Noise suppression and enhanced focusability in plasma Raman amplifier with multi-frequency pump

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Laser pulse compression–amplification through Raman backscattering in plasmas can be facilitated by using multi-frequency pump laser beams. The efficiency of amplification is increased by suppressing the Raman instability of thermal fluctuations and seed precursors. Also the focusability of the amplified radiation is enhanced due to the suppression of large-scale longitudinal speckles in the pump wave structure. [DOI: 10.1063/1.1621002]

I. INTRODUCTION

The amplification by resonant Raman backscattering in plasmas currently represents one of the most promising ways of generating ultra-intense short laser pulses. Compared to the conventional technique of chirped-pulse amplification, in principle unfocused output intensity can be 10^4–10^5 times higher.[1] In achieving these amplification effects, two optical systems may be utilized: One system for handling high power and fluence, and a second focusing system handling only low power. Since the focusing system does not operate near damage threshold limits nor is subject to thermal stresses, the focusing optics can be optimized for precise focusing.[2] Currently, a number of difficulties exist on the way to the experimental realization of a plasma Raman amplifier. One is propagating an intense laser pump through plasma to the region of interaction with the amplified pulse. For the most promising regimes of amplification, a pump intensity is needed on the order of 10^{14}–10^{16} W/cm^2 with pulse duration of a fraction of a nanosecond.[1] If the plasma cross-section is several centimeters, then tremendous power should be focused in target. For such application however, it is difficult to imagine such an energetic laser pulse using a single laser. However, using an intense pump comprising several laser beams with equal frequencies may not be the optimal solution.

One can imagine a number of difficulties in using multiple pumps. If the pump is formed by multiple but equivalent laser beams, large-scale longitudinal speckles appear in the pump structure. This results in the appearance of a small-scale transverse modulation of the amplified pulse and thus leads to poor focusability of the latter. Also, as an intense pump with a fixed frequency passes through plasma, thermal Langmuir fluctuations[1,3] and seed precursors are amplified by the same Raman mechanism being used for the desired signal amplification.[4] The precursor can absorb a significant part of the pump energy. The pump depletion leads to lower efficiency of the desired pulse amplification and, finally, to lower intensity of the output radiation. Similar problems have been addressed within the context of inertial confinement fusion, where amplification of fluctuations was avoided through various laser beam smoothing techniques.[5,6] However, in the case at hand, where backscatter from thermal fluctuations is to be avoided at the same time that backscatter of the desired seed pulse proceeds, the usual methods of noise suppression do not apply.

In ideally uniform plasmas, the Raman instability of the plasma noise and precursor amplification is suppressed by chirping the pump wave.[1,3] The idea of using a chirped pump can be briefly put as follows. Linear amplification of each spectral component of plasma noise is limited by detuning $\delta\omega$ from the three-wave resonance between the two electromagnetic pulses and the Langmuir wave. Providing that $\delta\omega$ is changing in time because of linear variation of the pump frequency ω_0, each component of the plasma thermal fluctuations spectrum can be amplified only by a finite factor. If that is small enough (meaning that ω_0 is changing sufficiently fast), thermal fluctuations, though amplified, remain in the linear regime and do not deplete the pump wave significantly. On the other hand, nonlinear amplification of the desired signal persists because of the spectral broadening of the latter, as the desired signal is being compressed during the interaction with the pump.

Though efficient for uniform plasmas, pump chirping itself may not provide focusability of the amplified pulse if quasi-static density perturbations are present in plasma. Effectively, density perturbations δn can be considered as additional chirping $\delta\omega \propto \partial(\delta n)/\partial z$, which, since random in the transverse direction, leads to random distortion of the amplified pulse phase front. As shown in Ref. 7, already for $\delta n/n \sim 3\%$ (where n is the mean electron density) with correlation length $l_{\rm corr} = 300\ \mu$m, the desired signal becomes practically unfocusable after amplification. As $l_{\rm corr}$ grows, the maximal possible amplitude of density perturbations allowing decent focusability decreases as $1/\sqrt{l_{\rm corr}}$.[7]

However, there exists an even more strict limitation on the amplitude of quasi-static density perturbations.[7] Even with pump chirping, the presence of those density inhomogeneous results in the development of an instability of thermal Langmuir fluctuations.[8] As follows from Refs. 8 and 9, this noise amplification can be considered as a parametric instability, most dangerous for $l_{\rm corr}\gamma/c \leqslant 2$, where $\gamma = a_0\sqrt{\omega_0\omega_p/2}$ is the linear growth rate of the Raman instability,[1] c is the speed of light, a_0, ω_0 are the amplitude and frequency of the pump and ω_p is the plasma frequency. Already at $\delta n/n = 0.3\%$, noise suppression by means of linear chirping (that is, when $\delta\omega$ is changing linearly on time) becomes inefficient for $l_{\rm corr}\gamma/c \leqslant 1$. In the parameter region of interest (pump intensity 10^{14} W/cm^2, pump wavelength $\lambda = 1\ \mu$m, $n = 7\times10^{18}$ cm^{-3}), this corresponds to $l_{\rm corr} \leqslant 130\ \mu$m.

The paper is organized as follows. In Sec. II we describe the equations being simulated and the used numerical code. In Sec. III we introduce the multiple beams pump (MBP) scheme and discuss its features. In Sec. IV we show how the MBP scheme can be used to enhance the focusability of the seed. In Sec. V we show the noise suppression in plasma with density fluctuations using the MBP scheme. In Sec. VI we show how the idea of MBP can be modified for a single beam pump. In Sec. VIII we suggest a number of practical recommendations for using the MBP and offer conclusions.

