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A new figure of merit for the control of laser beam propagation in inertial confinement fusion plasmas

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Controlling the propagation of randomized laser beams through large scale plasmas is a problem of ongoing concern in inertial confinement fusion (ICF). Optical smoothing techniques are used to limit the effect of self-focusing, to reduce reflectivities of backscattering instabilities and to improve laser irradiation uniformity onto the target. The resulting intensity distribution is made of many spikes, the so-called speckles, randomly distributed in space and time. The statistical properties of such laser beams are known in vacuum [1], but can be modified by the interaction with plasma. This phenomenon, referred to as plasma induced smoothing, arises from forward scattering of the laser light on the laser induced density perturbations in the plasma [2, 3, 4].

Several processes of forward scattering on such perturbations: self-focusing (SF), filament instability (FI), forward stimulated Brillouin scattering (FSBS) and multiple scattering (MS) have been considered. It is commonly assumed that the beam spray mainly follows from the SF in speckles carrying a power above the critical power $P_c \propto T_e/(n_o/n_c)$, where T_e is the electron temperature and n_o/n_c is the ratio of the electron density to the critical density. However, recent studies provide a growing evidence of the effect of FSBS in beam spraying and a comprehension of this phenomenon is of a great importance for design of future ICF experiments.

In this work it is demonstrated that the coherent excitation of FSBS outside the incident laser cone, and hence a strong beam spray, is to be expected speckle powers $P > (\nu_s/\omega)P_c$ and it cannot be prevented by the incident beam incoherence [5]. Here, ν_s/ω is the normalized ion-acoustic damping rate. For ICF-conditions $\nu_s/\omega \ll 1$ and it is therefore expected that beam spray will take place well below the SF threshold. The complementary case of FSBS driven by a spectrally broadened pump was studied in the limit of very short coherence times in Ref. [6].

A correct understanding of FSBS driven by a monochromatic, spatially incoherent pump wave requires a statistical model with the laser beam taken in the paraxial approximation. The pump $a_{\mathbf{k}}^{(p)}$ and scattered $a_{\mathbf{k}}^{(s)}$ electromagnetic waves are coupled to the ion acoustic wave $a_{\mathbf{k}}^{(s)}$

with frequency $\Omega_{\mathbf{k}}^{(s)}$:

$$\left(c\,\partial_z + i\,\Omega_{\mathbf{k}}^{(d)}\right) a_{\mathbf{k}}^{(d)} = \gamma_0 \int d\mathbf{k}_p\, a_{\mathbf{k}_p}^{(p)} a_{\mathbf{k}_p-\mathbf{k}}^{(s)*}, \tag{1}$$

$$\left(\partial_t + \nu_s + i\,\Omega_{\mathbf{k}}^{(s)}\right) a_{\mathbf{k}}^{(s)} = \gamma_0 \int d\mathbf{k}_p\, a_{\mathbf{k}_p}^{(p)} a_{\mathbf{k}_p-\mathbf{k}}^{(d)*}. \tag{2}$$

The FSBS coupling constant is $\gamma_0^2 = \Omega_{\mathbf{k}_s}^{(s)}\,\omega_0\,(n_0/n_c)\,\langle I\rangle/(8c\,n_c\,T_e)$, with $\langle I\rangle$ the average incident laser intensity. Statistical properties of the spatially incoherent, monochromatic, pump can be prescribed. For the usual spatial smoothing techniques, they follow Gaussian statistics with a zero mean value:

$$\langle a_{\mathbf{k}_p}^{(p)}\rangle = \langle a_{\mathbf{k}_p}^{(p)}\, a_{\mathbf{k}'_p}^{(p)}\rangle = 0\,,\; \langle a_{\mathbf{k}_p}^{(p)}\, a_{\mathbf{k}'_p}^{(p)*}\rangle = n_{\mathbf{k}_p}^{(p)}\,\delta(\mathbf{k}_p - \mathbf{k}'_p), \tag{3}$$

where $n_{\mathbf{k}_p}^{(p)} = (\rho_0^2/2\pi)\,\exp\left(-\rho_0^2\,\mathbf{k}_p^2/2\right)$ is the Gaussian pump spatial spectrum normalized to one. Due to the pump incoherence, the scattered and acoustic fields are stochastic quantities and their statistical properties have to be considered. An iterative approach allows to calculate average values for successive momenta of $a_{\mathbf{k}}^{(d,s)}$. From Eqs. (1) and (3) it follows:

$$c\,q\,\langle \hat{a}_{\mathbf{k}_d}^{(d)}\rangle = \left[\frac{\gamma_0^2}{\gamma + \nu_s + \Delta\omega_s} + \mathscr{O}(\gamma_0^4)\right] \langle \hat{a}_{\mathbf{k}_d}^{(d)}\rangle, \tag{4}$$

