

Relativistically Oscillating Plasma Surfaces - a route to intense attosecond science

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When a pulse of light is temporally and spatially coherent it means that its frequency components are longitudinally and transversely in phase, or have a *fixed phase relationship*. While coherent optical light permits the generation of femtosecond (10^{-15} s) pulses, coherent extreme ultraviolet (XUV) or X-ray radiation permits the production of attosecond (10^{-18} s) pulses due to its very short wavelength. Such pulses can be focused to approximately the size of a molecule (10^{-9} m). As a result coherent XUV radiation permits researchers to image the microcosm with unprecedented spatial clarity, on time scales that allow them to see events that are ordinarily 'blurred' (think short vs. long shutter speed for high speed photography).

To date the workhorse of attosecond science has been the generation of coherent extreme ultraviolet (XUV) harmonic in gases using intense optical laser pulses. While such endeavours have begun to reveal the inner dynamics of atomic processes, one of the key limitations has been the level of driving laser energy that can be converted directly into attosecond pulses. This constraint results primarily from a loss of phasematching between the driver and generated XUV radiation due to propagation over extended media lengths. Another key factor is that the driving laser intensity is limited by the saturation intensity for a given gas species ($<10^{16}$ Wcm²) – over ionise the medium there are no neutral atoms left with which to generate harmonics. Resolving these issues is a major goal for atto-science. For example, coupling more energy into the XUV will allow researchers to extend the illustrious pump-probe experiments from the femtosecond (molecular) to the attosecond (atomic) regime.

High harmonic generation from intense laser solid density interactions [1] provides an elegant solution to the above limitations. Over the last decade the relativistic plasma medium has demonstrated its clear potential as a next generation source of ultrafast, coherent X-rays. Recent observations of attosecond phase locking [2] and diffraction limited performance [3] have shown that the exceptional coherence properties of an intense driving laser ($>10^{20}$ Wcm²) can be transferred directly to the extreme ultraviolet (XUV) and X-ray regions of the spectrum with unprecedented efficiency. This is achieved via 2 physically distinct mechanisms: a) coherent wake emission (CWE) in the bulk plasma formed up to the maximum plasma frequency of the target [4], and b) the formation of a relativistically oscillating plasma at the critical density surface (1000's of orders [5]).

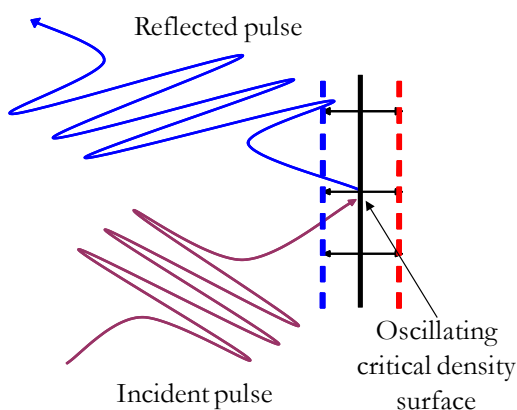


Figure 1 Schematic of a relativistically oscillating critical density plasma interaction.

When a high contrast laser pulse (i.e. ratio of peak to pre-pulse/pedestal level at ~ 500 fs is $>10^9$ for a 30fs pulse) is incident on a solid density target, a well defined critical density plasma surface is formed during the rising edge of the pulse. This results in a sharp rise to solid density over a distance less than the driving laser wavelength. Under these specific conditions the remainder of the incident laser pulse can couple directly to the critical density surface causing it to oscillate at approximately the speed of light. This effectively constitutes an oscillatory extension to Einstein's flying mirror for the relativistic Doppler effect. As described by Baeva et al using the theory of relativistic spikes [6] this mechanism permits rapid intensity scaling in the

relativistic limit to very high orders ($\propto \gamma^3$, where γ is the maximum relativistic Lorentz factor of the oscillating plasma). The formation of the smooth/well defined critical density surface for efficient harmonic generation is achieved by laser pulse contrast enhancing plasma mirrors [7].

