Terahertz Acoustics in Hot Dense Laser Plasmas

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We present a hitherto unobserved facet of hydrodynamics, namely the generation of an ultrahigh frequency acoustic disturbance in the terahertz frequency range, whose origins are purely hydrodynamic in nature. The disturbance is caused by differential flow velocities down a density gradient in a plasma created by a 30 fs, 800 nm high-intensity laser ($\sim 5 \times 10^{16}$ W/cm^2). The picosecond scale observations enable us to capture these high frequency oscillations (1.9 ± 0.6 THz) which are generated as a consequence of the rapid heating of the medium by the laser. Adoption of two complementary techniques, namely pump-probe reflectometry and pump-probe Doppler spectrometry provides unambiguous identification of this terahertz acoustic disturbance. Hydrodynamic simulations well reproduce the observations, offering insight into this process.

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The generation of acoustic waves in hydrodynamical systems has a long, rich, and surprising history in physics and engineering. This ranges from the relatively prosaic problems associated with acoustic wave generation in jet and rocket engines [1] to a number of aspects of solar physics [2,3], and even to much more recent speculations that acoustic processes may play an important role in core-collapse supernovae and associated issues in stellar astrophysics [4]. Acoustic generation has, thus, remained an important and fundamental problem in fluid dynamics and plasma physics.

The generation of sound in either natural or man-made systems is, in some instances, a straightforward phenomenon. In other situations, acoustic generation can be more subtle, e.g., advective-acoustic or vortical-acoustic cycles [1,5]. The role of acoustic waves and weak shocks in supernova remnants has been discussed by the astrophysical community for some time [6,7]. High-power laser-solid interactions are capable of achieving very high energy densities and can, thus, drive strong shocks and blast waves [8]. In an underdense plasma, the generation of strong ion acoustic waves can occur (especially through stimulated Brillouin scattering [9]). However, experimentally studying such ultrafast dynamics in laser-plasmas is rather challenging and can be achieved through suitable optical probing techniques [10–15].

In this Letter, we present the results of detailed pump-probe reflectometry and Doppler spectrometry experiments which, somewhat unexpectedly, indicate the generation of strong terahertz acoustic waves in a dense laser-produced plasma. Theoretical modelling indicates that this terahertz acoustic disturbance could be produced by intrinsically unsteady hydrodynamic processes in the heated plasma. The frequency of this acoustic disturbance produced in the laboratory is of the same order as the maximum allowed frequency that could be supported by this hot dense matter (see Supplemental Material [16]). This phenomenon, previously not noticed in the widely explored field of hydrodynamics, was found in the interaction of an intense ($\gtrsim 10^{16}$ W/cm^2) femtosecond laser with a dense plasma and observed (with $\sim$50 fs temporal resolution) apparently on a picosecond time scale.

The experiment was carried out (setup shown in Fig. 1) with a chirped-pulse-amplification-based 20 terawatt laser (Ti:sapphire, 30 fs, 800 nm) at TIFR. A polished BK-7 (5 mm-thick borosilicate glass) was irradiated by a p-polarized pump pulse after focusing down to a 15 μm spot (FWHM) by an off-axis parabolic mirror at an angle of incidence of 45°. A peak intensity of the order of 10^{16} W/cm^2 was kept on the target. The picosecond intensity contrast ($\sim 10^{-4}$) of the laser has been measured by a third-order cross correlator (SEQUOIA). A small fraction of the pump pulse is extracted, attenuated in energy, and used as a probe pulse in a series of measurements by converting it to its second harmonic. The probe pulse, passed through a high precision (1 μm) delay stage, is focused (FWHM $\sim$60 μm) to the laser-irradiated plasma at near normal incidence. The reflected probe is fed simultaneously into a photodiode and a high-resolution spectrometer (spectral resolution of 0.05 nm at probe wavelength) in order to obtain the reflectivity and Doppler shift of the reflected probe. The velocity of the critical surface was determined by the relation, $V_{\mathrm{cr}} = -0.5c(\delta\lambda/\lambda)$ where, c and λ are the speed of light in free space and the central wavelength of the probe pulse, respectively. The details of this technique are explained elsewhere [10,11].

