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Large amplitude electromagnetic solitons in intense laser plasma interaction*

Li Bai-Wen(李百文)[a], Ishiguro S[b], and Skoric M M[b]

[a] *Institute of Applied Physics and Computational Mathematics, Beijing* 100088, *China*

[b] *The Graduate University for Advanced Studies and National Institute for Fusion Science, Toki 509-5292, Japan*

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This paper shows that the standing, backward- and forward-accelerated large amplitude relativistic electromagnetic solitons induced by intense laser pulse in long underdense collisionless homogeneous plasmas can be observed by particle simulations. In addition to the inhomogeneity of the plasma density, the acceleration of the solitons also depends upon not only the laser amplitude but also the plasma length. The electromagnetic frequency of the solitons is between about half and one of the unperturbed electron plasma frequency. The electrostatic field inside the soliton has a one-cycle structure in space, while the transverse electric and magnetic fields have half-cycle and one-cycle structure respectively. Analytical estimates for the existence of the solitons and their electromagnetic frequencies qualitatively coincide with our simulation results.

Keywords: particle-in-cell (PIC), Raman cascade, photon-condensation, relativistic EM soliton

PACC: 5235P, 5335S, 5240D

1. Introduction

The theoretical and experimental study of nonlinear interaction of intense laser pulses in plasma is an important topic in current researches, because of its potential applications, such as, particle acceleration,[1] photon acceleration,[2] and fast ignition in inertial confinement fusion.[3] Relativistic solitons are electromagnetic (EM) structures self-trapped by locally modified plasma refractive index through the relativistic electron mass increase and the electron density redistribution by the ponderomotive force of an intense laser pulse. These solitons are generated behind the front of the laser pulse and are made of nonlinear, spatially localized low-frequency EM fields with a close to zero group velocity. A fairly large part of the laser pulse energy can be transformed into solitons. Recently, the research on solitons has received much attention because they are of fundamental importance in nonlinear science[4] and are considered to be essential components of turbulence in plasma.[5]

The mechanism of the EM soliton formation and its structure were analytically investigated and observed by particle simulation in the interaction of intense laser radiation with underdense and overdense plasmas.[6,7] The theory of solitons has been developed mainly within the framework of the approximation of immovable ions. An exact analytical solution of the electron Fluid–Maxwell equations representing one-dimensional (1D) circularly polarized relativistic EM subcycle soliton was obtained in perfect agreement with one-dimensional particle-in-cell (1D-PIC) simulations.[8] The soliton found in particle simulations consists of slowly or non-propagating electron density cavity inside which an EM field is trapped and oscillates coherently with a frequency below the unperturbed plasma frequency and with its spatial structure corresponding to half a cycle (subcycle soliton).[9] In homogeneous plasma, solitons have been found to exist for a long time, close to the regions where they were generated, and eventually decay due to their interaction with fast electrons, as a result, the soliton energy is transformed into the fast particle energy. In inhomogeneous plasmas, solitons are accelerated with the acceleration proportional to the gradient of the plasma density towards the low density side. When the soliton reaches some critical plasma region, for example, the plasma vacuum interface, it radiates away its energy in the form of a short burst of low-frequency EM radiation.[10]

In this paper, we present 1D simulation results on large amplitude relativistic EM solitons induced by intense laser pulse propagating in long underdense

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collisionless homogeneous plasma. We found that, in addition to the inhomogeneity of the plasma density, the acceleration of the solitons depends upon not only the laser amplitude but also the plasma length. The EM frequency of the solitons is between about half and one of the unperturbed electron plasma frequency. The electrostatic field inside the soliton has one-cycle structure in space, while the transverse electric and magnetic fields have half-cycle and one-cycle structure respectively. Finally, analytical estimates for the existence of the EM soliton and their EM frequencies qualitatively coincide with our simulation results.

