Single Zeptosecond Pulse Generation in the Interaction of Relativistic Laser and Plasma with Unfixed Ions

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Received: July, 11, 2023, Revised: Jan. 07, 2024, Accepted: Jan. 20, 2024, Available Online: Jan. 23, 2024,
DOI: 10.61186/ijop.17.1.39

ABSTRACT— The creation of single zeptosecond pulses is important in various scientific fields, particularly for studying time-resolved nuclear processes. In this study, a clean single sub-attosecond (270 zeptosecond) pulse is obtained in the simulation of a femtosecond laser with over dense plasma. First, the desired laser and plasma parameters are utilized to achieve the nano-bunches in the plasma surface and the desired spectrum up to 2000th harmonics is obtained. Then, different filters such as filtering the harmonics and different intensity filters are applied where, the special exponential function is due to a very clean single zeptosecond pulse.

KEYWORDS: Zeptosecond pulse, Laser, Plasma, Nanobunch.

I. INTRODUCTION

The motivation for generating short pulses is to study ultra-fast dynamic processes. Some molecular processes, such as the decay of excited levels, can be tracked with pulses longer than 100 fs. However, there are some nuclear phenomena where the investigation of the time-resolved dynamics requires much shorter pulses with zepto-seconds (zs) duration. The time scales of atomic and nuclear processes have been described by Krausz and Ivanov [1]. Atomic motion on molecular scales occurs at femtosecond to picosecond scales, electron motion in outer shells of atoms occurs on the time scale about tens atto-seconds, and electron motion in inner shells of atoms is expected to occur in the time scale of single attosecond. Faster scales as nuclear dynamics are predicted to occur in zeptosecond (10^{-21} s) time scales. Some of these nuclear phenomena are such as resonance fluorescence [2], internal resonance conversion [3], compound nuclei evolution [4], and photo disintegration of nuclei [5].

Numerous techniques have been suggested for producing short pulses, with a focus on creating linearly polarized (LP) single and isolated attosecond pulses [6]. However, there is a need for circularly-polarized (CP) isolated attosecond pulses due to their distinct properties, which are essential for various applications such as identifying molecular chirality [7], investigating magnetic properties [8-10], and studying spin dynamics [11].

In order to obtain such pulses, the concept of generating high harmonics through reflection the lasers from plasma, has been the subject of numerous researches [12-14] and various simulation and experimental works are devoted to laser interactions with over dense plasmas [15-19]. Plaja *et al.* investigated the potential of an oscillating plasma mirror in order to produce short pulses [13], Naumova *et al.* have studied the isolation of a single attosecond pulse when a laser pulse is reflected from a plasma surface Their idea is based on the following model. The laser pulse is up-converted as a result of the Doppler-shifted reflection from a plasma mirror [14]. Another successful approach towards coherent ultrashort pulse production is high harmonic generation (HHG) [20]. Gas jets have been used to achieve high photon energy of approximately 2.5 keV [21,22]. However, to obtain higher photon energies, relativistic intensities are required. Unfortunately, the relativistic drift of ionized electrons suppresses

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the HHG yield in atomic systems [23]. However, there are methods to counteract the drift in the weakly relativistic regime and achieve higher photon energies [24]. Shim *et al.* have investigated the zeptosecond isolated pulse generation using a free electron laser [25]. Gordienko *et al.* have obtained zeptosecond pulses via the interaction of overdense plasmas in ultra-relativistic laser pulses [26], and Klaiber *et al.* have obtained coherent zeptosecond pulses with MeV photon energy [27]. Studies have shown that controlling target material [28], plasma length scale [28], carrier phase [29,30], laser pulse polarization [30,31], and the laser cycles [32-33] can control the width of the short pulses.

In this study, LPIC^{++} (Particle In Cell) code is used to simulate the interaction between the laser pulse and the solid target in coherent synchronize emission (CSE) model. LPIC^{++} is a 1D3V (one spatial and three velocity dimensions) code which simulates the motion of charged particles in the electromagnetic field. The obtained results show that by controlling the intensity and duration of the laser pulse, as well as other properties such as target material and the angle of incident pulse, it is possible to obtain very wide spectrum of high harmonics via the nano-bunches. Also, regarding the immobility of ions in the ultra-relativistic regime, improves the spectrum of high harmonics. Then, the different filters are applied, in which a single 270 zs pulse is obtained by means of an exponential filter.

