Radiation resonance emission from steep overcritical plasma profiles illuminated by femtosecond laser pulses

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A radiation resonance effect observed in the reflection spectra from overdense plasmas illuminated by femtosecond laser pulses at normal incidence is reported from particle-in-cell simulations. Harmonic emission at multiple orders of the fundamental is found to exhibit resonance phenomena, with the number of resonances and power emitted depending on the electron plasma density. For relatively low laser intensities the reflected light at the laser frequency shows prominent resonant emission around specific values of the plasma density, mainly at 4, 16, and 36 times critical. For increasing laser intensities, strong harmonic emission around 4 and 16 times critical dominates the reflection spectra. In the case of the third laser harmonic, the emission is found to be resonant about those densities and presents, additionally, a distinctive resonant region around nine times critical. A simple radiation model for the power of the third harmonic was proposed confirming a resonant effect dependent on the electron plasma density. For higher harmonic numbers, weak radiation resonances persist in the emission spectra, with their number increasing with order. The resonance effect reported in this paper is found to occur at densities that approximately satisfy $n_e/n_c=4n^2$, where n_e and n_c are the plasma and the critical density, respectively, and n is an integer. For the third harmonic, the second resonance corresponds to $n=1.5$.

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I. INTRODUCTION

Laser devices capable of delivering ultrashort femtosecond light pulses at high intensities in the multi-terawatt range have been developed in recent years from the chirped-pulse amplification technique [1,2]. Laser-plasma interaction physics in this regime involves a number of processes that may occur when a target is irradiated by a light source: ionization, generation of large amplitude plasma waves, magnetic field generation, particle acceleration, hole boring, collisional absorption, and vacuum heating among other effects, which depend both on the plasma and laser parameters. For underdense plasmas, multiphoton effects, self-focusing, and scattering instabilities are among the interaction phenomena of interest.

In this work our main concern is harmonic generation from overdense plasmas. The study of harmonic emission apart from its intrinsic interest may find application in the development of coherent short x-ray sources.

In the past, harmonic emission from solid targets irradiated by laser light has been reported in the literature. Strong emission detected up to the 46th harmonic was first reported by Carman *et al.* [3,4] from nanosecond CO_2 laser pulses incident on carbon targets at intensities above 5×10^{14} W/cm^2. The highest harmonic emitted was interpreted as corresponding to an upper shelf density of the highly steepened profile with emission attributed to nonlinear resonant absorption. In passing, we remark that laser interferometry has verified steepening effects from the observation of density jumps of hundreds of times the critical plasma density.

Recent numerical simulations, with more accurate resolution, have shown no evidence of a cutoff at greater irradiances, with spectra extending to higher harmonic numbers [5]. Experiments have confirmed emission to high orders [6–8], up to the 75th harmonic for obliquely incident 1.053-μm pulses of 2.5 ps at 10^{19} W/cm^2 [8]. The vacuum heating effect [9], in which energetic electrons are dragged out of the plasma by the electric field of the driver and reinjected again to the plasma over an optical cycle, is thought to be responsible for part of harmonic emission [5].

A number of theoretical models have appeared in the literature interpreting harmonic emission in laser-plasma interactions. A mechanism for harmonic emission, based on phase modulation by the laser light upon reflection from an oscillating plasma-vacuum interface, was proposed by Bulanov *et al.* [10], who took into account the oscillatory motion of a reflecting charge sheet of plasma electrons. Applying this, Lichters *et al.* [11] obtained model spectra from plasma oscillations at the boundary, which agreed with particle-in-cell (PIC) simulations.

Important aspects dealing with harmonic emission have been reported in recent years. For instance, plasma density determination from transmission of surface harmonics was proposed as means of diagnostic by Gibbon *et al.* [12], who found from PIC simulations a cutoff in the transmission spectra for frequencies $\omega<\omega_p$, where ω_p is the electron plasma frequency.