2. Simulation model

Fully relativistic EM 1D3V-PIC simulation code is used in our simulations. The plasma layer which with length $L = 900c/\omega_0$, density $n = 0.032n_{\rm cr}$ and electron temperature $T_{\rm e} = 350$eV begins at $x = 0c/\omega_0$ and ends at $x = 900c/\omega_0$. In the front side and rear side of the plasma layer, long enough vacuum regions are used, where c, ω_0 and $n_{\rm cr}$ are the vacuum speed of light, the carrier frequency of laser pulse, and laser critical density respectively. Ions are typically kept immobile as a neutralizing background. The cell number is 10 per $1c/\omega_0$ and 80 particles are put in each cell. The linearly polarized laser, with electric field E_0 along the y-direction and normalized amplitude $a = eE_0/m_{\rm e}\omega_0 c$, is launched at the distance of $200c/\omega_0$ from the plasma front interface, where $m_{\rm e}$ and e are electron mass and charge respectively. The electrons which enter the vacuum build a potential barrier which prevents more electrons leaving the plasma layer. For these electrons as well as for outgoing EM waves, two additional numerical damping regions are used. The time, electric field and magnetic field are normalized to the laser period $2\pi/\omega_0$, $m_{\rm e}\omega_0 c/e$ and $m_{\rm e}\omega_0/e$ respectively, the time is taken zero, $\omega_0 t = 0$, when the laser pulse arrives at the vacuum–plasma boundary.

3. Large amplitude relativistic EM soliton due to strong photon condensation

When intense laser EM wave enters the low density plasma layer, the first stage is dominated by stimulated Raman scattering (SRS) which evolves into a complex nonlinear dynamical phenomenon. Parametric Raman cascade of the laser pulse into the higher-order SRS harmonics (backward and forward) saturates into the strong photon-condensation at the bottom of the light spectrum.[11,12] The continuing instability growth and laser energy transfer through stimulated Raman cascade downshifts EM energy from the fundamental to the bottom of the EM frequency spectrum, i.e. the low frequency trapped EM mode. It reveals a tendency of a transition from the Raman cascade regime to EM energy accumulation, i.e. the so-called photon condensation. The cascade-to-condensation transition becomes more pronounced with increasing laser amplitude and increasing plasma density.[11,12]

3.1. Standing EM soliton

In the regions of strong photon-condensation, first, a large part of the electrons are pushed away due to the large ponderomotive force of EM field, and the resulted electron density redistribution results in nonlinearity; second, dispersion effect comes into playing an important role due to the relativistic electron mass increase by responding to the intense laser EM field.

As time goes on, as shown in Fig.1 the snapshots for the electron plasma density $n_{\rm e}/n$ and the EM

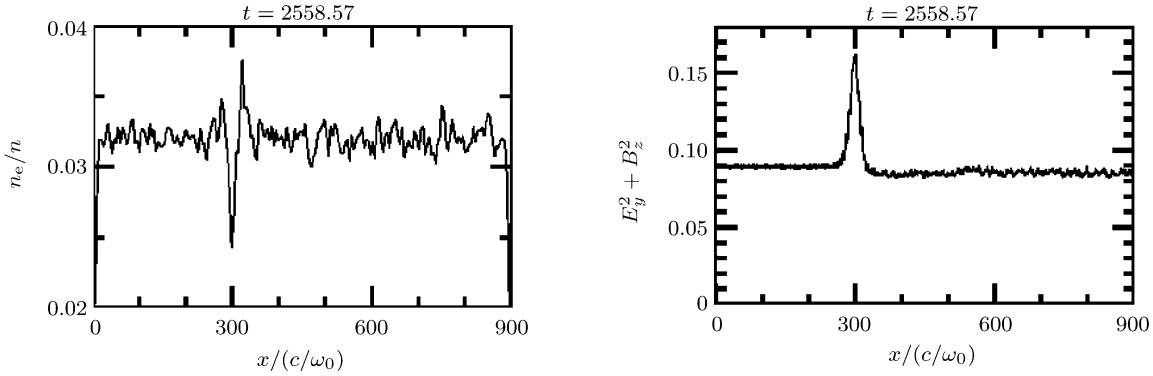


Fig.1. The snapshots for plasma density $n_{\rm e}/n$ and EM energy density $E_y^2 + B_z^2$ in the case of laser amplitude $a = 0.3$.

energy density $E_y^2+B_z^2$ (averaged over one laser wavelength) in the case of laser amplitude $a = 0.3$ are spatially localized, a non-propagating electron density cavity is created inside, and an EM field is trapped and oscillates coherently; that is, a large amplitude localized standing relativistic EM soliton comes into form. In Fig.2 (above), the frequency spectra of EM and electrostatic (ES) fields inside the EM soliton region are plotted. In addition to the dominant laser EM component and the perturbed electron plasma wave component, the EM component with frequency $\omega_{\rm sol}^{\rm sim} \approx 0.13\omega_0 = 0.72\omega_{\rm pe}$ and the corresponding ES component with frequency $\omega_{\rm sol}^{\rm ES} \approx 0.87\omega_0$ are also observed. If only from the point of view of the frequency, it seems that this phenomenon can be roughly explained as a three-wave resonant coupling process. The size of the EM soliton is about $\Delta x_{\rm sol} \approx \lambda_{\rm pe} \approx 5.6\lambda_0$, where $\lambda_{\rm pe} = c/\omega_{\rm pe}$ and $\lambda_0 = c/\omega_0$ are the wavelength of the

