Kinetic simulations of stimulated Raman and Brillouin scattering of Trident short-pulse laser in a single-hot-spot

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Abstract. Parametric coupling involving stimulated Raman and Brillouin scattering (SRS and SBS) of Trident short-pulse laser in a single-hot-spot [Kline J L et al. 2007 Investigation of stimulated Raman scattering using a short-pulse single-hot-spot at the Trident laser facility J. Phys.: Conf. Series in press] is examined using Particle-In-Cell simulations in the kinetic regime. The scaling of SRS reflectivity versus laser intensity at \( k\lambda_D = 0.35 \) is obtained from two-dimensional simulations in which SRS saturation level is in quantitative agreement with that in the experiments. At this high laser intensity regime \( (\geq 10^{16} \text{ W/cm}^2) \), it is found that SRS saturation is caused by electron plasma wavefront bowing and self-focusing from trapped particle modulational instability [Rose H A 2005 Phys. Plasmas 12 12318]; ion acoustic wave bowing also contributes to the SBS saturation. These results are consistent with our findings for long laser pulse at lower intensities [Yin L, Albright B J, Bowers K J, Daughton W and Rose H A 2007 Phys. Rev. Lett. 99 265004]. A frequency chirp in a short-pulse laser leads to significant reduction of the SBS reflectivity.

1. Introduction
A simulation study is conducted in support of the recent experiments at the Trident laser facility at Los Alamos where a short-pulse version of the single-hot-spot configuration was implemented [1]. The laser pulse length was reduced from \( \sim 200 \) ps previously used in the long-pulse Trident experiments to \( \sim 3 \) ps, making it possible to model the full length of the experiments using two-dimensional (2D) particle-in-cell (PIC) simulations. Stimulated Raman and Brillouin scattering (SRS and SBS) in a single speckle of a short-pulse laser are performed using the multi-dimensional (3D), massively parallel, electromagnetic, relativistic, fully explicit PIC code VPIC [2]. The simulations in this work are in 2D (see Ref.[3] for field and particle boundary conditions). A 527 nm laser enters from the left boundary. The laser spatial envelope is a 2D Gaussian and the simulation domain is 100 \( \mu \text{m} \) in length (and 14\( \mu \text{m} \) transverse to the laser) which is comparable to the length of a f/4.5 diffraction limited beam. The simulated plasma has temperatures \( T_e = 300 \text{ eV} \) and \( T_i = 100 \text{ eV} \) for the electrons and ions and a density \( n_e/n_{cr} = 0.0165 \), corresponding to \( k\lambda_D = 0.35 \) for the initial Langmuir waves (LW) coupled to SRS. A Gaussian temporal profile of the laser is used with a pulse duration of 3 ps at FWHM. These laser and plasma parameters resemble the conditions in the Trident short-pulse experiments. The simulation cell size is on the order of \( 1.0\lambda_D \) (where \( \lambda_D \) is the Debye length) to
resolve small-scale electrostatic waves; we use 512 simulation particles per cell for each species. The convergence of SRS and SBS with the number of simulation particles has been examined in the trapping regime in our earlier studies [3, 4]. Results at low intensity are more sensitive to the number of particles. Simulations at \( I_0 = 4.0 \times 10^{15} \, \text{W/cm}^2 \) in the long-pulse regime show that SRS reflectivities using 512, 750, and 1024 particles per cell are same. Although convergence at much lower intensity has not been examined, simulations shown in this work at intensity \( I_0 \geq 1.0 \times 10^{16} \, \text{W/cm}^2 \) describe the particle trapping and self-focusing accurately.

2. SRS simulation results

Motivated by achieving a quantitative comparison with the high quality data from the experiments, we examine SRS reflectivity scaling with laser intensity from 2D simulations. In the SRS simulation, we use immobile ions to eliminate SBS. Figure 1 (a) shows the calculated SRS reflectivity. The scaling shows an onset of enhanced SRS at an intensity just above \( I_0 = 1 \times 10^{16} \, \text{W/cm}^2 \) and a saturation level below 1%. The saturation level is in good agreement with the Trident data [1]. Our focus in this work is to understand the SRS saturation mechanism.

![Figure 1](image.png)

**Figure 1.** Results from 2D SRS simulations (immobile ions) at \( k \lambda_D = 0.35 \) with 3 ps laser (FWHM): (a) scaling of time-averaged SRS reflectivity vs. laser intensity, (b) instantaneous SRS reflectivity (solid curve) overlaid with laser drive profile (dashed curve; in arbitrary units), (c) zoomed-in view of the first SRS pulse (black curve) overlaid with laser drive profile (green) and electrostatic wave energy (red), (d) transverse profiles (in arbitrary units) for the laser (green) and EPW (red) at the nonlinear stage of self-focusing when the first SRS pulse is terminated, (e) EPW bowing and self-focusing shown at a time (\( t \omega_{pe} = 1639 \)) when SRS saturates. Results in (b) to (e) are at \( I_0 = 5 \times 10^{16} \, \text{W/cm}^2 \).

It has been shown [5] that in the large \( k \lambda_D \) regime the nonlinear frequency shift from electron trapping is larger than that induced by ponderomotive force, and that the electron trapped particle modulation instability (TPMI) becomes stronger than the ponderomotive modulational instability. TPMI requires a perpendicular component of the LW or electron plasma wave (EPW) vector and its nonlinear development leads to filamentation and self-focusing, which have been observed in PIC simulations in single- and multi-speckle configurations [3, 6]. In previous work modeling Trident long-pulse experiments [7], SRS saturation is from amplitude...
dependent LW/EPW self-localization, including wavefront bowing and self-focusing [4]. Here we extend the simulations and analysis to the short-pulse, high intensity regime to examine if SRS saturation is caused by the same mechanism.

