

The attosecond-science frontiers: generation, metrology and paths to applications

P. Tzallas^{a, c}, G.D. Tsakiris^a, K. Witte^a, L.A.A. Nikolopoulos^b,
E.P. Benis^c, D. Charalambidis^{c, d, *}

^a Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

^b Department of Telecommunication Sciences and Technology, University of Peloponnisos, GR22100, Greece

^c Foundation for Research and Technology-Hellas, Institute of Electronic Structure and Laser, P.O. Box 1527, GR71110 Heraklion (Crete), Greece

^d Department of Physics, University of Crete, P.O. Box 2208, GR71003 Heraklion (Crete), Greece

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Abstract

Recent developments in the generation, metrology and potential applications of XUV-attosecond (as) pulses, formed by the coherent superposition of harmonics of an infrared femtosecond (fs) laser pulse, are reviewed. Particular emphasis is given to the recently achieved second-order autocorrelation (AC) measurement of a sub-femtosecond (sub-fs) pulse train. The method is a non-trivial extension in the XUV spectral range of the well-established technique routinely used in 'fs' pulse metrology. Besides the direct visualization of a periodic attosecond structure and the quantitative information it supplies, the approach introduces a unique technique for the implementation of XUV-pump XUV-probe type of experimental studies of ultra-fast phenomena. It further relates to the metrology and time domain application interests of other advanced XUV radiation sources, such as the XFEL-based installations. While the implementation of the method and its refined versions with laser harmonics is a challenge at the limits of the realizable, the profoundly high scheduled intensities of XFEL sources are expected to sufficiently enhance its robustness and range of applicability.

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1. Introduction

Fascinating developments in optical pulse engineering over the last 20 years lead to the generation of laser pulses as short as few femtosecond [1], providing a unique tool for high resolution time domain spectroscopy. Sound results of dynamical studies in a large number of ultra-fast processes paved the way to the breakthrough of femtochemistry. However, a number of other processes in nature evolve with characteristic times of the order of 1 fs or even shorter. Time domain studies of such processes require at first place sub-fs resolution, offered by pulses depicting attosecond localization. The generation, characterization and proof of principle applications of such pulses is the mission of the

since recently debuting *attoscience*, attracting worldwide the strong interest and intensive efforts of laser laboratories.

The physical process underlying the formation of 'as' pulses is the non-linear scattering of intense 'fs' laser pulses by a medium, commonly a rare gas. The emitted superposition of the laser frequency harmonics may, subject to proper emission and propagation conditions, form a train of bursts of 'as' duration or even an isolated 'as' pulse. The unequivocal proof of this extreme temporal localization has turned into a highly challenging problem. Both 'as' metrology as well as 'as' time domain pump-probe type applications require non-linear procedures combined with high resolution dispersionless XUV devices. The limited intensity of harmonics, the extreme sensitivity of 'as' pulses to dispersion and the lack of dispersionless, broadband XUV optics have triggered the development of a number of alternative smart approaches to the problem, giving at the same time access to

* Corresponding author.

E-mail address: chara@iesl.forth.gr (D. Charalambidis).

appealing physics. Today *attophysics* is centered on two main categories: the generation, metrology and applications of (a) attosecond pulse trains and (b) isolated attosecond pulses.

The purpose of the present publication is to give to the VUV/XUV and X-ray research community an overview of the field. After a short introduction into the physical principles, we review recent progress in the generation and metrology of ‘as’ pulse trains and isolated pulses, presenting in some more detail our very recent achievements in extending well-known and widely used optical ‘fs’ metrology to as XUV pulses. A restricting parameter for a generalized applicability of this approach to any laser harmonics is at present the intensity of the harmonic radiation, which in turn is a consequence of the state of the art ‘fs’ laser technology. However, the approach is applicable to the existing family of intense harmonics and it further becomes highly pertinent and appropriate for the metrology and non-linear time domain application needs of other XUV sources, offering much higher intensities.

