LH+EC} (378.8$ kA) are changed slightly. This results in $F_{syn} (1.72)$ only changing a little. So therefore using 50 rays is adequate for the LH wave. Furthermore, if a $\sin^2x/x^2$ like $P(N_0)$ with
As shown in figure 3(b), the synergy driven current profile shifts slightly to right compared to the current profile of the EC driven alone, while it aligns with the current profile of the LH driven alone. This means that the EC and the LH power have a different impact on the synergy effect between the OKCD and LHCD. Scanning \( P_{\text{LH}}/P_{\text{EC}} \) with \( P_{\text{EC}} \) held constant and scanning \( P_{\text{EC}}/P_{\text{LH}} \) with \( P_{\text{LH}} \) held constant, the effects of the EC and LH power on the synergy factors are performed for the EC power deposited at three different radial locations, as shown in figure 5. It can be shown that increasing both the EC and LH power makes the synergy factors, but the LH power makes a bigger contribution to the \( F_{\text{syn}} \) compared to the EC power. Figure 5(a) shows that the synergy factor increases with the increase of \( P_{\text{LH}}/P_{\text{EC}} \), ranging from \( \sim 1.5 \) for \( P_{\text{LH}} = 0.5 \text{ MW} \) to \( \sim 2.5 \) for \( P_{\text{LH}} = 5.0 \text{ MW} \) at \( \rho = 0.78 \). Varying \( \beta \) to make the EC power deposited in the radial region of \( \rho \sim 0.67–0.78 \), the synergy factor can achieve a higher value (up to \( \sim 3.4 \)). However, keeping \( P_{\text{LH}} = 1.0 \text{ MW} \) constant, the synergy factor increases slowly with the increase of the EC power, indicating that the LH wave contributes more to the synergy effect under the same power level. The synergy factors change moderately at the three different radial locations for a constant ratio of \( P_{\text{LH}} \) to \( P_{\text{EC}} \).

Figure 6 shows spatial profiles of driven current density versus normalized velocity \( u/u_{\text{norm}} \) at the radial location \( \rho = 0.78 \) for the same power level (1 MW) of the two waves. Here, \( u_{\text{norm}} \) corresponds to 300 keV kinetic energy of electrons. \( j(u/u_{\text{norm}}) \) is the integrated current over pitch-angle in the infinitesimal near \( u/u_{\text{norm}} \), which satisfies the relation \( j(\rho) = \int j(u/u_{\text{norm}}) \, d(u/u_{\text{norm}}) \). The green solid line represents the Ohkawa current driven by the EC wave alone, this current is mainly driven by low velocity electrons with \( u/u_{\text{norm}} \approx 0.12 \). The blue dash–dotted line represents LHCD alone and shows that the vast majority of the total current is driven by the Landau damping in spite of a small amount of reverse Ohkawa current being driven by the LH wave at \( u/u_{\text{norm}} \approx 0.205 \). The red dash–dotted line expresses the combined current drive profile of the two waves. The sum of the EC alone and the LH alone is marked with blue dash–dotted line. Comparing the red dash–dotted and the blue dash–dotted lines, the synergy effect at \( \rho = 0.78 \) mainly comes from the contribution of high energy electrons \( (u/u_{\text{norm}} \geq 0.26) \) which are accelerated by the LH wave in a parallel direction. This is because the synergy current profile (marked by the red dash–dotted line) in \( u/u_{\text{norm}} \) space ranging from \( 0–0.16 \) is almost the same as the Ohkawa current profile driven by the EC wave. From the above analysis, we make a judgment that this synergy effect is not caused by the EC wave pushing some barely-passing electrons with low velocities into the trapped region, or by the LH wave pulling these electrons out of the trapped region and accelerating them to higher velocities. Detailed physical interpretation will be given in the next paragraph.

In order to reveal this new synergy mechanism, contours of quasi-linear diffusion strength due to \( \text{RF}(u^2D_{uu}) \) in velocity space are plotted separately both for the EC and the LH alone, as shown in figure 7, where \( D_{uu} \) is the quasi-linear diffusion coefficient in the velocity space. The OKCD traps the barely-passing electrons (trapping process), and the LHCD pulls some of the barely-trapped electrons out of the trapped region in the velocity space (detrapping process) and accelerates these detrapped electrons to a higher speed. The trapping process induced by the EC wave mainly acts on the low velocity barely-passing electrons \( (u/u_{\text{norm}} \sim 0.12) \), and these electrons are located just below the right trapped/passing boundary (TPB) in the velocity space. The detrapping process induced by the LH wave mainly acts on the barely-trapped electrons with high velocities \( (u/u_{\text{norm}} \geq 0.26) \) near to the left TPB. Furthermore, the quasi-linear diffusion strength due to

$$x = 2\pi \left( N_1 - N_0 \right) / \Delta N_0$$

is used in the GENRAY code, it results in \( F_{\text{syn}} = 2.0 \).

Figure 7. The physical picture of the synergy effect between OKCD and LHCD in the velocity space. \( P_{\text{EC}} = 1.0 \text{ MW}, P_{\text{LH}} = 1.0 \text{ MW}, \rho_{\text{EC}} = 0.78 \). Contours represent the LH and EC quasi-linear diffusion strength due to \( \text{RF}(u^2D_{uu}) \) in the velocity space with the perpendicular and parallel velocities normalized to \( u_{\text{norm}} \), respectively. The pink dotted lines are the TPBs.
the LH wave is much stronger than the EC wave. Once pulled out of the trapped region, these barely-trapped electrons are more easily accelerated by the LH wave to a higher parallel speed in the counter-\( F_p \) direction, and subject to less collisional resistance, resulting in them contributing more to the net synergy current of the two waves. It is for this reason that an increase of both the EC and LH power can improve the synergy factor, while the increase in LH power has a greater impact on the synergy effect.

4. Conclusion and discussion

In conclusion, a new synergy mechanism between the OKCD of EC waves and the LHCD has been discovered in far off-axis radial region. A synergy effect (up to a factor of \( F_{\text{syn}} \approx 2.5 \)) is predicted in the outer half region in EAST. The methodology to achieve this synergy effect is revealed and discussed. The major conditions include (i) passing electrons with different directions must be heated by EC waves and LH waves parallel to the background magnetic field lines of tokamak plasmas; (ii) the EC parameters must be carefully selected to let the resonant region of EC waves be just below the TPBs in the velocity space, making the Ohkawa mechanism dominant over the Fisch–Boozer mechanism; (iii) the LH and the EC power must be deposited simultaneously on the LFS mid-plane in the far off-axis radial region, and the profiles of the power deposition for the two waves must also be overlapped in the radial region. The underlying mechanism of the synergy effect is revealed and discussed. The OKCD traps some of the low velocity barely-passing electrons (trapping process), the LHCD pulls some of the high velocity barely-trapped electrons out of the trapped region (detrapping process) and accelerates the detrapped electrons to a higher speed. Increases of both the EC and the LH power can improve the synergy factor, but the synergy effect is more sensitive to the LH power. Therefore, this new synergy effect may be of useful application in far off-axis current drives for current profile control and suppression of some important magnetohydrodynamic instabilities. The results found in this letter will enable fusion communities to further understand the synergy effect between EC and LH waves, especially the negative synergy effect. It may be useful in present tokamak plasmas, such as in EAST and KSTAR, or in a reactor-scale plasma (e.g. K-DEMO [36]) with low collisionality.

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