Emission spectra from super-critical rippled plasma density profiles illuminated by intense laser pulses

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Abstract

High-order harmonic emission from the interaction of intense femtosecond laser pulses with super-critical plasmas characterized by a rippled density profile at the vacuum-plasma interface has been observed from particle-in-cell (PIC) simulations. A plasma simulation box several laser wavelengths in extent was prepared with a rippled density of a fraction of a laser wavelength. Emission spectra at the very initial stage of the interaction were recorded with spectral characteristics dissimilar to those previously reported in the literature. The reflected light spectra were characterized by a strong emission at the plasma line and by a series of harmonics at multiples of the ripple frequency. Harmonic spectra were obtained for different values of the plasma ripple frequency. In all cases the harmonics were emitted at the precise multiple harmonic number of the ripple frequency. Another important feature apparent from the simulations was that the emission peaks appeared to have a complex structure as compared with those for unrippled plasmas. For the cases when the plasma was rippled the peaks that corresponded to the multiples of the rippled density typically showed a double peak for the first few harmonics. The reflected emission plots for the main laser pulse showed strong emission at the plasma frequency and at multiples of that frequency as reported by the authors in the literature.

PACS number(s): 52.40.Nk, 52.50.Jm, 52.65.Rr

I. Introduction

Recent work on laser-plasma physics has drawn attention to the optical radiation phenomena that occur when a highly-intense and ultra-short laser pulse illuminates a dense plasma.[1-4] One facet of the interaction phenomena concerns to harmonic emission reflected and transmitted from the plasma. High-order spectral emission from solid targets was first reported by Carman *et al.*[5,6] in experimental setups that detected up to 46 harmonics from the irradiation with nanosecond CO_2 lasers at intensities $I_L > 10^{14}$ W/cm^2. In those experiments the emission was attributed to nonlinear resonant absorption effects, with the plasma wave coupling to the radiation field, in a plasma whose density profile at the vacuum plasma interface is strongly steepened by the action of the ponderomotive force from the external driver. The highest harmonic generated was interpreted as corresponding to the upper shelf density of the steepened profile. Although the numerical computations performed by these authors seemed to corroborate the cut-off in the spectra, the lack of spatial and time resolution made it difficult to resolve emission above the first ten harmonics or so. More recent simulation analyses[7] at higher input energies and shelf densities above several times the critical plasma density showed no evidence of a cut-off emission, with about 68 harmonics resolved. Harmonic emission from solid targets irradiated with femtosecond and picosecond laser pulses has been confirmed in experiments.[8-9] Emission up to the 7th harmonic was reported in the first of these experiments from a 150 fs Ti-Sapphire laser light at 10^{19} W/cm^2, the second detected up to 15 harmonics for 0.8 μm, 130 fs lasers at 10^{17} W/cm^2. Newly advances in laser technology have allowed to develop devices capable of delivering ultra-short pulses at intensities above 10^{19} W/cm^2. The experiments performed by Norreys *et al.*[10] registered spectra with harmonics up to the 75th order from Nd pulses of 2.5 ps at 10^{19} W/cm^2. In those experiments spectral characteristics featured without a cut-off were observed, as predicted from numerical simulations by Gibbon[7]. On the other hand, plasma harmonic emission has been reported from particle-in-cell (PIC) simulations of ultrashort laser pulses incident on overdense plasma layers[11-13] and where strong plasma radiation was found to be emitted at the frequency that corresponds to the upper shelf density. In those simulations[11] the first numerical evidence of emission at multiples of the plasma line emission was found. Experimental observation of plasma emission and its second harmonic from laser-produced plasmas was firstly reported by Teubner *et al.*[14]. Teubner *et al.* attributed the plasma line to surface emission and the harmonic to a bulk plasmon from the interior, where the plasma density is assumed to be lower. However, in the simulations reported in Ref. 12 reflected light spectrum appears on the blue side of the plasma line with a central frequency of $\omega \sim 1.5\,\omega_p$, a frequency, much closer to that reported in Ref. 14 and attributed to $2\,\omega_p$. Presumably, that emission at $1.5\,\omega_p$ - the so-called *combination line* - would originate from the coupling mechanism, involving ω_p and $\omega_p/2$, of two-plasmon decay of radiation at the plasma frequency.

