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Citation	Physical Review E. 2026, 114, p. 015202
Version Type	AM
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Effects of Spatial Beam Coherence and Plasma Scale Length on Stimulated Raman Scattering and Two-Plasmon Decay

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ABSTRACT

We present experimental investigations demonstrating that the suppression of parametric instabilities in laser-plasma interactions under conditions relevant to direct-drive inertial confinement fusion, specifically backward stimulated Raman scattering (SRS) and two-plasmon decay (TPD), shows the effects of spatial beam coherence and plasma-density scale length. Experiments were performed with the GEKKO-XII kilojoule laser, both with and without random phase plates. Results indicate that SRS suppression is enhanced under conditions of initial spatial incoherence, whereas TPD is influenced primarily by the plasma scale length. A comparison of the relationship between the SRS/TPD signals and hot-electron measurements suggests that TPD is the primary source of hot electrons across all experimental conditions. These findings underscore the importance of beam coherence in determining instability dominance and carry implications for mitigating hot-electron preheat in ignition-scale inertial-confinement implosions as well as for developing hot-electron-driven schemes such as shock ignition.

I. INTRODUCTION

Nonlinear interactions between intense laser pulses and plasmas give rise to three-wave parametric instabilities, wherein a pump electromagnetic wave decays into two daughter waves that satisfy energy and momentum conservation [1,2]. Stimulated Raman scattering (SRS) and two-plasmon decay (TPD) generate large-amplitude Langmuir waves, whose subsequent electron trapping accelerates electrons from the thermal Maxwellian background, producing a supra-thermal population of hot electrons.

Understanding the mechanisms responsible for hot-electron generation is crucial in high-energy-density physics, astrophysics, and especially laser-driven inertial confinement fusion (ICF). The nonlocal transport of hot electrons can drive return-current instabilities and, at sufficiently high return currents, excite ion-acoustic modes [3]. Anisotropy in the electron velocity distribution may also trigger the growth of Weibel instability [4]. In the context of ICF, hot electrons can preheat the fuel core, thereby reducing implosion efficiency and hindering ignition [5–11]. Conversely, nonlocal heat flow may slow the infilling of target-surface defects and suppress ablative hydrodynamic instabilities, potentially mitigating premature shell rupture [12]. In shock ignition [13], hot electrons could amplify ignitor-shock pressure to hundreds of megabars or even gigabar levels [14–16].

A key mechanism responsible for hot-electron generation arises from irradiation nonuniformity in high-power laser systems, where the laser beam typically contains large-scale hot spots in the focal intensity distribution. These hot spots can evolve through the filamentation instability driven by perturbations during propagation in the plasma corona, leading to enhanced SRS within the filaments [17]. Filamentation also provides favorable conditions for TPD and other parametric instabilities by lowering their effective thresholds and increasing the growth rates [18].

Among the most widely adopted strategies at high-power laser facilities to mitigate filamentation are optical beam-smoothing techniques. The use of random phase plates (RPPs) introduces spatial decoherence, reducing large hot spots and long scale modulation and producing focal spots with a smooth macroscopic intensity envelope and fine wavelength-scale speckles [19]. After RPP application, most of the speckles enclose a laser power which is lower than that needed to drive self-focusing, with the net result of a reduced formation of filaments. However, speckles in the tail of the intensity distribution, whose intensities significantly exceed the average beam intensity, can still undergo ponderomotive self-focusing, leading to an increased risk of backscattering [17,20].

To reduce the impacts of high-intensity speckles, additional methods are commonly combined with

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phase plates. Polarization smoothing superposes two independent speckle patterns in orthogonal polarizations, thereby reducing the speckle contrast [21,22]. Smoothing by spectral dispersion [23] and induced spatial incoherence [18,24] rapidly modulates the speckle pattern in time, thereby reducing the speckle lifetime. These techniques can suppress filamentation and thus indirectly reduce backscattering and the associated instabilities [17,25–28].

Beyond optical incoherence, plasma-based incoherence can be produced by the interactions of speckles with forward stimulated Brillouin scattering (FSBS). This process, known as plasma-induced smoothing, produces angular spreading and frequency redshifting of beamlets, even when speckle intensities remain below the ponderomotive self-focusing threshold imposed by thermal effects [29–34]. Plasma-induced smoothing reportedly strongly suppresses the growth of SRS and SRS as well as potentially affects TPD via reduced beam coherence time during laser propagation toward the quarter-critical density region [20,35–37].

Our previous study shows that the suppression of SRS and TPD depends strongly on the plasma-density scale length under spatially incoherent laser conditions with RPPs [37]. This suppression can be primarily attributed to plasma-induced smoothing, based on the theoretical prediction of the noticeable development of beam spray. Nevertheless, experimental verification of the contribution of the smoothing effect to the suppression of parametric instabilities, by directly varying the initial speckle structures of the interaction beams, has not yet been reported.

