Second-harmonic generation of upper-hybrid radiation in a plasma

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Employing the fluid model for the nonlinear response of electrons, we have studied the phenomenon of second-harmonic generation of upper-hybrid electromagnetic radiation in an inhomogeneous plasma. In the case of laser-pallet fusion, the maximum contribution for harmonic generation comes from the vicinity of the upper-hybrid layer, and the harmonic conversion efficiency turns out to be $\sim 0.1\%$ at the power densities $\sim 10^{14}$ W/cm^2 (CO_2 laser), the same order as observed experimentally. In the case of electron cyclotron heating experiments of tokamak, a strong second harmonic must be generated at the cyclotron resonance layer. The wave-number-matching condition could be satisfied in a tokamak, which adds to the conversion efficiency.

I. INTRODUCTION

The phenomenon of second-harmonic generation of laser radiation has been observed in a number of laser-pallet fusion experiments in recent years.[1,2] The yields of second-harmonic power are unexpectedly very high ($\geq 10^{-3}$) and one expects some kind of resonance effects playing a role. In an unmagnetized plasma, the wave-number-matching condition for second-harmonic generation, i.e., $k(2\omega) = 2k(\omega)$, is not satisfied. However, for a wave polarized in the plane of incidence and propagating at an angle to the density gradient, the electric vector obtains large values in the vicinity of plasma resonance ($\omega = \omega_p$) and might result in the enhanced efficiency of harmonic generation.[3]

Recent experiments on laser-pallet fusion have also revealed the generation of megagauss magnetic fields.[4-7] Under these magnetic fields the upper-hybrid mode of laser radiation exhibits a resonance at upper-hybrid frequency. Around the resonance, the longitudinal component of electric vector (parallel to the density gradient) takes very high values and one should obtain high efficiency of second-harmonic generation. Besides this, the magnetic field modifies the propagation vectors of both the fundamental and second-harmonic waves and might satisfy even the wave-number-matching condition. In the present state of experiments where $\omega_c \ll \omega_p$ (ω_c and ω_p are the electron gyro- and plasma frequencies, respectively), the wave-number-matching region falls deeper into the plasma (beyond the upper-hybrid layer) and hence does not contribute to the process of harmonic generation.

The phenomenon of second-harmonic generation of upper-hybrid waves is relevant to tokamak[8] also where rf-heating experiments in the electron cyclotron range of frequencies (ECRF) are very much in progress. In a tokamak, $\omega_p \lesssim \omega_c$, hence the wave-number-matching condition for harmonic generation is easily satisfied. Moreover, the cyclotron resonance could also cause tremendous enhancement in the harmonic efficiency.

In this paper we have analyzed the phenomenon of second-harmonic generation of upper-hybrid radiation in a plasma with particular emphasis to laser fusion and tokamak. In Sec. II we have discussed the wave-number-matching condition. In Sec. III we have obtained the nonlinear second-harmonic current density in a uniform plasma using the fluid equations. Using this current in the one-dimensional wave equation we have computed the second-harmonic power. The power shows a resonance enhancement when the wave-number-matching condition is satisfied. In Sec. III, we have studied second-harmonic generation in a laser-pallet plasma by using the fluid model for the response of electrons and employing the expressions of Grebogi, Liu, and Tripathi[9] for the electric field pattern of the fundamental wave in the vicinity of upper-hybrid resonance. In Sec. IV we have investigated the phenomenon of second-harmonic generation in a tokamak incorporating the contributions from the regions of wave-number-matching and cyclotron resonance. A discussion of results is given in Sec. V.

