Experimental Observation of Radiation from Cherenkov Wakes in a Magnetized Plasma

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(Received 4 April 2002; published 22 July 2002)

A proof-of-principle experiment demonstrates the generation of radiation from the Cherenkov wake excited by an ultrashort- and ultrahigh-power pulse laser in a perpendicularly magnetized plasma. The frequency of the radiation is in the millimeter range (up to 200 GHz). The intensity of the radiation is proportional to the magnetic field intensity as expected by theory. Polarization of the emitted radiation is also detected. The difference in the frequency of the emitted radiation between these experiments and previous theory can be explained by the electrons' oscillation in the electric field of a narrow column of ions in the focal region.

DOI: 10.1103/PhysRevLett.89.065003 PACS numbers: 52.38.–r, 41.60.Bq, 52.25.Xz, 52.35.–g

In the last decade, the phenomena of frequency up-shift of electromagnetic waves and the generation of short-pulse radiation have been experimentally [1] and theoretically investigated [2]. Photon acceleration using a relativistic ionization front has been studied by Mori [3]. In this scheme, the ionization front propagating relativistic velocity ($\sim c$) interacts with a counterpropagating electromagnetic wave (probe wave), and the frequency of the probe electromagnetic wave is up-shifted. This phenomenon takes place not only at the overdense ionization front but also at the underdense ionization front. The ionization front generated by laser has successfully interacted with an existing microwave, and its frequency increased from 35 to over 170 GHz [4,5]. Mori *et al.* have shown that the frequency up-shift occurs by the interaction between a static electric field and an ionization front [6]. This means a direct electromagnetic wave generation from the static electric field. Lai *et al.* have reported this phenomenon using a high-power short-pulse glass laser system and observed emitted radiation in the microwave region [7].

Recently Yoshii *et al.* have proposed a new mechanism in which the short electromagnetic pulse is radiated by the interaction between a laser wakefield or short electron bunch and a static magnetic field [8,9]. In the magnetized plasma, the wakefield has both electrostatic and electromagnetic components. Furthermore, the magnetized wakefield has nonzero group velocity. This enables the wake to propagate through the plasma and couples radiation into the vacuum. This phenomenon is called Cherenkov wake radiation, and the emitted frequency is expected to be close to the plasma frequency. The theory predicts the production of GHz to THz radiation at a power approaching GW level by using the wakefield excited by current laser systems and the appropriate magnetic field.

In this paper, we report, to the best of our knowledge, the first proof-of-principle experiment demonstrating the generation of the radiation from the Cherenkov wake excited by an ultrashort- and ultrahigh-power pulse laser in a perpendicularly magnetized plasma.

The geometry of the radiation scheme demonstrated here is simple. A short pulse of an ultrahigh-power laser beam propagates in the z direction and a dc magnetic field exists in the y direction. After the propagation of the laser pulse, the wakefield is excited behind it and couples with the magnetic field, and the radiation is generated. To understand the expected radiation, we consider the dispersion relation of the electromagnetic wave in the magnetized plasma. In the unmagnetized plasma, the dispersion relationship for the electromagnetic wave, $\omega^2 = \omega_p^2 + c^2k^2$, cannot couple with the Cherenkov radiation $\omega = kv_g \cos\theta$ where ω_p and v_g are the plasma frequency and the group velocity of the laser pulse in the plasma, respectively, and v_g is less than the speed of light c. However, the addition of the applied magnetic field alters the scenario. In the magnetized plasma, two branches [lower and higher of the extraordinary (XO) mode] appear in the dispersion relationship of the electromagnetic wave. The intersection of the lower dispersion curve and the disturbance excited by the laser beam ($\omega = v_g k \cos\theta$) gives the frequency and wave number of the excited radiation. In this case, most of the radiation power is emitted in the forward direction, i.e., the $\theta = 0$ or z direction, since the group velocities of waves matching the Cherenkov condition at other angles are very small. In the underdense plasma, $v_g \approx c$, the intersection appears at $\omega \approx \omega_p$. Therefore, resultant radiation of the frequency of $\omega \approx \omega_p$ is expected. Here the group velocity of the radiation is $V_g = d\omega/dk = (\omega_c^2/\omega_h^2)c$, where $\omega_c = eB_0/mc$ is the cyclotron frequency of the electron and ω_h is the upper hybrid frequency defined as $\omega_h^2 = \omega_p^2 + \omega_c^2$.

