

SIMULATION OF LASER PULSE DRIVEN TERAHERTZ GENERATION IN INHOMOGENEOUS PLASMAS*

Chenlong Miao[#], IREAP, University of Maryland, College Park 20740, USA
 John P. Palastro, Naval Research Laboratory, Washington DC 20375, USA
 Thomas M. Antonsen, IREAP, University of Maryland, College Park 20740, USA

Abstract

Intense, short laser pulses propagating through inhomogeneous plasma can ponderomotively drive THz radiation. Here we consider a transition radiation mechanism (TRM) for THz generation as a laser pulse crosses a plasma boundary. Full format PIC simulations and theoretical analysis are conducted demonstrating that TRM results in low frequency, broad band, coherent THz radiation. The effect of a density ramp is also considered and shown to enhance the radiated energy.

INTRODUCTION

Electromagnetic terahertz radiation (THz) spans frequencies from 300 GHz to 20 THz. A wide variety of THz applications [1] include spectroscopy, remote detection, and medical and biological imaging. Intense THz pulses can be generated at large scale accelerator facilities via synchrotron or transition radiation, but the size and cost of such facilities are prohibitive for widespread use. This motivates the development of small-scale table top terahertz sources.

Existing small-scale terahertz sources are based on laser-solid interaction and are limited to $\mu\text{J}/\text{pulse}$ levels [2]. This has led to the consideration of laser-plasma based THz generation schemes. Examples include the transition radiation of a laser accelerated electron beam passing from plasma to vacuum producing energies in excess of 100 $\mu\text{J}/\text{pulse}$ [3], and radiation produced during two-color laser pulses gas ionization[4]. Here, with a combination of theory and simulation, we investigate a mechanism of ponderomotively driven THz radiation, which offers the possibility of high conversion of optical pulse energy to THz.

The mechanism occurs as a laser pulse crosses a plasma boundary [5] and is analogous to transition radiation emitted by charged particle beams. The THz radiation resulting from this transition radiation mechanism (TRM) is characterized by conical emission and a broad spectrum with the maximum frequency occurring near the plasma frequency [6].

The THz generation mechanism is simulated using the full format PIC simulation TurboWAVE [7], with the goal of increasing the conversion of optical energy to THz radiation. A range of laser pulse and plasma parameters is considered. We conduct the simulations in the lab frame with a finite sized plasma target illuminated by a laser pulse incident from the left, as shown in Fig. 1 for the case of a

sharp boundary, uniform plasma. To investigate the power radiated from the plasma, we calculate the Poynting flux through the prescribed surfaces outside the plasma region. These represent the forward, backward and lateral radiation from the plasma.

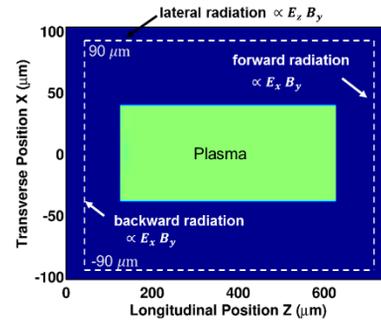


Figure 1: Diagnostic box outside the plasma channel. The Poynting flux through each surface is calculated.

TRANSITION RADIATION MECHANISM

We first consider a uniform plasma with sharp step boundaries as illustrated in Fig. 2. The plasma is 500 μm long and 90 μm wide with a density of $n = 2.8 \times 10^{18} \text{ cm}^{-3}$. When the laser pulse crosses the vacuum-plasma boundary, it drives ponderomotive currents that produce radiation with frequencies near the plasma frequency.

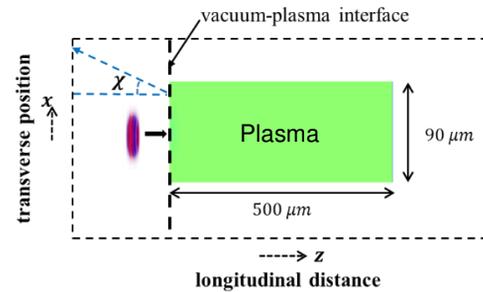


Figure 2: Diagram of simulation set up for transition radiation at the vacuum plasma boundary.

