Large-amplitude radial-plasma-wave generation during high-intensity laser interactions with underdense plasmas

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Forward-scattered radiation produced from the interaction of an ultraintense laser pulse ($P \sim 2$ TW) with underdense hydrogen and helium plasmas ($n_e \approx 10^{19}$ cm^{-3}) is measured. The coherently Thomson scattered satellites of the second harmonic at off-axis scattering angles are observed to be significant, in contrast to observations in the directly forward direction. These results are likely due to the existence of large-amplitude radial plasma waves generated by ponderomotive forces as the laser pulse propagates through the plasma. [S1063-651X(98)01901-1]

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During high-intensity laser-plasma interactions the ponderomotive forces associated with focused laser radiation can produce large-amplitude plasma waves in the ''wake'' of the laser pulse as it propagates through an underdense plasma. Since these waves have large longitudinal electric fields and phase velocities close to the speed of light, they have been proposed as a means of accelerating an injected electron beam to high energy [1]. Large-amplitude plasma waves for acceleration purposes can be produced either in the standard laser wake-field accelerator (LWFA) [1], if the intense laser pulsewidth (τ) is similar to the electron plasma period (i.e., $\tau_{pe} \sim 2\pi/\omega_{pe}$), or in the ''self-modulated'' (SM) (LWFA) regime [2] in which a wake field is generated as a long-duration, intense laser pulse undergoes a self-modulation instability as it propagates in higher-density plasma. This instability causes the pulse to break up into beamlets having a duration corresponding to the plasma period and the subsequent resonant interaction with the plasma can produce a large-amplitude wake field. There have been several recent experiments that have measured the temporal evolution of the wake field using both schemes [3–5] as well as the energy of electrons accelerated by these waves (up to 100 MeV in the SM-LWFA regime) [6,7].

In this paper we present results of recent high-intensity laser-plasma interaction experiments performed at the Naval Research Laboratory in which we find that second-harmonic radiation produced during such interactions can act as a probe of large-amplitude plasma waves created at the front of the laser pulse as it propagates through the plasma. The angular distribution and frequency structure of this scattered radiation reveals information concerning the properties of these waves and may have implications for the feasibility of the SM-LWFA concept. Our results show that at high plasma densities, as a very intense laser pulse undergoes self-modulation, radial plasma wave structures (large-amplitude cylindrical oscillations) can be generated and may dominate the coherently Thomson scattered spectrum. These results are distinct from and complementary to other recent experiments that measured the radial structure of plasma oscillations produced in the low-density standard LWFA regime using the technique of frequency domain interferometry [3].

Our experiments were performed by focusing a high-intensity laser pulse into a 3-mm-diam jet of neutral gas (either helium or hydrogen), which consequently undergoes optical field ionization and forms an underdense plasma. We used the Table Top Terawatt laser system at the Naval Research Laboratory ($\lambda = 1.054$ μm, $\tau \sim 400$ fs), which was operated at a maximum power of 2 TW. The beam could be focused to an intensity of 6×10^{18} W/cm^2 (in vacuum) using an $f/3$ off-axis parabolic mirror. For the gas densities used, the plasma had a typical electron density of about 10^{19} cm^{-3} ($\tau_{pe} \sim 30$ fs) for both He and H_2 when fully ionized. Directly forward-scattered light was recollimated by a parabolic mirror similar to that used to focus the beam while radiation scattered at off-axis angles was collected by a simple lens. The scattered light was then imaged onto the slit of a 0.25-m Czerny-Turner spectrometer that used a charge coupled device detector sensitive to visible and near infrared radiation.

Strong emission of a directly forward-propagating second harmonic was observed in these experiments and conveniently provided a copropagating low-intensity probe of the interaction. The spectrum of this forward-scattered light was examined in the region near 527 nm ($2\omega_0$) using either hydrogen or helium as the target gas. Typical spectra of the second harmonic in the directly forward-scattered direction for both helium and hydrogen are shown in Fig. 1 for an electron density of 10^{19} cm^{-3} and an incident laser power of about 2 TW. The second-harmonic emission is broadened and displays a blueshift, qualitatively similar to the observed blueshift of the fundamental (up to 100 nm) that was caused by the rapid optical field ionization process [8]. From Fig. 1 it can be seen that the total second-harmonic emission was about an order of magnitude greater in helium than in similar hydrogen plasmas and was accompanied by a larger blueshift. The spectral modulations seen in Fig. 1 are typically nonreproducible and fluctuate from shot to shot, although the integrated intensity remains similar.

