Attosecond pulse generation by applying a weak static electric field to a few-cycle pulse

Guangjiu Zhao$^{1,4}$, Xiaolv Guo$^{1,2}$, Tianjiao Shao$^3$ and Kang Xue$^2$

$^1$ State Key Laboratory of Molecular Reaction Dynamics, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, People’s Republic of China
$^2$ School of Physics, Northeast Normal University, Changchun 130024, People’s Republic of China
$^3$ School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, People’s Republic of China

E-mail: gjzhao@dicp.ac.cn

New Journal of Physics 13 (2011) 093035 (12pp)
Received 1 November 2010
Published 22 September 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/9/093035

Abstract. The high-order harmonic generation process under the combination of a few-cycle pulse and a static electric field was investigated in this work. A linear harmonic cutoff extension was observed with its dependence on the relative strength ratio of the static electric field with respect to a single-color, 2.5 optical cycle (oc), 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse as the fundamental driving field. Exploiting the relative strength ratio tuning from 0 to 0.1, a linear continuum width extending on the XUV spectrum up to 191 eV, which supports the creation of an 18 attosecond isolated attosecond pulse, was generated. Moreover, classical trajectory calculation and time–frequency analyses for explaining the mechanism are also presented.

$^4$ Author to whom any correspondence should be addressed.
1. Introduction

The creation of attosecond pulse trains or isolated attosecond pulses (IAP) is a hot topic, since their application opens up a novel avenue for time-resolved studies with unprecedented resolution [1–10]. Different techniques have been demonstrated for the generation of IAP in the extreme ultraviolet (XUV) such as Fourier synthesis of Raman sidebands, high-order harmonics and so on [11–17]. Since early experiments, high-order harmonic generation (HHG) has been suggested to be a powerful and promising approach to creating an attosecond light source. The HHG spectrum is characterized by a rapid drop in intensity at low orders, followed by a broad plateau on which a spread of harmonics have the same intensity and ended by a sharp cutoff with energy given by $\hbar \omega_{\text{max}} = I_p + 3.17U_p$, where $I_p$ is the ionization potential of the target atom and $U_p \propto I \lambda^2$ is the electron ponderomotive energy in the laser field, respectively. The HHG process is usually described by the well-known classical model, the three-step model (TSM) [18–21]. According to this model, firstly, the electrons tunnel through the barrier composed of strong electric field and the Coulomb potential; secondly, freed electrons will be accelerated by the strong electric field and get a large amount of kinetic energy; thirdly, the electrons are pulled back to recombine with their parent ions and emit harmonic photons with frequency equal to $\hbar \omega_{\text{max}} = I_p + 3.17E_k$. HHG from a few-cycle driving pulse [22] and the temporal confinement of HHG using polarization gating [23–36] are the two techniques currently available for creating IAP. According to the latter scheme, the fundamental driving field is shaped by employing a second pulse, and thus the IAP creation receives contributions from high-order harmonics from one sub-cycle of driving field. Recently, Feng et al experimentally demonstrated creation of IAP by utilizing 20–28 fs driving field [33].

In this paper, we report on IAP creation from the HHG process under a few-cycle pulse as the fundamental driving field with the modulation of a static electric field. Our idea is triggered by a series of previous works on the influence of a static electric field on HHG, where a weak static electric field plays a role in modulation [37–43]. Milošević and coworkers have systematically investigated the intensity dependence of the plateau in laser-assisted x-ray–atom scattering both with and without the presence of a static electric field [23, 25, 39, 40]. Borca et al [42] have demonstrated analytically and numerically two static-electric-field-induced effects: elliptic dichroism and elliptical polarization of harmonics produced by a linearly polarized driving field. Đžak and Milošević [43] developed a formulation of the modified saddle-point method; using this method, they found a combination of a strong laser
field and a parallel static electric field exhibiting a multiplateau structure with much longer plateaus than in the case of the presence of a linearly polarized laser field alone.