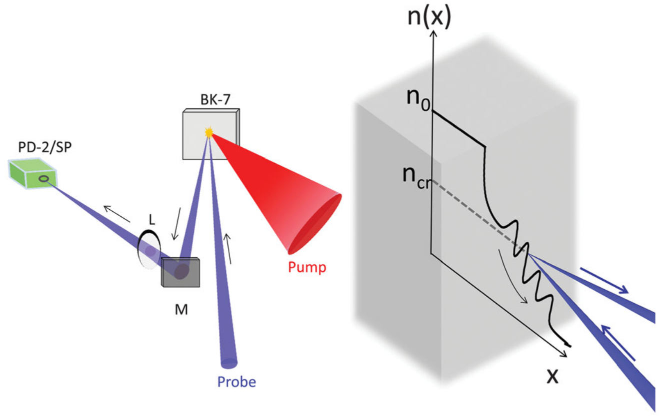

FIG. 1 (color). Schematic on the left: A pump pulse (800 nm, 30 fs) is focused on a polished BK-7 glass target at an angle of 45°, and the resulting plasma is probed by a second-harmonic probe pulse at near normal incidence. A small fraction of the input probe is split off by a beam splitter and fed to a photodiode PD-1 (not shown here) to sample the fluctuations in input probe intensity. The reflected probe, after collection by a lens (L), is fed into another photodiode (PD-2) and a spectrometer (SP) for simultaneous measurement of pump-probe reflectometry and spectrometry. Schematic on the right: The rectangular box portrays the BK-7 target, already irradiated by the pump pulse and, hence, having a plasma density gradient $n(x)$ along the x direction, where $n_{\rm cr}$ is the probe critical density.

Figure 2(a) shows the temporal behavior of the reflected probe intensity with a picosecond temporal resolution. At negative time delays (probe ahead of pump), only a few percent of the probe reflects from the "cold" BK-7 target. The arrival of the pump pulse creates a "plasma mirror" [18], which provides a strong reflection of the probe pulse, giving rise to a spike in the reflectivity. When the temporal resolution is improved to ~50 fs, the reflectivity shows an interesting oscillatory behavior [Fig. 2(b)]. Fourier analysis of this curve gives a clear frequency component at (1.9 ± 0.6) THz [Fig. 2(c)]. A systematic study on probe reflectivity for various laser intensities from 5.0×10^{16} to 1.4×10^{17} W/cm^2 by varying incident laser energy shows similar oscillations throughout this intensity range.

The oscillation in probe reflectivity $R(t)$ and, therefore, in probe absorption $A(t)$, depends on the process of collisional absorption of the probe in the plasma (other mechanisms such as resonance absorption and other instabilities can be neglected for this intensity regime and for normal incidence of the probe). Assuming a one dimensional plasma, $A(t)$ can be written as $A(t) = 1 - \exp\{-[\alpha\nu_{ei}^*(t)L(t)/c]\}$ [19], where $\nu_{\rm ei}^*(t)$ is the electron-ion collision frequency at the critical density of the probe, $L(t)$ is the scale length over which the probe gets absorbed at time t, and c is the speed of light in free space. The numeric constant α takes the values 8/3 and 32/15 for exponential and linear plasma density profiles, respectively [19]. Therefore, an oscillation in the reflectivity $R(t)$ clearly indicates an oscillation in the term $\nu_{\rm ei}^* L(t)$.

