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Towards efficient generation of attosecond pulses from overdense plasma targets

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Abstract. Theoretical studies and computer simulations predict efficient generation of attosecond electromagnetic pulses from overdense plasma targets, driven by relativistically strong laser pulses. These predictions need to be validated in time resolved experiments in order to provide a route for applications. The first available femtosecond sources for these experiments are likely to be 10 fs pulses of a few millijoules, which could provide focal intensities at about the relativistic threshold. With particle-in-cell simulations, we demonstrate that the radiation resulting from interaction of such pulses with solid targets is expected to be attosecond trains with very high conversion efficiency as relativistic effects start to act.

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Contents

1. Introduction

Success in attosecond science based on laser–gas interactions and imposed intensity limitations of the nonlinearities [1] has increased the interest to this research area using super-strong laser pulses and solid targets. Relativistically strong fields satisfy the condition: $a_0 = eE_0/m_e\omega_0 c \geqslant 1$, where E_0 and ω_0 are the electric field amplitude and frequency, e and m_e are the electron charge and mass, and c is the speed of light. In this domain it is convenient to represent intensity in terms of a dimensionless amplitude, a_0: $I_0[\mathrm{W\,cm^{-2}}] = 1.37 \times 10^{18} a_0^2/\lambda_\mu^2$, where λ_μ is the laser wavelength in micrometers. In such strong fields, electrons driven by the Lorentz force $\mathbf{F}_L = e\mathbf{E} + e[\mathbf{v} \times \mathbf{B}]/c$, move not only in transverse and forward directions, but also towards the incident pulse due to charge-separation fields arising in plasmas. In overdense plasma targets ($\omega_0 < \omega_p$, $\omega_p = (4\pi n_e^2/m_e)^{1/2}$) electrons driven with relativistic velocities can produce motion away from and toward the incident pulse, providing almost total reflection and Doppler shifting of the resulting radiation, and leading to efficient generation of attosecond electromagnetic pulses and electron bunches (http://www.eecs.umich.edu/CUOS/attosecond).

The strong fields of high power lasers have introduced optics into the relativistic regime [2]. Systems capable of testing laser–matter interaction in this regime are tending to ever-higher field strengths (http://eli-laser.eu/). They may even access the nonlinear regime of quantum electrodynamics, in which the radiation processes should be considered with an account of quanta recoil as well as electron–positron pair creation [2]–[4].

A great help in study of the relativistic nonlinearities is computer simulation with particle-in-cell (PIC) codes [5]. The Maxwell equations resolved together with the relativistic equation of motion for macroparticles in a self-consistent manner allow one to foresee the basic features of laser–plasma interaction. Computer experiments allow the extraction of many possible diagnostics, which are not accessible in real experiments. For the study of overdense plasma an important simplification was the introduction of a boosted frame [6], allowing for consideration of oblique incidence in one dimensional (1D) PIC simulations [7]. In this way the interaction with solid-density targets could be simulated within a reasonable time, allowing for the resolution of the plasma frequency of ionized matter and even higher. Simulations studying the effects of the transverse pulse width in 2D and 3D are still limited to a model plasma description with reduced plasma density. PIC codes have validity from below the threshold for relativistic behavior up to intensities where radiation reaction becomes important. A recent suggestion to keep an account of radiation reaction effects in PIC codes [8] allows the study of laser–plasma interaction up to the limit where the nonlinear regime of quantum electrodynamics comes into play.

In this paper, we discuss theoretical predictions and experimental observations in laser interaction with solid targets with respect to the production of efficient attosecond pulses. We review possible femtosecond sources capable of delivering proof-of-principle experiments on attosecond pulse production from solid targets. For the identified incident pulse parameters we provide PIC simulations demonstrating the expected results on attosecond pulse generation and influence of relativistic parameter a_0. In concluding, we discuss the future prospects and limitations of such attosecond pulse production and touch on the status of relativistic attosecond science in laser–solid interactions.

