Suppression of stochastic pulsation in laser-plasma interaction by smoothing methods

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The control of the very complex behavior of a plasma with laser interaction by smoothing with induced spatial incoherence or other methods was related to improving the lateral uniformity of the irradiation. While this is important, it is shown from numerical hydrodynamic studies that the very strong temporal pulsation (stuttering) will mostly be suppressed by these smoothing methods too.

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The nonsmooth complex interaction of laser radiation with plasmas has been considered to be mostly caused by laterally nonuniform irradiation. Smoothing techniques were introduced trying to modify the otherwise ideal coherent properties of the laser beam using induced spatial incoherence (ISI) [1] lens array [2], random-phase plate (RPP) [3] smoothing by spectral dispersion (SSD) [4], or broadband irradiation involving Raman scattering [5].

It seems evident that the motivation was mostly directed toward suppressing lateral nonuniformity of the laser intensity [6]. These techniques proved to be very successful, as evidenced, e.g., by the suppression of stimulated Raman scattering (SRS) from a few percent to hundred-times-lower values [7], or by much smoother and grainless pictures of the light reflected from a target [8]. The understanding of lateral uniformity in the laser intensity is indeed an important question [6].

In addition to this lateral beam uniformity, there may be another point in understanding the laser interaction with plasmas by smoothing. Apart from the lateral effects, a very complex temporal pulsation of interaction observed with irregular sequences was reported in the 10–40-psec range [9,10]. A special view into this direction is presented here and a detailed numerical analysis may permit an understanding and an explanation as to why the essential effect of smoothing may just be the suppression of this pulsation apart from the nonuniformity problem.

The first indication of the pulsation appeared from numerical studies. The Kinsinger code at Institute for Laser Energetics Rochester in 1973 described the one-dimensional interaction of a laser plane wave perpendicularly incident on a collisional plasma with some ramp profile of density. Using the correct nonlinear optical constants with respect to the intensity dependence of the collision frequency and the ponderomotive and nonponderomotive terms of the nonlinear force, the two-temperature model showed a very realistic response of the plasma (see Fig. 7.7a of Ref. [11] or Fig. 10.10a of Ref. [12]). First the light penetrated to the critical density from whence the light decayed exponentially with depth as expected and a strong mirror reflection produced a partial standing-wave pattern with swelling and wavelength stretching as known from the nonlinear force [12] within the plasma corona. The absorption was evidence that the standing wave was partial only. After this initial mirror reflection, one picosecond later, the laser pulse no longer penetrated to the critical density but decayed before reaching 1/1000th of its initial value. The light was then reflected at the very low plasma density by the Bragg–von Laue grating of the plasma-density ripple, which was self-generated by the nonlinear force in the standing waves. This was a phase reflection with a high-reflection coefficient while the mirror reflection showed low reflectivity due to the absorption in the corona.

In accordance to this, subsequent measurements of the reflectivity showed a variation from a few percent to nearly 100%, within 10 to 40 psec, irregularly up and down and the antiphased $\frac{3}{2}$-harmonics emission occurred only during the phases of mirror reflection [9]. In the recent years, similar pulsation or stuttering was observed, confirming experimentally that the light is reflected at the critical density by mirror reflection or at other times far out in the low-density corona by phase reflection. The time-resolved measurement shows how the plasma is accelerated only during the phases of mirror reflection [10]. This intermittent pushing of the plasma by each acceleration to velocities of about 10^7 cm/sec is seen then as a Doppler shift in the backscattered spectrum with an irregular modulation of about 4 Å [10].

Another pulsation in the 20-psec range was detected for the $\frac{3}{2}$ harmonics [13] and most importantly, when adding a random-phase plate [3] for smoothing of the interaction, the harmonics emission became completely smooth without pulsation. It was believed that this smoothing was a lateral-uniformity effect: Smoothing prevented some pulsating self-focusing [12–14]; therefore, with RPP, no pulsation of the $\frac{3}{2}$ harmonics occurred.

We are now going to explain the pulsation and the smoothing by an alternative model which we are presenting here based on a one-dimensional computation using a very detailed genuine two-fluid model with real-time out-put [12,15]. This included realistic nonlinear optical constants, nonlinear forces, equipartition time, and thermal conduction with time steps ten times below the shortest plasma oscillation time and with Maxwellian exact numerical computations of the temporally and spatially changing laser field in the corona.

Using a neodymium-glass-laser intensity of 10^{15} W/cm^2, the following initial conditions at time $t=0$ were chosen: electron and ion temperatures of 30 eV, electron and ion velocities taken as zero, and a deuterium plasma of 20-wavelength thickness with a linear ramp of electron and ion density growing from 0.5 at one side to 1.2 times the critical density at the other side. We see the following dependences up to the time of 34 psec: Figure 1 shows the ion density where the initially smooth slope is changed into ripples at about 5 psec. About 1 psec later, the laser electromagnetic-field density shows the strong standing waves (Fig. 2). For times after 5 psec, the laser field is nearly cut off at the low density (no standing-wave field patterns). Then the density ripples (Fig. 1) relax hydrodynamically during the time up to about 15 psec, when the wave field again can penetrate the corona, producing standing waves (Fig. 2) and subsequent density ripples, and cutting off the penetration of light, etc. These ripples are synchronous with the ion velocities (Fig. 3) where on top it can be seen that the whole plasma corona receives a push during the first 5 psec, the acceleration being then stopped and getting an additional push until 15 psec, etc.

