Bursts of Superreflected Laser Light from Inhomogeneous Plasmas due to the Generation of Relativistic Solitary Waves

Y. Sentoku,[1] T. Zh. Esirkepov,[2] K. Mima,[1] K. Nishihara,[1] F. Califano,[3] F. Pegoraro,[3] H. Sakagami,[4] Y. Kitagawa,[1] N. M. Naumova,[5] and S. V. Bulanov[5]
[1]*Institute of Laser Engineering, Osaka University, Osaka, Japan*
[2]*Moscow Institute of Physics and Technology, Dolgoprudnyi, Russia*
[3]*Physical Department of Pisa University and INFM, Pisa, Italy*
[4]*Himeji Technology University, Hyogo, Japan*
[5]*General Physics Institute RAS, Moscow, Russia*
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In an inhomogeneous plasma, low-frequency solitary waves, generated by superintense laser pulses, are accelerated towards the plasma-vacuum interface where they radiate their energy in the form of low-frequency electromagnetic bursts. The transverse inhomogeneity of the plasma inside the self-focusing radiation channel leads to guiding of the solitary waves. These solitary waves excite a two-ribbon magnetic field structure in their wake. These phenomena have been studied with two-dimensional particle-in-cell simulations and are expected to be observed in present-day laser-plasma experiments.

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The intensity of the light emitted by present-day lasers has exceeded by a good margin the value where the electron quiver energy becomes relativistic [1]. When propagating in a plasma this superintense laser radiation displays the effects of relativistic nonlinearities such as relativistic self-focusing [2], relativistic transparency of an overdense plasma [3], and the generation of relativistic solitary waves [4].

Relativistic solitons were predicted to occur when high intensity laser pulses interact with a plasma [5–7]. Recently, relativistic solitary waves were discovered in two spatial and three velocity dimensions (2D3V) particle-in-cell (PIC) simulations [4] (in the following we shall use the shorter term "soliton," bearing in mind, however, that the interaction between solitons has to be investigated further). These solitons are generated behind the laser pulse and are made of low-frequency, nonlinear, spatially localized electromagnetic fields with almost zero group velocity.

As shown in Ref. [4] nearly 30%–40% of the laser pulse energy can be transformed into solitons. This fairly high efficiency of electromagnetic energy transformation indicates that solitary waves, which are an essential component of turbulence in fluids and plasmas, can play an important role in the development of the interaction between the laser pulse and the plasma.

In homogeneous plasmas the solitons remain, for a long time, close to the region where they were generated, and eventually decay due to their interaction with fast electrons. In this case, the soliton energy is transformed into fast particle energy. However a real plasma is always inhomogeneous. In a nonuniform dispersive medium a wave packet moves according to the well-known equations of geometric optics: $\dot{x}_i = \partial_{k_i}\mathcal{H}$, $\dot{k}_i = -\partial_{x_i}\mathcal{H}$, where the Hamiltonian is the wave frequency $\mathcal{H}(x_i, k_i) = \omega = \sqrt{k^2c^2 + \omega_{\rm pe}^2}$. If we model the spatial dependence of the Langmuir frequency in a plasma channel localized in the y direction and inhomogeneous in the x direction as $\omega_{\rm pe}^2 = \omega_{\rm pe0}^2(1 + x/L_x + y^2/L_y^2)$, we find for the components of the wave packet acceleration $\ddot{x} = -c^2/2L_x$ and $\ddot{y} = -yc^2/L_y^2$. The wave packet is accelerated along the x axis toward the low density side, and oscillates in the transverse direction with frequency c/L_y.

The propagation in inhomogeneous media of solitons described by the nonlinear Schrödinger equation was discussed in Ref. [8], and it was shown that this problem admits multisoliton solutions that were obtained with the inverse scattering method. These exact solutions show that the solitons are accelerated toward the plasma-vacuum interface with an acceleration proportional to the gradient of the plasma density.

