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Tunable enhancement of coherent wake emission harmonics from laser solid interactions

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Introduction

Coherent Wake Emission (CWE) is a unique source of intense XUV radiation of attosecond duration. In this article a novel scheme is presented which demonstrates that enhancement and spectral control of the CWE radiation is achievable by modifying the interaction plasma density ramp.

Harmonic conversion processes at steep plasma-vacuum interfaces promise rapid advances in the generation of intense attosecond pulses [1] and provides an excellent diagnostic for the detailed and complex interaction of an intense laser with a solid target. This is of key importance for applications such as the Fast Ignitor scheme for fusion or laser driven ion accelerators, which depend sensitively on the plasma scale-length and temporal shape of the laser pulse, with remarkable variations in thermal X-ray and radiation yields observed experimentally [2,3].

As a source of intense XUV attosecond pulses, harmonics generated from the plasma vacuum interface have extremely exciting properties: near diffraction-limited spatial beam quality [4] with attosecond pulse duration [1] combined with high conversion efficiency, compared to other approaches [5]. The advantage of generating high harmonics from solid targets as an alternative to gases is that the plasma medium can withstand the use of much higher laser intensities, therefore the intensity of the attosecond pulses produced will be orders of magnitude greater. Consequently, this process is well suited to the latest generation of PW class femtosecond lasers and should allow the production of attosecond pulses with mJ pulse energies.

Theory

High order harmonic generation (HOHG) from solid density targets can be generated via two physically distinct processes, Coherent Wake Emission (CWE) [1,6] and Relativistically Oscillating Mirror (ROM) [3,4]. CWE harmonics are created within the plasma density ramp at densities $N_m = m^2 N_c$ (m: integer, N_c: critical density for driving laser frequency ω_0) that can be resonantly excited by the electrostatic density waves associated with bunches of Brunel electrons injected into the target once per laser cycle and emit electromagnetic waves via linear mode conversion. Since density oscillations can only be supported up to the maximum plasma frequency ω_p^{max}, CWE harmonics can only be generated up to a maximum cut-off order $n_{max} = \omega_p^{max}/\omega_0 = (N_{max}/N_c)^{1/2}$. CWE is the dominant process at lower intensities below around 10^{19} Wcm$^{-2}\mu$m^2 and provides an efficient means of generating harmonic radiation at wavelengths >20 nm. Note that CWE is not a pure surface-only effect, but instead is intrinsically linked to evolving plasma conditions in the plasma density ramp.

ROM harmonics are generated by the frequency up-shift of radiation reflected from the critical density surface, which oscillates at relativistic velocities in phase with the driving laser electric field [7]. Efficient ROM emission occurs only for relativistic laser interactions (>10^{18} Wcm$^{-2}\mu$m^2) and extends to few Å wavelengths with high efficiency [3] in the relativistic limit [9].

For CWE the cut-off frequency can be controlled by choosing materials of suitable density (e.g. for 800 nm laser BK7 glass results in n_{max} ~19). CWE is very sensitive to pre-plasma levels and, therefore the plasma scale length, L_s [10]. Tarasevitch *et al.* [10] show using 1-D PIC simulations that optimally efficient CWE harmonic generation is achieved for a short, but not infinitely steep, plasma gradient – $L_s > 0.1\lambda_{Laser}$. Such optimal generation is demonstrated for all orders and monotonically decreasing efficiency of the harmonic spectrum is maintained. If the scale length is reduced below this optimum the monotonic harmonic efficiency decays rapidly.

However it is still not known how the shape of the density profile effects generation. Simulations performed using the 1D PIC code PICWIG [8] show that enhancement of the higher CWE harmonic orders close to the plasma frequency may be possible depending on the plasma scale length. If a step like density profile (approaching solid density) is assumed the CWE harmonics emitted are tuned to a narrow band around the maximum plasma frequency (ω_p^{max}). A substantial enhancement of the signal (>10 times) is also observed [11].

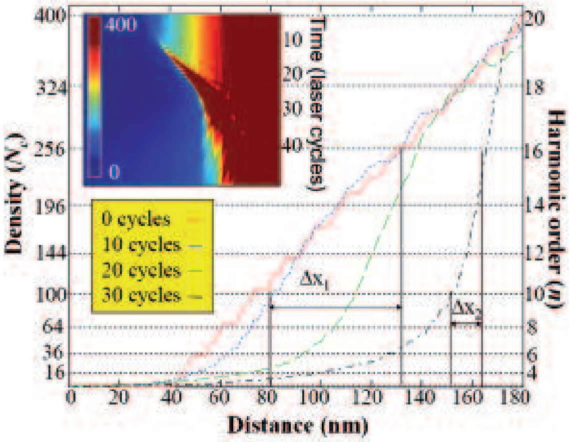

Figure 1. Density profiles from 1-D PIC simulation (mobile ions) showing the ponderomotive steepening of a 200 nm linear ramp from 0 to ~400N_c for a 45 fs pulse with a_0 = 7, with the peak of the pulse arriving at ~40 cycles (inset Figure 1). The horizontal dashed lines show the densities in the profile that correspond to the generation of a given harmonic order (n^2N_c). Lineouts/density profiles are shown for 0 cycles (red), 10 cycles (blue), 20 cycles (green) and 30 cycles (black).