This all reproduces the observation of the stuttering interaction: (i) the change from mirror reflection at the critical density (at about 14 μm while dynamically changing in due course); (ii) the pulsation of reflectivity; and (iii) the sequence of pushes of the acceleration. We can then explain the action of induced spatial incoherence due to its temporal incoherence of 1 to 3 psec. In the computations, we have completely coherent laser waves. If the coherence is changed by ISI within 1 to 3 psec, any standing-wave field phases will change and will not permit partial standing waves for a sufficient time nor the subsequent density ripple nor pulsation. We have followed this up by a numerical analysis of a broadband irradiation [16]. At a single frequency, the time-dependent ripples appeared, while with a 1%-frequency-bandwidth laser pulse [5], no pulsation or ripples appeared but a nearly time-independent (smooth) density and velocity field up to 50 psec was the result.

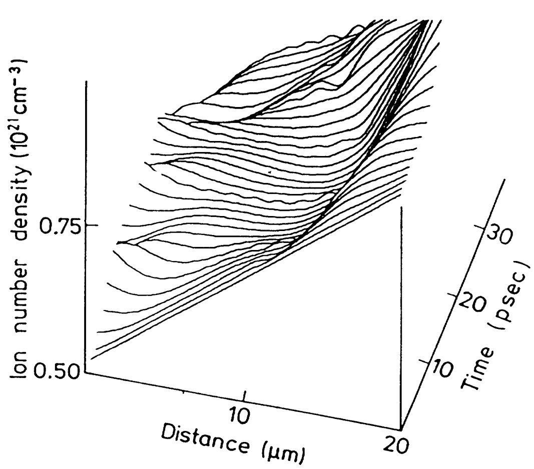

FIG. 1. Time development of a 0.02-mm-thick plasma slab initially at rest and temperature 30 eV with linearly increasing density from 0.5 to 1.2 times critical density, irradiated (from the left-hand side) by a neodymium-glass-laser pulse of 10^{15} W/cm^2.

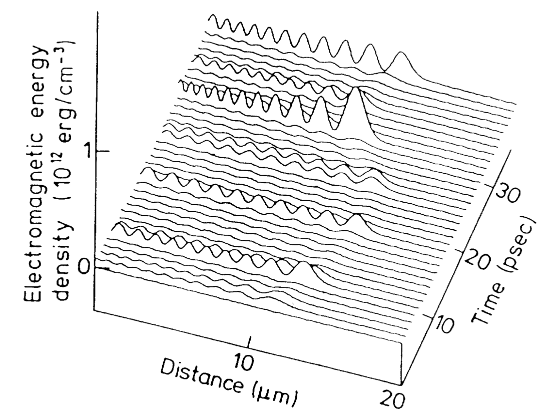

FIG. 2. Time development of the electromagnetic energy density of the laser field for the same case as in Fig. 1.

The action of the random-phase plate [3] or the smoothing by SSD [4] or by the lens array [2] may consist then in the generation of a highly complicated interference and diffraction field where again the standing-wave structure and the subsequent density rippling by the nonlinear force would be avoided.

As alternatives or modifications to the presented model, we should mention that the phase reflection at very low-density plasma was explained as a chaos mechanism of a three-wave stimulated Brillouin scattering (SBS) interaction [17]. Further, it was indicated [18] that an anomalously strong absorption may occur in the very peripheral low-density range of the corona. What has yet to be shown, however, would then be how and why this SBS or the anomalous absorption will stop after 10 to 30 psec, for which stopping no immediate reason can be seen from these mechanisms, while our hydrodynamic model has the thermal relaxation of the ripples for the recupera-

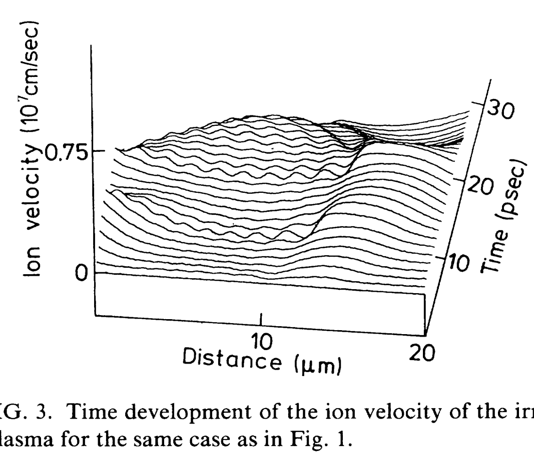

FIG. 3. Time development of the ion velocity of the irradiated plasma for the same case as in Fig. 1.

tion of the mirror reflection after about 10 to 20 psec. Furthermore, for the very peripheral absorption model, it would have to be shown how this leads to the observed very high reflectivity contrary to the experience that absorption within the corona is related to low reflection and high-energy transfer to the plasma.

As a test of our model, we propose to repeat the experiment of Sigel *et al.* [19], where the pattern of a question mark was put into the laser beam and the pattern in the reflected beam was then detected. We expect that the result irregularly changes within 10 to 30 psec from a weak upright pattern at mirror reflection to a strong upside-down pattern at phase reflection back and forth. This all may change into weak mirror reflection when using the mentioned smoothing. Even the degree and perfection of the smoothing technique could be tested by such an experiment. The fact of a 30-psec pulsation has been observed [20] from 10-keV ions emitted by neodymium glass laser irradiation of tantalum: 30-psec and 3-nsec pulses of equal intensity produced the same maximum ion energies that can be explained by pulsation only [21].

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