Double optical gating of high order harmonics from plasma surfaces

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Abstract
Laser driven high harmonic generation from relativistically oscillating plasma surfaces is a promising route to isolated attosecond pulses with high peak brightness. Here we investigate a double optical gating scheme to restrict the emission to only a single, intense, attosecond pulse even with a multi-cycle driving laser. This scheme, which uses a second harmonic field, combined with a pair of counter-rotating circularly polarized laser pulses, leads to more efficient attosecond pulse generation with improved temporal isolation when compared to a single colour polarization gating scheme.

1. Introduction
An attosecond scale light source is the first step towards attosecond scale science. Isolated attosecond bursts lead the way to probing dynamics within physical systems, such as the movements of electrons in an atom [1], giving insight into the inner workings of physical processes which can occur on time scales of the order of a few thousandths of a femtosecond (1 as = 10^{-18} s) [2]. Laser-driven high harmonic generation (HHG) mechanisms are a key source of attosecond scale radiation. HHG from gas targets is a well studied and documented area with extensive theoretical and experimental work conducted. They show great potential for a variety of applications due to their spatial coherence and short time scales [2]. Gas targets are the most prevalent source currently, but there exist limitations in the maximum intensity that can be used [3]. If the intensity of the incident laser is too high, ground state depletion occurs during the rising edge of the laser pulse. As a result, all neutral atoms are ionised before the peak of the pulse reaches the target and the free electron density, therefore, increases to the point where phase matching in the medium becomes extremely difficult. This results in low flux (energy in a single attosecond pulse) for HHG from gases, which makes experiments that use attosecond pulses for both the pump and probe difficult to conduct. Due to this, an attosecond pulse would typically be used to pump and then a laser field is used to probe as it needs to overcome the ionization potential. Since HHG from plasma surfaces can support higher intensity interactions, with comparable efficiencies to HHG from gas targets, attosecond pulses generated can have higher energies [4]. These sources have the potential to provide both a sufficiently bright pump and probe [5], however, the high power laser systems required for these experiments are typically multicycle, thus a mechanism for generating intense, isolated attosecond pulses is required.

A number of other techniques that have been investigated for gating these pulses include intensity gating and the attosecond lighthouse schemes [6, 7]. This work focusses on a polarization gating scheme (which will be discussed in more detail in section 1.2). This will then be combined with two-colour fields (which will be discussed in section 1.3) with the aim to improve the temporal isolation of extreme ultraviolet (XUV) pulses as well as enhancing their intensity.
1.1. High harmonic generation

HHG can occur through interactions between a high intensity laser and an overdense plasma surface. This process can be explained through a mechanism known as the relativistic oscillating mirror (ROM) model [8, 9]. This description is needed when the velocity of the electrons becomes relativistic. For the typical densities required for common laser frequencies, an initially solid density surface is used. Following ionization during the rising edge of the high intensity laser pulse, the high density plasma that is formed from the solid target almost completely reflects the incident pulse while strongly modulating its waveform so that it contains higher frequency components. The reflecting surface can be modelled as an oscillating mirror, the movement of which is driven by the laser pulse itself. Like HHG from gas targets, the reflected laser provides a coherent source of attosecond radiation, emitted in a train of pulses. With solid plasma surfaces however, the plasma medium can support much higher intensity interactions. This allows very high energy laser pulses to be used in a compact focussing geometry which, in turn, leads to the generation of very bright attosecond pulses.

For laser systems that have very short pulse durations, it has been shown that at oblique incidence, isolated attosecond pulses can be achieved directly [10]. In a paper by Böhle et al., a 3.5 fs, 1 TW peak power system was used. This is an important milestone, but at 1 TW, this is a relatively low peak power, extending this to a higher power system (10 TW and higher) is a major challenge. Facilities with the ability to have such short pulse durations and high energies are not easily accessible. Hence, there is still a need to develop temporal gating schemes that can isolate individual pulses generated from longer driving pulses, thus greatly expanding the range of laser systems that could achieve isolated attosecond pulses.

A paper published by Heissler et al. in 2015 [11] demonstrated the generation of multi-μJ high harmonic radiation from solid targets in a single shot. From previous studies by Tsakaris et al., this scales well to higher intensity driving pulses [12]. However, the main drawback to using a solid plasma surface target is its low efficiency in conversion from incident laser energy to XUV pulses. There is significant interest in methods to improve this efficiency including recent work exploring the use of two-colour fields (a laser pulse that is coincident on the target with another pulse with twice the frequency) [4, 13, 14].