II. THEORY

Different mechanisms are proposed in order to describe the high-order harmonics resulting from the interaction of lasers with solid targets. Among these mechanisms, the Coherent Wake Emission (CWE) [34,35], the Relativistic Oscillating Mirror (ROM) [36-38], and the Coherent Synchrotron Emission (CSE) [32,39] are important models in which describe the interaction of laser with plasma. The CWE mechanism is used in the region of non-relativistic intensity, the ROM mechanism is used for relativistic intensities, and the CSE mechanism is appropriate in the ultra-relativistic intensities. In the CSE mechanism, very dense and narrow electron nano-bunches are formed in the plasma-Vacuum boundary which causes the synchronize and coherent emission [32,39-41]. The spectrum in the CSE model can be discussed by means of one-dimensional current distribution and the reflected electric field can be written as follows [32]:

$$E_{y,CSE}(t,x) = \frac{2\pi}{c} \int_{-\infty}^{+\infty} j\left(t + \frac{x-x'}{c}, x'\right) dx', \quad (1)$$

The calculation of the spectrum is based on the following two assumptions:

1) The reflected field is produced by very narrow electron bunches. If the current layer is as $(t,x) = j(t)\,\delta(x - x_{el}(t))$, the optimal coherence is obtained for high frequencies. In order to include more realistic cases, a finite electron distribution is considered as:

$$j(t,x) = j(t)\, f\big(x - x_{el}(t)\big), \quad (2)$$

where $j(t)$ is the current, $x_{el}(t)$ is the location of electrons**,** and f(x) is the shape of function, which is a constant value [32].

2) In ultra-relativistic conditions($a_0 \gg 1$), it is reasonable to assume that the changes in the velocity components is controlled by changing the direction of motion, instead of the change in the absolute velocity. The movement of the electron in the momentum space is described as follows:

$$\big(p_x, p_y\big) = a_0 m_e c\big(\hat{p}_x, \hat{p}_y\big), \quad (3)$$

$$j(t) = ecn_e\hat{p}_y/(a_0^{-2} + \hat{p}_x{}^2 + \hat{p}_y{}^2), \quad (4)$$

$$\dot{x}_{el} = c\,\hat{p}_x/(a_0^{-2} + \hat{p}_x{}^2 + \hat{p}_y{}^2), \quad (5)$$

Considering Eq. 2, and the Fourier transform of Eq. 1, the following equation is obtained for the reflected electric field:

$$\tilde{E}_{y,CSE}(\omega) = \frac{2\pi}{c}\,\tilde{f}(\omega) \int_{-\infty}^{+\infty} j(t)\,\exp[-i\omega(t + x_{el}(t)/c)]dt, \quad (6)$$

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where, $\tilde{f}(\omega)$ refers to the Fourier transform of the function. The phase derivative ($\Phi = \omega(t + x_{el}(t)/c)$) at the points where $\dot{x}_{el} \approx -c$ tends to zero, so according to the second assumption at these moments $\hat{p}_y = 0$. Now, knowing that at a point where the phase is constant, the current changes sign, and by Taylor's expansion of the equations $j(t) = \alpha_0 t$ and $x_{el}(t) = -v_0 t + \alpha_1 t^3/3$, we can get Eq. 1 rewritten as follows [32]:

$$\tilde{E}_{y,CSE}(\omega) = i(2\pi)^2 e n_e c^{-1} \alpha_0 \alpha_1^{-2/3} \tilde{f}(\omega) \times \omega^{-2/3} Ai'\left(\frac{1-v_0}{\sqrt[3]{\alpha_1}}\omega^{2/3}\right), \quad (7)$$

And finally, the frequency spectrum envelope obtained as follows [32]:

$$I(\omega) \propto \left|\tilde{f}(\omega)\right|^2 \omega^{-\frac{4}{3}} \left[Ai'\left(\left(\frac{\omega}{\omega_{rs}}\right)^{\frac{2}{3}}\right)\right]^2, \quad (8)$$

where $\omega_{rs} \approx 2^{3/2}\sqrt{\alpha_1}\gamma_0^3$ and $\gamma_0 = (1 - v_0^2)^{-1/2}$ is the relativistic gamma factor of the electron bunch at the moment the bunch moves towards the observer. Considering that nano-bunches are responsible for generation of high harmonics, it is expected that the frequency spectrum obtained from the CSE model will be wider compared to the spectrum obtained from the ROM model with the cutoff frequency $\omega_{CO} = \sqrt{8\alpha}\omega_0\gamma^3$, and its intensity drop is also smoother. Ultra-short pulses also can be achieved by filtering the low frequencies of the spectrum. [42].