II. WAVE-NUMBER MATCHING

For the case of wave propagation perpendicular to static magnetic field ($\vec{k} \perp \vec{B}_0$), the propagation vector for the extraordinary (upper-hybrid) mode is given by

$$k^2=\frac{\omega^2}{c^2}\left(1-\frac{\omega_p^2}{\omega^2}\frac{\omega^2-\omega_p^2}{\omega^2-\omega_U^2}\right), \tag{1}$$

where ω_U is the upper-hybrid frequency and c is the velocity of light in vacuum. Figure (1) shows a graphical display of Eq. (1). Regions I and II of the figure represent the regions of wave propogation. The propogation vector k_2 for the second-harmonic could be written from Eq. (1) by replacing ω by 2ω. The wave-number-matching condition demands

$$k_2 = 2k ,$$

or (2)

$$\omega^2=\omega_R^2 =\tfrac{1}{8}[5\omega_p^2+\omega_p(9\omega_p^2-16\omega_c^2)^{1/2}] .$$

Figure 2 shows the wave-number-matching frequency ω_R as a function of ω_c/ω_p. We have also included the curves of lower cutoff ω_L, upper cutoff ω_H, and upper-hybrid frequency ω_U:

$$\begin{aligned}\omega_L^2&=\tfrac{1}{2}[2\omega_p^2+\omega_c^2-\omega_c(4\omega_p^2+\omega_c^2)^{1/2}],\\ \omega_H^2&=\tfrac{1}{2}[2\omega_p^2+\omega_c^2+\omega_c(4\omega_p^2+\omega_c^2)^{1/2}],\\ \omega_U^2&=\omega_p^2+\omega_c^2,\end{aligned} \tag{3}$$

where $\omega_L<\omega_U<\omega_H$. The wave propagates only when $\omega_L<\omega<\omega_U$ (region I of Fig. 1) or $\omega>\omega_H$ (region II of Fig. 1). It is clear from Eqs. (2)–(3) and Fig. 2 that ω_R always lies in region I ($\omega_L<\omega_R<\omega_U$) and 2 ω_R, the second harmonic, lies in region II ($2\omega_R>\omega_H$).

In a laser fusion experiment, $\omega_c^2\ll\omega_p^2$. As the laser penetrates deeper and deeper into the plasma, it hits the upper cutoff $\omega=\omega_H$ first and then the upper-hybrid layer $\omega=\omega_U$. ω_R lies beyond the ω_U layer (cf. Fig. 3).

In a tokamak, the upper-hybrid wave launched from the inside of the torus, enters in region I of Fig. 1. After a distance it hits the cyclotron resonance, then the wave-number-matching region and then the upper-hybrid resonance.

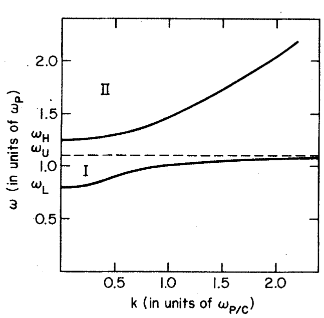

FIG. 1. The linear dispersion relation of upper-hybrid electromagnetic waves in a plasma for $\omega_c^2/\omega_p^2=0.2$.

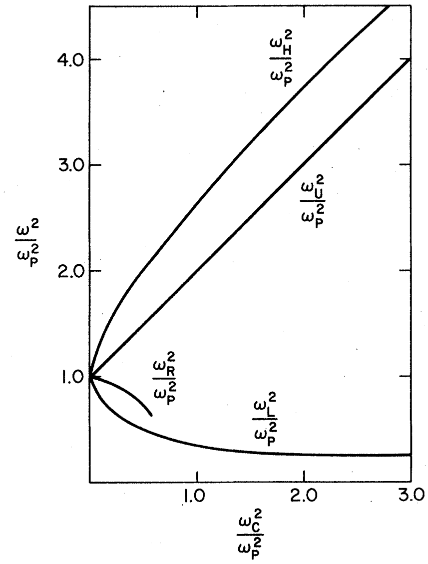

FIG. 2. The variation of ω_R (wave-number-matching frequency), ω_L, ω_H (lower and upper cutoff frequencies), and ω_U (upper-hybrid frequency) as a function of ω_c^2/ω_p^2.

