Subpicosecond, Electromagnetic Pulses from Intense Laser-Plasma Interaction

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Laser pulses with a power of 10^{12} W and a duration of 10^{-13} s were focused onto both gas and solid targets. Strong emission of pulsed radiation at terahertz frequencies was observed from the resulting plasmas. The most intense radiation was detected from solid density targets and was correlated with the emission of MeV x rays and electrons. Results indicate that radiative processes in such plasmas are driven by ponderomotively induced space charge fields in excess of 10^8 V/cm. This work constitutes the first direct observation of a laser-induced wake field.

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Plasmas created by high-intensity laser pulses with subpicosecond duration have received considerable attention as novel sources of radiation. The observed emission includes coherent radiation at high harmonics of the laser frequency [1], incoherent soft x-ray bursts with subpicosecond duration [2], and the generation of hard x rays with photon energies extending beyond 1 MeV [3]. At the low frequency end of the electromagnetic spectrum, strong emission of coherent far-infrared radiation (FIR) at terahertz frequencies was recently predicted [4]. This radiation results from the space charge fields developed in such plasmas. In this Letter we report the first observation of this effect.

The generation of strong electric and magnetic fields in laser produced plasmas has been considered before. Electric fields on the order of 10^7 V/cm have been inferred in experiments involving plasma-wave accelerators [5]. In the context of high-intensity short-pulse laser interaction with plasmas, electric fields of 10^8 V/cm [6] and magnetic fields of up to 10^9 G [7,8] were predicted by several groups. Our experiments allow a comparison with this previous work by direct measurement of such fields.

We note that the generation of terahertz radiation through the use of femtosecond laser pulses has been considered in a variety of schemes [9]. For example, intense pulses with energies up to 0.8 μJ were produced by illuminating a biased GaAs wafer with short laser pulses [10].

In our experiment, the mechanism of FIR generation involves ponderomotive forces present at the focus of an intense laser pulse. These forces generate a large density difference between ionic and electronic charges since the laser pulse length is short enough to inertially confine the ions [6,11]. This charge separation results in a powerful electromagnetic transient [4].

To estimate the magnitude of the terahertz emission we employed a hydrodynamic model for the plasma dynamics. We calculated the spatial and temporal dependence of the charge density and acceleration within the focal region and thereby determined the far-field radiation pattern. The electron fluid can be assumed to be cold, i.e., the thermal energy is small compared to the ponderomotive energy, $U_{\rm pon}$. $U_{\rm pon}$ is defined in Ref. [12]. The cold fluid approximation is justified since plasmas produced by short pulse lasers tend to have temperatures $\leq 10^3$ eV [13], while the ponderomotive energies for our experimental conditions are on the order of 10^5 eV. The dynamical equations of motion for the electron fluid [14] may then be linearized and decoupled to yield simple harmonic oscillator equations for the electron density and velocity [15]. We solved these equations for a temporally and spatially Gaussian pulse envelope while considering the natural divergence of the Gaussian mode. We obtain analytical solutions for the equations of motion in terms of an error function with a complex argument [16]. The far-field radiation pattern is then calculated by numerical integration of these expressions.

Losses are expected for terahertz frequencies below ω_p since the plasma becomes overcritical. However, due to the relatively small spatial extent of our plasma, the actual losses are not important; we determined an upper bound on the damping of FIR radiation to be about 10%, integrated over the viewing angle for our geometry and laser spatial profile. These losses are therefore not considered further.

Figure 1 gives two examples of such calculations. A strong resonant enhancement of the signal is predicted for $\omega_p \tau_0 = 2$, where ω_p is the plasma frequency and τ_0 is the temporal $1/e^2$ half-width of the pulse. In this regime (electron density $n \approx 2\times10^{17}$ cm^{-3} and $\tau_0 \approx 0.1$ ps) the emission is expected to last for many cycles of the plasma oscillation. This is shown in Fig. 1(a) for a plasma frequency $\omega_p/2\pi$ of 4.6 THz and $\omega_p \tau_0 = 2.1$. We note that the damping of the plasma oscillations due to electron-ion collisions is not important on a time scale of a few picoseconds since the plasma temperatures are relatively low [13,17]. For higher densities, i.e., excitations above the plasma resonance, the radiated power is predicted to decrease. At these densities the calculated pulse shape is approximately given by the derivative of the exciting optical pulse. Note that the spatial distribution of the radiation depends on the spot size of the focused laser beam. A smaller beam leads to a shift of the emission maximum in a direction perpendicular to the laser propagation.

