The effect of target thickness on the efficiency of high-order harmonics generated from laser-driven overdense plasma target

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Abstract
In this paper, we analytically and numerically studied the impact of the target thickness on the efficiency of laser-plasma based high-order harmonics generation (HHG). The optimal parametric region is acquired where the laser normalized amplitude $a_0$, the target density $n_t$ and thickness $d_0$ satisfy the relation: $a_0 n_t / 2\pi n_c \lesssim d_0 / \lambda < a_0 n_c / \pi n_c$ for $n_c \gg a_0 n_t$. In this region, the laser can partially penetrate the target, leading to efficient acceleration of the target. Meanwhile, the target is thick enough to oscillate along the rising edge of the laser without being broken, which guarantees the occurrence of HHG. Both one-dimensional and two-dimensional particle-in-cell simulation results verify our optimal target thickness theory, and a single attosecond pulse with $I = 3.0 \times 10^{20}$ W cm$^{-2}$ is generated under the driving of $8.6 \times 10^{20}$ W cm$^{-2}$, which is several hundred times more intense than that from a thick target.

1. Introduction
Attosecond XUV pulses can provide unprecedented resolution in both temporal ($\sim 10^{-18}$ s) and spatial domains ($\sim 10^{-9}$ m), which makes them indispensable tools for many research areas [1, 2]. For example, with nanometer wavelength, attosecond pulses can be used to measure the structure of molecules, and diagnose the properties of warm dense matter [3–5]; attosecond duration makes it possible to change and/or control the properties of materials through manipulating electrons [6–9].

High-order harmonics generated from laser-driven solid target has been identified as an efficient way to the production of intense attosecond pulses [10–12]. Due to the oscillating component of laser ponderomotive force, electrons within the skin depth of the solid target are driven back and forward periodically around the ion boundary, leading to alternate compression and stretching of the reflected laser based on the Doppler effect [13]. The spectrum of the reflected laser contains a series of high-order harmonics of the laser frequency, and its character is predicted and verified to accord with a power law: $I_n \propto n^p$, where $n$ is the order of harmonics, and $p$ indicates the conversion efficiency of HHG which is determined by properties of electron bunches [11, 14]. Generally $p$ is smaller than $-8/3$ until when the electron bunch is accelerated to nearly the speed of light $c$ [15, 16]. Recent study shows that $p$ can reach up to $-4/3$ when the electron bunch is energetic enough to be separated from bulk plasma and forms an isolated nano-sheet [17, 18].

In order to achieve HHG efficiently, and hence produce intense attosecond pulses, several approaches have been proposed, which is generally through employing an intense driving laser [19, 20], or adopting a low-density target [21], or inducing proper preplasma in front of the target [22, 23]. These studies can be classified as low $S$ case in principle, where $S = n_e / a_0 n_c$ is the similarity parameter used to describe electron dynamics in the laser-plasma interaction process [24]. Here $n_e$ is the electron density in the interaction region, $n_c = \omega_0^2 m_e / 4\pi e^2$ is the critical density for a laser with frequency $\omega_0$, and $a_0 = E_0 / m_e \omega_0 c$ is the normalized laser amplitude. For
normal incident geometry, the laser electric field that acts on the target can be expressed as
\[ E_x(x, t) = E_{0x}(t) \exp(-x/l_s) \propto a_{0x}(t) \exp(-x/l_s), \]
where \( l_s \) is the skin depth which is inversely proportional to \( \sqrt{\mu_0} \), and \( a_{0x} \) is the normalized laser amplitude on the left boundary of the electron bunch \( x_0 \). So in low \( S \) cases, the electron bunch is driven by a relatively larger electric field of the laser and oscillates with a larger amplitude, consequently gains higher energy [25, 26]. It has been verified that the most efficient HHG happens when \( S \approx 1 \) [27]. However, this parametric region is still a challenge for today’s technology, i.e. for a plastic target with density around 200Tn, to achieve efficient HHG, a laser pulse with intensity over \( 8.6 \times 10^{22} \) W cm\(^{-2} \) is required. Besides, the apparent curvature of the electron bunch in the low \( S \) case due to the driving of the Gaussian-shape laser leads to the wavefront deformation of the reflected laser and the obtained attosecond pulses disperse after transmitting a certain distance[28–30]. Therefore, it is necessary to find a solution to generate intense attosecond pulses with current laser technology in high \( S \) region.

