Compression of High Power Lasers in Plasma

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Abstract.
While achievable laser intensities have grown remarkably during recent years, mainly due to the method of chirped pulse amplification, to attain very much higher powers would demand suitable material gratings for handling very high power and very high total energy. However, plasma is an ideal medium for processing very high power and very high total energy, making feasible, in principle, much higher laser intensities than might otherwise be contemplated. The idea in plasma is to store energy in a long pump pulse which is quickly depleted by a short counterpropagating pulse. This counter-propagating wave effect has already been employed in Raman amplifiers using gases or plasmas. At very high power, there are nonlinear effects in plasma that enter which make such methods particularly suitable for high power pulse compression.

INTRODUCTION

Laboratory laser intensities have grown remarkably during recent years due to the method of chirped pulse amplification (CPA) [1, 2]. In CPA, optical gratings are used to strech a short pulse, separating it into its frequency components. A broadband optical amplifier is then employed to amplify the low-powr stretched signal. Complementary gratings then reconstitute the original, but now highly amplified, signal. This method has been extraordinarily successful, but it does require a final material grating subject to fluence limits. Currently, gratings for 1 μ light are imagined to be limited to the range of several J/cm^2. The method also requires uniform amplification over a larger bandwidth.

For example, using CPA technology, a 100 fs pulse can be expanded to 1 ns, pumped to 1 J/cm^2 and then recompressed to 100 fs, giving output intensities of 10 TW/cm^2. Using 10^3 cm^2 gratings, 1 kJ of laser power can then be delivered in 100 fs for an output power of 10 PW. With a vacuum focus to say a spot size 30 $\mu \times 30$ μ, *i.e.*, focusing by a factor of 10^8, intensities of 10^{21} W/cm^2 can be attained. However, the use of 10^3 cm^2 gratings withstanding fluences of 1 J/cm ^{2}, while feasible, is expensive and technologically challenging. Using CPA to attain much higher power will require gratings that will eventually be too large to produce. Moreover, for high power at wavelengths shorter than a micron, it would be necessary also to develop lasers, amplifiers, and gratings operating efficiently at short wavelengths. Whereas at one micron, fluences of several J/cm^2 can be contemplated, at shorter wavelengths, only much lower fluences can be imagined.

Yet plasma is an ideal medium to form a grating capable of processing very high power and very high total energy. We have in mind compression of powers to exawatts per square cm or fluences to kilojoules per square cm, prior to the vacuum focus. For energy applications, pulse compression does not need high fidelity within each frequency range. It turns out that the limiting effects in plasma are the nonlinear effects associated with nearly relativistic electron velocities in the wave fields; hence, at higher frequency, the plasma is even more capable of processing high power, since the velocities in a constant power laser scale inversely with frequency. Thus, plasma is ideal for applications for delivering simply the highest possible power.

