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# Suppression of stimulated Brillouin scattering in laser beam hot spots

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**Abstract**

In this article, filamentation of a high power laser beam in hot collisionless plasma is investigated considering the ponderomotive nonlinearity. We have studied the effect of self focusing (filamentation) of the laser beam on the localization of ion acoustic wave (IAW) and on stimulated Brillouin scattering (SBS) process. The nonlinear coupling between the laser beam and IAW results in the modification of the Eigen frequency of IAW; consequently, enhanced Landau damping of IAW and a modified mismatch factor in SBS process occur. Due to enhanced Landau damping, there is a reduction in the intensity of IAW wave, and the SBS process gets suppressed. For the typical laser plasma parameters: the laser power flux $= 10^{16}$ W/cm$^2$, laser beam radius $(r_0) = 12$ μm, $n/n_{cr} = 0.11$, and $(T_e/T_i) = 10$, the SBS reflectivity is found to be suppressed approximately by 10%.

**Keywords:** Filamentation; Ion acoustic waves; Ponderomotive nonlinearity; Stimulated Brillouin scattering

## 1. INTRODUCTION

The nonlinear interaction of high power lasers with high-density plasmas has been a subject of active research for decades due to its relevance to laser driven fusion (Kruer, 2000; Bruckner & Jorna, 1974). The increasing use of high power laser beams in various applications has worldwide interest in laser-plasma interaction (Borghesi *et al.*, 2007; Laska *et al.*, 2008; Dromey *et al.*, 2009) in the nonlinear regime. In collisionless plasmas, the nonlinearity arises through the ponderomotive force-induced redistribution of plasma. It is well known that various laser-plasma instabilities like, filamentation (Kaw *et al.*, 1973; Young *et al.*, 1988; Deutsch *et al.*, 2008), harmonic generation (Ozoki *et al.*, 2007; Baeva *et al.*, 2007; Dombi *et al.*, 2009), stimulated Raman scattering (SRS) (Kline *et al.*, 2009; Bers *et al.*, 2009), and stimulated Brillouin scattering (SBS) (Huller *et al.*, 2008; Hasi *et al.*, 2008; Kappe *et al.*, 2007; Wang *et al.*, 2009) might be generated from the interaction of laser pulses with plasmas. These instabilities affect the laser-plasma coupling efficiency and SRS can even produce energetic electrons (Estrabrook *et al.*, 1980), which can preheat the fusion fuel and change the compression ratio. Most of the theories of stimulated scattering and harmonic generation are based on the assumption of a uniform laser pump. This is contrary to almost all the experimental situations, where laser beams of finite transverse size, having non-uniform intensity distribution along their wavefront, are used. Such beams may modify the background plasma density and suffer filamentation (self-focusing). The non-uniformity in the intensity distribution of the laser also affects the scattering of a high power laser beam.

SBS is a parametric instability (Drake *et al.*, 1974; Hüller, 1991) in plasma in which an electromagnetic wave ($\omega_0$, $k_0$) interacts with an ion acoustic wave ($\omega$, $k$) to produce a scattered electromagnetic wave ($\omega_s$, $k_s$). SBS has been a concern in inertial confinement fusion (ICF) application because it occurs up to the critical density layer of the plasma and affects the laser plasma coupling efficiency. SBS produces a significant level of backscattered light; therefore, it is important to devise techniques to suppress SBS. In plasmas of heavy ions, this could be accomplished by introducing a small fraction of light ion species that could incur heavy Landau damping in the IAW and suppresses the SBS (Baldis *et al.*, 1998; Fernandez *et al.*, 1996).

Little agreement between theory (Baldis *et al.*, 1993; Baton *et al.*, 1994) and experiments (Chirokikh *et al.*, 1998) has been reported so far, in spite of intensive studies of SBS during the last two decades in both fields. Most of the earlier studies (on the discrepancy between theoretical expectations and experimental results) are focused with the

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saturation effects of SBS-driven IAW, such as kinetic effects, harmonic generation, and decay into sub-harmonic IAW components. But it has been shown recently (Myatt *et al.*, 2001; Fuchs *et al.*, 2001) that due to self-focusing, the laser pump beam looses coherence when propagating into the plasma. This incoherence could act as another potential saturation mechanism for the SBS instability. For such cases, when induced incoherence reduces SBS, the nonlinear saturation effects studied in the past may be of minor importance, because plasma waves stay at relatively low amplitudes. Recently, Huller *et al.* (2008) did the numerical simulation in two dimensions to support this idea. The spatial incoherence in the pump laser beam due to filamentation instability (self-focusing) and non-monotonous flow, cause an inhomogeneity and the SBS decreases. In their simulation, IAW amplitudes were kept small (around 1%) so that the traditionally assumed nonlinear saturation mechanisms of SBS through nonlinear IAW can be neglected.

Giulietti *et al.* (1999) have measured the stimulated Brillouin back scattering from the interaction of a laser pulse with preformed, inhomogeneous plasma in conditions favorable to self-focusing. Spectral and temporal features of the reflectivity suggest a strong effect of self-focusing on back-SBS. Baton *et al.* (1998) have experimentally shown the dependence of the SBS reflectivity on both the focusing aperture and the incident laser intensity for millimeter size, homogeneous, stationary plasmas. Baldis *et al.* (1998) have given the experimental evidence of the transverse localization of SBS emission to the laser beam axis, demonstrating that only a few small regions of plasma contribute to the emission. As a consequence, SBS reflectivity of these regions is much higher than the average SBS reflectivity, by a factor of 50–100. Eliseev *et al.* (1996) have shown that the SBS reflectivity from a single laser hot spot is much lower than that predicted by a simple three wave coupling model because of the diffraction of the scattered light from the spatially localized IAW.

In this article, we have studied the effect of self-focusing and localization of IAW on SBS process (as a specific case, backscattering, for which $k = 2k_0$), using paraxial ray approximation. The nonlinear coupling between the filamented laser beam and ion acoustic wave results in the modification of the Eigen frequency of IAW; consequently, enhanced Landau damping of IAW and a modified mismatch factor in the SBS process occur. Due to enhanced Landau damping, there is a reduction in intensity of IAW, and the SBS process gets suppressed.

In our present work also, the level of IAW amplitude (after nonlinear coupling between IAW and laser beam) is around 1%. Our work goes one step ahead from the Huller *et al.* (2008) simulation, and highlights the underlying possible physical process of this SBS saturation. This physical process involves the localization of IAW due to nonlinear coupling between pump laser beam (filamented/self-focused) and IAW due to ponderomotive nonlinearity (Sodha *et al.*, 2009). As a consequence, the Landau damping of IAW increases and hence the SBS reflectivity is suppressed. Therefore, the present work takes into account the mechanism proposed by Huller *et al.* (2008) in their simulation and IAW localization also for the saturation of SBS.

