플라즈마 항적장을 이용한 광자 가속 시뮬레이션

Simulation of Photon Acceleration with Plasma Wake Fields

Hae June Lee, Guang-Hoon Kim, Changbum Kim, Jong-Uk Kim, and Hyyong Suk
Center for Advanced Accelerators, Korea Electrotechnology Research Institute (KERI)
leehj@keri.re.kr

From the dispersion relation of an electromagnetic (EM) wave propagating through plasmas,

$$\omega^2 = \omega_p^2 + c^2 k^2,$$

the phase velocity (ω/k) of the wave is large at high density where ω_p is large, and small at low density. Therefore, when a laser pulse is located on a downward density gradient of a plasma wave, the phase velocity of the back of the pulse becomes faster than that of the front of the pulse and the pulse wavelength decreases. By this process, the frequency of the laser pulse is upshifted and the group velocity of the photons increases. This phenomenon is referred to as "photon acceleration"(1). If we assume an electron density perturbation of a sinusoidal form,

$$\delta n = -\delta n_0 \sin k_p \zeta,$$

where $\zeta = z - ct$ and $k_p = \omega_p / c$, the frequency will be upshifted as(2)

$$\frac{\omega}{\omega_0} = \left(1 + \frac{\omega_p^2}{\omega_0^2} \frac{\delta n_0}{n_0} k_p z \cos k_p \zeta\right)^{1/2}.$$

Here, the effect of transverse motion, nonlinear effects, and phase slippage are neglected.

With a plasma wake field generated by a short laser pulse propagating through plasmas, a sharp density gradient is possible to be made. In addition, it is also possible to accelerate a prove pulse for significantly long distance comparable to the Rayleigh length because the propagation speed of the wake field is same as that of the driver pulse. The acceleration is most effective when the phase velocity of the plasma wave matches the group velocity of the laser pulse.

In this study, we present simulation results of the photon acceleration by one-dimensional (1d) and two-dimensional (2d) electromagnetic particle-in-cell codes, 1d-XOOPIC(3) and OSIRIS(4). In 1d simulation, a linearly polarized EM wave with a pulse width of 50 fs (FWHM) and a normalized quiver velocity of $a_0 = eE/mc\omega = 1.0$ propagates through a plasma with electron density of 10^{18} cm^{-3} (plasma wavelength is 33 μm) and makes a plasma wake field with a density fluctuation more than 40%. A prove pulse with a pulse width of 12.5 fs (FWHM) and a_0 = 0.05 is launched with a time delay to locate the prove pulse at the downward density gradient, $\tau_{\mathrm{vay}} = 1.75 \lambda_p / c$. As shown in Fig. 1, the frequency upshift reaches up to 40% after the pulse propagates 2 cm. At this stage, acceleration is saturated because of dispersion and slippage of the prove pulse.

In 1d simulation, the laser pulse diffraction is not included and the laser pulse is assumed to be a planar wave while the actual pulse shape is Gaussian in transverse direction. These effect are considered in 2d simulations.

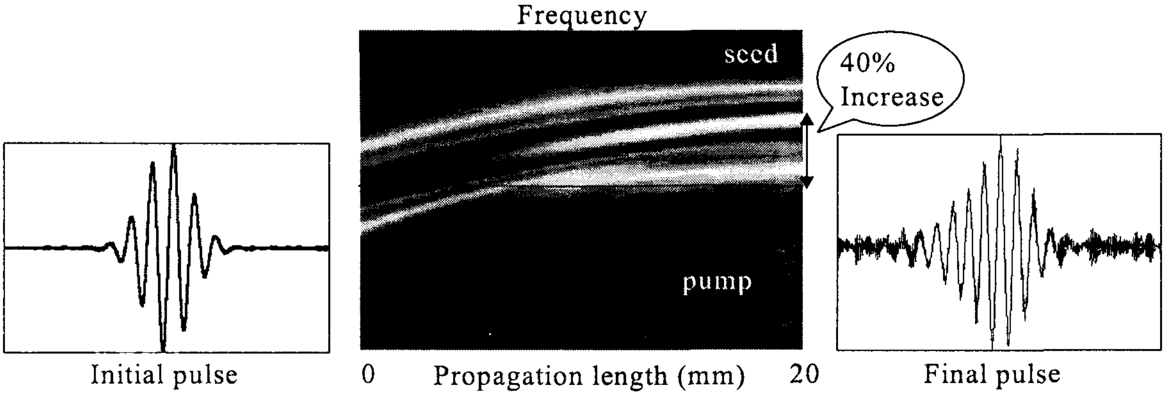

FIG 1. A one-dimensional simulation result of photon acceleration.

In 2d simulation, the effect of transverse motion plays an important role. Differently from the planar wave of 1d cases, the Gaussian shape pulse makes an elliptical wake field of which electron density gradient is not parallel to the propagation direction (z coordinate in this case). Therefore, the wave front of the prove pulse is deformed significantly when the spot size of the prove pulse is comparable to the transverse size of the wake field, which is determined by the spot size of the drive pulse. For this reason, the frequency upshift in 2d cases is not effective as that shown in 1d results. In order to increase acceleration efficiency, it is necessary to increase the transverse size of the wake field as well as to reduce the dispersion and slippage of the prove pulse.

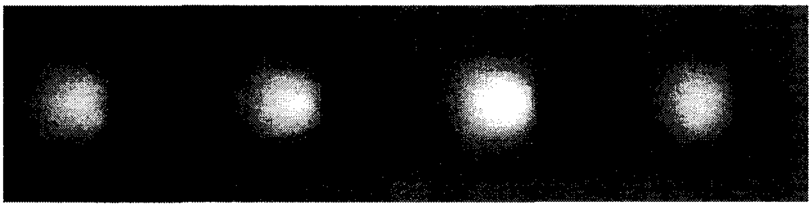

FIG. 2. 2d simulation result of a plasma wake field generated by a laser pulse of Gaussian shape.

This work is supported by the Creative Research Initiatives of the Korea Ministry of Science and Technology.

[1] S. C. Wilks, J. M. Dawson, W. B. Mori, T. Katsouleas, and M. E. Jones, Phys. Rev. Lett. **62**, 2600 (1989).
[2] E. Esarey, A. Ting, and P. Sprangle, Phys. Rev. A **42**, 3526 (1990).
[3] H. J. Lee, P. J. Mardahl, G. Penn, J. S. Wurtele, IEEE Trans. Plasma Science **30**, 40 (2002).
[4] R. G. Hemker, K. C. Tzeng, W. B. Mori, C. E. Clayton, and T. Katsouleas , Phys. Rev. E **57**, 5920 (1998).