Following Ref. 5, a formula can be derived for the radiated energy per unit frequency (ω) and length (recall the simulations have 2D planar symmetry) across the left diagnostic boundary shown in Fig. 2.

$$\frac{dW_L}{d\omega} = \frac{L}{|\omega|} \frac{\omega_{p0}^2}{\omega^2} \frac{k_z^2}{\omega^2} \frac{a_0^2}{\pi^{3/2} 4} U_L \int_0^1 dy \frac{y^2 \sqrt{1-y^2} \times \exp\left[-\frac{\omega^2}{2c^2} (L^2 + R_z^2 (1-y^2))\right]}{|\epsilon(\omega) y + \sqrt{y^2 - \omega_{p0}^2 / \omega^2}|^2} \quad (1)$$

*Work supported by DOE
[#]clmiao@umd.edu

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2015). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

where $\omega_p = (4\pi q^2 n / m_e)^{1/2}$ is the plasma frequency, ω_0 is laser frequency, a_0 is the normalized laser vector potential and U_L the laser pulse energy. The dielectric constant is given by $\epsilon(\omega) = 1 - \omega_p^2 / \omega^2$. The integration over y can be viewed as an integration over angles or position x on the left diagnostic surface, $y = \cos \chi$, where χ is observation angle as shown in Fig. 2.

In Fig. 3 results from the simulation are compared with Eq. (1). The laser has a total energy of 66mJ with wavelength 800 nm, spot size 15 μm and pulse duration 50 fs. Below the plasma frequency, there is a broad spectrum from the transition radiation. Simulation results are shown for plasma slabs of two different lengths indicating that, as expected, the radiation is not sensitive to the plasma length, as it originates from the axial boundary. Fig. 3(b) shows the radiated energy flux through the left diagnostic line as a function of position. The radiation peaks at approximately 50 μm , corresponding to an angle of about 25°.

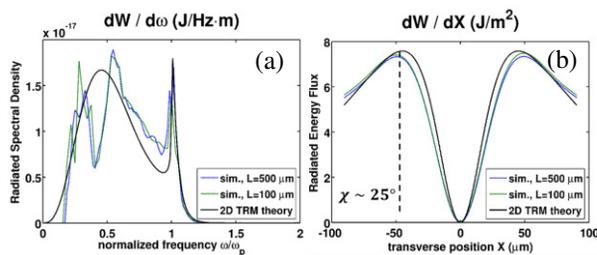


Figure 3: Comparisons of (a) radiated spectral density and (b) radiated energy flux along transverse position. Shown are theoretical values (Eq. (1), black solid), and simulations for plasma length $L=500 \mu\text{m}$ (blue dashed) and $L=100 \mu\text{m}$ (green dashed).

Eq. (1) depends on the plasma frequency, however the simulations predict that the total energy radiated is surprisingly insensitive to the density. In particular, the

radiated energy is nearly constant for densities above $1.5 \times 10^{18} \text{cm}^{-3}$. In this density range, the radiation spectra tend to a profile that is independent of density and determined by the Fourier transform of the laser pulse envelope. The interaction in this case is similar to that between a laser pulse and a perfect conductor. This implies that the laser pulse excites a current at the boundary that depends primarily on the properties of the laser pulse.

The previous results are for the case of a sharp boundary between plasma and vacuum. When the density transition has a ramp the results change in two ways. First there is an asymmetry between radiation generated when the laser enters and leaves the plasma. Second, the amount of radiation increases as the length of the transition region increases. The asymmetry is shown in Fig. 4. For a sharp boundary (4a) the radiation generated by the laser pulse entering and leaving the plasma is the same (4b). However, when the ramp is added (4c) the amount of energy radiated when the laser enters the plasma goes up while the amount radiated on leaving goes down (4d). Furthermore, as shown in Fig. 5, the radiation increases almost linearly with the upward ramp length.

