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Manipulating ultraintense laser pulses in plasmas

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An efficient way for manipulating ultraintense laser pulses in plasmas using resonant three-wave interactions is proposed. Poor quality ultraintense laser pulses can be efficiently transformed into high quality focused laser pulses, while the entropy is taken up by resonant plasma waves. This can be accomplished within plasma layers thin enough that parasitic scatterings and instabilities of laser pulses do not have enough time to develop. Combined with laser pulse compression in plasmas, this scheme, using, for example, the lasers that power the National Ignition Facility (see, for instance, the NIF project website: http://www.llnl.gov/nif/project), is potentially capable of producing vacuum breakdown intensities. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1881533]

No conventional material can withstand laser intensities exceeding several TW/cm^2 (TW=10^{12} W). This technological limit implies that higher laser powers cannot possibly be achieved within reasonable size lasers employing conventional materials, including the most advanced contemporary lasers using chirped pulse amplification (CPA) scheme (see, for instance, Ref. 1). For instance, to achieve zettawatt powers (ZW=10^{21} W), the final focusing material surface in such laser systems should have an area $\sim 10^9$ cm^2, i.e., about 300 m diameter.

These restrictions are relevant to the MJ (megajoule) laser systems that are currently built in the US (NIF—National Ignition Facility, see Ref. 2) and France (LMJ—Laser Megajoule, see Ref. 3). Megajoule energies are, in principle, sufficient for producing zettawatt powers and vacuum breakdown intensities ($\sim 10^{30}$ W/cm^2, see Ref. 4). However, it would be necessary to compress megajoule pulses to femtosecond durations and to focus the compressed pulses to submicron spots. This Brief Communication suggests a method of accomplishing that.

The scheme that we propose consists of a laser source, compressing block and focusing block. To be specific, we can assume, for example, that the source consists of one or more of the 192 NIF beams. These beams are 5 ns (150 cm long) square pulses of energy 10 kJ at the wavelength $\lambda = 1.053\ \mu\text{m}/3 = 0.351\ \mu\text{m}$, as described in Ref. 2.

To compress the source laser beam in the longitudinal direction, we can use stimulated Raman backscattering in plasmas, as proposed in Refs. 5 and 6. The 150 cm long beam can be effectively compressed in a 75 cm long plasma cylinder to nearly relativistic nonfocused intensities of $\sim 10^{17}$ W/cm^2. The cylinder length is such that the pump front meets the counterpropagating seed as the seed enters the plasma, and the pump rear meets the seed as the seed exits the plasma.

Note that the originally proposed compression scheme of Refs. 5 and 6 assumed the output pulse should already be well-focused, to avoid the problem of manipulating such intense pulses. Further studies confirmed that it is indeed possible to produced well-focused output pulses.[7] However, conditions for keeping the high focusability of output pulses appeared to be more strict than those for highly efficient pulse compression.[8]

The separation of compressing and focusing issues, as proposed here, broadens the operative parameter range of the compressing block. In particular, it appears to be possible then to pump the compression block directly by NIF lasers, without the intermediary CPA block envisioned in Ref. 9. Thus, expensive, large, and fragile gratings will not be needed. Moreover, the output pulse compression and focusability will improve due to relaxed constraints on the compressing block and new capabilities of the focusing block proposed below.

The focusing block consists of a thin dense plasma layer. The output pulse coming from the compressing block could easily traverse this thin plasma layer without being noticeably affected by it. The same is true for a well-focused seed pulse injected into the layer from the opposite side. However, when these two pulses meet each other inside the layer, they are resonantly coupled through the plasma waves. Then, within just a few Raman lengths (which are very small for intense pulses in dense plasmas), the high-quality seed pulse consumes the poor-quality pump pulse (coming from the compressing block), thus producing a second (and final) output pulse of high intensity and focusability. It is the plasma wave spectrum that adjusts to produce the required resonance and phasing in the three-wave interaction as the phase front of the pumped pulse propagates into fresh plasma. Therefore, the entropy is picked up by the plasma waves, while the energy goes primarily to the high-quality output pulse. Moreover, further pulse compression is accomplished in the course of the three-wave interaction in the denser plasma of the focusing block, since the output pulse compresses to a duration of several inverse plasma frequencies.

Note that the compression and focusing blocks, though accomplishing very different functions and operating in very different parameter regimes, both employ the same nonlinear coupling mechanism, namely, the stimulated Raman backscattering of laser pulses in plasmas. Therefore, the scheme proposed here can be treated as a two-step backward Raman amplification (BRA) scheme, which allows us to apply the already developed nonlinear BRA theory of Refs. 5 and 6 to each step separately. We will use now these previously derived results to show how the two-step BRA laser would work.