2. Generation schemes and dynamics of attosecond pulses and pulse trains

According to the superposition principle in wave mechanics, spatial or temporal energy localization comes about whenever mutually coherent waves are superimposed in time and space. In the simplest case of monochromatic waves of equally spaced and properly phased frequencies, the total field depicts a temporal beating with a repetition rate equal to half of the frequency spacing. As in mode locked ‘fs’ lasers, this is the basic principle underlying ‘as’ pulse train generation [2–4]. The degree of localization is inversely proportional to the number of the phase locked frequency components. As for an ‘as’ pulse train the entire IR, visible or UV spectral range is not sufficient, such pulses can only be generated in the VUV/XUV or X-ray spectral regions. Indeed, in the early 1990s it was recognized [3] that the already 30 years known non-linear process of higher-order harmonic generation, occurring when an intense laser field interacts with an atomic gas, offers promising prospects for the generation of ‘as’ pulses. If the spectral distribution of the phase locked frequencies is not discrete, but smoothly continuous, the resulting temporal distribution may have the form of an isolated ‘as’ pulse. In this context, the harmonic emission from atoms appears to be a most suitable candidate for the achievement of temporal localization of light to these unprecedented short time scales. Indeed, in the two approaches, successfully utilized so far for the generation of ‘as’ pulses, the underpinning process is harmonic generation from atoms. The first approach aims at the generation of isolated ‘as’ pulses [5,6] relying on driving laser pulses of few optical cycles, while in the second one many-cycle laser pulses are exploited for the production of ‘as’ pulse trains [7,8].

While the harmonic emission can be fully described by calculating the atomic dipole acceleration solving the time-

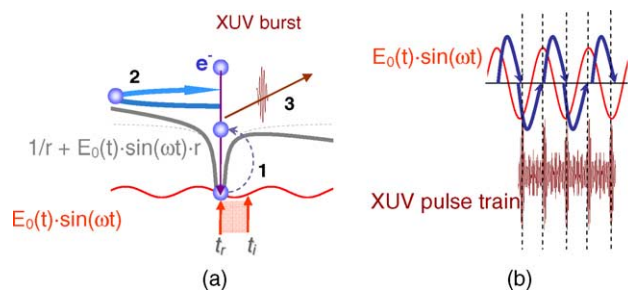


Fig. 1. The three-step model (the steps are numbered) of the single active electron dynamics and the emission of XUV bursts (a). Periodic repetition of the dynamics showed in (a) results in an emission of a pulse train (b).

dependent Schrödinger equation (TDSE), the generation of harmonics of an IR ‘fs’ laser with XUV-photon-energies higher than ionization-threshold of the generating atom is successfully described by a quasi classical three-step model offering rather intuitive views of the generation dynamics and allowing coupling of the atomic emission with propagation (Fig. 1a). The model relies on two approximations: the single active electron approximation (SAE) assuming a single electron interacting with the laser field and a frozen core and the strong field approximation (SFA) [9] assuming that once an electron is detached from the core its dynamics induced by the laser field are not affected by the core potential. In the classical [10] version of the model and its extension by a full quantum treatment [11,12], the combined oscillating potential of the atom and laser electric field forms a local time dependent barrier through which a bound electron can tunnel or escape over it at a given phase of the driving field (first step). Subsequently, the almost free electron moves classically in the continuum gaining energy from the driving field and eventually revisits the parent ion with a given kinetic energy that depends on the moment of its birth and its trajectory in the continuum (second step). Upon return to the vicinity of the parent ion (third body), the electron may recombine to emit a burst of energetic radiation (third step). Coherent periodic repetition of these dynamics twice per optical cycle, leads to a discrete emission spectrum of the odd harmonics (in accordance with angular momentum and parity conservation) of the driving laser field (Fig. 1b). The energy that the electron gains in its trajectory in the continuum and the time of recombination depend sensitively on the phase of the driving field at the moment the electron is ejected. In terms of Feynman’s path integrals, an infinite number of interfering quantum paths leading to recombination contribute to the harmonic spectrum [12,13]. The time dependent emitting non-linear dipole moment is given in atomic units by [13]

$$x(t) = i \int_{-\infty}^t dt' \int d^3 p E(t') d_x^* [p - A(t)] d_x [p - A(t')] \exp(-iS(p, t, t')) + \text{c.c.} \quad (1)$$

where $E(t)$ is the driving electric field polarized along the x -axis, $A(t)$ its vector potential, p the canonical momentum, d_x the dipole matrix element of the bound-free transitions and

