# Relativistic Single-Cycled Short-Wavelength Laser Pulse Compressed from a Chirped Pulse Induced by Laser-Foil Interaction

L. L. Ji (吉亮亮), B. F. Shen (沈百飞),* D. X. Li (李冬雪), D. Wang (王丁), Y. X. Leng (冷雨欣), X. M. Zhang (张晓梅), M. Wen (温猛), W. P. Wang (王文鹏), J. C. Xu (徐建彩), and Y. H. Yu. (郁亚红)

*State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, P.O. Box 800-211, Shanghai 201800, China*

(Received 9 April 2010; published 8 July 2010)

By particle-in-cell simulation and analysis, we propose a plasma approach to generate a relativistic chirped pulse based on a laser-foil interaction. When two counterpropagating circularly polarized pulses interact with an overdense foil, the driving pulse (with a larger laser field amplitude) will accelerate the whole foil to form a double-layer structure, and the scattered pulse (with a smaller laser field amplitude) is reflected by this flying layer. Because of the Doppler effect and the varying velocity of the layer, the reflected pulse is up-shifted for frequency and chirped; thus, it could be compressed to a nearly single-cycled relativistic laser pulse with a short wavelength. Simulations show that a nearly single-cycled subfemtosecond relativistic pulse can be generated with a wavelength of 0.2 $\mu$m after dispersion compensation.

DOI: 10.1103/PhysRevLett.105.025001 PACS numbers: 52.38.−r, 42.65.Re, 52.27.Ny, 52.65.Rr

An intense laser pulse interacting with a solid-density ultrathin foil becomes controllable since laser-light contrast has been greatly improved by means of the double plasma mirror [1] and other techniques [2]. Meanwhile, diamondlike foils as thin as several nanometers can now be fabricated [3]. Laser-foil interaction involves various important applications. On the one hand, protons or ions of the foil can be accelerated to a very high energy by the light pressure of the laser pulse, known as light-pressure or phase-stable acceleration [4–7]. In this accelerating scheme, the ponderomotive force of the laser field pushes electrons to form a skin layer, inducing a charge separation field. Protons are accelerated by this field and comove with the electron layer; thus, all electrons and protons are driven forward as a whole. The energy conversion efficiency is very high, and relativistic proton bunches could be obtained if the foil is ultrathin [8]. On the other hand, the laser pulse experiences abundant feedback after interacting with foils. High-order harmonics are generated by a laser interacting with a solid surface [9,10]. Laser energy can be trapped and accumulated to very high levels between two closely placed ultrathin foils when two oppositely directed ultraintense laser pulses impinge on them [11]. Another application is to use an ultrathin foil as a relativistic mirror for generating high-intensity ultrabright x- and gamma-ray radiation by relativistic Doppler shifting of the light [12]. Recently, a method of generating a quasi-single-cycle relativistic pulse by a laser-foil interaction is also proposed [13].

We report another application here by particle-in-cell simulation. When a circularly polarized (CP) laser pulse, the driving pulse (DR pulse), interacts with an overdense foil, the whole electron and proton layers are accelerated by light pressure and move at an ultrahigh velocity. With another counterpropagating CP pulse, named the scattered pulse (SC pulse), impinges on this high-speed double layer, the SC pulse would be reflected and hence its frequency is strongly Doppler shifted. Because the amount of the frequency shift is determined by the layer velocity, which varies with time, the SC pulse is highly chirped. Its chirped component can be regulated through controlling the layer velocity versus time by shaping the DR pulse. When group velocity dispersion is compensated roughly, such as inserting materials in the beam, the chirped pulses are compressed to nearly single-cycled relativistic pulses of short wavelength.

This method has its advantages. First, the intensity of the chirped pulse is extremely high, because only a laser-plasma interaction is involved. Second, by controlling the chirped component, the spectrum is more broadened than traditional optical approaches. After compression, the pulse intensity increases even more. Last, the wavelength of the reflected pulse is much shortened through reflecting.