We expect that the acceleration of the solitons in an inhomogeneous plasma will result in a number of important effects which will make it possible to detect the soliton generation and can be used for various applications. A soliton approaching the plasma-vacuum interface will eventually radiate away its energy in the form of low-frequency electromagnetic waves due to its nonadiabatic interaction with the plasma boundary. This causes a low-frequency burst of electromagnetic radiation. Since the solitons generated behind the laser pulse are predominantly s polarized [4], the reflected light will have its s-polarized component stronger that its p component.

Here, we discuss the interaction of a relativistic laser pulse with a weakly inhomogeneous plasma, using two-dimensional PIC simulations. The normalized amplitude of the incident laser pulse is $a = eE/m_e c\omega = 3.85$, which corresponds to the intensity $I = 2 \times 10^{19}$ W/cm^2 for a 1 μm wavelength laser. Here E is the electric field in the laser pulse, ω is the carrier frequency, e and m_e are the electron mass and charge, and c is the speed of

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light in vacuum. The laser pulse is taken to be semi-infinite. Its transverse profile is Gaussian with spot size equal to 15λ. Initially the plasma has a linear density profile with density varying along the x direction from zero, at the plasma-vacuum interface on the left-hand side of the computation region, to $n = 2n_{\mathrm{cr}}$. The scale length of the plasma inhomogeneity is 100λ. The critical surface is localized at $x = 50\lambda$. The ions are movable, and the ion-to-electron mass ratio $m_i/m_e = 3680$ corresponds to deuteron ions. The initial temperatures are 10 keV for the electrons and 0.1 keV for the ions.

The size of the simulation box is 112λ in the x direction and 28.8λ in the y direction, with 2000×512 cells. The boundary conditions for the fields and the particles are periodic in the y direction. The particles are reflected with their initial thermal velocity at the left- and at the right-hand side boundaries in the x direction. The total number of particles is 1.8×10^7, with the average number of particles per cell equal to 10. The total computation time corresponds to 257 periods of the electromagnetic wave.

Figure 1 shows the s-polarized laser beam in the x, y plane at $t = 160(2\pi/\omega)$. Figures 1(a)–1(c) show the square root of the electromagnetic energy density, the z component of the magnetic field, and the ion density, respectively. In Fig. 1(a) we see that the nonlinear interaction with the plasma leads to the filamentation of the laser pulse and then to the merging of the filaments in the transverse direction. The distribution of the z component of the magnetic field in Fig. 1(b) corresponds to the laser pulse filamentation: In each filament we see the magnetic field generated by the fast particles inside the filament. In the ion density distribution in Fig. 1(c), we see the channel formed due to the ion motion under the effect of the ponderomotive pressure. The localized minima in the ion density distribution in Fig. 1(c) correlate with the local maxima of the electromagnetic energy density around the critical density in Fig. 1(a). These are s-polarized solitons. Inside these s-polarized solitons the z component of the electric field oscillates with frequency Ω appreciably lower than the Langmuir frequency. The frequency and the size of the solitons depend on their amplitude [4]. The azimuthal magnetic field in the solitons oscillates with frequency Ω while the radial electric field oscillates with a frequency 2Ω. We note the solitons remain well localized in the x, y plane despite the ion motion.

A more detailed analysis of the time evolution of the laser-plasma interaction shows that the solitons are generated in the underdense plasma region near the critical surface and that they move in the backward direction towards the vacuum-plasma interface. This is illustrated in Fig. 2. This figure shows the x and y coordinates of the soliton marked by an arrow in Fig. 1(a), plotted versus time. The x component of the soliton velocity is negative and its value increases from approximately $0.33c$ at $x = 26$ to $0.83c$ near the left boundary. In the transverse direction, along the y axis, the soliton oscillates guided by the plasma channel. When the soliton reaches the left boundary, it radiates its energy in the form of a burst of electromagnetic radiation. We can estimate the soliton acceleration as $\approx 1.25 \times 10^{22}\ \mathrm{cm/s^2} = c^2/2L_x$ which corresponds to a plasma inhomogeneity scale $\approx 40\ \mu\mathrm{m}$ for a $1\ \mu\mathrm{m}$ laser. The period $2\pi L_y/c$ of the transverse oscillations of the soliton is approximately 6×10^{-14} s, which gives a