In this paper, we report on HHG from a combination of a single-color 2.5 optical cycle (oc), 800 nm few-cycle pulse as the fundamental driving field and a static electric field. The main theoretical results showed significant linear harmonic continuum extension by increasing the relative strength ratio of the static electric field with respect to the peak intensity of a few-cycle pulse. The concept of harmonic continuum is defined as the energy difference between the largest and the second-largest harmonic cutoffs (HCOs) on HHG spectra. Then, Fourier transformation is carried out to simulate the creation of IAP by synthesizing harmonics from continuum on HHG spectra with intensity \( I(t) = |\sum_{N} A_q \exp[-i w_q t + i \phi(w_q)]|^2 \), where \( A_q \) is the phase width and \( \phi_q \) is the phase of the \( q \)th harmonic. According to this equation, the duration of the synthesized IAP is allowed to be shortened to \( T_0/2N \) under the assumption that all the harmonics have the same phase; in other words, continuum with a broad spectral width and a flat profile leads to the creation of intense and short IAP. Thus, we superpose a static electric field onto a few-cycle pulse in order to obtain a continuum satisfying the above quality supporting the prerequisite for the creation of intense and short IAP.

This paper is organized as follows. In section 2, the field amplitude \( E^2 \) as well as the ionization probability of the helium gas target from the combination of a single-color, 800 nm few-cycle pulse as the driving field and a static electric field is given. The results indicate the expectation of broad continuum on HHG spectra by superposing a static electric field on a few-cycle pulse. In section 3, through a quasi-classical picture of HHG, an expression for the continuum bandwidth on HHG spectra as a function of the driving field intensity, wavelength and relative strength ratio is given. In section 4, by performing our time-dependent wave packet code, the dependence of HHG and IAP creation on the relative strength ratio of a static electric field is shown. In section 5, we carry out classical trajectory calculation and time–frequency analyses to shed light on the static electric field modulation scheme. Section 6 presents the conclusion. In addition, the time unit in this paper is the optical cycle of an 800 nm driving field, while the harmonic unit is the integral time of the fundamental few-cycle pulse frequency.

2. Effect of the static electric field on the driving pulse field

In our simulation, the laser parametric source is a 2.5 oc, 800 nm, \( 1.4 \times 10^{15} \text{ W cm}^{-2} \) few-cycle pulse, which is usually generated by an amplified Ti:sapphire laser system in the laboratory. The pulse duration 2.5 oc is equal to 6.667 fs, which corresponds to two and a half periods of the 800 nm laser field. A weak static electric field is employed to modulate the driving field with its maximum intensity of \( 1.4 \times 10^{14} \text{ W cm}^{-2} \). Although achieving a static electric field with such a high intensity is difficult with current technology, a low-frequency field can be a good alternative in practice.

The expression for the combination field can be expressed as

\[
E = E_1 \cos^2(\pi/2 \times t/\tau) \cos(wt) + k \times E_1, \quad |t| \leq \tau, \quad (1)
\]

where \( E_1 \) is the peak strength of the few-cycle pulse, \( \tau \) is the full-width at half-maximum (FWHM) of the few-cycle pulse, \( w \) is the frequency of an 800 nm few-cycle pulse and \( k \) is the relative strength ratio of a static electric field with respect to the peak strength of the few-cycle pulse. We choose the few-cycle pulse shape of \( f(t) = \cos^2(\pi/2 \times t/\tau) \); thus the few-cycle pulse in our simulation has finite duration and satisfies the physical prerequisite
Figure 1. (a) Field amplitude ($E^2$) of a 2.5 oc, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ pulse (green solid line), a combination of a 2.5 oc, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ field and a static electric field with $k = 0.05$ (blue dashed dotted line) and $k = 0.10$ (red dashed line), respectively. Insets show the field amplitude ($E^2$) of a 4 fs, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ pulse. (b) The ADK ionization probability of a helium atom calculated for the three driving fields shown in (a).

$$\int_0^\tau E(t') \, dt' = 0$$ [44–46]. When $k = 0$, the corresponding case is for a few-cycle pulse alone. In our simulation, the gas target used is a helium atom; a soft-core potential is used with the formula $V(x) = -1/\sqrt{a + x^2}$. In order to match the experimental value of 24.6 eV for the ionization potential $I_p$ of helium, the parameter $a = 0.484$ is chosen.

