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Mitigation of stimulated Raman backscattering by elliptical laser beam in collisionless plasma

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ABSTRACT

This paper presents theoretical and numerical study of the propagation of an elliptical laser beam in collisionless plasma with relativistic-ponderomotive nonlinearities and its effect on the excitation of electron plasma wave (EPW) and resulting stimulated Raman backscattering (SRBS) process. Nonlinear interaction between an intense elliptical laser beams with the electron plasma wave leads stimulated Raman backscattering. Following Wentzel Kramers Brillouin (WKB) and paraxial-ray approximations, non-linear differential equations for the beam width parameters of elliptical laser beam, electron plasma wave and back-scattered beam are set up and solved numerically. Numerical simulations have been carried out to investigate the effect of laser and plasma parameters on the focusing of elliptical laser beam in plasma and further its effect on the excitation of electron plasma wave and backreflectivity of stimulated Raman scattering (SRS). The focusing of an elliptical laser beam, EPW and scattered wave are reduced at higher values of laser intensity in plasma. The amplitude of excited electron plasma wave, which depends on the focusing of main laser beam and electron plasma wave reduce for higher values of incident laser intensity. The results indicate that the focusing of waves mitigates the backreflectivity of SRS. The results are also compared with only relativistic nonlinearity and the Gaussian profile of laser beam. It is observed that an elliptical laser beam mitigates the backreflectivity of SRS at higher values of laser intensity. This study is relevant to inertial confinement fusion scheme, where SRS plays very important role.

1. Introduction

Due to rapid progress in laser technology, nowadays very short duration laser pulse (femtosecond) with peak powers up to petawatt range are available [1,2]. The interaction of such ultra-intense laser pulse with plasmas has been a subject of experimental and theoretical research interest due to its potential applications in fast ignition in inertial confinement fusion (ICF) scheme [3,4], particle acceleration [5,6] and new radiation sources [7,8]. The yield of these applications depends critically on a long range propagation of laser beams (up to as much possible Rayleigh length) in plasmas. During the propagation of the laser pulse in plasma, the laser pulse encounters various instabilities and nonlinear phenomena such as self-focusing, filamentation, stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), two plasmon decay (TPD), etc., which creates a hindrance in laser plasma coupling [9]. In order to reduce these instabilities in laser plasma interaction at higher laser intensity, it is important to study these effects analytically and numerically.

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Self-focusing of laser beam and stimulated Raman backscattering (SRBS) in plasma are very important nonlinear processes in laser driven inertial confinement fusion scheme. Self-focusing plays a vital role in the propagation of laser pulse in plasma that occurs due to change in the refractive index of the medium on account of intense beam propagating through it [10]. The transverse and longitudinal gradient of nonlinear refractive index of plasma is mainly responsible for self-focusing. Self-focusing enhance the laser intensity over large distances in comparison to the Rayleigh length. The angular divergence of the beam is change due to self-focusing of laser beam in plasma [11]. In SRS, the incident laser beam decays resonantly into a backscattered wave and an electron plasma wave (EPW). This instability degrades the efficiency of laser absorption in the target by reflecting a fraction of the incident energy flux [9]. Furthermore, the plasma waves generated by SRS have phase velocities approaching the speed of light and can accelerate electrons (hot electrons) that can preheat the fusion fuel and degrade implosion performance. In addition, the back reflectivity of SRS process gets affected due to the self-focusing/filamentation of the laser beam in plasma [12]. These two instabilities reduce the coupling efficiency of the high power laser energy with the plasma as well as modify uniformity of energy deposition. The success of ICF depends partly on mitigating the undesirable effects of these instabilities.