For both gas targets and plasma surfaces, two-colour schemes are known to improve the efficiency of the XUV pulse generation process, but here only plasma surface effects will be discussed as they are most relevant to this work [14–16]. The intensity of the attosecond XUV pulses generated depends strongly on the steepness of the driving field [14]. By adding a frequency doubled component of the fundamental, it is possible to increase the steepness of the electric field at desired points, such that the effective interaction frequency is transiently higher at certain times in the incident waveform. For plasma surfaces, high frequency interactions are generally more efficient due to a match between the intensity and the electron density [14]. The intensity of any particular attosecond pulse in a train of pulses depends on the sub-cycle dynamics of the contributing electrons, which can be more favourable when driven by these two-colour field waveforms [17, 18].

Another key advantage of two-colour fields is that the resulting asymmetric waveforms can restrict the number of pulses that are generated each laser cycle thus relaxing the conditions to achieve isolated pulses. This is a concept that has been previously explored for gas harmonics [14, 19, 20] and will be discussed in more detail in section 1.3.

1.2. Polarization gating

Polarization gating is a scheme which can be used to generate isolated attosecond pulses [21, 22]. This scheme works by exploiting the ellipticity dependence of the XUV pulse generation mechanism, an idea that was originally developed for HHG from gases from the result that high harmonic emission is suppressed when circular polarization is used, as shown by Budil et al. [23].

The relationship between the efficiency of XUV pulse conversion from laser energy, and the ellipticity of the driving laser field as it varies between linear and circular, for HHG from plasma surfaces, follows a similar trend as seen in work conducted by Rykovanov et al. [24]. As the ellipticity is varied from circular to linear, the efficiency of conversion to XUV pulses changes as the linearly polarized amplitude varies. At normal incidence, a circular pulse results in no generation of XUV pulses (see figure 1) whereas when the pulse has a linear polarization the XUV pulse conversion is at a maximum. By taking advantage of this, the system can be exploited to ensure that attosecond pulses are only emitted at a specific temporal window of the laser pulse.

In 2015, Yeung et al. presented the first steps towards experimentally gating pulses with solid target harmonics using a non-collinear scheme [25]. This mechanism becomes possible by constructing a pulse from two counter-rotating pulses. They interfere with each other resulting in a linear section at a centre point. By varying the delay between the two circular pulses, the duration of the linear section also varies and finding the optimum gate width is extremely important.
Figure 1. A summary of the selection rules defining how the reflected waveform components are dependent on the incident pulse polarization direction and angle of incidence. (a) shows an oblique incidence, linearly polarized laser pulse, (b) shows an oblique incidence, circularly polarized laser pulse, (c) shows a normal incidence, linearly polarized laser pulse and (d) shows a normal incidence, circularly polarized laser pulse. A full description of these selection rules is discussed in a 1996 paper by Lichters et al [9].

The polarization gate width, $\delta t_G$, for two counter-rotating elliptically polarized pulses with a delay $T_d$ and an ellipticity $\varepsilon$ can be expressed as follows [19]

$$\delta t_G \simeq \varepsilon \frac{\xi_{th} \pi^2}{\ln(2) T_d},$$

where $\xi_{th}$ is the threshold ellipticity and $\tau_p$ is the laser duration at FWHM. Here we define an ellipticity of 1 as a pulse with circular polarization and an ellipticity of 0 as linear.

The threshold ellipticity $\xi_{th}$ defines a margin in which a pulse can be considered to be isolated, where the intensity of attosecond pulses generated outside the linear gate is 10 times lower than the isolated attosecond pulse within the linear gate. This value depends greatly on the peak intensity of the incident pulse as well as the harmonic range to be investigated [24]. From equation (1), it is clear that for a smaller ellipticity $\varepsilon$, a longer laser pulse can be used. However, $\varepsilon$ must be large enough that the emission of attosecond pulses is sufficiently suppressed to ensure that attosecond bursts are not generated outside of the linearly polarized region [19].

When working with equation (1), for a given laser pulse duration, achieving a suitably short polarization gate, $\delta t_G$, requires appropriate tuning of $T_d$. As apparent from equation (1), increasing the time delay between the elliptical pulses, will result in a shorter gate. However, this also means the intensity in the overlap region reduces which will be detrimental to the brightness of the resulting attosecond pulse.

