Simulation of Laser Pulse Driven Terahertz Generation in Corrugated Plasma Channels

Chenlong Miao[1], John P. Palastro[2], Andrew J. Pearson[1] and Thomas Antonsen[1]
[1] Insititute for Research in Electronics and Applied Physics, University of Maryland, College Park 20740
[2] Icarus Research, Inc., Bethesda, Maryland 20824

***Abstract*—Intense, short laser pulses propagating through inhomogeneous plasma generate THz radiation. Full format PIC simulations and theoretical analysis are conducted to investigate two mechanisms of ponderomotively driven THz radiation: a transition radiation mechanism (TRM) occurring as a laser pulse crosses a plasma boundary, and a slow wave phase matching mechanism (SWPM) that occurs in corrugated plasma channels.**

I. INTRODUCTION

In this research we consider both theoretical analysis and numerical simulation of two mechanisms of ponderomotively driven THz radiation in inhomogeneous plasmas with realistic density profiles. These schemes offer the possibility of high conversion of optical laser pulse energy to THz.

The first mechanism occurs as a laser pulse crosses a plasma boundary [1] 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. The second mechanism occurs in axially periodic plasma channels [2, 3, 4]. These channels support electromagnetic modes with slow wave (Floquet-type) dispersion, which can be phase matched to the ponderomotive current. The slow wave phase-matched radiation (SWPM) is characterized by lateral emission and a coherent spectrum.

These mechanisms are simulated using the full format PIC code TurboWAVE [5], 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 periodic modulated plasma channel. To investigate the power radiated from the plasma target, we calculate the Poynting flux through the prescribed surfaces outside the plasma region. These represent the forward, backward and lateral radiation from the plasma.

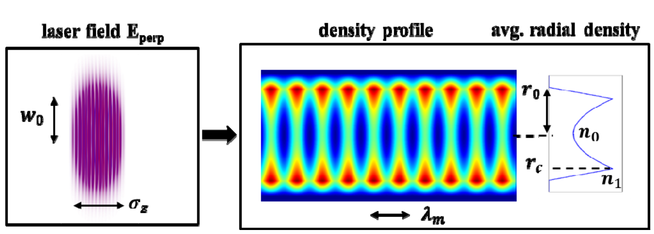

Fig. 1. Schematic diagram corrugated plasma channels. An intense laser pulse travels through the corrugated plasma channel with average parabolic transverse profiles, generating coherent THz.

II. RESULTS

The target plasma is now a corrugated channel as shown in Fig. 1, with the following parameters, the laser has wavelength $\lambda = 800\ nm$, spot size $w_0 = 15\ \mu m$ and pulse duration $\sigma_z = 50\ fs$ .The cutoff radius r_c is 30 μm and channel radius r_0 is 40 μm. The modulation amplitude is 0.9 with a period of $\lambda_m = 50\ \mu m$, $n_0 = 1.4\times10^{18}\ cm^{-3}$ and $n_1 = 4.2\times10^{18}\ cm^{-3}$.

From both theory and simulations, we found that ponderomotively driven currents contribute to THz radiation in corrugated plasma channels for both TRM and SWPM. As we can see from Fig. 2, TRM is generated at vacuum plasma boundary and SWPM occurs in corrugated channels.

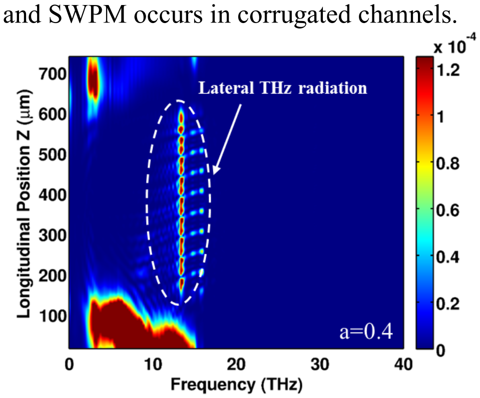

Fig. 2. THz generation due to corrugated channels is approximately perpendicular to lateral boundary (angle ~ 90 degrees) and the spectrum is narrow. Broad-band, low frequency THz generation in the channel end due to transition radiation is also observed.

Terahertz radiation from SWPM generally increases with channel length and by reducing density to allow better coupling of the radiation in the channel to the outside due to the lower plasma density. As shown in Fig. 3, THz radiation generated from SWPM peaks around plasma density of $1.4\times10^{17}\ cm^{-3}$ for the parameters we used in the simulation.

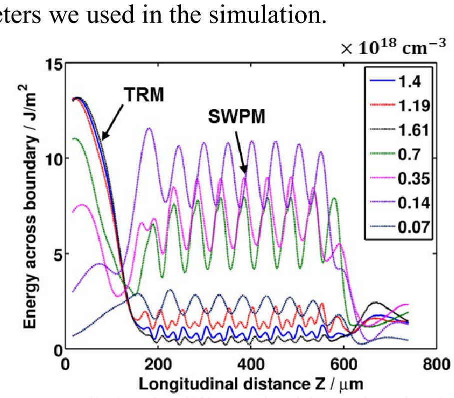

Fig. 3. SWPM: THz radiation for different densities. When density is reduced, more THz radiation leaks out the channel.

