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The cover design features time resolved resonance Raman spectra of a photo-excited molecule showing structural changes on a picosecond timescale (see P 147).

PLASMA INTERACTION WITH SMOOTHED OR MODULATED LASER BEAMS DIAGNOSED BY 2ω EMISSION AND BACKSCATTERING

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INTRODUCTION

Laser interaction with preformed plasmas is a powerful technique to investigate coronal instabilities of interest for laser fusion. A series of experiments has been performed at CLF since 1986 using line-focused beams to preform homogeneous plasmas with negligible motion along the interaction axis[1].

This new experiment was designed to study interaction with an expanding plasma whose transverse scalelength is larger than the interaction beam spot in order to avoid refractive effects. We succeeded in characterize the plasma both in density profile and temperature[2], thus providing a reliable background to interpret the interaction data. Most of the diagnostic means were based on second harmonic (SH) detected both forward and sidewards, extending methods already experienced at IFAM at lower irradiance[3]. A further diagnostic was supplied by time resolved spectroscopy of backscattered light. In this configuration we tested the effect on interaction of phase plates designed using an original code[4] and made at CLF. Both controlled and random phase plates have been used to modulate or smooth the interaction beam respectively. Other smoothing techniques have been also tested in a limited number of shots, including broad band operation with ISI or SSD devices.

Some two hundred laser shots were successfully fired on target. In this paper we partially report on data obtained from interaction and shortly discuss some of them.

SET-UP

The experiment was performed in TAE using two pairs of opposite beams (heating beams) from Vulcan, 600 ps, 1.053μm. They were focused in a 600 μm spot at a total irradiance of typically $6\ 10^{13}$ W/cm^2 to produce the plasma. Typical target consisted of 400 μm diameter, 500 nm Al dot coated on 100 nm plastic stripe, unless differently specified in the text. A fifth (interaction) beam was delayed by 2.5 ns and focused f/5 in a spot of 120 μm at an irradiance from 10^{13} W/cm^2 to $5\ 10^{14}$ W/cm^2. Further details on beam configuration and probe optics for interferometric measurements can be found in another paper[2] of this Report. Beside X-ray diagnostics and interferometry, three other detection channels were activated. A forward channel provided alternatively time resolved spectra of SH or time resolved images of SH sources. A sidewards channel provided time resolved spectra of SH emitted at 90°. Time integrated 2ω images were also obtained sidewards by the probe optics. Finally a backward channel provided time resolved spectra of laser backscattered light.

STUDY OF SECOND HARMONIC EMISSION

The probe channel supplied very important information on location and distribution of 2ω sources. We obtained time integrated images, some superimposed to the probe fringe pattern allowing to locate exactly the source of emission in the density profile, some other with probe off giving maximum contrast. The right portion of Fig 1 shows the sidewards SH emission from the triple spot obtained by a stripe phase plate[5]. In this case the interaction beam was focused directly on Al thick target. The 2ω image is compared with both simulation of the spot by FT code[4] and equivalent plane imaging of the phase modulated laser spot at fundamental frequency. The overall agreement is quite good. The 2ω image shows also details due to the interaction with the plasma and the mechanism of harmonic generation. In particular this kind of images generally showed that each source has maximum emissivity at its boundary where gradients are located, as expected from theory.

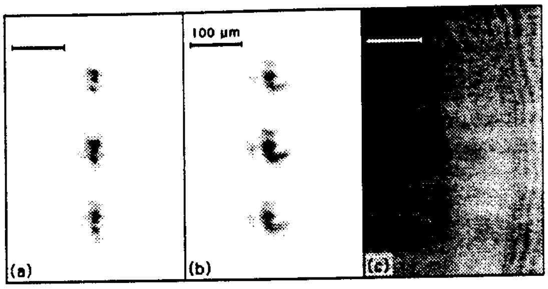

Fig 1 Effects of stripe phase plate on the focal spot of the interaction beam. From left to right: simulation of the intensity distribution in the focal plane by FT code; equivalent focal plane imaging of the same beam at laser frequency; side image of SH sources from interaction of the phase modulated beam with Al thick target.

In the case of interaction with preformed plasmas it is very important to know the location of 2ω sources. This information was provided by probe pictures with both source images and fringe pattern as reproduced in another paper[2] of this Report (Figs 6a and 6b of that paper). The fringe pattern evidences that the SH is mostly generated in a well confined spot located at the crossing between the boundary of the high density region and a channel of lower plasma density produced by the interaction beam. This is the place where both longitudinal and transverse gradients are maxima. An intense spot of 2ω is always visible at the laser side of the dense region with dimension comparable with the interaction beam spot. The spot is very often structured in filaments as shown in Fig 6b of that paper[2] where filaments of few microns diameter and less than 100 microns length are clearly visible. No SH is visible from the bulk of the dense region, while a weaker 2ω spot is sometime visible at the exit boundary of the dense region. No SH was visible sidewards from heating beams.