Figure 1(a) shows a comparison between $E^2$ of a 2.5 oc, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ few-cycle pulse alone and a combination of a few-cycle pulse and a weak static electric field with $k = 0.05$ and $k = 0.1$. The HHG process has the period of half the optical cycle of the driving pulse; the difference between the electric field strengths of a neighboring half-cycle induces the energy difference $\text{HCO}$ generated by each half-cycle. For this reason, we compare the intensity ratio $E^2_0/E^2_1$, which is the peak intensity of the combination field versus that of the side peak. The intensity ratio $E^2_0/E^2_1$ of the above three cases is 1.223, 1.508 and 1.846, respectively, whereas the insets of figure 1(a) show an intensity ratio of 1.776 from the 4 fs, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ few-cycle pulse alone. A noticeable enhancement of the intensity ratio $E^2_0/E^2_1$ from 1.223 to 1.846 was observed by increasing the relative strength ratio $k$ from 0 to 0.10. It is worth noting that when the relative strength ratio increases up to 0.1, the intensity ratio of the driving field even surpass the case of a 4 fs, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ few-cycle pulse alone, which is difficult to be achieve in current laboratory conditions.

In order to investigate the behavior of the ionization probability dependence on the relative strength ratio $k$, we employed the Ammosov–Delone–Krainov (ADK) [47] model to compare ionization probability in helium under different driving fields. Figure 1(b) shows the ionization probability generated by the 2.5 oc, 800 nm, $1.4 \times 10^{15} \text{ W cm}^{-2}$ few-cycle pulse alone (green solid line), superposed by a static electric field with relative strength ratios $k = 0.05$ (blue dashed dotted line) and $k = 0.1$ (red dashed line). We observed a decrease in ionization probability before $t = 0$ oc, and a significant increase in ionization probability at the time with a light delay after $t = 0$ oc when a static electric field is applied. In that case, harmonic emission in the sub-cycle of the driving field with the largest magnitude is afforded by a large number of freed electrons. Thus, we may expect a larger HCO and a continuum on HHG spectra with higher intensity.
Figure 2. (a) Amplitude of the electric fields of the 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse alone (green solid line) and its carrier envelope (black dashed line), a combination of a 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse and a static field with relative strength ratios $k = 0.05$ (blue dotted dashed line) and $k = 0.10$ (red dashed line). (b) The continuum bandwidth linear dependence on the static electric field relative strength ratio $k$. (c) The continuum bandwidth linear dependence on the few-cycle pulse’s intensity. (d) Continuum bandwidth as a second-order function of the few-cycle pulse’s wavelength.

3. Quasi-classical picture of the effect of a static electric field

Figure 2(a) shows the driving field of a 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse alone (green solid line) with its carrier envelope (black dashed line), and a few-cycle pulse superposed by a static electric field with relative strength ratio $k = 0.05$ (blue dashed dotted line) and $k = 0.1$ (red dashed line). We employed the quasi-classical picture to depict the harmonic generation under the combination of a few-cycle pulse and a static electric field. Clearly, there are five larger peaks labeled from A to E in all the driving fields in figure 2(a). According to the TSM, firstly, the helium gas target is ionized at peak A; secondly, freed electrons will be accelerated by peak B; finally, due to the change of direction of the linearly polarized few-cycle pulse in each half-cycle, electrons will be pulled back to recombine between B and C. In the above case, harmonic photons with an energy of $E_k + I_p$ are emitted. Since the HHG process has a period of half the optical cycle of the driving field, each driving field in figure 2(a) has three independent processes: A to B to C, B to C to D and C to D to E. We labeled the three processes as P1, P2 and P3, respectively. Next, we introduce two concepts in our work.
First, HCO is defined as to the maximum frequency of the emitted harmonic photons in each sub-cycle harmonic emission. Then the harmonic continuum bandwidth can be defined as the energy difference between the two largest HCOs.

A gas target atom was ionized at \( t = t_r \); after being accelerated, it was pulled back to recombine with parent ions at \( t = t_f \); the velocity obtained during this process is given by

\[
V = \int_{t_f}^{t_r} E(t) \, dt, \tag{2}
\]

where \( E(t) \) is the temporal profile of the driving field. During each sub-cycle harmonic emission, HCO is contributed by those recombined electrons that have maximum kinetic energy; this is approximated by

\[
\frac{1}{2} V^2 = 3.17 U_p = 3.17 \frac{E_p^2}{4w^2}, \tag{3}
\]

where \( U_p \) is the ponderomotive potential that is expressed as \( U_p = \frac{E_p^2}{4w^2} \). In this paper, HHG is under the combination of a few-cycle pulse and a static electric field \( E = E(t) + E_s \), so that equation (2) will become

\[
V' = \int_{t_f}^{t_r} (E(t) - E_s) \, dt = \int_{t_f}^{t_r} E(t) \, dt - E_s(t' - t'_f) = V - E_s(t'_f - t'_r). \tag{4a}
\]

