Powerful THz sources based on laser wakefields

Hui-Chun Wu¹, Zheng-Ming Sheng, and Jie Zhang
Institute of physics, Chinese Academy of Science, Beijing 100080, China
E-mails: hui-chun.wu@mpq.mpg.de, zmsheng@aphy.iphy.ac.cn

Abstract. MW-order coherent THz pulses with a broad spectrum can be produced from a laser-driven wakefield through linear mode conversion in inhomogeneous magnetized plasmas. The external dc magnetic field is a few tesla. By changing the strength and direction of the magnetic field, one can enhance or suppress the THz emission. The maximum energy conversion efficiency in the magnetized plasmas can be double that in the unmagnetized plasmas. We also propose that single-cycle THz pulse can be directly emitted from a transient net current driven by laser ponderomotive force in a THz-wavelength-scale plasma slab. Theory and simulations show that this THz source is capable of providing power of MW-GW, field strength of MV/cm-GV/cm, and tunability range of 0.1-10 THz, which would open up new horizons for nonlinear THz science and applications.

1. Introduction
Terahertz spectroscopy can probe the spectral properties of molecules in a previously inaccessible electromagnetic spectrum [1]. Most applications, such as matter characterization and T-ray imaging are based on the technique of THz time-domain spectroscopy (THz-TDS), which employs coherent broadband (2-5 THz bandwidth) THz pulses. Nowadays broadband THz sources are based on the excitation of different materials with ultrashort laser pulses, such as through photoconduction or optical rectification, but the damage threshold of the used materials limits the output power. Plasma has no thermal damage threshold and can sustain extremely intense light. New THz emission mechanisms in the context of intense laser plasma interactions may produce higher power THz sources. A possible THz emission source is based on laser wakefield.

A laser wakefield is an electron plasma wave driven by laser ponderomotive force in plasmas. Though it contains periodic plasma oscillation, the one-dimensional (1D) wakefield in uniform plasmas cannot emit electromagnetic waves due to exact compensation between its displacement and electron currents. So, the wakefield is a pure electrostatic structure. If one adds a static magnetic field on it, it can emit THz wave though Cerenkov emission mechanism in uniform plasmas [2]. In Ref. [3], authors find a wakefield in nonuniform plasmas can emit THz waves in the backward direction through the linear mode conversion mechanism. In Section 2, we investigate THz emission through the mode conversion in the nonuniform magnetized plasma [4]. One can enhance or suppress the THz emission by changing the strength and direction of the magnetic field. In the above THz emission schemes, the plasma size L is much larger than plasma wavelength $\lambda_p$ and THz pulse is multi-cycle. In section 3, we show a wakefield excited in a THz-wavelength-scale ($L \approx \lambda_p$) plasma can directly emit THz wave in both forward and reflecting directions [5]. This is an extremely simple scheme, which

¹ Now at Max-Planck-Institute of Quantum Optics, D-85748 Garching, Germany.
not only leads to deeper insight of wakefield emission, but also afford a promising THz source. Moreover, the THz radiation is in the single-cycle region, which is unique in the context of wakefield emissions and is important for many applications.

2. THz emission through the mode conversion in magnetized plasma

In this section, we study the THz radiation from the laser driven wakefield in an inhomogeneous magnetized plasma. Let us consider the laser wakefield excitation when a plane laser pulse propagates at an angle $\theta$ to the density gradient of an inhomogeneous plasma slab in the $xy$ plane as shown in figure 1. The plasma is underdense and the density rises linearly first up to $x=L$ at which the electron density is $n_0$, and then stays constant up to the plasma-vacuum boundary at $x=L+H$. The exterior dc magnetic field $B_0$ is along the $z$ direction.

In unmagnetized plasmas, THz emission source is proportional to $\tan \theta$ [3]. Thus there is radiation only when the laser light is incident obliquely on the plasma. However, in magnetized plasmas, the new source term related with $B_0$ appears and leads to a nonzero source even for normal incidence [4]. This is a distinct difference between these two cases. As in the unmagnetized case, THz emission is always $p$ polarized, with the electric field in the $xy$ plane and with an emitting angle $\theta$. It is necessary to find a proper plasma condition to make the electrostatic and electromagnetic waves phase matched, and get a high conversion efficiency. As shown in Ref. [3], this condition is that the plasma density increases linearly as $n_{0e}=n_0x/L$, where the plasma wave vector becomes zero along the line $t=3x$.

