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A current drive by using the fast wave in frequency range higher than two timeslower hybrid resonance frequency on tokamaks

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Abstract. An efficient current drive scheme in central or off-axis region is required for the steady state operation of tokamak fusion reactors. The current drive by using the fast wave in frequency range higher than two times lower hybrid resonance ($w>2w_{lh}$) could be such a scheme in high density, high temperature reactor-grade tokamak plasmas. First, it has relatively higher parallel electric field to the magnetic field favorable to the current generation, compared to fast waves in other frequency range. Second, it can deeply penetrate into high density plasmas compared to the slow wave in the same frequency range. Third, parasitic coupling to the slow wave can contribute also to the current drive avoiding parametric instability, thermal mode conversion and ion heating occured in the frequency range $w<2w_{lh}$. In this study, the propagation boundary, accessibility, and the energy flow of the fast wave are given via cold dispersion relation and group velocity. The power absorption and current drive efficiency are discussed qualitatively through the hot dispersion relation and the polarization. Finally, those characteristics are confirmed with ray tracing code GENRAY for the KSTAR plasmas.

1 Introduction

Continuous current drive is one of the key issues to be resolved fortokamaks to progress toward fusion reactor. Though it is expected to be achieved by self bootstrap current in advanced operation regime, the external non-inductive current drive scheme is still required to control the pressure gradient profile and fill the gap between target and bootstrap current.[1] The fast waves in various frequency ranges has been suggested as a current drive scheme for such a reactor grade tokamak. High Harrmonic Fast Wave(HHFW) current drive in frequency range of ($\omega_{ci} \ll \omega \ll \omega_{lh}$) was suggested in 1995[2] and it was observed that the current drive is in well agreement with the theory and simulation via MSE measurement.[3] The fast wave close to LHR(Lower Hybrid Resonance) with harmonic number about 20-40 ($\omega_{ci} \ll \omega < \omega_{lh}$) has beenrecently suggested for off-axis current drive. And it is planned to confirm the theory in KSTAR and DIIID.[4-6] The current drive using fast wave more close to LHR in frequency range $\omega \sim \omega_{lh}$ was noted in 1980 and the fast wave coupling is analyzed, where it is insisted that the fast wave can be operated in more lower frequency than LHCD since it does not suffer thermal mode conversion, and accessible parallel refractive index $N_{\|}$ is broadened with more viable RF system requirement.[7] The fast wave experiment in this frequency range had been tried in JIPPT-IIU, JFT-2M, and PLT.[8-10] It was found that the efficient current drive is impossible above density limit as LHCD, which was explained by mode conversion of fast wave to slow wave in confluence layer. The fast waves are depicted witha CMA diagram for hydrogen plasma to compare in various frequency range in Fig.1.

In this study, the current drive by the fast wave in more high frequency range than previously explored, i.e., $2\omega_{lh} \leq \omega \ll \omega_{ce}$ is suggested and the characteristics are analyzed theoretically and numerically. Hereinafter it is called Lower Hybrid Fast Wave(LHFW). The suggestion is based on three advantages as following. First, LHFW has higher electric field parallel to the magnetic field which is favorable to efficient current drive compared to the fast waves in other frequency range. Second, it can deeply penetrate into high density plasmas compared to the slow wave in the same frequency range. Third, though the antenna RF power with E_y polarization for LHFW launching is partly coupled to Lower Hybrid Slow Wave(LHSW) due to the high density gradient or other mechanisms, the parasitic coupling to slow wave can work as a LHCD without parametric instability, thermal mode conversion and ion heating occured in the frequency range $\omega < 2\omega_{lh}$ [11]. The boundary and accessibility of LHFW propagation are given via cold dispersion relation in section 2.1. The energy flow and density limit are analyzed through the group velocity comparing with LHSW in section 2.2. The energy absorption and current drive are discussed qualitatively through the hot dispersion relation and the polarizationin

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section 2.3. Finally, the analyzed characteristics of LHFW is verified with ray tracing code GENRAY[12] for the KSTAR plamsas in section 3.

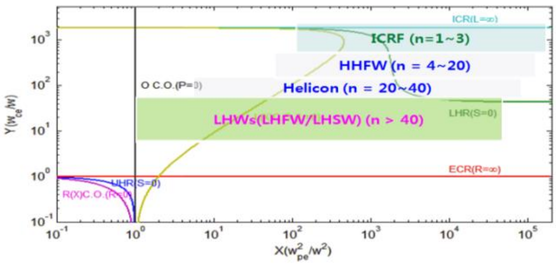

Fig. 1. Fast waves in various frequency range for hydrogen plasmas

2 Propagation, absorption and current drive of LHFW

2.1. Dispersion relation and propagation boundary

The dispersion relation of fast and slow wave in the frequency range of $\omega_{ci} \ll \omega \ll \omega_{ce}$ can be represented as follows.