Time resolved spectra of side emitted SH have been obtained with an optical streak camera coupled with a 1/2 m spectrometer. Two typical results obtained by interaction with preformed plasma are shown in Fig 2. Some features showed clear reproducibility, namely the signal duration which is generally shorter than the interaction pulse, the spectral shift which is toward the red increasing in time up to some 4Å, the spectral width also resulted to increase to comparable values. Bi targets gave generally more structured spectra, with both spectral and temporal modulations, if compared to the Al targets. Similar spectra have previously been observed[2,6] and a model[7] have been proposed for the emission mechanism, taking into account non-linear coupling of forward and backward propagating radiation. In this experiment no clear evidence was shown for such a mechanism. This is not surprising because we know from images discussed above that SH is emitted from well definite regions at the boundary of the dense region. On the contrary there are indications that SBS originates in the low density tail of the expanding plasma (see below).

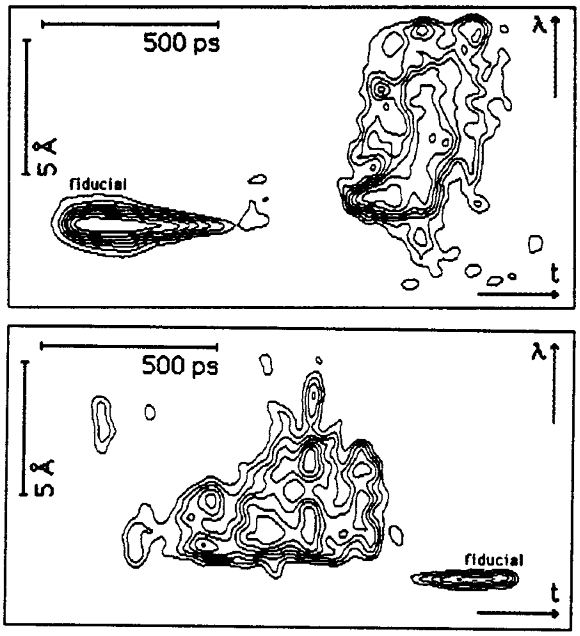

Fig 2 Time resolved spectra of SH emitted sidewards during interaction.
Top: 500nm Al dot target, heating irradiance 6 10^{13} W/cm^2, interaction 5 10^{14} W/cm^2.
Bottom: 120nm Bi dot target, heating irradiance 6 10^{13} W/cm^2, interaction 5 10^{14} W/cm^2.
In both cases the interaction pulse was delayed 2.5 ns.

Time resolved spectra of forward emitted SH were also obtained with preformed plasmas. The duration of emission was considerably shorter than the laser pulse duration. Red shift of few Å, lower than for side-emitted SH, was observed. One of those spectra is shown in Fig 3. In the second part of the experiment the forward SH channel was used to take time resolved images. Among a number of interesting pictures, Fig 4 shows two cases: left hand pictures refers to the beam modulated as in Fig 1 and interacting with the preformed plasma. The SH emission is earlier and stronger at the plasma boundary, later on SH "burns through" the plasma bulk where the central spot is located. Right hand picture was obtained in the same interaction condition but with broadband beam smoothed with RPP. It is relevant that in this case SH is produced by small sources with very short bursts.

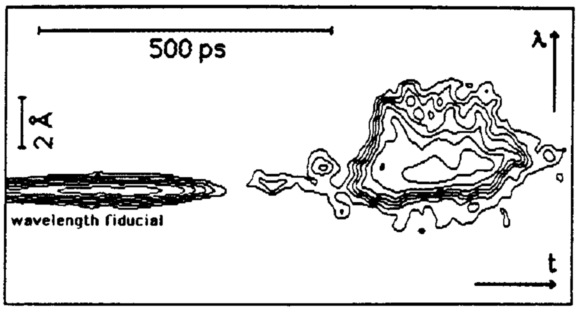

Fig 3 Time resolved spectrum of SH emitted forward during interaction. 500nm Al dot target, heating irradiance 6 10^{13} W/cm^2, interaction 5 10^{14}W/cm^2. Interaction pulse was delayed by 2.5 ns.

STUDY OF BACKSCATTERED LIGHT

Time resolved spectra of backscattered light were obtained with a 1m spectrometer coupled with an S1 streak-camera. Some reference spectra were taken by directly irradiating targets with the interaction beam only (Fig 5 left). They typically spread over some 20 Å moving in time from the blue to the red side with respect to the laser wavelength. There is some similarity with spectra recently obtained[8] and it is possible that dense region including $n_c/4$ layer could play an important role in exciting ion-acoustic waves.