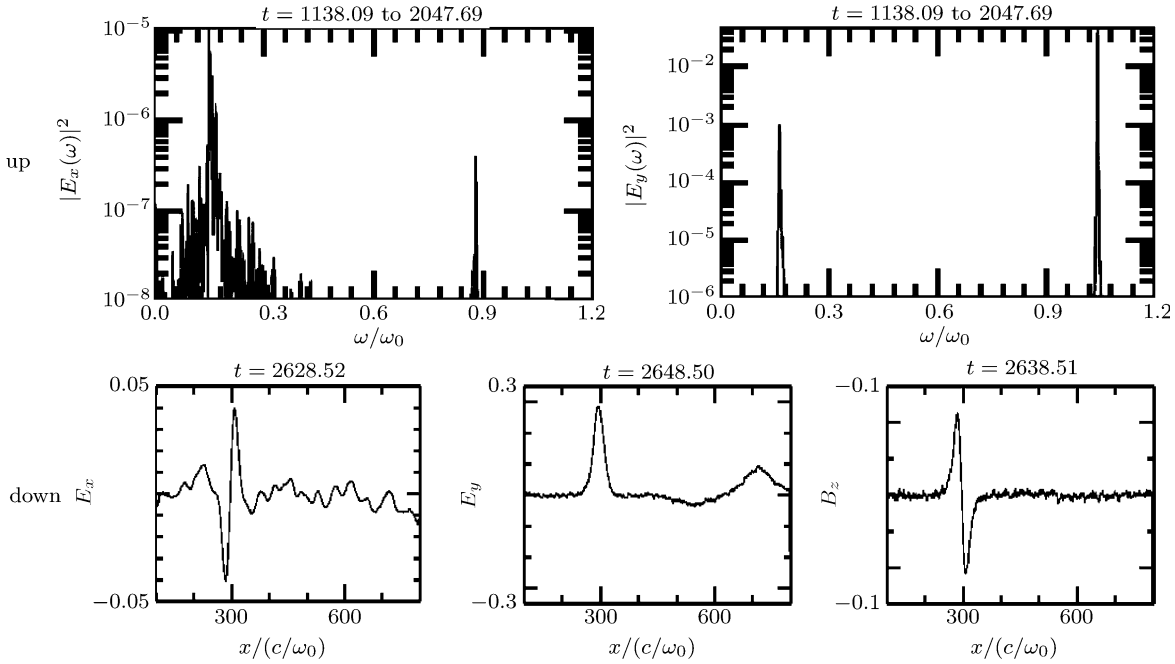


Fig.2. The plots for the frequency spectra of EM and ES waves trapped inside a soliton, the ES field E_x, the transverse electric field E_y, and the magnetic field B_z for the laser amplitude $a = 0.3$ case.

electron plasma wave and the laser EM wave in vacuum respectively. Figure 2 (below) shows the structure of the soliton, the ES field E_x (averaged over one $\lambda_{\rm pe}$) has the one-cycle structure, while the corresponding EM structure for electric field E_y (averaged over one λ_0) has half-cycle structure and for magnetic field B_z (averaged over one λ_0) has one-cycle structure respectively. The spatial EM structure is oscillatory in time, but the ES structure is not.[11,12]

3.2. Backward-accelerated EM soliton

However, by increasing laser amplitude to $a = 0.4$ and $a = 0.5$, the soliton dynamics appears different from that of the standing soliton in the case of laser amplitude $a = 0.3$. Figure 3 (above) shows the EM energy density snapshots for laser amplitude $a = 0.5$ case, the observed solitons are accelerated backward towards the plasma–vacuum interface. As the soliton approaches the plasma–vacuum interface, it starts to radiate its energy away in the form of a short burst of low-frequency EM wave due to a non-adiabatic interaction with the plasma boundary. As a result, during the soliton radiation, one observes a very high transient reflectivity much larger than that of the SRS backscattering process as shown in Fig.4. In order to show the process of the soliton acceleration, in Fig.4 the soliton trajectory for laser amplitude $a = 0.5$ is also given.

