Radiation emission from plasma oscillation

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ABSTRACT

It is well known that an infinite homogeneous Langmuir wave, formed by accelerating charged particles, it does not emit electromagnetic radiation because of its electrostatic nature, which is represented by the zero curl of the electric field. To realise emission, the plasma density must be tailored such that the Langmuir wave takes on a non-zero component of the curl of the electric field. The mechanisms of inverse mode conversion or travelling wave antennae leads to emission of radiation. In these mechanisms, the emphasis is on energy conversion of the Langmuir 'wave' to an electromagnetic wave. However, an interesting way to cause the plasma wave to emit radiation is to isolate a single 'oscillator' composed of a localized plasma block, i.e., a plasma dipole. An outstanding question in the realization of this idea is how to isolate the plasma oscillation from the Langmuir wave. To answer this question, we propose a novel idea of colliding detuned counter-propagating laser pulses in plasma. Simulation results show that radiation is emitted from the isolated plasma dipole.

Keywords: Plasma emission, plasma oscillation, terahertz emission

1. INTRODUCTION

The plasma oscillation is a fundamental behaviour of plasma. Because the plasma oscillation comprises accelerating motion of charged particles, from an elementary physical point of view, electromagnetic radiation is expected to be emitted from it. The plasma oscillation, especially that of electrons, may have practical advantages as a new radiation source; because the radiation intensity can be very high. As plasma is a broken-down medium, it can sustain huge electric fields without experiencing material damage. This allows the system to be driven by very high power sources, such as PW lasers. In addition, the frequency of the plasma oscillation is determined by the plasma density, which implies that the spectrum of the resulting radiation could be narrowband and can therefore readily tuned just by changing the plasma density. Furthermore, the plasma density available in the laboratory ranges from 10^9 cm^{-3} (low temperature plasma) through to 10^{24} cm^{-3} (solid state), which corresponds to radiowaves to XUV plasma frequency range. When high harmonics are employed, such as the oscillating electron mirror on the surface of a solid material [1], the X-ray regime could be reached.

Indeed, there have been diverse theoretical and experimental reports of radiation emission from plasma [2-4]. However, the mechanism of the plasma emission has been a subject of controversy. In most of the reported cases, the plasma oscillation is considered to be relevant indirectly only, or completely irrelevant. For example, the mechanism of the conical terahertz emission from a filament plasma driven by a laser pulse [3] is explained to originate from transient current or transition radiation. The strong terahertz emission from two-colour-driven plasma filaments [4] has been successfully explained by a symmetry-broken ionization current. In the original work of terahertz emission from plasma by Hamster et al. [2], the underlying mechanism was attributed to nonlinear coupling of the laser-driven current to the plasma oscillation. However, in this case the plasma oscillation is not a direct source of radiation.

The controversy of plasma oscillations playing a direct role as a source of radiation is primarily based on the fundamental dispersion properties of the Langmuir wave and the electromagnetic wave in plasma. The Langmuir wave, which is the sole way of obtaining plasma oscillations when driven by a laser pulse or particle beams, is a collection of infinitely many, infinitesimal plasma oscillations, oscillating with different phases. As can be seen in Fig. 1, the Langmuir wave and the electromagnetic wave are coupled only at $k = 0$, where the group velocity of the electromagnetic wave is zero. Therefore, any electromagnetic energy converted at $k = 0$ from the electrostatic energy of the plasma oscillation cannot escape from the plasma.

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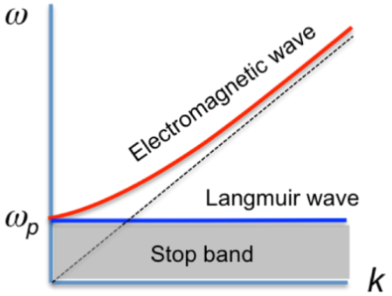


Figure 1. Dispersion curves of the Langmuir wave and electromagnetic wave in homogeneous plasma. ω and k are the frequency and wavenumber of the waves, respectively, and ω_p is the plasma frequency.

Interestingly, in the context of space plasma physics, it is widely accepted that the Langmuir wave is a direct source of radio-bursts from the solar corona [5]. For laboratory plasma, methods of obtaining radiation from plasma oscillations involve breaking the homogeneity of the system [6], or using an external magnetic field [7]. In the former case, even though the energy coupling between the two modes (electrostatic - the plasma oscillation, and the electromagnetic wave) still occurs only at zero group velocity and the radiation propagates through the density down gradient. This procedure is the inverse process of the well-known linear mode conversion from electromagnetic waves to electrostatic oscillations in plasma with increasing density. In the latter case, a transverse external magnetic field is employed to open a propagating band in the dispersion structure. Furthermore, two colliding Langmuir waves can generate radiation at the 2nd harmonic of the plasma frequency, where there is no zero group velocity problem [8].