$S(p, t, t')$ the quasi-classical action

$$S(p, t, t') = \int_t^{t'} dt'' \left(\frac{[p - A(t'')]^2}{2} + I_p \right) \quad (2)$$

I_p being the ionization potential of the atom. Due to the rapidly varying phase $-iS(p, t, t')$, the contribution of most of the trajectories vanishes upon integration. Only those having constant phase (i.e. $\partial S/\partial p = \partial S/\partial t = \partial S/\partial t' = 0$) survive. From these saddle-point conditions it turns out [11,12] that essentially only two trajectories contribute to the generation of a harmonic, all others interfering destructively. These two are known as the “long” and “short” trajectories due to the different duration τ_{exc} of the electron excursion in the continuum. Furthermore, proper propagation conditions are shown to eliminate the long trajectory [14]. The surviving short trajectory determines the ‘as’ generation dynamics. An illustration of the described dynamics is given in Fig. 1.

A decisive parameter for the attosecond pulse generation is the phase of each emitted individual q th harmonic. It is given by $\theta = -S(p, t_i, t_r) + q\omega_L t_r$, where ω_L being the laser frequency and t_i, t_r are the ejection and the recombination times of the electron.

The emitted frequency spectrum is given by the Fourier transform (FT) of the non-linear dipole $x(\omega) = \int_{-\infty}^{\infty} dt x(t) \exp(i\omega t)$, with an harmonic emission rate [15]

$$W(\omega) \propto \omega^3 |x(\omega)|^2 \quad (3)$$

This spectrum consists of equally spaced maxima around the frequencies of the odd harmonics of the fundamental carrier frequency as a consequence of the symmetry of the atomic potential and the periodicity in the electronic motion. Two regions of the spectrum are relevant to the dynamics described above: (a) the “cut off” region around the maximum emitted photon energy resulting when the two trajectories degenerate to a specific one. It corresponds to the highest energy $\omega_{\text{max}} = 3.17U_p + I_p F(I_p/U_p)$ (atomic units) [11] with which the electron may revisit the core, where $U_p = E_L^2/4\omega_L^2$ is the average (ponderomotive) energy of the electron in the laser field E_L . The tunnelling and diffusion term $F(I_p/U_p)$ has values close to unity and is commonly ignored, following the classical treatment [10]; (b) the “plateau region” at photon energies below ω_{max} , where different harmonics have approximately equal intensities, indicative of the non-perturbative character of the phenomenon. Experimental demonstrations of these ‘as’ electron re-scattering dynamics have been recently implemented in molecular fragmentation experiments [16]. For harmonics lower than the “plateau”, energies are below the ionization potential of the atom and the generation can be described by lowest order perturbation theory (LOPT). The “cut-off” and “plateau” regions associate with the generation of isolated ‘as’ pulses and pulse trains, respectively.

In the generation of isolated pulses utilizing few-cycle laser pulses [17–21], a quasi-continuum part of the cut-off spectral region is used. The emission in this spectral region comes about only during a small fraction of the optical cy-

cle with the highest field amplitude, during which the ejected electron gains the highest possible energy. An appropriate filter selects this spectral interval, transmitting isolated pulses with sub-fs duration [22,23]. A crucial parameter here is the stability of the relative carrier frequency—envelope phase [24,25] of the few-cycle pulse. Stabilization of this so-called “absolute phase” has been achieved by measuring and feedback compensating the drifting of the off-set in the frequency comb of the modes of an oscillator [25] and amplifier [26]. An alternative approach for isolated pulse generation relies on the so-called polarization gating method [27]. Although substantial spectral broadening, sufficient for the Fourier synthesis of an isolated sub-fs pulse, has been achieved by this method [28], no temporal confinement has been proven in these experiments.

