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Three-dimensional particle-in-cell modeling of parametric instabilities near the quarter-critical density in plasmas

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The nonlinear regime of laser-plasma interaction including both two-plasmon-decay (TPD) and stimulated Raman scattering (SRS) instabilities has been studied in three-dimensional (3-D) particle-in-cell simulations with parameters relevant to the inertial confinement fusion (ICF) experiments. SRS and TPD develop in the same region in plasmas, and the generation of fast electrons can be described accurately with only the full model including both SRS and TPD. The growth of instabilities in the linear stage is found to be in good agreement with analytical theories. In the saturation stage the low-frequency density perturbations driven by the daughter waves of the SRS sidescattering can saturate the TPD and consequently inhibit the fast-electron generation. The fast-electron flux in 3-D modeling is up to an order of magnitude smaller than previously reported in 2-D TPD simulations, bringing it close to the results of ICF experiments.

Since the 1960s, the pursuit of inertial confinement fusion (ICF) driven by lasers has led to large-scale research on laser interaction with the plasmas of ICF targets [1]. Decades of laser-plasma interaction (LPI) research [2] have concentrated on several processes in laser-produced plasmas that can grow as parametric instabilities at high-enough laser intensities, namely stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and two-plasmon decay (TPD).

Laser light can propagate in a plasma up to the critical density (n_c) determined by the laser frequency. The region near quarter-critical density ($1/4 n_c$) is a possible place for the interplay between SRS, SBS, and TPD as all three instabilities can develop at that region. plasmons produced by SRS and TPD generate fast electrons that can preheat the fusion fuel and degrade the performance of the ICF targets [1], making LPI a concern in ICF experiments. Several mechanisms of fast-electron acceleration have been studied before, namely staged acceleration [3, 4], Langmuir cavitation [5, 6], and wave breaking [7].

In this Letter, LPI is studied using particle-in-cell (PIC) modeling [8], which can describe the interplay between different instabilities and the particle distributions including fast-electron generation. Usually, few hot electrons are found in the simulations at the linear stage of the TPD and SRS instabilities. The electron acceleration becomes effective after the instabilities saturate [4].

The TPD-related waves are mostly localized in the plane of polarization [9], which is defined by the incident laser wave vector (in the x direction) and the laser electric field vector (in the y direction). The SRS sidescattering develops mostly outside of the polarization plane, and its scattered-light wave vector is almost perpendicular to the incident laser wave vector [10, 11]. Scattered light waves can also propagate in the direction parallel

or anti-parallel to the laser wave vector (forward- and backscattering, respectively) [12]. A 2-D simulation in the polarization plane (x - y) or in the perpendicular plane (x - z) will be referred to as p polarized (PP) or s polarized (SP), respectively. Two-dimensional simulations can model only the interaction where either (in PP) TPD or (in SP) SRS dominates except for the high-frequency hybrid instability (HFHI) [13] case when the SRS scattered light propagates in the backward direction and the SRS-related and TPD-related waves are in the same (x - y) plane. The 3-D simulations are required to study the interaction including both TPD and SRS. In this Letter, the results of several 3-D simulations for different plasma parameters and incident laser profiles are presented and compared with the respective 2-D simulations to illustrate that both TPD and SRS strongly influence the LPI near $1/4 n_c$. In the 3-D modeling including both TPD and SRS the fast-electron flux is reduced by up to an order of magnitude compared to 2-D TPD simulation results published before [4].

Here we describe in detail a 3-D simulation for the parameters relevant to ICF experiments [14, 21]. A CH plasma is initialized with the electron temperature $T_e = 2$ keV, and the temperatures for both ion species $T_i = 1$ keV. The incident laser beam with intensity $I = 9 \times 10^{14}$ W/cm² propagates in the direction of density inhomogeneity (x). A linear density profile with the scale length $L = 100 \mu\text{m}$ is assumed at the initial time. The size of the simulation box is $21 \mu\text{m} \times 8.4 \mu\text{m} \times 6.7 \mu\text{m}$ modeling the density range from $0.21 n_c$ to $0.26 n_c$.