The article is organized as follows: In Section 2, we give the brief summary of the basic equations of the propagation of laser beam. The modified equations for the excitation of IAW are studied in the Section 3. The effect of localization of the IAW is also presented in the same section. In Section 4, we derive the basic equations that govern the dynamics of SBS process and SBS reflectivity. The important results and conclusions based on the present investigation are presented in the last section.

## 2. EQUATION OF LASER BEAM PROPAGATION

A high power Gaussian laser (pump) beam of frequency $\omega_0$ and the wave vector $k_0$ is considered to be propagating in hot collisionless and homogeneous plasma along the $z$ axis. When a laser beam propagates through the plasma, the transverse intensity gradient generates a ponderomotive force, which modifies the plasma density profile in the transverse direction as (Sodha *et al.*, 1976)

$$N_{0e} = N_{00} \exp\left(-\frac{3}{4}\alpha \frac{m}{M} E \cdot E^*\right), \tag{1}$$

where

$$\alpha = \frac{e^2 M}{6 k_\beta T_0 \gamma m^2 \omega_0^2}.$$

$e$ and $m$ are the electronic charge and mass, $M$ and $T_0$ are, respectively, mass of ion and equilibrium temperature of the plasma. $N_{0e}$ is the electron concentration in the presence of the laser beam, $N_{00}$ is the electron density in the absence of the beam, $k_\beta$ is the Boltzman's constant and $\gamma$ is the ratio of the specific heats.

The wave equation for the pump laser beam has been solved using Wentzel-Kramers-Brillouin approximation and paraxial-ray approximation, and the electric field of the pump laser beam can be written as (Sodha *et al.*, 1976; Akhamanov *et al.*, 1968)

$$E = E_{00} \exp\{i[\omega_0 t - k_0(S_0 + z)]\}, \tag{2}$$

where wave number and Eikonal of the beam is given as

$$k_0^2 = \frac{\omega_0^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega_0^2}\right) = \frac{\omega_0^2}{c^2}\varepsilon_0, \tag{3a}$$

$$S_0 = \frac{r^2}{2}\frac{1}{f_0}\frac{df_0}{dz} + \phi_0(z). \tag{3b}$$

The intensity distribution of the laser beam for z > 0 may be written as (Akhamanov *et al.*, 1968)

$$E \cdot E^* = \frac{E_{00}^2}{f_0^2}\exp\left(-\frac{r^2}{r_0^2}\right), \tag{4}$$

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where $E_{00}$ is the axial amplitude, $r_0$ is the initial beam width, $r$ refers to the cylindrical coordinate system and $\varepsilon_0 = (1-\omega_p^2/\omega_0^2)$ is the linear part of the plasma dielectric constant. $\omega_p$ is the electron plasma frequency, and $f_0$ is the dimensionless beam width parameter, satisfying the boundary conditions: $f_0|_{z=0} = 1$ and $df_0/dz|_{z=0} = 0$, governed by the equation (Sodha *et al.*, 1976)

$$\frac{\partial^2 f_0}{d\xi^2} = \frac{1}{f_0^3} - \left(\frac{3}{4}\alpha\frac{m}{M}E_{00}^2\right)\frac{\omega_p^2 R_{d0}^2}{\varepsilon_0\omega_0^2 f_0^3 r_0^2}\exp\left\{-\frac{3}{4}\alpha\frac{m}{M}\frac{E_{00}^2}{f_0^2}\right\}, \tag{5}$$

where $R_{d0} = k_0 r_0^2$ is the diffraction length and $\xi = z/R_{d0}$ is the dimensionless parameter. The density of the plasma varies through the channel due to the ponderomotive force. Therefore, the refractive index increases and the laser beam get focused in the plasma. Eq. (4) gives the intensity profile of the laser beam in the plasma, which is shown in Figure 1, using the following parameters in numerical calculation: the incident laser intensity equals $\alpha\, E_{00}^2 = 1.22$ (laser power flux $= 10^{16}\ \mathrm{W/cm^2}$), $r_0 = 12\ \mu\mathrm{m}$, $n/n_{\mathrm{cr}} = 0.1$, and $(T_e/T_i) = 10$.

## 3. LOCALIZATION OF ION ACOUSTIC WAVE

Nonlinear interaction of an ion acoustic wave with the laser beam filaments leads to its excitation. To analyze this excitation process of IAW in the presence of ponderomotive nonlinearity and filamented laser beam, we use the fluid model as

$$\frac{\partial n_{is}}{\partial t} + N_0(\nabla\cdot V_{is}) = 0, \tag{6}$$

$$\frac{\partial V_{is}}{\partial t} + \frac{\gamma_i v_{thi}^2}{N_0}\nabla n_{is} + 2\Gamma_i V_{is} - \frac{e}{M}E_{si} = 0. \tag{7}$$

The electric field $E_{si}$ is associated with the IAW and satisfies the Poisson's equation,

$$\nabla\cdot E_{si} = -4\pi e(n_{es} - n_{is}), \tag{8}$$

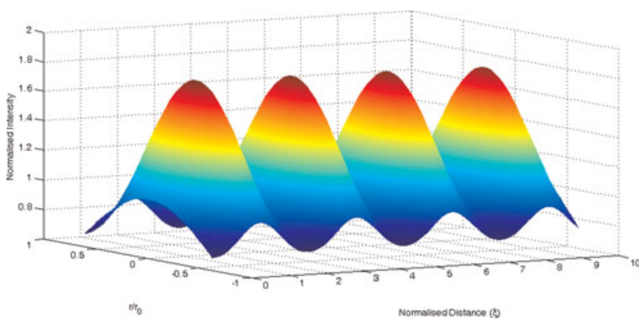


**Fig. 1.** (Color online) Variation in laser beam intensity with normalized distance ($\xi = z/R_{d0}$) and radial distance (r) for laser power $\alpha\ E_{00}^2 = 1.22$ and $r_0 = 11.5\ \mu\mathrm{m}$.

