Radiation emission from ultra-relativistic plasma electrons in short-intense laser light interactions

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Abstract. Intense femtosecond laser light incident on overcritical density plasmas has shown to emit a prolific number of high-order harmonics of the driver frequency, with spectra characterised by power-law decays. When the laser pulse is \(p\)-polarised, plasma effects do modify the harmonic spectrum, weakening the so-called universal decay index \(p = 8/3\) to \(5/3\). In this work appeal is made to a single particle radiation model in support of the predictions from particle-in-cell (PIC) simulations. Using these, we further show that the emission radiated by electrons –those that are relativistically accelerated inside the plasma, after being expelled into vacuum, the so-called Brunel electrons– is characterised not only by the plasma line but also by ultraviolet harmonic orders characterised by the \(5/3\) decay index.

1. Introduction

Solid density plasma targets irradiated by highly intense femtosecond laser pulses have over recent decades proved to be a substantial source of high harmonic generation. Derived from the increasing levels in laser intensity, nowadays attainable in laboratory experiments, a corresponding increase in the spectral range beyond a thousand harmonics can be observed [1]. The scaling of the power efficiency \(\eta_m\), with \(m \gg 1\) being the harmonic order, was first shown empirically to scale as \(\eta_m \sim 0.9 \left( I_{20} \lambda_L^2 \right)^2 (m/10)^{-p}\), [2], where \(I_{20}\) denotes light intensity normalized to \(10^{20}\) W cm\(^{-2}\), \(\lambda_L\) the wavelength expressed in microns, and \(p = 5\). In particular, this scaling showed that the spectral decay index \(p\) decreased as \(I\) increased from weakly relativistic values \((a_0 \lesssim 1)\) to moderately relativistic levels, typically \(a_0 \sim 5\), where \(a_0 \sim 8.54 \left( I_{20} \lambda_L^2 \right)^{1/2}\) is the normalized quiver momentum. For increasing values of \(I_{20}\) it was found that the decay index \(p\) weakened from \(5.5\) at \(a_0 \sim 0.6\) to \(3.4\) at \(a_0 \sim 2.7\) [3].

As laser intensities approached the ultra-relativistic range (UR) the spectral decay index \(p\) weakened further in the power-law decays \(P_m \sim m^{-p}\). Baeva \textit{et al.} (BGP) [4] formulated
a model based on the assumption that the interaction physics remains invariant for constant values of a similarity parameter defined as \( S = n_{e0}/n_{c0} \), where \( n_{e0}/n_c \) is the ratio of the initial electron plasma density to the critical density. This model predicted a decay index \( p = 8/3 \), claimed to be universal, over the entire harmonic spectral range and characterised by a cut-off. However, only a few experimental insights of the \( p = 8/3 \) decay have been found in spectra obtained from high-intensity laser-plasma interactions [5].

Boyd and Ondarza-Rovira (BOR) [6] identified a transition from the BGP index to one where \( p = 5/3 \) across a range of parameter combinations for \( 1 \lesssim S \lesssim 5 \), showing that the deviation in the spectra from the 8/3 decay reflected details of the interaction physics in which emission at the plasma frequency \( \omega_p \) and its harmonics distort the spectrum of laser harmonics. Plasma waves are excited by bunches of UR electrons, generated by Brunel absorption that couple strongly to the radiation field at the plasma surface. In this paper, we appeal to a hybrid particle-PIC code model and apply this to further explore the spectrum and its decay characteristics, together with that observed from the Larmor radiation of Brunel electrons.