Two 2-D simulations (PP and SP) with the same physical parameters were also performed. The TPD threshold parameter η [9] is 1.9 ($\eta = 1$ at threshold), and the SRS backscattering threshold parameter N [12] is 0.5 ($N = 0.26$ at threshold) for these simulations. The SRS sidescattering threshold [10, 11] is close to the backscat-

tering threshold. Both absolute TPD and absolute SRS instabilities are expected to grow. The threshold of the convective SRS [10] is not exceeded for the parameters described above. The time evolution of the energy of the field components in the simulation region is shown in Fig. 1. The field energy is defined as the square of the electric- or magnetic-field amplitudes integrated over the simulation region normalized to the respective laser field energy at early time (when there are no instabilities). In 2-D PP [Fig. 1(a)], the E_x field contains most of the energy of the TPD plasmons with a larger wave vector. One can see that the field energy associated with the TPD instability stays at about the same level (close to 70% of the energy of the incident laser electric field) after 2.5 ps, when one can assume that the saturation stage is reached. In 2-D SP, the energy of the B_x field [Fig. 1(b)] is used as an indicator for the level of SRS instability. The energy of the scattered light saturates at a level of about 8% of the energy of the incident laser magnetic field.

In the 3-D simulation, the diagram for TPD and SRS is shown in Fig. 1(c), where the incident light (\vec{k}_0) decays into a plasmon ($\vec{k}_{\text{SRS},1}$) and a light wave ($\vec{k}_{\text{SRS},2}$) in the case of SRS and into two plasmons ($\vec{k}_{\text{TPD},1}$ and $\vec{k}_{\text{TPD},2}$) in the case of TPD. The E_x field energy [red line in Fig. 1(d)] now includes the energy of the TPD plasmons and the SRS plasmons. The red line is overlaid with the dotted black line that represents the maximum TPD growth rate [9] ($7.7 \times 10^{-4} \omega_0$) minus the damping rate of plasma waves ($2.1 \times 10^{-4} \omega_0$) measured in the 3-D simulation. The E_x field saturates at a level of about 40% of the laser field energy, which is much lower than the saturation level in 2-D PP. The green line in Fig. 1(d) corresponds to the energy of the scattered light wave (propagating in the z direction) from the SRS and is overlaid with the dashed purple line representing the maximum growth rate of the SRS [10] ($8.2 \times 10^{-4} \omega_0$) minus the damping rate of the plasma waves. One can see from Fig. 1(d) that the growth of the B_x field energy in time is in reasonable agreement with the theoretical result [10]. The B_x field energy is under 10% of the incident laser field energy after reaching its peak value, which is consistent with the 2-D SP result.

The spectra of plasma waves ($|\vec{E}_L|$) obtained at a time interval between 0.3 ps and 1.0 ps in the 2-D PP and SP simulations are plotted in Figs. 2(a) and 2(b), respectively. From the 3-D simulation, the spectra of plasma waves at a time interval between 1.3 ps and 2.0 ps are plotted in Fig. 2(c) (close to $k_z = 0$ plane, where TPD dominates) and in Fig. 2(d) (far away from $k_z = 0$ plane, where SRS dominates). One can see from Figs. 2(c) and 2(d) that TPD and SRS co-exist near $1/4 n_c$. The spectra of the unstable modes for TPD and SRS are close to the linear theory results (see overlaid lines in Fig. 2).