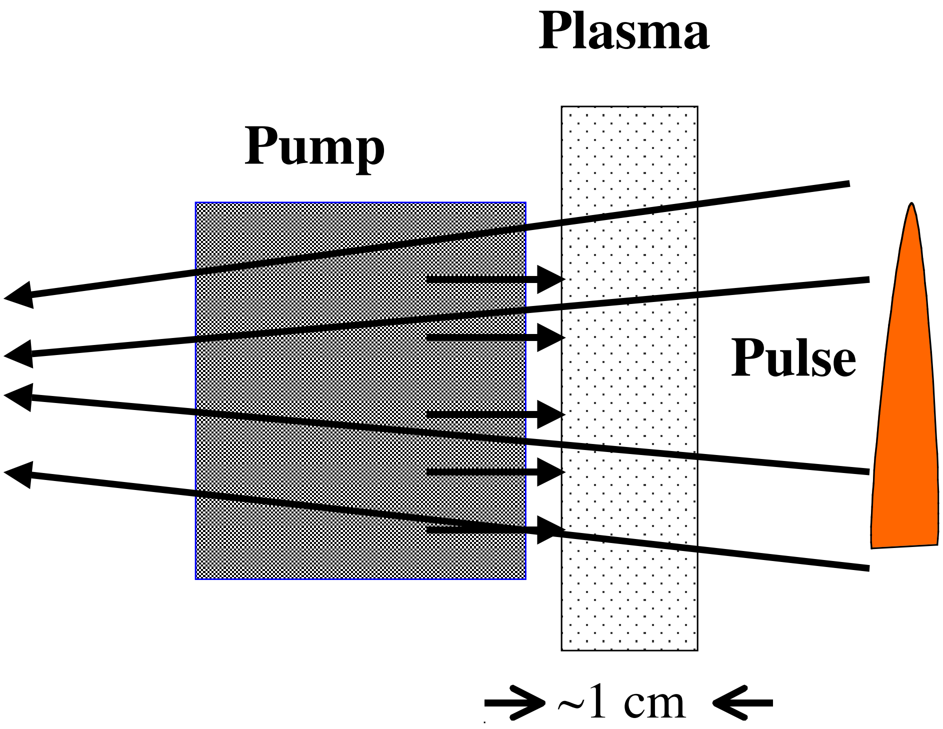

FIGURE 1. Schematic of the counter-propagating geometry: pump laser, about twice the 1 cm plasma length, travels to the right; a counter-propagating seed pulse interacts with the pump, and is timed to enter plasma just as pump leaves plasma; and the pulse is depicted as focusing to point beyond plasma.

The basic geometry for the use of plasma is shown in Fig. 1. A long pump laser loses its energy to a short counter-propagating short pulse, with the plasma serving as a coupling medium between the two lasers. Pulse compression occurs, since most of the energy of the long pulse then resides in the short pulse. Several effects in different plasma regimes can be contemplated to produce this backscattering compression. However, in addition to an efficient backscattering of pump energy into the short conterpropagating wave, several issues must be resolved successfully before the compression effect can be considered useful. For the compression effect to occur altogether, it important that the short pulse not only deplete the long pump pulse, but that it remain short as it propagates through the long pump. In fact, there are a number of pulse lengthening effects that must be avoided. Also, as can be seen from Fig. 1., the pump must propagate through transparent plasma to the seed pulse, without encountering deterioration. The pulse must not only be stable during amplification, but it also must retain its focus as it leaves the plasma. It turns out that the stability of the pulse is the major limitation on the plasma length. Thus, as soon as the pulse experiences instability, the plasma must be terminated, and the amplified pulse, however much it has been amplified, must be extracted from the plasma.

This paper briefly reviews some of the important issues in achieving useful pulse compression effects.

REGIMES OF PULSE COMPRESSION

Plasmas have, in fact, long been contemplated as media suitable for compressor/amplifiers. In particular, the compression of laser light through Raman backscatter has been suggested in gases, liquids and plasmas via the counter-propagating wave geometry depicted in Fig. 1. An early review of pulse compression of excimer lasers in gases is given by [4]. The advantages of using plasma were recognized by Capjack et. al [5]. Raman compression in gas mixtures, from tens of nanoseconds to tens of picoseconds, has been achieved at about 25% efficiency for energies in the range of 0.1 to 10 J [6, 7].

In the counter-propagating geometry, the energy is stored in a long low-intensity pump pulse, or possibly a train of low-intensity pump pulses. The short counterpropagating pulse, or “pumped pulse", can achieve intensities far higher than the pump pulse, so long as it remains short. Of course, for very high powers, Raman media other than plasmas will not be practicable. The early work on compression in plasma was focused on low-power regimes, where the Raman backscattering took place in the stationary regime, namely where the plasma wave was highly collisionally damped. The issues that plagued this early work in plasma were the stringent requirements on plasma homogeneity (because of narrow-bandwidth amplification) and because the amplification lengths were long, in part due to the collisional damping that reduced the efficiency of the interaction.

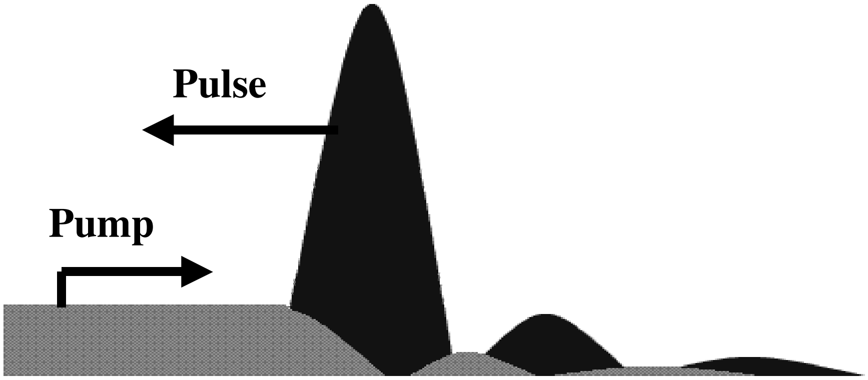

FIGURE 2. Depletion of pump by short pulse in time-asymptotic limit in resonant Raman backscattering regime.