Motivated by the results of pump-probe reflectometry, we performed a simultaneous measurement of Doppler shifts of the second-harmonic probe reflected from its critical density layer, which stays in the overdense region for the pump pulse. Figure 3(a) shows that the reflectivity of the plasma first increases and then slowly decreases with periodic oscillations [similar observation as in Fig. 2(b)]. Figure 3(b) indicates Doppler shifts of the reflected probe spectra. It is interesting to see the anticorrelation of the Doppler shift with the reflectivity oscillation. Whenever there is more absorption of the probe, the probe spectrum gets redshifted and similarly the lower absorption can be associated with the blueshift in the probe spectrum. The reason behind this may be the following: The recession of the probe critical surface in the inward direction results in an increment in propagation length which, in turn, is the cause of the increase in the probe absorption. Similarly, whenever the probe spectrum is blueshifted, there is less absorption of the probe in the plasma.

These observations, therefore, clearly indicate the presence of an oscillatory disturbance in the expanding plasma. What is the nature of this disturbance? The observation of

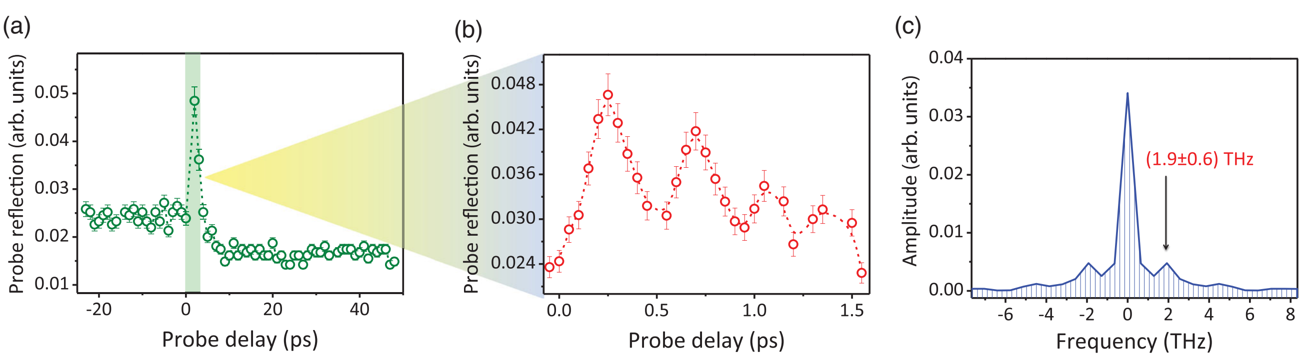

FIG. 2 (color). The pump pulse (800 nm, 30 fs) is focused to a plane BK-7 glass target at an intensity $\sim 5 \times 10^{16}$ W/cm^2. (a) Time evolution of the reflected probe intensity with picosecond temporal resolution. (b) Terahertz oscillation in the reflected probe intensity measured with a temporal resolution of 50 fs. (c) Fourier transform of the probe signal of Fig. 2(b) in the temporal range from 0 ps to 1.5 ps. Apart from the dc component (zero frequency), a clear ac component at (1.9 ± 0.6) THz is observed.

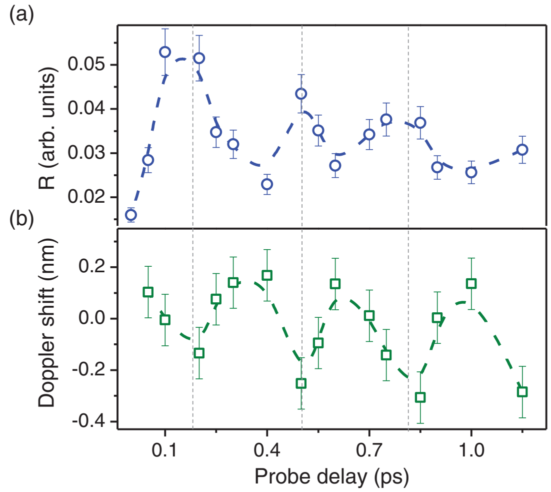

FIG. 3 (color). A time-delayed second-harmonic laser pulse is used to probe the plasma excited by an intense ($I_L = 6 \times 10^{16}$ W/cm^2) pump pulse. (a) An oscillatory reflectivity signal is clearly observed. (b) In the simultaneous measurements of the Doppler shifts of the reflected probe spectra, we observe clear anticorrelation between the reflectivity and the Doppler shifts; in other words, each dip in the Doppler shift corresponds to a peak in the reflectivity and vice versa.