Where $n_{es}$ is given by

$$n_{es} = n_{is}\left[1 + \frac{k^2\lambda_d^2}{(N_{0e}/N_{00})}\right]^{-1}. \tag{9}$$

The Landau damping coefficient for IAW is given by (Krall & Trivelpiece, 1973)

$$2\Gamma_i = \frac{k}{(1+k^2\lambda_d^2)}\left(\frac{\pi k_\beta T_e}{8M}\right)^{1/2} \times\left[\left(\frac{m}{M}\right)^{1/2} + \left(\frac{T_e}{T_i}\right)^{3/2}\exp\left(-\frac{T_e/T_i}{(1+k^2\lambda_d^2)}\right)\right], \tag{10}$$

where $T_e$ and $T_i$ are electron and ion temperatures, $V_{is}$ is the ion fluid velocity, $\lambda_d = (k_\beta T_0/4\pi\ N_{00}e^2)^{1/2}$ is the Debye length, and $v_{thi} = (k_\beta T_i/M)^{1/2}$ is the thermal velocity of ions. Combining Eqs. (6), (7), and (9) and assuming that the plasma is cold i.e., $v_{thi}^2 \ll c_s^2$, one obtains the general equation governing the ion density variation

$$\frac{\partial^2 n_{is}}{\partial t^2} + 2\Gamma_i\frac{\partial n_{is}}{\partial t} - c_s^2\nabla^2 n_{is} + k^2 c_s^2 \times\left(-1 + \frac{1}{1 + k^2\lambda_d^2\left(\frac{N_{0e}}{N_{00}}\right)^{-1}}\right)n_{is} = 0, \tag{11}$$

where $c_s = (k_\beta T_e/M)^{1/2}$ is the speed of the IAW for $T_e \gg T_i$. The solution of the above equation can be written as

$$n_{is} = n(r,z)\exp\{i[\omega t - k(z + s(r,z))]\}, \tag{12}$$

here s is the Eikonal for IAW. The frequency and wave number of the IAW satisfy the following dispersion relation in the presence of laser beam

$$\omega^2 = \frac{k^2 c_s^2}{1 + k^2\lambda_d^2(N_{0e}/N_{00})^{-1}}. \tag{13}$$

Substituting Eq. (12) into Eq. (11) and separating the real and imaginary parts, one obtains, the real part as

$$2\left(\frac{\partial s}{\partial z}\right) + \left(\frac{\partial s}{\partial r}\right)^2 = \frac{1}{nk^2}\left[\frac{\partial^2 n}{\partial r^2} + \frac{1}{r}\frac{\partial n}{\partial r}\right] + \frac{\omega^2}{k^2 c_s^2} + \left[1 - \frac{1}{1 + k^2\lambda_d^2(N_{0e}/N_{00})^{-1}}\right] \tag{14a}$$

and imaginary part as

$$\frac{\partial n^2}{\partial z} + \left(\frac{1}{r}\frac{\partial s}{\partial r} + \frac{\partial^2 s}{\partial r^2}\right)n^2 + \frac{\partial n^2}{\partial r}\frac{\partial s}{\partial r} + \frac{2\Gamma_i}{c_s^2}\frac{\omega n^2}{k} = 0. \tag{14b}$$

To solve the coupled Eqs. (14a) and (14b), we assume the initial radial variation of IAW density perturbation to be

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Gaussian, and the solution at finite $z$ may be written as

$$n^2 = \frac{n_0^2}{f^2}\exp\left(-\frac{r^2}{a^2 f^2} - 2k_i z\right) \tag{15a}$$

and

$$s = \frac{r^2}{2}\frac{1}{f}\frac{\mathrm{df}}{\mathrm{dz}} + \phi(z), \tag{15b}$$

where $k_i = \Gamma_i \omega / k c_s^2$, is the damping factor, $f$ is a dimensionless beam width parameter and $a$ is the initial beam width of the acoustic wave. We have used the following boundary conditions: $df/dz = 0$, $f = 1$ at $z = 0$. Using Eq. (15) in Eq. (14a) and equating the coefficients of $r^2$ on both sides, we obtain the following equation governing $f$

$$\frac{\partial^2 f}{\partial \xi^2} = \frac{R_{d0}^2}{R_d^2 f^3} - \left(\frac{3}{4}\alpha\frac{m}{M}\frac{E_{00}^2}{r_0^2}\frac{f}{f_0^4}\right)\frac{R_{d0}^2 k^2 \lambda_d^2}{(1 + k^2\lambda_d^2)^2} \times \exp\left(\frac{3}{4}\alpha\frac{m}{M}\frac{E_{00}^2}{f_0^2}\right), \tag{16}$$

where $R_d = ka^2$ is the diffraction length of the IAW. Eq. (16) represents the density profile of IAW in the plasma when the coupling between self-focused (filamented) laser beam and IAW is taken into account. It is interesting to compare Eq. (16) with Eq. (5) i.e., self-focusing of laser pump wave. In the absence of the coupling between the laser beam and acoustic wave, the second term in Eq. (16) is zero and the solution of Eq. (16) is given by

$$f = 1 + \frac{z^2}{R_d^2}.$$

Thus propagating a distance $R_d$, the width $a$ is enlarged by $\sqrt{2}$ and the axial amplitude of density perturbation in IAW is decreased by the same factor even in the absence of Landau damping.

We can, however, obtain an analytical solution of Eq. (16) in special case. When the laser beam has the critical power for self-focusing, the diffraction term (the first term on the right-hand-side of Eq. (5)) balances the nonlinear term in Eq. (5). Under such conditions ($f_0 = 1$), the main beam propagates without convergence and divergence and is generally known as the uniform waveguide mode. Therefore, the solution for $f$ is given by

$$f^2 = \frac{A + B}{2B} - \frac{A - B}{2B}\cos\left(2\sqrt{B}z\right),$$

where

$$A = \frac{1}{R_d^2} \text{ and } B = \left(\frac{3}{4}\alpha\frac{m}{M}\frac{E_{00}^2}{r_0^2}\right)\frac{k^2\lambda_d^2}{(1 + k^2\lambda_d^2)^2} \quad \exp\left(\frac{3}{4}\alpha\frac{m}{M}E_{00}^2\right).$$

Therefore, the amplitude of IAW (given by Eq. (15a)), which depends on $f$ will be oscillating with $z$ due to this nonlinear coupling, hence the IAW gets localized.

When the power of laser beam is greater than the critical power for self-focusing, we have solved Eq. (15a) numerically with the help of Eq. (16) to obtain the density perturbation at finite $z$. The result is shown in Figure 2a, for typical laser parameters as we have used in previous section. It is evident from the figure that the IAW gets excited due to nonlinear coupling with the high power laser beam because of the ponderomotive nonlinearity. If we take the zero Landau damping of IAW, we get the structure having the amplitude varying periodically with the $z$ coordinate as shown in Figure 2c.