The most likely source of the observed second-harmonic emission is the action of the ponderomotive pressure of the focused laser pulse that produces large density gradients as plasma electrons are expelled from the focal region by the laser. The interaction of intense laser radiation and large plasma density gradients has been shown previously to cause

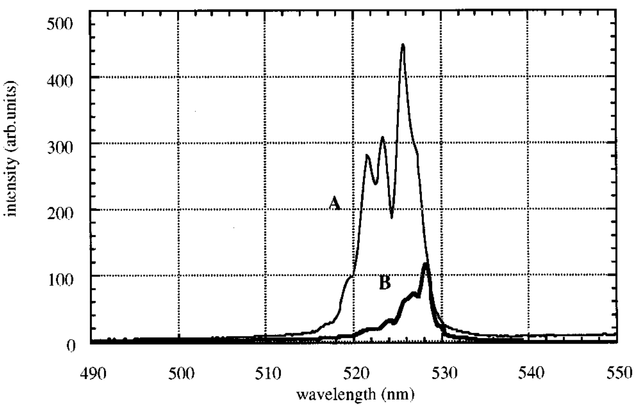

FIG. 1. Emission of a second harmonic in the directly forward forward direction at 2 TW, for hydrogen (light curve) and helium (bold curve).

second-harmonic emission [9]. Since the laser pulse has a duration of only 400 fs and the ion plasma period is greater than 1 ps, ions are effectively stationary during the interaction so that density gradients and filamentation effects are largely produced by displacement of plasma electrons. Emission of the second harmonic of backscattered stimulated Raman scattering (SRS) has been reported recently [10] and is attributed to a similar mechanism [10,11]. It is also possible that some of the forward-propagating second-harmonic emission in helium is due to the nonlinear polarization of He^+ ions in a static electric field produced by charge-separation effects created by the laser ponderomotive pressure [12].

Scattered radiation was also examined at off-axis angles in the spectral region near the second harmonic and was collected by an $f/3$ lens having a 10° acceptance angle. At 30° from the axis of laser propagation, the sidescattered spectrum was characterized by significant emission near 527 nm, which exhibited both Stokes and anti-Stokes sidebands of similar strength (see Figs. 2 and 3). The amplitude of the sideband emission was comparable to that of the sidescattered fundamental. The frequency shift of these sidebands ($\Delta\lambda \sim 25$ nm) corresponds to the electron plasma frequency $\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$, which is known from previous measurements of the plasma density under similar conditions. At a 45° angle, the scattered spectra in the second-harmonic region was similar to that at 30°, although it often showed higher orders of sidebands. Up to four orders of Stokes emission could be observed as well as two orders of anti-Stokes emission. This is in distinct contrast to the second harmonic in the directly forward direction (Fig. 1), which exhibited no sidebands. On a shot-to-shot basis, the relative strength of the sidescattered satellites varied by about 25%. Helium typically produced fewer sidebands than hydrogen (see Fig. 3) when similar experimental parameters were used. No satellite structure at frequency shifts of ω_{pe} near the second-harmonic wavelength were observed at 90° or in the backward direction.

The principal source of the sidescattered satellite radiation near 527 nm is probably coherent Thomson scattering of the forward-going second harmonic from part of a large-amplitude plasma-wave structure having **k** vectors at off-axis angles to the axis of propagation of the main laser beam.

