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Conference Paper *in* Proceedings of SPIE - The International Society for Optical Engineering · May 2009

DOI: 10.1117/12.820848

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Ultrabright Attosecond Sources from Relativistically Oscillating Mirrors

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ABSTRACT

The interaction of relativistically intense ($I\lambda^2$>>1.3 10^{18}Wcm$^{-2}\mu$m^2) laser pulses with a near step-like plasma density profile results in relativistic oscillations of the reflection point. This process results in efficient conversion of the incident laser to a phase-locked high harmonic spectrum, which allows the generation of attosecond pulses and pulse trains. Recent experimental results on efficiency scaling, highest harmonic generated and beam quality suggest that very high focused intensities can be achieved opening up the possibility of ultra-intense attosecond X-ray interactions for the first time.

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Keywords: X-ray generation, Coherent X-ray radiation, Relativistic Plasmas

1. INTRODUCTION

Resolving physical processes with attosecond time resolution has been made possible for the first time by exploiting the phase-locked nature of the harmonic frequency combs generated when a moderately intense (~10^{14}Wcm^{-2}) femtosecond laser interacts with gaseous medium[i]. The superposition of a number of harmonics leads to the production of an attosecond pulsetrain[ii] or – under suitable experimental conditions – an isolated attosecond pulse[iii]. Current attosecond sources are limited to fairly low photon energies (10s of eV) and have modest pulseenergy – largely due to the difficulty of phasematching harmonics efficiently.

A far more recent development is the detailed theoretical and experimental investigation of harmonics emitted when a relativistically intense laser pulse creates a relativistically oscillating plasma mirror (ROM)[iv,v,vi,vii,viii,ix]. Unlike harmonics from gaseous targets, this process requires relativistically intense laser pulses, ideally significantly above the relativistic threshold of 1.3 10^{18}Wcm$^{-2}\mu$m^2. At such intensities the conversion process becomes efficient with the harmonic spectrum displaying a slow decay to higher orders[vii] with a slope of $E_n/E_L \sim n^{8/3}$ (where E_n, E_L are n-th harmonic and laser energy respectively) and can extend to keV photon energies[viii]. Tantalizingly, ROM also offers the prospect of attosecond and zeptosecond duration pulses[v,vi] and ultra-high intensity[iv] X-ray pulses. Based on theoretical predictions and a 10J single cycle drive laser the peak source brightness of a 5 as pulse centred at ~500 eV photon energy should be around 10^{35} Photons s^{-1}mm^{-2}mrad^{-2}. These source properties present a quantum leap for attosecond pulses and appear achievable given the current state of the art of ROM harmonics discussed in this article. Particular attention is given to conversion efficiency, highest harmonic order, beam quality and temporal structure of the harmonics.

2. BACKGROUND

ROM[ix] essentially results from an oscillatory extension to Einstein's prediction for the frequency up-shift of light reflected off a perfect mirror moving at relativistic velocities – the relativistic Doppler effect[x]. In this theory a pulse of duration Δt at frequency ω_0 is shifted to a frequency of ω`=$4\gamma^2\omega_0$ (with the Lorentz factor γ>>1). Since the number of cycles in an electromagnetic pulse is a Lorentz-invariant the pulse is also compressed by a commensurate amount and the

Harnessing Relativistic Plasma Waves as Novel Radiation Sources from Terahertz to X-Rays and Beyond,
edited by Dino A. Jaroszynski, Antoine Rousse, Proc. of SPIE Vol. 7359, 73590G · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.820848

resultant pulse duration is $\Delta t` = \Delta t/4\gamma^2$ [x]. From this one can see that in principle it should be possible to achieve substantial frequency upshifts and extremely short pulses by reflecting a high power laser pulse of a mirror with suitable properties. The key difficulty is, of course, to create a reflective structure moving at a velocity close to the speed of light.

One approach to achieving such a mirror is to illuminate an initially solid target with an ultra-short, intense laser pulse to create a near discontinuous plasma-vacuum boundary. The electric field of the laser can efficiently couple to the plasma surface, causing the electrons to oscillate in phase with the laser, thus constituting a relativistic mirror oscillating at the laser frequency ω_0. Since the plasma density is higher than the critical density for such a scenario, the plasma acts as an efficient reflector of the incident laser light. In a seminal paper by Paul Gibbon[ix] it was shown that in such circumstances the incident laser-light is upshifted very efficiently to higher frequencies. The underlying process in the case of a relativistically oscillating mirror is in many ways similar to the process of the relativistic Doppler upshift described by Einstein[x]. The main difference is that instead of a constant value of γ describing the motion of the mirror surface, one now has Lorentz-factor that is a function of time γ (t).

