Simulations of ultra-relativistic high harmonic generation from a solid target using reduced mass ions

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Abstract

In this paper we investigate high harmonic generation in the ultra-relativistic regime for directly incident laser radiation on solid targets. Through the use of 1D simulations using the EPOCH particle in cell code, the effect of ultra-relativistic intensities, and potential ion motion, is mimicked by using artificial mass ratios within the simulation. The reflected laser pulses are analysed for harmonic content and this data is presented. Both the effects of increasing pulse intensity and mass reduction are demonstrated, and the robustness of high harmonic generation is demonstrated.

Introduction and Motivations

The generation of harmonics through the interactions of lasers with various materials and targets has been a subject of significant scientific interest since the advent of the laser itself. The intent is the production of intense, ultra-short wavelength coherent radiation for the investigation of novel physics. Solid targets have become a subject of inquiry in recent years, with a particular focus on the possibility of generating high intensity, coherent atto-second pulse trains from short pulse femtosecond lasers. Such harmonics are anticipated in the XUV and VUV region, with temporal duration the order of atto-second duration. This XUV radiation is useful for diagnostics of dense plasmas and for investigations into strong field ionisation, atto-second physics, warm dense matter studies, molecular imaging and ultimately QED investigations [2].

In a typical femtosecond laser-produced plasma, there is little time for the material to expand and therefore we expect a density profile with a very short scale length. Most prevailing theories for the mechanism of solid HHG assume a step like density profile with a highly overdense electron density ($n_e >> n_c$). This results in a specular reflective mirror.

Bulanov et al [3] described through simulation analysis that the electromagnetic radiation reflected from a plasma was sourced from the oscillatory motion of an apparent reflecting charge sheet, as well as characterising a polarization dependence. In further analysis, it was proposed that the electrons be treated as a rigid step function oscillating around a relatively fixed ion background, now known as the oscillating mirror model (OMM) [3]. This model predicts a
rollover harmonic number of $4\gamma_{\text{max}}^2$ where $\gamma_{\text{max}}$ is the maximal $\gamma$ factor of the oscillating mirror. Later work by Gordienko et al provided evidence for an intensity scaling of $\omega^{-5/2}$[4].

A further development of the oscillating mirror model is the more physically motivated analysis presented by Baeva et al, referred to as the relativistic spike model [5]. Under this model, the generation of harmonics occurs at peaks in the relativistic factor of individual electron motion. This occurs at an apparent reflection point embedded in the oscillating outer surface of the plasma which serves to mask the more complex physical behaviour of the electron mirror. This advanced the previous OMM predictions, suggesting instead a rollover at a harmonic number of $\sqrt{8\alpha\gamma^3}$ where $\alpha$ is on the order of unity. They also predict a high intensity limit for the harmonic spectrum of $\omega^{-8/3}$.

Independent experimentation confirmation by Dromey et al confirmed a number of physical predictions made by the above theoretical models with respect to relativistic lasers. Ultra-relativistic laser intensities remain a subject of interest however and are difficult to study. This paper presents the results of a computational attempt to probe this regime and determine the robustness of the physical portrait of solid HHG.

**Approach and challenges**

If as suggested by Baeva, solid HHG does scale $\propto \gamma_{\text{max}}^3$ where $\gamma_{\text{max}} \propto a_0$, probing the limit at which we expect significant background ion motion is problematic. We cannot simply increase the laser intensity as this then drives ever increasing frequencies of harmonics, which must then be resolved by the simulation. Further to this, at such high resolutions we may also see a confusion of the signal and it may be difficult to resolve, at least relative to lower order harmonics.

To get around this issue, we instead progressively reduce the mass of the ion species within the simulation. This allows us to produce a facsimile of the effect which occurs when the laser drives ion acceleration deeper into the target. We also compare simulation results for different laser intensities and reproduce the full harmonic spectrum for both intensities.

The simulation box contains a linear-polarised laser pulse of wavelength $0.8\mu m$ with a $4.3$ fs FWHM directly incident on a pre-ionised hydrogen plasma of density $n_e = 100n_c$. This is simulated in the EPOCH particle in cell code. EPOCH is a parallelised, explicit, second order relativistic particle in cell code featuring dynamic load balancing, and comes with a customisable input deck with built in maths parser [1].
Simulations and Conclusions

Our simulations involved six configurations: two pulses of 5 and 10 $a_0$ and three configurations of ion mass ranging from the ideal immobile case to a positron electron limiting case. The intent was to test the robustness of the OMM and determine if we could reproduce the behaviour of the ideal model.

Of note are a number of interesting structures. While it is difficult to make out a cutoff or rollover, it can be loosely stated that there are interesting harmonic effects around the boundaries we would expect them in each case. It is possible that there is interesting physics hidden in the plasma, which will be subject to further investigation. The large "hump" structure in Fig 2 is likely the result of the more extreme modulations seen in the $a_0 = 10$ case in Figure 1.

Of equal interest, we have been able to reproduce previous simulation results indicating a wide variability in the scaling of high harmonic generation in the plateau region [7]. Our simulations also confirm the robustness of the harmonic generation mechanism, which appears to be remarkably consistent despite significant recession.

Figure 1: Comparison of incident and reflected $E_y$ pulse structure

Figure 2: The resulting harmonics from simulations of a pulse strength of 10$a_0$ with immobile ions, ions of 100$m_0$ and of 1$m_0$ are shown along with theoretical fits and predictions.
of the target surface.

In conclusion, we have attempted to resolve the effect of a reduction of ion mass on the roll over region experienced in a harmonic spectrum. While we were unable to resolve this rollover convincingly, this is consistent with previous simulation results. We confirmed the robustness of solid HHG even in extreme, near unphysical conditions, suggesting that there exists good experimental leeway with increasing laser power. We also confirmed the difficulty of resolving harmonic generation using particle in cell codes.

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References