$$N_\perp^2 = \begin{cases} -\frac{P(N_\parallel^2 - S)}{S} & \text{for SW} \\ -\frac{(N_\parallel^2 - R)(N_\parallel^2 - L)}{(N_\parallel^2 - S)} & \text{for FW} \end{cases} \quad (1)$$

,where S, P, R, and L are Stix paramters of cold palsams, and $N_\parallel$ is a refractive index parallel to the magnetic field. The launching density of LHSW and LHFW are obtained from P=0 and $N_\parallel^2 = R$ of Eq.(1) as follows.

$$n_{launch} \cong \begin{cases} \frac{m_e \epsilon_0}{e^2} \omega^2 & \text{for SW} \\ \frac{m_e \epsilon_0}{e^2} (N_\parallel^2 - 1) \omega \omega_{ce} & \text{for FW} \end{cases} \quad (2)$$

The launching density of LHFW is much greater than that of LHSW. It makes the evanescent layer in front of antenna thicker and it gives rise to difficulty in coupling of LHFW. The coupling concerning this high launching density must be resolved to apply the LHFW current drive concept to reality.
Meanwhile, the uppder density of LHFW is limited by the confluence of two wave branches. It is obtained from the more general cold plasmas dispersion relation as Eq.(3).

$$n_{confluence} \cong \frac{1}{4} \frac{m_e \epsilon_0}{e^2} N_\parallel^2 \omega_{ce}^2 \quad (3)$$

It is a more generalized accessibility condition since the mode conversion takes place whenever Eq.(3) is satisfied by the change of the parallel refractive index and magnetic field during the propagation of LHWs.The confluence density in Eq.(3) is proportional to the square of the magnetic field for given $N_\parallel$. It means that the mode conversion will not easily appear in high magnetic field device. From Eq.(1)~Eq.(3), the propagative region of the fast and slow wave can be depicted on CMA diagram as shown in Fig.2.

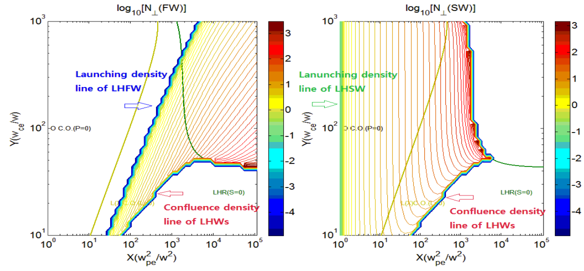

Fig. 2. The propagative region of FW and SW on CMA diagram($N_\parallel = 2.0$ is assumed.)

Considering that the parallel refractive index and magnetic field change as LHFW propagates in tokamak geometry, a kind of window for plasma density proiflecan be figured with Eq.(2) and (3) as shown in Fig.3. The plasma density profile must be sustained within the window for LHFW to propagate.

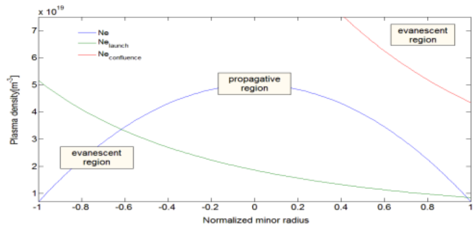

Fig. 3. Density window for LHFW propagation

2.2 Group velocity and penetration

Though the propagative region of LHFW is within the density boundaries, the real wave propagation and energy flow of LHFW can be figured with the direction of the group velocity to the magnetic field. The angle of group velocity of cold plasma waves is represented as Eq.(4).

$$\theta_g = \arctan\left\{ \frac{N_\perp}{N_\parallel} \frac{2SN_\perp^2 - [RL + SP - N_\parallel^2 (S+P)]}{2PN_\parallel^2 - [2SP - N_\perp^2 (S+P)]} \right\} \quad (4)$$

It is depicted for$N_\parallel$= 2.0 in Fig 4.

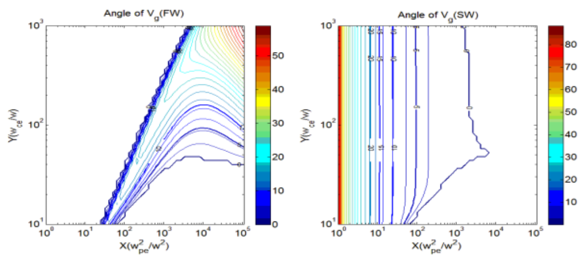

Fig. 4. The angle(degree) of group velocity of LHFW(left) and LHSW(right) to magnetic field

The LHSW group velocity is almost perpendicular to the magnetic field near the launching density, but it decreases rapidly with increase of density and gets to be less than that of LHFW near the launching density of LHFW. It means that the LHSW ray is easily aligned to the magnetic field during propagation into high density

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plasmas so it is not easy to use LHSW to drive thecurrent in high density plasmas. It might explain the LHCD density limit observed in experiments that the current drive efficiency decreases with increase of density. Meanwhile, the angle of LHFW is relatively greater than that of LHSW above LHFW launching density. So LHFW can be used to drive current inner high density plasma region than LHSW if once LHFW is launched and mode conversion is avoided. It will be shown more clearly at ray tracing simulation in section 3.