We first show the results of one-dimensional particle-in-cell simulations by the code VORPAL [14]. A CP pulse, with wavelength $\lambda_0 = 1$ $\mu$m and peak amplitude $a_0 = 50$, irradiates on a thin foil as the driving pulse. Here $\boldsymbol{a} = e\boldsymbol{E}_L/m_e\omega_0 c$ is the normalized dimensionless amplitude, where $e$ and $m_e$ are the electronic charge and mass, respectively, $\boldsymbol{E}_L$ is the laser electric field, $\omega_0$ is the laser frequency, and $c$ is the speed of light in vacuum. The driving pulse has a plateau shape, with a laser field rising from zero to $a_0 = 50$ in $5T_0$ ($T_0$ is the laser period ) and then remaining constant. Meanwhile, a counterpropagating CP pulse, with peak amplitude $a_{sc} = 5$ and FWHM (full width at half maximum) duration $\tau_{sc} = 30T_0$, impinges on the foil from the other side as the scattered pulse. The foil density is $n_0 = 100n_c$, and its thickness is $d = 0.2\lambda_0$, where $n_c = m_e \omega_0^2 / 4\pi e^2$ is the critical density. The simulation box is $100\lambda_0$ in the $x$ direction (propagating direction), and the foil is initially located between $x = 48\lambda_0$ and $48.2\lambda_0$. The simulation mesh size is $\lambda_0/250$.

Figure 1 shows the simulation results. Figure 1(a) displays the laser field distribution after interacting. We see that the whole foil is accelerated by the DR pulse in the light-pressure acceleration (phase-stable acceleration) scheme. The SC pulse, propagating in the opposite direction, interacts with the foil subsequently and then is totally reflected. Its frequency is Doppler shifted, which is determined by the foil velocity. The temporal frequency of the reflected laser field increases with the double-layer velocity. As a result, a positively chirped pulse is generated, as seen clearly in Fig. 1(b). The reflected field of the DR pulse is also chirped, of course, negatively. After being reflected from the fast-moving layer, the duration of the SC pulse is compressed by a factor of 5. We compare their spectrums in Fig. 1(c). The central frequency is shifted by a factor of about 5 due to pulse compression, which is consistent with the duration decreasing. An important feature is that the FWHM of the spectrum is enormously broadened, reaching $2.6\omega_0$. This effect is mainly caused by the pulse being chirped. Figure 1(c) also shows phase information. It is seen that the difference between the phase including full dispersion and the one with second-order dispersion can be neglected, indicating that second-order dispersion is dominant and the chirp is almost linear. After full dispersion compensation, a nearly single-cycled laser pulse with duration of $0.24T_0$ (0.8 fs) is obtained, as seen in Fig. 1(d).

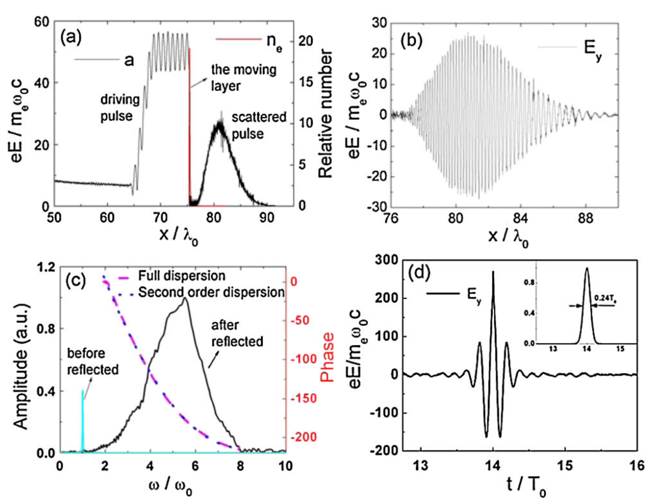


FIG. 1 (color online). Simulation results when the interaction is completed with the driving pulse of $a_0 = 50$, the scattered pulse of $a_{sc} = 5$, $\tau_{sc} = 30T_0$, and the foil of $n_0 = 100n_c$, $d = 0.2\lambda_0$. (a) Laser field and electron density $n_e$ distributions. (b) Transversal laser field $E_y$ of the reflected chirped pulse. (c) Spectrum and corresponding phase of the scattered pulse: phase including full dispersion (magenta dashed line) and phase with only second-order dispersion (blue dotted line). The cyan solid line shows the spectrum of the scattered pulse before being reflected. (d) Transversal laser field $E_y$ and laser intensity profile after compression.

One notices that the laser wavelength is much shortened, to about one-fifth of the original pulse (0.2 $\mu$m). In addition, its cycle number is also enormously decreased. The peak dimensionless amplitude of the scattered pulse is increased from $a_0 = 5$(normalized by the initial fundamental frequency) to $a_0 \approx 55$ (normalized by the central frequency of the compressed pulse itself) after compression, reaching a strong relativistic region, while it remains unchanged if only the Doppler shift is considered. In a word, we have gained a relativistic single-cycled pulse with short wavelength, which has not been realized with any method but is believed to be very useful in many applications. It should be mentioned that if only second-order dispersion is compensated, the pulse duration also reaches $0.36T_0$, very close to the case of full dispersion compression since the generated pulse is quasilinearly chirped.