As the position of this mirror surface is a temporal function of the incident optical laser cycle, the phase of the reflected light wave is modulated such that it is no longer sinusoidal. As can be understood from Fourier theory, such a waveform must contain many high order harmonics of the fundamental frequency.

The most recent theoretical development in the field by Gordienko et al. and Baeva et al.[iv,xi] identifies the sharp spikes in the temporal variation of the Lorenz factor γ as the key to the production of the highest harmonics. That this should be the case can be easily understood when one considers the temporal variation of $\gamma(t)$. Even assuming a very smooth variation of the actual surface velocity with time (e.g. $v(t)\sim\sin(\omega t)$) the corresponding variation of $\gamma(t)$ is sharply spiked. From Einstein's theory of relativistic Doppler upshift one would therefore expect the upshifting process to be restricted to a timescale of the order of the temporal width of each 'γ – spike' – substantially shorter than an optical half cycle – and the maximum upshift to take place when the Lorentz factor reaches its maximum γ_{max}. The physical origin of this substantially larger frequency upshift also derives directly from the γ–spikes. Since the emission of high harmonic orders only takes place for large values of γ a sharp temporal localization of the emitted harmonics results. The temporal duration of the γ–spikes reduces for increasing intensity as $T_{Spike}\sim T_0/\gamma_{max}$ (with $T_0=2\pi/\omega_0$)[xi]. The pulses of duration T_{spike} are upshifted and compressed by the factor of $4\gamma_{max}^2$ - familiar from the relativistic mirror. As a result the harmonics are emitted in short temporal bursts with $T_{burst}\sim T_{Spike}/\gamma_{max}^2\sim T_0/\gamma_{max}^3$ and hence, from Fourier Theory, must contain significant spectral components up to frequencies of $O\sim\omega_0\gamma_{max}^3$. In effect, the surprising new result of the theory of relativistic spikes is that the high energy cut-off and the ultimate slope of the spectrum is governed by the temporal compression and truncation of the electromagnetic pulse rather than the maximum upshift expected from a relativistic mirror moving at constant γ.

Note that at low harmonic orders another process – CWE harmonics – is also present[txii]. This process produces harmonic up to an order $n_{CWE}=N_{max}/N_{crit}$ (where N_{max} is the maximum plasma density and N_{crit} the critical density). For low intensities and low intensities (below $\sim10^{-19}$Wcm$^{-2}\mu$m^2) and suitable density scale lengths, CWE dominates over ROM harmonics.

3. EXPERIMENTAL

The main experimental difficulty is to achieve the near discontinous plasma density gradient required to form a well defined reflection point. The intrinsic contrast of a state of the art high power femtosecond laser is not sufficient to prevent a plasma from forming at times >1ps before the peak of the pulse at the high peak intensities required to achieve relativistic oscillations. Experimentally this imperfection of current day lasers can be corrected by the use of plasma mirrors(PM)[xiii], which are an ultrafast switch (~100 fs switch time) which can deliver about 20dB prepulse suppression per mirror with a throughput of typically 60-80%. All recent experiments investigating ROM have utilised PMs to achieve a controlled interaction. It should be noted that ROM has been observed using ps lasers without PMs. In this case the steep plasma density gradient is achieved by ponderomotive steepening[xiv]. While this does allow the phenomenon to be observed, this early approach leads to instabilities at the critical surface as a results of the steepening process[xiv] and consequently a very large divergence[xv].

The experiments discussed here investigating ROM harmonics were performed on the Astra[xvii] (Ti:Sapphire) and Vulcan[vii,viii] (Nd:Glass) lasers at the Rutherford Appleton Laboratory and employed PMs to reach sufficiently high contrast for ROM harmonics to be observed. Briefly, the parameter for the Vulcan runs were $I>10^{20}Wcm^{-2}$ in a 500fs pulse, while the Astra run was performed at $I\sim2\ 10^{19}Wcm^{-2}$ in 50fs.