2. Theoretical predictions and experimental observations

First theoretical studies in this domain concerned the generation of harmonics in the interaction of relativistically strong laser pulses with overdense targets [9]–[14]. To explain these findings an oscillating mirror model was suggested [9]. In this model it was assumed that an electromagnetic field is reflected from a thin layer of electrons, which oscillates under the action of the incident light in the direction perpendicular to the target surface. Such an understanding of collective behavior was motivated by PIC simulations [9].

Based on the oscillating mirror model a further suggestion was made to generate attosecond pulse trains in the reflection of intense laser pulses from solid surfaces [15]. Using extremely short pulse duration and tight focus [16], the λ^3 regime, efficient (10%) generation of isolated attosecond pulses via reflection, deflection and compression was also proposed [17] with the support of 2D, 3D PIC simulations, using different target geometries and plasma profiles, and a range of pulse amplitudes [17]–[20]. The scalability of attosecond pulses using higher laser pulse amplitudes for the generation of even shorter pulses of duration $\propto 1/a_0$ was shown using boosted frame 1D PIC simulations. 2D simulations have revealed discrimination in the coherent reflection of the light outside the specular cone due to the active role of the electric field and high spatial and temporal gradients of the incident pulse. 3D simulations have demonstrated potential focusability of the attosecond pulse using the same target where it was produced, and anisotropy of the attosecond pulse both in and out of focus. Beside the electromagnetic pulses, it was demonstrated that, with specific conditions of large angles of incidence, the electron bunches, driving the reflection of the light at the target, could be extracted synchronously into the vacuum, inheriting the attosecond duration [18].

One more proposal concerned a thin foil for the production of attosecond pulse trains [21]. In this study the optimal conditions for the foil were found for s- and p-polarized laser pulses, different angles of incidence, and validated with 2D PIC simulations. Spectral filtering and optimization of conditions for the generation of single attosecond pulses were also discussed.

Other proposals concerned the pre-existing techniques in attosecond science [1]: harmonic filtering and polarization gating [22]–[25]. Using conditions not optimal for a single attosecond pulse production, and introducing an ideal harmonic filter, it is possible to produce a train of even shorter attosecond pulses or to isolate a single attosecond pulse at the expense of the efficiency. However, these proposals have been validated only in 1D.

In [26] using output data from the PIC code for normal incidence and propagating the fields in a 3D space it was found that the harmonics were inside the pulse total shape. An anisotropic feature was also observed by these authors, in agreement with recent and earlier work [19, 20, 27]. Another group using a similar set-up has revealed that much stronger attosecond pulses could be observed in the far-field off the central axis, and they do not need to be filtered [28]. This means that the compression is stronger when the electric field is not parallel to the surface, i.e. at oblique incidence, as was observed in other work [17], [19]–[21].

A conceptual model for attosecond pulse production is the Doppler up-shift of the radiation from the moving mirror by a factor $4\gamma^2$, where $\gamma = (1 - v^2/c^2)^{-1/2}$, and v is the velocity of the mirror. A realization of such a 'flying' mirror in gas targets has also been proposed [29]. In the solid target case, the generation of electron current by the incident light in a thin layer of the target, along the direction of the incident pulse, providing Doppler up-shift or down-shift, or, the same, phase compression or decompression, leads to the transformation of the incident radiation into attosecond pulses [2, 17]. Analytical description of attosecond pulse production is limited by a number of assumptions, based on observations from PIC simulations. PIC simulations provide a self-consistent description limited by computational resolution.

A platform for attosecond pulse work was established in early experiments on harmonic generation from solid targets [30]–[33]. In recent experiments, using tens-of-femtosecond high-contrast laser pulses, a clear transition from non-relativistic to relativistic regime of high harmonic generation has been demonstrated [34, 35]. In addition, these observations were found to be in agreement with boosted 1D PIC simulations. Refined experiments with high contrast lasers [36] and with the introduction of controlled plasma gradients [34, 37] now allow more detailed study and optimization of harmonic output. Recently, experiments on the production of the 3000th order harmonics with 600 fs laser pulses focused using an $f/3$ paraboloid at intensities of 10^{20} W cm^{-2} were reported [38].

