Laser beam smoothing in plasma at powers below the filamentation threshold

M. Grech$^{1,2}$, V.T. Tikhonchuk$^1$, G. Riazuelo$^2$, S. Weber$^1$

$^1$Centre Lasers Intenses et Applications, Université Bordeaux 1, Talence, France
$^2$Commissariat à l’Énergie Atomique - DIF/DPTA, Bruyères-le-Châtel, France

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 filamentation instability occurs in hot-spots and it is responsible 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 developed [3]. The laser propagation is described in terms of the electric field correlation function:

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

where the angular brackets denote the statistical average. The correlation function $\Gamma_{EE^*}$ is normalized so that the laser intensity is given by $I = \Gamma_{EE^*}(\vec{R},0,T,0)$. 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 $\rho_0$ (typically a few microns). For interaction time $t \leq L_0/c_s$, where $c_s$ is the ion acoustic velocity, and for the propagation length shorter than the Rayleigh length of the beam envelop $z_R \sim k_0L_0\rho_0$ macroscopic effects are neglectable. The correlation function at the entrance of the plasma can be represented as $\Gamma_{EE^*}(\vec{R},\vec{\rho},T,\tau) = C(\vec{\rho})f(T,\tau)$, 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:

$$C(\vec{\rho},z=0) = \mathcal{F}_{\vec{\rho} \rightarrow \vec{\rho}_0} I(\vec{r}).$$

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 $\rho_0/c_s$ (typically a few picoseconds). 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 $\delta_n$ is the density fluctuations level. For ponderomotively driven fluctuations this characteristic length can be written as 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 $z_R$:

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

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 $\lambda_0 = 1.053 \mu$m 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 transverse 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, \( \Lambda_c \) 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 \( \Lambda_c \) 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 \( \Gamma_{EE^*} \). 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:

\[
p(I) = \frac{1}{\langle I \rangle} \exp\left(-\frac{I}{\langle I \rangle}\right),
\]

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 \( 4 \times 10^{13} \text{W/cm}^2 \). The gray line represents the intensity distribution after 400\( \mu \text{m} \) 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 \( z = 1.4 \) mm and \( z = 2 \) 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.](image)

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 deleterious 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**