As the instability evolves from the linear stage to the

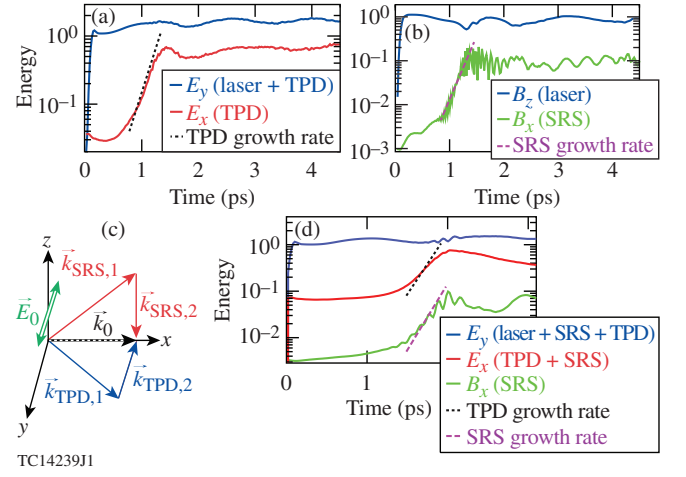


FIG. 1. The integrated energy of different field components in the simulation region as a function of time for the (a) 2-D p -polarized simulation, (b) 2-D s -polarized simulation, and (d) 3-D simulation. The wave-vector diagram for TPD and SRS is shown in (c).

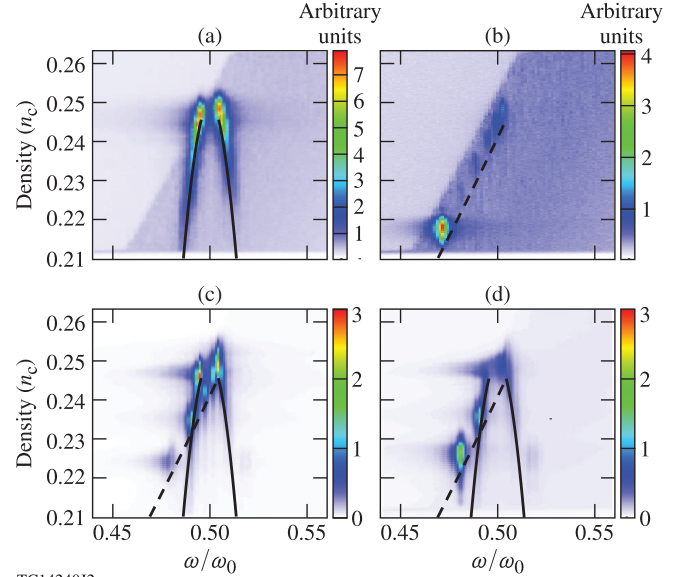


FIG. 2. (a) Plasma-wave spectra in the linear instability stage as a function of plasma density and the wave frequency normalized to laser frequency in 2-D PP, (b) 2-D SP, and (c) 3-D simulation for modes with $0 \leq k_z/k_0 < 0.2$ and (d) $0.2 \leq k_z/k_0 < 3$. The overlaid solid black lines and the dashed black lines represent the dispersion relations satisfying the matching conditions for TPD and SRS, respectively.

saturation stage, the frequency spectra shown in Fig. 2 evolve into the spectra shown in Fig. 3. One can see that the spectra in all these simulations are broader in the saturation stage compared to the linear stage. The density in Fig. 3 is calculated using the initial density

profile. Compared to 2-D PP [Fig. 3(a)], the TPD is much weaker at densities lower than $0.23 n_c$ in the 3-D simulation [Fig. 3(c)]. The weakening of the TPD modes at these densities is also illustrated in Fig. 4(a) [and Fig. 4(b)], where the spectrum of plasma waves at densities below $0.23 n_c$ in the saturation stage is integrated over k_z (and k_y). There are no prominent modes along the TPD hyperbola [15] [black solid line in Fig. 4(a)] at $k_x > k_0$, which corresponds to the TPD daughter waves with larger wave vectors. Two types of low-frequency density fluctuations are identified in our simulations [see Fig. 4(c)]. One type are the ion acoustic waves driven by the Langmuir-decay instability (LDI) [16, 17] and the other type are driven with the beating of the same-frequency daughter waves of SRS and TPD. The LDI modes form a broad feature at $k_x \approx 1.7 k_0$ (about $2 \times$ the laser wave vector in plasma) in the spectrum of the ion density fluctuations shown in Fig. 4(c). The beating of the SRS plasmons with wave vector $(k_x, k_y, k_z) = (0.87 k_0, 0, \pm 0.2 k_0)$ creates density perturbations $\langle \delta n \rangle$ with wave vector $(k_x, k_z) = (0, \pm 0.4 k_0)$. The coupling between SRS plasmons and $\langle \delta n \rangle$ generates higher-order modes in the field at $k_z = \pm(0.2 + m0.4 k_0)$, [$m = 1, 2 \dots$, see Fig. 4(b)] and in the density perturbation at $(k_x, k_z) = [0, \pm(0.4 + m0.4 k_0)]$ [see Fig. 4(c)].