In this study, we experimentally investigated the variation of the smoothing effects in SRS and TPD suppression with laser spatial coherence and plasma-density scale length. The experiments were performed at the GEKKO-XII laser facility [38], both with and without RPPs. The results indicated that SRS suppression was enhanced with RPPs, whereas TPD suppression in long-scale-length plasmas was insensitive to initial spatial coherence. Hot-electron diagnostics further underscored TPD as the primary source of hot electrons under the present experimental conditions. These findings provide a characterization of how SRS and TPD respond to optical smoothing across different plasma scale length, demonstrating that plasma-induced incoherence plays an effective role in the suppression of these parametric instabilities. This study highlights the critical role of beam coherence in laser-plasma interaction design for ICF.

The remainder of this paper is organized as follows. Section II presents the laser, target, and diagnostic conditions, as well as the plasma profiles obtained from one-dimensional (1D) radiation hydrodynamic

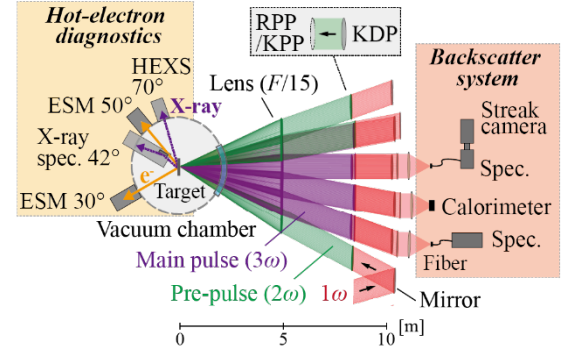


FIG 1. Schematic of the experimental geometry. Each laser beam was guided through turning mirrors, frequency converted, spatially smoothed, and then focused onto the targets at the center of the vacuum target chamber. RPPs were installed between the KDP crystals and the focusing lens and were removed only for shots without RPPs. The backscattered-light diagnostics were installed behind the turning mirrors, while the hot-electron diagnostics were mounted on the target chamber on the rear side of the target.

simulations, which are used to characterize the interaction conditions. Section III shows the experimental results obtained for SRS, TPD, and hot-electron generation. Section IV discusses the characterization of SRS and TPD responses under varying plasma scale-length conditions via comparison of shots with and without RPPs. Finally, Section V summarizes the study and presents the major conclusions drawn from the obtained results.

II. EXPERIMENTAL CONDITIONS

A. Laser and target conditions

The experiment was performed using a planar laser-target geometry as shown in Fig. 1. Three second-harmonic (2ω) beams (wavelength $\lambda = 527$ nm) were overlapped to produce a pre-pulse that generated pre-plasma (total energy $E_{\text{tot}} = 259\text{--}315$ J), and six or seven third-harmonic (3ω) beams ($\lambda = 351$ nm) served as the main pulse ($E_{\text{tot}} = 267\text{--}374$ J), inducing instability. Both the pre- and main pulses exhibited Gaussian temporal profiles with full width at half maximum (FWHM) values of approximately 300 ps. The pre-pulse, smoothed with kinoform phase plates (KPP) [39], produced a large focal spot of $\sim 1,000$ μm at the FWHM, yielding an approximately 1D expanding pre-plasma. The pre-pulse peak intensity, $I_L = (1.0\text{--}1.3) \times 10^{14}$ W/cm², was sufficiently low to suppress SRS and TPD. The main-pulse delays relative to the pre-pulse peak were varied from 0.2 ns to 1.4 ns to adjust the pre-plasma-density scale length. The main pulse was

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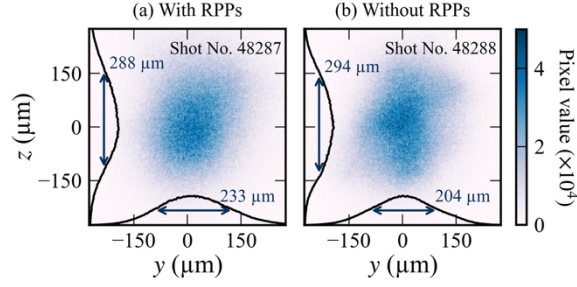


FIG 2. XPHC images of the laser spot: (a) seven overlapped beams with RPPs and (b) seven overlapped beams without RPPs.

focused to an overall $F/3$ configuration, corresponding to a nominal peak intensity of $I_L = (1.2-1.7) \times 10^{15}$ W/cm², calculated for an overall laser-spot diameter of approximately 300 μm , with each beam having an individual $F/15$ and a spot size of approximately 150 μm . The main-pulse beams were smoothed using the RPPs installed between potassium dihydrogen phosphate (KDP) crystals and the focusing lens; to capture shots without RPPs, they were removed from the beam path.