As for the generation of pulse trains, many cycle laser pulses excite periodically a number of electron wave packets into the continuum. Following different trajectories they finally recombine emitting the “plateau” harmonics. The two dominant trajectories that contribute to a given photon energy below the cut-off [29] have different return times, resulting in to two different phases for this energy. If the phase difference between neighbouring harmonics and within the spectral distribution of each harmonic is constant at any given time and proper, spikes of attosecond duration would appear in the time-domain spectrum as a result of frequency beating twice in a laser period. Additionally, propagation conditions should further maintain phase locking. Elimination of the long trajectory [14] through propagation improves substantially proper phase locking.

3. On the metrology of attosecond pulses

Well-established ‘fs’ metrology relies on a non-linear effect induced solely by the radiation to be characterized. Already a second-order (AC) allows the determination of the pulse duration to a satisfactory degree of accuracy. That is why it has been routinely used for many years in ‘ps’ and ‘fs’ laser laboratories. Its extension to sub-fs XUV pulses is far from trivial as they are orders of magnitude weaker than the laser radiation, spectrally much broader and in the notoriously most difficult spectral region to handle. No beam splitters are available for the autocorrelator and the fragility of the pulses requires highly dispersionless optical arrangements. The non-linear detector has to rely on a two-photon (or higher-order) process, such as two-photon ionization. Its cross-section requires high intensities and a detector with a flat response over the broad frequency spectrum. Those are the obstacles that prevented for several years a successful measurement of a second-order AC of ‘as’ pulses and have forced the diagnostics to cross-correlation based approaches between the IR laser field and that of the XUV radiation.

Thus, isolated ‘as’ pulses are measured with the so called ‘as’ streak camera [30] IR–XUV cross-correlation approach.

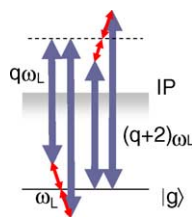


Fig. 2. Interfering channels contributing to a side band.

Here, an XUV pulse ionizes isotropically an atom. The released photoelectron is deflected by the field of a spatiotemporally overlapping IR pulse, acting as the ultra-fast ramping voltage of the streak camera. The net momentum transfer from the field to the electron depends sensitively on the phase of the few cycle pulse at which ionization occurs. The information about the duration of the XUV pulse is available in the modulation depth of the cross-correlation trace from which it can be deduced through its modelling [6,23,24].

In cross-correlation measurements of pulse trains, the atom is ionized by the mixing of the XUV and the IR waves. To the measured photoelectron peak contribute two subsequent harmonics through sum ($\omega_{q-2} + \omega_{\text{IR}}$) and difference ($\omega_q - \omega_{\text{IR}}$) frequency mixing (Fig. 2). The resulting four interfering channels through LOPT give an ionization yield $I_{q,q-2} \propto \cos(2\omega_{\text{IR}}\tau + \theta_q - \theta_{q-2} + \theta_{\text{atom}})$. Provided that the atomic phase θ_{atom} is negligible or known, the relative phase between subsequent harmonics $\theta_q - \theta_{q-2}$ can be retrieved. Treating each harmonic as a monochromatic wave, the ‘as’ pulse train can be synthesized and the phase of the fundamental at which the ‘as’ burst is emitted can be extracted as recently experimentally demonstrated [8]. An alternative mode selective cross-correlation approach [31] that accounts for the chirp within the bandwidth of each harmonic has been proposed and theoretically assessed but not yet implemented. Cross-correlation measurements of the chirp within one harmonic have also been reported [32].