Figure 1 shows the experimental setup and measurement system for the observation of the emitted radiation from the

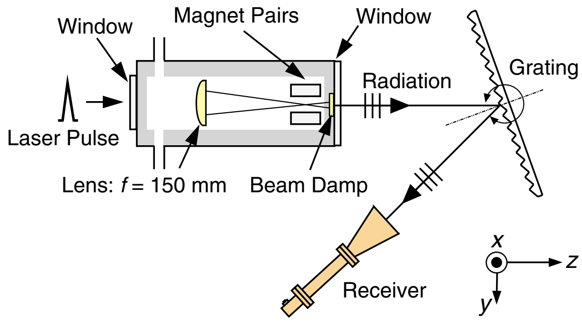

FIG. 1 (color online). Experimental setup and measurement system for the observation of the emitted radiation from the Cherenkov wake. Temporal waveform of radiation and polarization of the radiation were directly measured without the grating.

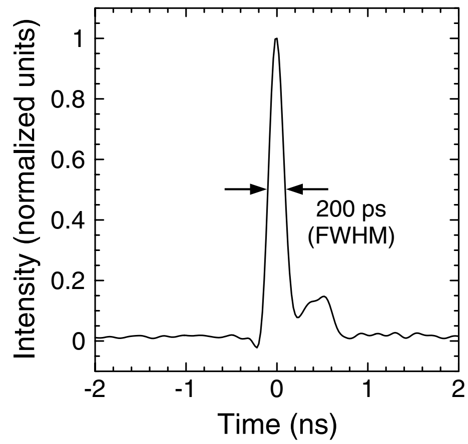

FIG. 2. Typical radiation waveform of Cherenkov radiation detected by the crystal detector.

Cherenkov wake. The dc magnetic field in the y direction is generated by the permanent magnet, and its field strength is varied from 0 to 6 kG. A 10 Hz Ti:sapphire laser beam at a wavelength of 800 nm, with a maximum energy of 100 mJ and a duration of 100 fs [full width at half maximum (FWHM)], is used for the wakefield generation. The laser beam is focused by an $f/5$ lens at the region where the static magnetic field is applied. The focal spot diameter is less than 20 μm and its maximum intensity is on the order of 10^{17} W/cm^2.

After the vacuum chamber is evacuated by a turbomolecular pump below 10^{-5} Torr, it is statically filled with nitrogen or argon gas, as a working gas to a maximum pressure of 1 Torr. When the high intensity laser beam is focused, the ionization is expected to occur by the tunnel ionization process.

In order to measure the emitted radiation, we used two methods. One was the combination of a waveguide and horn antenna for temporal evolution of the radiation waveform; the other is a spectrum measurement using a grating with 15 0.5 cm grooves blazed at a 30° angle. In both experiments, the radiation was detected by a crystal detector. The angle between the incident radiation and the receiving horn antenna is kept constant while the grating is rotated.

Figure 2 shows the typical output signal with the duration of 200 ps (FWHM). This is comparable to the instrument limited pulse length that can be measured with the response time of the crystal detector. Here the microwave detection system consists of a 31.4 GHz waveguide and horn antenna combination with the microwave detector of the time resolution of 100 ps displayed on the oscilloscope (Tektronix type; TDS-694C) with the analog frequency bandwidth of 3 GHz. The applied magnetic field is 6 kG and the gas pressure of nitrogen is 270 mTorr. The detected radiation power is estimated to be several tens of mW.

