Inst. Phys. Conf. Ser. No 140: Section 8
Paper presented at Laser Interact. with Matter Conf., Oxford, 19–23 September 1994

Evidence for "moving focus" in laser interaction with long scalelength plasmas

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Abstract. Laser interaction with a preformed expanding plasma has been experimentally studied. The plasma had an $n_c/10$ bulk surrounded by a large low-density region. Time-resolved spectra of the light backscattered during interaction show that, after a short phase of laser coupling with the whole plasma, the laser ligth decouples from the main plasma bulk. In fact, the interaction region moves outside at supersonic velocity due to dynamical self-focusing of the laser beam. Beam smoothing with RPP does not modify appreciaby the effect. This observation is relevant to the general problem of laser energy deposition in a plasma.

1. Introduction

Efficient laser energy deposition into a dense plasma surrounded by a low density corona is a goal for many applications, including ICF. In this latter case uniformity of energy deposition is also required. Among the problems to be faced in order to obtain both uniformity and efficiency, two instabilities play a crucial role: filamentation and stimlated Brillouin scattering (SBS). The usual picture simply relates filamentation to the non-linear growth of non uniformities in laser irradiation and SBS to a poor laser energy deposition due to possible high levels of backscattering. In fact, most of the theorical and experimental works considered the two instabilities as separated or simply co-existing phenomena.

Recently, the interplay between filamentation and SBS was considered theoretically [1] and some interesting numerical simulations showed that the reciprocal influence of the two instabilities is strong in particular conditions [2,3]. A few experiments have been also addressed to clarify this aspect. It has been proved that the filamentation threshold acts very often also as an *effective* threshold for SBS, and consequently the beam smoothing techniques, if properly used, can reduce the backscattering level via the suppression of filamentation [4]. An important piece of information to better understand the connection between the two instabilities is the location of the backscattering active region in the plasma. Very recent mesurements attempted to obtain such information using a Thomson scattering technique together with the usual SBS backward spectroscopy [5].

Usually a low level of backscatterig is considered as a signature of an efficient laser-plasma coupling. This is not always true. In this paper we present SBS data obtained in condition of strong filamentation, mostly in the sense of whole beam self focusing (WBSF), with a low level of backscattered energy. SBS spectra show however a substantial decoupling of the laser beam from the main absorbing bulk of the plasma. This observation supports the idea that in presence of a deep low density corona, dynamical self-focusing can make laser energy deposition very inefficient. In this case the backscattering level fails to be a good *indicator* of the laser energy deposition and a great amount of the laser light is expected to be scattered and diffracted sideward [2].

2. The experiment

The experiement essentially consisted in the study of the interaction of a powerful laser beam with a preformed plasma and was performed at the Central Laser Facility (Rutherford Appleton Laboratory,UK). Four 600-ps, 1.053-μm beams of the Vulcan laser were used to preform the plasma. These *heating* beams were superimposed in two opposed pairs, providing an irradiance of 6.0 10^{13} W/cm^2 on each side of the target. Target consisted of 0.5-μm-thick 400-μm-diam aluminium dots coated onto a 0.1-μm plastic stripe.

The evolution of the plasma was carefully characterised in terms of electron density and temperature [6]. The electron temperature was obtained from time-resolved x-ray spectra by line-ratio measurements, accounting for opacity effects. Two-dimensional electron density maps were reconstructed from Nomarski interferograms taken at different delays with respect to the heating pulse. They showed that the expansion was axially symmetric and reproducible shot by shot. The plasma was found to be substantially free from small-scale density inhomogeneities.

The 600-ps, 1.053-μm interaction beam was delayed by 2.5-ns with respect to the heating pulse and focused with an f/15 optics into the preformed plasma along the main symmetry axis of the exploded target, at an irradiance up to to 5.0 10^{14} W/cm^2. The focal spot diameter was typically 100-μm, i.e., smaller than the plasma transverse scalalength. The electron temperature of the preformed Al plasma, 2.5-ns after the heating pulse was measured to be 400 ± 50 eV. The electron density profile along the interaction axis, as inferred from interferometric data [6] at 3.0-ns and 4.3-ns after the heating pulse, is shown by the plots of Fig.1. The maximum density is close to $n_c/10$ and a plasma bulk extends along the interaction axis up to a distance comparable with the target diameter. A region of density lower than $n_c/100$ surrouds the denser plasma for a few millimetres. The corresponding profiles at 2.5-ns are expected to be very close to the ones shown in Fig. 1 for t = 3-ns.