Self-focusing and SRBS instability of an intense laser pulse in plasmas has been investigated in various studies in the past [13–22]. Barr et al. [23] studied the effect of filamentation on the temporal growth rate of SRS in underdense plasma. Short et al. [24] have studied the effect of self-focused light filaments on SRS instability in laser-produced plasmas. They observed that self-focusing of hot spots in the incident laser beam can greatly enhance the growth rate of the instability. In the last three decades new techniques has been emerged for mitigating these instabilities in laser plasma interaction. With the development of chirped-pulse amplification technique, Dodd and Umstadter [16] have proposed a novel method for the control of stimulated Raman scattering and hot electron production in short-pulse laser plasma interactions. Kalmykova and Shvets [17] have investigated Stimulated Raman backscattering (RBS) of intense laser radiation in deep plasma channels. The bandwidth of SRBS has been characterized by a strong transverse localization of resonantly driven electron plasma waves. They found that localization of EPW reduces the peak growth rate of RBS and increases the amplification bandwidth. Kirkwood et al. [25] have experimentally shown that the effect of incident laser intensity and plasma electron temperature on the scaling of SRS process in ignition scale plasmas. Sharma et al. [20] studied the effect of laser beam filamentation on SRBS process in homogeneous plasma under non-paraxial approximation and found that the backreflectivity of the Raman process is suppressed by 20%. Purohit et al. [21] investigated the effect of laser beam filamentation on localization of electron plasma wave and backreflectivity of SRS process in plasma. Singh and Walia [26] studied the effect of self focused Gaussian laser beam on the backreflectivity of SRS and observed that focusing of the incident laser wave, EPW and backscattered waves enhances the SRS backreflectivity. Rawat et al. [22] have investigated the combined effect of relativistic and ponderomotive nonlinearities on the propagation of ring rippled Gaussian laser beam in collisionless plasma and further its effect on SRBS process at relativistic laser powers. This study shows that the backreflectivity of SRS is reduced at higher intensities. Recently, Sharma [27] studied SRBS of filamented hollow Gaussian laser beam in a collisionless plasma and observed that self-focusing and back reflectivity reduces for higher order of hollow Gaussian beam.

It is observed that the extent of self-focusing of laser beam and back reflectivity of SRS in plasma depends on nonlinearities associated with plasmas and the spatial profile of laser beams. When an intense laser beam propagates through a plasma, the refractive index of plasma is modified by different mechanisms, which leads to the self-focusing of the laser beam [10]. Relativistic self-focusing is caused by the mass increase in electrons travelling at speed approaching the speed of light, which increases the refractive index by decreasing the plasma frequency at higher intensity. On the other hand, ponderomotive nonlinearity is set up by the relativistic-ponderomotive force, which pushes electrons away from the region where the laser beam is more intense and decreases the electron density. Consequently, the refractive index becomes higher at the higher intensity region and self–focusing becomes enhance due to relativistic mechanism. These nonlinearities are operative at different time scales according to the inequalities: i) $\tau < \tau_{pe}$ (when only relativistic nonlinearity is operative), ii) $\tau_{pe} < \tau < \tau_{pi}$ (when both i. e. relativistic and ponderomotive nonlinearities are present), where τ is the laser pulse duration, τ_{pe} is the electron plasma period, and τ_{pi} is the ion plasma period. Since relativistic nonlinearity arises instantaneously in the system, so it requires relatively higher threshold laser power than the ponderomotive nonlinearity. Ponderomotive nonlinearity modifies the intensity distribution of the laser beam and it is dominant when the characteristic time of observation is greater than the diffusion time of the charge carriers. Therefore, combined effect of relativistic and ponderomotive nonlinearities greatly affect self-focusing of laser beam and back reflectivity of SRS process in plasma. Similarly, various spatial profile of laser beam such as Gaussian beams [28,12], hollow Gaussian laser beams [27,29], rippled Gaussian laser beams [22,30] etc. has been used to study the self-focusing and SERB process in laser plasma interaction. In most of these studies, relativistic/ponderomotive nonlinearity has been separately taken in to the account. Only a few investigations have been reported on the self-focusing and SERB of Gaussian laser beam with relativistic-ponderomotive nonlinearity [22,31,32]. Apart from these, great interest has been evinced in elliptical laser beams [33–38]. It has been observed that the energy of a circularly or slightly elliptical laser beam is divided among several randomly distributed filaments. However, highly elliptical laser beam produce a regular filamentation pattern with most of the laser energy being concentrated in a single central filament, which may be useful to mitigating self-focusing/filamentation instability in plasma [39].

The effect of relativistic/ponderomotive nonlinearity on the propagation of elliptical laser beam in plasma and other associated instabilities have been analysed separately to a significant extent but their combined effect on self-focusing and SRBS process has not been discussed. In the present work, we have investigated self-focusing of intense elliptical laser beam in plasma and its effect on the electron plasma wave excitation and back reflectivity of stimulated Raman scattering along