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Harmonic generation from relativistically oscillating plasma surfaces

B. Dromey[1]*, D. Adams[1], D. C. Carroll[2], P. Foster[3], R. Hoerlein[4], S. Kar[1], K. Markey[1], P. McKenna[2], Y. Nomura[4], D. Neely[3], G. Tsakiris[4], M. Zepf[1]

[1] *Department of Physics and Astronomy, Queens University Belfast, BT7 1NN*
[2] *SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG*
[3] *Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot,OX11 0QX, UK*
[4] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1,D-85748 Garching bei München, Germany*
* *b.dromey@qub.ac.uk*

High order harmonic generation (HOHG) from intense laser - solid density interactions has emerged as a promising route to the generation of attosecond pulses extending to keV energies. With efficiency of the nth harmonic order, η_n, scaling as ~ $n^{-2.5}$-n^{-3} in the relativistic limit up to a maximum harmonic order n_{max}~ $8^{1/2}\gamma^3$ (where γ is the maximum relativistic Lorentz factor of the oscillating plasma surface), the potential for a bright solution to attosecond science is a distinct possibility. Here we present the first demonstration of $n_{max} \propto \gamma^3$ cut off scaling for both 500fs pulses and, excitingly, ultra short pulses (<50fs), giving clear indication that bright soft x-ray pulses can be generated using even modestly sized 'table-top' generation lasers. The angular distribution of the HOHG signal is also investigated. For ultrashort pulses there is distinct behaviour observed between the recently described coherent wakefield emission (CWE) process for harmonic generation and relativistic oscillating mirror (ROM) harmonics. Near diffraction limited performance for ROM HOHG is displayed with clear indication of source size shrinking for the cut-off orders (up to 40). CWE is observed to be emitted into cone angles several times that expected for diffraction limited performance. The close relation of the angular distribution of the emitted harmonic radiation to target roughness (χ) is shown confirming that in the absence of significant laser prepulse reflection takes place over a skin depth (σ_s), with near diffraction limited performance for $\chi < \sigma_s$.

High order harmonic x-ray generation (HOHG) has the potential to open up the world of physical processes on an attosecond timescale [1,2,3]. The key to this is converting high-power optical laser pulses into broad, phase-locked harmonic spectra extending to multi-keV photon energies – which can be achieved, with unprecedented efficiency and brightness, by reflection off relativistically oscillating plasmas [2,3]. Of particular note is the implication this has for the production of high brightness attosecond pulses [3]. For a fixed fractional bandwidth at a given central frequency, $n_{cf}\omega_{Laser}$, for the attosecond pulse, the energy in the pulse scales as η_{att}~$n_{cf}^{-1.5}$ (Eqn. 1) [3], where n_{cf} is the harmonic order of the carrier frequency and ω_{Laser} the laser frequency.

When an intense laser pulse interacts with 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 [1-3], effectively constituting a relativistic mirror oscillating at the laser frequency ω_{laser}. 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 and as can be understood from Fourier theory, contains many high order harmonics of the fundamental frequency. The most recent theoretical development in the field, based on similarity theory [4], identifies the sharp spikes in the temporal variation of the Lorenz factor γ as the key to the production of the highest harmonics. From this theory of '$\gamma-$ spikes' the conversion efficiency in the relativistic limit for the n^{th} harmonic is predicted to scale as $\eta(n)$~n^{-Prel} (Eqn. 1), with Prel = 8/3 [4]. Another important result of this theory is the prediction of the highest harmonic where the Eqn. 1 still applies up to an order n_{max} ~$8^{1/2}\gamma_{max}^{3}$, beyond which the conversion efficiency decreases more rapidly or 'rolls over' (where $\gamma_{max}=(1+3.6\times10^{-19}I\lambda^{2})^{1/2}$ corresponds to the maximum surface velocity, I (Wcm^{-2}) is the peak intensity and λ (μm) the wavelength of the laser).