III. HARMONIC GENERATION: UNIFORM PLASMA

In order to have a clear understanding of the process of second-harmonic generation, we start with the study of the process in a homogeneous plasma. We consider the propagation of an upper-hybrid electromagnetic wave along x axis in a plasma, with static magnetic field $\vec{B}_s$ along z axis

$$\begin{aligned}\vec{E}&=(E_{0x}\hat{x}+E_{0y}\hat{y})e^{i(\omega t-kx)},\\ \vec{B}&=(c/\omega)\vec{k}\times\vec{E},\end{aligned} \tag{4}$$

and k is given by Eq. (1). In the presence of the pump wave, electrons acquire a drift velocity $\vec{v}$ and a density fluctuation n,

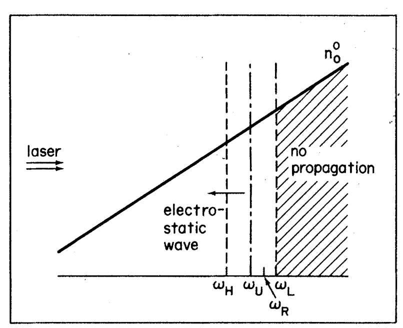

FIG. 3. Schematic representation of density profile and cutoff and resonance layers in a typical laser-pallet fusion plasma.

$$\vec{v} = e(i\omega\vec{E} - \vec{E}\times\vec{\omega}_c)/m(\omega^2 - \omega_c^2),$$
$$n = n_0^0\vec{k}\cdot\vec{v}/\omega$$
$$= n_0^0 ek(i\omega E_x - E_y\omega_c)/m\omega(\omega^2 - \omega_c^2), \quad (5)$$

where $-e$, m, and n_0^0 are the electronic charge, mass, and equilibrium density, respectively. In the vicinity of resonance we replace $(\omega^2 - \omega_c^2)$ by $[(\omega + i\nu)^2 - \omega_c^2]$ to account for collisional effects and thermal effects; ν is the effective collision frequency.

The equation of motion for second-harmonic component of velocity can be written as

$$2i\omega\vec{v}_2 = -\frac{e\vec{E}_2}{m} - \vec{v}_2\times\vec{\omega}_c + \vec{F}, \quad (6)$$

$$\vec{F} = -\tfrac{1}{2}[\vec{v}\cdot\vec{\nabla}\vec{v} + (e/m)\vec{v}\times\vec{B}]$$
$$= \frac{e^2}{2m^2\omega(\omega^2-\omega_c^2)}\left(i\omega E^2\vec{k} - k(i\omega E_x - E_y\omega_c)\times\frac{\omega_c^2\vec{E} - i\,\omega\vec{E}\times\vec{\omega}_c}{\omega^2-\omega_c^2}\right). \quad (7)$$

Equation (6) could be solved to obtain

$$\vec{v}_2 = \frac{e(2i\omega\vec{E}_2 - \vec{E}_2\times\vec{\omega}_2)}{m(4\omega^2-\omega_c^2)} - \frac{e^2}{2m^2\omega(\omega^2-\omega_c^2)(4\omega^2-\omega_c^2)}\left(i\omega E^2(2i\omega\vec{k} - \vec{k}\times\vec{\omega}_c) - \frac{k(i\omega E_x - E_y\omega_c)}{\omega^2-\omega_c^2}[3i\omega\omega_c^2\vec{E} - (\omega_c^2 + 2\omega^2)\vec{E}\times\vec{\omega}_c]\right), \quad (8)$$

where $\vec{E}_2$ is the self-consistent second-harmonic electric field. Using Eqs. (6) and (8) the second-harmonic current density could be written as

$$\vec{J}_2 = -n_0^0 e\vec{v}_2 - \tfrac{1}{2}ne\vec{v}$$
$$= -\frac{n_0^0 e^2(2i\omega\vec{E}_2 - \vec{E}_2\times\vec{\omega}_c)}{m(4\omega^2-\omega_c^2)} + \frac{n_0^0 e^3}{2m^2\omega(\omega^2-\omega_c^2)(4\omega^2-\omega_c^2)}\left(i\omega E^2(2i\omega\vec{k} - \vec{k}\times\vec{\omega}_c) - \frac{2\omega k(i\omega E_x - E_y\omega_c)}{\omega^2-\omega_c^2}[i(\omega_c^2+2\omega^2)\vec{E} - 3\omega\vec{E}\times\vec{\omega}_c]\right). \quad (9)$$

The first term on the right-hand side is the linear term, and other terms are the nonlinear terms $\vec{J}_2^{\rm NL}$.

