Superradiant Amplification in Laser Produced Plasma by KrF laser

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Abstract. Superradiant amplification (SRA) in laser produced plasmas by KrF laser system for the use of large pump energy is examined by one-dimensional particle in cell simulation code. Its ultra-violet laser wavelength has many advantages for SRA. The simulation code predicts that the required signal pulse width is shorter than ~ 100fs for out supposed conditions if the seed signal pulse shape is gaussian. Transient Raman scattering wavelength conversion in gaseous media can create truncated leading edge pulse. The simulation code showed the pulse can form leading edge spike by the amplification in plasmas.

INTRODUCTION

The development of the chirp pulse amplification enabled us to access ultra-intense laser up to 1PW so far. OPCPA[1] will realize wider bandwidth and is expected to generate higher intensity. However, the damage threshold of the final grating compressor still limit the total output energy.

The superradiant amplification (SRA) was proposed by Shvets, et. al. in 1998 [2]. This method uses plasmas as laser amplification media. The plasma media can handle very large laser fluence, so this is very attractive alternative scheme to generate ultra-high intensity laser pulse with large energy. It should be noted that the SRA can amplify ultrashort pulse shorter than plasma frequency. For example, for $n_e = 10^{20}$ cm$^{-3}$, $2\pi/c_{op} \sim 10$fs. This is one of the merit of SRA, because the amplification process finishes before other unwanted instabilities develop in plasma.

The experiment has started at Max-Planck Institute for Quantum Optics using Ti:Sapphire laser system, ATLAS[3]. To achieve ultimate intensity, it is necessary to use pump pulses of large energy which can generated by Inertial Fusion Energy (IFE) drivers.

We have large electron beam pumped KrF laser system, Super-ASHURA[4]. And this laser has additional advantages over Ti:sapphire or Nd:glass lasers because of its ultra-violet laser wavelength as following. 1) Rayleigh range is longer assuming same focal spot diameter $w$, $z_R = \frac{w^2}{\lambda}$. 2) Required spectral bandwidth to form ultra-short laser pulse is smaller, $\Delta \lambda = \frac{0.44\lambda^2}{c_{op}}$. This will be important point to avoid overlapping pump and signal spectrum. 3) Gas ionization is easy due to the larger photon energy, $h\nu \sim 5eV$ [5, 6]. 4) Stimulated Raman scattering can generate longer wavelength signal seed pulse very easily.

On the other hand, the largest problem for the use of KrF laser is the generation of short
In this paper, we will examine the feasibility of the superradiant amplification by electron beam pumped KrF laser using Particle in cell (PIC) simulation code.

THEORY

We will review the theory briefly [2, 7]. We assume counterpropagating pump $\tilde{a}_L$ and signal $\tilde{a}_S$ pulses as in Fig. 1, where $\tilde{a}_S = a_s \exp\{i(k_S z - \omega_S t)\} + \text{c.c.}$, $\tilde{a}_L = a_L \exp\{i(k_L z - \omega_L t)\} + \text{c.c.}$. The dominant ponderomotive potential formed by the two laser interference is represented as,

$$\phi_{\text{pond}} = -m c^2 a_L a_S \cos \psi$$  \hspace{1cm} (1)

where $\psi = (k_S + k_L)z - (\omega_L - \omega_S)t \sim 2k_S z - \Delta \omega t$. When $\omega_B^2 = 4\omega_S^2 a_L a_S > \omega_p^2$, the ponderomotive force is stronger than electrostatic force. The equation of $j$-th electron motion in the potential is represented simply as,

$$\dot{\psi}_j + \omega_B^2 \sin \psi_j = 0.$$  \hspace{1cm} (2)

Therefore, signal pulse receive both amplification and absorption alternatively in the period of $\omega_B$. As the signal amplitude grows, the pulse width decreases with increasing of $\omega_B$. The coherent scattering condition is automatically satisfied by the localized electron distribution determined by the potential.

In the case of stimulated Raman scattering, the three wave (pump, signal and electron plasma wave) have to satisfy phase matching condition. So, whole signal pulse grows.
PIC SIMULATION AND DISCUSSION

The results of the PIC simulation on the assumption of using KrF laser is shown in Fig. 2. The electron density is $8 \times 10^{19} \text{cm}^{-3}$, $n_e/n_c \sim 0.0045$. Other parameters are noted on the figure.

As in Fig. 2(b), the growth of the electric field is proportional to the propagation distance $z$. This is consistent with the SRA theory $I_{signal} \propto n^2 z^2$.

Fig. 2(c) shows pulse peak structure in detail to see the relation between the potential and the electron density. The potential is approximated by $\phi_{pond} \sim a_t a_s$. The electron density is higher in left hand side of the each ponderomotive potential cell. This is due to the direction of the potential movement is from left to right.

Fig. 3 shows the evolution of the signal pulse width and intensity for various its initial conditions. The conditions of pump intensity and plasma density are fixed ($I_L = 5 \times 10^{15} \text{W/cm}^2, n_e = 8 \times 10^{19} \text{cm}^{-3}$). We defined the pulse width as FWHM of the largest peak even for the case, whole pulse had several peaks. Basically initial points are upper left in the figure. The evolution lines are asymptotically close to the $2\pi/\omega_R$ line. We observed the conversion behavior also in weaker region than the Shvets's SRA criterion, $\omega_0^2 > \omega_R^2$.

For the longer incident signal pulse, we did not see such a behavior. This is because the long pulse has weak foot region, electron plasma wave was driven ahead and phases of the electrons are disturbed.

So, the signal pulse longer than 100fs would not likely to be SRA. KrF laser can amplify short pulse directly but the group velocity dispersion, nonlinear refractive index in the window, and the $3\omega$ conversion from Ti:Sapphire oscillator output prevent generating
FIGURE 3. The evolution of the signal pulse width and electric field for various initial pulse width and intensity conditions. Asymptotic conversion is observed.

amplified sub-100fs pulses in KrF wavelength.
We have one solution to the problem. As in Fig. 4 (a), gaussian signal pulse of 100fs break up into several pulses. On the other hand, the truncated leading edge pulse (4 (b)) form leading edge peak. In this case, we used one-cycle sin wave to simulate the truncated leading edge pulse..

FIGURE 4. 100fs signal pulse growth for (a) Gaussian, (b) truncated leading edge pulse (sin). Pump and Signal pulse incident intensity: $1.0 \times 10^{16}$W/cm$^2$, Plasma density: $8 \times 10^{19}$/cm$^3$, $T_e=100$eV. Propagation length $\sim 400$ μm. Co-propagating coordinate.

This types of pulse can be created by transient stimulated Raman scattering in gaseous media[8]. The leading edge growth rate is independent from transverse dephasing time, $T_2$ of the Raman media under the transient regime during the conversion. And the
conversion efficiency can be high if we use the group velocity mismatch technique.[9] The experimental investigation of this process will also be necessary.

CONCLUSION

SRA for KrF laser is examined by PIC simulation. SRA is also feasible for ultra-violet wavelength region. The signal pulse shorter than 100fs was found to be necessary for gaussian pulse shape. Transient stimulated Raman wavelength conversion is suitable not only for generating longer wavelength signal but also for having truncated leading edge. This seed pulse will create leading edge spike by the amplification in plasmas.

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