Intense single attosecond pulses from surface harmonics using the polarization gating technique

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\textbf{Abstract.} Harmonics generated at solid surfaces interacting with relativistically strong laser pulses are a promising route towards intense 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—the technique known for a long time from gas harmonics. In this paper, we investigate in detail a specific approach to this technique on the basis of one-dimensional-particle-in-cell (1D PIC) simulations, applied to surface harmonics. We show that under realistic conditions polarization gating results in significant temporal confinement of the harmonics emission allowing thus the generation of intense single attosecond pulses. We study the parameters needed for gating only one attosecond pulse and show that this technique is applicable to both normal and oblique incidence geometry.

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The advent of bursts of attosecond packets of light denoted the dawn of attoscience, which has as its main goal the investigation of molecular and atomic dynamic processes as well as electronic dynamics in dense matter with a temporal resolution corresponding to their natural timescale, the attosecond ($10^{-18}$ s). When physicists used intense femtosecond laser pulses to ionize a rare gas (such as neon) they found that a frequency upshift occurred in the form of high-order harmonics at odd multiples of the original optical pulse frequency. Soon thereafter the conjecture of Farkas and Tóth [1] and of Harris et al [2] was experimentally confirmed [3, 4]. It states that if these monochromatic light waves of equally spaced frequencies are in phase, the interplay between constructive and destructive interference in their superposition would give rise to temporal beating and therefore to generation of a train of attosecond pulses. Further innovations in short pulse laser technology gave rise to generation of even single attosecond XUV bursts [5]–[7], which was promptly followed by an upsurge of extraordinary applications [8]–[10]. Unfortunately, the number of photons per unit time obtained by the atomic medium up-converter is low with the consequence of severely limiting the scope of applications of this attosecond pulse generation technique. This pertains in particular to the envisaged pump–probe measurements: the attosecond pulse is split into two, the first one triggering the system into motion or starting a reaction, and the second one probing it after a controlled delay. But this approach is not feasible with attosecond pulses from atomic harmonics because they are too weak. Apparently, it needs another nonlinear medium operating at higher laser intensities and exhibiting higher efficiency. The relativistic interaction of an intense laser pulse with overdense plasma constitutes a very promising approach towards this objective. The main advantage over the process of harmonics generation in rarefied gases is that the plasma medium does not exhibit an inherent limit on the highest laser intensity that can be used. The projected specifications of the laser system envisioned for the near future allow for focused intensities of $10^{21}$ W cm$^{-2}$ or even higher at a few hundred hertz repetition rates. The plasma medium can exploit these relativistic intensities and thus provide a novel source of intense attosecond pulses that will open the road to investigations with unparalleled temporal resolution for a host of new phenomena.
This prospect has rekindled interest in the old mechanism observed more than 20 years ago [11] in which a rich harmonics spectrum from the interaction of intense laser pulses with solid targets was produced. Meanwhile, the feasibility of generating a robust harmonics spectrum using tabletop short pulse (fs) laser systems delivering high intensities has been documented in a number of reports [12]–[14]. The need for another nonlinear medium that will take advantage of even higher laser intensities as they become available, has put this process of harmonics generation from solid targets in a different prospective. It is viewed now not simply as an efficient XUV source, but more as a promising method of generating a train or even single attosecond pulses with intensities orders of magnitude higher than those currently available. This has resulted in an avalanche of theoretical [15]–[23] as well as experimental [24]–[30] reports dealing with the appropriateness of the mechanism for this purpose. They address issues like origin of the harmonics generation, spectral properties and cutoff dependence on the laser intensity, divergence of the XUV beam, over all conversion efficiency, coherence and temporal characteristics. In this connection, perhaps the most relevant results are the theoretical predictions by Gordienko et al [16] and Baeva et al [21] in which the spectrum emanating from the interaction of intense laser pulses with a solid target possessing sharp density boundary exhibits a universal power-law dependence of the form $I_{\text{XUV}} \propto \omega^{-q}$ with $q \approx 2.5$–2.7. Moreover, its maximum frequency (cutoff) increases with the laser intensity $I_L$ according to $\omega_{\text{co}} \propto I_L^{3/2}$, but unlike the case of harmonics from an atomic medium there is no limitation on the maximum intensity that can be used (no saturation intensity). These predictions have been experimentally confirmed by Dromey et al [27, 28] who demonstrated that under certain conditions the harmonics spectrum extends beyond the 1 keV range ($\sim 1.2$ nm). This finding alone has an outreaching consequence because it underlines the advantages of the plasma medium and clearly classifies it as a superior nonlinear medium for the generation of intense attosecond pulses [19]. Another advance in our understanding of the generation mechanism is the delineation into low and high laser intensity $I_L$ regimes according to whether $I_L \leq I_{\text{rel}}$ or $I_L \geq I_{\text{rel}}$ where $I_{\text{rel}} \lambda^2 = 1.37 \times 10^{18} \text{ W \mu m}^2 \text{ cm}^{-2}$. As recent experimental results demonstrated, at low intensities resonances in the plasma medium excited by fast electrons play an important role and generation occurs via coherent wake emission (CWE) [25, 29, 31]. Thus the plasma frequency $\omega_p$ being the maximum frequency that can sustain these resonances constitutes a natural cutoff for this generation mechanism. This puts to rest the old issue about the plasma frequency $\omega_p$ being a general cutoff for the harmonics emission. At relativistic intensities ($I_L \gg I_{\text{rel}}$) the so called oscillating mirror model (OM) provides an intuitive macroscopic picture of the physical process [19, 32, 33]. According to this model the electrons in the vacuum–plasma interface execute oscillations around the immobile ions. The reflected pulse from the relativistically moving surface is Doppler shifted, thus giving rise to a broad harmonics spectrum. The efficiency of the latter mechanism is considerably higher than that of CWE so that it becomes dominant at high intensities.