According to our theory, to be published, the radiation at a given frequency is generated at the point in the plasma where its frequency matches the local plasma frequency and with a range of transverse wavenumbers. The radiation must then tunnel out of the plasma to the point where it can propagate. The process has many similarities to resonant absorption in a diffuse plasma profile; a schematic is shown in Fig. 6. As the laser pulse propagates through the upward density gradient region, the THz generated during the transition process is below the plasma frequency, thus the plasma resonance is located in the ramp. Radiation of frequency ω is generated at the plasma resonance at z_1 (where the dielectric constant ϵ is zero), but needs to transit to the turning point at z_2 (where k equals zero) to tunnel out of the plasma.

The transverse electric field in the plasma evolves according to

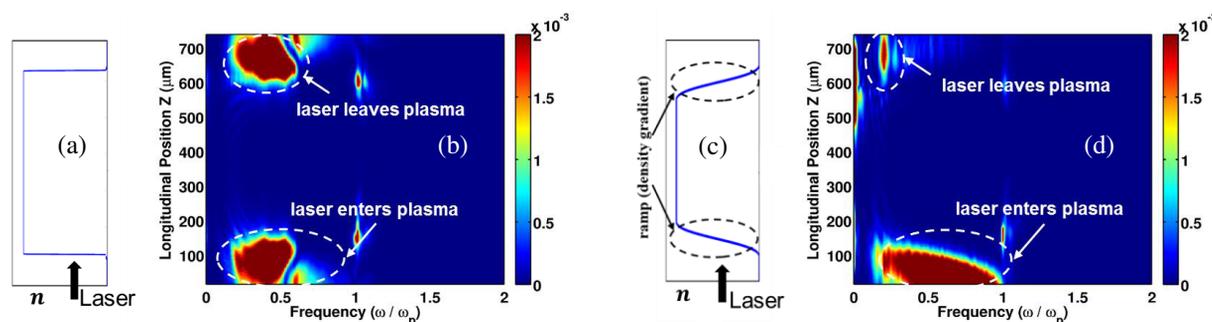


Figure 4: Comparisons of (a) plasma density with sharp step boundaries and (c) plasma density with upward and downward ramps ($\sim 25 \mu\text{m}$). Simulation results, radiation spectrum as a function of the longitudinal distance and frequency showing that (b) the step boundary is symmetric while (d) the upward and downward ramp causes asymmetry.

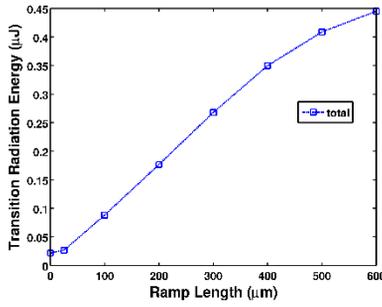


Figure 5: Transition radiation THz energy for different ramp length.

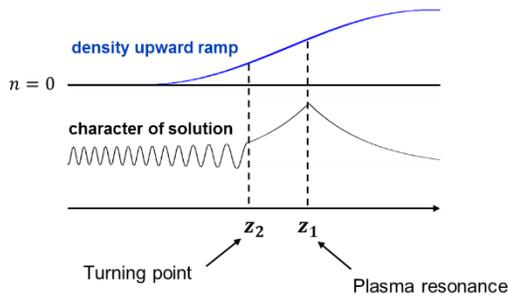


Figure 6: Schematic plot for THz generation during the density ramp region.

$$\frac{d}{dz} \left(\frac{\varepsilon(z)}{k^2(z)} \frac{dE_x}{dz} \right) + \varepsilon(z) E_x = ik_x \left(-i \frac{d}{dz} \frac{k_z}{k^2(z)} \frac{\omega_p^2(z)}{\omega^2} \right) \hat{\phi} \exp(ik_z z) \quad (2)$$

solving Eq. (2) near $\varepsilon(z) = 0$ gives,

$$\tilde{E}_x = \int_z^{k_z z = i\infty} \frac{dz'}{z' - iZ_\nu} \left(k_x k_z L \frac{\hat{\phi}}{e} \right) e^{ik_z z'} \quad (3)$$

where $Z_\nu = Lv / \omega$ with ν as the collision frequency and L as the ramp length, and without losing generality, we set the resonant point at $z = 0$.

