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Ultra- Intense EM Solitons in a Relativistic Laser-Plasma Interaction

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Large spatially-localized coherent electromagnetic (EM) structures were analytically predicted and observed by particle simulation in relativistic laser-plasma interactions [1-2]. Relativistic EM solitons are localized structures with downshifted light self-trapped by a locally modified plasma refractive index via the relativistic electron mass increase and the depleted electron density by the ponderomotive force. In low-density plasmas, stimulated Raman interactions via the cascade-into-condensate mechanism [2] down-shift the pulse frequency to the bottom of the light spectrum. By a phenomenon of light localization, a laser pulse is partially transformed into a train of slow short relativistic EM solitons [1-3]. In this paper, we study dynamics and saturation of large relativistic EM soliton structures. While the circular polarization was previously studied in detail [1], here we treat a realistic, however, a more complex linearly polarized laser propagating in a uniform plasma layer.

Simulation results

One-dimensional fully relativistic EM 1D3V-PIC (particle-in-cell) code was used. The length of a simulation system and plasma layer was 2700 c/ω_0 and 900 c/ω_0, respectively; with two vacuum and damping regions put at both sides of the system. The electron density and temperature were n= 0.032 n_{cr} and T_e=0.35 KeV, where $n_{cr}= \omega_0^2 m_e/4\pi e^2$. Laser light is linearly polarized in y-direction with the normalized amplitude $\beta= eE_0/ m_e\omega_0 c$. The time, electric and magnetic field is in units $2\pi/\omega_0$, $m_e\omega_0 c/e$ and $m_e\omega_0/e$, respectively. At t=0, the laser pulse was taken to arrive at the front plasma-vacuum interface. Ions were immobile.
In simulations, apart from standing-, also backward- and forward propagating relativistic EM solitons were observed in uniform plasmas (Fig. 1-3). EM solitons accelerated toward the plasma-vacuum interface irradiate energy in the form of coherent low-frequency EM bursts. The soliton acceleration is controlled by both, the laser intensity and the plasma length. In a weakly relativistic model, we derived the original nonlinear Schroedinger type of equation with a local and nonlocal nonlinearity, that well explains simulation data [2-3]. Here, we present an analytical estimate for the case of large ultra-relativistic EM solitons; such as, the maximum amplitude and eigen-frequency of moving ultra-relativistic EM solitons, that in saturation are practically independent on the laser intensity.

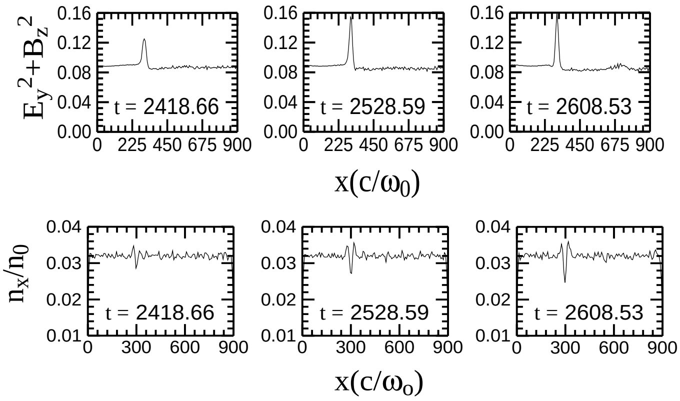

Fig. 1 EM energy (top) and electron density (bottom) snapshots for laser pulse with β=0.3.

In Fig. 2 the EM and ES frequency spectra inside the soliton region are plotted. In addition to the laser fundamental, the low-frequency EM soliton component is found; which can decrease down to about one-half of the electron plasma frequency. Furthermore, the transverse electric, magnetic and electrostatic field of the soliton reveals: half-, one- and one-cycle spatial period structure, respectively. The EM soliton width is typically close to the electron plasma wave wavelength ($\lambda_p=c/\omega_p$). These facts observed in PIC simulations are found to be consistent with our analytical modelling (*vide infra*). Since, the electron quiver velocity scales inversely with the frequency; a large down-shift in laser pulse frequency (Fig. 2) brings the EM soliton interaction into the ultra-relativistic regime.

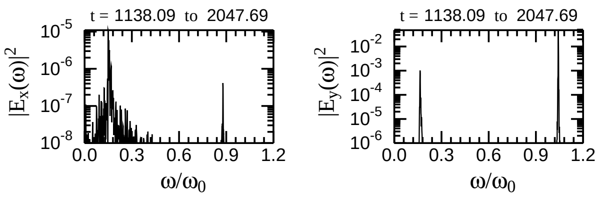

Fig. 2 Spectrum of ES and EM waves trapped inside the soliton for β=0.3.

Moreover, by increasing the laser intensity more intense EM solitons are generated which tend to move and accelerate inside plasma. First, for a larger intensity, solitons start to move in backward direction (Fig. 3- top). However, interestingly, even larger laser intensity can reverse the soliton motion into forward direction (Fig. 3 –bottom). Arriving at the front/ rear plasma interface, the soliton energy is irradiated as a coherent low-frequency EM burst. It seems that the EM soliton motion is controlled by the balance of the forward pushing ponderomotive force and backward motion of a bulk electron return current due to ES field.