Let the average square of quiver electron velocity in pump laser field be $a_0^2c^2$, where c is the speed of light in vacuum, $a_0 \ll 1$. The pump intensity is then

$$I_0 = 27.36\, a_0^2\ \mathrm{GW}/\lambda^2.$$

For a given input laser-pump intensity, the maximum achievable output fluence is a decreasing function of plasma electron concentration n_0. This is because deleterious filamentation instabilities develop slower in more rarefied plasmas, thus allowing a longer length L of the amplifying plasma layer, which means, in turn, the longer length $2L$ of laser pump that can be consumed by a counterpropagating laser seed before the seed leaves the plasma layer.

There is, however, a minimum concentration n_0 of plasma capable of tolerating the intense short (about $\lambda/2$)-wavelength Langmuir wave that mediates the energy transfer from the long pump laser beam to the short pumped laser pulse. The Langmuir wave breaking that occurs in plasmas more rarefied than n_0 reduces the efficiency of energy transfer from the pump beam to the pumped pulse. The threshold n_0 for Langmuir wave breaking is given by the formula

$$\omega_{p0} \equiv (4\pi n_0 e^2/m_e)^{1/2} = (4a_0)^{2/3}\omega, \tag{1}$$

where e and m_e are electron charge and mass, respectively, and $\omega = 2\pi c/\lambda$ is the pump laser frequency, which is much larger than the electron plasma frequency ω_{p0}, for $a_0 \ll 1$.

The largest value of the dimensionless quiver velocity b_1 of the output pumped pulse is achieved in the threshold regime of Langmuir wave breaking and is given by the formula

$$b_1 = Q_0 a_0^{1/3}, \tag{2}$$

with factor $Q_0 \sim 1$ depending logarithmically on an integral

$$\epsilon_0 = \sqrt{\omega\omega_{p0}} \int b_0 dt$$

of the amplitude b_0 of input seed pulse. The input seed pulse duration Δt_0 is assumed here to be much shorter than the time of linear BRA e-folding γ_0^{-1},

$$\gamma_0 = a_0 \sqrt{\omega\omega_{p0}/2}.$$

The output pumped pulse duration is limited to about an electron plasma period,

$$\Delta t_1 = 2\pi R_0/\omega_{p0}, \quad R_0 \sim 1. \tag{3}$$

The output pulse fluence,

$$w_1 = b_1^2 \Delta t_1 \times 27.36 \frac{\mathrm{GW}}{\lambda^2} = 0.36\, Q_0^2 R_0 \frac{\mathrm{J}}{\mathrm{cm} \times \lambda} \tag{4}$$

is very large (kJ/cm^2 in micrometer wavelength range) and insensitive to the input pump intensity I_0. Due to this insensitivity, the optimal input pump length $2L$ is, basically, inversely proportional to the input pump intensity I_0 ($L = cw_1/2\chi_0 I_0$, where $\chi_0 \sim 1$ is the efficiency of the pump energy conversion into the pumped pulse energy).

The first BRA output pulse of amplitude b_1 can be used as in input pump pulse for the second cycle of BRA. The plasma concentration n_1 corresponding to the Langmuir wave breaking threshold in the second BRA cycle is determined by the formula

$$\omega_{p1} \equiv (4\pi n_1 e^2/m_e)^{1/2} = (4b_1)^{2/3}\omega. \tag{5}$$

The output pulse of the second BRA cycle can reach an amplitude as high as

$$b_2 = Q_1 b_1^{1/3}, \quad Q_1 \sim 1, \tag{6}$$

and a duration as short as

$$\Delta t_2 = 2\pi R_1/\omega_{p1}, \quad R_1 \sim 1. \tag{7}$$

With the above simple formulas, we are ready now to consider an example of two-step BRA employing NIF lasers as inputs.

Consider, first, a laser pump consisting of just one of the 192 NIF beams. According to Eq. (4) (using, conservatively, $Q_0^2 R_0 = 1$), the 10 kJ laser pump can be accommodated in a plasma cylinder of just 1 cm^2 transverse area. Thus, the NIF beam has to focused to a 1 cm^2 transverse area from the original 40×40 cm^2 aperture. The respective input pump intensity is then

$$I_0 = 2\ \mathrm{TW/cm}^2,$$

and the pump amplitude is

$$a_0 = 0.0003.$$

The plasma to laser frequency ratio at the Langmuir wave-breaking threshold is then

$$\omega_{p0}/\omega = (4a_0)^{2/3} = 0.0113,$$

corresponding to plasma frequency $\omega_{p0} = 6 \times 10^{13}\ \mathrm{s}^{-1}$, and plasma concentration