The localization may be understood as follows: Because of the ponderomotive force exerted by the pump laser beam, the electrons are redistributed from the axial region. According

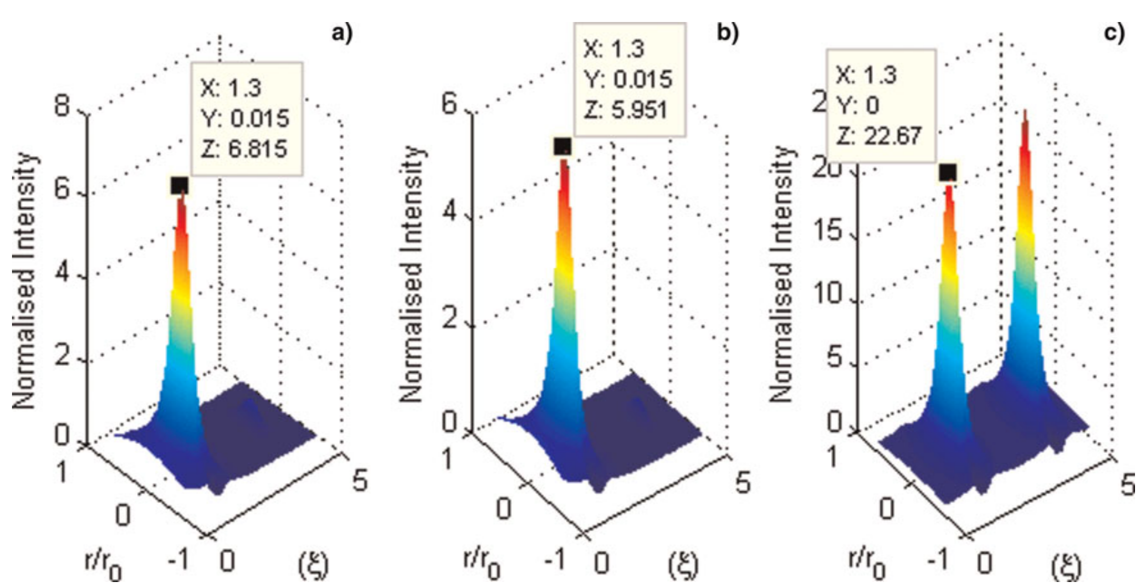


**Fig. 2.** (Color online) Variation in IAW intensity with normalized distance ($\xi = z/R_{d0}$) and radial distance ($r$), for $a = 19$ μm, (a) with Initial Landau damping $(\Gamma_i/\omega) = 0.0142$ (b) with modified Landau damping $(\Gamma_i/\omega) = 0.0155$ (c) with zero Landau damping.

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to the dispersion relation $\omega^2 = k^2c_s^2/(1 + k^2\lambda_d^2(N_{0e}/N_{00})^{-1})$, the phase velocity $\omega/k$ of the acoustic wave has a minimum on the axis and is increasing away from the axis. If we consider the initial wavefront of the electrostatic wave, the secondary wavelets travel with minimum velocity along the axis and with higher velocity away from the axis. As the wavefront advances in the plasma, focusing occurs, and the amplitude of the density perturbation increases. When the size of the wave front reduces considerably, diffraction effects also become important and hence the amplitude of the density perturbation starts to decrease.

We can calculate the periodicity length $L$ of localized structures by putting $r = 0$ in Eq. (15a), as shown in Figure 3. According to Figure 3, value of $L$ comes out to be $2.62R_{d0}$. If we take the fast Fourier transform (FFT) of the structure as shown in Figure 3, we get the spectral lines in one structure at a separation of $k_A = 2\pi/L$, and the value of $k_A$ is coming out to be 2.4 $R_{d0}^{-1}$. We have shown these structures in Figure 4a. These periodic localized structures are similar to the structures in a periodic potential well. This situation can be modeled by representing Eq. (11) in the form of Mathew's equation in a periodic potential well. Therefore, taking the density variation as $e^{i\omega t}$ in Eq. (11), one can write

$$i\left(\frac{\partial}{\partial T} + \Gamma_L\right)n_{is} + \frac{\partial^2 n_{is}}{\partial Z^2} - Nn_s = 0, \tag{17}$$

here,

$$T = \frac{t}{(1/2\omega)}, \quad \Gamma_L = (\Gamma_i/2\omega), Z = \frac{z}{(c_s/2\omega)}, \text{ and} \quad N = \mu \exp(ik_A z) \tag{18}$$

where $\mu$ represents the dimensionless amplitude of the density perturbation in $k$-space. The normalized density of the first spectral component in Figure 4a is 5.801, which is at a distance of $k_A$ from the central component. The value of $\mu^2$ comes out to be $\mu^2 = (N_k^2/N_{00}^2) = 0.0058$, in which we have used the seed value of IAW$(N_0^2/N_{00}^2) = 10^{-3}$. If $n_{is}$ is of the form $n_{is} = \psi \exp(-i\int_0^T d\tau\Lambda)$, then we may write Eq. (17) in the form of Eigen value equation (Rozmus *et al.*, 1987)

$$(\Lambda + i\Gamma_L)\psi + \frac{\partial^2}{\partial Z^2}\psi - N\psi = 0. \tag{19}$$

We assume the solution of Eq. (19) in the form of Bloch wave function as

$$\psi = \sum_n \exp[i(k + nk_A)Z]\psi_n. \tag{20}$$

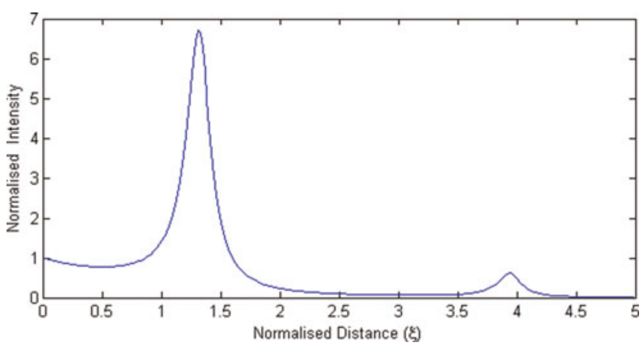


**Fig. 3.** (Color online) Variation in IAW intensity with normalized distance ($\xi$) in real space at $r = 0$ corresponding to Figure 2.