Key experimental results to date obtained using the lasers at the CLF include the demonstration of harmonic scaling in the relativistic limit (Figure 2) [1], keV harmonic radiation and confirmation of the $\propto \gamma^3$ rollover (Figure 3) [5] and diffraction limited performance of harmonics emitted in reflection from solid density targets (Figure 4) [3].

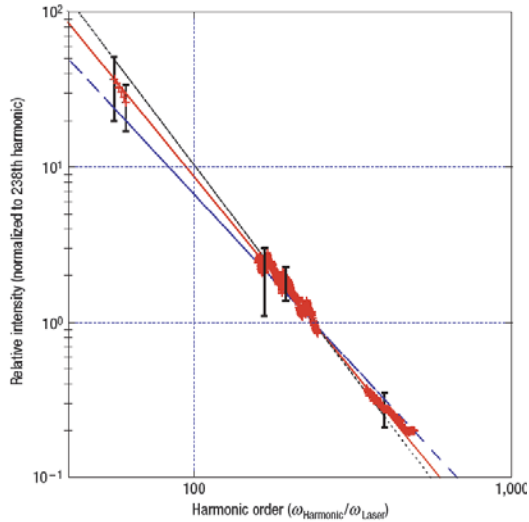


Figure 2 Harmonic scaling in the relativistic limit, $n^{-2.5 (+0.2, -0.3)}$ [1].

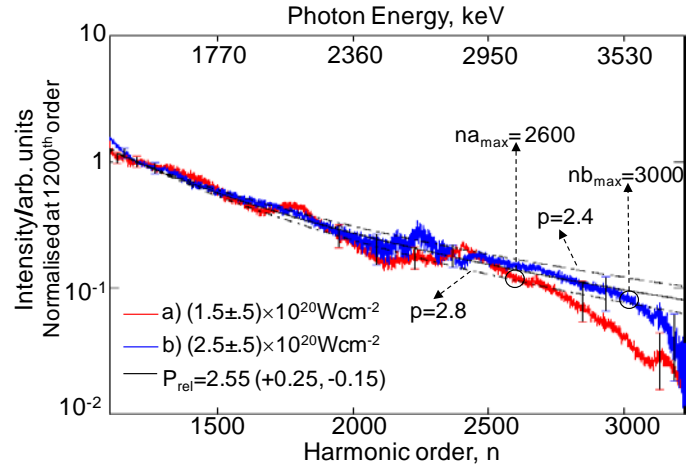


Figure 3 keV harmonic radiation and the γ^3 rollover [5].

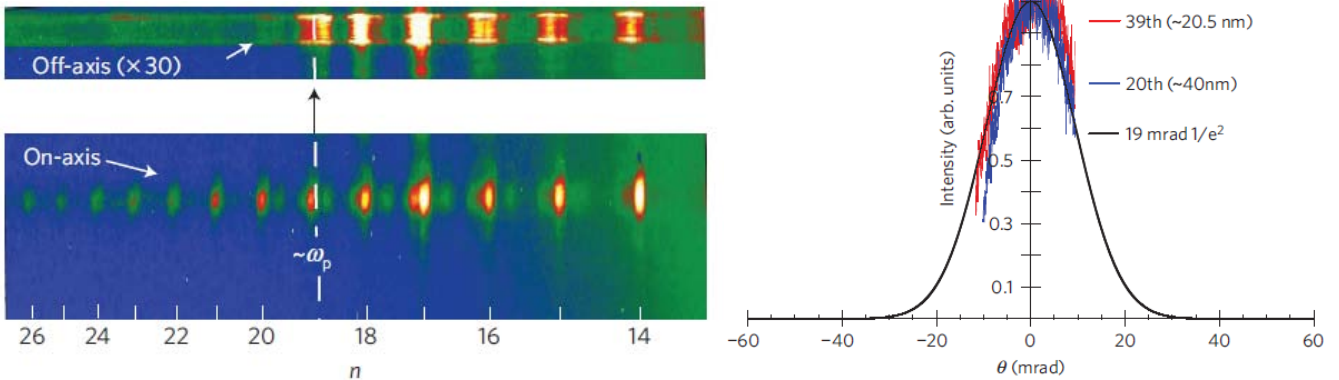


Figure 4 Diffraction limited performance of harmonic emission in reflection from solid density plasmas [3].

