Picosecond laser-driven terahertz radiation from large scale preplasmas of solid targets

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Abstract. The terahertz (THz) radiation from the front of solid targets with a large-scale preplasma irradiated by relativistic picosecond laser pulses has been studied. The THz radiation measured at the specular direction nonlinearly increases with laser energy and an optimal plasma density scalelength is observed. Particle-in-cell simulations indicate that the radiation can be attributed to the model of mode conversion. While the THz radiation near the target normal direction is saturated with laser energy and plasma scalelength. Unlike the radiation in the specular direction, the transient current formed at the plasma-vacuum interface could be responsible for the radiation near the target normal.

1. Introduction

The generation of high-power terahertz (THz) radiation sources is one of the biggest challenges to nonlinear THz photonics, in which regime new frontier applications in many fields will be opened up [1]. Various THz sources based on different mechanisms have been developed over last decades. Recently the THz generation from laser-produced plasmas has attracted much attention [2-5] since the plasma is free of breakdown restrictions. The THz pulses with energies of >100 μJ/pulse have been demonstrated from the rear side of foils irradiated by relativistic femtosecond (fs) laser pulses [6]. The THz generation critically depends on the laser and plasma conditions. For the THz generation from laser-solid interactions reported so far, most experiments are performed with fs-lasers and plasmas with a short density gradient. The generation mechanisms are attributed to transient electron currents.

To exploit new THz sources and get a more comprehensive understanding on the THz generation mechanisms, here we report on the THz radiation by the relativistic picosecond (ps) laser pulses interacting with large-scale plasmas in front of solid targets. We have studied the THz radiation as a function of the laser energy and plasma density scalelength. The different THz characteristics observed at different directions imply different generation mechanisms. The plasma wave-based and transient current-based models are used to explain the THz radiation.
2. Results and discussions

The experiment was performed using the COMET laser system at the Lawrence Livermore National Laboratory. The experimental layout was similar to that described in Ref. [5]. A \( p \)-polarized 1053 nm, 0.5 ps laser pulse with a contrast ratio of \( \sim 10^{-5} \) was focused onto a 1 mm thick, 10 mm \( \times \) 20 mm copper (Cu) slab at an incidence angle of 62.5°. The laser focal spot diameter was \( \sim 7 \ \mu m \), and the corresponding intensity was \( \sim 5 \times 10^{17} \ \text{W/cm}^2 \) for 1 J laser energy. The THz radiation was measured at 62.5° (specular), 0° (normal) and -17.5° with respect to the target normal (minus means the backward direction relative to the laser propagation direction). In the experiment, we adjusted the preplasma profile by introducing a prepulse in advance of the main pulse and varying the timing between the prepulse and main pulse. The plasma density scalelength was inferred from the Abel inversion of interferograms measured by a Normaski interferometer.

Figure 1 shows the THz radiation at different directions as a function of the laser energy. With the increase of laser energy, the radiation increases first. However, when the laser energy is \( \sim 3.5 \ \text{J} \), the radiation at 0° and -17.5° starts to get saturated, and even decreases slowly with the laser energy. While the THz radiation at 62.5° is still increased. Fitting the data for the laser energies \( > 3.5 \ \text{J} \) with a power law gives a power exponent \( \sim 3 \pm 0.5 \), as shown with the red dashed curves in figure 1. There is no evidence of saturation for the THz radiation at 62.5°. Regarding the relative strength, the THz radiation at 0° is the lowest. With increasing of laser energy, the THz radiation at 62.5° will surpass those at other directions. At the laser energy of \( \sim 9 \ \text{J} \), the THz radiation at 62.5° is \( \sim 10 \) times higher than that at -17.5°.