However, at very high power, there are nonlinear effects that enter which may make for better compression. At high power the wave backscattering tends to occur faster, while the large velocities of electrons oscillating in the wave fields tend to reduce collisonal damping. There are several mechanisms by which the pump power might be coupled into the counterpropagating pulse. One coupling mechanism involves a so-called "superradiant" or Compton scattering, where the nonlinear interaction of the plasma electrons with the lasers dominates the plasma restoring motion due to charge imbalance [8]. A second mechanism is resonant backward Raman scattering (see Fig. 2), which can occur fast enough that the amplification process outruns deleterious processes associated with the ultraintense pulse [9]. A third mechanism involves coupling at an ionization front [10].

In the Compton scattering regime, the counter-propagating waves are coupled to each other by electrons that execute nonlinear motion in the beats of the counter-propagating waves. The restoring force arising from the displacement of electrons from positive charge centers is essentially negligible. In this regime, the pump laser is of somewhat higher frequency than the pumped laser; the pulse length of the pumped pulse is less than a plasma length, c/ω_p; and the laser intensities satisfy $ab > \omega_p^2/4\omega^2$, where a and b are the pump and pumped pulse normalized vector potentials. In this regime, a short weak pulse can be very significantly amplified, but the pump depletion tends not to be complete. Of course, as the amplified pulse intensity grows, the pump depletion becomes greater. For small pump depletion, under Compton scattering, the pulse energy grows like $z^{3/2}$, where z is the distance into the plasma. The available pump energy for depletion grows like z, so the depletion fraction grows like $\sqrt{z}$. The numerical example quoted in Ref. [8] gives about 40% pump depletion. At issue, however, is whether the short pulse can grow to large enough amplitude to deplete the pump before the pulse itself succumbs to modulational [11, 12] or other instabilities. The advantage of this regime, however, may be that exact resonance is not required.

On the other hand, in the Raman scattering regime, where resonance is required, it can be shown that the pulse grows so fast that it can outrun the deleterious instabilities. As shown in Ref. [9], within several growth times of the deleterious instabilities, the pulse grows to amplitudes far exceeding the instability thresholds, *i. e.*, to overcritical powers. Pump depletion quickly ensues, so that the efficiencies are limited in principle only by the so called “Manley-Rowe” relations; in other words, since a pump photon is converted to a counter-propagating pulse photon downshifted by the plasma frequency, the fraction of pump energy that will be left in the plasma wave is ω_p/ω. Typically, this fraction would be about 1/10. The remaining 90% of the pump power can, in principle, be converted entirely to the backscattered short pulse.

In this resonant Raman scattering regime, there are many laser wavelengths in the pump pulse and at least several laser wavelengths in the short seed pulse. Hence, the solution to these equations may be envisioned as the interaction between slowly-varying wave envelopes. This interaction between the pump and pulse wave envelopes is shown schematically in Fig. 2. Here the right-going pump is depleted as it encounters a left-going short pulse. Note that both the pump and the pumped pulse envelopes assume a fluctuation in amplitude. Note too that there is virtually no pump energy going off to the right after the encounter with the pulse. This is the well-known “π-pulse” solution, which is a self-similar solution for the three-wave coupled equations of a constant pump encountering a very short counterpropagating downshifted seed pulse [9]. Moreover, it is an attractor solution, in the sense that many initially prepared waves will evolve to the same asymptotic state. What happens is that the pump amplifies the leading edge of the seed pulse, which consumes all the pump energy, with ω_p/ω of the pump energy going into the Langmuir wave. Since the pump is effectively depleted by the leading edge of the seed, the trailing edge of the seed is shadowed, resulting in a reshaping of the seed pulse so that it narrows as it grows. Also, after the pump depletes, the amplified pumped pulse, together with the generated Langmuir waves, regenerate the pump wave via the same 3-wave interaction. The regenerated pump, moving to the right, subsequently decays into the another Langmuir phonon and counterpropagating pulse photon, with the process repeating until no pump energy remains. This repetition results in the the characteristic amplitude variation of the pump and seed pulse in the π-pulse solution.