The evidence of harmonics is a potential signature for the identification of attosecond pulses in laser–solid experiments. This is still valid for relatively long tens-of-femtosecond laser pulses. However for few-cycle laser pulses the spectrum is expected to be broadband [19] and the harmonics, if observed, might not necessarily be centered on the integer values. Time-resolved measurements will be the main diagnostics in these experiments. While relativistic-intensity experiments have been performed at low repetition rate, $\leqslant$10 Hz, to provide sufficient statistics to characterize attosecond pulses, kilohertz laser systems are needed.

3. Relativistically strong femtosecond sources for attosecond pulse generation

The formation of isolated attosecond pulses in the λ^3 regime needs intense and ultra-short laser bursts with only a few (i.e. 1–3) cycles. In order to reach relativistic intensities ($\geqslant 10^{18}$ W cm^{-2}) and conditions for driving attosecond pulse generation at a high repetition rate (i.e. $\geqslant$1 kHz), the pulse energy provided by conventional kilohertz laser systems (typically a few millijoule) requires tight focusing of the laser beam to a spot size close to its diffraction limit ($\approx 1 \times 1\ \mu$m^2). Such small spot sizes are achieved routinely by wave front optimization with a deformable mirror [39]. The quest to confine the pulse energy to a few femtoseconds declares high demands on amplifier technology since the widely used Ti:sapphire systems provide typically 'long' (25–50 fs) pulses. Therefore further compression by external means is required.

The key concept for compression of amplified pulses is based on spectral broadening induced by the optical Kerr effect in a gas. In [40] the technique of spectral broadening in a gas-filled hollow fiber with subsequent chirped-mirror compression was introduced. Thereby pulses of 5 fs with $\approx$100 μJ were demonstrated. An up-scaling towards several millijoule has been shown feasible by post-amplification of broadband hollow-fiber pulses in a subsequent Ti:sapphire amplifier [41] or by adapting the waveguide parameters in order to increase the laser energy transmitted through the waveguide [42].

A conceptually simpler technique for intense few-cycle pulse compression is based on self-guiding (‘filamentation’) making an external waveguide obsolete. As a source of 5 fs, 200 μJ pulses [43] this technique provides a performance comparable to the hollow-fiber approach. Recently, it has been shown that the filament-based spectral broadening concept is scalable to higher energies. Sub-10 fs, 1.8 mJ pulses could be demonstrated with a contrast well suited for relativistic applications [44]. Both, the capillary and filament based method preserve the carrier-envelope phase [43, 45], which is an important prerequisite for reliable attosecond pulse sources.

Another emerging laser scheme delivering intense few-cycle pulses is optical parametric chirped pulse amplification (OPCPA). The large spectral gain of some nonlinearly phase-matched crystals is suitable to directly amplify few-cycle pulses without subsequent spectral broadening. Powerful sub-10 fs pulses are successfully generated in a multi-stage non-collinear β-barium borate (BBO)-based optical parametric amplifier [46, 47] with peak powers up to the terawatt level. However, technical challenges in the pump laser design currently restrict the repetition rate of such systems to 10–30 Hz, which is a severe drawback for spectroscopic applications.

4. Anticipating first results

Few millijoule, near-10 fs, pulses are expected to excite attosecond dynamics in dense targets. These are the initial parameters for the simulations of potential experiments. Intensities in focal spots of 1 or 2λ fall in the range between 10^{18} and 10^{19} W cm^{-2} ($\lambda = 0.8\,\mu$m).

We perform 2D PIC simulations for a 10 fs (3.75 cycles) p-polarized laser pulse with a focal spot of 2λ. The plasma target has a typical exponential profile $n_e = n_0 \exp(x/L)$, where $L = 0.1\lambda$ is a scalelength, $n_0 = 16n_{\rm cr}$ ($n_{\rm cr} = m_{\rm e}\omega_0^2/4\pi e^2$), and is rotated at 45°. The pulse is initiated in vacuum at $x = -10\lambda$, and focused on the target at $x = 0$ and $y = 0$. After the interaction, the pulse propagates in vacuum along the central specular direction up to $y = 40\lambda$.