II. Harmonic emission from a rippled plasma

It is the aim of this paper to report a new emission effect observed by means of computer simulations of laser-plasma interactions when super-critical plasmas characterized by a rippled density profile at the plasma-vacuum interface is illuminated by intense femtosecond laser pulses. We used a 1 1/2-D fully relativistic, electromagnetic, immobile ion PIC code to study a plasma composed of around 10^6 particles distributed in a region of 4-6 laser wavelengths and containing a number of 1000 grid cells per wavelength. Two vacuum gaps of one wavelength each at both sides of the simulation box were used to allow for electromagnetic propagation. The electron temperature was taken below 1 keV and collisions were neglected. The ions were considered as an immobile neutralizing background. The electron density profile was prepared by placing the simulation particles according to an initial distribution function for particle positions and velocities. The ripple in the density profile at the interface was produced by placing the simulation particles in the phase space over a small region having an extension of only a fraction of a laser wavelength in front of the plasma-vacuum interface and with the rest of the density profile unaltered. Figure 1 shows a typical density profile for a plasma with density $n_e = 200\,n_c$ in which a ripple was introduced at the plasma-vacuum interface, here n_c denotes the critical density. The length of the plasma was chosen as $4\,\lambda_L$ containing 36 ripples over a region of $1.5\,\lambda_L$ at the interface. This makes each ripple to be $0.042\,\lambda_L$ long and $k_r/k_L \sim 24$.

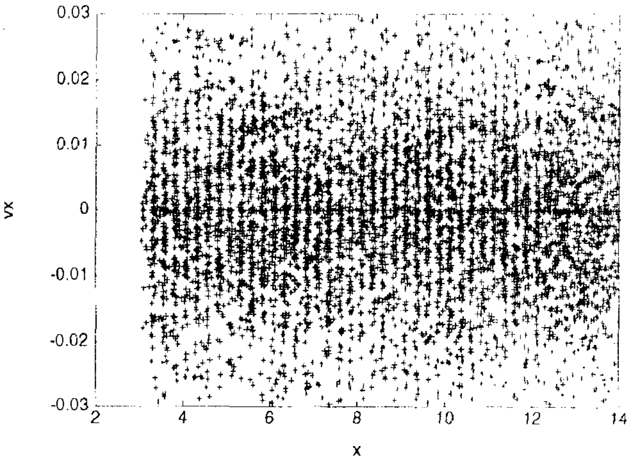

Figure 1: Initial rippled density profile.

Figure 2 plots the evolution of the reflected electric field for the case of the rippled plasma and shows the three main time intervals for which we have obtained the emission spectra. The first interval (A) represents the very initial stage of the interaction (10 fs), the second interval (B) is the main laser pulse (120 fs)and the post-pulse is shown in the last interval (C) (35 fs). The emission from reflection for the time interval (A) is shown in Fig. 3. The radiation spectrum exhibits emission lines at harmonic numbers that are multiples of $\omega_m \sim m\,\omega_r$, where $\omega_r = 24\,\omega_L$ is precisely the ripple frequency.