The effects, on the interaction, of beam manipulation or smoothing were also studied. The unsmoothed beam spot nonuniformities were limited to an amplitude of about 20% of the mean irradiance. The spot patterm was modualted in some mesurements using specially designed phase plates [7]. Other series of measurements were performed with the interaction beam smoothed using Randon Phase Plates (RPP), Induced Spatial Incoherence (ISI), or Smoothing by Spectral Dispersion (SSD) devices respectively.

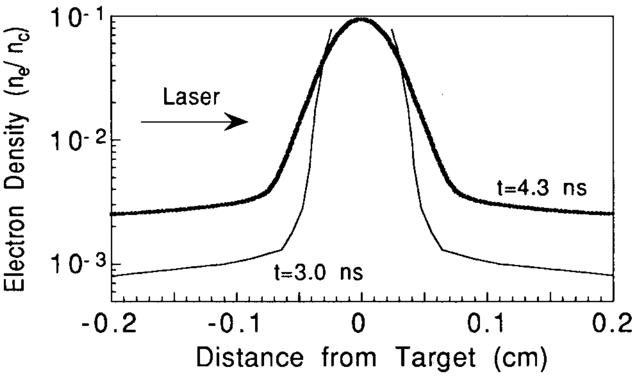


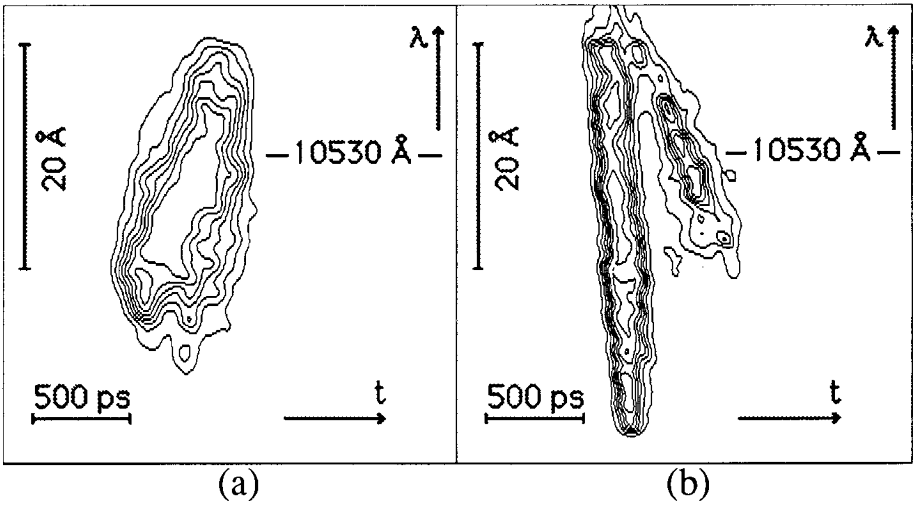
Fig.1 - Electron density profile v/s distance, 3.0-ns and 4.3-ns after the heating pulse. Density is in unit of the critical density.

3. Backscattering measurements

Time resolved spectra of backscattered light were obtained with a 1-m spectrometer and an optical streak-camara. Some reference spectra were taken by directly irradiating the cold target with only the interaction beam. One of these spectra is shown in Fig. 2 (a). They are some 20 Å wide and their mean wavelength moves from the blue to the red side with respect to the laser wavelength. They show similar features to other SBS spectra obtained by direct irradiation of solid targets [8]. Also the rate of energy backscattered in the solid angle of the focusing optics (a few percent of the laser energy) is close to values obtained in similar conditions.

On the contrary, the spectra obtained by interaction with the preformed plasma show novel features, highly reproducible in a large number of shots. A typical spectrum obtained from irradiation of the preformed Al plasma is shown in Fig.2 (b). Two temporally separated phases can be observed in these spectra. First, a short flash of backscattered light is observed with a broad spectrum, more than 30 Å wide. The temporal resolution of our detection system was limited by the spectral dispersion to 120-ps, and this is the upper limit we can give to the duration of the first phase of the backscattering process. In the second phase, the backscattering ligth is rather narrow at a given time (a few Ångstroms). The spectrum moves from the red side of the previous broadband flash to the blue side at an almost constant rate. The level of energy backscattered in the same solid angle was very low in this case, oscillating shot by shot from 7 10^{-5} to 2 10^{-4} of the laser energy.

