New envelope-kinetic scheme for the simulation of Raman backward laser amplification

Min Sup Hur, Hyyong Suk *

Center for Advanced Accelerators, KERI, Changwon 641-120, Republic of Korea

---

Abstract

A new fast and accurate scheme is introduced to simulate the Raman backscattering of laser pulses in a plasma. In the proposed method, the envelope-kinetic equation of a plasma wave is solved along with conventional laser envelope equations. The kinetic term, which is the most noticeable feature of the envelope-kinetic plasma equation, can be self-consistently solved by employing some test particles. The benchmarkings of the new code against the averaged particle-in-cell results show quite a reasonable agreement, while the computation speed is enhanced by more than a factor of ten.

Key words: test particle method; envelope-kinetic equation; Raman baskscattering; laser-plasma

---

1. Introduction

The ultraintense and ultrashort laser pulse generation using Raman backscattering (RBS) has been an interesting issue [1]. In this novel scheme, a weak and long pump laser interacts with a counter-propagating seed laser in a plasma, by which the pump energy is transferred to the seed via RBS. The final goal of this system is to achieve more than a petawatt and several tens of femto second level laser pulse from a compact and cheap device.

From a series of analytic and simulation studies, it was found that the Raman amplification can be deteriorated significantly by electron trapping. This was shown from averaged particle-in-cell simulations and envelope-kinetic analysis [2–4]. Because the fluid based three-wave model [1] cannot reflect the kinetic effects such as trapping, the calculation from the fluid model shows much higher amplification level, which is unrealistic in the kinetic regime. Thus it is important to develop a fast and accurate kinetic scheme for systematic simulation studies of the system.

For this purpose, the averaged PIC (aPIC) code which combines the envelope laser and particle plasma has been developed [3]. Recently a new technique using the envelope-kinetic plasma equation was invented, which calculates the system even faster than the aPIC. In this paper we present basic equations and how the envelope-kinetic equation is treated for the fast and accurate simulations of RBS.

2. Method

2.1. *Basic equations*

The following fluid based three-wave equations are commonly used for the analysis of RBS system;

$$\frac{\partial a_1}{\partial t} + c\frac{\partial a_1}{\partial z} = -\frac{\omega_p}{2}a_2 f^*, \frac{\partial a_2}{\partial t} - c\frac{\partial a_2}{\partial z} = \frac{\omega_p}{2}a_1 f, (1)$$

---

* Corresponding author.
Email address: `hysuk@keri.re.kr` (Hyyong Suk).

$$\frac{\partial f}{\partial t} + i\delta\omega f = -\frac{\omega}{2} a_1^* a_2, \quad (2)$$

where $a_{1,2}$ are the seed and pump envelopes, respectively, f the plasma wave envelope, and $\delta\omega = \omega_p - \omega_2 + \omega_1$. In the test particle method, the plasma envelope equation is replaced by the envelope-kinetic equation [4],

$$\frac{\partial f}{\partial t} + i\delta\omega f + 2\omega\langle\beta_j^2 e^{-i\phi_j}\rangle = -\frac{\omega}{2} a_1^* a_2 \ , \quad (3)$$

where $k_{1,2}$ are the wavenumbers of the seed and pump, respectively, β_j the j'th particle velocity normalized by the speed of light, $\phi_j = -(k_1 + k_2)z_j - (\omega_2 - \omega_1)t$ is the ponderomotive phase of the j'th particle. The $\langle \ldots \rangle$ represents an ensemble average over particles.

2.2. *Test particle method*

The kinetic term in Eq. 3 represented by the ensemble average requires information about positions and velocities of particles, which can be obtained by following the test particle motion. The electric field which drives the test particle motion is reconstructed from the plasma wave envelope by $eE/mc\omega_p = 0.5(fe^{i\phi} + f^* e^{-i\phi})$.

In the test particle scheme, there does not exist any numerically enhanced thermal noise and its effect on RBS, since the electric field is calculated from the fluid based envelope-equation (modified by the kinetic term). Therefore the number of simulation particles, i.e. the test particles, can be greatly reduced, which enables much faster simulations.

3. Results

A benchmarking result of the test particle simulation against the aPIC is presented in Fig. 3. The amplitudes of the leading peaks from the kinetic simulations agree well with each other, while the fluid result greatly deviates from them. Since the envelope equation is valid only for well-defined plasma waves, the discrepancy of the test particle result is relatively large in the pulse tail, where the plasma wave is completely wave-broken. However, only the leading peak is considered to be interesting in the amplification process. Note that the fluid model shows a pulse train, which is called the π-pulse [1]. Such a structure cannot be observed from kinetic simulations because of the wavebreaking [1]. For the case of test particle scheme, the number of simulation particles was 256 in a mesh, while 4096 particles were used for the aPIC simulation. It was found that more than 2560 particles were required to prevent the numerically enhanced RBS. Since the computation time is dominated by the number of particles, the test particle scheme is faster than the aPIC by more than a factor of 10.

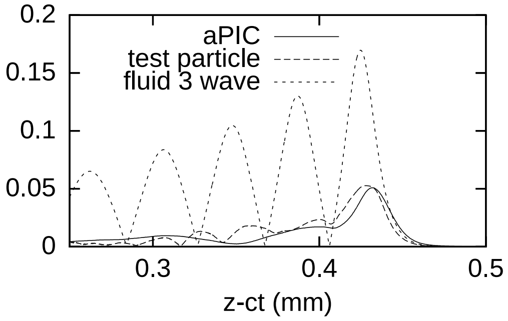

Fig. 1. Amplified seed envelope measured after 1.8 mm propagation. The pump amplitude was $a_2 = 0.02$, the plasma density $n_e = 1.05 \times 10^{19}\text{cm}^{-3}$, the temperature 50 eV.

4. Summary

A method using test particles has been developed to simulate RBS and its application in the laser amplification. Since the new method enables to simulate the system much faster than the aPIC or conventional full PIC, it is quite useful in the systematic simulation study of RBS. The benchmarking result shows quite a reasonable agreement.

Acknowledgements

This work was supported by the Creative Research Initiative of KOSEF/Korean Ministry of Science and Technology.

References

[1] V.M. Malkin, G. Shvets, and N.J. Fisch, Phys. Rev. Lett. 82 (1999) 4448; Phys. Plasmas 7 (2000) 2232.

[2] G. Shvets, N.J. Fisch, A. Pukhov, and J. Meyer-ter-Vehn, Phys. Rev. Lett. 81 (1998) 4879.

[3] M.S. Hur, G. Penn, J.S. Wurtele, and R.R. Lindberg, Phys. Plasmas 11 (2004) 5204.

[4] M.S. Hur, R.R. Lindberg, A.E. Charman, J.S. Wurtele, and H. Suk, Phys. Rev. Lett. 95 (2005) 115003.