In case of the higher laser amplitude $a = 0.5$, due to the larger acceleration, the 'lifetime' of a soliton inside plasma is shorter than that in the $a = 0.4$ case. By analysing the frequency spectra in vacuum after soliton radiation, we obtained that the soliton EM frequencies are $\omega_{\rm sol}^{\rm sim} \approx 0.67\omega_{\rm pe}$ for $a = 0.4$ and $\omega_{\rm sol}^{\rm sim} \approx 0.61\omega_{\rm pe}$, for $a = 0.5$ respectively.

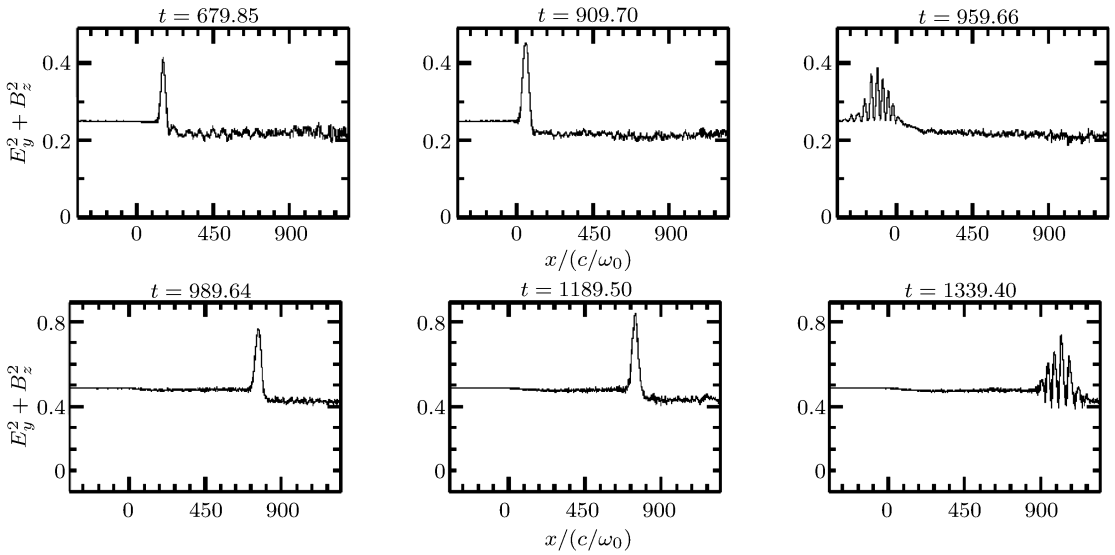


Fig.3. The EM energy density snapshots for laser amplitude $a = 0.5$ (upper plots) and $a = 0.7$ (lower plots) respectively.