The radiation duration, τ, is predicted to be the damping time of the wakefield, when the damping is strong. In the case of weak damping, however, the duration is determined by the cycles of the wakefield in the plasma, N, and the group velocity of the radiation, V_g, in the plasma, i.e., [8]

$$\tau \approx \frac{2\pi N c}{\omega_p V_g} = \frac{L_p}{c}\frac{\omega_h^2}{\omega_c^2}, \tag{1}$$

where L_p is the length of plasma. In our experiments, the plasma is weakly magnetized, $\omega_p^2/\omega_c^2 \sim 0.01$, i.e., $\omega_p^2 \ll \omega_c^2$, and this equation is approximately written as

$$\tau \approx \frac{L_p}{c}\frac{\omega_p^2}{\omega_c^2}. \tag{2}$$

For our experimental conditions, the time scale of the damping of the wakefield may be estimated to be on the order of 10 ps [10]. This is shorter than the upper limit based on the length of the plasma, L_p. L_p will be on the order of the Rayleigh length z_R, and the Rayleigh length for the optical parameters of our experiments is 1.6 mm. This gives a maximum pulse duration of 700 ps. Although the experimental value is on the same order as the theoretical predictions, instrument limits and dispersion in the waveguide allow us to conclude only that the measured value of 200 ps is an upper limit on the pulse duration.

Figure 3 shows the frequency spectrum of the radiation measured at nitrogen pressures of 60, 120, and 270 mTorr (denoted by solid circles) and argon pressures of 40 and 80 mTorr (denoted by open circles), leading to center frequencies of 104 and 116 GHz (in the $m = 1$ order) and 179, 195, and 199 GHz (in the $m = 2$ order). Intensity is normalized by its maximum value in each gas. The incident wave is s polarized, and the signal is observed in the $m = 1$ and 2 reflection orders of the grating spectrometer. In this experiment, frequencies under 120 GHz are observed in the $m = 1$ order, and frequencies from 120 to 240 GHz are observed in the $m = 2$ order. The crystal detector response is flat under 250 GHz and decays over 250 GHz. We observed even larger radiation signals in

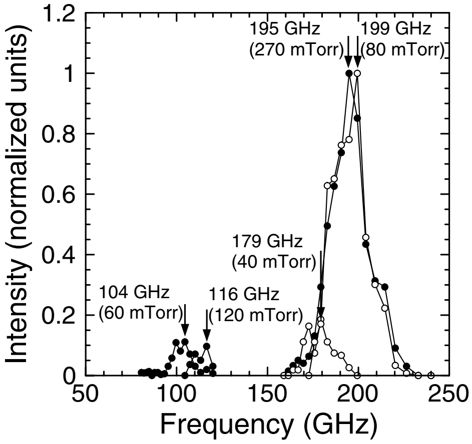

FIG. 3. Frequency spectrum of Cherenkov radiation measured by the grating spectrometer.

higher gas pressure; however, we cannot determine the frequency of the radiation.

From the 1D plasma theory, the radiation is expected at the plasma frequency ω_p, and the plasma density corresponding to the frequency of 200 GHz is 4.9×10^{14} cm^{-3}. However, in the experiment, nitrogen gas is expected to be 5 times ionized by the laser pulse, yielding a plasma density of 4.5×10^{16} cm^{-3}. Therefore the detected frequency of the radiation ω is approximately $\omega_p/10$. We will explain this discrepancy below.

The emitted radiation is expected to be polarized in the x direction, i.e., vertical to the dc magnetic field. The polarization is measured by rotating the microwave horn antenna around the z axis. The signal is detected by the 31.4 GHz cutoff waveguide and the horn antenna. Figure 4 shows the relationship between the electric field of the emitted microwave and the angle of the antenna. The data are normalized to the maximum value at $\theta = 0°$. Here the gas pressure of nitrogen is 270 mTorr and the static magnetic field is 6 kG. The polarization angle of 0° corresponds to polarization in the x direction. The solid line indicates the electric field intensity distribution $\cos^2\theta$ which is what is expected for a tiny dipole antenna oriented along x. The data are in fairly good agreement with the expectation, suggesting that the radiation is polarized as expected for radiation emitted by a Cherenkov wake.

The direction of the emitted radiation is also measured (not shown here). The distribution angle of radiation is $\pm 5°$ in the forward direction. This is much narrower than expected from recent 2D and 3D simulations [9] or from considerations that the radiation emanates from a narrow (essentially point) source at the plasma exit. We have no explanation for this observation.