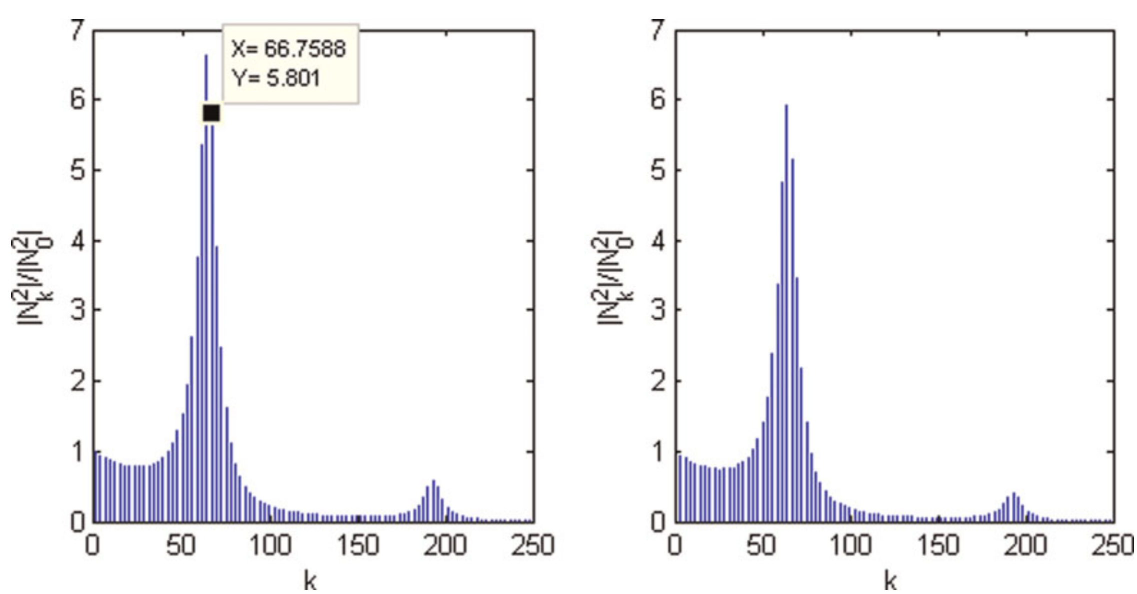


**Fig. 4.** (Color online) Comparison of Power spectrum of IAW, for $\alpha\ E_{00}^2 = 1.6$ (a) with Initial Landau damping $(\Gamma_i/\omega) = 0.0142$ (b) with modified Landau damping $(\Gamma_i/\omega) = 0.0155$.

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Substituting this solution in Eigen value Eq. (19), we obtain the equation

$$(\Lambda + i\Gamma_L^0)\psi_0 - K^2\psi_0 = \mu(\psi_{+1} + \psi_{-1}), \tag{21a}$$

and

$$(\Lambda + i\Gamma_L^n)\psi_n - (K + nK_A)^2\psi_n = \mu(\psi_{n-1} + \psi_{n+1}), \tag{21b}$$

where

$$\Gamma_L^n \equiv \Gamma_L(k + nk_A).$$

keeping only $\psi_0$, $\psi_{\pm1}$ components, we obtain (Rozmus *et al.*, 1987) for $\Lambda = \Lambda_1 + i\Lambda_2$,

$$\Lambda_1 = k^2\left(1 + \sqrt{(1 + 4\mu^2/k^4)}\right)/2 \text{ and } \Lambda_2 = -\bar{\Gamma}_L/(1 + \Delta/\Lambda_1), \tag{22}$$

where the effective damping $\bar{\Gamma}_L$ is

$$\bar{\Gamma}_L = \Gamma_L(k) + \mu^2\frac{\Gamma_L(k + k_A)}{(k + k_A)^4}, \tag{23}$$

and mismatch factor has the form

$$\Delta = \Lambda_1 - k^2 \tag{24}$$

Eqs. (22) and (23) give the expression for modified frequency and enhanced Landau damping of the IAW, respectively. The value of the enhanced Landau damping is 0.0155, whereas the initial damping value was 0.0142. Therefore, we have approximately 10% increment in Landau damping of IAW, and the mismatch factor in Eigen frequency is coming out to be 0.0338. It is obvious that Landau damping governs the intensity of the IAW, and due to localization of IAW, the effective damping of the acoustic wave increases, therefore, as a result, the intensity of IAW reduces accordingly, as shown in Figure 2b. The enhanced Landau damping effect is also observable in the modified spectra of the IAW, as shown in Figure 4b.

## 4. STIMULATED BRILLOUIN SCATTERING

The high frequency electric field $E_T$, satisfies the wave equation

$$\nabla^2 E_T - \nabla(\nabla\cdot E_T) = \frac{1}{c^2}\frac{\partial^2 E_T}{\partial t^2} + \frac{4\pi}{c^2}\frac{\partial J_T}{\partial t}, \tag{25}$$

where $J_T$ is the total current density vector in the presence of the high frequency electric field $E_T$ and it is given by

$$J_T = -e\left(N_0 v_t + \frac{1}{2}n_{es}v_{t'}\right) - e\left(N_0 v_t + \frac{1}{2}n_{es}^* v_t\right). \tag{26}$$

$E_T$ may be written as the sum of the electric field $E$ of the pump laser beam and of the electric field $E_S$ of the scattered wave, i.e.,

$$E_T = E\exp(i\omega_0 t) + E_S\exp(i\omega_S t). \tag{27}$$

Substituting Eqs. (26) and (27) into Eq. (25), and separating the equation for pump and scattered field

$$\nabla^2 E + \frac{\omega_0^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega_0^2}\frac{N_{0e}}{N_{00}}\right)E = -\frac{4\pi e}{c^2}\frac{1}{2}\frac{\partial}{\partial t}(n_{es}v_{t'}), \tag{28a}$$

$$\nabla^2 E_S + \frac{\omega_S^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega_s^2}\frac{N_{0e}}{N_{00}}\right)E_S = -\frac{4\pi e}{c^2}\frac{1}{2}\frac{\partial}{\partial t}(n_{es}^* v_t). \tag{28b}$$