In this paper, we point out that besides the value of \( S \), the target thickness also has a great impact on HHG efficiency, and the optimum target thickness region for normal incident interacion is proposed analytically and verified through particle-in-cell (PIC) simulations, which lies in \([\lambda/2\pi S, \lambda/\pi S]\). In this region, the peak laser ponderomotive force is approximately equal to the maximum electrostatic force of the target. The target performs as a gate that, in the time window around the laser peak, the target absorbs the maximum laser energy and stores it in form of the electrostatic energy when electrons are piled up at the rear side of the target and compressed into a nanobunch. Thus the laser energy is utilized more efficiently than in cases where the target is so thin that it has been broken before the laser peak arrives. After then, the stored electrostatic energy converts to the kinetic energy of the electron bunch when the laser ponderomotive force decreases, thus the maximum energy conversion efficiency from the laser to the electron bunch is achieved. Besides, since the thickness of the formed electron bunch is less than the skin depth at the laser peak cycle, the laser electric field does not decay to zero, which after reflection leads to more intense HHG radiation than in thick target case. Before the time window, the instantaneous laser intensity is small that the formed electron bunches are less energetic, and the interaction process is similar to thick target case. While after the time window, the decreasing laser electric field can not constrain energetic electrons any more, and electrons start to debunch, unabling to produce short wavelength radiation coherently. Therefore, attosecond pulses can be efficiently constrained within this narrow time window. A series of PIC simulations confirm that the optimum thickness region is applicable to different laser interaction with a step-like target cases, and a single relativistically intense attosecond pulse is obtained in two-dimensional PIC simulation with intensity several hundred times higher than that from the thick target case.

2. Theoretical analysis

According to the Doppler effect, when an electromagnetic wave is totally reflected from an ideal counterpropagating mirror at a velocity \( v_s \rightarrow c \), its frequency and amplitude can be multiplied by a factor of \( 4\gamma^2 \) [31], where \( \gamma = \sqrt{1 - (v_s/c)^2} \). Hence, there are two ways to enhance the HHG radiation generated from relativistic laser-plasma interaction process. One is to increase the longitudinal velocity \( v_s \) of the oscillating electron bunch, and the other is to enlarge the laser amplitude that is to be compressed by the electron bunch. Since the oscillating period of the electron bunch formed in the laser-plasma interaction process is fixed, which is half a laser optical period in normally incident geometry, \( v_s \) of the electron bunch can be represented by its longitudinal oscillating amplitude, which is roughly equal to the maximum depletion length \( \delta_x \) of electrons in each process. For a given target and a laser pulse, \( \delta_x \) can be deduced through the balance between the laser ponderomotive force and the electrostatic force

\[ e\nu_s/e \times B_z(1 + R) = eE_x. \]

(1)

Here \( \nu_s \) is the transverse velocity of electrons, \( B_z = E_z/c \) is the laser magnetic field, \( R \) is the reflectivity of the laser and \( E_x \approx 4\pi n_e e\delta_x \). For a solid target with thickness \( d_0 \) and density \( n_e = N \gg 1 \), the laser reflectivity is

\[ R = \left( \frac{r \left( \exp(2kd_0\sqrt{N - 1}) - 1 \right)}{r^2 - \exp(2kd_0\sqrt{N - 1})} \right)^2, \]