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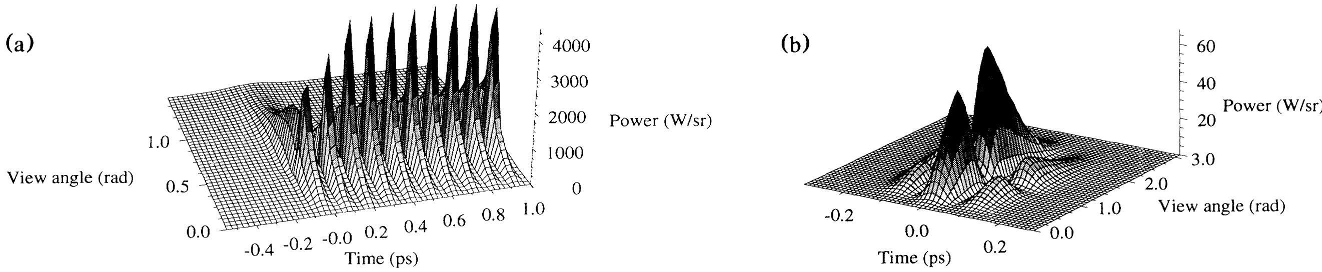

FIG. 1. Calculated terahertz radiation patterns. The view angle is with respect to the beam propagation direction. Calculations assume a pulse length of 120 fs (FWHM), a pulse energy of 50 mJ, and a beam diameter of 3 μm. (a) Resonant plasma response when the electron density is 2.5×10^{17} cm^{-3}. (b) FIR signal due to $\mathbf{J}^{\rm NL}$ [Eq. (1)] at a density of 10^{19} cm^{-3}.

The radiation discussed so far arises solely from a current set up by a *time averaged* driving force. There will be an additional radiative contribution which arises from the mixing of frequencies at $\omega\pm\Delta\omega$, where ω is the carrier frequency and $\Delta\omega$ is the bandwidth of the laser pulse. This nonlinear current $\mathbf{J}^{\rm NL}$ has been previously calculated for the case of second harmonic generation in a plasma [18]. In a similar fashion we estimate the leading contribution due to this effect at low frequencies to be given by

$$\mathbf{J}^{\rm NL}(\Delta\omega,\omega,-\omega)=\frac{4\pi e^3}{\omega^3 m_e^2 c}\left[\frac{1}{1-(\omega_p/\omega)^2}\right]I(\nabla n\cdot\mathbf{e}_{\rm pol})\mathbf{e}_{\rm pol}\,. \quad (1)$$

$\mathbf{e}_{\rm pol}$ is the polarization vector of the exciting electromagnetic field, I is the laser intensity, and e and m_e are the electron charge and mass. We compute the far-field radiation pattern by obtaining ∇n from our hydrodynamic model. The result of one such calculation is shown in Fig. 1(b) for $n=10^{19}$ cm^{-3} and $I=5\times10^{18}$ W/cm^2.

In order to measure these effects, we used a terawatt laser system [19] at a focused intensity of up to 10^{19} W/cm^2. We achieved a pulse length of typically 120 fs and an energy of up to 0.5 J at 0.8 μm wavelength. The beam was focused with a 5 cm focal length off-axis paraboloidal reflector to a diameter of 3 μm.

The first series of experiments was performed at gas pressures up to 10^5 Pa. The FIR was collected by using a $f/0.5$ off-axis paraboloidal mirror. A liquid helium cooled bolometer was used in conjunction with a Fourier transform spectrometer to characterize the emitted radiation [20]. Figure 2 shows the total detected terahertz signal as a function of pressure in comparison with our model calculation. As expected, we observe strong resonant enhancement of the radiation if the plasma frequency is close to the inverse pulse length of the laser. However, our linearized model fails to accurately predict the observed behavior at high pressures. Interferograms reveal that the strong signal around 400 Pa is indeed due to the oscillation at the plasma frequency. We observed several cycles of radiation extending over a period of about 2 ps. Assuming that the damping of the radiation is due to electron-ion collisions in a thermal plasma, we infer a temperature of 0.5 eV, which seems too low. However, we estimate that the radiative losses are considerable [16]. In addition, other nonlinear damping mechanisms may have to be considered. The frequency of the emission of the resonant signal varies with gas density and is close to the bulk plasma frequency as shown in Fig. 3. Note that this observation is not trivial since the size and shape of plasma are expected to lead to a deviation from the bulk plasma frequency. At densities above 4×10^{17} cm^{-3} a new peak in the spectrum appears which is centered around 1.5 THz. This spectral peak remained essentially at the same frequency for all higher densities. The autocorrelation signal of such a pulse is shown in Fig. 4 and has a FWHM of 0.3 ps. The pulse shape resembles the temporal characteristics calculated in Fig. 1(b), indicating that this signal is probably due to $\mathbf{J}^{\rm NL}$. The signal is polarized parallel to the exciting 0.8 μm radiation, as expected from Eq. (1).

