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Beam cleaning of an incoherent laser via plasma Raman amplification

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We show that backward Raman amplification in plasma can efficiently compress a temporally incoherent pump laser into an intense coherent amplified seed pulse, provided that the correlation time of the pump is longer than the inverse plasma frequency. An analytical theory for Raman amplification using pump beams with different correlation functions is developed and compared to numerical calculations and particle-in-cell simulations. Since incoherence on scales shorter than the instability growth time suppresses spontaneous noise amplification, we point out a broad regime where quasi-coherent sources may be used as efficient low-noise Raman amplification pumps. As the amplified seed is coherent, Raman amplification additionally provides a beam-cleaning mechanism for removing incoherence. At near-infrared wavelengths, finite coherence times as short as 50 fs allow amplification with only minor losses in efficiency. *Published by AIP Publishing.*
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INTRODUCTION

The construction of lasers with peak powers beyond the multi-petawatt scale[1,2] requires avoidance of the material damage threshold limits of solid-state chirped-pulse amplification (CPA)[3] and optical parametric CPA (OPCPA).[4] Plasma-based parametric amplification, using either the Langmuir wave [stimulated Raman scattering (SRS)][5–20] or the ion-acoustic response [stimulated Brillouin scattering (SBS)][21–37] to mediate energy transfer from a long-duration high-energy pump to a short high-peak-power seed pulse, has an intensity limit set by relativistic ($10^{18}\,\mathrm{W/cm^2}$ at $1\,\mu$m) rather than ionization ($10^{12}\,\mathrm{W/cm^2}$) effects, so that exawatt powers can be reached in centimeter-diameter beams. Plasma amplification requires a high-energy laser to pump the high-peak-power seed, and relaxation of coherence requirements may broaden the range of available pump sources and provide a mechanism for cleaning incoherence; the sole high-pulse energy sources available for x-ray plasma amplification[38–42] are free-electron lasers (FELs), which produce inherently quasi-coherent radiation.[43–45] Furthermore, incoherent beams are less susceptible to noise-seeded instabilities,[46] allowing higher pump power. Since the plasma amplification process is coherent and requires phase-matching conditions between the pump, seed, and plasma wave, pump coherence might be expected to be necessary for plasma amplification; incoherence is used to suppress deleterious Raman and Brillouin scattering in inertial confinement fusion targets.[47–49] However, here we show that the high-power stimulated Raman amplification process tolerates a high degree of incoherence without catastrophic losses in efficiency, overcoming a major obstacle in using plasma amplification at high-power facilities and offering a route to extreme-intensity coherent radiation pulses.

The behavior of parametric instabilities for partially coherent laser beams in plasma has been the subject of a range of studies, primarily focused on the suppression of SRS and SBS in laser-driven inertial confinement fusion (ICF) plasmas.[50–59] It has generally been found that when the coherence time is shorter than the amplification time, i.e., the laser bandwidth $\Delta\omega$ is larger than the growth rate Γ, the instability growth rate decreases as $1/\Delta\omega$.[56] This suppresses noise-seeded spontaneous Raman scattering, which leads to reflection of the driving lasers in ICF and causes premature pump depletion in Raman amplification.[60] Previous efforts to address noise in Raman amplification include pump[61] or seed[62] chirping and Langmuir wave damping.[63,64] Some resilience of Raman amplification to large scale plasma and laser amplitude fluctuations has been observed, particularly in the non-linear regime.[65,66] A set of hydrodynamic simulations using multiple pump beams at varied angles suggested that the finite bandwidth of a multiple frequency pump may provide noise suppression and enhanced focusability during Raman amplification,[67] and experimental results have hinted that large-scale speckles may not prevent the amplification process.[68] Analogously, Raman scattering in non-ionized media was considered for beam cleaning, i.e., producing a coherent seed from an incoherent pump, although the underlying medium response is different than that in a plasma.[69–71] However, the limiting effect of temporal incoherence on plasma amplification has not yet been examined quantitatively. Unlike stationary speckles, where the slow-moving plasma wave maintains coherence with the local phase of light, temporal incoherence associated with the pump beam causes dephasing between the pump wave and the plasma wave, leading to a stronger decoherence effect.

