EPJ Web of Conferences **205**, 02011 (2019) https://doi.org/10.1051/epjconf/201920502011
UP 2018

Minimizing attosecond CEP jitter by carrier envelope phase tuning

Mark. J. Prandolini[1], *Thomas* Gaumnitz[1], *Alexander* Kothe[1], *Jost* Henkel[2], *Joachim* Schneider[1], *Julia* Hengster[1], *Markus* Drescher[1], *Manfred* Lein[2], and *Thorsten* Uphues[1,*]

[1]Institut für Experimentalphysik, Universität Hamburg and Center for Free-Electron Laser Science (CFEL), Luruper Chaussee 149, 22761 Hamburg, Germany
[2]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany

Abstract. Minimizing the CEP jitter of isolated attosecond pulses (IAP) will be important for future applications. This jitter is experimentally and theoretically investigated and can be minimized when the driving pulse is near its Fourier limit but with slightly negative chirp. Thus, understanding and characterization of the CEP jitter of IAPs is a first step towards exact control of the electric field of IAP pulses.

1 Introduction

The generation of isolated attosecond pulses (IAP) by high harmonic generation (HHG) requires ultrafast carrier envelope phase (CEP) stabilized optical driving pulses. The optical dispersion and the CEP of these pulses are usually controlled by a pair of wedges [1]. For a given optical dispersion (ϕ_{D}), a residual jitter of the CEP (ϕ_{CEP}) of the driving laser still remains. In this work we assume the CEP jitter of the driving laser is the main source of CEP jitter of the generated IAPs (ϕ_{atto}). This effect will be analyzed experimentally and theoretically by solving the time-dependent Schrödinger equation (TDSE).

2 CEP-Scans: Experimental

We use a CEP-stabilized sub-6 fs few-cycle Ti:Sa laser system to generate isolated attosecond pulses by amplitude gating and spectral filtering of the HHG cut-off region [2]. Experimentally, the CEP is controlled by a pair of wedges introducing either a positive or negative chirp to a Fourier-limited pulse by material dispersion. The CEP stabilization and control are realised with a f-to-0f interferometer in the oscillator and a f-to-2f interferometer in the amplifier averaging over 30 shots. For this laser system, the CEP jitter was measured to be 60 mrad. A neon-gas filled hollow-core fiber spectrally broadens the pulses and a set of chirped mirrors compresses the octave spanning spectrum to Fourier-transform-limited pulses of 5.9 fs. The beam is focused into a neon filled target with a

* Corresponding author: Thorsten.Uphues@cfel.de

propagation length of ~2 mm for HHG. HHG spectra were recorded over many CEP periods (Fig. 1), with a slit grating spectrometer to identify the highest cut-off energy in the HHG spectrum.

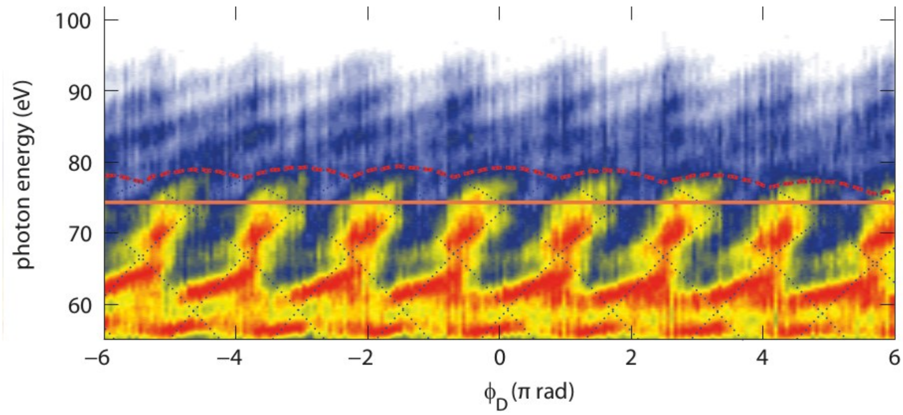

Fig. 1. CEP-scan: HHG spectra recorded over many CEP periods. The cut-off energy is calculated with the intensity model ([3], dashed red line). The half-cycles cut-offs are given as dotted blue lines. (adapted from [2]).

We estimate the cut-off bandwidth by a simple intensity model [3] in perfect agreement with the half-cycle cut-off model [4]. The classical cut-off depends linearly on the ionization potential of the medium (I_p) and the instantaneous intensity (I) resulting in $E_{cut} - I_p \propto \lambda^2 I$ [5]. Thus the simple relation

$$E_{continuum} = (E_{cut} - I_p)\,\frac{|I_{max1} - I_{max2}|}{I_{max2}} \tag{1}$$

describes the energy range of the continuum, where I_{max1} and I_{max2} are the values of the intensity maxima of the two neighbouring half-cycles contributing to the highest energy part of the HHG process.