$$n_0 = 1.15 \times 10^{18}\ \mathrm{cm}^{-3}.$$

The output pulse amplitude (for a conservative $Q_0 = 1$) is

$$b_1 = 0.067$$

and the output duration (for $R_0 = 1$) is

$$\Delta t_1 = 0.1\ \mathrm{ps}.$$

The input seed of duration $\Delta t_0 = 0.1$ ps and intensity 1 PW/cm^2, carrying just 1% of the output energy, would have the dimensionless integrated amplitude $\epsilon_0 = 0.4$ large enough to achieve nearly complete conversion of the pump energy into the pumped pulse in a near-threshold Langmuir wave-breaking regime of Ref. 5. Thus, the first BRA output power is 100 PW, and the nonfocused intensity is 100 PW/cm^2.

Note that the time of Langmuir wave collisional damping in a hydrogen plasma of the concentration $n_0 = 1.15 \times 10^{18}\ \mathrm{cm}^{-3}$ at the electron temperature $T_e = 10$ eV is 6.7 p. It follows, that the Langmuir wave collisional damping can be neglected within the 2 mm long domain of the backscattered radiation trailing the seed front. In this domain, the BRA is transient so that the formation of the output pulse indeed occurs in the transient regime, as was assumed in the above formulas. The Langmuir wave Landau damping is supposed to be suppressed because of the large electron bounce frequency which is close to the electron plasma frequency in these regimes close to the wave-breaking.

Note also that the input pump intensity $I_0=2\ \mathrm{TW/cm^2}$ is relatively small, so that the pump could propagate through a neutral gas without causing ionization. It could simplify the pump delivery to the seed and help to have a more uniform plasma in the domain relevant to useful BRA.

The BRA modification where the gas is ionized by the pumped pulse was proposed in Ref. 10 and further studied in Ref. 11. Plasma concentration within an ionization front strongly depends on the local laser intensity. This might cause transverse inhomogeneity in the front plasma and distortion of the ionizing pulse wave fronts. The issue is not sufficiently studied so far. To exclude potential risks, it might be preferable to modify the scheme and produce the ionization by a precursor to the seed pulse rather than by the seed pulse itself. Then, the seed propagates in the completely ionized plasma and is not distorted.

The laser energy per electron of the plasma cylinder in our example is 720 eV. Thus, to completely ionize a hydrogen gas of concentration n_0, just about 2% of the laser energy is needed. It leaves enough room for replacing hydrogen for helium or even somewhat higher elements, if necessary.

Consider now the second BRA cycle, for which the plasma length is $c\Delta t_1/2=15\ \mu\mathrm{m}$, the plasma to laser frequency ratio in the Langmuir wave-breaking threshold regime is

$$\omega_{p1}/\omega = (4a_1)^{2/3} = 0.4,$$

corresponding to plasma frequency $\omega_{p1}=2.23\times10^{15}\ \mathrm{s}^{-1}$, and plasma concentration

$$n_1 = 1.56\times10^{21}\ \mathrm{cm}^{-3}.$$

The output pulse amplitude (for $Q_1=1$) is

$$b_2 = 0.4$$

and the output duration (for $R_1=1$) is

$$\Delta t_2 = 2.8\ \mathrm{fs}.$$

The output nonfocused intensity is $3.5\ \mathrm{EW/cm^2}$. Taking into account that the fraction $\omega_{p1}/\omega=0.4$ of the input pump energy goes to the Langmuir wave, the plasma transverse area in the second BRA cycle has to be $0.6\ \mathrm{cm}^2$, so that the output power is 2 EW. For this cycle, the input seed of duration Δt_2 and intensity $35\ \mathrm{PW/cm^2}$, carrying just 1% of the output energy, would have the dimensionless integrated amplitude $\epsilon_1=0.4$. The optimal way of producing such seed pulses, down-shifted from the pump by the plasma frequency ω_{p1}, needs further examination. Here we note just that seed might in fact be longer, but it should have such a steep front.

Thus, the two-step scheme of backward Raman amplification might be capable of producing exawatt (10^{18} W) output pulses in tabletop size devices.

At the first step, a 2 TW (2×10^{12} W), 5 ns duration, 0.351 μm wavelength input laser beam (just like one of 192 NIF beams) is compressed into 100 PW (10^{17} W), 0.1 ps duration output laser pulse (within a 75 cm long plasma cylinder of 1 cm^2 transverse area and $n_0=1.15\times10^{18}\ \mathrm{cm}^{-3}$ concentration, with efficiency close to 1).