We analyze in detail in the following. Considering a laser pulse reflected from a flying mirror, the Doppler effect gives

$$\frac{\omega(t)}{\omega_0} = \frac{1 + \beta(t)}{1 - \beta(t)} = f(t), \qquad (1)$$

where $\omega(t)$ is the temporal frequency of the reflected laser field and $\beta$ is the layer velocity normalized by light speed $c$. Here $f$ is defined as the ratio between the frequencies of the reflected and incident pulses. As the layer velocity increases, the reflected pulse gets chirped with time accompanying the frequency increasing. That is to say, the character of the reflected pulse is totally determined by the layer motion. In Fig. 2, we show the layer velocity versus time and the corresponding frequency increment calculated from Eq. (1). It is clearly seen that the layer velocity evolves in such a way that an optimistic linear frequency increment is induced on the reflected pulse. Since most pulse compression techniques require a linearly chirped pulse, this character should be very useful and convenient for experiments.

In our simulation, the SC pulse impinges on the flying layer at about $t = 50T_0$ and leaves at $t = 90T_0$. During this period, the whole foil is accelerated by the DR pulse to a velocity of 0.77, as seen in Fig. 2(a), which offers a frequency region of about $\omega_0 \sim 8\omega_0$ according to Fig. 2(b). The peak laser field interacts with the layer at about $t = 70T_0$, corresponding to a central frequency of $5\omega_0$. These results are in perfect coincidence with Fig. 1(c). The results in Fig. 2(b) provide approaches of controlling the spectrum of the reflected pulse by choosing the interacting window. One could change the impinging time and/or pulse duration to control the low- and/or high-frequency bounds.

The whole proposal shows high controllability. According to Eq. (1), we suggest that the frequency character of the chirped pulse can be well defined by controlling the layer velocity. In the light-pressure acceleration scheme, the layer motion is described as [5]

$$\frac{d}{dt}(\gamma\beta) = \frac{1}{2\pi m_i n_0 dc}\frac{1-\beta}{1+\beta}E_L^2(t-x/c). \qquad (2)$$

Here $m_i$ is the ion mass and $\gamma = (1-\beta^2)^{-1/2}$ is the relativistic factor of the layer. As electrons and ions are accelerated as a whole, the longitudinal momentum of electrons is ignored. So $\beta$ can be expressed as a function of $\omega$ from Eq. (1), and we insert it into Eq. (2) and, thus, gain the form of the required laser electric field

$$E_L^2(t-x/c) = 2\pi m_i n_0 dc \frac{f+1}{4f^{1/2}}\frac{df}{dt}, \qquad (3)$$

$$\frac{x}{c} = \int_0^t \beta(t')dt'. \qquad (4)$$

From Eqs. (3) and (4) it is convenient to choose the appropriate laser field while requiring a certain frequency-varying pulse. For example, if one needs a linearly chirped pulse, $f$ then has the form of $1 + kt$, and the calculated laser electric field should be

$$E_L(t) = \sqrt{2\pi m_i n_0 dc}\sqrt{\frac{k}{2}}\left(\frac{e^{kt}}{2e^{kt/2}-1}\right)^{1/4}. \qquad (5)$$

Equation (5) shows the accurate laser field form for generating an exactly linearly chirped pulse, while in the above simulation we set the laser field in a plateau form; hence, the generated pulse is only roughly linearly chirped, as seen in Fig. 2(b).

To generate a well linearly chirped pulse, several major requirements should be satisfied. First, the layer motion should not be affected by the SC pulse during interaction. This requires that the light pressure of the SC pulse $P_{sc} \sim a_{sc}^2(1+\beta)/(1-\beta)$ shall be ignored compared to that of the DR pulse $P_{dr} \sim a_0^2(1-\beta)/(1+\beta)$. Hence it gives the following relationship:

$$\frac{a_{sc}}{a_0} \ll \frac{1-\beta}{1+\beta}. \qquad (6)$$

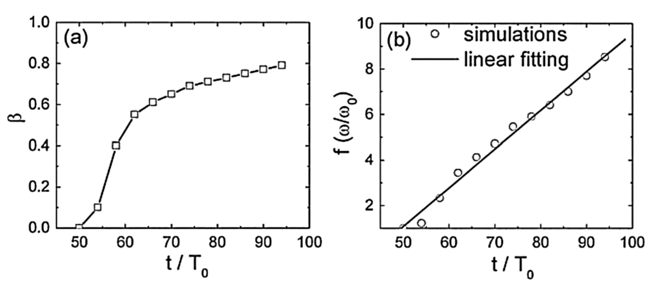


FIG. 2. (a) Velocity of the flying layer versus time. (b) The induced frequency shift increment factor $f$ versus time. The velocity is obtained from simulation, and the factor $f$ is calculated according to Eq. (1).