(2)

where \( k \) is the wave number of the laser. In general, \( r = (\sqrt{N - 1} + i)/\sqrt{N - 1} - i \) becomes \( r = (\pi Nd_0/\lambda)/(\pi Nd_0/\lambda + i) \) when \( d_0 \ll \lambda [32] \). Thus for thick solid targets, \( R \) is approximately equal to 1. After a simple mathematical derivation, the maximum \( \delta_x \) equals to \( \lambda/\pi S \) with \( \nu_s = c \) is used. Actually, even though the incident laser is relativistically intense, the laser energy decays exponentially in the skin depth (figure 1(a)), thus electrons in the inner layer are of moderate velocities and \( \delta_x \) is smaller than \( \lambda/\pi S \). Anyway, for thick targets with \( R \approx 1 \), \( \delta_x \) of the electron bunch in each oscillating cycle is already determined. Besides, the reflected electric field \( E_x \) cancels the incident electric field \( E_x \) totally, which is known as the Leontovich boundary.
condition [14], leading to weak electric field acting on the electron bunch during the entire process. Thus the conversion efficiency from the laser to HHG radiation is pretty low.

Things becomes tremendously different when the target thickness $d_0$ approaches to the order of $\lambda/\pi S$, where the target is so thin that the laser can penetrate around its peak cycle. In these cases, the target is gradually accelerated and eventually broken through by the driving laser. At the rising edge of the laser when the target is opaque, the HHG process is similar to the thick target case. Near the laser peak, electrons are compressed to the rear side of the target, forming a nanobunch. At this time, the laser field can transmit through the electron bunch rather than attenuation to 0 (figure 1(b)), realizing both coherent acceleration of the whole bunch and increase of the laser amplitude to be compressed. Therefore, HHG radiated from this nanobunch can be constructively added and its efficiency is significantly improved. At the falling edge, the electron bunch starts to expand, its density decreases, and laser transmissivity increases, leading to further expansion of the electron bunch. Finally, the coherence of the electron bunch is greatly reduced and efficient HHG radiation terminates.

However, the target thickness can not be too thin. If the target thickness is so thin that at some point all electrons are blown out and co-move with the driving laser, as shown in figure 1(c), then the oscillating motion of the bunch disappears, further no HHG produces. Hence, the thinnest target for efficient HHG satisfies that, the target is not broken until the laser peak, at which the laser reflectivity reduces to 0, and the corresponding thickness is $\lambda/2\pi S$. For targets thinner than $\lambda/2\pi S$, electrons have already been blown out before the laser peak, resulting in a waste of laser energy. Thus, the optimum thickness region for efficient HHG is:

$$\frac{1}{2\pi S} \leq d_0 \leq \frac{1}{\pi S},$$

where not only the electron bunch can be effectively accelerated by the laser peak, but also the laser electric field to be compressed by the bunch is enlarged due to the transparency of the target.

3. 1D simulations

One-dimensional PIC simulations using the EPOCH code [33] are carried out to verify the above theoretical analysis. In this paper, the laser propagates along x axis with wavelength $\lambda = 800$ nm, and its carrier envelope phase (CEP) is fixed at 0 and temporal profile $a = a_0 \exp(-t^2/\tau_0^2)$, unless otherwise specified. In figure 2, $a_0 = 10$, $\tau_0 = \text{FWHM}/\sqrt{2 \log 2}$ and full width at half maximum (FWHM) of the laser intensity FWHM = $2T_0$ ($T_0$ is the laser period). The simulation box is 24$\lambda$ in total and the resolution is 2000 cells/$\lambda$ with 200 pseudoparticles per cell. The target is placed at 12$\lambda$ and the initial electron density is $80n_e$ with thickness varying from 0.03$\lambda$ to 0.5$\lambda$. Both fields and particles are absorbed when they travel to the simulation boundary. According to the above analysis, the optimal thickness region for efficient HHG is $[0.02\lambda, 0.04\lambda]$. Parameters in all figures of this paper are normalized, with thickness $d_0$ and $x$ by $\lambda$, and electric field $E$ by $m_e\omega_0^2/c$. HHG conversion efficiency and amplitudes of attosecond pulses are calculated through filtering radiation with frequency lower than 15$\omega_0$.