2. Routes to single attosecond pulse

The most straightforward method of generating attosecond pulses is by slicing a part of the reflected spectrum by a bandpass filter that suppresses the fundamental and low lying harmonics [19]. If the driving pulse is a many-cycle laser pulse (consisting of several periods of the 2.63 fs period for a commonly used Ti:sapphire laser system), the plasma mirror executes accordingly also oscillations and the process is repetitive. This gives rise to a discrete spectrum
within the filtered part, which in the time domain corresponds to a train of attosecond pulses. If by some means, the number of oscillations of the plasma mirror is reduced to a single excursion, it generates a continuous spectrum. The spectral width of the filtered part determines the duration of the single attosecond pulse thus induced. In the case of the atomic medium, there are two approaches that have been successfully used to reduce the number of attosecond pulses produced to a single one. The first approach is the reduction of the number of cycles that the driving laser pulse consists of to a few cycles (2–3 cycles). The second approach is to use many-cycle pulses and incorporate a time varying switch or gate that allows harmonics emission only during a very short time interval. A possible switch is based on the dependence of the harmonics efficiency on the polarization state of the driving pulse. In both cases, since the driving pulse or the gate can be reduced to 2–3 periods only, the positioning of the carrier frequency field under the envelope of the pulse, and therefore the carrier-envelope phase (CEP) stabilization plays an important role [7, 34]. It is not surprising that both methods work in exactly the same way for the case of a plasma medium. As in the case of the atomic medium, due to the highly nonlinear character of the process, few-cycle laser pulses [19] as well as polarization gating of many-cycle laser pulses [22] have been shown theoretically to produce single attosecond pulses.

Several studies based on one-dimensional-particle-in-cell (1D-PIC) simulations predict that few-cycle, phase-stabilized, relativistically intense \((I_L \gg I_{rel})\) laser pulses are suitable for the generation of a single burst of XUV light, i.e. of a single attosecond pulse [17]–[20]. However, the laser systems with the required specifications are still under development, and more time is needed to make them fully operational [35]. Most of the high power (10–100 TW) laser systems currently in operation in several laboratories deliver pulses with a duration of \(\tau_L \approx 50\) fs. For these systems, the technique known for almost 10 years in connection with harmonics generation from atomic media—polarization gating [36]–[38]—appears to be apropos. In this technique, the laser pulse is appropriately manipulated so that the rapid switching between circular and linear polarizations within the same pulse occurs for a very short time interval, thus creating a gate that temporally confines the harmonics generation process. As reported in the pioneering work by Baeva et al [22], the same technique is in principle applicable to harmonics from solid targets. The aim of the present work is to study in detail the conditions under which the specific polarization gating technique used in gas harmonics can effectively be applied to surface harmonics. The study of the dependence of harmonics generation efficiency on the ellipticity of the laser pulse for both normal and oblique incidence allows us to estimate the parameters under which the gate would effectively confine the emission in only one attosecond pulse. The results presented in this paper are based on 1D-PIC simulations (section 5). We have also performed 3D-PIC simulations on polarization gating using the code ILLUMINATION [23]; they show similar results and will be the subject of future reports.