Cross-correlation is a powerful metrology tool but an indirect approach, based on appropriate modelling that correctly describes the correlation process. This becomes rather complicated in the presence of the strong IR field. The first successful direct observation of a sub-fs pulse train by means of a second-order AC has been achieved recently. The two key factors towards this accomplishment have been: (i) the development of the split-mirror volume autocorrelation technique and (ii) the demonstration of the two-XUV-photon He ionization non-linear detector [33]. The method is extendable to different spectral regions by an appropriate choice of the ionizing atomic (or ionic) medium. Extension to isolated pulses is in principle possible, but upon substantial increase of the currently available XUV fluencies. The two-XUV-photon ionization process founds further the basis of XUV-pump XUV-probe applications of intense ultra-short XUV pulses. As such the method is highly relevant to the metrology and applications of any source of intense, short XUV and X-ray

pulses and thus of interest to the entire VUV/XUV and X-ray community. For this reason its principles will be illustrated to some extent in the next section.

4. The second-order AC of an attosecond pulse train

The experimental runs have been performed at the ATLAS facility of the Max Planck Institut für Quantenoptik. The harmonic generation occurs in a xenon gas-jet using up to 10 mJ, 130 fs laser pulses at $\lambda = 790$ nm from the 10 Hz Ti:sapphire laser. For optimum phase locking [14], the annular laser beam [34] focus was placed 6 mm before the Xe gas jet generating harmonics of up to the 15th. The combination of the annular geometry, a $0.2 \mu\text{m}$ thick In filter and the laser intensities used selects harmonics from 7th to 15th with relative intensity amplitudes 0.32:1.0:0.30:0.11:0.01, respectively. The XUV pulse radiation is focused in a helium gas jet through a spherical gold mirror cut into two halves, with a 30 cm radius of curvature. He atoms can be ionized only via two-photon absorption occurring through a multitude of two-XUV-photon combinations. The harmonic radiation is monitored by a XUV monochromator. The ionization products are detected by a time of flight (TOF) mass spectrometer.

The experimental evidence of observed two-XUV-photon ionization is given by the measurement of the three different ions (He^+ , H_2O^+ and Xe^+) yields as a function of the XUV intensity. H_2O and Xe have low ionization potentials (IPs), 12.6 and 12.1 eV respectively, as compared to the 24.6 eV IP of He and thus for the given XUV wavelengths ionize predominantly through single photon absorption. In log–log scale, the intensity dependence for He^+ is very nearly quadratic while for H_2O^+ and Xe^+ is linear. Based on LOPT, the measured slopes provide clear evidence of a two-photon ionization of He.

This two-XUV-photon detector further fulfils all requirements relevant to a second-order AC measurement. Its spectral and temporal response has been theoretically investigated. The energy resolved yields for the same harmonic superposition have been ab initio calculated by numerically solving the TDSE of He in the polychromatic field of the harmonic superposition [33]. For the spectral region of interest, the maximum deviation from an entirely flat response is of the order of 30% and for its largest part less than 10% [35]. This deviation does not affect the measured duration, as verified by further quantum calculations of second-order AC traces. The retrieved pulse durations from the AC are identical to the durations of the superpositions used in the calculation [35]. These calculations further provide clear evidence that the time response of the detector is also not distorting the measured durations, at least at the temporal level of 100 as. Note that an instantaneous temporal response is not a priori valid for the two photon process at this temporal scale. This rigorous assessment of the detector indicates optimal operational specifications.