II. BASIC EQUATIONS AND CODE OUTLINE

Below, we present the results of numerical simulations of the seed pulse Raman amplification. The numerical scheme involved solving the two-dimensional equations describing the three-wave interaction process:[1]

$$\partial_t a + \partial_z a - i\nabla_\perp^2 a = bf, \tag{1}$$

$$\partial_t b - \partial_z b - i\nabla_\perp^2 b = -af^*, \tag{2}$$

$$\partial_t f + i\delta\omega f = -ab^* + S, \tag{3}$$

where a and b are the amplitudes of the vector potentials of the pump wave and the amplified pulse, respectively, measured in units $m_e c\omega_0/e$, f is the amplitude of the plasma wave electric potential measured in units $(m_e c\omega_0/2e)\sqrt{\omega_p/2\omega_0}$, S is the thermal plasma fluctuations source, the pump frequency ω_0 is much larger than the plasma frequency $\omega_p = \sqrt{4\pi ne^2/m_e}$ and can be considered in all these coefficients equal to the amplified pulse frequency, e and m are the electron charge and mass, respectively; the time t is measured in units $t_0 = \sqrt{2/\omega_0\omega_p}$, the longitudinal coordinate z is measured in units ct_0, the detuning $\delta\omega$ is measured in units t_0^{-1}. We use delta-correlated thermal noises due to the smallest of its correlation radius in comparison with numerical grid step. We could really use a smoother noise distribution because the amplification of high noise harmonic is suppressed due to detuning limitation for linear stage amplification.

In the calculations presented below, the pump wave amplitude is $a_0 = 0.006$ with Gaussian transverse profile with width 10 cm, and the frequency of pump is $\omega_0 = 2\times10^{15}$ s^{-1}. For such parameters, the linear e-folding length, calculated according to the linear growth rate of monochromatic pump backscattering instability $\gamma = a_0\sqrt{\omega_0\omega_p/2}$, is $c/\gamma = 130\ \mu$m. We used the length of plasma 7 mm or $55c/\gamma$. Note that the plasma length is much smaller than the diffraction length $d \approx 10^5$ cm for these parameters. As a result the effect of diffraction is not essential in further simulations but is still included in all cases. However, the diffraction smooths the small-scaled perturbation due to plasma inhomogeneity and so plays a minor positive role. The initial seed pulse had the same transverse Gaussian profile as the pump, but a two-times smaller amplitude and duration of 40 fs (length is 12 μm):

$$b_0 = \frac{a_0}{2} e^{-(t/40\ \text{fs})^2/2} F(r), \quad F(r) = e^{-(r/10\ \text{cm})^2/2}. \tag{4}$$

Numerical simulation was performed by a new very fast (mainly due to parallelizing scheme) hydrodynamic code "MBRS" which was created specifically for BRA simulation. This code allows one to include into consideration a wide spectrum of effects. Three-wave interaction, nonlinearity of EM waves, plasma thermal noises, plasma density fluctuations, plasma wave dumping and wave-breaking (we should note that effects of plasma wave breaking and dumping do not take place for considered range of parameters), transverse broadening due to diffraction and other effects are included in the code at the current time. The structure of the code is such that any hydrodynamic-like effects can be easily included into consideration. The code uses the exact solution of the part of equations (like method of "exponent operator" [10]) to maximize the internal calculation step and reduce the numerical errors. We assume the two electromagnetic waves have equal and opposite group velocities of magnitude c and choose the time step such that $cdt = dz$. The code is fully parallelized for using in computer cluster so that the calculation time of typical two-dimensional (2D) variant with grid size 128×2750 points is 10 minutes or less on 15 processes AMD Athlon 1.7 GHz. Analogous three-dimensional (3D) simulation with grid size $64\times64\times2750$ points takes 8 hours on equal cluster. The code was tested with the program described in Ref. 11.

III. MULTIPLE BEAMS PUMP

We propose a method of efficient compression and focusing in the presence of thermal plasma fluctuations and plasma density fluctuations of arbitrary correlation length $l_{\rm corr}$. The proposed method leads also stabilizes the seed precursors and preserves good focusability of the amplified pulse. The method consists of using a pump wave formed by multiple laser beams of slightly different frequencies $\omega_0 + i\Delta\omega_n$ ($\Delta\omega_n \ll \omega_0$) and wavevectors $\boldsymbol{k}_0 + \Delta\boldsymbol{k}_n$ (Fig. 1):

$$a = \frac{a_0 F(r)}{\sqrt{N}} \sum_{n=1}^{N} \exp(i\Delta\boldsymbol{k}_n\cdot\boldsymbol{r} - i\Delta\omega_n t + i\phi_n), \tag{5}$$

where $\boldsymbol{k}_0 = \boldsymbol{z}^0\omega_0/c$.

As seen from Fig. 2, a mono-frequency pump (of sufficiently small angular spread θ in order few degrees) produces long speckles, which spoil the output pumped pulse

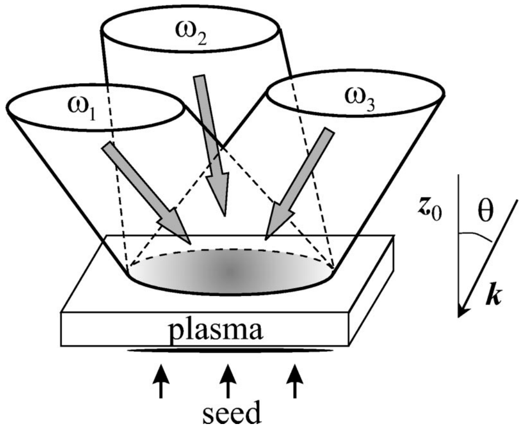

FIG. 1. Schematic of pump incident on plasma.

focusability. A relatively small frequency spread (less or order of the linear growth rate γ) in a multi-frequency pump bends and breaks the speckles.

We expect a twofold effect of such a "mixed" pump. First, the interference of different beams constituting the pump wave enhances the amplified pulse focusability, primarily spoiled by speckled structure of the pump: On each geometric ray of the amplified pulse, the amplification gain is determined by the local (in the transverse direction) pump intensity. If the latter varies significantly across the interaction region, during amplification, the transverse seed structure evolves into multiple, extremely intense peaks. Because of their small spatial scale, each of those diffracts drastically, and thus the whole pulse cannot be focused efficiently into a narrow spot after amplification.