Here, we use particle-in-cell (PIC) simulations, three-wave calculations, and a comprehensive analytic theory to quantify the role of temporal incoherence in Raman amplification, showing that Raman amplification in the non-linear regime permits the degree of incoherence to be hundreds of times higher

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than the growth-rate limit of the linear regime. Like quasitransient backward Raman amplification (QBRA),[63,64] where amplification is possible even if the plasma response is heavily damped, incoherence up to the plasma frequency does not prevent amplification. A bandwidth ($\Delta\omega$) window therefore exists between the noise suppression threshold (Γ) and the amplification suppression threshold (ω_p) where an incoherent pump prevents premature backscattering while allowing efficient Raman amplification. Since the amplified seed pulse is coherent, this mechanism can be used to clean incoherence from a pump beam.

THEORY

The interaction between the laser fields and the plasma wave can be described by the coupled wave equations[55]

$$(\partial_t^2 - c^2\partial_z^2 + \omega_p^2)a = -\omega_p^2 a(\delta n/n_e), \tag{1}$$

$$(\partial_t^2 + \omega_p^2)\delta n/n_e = c^2\partial_z^2 a^2/2, \tag{2}$$

where $a = eE/(m_e c\omega_a)$ is the normalized vector potential, with E being the electric field, ω_a the laser central frequency, c the speed of light, and e and m_e the elementary charge and electron mass, respectively. The electron density deviation $\delta n/n_e$ characterizes the plasma Langmuir wave, with plasma frequency $\omega_p = \sqrt{n_e e^2/(m_e\epsilon_0)}$.

The longitudinal (temporal) coherence of an electromagnetic field can be characterized by its first order correlation function $g(\Delta t)$, given by

$$g(\Delta t) = \frac{\langle a^*(t-\Delta t)a(t)\rangle}{\langle |a(t)|^2\rangle}, \tag{3}$$

where the angular brackets denote an average over time t. The coherence time is defined as:

$$t_c = \int_{-\infty}^{\infty} |g(\Delta t)|^2 d(\Delta t), \tag{4}$$

so that an exponential correlation function may be written as $g(t) = \exp(-t/t_c)$ and the Gaussian correlation function is $g(t) = \exp(-[\pi/2][t/t_c]^2)$. Temporal coherence may also be related to the frequency bandwidth ($\Delta\omega$ for FWHM); for a Lorentzian distribution $\Delta\omega = 2/(\pi t_c)$, and for a Gaussian frequency distribution $\Delta\omega \approx 2.95/t_c$. When the pump is incoherent, its magnitude and phase fluctuate, making the coupled-wave equations fully nonlinear even without pump energy depletion. As in Fig. 1(c), narrower bandwidths are associated with longer coherence times.

In a Raman amplifier, the frequency of the seed pulse is downshifted from the pump frequency by the plasma frequency, i.e., $\omega_b = \omega_a - \omega_p$. The seed may be evaluated in a frame moving at its group velocity v_b, using the new variables $\zeta = t - z/v_b$ and $\tau = z/v_b$. Neglecting dispersion and relativistic effects, Eqs. (1) and (2) can be reduced to

$$(2\partial_\zeta - \partial_\tau)a = -Vbf, \tag{5}$$

$$\partial_\tau b = Vaf^*, \tag{6}$$

$$(\partial_\zeta + \nu)f = -Vab^*, \tag{7}$$

where b denotes the amplitude of the seed envelope (with the same normalization as a), and $f = i(\omega_p/2\omega_a)\delta n/n_e$ denotes the amplitude of the Langmuir wave envelope. The parameter $V \approx \sqrt{\omega_a\omega_p}/2$ is the coupling coefficient. The plasma wave damping rate is represented by ν.

Equations (5)–(7) have two distinct regimes, distinguished by whether the depletion of the pump during the interaction is negligible [the linear regime, Fig. 1(a)] or substantial [the non-linear regime, Fig. 1(b)]. In the linear regime, Eq. (5) may be neglected, and for a coherent pulse, a is a constant. To account for the statistical nature of an incoherent pump, we transform Eqs. (6) and (7) into an integral equation

$$b(\zeta,0) = b(\zeta,\tau) - \int_0^\zeta\int_0^\tau e^{\nu(\zeta'-\zeta)}V^2 a(\zeta,\tau') \times a^*(\zeta',\tau')b(\zeta',\tau')\mathrm{d}\tau'\mathrm{d}\zeta'. \tag{8}$$

The terms on the left correspond to the initial seed. The integral kernel determines the seed amplification rate.