Both the Compton scattering regime and the resonant Raman backscattering regime require, at least in the most simple implementation, that the pump traverse the plasma before encountering the pulse. The pump length is then optimally twice the plasma length, with the pump front leaving the plasma just as the seed pulse enters the plasma, and with the pump tail entering the plasma just as the amplified seed leaves the plasma slab. Thus, compressing a 50 ps pump requires a plasma length of about 1 cm. In the case of resonant Raman backscattering, with say ω_p/ω about 0.1, the plasma electron density must be about $10^{19}\mathrm{cm}^{-3}$. If the pump were at 10^{14} W/cm^2, the compression could give output pulses of 10^{17} W/cm^2. The Compton scattering regime might be accessed at much lower plasma density, depending upon the pump and pulse intensities.

In traversing the plasma, which could be noisy, the pump is subject to collisionless instabilities, such as Raman backscattering and forward scattering. One way to avoid the issues in pump traversal of the full plasma is to inject the pump somewhat from the side of the plasma. However, that can be quite complicated, since the interaction region is moving axially. In the case of ionization-front scattering, this issue is avoided, since the pump propagates through a neutral gas. The ionization front is formed by the high power pulse, as it traverses the same gas. Once the plasma is formed, the coupling can occur by means of the resonant backward Raman backward scattering effect. However, to avoid ionization in cases of typical interest, it may be necessary to employ lower pump power densities, say about 10^{12} W/cm^2. The lower pump power density would imply that the interaction length to achieve the output power of the above example would have to be on the order of a meter rather than a centimeter. However, in a gas, the longer interaction length is still quite practicable.

The compression effect is likely best achieved through the careful preparation, alignment, and timing of a counterpropagating seed pulse. However, more advantageous scenarios might also be imagined. For example, it would be to great advantage if the timing could be achieved automatically, i. e., if the backscattered wave arose spontaneously at just the right spot and time in the plasma, namely just at the point of the pump front as it is about to exit plasma. In principle, backscattering off of stationary plasma oscillations near the plasma exit could accomplish this (see Fig. 3). The seed is then the plasma oscillation, which has nearly vanishing group velocity, and hence does not need to be timed precisely. The backscattered pulse is then generated by the same resonant backward Raman scattering process off of a prepared plasma wave, acoustic turbulence, or any other slow moving plasma perturbation. While this method, in principle, is the most simple to implement, it is an open question whether the simplified method can result in a backward-propagating seed signal with the correct parameters to enter into a useful

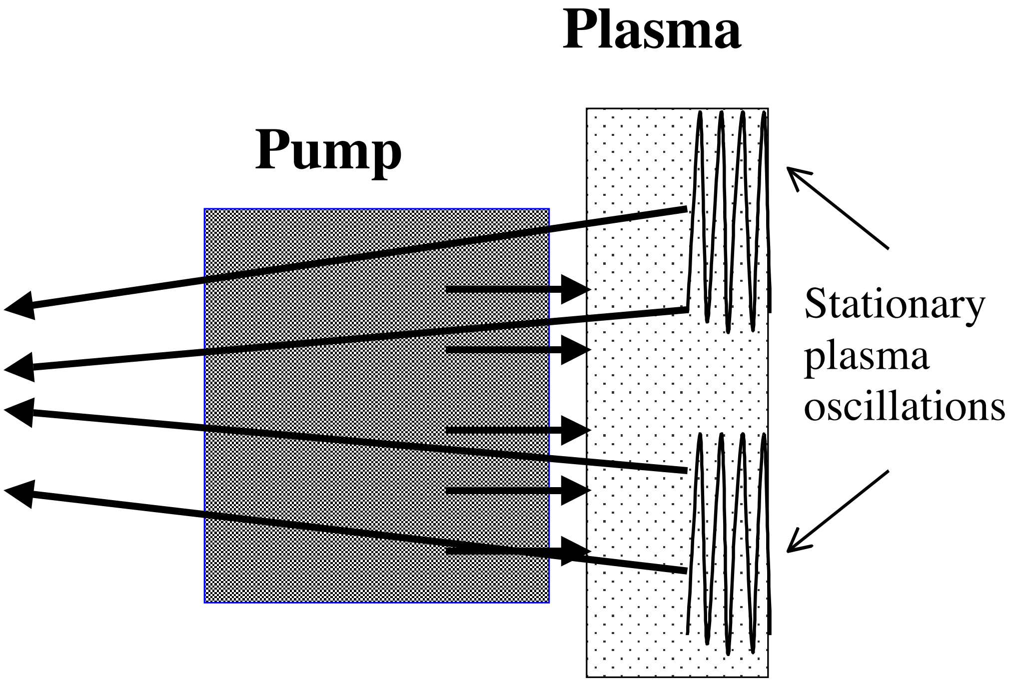

FIGURE 3. No seed pulse is employed. Instead seed is essentially stationary plasma wave or acoustic wave at far end of plasma.

compression regime.