Figure 1 shows the generation of the highest harmonic orders observed to date (>3000), generated for on target intensities $>10^{20}Wcm^{-2}$ using the Vulcan Petawatt laser (600J, 500fs) at the Rutherford Appleton laboratories, with scaling in the relativistic limit up to an intensity dependent $n_{max}(\propto \gamma^{3})$. This result is repeated (Figure 2) for lower intensities (~$10^{19}Wcm^{-2}$) and orders (up to ~40^{th}) at the Astra laser (~1J, 40fs) at the same facility when using sub nm, (a) and (b), and 20nm, (c) and (d), root mean square (rms) roughness targets.

This is the first indication that a bright source of harmonic radiation from solid targets extending to soft x-ray wavelengths is indeed possible using current generation table top lasers with modest intensity (~$10^{19}Wcm^{-2}$). In both cases the contrast of the incident pulse was improved using plasma mirrors (either single or double as required) [5]. The keV spectra were detected using a broad band mica crystal spectrometer with image plate detector while the soft x-ray spectra were obtained using an XUV flatfield spectrometer and Andor CCD detector.

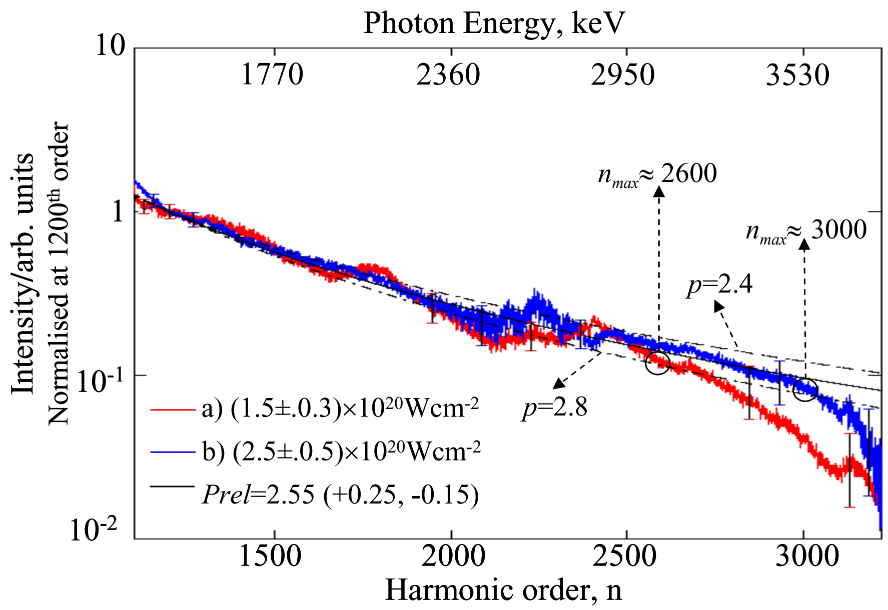

Figure 1. The relative intensity of the harmonic spectra for two intensities: a) (1.5±0.3)×10^{20} Wcm^{-2} (red trace) and b) (2.5±0.5)×10^{20} Wcm^{-2} (blue trace). Spectra are integrated along the spatial dimension and normalised at the 1200th harmonic (~1.4 keV, 8.8 Å). The lines are fits to the data such that $I(n)/I(1200)=n^{-P}/1200^{-P}$, where p is the fitting parameter. The best fit (solid line) is for a value of *Prel* = 2.55 for a) in the range 1.2 keV – 3 keV and b) in the range 1.2 keV – 3.5 keV, and is consistent with that expected for harmonic generation in the relativistic limit. The dashed lines represent p=2.4 and p=2.8 scaling, as labeled. Error bars (red ends for red trace, blue ends for blue trace) represent the uncertainty in the relative signal strength arising from the detector and filter transmission, taking into account the individual uncertainty in each of the relevant quantities. The absence of strong modulation in the spectra is due the limited resolution of the crystal spectrometer used.

The results presented in Figure 2 show the angular divergence of the ROM harmonics in the range 20th -30th order scaling with a linear α/n relationship (where n is harmonic order and α the incident laser cone angle) for intensities of ~10^{19}Wcm^{-2} and 50fs pulse length. The angular divergence of the cut off orders is observed to be ~ 2 × α/n, indicating approximately 50% source size shrinking due to nonlinear source scaling with intensity in the generation region. These spectra were only observed for targets with χ <20nm. As can be seen from Figure 2, CWE harmonic radiation is emitted into much larger cone angles (~2-3 times that expected from a near diffraction limited source).