The wave equation governing the propagation of second-harmonic wave is written as

$$\nabla^2\vec{E}_2 - \vec{\nabla}(\vec{\nabla}\cdot\vec{E}_2) = -\frac{4\omega^2}{c^2}\vec{E}_2 + \frac{8\pi i\omega}{c^2}\vec{J}_2, \quad \vec{\nabla} = \hat{x}\partial/\partial x. \quad (10)$$

The x component of Eq. (10) yields

$$E_{2x} - (2\pi i/\omega)J_{2x} = 0$$

or

$$E_{2x} = \frac{2\pi i}{\epsilon_{2xx}\omega}J_{2x}^{\rm NL} - \frac{\epsilon_{2xy}}{\epsilon_{2xx}}E_{2y}, \quad (11)$$

where

$$\epsilon_{2xx} = 1 - \frac{\omega_p^2}{4\omega^2-\omega_c^2}, \quad \epsilon_{2xy} = i\frac{\omega_c}{2\omega}\frac{\omega_p^2}{4\omega^2-\omega_c^2}.$$

Using Eq. (11) the y component of Eq. (10) gives

$$\frac{\partial^2 E_{2y}}{\partial x^2} + k_2^2 E_{2y} = fE_{0y}^2 e^{2i(\omega t - kx)}, \quad (12)$$

where

$$f = \frac{i\omega_p^2}{(\omega^2-\omega_c^2)(4\omega^2-\omega_c^2)}\frac{ek}{mc^2}\left\{i\omega\left(\omega_c + 2i\omega\frac{\epsilon_{2xy}}{\epsilon_{2xx}}\right)\left(1+\frac{\epsilon_{xy}^2}{\epsilon_{xx}^2}\right) + \frac{2\omega(i\omega\epsilon_{xy}/\epsilon_{xx} + \omega_c)}{\omega^2-\omega_c^2}\left[i(\omega_c^2 - 2\omega^2)\left(1 - \frac{\epsilon_{2xy}}{\epsilon_{2xx}}\frac{\epsilon_{xy}}{\epsilon_{xx}}\right) - 3\omega\omega_c\left(\frac{\epsilon_{xy}}{\epsilon_{xx}} + \frac{\epsilon_{2xy}}{\epsilon_{2xx}}\right)\right]\right\}. \quad (13)$$

Equation (12) may be integrated to obtain

$$E_{2y}=A_1 e^{i(2\omega t-k_2x)}+A_2 e^{i(2\omega t+k_2x)} + \frac{fE_{0y}^2}{k_2^2-4k^2} e^{i(2\omega t-2kx)} . \tag{14}$$

The constants of integration A_1 and A_2 are to be obtained from the boundary conditions. Equation (14) shows a resonant enhancement in the second-harmonic electric field at $k_2=2k$ and $\omega=\omega_c$. These resonances are checked by the collisional effects and thermal effects. Using Eq. (14) the second-harmonic power density P_2 may be written as

$$P_2 \simeq \frac{c^2}{8\pi}\frac{k}{\omega}E_{2y}^2 , \quad \frac{P_2}{P_1}\simeq \frac{ff^* E_{0y}^2}{(k_2^2-4k^2)^2} , \tag{15}$$

where P_1 is the power density of the fundamental wave. For a typical case of $\omega_p^2/\omega^2 \simeq 0.9$, $\omega\simeq 10^{15}$ rad/sec, $\omega_c/\omega \simeq 0.5$, we obtain $P_2/P_1 \simeq 10^{-3}$ at power densities of the order of 10^{16} W/cm^2.