To demonstrate this effect in more detail, one can represent the focused pulse amplitude b_{foc} in terms of the transverse Fourier spectrum of the pumped pulse after plasma, $(b_{\mathrm{amp}})_{\boldsymbol{k}_\perp}$. As can be shown easily for 2D case,

$$b_{\mathrm{foc}}(\boldsymbol{r}_\perp)=2\sqrt{\pi\alpha}(b_{\mathrm{amp}})_{\boldsymbol{k}_\perp=2\alpha\boldsymbol{r}_\perp}, \tag{6}$$

where $\alpha=k_0/F$ is the phase front curvature of the amplified pulse, and F stands for the focal length. From Eq. (6) it follows that the spatial width of the focused pulse is proportional to the spectral width of the pulse before focusing. Thus, narrow peaks in the latter would result in focal spot broadening, i.e., bad focusability of the amplified pulse. Using a pump wave consisting of multiple beams prevents speckles formation because of interbeam phase mixing, which effectively averages out the speckled structure during amplification and thus leads to better focusability. At the same time, the inhomogeneity of the pump phase front itself is "absorbed" by the plasma wave (see Ref. 12), and thus does not impact the phase front of the output radiation.

The second effect produced by multiple pump beams of different frequencies consists of decreasing the amplification gain of plasma thermal fluctuations and seed precursors (considered as a sort of electromagnetic noise). Since each spectral component of plasma noise can be amplified at most by one of the beams, the linear increment of thermal fluctuations exponential growth γ is effectively reduced by a factor of $\sqrt{N}$, since γ is linear with respect to the amplitude of the resonant pump. On the other hand, the nonlinear amplification of the desired signal is determined by its interaction with the whole pump, because of the seed pulse spectrum broadening provided by the nonlinear compression of the amplified pulse. Furthermore, additional chirping of each of the beams is numerically shown to stabilize Raman instability of thermal fluctuations and precursors, and, what is most important, using pump wave formed by multiple beams of different frequencies allows suppressing the parametric instability appearing at $l_{\mathrm{corr}}\gamma/c=1$ (see above).[8]

It is interesting to note that our smoothing technique follows a similar method (the so-called "SSD method"[6]), which was developed for smoothing the radiation envelope compressing an ICF target. This method consists of using laser beams with sinusoidal phase modulation (like we use in Sec. VI). The SSD method leads to breaking the speckles in the pump much like our MBP method. However, the SSD method cannot be used without some modification for seed compression in the BRA scheme. For the purposes of resonant BRA, a small amplitude modulation of the pump phase leads to an insufficient number of harmonics in the pump spectrum. This results in each harmonic having too large an intensity, so that noise effects are important in depleting the pump. An increase of the modulation frequency tends to sup-

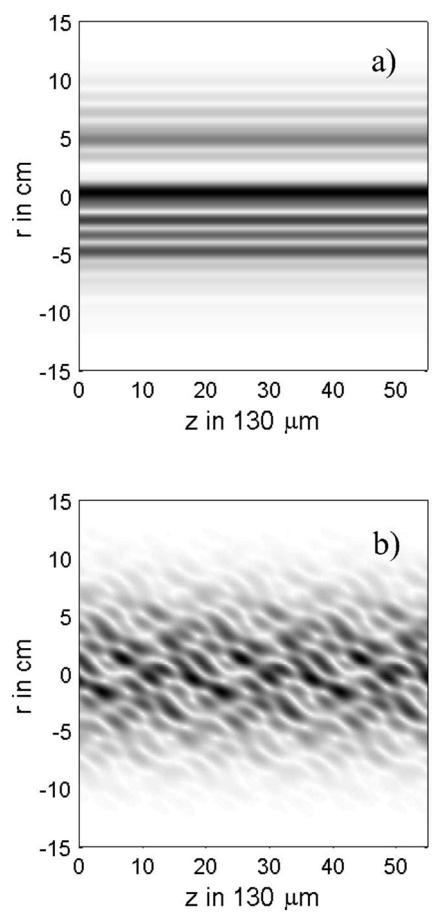

FIG. 2. An example of the spatial intensity patterns for mono-frequency (a) and multi-frequency (b) pumps consisting of seven sub-beams; darker region correspond larger pump intensity. For clarity we use the angular spread 0.1° on this figure.

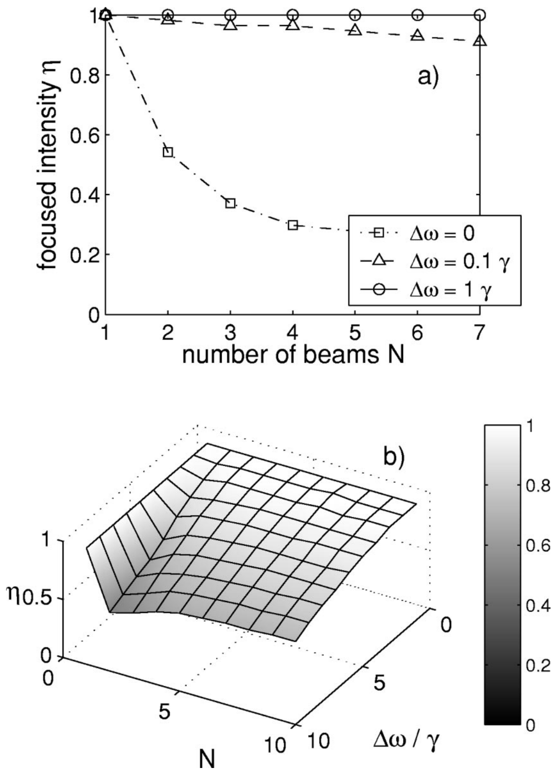

FIG. 3. The relative focused pulse intensity η versus the number of the beams N constituting the pump; $\Delta\omega$ stands for the spectral half-width of the pump.