The targets consisted of a three-layer planar structure. From the laser-irradiated side, the first layer was a CH ablator (10 μm thick), followed by a copper layer (25 μm) that served as a tracer for hot electrons via $K\alpha$ emission; finally, a quartz layer (50 μm), viz. the third layer, was used to measure the shock temperature with a streaked optical pyrometer (not shown in this paper).

B. Diagnostic conditions

The experimental setup was designed to diagnose SRS, TPD, and hot electrons [37,40–42]. Backscattered laser light was collected to evaluate SRS and TPD using three diagnostics: a time-resolved optical spectrometer (A6365, Hamamatsu Photonics) coupled to a streak camera (C7700, Hamamatsu Photonics), a time-integrated optical spectrometer (HR2000 UV–NIR, Ocean Insight), and a calorimeter. Each diagnostic was placed behind the last turning mirror of a different 3ω laser beam. Long- and short-pass filters, along with a notch filter, were used to eliminate unwanted spectral components in the ultraviolet (< 440 nm), infrared (> 1000 nm), and at the second-harmonic wavelength (~ 527 nm). The streak camera in the time-resolved spectrometer operated with a sweep-time window of 5.26 ns and a temporal resolution of approximately 50 ps.

Hot electrons generated by SRS and TPD were measured using four diagnostic instruments: two electron spectrometers (ESMs) positioned behind the target at 30° and 50° from the target normal, where 30° corresponds to the minimum accessible angle imposed

by the target chamber geometry, an X-ray spectrometer, and a high-energy X-ray spectrometer (HEXS). The ESMs recorded the electron energy spectra using magnetic fields and imaging plates (IPs; BAS-SR, Fujifilm) [43–45] over the energy range from 60 keV ($\Delta E = 0.1$ keV) to 1 MeV ($\Delta E = 0.8$ keV). The X-ray spectrometer, equipped with a highly oriented planar graphite crystal and an IP (BAS-SR), was positioned at 42° from the target normal. It measured Cu- $K\alpha$ lines arising from L–K transitions, induced by hot-electron inner-shell ionization, in the copper layer with a photon energy resolution of approximately 0.05 keV. Although spatial resolution was not available, the observed photon energy range 7.4–8.4 keV encompassed the 8.048 keV Cu- $K\alpha$ line. The HEXS was positioned at 70° from the target normal and measured continuous bremsstrahlung X-rays, produced by hot electrons propagating forward through the target, using IPs (BAS-MR, Fujifilm) and alternately stacked metal filters. Photo-stimulated luminescence (PSL) values recorded from each layer after the shots were analyzed to evaluate the hard X-ray yields across different energy bands.

The laser-spot diameter was measured using an X-ray pinhole camera (XPHC) positioned on the laser-irradiated side. X-rays emitted from the ablator passed through a 25- μm -diameter pinhole and were imaged onto a charge-coupled device camera, yielding a spatial resolution of approximately 30 μm for the system. Figure 2 shows the laser-spot image obtained with the XPHC using a 30- μm -thick aluminum filter. The images correspond to a main-pulse-only shot from a separate experimental series, in which seven beams were overlapped and focused onto a 50- μm -thick

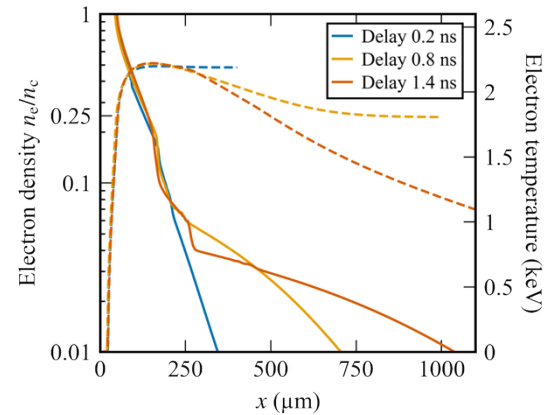


FIG 3. Plasma profiles at the main-pulse peak, calculated with the ILESTA for different main-pulse delays (0.2 ns, blue; 0.8 ns, yellow; 1.4 ns, orange). Solid curves represent the electron density normalized to the critical density for 3ω (left axis), while dashed curves represent the electron temperature (right axis).

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aluminum foil target. The XPHC viewed the target at an azimuthal angle of 10.0° and an elevation angle of 28.4° , and the images were corrected to represent the view from the laser-incident direction. Compared with the case using RPPs (Fig. 2(a)), the case without RPPs (Fig. 2(b)) exhibited a slightly narrower horizontal profile and more non-uniform focal distribution.