![Figure 1. Measured THz intensity at 62.5° (black dot), 0° (green square) and -17.5° (blue triangle) as a function of the laser energy. The red dashed curves show the power-law fit.](image)

Figure 2 shows the THz radiation at 62.5° and -17.5° versus the plasma density scalelength \( L \). The radiation at -17.5° decreases slowly with the plasma scalelength. While the radiation at 62.5° is much different. As the plasma scalelength is increased, the radiation is enhanced substantially. The radiation at \( L \sim 45 \ \mu m \) is \( \sim 10 \) times stronger than that at \( L \sim 30 \ \mu m \). Interestingly, with the further increase of \( L \), it drops dramatically. When \( L \) is \( \sim 60 \ \mu m \), the radiation becomes comparable to that at \( L \sim 30 \ \mu m \). The ratio of the radiation intensity at \( L \sim 60 \ \mu m \) to that at \( L \sim 30 \ \mu m \) is \( \sim 1.2 \). It is indicated that there exists an optimal \( L \) for the THz radiation at 62.5°.
Additionally, we measured the polarization of THz radiation by inserting a wire-grid polarizer in the detection path. The THz radiation at 62.5° behaves like $p$-polarized. Nevertheless, the THz intensity detected at 0° and -17.5° does not change much when varying the angle of the polarizer, indicating that it could be circularly or radially polarized.

Given the THz radiation at 0° and -17.5° has similar features, while the radiation at 62.5° is rather different, there could be two generation mechanisms, among which one is responsible for the THz radiation at 62.5° while the other for the radiation at 0° and -17.5°.

The model of linear mode conversion [7] can well explain the THz radiation at 62.5°. The model predicts there should be an optimal plasma configuration for the most efficient THz generation, which is in good agreement with the experimental. The laser pulse is too long (0.5 ps) to excite strong high-frequency laser wakefields directly. Nevertheless, in this case where the intense laser pulses propagating in large-scale plasmas, stimulated Raman scattering (SRS) will occur [8] and excite large-amplitude plasma waves. Besides, plasma waves could also be induced by the self-modulation instability (SMI) [9]. In the plasma with an increasing density, a part of the excited plasma waves could be converted into the electromagnetic waves through mode conversion. The mode-converted electromagnetic radiation emits mainly in the specular direction of the laser incidence. Hence the model is mainly valid for the THz radiation at 62.5° in our case. We have performed particle-in-cell (PIC) simulations. In the simulations, strong $p$-polarized multi-cycle THz radiation is observed to be emitted in the specular direction. The THz radiation as a function of the plasma scalelength $L$ are simulated. We find that the dependence of the THz radiation on $L$ is similar to the experimental. A similar optimal $L$ is also observed in the simulations. In the non-relativistic case, according to the model of linear mode conversion, the THz energy is predicted to scale with the square of the laser intensity since the laser wakefield is approximately proportional to the laser intensity [7]. While in our present relativistic case, the instability growth rates of both SRS and SMI increase with the laser intensity, and subsequently the THz energy will increase with the laser intensity faster than the square law. This can explain the observed dependence of the THz radiation at 62.5° on the plasma scalelength and laser energy. More detailed discussions can be found in Ref. [5].

The transverse transient current induced by the lateral ponderomotive force in the underdense region may explain the radiation at 0° and -17.5°. Our previous two-dimensional PIC simulations show that, no matter the laser pulses irradiate the inhomogeneous underdense plasmas either normally or obliquely, a single-cycle THz pulse is observed to be emitted from front of the plasma slab in both cases [10]. The velocity of the hot electrons lateral transport current is usually much lower than the light velocity in vacuum [11]. And hence the generated radiation mainly locates near the target normal. Considering the two-dimensional radial distribution of the lateral current [12] in the case with large-scale plasmas, the induced radiation would be radially-polarized. This agrees with our polarization measurements for the radiation at 0° and -17.5°.
In previous experiments [13], the x-ray emission generated by hot electrons is also observed to be saturated with the laser energy and preplasmas. The similar features between the THz radiation and lateral electron transport imply that the THz radiation at 0° and −17.5° is generated by the lateral electron transient current. We have also observed similar saturation in the fs laser-driven THz radiation at a small laser incidence angle [14].

3. Conclusions
We have studied the THz radiation from relativistic ps laser interactions with large-scale plasmas in front of solid targets. The characteristics of THz radiation are observed to be dependent on the observation angle, which implies that there could be more than one generation mechanism. By using PIC simulations, we attribute the THz radiation in the specular direction mainly to the mode conversion of SRS-excited plasma waves, and the THz radiation near the target normal to the transient current at the plasma-vacuum interface. The integrated different types of THz radiation from laser-solid interactions may enable diverse applications with different requirements.

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