Effects of plasma emission on the harmonic spectrum for moderately intense pulses incident on overdense plasma slabs were reported by Boyd and Ondarza [13,14], who found from PIC simulations strong radiation at multiples of the plasma frequency. Plasma radiation was also observed by Lichters *et al.* [15]. Teubner *et al.* [16] reported on an observation of a plasma line and emission close to the second harmonic from a laser-produced plasma. Strong emission in the plasma line with harmonics up to the fifth one (detected in both reflection and transmission) has been observed in simulations by Boyd and Ondarza-Rovira [17]. A feature of the reflection spectrum was a broad combination line between ω_p and $2\omega_p$, generally about $\omega \sim 1.5\omega_p$, which appeared to be a robust feature of the spectra.

Recent work has reported on the modulation of reflected light at high laser intensities from femtosecond pulses in interactions with solids [18,19]. The modulation was shown to be produced by the higher modes of oscillation of the critical surface. The detected modulation structures were found to depend on the initial scale length as well as on input energy. This phenomena may afford a means of studying the dynamics of the critical layer. The effect of the electron density gradient has also been shown to play an important role in the conversion efficiency of harmonics generated in laser-produced plasmas [20,21]. In those experiments, by controlling the density scale length it has been possible to enhance the harmonic emission.

Harmonics of the incident laser light have also been used in a novel method to estimate indirectly the magnitude of magnetic fields generated in laser-plasma interactions [22]. In that work polarization measurements of the self-generated harmonics and observation of the x wave were used to measure the magnetic field present in the plasma.

In the present paper we report on a radiation effect observed from PIC simulations of laser interactions with overcritical plasmas characterized by very steep density profiles. It is found that laser harmonic emission reflected from the plasma and generated at the critical layer exhibits a resonance phenomena, with enhancement of the emission at specific multiples of the critical density. It is shown that the power of the reflected emission depends on the plasma density and resonant enhancement appears at densities 4, 16, and 36 times critical, for the lower harmonic multiples of the laser frequency. In the case of the third harmonic the second resonance appeared instead at nine times critical. For the fifth and higher harmonics, weak resonances persist in the radiation spectra, with their number increasing with increasing density.

In the following section we describe the procedure for simulating the interaction of a short laser pulse with an overdense plasma, and emission plots showing the dependence on the plasma density are presented for a given laser intensity. In Sec. III we formulate a physical model that in some extent enables us to explain the radiation mechanism that generates the resonant enhancement of reflected harmonics when a laser pulse illuminates a dense plasma. In Sec. IV some conclusions are drawn from the work performed.

II. HARMONIC RESONANT ENHANCEMENT

The nonlinear response from the plasma under the influence of an external radiation field was studied by means of PIC kinetic simulations. We used a $1\frac{1}{2}$-D, fully relativistic and electromagnetic code with immobile ions as a neutralizing background. We have performed simulations including ion dynamics and found no appreciable effects for the relatively low range of energies considered in this paper.

For all the simulations, the density scale length was chosen as a small fraction of a laser wavelength, allowing to prepare the simulation box with a very steep density gradient at the front boundary.

In this paper we show particle simulations for laser light of femtosecond pulse duration. The laser pulses were launched to the front of the plasma interface at normal incidence. The plasma was distributed over a region of some 4–6 laser wavelengths in extent and a number of 2000 grid cells per wavelength, containing 2×10^6 particles, were used, which was adequate for a Debye length resolution with acceptable accuracy. Two vacuum gaps to the left and to the right boundaries of the simulation box of the order of half a wavelength each were used to allow for particle and electromagnetic propagation. The electron temperature was taken as 1 keV.

Considering the input intensities, time scales, and the highly steepened vacuum-plasma interface, collisions between plasma particles were neglected.