One can straightaway obtain from Eq. (15) the dependence of power conversion efficiency on the parameters of the plasma. This analysis, though not applicable to tokamak and laser-pallet plasmas, nevertheless gives an insight into the contributions from the phase-matching region. The analysis should be applicable to laboratory plasmas where turning points and upper-hybrid resonance do not occur for the fundamental and second-harmonic waves.

IV. LASER FUSION

In this case we have assumed a planar model of plasma having linear density profile along x axis. The plasma has a static-magnetic field along z axis ($\omega_c \ll \omega_p$). As the upper-hybrid radiation propagates into the plasma (in the direction of density gradient), it hits the cutoff $\omega=\omega_H$ and then the upper-hybrid resonance; ω_R lies beyond this layer. We refer to the upper-hybrid layer as $x=0$ and assume the density profile as

$$\omega_p^2=(\omega^2-\omega_c^2)(1+x/L) . \tag{16}$$

The cutoff $\omega=\omega_H$ falls at $x=-\omega_c L/\omega$. In the vicinity of $x=0$, the electric-field pattern of the pump (ω) wave is predominantly determined by thermal effects.

Let the electromagnetic wave, at the entrance of the plasma be

$$E_y=Ae^{i[\omega t-(\omega/c)x]}, \quad E_x=0 . \tag{17}$$

As the wave penetrates into the plasma, E_x becomes finite and rises very fast in the vicinity of the upper-hybrid (UH) resonance. Following Grebogi, Liu, and Tripathi,[9] one may write

$$E_x(0)\simeq i\left(\frac{L_\omega}{v_e}\right)^{2/3}\frac{\omega_c}{\omega}E_y(0) , \quad E_y(0)\simeq -\frac{1.5A}{[1+2.5(\omega_c^2/\omega^2)(L\omega/c)^{4/3}(0.66-i)]} . \tag{18}$$

$E_x(0)$ is much greater than A, the amplitude of the incident wave in free space and one should get maximum contribution to harmonic generation [which goes as $E_x(\partial/\partial x)E_x$] from the upper-hybrid resonance region (i.e., the vicinity of $x=0$).

In order to obtain the expression for second-harmonic current density in the neighborhood of $x=0$, we write

$$n\simeq -\frac{en_0^0}{m\omega^2}\frac{\partial}{\partial x}E_x , \quad B_z=i\frac{c}{\omega}\frac{\partial}{\partial x}E_y , \quad \vec{F}\simeq -\frac{1}{2}\frac{\partial v_x}{\partial x}\vec{v} . \tag{19}$$

Using the value $\vec{F}$ in Eq. (6) and using Eq. (5) one obtains the expression for $\vec{v}_2^{NL}$

$$\vec{v}_2^{NL}\simeq -\frac{e^2(2i\omega\vec{E}-3\vec{E}\times\vec{\omega}_c)}{8m^2\omega^4}\frac{\partial E_x}{\partial x} . \tag{20}$$

The second-harmonic current density can be written as

$$\vec{J}_2^{NL}=-n_0^0 e\vec{v}_2^{NL}-\tfrac{1}{2}ne\vec{v} = \frac{e^3n_0^0}{8m^2\omega^4}\frac{\partial}{\partial x}E_x(6i\omega\vec{E}-7\vec{E}\times\vec{\omega}_c) , \tag{21}$$

$$\frac{8\pi i\omega}{c^2}\left(J_{2y}^{NL}-\frac{\epsilon_{2xy}}{\epsilon_{2xx}}J_{2x}^{NL}\right)\simeq i\frac{3}{4}\frac{\omega_p^2\omega_c}{c^2\omega^3}\frac{e}{m}\frac{\partial}{\partial x}E_x^2 . \tag{22}$$

Using Eq. (22) in the wave equation for E_{2y}, one may write

$$\frac{\partial^2 E_{2y}}{\partial x^2}+k_2^2E_{2y}=i\frac{3}{4}\frac{\omega_p^2\omega_c}{c^2\omega^3}\frac{e}{m}\frac{\partial}{\partial x}E_x^2 . \tag{23}$$