The results of such simulations for two laser pulse amplitudes: $a_0 = 1$ and 3 are presented in figures 1 and 2. In figure 1 the intensity of the electromagnetic field, B_z^2, is shown 30 cycles after the interaction with the target. We observe a number of characteristics in the reflected radiation. The radiation is compressed most strongly only once per cycle. The degree of compression is greater for higher pulse amplitude. The peaks corresponding to each half-cycle are reflected with different delays, which is a sign that the radiating electrons have relativistic velocities from or toward the observer. The durations of strongest attosecond peaks are 370 and 260 as for these two cases; this being an indication of relativistic compression.

Figure 2 shows the spectrum of the radiation collected at $y = 15\lambda$. The spectral energy $B_z^2(x, \omega)$ is shown together with its lineout at $x = 0$ (dash-dotted line) and averaged value across the transverse direction (solid line). For these simulations 73 and 79% of the incident radiation has passed the collecting antenna. We observe that the relative conversion into harmonics is very high. The energy in the harmonics (not including the fundamental) in proportion to the total energy in the reflected radiation is 28 and 57%, for $a_0 = 1$ and 3, respectively.

These simulations provide motivation to identify attosecond pulse characteristics using moderate laser energies, at the very threshold relativistic intensity, and the λ^3 domain. The further study of attosecond features and verification of theoretical predictions needs to be done in close connection between experiments and simulations. The active role of the

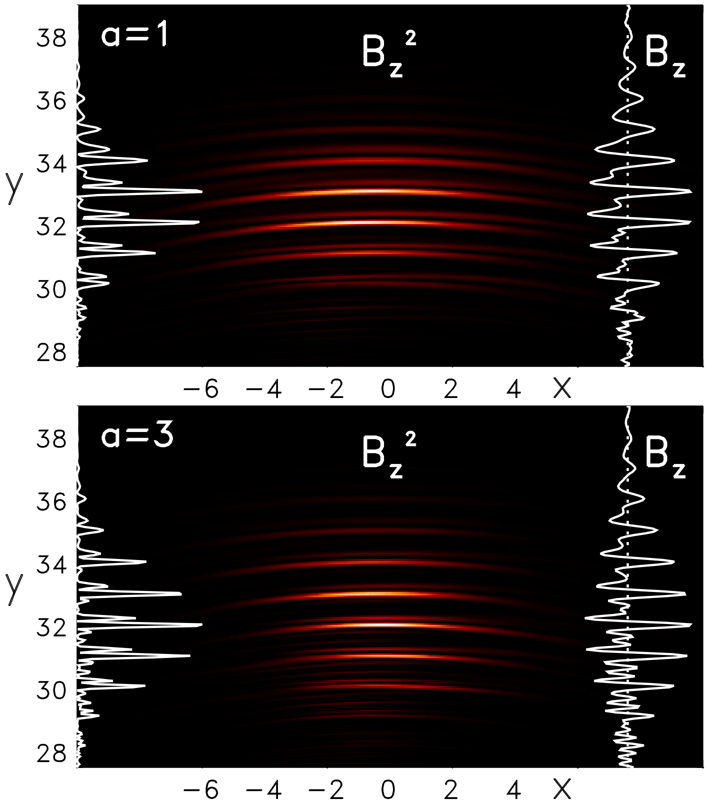

Figure 1. The instantaneous electromagnetic energy density, B_z^2, of the reflected light with its intensity profile and field, B_z, on a linear scale, 30 cycles after the interaction. Simulation parameters: 10 fs p-polarized pulse with amplitude $a_0 = 1$ and 3, incident with a focal spot size of 2λ at 45° on a plasma target having an exponential profile with a scalelength of 0.1λ. Here x and y are in units of λ.

plasma gradient has been observed already in experiments on harmonic production and in corresponding PIC simulations [34, 37]. Similar verification and optimization can now be done in studying attosecond features.