The investigation of the temporal structure of the CWE harmonics reported in section 6 was performed on the ATLAS laser (Ti:Sapphire) at the Max-Planck-Institute for Quantum Optics. These experiments were performed at $I\sim4\ 10^{18}Wcm^{-2}$ in 45fs and without a PM.

a) **b)**

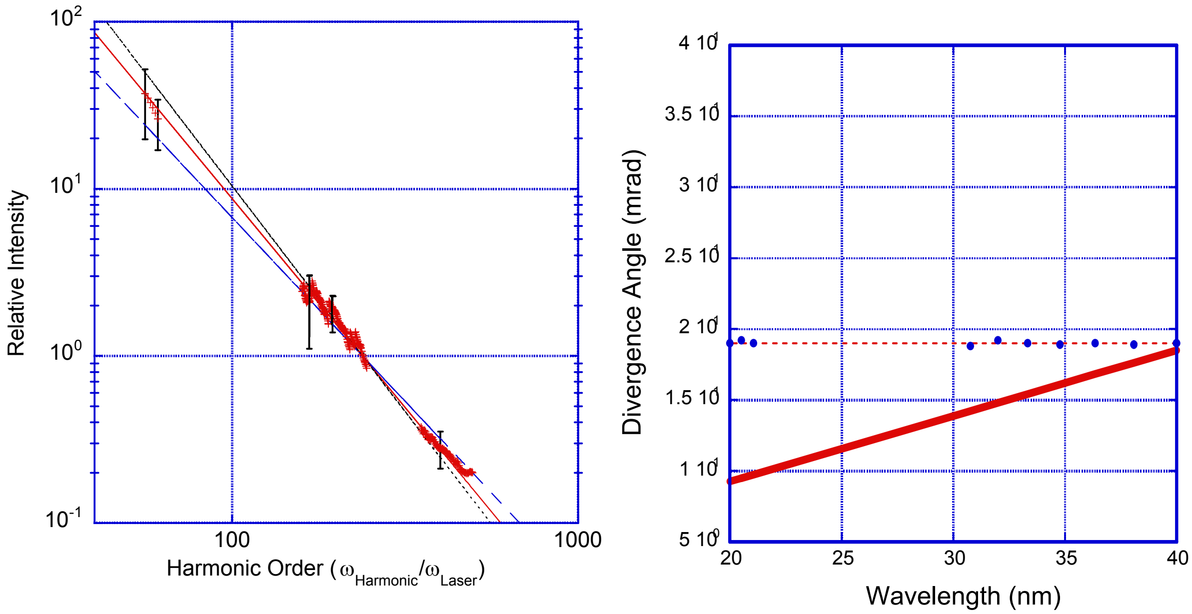

Fig. 1. a)Efficiency scaling of ROM harmonics (normalized to the 238th harmonic) measured on the Vulcan PW laser. The efficiency is fitted by a slope of $n^{-2.5\pm.2}$ in good agreement with theoretical predictions. b) Divergence of harmonic radiation. The solid line shows the diffraction limited divergence for the given wavelength and source size. The ROM harmonics between at 40nm can be seen to be diffraction limited with constant divergence to shorter wavelengths - consistent with a critical surface curved due to hole-boring.

4. CONVERSION EFFICIENCY AND HIGHEST HARMONIC ORDER

Our early work using ps duration pulses[xv] showed the conversion efficiency followed a powerlaw scaling such that the conversion efficiency $\eta\sim n^{-p}$ with p scaling from 5.5 to 3 in the intensity range of 10^{17}- 10^{19} $Wcm^{-2}\mu m^2$. Theoretical work by Baeva et al.[xi] found the ulimate limit of the exponent p=8/3 in the relativistic limit, i.e. where the dimensionless parameter $a_0=(I\lambda^2/1.3\ 10^{18}Wcm^{-2}\mu m^2)^{1/2}>>1$, suggesting that the conversion efficiency from laser to harmonic radiation can be substantial. For a 800nm laser wavelength, the efficiency into a single harmonic in the VUV at 80nm is then expected to be $\sim2.5\ 10^{-3}$ of the incident laser energy corresponding to pulse energies of 25mJ for a 10J driving laser, corresponding to peak powers in excess of TW and constituting the most powerful VUV source known to date. Even at higher orders the conversion efficiency is still appreciable for such a short pulse source with pulse energies of ~ 63µJ at 8nm and 0.15µJ at 0.8nm (or 1.5 keV). Note that attosecond pulses (or trains) span many harmonic orders and that the conversion efficiency would therefore be correspondingly higher – around 10^{-3} for an attosecond pulse centred at 100eV (or 10mJ for 10J driving laser) and achieving a peak power of in excess of a 100s of TW. Such performance corresponds to a step change in the field of attosources.