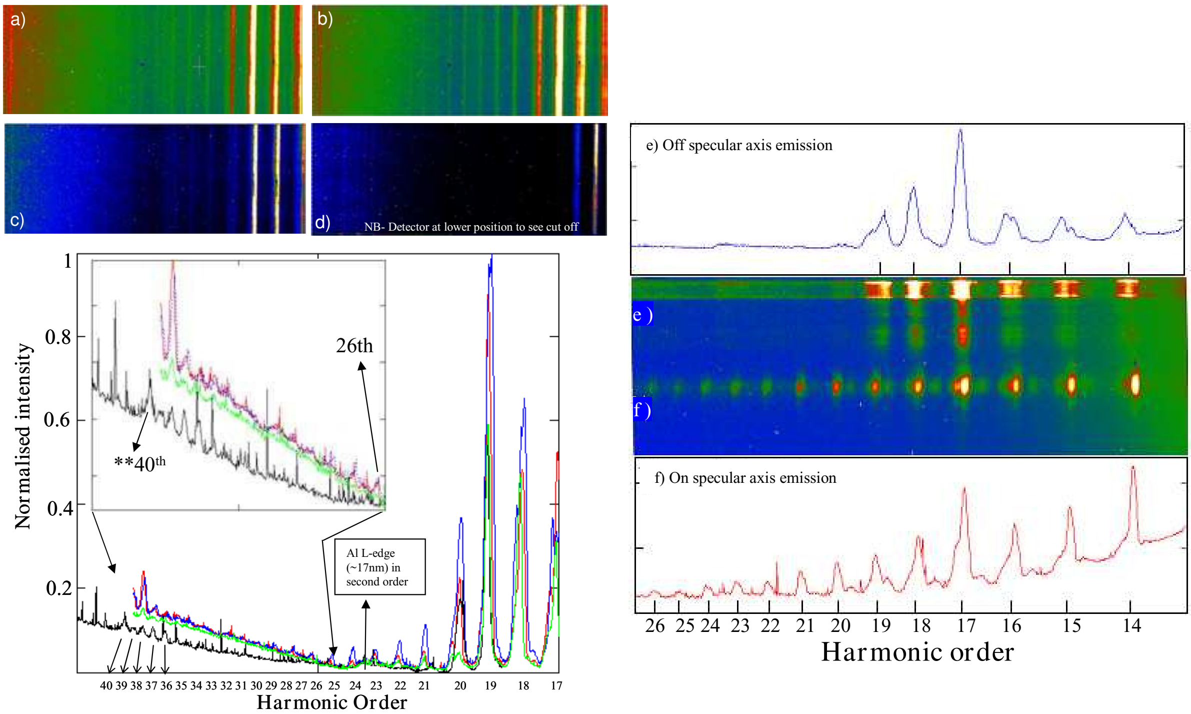

Figure 2 Harmonic generation from sub nm – a), red trace, and b),blue trace – and 20nm – c), green trace, and d), black trace, – root mean square (rms) roughness targets. CWE harmonic radiation extending to ~19th order and ROM harmonics extending to ~40th order are routinely observed for intensities of $1.5\pm0.5\times10^{19}$Wcm^{-2}. Figures 2 e) and f) show the distinct nature of the two generating processes. For this data the harmonic radiation emitted along the specular axis was apertured using a narrow slit while the radiation ~2.5cm off the specular axis was collected using a glancing angle gold focusing optic and redirected onto the ccd detector. The signal is rising towards higher harmonic orders due to increased spectrometer response to shorter wavelengths

For targets with χ~150nm the signal was observed to be scattered into large angles. This is clear evidence that the generation of harmonics takes place over approximately a skin depth σ_s at the critical density surface. For <50fs pulses at least, as $\chi\rightarrow\sigma_s$ reflected harmonic radiation is scattered into large angles even if the incident laser contrast is sufficient to generate orders extending up to n_{max} on targets with $\chi<<\sigma_s$.

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