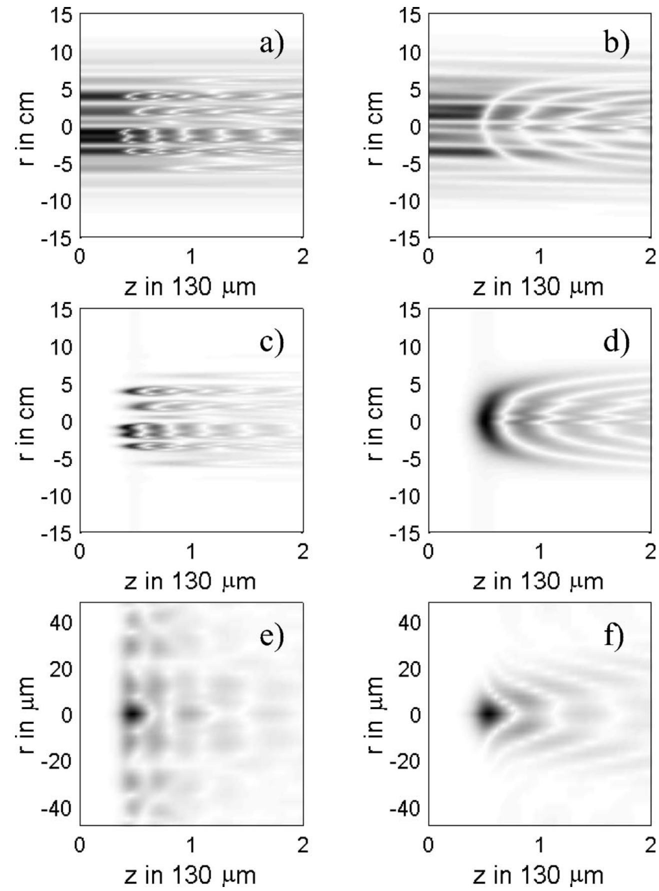

FIG. 4. An example of the spatial distribution of pump amplitude [(a) and (b)], seed amplitude at the plasma exit [(c) and (d)] and at the focus plane [(e) and (f)] for pump beams with equal frequency [(a), (c), and (e)] and for pump beams with different frequencies [(b), (d) and (f)]. Pump contains seven beams. Darker regions correspond to larger pump intensity.

press the noise, but decrease the seed amplification (see Sec. VI). On the other hand, a large amplitude modulation of the pump phase will contains two ultra-intense spikes at its edges, much like the case of only two very intensive ‘‘quasi-monochroamtic beams.'' Each of these beams may suppress thermal noise (although not as effectively as in the MBP scheme), but the seed amplification is not optimal. However, using the SSD method with an additional linear chirping can lead to good noise suppression (as shown in Sec. VI).

IV. FOCUSABILITY OF THE PUMPED PULSE

Consider more specifically the effect of speckles on focusability of the pumped output pulse in a plasma without thermal or quasi-static density fluctuations. Assume also seed precursors to be absent. Figure 3(a) shows the relative focused pulse intensity η which is a fraction of the focused pulse maximal intensity that survives in real pump (compared to ideal nonspeckled pump) as a function of the number of beams N constituting the pump. Here $\Delta\omega$ is the spectral half-width of the pump. For a mono-frequency pump ($\Delta\omega=0$, dashed line), the focused intensity is extremely poor and constitutes less than 30% of $I_{\max}$. However, even a small pump spectrum broadening ($\Delta\omega=0.1\gamma$) leads to substantial focusability enhancement. Spectrum broadening with $\Delta\omega=\gamma$ (solid line) almost completely restores the focusability.

Note that an excessive increase of the pump bandwidth reduces the fraction of pump energy transferred to the pumped pulse because of the detuning out of resonance, which effect can be seen in Fig. 3(b), especially for a pump of two beams. The numerical simulation shows that the efficiency of amplification and, as result, the focused intensity, decreases with increasing spectral width. However, the effect diminishes for a pump containing many beams, since a strong enough seed might absorb energy from several beams in an early stage of amplification.

As example of focusability enhancement, the comparison of focused seed pulses for cases of beams with equal frequencies and with different frequencies is presented in Fig. 4. The darker regions correspond to larger seed amplitude. Note that the use of pump beams with multiple frequencies results in a larger and more highly focused output, which is ever more apparent at the focus plane than it is at plasma exit.

There is an interesting advantage of thermal noise in the plasma. Since the thermal noise depletes the pump preferably when the pump is largest, the pump profile encountering the pulse will tend to be transversely flat. The seed amplified by this pump tends to be easier to focus.

For example, in Fig. 5 we show the comparison between amplification and focusing in the ideal case (without thermal or density fluctuation) and in the presence of thermal fluctuation. The amplitude of the thermal fluctuations corre-

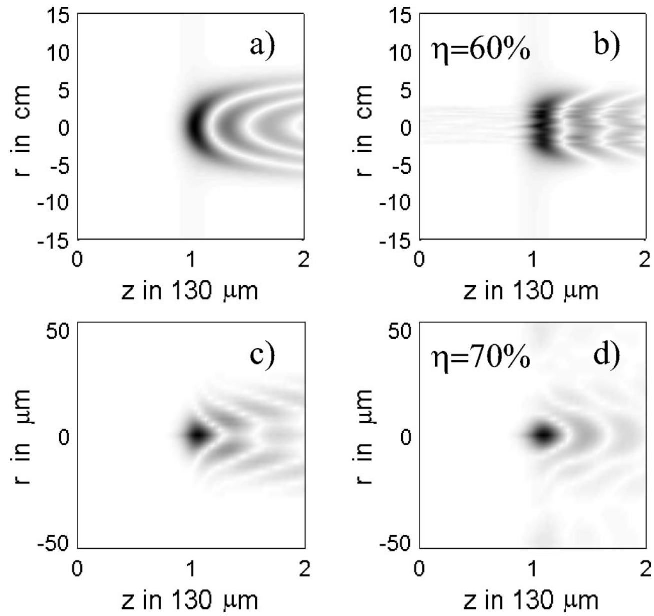

FIG. 5. An example of the spatial distribution of seed amplitude at the plasma exit [(a) and (b)] and at focus plane [(c) and (d)] for the ideal situation [without thermal or density fluctuations, (a) and (c)] and for plasma with noise and density fluctuations [(b) and (d)]. Darker region correspond to larger pump intensity.

sponds to a temperature 40 eV. It is easy to see that, in spite of sufficient losses during amplification (intensity of seed nearly twice smaller), the remaining energy can be better focused. In this case the seed retains an intensity at focus only one-third smaller than in the ideal case.