C. Interaction conditions

Figure 3 shows plasma profiles at the main-pulse peak calculated with the 1D radiation-hydrodynamics code ILESTA [46] for different main-pulse delays. Solid curves represent the electron density n_e normalized to the critical density n_c for 3ω (left axis), while dashed curves represent the electron temperature T_e (right axis), where critical density is given by $n_c = 1.1\lambda^{-2} \times 10^{21} \text{ cm}^{-3} = 9.0 \times 10^{21} \text{ cm}^{-3}$ for λ in μm . The simulations employed a flux-limited Spitzer-Harm model, and thus the nonlocal heat transport of hot electrons was not incorporated. Around $0.25n_c$, where the growth rates of SRS and TPD maximize, the density scale length $L_n = n_e/(dn_e/dx)$ remains nearly unchanged across all the conditions, with a value of approximately $70 \mu\text{m}$, and T_e is $\sim 2.2 \text{ keV}$. In contrast,

at $0.01n_c$, L_n increases with the main-pulse delay; $L_n = \sim 70, \sim 220$, and $\sim 480 \mu\text{m}$ for delays of 0.2, 0.8, and 1.4 ns, respectively, indicating the expansion of low-density plasma with increasing delay. T_e at $0.01n_c$ also decreases (approximately 2.2, 1.8, and 1.2 keV) with increasing main-pulse delay (0.2, 0.8, and 1.4 ns, respectively) owing to the development of a temporal gap between the pre-pulse and main pulse. The role of the extended low-density plasma in laser propagation and instability behavior is discussed in Sec. IV. Between these regions, density steepening is observed in the range from $0.04n_c$ to $0.2n_c$.

III. EXPERIMENTAL RESULTS

A. SRS and TPD

Figure 4 presents the backscattered-light spectra for convective SRS (panels a and c) and TPD (panels b and d), obtained with a time-integrated optical spectrometer. Panels (a) and (b) correspond to the case with RPPs, and panels (c) and (d) to the case without RPPs. In Fig. 4(a) and 4(b), for a main-pulse delay of 0.2 ns (blue curve), the spectra are nearly identical to those reported in previous studies [37,40–42]. Convective SRS during the main-pulse peak appeared between 550 and 650 nm. The hybrid absolute SRS/TPD was sharply detected around 702 nm,

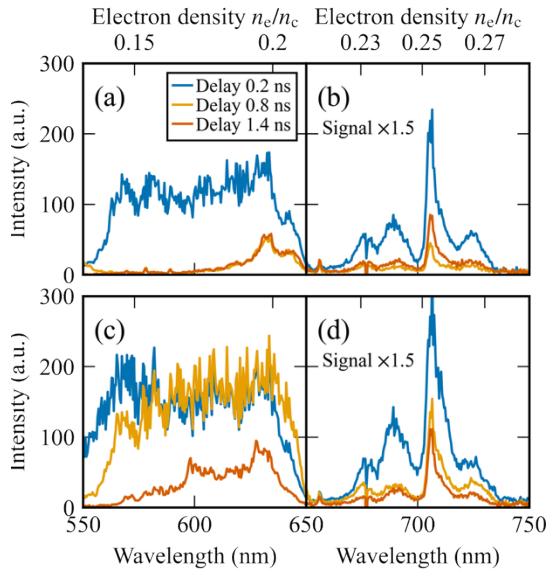


FIG 4. Backscattered-light spectra obtained with a time-integrated optical spectrometer for different main-pulse delays (0.2 ns, blue; 0.8 ns, yellow; 1.4 ns, orange). The top panels (a) and (b) show results with RPPs, and the bottom panels (c) and (d) show results without RPPs. Panels (a) and (c) correspond to convective SRS at electron densities of $0.13n_c$ – $0.21n_c$, while panels (b) and (d) correspond to $\omega_0/2$ emissions associated with TPD. The electron densities indicated by the top ticks are based on the dispersion relation without considering temperature effects.

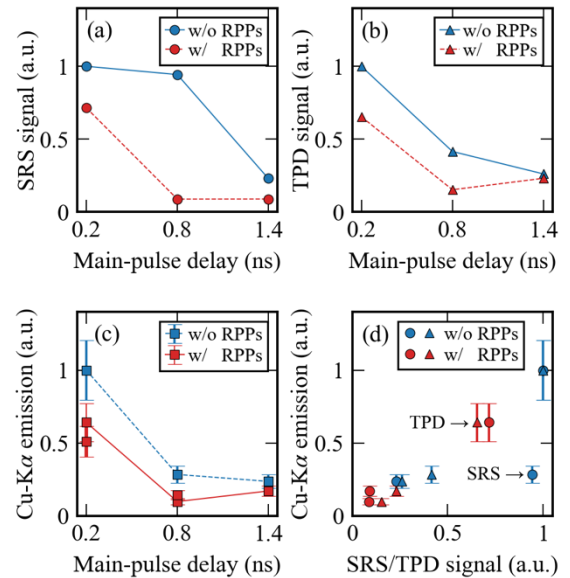


FIG 5. (a) SRS signal integrated intensity over the wavelength range 550–650 nm, (b) TPD integrated intensity over 650–700 nm, and (c) Cu-K α emission, all shown as functions of the main-pulse delay. (d) Relationships between SRS/TPD signals and the amounts of hot electrons (SRS: circles; TPD: triangles). Blue markers denote cases without RPPs, and red markers denote those with RPPs.

