

Simulations of drastically reduced SBS with laser pulses composed of a Spike Train of Uneven Duration and Delay (STUD pulses)

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Abstract. By comparing the impact of established laser smoothing techniques like Random Phase Plates (RPP) and Smoothing by Spectral Dispersion (SSD) to the concept of “Spike Trains of Uneven Duration and Delay” (STUD pulses) on the amplification of parametric instabilities in laser-produced plasmas, we show with the help of numerical simulations, that STUD pulses can drastically reduce instability growth by orders of magnitude. The simulation results, obtained with the code HARMONY in a nonuniformly flowing mm-size plasma for the Stimulated Brillouin Scattering (SBS) instability, show that the efficiency of the STUD pulse technique is due to the fact that successive re-amplification in space and time of parametrically excited plasma waves inside laser hot spots is minimized. An overall mean fluctuation level of ion acoustic waves at low amplitude is established because of the frequent change of the speckle pattern in successive spikes. This level stays orders of magnitude below the levels of ion acoustic waves excited in hot spots of RPP and SSD laser beams.

1. INTRODUCTION

The concept of “Spike Trains of Uneven Duration and Delay” (STUD pulses [1]) is a novel approach that aims to overcome the problem of strongly growing parametric instabilities in laser-produced plasmas in the context of inertial confinement fusion (ICF) and high energy density physics (HEDP) more generally. The method was conceived in 2009 by B. Afeyan [1] and is explained in detail in a companion article by Afeyan [2] in this volume. The physical implementation of STUD pulses in large laser systems offers the prospect of controlling the unbridled growth of electron plasma or ion acoustic waves driven by Raman or Brillouin scattering.

So-called optical smoothing techniques, like Random Phase Plates (RPP), Smoothing by Spectral Dispersion (SSD), and Induced Spatial Incoherence (ISI) have been developed in the last three decades to diminish the risk of hydrodynamic instabilities in fusion capsules, as well as with the hopes that residually, they may limit the growth of laser-plasma instabilities. The impact of these smoothing techniques on parametric instabilities, like stimulated Brillouin scattering, is the subject of the work presented here. Unfortunately, neither RPP nor SSD can efficiently inhibit growth of parametric instabilities inside potentially cooperative regimes between thousands of laser-intensity “hot spots” that form the typical speckle patterns of smoothed laser beams.

“Spike Trains of Uneven Duration and Delay” require the use of phase plates such as RPP (or “CPP”), where the laser beam spatial profiles are a speckle pattern. However, two essential features distinguish STUD pulses from previous techniques[2]:

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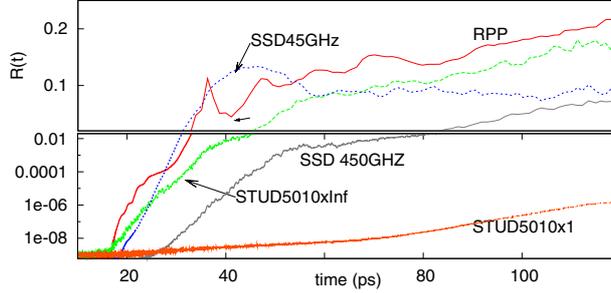


Figure 1. Reflectivity of SBS backscatter as a function of time from simulations with HARMONY for different the different smoothing methods discussed here: RPP, SSD at 45GHz and 450GHz bandwidth, STUD5010 \times , and STUD5010 with a fixed speckle pattern STUD5010 \times Inf. Note: upper/lower subplot in linear/logarithmic scale.

(i) instead of following a continuous profile, the laser pulse is subdivided in spikes in which the intensity is partially “on” and partially “off”. The average intensity over the spike duration, however, equals the value equivalent to a continuous pulse, while the peak intensity of the spike is increased by a factor that depends on the duty cycle;

(ii) the speckle patterns are scrambled in between spikes either each time or after a number of spikes. If the scrambling is in between each spike, they are called STUD \times 1 pulses. In the case of STUD \times Inf (STUD \times ∞) pulses, a single RPP or speckle pattern will be deployed during the entire pulse with no speckle pattern changes. Note that a STUD \times Inf pulse with 100% duty cycle is equivalent to an RPP (or CPP) beam.