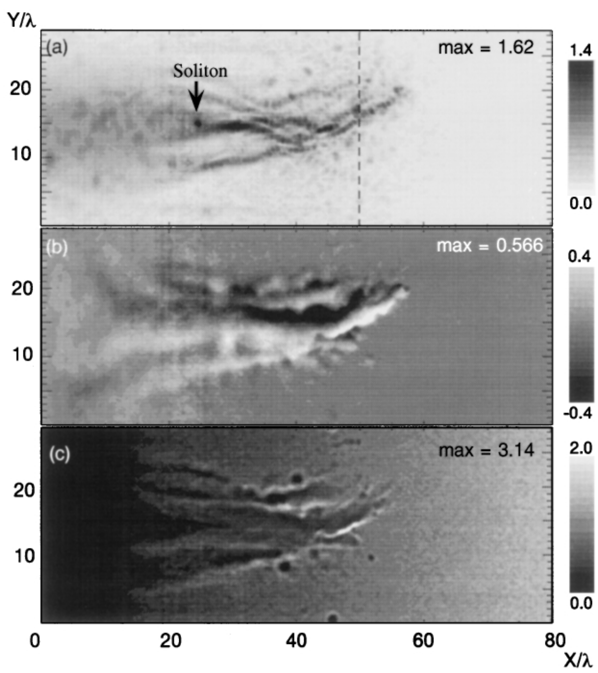

FIG. 1. The s-polarized laser beam in the x, y plane at $t = 160(2\pi/\omega)$: (a) the square root of the electromagnetic energy density, (b) the z component of the quasistatic magnetic field, and (c) the ion density. These plots are normalized on the square root of the incident laser intensity, on the laser B-field, and on the critical density, respectively. All plots are time averaged over a laser oscillation period. The dashed line in (a) shows the critical surface.

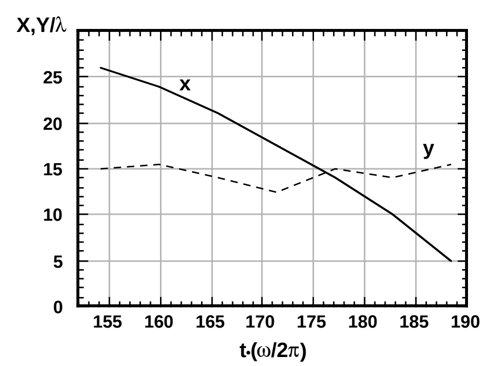

FIG. 2. Soliton acceleration and guiding inside the self-focusing channel. The solid (dashed) line gives the x (y) coordinate versus time for the soliton indicated by the arrow in Fig. 1(a).

channel width $\approx$10 μm, in agreement with the value that can be obtained from Fig. 2(a) and from the amplitude of the oscillations.

We have also performed similar PIC simulations of the interaction of a p-polarized pulse with an inhomogeneous plasma (not shown here). The main pattern of the laser-plasma interaction is similar to that of the s-polarized pulse. Soliton formation is also observed: The magnetic field of p-polarized solitons is along the z direction and their electric field is azimuthal. However, p-polarized solitons are not as distinctive as s-polarized solitons because of the more turbulent plasma conditions, the interference with the y component of the pulse electric field, and, finally, because of their interaction with the fast particles and with the quasistatic magnetic field generated by the fast particles [9]. The lifetime of the p-polarized solitons is much shorter than the lifetime of the s solitons and they lose most of their energy inside the plasma.

The formation of the solitons and their acceleration towards the left boundary leads to an enhanced plasma reflectivity. Because of the difference in the lifetime of the s- and p-polarized solitons, the excess in the intensity of the reflected radiation is determined mainly by the s -polarized solitons. This is seen in Fig. 3, where the relative amplitudes of the reflected radiation versus time are shown for the s-polarized (a) and the p-polarized (b) laser beams. The total absorption of the p-polarized and s-polarized laser light is 95.7% and 80.6%, respectively. The reflected radiation is strongly modulated. The width of the bursts in time is larger than the laser period. The frequency of the electromagnetic radiation trapped and carried out of the plasma by the solitons is well below the laser frequency. The downshift of the frequency of the reflected radiation is confirmed by the frequency spectra presented in Fig. 4: Figure 4(a) gives the frequency spectra of the reflected s-polarized radiation versus y, and Fig. 4(b) gives the spectra of the reflected p-polarized radiation. We see that the frequency is downshifted by a factor of the order of 4, and that the reflected radiation is modulated in the transverse direction.