V. NOISE GROWTH SUPPRESSION

Consider now how the multiple beam pump structure influences the noise amplification. As pointed out above, one of the most challenging problems for the realization of the plasma Raman amplifier consists of suppressing the amplification of plasma thermal fluctuations and seed precursors. Though, in uniform plasmas, this problem can be solved by linearly changing the pump frequency.[1] The presence of plasma inhomogeneities can lead to another parametric instability, completely undermining the stabilizing effect of pump chirping. However, the numerical simulations given below show that using a pump wave formed by multiple beams of different frequencies can suppress this instability. Also the original Raman instability of plasma thermal fluctuations (and seed precursors considered as a sort of electromagnetic noise) is slowed down by a factor of $\sqrt{N}$. Furthermore, chirping each of the beams constituting the pump wave leads to complete stabilization of the noise growth.

Note that one needs the pump bandwidth to be as wide as possible in order to avoid backscatter from noise in the linear regime of amplification. On the other hand, the bandwidth should be small enough so that the amplification of the useful seed, which is already in a nonlinear regime, is not disturbed. There is a window of opportunity to accomplish this, because the useful bandwidth of the pump in the nonlinear stage is increased with increasing seed intensity. However, for the linear stage (for thermal noise) the amplifiable bandwidth is small enough (on the order of γ).

We found numerically that, for plasma length of 55 increments, the optimal bandwidth for efficient BRA is of order of $\Delta\omega = 2*10\gamma$. Moreover, we note that for a small number of beams (less than 7...10), the dominant parameter is the frequency difference between each two beams. For this case, the efficiency decreases with decreasing the number of beams. For the opposite case of a large number of beams (more than 10), the dominant parameter is the maximum bandwidth of the full pump frequency spectrum for which the seed is still well amplified. For a large number of beams, the efficiency of BRA will not depend on number of beams. The examples simulated employ a "critical" number of beams (equal to 7, which is essentially a large number) and for a small number of beams (equal to 3).

The numerical simulations given below demonstrate the benefits of using a "mixed" pump in plasmas with thermal fluctuations and precursors. Calculations were performed for plasma with temperature of 40 eV for pump containing $N = 7$ beams with frequencies equally distributed over the interval $(-\Delta\omega, \Delta\omega)$ with random phases ϕ_n and equal chirping:

$$a = \frac{a_0 e^{iq\gamma^2 t^2/2} F(r)}{\sqrt{N}} \sum_{n=1}^{N} \exp(i\Delta \boldsymbol{k}_n \cdot \boldsymbol{r} - i\Delta\omega_n t + i\phi_n), \tag{7}$$

where q is the conventional parameter that determines the chirping rate.

The results for homogeneous plasma are given in Fig. 6. As stated above, in this case, a chirped pump provides better noise suppression in comparison with a pump formed by multiple laser beams of different frequencies. The optimal value of the parameter of pump chirping q coincides with the one predicted in Refs. 1 and 3. Including small precursors into the model (with the total energy equal to 10% of the original seed energy) does not influence significantly the amplification and the compression of the desired signal as can be seen from Fig. 6(b). Numerical simulations show that about 70% of the total pump energy can be transferred to the focusable part of the amplified seed.

The addition of small random density perturbations $\delta n/n = 1\%$ decreases the efficiency of the chirped pump scheme dramatically. Even for large-scale perturbations with $l_{\mathrm{corr}} = 300\ \mu\mathrm{m}$ (Fig. 7), a significant drop of the focused pump intensity can be seen in the case when the conventional chirped single-beam pump is used. Namely, less than 20% of the total pump energy is transferred to the focusable part of the amplified pulse. However, the multiple-beams scheme with $N = 7$ results in about 50% of the maximal energy in focus, both with and without precursors. The optimal conditions, which readily follow from the results given in Fig. 7 are the following: $\Delta\omega = 7 - 8\gamma$, which corresponds to a 2γ frequency difference between each two beam frequencies. The optimal values of chirping parameter q has range $q \approx 0.05 \ldots 0.1$. Note that the optimal value of q for the multiple-beam pump is 3...4 times smaller than the one for

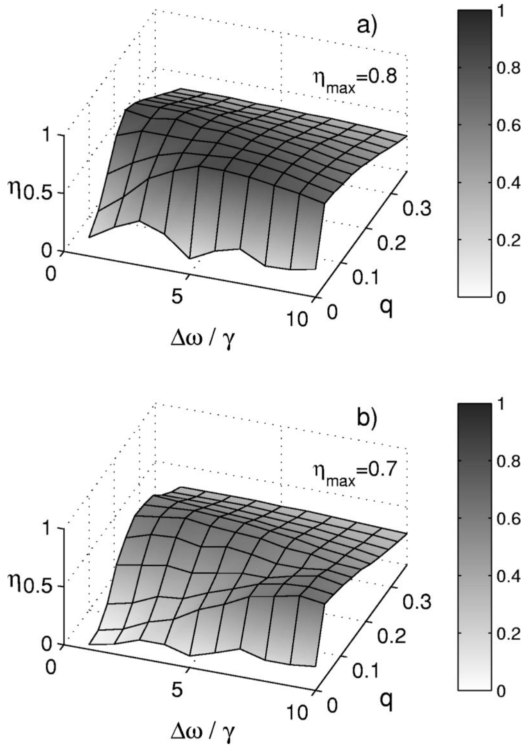

FIG. 6. The focused pulse relative intensity η versus the parameter of pump chirping q and the pump spectral width $\Delta\omega$. The plasma thermal fluctuations are calculated for electron temperature 40 eV; no quasi-static density perturbations are present ($\delta n/n=0$): upper figure—no precursors, lower figure—precursors included.