The principal idea behind STUD pulses is to control parametrically excited waves from getting re-amplified continuously, there where they have been excited previously. The frequent change of speckle pattern in between spikes has the effect that re-amplification of a plasma mode, generated in a hot spot, is very unlikely due to the exponential statistics of the intensities of hot spots. Our results validate the picture that the interaction volume tends towards being successively filled with relatively low-level ion acoustic waves (IAW). In contrast to this, speckle patterns in RPP beams, constantly amplify IAWs in situ, in particular in intense speckles. In case of SSD we can speak of repeated re-amplification which is very deleterious.

Here we show the results of STUD pulses with a 50% duty cycle (equal “on” and “off” time intervals, on average, and twice higher peak intensity with respect to a continuous pulse). We also introduce a random jitter to the width of the on pulses which is 10% in magnitude. This is in order not to excite ion acoustic waves by the harmonics of the periodic picket fence skeleton of the pulse. This gives rise to so-called STUD5010 \times 1 pulses. For details and other constructions, see [2]. We will show the advantages of STUD5010 \times 1 over the performance of STUD5010 \times Inf pulses and the advantages of both of these over SSD and RPP beams.

2. SIMULATIONS WITH HARMONY

We have explored the performance of STUD pulses in the case of SBS. On the acoustic spatial and temporal scales, it is possible to consider laser-plasma interactions in 2D that include thousands of laser speckles. This guarantees sufficiently good speckle statistics and can be run for upwards of a 100 ps at moderate computational expense. With the help of numerical simulations using the code HARMONY [3], we have compared the evolution of this instability to cases where the driving laser is RPP, SSD, and 50% duty cycle STUD pulses with changing speckle patterns with each spike, STUD5010 \times 1, and with nonchanging speckle patterns, STUD5010 \times Inf. HARMONY solves two paraxial wave equations for the incident light field with the complex-valued amplitude E_0 (with principal frequency and wavenumber

ω_0, k_0) and for a backscattered light field amplitude E_1 (with ω_1, k_1) propagating in opposite direction to each other ($k_1 \simeq -k_0$). In the version of HARMONY used here, the ion acoustic wave (IAW) relevant in the 3-wave coupling of SBS is resolved by a set of 3 (scalar) equations for continuity and for the momenta in z and x_\perp of this short-wavelength component ($k_z \simeq 2k_0$), (while in the version described in Ref. [5], a single envelope approach is used for the SBS-driven IAW)

$$(\partial_t + \mathbf{u}_0 \cdot \nabla) n_1 + n_0 \nabla \cdot \mathbf{u}_1 + n_1 \nabla \cdot \mathbf{u}_0 = 0 \quad (1)$$

and

$$(\partial_t + \mathbf{u}_0 \cdot \nabla + 2\nu_{IAW}) \mathbf{u}_1 + c_s^2 \nabla n_1 = \mathbf{f}_{SBS} \quad (2)$$