Although SRS and TPD grow independently in the linear stage, in the nonlinear stage they interact through low-frequency density perturbations. TPD growth starts from the region near $1/4 n_c$ and spreads to lower densities [4]. Although the peak values of $\langle \delta n \rangle$ are similar in 2-D and 3-D simulations, the peaks are reached at different densities in different simulations: in 2-D PP (without SRS) $\langle \delta n \rangle$ peaks at densities where absolute TPD modes dominate (around $0.245 n_c$); in 3-D (with both SRS and TPD) $\langle \delta n \rangle$ peaks at densities where the frequencies of TPD and SRS plasmons are close. In this region where the dispersion lines for TPD and SRS plasmons intersect [near $0.23 n_c$ in our simulations, see Fig. 3(c) and 3(d)] multiple pairs of SRS and TPD daughter waves have close frequencies and can drive $\langle \delta n \rangle$ through the ponderomotive force to much higher levels compared to other density regions [see the black line in Fig. 4(d)]. The level of $\langle \delta n \rangle$ near $0.23 n_c$ is lower in 2-D PP than in 3-D simulations. In the 3-D simulation the growth of TPD plasmons at densities below $0.23 n_c$, seeded by plasmons from above $0.23 n_c$, is disrupted by these enhanced ion density perturbations, as illustrated by a decrease in the level of TPD-driven plasmons below $0.23 n_c$ in Fig. 3(c).

The correlation between the local plasmon intensity $|E_L|^2$ and the density fluctuations δn is captured using the caviton correlator [5] $C_{E,n} = \langle -\delta n |E_L|^2 \rangle / (\langle (\delta n)^2 \rangle^{1/2} \langle |E_L|^2 \rangle)$. As shown in the lower panel of Fig. 4(d), the plasma waves and the density fluctuations are weakly correlated between $0.255 n_c$ and $0.235 n_c$: $C_{E,n} = 0.1 - 0.2$ in spite of a significant level of

plasmons in this density range. At densities close to $0.23 n_c$, lower panel of Fig. 4(d) shows the increase not only in the plasmon intensity and density fluctuations, but also in the correlation between them with $C_{E,n}$ reaching up to 0.6. The large caviton correlator indicates that the plasma waves are strongest in areas where density is depleted. The ponderomotive force of multiple pairs of SRS and TPD daughter waves with close frequencies is responsible for driving the enhanced density perturbations. The nonlinear coupling of TPD and SRS through ion perturbations leads to a lower TPD saturation level in the 3-D simulation compared to the 2-D PP simulation, which is illustrated in the upper panel of Fig. 4(d).