$$\left(\gamma + \nu_s\right)\,\langle \hat{a}_{\mathbf{k}_s}^{(s)}\rangle = \left[\frac{\gamma_0^2}{c\,q + \Delta\omega_d} + \mathscr{O}(\gamma_0^4)\right] \langle \hat{a}_{\mathbf{k}_s}^{(s)}\rangle, \tag{5}$$

where $\langle a_{\mathbf{k}}^{(d,s)}\rangle = (2\pi)^{-2}\int dq\,d\gamma\,\langle \hat{a}_{\mathbf{k}}^{(d,s)}\rangle\,\mathrm{e}^{qz+\gamma t}$.

Under suitable assumptions the iterative procedure converges and the following results can be extracted. Concerning the scattered wave: for long times, $t > t_{sat}^{(d)} \equiv (\gamma_0/\Delta\omega_s)^2\,z/c$, one finds a spatial amplification, $\langle a_{\mathbf{k}_d}^{(d)}\rangle \simeq \exp q_{incoh}^{(d)}\,z$, with the spatial growth rate $q_{incoh}^{(d)} \equiv \gamma_0^2/(c\,\Delta\omega_s)$. This result suggests that the spatial growth rate of the average amplitude $\langle a_{\mathbf{k}_d}^{(d)}\rangle$ is limited by the pump incoherence. For shorter times $t < t_{sat}^{(d)}$, the scattered wave behaves asymptotically in time and z as: $\langle a_{\mathbf{k}_d}^{(d)}\rangle \simeq \exp\left(2\,\gamma_0\,\sqrt{t\,z/c} - \Delta\omega_s\,t\right)$. In this transient regime, the spatial growth rate is smaller than $q_{incoh}^{(d)}$ and thus stays negligible compared to $\Delta\omega_d$. In both, convective and transient regimes, the growth of average amplitude of the scattered wave, $\langle a_{\mathbf{k}_d}^{(d)}\rangle$, is strongly reduced by the pump incoherence. This is the regime of incoherent amplification of FSBS.

Similarly, one obtains the evolution of the ion acoustic wave average amplitude $\langle a_{\mathbf{k}_s}^{(s)}\rangle$. For times $t > t_{sat}^{(s)} \equiv (\gamma_0^2/\nu_s)^2\,z/c$, the ion acoustic wave grows spatially: $\langle a_{\mathbf{k}_s}^{(s)}\rangle \simeq \exp(q_{coh}^{(s)} - \Delta\omega_d/c)\,z$, where $q_{coh}^{(s)} = \gamma_0^2/(c\,\nu_s)$ is the spatial growth rate of FSBS driven by a coherent pump. For shorter times $t < t_{sat}^{(s)}$, the ion acoustic wave is in a transient regime $\langle a_{\mathbf{k}_s}^{(s)}\rangle \simeq \exp\left(2\,\gamma_0\,\sqrt{t\,z/c} - \Delta\omega_d\,z - \nu_s\,t\right)$. In this regime, Eq. (5) is valid only for times $t > t_{val}^{(s)} \equiv (\gamma_0^2/\Delta\omega_s)^2\,z/c$. This time $t_{val}^{(s)} \ll t_{sat}^{(s)}$ does not exceed a few picoseconds for a millimetric plasma.

The condition for spatial growth of $\langle a^{(s)}_{\mathbf{k}_s}\rangle$ reads: $c q^{(s)}_{coh} > \Delta\omega_d$. It defines a threshold for the average power in a speckle: $\langle P\rangle/P_c > \sqrt{2/\pi}\,(\nu_s/\Omega^{(s)}_{\mathbf{k}_s})\,(\theta_d/\theta_p)$. Above this threshold, one observes a coherent spatial amplification $\langle a^{(s)}_{\mathbf{k}_s}\rangle \simeq \exp q^{(s)}_{coh} z$, that is not reduced by the pump incoherence. This result is so far valid only for times $t > t^{(s)}_{sat}$. However, defining the effective spatial growth rate in the transient regime as $q^{(d)}_{eff} \equiv \left(\gamma_0^2 ct/z\right)^{1/2} - \Delta\omega_d$, one obtains that the pump incoherence does not affect the spatial amplification of $\langle a^{(s)}_{\mathbf{k}_s}\rangle$ for times $t \gg (\Delta\omega_d/\gamma_0)^2 z/c$. For a millimetric plasma, this time ranges between a few tenth to a few hundreds picoseconds, much shorter than the characteristic durations of ICF laser pulses. One has thus the following figure of merit (FOM):

$$C \equiv \sqrt{\frac{\pi}{2}}\,\gamma_T\,\frac{\langle P\rangle/P_c}{\nu_s/\Omega^{(s)}_{\mathbf{k}_s}}\,, \tag{6}$$

where $\gamma_T = 1 + 1.66 Z^{5/7}(\rho_0/\lambda_{ei})^{4/7}$ accounts for thermally enhanced density perturbations [7].