III. DESICCATION

Particle-In-Cell simulations (PIC) are well-established tools for the kinetic treatment of several topics related to the interaction of high-intensity pulses with plasmas. They self-consistently treat the underlying physical processes albeit for a reduced number of dimensions, in most cases in one dimension. Despite this shortcoming, PIC codes have helped to understand some details associated with the generation mechanism of high harmonics in overdense plasma [44-49].

In order to obtain desired ultra-short pulses, a very wide and flat spectrum of high harmonics must be generated. The initial conditions are important in order to obtain the desired spectrum. The incident pulse is regarded as Ti-Sapphire laser (λ_0=800nm) which is the most famous femtosecond laser in the laser-plasma applications. The researches indicate that very low cycle pulses can produce wide spectrum [32,33], therefore, one cycle pulse with the duration of $\tau_0 = 2\pi/\omega$=2.7 fs is regarded. In order to produce single atto-second pulsevia nano-bunch, Brügge *et al.*, have proposed the desired initial conditions as the P polarized ultra-relativistic beam, which impact on plasma with incident angle as 63 degrees. The desired electron density is also proposed as $n_e = 95 n_{cr}$ [33]. The normalized intensity parameter is regarded as $a_0 = 40$ with the carrier-envelope phase as $\varphi_{CEP} = 180^\circ$ and the target material is considered to be Aluminum [28,29, 33], also the desired plasma thickness is regarded equal to $L = 0.65\lambda_0$ and the ions are regarded as mobile. Regarding the mobility of ions in the ultra-relativistic regime, improved the spectrum considerably. The nano-bunch which is formed in the plasma – vacuum boundary is shown in Fig. 1. As it is shown the distribution of electrons is localized with the peak of nanometer width.

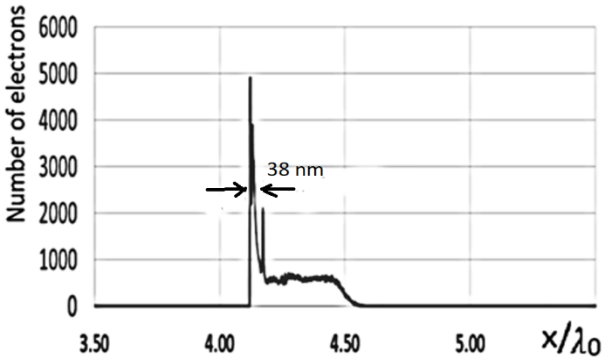


Fig. 1. Localized distribution of electrons (nano-bunch) which are formed in the plasma-vacuum boundary. Here λ_0 is 800 nm.

Figure 2 shows the spectrum of the obtained high harmonics. The results indicate the broadband spectrum of harmonics with a frequency range of $\Delta\omega \approx 2000\omega_0$. The attosecond pulse train which is produced in the reflection from the plasma surface, is shown in Fig. 3. According to the uncertainty principle, for the spectrum with a high-frequency width, a pulse with an ultra-short time-width can be produced in the case of optimal coherence.

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Therefore, in order to have sub zeptosecond pulses, $\Delta\omega$ must be in the order of 10^{19} Hz and a very broadband spectrum is needed, i.e., for the incident pulse of Ti-Saphhire laser (λ_0=800nm), high harmonics must be generated at least in the order of 2000th harmonic. Another critical point is that this spectrum must be flat as much as it is possible.