We also performed a direct measurement in the time domain. The terahertz radiation was transmitted through a semi-insulating GaAs wafer which functioned as a transient mirror when illuminated with femtosecond optical radiation [10,21]. The results showed that for the case of

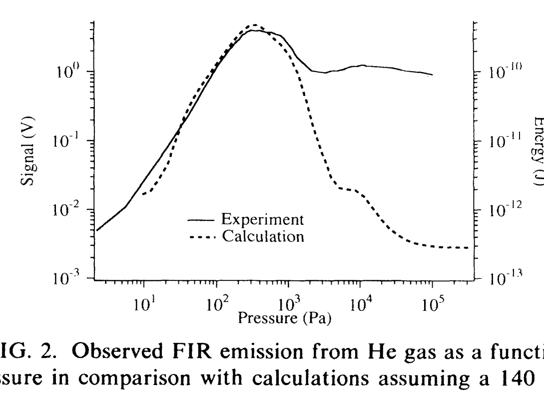

FIG. 2. Observed FIR emission from He gas as a function of pressure in comparison with calculations assuming a 140 fs, 50 mJ laser pulse.

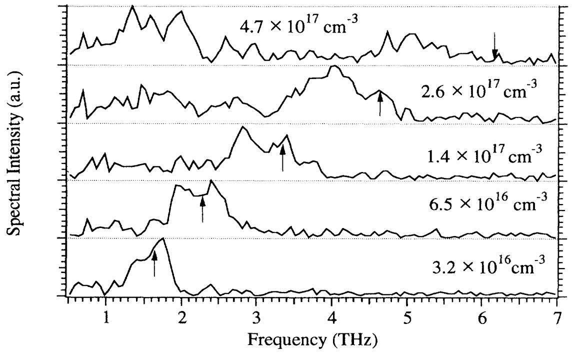

FIG. 3. Spectra for a resonant excitation of the plasma where $\omega_p \tau_0 \approx 2$. The arrows indicate the plasma frequency $\omega_p/2\pi$ at each density. Note the emerging nonresonant signal around 1.5 THz at the highest densities. Data are for a He gas and 120 fs, 50 mJ laser pulses.

nonresonant excitation most of the FIR is emitted in a time interval of less than 0.8 ps (10% to 90% points). The resonant excitation signal is emitted in a time interval of 1.7 ps.

In a second set of experiments we investigated the emission of terahertz radiation from a solid target. The laser was p polarized and incident on the target at 60° with respect to normal. Al-coated glass slides were used as targets. Since the radiation is emitted from a spatially fixed interface and not from a moving focus, we expect the emission pattern to be peaked in the backward direction [4,16]. Using a pyroelectric detector in conjunction with a collection cone and a light pipe we observe 0.5 μJ of p-polarized FIR emitted into a solid angle of 1.5 sr at an incident laser pulse energy of 200 mJ. Because of coupling losses into the detector and low absorption by the detector element we estimate the actual radiative yield to be a factor of 3 higher. We therefore infer a peak power for the FIR of greater than 1 MW. We also observed that the laser pulse must be preceded by a small amount of prepulse energy in order to optimize the terahertz radiation.

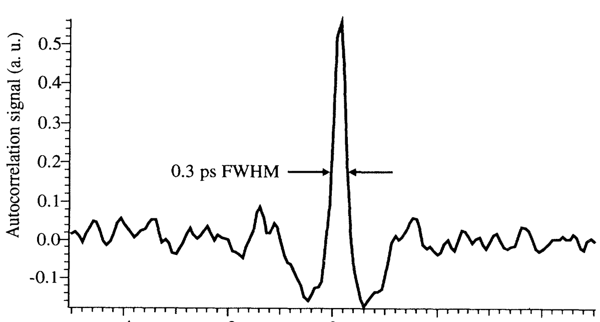

FIG. 4. Autocorrelation of FIR signal in He gas for 120 fs, 50 mJ laser pulses. Nonresonant excitation at an electron density of 2×10^{19} cm^{-3} is observed.