HHG from a few-cycle pulse alone is given by

\[
V' = \int_{t_f}^{t_r} (E(t) - E_s) \, dt = \int_{t_f}^{t_r} E(t) \, dt = V. \tag{4b}
\]

The time spent during each sub-cycle harmonic emission from P1, P2 to P3 is approximately be the same, so that

\[
\Delta t = t' - t'_f = t'_r - t'_s = t'_D - t'_B = t'_E - t'_C.
\]

Firstly, we consider the HCO, which is determined by the ionization potential of the gas target and the kinetic energy. The energy of harmonic photons in P1 is given by

\[
nw_{\text{HCO}} = I_p + E_k = I_p + \frac{1}{2} V^2. \tag{5}
\]

Putting equations (4) into equation (5), we obtain the HCO from P1 under the combination of a few-cycle pulse and a static electric field:

\[
n'_1 w_0 = E'_1 + I_p = (E'_1 - E_k) + E_k + I_p
\]

\[
= \frac{1}{2} \left( (V'_1)^2 - V_1^2 \right) + E_k + I_p = -E_s \Delta t V_1 + E_k + I_p = -E_s \Delta t V_1 + n_1 w_0, \tag{6}
\]

where \( n'_1 \) is the HCO order from P1 under the combination field and \( n_1 \) is the HCO order from P1 under a few-cycle pulse alone.

The HCO from the corresponding P2 is given by

\[
n'_2 w_0 = E'_2 + I_p = (E'_2 - E_k) + E_k + I_p
\]

\[
= \frac{1}{2} \left( (V'_2)^2 - V_2^2 \right) + E_k + I_p = E_s \Delta t V_1 + E_k + I_p = E_s \Delta t V_2 + n_2 w_0, \tag{7}
\]

where \( n'_2 \) is the HCO order from P2 under the combination field and \( n_2 \) is the HCO order from P2 under a few-cycle pulse alone.

\[\text{New Journal of Physics 13 (2011) 093035 (http://www.njp.org/)}\]
Figure 3. (a) Classical calculation of the frequency of the HHG’s two largest HCOs under the combination of a 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse and a static electric field. The relative strength is regularly varied every 0.004 up to a maximum of 0.1. (b) The intensity of the high-order harmonic as a function of harmonic order and the relative strength ratio $k$.

It is worth noting that the direction of HCO shift from P1 and P2 is inverted because a few-cycle pulse field changes its direction every half-optical cycle, whereas a static electric field does not. The entire extension of harmonic continuum on HHG spectra is obtained by subtracting $n'_1$ from $n'_2$:

$$(n'_2 - n'_1)w_0 = (n_2 - n_1)w_0 + E_s\Delta t(V_2 + V_1).$$

According to equation (4b), the velocities $V_2$ and $V_1$ obtained in a few-cycle driving field are dependent on the time of acceleration $\Delta t$ and the strength of the electric field; we take an approximation $V \propto T \times E$, while due to the half-circle period of HHG, $\Delta t$ is proportional to the period of the few-cycle pulse $\Delta t \propto T \propto \lambda$. Finally, we generate the harmonic continuum bandwidth by taking the above linear approximations:

$$(n'_2 - n'_1)w_0 = (n_2 - n_1)w_0 + E_sE\lambda^2 = (n_2 - n_1)w_0 + kE^2\lambda^2 = (n_2 - n_1)w_0 + kI\lambda^2,$$

where $k = E_s/E_0$ is the relative strength ratio of the static electric field with respect to the few-cycle pulse field. By taking the approximation, we obtain the following: the continuum...
bandwidth on HHG spectra is directly proportional to the intensity of the few-cycle pulse, square of the wavelength of the few-cycle pulse and the relative strength ratio $k$ of the static electric field. In order to illustrate this relation, we calculate the continuum bandwidth as a function of the relative strength ratio $k$, the few-cycle pulse’s intensity and the few-cycle pulse’s wavelength by taking classical trajectory calculation. In this simulation, a single-color 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse is employed as the fundamental field and helium with an ionization of 24.6 eV is used. By varying the relative strength ratio from 0 to 0.1 in each 0.004, we observed a linear increase in continuum bandwidth with increasing relative strength ratio, which is comparable with the theoretical prediction in equation (9). Next, fixing the relative strength ratio $k$, a linear increase in the continuum with increasing intensity of the few-cycle pulse is shown in figure 2(c). Finally, in figure 2(d), the results of our classical trajectory calculation show that the continuum bandwidth is a second-order function of the few-cycle pulse wavelength. Thus, the continuum bandwidth on the HHG spectrum estimated from equations (9) is clearly discernible from figures 3(b)–(d) through classical trajectory calculation.