COMPRESSION BY RESONANT RAMAN BACKSCATTERING

The beauty of pulse compression via the resonant Raman backscattering effect is that the effect is both well-studied and inherently one of the simplest plasma effects. The output pulse reaches very high intensities, but only in the sense that it leads to extreme pulse intensities on target. However, within the plasma, the non-focused power is not particularly high, in the sense that the plasma effects are fundamentally not extreme. The coupling occurs between essentially low-intensity counter-propagating light waves via essentially low-amplitude longitudinal cold plasma oscillations. The motion of electrons in the cold plasma wave is coherent, essentially sinusoidal motion, with no overtaking or wave-breaking. The motion of electrons in the lasers are also non-relativistic. Only as the pulse is amplified to its maximum value, which is essentially at the point that these effects are no longer so simple, do the electron trajectories begin to become complicated. At that point, other effects indeed enter, and that is roughly the boundary of the regime which can be considered to be the resonant Raman backscattering regime. And at that point the plasma is terminated and the pulse is extracted.

Hence, in the resonant Raman backscattering regime, there should be only a limited number of surprises in our understanding of the plasma effects. The short time scales involved mean that only electron dynamics, rather than ion dynamics, enter importantly.

This further limits the possibilities of unintended effects that could hinder the useful effects. Yet in this regime the time scales are not so short that the waves cannot be simply described as envelope pulses with a central carrier frequency. In compressing from tens of picoseconds to tens of femtoseconds, there will still be many laser wavelengths in the pulse wavepacket. Thus, there should be high confidence in using relatively simple analytical tools to describe this interaction.

The resonant Raman backscatter equations can thus be written as

$$\begin{aligned} a_t + c a_z &= \omega_p f b, &(1)\\ b_t - c b_z &= -\omega_p f^* a, &(2)\\ f_t &= -\omega a b^*/2, &(3) \end{aligned}$$

Here a and b are vector-potential envelopes of the pump and pulse, respectively, in units of $m_e c^2/e \approx 5 * 10^5$V, and f is the envelope of the Langmuir wave electrostatic field $\vec{E} = E\vec{e}_z$ in units of $m_e c\omega_p/e = c\sqrt{4\pi m_e n_e} \approx \sqrt{n_e}[\mathrm{cm}^{-3}]\mathrm{V/cm}$, defined by formulas

$$\begin{aligned} (A_x + iA_y)e/m_e c^2 &= a e^{i(k_a z - \omega_a t)} + b e^{i(k_b z - \omega_b t)}, &(4)\\ Ee/m_e c\omega_p &= f e^{i[(k_a - k_b)z - \omega_p t]} + c.c., &(5) \end{aligned}$$

where A_x and A_y are components of the real vector-potential $\vec{A}$ in the plane transverse to the propagation direction z; for the pump propagating in the positive and the seed-pulse in the negative direction, $k_a = \sqrt{\omega_a^2 - \omega_p^2}/c$ and $k_b = -\sqrt{\omega_b^2 - \omega_p^2}/c$; ω_p, ω_b, and ω_a are the plasma, laser-seed and laser-pump frequencies, and subscripts t and z denote time and space derivatives. The pulse duration is larger than ω_p^{-1}. Both lasers are circularly polarized. Self-nonlinearities of lasers and Langmuir wave are neglected. Plasma ions are assumed to be immobile. The Langmuir wave group velocity is neglected in comparison with the speed of light. For $\omega_b \gg \omega_p$, one may assume, as it is done above, $\omega_a \approx \omega_b = \omega$ and $k_a \approx -k_b \approx \omega/c$ in all the equation coefficients.

