Electromagnetic soliton generation in an over-dense plasma through Laser-plasma interaction: Using PIC simulation

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Abstract

During laser propagation through an over-dense plasma a huge amplitude electromagnetic soliton is shown to evolve under the impact of external magnetic field. For investigating this phenomenon, Particle-in-Cell (PIC) simulations inside the EPOCH-4.17.10 framework are carried out for a finite laser pulse. While the transverse magnetic and electric fields have 1/2-cycle and 1-cycle structures, respectively, the electrostatic field inside the soliton has a 1-cycle structure in space. Soliton propagation for a longer time is shown to occur in the plasma without any changes in its structure. The soliton width grows in tandem with an increase in the temperature of both the plasma species. Such a soliton structure may be useful for particle acceleration, particle trapping, and in communication.

Keywords: Over-dense plasma, strong magnetic field, electromagnetic solitons, plasma species temperature

1. Introduction

The nonlinear interaction of powerful lasers with plasma is vital to examine. Understanding laser pulse propagation modes in strong magnetic fields is crucial. Laser propagation modes are determined by plasma densities, laser intensity, pulse polarization, and external magnetic field strength. Magnetic fields can change laser propagation modes. A soliton is produced by laser energy trapped in the plasma depletion region. The plasma converts a considerable portion of laser energy into solitons, which are structures with a nonlinear, continuous localized electromagnetic field [1,2]. During laser-plasma interaction, electromagnetic soliton formation and its propagation have been previously studied [3-7]. Experimentally, relativistic solitons have also been studied [8,9]. In the present study, we propose a 1D PIC simulation of electromagnetic solitons created by an intense laser pulse propagating in an over-dense plasma under the impact of a high magnetic field. The inquiry involves three cases. We first investigate how plasma solitons are formed. Soliton propagation via plasma is explored in the second instance. Solitons are explored at varied plasma species temperatures in the third scenario.

2. Simulation setup

In an external magnetic field, we have used EPOCH for carrying out 1D particle-in-Cell (PIC) simulations to study the laser-plasma interaction. A recently built mega-Gauss producing equipment produced a 1.2 kT peak magnetic field utilizing electromagnetic flux-compression (EMFC) [11]. We may now deduce from multiple scientific articles that the solitons can be created near kilo-Tesla magnetic fields. Several research tests use an intensity of 10^{23} Wm^{-2} [10]. For our work, a 1D simulation box of length $L_x = 220\ \mu m$ has been chosen, and the plasma medium is set to start at $x = 0$. The laser's electric field is directed along the y-direction, and an external magnetic field is applied along the z-direction. It means the laser is plane polarized since its electric field is along the y-direction. We consider a short-pulse laser of wavelength $\lambda_l = 16$ μm. The laser profile is Gaussian with the intensity of $\mathrm{I} = 4.5 \times 10^{25}\ \mathrm{Wm}^{-2}$. The right side of the simulation box is open, and the laser is incident on the plasma from the left side of the box. The laser propagates along the x-direction, and the applied external magnetic field (**B**) is also along the same direction as the direction of laser propagation. The strength of the applied external magnetic field is $B_0 = 5\ kT$. The uniform plasma density is taken as $n_0 = 3.5\times10^{26}\ \mathrm{m}^{-3}$ for $\mathrm{x} = 0$ to $\mathrm{x} = 200$μm. The temperature of both the plasma species (electrons and protons in hydrogen plasma) is taken as T = 150eV, until and unless defined.

3. Results and discussion

From the laser pulse, electrons and ions are pushed away. Higher laser intensity causes the electrons to travel at relativistic speed and a change in their rest mass. The electromagnetic field of a strong laser increases the relativistic electron mass, and the dispersion effect becomes important. Fig. 1(a) shows the initial electron and proton densities. On the other hand, Fig. 1(b) shows the electron and proton densities at t = 1.49ps. The effect of strong magnetic field changes the nature of laser pulse from its linear polarization to elliptical polarization. Also, the evolved soliton is elliptically polarized. This is because of trapping of laser's energy in the density cavity. Fig. 2(a) shows that the electrostatic field E_x has a 1-cycle structure when analyzing the soliton structure. Fig. 2(b) shows that the electromagnetic structure's electric field E_y has a 1/2-cycle. At t = 1.49ps, Fig. 2(c) shows that the magnetic field B_z exhibits a 1-cycle structure. These 1D PIC simulation findings obtained in different laser and plasma parameter regimes confirm the observation of Li et al. [12,13], although the soliton amplitude and energy