4. Numerical results

We investigated the HHG dependence on the relative strength ratio of the static electric field in extending the continuum bandwidth. Firstly, the largest and the second-largest HCO were calculated from a combination of a 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse and a static electric field with a relative strength ratio varying from 0 to 0.1 in steps of 0.004. Figure 4(a) shows the linear dependence of both HCOs on the relative strength ratio $k$ of the static electric field. A noticeable linear continuum extension is clearly discernible. Next, we analyze the HHG spectra as a function of relative strength $k$ by quantum calculation through our time-dependent wave packet code [48–59]. In figure 3(b), the intensity of HHG spectra is plotted as a function of harmonic order and the relative strength ratio $k$. The relative strength

Figure 4. Harmonic spectrum of a helium atom. Green dotted line: generated by a 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse; blue dashed line: generated under the influence of a combination of an 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse and a static electric field with $k = 0.05$. Red solid line: the same driving field as the former except for $k = 0.10$. (b) IAP calculated by synthesizing the continuum on the above harmonic spectra.
Figure 5. (a) Classical trajectory calculation shows the kinetic energy of the electrons as a function of recombination time with their parent ions. Red dots correspond to the case under a 2.5-oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse and a static electric field with the relative strength ratio $k = 0.02$; black dots correspond to the case under a few-cycle pulse alone. (b, c) Gabor transform is performed for time–frequency analysis of the photon energy as a function of time and harmonic order. The laser parameter used in (b) is a 6 fs, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse, without modification from a static electric field; in (c), the same driving field plus a static electric field with the relative strength ratio $k = 0.02$. 

*New Journal of Physics 13 (2011) 093035 (http://www.njp.org/)*
ratio $k$ is shifted from 0 to 0.1 in steps of 0.004. Each color bar in figure 3(b) represents an HHG spectrum, and both the largest and second-largest HCOs are clearly visible in each bar. We observed the largest HCO shifted linearly to higher order, whereas the second-largest one moved linearly to lower order with an increase in the relative strength ratio. The consistent results of both classical and quantum calculations proved equation (9).

We will now show the HHG spectra under a few-cycle pulse alone (green solid line), a combination of a few-cycle pulse and a static electric field with $k = 0.05$ (blue dashed line) and $k = 0.1$ (red solid line). As shown in figure 4(a), by increasing $k$ from 0 to 0.05 to 0.1, the second-largest HCO decreases from 167 to 147 to 128, while the largest HCO increases from 189 to 219 to 252, leading to extension of the continuum bandwidth from 34 to 110 to 191 eV. By taking Fourier transformation of the harmonics from the continuum on HHG spectra, IAP with duration from 81.3 attoseconds (as) to 25.6 as to 18.1 as were created. At the same time, a noticeable intensity increase of the created IAP was observed; as can be seen from figure 4(b), the intensity of the created IAP under a combination field with $k = 0.1$ is 30 orders greater than the corresponding case under a few-cycle pulse alone.

5. Classical trajectory calculation and time–frequency analyses

In order to better clarify the static electric field’s effect on HHG, we report classical trajectory calculation and time–frequency analysis in figure 5. In figure 5(a), each point represents the harmonics photon energy and the corresponding recombination time. The harmonic cutoff photons from a neighboring sub-cycle shows an energy difference of 40.7 eV under a 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ few-cycle pulse alone, 72.6 eV under the combination field of the same few-cycle pulse and a static electric field with $k = 0.02$. The three-dimensional time–frequency analysis from the above two cases is shown in figures 5(b) and (c), respectively. Time–frequency analysis is performed by taking the Gabor transformation of the dipole acceleration [60, 61] code. The intensity of harmonic photons is plotted as a function of time and harmonic order in figures 5(b) and (c). Five emission peaks are clearly observed; we label the largest three from A1 to A3, from the top to the bottom. While the energy difference between the largest HCO A2 and the second-largest HCO A2 was broadened by adding a static electric field with the relative strength ratio $k = 0.02$, this induces the extension of continuum bandwidth on the HHG spectra.

