PHYSICAL REVIEW E VOLUME 55, NUMBER 6 JUNE 1997

# Plasma density determination by transmission of laser-generated surface harmonics

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(Received 27 February 1997)

A diagnostic is proposed for determining the density of laser-generated plasmas. The scheme exploits surface harmonics generated by short, intense laser pulses reflected from an overdense plasma layer. At sufficiently high intensities ($I\lambda^2 > 10^{18}$ W cm$^{-2}$), the reflected spectrum contains harmonics well above the plasma frequency, corresponding to the maximum plasma density. The *transmitted* spectrum, on the other hand, exhibits a low-frequency cutoff for $\omega < \omega_p$, offering a simple means of deducing the plasma density. [S1063-651X(97)50706-9]

PACS number(s): 52.40.Nk, 42.65.Ky, 52.65.−y

Knowledge of the plasma density is a prerequisite for much basic and applied research using laser-produced plasmas. Conventional techniques for obtaining the density rely on spectroscopy [1], in which the plasma line radiation is compared to synthesized density-dependent spectra; or interferometric [2] and scattering techniques [3,4], in which an electromagnetic probe beam is sent through the plasma. The higher the density, however, the harder it becomes to find a coherent light source of suitably short wavelength for this type of diagnostic.

Recently, an elegant scheme has been demonstrated which uses harmonics generated in a gas jet to probe a preformed plasma [5]. While this method offers significant improvements in time-resolution and density range over spectroscopic techniques (which generally collect radiation emitted from a large region of plasma), it still relies on precise timing control between the ionizing pulse and the probe harmonics. In this Rapid Communication we propose a single-pulse version of the harmonic transmission scheme in which the harmonics are generated by nonlinear plasma oscillations on the surface of the target. The removal of the timing requirement makes this scheme particularly apt for basic physics studies of femtosecond laser interactions with solids [6,7].

Physically, the mechanism responsible for the transmitted harmonics is the same as that which generates harmonics in the specularly reflected light [8–10]. At intensities above $I\lambda^2 \sim 10^{18}$ W cm$^{-2}$, the power spectrum of the latter shows a smooth fall-off with harmonic number $n$, whereas the transmitted spectrum exhibits a low-frequency cutoff at the plasma frequency corresponding to the highest electron density $N_e$ [11]. Thus only harmonics with $n > \sqrt{N_e/N_c}$ are transmitted — albeit with reduced efficiency — where $N_c$ is the critical density for the incident light with frequency $\omega_0$, given by $\omega_0^2 = 4\pi e^2 N_c/m_e$. This feature has also been pointed out by Lichters and Meyer-ter-Vehn [12].

A high-frequency cutoff in the *reflected* harmonic spectrum was originally proposed as a density diagnostic by Carman, Forslund, and Kindel [13], who argued that only harmonics resonant with some point in the density profile could be generated. In fact, the presence or absence of a cutoff in the reflected harmonics was never unequivocally demonstrated in the early long-pulse (nanosecond) experiments. However, evidence from the current series of experiments with short-pulse (femtosecond) lasers [8–10] supports more recent simulations and semi-analytic models [11,14,15] which do not predict a cutoff — at least for steplike profiles and relativistic intensities.

While this result is very encouraging for the application of harmonics as a high-power, coherent vacuum-ultraviolet (vuv) light source – since harmonic orders $n \gg \sqrt{N_e/N_c}$ may be produced with sufficiently intense, high-contrast lasers — it begs the question of whether one can still exploit harmonics to extract information on the plasma properties. The purpose of this Rapid Communication is to address this point in detail, and to illustrate the use of self-generated transmitted harmonics in various scenarios of laser-solid interaction which are easily realized experimentally. To do this, we use a combination of hydrodynamic and particle-in-cell (PIC) simulation to model the plasma properties and harmonic generation, respectively.