2.3 Absorption and current drive

The power absorption of LHFW can be obtained from the imaginary part of refractive index as given in Eq.(5) which is obtained from a hot plasma dispersion relation.

$$N_{\perp i} = \begin{cases} N_{\perp r,S}\pi^{1/2}\eta^3 e^{-\eta^2} & \text{for LHSW} \\ N_{\perp r,F}\dfrac{\pi^{1/2}\eta^3 e^{-\eta^2}}{\omega_{ce}^2 N_\parallel^2/\omega_{pe}^2 - 1} & \text{for LHFW} \end{cases} \quad (5)$$

Since the slow wave has very high real refractive index, the imaginary refractive index of LHSW is very large. It means that it can absorbed very quickly as it propagates into plasmas once the Landau damping condition is satisfied. Meanwhile, the absorption of fast wave increases only if the plasma density increases enough and the Landau damping condition is satisfied. It means that LHFW is suitable for bulk plasma heating and current drive since the absorption is weak in the edge low density region and becomes stronger as it propagates into high density bulk plasma region.

The current drive depends on the polarization of wave electric field and resultant power absorption. The main mechanism of electron heating and current drive of fast waves are Transit Time Magnetic Pumping(TTMP) by $B_z(E_y)$ field and Landau Damping(LD) by E_z field. Generally the TTMP can be as efficient as LD. But it tends to be concentrated in central region due to the dependence on plasma betaand the trapped particle effect. In addition, TTMP is vulnerable to competitive absorption of alpha particle in reactor grade plasmas. On the contrary, the LD is very effective only if the resonance condition is satisfiedand E_z is high. Therefore, higher E_z compared to E_y is favorable to current drive. The electric field polarization of fast waves can be represented as follows.

$$\begin{cases} \left|\dfrac{E_y}{E_z}\right| \simeq i\dfrac{N_\parallel D}{N_\perp(N_\parallel^2 - S)} \sim \dfrac{\omega\omega_{ce}}{\omega_{pe}^2}\left(\dfrac{m_e}{m_i}\dfrac{\omega_{ce}^2}{\omega^2} - 1\right)^{-1} & \text{for SW} \\ \left|\dfrac{E_z}{E_y}\right| \simeq -N_\parallel N_\perp \dfrac{D}{P(N_\parallel^2 - S)} \sim \left(\dfrac{m_e}{m_i}\dfrac{\omega_{ce}^2}{\omega^2} - 1\right)^{-1} & \text{for FW} \end{cases} \quad (6)$$

The field ratio of E_z to E_y for fast wave increases as the driving frequency increases.Therefore, it is advantageous to use the fast waves in high frequency range as possible. The electric field polarization is depicted with that of slow wave in Fig.5. The E_z field of fast waves is usually lower than that of slow wave, but it increases with the driving frequency increase and it becomes comparable to that of slow wave in the frequency range of $\omega \geq 2\omega_{lh}$.

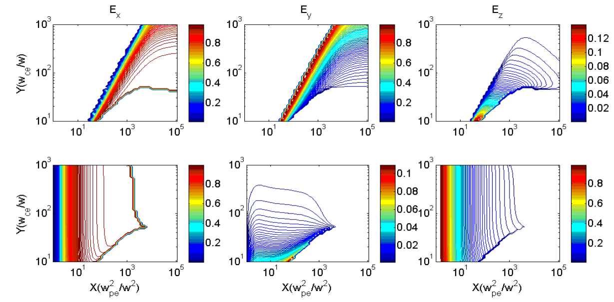

Fig. 5. Electric field polarization of fast wave(top line) and slow wave(botton line). They are normalized to total electric field of each wave branch.

Concering the difference of absorption and current drive between LHSW and LHFW, it was already simulated for ITER LHCD study[13] and for the identification of the role of mode converted FW in LHCD[14]. And it was found that LHFW current drive can be as efficient as LHSW.