One main difficulty with combining oblique incidence experimental set-ups with polarization gating techniques is that circular pulses still generate XUV pulses. Figure 1 shows a summary of the generation of XUV pulses for four different cases. In order to take advantage of the techniques discussed, a circularly polarized pulse at normal incidence must be used, which in turn results in more challenges. The $v \times B$ component of the Lorentz force is the driver of the motion perpendicular to the surface for normal incidence interactions. As this drives the electron motion in the laser direction at twice the laser frequency, there are two emission events per laser cycle as opposed to one, as is the case for oblique incidence.
interactions. This restricts the range of values that $\delta t_c$ must take to isolate a single pulse hence limiting the potential intensity that can be achieved with this gating technique when using a single colour driver.

1.3. Double optical gating

As discussed in section 1.1, it has been shown that combining the fundamental frequency with a second harmonic increases the efficiency of the generation process [4, 14]. This observed enhancement of efficiency, provides insight into the microscopic processes that govern laser–plasma interactions, however its application in this field will not be discussed in great detail in this paper, further detail can be found in [4].

In section 1.2, methods for isolating single attosecond bursts have been discussed. Adding the second harmonic (two-colour scheme) not only increases the efficiency of conversion to XUV pulses, but also breaks the symmetry of the electric field. For HHG from gas targets, this results in the gating of single attosecond pulses [20]. For solid-plasma targets at normal incidence, the same effect is expected with the gating of XUV pulse emission to once per cycle.

In this work, the feasibility of double optical gating (DOG), a method that combines two-colour schemes with polarization gating, is investigated for plasma–surface HHG sources. If successful, it will be possible to generate more intense, isolated attosecond bursts than compared to single colour schemes.

2. Simulation set-up

The numerical studies reported here were performed using the one dimensional version of the readily available, parallelized, second order relativistic particle-in-cell (PIC) code EPOCH [26]. In the simulations performed for this work a Gaussian laser pulse was directed at an over-dense plasma target at normal incidence.

Two separate sets of simulations were performed using different laser pulses in order to allow for an investigation into longer pulse durations as well as an increased peak intensity. The first set of simulations investigated a relatively short 10 fs (FWHM) pulse, modelled on a home system located at Queen’s University Belfast, which could potentially be pumped to reach this simulated intensity. While the parameters of the second set of simulations were chosen to emulate a higher intensity, 17 fs (FWHM) laser, such as the system at ELI-Alps [27, 28], or the JETI200 system at the Helmholtz Institute Jena [29]. By choosing two distinct laser systems, the feasibility of this scheme can be tested for both a large scale facility and a small table-top system with differing powers and pulse durations.

All simulations were conducted with 1000 electrons per cell and 1000 cells per micron. The simulations for a 10 fs pulse duration used a wavelength of 0.82 $\mu$m and a peak intensity of $1 \times 10^{20}$ W cm$^{-2}$ ($a_0 \approx 7$). The effect of a two-colour field was investigated by frequency doubling 10% of the peak intensity. The remaining energy in the fundamental laser pulse was then split evenly to form two circularly polarized pulses with opposite handedness. In all simulations we assume the frequency doubling and beam splitting processes conserve all energy, such that the second harmonic has exactly 10% of the peak intensity and the two circularly polarized polarization gating pulses have exactly half of the remaining 90% (45% each, of the peak intensity of the pulse).

The parameters used for the longer pulse length investigation were a pulse length of 17 fs at a wavelength of 0.80 $\mu$m with an intensity of $8.55 \times 10^{20}$ W cm$^{-2}$ ($a_0 \approx 20$), of which 20% was converted to the second harmonic. Similarly here, we assume the second harmonic has exactly 20% of the peak intensity and the circularly polarized polarization gating pulses each have 40% of the peak intensity. Figure 2 shows how a polarization gating pulse could be generated experimentally using quartz plates.

The intensity of the second harmonic has a large impact on the efficiency of conversion of laser energy to XUV pulses [14]. For both intensity regimes, scans were conducted to find the optimum values that would provide the best conversion efficiency possible and thus increase the intensity of the attosecond bursts.

