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BEAM SMOOTHING AND LASER INTERACTION WITH CORONAL PLASMAS

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A collaborative scientific campaign on laser plasma interaction is in progress involving two groups, namely one from the Blackett Laboratory (London,UK), the other from Pisa, Italy (at Istituto di Fisica Atomica e Molecolare and at Dipartimento di Fisica, Universita'). The Nd "Vulcan" laser facility at the Rutherford Appleton Laboratory (Oxon, UK) has been used. The aim of the program is to obtain experimental information useful for laser fusion, but keeping as much control as possible of the physical parameters involved in the interaction. Most of our investigation was devoted to filamentation, stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) and to the possibility of their control with beam smoothing techniques. Results on convective instability and self-phase modulation were also obtained.

A long- scalelength, preformed plasma was generated by irradiating a thin metal foil stripe, 0.5 to 1 mm long, 0.3 mm wide, supported on a 100 nm thick plastic substrate. The stripe thickness ranged from 50 to 700 nm, depending on the atomic number of the metal, in order to match the most interesting conditions for the interaction. Four green beams at the second harmonic of the Vulcan glass laser system were superimposed in a line focus configuration as heating beams to form the plasma. The line focus assembly was obtained from an original design for x-ray experiments [1], and slightly modified in order to match the stripe configuration with a uniform light distribution. During the experimental campaign both 70 and 600 ps FWHM pulse durations were used for the heating beams in different experiments. Typical irradiance of the heating beams on the stripe target was 10^{14} W/cm^2.

A fifth beam (λ = 527 nm, 600 ps) was focused and used to interact with the plasma along its longitudinal axis. The novelties of this configuration are that: the laser beam interacts with a millimeter scalelength fairly homogeneous plasma, with well-defined input and exit planes; by delaying the time of arrival of the interaction beam with respect to the heating beams, the density and temperature of the preformed plasma at the time of interaction could be controlled; contribution of critical density to interaction is avoided, thus allowing to a more accurate study of coronal phenomena; the expansion of the plasma is perpendicular to the laser beam, so that Doppler shift can be virtually ignored in spectra analysis.

Most of our data were obtained with delays of either 1.2 or 1.8 nanoseconds, at which electron densities of 0.16 and 0.08 n_c, temperatures of 700 and 500 eV respectively are expected for Aluminium plasmas. These values, roughly consistent with the 1-D model [2], were calculated with an hydro-code. Measurements of density by interferometry and from SRS spectra, of temperature from X-ray and SBS spectra, reasonably confirmed those values. All our data were obtained at density definitely lower than $n_c/4$, avoiding the generation of a host of possible instabilities other than filamentation, SBS, SRS. A variety of techniques were used to diagnose these instabilities , including calorimeters and diodes for time integrated measurements of incident, transmitted and backscattered light; 1-D time resolved imaging and spectroscopy both in visible and X-UV domain using streak-cameras; 2-D time-resolved imaging of the input and exit planes with a gated image intensifier; 2-D time-resolved multiframe X-UV imaging of the plasma with a new special device.

Our experimental findings showed that the leading intability in long scalelength interaction is filamentation; also SBS and SRS were found to originate mainly from filaments [3]. It is well known that filamentation is seeded by nonuniformities already present in the focal spot as shown in Fig 1. Nonuniformities are in turn mostly a consequence of the coherence of the laser light. Consequently the major consideration for reducing these instabilities was to determine the effectiveness of laser beam smoothing techniques based on the reduction of the coherence of the laser light focused on target. Two distinct methods were tested in our experiment, and their effects were compared with the results obtained with the coherent beam [3,4].

In the first one a random phase plate (RPP) [5] was used, that breaks the incident laser beam up into a large number of individual beamlets randomly distributed in space which are dephased to each other by $\delta\phi = \pi$. These beamlets are then overlapped onto target by the focusing optics. The resulting interference pattern produced eliminates any gross scalelength nonuniformities from the laser beam profile but introduces pronounced short-scalelength intensity fluctuations which remain stable in the focal spot throughout the laser pulse. Fig. 2 shows the intensity distribution obtained in the focal spot after random phasing of the laser beam. The optimization of this kind of device to a given experiment needs to match correctly the f/number of the focusing optics with both beam diameter and dimension of the dephasing structures in the plate, in order that the nonuniformities introduced by the RPP are so small that they cannot seed the filamentation instability (because of diffraction).

The second device we tested was based on induced spatial incoherence (ISI) [6] and essentially consists in a pair of cross echelons, whose steps introduce a given optical delay δt. The resulting beam is composed of a limited number of beamlets delayed of δt with respect to the neighbours. With this system the use of a broadband laser of coherence time $t_c < \delta t$ is necessary. This causes the instantaneous interference pattern produced to be averaged out over times long compared to t_c leaving a smooth focal spot as evidenced in Fig. 3. In the case of long scalelength interaction the f/number of the focusing optics has to be large enough to ensure that all the interaction region is in the quasi far-field. If this condition is not fulfilled, the strong field gradients of relatively large scalelength introduced by the echelons grow easely in the plasma and the effect of filamentation are even worse than with the ordinary beam, as was observed [3].