an electron-based perturbation can be ruled out on the basis of time scales involved, as the electron plasma period at the probe critical density is 1.3 fs, which is about 500 times faster than the oscillation period inferred from these measurements. Furthermore, on assuming a temperature of 100 eV, the typical collision times are all substantially less than 1 ps. This does not favor the hypothesis that a kinetic microinstability [20] is the physical cause of the observed disturbance. Strong magnetic fields can be produced in laser-solid interactions by various means and may, therefore, be involved. We estimate that a magnetic flux density >500 T (5 MG) would be needed for a magnetic energy density equal to the thermal energy density. This is not inconceivable, but the exact origin and geometry of the magnetic field must also be considered. The remaining possibility is that we are observing an almost purely acoustic disturbance which is essentially hydrodynamic in origin.

In order to evaluate this final possibility, we constructed a simple one dimensional numerical model using a Lagrangian hydrodynamic code. This model treated the plasma as a uniformly heated ideal gas evolving via the Euler equations. There is no thermal conduction or radiation transport in this model, and the plasma is treated as a single fluid. As well as being uniformly heated (to 300 eV), the initial density profile of the plasma is a fit to the density profile that would be produced by the laser prepulse according to a separate radiation hydrodynamics model. The model then calculates the evolution of this plasma over a few picoseconds, and we calculate the Doppler shift that would be observed from probing the second-harmonic critical surface. Both the initial density profile and the results are shown in Fig. 4.

As can be seen from Fig. 4(c), the oscillatory behavior in the wavelength shift found in the numerical model is very similar to that obtained in the experimental Doppler spectrometry results. Some aspects of the physical behavior of the numerical model are clear. First, we note that the initial density profile consists of a sharp decrease in density (region I), which transitions into a shallower density gradient at a greater distance from the dense plasma (region II). With an initially uniform temperature, at early times, the pressure $P \propto e^{-x}$ (since the density $\rho \propto e^{-x}$). This leads to two regions with quasiuniform velocity profiles, the velocity being greater in region I, (where the density falls off more steeply) in comparison to region II [as indicated in Fig. 4(a)]. Therefore, during this initial transient phase, there is a transition zone between the region of high mass flux (region I) and the region of low mass flux (region II). As a result, the advection of mass density alone acts to

