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Laser beam smoothing in plasma at powers below the filamentation threshold

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Recent experiments have shown that the coherence properties of spatially randomized laser beams are modified during their propagation through low density plasmas. For sufficiently high powers, the filamention instability occurs in hot-spots and it is reponsible for the observed temporal incoherence [1]. However, this regime is not appropriate for applications because the filamentation instability is associated with enhanced backscattering.

In [2] the authors have identified the mechanism of laser beam smoothing in plasma at powers below the filamentation threshold. In this paper we focus our attention on this regime that can be an attractive possibility for an efficient control of the laser transport and energy deposition in the ICF target.

To describe the propagation of spatially and/or temporally incoherent laser beam we employ the statistical model of the laser-plasma interaction recently developped [3]. The laser propagation is described in terms of the electric field correlation function :

$$\Gamma_{EE*}\left(\vec{R},\vec{\rho},T,\tau,z\right) = \left\langle E\left(\vec{R}+\frac{\vec{\rho}}{2},T+\frac{\tau}{2},z\right) E^*\left(\vec{R}-\frac{\vec{\rho}}{2},T-\frac{\tau}{2},z\right)\right\rangle ,$$

where the angular brackets denote the statistical average. The correlation function Γ_{EE*} is normalized so that the laser intensity is given by $I = \Gamma_{EE*}\left(\vec{R},\vec{0},T,0\right)$. It contains two very different scales. The macroscopic one corresponds to the beam envelop width L_0 (typically a few hundred microns) whereas the microscopic one is associated to the speckle width ρ_0 (typically a few microns). For interaction time $t \le L_0/c_s$, where c_s is the ion acoustic velocity, and for the propagation length shorter than the Rayleigh length of the beam envelop $z_R \sim k_0 L_0 \rho_0$ macroscopic effects are neglectable. The correlation function at the entrance of the plasma can be represented as $\Gamma_{EE*}\left(\vec{R},\vec{\rho},T,\tau\right) = C(\vec{\rho})\, f(T,\tau)$, where we suppose that spatial and temporal coherence properties of the laser are independant. Function f denotes the temporal component of the electric field correlation function. The transverse correlation function C at the focal plane is given by the Fourier Transform of the intensity distribution in the near-field :

$$C(\vec{\rho},z=0) = \mathbf{TF}_{\vec{r}\rightarrow\frac{\pi\vec{\rho}}{\lambda_0 f}}\, I(\vec{r})\,.$$

The statistical model for the laser-plasma interaction in the case of small angle scattering [3] accounts for the density fluctuations that can also be described in terms of their correlation function. A system of coupled equations describes the paraxial propagation of the laser beam through the driven density fluctuations that propagate in a transverse plane with the sound velocity. The multiple scattering of the beam on these density fluctuations is responsible for the spectral broadening of the transmitted light. The coherence time is then reduced to the characteristic period of density fluctuations ρ_0/c_s (typically a few picosecondes). Smoothing effect appears after a distance :

$$\Lambda_c = \frac{4/\sqrt{2\pi}}{L_R\, k_0^2\, n_e^2\, \delta_n^2},$$

where $L_R \sim k_0\rho_0^2$ is the Rayleigh length of the speckle, n_e is the plasma density normalized to the critical density and δ_n is the density fluctuations level. For ponderomotively driven fluctuations this characteristic length can be written has a function of the power in the speckle P_{sp} normalized to the critical power for filamentation, the number of speckles in the focal spot N, and the Rayleigh length of the beam envelop z_R :

$$\Lambda_c = \frac{6.6\times 10^{-2}}{\sqrt{N}\,(1-n_e)\,P_{sp}^2}\, z_R\,. \tag{1}$$

For example, in the experiment [2], the quantity $z_R/\sqrt{N} \sim 100\mu$m is the Rayleigh length of the speckle, the power in an average speckle is nearly 5% of P_c and density about 1% of n_c. The characteristic length for plasma smoothing is therefore of the order of 2,7 mm whereas the Rayleigh length of the beam is 4,5 mm. For the large-scale FCI facilities the number of speckles in the transverse direction of the focal spot is $\sqrt{N} \sim 200$. For a power in the speckle of 5% of the critical power, Eq.1 predicts a smoothing distance of 0,13 z_R.

In order to confirm these analytical predictions, numerical simulations of the interaction of a spatially incoherent beam with plasmas have been performed using the code PARAX [4]. The laser propagation through low density plasmas is described by the paraxial equation. The plasma response in a transverse plane is obtained by using an acoustic wave model. In following calculations a λ_0 =1,053 μm beam is focused through a Random Phase Plate (RPP) with $h = 2$ mm square elements into Helium preformed plasmas with the electron temperature $T_e = 500$ eV and the density from 1 to 5% of n_c. Figure 1 presents the time-resolved intensity distribution in a tranverse direction for different plasma densities and after a 2 mm propagation. In figure 1,a the density is $n_e = 1\%\, n_c$ and we observe no modification of the temporal properties of the beam. Figure 1,b corresponds to $n_e = 2\%\, n_c$ and one can observe intensity fluctuations. Lastly, the intensity temporal coherence is deeply modified in a plasma with density $n_e = 5\%\, n_c$ as one can see on figure 1,c.

Indeed, according to Eq.1, Λ_c depends on the ratio P_{sp}/P_c. For given laser characteristics and electronic temperature, the variation of plasma density leads to different critical powers for the filamentation as $P_c \propto T_e/n_e$. Therefore, if n_e increases, P_c decreases and the ratio P_{sp}/P_c increases: the characteristic length Λ_c is shorter. Thus the length needed for an effective smoothing of the beam is larger than the plasma thickness for the lowest densities.