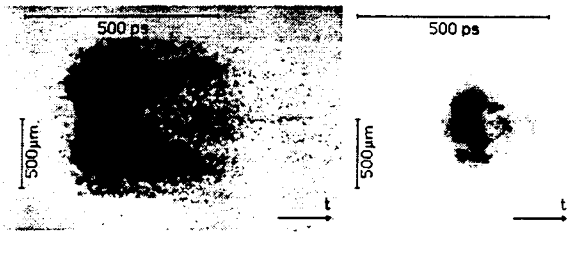

Fig 4 Time resolved images of SH emitted forward during interaction.
Left: 500 nm Al dot target, heating irradiance 9 10^{13} W/cm^2, interaction 10^{14} W/cm^2;
the interaction beam was modulated in three spots as in Fig 1 and delayed 2.5 ns.
Right: 500 nm Al dot target, heating irradiance 7 10^{13} w/cm^2, interaction 10^{14} W/cm^2;
the interaction beam was 150 mm apodized, broad band, RPP smoothed.

With preformed plasma, we obtained 25 spectra showing interesting features very reproducible shot-by-shot. A typical spectrum is shown in Fig 5 right. Two temporally separated phases with different spectral behaviour can be noticed. First, a short flash is emitted in a broad band of more than 30 Å, more extended in the blue side than in the red one. A second emission follows in time: it is narrow-band and shifts quite regularly from the red to the blue side of the spectrum. A possible explanation of these novel spectra can be given in terms of the ordinary theory of Stimulated Brillouin Scattering. The background of the interpretative model is shown in Fig 6.

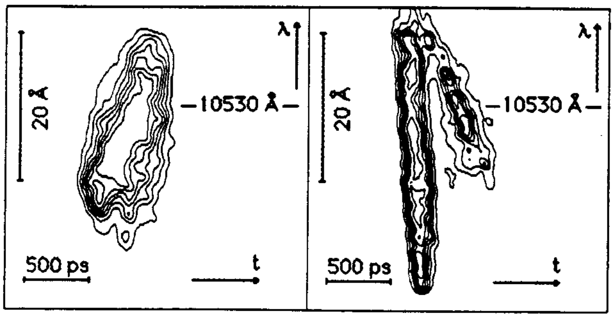

Fig 5 Time resolved spectra of light backscattered during interaction.
Left: 500nm Al dot target, no preformed plasma, interaction 4 10^{14} W/cm^2.
Right: 500nm Al dot target, heating irradiance 5 10^{13} W/cm^2, interaction 4 10^{14} W/cm^2; the interaction pulse was delayed 2.5 ns.

The relative red shift of the backscattered light is expected to be $(2/c)(v_s + v_f)$ where v_s is the ion-sound velocity and v_f is the flow velocity which is positive in the direction of propagation of the laser beam. The absolute value of v_f is expected to increase, along the laser beam, about linearly with distance from the original target position, i.e. the maximum plasma density position. In a plasma or plasma region where

$v_s >> v_f$, the red shift is simply proportional to v_s. In an expanding plasma as we have, three regions can be identified in terms of shift: the subsonic region where $v_f<0$ and $v_s>v_f$ and the region beyond the target plane where $v_f > 0$ both give red shift increasing with distance from the first sonic layer (from where unshifted back-scattering originates); on the contrary, the supersonic region where $v_f<-v_s$ gives blue shifted backscattered light.