6. Conclusion

In summary, we reported HHG from a combination of a single-color 2.5 oc, 800 nm, $1.4 \times 10^{15}$ W cm$^{-2}$ pulse and a static electric field. We obtained the expression for continuum bandwidth, which is a function of the relative strength ratio $k$ and the few-cycle pulse’s intensity and wavelength through the classical perspective. We demonstrated the relation by performing classical calculation and the time-dependent wave packet code. Our numerical results show a significant linear extension of continuum bandwidth on HHG spectra by superposing the static electric field onto the few-cycle pulse. After Fourier transforming the harmonics from the continuum on HHG spectra, a 18 as IAP with improved intensity was created from a combination of a few-cycle pulse and a static electric field with $k = 0.1$. Finally, classical trajectory calculation and time–frequency analysis were used to shed light on the physical scheme.
Acknowledgments

This work was supported by the NSFC (numbers 10974198 and 20903094) and the 863 project (numbers 2006AA01A119 and 2009AA01A130). The authors sincerely thank Professor Keli Han and Dr Ruifeng Lu for providing us with the LZH-DICP code. GJZ also acknowledges financial support from DICP through a PhD grant.

References

[1] Corkum P B and Krausz F 2007 Nature Phys. 3 381
[2] Kapteyn H, Cohen O, Christov I and Murnane M 2007 Science 317 775
[3] Drescher M, Hentschel M, Kienberger R, Uiberacker M, Yakovlev V, Scrini A, Westerwalbesloh T, Kleineberg U, Heinzmann U and Krausz F 2002 Nature 419 803
[4] Kienberger R et al 2004 Nature 427 817
[5] Uiberacker M et al 2007 Physics A 366 627
[6] Niikura H, Legare F, Hasbani R, Bandrauk A D, Ivanov M Y, Villeneuve D M and Corkum P B 2002 Nature 417 917
[7] Drescher M, Hentschel M, Kienberger R, Uiberacker M, Yakovlev V, Scrini A, Westerwalbesloh T, Kleineberg U, Heinzmann U and Krausz F 2002 Nature 419 803
[8] Hentschel M, Kienberger R, Spielmann C, Reider G A, Milosevic N, Brabec T, Corkum P, Heinzmann U, Drescher M and Krausz F 2001 Nature 414 997
[9] Johnsson P et al 2005 Phys. Rev. Lett. 95 013001
[10] Xiang Y, Niu Y and Gong S 2009 Phys. Rev. A 80 023423
[11] Brabec T and Krausz F 2000 Rev. Mod. Phys. 72 545
[12] Borghesi M et al 2004 Phys. Rev. Lett. 93 195003
[13] Luttikhof M J H, Khachatryan A G, van Goor F A and Boller K-J 2010 Phys. Rev. Lett. 105 124801
[14] Kulagin V V, Cherepenin V A, Hur M S and Suk H 2007 Phys. Rev. Lett. 99 124801
[15] Karmakar A and Pukhov A 2007 Laser Part. Beams 25 371
[16] Liseykina T V, Firner S and Bauer D 2010 Phys. Rev. Lett. 104 095002
[17] Ma Y-Y et al 2006 Phys. Plasmas 13 110702
[18] Krause J L, Schafer K J and Kularnder K C 1992 Phys. Rev. Lett. 68 3535
[19] Corkum P B 1993 Phys. Rev. Lett. 71 1994
[20] Kularnder K C, Schafer K J and Krause J L 1993 Superintense Laser–Atom Physics (NATO Advanced Study Institute Series B: Physics) vol 316, ed B Piraux, A L’Huillier and K Rzazewski (New York: Plenum) chapter 19, p 95
[21] Schafer K J, Yang B, DiMauro L F and Kularnder K C 1993 Phys. Rev. Lett. 70 1599
[22] Sansone G et al 2006 Science 314 443
[23] Milošević D B 2000 J. Phys. B: At. Mol. Opt. Phys. 33 2479
[24] Oron D, Silberberg Y, Dudovich N and Villeneuve D M 2005 Phys. Rev. A 72 063816
[25] Milošević D B, Bauer D and Becker W 2006 J. Mod. Opt. 53 125–34
[26] Zeng Z N, Cheng Y, Song X, Li R X and Xu Z Z 2006 Phys. Rev. Lett. 97 163901
[27] Sola I J et al 2006 Nature Phys. 2 319
[28] Chang Z H 2007 Phys. Rev. A 76 051403
[29] Tzallas P, Skantzakis E, Kalpouzos C, Benis E P, Tsakiris G D and Charalambidis D 2007 Nature Phys. 3 846
[30] Sansone G 2009 Phys. Rev. A 79 053410
[31] Sansone G et al 2009 Phys. Rev. A 80 063837
[32] Yu Y L et al 2009 Phys. Rev. A 80 063837
[33] Feng X M, Gilbertson S, Mashiko H, Wang H, Khan S D, Chini M, Wu Y, Zhao K and Chang Z H 2009 Phys. Rev. Lett. 103 183901