3. The oscillating mirror model

A number of aspects related to the harmonics generation from solids interacting with intense laser pulses can be understood in terms of the so called oscillating mirror model. It was proposed by Bulanov et al [32] and later formulated and developed in detail by Lichters et al [33]. More recently, this model has been refined and extended to yield new and important results on a microscopic scale that have greatly advanced our understanding of the process [16, 21].

The basic idea behind the oscillating mirror model is that the electrons at the plasma–vacuum interface execute forced oscillations near the edge of an immobile step-like...
Figure 1. Plasma surface motion (vertical axis represents the time and horizontal axis the space coordinate, both in arbitrary units) under the influence of linearly (a), circularly (b) and (c) gated pulses. In the case of linear polarization (a) surface oscillations (red color) are clearly seen. The generated train of attosecond pulses propagating with the speed of light are shown in yellow. Circular polarization (b) exhibits no oscillations and as a consequence no harmonics are generated. In the case of a polarization gated pulse (c) the surface oscillations are highly suppressed during the time of circular polarization and only a few of them survive. One clearly sees that only one attosecond pulse is generated. The simulation parameters are: $a_L = 10$ ($I_L = 100I_{rel} \approx 2.0 \times 10^{20}$ W cm$^{-2}$, $\lambda_L = 0.8$ $\mu$m), $\tau_L = 5$ cycles (15 fs), $n_e = 40n_{cr}$ and normal incidence.

For near-normal incidence, the oscillations are driven by the Lorentz force $F_p$ of the incident laser pulse. In the case of linear polarization of the incident pulse, this force varies as $F_p \sim a^2(t) \cdot [1 + \sin(2\omega_L \cdot t)]$, where $a^2(t) = I_L(t) \cdot \lambda^2_L/(1.37 \times 10^{18}$ W$\mu$m$^2$ cm$^{-2}$) is the normalized vector potential envelope. Charge separation and induced electrostatic fields give rise to a restoring force and thus to surface oscillations. Due to the relativistic Doppler shift, light reflected from such an oscillating mirror comprises a broad harmonic spectrum. Moreover, the harmonics are generated only during the short time when the electrons that the mirror consist of move towards the laser pulse, which results in their phase-locking and attosecond duration. In the case of the circularly polarized pulse the Lorentz force is of the form $F_p \sim a^2(t)$ and thus it exhibits no fast oscillations. The slowly-varying laser pressure following the envelope of the laser pulse pushes the electrons against the restoring force due to charge separation, creating only a smooth depression in the electron cloud. The absence of fast surface oscillations means also absence of harmonics emission. These basic assumptions of the OM are clearly supported by the 1D-PIC simulations shown in figure 1, where the motion of the surface under the influence of linearly and circularly polarized light has been calculated.

4. Polarization gating technique

Now as the basic features of the plasma–vacuum interface motion and the accompanying harmonics generation have been described, the idea of polarization gating becomes straightforward. When the polarization over the pulse duration rapidly evolves from circular to linear and back to circular then the harmonics will be generated only during the linear period, and the shorter it is—the fewer attosecond pulses will be generated. It is even possible to gate only one attosecond pulse (see section 5).
$\Delta \tau = L \left( \frac{1}{v_e} - \frac{1}{v_o} \right) e^{-L}$

Figure 2. A technique for generating a pulse with time-varying ellipticity. The first crystal plate (the optical axis is set to 45° with respect to the initial polarization) splits a linearly polarized pulse into two delayed pulses linearly polarized in two mutually perpendicular planes. The thickness of the plate is chosen in such a way as to dephase the two pulses proportionally to $(2n + 1)\pi/2$ $(n$ is a natural number) so that the plate serves as the multiple order quarter wavelength plate ($\Delta t = L(1/v_e - 1/v_o)$, where $L$ is the thickness of the plate, $v_e$ and $v_o$ are the velocities of extraordinary and ordinary components, respectively). The field after the first plate is linearly polarized at the beginning and at the end and has circular polarization in the middle. The second plate (the optical axis is set at 45° to both components) serves as a zero-order quarter wavelength plate and transforms linear polarization into circular and vice versa.