In solving Eq. (28b), the term $\nabla(\nabla\times E_T)$ may be neglected in the comparison to the $\nabla^2 E_S$ term, assuming that the scale length of variation of the dielectric constant in the radial distance is much larger than the wavelength of the pump wave. Substituting $v_t = (ieE/m\omega_0)$ in Eq. (28b), one obtains

$$\nabla^2 E_S + \frac{\omega_S^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega_S^2}\frac{N_{0e}}{N_{00}}\right)E_S = \frac{1}{2}\frac{\omega_p^2}{c^2}\frac{\omega_S}{\omega_0}\frac{n_{es}^*}{N_{00}}E, \tag{29}$$

let the solution of Eq. (29) be

$$E_S = E_{S0}(r,z)e^{+ik_{S0}z} + E_{S1}(r,z)e^{-ik_{S1}z}, \tag{30}$$

where $k_{S0}^2 = (\omega_S^2/c^2)(1 - (\omega_p^2/\omega_S^2)) = (\omega_S^2/c^2)\varepsilon_{S0}$ and $k_{s1}$ and $\omega_s$ satisfy the matching conditions

$$\omega_S = \omega_0 - \omega, \quad k_{S1} = k_0 - k.$$

Using Eq. (30) in Eq. (29), one gets

$$-k_{S0}^2 E_{S0} + 2ik_{S0}\frac{\partial E_{S0}}{\partial z} + \left(\frac{\partial}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)E_{S0} + \frac{\omega_S^2}{c^2}\left[\varepsilon_{S0} + \frac{\omega_p^2}{\omega_S^2}\left(1 - \frac{N_{0e}}{N_{00}}\right)\right]E_{S0} = 0, \tag{31}$$

$$-k_{S1}^2 E_{S1} + (-2ik_{S1})\frac{\partial E_{S1}}{\partial z} + \left(\frac{\partial}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)E_{S1} + \frac{\omega_S^2}{c^2}\left[\varepsilon_{S0} + \frac{\omega_p^2}{\omega_S^2}\left(1 - \frac{N_{0e}}{N_{00}}\right)\right]E_{S1} = \frac{1}{2}\frac{\omega_p^2}{c^2}\frac{\omega_S}{\omega_0}\frac{n_{es}^*}{N_{00}}E_0\exp(-ik_0 s_0), \tag{32}$$

to a good approximation, the solution of Eq. (32) may be written as

$$E_{S1} = E'_{S1}(r,z)e^{-ik_0 S_0}, \tag{33}$$

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substituting this into Eq. (32), one obtains

$$E'_{S1} = -\frac{1}{2}\frac{\omega_p^2}{c^2}\frac{n^*}{N_0}\frac{\omega_S}{\omega_0}\frac{E_0}{\left[k_{S1}^2 - k_{S0}^2 - \frac{\omega_p^2}{c^2}\left(1 - \frac{N_{0e}}{N_0}\right)\right]}. \tag{34}$$

Simplifying Eq. (31) and substituting $E_{S0} = E_{S00}e^{ik_{S0}S_c}$, one obtains after separating the real and imaginary parts

$$2\left(\frac{\partial S_c}{\partial z}\right) + \left(\frac{\partial S_c}{\partial r}\right)^2 = \frac{1}{k_{S0}^2 E_{S00}}\left(\frac{\partial}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)E_{S00} + \frac{\omega_p^2}{\omega_S^2 \varepsilon_{S0}}\left(1 - \frac{N_{0e}}{N_{00}}\right), \tag{35a}$$

$$\frac{\partial E_{S00}^2}{\partial z} + E_{S00}^2\left(\frac{\partial^2 S_c}{\partial r^2} + \frac{1}{r}\frac{\partial S_c}{\partial r}\right) + \frac{\partial S_c}{\partial r}\frac{\partial E_{S00}^2}{\partial r} = 0. \tag{35b}$$

The solution of these equations may again be written as

$$E_{S00}^2 = \frac{B'^2}{f_S^2}\exp\left(-\frac{r^2}{b^2 f_S^2}\right), \tag{36a}$$

$$S_c = \frac{r^2}{2}\frac{1}{f_S}\frac{\partial f_S}{\partial z} + \phi(z), \tag{36b}$$

where $b$ is the initial beam width of the scattered wave. Substituting the above solution in Eq. (35a) and equating the coefficients of $r^2$ on both sides, we get the equation of the spot size of scattered wave as

$$\frac{d^2 f_s}{d\xi^2} = \frac{R_{d0}^2}{R_{ds}^2 f_s^3} - \frac{\omega_p^2}{\omega_s^2 \varepsilon_{S0}}\left(\frac{3}{4}\alpha\frac{m_e}{m_i}E_{00}^2\right)\frac{f_s}{f_0^4}\frac{R_{d0}^2}{r_0^2} \times \exp\left(-\frac{3}{4}\alpha\frac{m_e}{m_i}\frac{E_{00}^2}{f_0^2}\right), \tag{37}$$

where $R_{dS} = k_{S0}b^2$ is the diffraction length of the scattered radiation.

It is easy to see from Eq. (15) that the IAW is damped, as it propagates along the $z$-axis. Consequently, the scattered wave amplitude should also decrease with increasing $z$. Therefore, expressions for $B'$ and b may be obtained on applying suitable boundary conditions $E_S = E_{S0}\exp(ik_{S0}z) + E_{S1}\exp(-ik_{S1}z) = 0$ *at* $z = z_c$; here $z_c$ is the point at which the amplitude of the scattered wave is zero. This immediately yields

$$B' = -\frac{1}{2}\frac{\omega_p^2}{c^2}\frac{\omega_S}{\omega_0}\frac{n_0}{N_{00}}\frac{E_{00}f_S(z_c)}{f(z_c)f_0(z_c)} \times \frac{\exp(-k_i z_c)}{\left[k_{S1}^2 - k_{S0}^2 - \frac{\omega_p^2}{c^2}\left(1 - \frac{N_{0e}}{N_{00}}\right)\right]} \times \frac{\exp[-i(k_{S1}z_c + k_0 S_0)]}{\exp[i(k_{S0}S_c + k_{S0}z_c)]}, \tag{38}$$

with condition

$$\frac{1}{b^2 f_s^2(z_c)} = \frac{1}{r_0^2 f_0^2(z_c)} + \frac{1}{a^2 f^2(z_c)}.$$