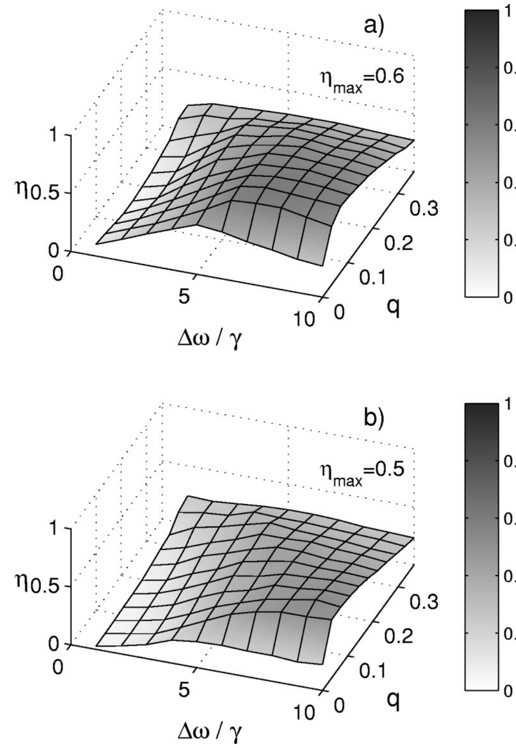

FIG. 7. The focused pulse relative intensity η versus the parameter of pump chirping q and the pump spectral width $\Delta\omega$. The plasma thermal fluctuations are calculated for electron temperature 40 eV; quasi-static density perturbations are present with $\delta n/n=1\%$ and the correlation length $l_{\mathrm{corr}}=300$ μm: upper figure—no precursors, lower figure—precursors included.

the conventional single-beam chirped pump in homogeneous plasma.

A similar picture can be seen for a plasma with a smaller correlation length of quasi-static density perturbations. But, the efficiency of a chirped pump shows a greater decrease. It can transfer less than 5% of pump energy to the focused part of seed. However, the multiple-beams scheme with $N=7$ still results in about 50% of the maximal energy in focus, both with and without precursors. The optimal conditions also stay the same as previously. The results of numerical simulations with $l_{\mathrm{corr}}=130$ μm are presented in Fig. 8. We can see even a small increasing of focused intensity η in comparison with a case shown on Fig. 7. This takes place due to the following. The small density modulation has a similar effect as some detuning due to pump chirping and helps to slightly suppress the noises when the parametric instability is absent.

Decreasing the number of beams is not recommended, since increasing the intensity of each beam leads to a higher growth rate of noise. This fact is demonstrated in Fig. 9. But even here, the amplification efficiency reaches 40%. This is twice as high than for a pump containing only one beam with chirping. The optimal parameters of the pump differ from the case of $N=7$. Better spectral width has a value close to $\Delta\omega\approx 3\gamma\ldots 6\gamma$, which corresponds to a $2\gamma...4\gamma$ frequency difference between each two beam frequencies. The optimal values of the chirping parameter q has range $q\approx 0.15\ldots 0.25$ greater than in the case of seven beams in a pump.

VI. SINGLE BEAM WITH COMPLEX CHIRP

Similar effects could be achieved by a single-beam pump chirped in such a manner that its spectrum contains many frequencies, similar to the spectrum of pump containing several beams. For example, the spectrum of the pump in the form

$$a=a_0F(r)e^{iq\gamma^2t/2+i\alpha\sin\omega_s t}, \tag{8}$$

can be easily found via Bessel functions. For example, in Fig. 10 we present the spectrum for $\alpha=1.5$. It is easy to see that this spectrum has only three large enough harmonics and is qualitatively similar to the spectrum of a pump containing three beams with a constant frequency difference ω_s between each of them. As a consequence, we can expect that the pump in form (8) will have an effective noise suppression similar to a pump containing three beams (Fig. 9). We made a numerical simulation and obtain the similar figure (Fig. 11).

Increasing of the parameter α or the number of harmonics of the pump phase may lead to further increases of the relative intensity η. As in the case of several beams we can achieve relative intensity at level of 60%. At the same time, for a wider pump spectrum (8) the picture becomes sensitive to the variation of parameters (α or frequencies of pump phase). This small variation can sufficiently change the relative intensity η up to 2...3 times. So devices which prepare the necessary phase of a single beam should be very precise. Increasing the parameter of linear chirping q makes the fig-

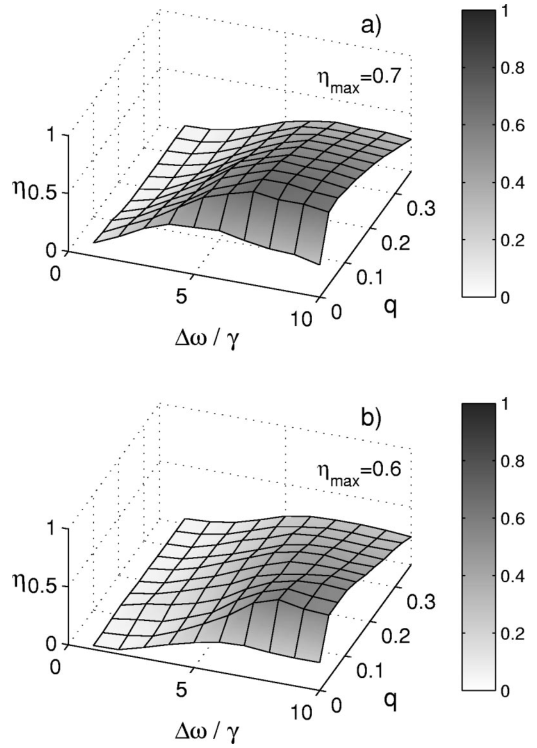

FIG. 8. The focused pulse relative intensity η versus the parameter of pump chirping q and the pump spectral width $\Delta\omega$. The plasma thermal fluctuations are calculated for electron temperature 40 eV; quasi-static density perturbations are present with $\delta n/n=1\%$ and the correlation length $l_{\mathrm{corr}}=130\ \mu$m: upper figure—no precursors, lower figure—precursors included.