Since k_2 is a slowly varying function of x Eq. (23) can be easily integrated to obtain the reflected component of second harmonic

$$E_{2y}\simeq \frac{3}{8k_2}e^{ik_2x}\frac{e}{m}\frac{\omega_p^2\omega_c}{\omega^3c^2}\int_0^x e^{-ik_2x}\frac{\partial}{\partial x}E_x^2dx \simeq \frac{\omega_c}{4\omega}e\frac{E_x^2(0)}{m\omega_c}e^{ik_2x}2\left(\frac{v_e}{c}\right)^{2/3}\left(L\frac{\omega}{c}\right)^{1/3} . \tag{24}$$

From Eq. (24) one obtains the power conversion ratio as $P_2/P_1\simeq 0.1v_0^2/c^2$ for $B_0=3$ MG: $T=1$ keV, $L=100$ μm, $\lambda_0=10.6$ μm, where $v_0=eA/m\omega$. For $v_0/v_e \sim 1$ (power density 10^{14} W/cm^2)$P_2/P_1\sim 0.3\%$. The contribution from the bulk of the plasma makes an additional contribution of $\leq 0.1\%$.

V. TOKAMAK

In a tokamak, as we start from the inner wall and pass through the minor radius, the static magnetic field decreases as $1/R$ (R being the major radius) and the electron density has some kind of parabolic profile, with maximum at the midpoint. Consequently ω_c decreases gradually with x (the outward distance) and ω_{UH} increases rapidly, attains a peak, somewhat before the midpoint and then decreases again. We refer to the inner boundary of the torus as $x=0$. We launch an upper-hybrid wave at $x=0$ into the torus. The frequency of the wave ω is less than $\omega_c(0)$, otherwise the wave would be reflected back from the upper-hybrid layer before reaching the central region of the plasma. As the wave proceeds it encounters the cyclotron resonance layer at $x=x_c$ $[\omega=\omega_c(x_0)]$, then it reaches the region $x=x_R$ where $\omega=\omega_R$; i.e., the wave-number-matching condition for second harmonic is satisfied. After propagating further (on the other side of the midpoint) the wave encounters the upper-hybrid layer from which it is partially reflected back. Since the nature of wave pattern around $\omega=\omega_U$ is not known in a tokamak, we would not evaluate the contribution of this region to the generation of second harmonic. We would calculate the contributions from the vicinity of $x=x_R$ and $x=x_c$ separately.

Wave-number-matching region ($x \cong x_R$)

As long as we are away from cyclotron resonance, the wave equation governing the second-harmonic generation is the same as Eq. (12) with f given by (13). The solution of this equation around $x \simeq x_R$ may be written as

$$E_{2y} \simeq e^{-ik_2x}\frac{f}{2ik_2}\int \exp\left(+i\int (k_2-2k)dx\right)dx, \qquad (25)$$

where the integration is to be carried out through the point $x=x_R$. The maximum contribution to the integral should come from the region of zero phase. We might expand

$$(k_2-2k) \simeq [(\partial/\partial x)(k_2-2k)](x-x_0)\,,$$
$$\frac{\partial}{\partial x}(k_2-2k) \simeq -\frac{6}{k_2}\frac{\omega_p^4\omega_c^2\omega_p^2(\partial/\partial x)\omega_p^2}{c^2(\omega^2-\omega_U^2)^2(4\omega^2-\omega_p^2)^2}. \qquad (26)$$

Then Eq. (25) gives

$$E_{2y} \simeq \frac{f}{2ik_2}de^{-ik_2x}\,, \qquad (27)$$

$$d \simeq \left(\frac{k_2}{3}\frac{c^2(\omega^2-\omega_U^2)^2(4\omega^2-\omega_p^2)^2}{\omega_c^2\omega_p^8}L\right)^{1/2}, \qquad (28)$$

where L is the density scale length and d is the effective width of wave-number-matching region. Had there been no region of $\omega=\omega_R$, Eq. (27) would have d replaced by $i/(k_2-2k)$. Thus $[(k_2-2k)d]^2$ is a measure of enhancement of second-harmonic power due to wave-number matching. For typical tokamak parameters $n_0^0 \simeq 10^{14}$ cm^{-3}, $T \sim 1$ keV, $B_0 \simeq 20$ kG, $L \simeq 3$ cm, this factor turns out to be ≈ 20.