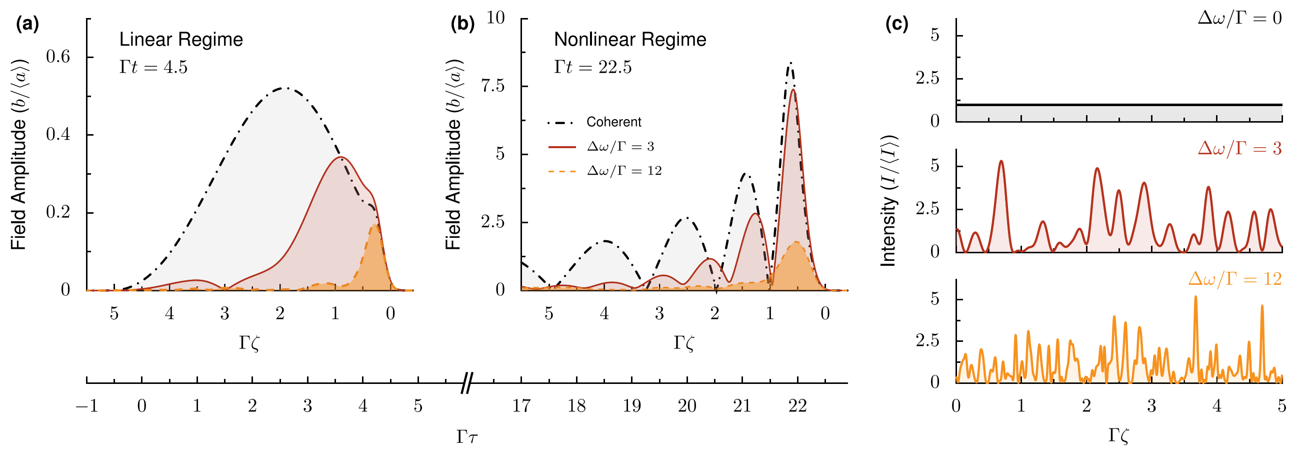

FIG. 1. Three-wave model simulations of Raman amplification with both coherent and incoherent pump beams. (a) Amplified seed shapes in the linear (negligible pump depletion) regime. (b) Amplified seed shapes in the nonlinear (substantial pump depletion regime). (c) Intensity envelopes of the coherent and incoherent ($\Delta\omega/\Gamma = 3$, $\Delta\omega/\Gamma = 12$) pumps used for this simulation. The incoherent pumps have exponentially decreasing correlation functions. Langmuir wave damping is neglected ($\nu = 0$).

In the linear amplification stage, the pump satisfies $a(\zeta,\tau) = a(2\zeta+\tau)$, and the last term in Eq. (8) may be evaluated using $\langle a(2\zeta+\tau')a^*(2\zeta'+\tau')\rangle_{\tau'} = \langle a\rangle^2 g(2\zeta-2\zeta')$ with the quantum regression theorem,[72] yielding

$$b(\zeta,0) = b(\zeta,\tau) - \int_0^{\zeta} \Gamma^2 g(2\zeta-2\zeta')e^{\nu(\zeta'-\zeta)} \int_0^{\tau} b(\zeta',\tau')\mathrm{d}\tau'\mathrm{d}\zeta', \quad (9)$$

where $\Gamma = \langle a\rangle V$ and $\langle a\rangle = \sqrt{\langle |a|^2\rangle}$. A similar equation for the plasma wave dynamics can also be obtained. Equation (9) shows that an incoherent pump beam can amplify a coherent seed if the pump has a non-zero correlation length. The plasma wave damping term multiplies the autocorrelation function in the integral kernel; incoherence and plasma wave damping therefore have a similar effect on seed amplification. The analogy in the underlying physics arises because the plasma wave produced by the beating of the pump and seed drifts out of phase with the pump over the coherence time of the pump, leading to destructive interference and no net interaction beyond the pump coherence length. Similarly, damping of the plasma wave leaves no wave to interact with beyond the damping time.

Equation (9) can be solved using a Laplace transform to find the seed dynamics, yielding:

$$b(\zeta,\tau) = \int_0^{\zeta} G(\zeta-\zeta',\tau)b(\zeta',0)\mathrm{d}\zeta', \quad (10)$$

where $G(\zeta,\tau)$ is the Green's function. We plot in Fig. 2 the Green's functions associated with different pump autocorrelation functions. The plots show that finite correlation lengths reduce the overall rate of amplification. At $\zeta \sim 0$, we find from the integral kernel of Eq. (9) that the Green's function grows proportionally to τ regardless of the incoherence or Langmuir wave damping. Curves in Fig. 2(b) show the shapes of amplified pulses assuming that the seed is short. As with QBRA, reduced growth rates for small t_c correspond to a shift of the pulse maxima towards the wavefront.