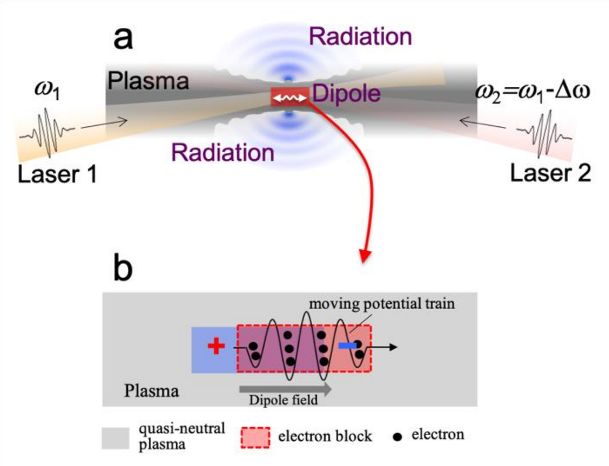


Figure 2. Schematics of the generation of PDO by colliding detuned laser pulses.

In this paper, we introduce a totally different idea of obtaining electromagnetic waves from an isolated, localized plasma dipole oscillation (PDO). The PDO is a local block of electrons that all oscillate in phase at the plasma frequency. This model is frequently employed as a pedagogical model to explain plasma oscillations, but has not been, to our knowledge, realized physically, at least in a controlled way. The in-phase motion of a group of electrons can be considered as a piece of an infinitely large $k = 0$ mode. Since the PDO contains the $k = 0$ mode dominantly, there is a high probability of coupling the respective oscillation energy of the PDO with the electromagnetic energy of emission. Again, a density gradient enables the electromagnetic energy generated in the region where $k = 0$ to escape from the plasma. The novel aspect of our work is in conceiving a new method of generating the local PDO using colliding, detuned laser pulses (Fig 2). This generation mechanism of the PDO is described in the following section.

2. GENERATION OF THE PDO

2.1 The mechanisms

A Langmuir wave, especially a very strong one, can be generated by driving the plasma using an ultra-intense laser pulse or a particle beam, which leaves behind a wakefield. In this case, the plasma oscillation exists in the form of waves that have non-zero wave vectors. In contrast, we propose colliding two laser pulses that are slightly detuned, at any desired position, to obtain an independent, localized, plasma oscillation. As shown in Fig. 2, the beat wave produces a ponderomotive potential in the overlap region of the two pulses. Electrons subject to this potential move and build up a dipole field by two different mechanisms, depending on the intensity of the driving pulses.

2.2 Build-up of the dipole field by a nonlinear current

When the driving laser pulses are moderate (typically $a < 0.01$, where a is the normalized vector potential of the laser field), the plasma wave driven by the beat ponderomotive potential remains below the wavebreaking threshold. In this case, the perturbed plasma density and the fluid velocity are given by

$$\delta n = \frac{1}{2}\hat{n}\left(e^{ik_1 x - i\omega_1 t} + e^{-ik_2 x - i\omega_2 t}\right) + c.c. \tag{1}$$

and

$$\delta v = \frac{1}{2}\hat{v}\left(e^{ik_1 x - i\omega_1 t} + e^{-ik_2 x - i\omega_2 t}\right) + c.c. \tag{2}$$

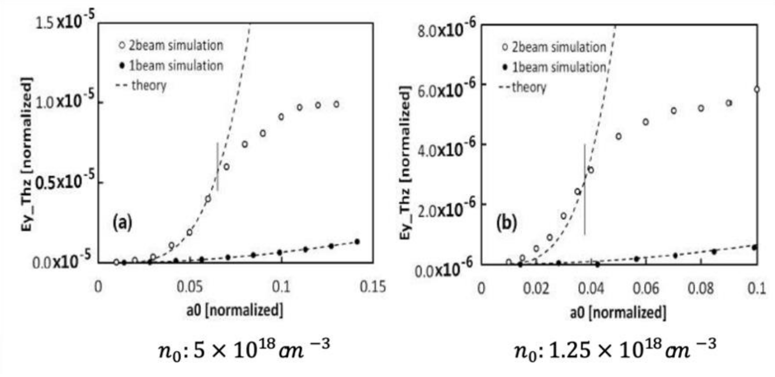
The current density is then described by

$$\delta J = -en_0\delta v - e\delta n\delta v. \tag{3}$$

The fast oscillating part of the current is averaged out, and does not contribute to the dipole field generation. However, the dc (direct-current) part of J survives in the nonlinear component through the average.

$$J_{\mathrm{dc}} = -\frac{1}{2}e\left(\hat{n}\hat{v}^* + \hat{n}^*\hat{v}\right). \tag{4}$$

Since J_{dc} exists where the pulses overlap, it builds up a dipole field with dimension comparable to the pulse duration. The build-up of the dipole field lasts as long as the pulse collision time, which is approximately the pulse duration. Figure 3 shows the scaling of the radiation emission from the oscillation of the dipole made in this way [9].