Cyclotron resonance region

In this region Eq. (12) still holds; however, f is modified on account of sharp dependence of $1/(\omega-\omega_c)$ on x. We take

$$\omega-\omega_c \simeq \omega_c(x-x_c)/R$$

in the neighborhood of resonance. The resonance denominators in f [going as $1/(\omega-\omega_c)$ and $1/(\omega-\omega_c)^2$] must be modified to incorporate thermal effects or collisional effects. We replace ω by $\omega+i\nu$ in these resonance denominators to account for these effects.

Following the procedure of Sec. III, one could obtain the following expression for f in the vicinity of $\omega=\omega_c$:

$$f \simeq -\frac{ekE_y^2}{mc^2}\frac{3(2\omega_c^2-\omega_p^2)\omega_p^2}{(3\omega_c^2-\omega_p^2)} \times\left(\frac{1}{[(\omega-\omega_c)^2+2i\nu\omega]}+\frac{i}{2k}\frac{\partial}{\partial x}\frac{1}{[(\omega-\omega_c)^2+2i\nu\omega]}\right). \qquad (29)$$

Equation (12) then gives

$$E_{2y} \simeq -e^{-ik_2x}I\frac{1}{2ik_2}\frac{3ekE_y^2(x_c)(2\omega_c^2-\omega_p^2)\omega_p^2}{mc^2(3\omega_c^2-\omega_p^2)},$$
$$I=\int e^{i(k_2-2k)x}\left(1+\frac{i}{2k}\frac{\partial}{\partial x}\right)\times\frac{1}{(\omega-\omega_c)^2+2i\nu\omega}dx \approx \frac{R^2}{\omega_c^2}\int\frac{e^{i(k_2-2k)x}}{(x-x_0)^2+2i(\nu/\omega_c)R^2}dx. \qquad (30)$$

For $\omega_c \sim \omega_p$,

$$\frac{P_2}{P_1} \approx \frac{v_0^2}{c^2}\left|\frac{\omega^3}{c}I\right|^2 = \frac{v_0^2}{c^2}\left|\frac{\omega}{c}I\omega_c^2\right|^2, \quad v_0=\frac{eA}{m[\omega-\omega_c(0)]}. \qquad (31)$$

For a typical set of parameters $B_0 \simeq 10$ kG, $\omega_c \simeq 2\times10^{11}$, $\omega=30$ GHz, $T=200$ eV $n_0^0 \simeq 3\times10^{13}$, $R \sim 70$ cm, $\nu/\omega_c \sim 10^{-2}$, Eq. (31) gives $P_2/P_1 \simeq 1\%$ at power densities $\simeq 1$ MW/cm^2. It may be mentioned here that the power conversion efficiency due to electron cyclotron resonance effects is one order of magnitude higher than that due to wave-number-matching effects. Though in the present day ECRF experiments in tokamak, we expect rather weak levels of second-harmonic power, the larger powers envisaged in future experiments would give higher yields.

VI. CONCLUSIONS

In the present-day laser-pallet fusion experiments, the maximum contribution for harmonic generation should come from the neighborhood of upper-hybrid resonance. The main nonlinearity arises from the longitudinal component of electric vector and attains maximum value for the parameters corresponding to maximum resonance absorption. For currently employed lower densities ($\sim 10^{14}$ W/cm^2 for a CO_2 laser) the harmonic conversion efficiency turns out to be $\sim 10^{-3}$.

The phenomenon of second-harmonic generation is relevant to electron cyclotron resonance heating experiments of tokamak also, where electron cyclotron resonance and wave-number-matching play predominant roles. However, the yields of the order of 1% would require power densities of the order of 1 MW/cm^2, envisaged in future experiments.

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