To find an effective growth rate, we consider an example of an exponentially decreasing autocorrelation function $g(\zeta) = e^{-\zeta/t_c}$, for which the Green's function is:

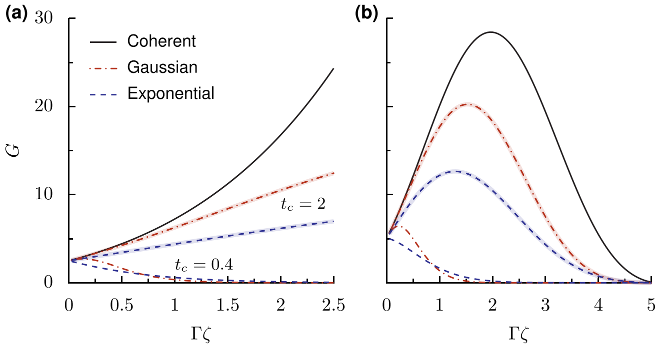

FIG. 2. The Green's functions for pump beams with different autocorrelation functions: $g(\zeta) = 1$ (coherent), $g(\zeta) = \exp(-2\zeta/t_c)$ (exponential), and $g(\zeta) = \exp[-\frac{\pi}{2}(\frac{t}{t_c})^2]$ (Gaussian). In (a), $\Gamma\tau = 2.5$ is fixed. In (b), $\Gamma t = 5$ is fixed. Langmuir wave damping is neglected.

$$G(\zeta,\tau) = e^{-(\nu+2/t_c)\zeta}\partial\zeta\left[I_0(2\Gamma\sqrt{\zeta\tau})\right]. \quad (11)$$

Note that in the case of a coherent pump, i.e., $t_c \to \infty$, this reduces to the QBRA solution.[63] In the asymptotic limit of infinite linear amplification, the Green's function can be approximated as $\exp[2\Gamma\sqrt{\zeta\tau} - (\nu+2/t_c)\zeta]$, from which we find that the seed maximum is located at

$$\zeta_M = \frac{ct}{2}\left(1 - \sqrt{\frac{(\nu+2/t_c)^2}{1+(\nu+2/t_c)^2}}\right). \quad (12)$$

with an amplitude growth rate of

$$\bar{\Gamma} = \frac{\Gamma^2}{(\nu+2/t_c) + \sqrt{\Gamma^2+(\nu+2/t_c)^2}}. \quad (13)$$

In the limit of no damping and a fully coherent pump, the plasma wave, once generated, scatters the pump continuously, producing a monotonically growing wavefront along ζ. For damping and a finite correlation length, the plasma wave scatters the pump only for a finite amount of time and then the interaction stops. This reduces the growth rate at the seed tail; hence, the pulse maximum shifts towards the front and the peak growth rate is reduced.

In the nonlinear regime [Fig. 1(b)], the seed is sufficiently strong to cause substantial depletion of the pump energy; the front of the seed therefore sees a stronger pump and is preferentially amplified, leading to a sharpened wavefront. The compression of the amplified pulses shortens the time over which the pump must retain its coherence with the plasma wave in order for the interaction to be treated as coherent. The key time for determining whether incoherence hinders the amplification process then becomes the duration of the final amplified pulse. Since the pulse duration can reach the order of the inverse plasma frequency (ω_p), which may be several orders of magnitude shorter than the inverse Raman growth time, the regime of efficient nonlinear amplification is much broader than that of linear amplification.

The reduced influence of incoherence in the nonlinear regime can be seen when comparing the linear and non-linear regimes in Fig. 1, where despite the readily visible difference in linear seed growth for a coherent pump and one with $\Delta\omega/\Gamma = 3$, the leading seed spike in the non-linear regime has almost the same amplitude. When the maximum seed intensity is examined as a function of time, as in Fig. 3, it is apparent that when the seed is sufficiently strong to have entered the non-linear regime, the rate at which the seed grows is almost independent of the degree of pump incoherence, even for $\Delta\omega/\Gamma > 12$. The different final intensities in this figure are almost entirely a result of the much lower linear growth rate for incoherent pumps.