We expect that in the 3D case an analog of the s and p solitons is the TE and TM solitons. In the TE soliton the magnetic field is the poloidal component and the electric field is toroidal; the TM soliton has the poloidal component of the electric field and the toroidal component of the magnetic field. The interaction of the TE solitons, similar to the s solitons in the 2D case, with plasma waves and fast particles is suppressed, that is why we expect that in the 3D case the reflected light will be formed by the TE solitons.

In order to investigate the interaction of a soliton with the plasma-vacuum interface, we studied the generation of electromagnetic solitons by a laser pulse propagating in a plasma inhomogeneous in the transverse direction. In this case, the soliton propagates in the direction perpendicular to the laser beam and abandons the region behind the laser pulse where the wake field and electron vortices are localized. As a result, the soliton is less perturbed by nonlinear plasma waves, vortices, and fast particles. Figure 5 shows the 2D3V PIC simulation of the interaction of a circularly polarized pulse with an underdense plasma. The incident laser pulse propagates along the x direction in a simulation box $60 \times 60\lambda^2$ wide. The pulse dimensionless amplitude in the vacuum region is $a = 3$, its width is $l_{\perp} = 16\lambda$, and its length $l_{\parallel} = 4\lambda$. In this case, the wave is not exactly circularly polarized; however, the difference is small because the width of the wave packet is small as compared with the wavelength. The plasma density varies from $n = 0$ at the plasma-vacuum interface at $y = 0$ to $n = 0.6n_{\mathrm{cr}}$ at $y = 60\lambda$. The ions are assumed to be at rest. In Fig. 5 the z component of the electric field is presented in the

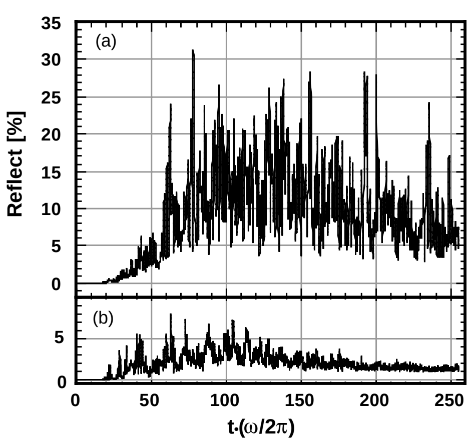

FIG. 3. The relative amplitude of the reflected radiation versus time for the s-polarized (a) and the p-polarized (b) laser beams.

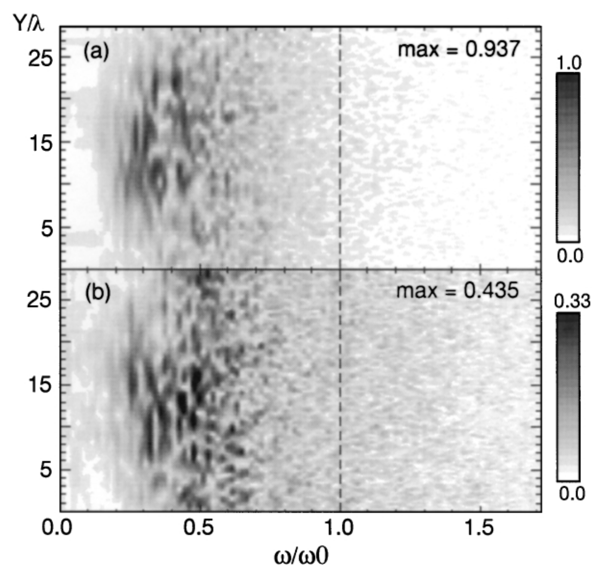

FIG. 4. Frequency spectra versus y of the reflected s-polarized radiation (a) and of the reflected p-polarized radiation (b) at $t \approx 100(2\pi/\omega)$.