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corresponding to $0.25n_c$ for 3ω [47]. Half-harmonic emissions from convective TPD, blueshifted and redshifted, were observed near $0.25n_c$ [47,48]. The dip between convective SRS and convective TPD is referred to as the Raman gap, for which various possible causes have been proposed [49]. In most delayed shots, SRS was also observed in the low-density region around $0.05n_c$ – $0.1n_c$, appearing only at the beginning of the main pulse and no longer observed at the peak, consistent with Ref. [37], indicating that it does not affect the characterization of SRS and TPD discussed here.

In Fig. 4(a) and 4(b), as the main-pulse delay and density scale length in the low-density region increase, the spectra exhibit suppression of both SRS and TPD, consistent with the results shown in Ref. [37]. Figure 5(a) and 5(b) show the SRS and TPD signals as functions of the main-pulse delay, respectively; these signals are obtained by integrating the backscattered-light spectra over the wavelength ranges of 550–650 nm for SRS and 650–700 nm for TPD. The signals are normalized to the value measured at a main-pulse delay of 0.2 ns without RPPs (Shot No. 47919). For SRS with RPPs (red), the signal intensity decreases by 88% when the main-pulse delay is increased from 0.2 ns to 0.8 ns, whereas the signal levels at 0.8 and 1.4 ns are comparable. For TPD, the signal intensity decreases by 77% from 0.2 ns to 0.8 ns, whereas it increases by a factor of 1.5 from 0.8 ns to 1.4 ns. Notably, at main-pulse delays of 0.2 ns (Shot No. 47927) and 0.8 ns (Shot No. 47929), data are obtained using six main-pulse beams, whereas the data at 1.4 ns (Shot No. 47912) are obtained using seven beams. Although the total energy is nearly the same, a larger number of overlapping beams favor TPD over SRS [50].

As shown in Fig. 4(a)–(d), the signal intensities are consistently higher in the cases without RPPs (using seven main-pulse beams) than in those with RPPs, irrespective of the scale-length conditions. Although this difference is not evident in the calorimeter data, the results indicate that the RPPs contribute to suppressing parametric instabilities over a wide range of plasma-density scale lengths. Notably, while the level of TPD suppression remains comparable between cases with and without RPPs, the degree of SRS suppression varies with increasing density scale length. For the cases without RPPs, the SRS signal intensity (shown by the blue circles in Fig. 5(a)) decreases by only 6% as the main-pulse delay increases from 0.2 ns to 0.8 ns, whereas at 1.4 ns, the intensity is 77% lower than that at 0.2 ns. In contrast, the TPD signal intensity without RPPs (shown by blue triangles in Fig. 5(b)) decreases by 58% from 0.2 ns to 0.8 ns, and at 1.4 ns, the intensity becomes 26% of that at 0.2 ns.

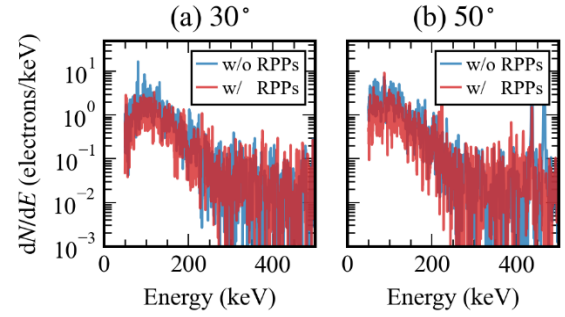


FIG 6. Energy spectra of hot electrons measured with two ESMs positioned at (a) 30° and (b) 50° from the target normal for a main-pulse delay of 0.2 ns. The spectra are shown as the differential electron number dN/dE . Blue curves denote cases without RPPs (Shot No. 47919), and red curves denote cases with RPPs (Shot No. 47927).

B. Hot-electron generation

Figure 5(c) shows the number of hot electrons inferred from the Cu-K α emission, measured with an X-ray spectrometer, as a function of the main-pulse delay. Blue squares denote cases without RPPs, and red squares correspond to those with RPPs. The without-RPPs cases exhibit large amounts of hot electrons, irrespective of the scale-length conditions.

Figure 6 shows the energy spectra of hot electrons measured with two ESMs positioned at (a) 30° and (b) 50° from the target normal for a main-pulse delay of 0.2 ns. The number of hot electrons in the cases without RPPs is slightly larger than that in the cases with RPPs. Maxwellian fits to the electron energy spectra in the range of 150–300 keV yield hot-electron temperatures of the order of 30–50 keV. At 30°, the inferred temperature is higher in the case with RPPs than in the case without RPPs, whereas at 50°, the temperatures for the two cases are comparable (≈ 35 keV).