As is shown in figure 2(a), when target thickness is larger than 0.04$\lambda$, the laser reflectivity $R$ is almost 1 and the corresponding energy absorbed by plasma $E_{\text{absorb}}$ is negligible. According to the maximum electrostatic fields $E_{\text{c,max}}$ in each case, we can deduce the actual maximum $d_0$ through $E_{\text{c,max}} = 2\pi n_e \delta_c/n_e \lambda$, which are around 0.033$\lambda$ when $d_0 > 0.04\lambda$ and is slightly smaller than its theoretical value 0.04$\lambda$. The discrepancy between the theoretical value and the actual value of $\delta_c$ is due to that the longitudinal velocities of the electron bunches in

![Figure 1](image1.png)

Figure 1. (a)–(c) schematically shows the laser electric field (red) and electron density distribution (dark green) for target with thickness larger than (a), lies in (b) and smaller than (c) the optimum thickness region. Here the electron depletion layer is represented in light green and the neutral region is in gray.
simulations are only around 0.8c. This is the result of both the small electric field acting on the target due to the interference of incoming and reflected laser wave [34] and heavy damping of the laser electric field in the skin layer. Low-energy electrons leads to weak Doppler effect during the reflection process, consequently, as shown in figure 2(b), both the conversion efficiency and amplitudes of attosecond pulses are pretty low. The situation changes when the target thickness is 0.03λ. In this case, the laser energy is effectively absorbed by the target electrons (figure 2(a)). Both HHG efficiency and the maximum amplitude of the obtained attosecond pulse increase remarkably (figure 2(b)). PIC simulations show that to achieve similar conversion efficiency, a laser pulse with intensity 2.6 times more intense is needed when the target thickness is 0.5λ.

The spectra of the reflected laser in different cases are compared in figure 2(c). Clearly, in cases where thicknesses are larger than 0.04λ, the spectra in the low frequency domain are almost the same. While in the high frequency domain, there is a slight increase when target thickness decreases, which is due to the increase of electron energy. A significant increase can be seen when the target thickness is 0.03λ, and the spectra agrees well with the ideal relativistic oscillating mirror model [14].