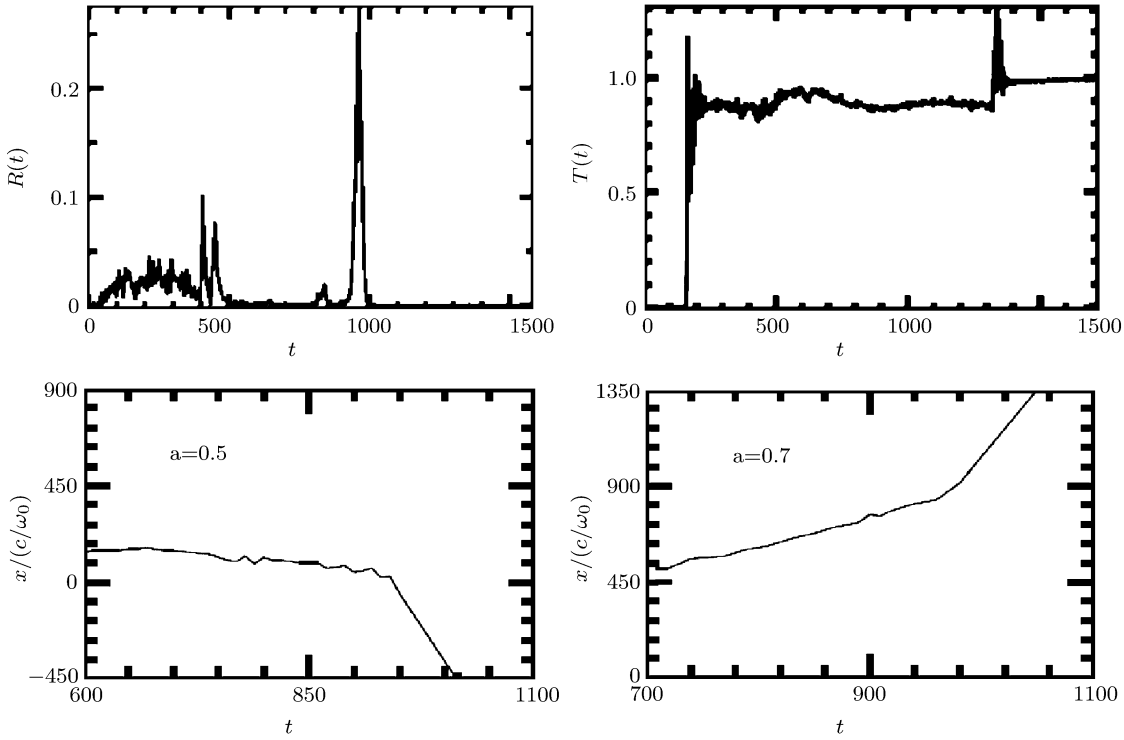


Fig.4. The temporal reflectivity for laser amplitude $a = 0.5$, the temporal transmissivity for $a = 0.7$, and the EM soliton orbits for $a = 0.5$ and for $a = 0.7$ respectively.

3.3. Forward-accelerated EM soliton

If we continue to increase the laser amplitude to $a = 0.6$ and $a = 0.7$, the interesting phenomenon is that, in the two cases, the observed EM solitons are neither the standing ones nor the backward-accelerated ones; as shown in the Fig.3 (below) and in the Fig.4 for the laser amplitude $a = 0.7$ case, the observed large amplitude relativistic EM solitons are now accelerated forward. When the solitons arrive at the plasma–vacuum interface where they radiate their energy away in the form of a short burst of low frequency EM waves. As expected, very high transient transmittivity during the soliton radiation can be detected. To show the process of soliton acceleration, in Fig.4 the EM soliton trajectory for the laser amplitude $a = 0.7$ case is also given. Similarly, in the higher laser amplitude $a = 0.7$ case, the 'lifetime' of soliton inside plasma is shorter than that in the $a = 0.6$ case. Again, by analysing the frequency spectra in vacuum, we obtained that the EM frequencies of the soliton are $\omega_{\rm sol}^{\rm sim} \approx 0.56\omega_{\rm pe}$ for $a = 0.6$ and $\omega_{\rm sol}^{\rm sim} \approx 0.50\omega_{\rm pe}$ for

$a = 0.7$ respectively.

Actually, in the appropriate unitary normalization with the low-frequency of the soliton, the soliton dimensionless amplitude greatly exceeds the laser pump more than $\omega_0/\omega_{\rm pe}$ times, the EM soliton corresponds to a type of ultra-relativistic EM soliton.[5,11,12]

4. Analytical estimates for EM soliton

To explain the existence of the standing and moving soliton solutions, we consider an intense laser pulse propagating through a cold collisionless plasma with fixed ions and start with the fully nonlinear relativistic 1D model. In Coulomb gauge, the EM wave equation, the continuity equation and the electron momentum equation are as follows:

$$\left(\frac{\partial^2}{\partial t^2} - c^2\frac{\partial^2}{\partial x^2}\right)a = -\frac{\omega_{\rm pe}^2 n}{n_0\gamma}a, \tag{1}$$

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}\left(\frac{np}{m_{\rm e}\gamma}\right) = 0, \tag{2}$$

$$\frac{\partial p}{\partial t} = -eE_{//} - m_{\rm e}c^2\frac{\partial \gamma}{\partial x}, \tag{3}$$

where $\gamma = \sqrt{1 + a^2 + (p/m_{\rm e}c)^2}$ is relativistic factor and $a = eA/m_{\rm e}c^2$ is the normalized vector potential; n, n_0, and $\delta n = (n - n_0)/n_0$ are the perturbed, unperturbed and normalized perturbed electron densities; p and $E_{//}$ are the electron momentum in x direction and the longitudinal electric field respectively. From now on, the dimensionless variables $x \to (c\omega_{\rm pe}^{-1})x$, $t \to \omega_{\rm pe}^{-1}t$ and $\omega \to \omega_{\rm pe}^{-1}\omega$ will be used.