Simultaneous with the far-infrared emission we observe a hard x-ray signal from the laser plasma. The x rays must penetrate the 5 mm thick steel wall of the target chamber, which provides a low-energy cutoff of 0.1 MeV, and are then detected with a 7.5 cm diameter NaI detector. We observe the same signatures for hard x-ray emission as reported previously [3]. The x rays and FIR are correlated on a shot-to-shot basis. Figure 5(a) shows the x-ray signal on the NaI detector versus the FIR signal. FIR and x-ray emission are correlated by a power law with an exponent of 0.7. In addition, we detected the emission of energetic electrons from the plasma. We used a 5 mm thick piece of BC408 scintillator plastic to detect hot electrons. By using a Sm:Co magnet we verified that the signal here was indeed due to electrons and not x rays. Al sheets of varying thickness were used to determine the electron energy [22]. We estimate that the bulk of the electrons have an energy of about 0.6 MeV. This energy is somewhat larger than predicted by computer simulations [7]. The ponderomotive energy of the focused laser is only 0.1 MeV. However, we believe that the electrons originate close to the critical surface where the electric field is strongly enhanced [23]. This is supported by the observation that strong emission is detected only if the target is prepulsed; we observe simultaneously light at the $\frac{3}{2}$ harmonic of laser frequency which originates from a region with quarter critical density [24]. Similar to the x-ray signal, the electron yield is also correlated to the terahertz emission. We measure a power law with an exponent of 0.4 between the electron scintillator and FIR signals [see Fig. 5(b)].

One may explain these correlations as follows. The

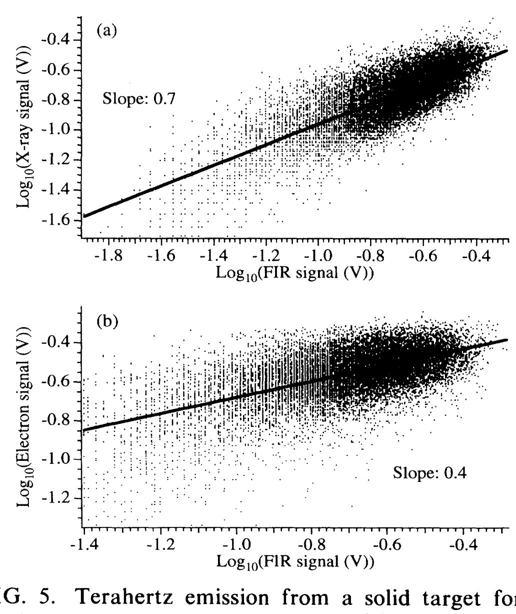

FIG. 5. Terahertz emission from a solid target for 16000 laser shots at a pulse energy of 25 mJ. (a) X-ray and (b) electron scintillator signal versus FIR signal.

simultaneous occurrence of a strong x-ray, β, and FIR emission indicates that the radiative processes are driven by ponderomotively induced space charge fields at the critical surface. The space charge fields which give rise to the emission of terahertz radiation also accelerate the hot electrons, which then in turn produce energetic x rays via bremsstrahlung. The scaling for such a process is well known for x-ray tubes [25]. However, we fail to explain the measured power laws for the x-ray yield on the basis of this simple analogy [16].

The relation between the electron signal P_e and FIR signal $P_{\rm FIR}$ is given by $P_e \propto (P_{\rm FIR})^{0.5}$ if both signals are caused by the same electric field. This compares well to the measured exponent of 0.4.

It is interesting to compare the yields for the three types of radiation. Assuming that the electron emission from the plasma has an average energy of 0.6 MeV and is isotropic, we estimate that 2×10^9 electrons are emitted by the plasma per shot at a laser pulse energy of 20 mJ. The electron to x-ray energy conversion is then 0.2%. This compares well with a calculated bremsstrahlung yield of 0.4% for 0.6 MeV electrons in glass [22]. An estimate may also be obtained for the strength of the low frequency electric field in the focal region. The observed 0.6 MeV electrons indicate a field strength on the order of 10^9 V/cm assuming that the electrons are accelerated over a distance comparable to the diameter of the focused beam. At the same time we can infer a field strength on the order of 10^8 V/cm from the observation of terahertz radiation with a peak power of several MW emerging from a spot a few microns in size. This corresponds to a strength of the magnetic field of the electromagnetic wave of $\approx 3\times10^5$ G. The discrepancy in the field strength may be reconciled if one considers that there will be a coupling loss since the FIR has to penetrate a dense plasma.

In conclusion, we have demonstrated that a short-pulse laser-produced plasma is a powerful source of subpicosecond terahertz radiation. From solid targets we measured peak powers in excess of 1 MW. We also report the first direct observation of a laser-induced wake field. Further, we have shown that the emission of FIR is strongly correlated with the production of x rays and electrons with MeV energies. This may allow novel experiments with ultrafast time resolution that cross-correlate radiation which spans the electromagnetic spectrum from meV to MeV energies.

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