Figure 7 displays the continuous X-ray signal obtained in different IPs in the HEXS under different pre-pulse and main-pulse delay conditions. Panel (a) corresponds to the case without a pre-pulse, while panel (b), (c), and (d) show the results for main-pulse delays of 0.2, 0.8, and 1.4 ns. Consistent with the results from other diagnostics, the X-ray signals are higher in the cases without RPPs than in the cases with RPPs. In Fig. 7(b), the dashed lines show the expected X-ray signals for hot-electron temperatures of $T_h = 10, 20, 30,$ and 40 keV, calculated using the particle and heavy-ion transport code system (PHITS) [51] and normalized to the signal of the first IP for the case without RPPs. These comparisons indicate that the hot-electron temperature is of the order of 10–40 keV.

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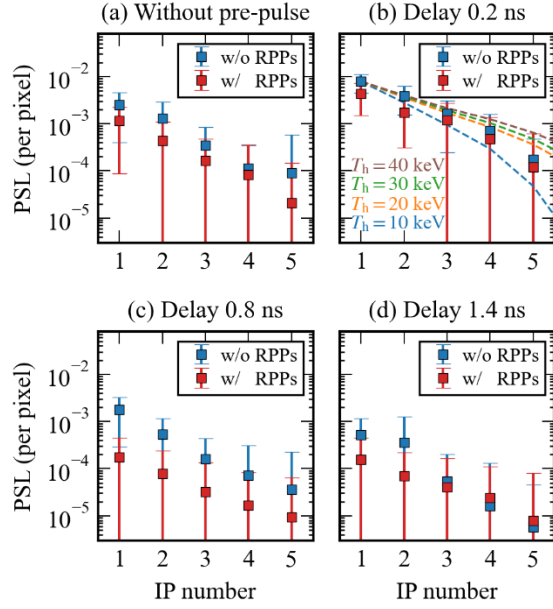


FIG 7. X-ray spectra measured with the HEXS under different pre-pulse and main-pulse delay conditions: (a) without pre-pulse, (b) main-pulse delay of 0.2 ns, (c) 0.8 ns, and (d) 1.4 ns. Blue and red squares denote the averaged values on the IPs for cases without and with RPPs, respectively. Error bars represent the statistical uncertainty. In panel (b), the dashed lines indicate the expected X-ray for hot-electron temperatures $T_h = 10, 20, 30$, and 40 keV, calculated using PHITS and normalized to the first IP signal for the case without RPPs.

IV. DISCUSSIONS

For both SRS and TPD, the signal intensity is consistently higher without RPPs than with RPPs for each scale-length condition. To interpret the differential behavior between cases with and without RPPs, the difference in the spatial distribution of the laser energy into the laser spot should be considered.

In the absence of RPPs, the beams contain irregular large-scale hot spots on the order of several tens of micrometers (see Fig. A1 in the Appendix), which concentrate a significant fraction of the laser energy. Figure 8 shows the critical power for ponderomotive self-focusing P_c as a function of the electron density for different main-pulse delays. The critical power is given by $P_c = 3.4 \times 10^7 (1-n_0)^{0.5} T_e / n_0$, where $n_0 = n_e / n_c$ [2]. The temperature values are obtained from the ILESTA simulation (Fig. 3). The horizontal lines in Fig. 8 denote the laser power contained within hot spots, P_{hs} , estimated by assuming a single-beam energy of 45 J. As shown in Fig. 8, the power contained in large-scale hot spots ($\sim 25 \mu\text{m}$) exceeds P_c

at $n_e = 0.02n_c$. The transverse size of the subsequently formed filament is given by $\Delta y_{fil} \approx 4\pi\lambda_{De}a_0^{-1}$, where λ_{De} is the Debye length and a_0 is the normalized vector potential [2]. Using the electron temperatures derived at $n_e = 0.02n_c$ via ILESTA simulations (Fig. 3), the filament size is estimated as $\Delta y_{fil} \approx 26\text{--}33 \mu\text{m}$, which is comparable to the transverse scale for the hot spots. Some beams are composed of hot spots with characteristic sizes of $10\text{--}20 \mu\text{m}$ (e.g., Fig. A1(d) in the Appendix). For such structures, the filaments are formed at higher densities, closer to the SRS region, with correspondingly smaller transverse scales. This can lead to strong SRS and can also contribute to the enhancement of TPD.

In contrast, when RPPs are used, while self-focusing within speckles can still occur in the high-intensity tail of the distribution, the laser energy is distributed over small-scale intensity modulations. The maximum transverse size is limited by the speckle size, $F\lambda \approx 5.3 \mu\text{m}$ [2], which is more than one order of magnitude smaller than the filament scale expected without RPPs. As a result, the energy contained in each structure is reduced by more than one order of magnitude, and the resulting speckles are less effective in driving strong parametric instabilities.