An initially weak seed b will be amplified by an undepleted pump field; in the constant pump or linear regime, exact solutions exist which show that while the seed front moves with the velocity of light c, the envelope maximum only moves with $c/2$ [13]. Hence, in this regime the counter-propagating wave is stretched. It is only in the nonlinear regime, *i.e.*, the pump-depletion regime, that the pulse is compressed. In this regime, the pulse front effectively shadows the pulse maximum and tail, so that the maximum catches up to the front. Also, in this regime, all short enough and intense enough initial seeds will asymptotically reach the π-pulse solution [9]. That a self-similar solution, depending only on the ratio z/t, exists can be seen from a scaling of the equations. Essentially, the Raman depletion of the pump by the seed takes place in a distance that varies inversely with the seed pulse amplitude. This is also the effective width of the seed pulse, since what is further than this distance behind the seed front is effectively shadowed. However, at complete pump depletion, the pulse energy must grow linearly with distance (or time) traveled, because that is all the available energy in the pump. Thus, the amplitude and energy of the seed pulse must grow linearly with distance, while the width contracts inversely with distance. Thus we expect a self-contracting self-similar asymptotic solution.

The π-pulse solution has about 50% of the energy in the first lobe (see Fig. 2), and the rest of the pulse energy appears in succeeding lobes. If there is a process that disrupts the Langmuir wave, say Langmuir wavebreaking or collisional damping of the Langmuir wave, then as much as 80% of the pulse energy can be captured in the first lobe, since the regeneration of the pump will be incomplete. However, the effects that disrupt the Langmuir wave should not be so disruptive that the desired amplification process is also disrupted. Hence, the wavebreaking should only be arranged near threshold. Alternatively, the collisional damping length of the Langmuir wave should be no shorter than the width of the first lobe.

The effects that first disrupt the process as described are the modulational and near-forward Raman scattering instabilities of the pulse, once it has grown to amplitudes much greater than the pump amplitudes. However, within a few growth times of these instabilities, the pulse can reach very high levels of unfocused power within the plasma [9]. Table 1 gives examples of the output parameters that can be expected under various parameters for the resonant Raman pulse compression.

TABLE 1. Examples of resonant Raman backscatter pump and output pulse parameters, for different laser wavelength, near the threshold of Langmuir wave breaking.

Laser wavelength (μm)	1/40	1/4	1	10
Pump duration (ps)	1.25	12.5	50	500
Pump intensity (W/cm^2)	1.6×10^{17}	1.6×10^{15}	10^{14}	10^{12}
Pump vector-potential (a_0)	0.006	0.006	0.006	0.006
Laser-to-plasma frequency ratio	12	12	12	12
Concentration of plasma (cm^{-3})	1.1×10^{22}	1.1×10^{20}	7×10^{18}	7×10^{16}
linear e-folding length (cm)	0.00043	0.0043	0.013	0.13
Total amplification length (cm)	0.018	0.18	0.7	7
Output pulse duration (fs)	1	10	40	400
Output pulse fluence (kJ/cm^2)	160	16	4	0.4
Output pulse intensity (W/cm^2)	1.6×10^{20}	1.6×10^{18}	10^{17}	10^{15}

Note in particular that at shorter wavelength, the plasma is even more accomodating in processing high power. By way of comparison, if they can be built at all, material gratings will withstand much less fluence at short wavelength. Hence, if compression is to be done at very short wavelengths, the practical issue is the suitable high-energy low-power pump laser worthy of compression.

Even at 1 μ, however, the fluences and unfocused powers are quite remarkable compared to what might be achieved with mateial gratings prior to the vacuum focus. One important issue is the extent to which this power can be focused on target by retaining the integrity of the seed pulse phase fronts prior to entering the plasma. Another important issue is the ability of th pump to traverse the full plasma length without undergoing premature Raman backscattering off plasma noise, prior to encountering the pulse. This second issue is addressed in the next section.

DETUNED RAMAN BACKSCATTERING

The issue of pump stability was, in fact, recognized in early studies of Raman compressors in gases and other Raman media. It was recognized that not only were instabilities of the amplified seed pulse worrisome, but so were the possibilities for both the forward scattering and the backscattering of the pump (see Fig. 4). In gases, the forward scattering is slightly larger than the backward scattering.