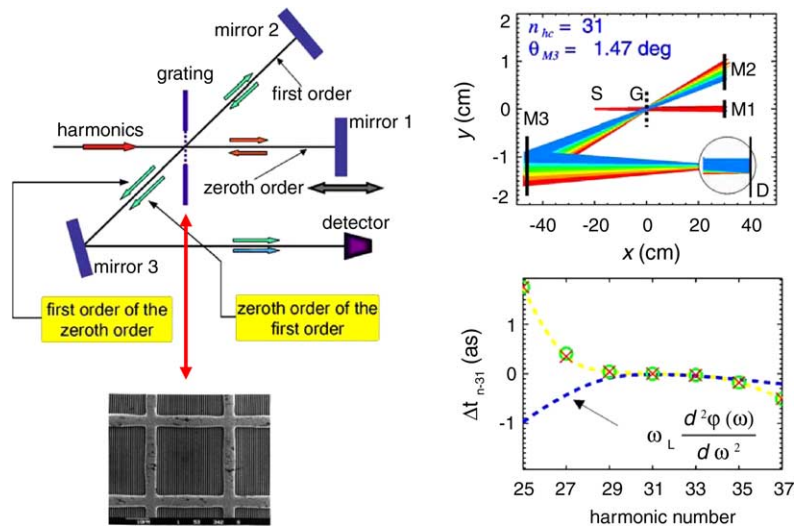


Fig. 3. The transmission grating interferometer. The principle (a). Dispersionless geometry imaging the grating on the detector (b). Dispersion characteristics (difference in arrival time between 31st and another harmonic (c)) (see also Ref. [36,37]).

In the quest of a solution to the problem of the dispersionless broadband XUV autocorrelator two different set-ups have been designed, developed and tested. Although the first one could not be used in the second-order AC measurement of higher harmonics at their present intensity level, its excellent properties offer a valuable tool to the metrology and applications of the XUV radiation of brighter sources and thus it is worth outlining its operation here. It is a Michelson type interferometer arrangement in which the beam splitter/combiner is a free standing transmission grating (Fig. 3). Zero- and first-order diffraction rays of the same frequency are retro-reflected and recombined at the grating through first- and zero-order diffraction, respectively. Correlation measurements can be performed by translating one of the two spherical mirrors (M1 or M2). For the ideal case of a single ray it becomes immediately apparent that equal optical paths guarantee dispersionless operation. For the realistic case of extended and diverging beams, ray tracing analysis [36] has shown that by imaging the grating on the detector, the set-up is dispersionless down to the 1 as regime. The interferometer has been tested in the ‘fs’ regime in measuring a second-order

autocorrelation of the third harmonic [37] of the Ti:Sapphire laser system of FORTH-IESL (800 nm, 2 mJ, 50 fs, 1 kHz rep. rate). The set-up has a flat spectral response for a very large energy range, with lower and upper limits set by the grating constant and the absorption edge of the grating material. At the same time it allows for wavelength selection using slits or knife edges in the parts where the radiation is spatially dispersed. A serious drawback is its lower than 1% throughput, due to the double diffraction. Thus this arrangement is only appropriate for cross-correlation measurements of higher harmonics with the IR fundamental frequency or for non-linear AC measurements of intense XUV radiation like that foreseen for the advanced XUV/X-ray sources based XFELs.

A more efficient autocorrelator design is that of the slit spherical mirror [38] (Fig. 4a). This arrangement can be used for a second-order AC measurement by piezoelectrically translating one of the two mirror halves. Unlike the amplitude splitting arrangements (conventional Michelson), this technique is a wavefront splitting device [39]. As such, a delay variation results not in a change of the total energy reaching the detector, but simply in a spatial redistribution

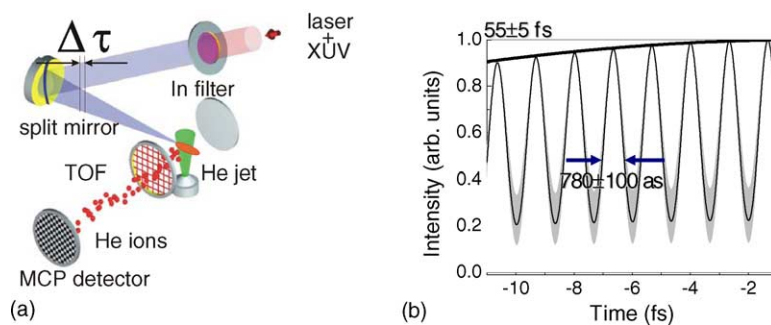


Fig. 4. The second-order AC measurement. Autocorrelator set-up (a). Attosecond pulse train constructed from the measured pulse and envelope duration values (b).

of the energy in the focal volume. This local intensity rearrangement induces a modulation in the measured signal. For a quantitative analysis of the AC traces a thorough study of the volume intensity autocorrelator is presented elsewhere [38]. The main result of this study is that its peak to background ratio is reduced to two as compared to the ratio of three of a conventional AC, but is still high enough to observe a modulated signal from which the mean value of the ‘as’ individual train pulses (“wagons”) is extracted.