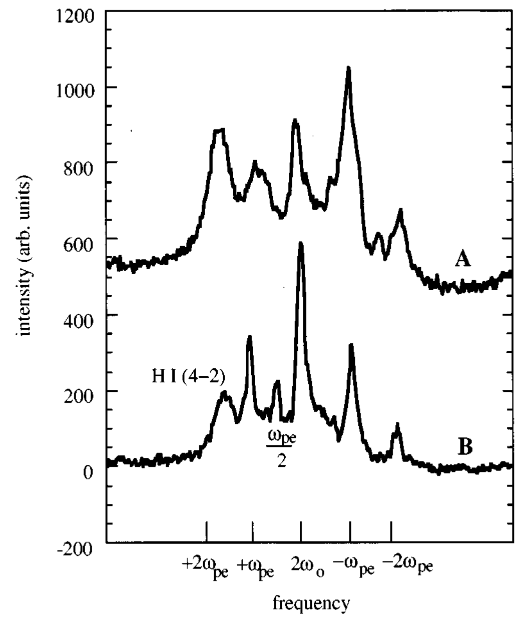

FIG. 2. Change in satellites of sidescattered second-harmonic emission with respect to laser intensity at a 30° sidescattered angle: (A) $P = 2$ TW, $n_e = 1\times10^{19}$ cm^{-3} and (B) $P = 1.5$ TW, $n_e = 1\times10^{19}$ cm^{-3}. Note that the intensity scale is similar for both spectra. The feature on the extreme left of each spectrum that obscures the second-order anti-Stokes line is emission from the hydrogen 4-2 transition (4861 Å). The spectra have been offset for clarity.

Emission of sidebands of the second harmonic shifted by the plasma frequency is not primarily due to doubling of forward Raman scattered light since frequency shifts observed between orders in the off-axis direction were ω_{pe} rather than $2\omega_{pe}$. This is in contrast to the $2\omega_{pe}$ shift observed in the backscattered second-harmonic radiation as previously ob-

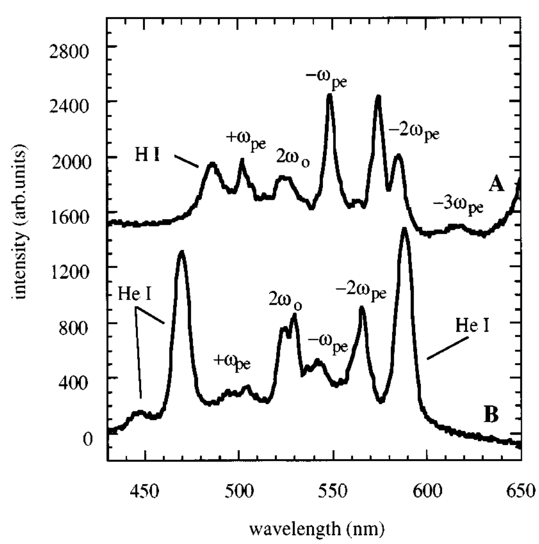

FIG. 3. Thomson scattered spectra at a 30° scattering angle for (A) hydrogen ($P = 2$ TW, $n_e = 1.3\times10^{19}$ cm^{-3}) and (B) helium ($P = 2$ TW, $n_e = 1\times10^{19}$ cm^{-3}). Atomic emission lines are indicated. The spectra have been offset for clarity.

served in Ref. [10], which was due to frequency doubling of backward SRS. However, it is probable that some of the second-order Stokes sideband (at $\omega_0 - 2\omega_{pe}$) is generated by this process, especially in helium or at higher electron densities (see Fig. 3).

The higher-order sidebands of the Thomson scattered satellites indicate the scattering plasma waves are large amplitude and nonlinear. Since the amplitudes of the higher-order Stokes sidebands are similar (note that the spectra in Fig. 3 are displayed on a linear scale), this implies that the amplitude of these radial plasma oscillations is such that $\Delta n_e / n_e \sim 1$. Broadening of Thomson scattered satellite emission was observed as the laser power increased (Fig. 2, curve A) and as the plasma density increased (Fig. 3, curve A). Similar observations at the fundamental frequency in other experiments at higher powers have been attributed to wave-breaking effects for very large amplitude waves [7]. In our experiment, it is likely that the observed broadening is due to the increasing density gradients in the focal region caused by deeper channel formation [13] as the plasma density and laser power are increased.