In contrast, we found THz energy from TRM is insensitive to the plasma length and density above $1.5\times10^{18}\,cm^{-3}$ (see TRM in Fig. 3) for the laser parameters in our simulation and can be further modified by adding a density upward or downward ramp via the resonant transition radiation (RTR) process [6], which will be discussed in detail in an upcoming publication. 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. 4. As the laser pulse propagates through the upward density gradient region, the THz generated from TRM during the transition process is below the plasma frequency (see TRM spectrum in Fig. 2, where the plasma frequency is around 15THz), 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 wavenumber k equals zero) to tunnel out of the plasma.

By adding the density upward ramp length, the amount of THz energy generated from TRM generally increases and opposite phenomenon is observed from the simulation for the downward density ramp. For a sharp boundary the radiation generated by the laser pulse entering and leaving the plasma is the same. However, when the ramp is added, the amount of energy radiated when the laser enters the plasma goes up while the amount radiated on leaving goes down. Details and explanation about this asymmetry will also be discussed in the forthcoming publication.

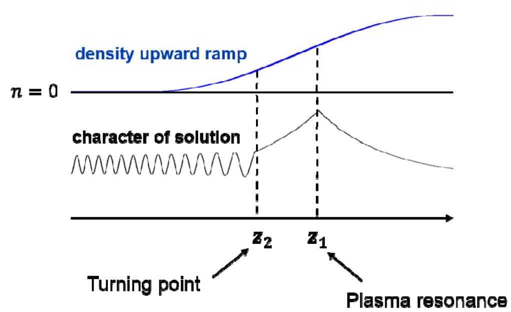

Fig. 4. TRM: Schematic plot for THz generation during the density ramp region.

Ponderomotively driven radiation is expected to scale as $a_0^4/\gamma^2 \sim a_0^4/\left(1+a_0^2\right)$ where a_0 is the laser vector potential. One can see both ponderomotively driven THz generation (TRM and SWPM) can be enhanced by increasing the laser intensity in our results. However, for large a_0 above $a_0 = 2$, the terahertz radiation is enhanced above the scaling estimate. This enhancement phenomenon is accompanied by a change in the spectrum as illustrated in Fig. 5. We find that in this case higher order channel modes are excited by nonlinear currents and interference between higher order modes is also observed.

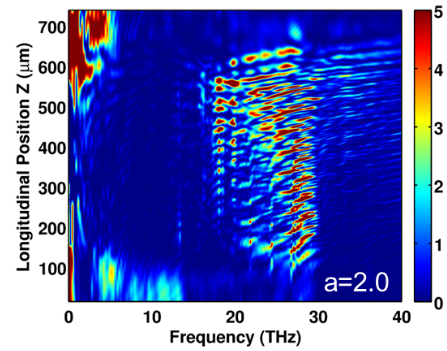

Fig. 5. SWPM: THz radiation for high intensity showing spectral modification.

Our goal is to optimize the efficiency of the optical laser pulse energy converted to THz. Channel lengths in our simulations are limited by computation time, so we are not able to simulate a channel long enough to substantially deplete the laser pulse. We define an alternate efficiency that is the fraction the depleted laser energy transferred to THz, $\eta = E_{THz}/\left|\Delta E_{Laser}\right|$. By maximizing this efficiency, less power is expended driving the plasma oscillations, thus freeing it to drive THz over longer distances. We've achieved an energy conversion efficiency of approximate 6% for the THz generation (see Fig. 6 for the total conversion efficiency, black) and this could be further optimized by varying the corrugated density profiles.

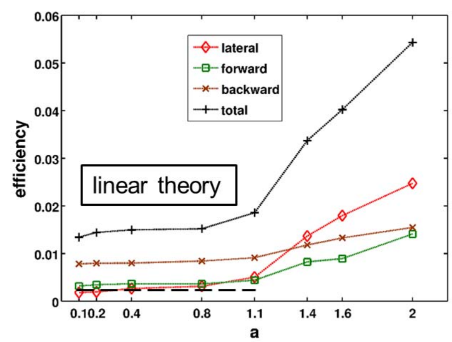

Fig. 6. Conversion efficiency for different laser intensities.

III. Summary

We have investigated two mechanisms by which an intense, ultrashort laser pulse can ponderomotively drive THz radiation in an underdense plasma. As an example, a fixed driver pulse (1.66 J) in a short 500-micrometer-long modulated channel, the THz radiation is 33.6 μJ and 83.7 μJ from TRM and SWPM, respectively. THz generated from SWPM in centimeter-long channels typically created in the experiment will be simulated.

References

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