Linearly polarized EM waves possess odd harmonics for the vector potential and even harmonics for the electron density[13] respectively; therefore, a stationary spatially localized soliton solution can be sought as[14]

$$a(x,t) = A(x)\cos(\omega t), \tag{4}$$

$$p(x,t) = P(x)\sin(2\omega t), \tag{5}$$

$$\delta n(x,t) = N_0(x) + N_2(x)\cos(2\omega t). \tag{6}$$

Assuming $a \gg p$ and after Legendre's polynomial expansion we have $\gamma \approx (\gamma_0+1)/2 + (\gamma_0-1)\cos(2\omega t)/2$, where $\gamma_0 = \sqrt{1 + A^2}$.

Substituting Eqs.(4)–(6) into Eqs.(1)–(3) and selecting appropriate harmonics, we can readily obtain

$$A_{xx} - \frac{\gamma_0 + 5}{8\gamma_0}A\gamma_{0xx} = \left(\frac{\gamma_0 + 3}{4\gamma_0} - \omega^2\right)A + \omega A P_x/\gamma_0. \tag{7}$$

For the EM soliton profile, $A(x)$ is maximum at the centre $x = 0$, by means of simple algebra Eq.(7) can be written as

$$A_{0xx}\left(1 - \frac{\gamma_0 + 3}{8\gamma_0^2}A_0^2\right) = \left(\frac{\gamma_0 + 3}{4\gamma_0} - \omega^2\right)A_0. \tag{8}$$

The condition that at the maximum $A_{0xx} < 0$ requires:

$$\frac{\gamma_0 + 3}{4\gamma_0} - \omega^2 < 0 \quad \text{and} \quad 1 - \frac{\gamma_0 + 3}{8\gamma_0^2}A_0^2 > 0. \tag{9}$$

This estimates the maximum soliton amplitude and minimum eigen-frequency allowed by the nonlinear dispersion $\omega(A)$ curve to be ultra-relativistic, $A_0 < 5.2$ and $\omega_{\rm sol} > 0.63\omega_{\rm pe}$. The obtained EM frequency of the soliton coincides qualitatively with our standing soliton $\omega_{\rm sol}^{\rm sim} \approx 0.72\omega_{\rm pe}$ case.

Apart from the existence of the standing EM soliton solution, the moving soliton solution can be found in homogeneous plasma. In a weakly relativistic limit for $|a| \ll 1$ and $|\delta n| \ll 1$, the wave equation for the vector potential envelope A is obtained[13]:

$$\mathrm{i}\frac{\partial A}{\partial t} + \frac{1}{2}A_{xx} + \frac{3}{16}|A|^2 - \frac{1}{8}(|A|^2)_{xx}A + \frac{1}{24}(A^2)_{xx}A^* = 0. \tag{10}$$

Equation (10) has the form of a generalized nonlinear Schrödinger equation with two extra nonlocal (derivative) nonlinear terms, and Eq.(10) has a localized moving soliton solution[14]:

$$A = \rho(u)\mathrm{e}^{\mathrm{i}\theta(u) + \mathrm{i}\lambda^2 t}, \tag{11}$$

where $u = x - \upsilon t$ and υ is the soliton velocity. Under the boundary conditions ρ, ρ_u, $\rho_{uu} \to 0$ when $u \to 0$, the first integration of Eq.(10) gives

$$\theta_u(u) = \upsilon, \quad (\rho_u)^2 = \frac{\left(2\lambda^2 - \upsilon^2 - (3/16 - \upsilon^2/6)\rho^2\right)\rho^2}{1 - \rho^2/3}. \tag{12}$$

Additional integration of Eq.(12) yields a moving soliton solution in an implicit form:

$$\pm u = \frac{1}{2\sqrt{2\lambda^2 - \upsilon^2}}\ln\frac{\sqrt{1 - X\rho^2} + \sqrt{1 - \rho^2/3}}{\left|\sqrt{1 - X\rho^2} + \sqrt{1 - \rho^2/3}\right|} - \sqrt{\frac{1}{3X}}\ln\frac{\sqrt{1 - \rho^2/3} + \sqrt{1/(3X) - \rho^2/3}}{\sqrt{|1 - 1/(3X)|}}, \tag{13}$$

where $X(\lambda, v) = (3/16 - v^2/6)/(2\lambda^2 - v^2)$.