The polarization gating technique was first proposed by Corkum et al [36] along with a technique of using two pulses with slightly different frequencies to generate the polarization gate. Platonenko and Strelkov [37] proposed to use only linear optics to construct a gate, and this idea was experimentally realized by Tscherbakoff et al [38]. The shortest attosecond pulses from an atomic medium (130 as) were produced using this technique by Sansone et al [39]. Recently, coherent continuum XUV radiation was generated in gases using many-cycle laser pulses by means of the interferometric polarization gating (IPG) scheme [40, 41]. The polarization gating technique was also discussed for the surface harmonics [22]. In view of forthcoming experiments, we restrict ourselves to studying the experimentally most common technique based on two crystal plates (see figure 2) and we investigate the details associated with the application of this technique to the surface harmonics.

5. Results and discussion

We conduct our numerical studies using 1D-PIC simulations. It allows the simulation in planar geometry of the interaction of intense laser pulses with pre-ionized non-collisional plasma. The typical plasma density is 80 times overcritical ($n_e = 80n_{cr}$). The plasma slab width is $2\lambda_L$, and each plasma cell is initially occupied by 100 macro-particles of each kind (‘macro’-electrons and ‘macro’-ions). The laser pulse has a Gaussian envelope function and its duration is measured in units of the full width half maximum (FWHM) of the electric field envelope. For example, the term 2-cycle laser pulse corresponds to a $\tau_L = 5.3$ fs laser pulse for $\lambda_L = 0.8 \mu m$. The size of the simulation box is $7\lambda_L$, the time step is $T_L/2000$ (the spatial step is $\lambda_L/2000$), where $\lambda_L$ and $T_L$ are laser wavelength and period, respectively. In all the simulations presented in this work, the density gradient scale length at the plasma–vacuum interface was taken to be zero, i.e. the laser pulse interacts with a step-like density profile.

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5.1. Dependence of harmonics generation efficiency on ellipticity

The study of the behavior of harmonics generation efficiency as a function of ellipticity $\epsilon$ of the incident pulse allows us to define the gating time. We call gating time—the time interval when the efficiency of a certain range of harmonics lies above the value of 0.1 of its maximum. The ellipticity corresponding to this harmonic efficiency is the threshold ellipticity $\epsilon_0$.

As was already mentioned, the harmonics generation becomes less efficient as the amplitude of the linearly polarized part decreases with the growth of ellipticity. In order to determine the threshold ellipticity $\epsilon_0$ one has to calculate the harmonic efficiency (for a single harmonic or a range of harmonics) as a function of ellipticity. The efficiency within the spectral range between the $n_1$th and $n_2$th harmonics is given by:

$$\eta_{n_1,n_2} = \frac{\int_{n_1}^{n_2} |E_{\text{refl}}(n)|^2 dn}{\int_0^{\infty} |E_{\text{refl}}(n)|^2 dn}, \quad (1)$$

where $|E_{\text{refl}}(n)|^2$ is the reflected spectrum and $\int_0^{\infty} |E_{\text{refl}}(n)|^2 dn$ is approximately the incident pulse energy. Figure 3 shows the results of the PIC simulations for the efficiency as given by equation (1) as a function of ellipticity of the incident pulse in the range from the 10th to the 20th harmonics for $a_L = 10$ and in the range from the 20th to the 100th harmonics for $a_L = 20$. From figure 3 one can see that the harmonics lose 90% of efficiency near the value of threshold ellipticity $\epsilon_0 = 0.4$ for $a_L = 10$ and $\epsilon_0 = 0.2$ for $a_L = 20$, respectively. We performed several PIC simulations showing that the value of ellipticity at which the harmonic efficiency is reduced by 90% slightly changes with the parameters of the laser pulse, plasma density and the harmonics.
range, but we find the value of threshold ellipticity $\epsilon_0 = 0.4$ to be an adequate estimate for effective gating.