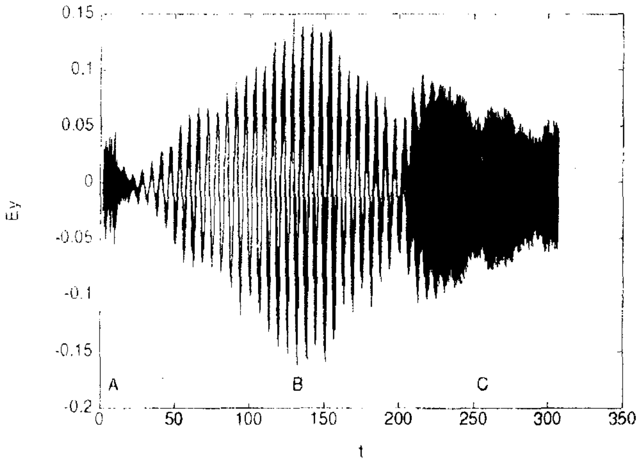

Figure 2: Reflected electric field for a rippled plasma, $I_L = 1.4 \times 10^{16}$ W/cm^2, $\lambda_L = 1\,\mu$m, $n_e/n_c = 200$ and $\omega_r/\omega_L \sim 24$.

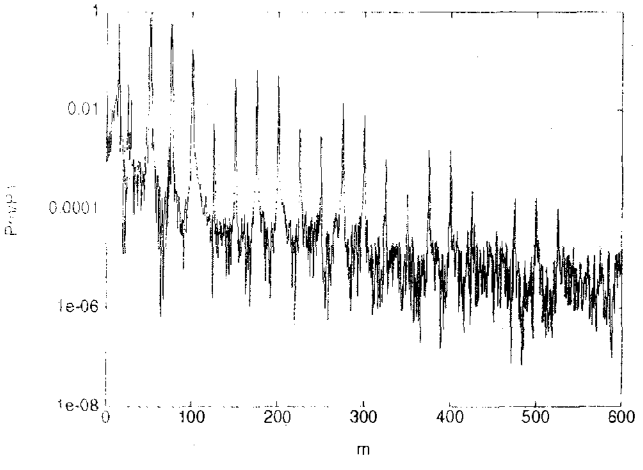

Figure 3: Reflected emission for time interval (A) in Fig. 2, parameters as in Fig. 2.

Figures 4 and 5 show the emission for the time intervals (B) and (C), respectively. Figure 4 shows that plasma emission and its first two harmonic multiples corresponding to the plasma frequency are emitted, as reported previously by the authors in Ref. 11. From this figure it is also shown that emission at multiples of the ripple frequency are emitted. A number of ten of those multiples are observed. A characteristic spectral feature is also observed from the 3rd to the 5th emission line. For each of those emission lines a double peak is observed and originate from the coupling effect between the harmonic multiples of the plasma emission and those corresponding to the multiples of the ripple frequency. Figure 5 shows that the emission for the post-pulse is weaker than the main pulse without emission at multiples of the ripple frequency.

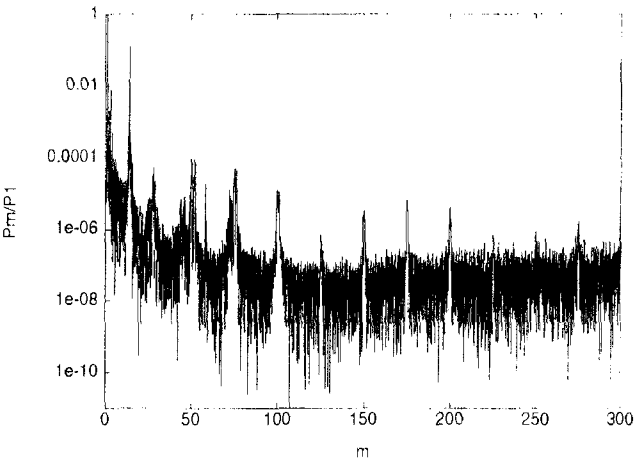

Figure 4: Reflected emission for time interval (B) in Fig. 2, parameters as in Fig. 2.

For the same choice of parameters but for an unrippled plasma Figs. 6 and 7 show, respectively, the reflected field and its radiation spectrum. The reflected emission contains laser harmonics over the first twelve orders with a strong emission peak at the frequency that corresponds to the electron plasma frequency $\omega_p \sim 14\,\omega_0$. Emission at $2\,\omega_p$ is also shown in this figure. For this case there is no effect from the rippling of the vacuum-plasma interface and the emission is as that reported in Ref. 11.