Moreover the PARAX calculations allow us to confirm the hypothesis that the laser electric field follows gaussian statistics [3]. Indeed, this hypothesis is necessary to assure that the electric field distribution is completely described by its correlation function Γ_{EE*}. For the laser beam without plasma, the gaussian hypothesis is justified by a sufficiently large number of speckles in the transverse plane and the central limit theorem. However the statistical properties of the beam can be modified during the propagation through plasma. Our calculations show that the gaussian hypothesis is still pertinent for the powers under the filamentation threshold. In figure 2,a we show the probability distribution for the real and imaginary parts of the electric field. One can see that they follow the same gaussian law, and therefore the probability intensity can be written as :

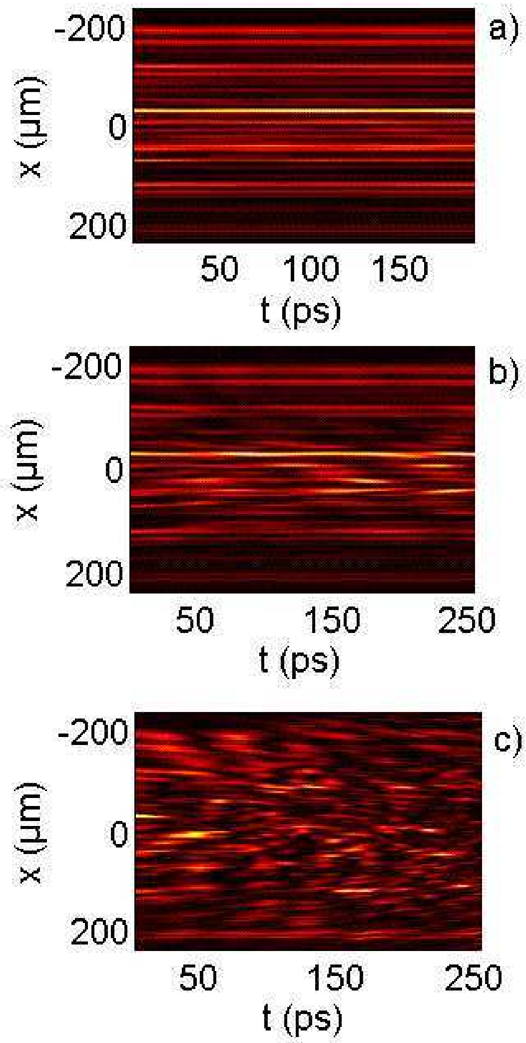

Figure 1: Time resolved intensity distribution in a transverse direction after 2mm of propagation in different density plasmas.

$$p(I) = 1/\langle I \rangle \exp\left(-I/\langle I \rangle\right), \tag{2}$$

where $\langle I \rangle$ is the average intensity in a hot-spot. On figure 1,b we present the intensity probability variation in function of the propagation length. The solid line represents the intensity distribution at the entrance of the plasma. The average intensity $\langle I \rangle$ can be calculated from the slope of that curve according to Eq.2. It is about $4 \times 10^{13}\mathrm{W/cm}^2$. The gray line represents the intensity distribution after 400μm inside the plasma which corresponds to the focal plane of the beam. The intensity is therefore somewhat higher. The dot-dashed and dashed curves correspond respectively to intensity distribution at $z = 1.4\,\mathrm{mm}$ and $z = 2\,\mathrm{mm}$. The intensity distribution follows an exponential law.

To illustrate the coherence loss along the propagation direction, we show in figure 3 the fraction of energy that is not yet smoothed in function of z. The plasma fluctuations are driven by the ponderomotive force and also by taking into account the effects of laser heating and the non-local thermal transport. The dashed and dot-dashed lines are the exponential fits. The characteristic length for the ponderomotive case is of the order of 1 mm which is in agreement with Eq.1. The non-local effects enhance the plasma fluctuations and the characteristic length decreases.

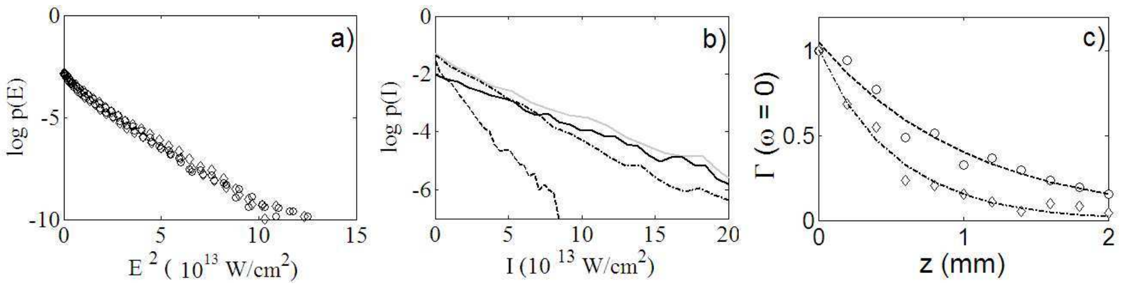

Figure 2: a) Probability distributions of the real (◇) and imaginary (○) part of the electric field. b) Probability distribution of the intensity in several transverse planes. c) Fraction of the energy in the static peak of the time correlation function : (○) ponderomotive case, (◇) non local and thermal transport effects.

In conclusion, the laser beam multiple scattering on plasma density fluctuations provides a robust mechanism for the spatio-temporal coherence loss of the transmitted light. In the context of ICF, using such a smoothing is especially promising in that it requires only a static optical smoothing of the incident laser light. For the direct drive scheme, micrometric defaults in the laser intensity distribution create imprint which is deletorious for a homogeneous implosion of the target. The multiple scattering of the laser beams in a low-density shell around the target could be an efficient solution for this problem.

References

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