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Properties of the harmonic emission from the interaction of intense laser pulses with overdense plasma

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Abstract

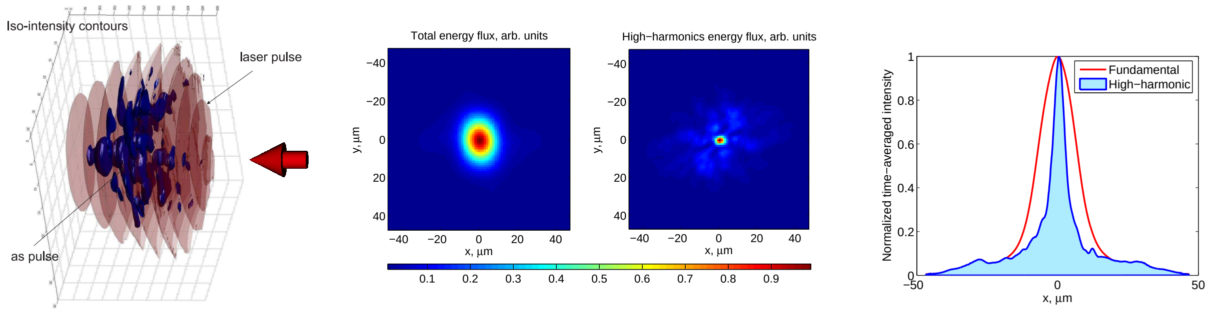
In a series of Particle-In-Cell (PIC) simulations we have studied the feasibility of generation of single intense attosecond pulses using the surface harmonics mechanism and investigated the effect of various parameters to the generation process. In 3D-PIC simulations we found that the plasma scale-length greatly affects the generation process. We have also demonstrated that the polarization gating technique for the generation of single attosecond pulses is applicable to the mechanism under realistic conditions of oblique incidence. Results of the systematic study are presented and discussed.

Introduction

The prospect of generating a train or even single attosecond pulses with intensities orders of magnitude higher than those currently available has rekindled the interest in the old mechanism of harmonic generation from solid targets observed more than 20 years ago [1]. The headways in laser technology making laser systems delivering relativistic intensities readily available, have fuelled the interest in the interaction of intense laser pulses with overdense plasma [2]. It is seen not simply as an efficient XUV source, but also as a promising method to generate intense attosecond pulses [3, 4], enabling XUV pump - XUV probe experiments with unparallel temporal resolution in biology, surface science, atomic, molecular and plasma physics. Furthermore, it suggests a possible route [5] for generating intensities reaching the Schwinger limit ($10^{29} W/cm^2$).

Effects of plasma inhomogeneities

An important experimental issue in the generation of harmonics from solid targets is the influence of the plasma scale length resulting from the ionization and heating of the target by the presence of the inevitable pedestal and/or prepulse in the laser pulse.



(a) (b) (c)

Figure 1: Intensity (a), spot size (b) and the line-out (c) at y=0 in the far-field at 200 μm from the reflecting surface for the fundamental and the high harmonic pulse for the case of a steep gradient

Using the 3D capabilities of the ILLUMINATION code, we studied the influence of the scale length of the expanding plasma L_p on the overall development of the 5fs pulse interaction with the overdense plasma. The emphasis is on the efficiency of the high harmonic generation, but more importantly on the spatial coherence of the back reflected XUV radiation. The vacuum-plasma interface is modelled with an exponentially decaying density profile $n = n_0 exp(z/L_p)$, where z is the propagation direction coordinate, L_p is the plasma scale length and n_0 is the plasma electron density. It is chosen as $n_0 = 10^{22} cm^{-3}$, corresponding to $\approx$ 6 times the critical density for $\lambda_0 = 800$ nm light. In the simulations of the plasma scalelength influence presented below, all the parameters are held fixed with the intensity at $I = 5.5 \cdot 10^{19} W/cm^2$. Only the plasma scale length L_p in front of the target is varied between 0 and 5 μm. In order to investigate coherence, focusability, and divergence of the high harmonic pulse we have applied the standard Kirchhoff diffraction theory.

In figure 1(a) we have plotted the 3D iso-intensity contour of the infrared (red) and XUV (blue) pulse resulting from the filtering of the 5th to 10th harmonic. The localization in space of the attosecond pulse train is clearly seen. In Fig. 1(b) the energy flux is plotted for the fundamental and the high harmonic pulse and figure 1(c) presents the line-out of the spot. The far-field exhibits excellent symmetry of both pulses with considerably narrower angular distribution for the XUV pulse. This clearly indicates the coherent nature of the high harmonic generation and the focusability of the high harmonic pulse.