2. Single particle model and PIC simulations
The model used in this paper was due originally to Weatherall [7], to provide insight into the generation of radiation from sources as diverse as relativistic electron beam devices in the laboratory to galactic jets. The original model provided a representation of highly localised intense electrostatic fields by a soliton-like structure. In the case of laser-plasma interactions, the Brunel electrons – those that are first pulled out of the plasma by the electric field of the laser pulse and then relativistically accelerated back into the plasma during the consecutive half optical cycle (Figs. 1a and 1b) – bunch to excite plasma waves, that in turn couple to the radiation field in the strong density gradients at the plasma surface. The bunching of Brunel electrons provides the driver for the generation of Langmuir waves. Figure 2a shows the density contours of the Langmuir field that increases in a confined region inside the plasma, and Fig. 2b the corresponding correlation of electron trajectories and beam crossings that generate the electrostatic field [8].

![Image](image-url)

**Figure 1:** Brunel electrons followed when first expelled from the plasma and then reinjected back through the plasma surface: (a) particle trajectories and (b) normalized velocities.

These localised intense electrostatic fields are represented by a soliton-like structure \( E_{Lang} = -\frac{2}{3} \pi e n_e D \exp(-i \omega_p t) \hat{p} \), where \( D \) is the scale length and the dipole moment is oriented in the direction \( \hat{p} \). In this context, relativistic electrons serve as the agent driving beam-resonant Langmuir waves. We have chosen \( n_e \) and \( D \), tailored to conform to values measured in our PIC simulations.
Weatherall computed the emission spectrum from $E_{\text{Lang}}$, using the relativistic Larmor formula under the assumption that the soliton was decoupled from the electron beam, so that electrons followed an unperturbed linear trajectory in passing through its centre. Summing individual particle radiation over the electrons constituting the beam results in intrinsically weak emission, on account of a lack of coherence. However, Benford and Weatherall [9] noted that allowing for a spectrum of density correlations led to a plasma condensate spectrum characterised by a power-law decay, with decay index $p = 5/3$ across a range $\omega_p \lesssim \omega \lesssim \omega_c$; the cut-off frequency $\omega_c = 2\gamma_b^2 c / D$ where $\gamma_b$ is the relativistic beam gamma and $c$ the speed of light in vacuum. Our approach differs in that we adopt $E_{\text{Lang}}$ as a source field in the relativistic Lorentz equation, that allowed us to compute the radiation from an electron subject simultaneously to the electromagnetic laser fields and the electrostatic Langmuir field, this aligned along the pulse propagation. Whereas Weatherall appealed to plasma turbulence to provide beam coherence, in our case coherence results from relativistic electrons driven by the laser pulse itself.

In Figs. 3 a-b we present a comparison of two spectra generated from a PIC simulation and from the model here outlined, for the parameter combination $a_0 = 60, n_{e0}/n_c = 95$.

**Figure 2:** (a) Electron density contours inside the plasma where a high electrostatic field $E_{\text{Lang}}$ is generated, and (b) the correlation of this field with Brunel trajectories and beam crossings.

**Figure 3:** (a) PIC and (b) single particle emission for $a_0 = 60, n_{e0}/n_c = 95$ and $\tau_p = 3$ osc showing transitions from regions characterised by $p = 5/3$ to $p = 4$. Plasma modulation effects and emission at $\omega_p$ are discerned.

### 3. Radiation from Brunel electrons

Once we observed the similarities of the radiation spectra from both the particle model described above and from PIC simulations, we further explored the radiated emission from those selected Brunel electrons, previously tracked from numerical runs. We computed the emission
from the Larmor formula of a moving charged particle, to perceive that the contribution to the reflected field from the plasma electrons had in fact two significant characteristics: a robust emission at the plasma line and emission at high harmonic orders governed by a 5/3 power decay index. Figures 4 a-b show the harmonic spectra from two arbitrarily chosen Brunel plasma electrons.

4. Conclusions
In this work we have shown from PIC simulations that the radiation emission observed from the interaction of UR short pulses of laser light with dense plasma targets are in agreement with the single particle radiation model proposed, based on Brunel electrons perturbed by a strong localised electrostatic field that is generated inside the plasma by the action of the laser field. Furthermore, the Larmor radiation from Brunel electrons is consistent with both the harmonic spectrum reflected from the plasma, observed from simulations, and from that obtained from the single particle model.

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