It is well known that at normal incidence, only odd laser harmonics are generated. Two sources are responsible for harmonic emission, one due to the oscillatory motion of the perturbed electron density and the other from the relativistic factor γ [23]. Denoting a_0 as the normalized vector potential, $a_0 \sim 0.854(I_{18})^{1/2}\lambda_L$ (where I_{18} is the intensity, measured in units of 10^{18} W/cm^2, and λ_L the wavelength in μm), the wave equation for the vector potential can be written as

$$\Box^2 \boldsymbol{a}_0 = k_p^2 \left(\frac{n}{n_0}\right)\left(\frac{\boldsymbol{a}_0}{\gamma}\right), \tag{1}$$

where $k_p = \omega_p / c$, n_0 is the ion background density, c is the speed of light in vacuum, $\gamma = (1 + a_0^2)^{1/2}$ is the relativistic factor, and where $\Box^2 = \partial^2/\partial x^2 - (1/c^2)\partial^2/\partial t^2$. The laser harmonics are generated from the harmonic content of the plasma density, which is driven by the ponderomotive force $\boldsymbol{v}\times\boldsymbol{B} \sim a_0^2/(1+a_0^2)$, and contributes only even harmonics. Clearly, the relativistic γ factor also contains only even harmonics, with the result that the current term generates only odd harmonics. The analytical model in Ref. [23] suggested a nonlinear resonance effect for the third laser harmonic at a density four times critical. This resonance phenomenon is captured by our simulations about that frequency, exhibiting a prominent feature in the emission spectra.

Even laser harmonics can be generated for oblique incident interactions since the component E_x of the electric field of the laser pulse in the direction of wave propagation and along the density gradient excites electron plasma waves that couple the radiation field generating both odd and even harmonics. The study of harmonic resonance effects from obliquely incident laser pulses will be discussed elsewhere.

For our simulations we have used laser light with wavelength of 0.248 μm and pulse duration of 40 fs incident on an overdense plasma characterized by a steep density profile at the interface.

Figure 1 shows a schematic, in arbitrary units, of the time evolution of a laser pulse incident on a dense plasma. The laser pulse becomes evanescent for the region of the space occupied by the plasma where it can be discerned the weak decaying electric field amplitude. The plasma-vacuum interface is indicated by an arrow in the figure.

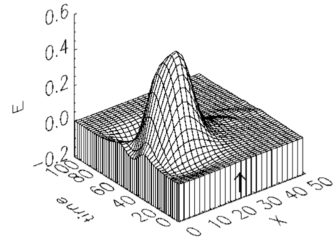

FIG. 1. Time evolution of a laser pulse incident on a dense plasma slab, $a_0 = 0.5$, $\lambda_L = 0.248$, and $n_e / n_c = 10$, in arbitrary units.

Inside the plasma, the nonlinear response to the external field produces electron density fluctuations. These can be observed from Fig. 2, where plasma waves are produced during the laser pulse interaction. The interface is shown at the same position as in the previous figure and from where the density grows abruptly.

We have Fourier analyzed the reflected signal to resolve the emission spectra. Figures 3–7 show the reflected power of the fundamental and its first four odd harmonics, normalized to the incident power, as a function of the plasma density. The reflected power calculated at different points is shown in the plots. Laser pulses of different strength were used in the simulations. In this paper we show results for $a_0 = 0.5$, which corresponds to a laser intensity of 5.57×10^{18} W/cm^2. For greater and lower intensities the resonance effect reported in this work was still observed with similar spectral characteristics.

Figure 3 shows the radiated power at the fundamental frequency. Resonance effects characterize the emission around multiples of the critical density. A resonance at densities around 4 and 16 times critical is observed. The conversion efficiency for the first resonance is nearly 80% of the input energy, and decreases for higher densities, with a resonant gain of 70% for the resonance at $m_r = n_e / n_c = 16$. For the third harmonic, two resonances about four times critical and $m_r = 9$ are found. This is shown in Fig. 4. As expected, the conversion efficiency is lower than the emission at the fundamental and decreases again with density, although the reflected power of the resonance at $m_r = 9(4 \times 10^{-2})$ result to be greater than that around $m_r = 4(2 \times 10^{-2})$. This is a characteristic feature that distinguishes the third harmonic from higher orders for any laser intensity.

For the fifth laser harmonic resonances are found around 4 and 16 times critical, with similar strength in the power emitted. The strength of the emission is found to decay for higher densities. This is shown in Fig. 5. In Fig. 6, the seventh harmonic exhibits resonant emission around 4, 16, and 36 times critical.