An intriguing aspect of this data has been the observation of beaming of both XUV and X-ray harmonics from targets with initial surface roughness greater than that of the emitted harmonic wavelength [3, 5]. As a result an analytic theory has been developed, supported by particle-in-cell code simulations, to study the process via which ultrafast plasma dynamics in the relativistic regime can account for the extreme smoothing of the initial surface roughness of a solid density target [8]. This ultrafast (few laser cycle) smoothing is shown to permit the formation of a relativistically oscillating plasma surface with qualities suitable for the experimentally observed coherence properties in emitted harmonic beams, namely diffraction limited performance and attosecond phase-locking [2]. This is a key step along the road towards realising a source of intense attosecond radiation.

More recently, in a novel series of experiments, the generation of harmonics in transmission from ultra thin (nm thick foils) foils has been examined (Figure. 5). This work has confirmed the existence

of matching conditions not only in reflection but also in the laser forward (transmitted) direction, leading to the novel observation of universality of scaling in the relativistic limit for harmonics from oscillating plasmas. These harmonics have been used to probe the density profile of a preheated near solid density target, demonstrating the clear application of ROM harmonics as a broadband ultrafast XUV/X-ray density probe, suitable for the *in-situ* study of warm dense matter and inertial confinement fusion targets.

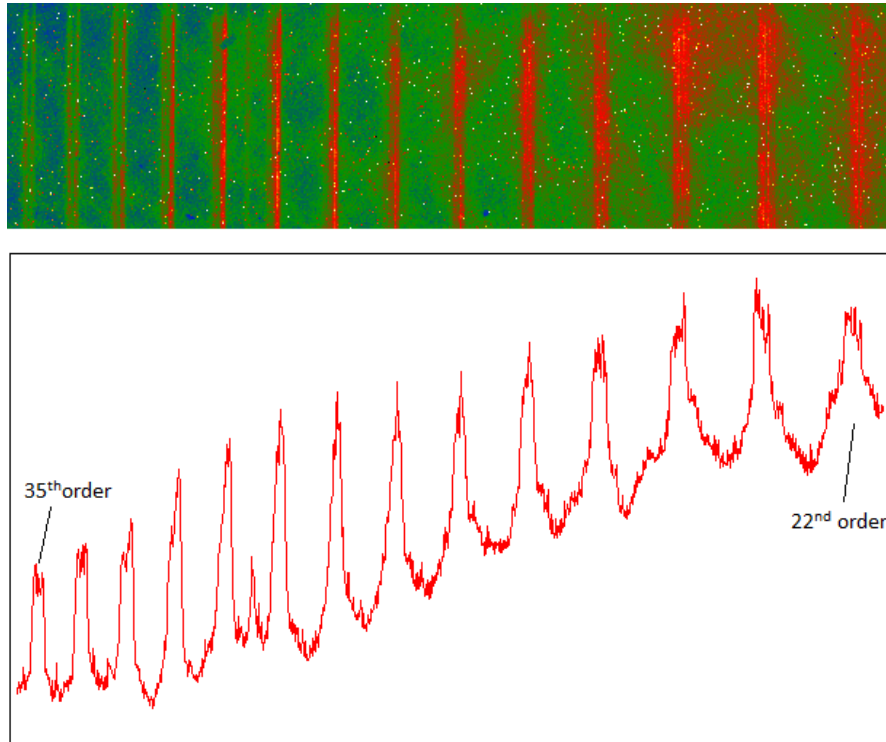


Figure 5 Transmitted ROM harmonics from thin foil experiments

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