For the polarization gating scheme shown in figure 2, the evolution of ellipticity with time is given by:

$$\epsilon(t) = \exp \left( -\frac{4 \ln 2 \times |(t - \Delta)^2 - t^2|}{\tau_L^2} \right),$$

(2)

where $\Delta$ is the delay between two mutually perpendicular field components produced by the first plate (see figure 2). Given the value of the threshold ellipticity $\epsilon_0$, the width of the ellipticity curve (the gating time) is given by:

$$\delta_{gating} = \frac{|\ln(1 - \epsilon_0)|}{4 \ln 2} \cdot \frac{\tau_L^2}{\Delta}.$$  

(3)

For a threshold ellipticity value of 0.4 the formula (3) yields:

$$\delta_{gating} = \frac{0.2 \tau_L^2}{\Delta}.$$  

(4)

In order to keep the gating time constant (5 fs) when increasing the pulse duration, one has to increase the delay produced by the first plate according to (4) (see figure 2). Figure 4 also shows the amplitude of the electric field in the region of linear polarization (blue color). As one can see, the delay needed for a 5 fs gating time increases with increasing laser pulse duration, and the amplitude decreases dramatically. This is also depicted in figure 4 where the normalized field amplitude for the two perpendicular components is shown for three selected pulse durations. We estimate that the maximum reasonable pulse duration for polarization gating using two plates is about 50 fs. For longer pulses, there is at least a loss of one order of magnitude in the region of linear polarization and the energy waste makes this scheme inefficient. Such a limitation, however, can be overcome by using a different polarization gating scheme, for example, the one based on the double Michelson interferometer [40, 41].

5.2. Results of the simulations of the polarization gating

The results of the simulations are summarized in figure 5. The initial pulse duration is 7 cycles (19 fs) and the delay (15 fs) is chosen in a way to keep the gating time 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. The surface motion in this case is shown in figure 1(c). The wavelet analysis [42] depicted in figure 5 also shows that the use of higher-frequency filtering allows the generation of single attosecond pulse with better contrast by more effectively suppressing the satellites. As was mentioned above, the harmonics are phase-locked due to the mechanism of generation, and owing to the repetitiveness of the process they give rise to a train of attosecond pulses. When polarization gating is applied, one should be able to see its effect on the spectrum of the reflected light. If a single attosecond pulse is thus produced, the discrete spectrum should turn continuous. But even if few attosecond pulses are captured by the gate, a broadening of the individual harmonics should be visible. Figure 5 depicts this difference in the spectrum for linear polarization and polarization gating. One can clearly see the broadening of the individual harmonics.
Figure 4. Delay needed for a 5 fs gate as a function of incident pulse duration (red curve) and the amplitude in the linear region of the pulse for this delay (blue curve). For selected pulse durations, the amplitude of the two field components are shown along with the variation of ellipticity in the lower panel. Within the polarization gate one of them is reduced to a level that renders a value for the ellipticity below the threshold.

5.3. Dependence of harmonics generation efficiency on the angle of incidence

All the results described above are obtained for the case of normal incidence of the laser pulse. However in experiments for practical reasons, e.g. to avoid back reflection into the laser chain or to provide access to diagnostic instruments, the angle of incidence with respect to the target normal should differ from zero. The question arises whether polarization gating works as well for oblique incidence. It is well known that even circularly polarized light generates harmonics when incident obliquely [33] as there is a component of electric field parallel to the normal that drives surface oscillations. With the increase of the angle of incidence $\theta$, this part grows proportionally to $\sin \theta$. To see the effect of oblique incidence on the effectiveness of the polarization gating scheme, we have performed a series of 1D-PIC simulations for angles of incidence between 0° and 45°. The oblique incidence case was incorporated into the 1D code using a Lorentz transformation to a moving frame in which the light is normally incident [43]. The efficiency of harmonics generation as a function of both ellipticity and angle of incidence...
Figure 5. Results of PIC simulations with parameters: $a_L = 20$ ($I_L = 400 I_{rel} \approx 9 \times 10^{20}$ 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.
Figure 6. Harmonics generation efficiency as a function of both ellipticity and angle of incidence. Parameters of the simulations are the same as in figure 5. The incident field for $\epsilon = 0$ is p-polarized. Results for harmonics within the range from 10th to 20th (a) and from 20th to 50th (b) are presented. For both ranges, the threshold ellipticity $\epsilon_0$ for 10% harmonic efficiency as a function of angle of incidence is shown in the lower part.