The theory gives the output power p of the emitted radiation to be

$$p \approx \Gamma^2 \left(\frac{\omega_c}{\omega_p}\right)^2 \frac{cE_z^2}{8\pi}, \tag{3}$$

where E_z and Γ are the longitudinal electric field of the excited wakefield and the damping factor of the radiation at the plasma-vacuum boundary, respectively [8]. The longitudinal wakefield can be estimated from the 1D unmagnetized plasma theory, and its value is calculated to be 2.0×10^5 V/cm. The damping factor Γ is calculated when a linear plasma density with a ramp length of L is assumed, and is given as $\Gamma = e^{\alpha L \omega_p / c}$, where α is called the damping coefficient which is a function of ω_c/ω_p. Figure 5 shows the output power of the radiation as a function of the applied dc magnetic field. The power of the vertical axis is in arbitrary units because the measurement system is not calibrated. The circles with error bars and the dotted line indicate the experimental results and the theoretical value given by the above model which takes the damping phenomena at the boundary into account. The length L is assumed to be 2 mm in our experiments. The dependence of the output power on the dc magnetic field is

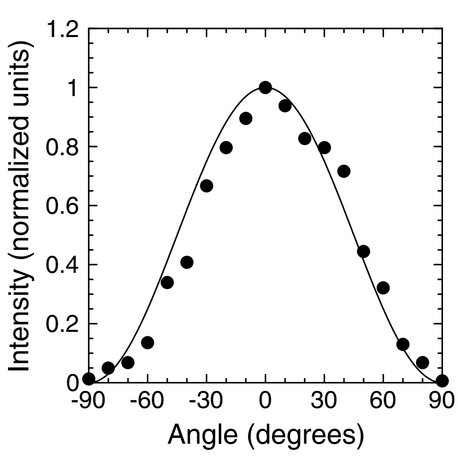

FIG. 4. Relationship between the electric field of the emitted microwave and the angle of the horn antenna.

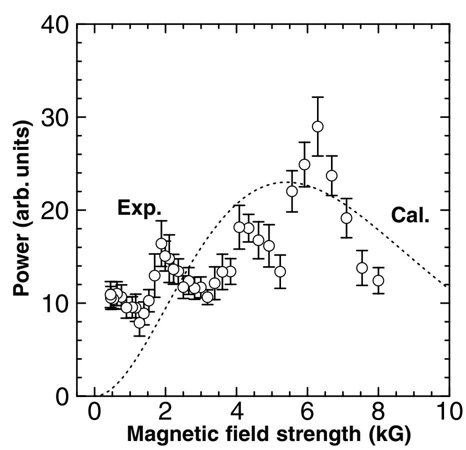

FIG. 5. Output power of the radiation as a function of the applied dc magnetic field. Dashed line indicates the theoretical value.

in good agreement with the theory. The details of structure in the data cannot be explained so far. Even if no magnetic field is applied, a weak signal is detected. This might be caused by the radiation due to nonlinear currents which has been reported by Hamster *et al.* [11].

The theory predicts that the frequency of emitted radiation is equal to the plasma frequency ($\omega \sim \omega_p$); however, the frequency of the radiation in the experiments is much lower than the expected value ($\omega \sim \omega_p/10$) as stated above. This discrepancy can be explained by taking the radial oscillation of electrons into account. At the focal region of the laser beam, the extreme ponderomotive force on the plasma can expel all the plasma electrons beyond the boundary of ionized plasma. Thus the oscillation is not the usual Langmuir oscillation but rather the oscillation of electrons about the narrow line charge of the (relatively immobile) remaining ions. The line charge per unit length is $\pi n_0 e w^2$, and the approximate equation of motion for electrons in the radial field of the line charge is

$$m\frac{d^2r}{dt^2} = -2\pi n_0 e^2 \frac{w^2}{r},$$

where w is the focal radius of the laser beam. The frequency of the electron oscillations can be estimated by the integration of the above equation,

$$f/f_p \sim \frac{\sqrt{\pi} w}{2r_0},$$

where r_0 is the maximum oscillation amplitude of the electron which is initially accelerated by the laser ponderomotive force, and $2\pi f_p = \omega_p$. Since r_0 is itself inversely related to the spot size w, this formula suggests that the frequency of the oscillation strongly reduced as the focal size of the laser beam is reduced. Particle-in-cell simulation using our experimental values showed the frequency of the Cherenkov wake to be $\omega_p/5 \sim \omega_p/4$ in 2D slab geometry. Detailed PIC simulations in 3D are underway and will be published elsewhere [12].