The reduction in both SRS and TPD with increasing density scale-length can be understood in terms of different mechanisms for the cases with and without RPPs. In the presence of RPPs, the suppression can be primarily attributed to plasma-induced smoothing. As

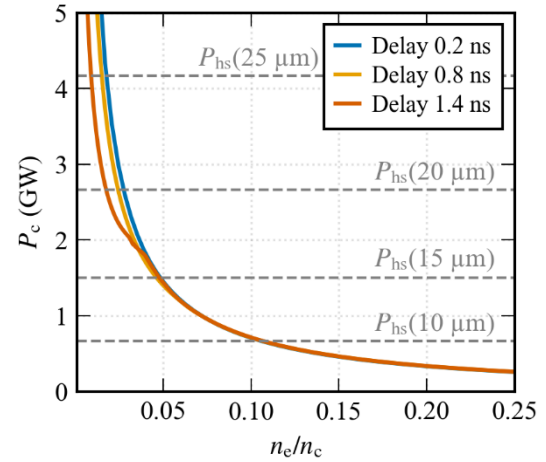


FIG 8. Critical power for ponderomotive self-focusing, P_c , as function of electron density for different main-pulse delays (0.2 ns, blue; 0.8 ns, yellow; 1.4 ns, orange). The horizontal dashed lines indicate the laser power contained within hot spots of characteristic diameter of 10, 15, 20, and 25 μm (P_{hs}). The condition $P_{hs} > P_c$ defines the density range where filamentation is expected to occur.

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the beam propagates through an extended plasma corona, the beam spray reduces the spatial coherence and homogenizes the intensity distribution, thereby weakening the effective drive of both SRS and TPD. Without RPPs, the behavior differs in the intermediate scale-length regime. As shown in Fig. 4(c) and Fig. 4(d), between main-pulse delays of 0.2 ns and 0.8 ns, SRS does not show a clear reduction, while TPD is suppressed. This can be interpreted based on the preceding discussion: strong filaments formed from large-scale hot spots can persist into the SRS density region, maintaining a sufficiently high local intensity to drive SRS. At longer delays (1.4 ns), SRS is also suppressed. This reduction could be due to the depletion of the laser energy in the extended low-density corona. In addition, the steepening of the density profile in the SRS region ($0.13n_c$ – $0.21n_c$) results in a shorter scale length, as shown in Fig. 3, allowing the convective SRS threshold to be exceeded at higher densities. As shown in Fig. 4(c), the SRS spectra shift toward higher densities with increasing delay, which is consistent with the influence of density steepening. These effects are expected to be common to both cases (with and without RPPs). However, in the absence of RPPs, strong self-focusing leads to locally enhanced intensities even in lower-density regions, resulting in a weaker dependence of the SRS spectra on the delay.

Overall, these results indicate that the effectiveness of plasma-induced incoherence increases for the suppression of SRS and TPD with the density scale-length. The use of RPPs enhances the suppression of parametric instabilities by mitigating filamentation and promoting smoothing effects. To obtain a more quantitative conclusion, multibeam configurations with and without RPPs should be directly compared through numerical simulations; however, faithfully reproducing such experimental conditions remains challenging.

As shown in Fig. 5(d), the observed decrease in both the TPD signal and hot-electron yield with increasing main-pulse delay follows the trend expected from TPD rather than that obtained from SRS. This result suggests that TPD is the primary source of hot electrons under all the experimental conditions. This conclusion is supported by previous GEKKO-XII experiments, which reveal that the reflectivity of convective SRS (0.03–0.16%) is considerably smaller than the energy-conversion efficiencies of hot electrons (0.3–0.6%) [41,42]. The difference in the inferred hot-electron temperature range between the ESM and HEXS diagnostics can be ascribed to the absorption of low-energy electrons in the rear-side target components.

V. CONCLUSION

In this study, we experimentally observed the differential sensitivity of the suppression of SRS and TPD to laser spatial coherence by comparing shots with and without RPPs at the GEKKO-XII laser facility. Evidently, SRS suppression became less dependent on the plasma-density scale length in the absence of RPPs, whereas it was significantly enhanced with the RPPs. In contrast, TPD was suppressed in long-scale-length plasma coronas irrespective of the initial beam coherence. These findings suggest that filamentation and smoothing effects play key roles in suppressing instabilities, with spatial coherence determining the selective suppression of SRS and TPD. In large-scale implosions, where SRS-dominated regimes are anticipated, combining optical smoothing techniques is crucial for suppressing SRS. Conversely, in shock ignition, where SRS-generated hot electrons can contribute to ignitor-shock formation, this strategy may need reconsideration. Therefore, controlling SRS, while preserving some degree of spatial coherence, is desirable and may be achieved by optimizing the phase-plate element size or focal ratio, which determines the speckle spatial frequency. However, such modifications inevitably alter the focal spot size and may require high input energies.