The reflectivity is defined as the ratio of scattered flux and incident flux, $R = (|E_S|^2/|E_{00}|^2)$. By using Eqs. (30), (33), (34), (36), and (38), we get $E_S E_S^* = E_{S0}E_{S0}^* + E_{S0}E_{S1}^*\exp[i(k_{S0} + k_{S1})z] + E_{S1}E_{S0}^* \exp[-i(k_{S0} + k_{S1})z] + E_{S1}E_{S1}^*$ and

$$R = \frac{1}{4}\left(\frac{\omega_p^2}{c^2}\right)^2\left(\frac{\omega_s}{\omega_0}\right)^2\left(\frac{n_0}{N_{00}}\right)^2 \times \frac{1}{\left[k_{s1}^2 - k_{s0}^2 - \frac{\omega_p^2}{c^2}\left(1 - \frac{N_{0e}}{N_{00}}\right)\right]^2} \times \left[\begin{array}{l} \frac{f_S^2(z_c)}{f^2(z_c)f_0^2(z_c)}\frac{1}{f_S^2}\exp\left(-2k_i z_c - \frac{r^2}{b^2 f_s^2}\right) \\ + \frac{1}{f^2 f_0^2}\exp\left(-\frac{r^2}{a^2 f^2} - \frac{r^2}{b^2 f_0^2} - 2k_i z\right) \\ + \frac{1}{2}\frac{1}{f f_0 f_s}\frac{f_s(z_c)}{f(z_c)f_0(z_c)} \\ \times \exp\left(-\frac{r^2}{2b^2 f_s^2} - \frac{r^2}{2a^2 f^2} - \frac{r^2}{2b^2 f_0^2}\right) \\ \cdot \exp\{-k_i(z + z_c)\}\cos\{(k_{S0} + k_{S1})(z - z_c)\} \end{array}\right]. \tag{39}$$

It is apparent from the above equation that the reflectivity is dependant on the intensity of IAW and damping factor. To observe the effect of localization of IAW on SBS reflectivity, we have included the expression of modified Eigen frequency, (Eq. (22)) and effective damping, (Eq. (23)) in the above equation. It is clearly evident from Figure 5 that the SBS reflectivity gets reduced in the presence of the new Eigen frequency and damping values by almost the same factor as the intensity of the IAW decreases. In Figure 5, the solid red line (online only) shows the reflectivity with initial damping value and the dashed blue line (online only) shows the reflectivity including the effective enhanced Landau damping. If we calculate the integrated SBS

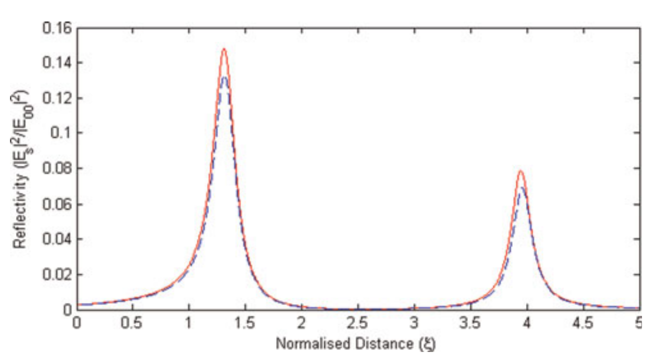


**Fig. 5.** (Color online) Variation in normalized back scattered reflectivity of SBS, $|E_s|^2/|E_{00}|^2$ with normalized distance, (**i**) when $(\Gamma_i/\omega) = 0.0142$ (solid red line) and (**ii**) when $(\Gamma_i/\omega) = 0.0155$ (blue dashed line).

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reflectivity in two cases: namely (1) with initial damping of IAW and (2) with modified enhanced damping of IAW, we find that the reduction in SBS reflectivity comes out to be approximately 10%.

## 5. CONCLUSION

In the present article, we studied the filamentation of the laser beam in paraxial regime considering ponderomotive nonlinearity in hot collisionless plasma. It is evident from the results that the IAW gets excited due to nonlinear coupling with the high power filamented laser beam, and due to Landau damping, it gets damped as it propagates. The coupling is so strong that the IAW becomes highly localized and produces periodic structures. Further we discussed the effect of localization of IAW, this resulted in the modification of the Eigen frequency of IAW; consequently, an enhanced Landau damping of the IAW and a modified mismatch factor in the SBS process occurred. Solving the Eigen value problem we obtained an enhanced Landau damping, which resulted in a reduction in the intensity of the IAW. As a consequence, the back-reflectivity of the SBS process is suppressed by a factor of approximately 10%. These results should find applications in the laser induced fusion scheme where a reduction in SBS will improve the laser plasma coupling efficiency.

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## REFERENCES

Akhmanov, A.S., Sukhorukov, A.P. & Khokhlov, R.V. (1968). Self-focusing and diffraction of light in a nonlinear medium. *Soviet. Phys. Usp.* **10**, 609–636.

Baeva, T., Gordienko, S. & Pukhov, A. (2007). Relativistic plasma control for single attosecond pulse generation: Theory, simulations and structure of the pulse. *Laser Part. Beams* **25**, 339–346.

Baldis, H.A., Labaune, C., Moody, J.D., Jalinaud, T. & Tikhonchuk, V.T. (1998). Localization of stimulated Brillouin scattering in random phase plate speckles. *Phys. Rev. Lett*. **80**, 1900–1903.

Baldis, H.A., Villeneuve, D.M., Fontaine, B.La., Enright, G.D., Labaune, C., Baton, S., Mounaix, Ph., Pesme, D., Casanova, M. & Rozmus, W. (1993). Stimulated Brillouin scattering in picoseconds time scale: Experiments and modeling. *Phys. Fluids B* **5**, 3319–3327.

Baton, S.D., Amiranoff, F., Malka, V., Modena, A., Salvati, M. & Coulaud, C. (1998). Measurement of the stimulated Brillouin scattering from a spatially smoothed laser beam in a homogeneous large scale plasma. *Phys. Rev. E* **57**, R4895–R4898.

Baton, S.D., Rousseaux, C., Mounaix, Ph., Labaune, C., Fontaine, B.La., Pesme, D., Renard, N., Gary, S., Jacquet, M.L. & Baldis, H.A. (1994). Stimulated Brillouin scattering with a 1 ps laser pulse in a performed underdense plasma. *Phys. Rev. E* **49**, 3602–3605.

Bers, A., Shkarofsky, I.P. & Shoucri, M. (2009). Relativistic Landau damping of electron plasma waves in stimulated Raman scattering. *Phys. Plasma* **16**, 022104.

Borghesi, M., KAr, S., Romagnani, L., Toncian, T., Antici, P., Audebert, P., Brambrink, E., Ceccherini, F., Cecchetti, C.A., Futchs, J., Galimberti, M., Gizzi, L.A., Grismayer, T., Lyseikina, T., Jung, R., Macchi, A., Mora, P., Osterholtz, J., Schiavi, A. & Willi, O. (2007). Impulsive electric fields driven by high intensity laser matter interactions. *Laser Part. Beams* **25**, 161–167.

Bruckner, K.A. & Jorna, S. (1974). Laser driven fusion. *Rev. Modern Phys.* **46**, 325–367.

Chirokikh, A., Seka, W., Simon, A., Craxton, R.S. & Tikhonchuk, V.T. (1998). Stimulated Brillouin scattering in long-scale-length laser plasmas. *Phys. Plasmas* **5**, 1104–1109.