A limited number of measurements on backscattering were also performed with the interaction beam smoothed by RPP, ISI or SSD methods respectively. The comparison between spectra obtained with smoothed or unsmoothed interaction beam at the same irradiance, show a relevant feature: as the interaction beam was narrow-band (<10^{-2}Å), time resolved spectra were substantially similar to the one shown in Fig. 2 (b), no matter if unsmoothed, RPP or ISI smoothed beam was used. The amount of backscattering was still very low, 3 10^{-4} in the case of RPP smoothing, 1 10^{-4} in the case of ISI. With the broadband beam (13 Å), the wide laser spectrum did not allow observation of spectral details as those shown in Fig. 2 (b). The backscattered energy was not measured in this case.



(a) (b)

Fig.2 - Time-resolved spectra of light backscattered during interaction.
(a) 500 nm Al dot target; no preformed plasma; irradiance of the interaction beam: 4.0 10^{14} W/cm^2.
(a) 500 nm Al dot target; irradiance of the heating beams: 5.0 10^{13} W/cm^2; interaction beam: 4.0 10^{14} W/cm^2; delay between heting and interaction pulses: 2.5ns.

4. Discussion

Due to the Doppler effect of the expanding plasma, the relative red shift of the SBS backscattered light is expected to be (2/c)(S+F) where S is the ion-sound velocity and F the flow velocity, which is positive in the direction of propagation of the laser beam. The absolute value of F is expected to increase about linearly with the distance from the maximum density position (see Fig.1). Moving into the expanding plasma in the direction of laser light propagation one find the supersonic region, where $F < - S$, giving blue shifted backscattered light; the first sonic layer, $F = - S$, no shift; the subsonic region $0 > F > - S$, red shift; the maximum density layer, $F = 0$, relative shift (2/c)(S); the region beyond the maximum density, $F > 0$, with increasing red shift.

In terms of Doppler modified SBS spectra, and considering a temperature of 400-eV, the first short flash of backscattered light which is visible in Fig. 2 (b) should originate in a plasma region between the layers $F \approx 0$ and $F \approx - 3$ S. In the second phase the plasma region involved at a given instant is much narrower and moves regularly from the $F \approx 0$ to the $F \approx -1.5$ S. An estimation of the flow velocity profile at 2.5-ns after the heating pulse, shows that the first flash of backscattering should involve a region from the maximum density to a distance of the order of 1.5-mm in the direction of the focusing lens. The pure Doppler picture could be inadequate to describe this first phase of the scattering process, which is rather intense and some non linear effects on SBS cannot be excluded. On the contrary we believe that the second phase can be described in terms of linear SBS. We are in presence of a *moving focus* produced by dynamical self-focusing from the maximum density to a distance of the order of 0.8 mm. This *focus* actually is the interaction volume were the intensity is above threshold for SBS, and moves at a rate of about 4 10^8 cm/s into the plasma. The direction of this motion was correctly predicted in the "supersonic limit" approximation by the model of Lontano *et al* [9]. Simulations based on a laser beam focused on the surface of an omogeneous plasma slab lead to a motion in the opposite direction [3,10], which is not realistic to describe the interaction with a corona of decreasing density.

Time resolved spectra show that there is a very short time of effective coupling of the laser light with the plasma up to the maximum density region where an important level of absorption is expected. Suddenly, as a consequence of the local heating of the plasma, the beam suffers a process of self focusing with a growth-time of the order of 100-ps. This process progressively decouples the laser beam from the plasma. This is the reason of the very low level of backscattered energy measured in this condition. Actually the backscattered power is much higher in the first short flash and drops during the moving focus phase. This is due to the low density of the plasma regions involved at this stage and to the reduced volume of the moving focus. On the other hand it is possible that an important fraction of the laser energy is side-scattered in our experimental condition, as expected from 2-D simulation in the case that the interaction length is comparable with the beam size [2], which is the case with strong self focusing.

In conclusion the SBS data presented here seem to be very interesting both in terms of the study of SBS instability in flowing plasmas and in terms of the general problem of the laser coupling with coronal plasmas.

This work was supported by CNR, Italy, SERC, UK, and ECC in the framework of the Uman Capital and Mobility Programme.

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