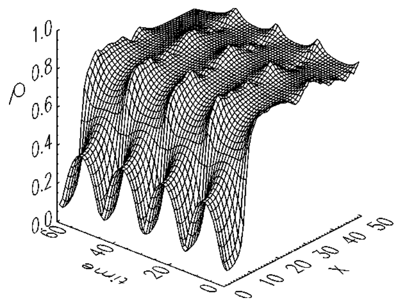

FIG. 2. Electron density perturbation for the interaction of Fig. 1, in arbitrary units.

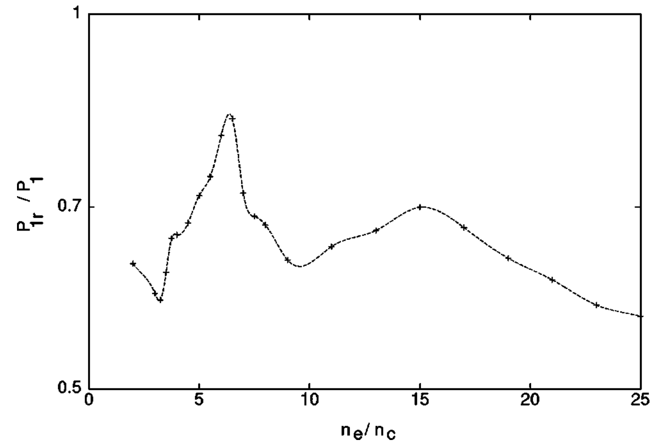

FIG. 3. Reflected power at the laser frequency as a function of plasma density, parameters as in Fig. 1.

Figure 7 shows that for the ninth harmonic further resonances appear in the spectrum around $m_r = 52$ and 70, with conversion efficiency weaker than for lower densities. The conversion efficiency for the resonance around $m_r = 4$ is found to be 10^{-4}, and is one order of magnitude higher than the resonance around $m_r = 70$. One remarkable feature observed in the emission plots for the third and fifth laser harmonics is the resonance structure around the density four times critical. A number of two and three emission peaks can be discerned in this region, indicating a strong coupling effect, predominantly among oscillation modes of the plasma at densities around critical and four times critical. This feature repeats independently, in the emission spectra, for all the laser intensities considered.

With the purpose of exploring the origin of the harmonic emission resonances, we have performed simulations to calculate the magnitude of the evanescent electric field inside the plasma. In Fig. 8 the magnitude of the transmitted electric field, normalized to the incident, is shown as a function

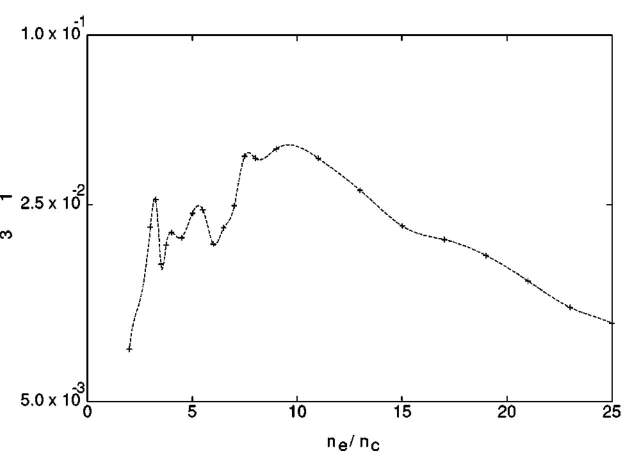

FIG. 4. Reflected power for the third laser harmonic as a function of plasma density, parameters as in Fig. 1.

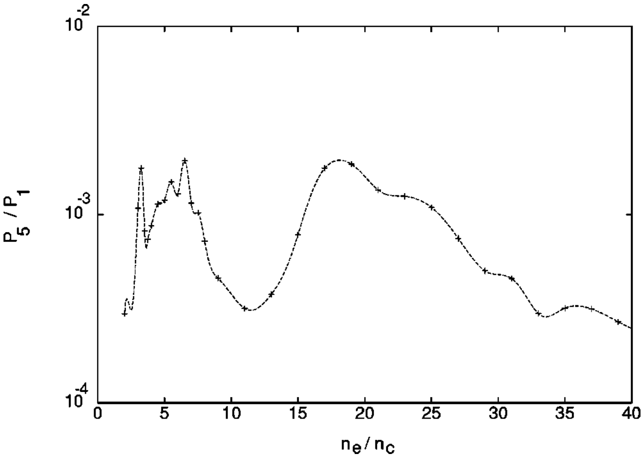

FIG. 5. Reflected power for the fifth laser harmonic as a function of plasma density, parameters as in Fig. 1.