Deutsch, C., Bret, A., Firpo, M.C., Gremillet, L., Lefebrave, E. & Lifschitz, A. (2008). Onset of coherent electromagnetic structures in the relativistic electron beam deuterium–tritium fuel interaction of fast ignition concern. *Laser Part. Beams* **26**, 157–165.

Dombi, P., Racz, P. & Bodi, B. (2009). Surface plasmon enhanced electron acceleration with few cycle laser pulses. *Laser Part. Beams* **27**, 291–296.

Drake, J.F., Kaw, P.K., Lee, Y.C., Schmidt, G., Liu, C.S. & Rosenbluth, M.N. (1974). Parametric instabilities of electromagnetic waves in plasmas. *Phys. Fluids* **17**, 778–785.

Dromey, B., Bellei, C., Carroll, D.C., Clarke, R.J., Green, J.S., Kar, S., Kneip, S., Markey, K., Nagel, S.R., Willingale, L., Mckenna, P., Neely, D., Najmudin, Z., Krushelnick, K., Norreys, P.A. & Zepf, M. (2009). Third harmonic order imaging as a focal spot diagnostic for high intensity laser solid interactions. *Laser Part. Beams* **27**, 243–248.

Eliseev, V.V., Rozmus, W., Tikhonchuk, V.T. & Capjack, C.E. (1996). Effect of diffraction on stimulated Brillouin scattering from a single laser hot spot. *Phys. Plasmas* **3**, 3754–3760.

Estrabrook, E., Kruer, W.L. & Lasinski, B.F. (1980). Heating by Raman backscatter and forward scatter. *Phys. Rev. Lett*. **45**, 1399–1403.

Fernandez, J.C., Cobble, J.A., Failor, B.H., Dubois, D.F., Montgomery, D.S., Rose, H.A., Vu, H.X., Wilde, B.H., Wilde, M.D. & Chrien, R.E. (1996). Observed dependence of stimulated Raman scattering on ion-acoustic damping in hohlraum plasmas. *Phys. Rev. Lett*. **77**, 2702–2705.

Fuchs, J., Labuane, C., Depierreux, D., Baldis, H.A., Michard, A. & James, G. (2001). Experimental evidence of plasma-induced incoherence of an intense laser beam propagating in an underdense plasma. *Phys. Rev. Lett*. **86**, 432–435.

Giulietti, A., Macchi, A., Schifano, E., Biancalana, V., Danson, C., Giulietti, D., Gizzi, L.A. & Willi, O. (1999). Stimulated Brillouin scattering from underdense expending plasma in a regime of strong filamentation. *Phys. Rev. E* **59**, 1038–1046.

Hasi, W.L.J., Gong, S., Lu, Z.W., Lin, D.Y., He, W.M. & Fan, R.Q. (2008). Generation of plasma wave and third harmonic generation at ultra relativistic laser power. *Laser Part. Beams* **26**, 511–516.

Hüller, S. (1991). Stimulated Brillouin scattering off non-linear ion acoustic waves. *Physics of Fluids B* **3**, 3317–3330.

Huller, S., Masson-Laborde, P.E., Pesme, D., Labaune, C. & Bandulet, H. (2008). Modeling of stimulated Brillouin scattering in expanding plasma. *Journal of Phys.* **112**, 022031.

Kappe, P., Strasser, A. & Ostermeyer, M. (2007). Investigation of the impact of SBS- parameters and loss modulation on the mode locking of an SBS- laser oscillator. *Laser Part. Beams* **25**, 107–116.

Kaw, P.K., Schmidt, G. & Wilcox, T. (1973). Filamentation and trapping of electromagnetic radiation in plasmas. *Phys. Fluids* **16**, 1522–1525.

Kline, J.L., Montgomery, D.S., Rousseaux, C., Baton, S.D., Tassin, V., Hardin, R.A., Flippo, K.A., Johnson, R.P., Shimada, T., Yin, L., Albright, B.J., Rose, H.A. & Amiranoff, F. (2009). Investigation of stimulated Raman scattering using a short-pulse diffraction limited laser beam near the instability threshold. *Laser Part. Beams* **27**, 185–190.

Krall, N.A. & Trivelpiece, A.W. (1973). *Principle of Plasma Physics*. Tokyo, Japan: McGraw Hill-Kogakusha.

Kruer, W.L. (2000). Interaction of plasmas with intense laser. *Phys. Plasma* **7**, 2270–2278.

Laska, L., Jungwirth, K., Krasa, J., Krousky, E., Pfeifer, M., Rohlena, K., Velyhan, A., Ullschmied, J., GAmmino, S., Torrisi, L., Badziak, J., Parys, P., Rosinski, M., Ryc, L. & Wolowski, J. (2008). Angular distribution of ions emitted from laser plasma produced at various irradiation angles and laser intensities. *Laser Part. Beams* **26**, 555–565.

Myatt, J., Pesme, D., Huller, S., Maximov, A.V., Rozmus, W. & Capjack, C.E. (2001). Nonlinear propagation of a randomized laser beam through an expanding plasma. *Phys. Rev. Lett.* **87**, 255003.

Ozoki, T., Bom Elouga, L.B., Ganeev, R., Kieffer, J.C., Sazuki, M. & Kuroda, H. (2007). Intense harmonic generation from silver ablation. *Laser Part. Beams* **25**, 321–325.

Rozmus, W., Sharma, R.P., Samson, J.C. & Tighe, W. (1987). Nonlinear evolution of stimulated Raman scattering in homogeneous plasmas. *Phys Fluids* **30**, 2181–2193.

Soadha, M.S., Mishra, S.K. & Mishra, S. (2009). Focusing of dark hollow Gaussian electromagnetic beams in a plasma. *Laser Part. Beams* **27**, 57–68.

Sodha, M.S., Ghatak, A.K. & Tripathi, V.K. (1976). Self focusing of laser beams in plasmas and semiconductors. *Prog. Optics E* **3**, 169–265.

Wang, Y.L., Lu, Z.W., He, W.M., Zheng, Z.X. & Zhao, Y.H. (2009). A new measurement of stimulated Brillouin scattering phase conjugation fidelity for high pump energies. *Laser Part. Beams* **27**, 297–302.

Young, P.E., Baldis, H.A., Drake, R.P., Campbell, E.M. & Estrabrook, K.G. (1988). Direct evidence of ponderomotive Filamentation in laser-produced plasma. *Phys. Rev. Lett.* **61**, 2336–2339.