The target for these simulations was a fully pre-ionized plasma of SiO$_2$, with an electron density $n_e = 400n_c$, where $n_c$ is the critical density of the plasma for the incident laser wavelength. The target thickness for both pulses was 2 $\mu$m, with a scale length, $L_s$ of $\lambda/10$. A series of parameter scans were conducted to investigate the effects that different variables have on the attosecond pulse structure and intensity. In order to determine the appropriate threshold ellipticity $\xi_{th}$ as defined in equation (1), an ellipticity scan was conducted and the efficiency of XUV pulse generation was reviewed. The threshold ellipticity, $\xi_{th}$ was found to be 0.4 for both pulse durations, values which are broadly consistent with that observed in other work for similar parameter ranges [19, 24].
Figure 2. Potential practical method of creating a DOG waveform. The laser pulse is incident on a quartz plate with its polarization direction at 45° to the optical axis. This plate divides the beam into horizontally and vertically polarized components with a time $T_d$ between the centre of the pulses. They are not spatially separated, but are represented as such here for ease of viewing. The beam is then passed through a quarter wave plate, where the vertically and linearly polarized components emerge circularly polarized with opposite handedness. In the region where overlap occurs the pulse is linearly polarized. The length for which it is linearly polarized can be controlled by varying the thickness of quartz plate, which in turn varies $T_d$. This is then combined with the frequency doubled pulse at a controlled relative phase [4], before being incident on a target.

3. Discussion of results

3.1. Polarization gating and double optical gating using a 10 fs pulse

In order to analyse the data, the reflected waveform was first frequency filtered using a step filter, where harmonics below the 20th are removed. This removes low harmonic orders that can dominate the reflected field, allowing close inspection of the attosecond pulses being generated. Figure 3 shows the attosecond pulses obtained from simulations using the techniques discussed above, with the parameters as defined in the previous section.

In order to investigate the extent of the impact that the delay has on the generation of attosecond pulses, a scan of the delay between the two circularly polarized components was conducted. As expected, the production of attosecond bursts depends heavily on the delay between the circularly polarized components. This relationship can be seen clearly in figure 3(a) where a delay of 0 optical cycles defines a pulse which is fully linearly polarized due to the complete overlap of the circularly polarized components. This gives rise to the expected train of attosecond bursts appearing twice every laser cycle (see figure 1).

As the delay increases the number of attosecond bursts that are generated decreases, moving towards an isolated pulse. However, as expected, the peak intensity of the attosecond bursts also decreases. As for the single colour polarization gating case, a delay scan was conducted for the two-colour pulse (see figure 3(b)). As expected, as the delay increases, the gate becomes narrower thus limiting the region in which pulses can be generated. It is clear from figure 3(b), that for the two-colour scheme, every second attosecond burst is suppressed, as the attosecond bursts are now produced once per cycle instead of twice per cycle, thus improving the isolation. Depicted in white is the gate width for each of the delays calculated using equation (1).

To further compare the outcome of the DOG scheme to the polarization gating scheme, figure 4 presents a direct comparison between the attosecond bursts produced when using the single colour, polarization gating scheme and the two-colour, DOG scheme both taken at a delay of 2 optical cycles. A lineout of the data for a delay of 4 optical cycles is also shown. The equivalent data sets in figures 3(a) and (b) are marked with a dashed line of colour corresponding to the data set in figure 4. In order to allow for direct comparison of the efficiency of conversion to XUV pulses between the two schemes, the data presented in figure 4 is normalized to the maximum intensity of the attosecond burst produced by the DOG scheme.

Figure 4 shows more than a two-fold increase in the relative strength of the attosecond burst when the two-colour gating scheme is used in comparison to only the polarization gating scheme at a delay of 2 optical cycles, thus showing that the DOG technique improves on the efficiency of the polarization gating technique while also isolating and enhancing a single attosecond burst. This enhanced burst has a peak intensity that is stronger than all bursts generated using a single colour pulse, which at a delay of 0 optical cycles, is a fully linear system with no gating present. The pulse generated for the single colour scheme at a delay of 4 optical cycles is also shown. Although this pulse is isolated, its maximum intensity is less than 10% of the maximum intensity of the isolated pulse generated from the two-colour scheme at a delay of 2 optical cycles.