PIC SIMULATION RESULTS

To fully simulate the Raman amplification process without the envelope approximation and including bandwidth and detuning effects, we use the fully relativistic PIC simulation code EPOCH.[73] Seed pulses were amplified from 1.4

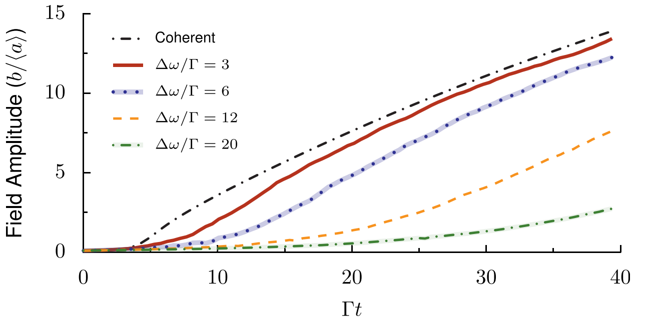

FIG. 3. Maximum field strength of the seed as a function of amplification time for different degrees of pump incoherence from a three-wave simulation of the amplification process. The seed amplitude is normalized by the pump amplitude.

$\times 10^{12}$ W/cm^2 to up to 6×10^{16} W/cm^2 by pumps with wavelength $\lambda_0 = 1\,\mu$m and average intensity 1.4×10^{14} W/cm^2 ($a_0 = 0.01$) in a plasma with density $n_e = 1.1 \times 10^{19}$ cm^{-3} and temperature $T_e = 40$ eV, as shown in Fig. 4 The dimensionless plasma density is $\mathrm{N} = n_e/n_c = 0.01$, where $n_c = m_e\epsilon_0\omega_a^2/e^2$ is the critical plasma density. The incoherent pump beams were produced by adding together 1000 components with frequencies randomly selected from a normal distribution (FWHM bandwidth of $\Delta\omega$), and the simulations

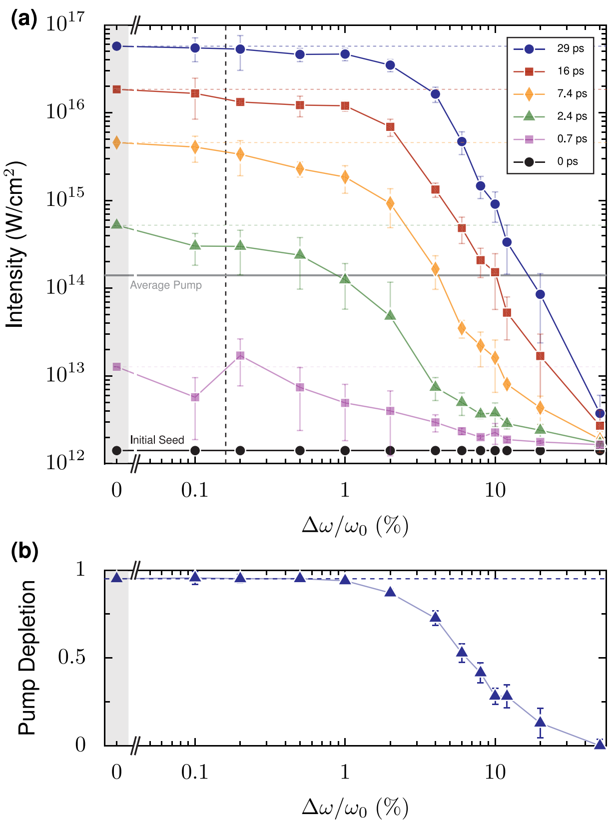

FIG. 4. PIC simulations of amplification with pumps of different degrees of incoherence, characterized by the bandwidth ($\Delta\omega$). (a) Peak seed intensity for different amplification times; the dashed lines show the intensity found in simulations with a coherent pump. $N = 0.01$, $a_0 = 0.01$, $T_e = 40$ eV and the initial seed has a duration of 150 optical cycles and maximum field strength $b_0 = 0.001$. The dashed vertical lines indicate where $\Gamma/\omega = 1$ for these conditions. (b) Efficiency of pump depletion in the non-linear regime for different bandwidths; $\eta = 1 - I_f/I_0$. $N = 0.02$, $a_0 = 0.005$, $T_e = 10$ eV. The initial seed intensity is 150 times the average pump intensity.