3 CEP-scans: Simulations

For this work we simulated optical pulses with a bandwidth supporting 3.8 fs and an intensity of $4{\cdot}10^{14}$ W/cm^2. The results of a simulated CEP-scan for IAPs are shown in Fig. 2a and 2b; where the left upper panel displays the time dependence of the IAPs as a function of ϕ_D (Fig. 2a) and the lower three panels (Fig. 2b) show the time dependence, where the wedge position is fixed at a given ϕ_D, and the CEP phase ϕ_{CEP} of the driving laser is varied over a range from −50 to 50 mrad. For the negatively and the positively chirped pulses, CEP jitter can lead to the formation of two attosecond pulses with a probability of ~50%. In the Fourier limited case ($\phi_D = 0$, Fig. 2b, center), it is possible to generate a single IAP independent of CEP jitter within the considered range.

The influence of the CEP-jitter of the driving laser on the CEP of the IAP (ϕ_{atto}) is depicted in Fig. 2c and 2d. Three positions from a CEP-scan of the driving laser at ϕ_D = -2π, -1π, and 0 rad are considered. For each ϕ_D, the dependence of ϕ_{atto} on driving laser CEP without dispersion is calculated (Fig. 2c). In each case, the dependency is found to be approximately linear over the considered ϕ_{CEP} range; the slopes of the linear dependency are provided in Fig. 2c. For the strongest up- and down-chirp, the slopes are steeper than the slope at $\phi_D = -1\pi$ rad. For further analysis corresponding histograms are generated for the CEP jitter of the IAP (ϕ_{atto}), assuming a CEP-jitter of the driving laser from −100 to 100 mrads (Fig. 2d). The minimum attosecond CEP jitter is observed for the case of ϕ_{D} close to -1π rad.

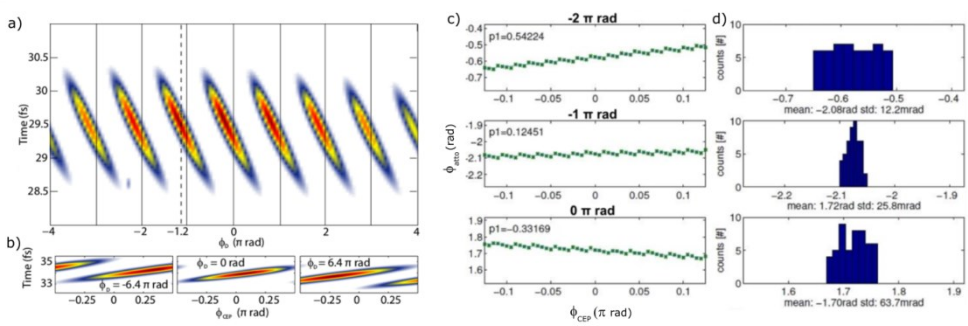

Fig. 2. a) Fourier transformed CEP-scan IAPs (in the time domain): In this case, CEP phase change ϕ_{D} is introduced by glass wedges causing additional optical pulse dispersion. The calculated HHG pulses are shown in a false color representation. The dashed vertical line represents the ϕ_{D} value with the smallest IAP CEP jitter. b) Dispersion-free scan (for varying ϕ_{CEP}) for three chirped pulses at $\phi_{\mathrm{D}} = -6.4\pi$ rad (left), $\phi_{\mathrm{D}} = 0$ (center), and $\phi_{\mathrm{D}} = 6.4\pi$ rad (right). c) The dependence of the CEP of the IAP (ϕ_{atto}) on the CEP of the driving laser (ϕ_{CEP}) is calculated for three driving laser pulses at $\phi_{\mathrm{D}} = -2\pi$, -1π, 0 rad with different chirp. The dependence of ϕ_{atto} on ϕ_{CEP} is approximately linear over the considered range, where $p1$ is the slope. d) Corresponding histograms from the results of the left panel c), assuming a driving laser CEP jitter from −100 to 100 mrads. For each case, the corresponding ϕ_{atto}-jitter (std.) in rms is given, (adapted from [2, 3]).

In this work the possibility to optimize the driving laser's spectral phase ϕ_{D} to generate ideally stable attosecond pulses using TDSE simulations including dispersion-free jitter ϕ_{CEP} was demonstrated. Generally, by changing ϕ_{D} in a CEP-scan, a value for a theoretical minimum of the CEP jitter of the attosecond pulses ϕ_{atto} can be identified. This value is accessible in the experiment by choosing the corresponding dispersion controlled by a pair of wedges. According to our simulations, a slight negative chirp of near -1π rad yields optimal IAP formation and stability.

References

1. F. Frank, C. Arrell, T. Witting, W. A. Okell, J. McKenna, J. S. Robinson, C. A. Haworth, D. Austin, H. Teng, I. A. Walmsley, J. P. Marangos, and J. W. G. Tisch, Rev. Sci. Instrum. **83**, 071101 (2012)
2. T. Gaumnitz, "Development, set-up, and characterization of an apparatus for attosecond electron spectroscopy", PhD thesis, University of Hamburg (2015)
3. A. Kothe, T. Gaumnitz, J. Henkel, J. Schneider, M. J. Prandolini, J. Hengster, M. Drescher, M. Lein, and T. Uphues, J. Opt. Soc. Am. B **35,** A22 (2018)
4. C. A. Haworth, L. E. Chipperfield, J. S. Robinson, P. L. Knight, J. P. Marangos, and J. W. G. Tisch, Nat. Phys. **3**, 52 (2007)
5. P. Corkum, Phys. Rev. Lett. **71**, 1994 (1993)