This FOM has a straightforward physical meaning. The light scattered outside the cone with aperture $C\theta_p$ is amplified in the incoherent regime. On the contrary, the light scattered inside this cone demonstrates a strong, coherent amplification. Thus, for $C < 1$, coherent excitation of FSBS occurs only for scattering angles $\theta_d < \theta_p$, *i.e.* in the cone of the incident wave. Enhanced FSBS in the incident aperture enhances plasma induced smoothing and in turn reduces the reflectivity of backward instability. Conversely for $C > 1$, coherent excitation of FSBS can occur outside the incident cone. In this regime $C > 1$, beam spray is thus expected. Because the ion acoustic damping rate $\nu_s/\Omega^{(s)}_{\mathbf{k}_s} \ll 1$, the threshold is well below the SF threshold.

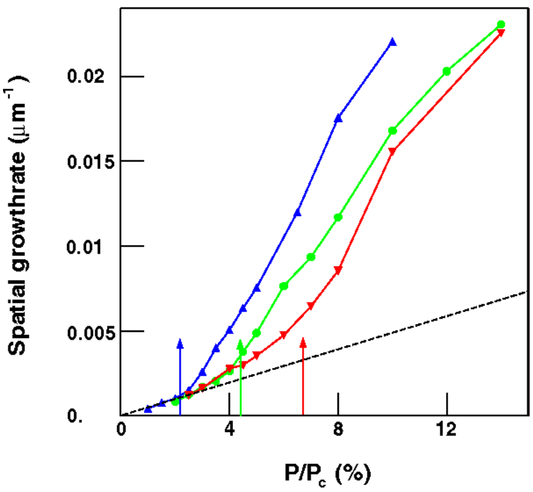

Figure 1: Dependence of the spatial growth rate of the scattered wave intensity after 2 ns on the normalized average power $\langle P\rangle/P_c$. The dashed curve shows the incoherent growth rate.

From the above FOM follows immediately the following criterion for beam spray:

$$0.1\,\gamma_T\,\frac{\Omega^{(s)}_{\mathbf{k}_s}}{\nu_s}\,\lambda_0^2[\mu\mathrm{m}]\,I_{13}\,\frac{n_0}{n_c}\,\frac{3}{T_e\,[\mathrm{keV}]}\left(\frac{f_\sharp}{8}\right)^2 > 1\,. \tag{7}$$

All the above given analytical considerations were confirmed using three-dimensional paraxial simulations. We considered a Helium plasma with an electron density $0.03\,n_c$, and the electron and ion temperatures 500 and 50 eV, respectively. The ion acoustic damping rate,

$\nu_s/\Omega_{\mathbf{k}_s}^{(s)} = 2.75$, 5.5 or 8.25%, is chosen independently. A Gaussian laser beam is focused through a random phase plate providing a speckle pattern with coherence width $\rho_0 \simeq 4.3\,\mu$m. The average intensity is varied in the range $(1.1-16)\times 10^{13}\,\mathrm{W/cm^2}$, corresponding to variation of the average power in a speckle $\langle P\rangle = \pi\rho_0^2\,\langle I\rangle$ from 1 to 14% of P_c.

The spatial growth rate of light scattered at the frequency $\omega_0 - 2c_s/\rho_0$ is plotted as a function of $\langle P\rangle/P_c$ in Fig. 1. In the low power regime, the spatial growth rate is less than $0.5\times 10^{-2}\,\mu\mathrm{m}^{-1}$. It evolves almost linearly with $\langle P\rangle/P_c$ and agrees rather well with predictions in the incoherent regime (dashed line). These numerical results confirm that, below the threshold power (6), the growth of FSBS is limited by the pump incoherence. On the contrary, when the power in a speckle is above the threshold power (see vertical arrows), much higher growth rates are observed. These results are consistent with expectations for the coherent regime.

In conclusion it has been shown that the instability growth rate for FSBS is not limited by pump incoherence. This instability leads to a strong deterioration of the beam propagation which is not stabilized by the laser beam spatial smoothing. As future ICF experiments will be operating in exactly this regime a detailed understanding of the propagation of randomized beams through plasmas is of fundamental importance. A new FOM has been obtained to characterize parametric instabilities in this regime.

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