Further work is required to independently diagnose the plasma density along the direction of laser propagation and the electric field of the longitudinal wakefield. In higher density experiments, higher frequency radiation is expected. Therefore, a direct measurement of the radiation electric field will require for a precise frequency measurement another technique such as EO (electro-optical) sampling [13]. The use of a supersonic gas jet valve may be appropriate for the creation of the sharp boundary plasma-vacuum interface and more efficient extraction of the radiation energy from the plasma to vacuum.

We have verified the physical mechanism of the generation of radiation from Cherenkov wakes in a magnetized plasma. In the present experiment, radiation frequencies up to 200 GHz were detected and tuned by varying the gas pressure. The relative power of the signal was measured to scale with the square of the dc magnetic field strength. The results support the potentiality of developing high-power, tunable, and short-pulse coherent radiation sources with a frequency ranging from microwaves to THz.

We acknowledge useful discussion with Professor M. Bakunov. A part of the present work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan. We are grateful to D. Gordon for the use of his code TURBOWAVE. We also are grateful to Cooperative Research Center and Satellite Venture Business Laboratory (SVBL) of Utsunomiya University for providing us with the laser system. One of the authors (T. K.) is supported by NSF Grant No. PHY 0078715 and DoE Grant No. DE-FG03-92ER40745.

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[1] Special Issue on the Generation of Coherent Radiation Using Plasmas, edited by W. B. Mori [IEEE Trans. Plasma Sci. **21**, No. 1 (1993)].
[2] S. C. Wilks, J. M. Dawson, W. B. Mori, T. Katsouleas, and M. E. Jones, Phys. Rev. Lett. **62**, 2600 (1989).
[3] W. B. Mori, Phys. Rev. A **44**, 5118 (1991).
[4] R. L. Savage, Jr., C. Joshi, and W. B. Mori, Phys. Rev. Lett. **68**, 946 (1992).
[5] R. L. Savage, R. P. Brogle, W. B. Mori, and C. Joshi, IEEE Trans. Plasma Sci. **21**, 5 (1993).
[6] W. B. Mori, T. Katsouleas, J. M. Dawson, and C. H. Lai, Phys. Rev. Lett. **74**, 542 (1995).
[7] C. H. Lai, R. Liou, T. Katsouleas, P. Muggli, R. Brogle, C. Joshi, and W. B. Mori, Phys. Rev. Lett. **77**, 4764 (1996).
[8] J. Yoshii, C. H. Lai, T. Katsouleas, C. Joshi, and W. B. Mori, Phys. Rev. Lett. **79**, 4194 (1997).
[9] N. Spence, T. Katsouleas, P. Muggli, W. B. Mori, and R. Hemker, Phys. Plasmas **8**, 4995 (2001).
[10] J. R. Marquès, F. Dorchies, F. Amiranoff, P. Audebert, J. C. Gauthier, J. P. Geindre, A. Antonetti, T. M. Antonsen, Jr., P. Chessa, and P. Mora, Phys. Plasmas **5**, 1162 (1998).
[11] H. Hamster, A. Sullivan, S. Gordon, W. White, and R. W. Falcone, Phys. Rev. Lett. **71**, 2725 (1993).
[12] T. Katsouleas, D. Gordon, and W. B. Mori (private communication).
[13] D. H. Auston *et al.*, Phys. Rev. Lett. **53**, 1555 (1984); Y. Cai *et al.*, Appl. Phys. Lett. **73**, 444 (1998); F. G. Sun *et al.*, Appl. Phys. Lett. **73**, 2233 (1998).