Experimentally, no angularly integrated measurement of the conversion efficiency has yet been performed. However, the slope efficiency has been measured in the range from the 60th to the 3000th. Figure 1a shows the slope efficiency in the XUV part of the spectrum which was found to be p=2.5±.2, in good agreement with Baeva's predictions. Note that it has been previously observed[xx] that the slope efficiency depends on the density scalelength, whereas Baeva's model calculates the ultimate limit. It is therefore likely that detailed control of the density scalength is required to reach the ultimate conversion efficiency predicted by theory.

The observation of the theoretically predicted efficiency slope versus harmonic order provides strong support that the theoretical interpretation of the ROM harmonics is indeed correct. Another key prediction – and hence an apt way to test the theory – is the to establish the highest order to which the power-law slope extends. Baeva et al. predict that the harmonic efficiency should roll over from the power-law scaling and decrease more rapidly above an order $n_{RO}{\sim}8^{1/2}\gamma^3$. Combining the results from several experimental campaigns investigating ROM harmonics shows gives strong support to the current theoretical framework (Figure 2).

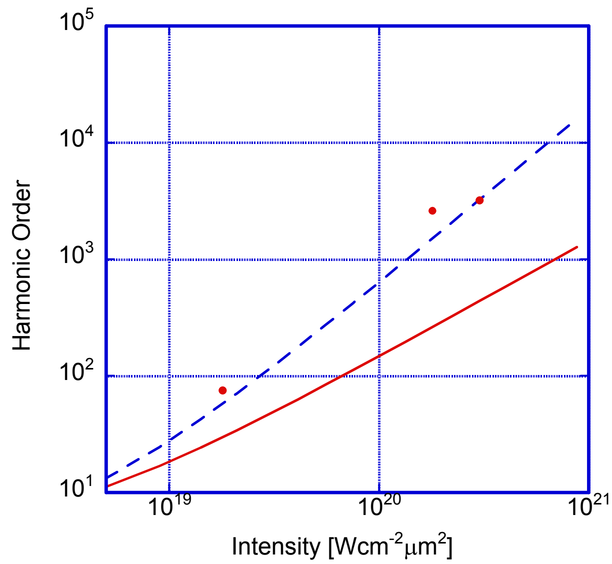

Fig. 2. Scaling of the highest observed harmonic before the conversion efficiency roll over vs intensity for experiments performed at λ=1.054nm. The highest observed harmonic clearly follows a γ^3 in excellent agreement with recent theory.

5. ANGULAR DISTRIBUTION AND BEAM QUALITY

The ultimate limits of brightness and therefore focused intensity of ROM harmonics as a source of coherent X-rays depends on the beam quality (transverse coherence), which ideally should be as close as possible to diffraction-limited. Theoretical investigation suggests that the harmonic radiation can display excellent (near diffraction-limited) performance[iv,xvi].

Under perfect conditions (spatially constant conversion efficiency on a planar surface) the angular divergence of the nth harmonic (θ_n) should simply be the diffraction limited divergence for the given wavelength, or, expressed in terms of the harmonic order n,

$$\theta_n \sim \frac{\theta_{Laser}}{n} \tag{1}$$

where θ_{Laser} is the divergence of the incident laser beam. Typical values of θ_{Laser} are ~15-30° (corresponding to f/4 - f/2 focusing). Of course, in a real experimental situation both the laser quality and surface shape may deviate from this idealised case. In the case of an intense laser interacting with an initially flat oscillating plasma, the laser pressure, $P{\sim}I/c$ (>10^9 bar for our parameters) results in the reflecting surface being initially pushed inwards due to the ponderomotive pressure[xiv]. The impact on the reflected harmonic radiation is that it is effectively reflected from a curved mirror and so will tend to exhibit a curved wavefront, passing through focus at some distance after the target. Since wavefront curvature of all harmonics is identical in this case all orders should display a constant divergence (unless diffraction is significant). Figure 1b shows results from a recent experimental campaign[xvii] which demonstrate that the ROM harmonics indeed have a constant divergence consistent with surface denting and that the 20th harmonic is diffraction limited in divergence. Clearly, if the surface has the appropriate shape, the increased divergence at harmonic orders >20 does not necessarily lead to a reduced focusability of the harmonic beam and may correspond to a very high intensity in the primary harmonic focus close to the target[iv]. This result also suggests, that the divergence of the harmonic beam can be controlled by changing the either the laser intensity distribution, pulse duration (reducing the surface deformation) or the surface shape. An approximately flat-top intensity distribution (e.g. a super-Gaussian) should lead to diffraction limited divergence angles[xviii].

A further remarkable and counterintuitive result of this experiment[xvii] is that the harmonic emission is insensitive to surface roughness of the order of the harmonic wavelength. This is contrary to the typically accepted principles of optics, which state that the roughness of a reflecting surface of the order of the wavelength of light will result in diffuse scattering.