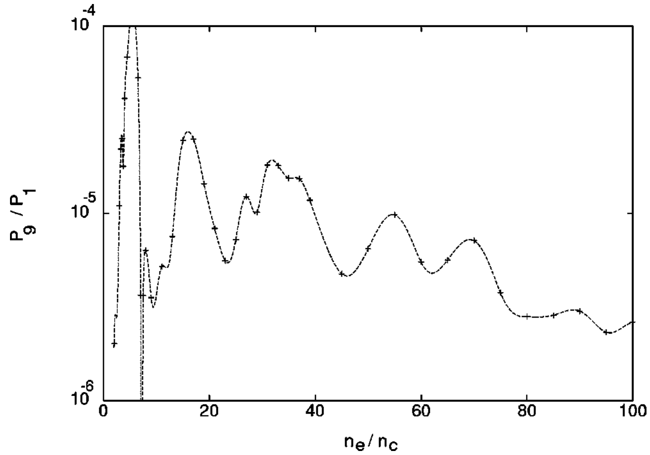

FIG. 7. Reflected power for the ninth laser harmonic as a function of plasma density, parameters as in Fig. 1.

of the plasma density. It shows that the harmonics of the transmitted wave present a similar resonant behavior as that found from reflection. The electric field was calculated at a distance of $0.23\lambda_L$ from the vacuum-plasma interface. In the following section we formulate a physical model for the radiation enhancement of the third laser harmonic, with the end of having an insight of the role of the radiation field in the plasma.

Table I summarizes the conversion efficiencies observed around the resonances for the first four harmonics and for the fundamental one. It shows that the power reflected from the plasma for a particular resonance decays an order of magnitude for increasing harmonic numbers.

III. RADIATION MODEL FOR HARMONIC ENHANCEMENT

In what follows, a physical model for the radiation enhancement of the third laser harmonic is followed for a relatively low laser amplitude. This model will be discussed in detail elsewhere. From Maxwell's equations and the conservation of canonical momentum, the wave equation can be written in terms of the plasma density and the relativistic factor γ as in Eq. (1). Performing a perturbative expansion and expressing the vector potential to second order in the form $a_\perp = a_0 + \epsilon a_3 + O(\epsilon^2)$, where a_0 represents the fundamental wave and a_3 the third harmonic, we obtain the wave equations

$$(\Box^2 - k_p^2) a_0 = 0, \tag{2}$$

$$(\Box^2 - k_p^2) a_3 = k_p^2 a_0 \left(\frac{\delta n}{n_0} - \frac{1}{2} a_0 \right), \tag{3}$$

where the perturbation δn of the density is given by $n = n_e + \delta n$ to first order, with the assumption that $a_0^2 \sim \epsilon$ and $\delta n \sim \epsilon$, and where ϵ is the ordering parameter used to separate terms. After linearizing the continuity and Poisson equations, the dynamics for δn is described by the equation

$$\frac{\partial^2 \delta n}{\partial t^2} + \omega_p^2 \delta n = \frac{n_0}{2} c^2 \frac{\partial^2 a_0^2}{\partial z^2}, \tag{4}$$