This ability of the two-colour gating scheme to isolate attosecond pulses and enhance their intensity is highly dependent on the relative phase between the second harmonic and the circularly polarized
Figure 3. Colour maps showing the results of PIC simulations using the polarization gating technique (single colour) and the DOG technique (two-colour) as sub-figures (a) and (b) respectively. The parameters of the incident pulse were $\lambda = 0.82 \, \mu m$, the pulse length was 10 fs (FWHM), with initial intensity $1 \times 10^{20} \, W \, cm^{-2}$, in the two-colour image 10% of which had been frequency doubled. The target used was a fully pre-ionized SiO$_2$ plasma, with $n_e = 400 \, n_c$ and with a scale length of $\lambda/10$. The horizontal axis displays the time (in number of laser cycles). The time delay between the circularly polarized laser pulses is varied along the vertical axis, from a delay of 0 laser cycles to a delay of 5 laser cycles in steps of 1. The dashed coloured lines correspond to data sets presented in figure 4.

components of the pulse. Experimentally, precise control of the relative phase difference can be achieved by using, for example, a simple glass plate that exploits the different refractive indices at each frequency [4].

To investigate the dependency of both the isolation of the bursts and their relative intensity on the phase of the second harmonic pulse, a scan was conducted where the relative phase of the second harmonic pulse to the circularly polarized pulses was varied from 0 to $2\pi$ in steps of $\pi/4$. The enhancement and suppression of alternate attosecond bursts can be seen in figure 5. As the relative phase difference is increased, alternate half cycles are enhanced and suppressed. While this describes the global trend, there are some pulses which do not follow this. The exact cause is not fully understood but deviations from the simple ROM description of attosecond pulse generation has been observed previously in simulations and shown to be sensitive to the exact plasma conditions at the time of emission [17]. The propagation of the
Figure 4. Lineouts taken from figures 3(a) and (b). In cyan and magenta, are the attosecond bursts generated using the single colour, polarization gating scheme with a delay of 2 optical cycles and 4 optical cycles between the circularly polarized pulses, respectively. In orange, the attosecond burst generated using the two-colour gating scheme with a delay of 2 optical cycles between the circularly polarized pulses where the relative phase between the circularly polarized pulses and the second harmonic is $\pi/4$ radians.

Figure 5. Results of PIC simulations varying the relative phase between fundamental ($\lambda = 0.82 \mu m$) and second harmonic beams. A pulse with a duration of 10 fs (FWHM) and is incident on a fully pre-ionized SiO$_2$ plasma with $n_e = 400n_c$, and with a scale length of $\lambda/10$. The horizontal axis displays the time (in number of laser cycles). The relative phase between the fundamental and second harmonic pulses is varied along the vertical axis, from 0 to $2\pi$ in steps of $\pi/4$. The initial intensity of the fundamental beam was $1 \times 10^{20} \text{ W cm}^{-2}$, before 10% of the beam was converted to the second harmonic.

two-colour field through the short pre-plasma simulated here may also affect the optimal phase for a particular attosecond pulses emission.

3.2. Investigation with a longer pulse length
In section 3.1, it was shown that for a pulse length of 10 fs, the DOG scheme offers great advantages over the single colour scheme for isolating a single XUV burst, from a train of pulses generated through HHG from plasma surfaces. Implementing the scheme for longer pulse durations would make it applicable for higher intensity laser systems (PW scale power). For longer pulse durations, a longer delay between the two circularly polarized pulses is required to gate the interaction to a reasonable gate width. Here, we have
Figure 6. Colour maps showing how the inclusion of the second harmonic pulse affects the intensity and frequency of attosecond burst generation for a 17 fs pulse duration laser system. The parameters of the incident pulse were $\lambda = 0.80 \mu m$ with initial intensity of $a_0 = 20 (\approx 8.55 \times 10^{20} \text{ W cm}^{-2})$ of which 20% was frequency doubled, pulse duration 17 fs (FWHM). The target used was a fully pre-ionized SiO$_2$ plasma, with $n_e = 400 n_c$ and with a scale length of $\lambda/10$. The horizontal axis displays the time (in number of laser cycles). The time delay between the circularly polarized laser pulses is varied along the vertical axis, from a delay of 0 laser cycles to a delay of 6 laser cycles in steps of 1. The dashed coloured lines correspond to data sets presented in figure 7.

Figure 6 shows the delay scans conducted for this 17 fs pulse duration system. As for the 10 fs case, the gate width as calculated using equation (1) is shown in white and the dashed coloured lines correspond to

simulated a 17 fs (FWHM) pulse duration to investigate whether this scheme could be used effectively for a longer pulse duration which would have an experimentally reasonable gate width. This system has been modelled with a peak intensity of $8.55 \times 10^{20} \text{ W cm}^{-2}$ ($a_0 \approx 20$).