where n_0 and \mathbf{u}_0 stand for the average density and for advective flow, respectively, ν_{IAW} for IAW damping, c_s for the sound speed, and \mathbf{f}_{SBS} for the acceleration due to the SBS coupling with both light field components, $\mathbf{f}_{SBS} \propto n_0 \nabla E_0 E_1^* \exp(i2k_0 z)$. Equations (1–2) for n_1 and $\mathbf{u}_1 \equiv (u_{1,z}, u_{1,x})$ are solved with the help of a conservative Eulerian scheme, with flux correction, for the two vectors $U_\pm \equiv c_s n_1 \pm n_0 u_{z,1}$ for the (complexed-valued) density and velocity perturbations, $n_1, u_{1,z}$, and $u_{1,x}$. The vectors U_\pm follow the counter-propagating characteristics of sound, as well as for the 3rd x -component of Eq. (2) for $c_s u_{1,x}$. The IAW density perturbation $n_1 = (U_+ + U_-)/2c_s$ is then used for the 3-wave coupling terms for the paraxial equations for E_0 and E_1 (see [3]). The usual 1st order equation for n_1 for ‘weak coupling’, when temporal growth is slower than the ion acoustic oscillations, corresponds to the case when the counter-propagating wave U_- is not excited. Solving Eqs. (1) and (2) allow to access the regime of ‘strong coupling’ of SBS [4] that may easily appear to be relevant in high-intensity speckles of the smoothed beam. The dominant term for advection in the laser propagation direction in Eqs. (1–2) corresponds to a frequency shift $\mathbf{u}_0 \cdot \nabla \simeq i2k_0 u_{0,z}$. A flow profile is used in our simulations with $u_{z,0}(z) = u(L_z)[1 - (z - L_z)/u(L_z)L_u]$. In order to seed SBS growth of possibly unstable modes with frequency $\sim 2k_0[c_s - u_{z,0}(z)]$, everywhere in the simulation box, a small-amplitude seed in the field E_1 is introduced at the right-hand-side (RHS) boundary $z = L_z$, having a broadband spectrum with $\delta\omega \sim 25k_0 c_s$ around the laser frequency ω_0 . This is done via a Langevin equation $(\partial_t + \delta\omega)E_1(L_z, t) = \delta\omega S(t)$ with random noise generation each Δt , respecting $\delta\omega\Delta t \ll 1$. The module for the 3-wave coupling, describing propagation of laser- and backscattered light, and for the short-wavelength IAWs driven by backscatter SBS, solved via Eqs. (1)–(2), is coupled to a nonlinear hydrodynamics module that describes both the plasma expansion as well as the (long-wavelength) acoustic waves associated with forward-SBS and self-focusing, Harmony takes into account the momentum transfer between the short- and long-wavelength components, see herefore Ref. [5]. The algorithm of HARMONY has the options to take into account, or to exclude, (i) self-focusing and momentum transfer, (ii) pump depletion, and (iii) higher harmonics of the IAW. The simulations whose results are shown here have been carried out in two-dimensional (2D) geometry in a box of 4000 laser wavelengths, λ_0 , along the laser propagation direction (spatial resolution $\Delta z = 2\lambda_0$) and $8192\lambda_0$, in the transverse direction ($\Delta x = \lambda_0$), with the wavelength chosen to be $\lambda_0 = 0.53\mu\text{m}$. For a laser $f_\#$ -number of $f_\# = 8$, the box length L_z contains ~ 9 effective hot spots with an equal number of hot spot lengths in between them. The effective hot spot length is $L_{HS} = \pi f_\#^2 \lambda_0 \simeq 220\lambda_0$. The non-periodic boundary conditions in x result in an effective box-width of $\sim 4000\lambda_0$ (about half the entire box width), resulting in a number >1500 potential speckles, sufficiently numerous to avoid too strong a fluctuation from realization to realization [6]. In all of the simulations, a laser pulse with a flat intensity profile in x , lasting 3 times the transit time of the box, $3L_z/c$, precedes the main laser pulse. This pulse is used to initialize equivalent conditions for the noise in the plasma for each of the different types of main laser pulses that follow, either RPP, SSD, or STUD pulses. The main pulse is smoothly switched on over L_z/c . The simulated plasma at $T_e = 2\text{keV}$, has 10% critical density, $n_0 = 0.1n_c$, with a inhomogeneous flow profile in the interval $u_{0,z}/c_s = -3 \dots -7c_s$ with an inhomogeneity length (at $z = L_z$) of $L_v = |u(L_z)|L_u = 3000\lambda_0$. The IAW damping coefficient is $(\nu/\omega)_{IAW} = 0.025$. The corresponding SBS (Rosenbluth) gain for the average intensity of a RPP and SSD runs at $I_L = 5.5 \times 10^{14}\text{W/cm}^2$ (and twice this value for STUD