Applying this technique to the superposition of the 7th–15th harmonics, a mean pulse duration of 780 ± 80 as has been extracted [38]. Using the same technique at lower temporal resolution and a larger delay interval, the duration of the train envelope has been determined to be 55 ± 5 fs. From the measured values of the pulse and envelope durations and assuming Gaussian distributions for both the pulse train has been roughly constructed (Fig. 4b). The total number of photons in the train is $\sim 10^{14}$ and in each burst $\sim 10^{13}$. The focused intensities reached are of the order of 10^{11} W/cm². This measured duration of the individual pulses is more than twice its Fourier transform limited (FTL) value of $\tau_{\text{XUV}} = 315$ as. An estimation of this duration, from the phases resulting by the short trajectory [12] including the additional spatiotemporal chirp of each harmonic originating from the spatiotemporal laser intensity distribution at the generation volume is in reasonable agreement with the measurement [35].

5. Outlook

The main developments in the recently initiated and far from mature *attoscience* front have been reviewed. All different metrology approaches described above are currently rapidly improving and extended. Proof of principle applications are making their debut [40]. From all approaches described here emphasis has been given to our recent second-order AC measurement. This is partially in order to attract the attention of other XUV radiation communities and in particular to highlight the metrology and application solutions it offers for future research to be conducted with XFEL based light sources. Due to the high repetition rate and delivered photon fluxes from such sources our developments are expected to become particularly useful. The approach is straightforward extendable, by employing energy resolved photoelectron spectroscopy, to a second-order frequency resolved XUV gating [41], for nearly complete reconstruction of ‘as’ pulses or pulse trains. This development is complementary to the cross-correlation SPIDER [42] or FROG type [43] approaches particularly suitable for intense XUV sources.

It is finally worth reiterating that the described second-order AC experiment further opens up the field of applications of ‘as’ pulses by means of XUV-pump XUV-probe studies of ultra-fast dynamics. The present experiment is in fact an example of such an application. The ‘as’ pulse train

pumps an electronic wave packet in the virtual state of the two-photon ionization process. The temporal evolution of this wave packet is probed through the ionization step of the two-photon process. Since the evolution of the wave packet follows the *E*-field of the harmonic superposition [35], ionization reveals the temporal characteristics of the radiation field.