The electron density distribution in x – t space in the case where d0 = 0.03λ is shown in figure 3(a), and the laser electric field Eξ is overlaid in red-white-blue. The laser front irradiates the target at t = 12T0 and arrives peak at t = 16.0T0. During the rising edge of the laser, electron surface oscillates twice in one laser cycle with its amplitude increases gradually, as a result, the HHG efficiency and its spectral width is enlarged with time as is shown in figure 3(b). Simultaneously, laser transmissivity increases with time due to the decrease of effective plasma frequency resulting from the increase of effective electron mass. Figure 3(c) shows the electron density nξ (solid line) and the laser electric field Eξ (dotted line) at t = 15.52T0 (blue) and t = 16.06T0 (green), which correspond to the two adjacent moments with the highest HHG efficiency in the rising edge process. We can find that at t = 16.06T0 not only the electron bunch is denser and thinner, but also the magnitude of Eξ acting on the electron bunch is larger, which leads to larger oscillating amplitude of the electron bunch than t = 15.52T0 (figure 3(a)). All of these results in more intense and wider harmonic spectrum at t = 16.06T0 than at t = 15.52T0 (figure 3(b)). On the trailing edge of the laser, even though electrons are energetic, oscillating with even larger amplitude, the laser reflects partially through the evolving expanding electrons, resulting in
In order to verify the theoretical optimal thickness region, a serial of 1D PIC simulations are carried out. Here, the laser profile remains the same while its amplitude $a_0$ increases from 10 to 50, and the initial target density changes according to the laser amplitude to keep $S = 8$. The results are shown in figure 4 and the similarity phenomenon can be observed from the first row. For a target of a specific thickness, the laser reflectivity is almost the same in different $a_0$ cases, and the energy absorption and the conversion rate from the laser to radiation with frequency larger than $15\omega_0$ have similar trends in different $a_0$ cases. For a target with thickness in $[0.02\lambda, 0.04\lambda]$ region, the laser reflectivity is smaller than 1 (figure 4(a)) and part of the laser energy is absorbed by the plasma (figure 4(b)), consequently, the energy conversion efficiency from the laser to HHG is larger as predicted theoretically (figure 4(c)). Besides, higher conversion efficiency is achieved in larger $a_0$ cases due to the improvement of the electron energy. The maximum amplitudes of attosecond pulses in the reflected direction are plotted in figure 4(d) and obviously bright attosecond pulses are generated in the optimum thickness region. Here, the amplitudes are normalized by the maximum in each $a_0$ case which are listed on the right side of the figure. Because the amplitude of the attosecond pulse is not only related to the characters of the electron bunch, but also is highly sensitive to the laser phase when the electron bunch compresses the laser, there are fluctuations when the thickness changes. Besides, since the laser reflectivity decreases as the target thickness decreases (figure 4(a)), the thickness region for bright attosecond pulses tends to the thicker part of the theoretical region (figure 4(d)). Figure 4(e) shows the square of the reflected/transmitted laser electric amplitudes (in black) as well as the corresponding attosecond pulses (in red) in the case $a_0 = 10$ and $d_0 = 0.026\lambda$, where the most intense attosecond pulses are obtained in $a_0 = 10$ cases. We can see that at some point during the rising edge, the laser partially penetrates the target and the most intense attosecond pulse is generated. As more laser energy transmits through the target, the reflected attosecond pulses get weaker due to both the debunching of the electron bunch and the decrease of the laser field on the left side of the electron bunch. When the laser reflectivity is close to 0, attosecond pulses in the reflected direction can not be produced anymore. For the transmission direction, the electron bunch can never catch up with the transmitted laser, so no up-shift of the laser frequency happens. The transmitted attosecond pulse obtained here may result in deteriorative coherence of the interaction and destructive interference of short-wavelength radiation, which can be seen from the spectrum in figure 3(b). Therefore, the target in this parameter region functions as a gate that localizes the efficient HHG in the narrow temporal window around the laser peak, which can greatly reduce the number of attosecond pulses.
from the wavefront deformation when the laser penetrates the target and dispersion during the transmission in the plasma.

In order to testify the universality of our theory, simulations with \(S = 15\) and \(S = 20\) are carried out, where the driving laser temporal profile remains the same with \(a_0 = 10\) while the initial target density is determined by \(S \times a_0\), and the results are shown in figure 5. According to the above theory, the optimum thickness lies in \([0.011 \lambda, 0.021 \lambda]\) for \(S = 15\) and \([0.008 \lambda, 0.016 \lambda]\) for \(S = 20\). As is shown in figure 5, in both cases, the most efficient and intense short-wavelength radiation is generated when the target thickness lies around the optimal region that is predicted theoretically. Meanwhile, we can find that the conversion rate in \(S = 15\) case is higher than \(S = 20\) case but is lower than \(S = 8\) case. This is related to the electron energy which is higher in low \(S\) cases when the same laser is employed. The effect of CEP on the conversion efficiency of HHG in few-cycle laser case with FWHM = \(2T_0\) is simulated and results are shown in figure 5(e). In addition, the effect of pulse duration is also considered, and figure 5(f) shows the result when laser FWHM = \(5T_0\). Obviously, in these two cases, the efficient HHG radiation all happens in the optimal thickness region, which proves our theory.

Finally, as analyzed above, the attosecond pulses produced from a target with optimal thickness are temporally localized around the laser peak cycle, which makes it possible to generate an isolated attosecond pulse. To prove it, same laser pulse with only CEP being changed to \(\pi/2\) is used. Normally, there are at least two attosecond pulses emitted in thick target case since the driving laser has two peak cycles under the envelope. However, when irradiating on a target of optimal thickness, a single attosecond pulse can be generated successfully as shown in figure 6(a). This is because that after the first peak cycle, the target has been heated greatly and destroyed violetely, which leads to the destructive interference of short radiation and low laser reflectivity at the second peak cycle. In addition, figure 6(b) shows the result of the case where the FWHM of the driving laser pulse is \(5T_0\). Clearly, a single attosecond pulse can also be obtained with a relatively long laser pulse.