For the PIC simulations, we consider a preformed plasma target whose thickness $d \gg \delta$, the collisionless skin depth $c/\omega_p$, where $\omega_p^2 = 4\pi e^2 N_e/m_e$. The geometry is depicted in Fig. 1: the laser is incident on the target at 45° to normal, and is $p$ polarized for efficient coupling. For simplicity we assume that the target is perfectly smooth and the laser spot size $\sigma$ is large compared to a wavelength, that is, $\sigma \gg \lambda$, so that we may neglect two-dimensional effects. Light is then either reflected specularly or transmitted along the laser axis. This configuration can be reduced to one spatial dimension using the boosted-frame-of-reference technique [16], thereby permitting calculations to be performed economically with

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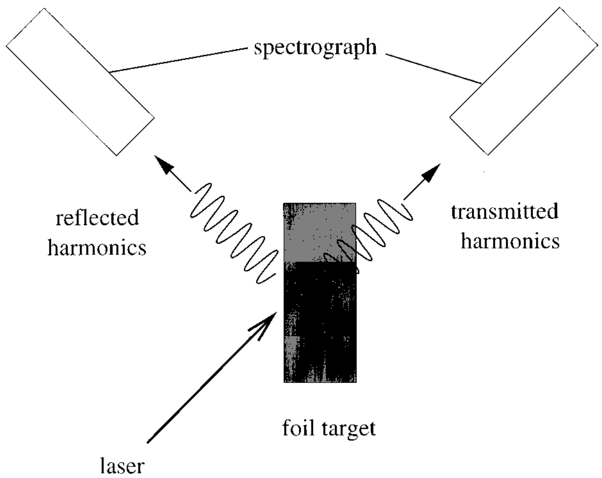


FIG. 1. Geometry of the density diagnostic scheme using surface harmonics.

the high spatial and temporal resolution necessary to resolve the high harmonics. In the simulations that follow, the laser is modeled by an electromagnetic wave of the form: $I(t)=I_0|\sin(t/t_p)\sin(\omega_0 t)|^2$, launched from the left boundary of a simulation box with length $(2-3)\lambda$, divided into 4000 grid points. The plasma is typically represented by 70 000 electrons in a slab $(\frac{1}{3}-\frac{2}{3})\lambda$ thick, situated at the end of the simulation box.

In the first set of runs, the laser intensity $I_0=(5-16)\times 10^{18}$ W cm$^{-2}$ for 0.8-$\mu$m light; the pulse length is 80 fs, and the foil thickness is fixed at 250 nm. The ions are kept fixed to avoid changes in the upper shelf density $N_e$ — for example, due to shock formation — which might result from pressure imbalance while the pulse is incident. The density gradient $L^{-1}\equiv(N_e^{-1}dN_e/dx)_c$ is also fixed at a value

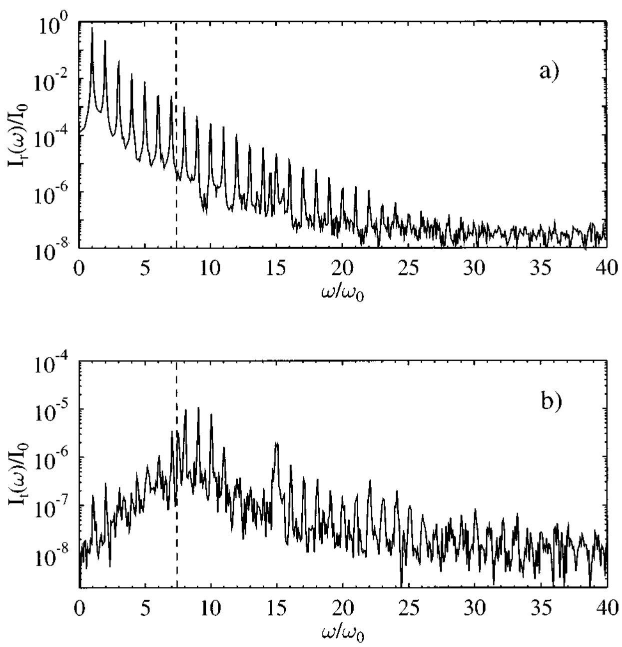


FIG. 2. (a) Reflected and (b) transmitted light spectrum for $I=5\times 10^{18}$ W cm$^{-2}$ and $N_e/N_c=55$. The dashed line shows the plasma frequency $\omega_p$ corresponding to the upper shelf density.