Next, we study the case of a plasma having $n_e/n_c = 200$ and rippled at the interface over a re-

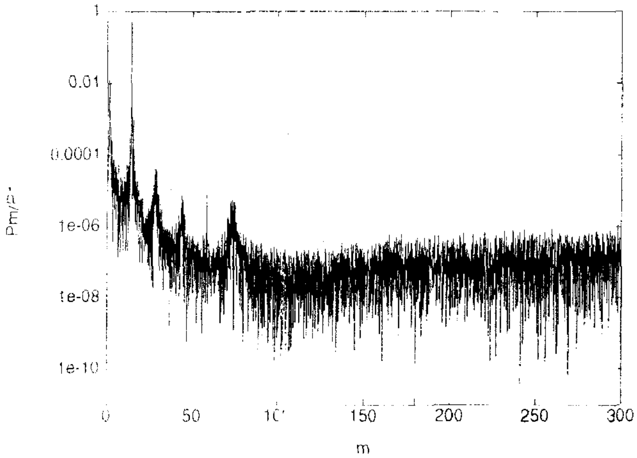

Figure 5: Reflected emission for time interval (C) in Fig. 2, parameters as in Fig. 2.

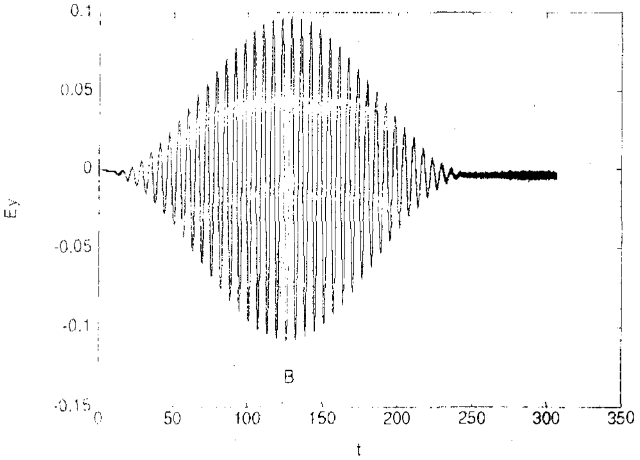

Figure 6: Reflected electric field for an unrippled plasma, parameters as in Fig. 2.

gion of 1.5 λ_L with a number of 73 ripples with extension of 0.02 λ_L, and which $k_r/k_L = 50$. Figure 8 shows the corresponding emission reflected from the plasma. In this case, harmonic lines at the plasma frequency $\omega_p = 14\,\omega_L$ and at multiples of the ripple frequency $\omega_m = m\,\omega_r$ with $\omega_r = 50\,\omega_L$ are emitted. In Fig. 9 the emission for the main pulse is shown. This emission spectrum shows some few laser harmonics over the first orders, a strong peak at the plasma frequency and emission at multiples of $\omega_m = m\,\omega_p$ with $\omega_p = 14\,\omega_L$. It is shown that the third harmonic of the plasma emission is strongly emitted since an effect of resonance with $w_r/w_L = 50$ takes place.

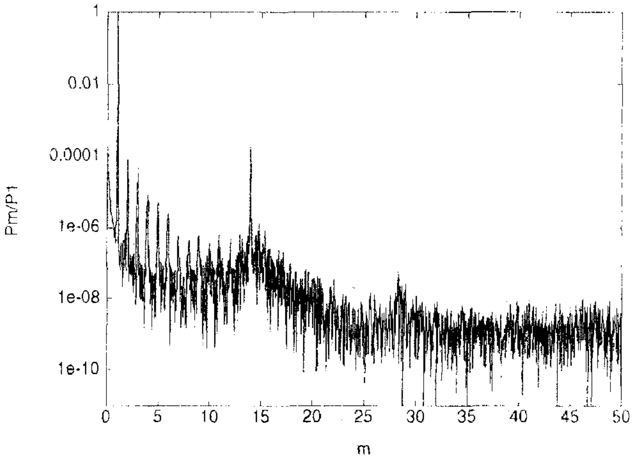

Figure 7: Reflected emission for an unrippled plasma, parameters as in Fig. 2.