$n_0: 5 \times 10^{18} cm^{-3}$ $n_0: 1.25 \times 10^{18} cm^{-3}$

Figure 3. The field strength of the emitted radiation from PDO. The radiation field scales with I^2 (or a^4) up to the wavebreaking limit (indicated by a short vertical line) and saturates beyond wavebreaking.

2.3 Dipole build-up by trapped particles

When the driving pulse is moderately intense (typically $a > 0.1$), the plasma wave generated by the beat ponderomotive potential readily exceeds the wavebreaking threshold, leading to strong particle trapping in the ponderomotive potential. Becasue the potential travels with the phase velocity of the beat wave, all the trapped electrons, i.e., the micro bunches inside the potential troughs, move together with the same velocity. As the bunches of electrons are conveyed by the beat potential train, a restoring electrostatic field, i.e., the dipole field is built up. This procedure is schematically illustrated in

Fig. 2. As the driving pulses transmit through each other, the beat ponderomotive potential diminishes and the micro-bunches of electrons are phase-mixed to form a single macrobunch [10].

In the trapped-particle regime for PDO, the force-balance model can be used to estimate the maximum field of the dipole, as in Fig. 4. The conveyance of electrons by the beat potential begins at wavebreaking and lasts until the ponderomotive force decreases below the restoring electric force. During this period of conveyance of electrons, the dipole field grows.

2.4 Comparison of the nonlinear current and trapped particle regimes

There are several major differences between the nonlinear current and trapped-particle regimes. In the nonlinear current regime, the electron motion remains bounded. On average, each electron is not displaced. The electron excursion does not exceed the beat wavelength and that the overall dipole is built up as a sum of dipoles spaced at the beat wavelength. In the trapped-particle regime, the electrons break their bounded motion and are directly displaced.

In the nonlinear current regime, the dipole field can be most effectively built up when the following resonance condition is satisfied:

$$|\omega_1 - \omega_2| = \omega_p. \tag{5}$$

In contrast, the resonance is much less relevant in the trapped-particle regime. Wavebreaking can be reached slightly earlier when the plasma wave is driven resonantly, but this contributes a minute change to the maximum dipole field. The phase velocity, which is determined by the detuning of the pulses, is a more important parameter for determining the maximum dipole field strength.

The field strength of the dipole radiation scales with I^2, where I is the laser intensity, but saturates very quickly due to electron trapping (see Fig. 3). Beyond this point, the scaling is much slower (no simple power-law), but the dipole can be driven by very intense laser pulses, leading to much stronger radiation emission.

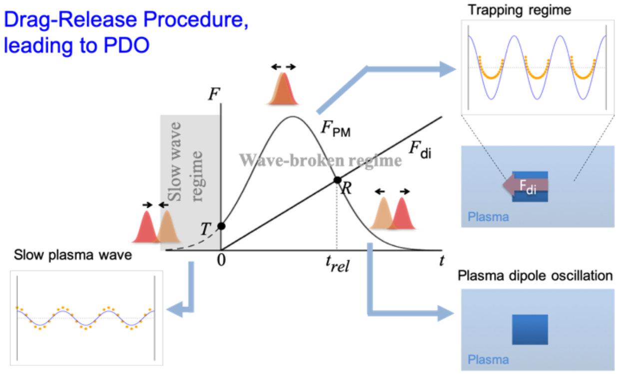


Figure 4. Force-balance model to estimate the maximum build-up of the dipole field. In the figure, wavebreaking occurs at $t = 0$ and T is the wavebreaking threshold. The Gaussian curve represents the time-evolution of the ponderomotive force, while the straight line represents the build-up of the electrostatic dipole field. Beyond the point R, where the ponderomotive force drops below the restoring force by the dipole field, the displaced PDO commences oscillation.

3. SIMULATION RESULTS

To verify the radiation emission by the PDO, we have conducted two-dimensional (2D) particle-in-cell (PIC) simulations. Note that the radiation is observed for more for 2D, because the dipole radiation is most dominant in the direction perpendicular to the dipole oscillation. In the simulation, two detuned and counter-propagating laser pulses are launched from the left and right boundaries of the simulation domain, respectively. The laser pulses propagates through a pre-loaded, narrow plasma strip, which has a width that is just wide enough to cover the pulse spot size. The pulses leave wakefields behind themselves and collide at the centre of the plasma strip. At the collision point, a very strong dipole field, much stronger than the adjacent wakefields, is generated. After the pulse collision, the dipole commences the plasma oscillation and emits radiation.