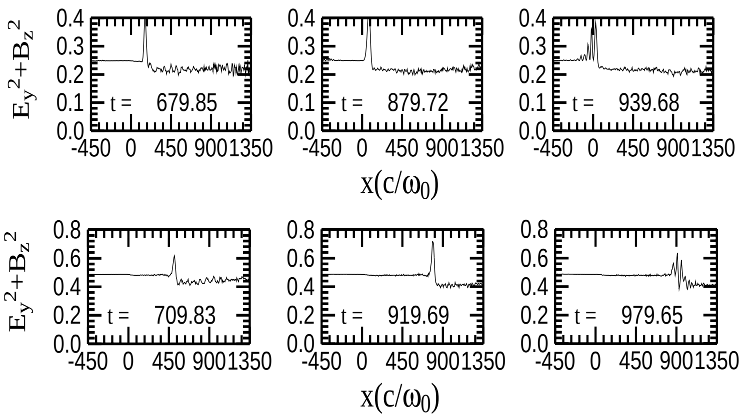

Fig. 3 EM energy for bwd. [β=0.5 (top)] and fwd. accelerated solitons [β= 0.7 (bottom)].

Our complete results, apart from the standing soliton case, do not comply with earlier explanations. Namely, the EM soliton acceleration was only expected along the density gradient in non-uniform plasmas [1]. Still, in uniform plasmas, apart from standing solitons, by varying the laser intensity, we detect backward and forward accelerated EM solitons.

Analytical estimates

A basic set of one-dimensional relativistic cold plasma equations, in the Coulomb gauge, is

$$a_{tt} - a_{xx} + \frac{na}{\gamma} = 0; \quad p_{xt} - n + 1 + \gamma_{xx} = 0; \quad n_t + \left(\frac{pn}{\gamma}\right)_x = 0 \qquad (1\text{-}3)$$

where, the relativistic factor, $\gamma = \sqrt{1 + a^2 + p^2}$. Linearly polarized EM waves possess odd harmonics for the vector potential and even harmonics of the electron density [3]; therefore, a stationary spatially localized soliton solution can be sought as

$$\begin{gathered} a(x,t) = A(x)\cos(\omega t); \quad p(x,t) = P(x)\sin(2\omega t); \\ \delta n(x,t) = N_0(x) + N_2(x)\cos(2\omega t) \end{gathered} \qquad (4)$$

with the phase shift included in the spatial amplitude of above quantities (ω in ω_{po} units). Assuming, $a >> p$, after Legendre's polynomial expansion, expression for γ approximates to

$$\gamma \approx \frac{\gamma_0 + 1}{2} + \frac{\gamma_0 - 1}{2}\cos(2\omega t) \ldots. \qquad (5)$$

where, $\gamma_0 = \sqrt{1 + A^2}$.

By substituting (4,5) into (1-3) and selecting appropriate harmonics, we can readily get

$$N_0 = 1 + \frac{1}{2}\gamma_{0xx}; \qquad N_2 = \frac{1}{2}\gamma_{0xx} + 2\omega P_x; \quad \text{gives}$$

$$A_{xx} - \frac{\gamma_0 + 5}{8\gamma_0} A\gamma_{0xx} = \left[\frac{\gamma_0 + 3}{4\gamma_0} - \omega^2\right] A + \omega \frac{A}{\gamma_0} P_x \tag{6}$$

For the soliton profile, $A(x)$ is maximum in the centre; then at x=0; $\gamma_{0xx} = (A_{0xx} A/\gamma_o)$, and we estimate P_{0x} from (3) to approximately $P_{0x} \approx A_0 A_{0x} / 4\omega\gamma_0$. Simple algebraic (6) reads

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

The condition that, $A_{0xx} < 0$, at the maximum, would require

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

This estimates the maximum soliton amplitude and the minimum eigen-frequency allowed by the nonlinear dispersion $\omega(A)$ curve (9), to be ultra-relativistic, $A_0 < 5.2$ and $\omega_{sol} > 0.63$. We write the conservation for $\langle W \rangle$, the EM soliton energy averaged over the light period,

$$\langle W \rangle = \left\langle \int \left(E_y^2 + B_z^2\right) dx \right\rangle = \int \left(\omega^2 |A|^2 + \left|A_x\right|^2\right) dx. \tag{10}$$

The stable soliton corresponds to the minimum energy solution [3]; so, one expects, for any given amplitude A_{sol}, the soliton with minimum frequency (9) to be found in simulations. However, we note that analytical estimates for the frequency of large saturated EM solitons are still beyond the lowest simulation values. This might be due to a neglected soliton motion; that, in a preliminary study, appears to "Doppler- downshift" the self-frequency [4].

In summary, to our knowledge, above results on ultra- relativistic EM solitons in underdense plasmas, haven't appeared in previous theoretical and simulation studies [1-3]. Moreover, despite a large volume of earlier works, a clear interpretation of the nature of the acceleration of EM solitons in uniform plasmas appears to be lacking.

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[1] Bulanov et al., *Phys. Rev. Lett.* 82 (1999) 3440; Eserkipov et al.,ibid., 89 (2003) 275002

[2] Mima, Jovanovic, Sentoku, Z-M Sheng, Skoric and Sato, *Phys. Plasmas* 8 (2001) 2349

[3] Hadzievski, Jovanovic, Skoric and Mima, *Phys. Plasmas* 9 (2002) 2569

[4] Mancic, Hadzievski and Skoric, in *Proc. 22nd SPIG* (2004); to be published