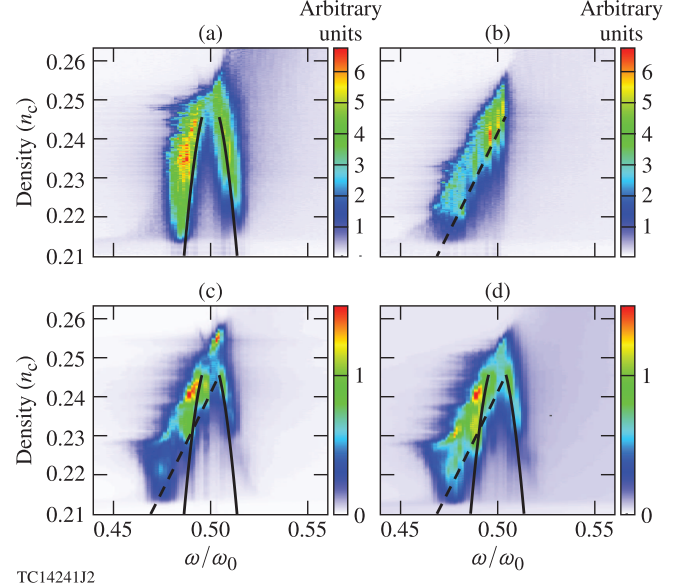
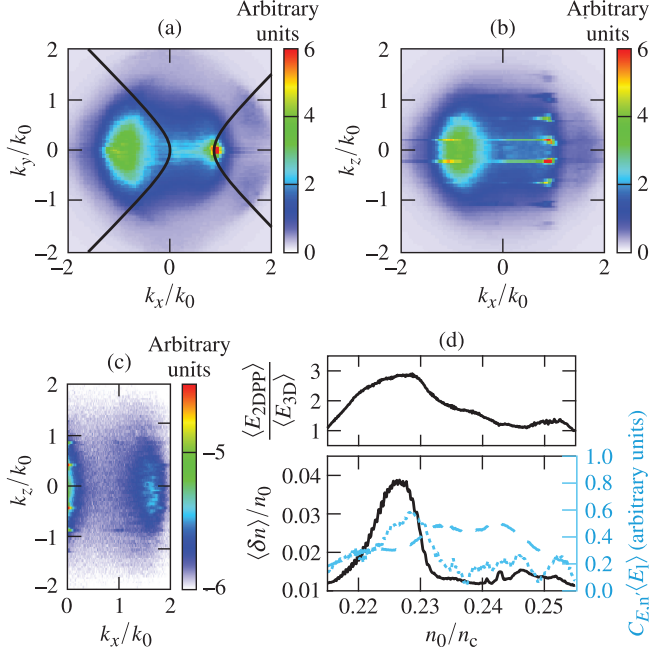


FIG. 3. Plasma-wave spectra in the saturation stage in the 2-D (from 3.3 ps to 4.1 ps) and 3-D (from 2.3 ps to 3.1 ps) simulations as a function of plasma density and the wave frequency. Each panel displays the same quantity as in Fig. 2.

The fast-electron flux is defined as the energy flux carried by electrons with kinetic energy above 55 keV leaving the simulation box minus the energy flux carried by the thermal electrons injected into the simulation region from the thermal boundaries (in the x direction). Information about the hot electrons is collected during the saturation stage in each simulation for 0.5 ps. In the 3-D simulation, the fast-electron flux associated with the forward- and backward-going hot electrons was found to be 1.7% and 0.8%, respectively. The plasma-wave spectrum in the 3-D simulation corresponds to a smaller k -space domain than the spectrum in 2-D PP, which makes the staged acceleration mechanism less efficient in 3-D than in 2-D and explains a smaller number of hot electrons in the 3-D simulation compared to 2-D PP (6.6% and 3.4% in the forward and backward direction, respectively). The influence of wave-breaking on the fast-electron generation is small as the maximal electric field amplitude (0.04

$m_e \omega_0 c / e$) is below the wave-break limit ($0.1 m_e \omega_0 c / e$) [7].



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FIG. 4. (a) The spectrum of plasmons in the saturation stage of 3-D simulation at densities lower than $0.23 n_c$ plotted in the k_x - k_y plane and (b) the k_x - k_z plane. (c) The spectrum of ion density fluctuation plotted in the k_x - k_z plane on a logarithmic scale. (d) Lower panel: Ion density fluctuations RMS (root-mean-square average over the transverse direction and time) normalized to background density (black solid line), longitudinal electric field RMS (blue dashed line) and caviton correlator $C_{E,n}$ (blue dotted line). Upper panel: the ratio of the electric field amplitude of the TPD plasmons with larger wave vector between 2-D PP and 3D simulations.