2.1. THz emission for normal incidence

Firstly, we consider the normal incidence case, and give 1D-PIC simulation results. Figure 2 shows the longitudinal and transverse fields in the $x$-$t$ plane, where the laser pulse is normally incident and the applied dc magnetic field $B_0=7.7$ T. One notes that the phase velocity changes its sign in the region of increasing electron density along the line $t=3x$ in figure 2(a). Around this line, mode conversion...
occurs, and the electrostatic field energy is depleted soon after and converted into electromagnetic energy. Figure 2(b) shows $B_z$ of the THz wave. Figure 2 clearly demonstrates that there are THz emissions for normal incidence of laser pulses in a nonuniform magnetized plasma.

Figure 3(a) shows the temporal profiles of the THz pulses for different magnetic fields $B_0$. The peak field strength is over 0.0002, i.e., 6.4 MV/cm. The corresponding intensity is $5.5 \times 10^{10}$ W/cm$^2$. For a focus spot size of 150µm, the corresponding peak power is about 9.7 MW and energy about 64µJ (THz pulse duration is about 6.6 ps). The spectrum of the THz pulses in figure 3(a) is compared with that of the model calculations in figure 3(b). Analysis model follows Ref. [3], and uses a different conversion efficiency $\eta$ formula in magnetized plasma [4]. This conversion efficiency $\eta$ is deduced from its inverse problem, the upper-hybrid resonance absorption for normally incident laser light in magnetized plasmas.

2.2. THz emission for oblique incidence
Unfortunately, there is not a conversion efficiency $\eta$ formula like normal incidence case. Numerical calculation found that $\eta$ is increased (decreased) when the external $B_0$ has the same (opposite) sign as the incident angle $\theta$, in the interaction geometry shown in figure 1. $\eta_{\text{max}}$ approaches 0.99 at the optimal $B_{0,\text{opt}}$ and $\theta_{\text{opt}}$. $B_{0,\text{opt}}$ is about half of the optimal $B_0$ for the normal incidence case. Therefore, for obliquely incident light, one can obtain higher conversion efficiencies at lower magnetic fields.

Figure 4 show the energy conversion efficiencies of the THz emissions as a function of the incident angle $\theta$ for the magnetized and unmagnetized plasmas.

3. Single-cycle THz pulse radiated from a wavelength-scale plasma oscillator
In this section, we discuss a very simple and promising THz emission mechanism [5]. As discussed in introduction, an infinite 1D plasma wave can never emit electromagnetic waves at frequency $\omega_p$ (or
wavelength $\lambda_p$). Up to now, all THz emission mechanisms based on the wakefield are with a plasma length $L >> \lambda_p$ and generated THz pulses are multi-cycle. Here we introduce a scheme, which can uniquely generate a single-cycle THz pulse. This is realized by exciting a laser wakefield in a plasma slab with $L \approx \lambda_p$. This limited plasma oscillator could radiate electromagnetic waves for the following reasons. Firstly, for such a few-wavelength plasma oscillator, its displacement and plasma currents cannot completely counteract each other, in particular near the plasma boundaries. Secondly, since the plasma skin depth of the radiation at frequency $\omega_p$ is $1/k_p$, which is comparable to the plasma length $L$, the radiation can tunnel through the plasma into vacuum. Figure 5 is a schematic of this THz emission mechanism.

Theory analysis obtains electric field of THz wave $E_{\text{THz}} \propto n^{1/2}a_0^2 \sin \theta$ [5]. The emission electric amplitude is proportional to $n^{1/2}a_0^2$ is due to the laser-driven wakefield amplitude is proportional to $n^{1/2}a_0^2$. It also predicts that the emission field increases monotonically with $\sin \theta$ for $\theta<90^\circ$. Physically, it can be attributed to the fact that the emission source area is increased when the incident angle is increased. Both 1D and 2D-PIC simulations confirm the above scaling. Figure 6 shows a typical result. It is found that there are indeed two single-cycle THz pulses in the reflection and transmission directions. The THz field strength is 42 MV/cm, i.e., an intensity of $2.5 \times 10^{12}$ W/cm$^2$. Since the radiation radius is about 30 $\mu$m, this is equivalent to a peak power of 70 MW.

This THz emission works well in higher laser intensities. Such as for $I = 3.4 \times 10^{19}$ W/cm$^2$ ($a_0=5$), the simulations shows that the THz field strength can be 0.33 GV/cm, and the corresponding power is about 45 GW (assuming a source radius of 100$\mu$m). This THz source can tunable in 0.1-10 THz by adjusting $n_0$.

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