The second harmonic is generated synchronously with the main laser pulse as it propagates over steep plasma density gradients. Longitudinal plasma wake fields trailing the main laser pulse are therefore not sampled by the second harmonic. The fact that the second-harmonic plasma satellites are not seen in the directly forward direction but are seen off axis indicates that the plasma waves sampled by the second harmonic are nonrelativistic with wave vectors nearly perpendicular to the beam axis. These plasma waves are likely radial plasma waves with cylindrical symmetry similar to those observed in two-dimensional particle-in-cell simulations [14]. The radial structure of the plasma waves is important in these types of experiments since the focal spot size ($\sim 10\ \mu$m) is approximately the same as the wavelength of relativistic plasma waves ($\lambda_p = 2\pi c / \omega_{pe}$). It should be noted that the radial structure of plasma oscillations has also been found to be important for understanding the nonlinear plasma waves produced in beat-wave accelerator experiments [15].

Coherent Thomson scattering requires that the incident and scattered electromagnetic waves and the plasma wave satisfy Bragg scattering conditions, i.e., $\omega_{\mathrm{scat}} = \omega_{\mathrm{incident}} \pm \omega_{pe}$ and $\mathbf{k}_{\mathrm{scat}} = \mathbf{k}_{\mathrm{incident}} \pm \mathbf{k}_{pe}$. The phase velocity and the direction of the **k** vectors of the plasma waves that interact with a collinearly propagating probe beam that satisfy these conditions are shown in Fig. 4. In our experiments, scattered satellite radiation was observed at off-axis angles (i.e., for 30° and 45°), indicating that the plasma waves that interact to scatter the second harmonic have **k** vectors that are approximately at right angles to the laser axis of propagation and have a phase velocity about 10% the speed of light.

Cylindrically symmetric plasma oscillations are anharmonic and the plasma frequency of these waves should be slightly greater [3,16] than that of longitudinal plasma waves, which are those ordinarily observed. This nonlinear correction to the plasma period is proportional to the square

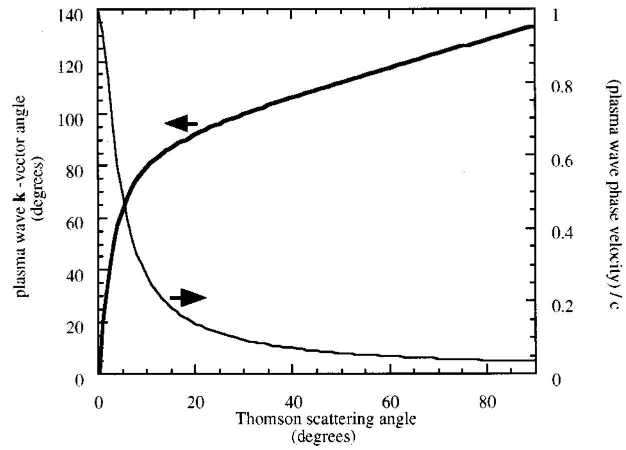

FIG. 4. Plot of the plasma wave phase velocity and **k** vector direction versus the coherent Thomson scattering detection angle (with respect to the probe beam axis of propagation).

of the plasma-wave amplitude; however, for large-amplitude waves fine scale mixing results and the oscillation is quickly destroyed [16]. The large-frequency shifts from ponderomotive charge displacement effects [13] that dominate laser-plasma interactions at very high laser intensity result in broadening of the observed Thomson scattered satellites and made observation of this effect difficult in our experiments.

We also observed Thomson scattered satellites at shifts of $\omega_{pe}/2$ in the region of the second harmonic (see Fig. 2). The source of this emission was not clear. Recent theoretical work [17] has predicted the existence of an explosive Raman scattering instability that can occur during high-intensity laser-plasma interactions and results in forward-scattered light, frequency shifted by $\omega_{pe}/2$ from the fundamental. Although such emission near the fundamental has been measured recently by another group [18], in our experiments $\omega_{pe}/2$ shifted satellites were only definitively measured in the spectral region near the second harmonic.

In conclusion, we have shown that the spectral characteristics of second-harmonic emission changes significantly depending on the observation angle. We believe that the source of this angular variation is due to the presence of large-amplitude cylindrical oscillations produced around the pulse during the propagation of intense laser pulses through underdense plasma. Such radial wake fields, if not adequately controlled, would likely be important for practical applications of the laser wake-field accelerator concept since they will greatly increase the emittance of any injected electron beam. For a practical laser wake-field accelerator the confocal parameter should be significantly longer than that used in our experiments in order to minimize the effect of the focusing geometry and the production of undesirable transverse accelerating structures.

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