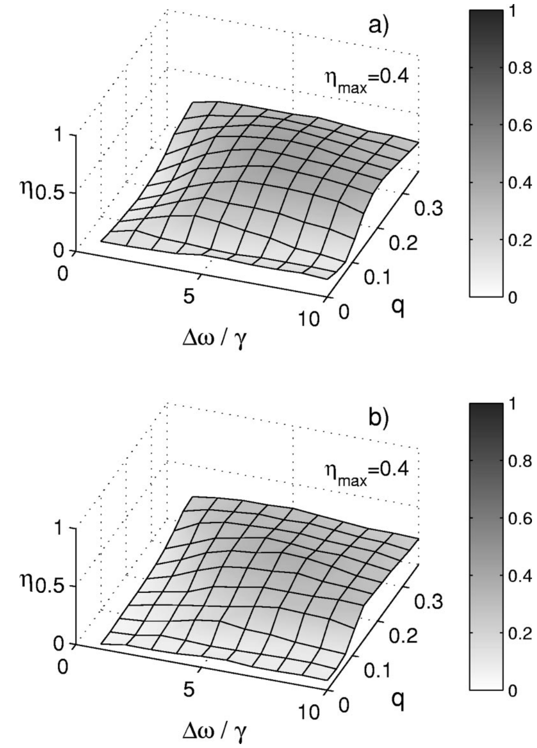

FIG. 9. The focused pulse relative intensity η versus the parameter of pump chirping q and the pump spectral width $\Delta\omega$ containing three beams. The plasma thermal fluctuations are calculated for electron temperature 40 eV; quasi-static density perturbations are present with $\delta n/n=1\%$ and the correlation length $l_{\mathrm{corr}}=300\ \mu$m: Upper figure—no precursors, lower figure—precursors included.

ures smoother but decreases the maximal relative intensity η to level 40%...50%, which is close to that shown in Fig. 11. Decreasing the parameter α is not recommended because the pump spectrum becomes too tight and no longer stabilizes the parametric instability.

For example, in Fig. 12 we present the result of numerical simulation for a pump with phase containing two sinusoids with different frequencies and linear chirping:

$$a=a_0F(r)\exp(i\alpha\sin\omega_{s1}t+\alpha\sin\omega_{s2}t+iq\gamma^2t/2). \quad (9)$$

As earlier we see practically the absence of useful seed amplification for the case than only linear chirping is present with frequencies $\omega_s=0$. For low values of linear chirping q we see a rather complex distribution with narrow peaks. The value of focused intensity is sensitive to a small variation of frequencies ω_s or parameter q. With the increase in the linear chirping, the distribution becomes smoother but the maximum of focused intensity decreases. As a result, the focused intensity will have the values close to the case shown in Fig. 11, i.e., to a level of 40% in optimal case.

The physical picture of the process is also rather clean. Let us consider a pump (8) with defined parameter $\alpha=1.5$ and some small enough chirping q. First of all, the strong sinus chirp of the pump phase will prevent the appearance of the parametric instability, but there will be still dangerous places where the frequency of pump varies slowly. These places lie in the maximums of sinus (Fig. 13). In the case of linear chirping absence, a noise with frequency $\delta\omega\approx4\gamma$ can be effectively amplified along all the maximum. The exponential growth of these noises will be weaker than in the case of an ideal pump but fast enough. As a result, the pump will be rather depleted. The appearance of small linear chirping will shift the cosine maximums in the vertical direction so that noises in the linear stage can grow only on a limited number of maximums. So the presence of linear chirping will limit the number of dangerous maximums for each noise wave by three for this example. Other maximums will have large enough detuning and will not influence this noise wave.

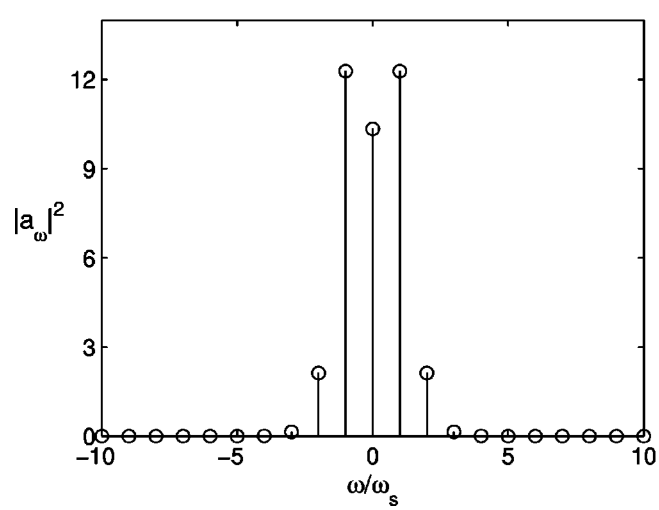

FIG. 10. The spectrum of pump (8) for $\alpha=1.5$ and $q=0$.

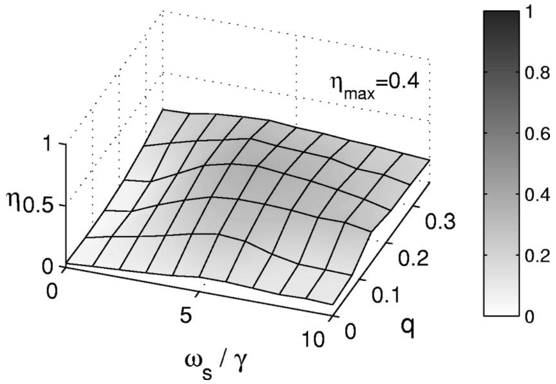

FIG. 11. The focused pulse relative intensity η versus the parameter of pump chirping q and the pump spectral width $\Delta\omega$ in form (8) for $\alpha = 1.5$. The plasma thermal fluctuations are calculated for electron temperature 40 eV; quasi-static density perturbations are present with $\delta n/n = 1\%$ and the correlation length $l_{\mathrm{corr}} = 300$ μm, precursors included.

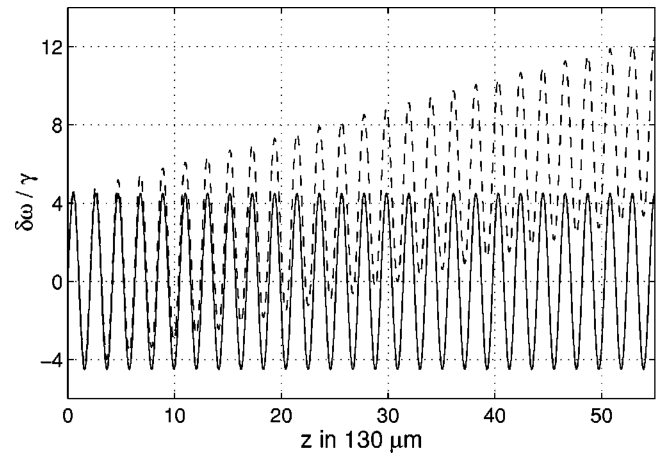

FIG. 13. The scheme of dangerous places on phase chirped with sinus with (dashed line) and without (solid line) linear chirping. The sinus frequency is $\omega_s = 3\gamma$ and parameter $\alpha = 1.5$.