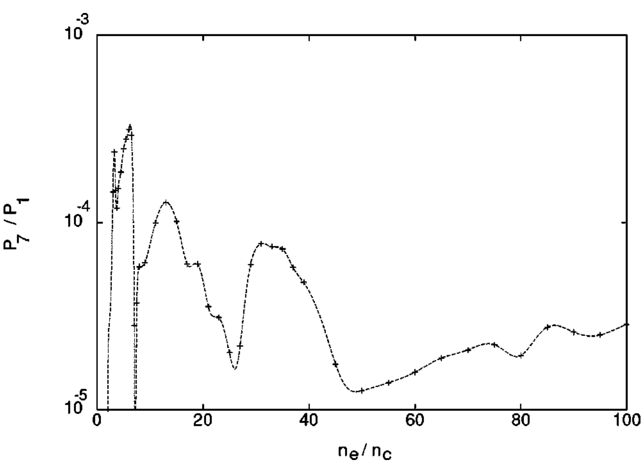

FIG. 6. Reflected power for the seventh laser harmonic as a function of plasma density, parameters as in Fig. 1.

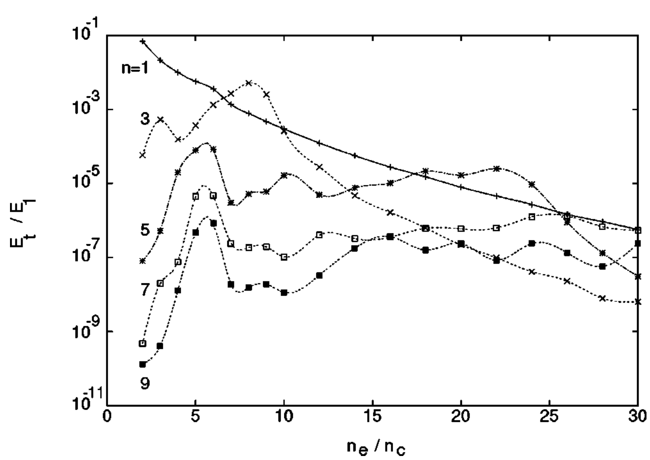

FIG. 8. Transmitted electric field as a function of density at a distance of $0.23\lambda_L$ inside the plasma, parameters as in Fig. 1.

TABLE I. Conversion efficiencies around the resonances.

ω_n/ω_0	n_e/n_c	P_n/P_1
1	4	8.0×10^{-1}
	16	7.0×10^{-1}
3	4	2.0×10^{-2}
	9	4.0×10^{-2}
5	4	1.7×10^{-3}
	16	1.9×10^{-3}
	36	3.2×10^{-4}
7	4	3.0×10^{-4}
	16	1.3×10^{-4}
	36	7.7×10^{-5}
9	4	1.0×10^{-4}
	16	2.5×10^{-5}
	36	1.8×10^{-5}
	52	9.8×10^{-5}
	64	7.1×10^{-6}

where z has been taken as the direction of propagation of the laser field. It can be shown from the continuity conditions of the field and its derivative that the transmitted wave can be written as

$$A_t = 2\left(\frac{\omega_0}{\omega_p}\right) a_0 e^{-x/\delta}\cos(-\omega_0 t + \phi), \tag{5}$$

where $\delta = \sqrt{c^2/(\omega_p^2 - \omega_0^2)}$ is the plasma skin depth.

Solving for δn and using the field amplitude as in Eq. (5), we have that the oscillation mode for $\delta n(t)$ apart from that of the plasma is

$$\delta n(t) \sim 4 n_0 \beta^2 (1-\beta^2) a_0^2 e^{-2x/\delta}\left\{1 + \frac{1}{1-4\beta^2}\cos 2\omega_0 t\right\}, \tag{6}$$

where $\beta = \omega_0/\omega_p$. This corresponds to an oscillation mode at twice the laser frequency, driven by the ponderomotive force. Using expression (5) it can be shown that the third-harmonic wave in Eq. (3) can be solved to obtain

$$a_3 = \frac{3}{8}\left(\frac{\omega_0\omega_p}{\omega_p^2 - 4\omega_0^2}\right) a_0^3 \cos 3\omega_0 t. \tag{7}$$

The important result of this is that the third harmonic scales with the third power of the laser field and shows a resonance at a density four times critical, as observed in the numerical simulations.

For higher harmonics the procedure followed here turns out to be more difficult and less accurate. For the fifth harmonic it can be shown that two resonances at densities 4 and 16 times critical emerge from the approximation, as expected.