ACKNOWLEDGMENTS

The authors would like to acknowledge the technical-support staff at the Institute of Laser Engineering (ILE), The University of Osaka (UOsaka), for assistance with the laser operation, target fabrication, plasma diagnostics, and computer simulation. This study was supported by the Collaboration Research Program between the National Institute for Fusion Science and ILE, UOsaka (No. 2024NIFS21KUGK136); JST SPRING, Grant Number JPMJSP2138; “Power Laser DX Platform” as research equipment shared in The MEXT Project for promoting the public utilization of advanced research infrastructure (Program for advanced research-equipment platforms), Grant Number JPMXS0450300124; the Japan Society for the Promotion of Science (JSPS) International Leading Research, Grant Number JP23K20038. This work has been carried out within the EUROfusion Enabling Research Projects AWP24-ENR-IFE-02-CEA-02 and CfP-FSD-AWP26-ENR-01, funded by the Euratom Research and Training Programme (Grant Nos. 633053 and 101052200). This work was partly achieved through the use of SQUID at D3 Center, UOsaka. D. T. and Y. T. were partially supported by the Grant-in-Aid for JSPS Fellows, Grant Numbers 23KJ1526, 23KJ1444.

DATA AVAILABILITY

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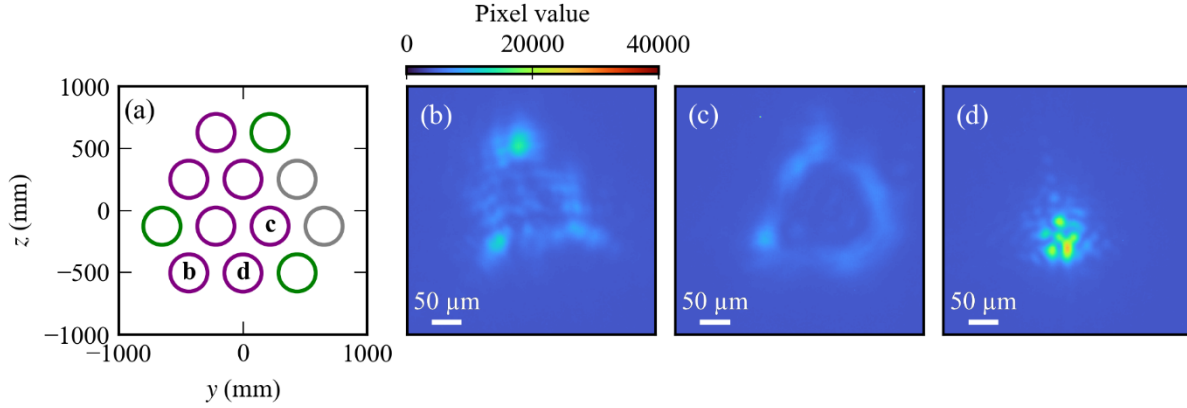


FIG A1. Rear view of the beam port configuration. Purple circles indicate the main 3ω laser beams, green circles represent the 2ω pre-pulse beams, and gray circles denote ports not used in this study. The ports labeled b, c, and d correspond to beamlines used for the measurements shown in panels (b)–(d), respectively. (b)–(d) Focal spot images of the 1ω laser beam at the target chamber center without a random phase plate, recorded by a charge-coupled device camera. The beam is injected through the ports labeled in panel (a): (b) port *b* equipped with a time-integrated spectrometer, (c) port *c* with a time-resolved spectrometer, and (d) port *d* with a calorimeter.

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

APPENDIX

The spatial configuration of the laser beam ports at the GEKKO-XII laser facility at the Institute of Laser Engineering, The University of Osaka, is shown in Fig. A1(a). The main interaction beams at 3ω are indicated by purple circles, while the 2ω pre-pulse beams are shown in green. Gray circles denote ports that were not used in the present experiment. Among the available ports, three beamlines labeled *b*, *c*, and *d* were selected for the measurements discussed in the main text.

Figures A1(b)–A1(d) show the focal spot intensity distributions of the corresponding 1ω laser beams at the target chamber center, recorded by a charge-coupled device camera (DMK37BUX178, The

Imaging Source) without an RPP. The spatial resolution of the imaging system is $2.4 \mu\text{m}/\text{pixel}$. These images represent the spatial intensity modulation of the beams in the absence of optical smoothing. The beam in Fig. A1(b) was injected through port *b*, where a time-integrated spectrometer was installed. Similarly, the beams in Fig. A1(c) and Fig. A1(d) correspond to ports *c* and *d*, which were equipped with a time-resolved spectrometer and calorimeter, respectively. The observed focal spot structures exhibit significant spatial nonuniformity, including large-scale hot spots on the order of several tens of micrometers. Such localized intensity enhancement may influence the development of filamentation.

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