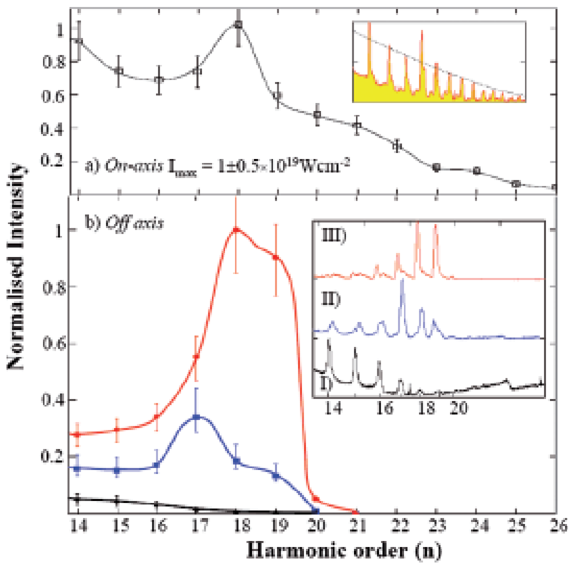

Figure 2. Experimental results demonstrating the enhancement of CWE harmonics due to density profile steepening. Figures display a sum over the background subtracted signal in individual harmonic orders (bars show the spread in experimental data and uncertainty in the background subtraction) with lineouts of raw spectra obtained shown in the insets. Figure 2a contains the on specular axis spectrum. Figure 2b contains the off axis signals detected outside the diffraction limited cone of the ROM harmonics (i.e. CWE orders only) for the following intensities I) 8±3×10^{17} Wcm^{-2} (black), II) 5±2×10^{18} Wcm^{-2} (blue) III) 1±0.5×10^{19} Wcm^{-2} (red). The observed change in relative signal of harmonic orders is calculated from the ratio of n=14 and n=19 for I) and III), giving an enhancement factor of >50. The tunability of the enhancement is observed clearly in the transition from 8±3×10^{17} Wcm^{-2} to 1±0.5×10^{19} Wcm^{-2}.

This spectral modification and enhancement can be interpreted as direct coupling of the laser energy (via Brunel electrons) to higher frequency resonant oscillations in the density profile, due to the localization of the emission region for the mth harmonic to the part of the density ramp with a density of approximately N_m=m^2N_c. Low order harmonic emission is suppressed due to the extremely steep density gradients in the vicinity of N_m, where the plasma oscillations are no longer efficiently excited. This weaker coupling to lower orders suppresses the low order harmonics and also allows stronger excitation of the higher density plasma due to reduced energy loss of the electron bunch in the low density plasma. Note that the relative intensity of CWE harmonics carries information about the shape of the density profile in the ramp from N_c to N_{max} which is not obtainable by other methods.

The density scale length used in the PIC code simulations [11] is simply an idealized case of the density profile in a ponderomotively steepened plasma with a laser pulse duration of tens of cycles. Figure 1 shows a 1-D PIC simulation of the evolution of a plasma with an initial linear density ramp of 200 nm length from vacuum to solid density for a 40 fs pulse with a_0=7. The density profile steepens rapidly over the duration of the interaction with a particularly steep ramp forming for the densities corresponding to the mid range harmonics (compare Δx_1 to Δx_2 in Figure 1), while the density profile for the highest harmonics remains largely unaffected. Clearly mid-range orders will therefore be suppressed and the highest orders near the cut-off should be enhanced during the most intense part of the laser pulse.

Experiment

The enhancement of harmonic orders near the plasma frequency was investigated using the Astra Titanium:Sapphire laser at the Rutherford Appleton Laboratory, which delivered 800 mJ on target in 50 fs with a central wavelength of λ_{laser}~800 nm. The pulse contrast was improved from a ratio ~10^8:1 to ~10^{10}:1 from peak to at ~1 ps prior to the main pulse using a plasma mirror which reduced the on-target energy to ~500 mJ. The maximum intensity that could be delivered on target was estimated at 2±0.5×10^{19} Wcm^{-2} (a_0~3). The target material was polished fused silica with a solid density of ~380N_c. Therefore for these experimental conditions, the maximum harmonic order expected from the CWE process is n_{max} ~19 which corresponds to the maximum plasma frequency. All orders above this are due unambiguously to ROM harmonic generation.

One of the key experimental challenges was to accurately separate ROM and CWE for precise estimation of CWE harmonic enhancement on a given shot. For this, a specially designed XUV flatfield spectrometer allowed angular separation of the harmonic signal on a single shot basis (Full description of setup given in B.Dromey *et al.* [4]). ROM orders were observed to be beamed into ~19 mrad 1/e^2 radius while CWE were observed to be beamed into >35 mrad 1/e^2 radius [4].