Figure 9 shows the reflected power of the third harmonic for $a_0 = 0.5$ as a function of the plasma density, according to Eq. (7), and is compared to the emission spectrum from the PIC simulations. This figure shows a good agreement between the analytical model and simulations but is limited to wave fields of small amplitudes ($a_0 \leqslant 1$).

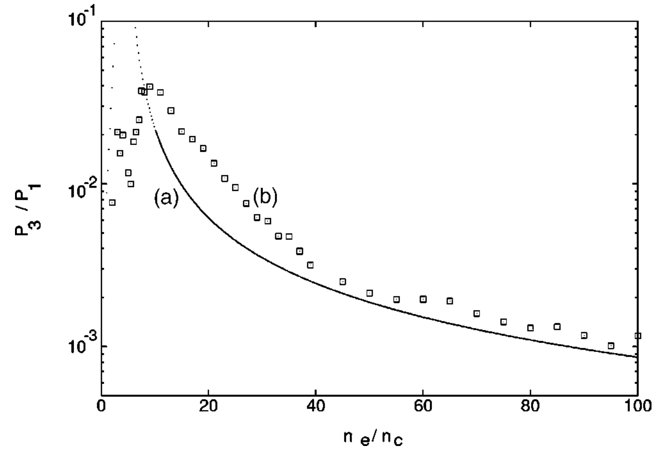

FIG. 9. Reflected power of the third harmonic: (a) analytical (dashed) and (b) from simulation (squares), parameters as in Fig. 1.

IV. CONCLUSIONS

We have reported for the first time resonance emission effects from the interaction of short laser pulses with plasmas of overcritical density. It is found that resonances in the emission appeared as a distinctive feature in the reflection spectra. The resonances occur around values of the plasma density that closely satisfy $m_r = n_e/n_c = 4n^2$, where n_e and n_c are the plasma and the critical density, respectively, and n is an integer. The reflected light at the fundamental frequency showed two prominent resonances about 4 and 16 times critical with the power of the emission decaying with increasing density. For the third laser harmonic, the second resonance is shown to be enhanced around $n_e/n_c = 9$, which instead corresponds to $n = 1.5$. For this harmonic number the resonance around $m_r = 9$ is greater than the resonance around $m_r = 4$. The opposite is true for higher harmonics, where more resonances are observed with conversion efficiency decreasing with density. The radiation phenomenon reported in this paper resembles some other results that have observed enhancement of harmonic efficiency from laser-produced plasmas of modified electron density gradient [21]. One possible mechanism that may explain this effect is resonance absorption, which provides an efficient way for converting electromagnetic waves into electron plasma waves, which combine at the critical density to generate harmonic emission that propagates up to regions of higher density exciting further harmonic waves. At high intensities in very steep density profiles, this mode-coupling mechanism breaks down since the electron oscillation amplitudes become comparable to the density scale length. The proposed physical model in Sec. III considered light harmonics generated from a coupling effect among the electron plasma oscillations, driven by the $\boldsymbol{v}\times\boldsymbol{B}$ force and the electromagnetic source. This coupling mechanism explains, as well, the generation of odd harmonics for normally incident laser pulses. It was shown through a perturbation analysis that the density fluctuations oscillate at $2\omega_0$, which corresponds to the oscillation frequency of the ponderomotive force. It was also shown that the expression of the time evolution of the density oscillations, to first order, predicts a resonant effect at a density four times critical, and can explain the harmonic enhancement observed from numerical simulations. Calculations to second order showed the existence of resonances at those observed densities. Calculation of the magnitude of the transmitted electric field inside the plasma with the aid of particle simulations showed a resonant behavior with density as obtained from the physical model proposed for the third laser harmonic. This gives an insight of the field enhancement with the plasma density. On the other hand, the $\boldsymbol{v}\times\boldsymbol{B}$ mechanism can explain the efficiency of converting the incident energy into energetic electrons that arise from wave-breaking of the density oscillations generating the harmonics. Thus, we can assume that the harmonic enhancement effect involves a mechanism resulting from mode-coupling of laser harmonics and excitation of electron plasma waves.

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