These results suggest that excellent, near diffraction limited beam quality is indeed possible for ROM harmonics. For the highest harmonic orders the phase of the laser focus is possibly the dominant factor in determining the beam quality. Since the phase of the surface motion at any point of the plasma surface is locked to the local phase of the driving laser field[xix], laser phase variations will directly affect the phase front of the emitted harmonic radiation. Even small fluctuations in the local laser phase $\Delta\phi_{Laser}$ from an ideal flat (or spherical) wavefront will lead to substantial aberrations in the phase of the emitted harmonic radiation. The phase error for the n^{th} harmonic preserves the absolute wavefront error and hence the relative phase error $\Delta\phi_n$, measured in terms of the harmonic wavelength λ_n, is $\Delta\phi_n = n(\Delta\phi_{Laser})$. This implies that the generation of high quality keV beams (n>1000) requires excellent quality of the high intensity laser driving the interaction. In the focus of near diffraction-limited laser beams, such as in our experiment, this may not present a significant limitation, as the harmonics are typically only generated over a fraction of the central diffraction limited peak[xx] and hence in a region where the phase is highly flat.

6. TEMPORAL STRUCTURE

To date, no direct measurement of the temporal structure of ROM harmonics has been performed. However, it is clear from our understanding of the physical processes and linked experimental data that the harmonic emission must indeed take place in the form of attosecond bursts. As can be seen from discussion of the basic mechanism in section two, temporal compression is intrinsic to the frequency upshift that takes place with both a relativistic mirror at constant γ and a ROM. In the case of ROM, the compression is simply periodic which leads to the spectrum being modulated with the period of process ω and hence the emission of harmonics of laser frequency. Note that in general both odd and even harmonics are produced. There are however two exceptions: For normal incidence only odd harmonics are produced, since the ROM is only driven by the jxB at twice the laser frequency, while in the case of a single cycle pulse a continuum is emitted. Remember, that the fact that the harmonics extend to substantially higher frequencies than would be expected from the conventional moving mirror model is a direct result of the attosecond temporal bunching of the emitted harmonics. Consequently the observation of the $n_{RO} \sim 8^{1/2}\gamma_{max}{}^3$ scaling is evidence for the attosecond temporal bunching of the harmonic emission.

Recent work has identified a significant difference in the spectral phase of the harmonics emitted by the CWE[xxi] and ROM harmonics. The results of this work is that CWE harmonics are intrinsically chirped due to the spatially separated generation region of each harmonic, while the phase of ROM harmonics is shown to be essentially flat with regards to laser intensity and harmonic order. The intrinsic chirp of CWE harmonics leads to non transform limited pulse duration (though still in the attosecond regime). The attosecond nature of of CWE harmonics has recently been confirmed in an experiment performed on the Atlas laser[xxii]. The CWE harmonics were found to be emitted in pulses with a ~900fs FWHM. This result effectively provides an upper limit for the duration of ROM harmonics based on the underlying physics and also demonstrates that for harmonics $<n_{max}$ CWE provides an excellent, high conversion brightness source of attosecond pulses.

For multi-cycle pulses, the spectrum shows distinct harmonics corresponding to an attosecond pulse train. Single attosecond pulses can in principle be produced by either intensity gating or polarisation gating. Polarisation gating exploits the polarisation dependence of ROM[xxiii] and is effectively analogous to the polarisation gating concept used for HHG in gases[xxiv]. Intensity gating is ideally achieved using a single cycle pulse similar to the gas harmonic analog.

However, unlike HHG from gases, the highest harmonic scales much more rapidly with intensity ($\propto I^3$ as opposed to $\propto I$ in the case of gases). This implies that for a 3 cycle pulse (10 fs FWHM @ 800nm) orders above $0.8n_{RO}$ must be emitted in single attosecond pulse (and for normal incidence above 0.4 n_{RO}), making isolated attosecond pulses easier to achieve with multi-cycle pulses.

7. CONCLUSION

Harmonic Generation from Relativistic Oscillating Mirrors is a source of extremely bright attosecond pulses and allows high power lasers to be up-shifted to very high photon energies (many keV) with remarkable efficiency. ROM harmonics provide a step change in performance available for attosecond physics and open the realm of high intensity X-ray physics to experimental investigation.

Acknowledgements

The authors acknowledge the excellent support from the staff at the Rutherford Appleton Laboratory and MPQ and funding via EPSRC. MZ acknowledges support from the Royal Society.

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