5. Discussion

For much higher intensity the details of attosecond pulse generation may change due to radiation reaction effects or quantum effects [2]–[4]. For example, in the second stage of the extreme light infrastructure (ELI) project (http://eli-laser.eu/) it is expected that 10 fs 1.5 kJ laser pulses focusable to a λ^2 spot will be obtained. At these high intensities (10^{25} W cm^{-2}) it is evident that new physics will be essential. The fastest electrons, supposedly responsible for reflecting the incident light, will lose their energy during this interaction, generating x-rays and γ-rays. For example, even at the level of 10^{22} W cm^{-2}, the total losses could be on the order of a per cent with respect to the incident laser energy [8]. Taking into account that these losses concern only a small group of the fastest particles, radiation reaction effects should be taken into account whenever one is considering such high intensities.

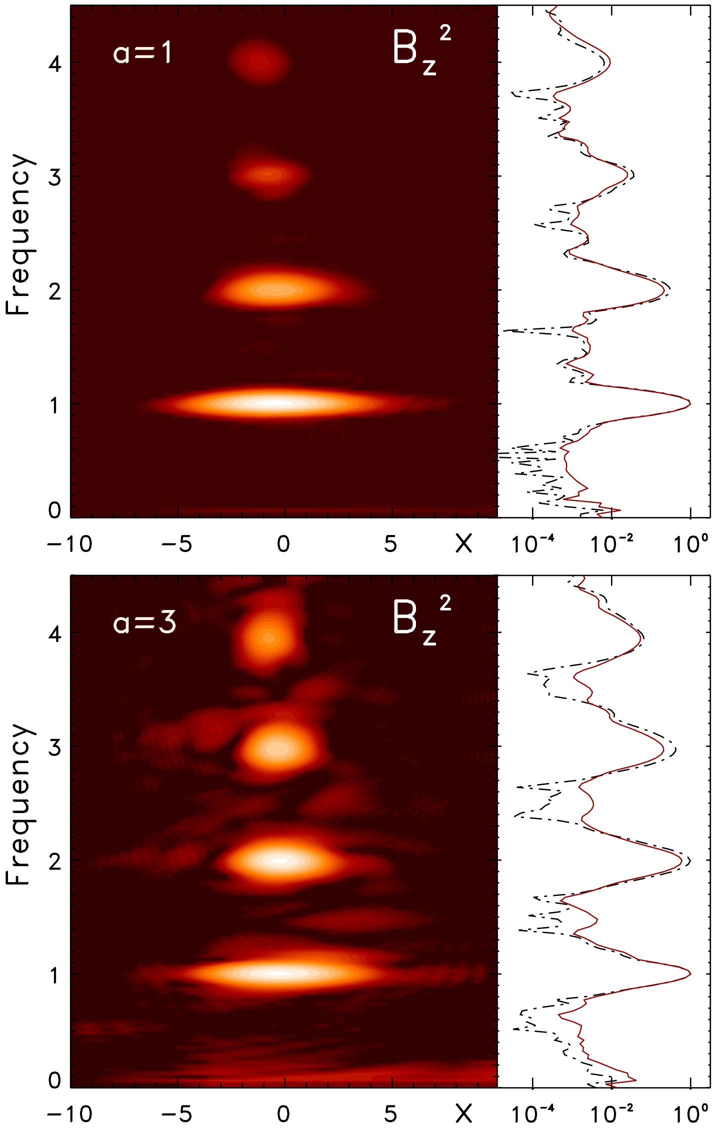

Figure 2. Spectral energy $B_z^2(x,\omega)$ on a logarithmic scale of the radiation passing antennas at a distance of 15λ from the target for the simulations corresponding to figure 1, and its lineout at $x = 0$ (dash-dotted line) and averaged value across the transverse direction (solid line) in arbitrary units. Here x is in units of λ, and frequency is normalized to laser frequency: ω/ω_0.