Shown in Figure 1b to Figure 1e are the results from a simulation at $I_0 = 5 \times 10^{16}$ W/cm$^2$. Of the many reflected pulses displayed in Figure 1b during the full length of the simulation, we examine the detailed processes during the first pulse shown in Figure 1c (black curve). While both the laser drive amplitude (green) and the electrostatic wave energy (red) are increasing, the reflectivity is, however, decreasing. As the reflectivity reduces, bowing and self-focusing of EPW, shown in Figure 1e at $t \omega_{pe} = 1639$ (where $\omega_{pe}$ is the electron plasma frequency), dominate the wave dynamics and saturate SRS. From the transverse profiles of the laser and EPW in Figure 1d (shown at the nonlinear stage of self-focusing), SRS saturation is due to cancellations in the SRS source $\int E_{EPW} E_{laser} dz$ during bowing and self-focusing.

During self-focusing, velocity diffusion by transverse modes is observed. In addition, the channels of narrow transverse extent formed from self-focusing (see Figure 1e) give rise to a rapid loss of trapped electrons. These processes lead to dissipation of wave energy and an increase in Landau damping in spite of strong electron trapping that reduces Landau damping initially [4]. EPW bowing and self-focusing occur also in SRS simulations at $k\lambda_D = 0.35$ ($T_e = 340$ eV and $T_i = 95$ eV) for 3ps laser pulse at FWHM and are generic processes. Although the laser intensities are high in these simulations, EPW bowing and self-focusing are not caused by relativistic effects since simulation results using a non-relativistic particle pusher are essentially the same as those discussed above.

3. SBS simulation results

In our previous work on SBS reflectivity scaling with ion composition using a longer laser pulse length [8], it was shown that a SBS-dominated regime can be obtained in simulations by using 100% He$^{2+}$ ions (in the absence of H$^+$) to reduce the ion acoustic wave (IAW) damping. Simulations in this work show similar effects of ion composition for a 3 ps laser pulse. Here we use a SBS-dominated case to effects of IAW bowing on SBS saturation. We then show that sufficient laser frequency chirp could lead to significant reduction on the SBS reflectivity.

**Figure 2.** Results from a 2D simulation in SBS-dominated regime (100% He$^{2+}$ ions) at $k\lambda_D = 0.35$ and $I_0 = 5 \times 10^{16}$ W/cm$^2$ (a 3 ps laser at FWHM): (a) instantaneous reflectivity (black curve) overlaid with laser drive profile (green curve, in arbitrary units) and electrostatic wave energy (red), (b) $k$-spectrum of electrostatic waves $|E_x(\omega, k_x)|^2$ integrated over $\omega$ during time interval when SBS dominates over SRS ($t \omega_{pe} = 2300 - 2700$), showing IAW, EPW, their beat, and spectral components at higher harmonics, (c) transverse profiles (in arbitrary units) for the laser (green) and IAW (red) at a time when the SBS pulse is reducing. Also shown in (a) by the blue curve is the reflectivity from a chirped laser.
In the SBS-dominated simulation at $k\lambda_D = 0.35$ in Figure 2 (using a 3 ps laser at $I_0 = 5 \times 10^{16}$ W/cm$^2$ and 100% He$^{2+}$ ions), a SRS pulse occurs first around $t \omega_{pe} \sim 1600$, which is saturated by EPW bowing and self-focusing, followed by strong SBS scattering, as shown by the instantaneous reflectivity in Figure 2a (black curve). The spectral peak for the EPW from SRS is at $k_x \lambda_D = 0.35$ ($x$ is the laser direction), whereas the IAW from SBS is shown by the nearby sharp peak at a slightly higher wavenumber around $k_x \lambda_D = 0.38$. These two waves beat and produce the low negative $k$ spectral component near $k = 0$, as discussed previously [8]. Here, however, the nonlinearity is strong, leading to the generation of IAW at higher harmonics as well as beats at higher harmonics. The $k$-spectrum is obtained during a time interval when SBS dominates but begins to decrease. IAW bowing is observed at this time interval, whose transverse profile is shown in Figure 2c (red) together with that of the laser (green). Cancellations in the SBS source $\int E_{IAW}E_{laser}dz$ contribute to SBS saturation, similar to the findings in the long pulse, low intensity regime [4].

If a laser frequency chirp were present with a bandwidth sufficient to detune SBS, this could reduce SBS reflectivity. In order to study the effects of a laser frequency chirp on SBS, a linear frequency chirp of the laser is used. We found that the time-averaged SBS reflectivity reduces from 20% for the case presented in Figure 2 without chirp to 4.3% when a chirp included with $2\% \omega_0$ frequency change at the peak intensity ($\omega_0$ is the initial laser frequency). However, the bandwidth is greater than 4 nm to obtain these results, which is more than the expected $0.5 - 1.5$ nm bandwidth in the experiments. The SBS results from simulations cannot be compared at the present with experiments in which SBS may be much weaker than SRS [1]. Perhaps these issues can be reexamined in future work.

4. Discussion

Full-length 2D PIC simulations of recent Trident short-pulse single-hot-spot experiments show that SRS saturation level is in quantitative agreement with the experiments. Furthermore, SRS saturation by EPW bowing and self-focusing from TPMI is demonstrated in both regimes for short-pulse at high laser intensities and for long pulse at lower intensities. Ion acoustic wave bowing also contributes to the SBS saturation in both regimes. The recent short-pulse experiments and simulations provide timely and detailed data for developing predictive SRS and SBS models for NIF ignition design.

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