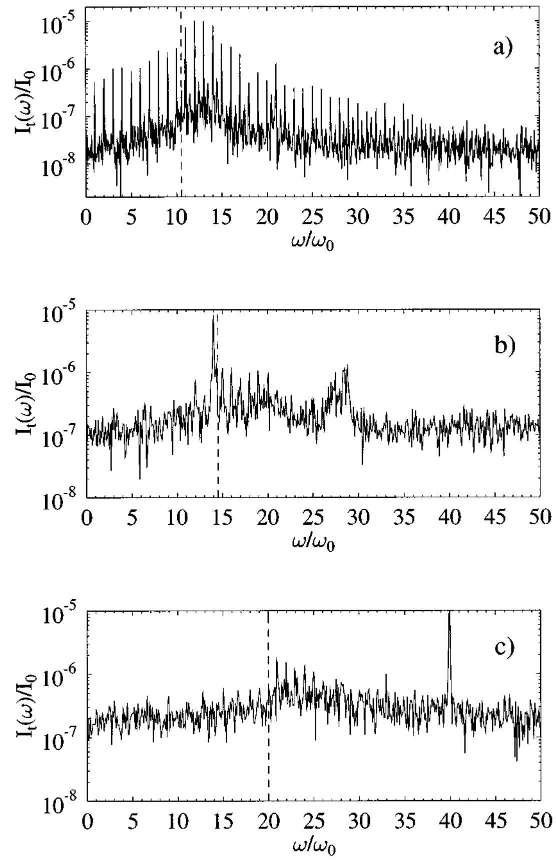


FIG. 3. Transmitted spectra for fixed electron densities $N_e/N_c$ of (a) 110, (b) 210, and (c) 400. The dashed line shows the position of $\omega_p$. The intensities used in each case were $5\times 10^{18}$, $7.8\times 10^{18}$, and $1.6\times 10^{19}$ W cm$^{-2}$, respectively.

$L/\lambda=0.05$, taken from density profiles near the pulse maximum predicted by the FILM hydrocode [17] for similar laser parameters. Although this is not completely realistic, it serves to demonstrate the principle of the diagnostic technique without ambiguity in the density. The reflected and transmitted light spectra are shown in Fig. 2 for an electron density of $55N_c$. The reflected spectrum shows an intensity-dependent fall-off similar to the scaling determined in Ref. [11], with no discernible change between frequencies below and above $\omega_p=7.4\omega_0$, the plasma frequency of the upper density shelf. By contrast, the transmission spectrum [Fig. 2(b)] exhibits a *low*-frequency roll-off for $\omega<\omega_p$.

This effect can be seen more clearly if we vary the upper shelf density—as shown in Fig. 3 for a range of densities from $100N_c$ to $400N_c$. In each case, we find either a maximum or an ''onset'' in the harmonic transmission at the plasma frequency. In principle, one would expect this technique to work best with low densities and ''thick'' foils to inhibit the tunneling of evanescent waves at frequencies below $\omega_p$ — an effect which can be seen in Figs. 2(b) and 3(a). Note that we have used intensities well below the threshold for induced transparency [18,19], namely, $I\lambda^2<2.3\times 10^{18}(N_e/N_c)^2$. Above this value, we might expect additional effects such as surface oscillations on the rear side of the target, which could compromise the effectiveness of the diagnostic.

High densities present a different problem because the

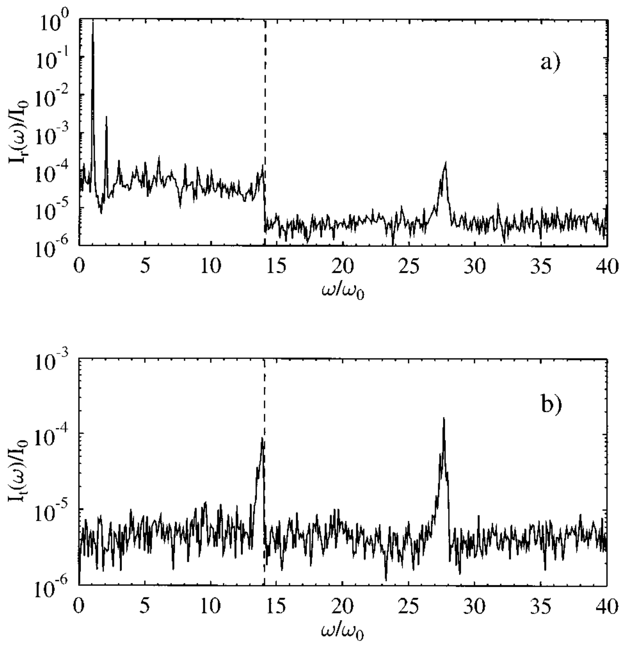


FIG. 4. (a) Reflected and (b) transmitted light spectrum for $I=1.6\times10^{17}$ W cm$^{-2}$ and $N_e/N_c=200$.