This is a moving soliton with a vector potential a and eigenfrequency $\Lambda = \lambda^2 - v^2$; its amplitude is $\rho_{\max} = \sqrt{(2\lambda^2 - v^2)/(3/16 - v^2/6)}$. When the soliton velocity $v = 0$, this solution coincides with the standing soliton solution of Eq.(9). If we take $\lambda^2 = \omega_{\rm sol}$ as the EM frequency of standing soliton, then, in the case of moving soliton, its EM frequency Λ will decrease with the increase of the soliton velocity v.

In our simulation results, the EM frequency for the accelerated solitons is smaller than that of the standing case $\omega_{\rm sol}^{\rm sim} \approx 0.72\omega_{\rm pe}$, and with the increase of the laser amplitude, the moving velocity of soliton becomes larger and larger, and the corresponding EM frequency becomes smaller and smaller. Our simulation results qualitatively coincide with above analytical solution. However, the above analytical solution cannot explain why the EM solitons can be accelerated backward or forward under the different laser amplitude condition.

For both standing and accelerated solitons, the EM energy density profile shows a difference between the front and rear side of the soliton, the front value is always large; with the increase of the laser amplitude, the difference becomes larger and larger. This is because in the large laser amplitude case, the amplitude of the observed EM soliton is larger than that in the lower laser amplitude case. The difference of EM energy density is mainly converted into the EM soliton. The steep EM energy density gradient in the short transition layer of the soliton length ($c/\omega_{\rm pe} \sim$ classical skin depth) corresponds to the ponderomotive force which acts on plasma electrons and therefore pushes the electron cavity with the soliton in the forward direction.

Basically, the longitudinal electron motion is determined by the balance of the ES field and the ponderomotive force terms. The large flow of relativistic electrons generated in forward direction (due to SRS, etc.) which drives ES fields, is compensated by a cold (bulk) return current which moves plasma electrons backwards. Possibly, this is why moderately large solitons are found to move backwards. However, at very large amplitudes, the ponderomotive term prevails, the acceleration is reversed and the EM solitons is pushed forwards.

Apart from the standing soliton case, our simulation results do not comply with the earlier author's explanations:[10] i.e., due to the inhomogeneity of the plasma density, the EM solitons accelerate with an acceleration proportional to the density gradient towards the low density side. From our simulation results, we found a new phenomenon that the acceleration of the EM soliton in homogeneous plasma depends upon the laser amplitude. In fact, by some other simulations, we found that the acceleration of the EM soliton also depends upon the plasma length. That is, in homogeneous plasma, by varying the laser amplitude or the plasma length, in addition to the standing EM soliton, one could detect not only the backward- but also the forward-accelerated EM solitons.

However, to data, the theoretical analysis for the acceleration of the relativistic EM soliton in the homogeneous plasma condition is still lacking.

5. Influence of ion dynamics on the formation of the EM soliton

The ion dynamics has already some influence on the soliton formation, because the observed EM solitons were formed a little later moment.

In order to investigate the effect of the ion dynamics, in the case of plasma length $L = 900\ c/\omega_0$, density $n = 0.032n_{\rm cr}$, laser amplitude $a = 0.3$, and taking the mass ratio of ion to electron $m_{\rm i}/m_{\rm e} = 1836$ and the same temperature $T_{\rm i} = T_{\rm e} = 350$eV, by performing a new simulation we found that the ion motion could reduce the EM energy density of the soliton and slightly change its size; however the same type of large amplitude localized relativistic EM soliton could still be observed. Note that a large ion density cavity was also formed during the formation and existence of the EM soliton.

6. Conclusions

In conclusion, we present 1D particle simulation results on large amplitude relativistic EM solitons induced by intense laser pulse interacting with long underdense collisionless homogeneous plasma. The standing, backward-accelerated and forward-accelerated solitons were observed. It was found that, in addition to the inhomogeneity of the plasma density, the acceleration of the EM solitons depends upon not only the laser amplitude but also the plasma

length. The ES field inside the soliton has one-cycle structure in space, while the transverse electric and magnetic fields have half-cycle and one-cycle structure respectively. The accelerated EM solitons propagate towards the plasma–vacuum interface where they radiate their energy in the form of a short burst of low-frequency EM radiation. Analytical estimates for the existence of the solitons and the EM frequencies of the solitons coincide with our simulation results. Finally, the influence of the ion dynamics on the formation of the EM soliton was also discussed briefly.

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