According to our preliminary analysis, the total radiated energy Γ is related to the jump of \tilde{E}_x across the plasma resonant point. The upward and downward asymmetry can be mathematically explained as follows. If the laser experiences an upward ramp, as in 7a, $k_z > 0$, and the integral in Eq. (3) should be performed in the upper half plane where the pole contributes to this jump of \tilde{E}_x across the plasma resonant point. However, if the laser sees a downward ramp, as in 7b, $k_z < 0$, and the integration contour should lie in the lower half plane where there is no pole, no jump in \tilde{E}_x , and thus no radiation is generated. This analysis agrees with the simulation, however, to understand the physics of the asymmetry, a numerical simulation to solve Eq. (2) considering the different density gradients has been developed and will be included in an forthcoming publication.

Finally, we explore the scaling of the radiation with laser intensity. According to the theory, the ponderomotively driven radiation should scale as a_0^4 in the linear regime when $a_0 \ll 1$. This is verified in the simulation. However, for larger a_0 the radiation saturates. As an example, the radiated energy is about 140 μJ with $a_0 = 4$ and 48 nJ with $a_0 = 0.4$. In addition harmonics $\omega_h = n \cdot \omega_p$ appear.

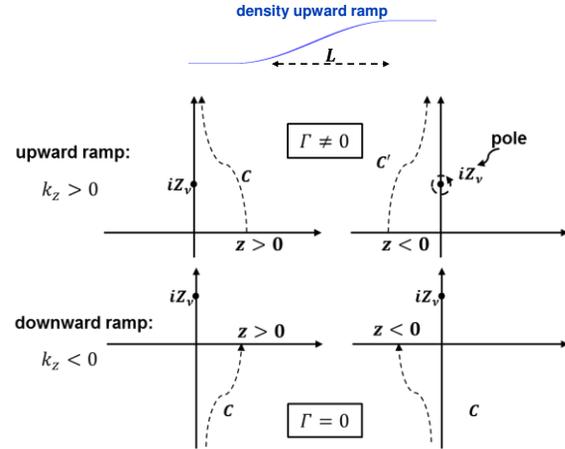


Figure 7: Explanation for the asymmetry between upward (a) and downward (b) ramps.

CONCLUSION

We have investigated a transition radiation mechanism (TRM) for ponderomotively driven THz generation at plasma boundaries. TRM is generated at vacuum plasma boundary and preferentially enhanced as laser crosses an upward density gradient. THz energy is insensitive to the plasma length and density above $1.5 \times 10^{18} \text{ cm}^{-3}$. As an example, a fixed driver pulse (1.66 J) excites THz radiation of 280.7 μJ in a 400 μm upward density ramp.

REFERENCES

- [1] D. M. Mittleman, R. H. Jacobsen, and M. C. Nuss, IEEE J. Sel. Top. Quantum Electron. 2, 679 (1996).
- [2] E. Budiartoet et al., IEEE J. Quantum Electron. 32, 1839-1846 (1996).
- [3] W. P. Leemans, C. G. R. Geddes et al., Phys. Rev. Lett. 91, 074802 (2003).
- [4] K. Y. Kim, J. H. Glowonia, A. J. Taylor, and G. Rodriguez, Opt. Express 15, 4577-4584 (2007).
- [5] L. M. Gorbunov and A. A. Frolov, Plasmas Physics Reports 32, 850-865 (2006).
- [6] C. Miao, Proceedings of 16th Advanced Accelerator Concepts Workshop, A. I. P., in press (2014).
- [7] D. F. Gordon, IEEE Trans. Plasma Sci. 35, 1486 (2007).