New Journal of Physics 13 (2011) 093035 (http://www.njp.org/)
[34] Skantzakis E, Tzallas P, Kruse J, Kalpouzos C and Charalambidis D 2009 Opt. Lett. 34 1732
[35] Gilbertson S, Wu Y, Khan S D, Chini M, Zhao K, Feng X M and Chang Z H 2010 Phys. Rev. A 81 043810
[36] Takahashi E, Lan P, Mücke O D, Nabekawa Y and Midorikawa K 2010 Phys. Rev. Lett. 104 233901
[37] Bao M-Q and Starace A F 1996 Phys. Rev. A 53 R3723
[38] Gottlieb B, Lohr A, Becker W and Kleber M 1996 Phys. Rev. A 54 R1022
[39] Milošević D B and Starace A F 1998 Phys. Rev. Lett. 81 5097
[40] Milošević D B and Starace A F 1999 Phys. Rev. A 60 3943
[41] Wang B, Li X and Fu P 1999 Phys. Rev. A 59 2894
[42] Borca B, Flegel A V, Frolov M V, Manakov N L, Milošević D B and Starace A F 2000 Phys. Rev. Lett. 85 732
[43] Odžak S and Milošević D B 2005 Phys. Rev. A 72 033407
[44] Volkova E A, Popov A M and Tikhonova O V 2001 J. Exp. Theor. Phys. 93 1155
[45] Gavrila M 2002 J. Phys. B: At. Mol. Opt. Phys. 35 R147
[46] Strelkov V V 2006 Phys. Rev. A 74 013405
[47] Yudin G L and Ivanov M Y 2001 Phys. Rev. A 64 013409
[48] Lu R F, Zhang P Y and Han K L 2008 Phys. Rev. E 77 66701
[49] Hu J, Han K L and He G Z 2005 Phys. Rev. Lett. 95 123001
[50] Han K-L, He G-Z and Lou N-Q 1996 J. Chem. Phys. 105 8699
[51] Zhang H, Han K L, Zhao Y, He G Z and Lou N Q 1997 Chem. Phys. Lett. 271 204
[52] Hu J, Wang M S and Han K L 2006 Phys. Rev. A 74 63417
[53] Zhang H, Han K L, Zhao Y, He G Z and Lou N Q 1998 Chem. Phys. Lett. 289 494
[54] Chu T S, Zhang Y and Han K L 2006 Int. Rev. Phys. Chem. 25 201
[55] Han K-L and He G-Z 2007 J. Photochem. Photobiol. C: Photochem. Rev. 8 55
[56] Shao T J, Zhao G J, Wen B and Yang H 2010 Phys. Rev. A 82 063838
[57] Lu R F, He H X, Guo Y H and Han K L 2009 J. Phys. B: At. Mol. Opt. Phys. 42 225601
[58] Chu T-S and Han K-L 2008 Phys. Chem. Chem. Phys. 10 2431
[59] Guo Y H, Lu R F, Han K L and He G Z 2009 Int. J. Quantum Chem. 109 3410
[60] Antoine P, Piriaux B and Maquet A 1995 Phys. Rev. A 51 R1750
[61] Yakovlev V S and Scrinzi A 2003 Phys. Rev. Lett. 91 153901

New Journal of Physics 13 (2011) 093035 (http://www.njp.org/)