for two harmonic ranges of practical interest is shown in figure 6. Two different tendencies of the harmonic efficiency are to be noted here: firstly, with the increase of the angle of incidence and for all the ellipticity values it increases by more than an order of magnitude (see also [44]) and, secondly, for large angles of incidence it becomes less sensitive to the ellipticity. Simulations made with different parameters of laser pulse and plasma show similar results, i.e. the curve of efficiency as a function of ellipticity becomes broader with increasing angle of incidence, indicating longer gating width. This trend is depicted in the lower part of figure 6, where the threshold ellipticity (the 10% level efficiency) is seen to increase as a function of the incident angle approximately linearly. It appears that the greater the angle of incidence the higher the threshold ellipticity and therefore, the less confined in time the gate is. Both harmonic ranges exhibit the same general behavior, but the higher harmonic range (20th–100th) appears to be slightly more sensitive to ellipticity variation. For 45° target irradiation, the 10% efficiency level is reached for $\epsilon_0 \approx 0.6$, and this makes target irradiation under 45° questionable for experimental realization of an adequately short gate. However, it is experimentally practicable to irradiate the target under 10°–15° in which case the results of the simulations show that 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...
Figure 7. Intensity of the single attosecond pulse (blue color, 20–100 harmonics) as well as the intensity of the incident pulse (red color) and the ellipticity (black color) for the simulation with the same parameters as in figure 5 but with the angle of incidence $\theta = 15^\circ$.

generate a gate with duration short enough to restrict the emission to practically a single cycle. This is confirmed by the results in figure 7, where the simulations with parameters as in figure 5, but with oblique incidence ($\theta = 15^\circ$), are shown.

6. Conclusions and outlook

We have studied the polarization gating technique applied to the surface harmonics, using 1D PIC simulations and the oscillating mirror model. This paper gives the estimates for the gating time and thus for the parameters of the experimental set-up needed for obtaining a 5 fs gate. We find that the polarization gating by means of two plates has a limitation in the incident pulse duration due to the large delays needed, which in turn can be overcome by a different scheme (for example using the double Michelson interferometer technique [40, 41]). We show that polarization gating is also feasible for oblique incidence of the laser pulse, at least for angles of incidence $\theta \leq 15^\circ$, which makes this scheme a candidate for experimental generation of intense single attosecond pulses using multi-cycle laser pulses.

In comparison with the gas harmonics, it appears that the method is more suitable for the case of surface harmonics since the shortcoming encountered with gas harmonics where the circular part induces unwanted ionization does not play a role in this case. In addition, the surface oscillations in the case $\theta > 0^\circ$ are driven not only by the light pressure force that oscillates at $2\omega$, but also by the normal to the surface component of the electric field that oscillates at $\omega$. Subsequently as the angle of incidence increases, a regime is reached where all harmonics (odd and even) are efficiently generated and the attosecond pulses in the resulting train appear on every cycle and not every half-cycle as in the case of gas harmonic (odd orders only). This is a factor that should be taken into account in determining the optimum angle of incidence since it has the advantage that twice as long gates can be used to isolate a single
as far as the sensitivity of the harmonic efficiency to the ellipticity in the two media is concerned, the atomic medium appears to be slightly more sensitive since for ellipticity $\epsilon_0 \approx 0.2$ the harmonic emission is practically suppressed in all orders [45]. In our analysis however, we have concentrated on the sensitivity of a range of harmonics and not of individual harmonics. To quantify the question of sensitivity, a more detailed study of the individual harmonics is necessary.

Up to now there have been no reports on temporal characterization of the harmonics which due to the nature of their generation are believed to have attosecond structure. A technique for temporal characterization of the harmonics emission from solid targets would be necessary to assess the effectiveness of polarization gating. The only other possibility available to us to judge the performance of the gate is the broadening of the spectrum, which however is an indication, but not a proof, of single attosecond pulse generation. The method of polarization gating is primarily intended for many-cycle high power laser systems currently available. These systems normally do not have the capability of controlling the CEP in the output pulse and therefore its value is random. The effect of the CEP in multi-cycle laser pulses using the gating technique to generate single attosecond pulses is expected to be similar as in few-cycles laser pulses without gating. For sufficiently narrow gates encompassing a single attosecond pulse, CEP fluctuations would result in random appearance of the attosecond pulse [40]. The capability of controlling the CEP would provide the means of optimizing the temporal position of the polarization gate with respect to the carrier wave, thus generating a single attosecond pulse.

There are a number of related issues that have to be investigated in more detail. A density gradient at the plasma–vacuum interface is expected to have a detrimental effect on the effectiveness of the polarization gating. However, to provide a quantitative answer a systematic study has to be performed. In general, an investigation should be contacted in which the optimum range of each of the key parameters (gate duration, angle of incidence, CEP and density gradient scale length) influencing the contrast of the generated attosecond pulse is determined. These issues will be addressed in a future study.

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