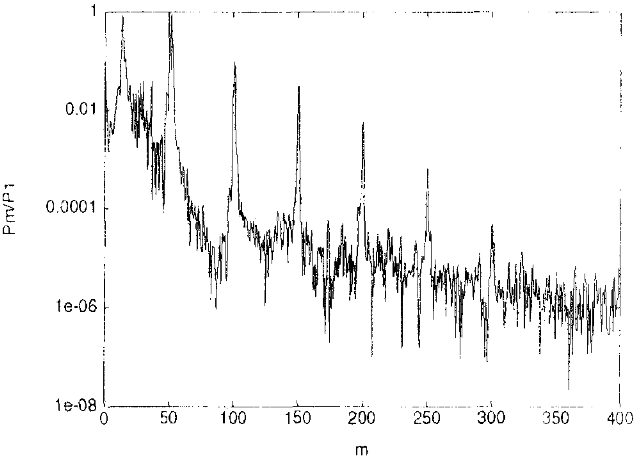

Figure 8: Reflected emission for time interval (A) of a rippled plasma of $\omega_r/\omega_L \sim 50$, parameters as in Fig. 2.

III. Conclusions

Reflected spectral emission from laser pulses irradiating dense plasma slabs, featured by a rippled density profile over a fraction of a laser wavelength at the vacuum-plasma interface, were obtained. It is shown that for the very initial stage of the laser-plasma interaction emission at harmonic numbers multiples of the ripple frequency can be generated. From the emission spectra presented in this paper it is shown that the reflected light from the plasma can contains lines emitted at frequencies that depend on the way in which a narrow rippled interface is prepared. High-order harmonic emission extending over as much as 500

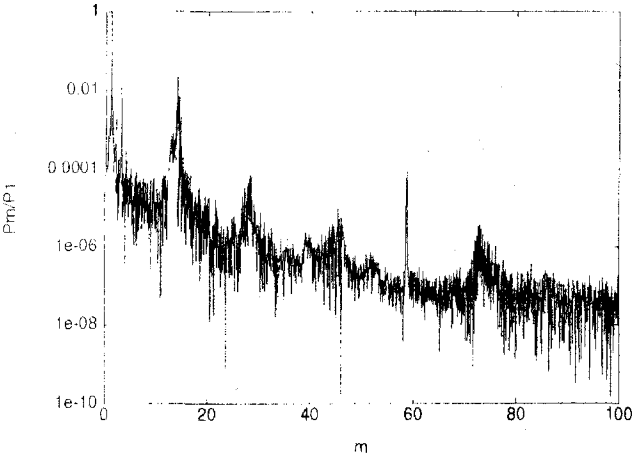

Figure 9: Reflected emission for time interval (B) of a rippled plasma, parameters as in Fig. 8.

laser harmonics were observed from laser-dense plasma interactions. It was found that when the ripple frequency is small, a few number of lines emitted can be generated with multiples extending over the region of high harmonic orders. These simulation results show that strong emission in the range of x-rays can be produced when a plasma is prepared and initially perturbed with a rippled density profile. Subsequent reflected emission comming from the main laser pulse also shows to be composed of different spectral characteristics as compared to those cases for unrippled plasmas. Plasma emission and multiples of the plasma line are emitted along with radiation at multiples of the ripple frequency. In the rippled cases and depending on the choice of parameters a characteristic feature in the emission was observed with double peaks at the emission lines. This effect can be explained in terms of the coupling mechanism between the frequencies of the plasma and the ripple. For those cases in which the multiples of the ripple frequency are close enough to those multiples of the plasma line a strong coupling takes places producing a resonance with emission of a double peak.

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