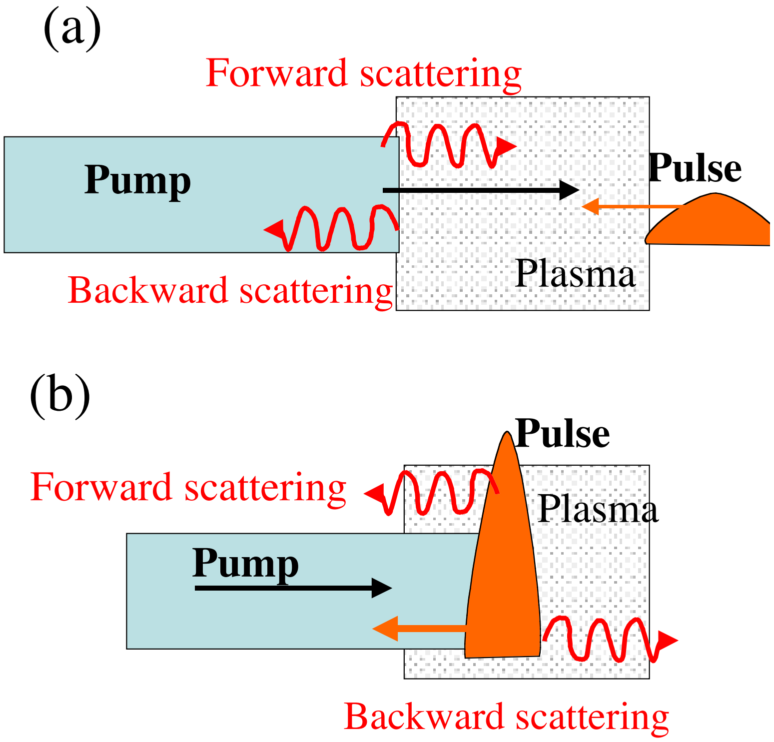

FIGURE 4. Instability of pump and pulse to forward and backward Raman backscattering instabilities. (a) pump is susceptible as it traverses full plasma to meet pulse. (b) pulse is similarly unstable as it reaches amplitude larger than pump.

In Fig. 4a, we schematically depict the forward and backward scattering instabilities associated with the pump in a Raman media, which is taken here to be plasma. Although the pump is of smaller amplitude than the pulse, it has to propagate the full plasma length before reaching the pulse. Hence, instabilities associated with the pump can be serious even at lower amplitude. Note that both the backward scattered wave and the forward scattered wave can draw pump energy for essentially the plasma length.

In Fig. 4b, we schematically depict the forward and backward scattering instabilities associate with the pulse in a Raman media, which is also taken here to be the plasma. The backward scattering of the pulse in gases would be less important than the forward scatering, because the backscattered light quickly goes through the short pulse, whereas the forward scattered light propagates with the short pulse. In plasmas, this issue is balanced by the fact that the backward scattering occurs with a larger growth rate.

In contemplating gas-based Raman compressors, it was also recogized that these issues could be addressed by detuning the resonant interaction. The Raman medium could be made to have a Raman gradient, where the Raman frequency would change with axial position (see Fig. 5). Thus, forward scattered light co-propagating with a pump (or pulse) would be born in resonance with the pump, but as both pump and scattered signal co-propagate some distance, the Raman media no longer accomodates a resonant interaction between the two waves. Moreover, it was also recognized [14], that the pump entering the plasma could be chirped too, so that the front of the pump would be at one frequency, while the back of the pump could be at a higher or lower frequency. Thus, should the front of the pump be backscattered off of some noise, then as the unwanted backscattered energy propagates through the pump, it will encounter pump power with which it is not resonant, which will halt the resonant backscatter. Now, if both the Raman gradient and the pump are graded or chirped, as depicted in Fig. 5b, then the chirps add. So for example, it would be possible to use the Raman gradient to detune the forward scattering effect, and then use a chirped pump to compensate the Raman gradient, so that the backscattering is not detuned at all.