Figure 5 shows a typical case of radiation emission from the dipole. The physical and simulation parameters leading to this result are summarized in Table 1. Figure 5 (a) and (b) represent the electric field in x-direction and the magnetic field in z-direction. The time-traces of the fields acquired at two different virtual probes (one at the dipole centre and the other on the vacuum side) shows that the electric and magnetic fields oscillate with the same phase on the vacuum side and their normalized values are comparable, strongly indicating that they constitute “radiation” rather than just an evanescent-like field. The spectral peaks of the fields are located exactly at the plasma frequency, which is evidence that the radiation is emitted by the plasma oscillation.

Figure 6 represents the conversion efficiency from the driving pulse energy to the emission energy. The efficiency η is of order 10^{-3}, in mJ-class terahertz, and quasi-narrowband.

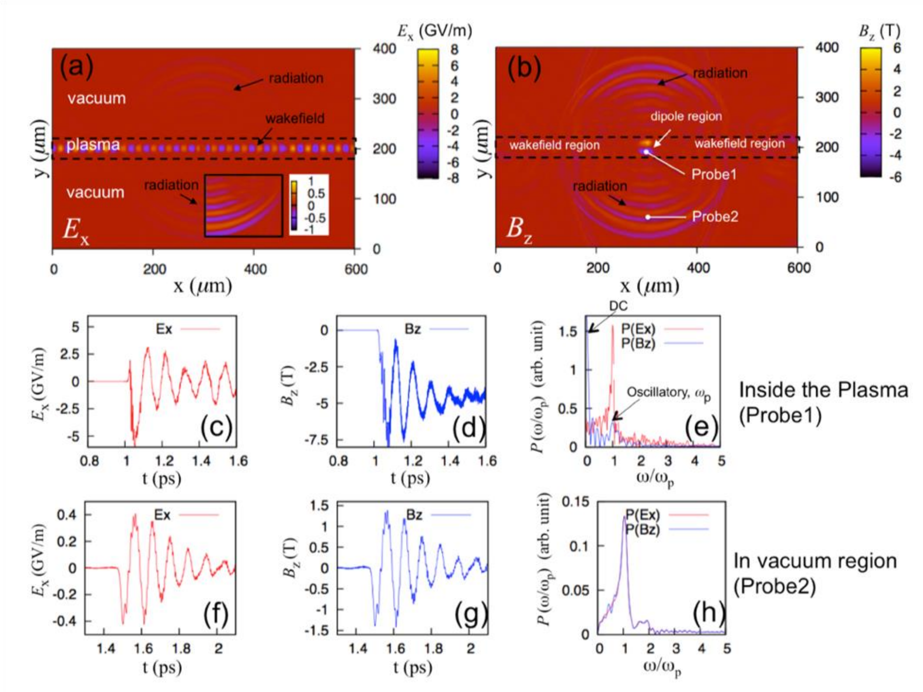


Figure 5. Two dimensional PIC simulation of radiation emission from the PDO. (a, b) snapshots of the electric and magnetic fields. Temporal evolution of the electric and magnetic fields and the corresponding spectrum at (c, d, e) the centre of the dipole and (f, g, h) in vacuum.

Table 1. Physical and simulation parameters for Fig. 5.

Parameters	**Value**
Laser amplitude	$a = 0.5$
Pulse duration	30 fs
λ_1 and λ_2	0.8 μm and 0.759 μm
Plasma density	1.24 x 10^{18} cm^{-3}
dx dy dt	0.05 μm, 0.2 μm and 1.5x10^{-16} s

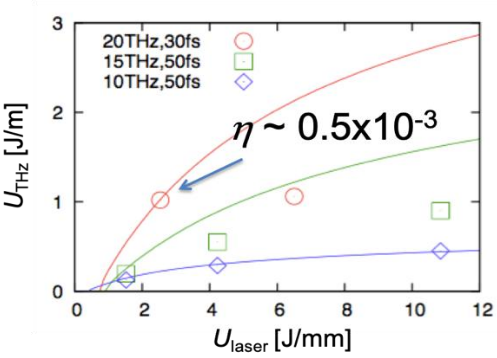


Figure 6. Energy of the radiation vs. the energy of the driving laser pulses. They are determined per unit lateral dimension (*z*-direction) and the simulation is two-dimensional.

4. CONCLUSION

We have demonstrated a new method of generating an isolated plasma dipole oscillation. It has also been shown that strong radiation can be emitted from the generated PDO. The PDO, which is readily tuneable and can sustain a very strong electric field without material damage, is potentially a good candidate for a strong, quasi-narrowband, tuneable radiation source.

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