At the second step, using the first step output as an input pump, the above 100 PW pulse is compressed into 2 EW (2×10^{18} W) output pulse of duration 3 fs (within a 15 μm long plasma layer of 0.6 cm^2 transverse area and $n_1=1.56\times10^{21}\ \mathrm{cm}^{-3}$ concentration, with efficiency close to 0.6).

Note that the first step BRA in the parameter regime considered above might be by itself of significant interest for applications, as an effective alternative way of compressing intense laser beams from nanosecond to picosecond range without expensive fragile gratings. For instance, it might be used to compress 5 ns NIF laser beams to 0.1–5 ps for fast ignition of Ref. 12, in particular, for ultrarelativistic modification of fast ignition scenario, wherein much more powerful lasers would produce a more energetic beam of electrons to ignite the plasma core through a fast collective relaxation there, as proposed in Ref. 13.

The two-step scheme, however, can open up a new class of ultrahigh power applications. For instance, each of 4 NIF's 48-beamlet arrays can produce 100 EW output pulse (thus giving 400 EW total output power). After focusing to a $\lambda=0.35\ \mu\mathrm{m}$ diameter spot, such an output laser would reach intensity $3\times10^{29}\ \mathrm{W/cm^2}$. If the above four 100 EW output pulse interfere constructively, an even higher intensity $\sim10^{30}\ \mathrm{W/cm^2}$ could be formally be expected within the focal spot. This however is likely to be prevented by a strong space-charge screening coming from the vacuum breakdown that already starts at smaller electric fields, see Ref. 14.

Note that producing the vacuum breakdown could be further simplified by the development shorter-wavelength laser sources. Indeed, if the critical electron field E_c is to be obtained by means of compression and focusing laser pulses to a spot of linear sizes about the laser wavelength λ, the energy located within such a spot would be

$$\varepsilon \sim \frac{E_c^2\lambda^3}{8\pi} \sim 8\ \mathrm{MJ}\frac{\lambda^3}{\mu\mathrm{m}^3}. \tag{8}$$

Since BRA also should work well for shorter wavelength pulses (and even might be simplified for condensed matter densities plasmas), a reasonably efficient laser frequency upshifting to, say, less than 100 nm wavelength range would make feasible the vacuum breakdown initiation by just a few of the NIF beams.

We might note that a highly speculative alternative scheme of Ref. 15 for light intensification towards the Schwinger limit has been proposed, which contemplates huge frequency upshifts of laser pulses by means of reflection from ultrarelativistic plasma wakes. Were that scheme, or any other scheme, successful in an efficient producing even modest upshifts in frequency, then those upshifts in frequency could be used together with the methods proposed here to achieve the vacuum breakdown laser intensities even in more compact devices.

In summary, the method proposed here for manipulating ultraintense laser pulses in plasmas is capable of extending to much higher intensities the laser outputs envisioned in backward Raman amplification methods. The method consists in arranging conditions for a high quality laser seed to consume a laser pump within just few Raman lengths in a plasma, which distance is small enough to avoid a noticeable distortion of seed wave fronts. The pump entropy is taken by low energy plasma waves mediating the energy transfer from pump to seed laser pulses. The range of possible manipulations includes focusing an ultraintense nonfocused laser outputs of backward Raman amplifiers. This opens the possibility of focusing ultraintense laser pulses at the very last stage of a multistage backward Raman compression scheme and removes constraints on the focusability of the intermediate output pulses during the major longitudinal compression of the laser beams. The new methodology is capable of reaching the vacuum breakdown laser intensities without a 300 m diameter CPA compressor (consisting of expensive and fragile gratings), to be replaced by just a meter-size plasma BRA compressor (see note[16]). A hybrid scheme, consisting of both the CPA and BRA laser compressors, would have an intermediate size and costs determined primarily by those of CPA block. The advantages of the plasma BRA compressors should become even more impressive at shorter laser wavelengths, where the BRA compressors are even more compact while material gratings are even more challenged.

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$$E_c = \frac{m_e^2 c^3}{e\hbar} = 1.32 \times 10^{16}\ \mathrm{V/cm} \tag{9}$$

(c is the speed of light in vacuum, m_e is the electron mass, e is the positron charge, and $\hbar$ is the Plank constant). The critical field E_c is such that an electron (or positron) acquires energy $m_e c^2$ within the distance $\hbar / m_e c$. This causes significant tunneling of electron-positron pairs through $2m_e c^2 = 1$ MeV gap in the Dirac sea, thus leading to a "vacuum breakdown." The intensity (i.e., power density) of a linearly polarized laser pulse having maximal electric field E_c is

$$I_c = \frac{cE_c^2}{8\pi} = 2.3 \times 10^{29}\ \mathrm{W/cm^2}. \tag{10}$$

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