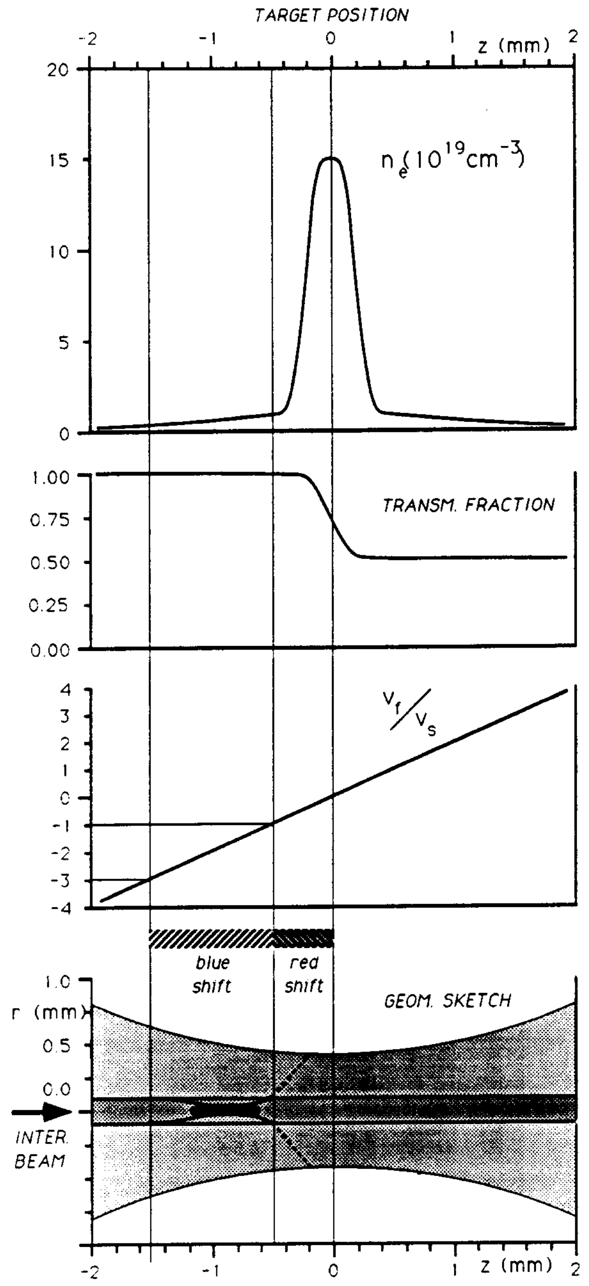

Fig 6 Elements for an explanation of SBS spectra from expanding preformed plasma (as in Fig 5 right). From top to bottom: plasma density profile at the beginning of interaction (2 ns after heating pulse peak) extrapolated from interferometric data; transmitted fraction of laser light at 2 ns; ratio between flow and sound velocities at 2 ns (T_e= 600 eV; configuration of the interaction region with the unperturbed laser beam penetrating the plasma and possible self-focusing effect.

Following this simple scheme and considering the electron temperature measured at the beginning of interaction and later on[2], we found that the initial broad-band flash (Fig 5 right) originates between the layer with $v_f \approx 0$ and a layer with $v_f \approx -3\ v_s$. In the second phase of scattering the involved plasma region is much narrower and moves regularly from the $v_f \approx 0$ layer to the $v_f \approx -1.5\ v_s$ layer. In terms of length it means that more than 1 mm of plasma is involved in the backscattering process initially. In terms of density, because of the strong deviation from the 1-D expansion observed at distance >0.5 mm from the target[2], it means that the region involved in the backscattering process is mostly at very low density, down to few units of 10^{18} cm^{-3}.

The physical meaning of this interpretation is that the interaction beam initially stimulates Brillouin scattering in a large region of the plasma up to the the high density peak where the short scalelength inhibits the parametric coupling and do not allow the beam to penetrate uniformly the region beyond, due to both absorption (estimated of about 50%, see Fig 6) and refraction. Suddenly, as a consequence of the local heating of the plasma, the beam suffers a self-focusing process with a growth-time of the order of 100 ps. This process decouples the beam from the whole plasma region and restricts the scattering region to the reduced beam waist which moves backward from the original lens focus due to the effect of the increasing optical power of the perturbed density profile. At the same time this "additional variable lens" just allowed the backscattered light coming from the moving waist to be collected in the backward channel of the experiment.

In conclusion we obtained a great number of data on interaction of powerful laser beams with coronal plasmas in a variety of conditions providing a coherent set of information on the physics involved.

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REFERENCES

1. O.Willi, T.Afshar-rad, S.Coe and A.Giulietti; Phys.Fluids B **2**, 1318 (1990)
2. L.A.Gizzi, T.Afshar-rad, V.Biancalana, P.Chessa, C.Danson, A.Giulietti, D.Giulietti, E.Schifano, S.M.Viana and O.Willi; "Production and characterization of long-scalelength expanding plasmas for ICF coronal studies" in this Report (1993)
3. A.Giulietti, D.Giulietti, D.Batani, V.Biancalana, L.A.Gizzi, L.Nocera and E.Schifano; Phys.Rev.Lett. **63**, 524 (1989)
4. V.Biancalana and P.Chessa; to be published in Applied Optics (1993)
5. V.Biancalana, P.Chessa, C.Danson, D.Pepler; in this Report (1993)
6. E.Schifano, S.Baton, C.Labaune, T.Jalinaud, V.Biancalana and D.Giulietti; Rapp.Scient. LULI-Ec.Pol. (Palaiseau France 1991)
7. J.A.Stamper, R.H.Lehmberg, A.Schmitt, M.J.Herbst, F.C.Young, J.H.Gardner, S.P.Obenschain; Phys. of Fluids **28**, 2563 (1985)
8. P E Young, H A Baldis and K G Estabrook, Phys.Fluids B **3**, 1245 (1991)