3 LHFW simulation by using GENRAY for KSTAR plasmas

3.1. Simulation condition

The ray tracing simulation of LHWs is carried out for KSTAR plasmas to confirm the analysis. The major radius is 1.8m, the minor radius is 0.5m, and the B_0 is 2T. The density profile is parabolic with central and edge density of $5\times10^{19}m^{-3}$ and $1\times10^{19}m^{-3}$, respectively. The temperature profile is linear. The central and edge temperaturesareare 3.5 keV and 1.0keV. The RF frequency is 2.45 GHz and the $N_\parallel$ of the antenna are set to 2.3 and 2.7 to evaluate the LHFW propagations in relation to accessibility condition. The dispersion relation for two cases are shown in Fig. 6. In case of $N_\parallel$= 2.3 the accessibility condition is not satisfield. The confluence point exists and the evanescent layer develops interior of bulk plasmas. As a result, the launched fast and slow wave cannot penetrate into bulk plasmas. In the case of of $N_\parallel$= 2.7, on the contray, the confluence point does not exist so the evanescent layer disappear and the fast wave and slow wave can penetrate into central region. It is needed to note that it just give a rough probable propagation of LHWs for prediction becausethe parallel refractive index continuously changes by refraction during propagation in toroidal geometry. In somes cases the accesibility can be satisfied although it is not satisfied during intial propagation in edge region.

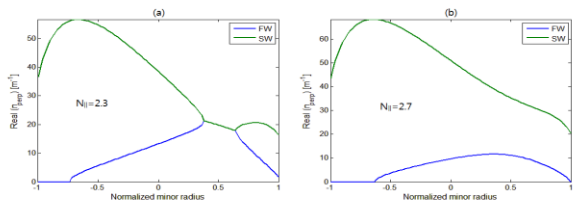

Fig. 6. Density window and dispersion relation for (a) $N_\parallel$ = 2.3 and (b) $N_\parallel$ = 2.7

3.2. Results of simulation

The ray tracing result with GENRAY is shown in case of $N_{\|}$=2.3 in Fig.7. One wave branch is mode converted to the other branch in outer region, and vice-versa, several times. This is because the accessibility condition is not satisfied. As a result, wave field is intensively localized in the outer region and the wave can penertrate into central region only after several multi-pass and severe change of refractive index by the edge reflection. In this case, considerable collsional absorption is expected in the edge region though it is not included here. Meanwhile, both the two wave branches can propagate into bulk plasma region with $N_{\|}$= 2.7 as shown in Fig.8 since accessibilty condition is satisfied. As expected, the LHFW penetrates into more central region than the LHSW and driven current of 147 kA for 1MW injection which are comparable to 121 kA of LHSW. The driven current density profiles for LHFW and LHSW are shown in Fig.9. The current figure of merit of LHFW is about 0.1 A/m^2/W which is less than the best result ~0.3A/m^2/W in previous LHCD experiments using LHSW. It is related with higher parallel refractive index which cuases kinetic resonance to invovle more collisioanl electrons compared to lower $N_{\|}$. It is expected to increase in reactor grade tokamaks with lower $N_{\|}$ and higher temperature.

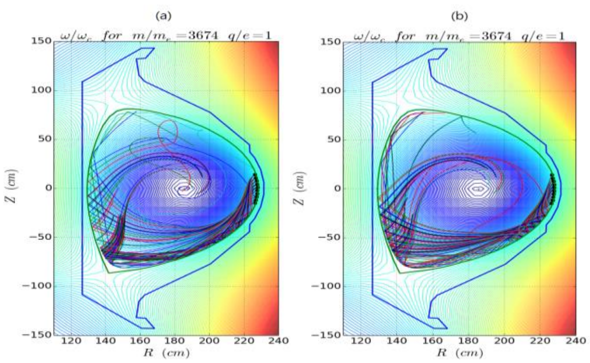

Fig. 7. Ray tracing result for (a) LHFW launching case and (b) LHSW launching case when $N_{\|}$ = 2.3. Wave is launched at equatorial port.

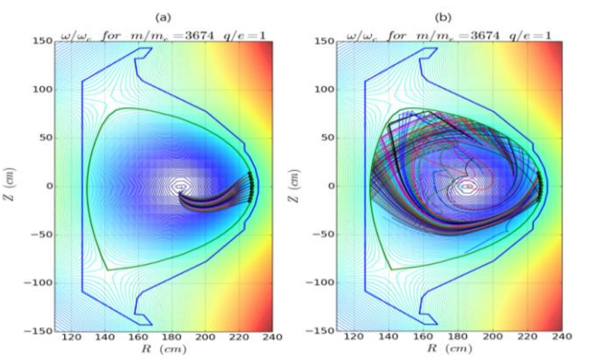

Fig. 8. Ray tracing result for (a) LHFW launching case and (b) LHSW launching case when $N_{\|}$ = 2.7. Wave is launced at equatorial port.

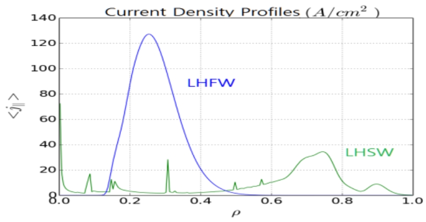

Fig. 9. Driven current density profile when $N_{\|}$ = 2.7

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