As a result the growth of noises will be stabilized. Of course, this stabilization will be worse than just chirp stabilization in a homogeneous plasma, but in contrast to linear chirp, the combined (sinus and linear) will still work in inhomogeneous plasma.

The only limitation of this scheme (scheme of combined chirping) is amplification of the useful seed. A high enough frequency of sinus chirping will prevent not only noise growth but also the seed amplification. So there are some windows in the parameters. Numerical simulation gives us the optimal parameters of sinus frequency as $\omega_s = 4...6\gamma$ for $\alpha = 1.5$. The value of chirping q has wider diapason $q \approx 0.15\ldots0.25$. This region of parameters provides amplification efficiency at level 40%. These optimal parameters are close to the optimal parameters of a pump containing three beams. This fact is a direct consequence of the similarity between the MBP scheme and a scheme of combined (linear and sinusoidal) chirping noted above.

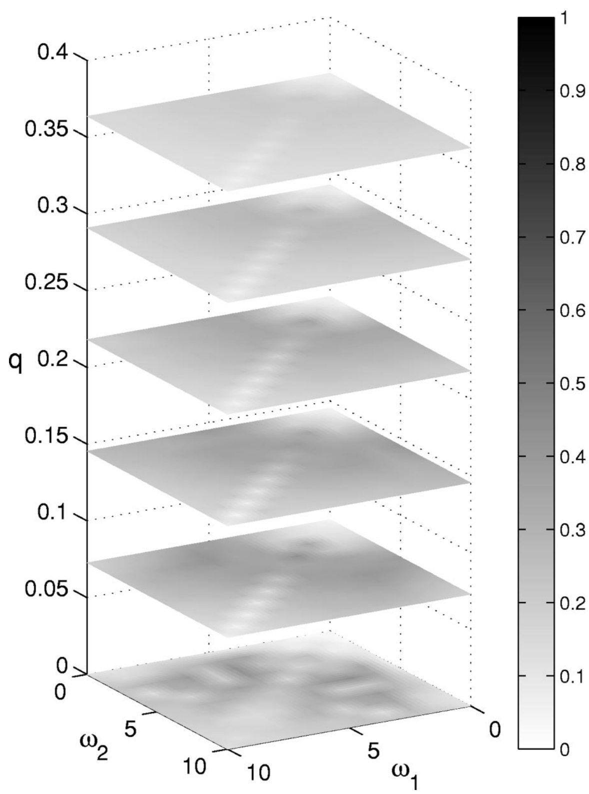

FIG. 12. The focused pulse relative intensity η versus the parameter of pump chirping q and the frequencies ω_s for pump in form (9) with $\alpha = 0.5$. The plasma thermal fluctuations are calculated for electron temperature 40 eV; quasi-static density perturbations are present with $\delta n/n = 1\%$ and the correlation length $l_{\mathrm{corr}} = 130$ μm, precursors included.

VII. DISCUSSION AND CONCLUSION

A number of practical recommendations for experimental realization of the plasma Raman amplifier with multiple-beam pump flow from these results. First, consider those connected with pulse focusability. In uniform plasma, where the influence of thermal fluctuations and seed precursors instabilities is negligible, the focusability itself is relatively easy to provide. As seen from the numerical simulations presented above and those obtained but not included in this paper, two beams with frequency difference $\Delta\omega \approx 0.1\gamma$ are already enough to prevent the appearance of large-scale speckles in the pump structure and provide almost ideal focusability with efficiency $\eta > 90\%$.

On the other hand, suppressing the instability of plasma thermal fluctuations, which is the second reason for using multiple-beam pumps, represents a much more significant challenge. First of all, in order to deal with those, a large number of beams is found to be necessary in order to decrease the linear increment of Raman instability by distributing the pump energy over a larger bandwidth (which scales like $1/\sqrt{N}$, as discussed above). On the other hand, distributing the pump energy over too wide a bandwidth will result in poor absorption of the pump by the desired signal, which would lead to inefficient amplification of the latter. The optimum for constraining the amplification of thermal fluctuations, while sustaining decent amplification gain of the desired signal, was numerically found to correspond to $N = 7-10$ beams, distributed over the spectral width $\Delta\omega \sim N\gamma$. However, if one uses a sufficiently intense seed, which enters the nonlinear amplification stage from the very beginning of the interaction process, the number of the beams can be made larger and the pump bandwidth can be increased proportionally. In this case, because of a broader spectral width of the desired signal, amplification by a larger number of pump beams can be sustained, while the growth of plasma thermal fluctuations will be slowed down inverse proportionally to a larger $\sqrt{N}$.

Another parameter, which can also be optimized in order to achieve better results for Raman amplification of the desired signal, is the pump frequency chirping q. Two major limitations are imposed. First of all, q cannot be too large, since, at larger q, the pump propagates through the seed pulse without substantial absorption, and the efficiency of the desired signal amplification decreases significantly. On the other hand, sufficiently large chirping is needed in order to stabilize the instability of the plasma thermal fluctuations together with parasitic amplification of seed precursors. With these limitations taken into account, the optimal value of the parameter of chirping found numerically is $q \leqslant 0.1$, which, though it varies slightly depending on plasma parameters, is significantly smaller than the one predicted for homogeneous plasma.[1,3]

Summarizing, we suggest a novel concept of a so-called mixed pump for the promising scheme of short ultra-intense laser pulses amplification by Raman backscattering in plasmas. A mixed pump represents a superposition of several laser beams of slightly different frequencies and allows a number of advantageous properties of the desired signal amplification. Among those, using a mixed pump can result in decreasing the growth rate of the instabilities of plasma thermal fluctuations and seed precursors, while simultaneously providing enhanced focusability of the desired signal. Combining the multiple beam scheme with small chirping of each beam has a cumulative effect that effectively suppresses the noise amplification in nonuniform plasmas where using the conventional single-beam pump is not efficient. Even with thermal fluctuations and seed precursors, a mixed pump can result in the transfer up to 50% of the pump wave total energy into the well-focusable part of the amplified pulse.

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