The situation is quite different in the case where an exponential density profile with a scale length of $L_p = 5$ μm is present. IR and XUV beams that are strongly divergent as depicted in Fig. 2 where a line-out of both fields along the x-axis is given. The spot size in this case has

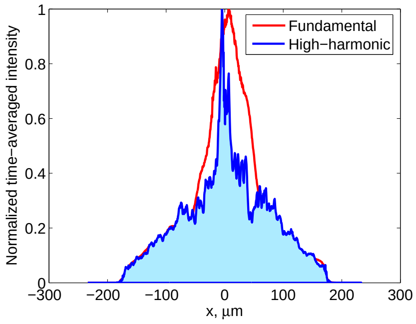


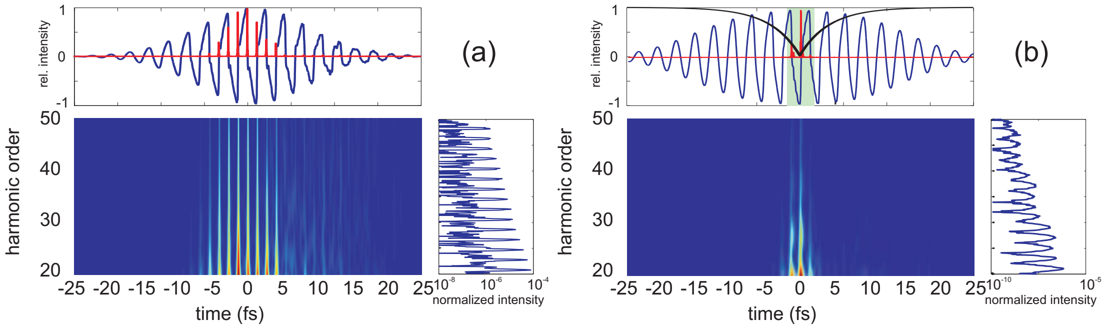
Figure 2: Line-out along the x-axis of the far-field at 200 μm from the target for the case with gradient length of $L_P = 5$ μm

increased by a factor of 8 compared to the step-like density profile. This is attributed mostly to the strong deformation of the “soft” interaction layer and the reflection of different parts of the pulse in different directions due to indenting of the plasma surface, resulting not only in increasing the spot size but also leading to a much broader and higher pedestal for the XUV-pulse compared to the sharp gradient case.

Thus, plasma scale length plays a major role even for 5 fs pulses. The detailed results of this study can be found in [6].

Polarization gating for generation of single attosecond pulses

In order to obtain single attosecond pulses one can use few-cycle laser pulses with carrier-envelope phase stabilization. However, it appears feasible to use longer pulses using polarization gating. This technique makes use of the fact that the harmonic emission is suppressed when circularly polarized pulse is normally incident onto the target. The idea of polarization gating is to create a pulse that has linear polarization only during the short "gating" time and has circular polarization otherwise. The results of the 1D PIC simulations using the code PICWIG are summarized in figure 3. The initial pulse duration is 7 cycles (19 fs) and the gating time is approximately equal to 5 fs. One clearly sees the train of attosecond pulses generated in the case of the linearly polarized laser pulse, whereas, in the case of the pulses with polarization gating, practically all the attosecond pulses but one are suppressed and thus the polarization gating effectively works as a 2-cycle laser pulse. Due to the mechanism of generation [3] the harmonics are phase-locked. When polarization gating is applied, one should be able to see its effect on the spectrum of the reflected light. Figure 3 depicts the difference in the spectrum for linear polarization and polarization gating. One can clearly see the broadening of the individual harmonics. The results of the simulations [7] show that in the case of angles of incidence of 10-



(a) (b)

Figure 3: Results of PIC simulations with parameters $I_L = 400 I_{rel} \approx 9 \times 10^{20} W/cm^2$, $\tau_L = 7$ cycles (19 fs), $n_e = 80 n_{cr}$ and normal incidence for linear p-polarization (a) and pulse with polarization gating (b). In both figures the color coded image shows the wavelet analysis (time-frequency analysis) with the vertical axis as the frequency axis and the longitudinal axis as the time axis. The graph on the right of the image represents the spectrum of the reflected light with frequencies on the vertical axis and normalized intensity on the longitudinal axis. The graph at the top shows the reflected light (blue color) and the filtered pulse (20-100 harmonics, red color). For the case of polarization gating(b) the ellipticity evolution (black color) and the gating time (green rectangle) are also shown.

15 degrees the efficiency of harmonic generation decreases rapidly at small values of ellipticity, deviating only slightly from the case of normal incidence. Thus it appears quite feasible even under oblique incidence to generate a gate with duration short enough to restrict the emission to practically a single cycle.

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