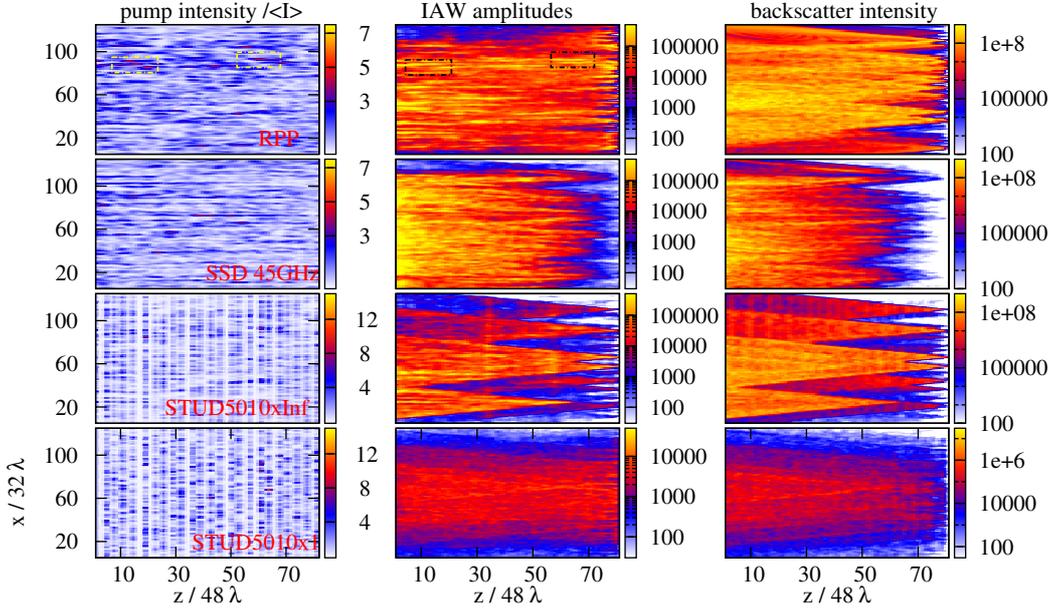


Figure 2. Snapshots in the $x - z$ -plane, taken at $t = 100\text{ps}$, of laser pump intensity (left column), of backscattered light intensity (center), and of IAW amplitudes (right), for the cases (top to bottom) RPP, SSD at 45GHz, STUD5010 \times Inf, STUD5010 \times 1 pulses. The pump intensity is normalized to the beam average intensity $\langle I \rangle$, both other quantities to the level after the pulse preceding the main pulse. Note the difference in the levels (see color bars) for the STUD5010 \times 1 case with respect to the other cases. RPP case (upper line): two regions with particularly high IAW amplitudes (center) coinciding with intense speckle locations (left) are high-lighted in frames.

pulse peaks) in the inhomogeneous profile hence was $G_{\text{SBS}} = 5.5$ at $z = L_z$ and the interaction length $L_{\text{int}} = 2(v/\omega)_{\text{IAW}}[c_s + u_{0,z}(z)]L_v/u_{0,z}(z)$ thus $L_{\text{int}} = 100 \dots 128\lambda_0$. For the applied STUD pulses the spike duration chosen was $ct_{\text{spike}} = 173 \lambda_0$. For the pulses following SSD a bandwidth of 45GHz was chosen. An alternative simulation with a 10 times larger bandwidth at 450GHz was also carried out to see the impact of faster smoothing, even if it lies outside any realistic modulation pace of SSD systems.

Simulation results: The simulations with HARMONY have been carried out starting from a noise level of $\sim 3 \times 10^{-9}$ of the incoming laser light pump intensity (of the late time RPP beam) in the backscattered light intensity. As illustrated in Fig. 1, the cases for RPP and SSD at 45 GHz rapidly attain pump depletion in numerous speckles, attaining a SBS reflectivity around 10-20% [7]. SSD proves to show a reduction with respect to RPP on a longer time scale [8], but the efficiency of reduction is less than an order of magnitude for the realistic bandwidth value of 45 GHz. The reflectivity for the 10 times higher bandwidth value exhibits a slower growth, but tends again to reflectivities above 1%. As can be seen from Fig. 2, the RPP case (and to a lower degree the SSD case) exhibits high-amplitude IAW structures in space due to repeated amplification in close vicinity to high-intensity speckles (see zones put in frames). Apparently the SSD technique, that can be associated with moving speckles within a limited volume, cannot avoid that IAWs are re-amplified sufficiently often by intense speckles. Compared to both the RPP and the SSD technique, the use of STUD pulses results in a drastic reduction of SBS backscattering. Figure 2 furthermore illustrates that the mean level of IAW fluctuations for the STUD pulse stays of at least 2 orders of magnitude below the levels seen for all other cases. In particular, spatial structures that can be associated with the speckle pattern are washed out. It is also instructive to note that the STUD5010 \times Inf pulse case, based on a fixed speckle pattern, but using the same spikes, attains similar levels as RPP and SSD 45 GHz. This underlines the fact that a frequent scrambling of hot spots into uncorrelated speckle patterns is an important factor for the success of the STUD pulse program.

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