harmonic efficiencies decrease with density — although we find a much weaker dependence on $N_e/N_c$ than the $(N_c/N_e)^3$ scaling predicted by the ''moving mirror'' model [14,15]. This is partly because we have used a finite density gradient, which for $p$-polarized light results in a more elastic motion of the charge sheets at the vacuum-plasma interface. Nonetheless, progressively higher intensities were needed in each case to compensate for the reduced efficiency and to ensure that the transmitted harmonics were above the background noise level. The latter is purely numerical in these simulations: in an experiment the noise level would be determined by stray laser and plasma light, as well as line and bremsstrahlung radiation produced by fast electrons.

To illustrate the effect of reducing the harmonic intensities below the detection level, spectra from an otherwise identical run to that in Fig. 3(b) but with $I\lambda^2=10^{17}$ W cm$^{-2}$ $\mu$m$^2$ and $L/\lambda=0$ are shown in Fig. 4. The reflected spectrum is now reminiscent of those obtained from the two-dimensional simulations in Ref. [13], and appears to exhibit a cutoff at $\omega_p$. Note, however the broad additional peaks at $\omega_p$ and $2\omega_p$, also seen in the transmitted spectrum and in Fig. 3. This effect was recently studied in detail by Lichters and Meyer-ter-Vehn [12], who attributed it to a nonlinear coupling of fast-electron-generated plasma waves to the laser field in a process analogous to two-plasmon decay. The effect appears to be most pronounced when the plasma frequency is an exact multiple of $\omega_0$, so for the simulations in Figs. 2 and 3 we have attempted to suppress the emission by choosing $\omega_p$ to lie at half-integer multiples of $\omega_0$. Further simulations with mobile ions, however, show that the emission is sensitive to changes in the maximum density due to shock formation.

In summary, we demonstrated that transmitted surface harmonics can in principle be used to determine the maximum electron density of plasmas created by intense laser interaction with thin (submicron) foil targets. The technique appears to work best with moderately overdense plasmas ($N_e/N_c=10$–50), but should also be applicable for near-solid densities ($N_e/N_c=400$–600 at wavelengths of 0.8–1.0 $\mu$m) as long as the laser intensity is high enough to produce (transmitted) harmonic efficiencies well above the detection threshold of the diagnostic system and background noise levels. Strong emission at multiples of the plasma frequency are also observed in both reflection and transmission, providing an independent, complementary means of deducing the density.

A potentially important issue which has not been addressed here is target opacity, which may ultimately limit the usefulness of both this technique and the pump-probe version in Ref. [5] at extreme densities and target thickness. Harmonics in the vuv to soft-x-ray range can be strongly absorbed by the plasma — especially in the vicinity of $K$- and $L$-shell transition wavelengths, or for high-$Z$ materials. In an experiment, therefore, some selective attenuation of transmitted harmonic efficiency might be expected, depending on the target. On the other hand, provided the harmonics are not completely absorbed, this limitation might actually be turned around and exploited to determine the plasma opacity. A second limitation of the present study is that profile steepening has (deliberately) not been included. Preliminary simulations with mobile ions indicate that the low-frequency roll-off point is shifted to higher values corresponding to the *time-averaged* maximum density over the period when the laser pulse is incident. This indicates that in practice, ion motion will introduce a small uncertainty into the inferred density depending on the pulse length.

*Note added in proof.* The density diagnostic described here has been demonstrated in a recent experiment with the Jena Ti: Sapphire TW-laser system [20].

One of us (P. G.) is indebted to R. Lichters and J. Meyer-ter-Vehn for discussions concerning the origin of the $2\omega_p$ emission. The Laboratoire d'Utilisation des Lasers Intenses (LULI) and the Laboratoire d'Optique Appliquée (LOA) are funded by the Centre National de la Recherche Scientifique. This work was also supported by INTAS Contract No. 94-0934 and TMR Network Grant No. ERB4061PL95-1313.

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