### 4. 2D simulations

Two-dimensional PIC simulations are performed and the results are shown in figure 7. A laser with \(a_0 = 20\) is normally incident onto a target with \(n_0 = 160n_e\), and its temporal profile remains the same with FWHM of the spatial profile is \(3\lambda\). The simulation box is \(24\lambda \times 14\lambda\) with resolutions in both directions are 1000 \(\lambda\), and for each cell 64 pseudoparticles is filled. The boundary condition of \(x\) direction is same as in 1D simulations and is periodic in \(y\) direction. Figure 7(a) shows the HHG conversion rate, and figure 7(b) are the maximum amplitudes of attosecond pulses in the reflected direction. Obviously, the optimum thickness region is still consistent with our theoretical prediction when multi-dimensional effect is considered. In figures 7(c) and (d),

![Figure 5](image1.png)

**Figure 5.** 1D PIC simulations results to testify the universality of our theory. (a), (c) are the results when \(a_0 = 10\) and \(S = 15\), and (b), (d) are the results when \(a_0 = 10\) and \(S = 20\). The theoretical optimum thickness regions are shown by black dashed lines in all figures. (a) and (c) show the conversion rate, (b) and (d) show the maximum electric amplitudes of attosecond pulses in the reflected direction. (e) and (f) show the conversion rate when \(a_0 = 10\) and \(S = 8\), and only the CEP in (c) and FWHM in (f) of the laser are changed. Here attosecond pulses are obtained with radiation \(\omega < 15\omega_0\) is filtered.
the attosecond pulse in the case with $d_0 = 0.025 \lambda$ is showed, while figures 7(e) and (f) are the results in the case $d_0 = 1.0 \lambda$. In the thin target case, the produced attosecond pulse is much more intense and shorter than that in the thick target case, and a single attosecond pulse with $\omega \gtrsim 20 \omega_0$ is produced in the reflected direction. In the thick target case, the energy of the electron bunch only depends on the instantaneous laser amplitude acting on the target surface and the spectral widths of the two adjacent moments around the laser peak differs little. By contrast, in the thin target case, the energy of the electron bunch abruptly increased at around the peak laser cycle due to the penetration of the laser, coupled with the large laser electric field acting on the electron bunch, so it is easier to produce much broader HHG radiation than former cycles. Even if the electric fields at two adjacent moments near the laser peak are of similar amplitudes, as long as the target becomes transparent at the former half cycle, more laser energy transmits through the target at later half cycle and the coherence of the electron bunch gets worse, leading to weaker attosecond pulse than the former half cycle, and it is also possible to generate...
a single attosecond pulse. Therefore, in this parametric region, not only HHG efficiency is higher, but also it is possible to get an isolated attosecond pulse.

5. Conclusion

In this paper, we systematically studied the effect of the target thickness on the efficiency of high-order harmonics and an optimum target thickness region is theoretically proposed, that is \( a_0n_e/2\pi n_e, a_0n_e/\pi n_e \). Both 1D and 2D PIC simulations confirm that in this parametric region, not only laser energy can be transferred efficiently to the target electrons, but also the laser electric field that is to be compressed by the electron bunch is enlarged due to the generation of the laser, therefore, the HHG efficiency is dramatically improved. Meanwhile, the target functions as a gate that limits the broadest and the most efficient HHG to radiate in a narrow time window around the laser peak intensity, thus it is possible to generate a single attosecond pulse with a proper filter. Nowadays, targets with nanometer thickness have been successfully produced [35], and laser contrast can be as high as \( 10^{-12} \) on picosecond scale in experiment [36], which makes it possible to research the HHG from nanofoils. However, to test the optimal parametric region proposed in this paper, a laser with higher contrast would be better.

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