In this simulation, the generalized double optical gating method was implemented [19]. For the longer pulse length of this laser system, it was found that this method had a beneficial effect when trying to isolate a single attosecond burst. The only difference with this method is that rather than using circularly polarised pulses, an ellipticity of $\epsilon = 0.5$ is used instead. As can be seen from equation (1), this results in a shorter linear gate. Experimentally this can be implemented by transmission through Brewster windows set to reflect away some light that is polarized in the same direction as the linear gate [19].
Figure 7. Lineouts showing the attosecond pulse trains emitted for three different simulation parameters. In cyan, is the data for the single colour polarization gating scheme at a delay of 2 optical cycles. In orange and magenta, is the data for the two-colour gating scheme at a delay of 2 optical cycles and 4 optical cycles respectively.

As stated previously, the evolving plasma conditions can influence the precise attosecond pulse intensity at a particular cycle [17] and we again see evidence of this here. For example, an interesting feature of figure 6(b) is the isolated pulse for the 4 optical cycle delay with the two-colour field. This pulse, appears quite broad in time due to the appearance of a rising edge. Although this feature is present, the rising edge is still relatively steep (see figure 7), the FWHM of the pulse is comparable to other pulses that do not have this unique shape, this feature is likely due to the individual bunch dynamics for this particular pulse.

It is clear that by implementing the techniques previously discussed, isolated attosecond pulses are also possible at these longer pulse durations. As the delay between the driving pulse and the second colour is varied the number of pulses varies as well as the peak intensity. Additionally, as seen with the shorter, 10 fs pulse duration, the intensity of the isolated burst generated from the two-colour scheme, has a stronger peak intensity than the strongest single colour pulse, even when no gating is applied.

Figure 7 shows lineouts showing the attosecond burst emission for the single colour case and for the two-colour case at two different delays. By firstly comparing the single colour case to the two-colour case with a delay of 2 optical cycles, it is clear that the intensity increases greatly, and as predicted, there are now attosecond bursts emitted only once per cycle. By comparing the two-colour case lineouts, it can be seen that although for a delay of 4 optical cycles the intensity is lower, the pulse is more clearly isolated than in the 2 optical cycle delay case. This lower intensity is however comparable to the maximum intensity under the single colour set-up meaning that overall there has been no decrease in efficiency of XUV pulse conversion by implementing these extra steps and taking advantage of the polarization gating process.

Although two very distinct delay settings have been chosen here, this is purely for illustrative purposes. As discussed in section 1.2, the cut off as defined by the gate width scaling equation (equation (1)) is 10% thus in certain cases, isolation of the pulse has occurred when comparing the intensity of the main pulse to the additional surrounding pulses.

We estimate that the conversion efficiency into an isolated pulse for the single colour, 10 fs case is $3.47 \times 10^{-5}$ and the two-colour, 10 fs case is $4.66 \times 10^{-4}$. The conversion efficiency for the two-colour, 17 fs case is $2.48 \times 10^{-4}$. These values agree with previous experimental values for single colour [11, 30] and two-colour schemes [4]. For the 17 fs single colour case, no isolated pulse could be observed above the numerical noise level for any case. By combining the second harmonic with the fundamental frequency, there is an order of magnitude increase in the efficiency in the conversion from laser energy to XUV pulse. By using a two-colour scheme, not only is the efficiency of conversion from laser energy to XUV pulses
improved, the number of emitted attosecond pulses reduces from twice per cycle to once per cycle at normal incidence which permits the use of shorter delays between the circular pulses further improving the driving intensity in the gate region.

4. Conclusion

An investigation into isolating single attosecond pulses using a combination of two-colour HHG from solid plasma surfaces and polarization gating at normal incidence was conducted using the 1D PIC code EPOCH. Our results show that the addition of a second harmonic driving pulse softens the gating requirements by breaking the interaction symmetry and restricts the attosecond pulse emission to once per laser cycle rather than twice. Furthermore, consistent with previous work with two-colour fields at oblique incidence, we observe a clear increase in the generated attosecond pulse intensity.

By implementing the techniques discussed, generating high harmonics from solid plasma targets provides an accessible method of producing isolated attosecond bursts on increasingly widely available high power, short pulse laser systems.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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