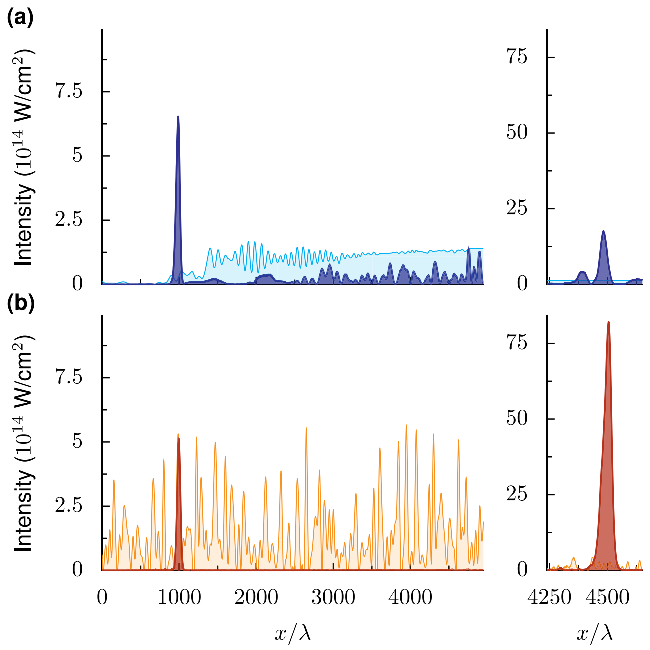

FIG. 5. One-dimensional PIC simulations (EPOCH) with coherent (a) and incoherent (b) pumps showing amplification of a seed (blue, red). In (a), the pump spontaneously scatters from noise, causing pre-depletion of the pump before arrival of the seed and reducing amplification efficiency. At right, the final amplified pulse is much stronger when using an incoherent pump, due to the reduced loss of pump energy. $N = 0.01$, $a_0 = 0.01$, and $T_e = 25$ eV. For (b), $\Delta\omega/\omega = 0.04$. The simulations use 40 particles/cell and 40 cells/λ_0. The initial seed has a duration of 50 optical cycles and maximum intensity equal to the average pump intensity. $\lambda_0 = 1\,\mu$m.

were conducted in a moving window to avoid incoherence-related backscatter suppression. In Fig. 4, each solid line corresponds to the seed intensity reached for different pump bandwidths at after a particular amplification time. Each point represents the average intensity from five separate simulations, to minimize the effect of amplitude fluctuations on growth. The error bars indicate the standard deviation for these five trials, which is higher for shorter amplification times and longer coherence lengths due to the smaller number of fluctuations. The dashed lines and left-most points indicate the amplitudes achieved with a coherent pump.

At $t = 0.7$ ps, all of the simulations are still in the linear regime, with the seed intensity substantially lower than the pump intensity. These points show a strong dependence on bandwidth for $\Delta\omega/\Gamma > 1$. As the amplified seed pulses become more intense than the pump, they enter the non-linear regime, and the dependence of the growth rate on the bandwidth weakens. In the non-linear amplification stage, the efficiency of the interaction can be characterized by the fraction of the pump energy which is transferred to the seed, particularly the energy transferred to the leading pulse. To remove lingering effects of the slower linear growth at large bandwidths, in Fig. 4(b), the simulations are started in the nonlinear regime by taking the initial seed intensity to be 150 times the average pump intensity. These results show a reduction in the sensitivity of the interaction to incoherence, with almost full pump depletion for $\Delta\omega/\omega_0 < 0.02$ ($\Delta\omega/\Gamma < 20$).

This discrepancy in the incoherence thresholds for the linear and nonlinear regimes offers a means to suppress