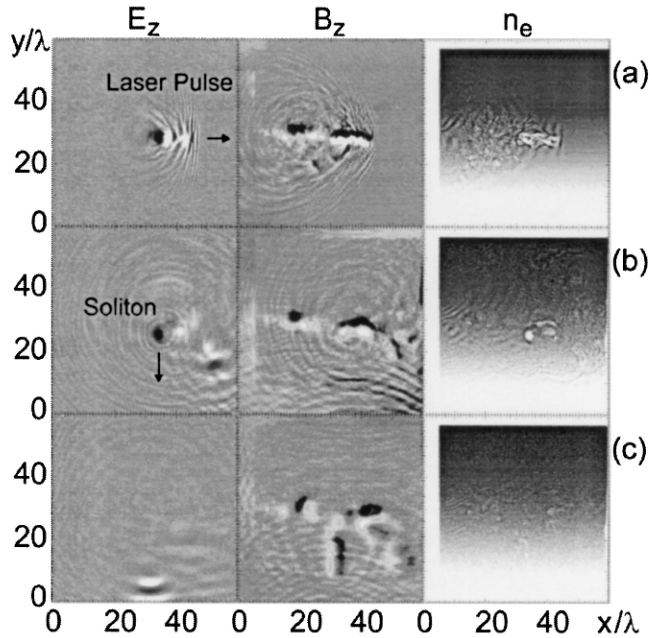

FIG. 5. Interaction of the circularly polarized laser pulse with the transversely inhomogeneous plasma: the z component of the electric field (first column), the z component of the magnetic field (second column), and the electron density (third column) in the x, y plane at $t = 50(2\pi/\omega)$ (first row), $t = 100(2\pi/\omega)$ (second row), and $t = 150(2\pi/\omega)$ (third row).

first column, the z component of the magnetic field in the second column, and the electron density in the third column. The upper row corresponds to $t = 50(2\pi/\omega)$, the middle row to $t = 100(2\pi/\omega)$, and the lower row to $t = 150(2\pi/\omega)$.

In the evolution of the z component of the electric field we see the refraction of the laser pulse and the accelerated motion of the soliton due to the plasma inhomogeneity. The s-polarized soliton formed at $x = 35$, $y = 29$ moves along y toward the plasma-vacuum interface. When the soliton reaches the plasma-vacuum interface it disappears suddenly and is transformed into a diverging electromagnetic wave.

The pattern of the wake waves generated by the laser pulse is seen very clearly in the electron density evolution. The wake wave breaking in the transverse direction discussed in Ref. [10] results in the appearance of bunches of fast electrons propagating at a finite angle with respect to the laser pulse axis. Each electron bunch excites wake plasma waves. We also see that the vacuum-plasma interface is distorted. There is a strong depression of the electron density inside the soliton, due to the ponderomotive pressure of the trapped radiation. The shape of the soliton changes as it moves toward the low density region. We also see local depressions of the electron density inside the electron vortices, both in the magnetic wake behind the laser pulse and behind the soliton. The pattern of the magnetic field B_z exhibits the structure with two ribbons of opposite polarity behind the laser pulse discussed in Ref. [9]. A magnetic wake is also formed behind the soliton: This indicates that the structure of the nonlinear electromagnetic wave packet, which would correspond to a soliton in a homogeneous plasma, is changing. Rigorously speaking, since the nonlinear packet leaves a magnetic wake behind, it loses its soliton properties. However, since its relative amplitude is small, the wake can be regarded as a perturbation of the soliton. This wake formation corresponds to the generation of the wake field and to the acceleration of fast electrons by the soliton breaking discussed in Ref. [7].

In conclusion, we have shown that the transformation of a significant portion of the laser pulse energy into relativistic low-frequency solitons and their acceleration toward the plasma-vacuum interface in an inhomogeneous plasma result in a regime characterized by bursts of reflected electromagnetic waves. This effect can be observed experimentally with present-day lasers.

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