Recent experiments on high harmonic generation at relativistic intensity [34, 35, 38] are a good starting point in relativistic attosecond science. Theoretical predictions bring a variety of realizations for efficient attosecond pulse production [15], [17]–[25], using solid targets or thin foils, to produce ultra-intense attosecond ultraviolet or soft- or even hard-x-ray pulses. Scalability of attosecond pulses to higher intensity and shorter duration under specific conditions, and the limitations of such scaling might soon be verified in experiments. Radiation reaction effects and their influence on attosecond dynamics can also be studied with present-day lasers, which have produced intensities of 10^{22} W cm^{-2} [48].

The first possible experiments studying the temporal characteristics of radiation from laser driven overdense plasma interactions can be done nowadays using kilohertz laser systems delivering 10 fs, and few-millijoule pulses. Simulations for this specific range of parameters provide motivation for these experiments. Proposed auto-correlation techniques [19, 49, 50] may also be tested using such tools, the simplest of which is based on conventional optics coated in the visible to near ultraviolet. Despite inspiring theoretical understanding and many-dimensional-simulation evidence of efficient attosecond pulses, proof of principle experiments are still of high priority in order to validate the prediction of attosecond duration light pulses from laser–solid interactions.

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References

[1] Corkum P B and Krausz F 2007 *Nat. Phys.* **3** 381

[2] Mourou G A, Tajima T and Bulanov S V 2006 *Rev. Mod. Phys.* **78** 309

[3] Marklund M and Shukla P K 2006 *Rev. Mod. Phys.* **78** 591

[4] Salamin Y I, Hu S X, Hatsagortsyan K Z and Keitel C H 2006 *Phys. Rep.* **427** 41

[5] Birdsall C K and Langdon A B 1991 *Plasma Physics via Computer Simulation* (*Plasma Physics Series*) ed S Cowley, P Stott and H Wilhelmsson (Philadelphia, PA: Institute of Physics Publishing)

[6] Bourdier A 1983 *Phys. Fluids* **26** 1804

[7] Gibbon P and Bell A R 1992 *Phys. Rev. Lett.* **68** 1535

[8] Sokolov I V, Nees J A, Yanovsky V P, Naumova N M and Mourou G A 2007 *Bull. Am. Phys. Soc.* **52** 144
Sokolov I V, Naumova N M, Nees J A, Mourou G A and Yanovsky V P 2007 *Phys. Rev.* E submitted

[9] Bulanov S V, Naumova N M and Pegoraro F 1994 *Phys. Plasmas* **1** 745

[10] Gibbon P 1996 *Phys. Rev. Lett.* **76** 50

[11] Lichters R, Meyer-ter-Vehn J and Pukhov A M 1996 *Phys. Plasmas* **3** 3425

[12] Gibbon P 1997 *IEEE J. Quantum Electron.* **33** 1915

[13] Vshivkov V A, Naumova N M, Pegoraro F and Bulanov S V 1998 *Phys. Plasmas* **5** 2752

[14] Bulanov S V, Esirkepov T Zh, Naumova N M and Sokolov I V 2003 *Phys. Rev.* E **67** 016405

[15] Plaja L, Roso L, Rzążewski K and Lewenstein M 1998 *J. Opt. Soc. Am.* B **15** 1904

[16] Mourou G, Chang Z, Maksimchuk A, Nees J, Bulanov S, Bychenkov V, Esirkepov T, Naumova N, Pegoraro F and Ruhl H 2002 *Plasma Phys. Rep.* **28** 12

[17] Naumova N M, Nees J A, Sokolov I V, Hou B and Mourou G A 2004 *Phys. Rev. Lett.* **92** 063902

[18] Naumova N, Sokolov I, Nees J, Maksimchuk A, Yanovsky V and Mourou G 2004 *Phys. Rev. Lett.* **93** 195003

[19] Nees J *et al* 2005 *J. Mod. Opt.* **52** 305

[20] Naumova N M, Nees J A and Mourou G A 2005 *Phys. Plasmas* **12** 056707

[21] Pirozhkov A S, Bulanov S V, Esirkepov T Zh, Mori M, Sagisaka A and Daido H 2006 *Phys. Plasmas* **12** 013107

[22] Gordienko S, Pukhov A, Shorokhov O and Baeva T 2004 *Phys. Rev. Lett.* **93** 115002