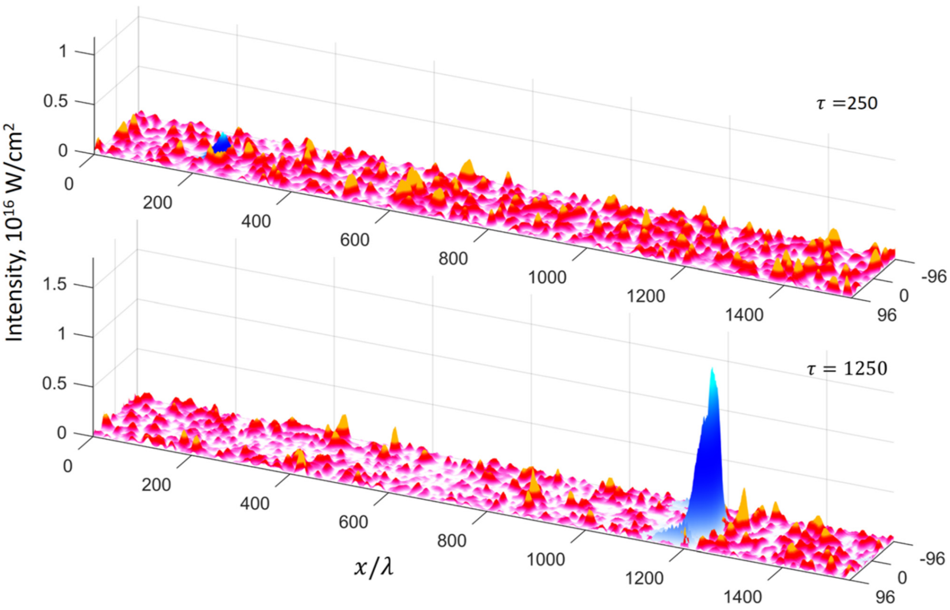

FIG. 6. Two-dimensional PIC simulation of Raman amplification in a spatially and temporally incoherent pump. Intensity envelopes of the pump (red/yellow) and seed (blue) are shown at $\tau = 250$ and 1250. The average pump ($\lambda_0 = 1\,\mu$m) intensity and initial seed maximum intensity were both 5.5×10^{14} W/cm^2 ($a_0 = 0.02$) with $\Delta\omega/\omega_0 = 0.04$ for the pump. The initial seed duration was 160 fs. The plasma properties are $N = 0.02$ and $T_e = 100$ eV, and the simulation uses 16 cells/λ_0 longitudinally and 4 cells/λ_0 transversely.

unwanted seed precursors and parasitic noise-seeded Raman scattering, the implications of which are illustrated by the PIC simulations presented in Fig. 5. Noise-seeded spontaneous Raman backscattering will grow at the effective Raman growth rate $\bar{\Gamma}$, as given for a pump with exponentially decreasing coherence by Eq. (13). However, the amplification of a short, strong seed is not affected by the finite bandwidth. In Fig. 5(a), a significant fraction of the pump is depleted by spontaneous Raman scattering before it has a chance to interact with the seed, leading to a loss of energy and the formation of substantial precursors before the seed. In Fig. 5(b), the finite bandwidth of the pump ($\Delta\omega/\omega_0 = 0.04$) suppresses premature noise scattering. In this case, the final amplified seed is almost four times more intense in the incoherent-pump case; amplification with an incoherent pump is more efficient than with a coherent pump.

Although a one-dimensional treatment captures the interaction between Raman amplification and longitudinal incoherence, the transverse spatial incoherence which may also be present must be considered in at least two dimensions. In Fig. 6, a two-dimensional PIC simulation shows efficient amplification in the presence of substantial longitudinal and transverse incoherence. This simulation is in the non-linear regime, with pump depletion observable after the amplified pulse in the second frame. Each transverse slice of the seed is amplified almost independently; over the length of the amplification, the instantaneous variations in pump amplitude average together. The final transverse profile is therefore not disrupted by the transverse incoherence in the pump, suggesting that plasma Raman amplification can be used for cleaning and compressing a broad range of high energy incoherent beams.

It should be noted that properties useful for amplification are often not ideal for suppression applications. Thus, while the robustness of Raman amplification to incoherence is advantageous for the development of Raman lasers, it may be deleterious for inertial confinement, where a reduced level of Raman scattering is desirable. Although the present work does not directly address incoherence in inertial confinement, it does suggest that complete suppression of Raman scattering using incoherent pump beams will require a rather high degree of incoherence.

CONCLUSION

In summary, we have analytically and numerically investigated backward Raman amplification using incoherent pump beams with different correlation functions and correlation lengths. This analysis suggests the use of moderately incoherent pumps to suppress noise-seeded instabilities like spontaneous scattering and filamentation, and in particular indicates that parametric plasma amplification with quasi-coherent sources like FELs is both feasible and a route to improving the coherence of x-ray sources. Raman amplification is far more robust to incoherence than linear-regime stimulated Raman scattering, permitting amplification to relativistic intensities with pump correlation times on the scale of the inverse plasma frequency.

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