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References

- [1] G. Steinmeyer, et al., *Science* 286 (1999) 1507.
- [2] T.W. Hänsch, *Opt. Commun.* 80 (1990) 71.
- [3] Gy. Farkas, et al., *Phys. Lett. A* 168 (1992) 447.
- [4] S.E. Harris, et al., *Opt. Commun.* 100 (1993) 487.
- [5] I.P. Christov, et al., *Phys. Rev. Lett.* 78 (1997) 1251.
- [6] M. Hentschel, et al., *Nature* 414 (2001) 509.
- [7] N.A. Papadogiannis, et al., *Phys. Rev. Lett.* 83 (1999) 4289.
- [8] P.M. Paul, et al., *Science* 292 (2001) 1689; Y. Mairesse, et al., *Science* 302 (2003) 1540; H.G. Muller, *Appl. Phys. B* 74 (Suppl.) (2002) 17.
- [9] L.V. Keldysh, *Sov. Phys. JETP* 20 (1964) 1307; F.H.M. Faisal, *J. Phys. B* 6 (1973) L89; H.R. Reis, *Phys. Rev. A* 22 (1980) 1786.
- [10] P.B. Corkum, *Phys. Rev. Lett.* 71 (1993) 1995; W. Becker, et al., *Adv. At. Mol. Opt. Phys.* 48 (2001) 36; F. Lindner, et al., *Phys. Rev. A* 68 (2003) 013814.
- [11] M. Lewenstein, et al., *Phys. Rev. A* 49 (1994) 2117.
- [12] P. Salières, et al., *Science* 292 (2001) 902.
- [13] G. Sansone, et al., *Phys. Rev. A* 70 (2004) 013411.
- [14] M.B. Gaarde, et al., *Phys. Rev. Lett.* 89 (2002) 213901.
- [15] D.B. Milošević, et al., *Phys. Rev. A* 66 (2002) 063417.
- [16] H. Niikura, et al., *Nature* 417 (2002) 917; H. Niikura, et al., *Nature* 421 (2003) 826.
- [17] A. Baltuška, et al., *Appl. Phys. B* 65 (1997) 175.
- [18] M. Nisoli, et al., *Appl. Phys. B* 65 (1997) 189.
- [19] U. Morgner, et al., *Opt. Lett.* 24 (1999) 411.
- [20] D.H. Sutter, et al., *Opt. Lett.* 24 (1999) 631.
- [21] A. Shirakawa, et al., *Appl. Phys. Lett.* 74 (1999) 2268.
- [22] T. Brabec, et al., *Rev. Mod. Phys.* 72 (2000) 545.
- [23] R. Kienberger, et al., *Science* 297 (2002) 1144.
- [24] G.G. Paulus, et al., *Nature* 414 (2001) 182.
- [25] D.J. Jones, et al., *Science* 288 (2000) 635.
- [26] A. Baltuška, et al., *Nature* 421 (2003) 611.
- [27] P.B. Corkum, et al., *Opt. Lett.* 19 (1994) 1870; M.Y. Ivanov, et al., *Phys. Rev. Lett.* 74 (1995) 2933; E. Constant, et al., *Phys. Rev. A* 56 (1997) 3870.
- [28] N.A. Papadogiannis, et al., *Proceedings of the XIV GCL-HPL*, vol. 5120, SPIE, 2002, p. 269; M. Kovačev, et al., *Eur. Phys. J. D* 26 (2003) 79.
- [29] Ph. Antoine, et al., *Phys. Rev. Lett.* 77 (1996) 1234.
- [30] J. Itatani, et al., *Phys. Rev. Lett.* 88 (2002) 173903.
- [31] E. Hertz, et al., *Phys. Rev. A* 64 (1) (2001) 051801(R); M.G. Makris, et al., *Phys. Rev. A* 66 (2002) 053414.
- [32] J. Norin, et al., *Phys. Rev. Lett.* 88 (2002) 193901.

- [33] N.A. Papadogiannis, et al., *Phys. Rev. Lett.* 90 (2003) 133902;
N.A. Papadogiannis, et al., *Appl. Phys. B* 76 (2003) 721.
- [34] J. Peatross, et al., *Opt. Lett.* 19 (1994) 942.
- [35] L.A. Nikolopoulos, et al., *Phys. Rev. Lett.*, in press.
- [36] E. Goulielmakis, et al., *Appl. Phys. B* 74 (2002) 197.
- [37] N.A. Papadogiannis, et al., *Opt. Lett.* 27 (2002) 1561.
- [38] P. Tzallas, et al., *Nature* 426 (2003) 267.
- [39] E. Constant, et al., *J. Phys. IV Fr.* 11 (2001) Pr2-537.
- [40] M. Drescher, et al., *Nature* 419 (2002) 803;
R. Kienberger, et al., *Nature* 427 (2004) 817.
- [41] T. Sekikawa, et al., *Phys. Rev. Lett.* 88 (2002) 19390.
- [42] F. Quéré, et al., *Phys. Rev. Lett.* 90 (2003) 073902.
- [43] R. Trebino, et al., *JOSA A* 10 (1993) 1101.