To investigate filamentation and self-focusing, the exit plane of the interaction volume was imaged both on a streak-camera slit and a gated image intensifier, in order to obtain streaked 1-D images and 2-D images with different delay. With the ordinary beam at a nominal irradiance of the order of 10^{15} W/cm^2 both imaging devices showed that the plasma smoothed out the beam profile early in time before filamentation could grow. After a few hundreds of picoseconds, however, considerable break-up of the laser beam propagating through the plasma was observed due to filamentation [3,7]. This caused up to sevenfold enhancements in local irradiance to occur in the individual filaments. From the results of the ordinary quasi-steady theory of filamentation we know that under the conditions of this experiment the dominant mechanism driving the filamentation process was the ponderomotive force rather than the thermal effect, at least for low-Z plasmas and relatively small structures. This perfectly agrees with our measurements in Aluminium. Different behaviour was observed with heavier plasmas, as those from Gold and Bismuth targets. In this case thermally driven whole beam self focusing was a precursor to filamentation. The threshold for filamentation was experimentally observed to be between 7.9 10^{13} W/cm^2 and 4.5 10^{13} W/cm^2 for Aluminium plasma, which is consistent with theoretical predictions at the given density and temperature.

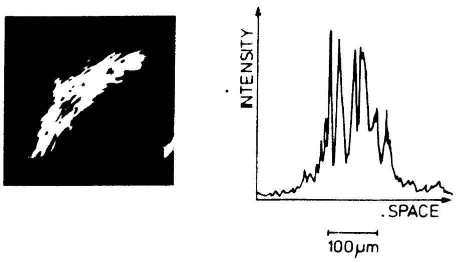

Fig.1 - Equivalent plane imaging of the focal spot with the ordinary coherent beam. Focusing optics f/10. Dominant modulation scalelenght 15-20 μm; peak-to-valley ratio 5:1.

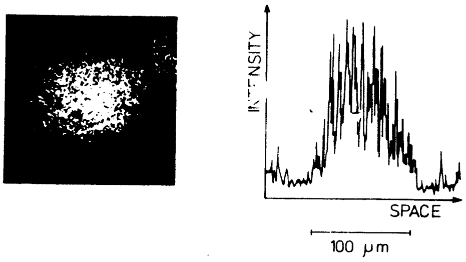

Fig.2 - Equivalent plane imaging of the focal spot with the random phased beam. Dephasing structure size to bem size 1:50. Focusing optics f/2.5. Modulation scalelenght 2-3 μm; peak-to-valley ratio 5:1.

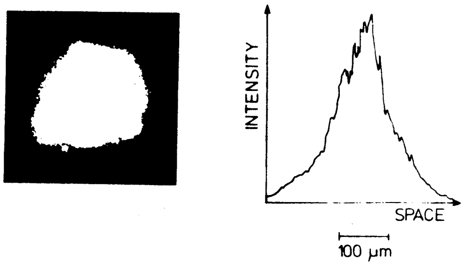

Fig.3 - Equivalent plane imaging of the focal spot with the ISI smoothed beam. ISI parameters: t_c=2ps; 5x5 beamlets with δt=5ps. Focusing optics f/10. Dominant modulation scalelenght : beam size.

We measured "reflectivities" due to both SBS and SRS. At the same time a careful time resolved spectroscopy of the backscattered light was carried out. Concerning SBS, in the simple assumption of a pure parametric coupling of the pumping laser wave with ion-acoustic and backscatterd waves, this latter is expected to be red-shifted of the amount $\omega_0 - \omega_B = [\, 2\, v_s/c\ F(n_e)\,]\, \omega_0$, where ω_B is the frequency of the backscattered wave, v_s is the sound speed and $F(n_e)$ is a function weakly depending on temperature. As long as the factor $F(n_e) \approx 1$, the shift will depend only on temperature, but this is not true in general as discussed in ref.8, where the effect of plasma flow is also discussed. These two latter effects can be ignored in our preformed plasma. However the high mean value of the irradiance in the interaction region, further enhanced by filamentation, makes the wave-coupling mechanism non linear and complex spectra were in fact observed. Some of the spectral features are explainable in term of self-phase modulation of the laser light in plasma channels where the refractive index is rapidly varying because of the electron density decrease due to self-focusing.

In the Raman process the e.m. wave is scattered back from the parametrically excited electron plasma waves. From the phase matching conditions we obtain for the wavelength λ_R of the Raman scattered light :

$$\lambda_R = \lambda_0 [\, 1 - (n_e/ n_c)^{1/2} (1 + 3k^2 \lambda_D^2)^{1/2} \,]^{-1} \ ,$$

where k is the plasmon wavevector. An absolute upper density limit for the process to occur is $n_c/4$. In our experiment density was always well below this limit, so that by changing the delay between the heating pulses and the interaction pulse we could verify the previous relation in what concerns the longer wavelength limit. A beautiful confirmation of the theory was obtained from Raman spectra of Au target plasmas at different times as reported in ref. 9. The peak density was found to drop approximately as t^{-1}, which is in agreement with an isothermal expansion [2]. Time-resolved SRS spectra showed very interesting features that can be related to filamentation. The complete analysis of some of these features is still in progress.

Using the smoothing devices with optimized focusing optics, both random phasing and ISI produced a strong reduction of SBS and SRS. In what concerns filamentation we observed experimentally that it is "frozen" by RPP and virtually suppressed by ISI. ISI was found to be the more effective device, but its use for laser fusion is limited by the necessity of large f/number focusing optics. An important applicative results we obtained was the combination of RPP and ISI in a configuration that allowed us to use small f/number focusing optics. An open problem is whether whole beam self-focusing is still possible with smoothed beams and what is its threshold. The problem is relevant for laser fusion where, even smoothed beams may introduce large scale modulations when overlapped. It is also an intersting problem from the point of view of instability physics, because the mutual influence between large scale modulation (more sensitive to thermal effects) and small scale modulations (more sensitive to the ponderomotive action) is still unclear. At the moment we only had evidence of local extra heating in some shot by x-ray multiframe imaging of the plasma during interaction with an ISI smothed beam. The localisation and shape of the hot regions, as well as the time and duration of the enhanced x-ray emission, suggest that whole beam self focusing occurred in some shot.

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