Spectra for on and off specular axis emission generated for an intensity I_{max} = 1±0.5×10^{19} Wcm^{-2} are shown in Figures 2a and 2b-III respectively. As can be

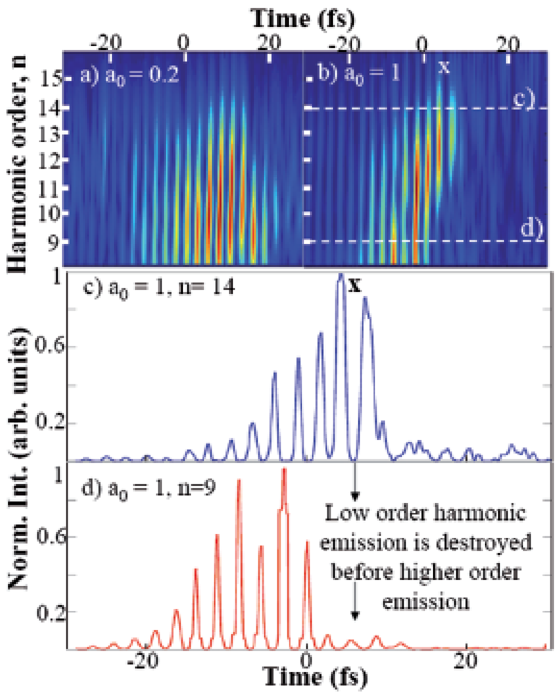

Figure 3. Effect of increased intensity on the temporal evolution of solid target harmonic emission harmonic spectra. Time-frequency analysis of 1-D PIC simulations (mobile ions) for a 40 fs Gaussian laser pulse incident at 45° on a 200 N_c maximum density plasma with a density ramp of 200 nm for two intensities, a) a_0=0.2 and b) a_0=1. Clear departure from monotonically decaying spectra is demonstrated in Figure 3b. Lineouts of the temporal evolution of the 14th and 9th harmonics for a_0=1 (white dashed lines in Figure 3b are shown in Figures 3c and 3d respectively).

seen, the off-axis emission contains only harmonics up to the order corresponding to the plasma cut-off harmonic (n_{max}~19), and therefore CWE only, while the on-axis emission clearly contains orders extending beyond this to n=26.

Experimental results for enhancement of CWE via density profile steepening are shown in Figure 2b. From the off-axis spectra (outside the diffraction limited ROM cone angle and therefore containing only harmonics produced via CWE) shown in the inset of Figure 2b it is clear that as intensity is increased there is a dramatic change in the shape of the observed CWE spectrum. For low intensities, the signal decays slowly towards ω_p^{max} (black trace) consistent with a ramp of sufficiently large gradient for all harmonic orders to be produced. However, as the intensity is increased the harmonic signal in higher orders is observed to be enhanced relative to lower orders, as can be seen in the blue and red traces. The observed factor relative enhancement between 8±1.75×10^{17} Wcm^{-2} to 1±0.5×10^{19} Wcm^{-2} for the 19th harmonic is >50 (see Figure 2 caption). For these experimental conditions the higher intensity gives a conversion efficiency of approximately 5×10^{-4} at ~42 nm, corresponding to an energy of ~0.25 mJ per harmonic peak per pulse.

The on-axis spectrum in Figure 2a contains both CWE and ROM orders and has a very different overall spectral shape and content to that of the off-axis spectra. The spectrum is observed to decay slowly to higher orders, with a characteristic ROM power law scaling[4]. However, the spectrum shown in Figure 2a, i.e. that of an enhanced CWE peak at ω_p rising over the ROM background, is clear illustration that CWE enhancement via density profile steepening is robust.

Time-frequency analysis of PIC simulations performed using longer duration pulses (Figure 3) show clearly that the principles derived from the fixed gradient PIC simulations[11] are applicable under conditions where there is substantial profile steepening, permitting the observed enhancement.

In Figure 3a, a 45 fs pulse with low intensity (a_0=0.2), and hence negligible profile steepening, demonstrates that the relative intensity of the harmonics barely vary from one optical cycle to the next and all harmonics peak in the cycles immediately after the peak of the laser pulse (Time = 0 fs). For higher intensities (a_0=1, Figure 3b), where profile steepening is significant, production efficiency of the mid-orders collapses before the peak of the pulse, as expected from the evolution of the density gradient[10] and only a narrow band of high harmonics near the cut-off is produced at the peak of the pulse. This demonstrates clear departure from monotonically decaying spectra expected for CWE[6]. Direct comparison of Figure 3b) a_0=1, intensity I ~ 1.8×10^{18} Wcm^{-2}μm^{-2} ≈ 3×10^{18} Wcm^{-2} at 800 nm, and Figure 2b II) with I = 5±2×10^{18} Wcm^{-2} show excellent agreement between simulation and experiment for the enhancement of harmonics near the CWE cut-off.

Conclusion

In conclusion we have demonstrated the first narrowband enhancement of harmonics generated during intense laser solid target interaction. Importantly this enhancement has been shown to provide the basis for a tunable source of coherent XUV radiation, but also a powerful ultrafast plasma diagnostic i.e. spectral enhancement at ω_p^{max} indicates the onset of very steep plasma density gradient interactions. This work improves the outlook for the accurate metrology of advanced plasma sources for ultrafast XUV pulses and ion beams.

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