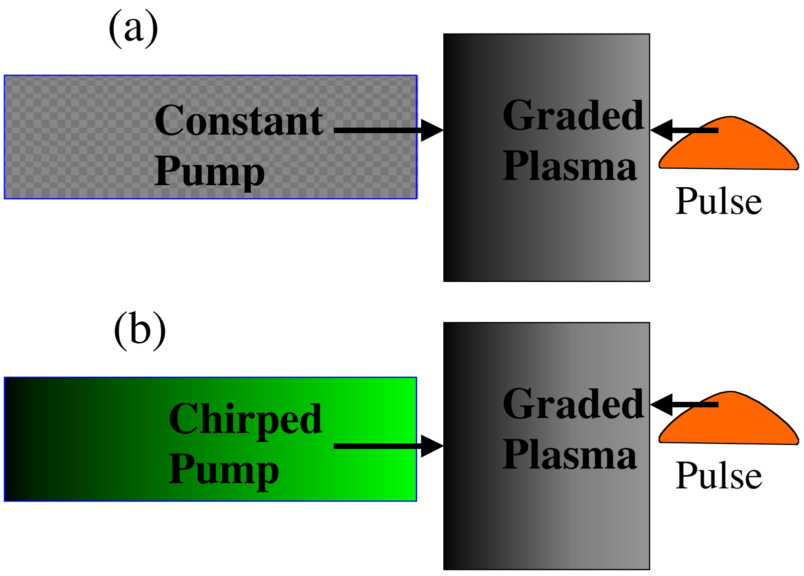

FIGURE 5. Schematic implementation of detuning. (a) Pump is susceptible to Raman instabilities as it traverses full plasma to meet pulse, but graded plasma density produces a plasma frequency gradient so that a forward or backward scattering resonance cannot be satisfied over appreciable distances. (b) pump is chirped to compensate the Raman frequency gradient. As seen by a counterpropagating wave, the detuning caused by density gradient is compensated by encountering a gradient in the pump laser frequency.

In gases, these effects might be usefully used therefore to handle unwanted forward scattering effects, which are the more worrisome effects, while retaining effective backscattering. In plasma, the backscattering is the more serious worry, but it cannot be detuned altogether, because it is also the effect that amplifies the useful pulse. However, quite remarkably, at high power, there is an important nonlinear filtering effect that occurs in plasma [15]. This filtering effect is that the resonance detuning affects differently the amplification of the desired signal through backscattering of the pump and the amplification of noise, also through backscattering of the pump.

On the one hand, the amplification of the desired signal occurs only linearly with distance in the pump-depletion or π-pulse regime, whereas the amplifcation of noise occurs exponentially in time or distance. Hence, one would expect that eventually the plasma length for amplification might be limited by this effect at any noise level. On the other hand, although the pumped pulse grows only linearly with distance, it also contracts as grows, rendering its bandwidth larger. In the pump-depletion regime, as the short pulse becomes even shorter and acquires larger bandwidth, it can tolerate detuning equal to its bandwidth. Thus, it will continue to be amplified, even as a pulse arising from noise, initially growing exponentially with distance, will eventually be saturated due to detuning.

The fact that the Raman interaction in the pump-depletion regime tolerates large detuning effects is quite important. It can be used not only to stabilize the pump, even as the signal amplification is unaffected, but it can also be used to destabilize other unwanted resonant instabilities even as the signal amplification is unaffected (see, for example, Ref. [16]).

OUTSTANDING ISSUES AND CONCLUSIONS

Plasma is the natural medium for processing high power and high fluence lasers. There are, in fact, several backscatter effects, in somewhat different regimes, that may lead to compression of lasers at high power in plasma. Each of the regimes and each of the mechanisms imagined here has its own set of outstanding issues that must be resolved both theoretically and experimentally, before one can have confidence that the favorable compression regimes discussed here can in fact be accessed. Among these issues is the extent to which the pulse can retain its focus as it emerges from the plasma.

Moreover, the practical realization of these effects depends upon the robustness of these effects to deviations from the ideal conditions contemplated. However, until one method is shown to work, there is some comfort to be derived from the fact that a number of rather different mechanisms might be useful in producing compression at high power.

Particular attention was paid to the resonant Raman backscatter effect. It is encouraging that this is an essentially simple effect in the sense that electron motion is quite coherent even as high power pulse compression is achieved. Significantly, since the effect relies on resonance, it is possible to introduce detuning in such a way that the amplification of unwanted noise can be suppressed even as the useful amplification persists.

It should be recognized that while there have been many related experiments, none have realized compression at high power. Recently, backscattered amplification was reported in a Li-F recombining plasma [17], but a π-pulse solution, or even any compression solution, has yet to be demonstrated in plasma.

Yet the compression of lasers in plasma is likely to be a key component to the eventual realization of much higher laser intensities than are presently achieved. As applications emerge particularly for submicron wavelengths, the compression effect in plasmas will become even more central to the development of suitable high-power lasers, since alternative means of pulse compression are not suited to short wavelength.

As a first step to improving present technology, a laser system might employ a plasma component as well as conventional CPA components. A high saturation-fluence amplifier, but possibly with relatively narrow gain bandwidth, might be used to produce a suitable laser pump for use in plasma-based compression.

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