[23] Mikhailova Yu M, Platonenko V T and Rykovanov S G 2005 *JETP Lett.* **81** 11

[24] Tsakiris G D, Eidmann K, Meyer-ter-Vehn J and Krausz F 2006 *New J. Phys.* **8** 19

[25] Baeva T, Gordienko S and Pukhov A 2006 *Phys. Rev.* E **74** 065401

[26] Geissler M, Rykovanov S, Schreiber J, Meyer-ter-Vehn J and Tsakiris G D 2007 *New J. Phys.* **9** 218

[27] Naumova N M, Bulanov S V, Nishihara K, Esirkepov T Zh and Pegoraro F 2002 *Phys. Rev.* E **65** 045402

[28] an der Bruegge D and Pukhov A 2007 *Phys. Plasmas* **14** 093104

[29] Bulanov S V, Esirkepov T and Tajima T 2003 *Phys. Rev. Lett.* **91** 085001
Kando M *et al* 2007 *Phys. Rev. Lett.* **99** 135001

[30] Carman R L, Rhodes C K and Benjamin R F 1981 *Phys. Rev.* A **24** 2649

[31] Kohlweyer S, Tsakiris G D, Wahlstrom C G, Tillman C and Mercer I 1995 *Opt. Commun.* **117** 431

[32] von der Linde D, Engers T, Jenke G, Agostini P, Grillon G, Nibbering E, Mysyrowicz A and Antonetti A 1995 *Phys. Rev.* A **52**

[33] Norreys P A *et al* 1996 *Phys. Rev. Lett.* **76** 1832

[34] Tarasevitch A, Lobov K, Wuensche C and von der Linde D 2007 *Phys. Rev. Lett.* **98** 103902

[35] Thaury C *et al* 2007 *Nat. Phys.* **3** 424

[36] Monot P *et al* 2004 *Opt. Lett.* **29** 893

[37] Tarasevitch A, Orisch A, von der Linde D, Balcou Ph, Rey G, Chambaret J-P, Teubner U, Kloepfel D and Theobald W 2000 *Phys. Rev.* A **62** 023816

[38] Dromey B *et al* 2007 *Phys. Rev. Lett.* **99** 085001

[39] Albert O, Wang H, Liu D, Chang Z and Mourou G 2000 *Opt. Lett.* **25** 1125

[40] Nisoli M, Stagira S, De Silvestri S, Svelto O, Sartania S, Cheng Z, Lenzner M, Spielmann Ch and Krausz F 1997 *Appl. Phys.* B **65** 189

[41] Seres J, Mueller A, Seres E, O'Keeffe K, Lenner M, Herzog R, Kaplan D, Spielmann C and Krausz F 2003 *Opt. Lett.* **28** 1832

[42] Suda A, Hatayama M, Nagasaka K and Midorikawa K 2005 *Appl. Phys. Lett.* **86** 111116

[43] Hauri C P, Kornelis W, Helbing F W, Heinrich A, Couairon A, Mysyrowicz A, Biegert J and Keller U 2004 *Appl. Phys.* B **79** 673

[44] Hauri C P, Trisorio A, Merano M, Rey G, Lopez-Martens R and Mourou G 2006 *Appl. Phys. Lett.* **89** 151125

[45] Baltuska A *et al* 2003 *Nature* **421** 611

[46] Witte S, Zinkstok R, Wolf A, Hogervorst W, Ubachs W and Eikema K 2006 *Opt. Express* **14** 8168

[47] Tavella F, Marcinkevicius A and Krausz F 2006 *Opt. Express* **14** 12822

[48] Bahk S-W, Rousseau P, Planchon T, Chvykov V, Kalintchenko G, Maksimchuk A, Mourou G and Yanovsky V 2004 *Opt. Lett.* **29** 2837

[49] Tzallas P, Charalambidis D, Papadogiannis N A, Witte K and Tsakiris G D 2003 *Nature* **426** 267

[50] Power E, Pentland J, Nees J, Hauri C P, Merano M, Lopez-Martens R and Mourou G 2006 *Opt. Lett.* **31** 3514