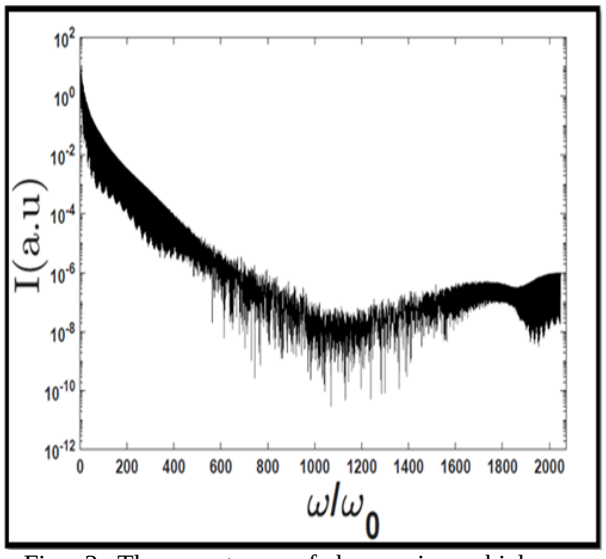


Fig. 2 The spectrum of harmonics which are generated in the plasma- vacuum boundary

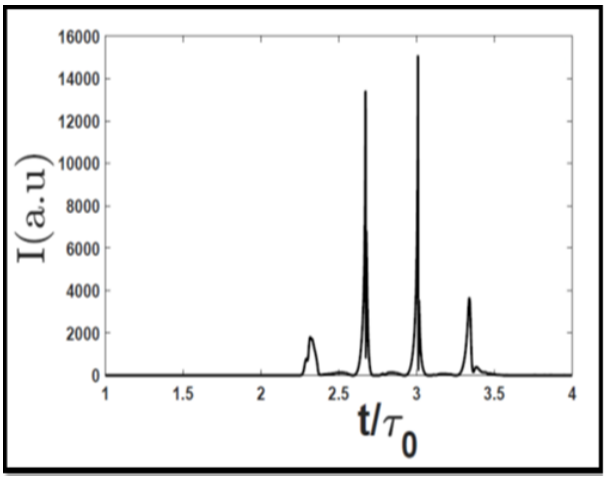


Fig. 3 Attosecond pulse train based on the inverse Fourier transform of Fig. 2. Here τ_0 is the duration of incident pulse and it is equal to 2.7 fs.

To obtain the ultra-short single pulse different filters are applied for the spectrum of Fig. 2. Initially, two first harmonics are filtered completely then the different functions are tested to filter the spectrum and it is found that the exponential function is the best. This function is founded as:

$f(\omega/\omega_0) = 1 + \exp(-((\alpha(\omega/\omega_0) - \beta)/\gamma))$ with the coefficients as α=1, β=3.19, and γ=0.01. The single pulse of 270 zs is obtained which is shown in Fig. 4. The time is normalized to τ_0, the duration of incident pulse.

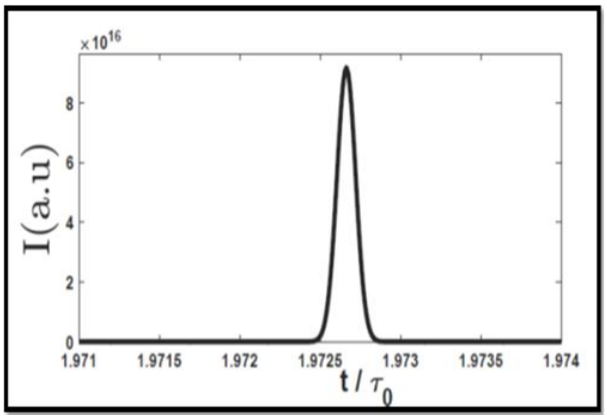


Fig. 4 Single zeptosecond pulse with time- width of 270 zs

IV. CONCLUSION

The interaction of ultra-relativistic laser with overdense plasma based on the Coherent Synchrotron Emission (CSE) model and in certain conditions leads to the desired nano-bunches which produced the flat and very wide spectrum up to 2000th harmonics. The initial conditions are regarded as the laser pulse of Ti:Saphhire laser, the carrier-envelope phase as $\varphi_{CEP} = 180^{\circ}$ and linear P polarization whith the incident angle of 63°. The plasma electron density is $n_e = 95n_{cr}$, the plasma thickness is equal to $L = 0.65\lambda_0$ and the motion of ions is regarded in the simulation. Applying the special exponential filter leads to a cleanly isolated zeptosecond (270 zepto-seconds) pulse.

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