The nonlinear regime including both TPD and SRS is also observed in simulations with the speckled laser beam [18, 19] and electron-ion collision effects included. In PIC simulations with periodic boundary conditions, the limited-size simulation region effectively represents a much larger volume of plasmas and the single speckle in the simulation region mirrors itself in the transverse directions. A series of simulations has been performed to study how the speckles affect the generation of hot electrons. All parameters are the same as the simulations described previously except for the temperatures of electrons and ions being 1.5 times higher. The peak intensities in the laser speckles are $1.8 \times 10^{15} \text{ W/cm}^2$ (twice of the average intensities). A collision package (CP) is available for the PIC code OSIRIS [20]. The main physics processes are observed to be the same in simulations with plane-wave beams and speckled beams.

The fast-electron flux values in simulations are listed in Table I for different incident laser beams as well as with CP turned on and off. By comparing the left and right columns of Table I, one can see that adding colli-

Fast-electron flux	Forward/Backward	
Collision package	On	Off
Plane wave 2-D PP	1.6%/1.3%	5.5%/3.8%
Plane wave 2-D SP	(< 0.1%)/0.2%	(< 0.1%)/0.5%
Speckle 2-D PP	6.8%/1.7%	9.4%/3.8%
Speckle 2-D SP	(< 0.1%)/0.3%	(< 0.1%)/0.7%
Speckle 3-D	0.4%/0.3%	0.8%/0.5%

TABLE I. Fast-electron flux normalized to the incident laser energy flux.

sions can reduce the fast-electron flux by about 50% and in the case of plane-wave 2-D PP simulation by almost 70%. Also note that the reduction of the fast-electron flux caused by collisions affects both the forward-going electrons and backward-going electrons since the collisional damping rate affects all the plasma waves. The fast-electron flux generated in 2-D SP is much smaller than the fast-electron flux generated in 2-D PP, which indicates that the plasma waves driven by TPD are the main source of the electron acceleration.

The hot electron fraction observed in the ICF experiments on the OMEGA laser system does not exceed few percent [21]. At the same time, in the previous PIC simulations of TPD in 2-D the hot electron fraction was close to an order of magnitude larger than in the experiments. The 3-D PIC simulations presented in this Letter for the first time produce the results for the hot electron fraction that are close to the experimental levels.

laser-plasma interaction near $1/4 n_c$ determines the generation of fast electrons that are crucial for the performance of ICF targets. The fast-electron flux in simulations is found to be closely related to the plasma-wave spectra. The TPD-driven plasma waves with large wave vectors are very important for accelerating electrons. At the same time, the SRS-driven plasma waves are less effective in accelerating electrons. Therefore the modeling including the nonlinear coupling of TPD and SRS in 3-D is the only way to correctly describe the generation of fast electrons in laser-driven ICF.

Our 3-D PIC simulations have shown the large decrease (up to an order of magnitude) in the fast-electron flux compared to 2-D TPD modeling. The reason is the nonlinear coupling between SRS and TPD which is especially pronounced at densities lower and around $0.23 n_c$. In this region plasma waves and growing density perturbations are localized in same areas as illustrated by the caviton correlator. Enhanced density perturbations detune and weaken the TPD-driven plasmons effective in the fast electron generation. In addition to the TPD suppression, the plasma wave spectra in 3-D simulations are much more narrow compared to the spectra in 2-D TPD modeling. To conclude, 3-D PIC simulations presented in this Letter fully model the laser-plasma interaction near $1/4 n_c$ including SRS and TPD, and obtain the fast elec-

tron fraction level close to experimental results, resolving the large discrepancy between ICF experiments and PIC simulations that existed for many years before.

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