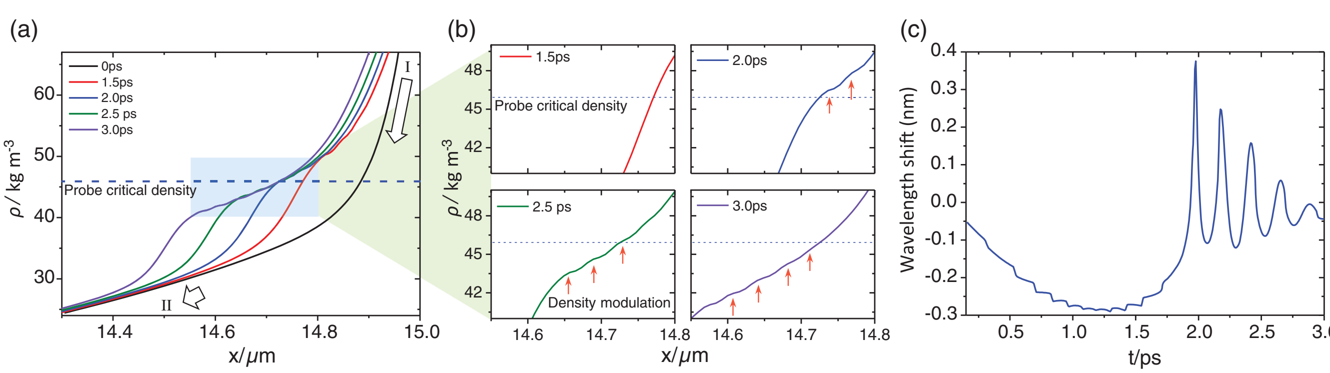

FIG. 4 (color). (a) Initial density profile used in the 1D numerical model (black line); the longer arrow indicates high mass flux in the region where the density gradient is steepest (region I), and the shorter arrow indicates a lower mass flux in the region of shallower density gradient (region II). Density profiles at delays of 1.5, 2, 2.5, and 3 ps are also shown. (b) Magnified view of these density profiles near the "transition zone" (as identified in the main text); arrows highlight the density modulations. (c) Doppler shift as a function of time from the results of the 1D numerical model.

generate a peak in the mass density in this zone. Of course, this will also lead to a buildup of pressure, which acts to slow the inflow of material, thereby causing the effect to repeat upstream, and so on. Thus, this region, where the material is built up, acts as the generator of an acoustic disturbance [depicted in Fig. 4(b)]. This behavior can only occur at very early times, when the system is dominated by its initial state, and not at later times, when the system is much closer to being in a self-similar state. Notably, the Doppler shift behavior in the simulation is delayed by approximately 2 ps relative to the experimental result. This is a consequence of the plasma in the hydrodynamic model being initially stationary. In reality, the plasma is already moving at this point in time. A number of simulations were run with a range of input parameters, and it was found that the results were qualitatively similar over quite a broad range of parameter space: sound waves were generated provided that the density profile had two different scale lengths with the steeper gradient at higher densities. For very high levels of laser contrast, however, we would not expect to see this phenomenon since preplasma formation is required for it to occur.

It is worth noting why this phenomenon may have defied observation so far. First, it is important to have a high temporal resolution (50 fs) in the experiment to clearly observe the terahertz oscillations. Second, the simultaneous study of the reflectivity and Doppler shift of the probe brings out the anticorrelation between the two, providing a clear and conclusive signature of the process. Third, it is important to choose the right composition of the target. For instance, low-Z targets like hydrocarbons would not support terahertz oscillations, since the maximum allowed frequency of sound wave can be shown to scale as $(Z^*)^4$, Z^* being the average ion charge state [16].

In summary, we have presented the results of detailed optical probing of a dense plasma produced by a high-intensity femtosecond laser. The Doppler spectrometry and reflectivity measurements indicate oscillatory behavior in the expanding plasma. Given the nature of the region being probed, in particular the collisionality, we do not believe that we are observing a kinetic microinstability. The time scale indicates an acoustic disturbance. A simple hydrodynamic numerical model has shown that such a disturbance can be produced through a purely hydrodynamic mechanism. We have interpreted this mechanism by resolving the transient behavior as the heated plasma evolves towards a self-similar solution when it is initially far from this solution. The hydrodynamic instability is caused by the rapidly moving upstream plasma encountering a stagnant flow in the plasma corona. This causes a localized buildup of pressure, which then saturates, seeding a similar cycle further upstream. This phenomenon repeats until the system equilibrates to a self-similar behavior. In the hydrodynamic modelling of astrophysical phenomena, there has been considerable discussion about transient behavior and sound waves. The results we present here indicate that it is possible to carry out detailed laboratory experiments to study even such fine details of relevant hydrodynamic systems.

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[1] F. E. Marble and S. M. Candel, Acoustic disturbance from gas non-uniformities convected through a nozzle, J. Sound Vib. **55**, 225 (1977).

[2] H.-K. Chang, D.-Y. Chou, B. LaBonte, and the TON Team, Ambient acoustic imaging in helioseismology, Nature (London) **389**, 825 (1997).

[3] A. Fossum, and M. Carlsson, High-frequency acoustic waves are not sufficient to heat the solar chromosphere, Nature (London) **435**, 919 (2005).

[4] A. Burrows, E. Livne, L. Dessart, C. D. Ott, and J. Murphy, A new mechanism for core-collapse supernova explosions, Astrophys. J. **640**, 878 (2006).

[5] T. Foglizzo and M. Tagger, Entropic-acoustic instability in shocked accretion flows, Astron. Astrophys. **363**, 174 (2000).

[6] L. Spitzer, Acoustic waves in supernova remnants, Astrophys. J. **262**, 315 (1982).

[7] D. F. Cioffi, C. F. McKee, and E. Bertschinger, Dynamics of radiative supernova remnants, Astrophys. J. **334**, 252 (1988).

[8] B. A. Remington, R. P. Drake, and D. D. Ryutov, Experimental astrophysics with high power lasers and Z pinches, Rev. Mod. Phys. **78**, 755 (2006).

[9] D. W. Forslund, J. M. Kindel, and E. L. Lindman, Theory of stimulated scattering processes in laser-irradiated plasmas, Phys. Fluids **18**, 1002 (1975).

[10] S. Mondal, A. D. Lad, S. Ahmed, V. Narayanan, J. Pasley, P. P. Rajeev, A. P. L. Robinson, and G. Ravindra Kumar, Doppler Spectrometry for Ultrafast Temporal Mapping of Density Dynamics in Laser-Induced Plasmas, Phys. Rev. Lett. **105**, 105002 (2010).

[11] A. Adak, D. R. Blackman, G. Chatterjee, P. K. Singh, A. D. Lad, P. Brijesh, A. P. L. Robinson, J. Pasley, and G. Ravindra Kumar, Ultrafast dynamics of a near-solid-density layer in an intense femtosecond laser-excited plasma, Phys. Plasmas **21**, 062704 (2014).

[12] Z. Li *et al.*, Single-shot tomographic movies of evolving light-velocity objects, Nat. Commun. **5**, 3085 (2014).

[13] Z. Li, H.-E. Tsai, X. Zhang, C.-H. Pai, Y.-Y. Chang, R. Zgadzaj, X. Wang, V. Khudik, G. Shvets, and M. C. Downer, Single-Shot Visualization of Evolving Laser Wakefields Using an All-Optical Streak Camera, Phys. Rev. Lett. **113**, 085001 (2014).

[14] A. Benuzzi-Mounaix, M. Koenig, J. M. Boudenne, T. A. Hall, D. Batani, F. Scianitti, A. Masini, and D. Di Santo,

Chirped pulse reflectivity and frequency domain interferometry in laser driven shock experiments, Phys. Rev. E **60**, R2488 (1999).

[15] P. K. Singh, G. Chatterjee, A. Adak, A. D. Lad, P. Brijesh, and G. Ravindra Kumar, Ultrafast optics of solid density plasma using multicolor probes, Opt. Express **22**, 22320 (2014).

[16] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.114.115001 for a simple estimate of maximum allowed acoustic-frequency in a hot dense plasma and its dependents on the average ionization state, which includes Ref. [17].

[17] *NRL Plasma Formulary* (Naval Research Laboratory, Washington, DC, 2011), p. 28.

[18] C. Thaury *et al.*, Plasma mirrors for ultrahigh-intensity optics, Nat. Phys. **3**, 424 (2007).

[19] W. L. Kruer, *The Physics of Laser Plasma Interactions* (Westview Press, Boulder, Colorado, 2003), Chap. 5.

[20] T. J. M. Boyd and J. J. Sanderson, *The Physics of Plasmas* (Cambridge University Press, Cambridge, England, 2003).