In the above simulation, $\beta_{max} \approx 0.77$ and we have $a_{sc} < 6.5$, which is well fulfilled.

Another important condition concerns the two pulses interacting with each other in the confined electron layer. It was first studied by Shen *et al.* in Ref. [15], where high harmonics are generated if the two CP pulses have the same polarization direction. To avoid this harmonic generation, we demonstrated that the foil thickness should be larger than a critical value $D$ (which will be presented elsewhere)

$$d > D \approx \frac{a_0 + a_{sc}}{n_0}\frac{\lambda_0}{\pi}. \qquad (7)$$

Under the above parameters, $D$ is calculated to be about 0.18 $\mu$m; thus, we choose $d = 0.2$ $\mu$m. One can also avoid this effect by altering the polarization direction [15]. Besides, by considering Doppler shifting the foil density should be high enough to keep opaque for the SC pulse; hence, it gives $n_0 > f_{max}n_c$. In the above simulation $f_{max} \sim 10$, and the chosen parameter $n_0 = 100n_c$ fulfills the requirement adequately.

As mentioned, this method involves only a laser-plasma interaction, thus presenting no limit for laser intensity. Another laser-plasma approach to compress the laser pulse is the pure-Doppler-shifting method, by which the laser wavelength is decreased after being reflected from a flying layer while its cycle number remains the same. This method seems much simpler because no chirped pulse compression techniques are required. However, our proposal shows several advantages. In the first place, for the pure-Doppler-shifting method the dimensionless laser field amplitude, which denotes the relativistic factor, remains unchanged after being reflected, while in our proposal it is greatly increased after compressed by optical approaches. Second, the spectrum of a generated pulse with the pure-Doppler-shifting method is monochromatic, while in our case we consider furthermore that the frequency increment is induced by designing the DR pulse; therefore, the spectrum of the chirped pulse is highly broadened and no longer monochromatic. The required layer velocity to obtain a short pulse is much smaller. As a comparison, to compress a 30-fs (normally used) laser pulse to about 1 fs, the pure-Doppler-shifting method requires a moving layer with proton energy of about 3 GeV, while using this relativistic chirped pulse compression, as $\beta_{max} \approx 0.77$, one needs proton energy of only about 500 MeV.

Two-dimensional (2D) simulation is performed to verify the practical efficiency. The simulation is run in a box of $70\lambda_0 \times 70\lambda_0$, with cells of $3500 \times 700$. The amplitude of the DR pulse rises to $a_0 = 60$ in $2T_0$ and remains constant temporally. The SC pulse is with peak amplitude $a_{sc} = 5$ and duration $\tau_{sc} = 10T_0$. Both pulses are transversely super-Gaussian: $\boldsymbol{a} = a(t)\exp(-y^4/w_y^4)[\sin(\omega_0 t)\hat{e}_y + \cos(\omega_0 t)\hat{e}_z]$, where $w_y = 15\lambda_0$ for the DR pulse and $16\lambda_0$ for the SC pulse. The foil density is $n_0 = 40n_c$, and

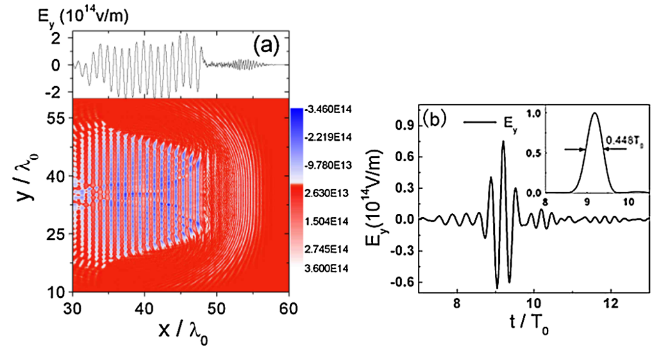


FIG. 3 (color online). (a) Distribution of transversal laser field $E_y$. (b) Transversal laser field $E_y$ and laser intensity after compression.

hence we choose its thickness as $d = 0.6\lambda_0$ according to Eq. (6). The foil is located at $34\lambda_0$–$34.6\lambda_0$.

Because of multidimensional effects, such as hole boring and Rayleigh-Taylor–like or Weibel-like instabilities [16–19], the foil accelerated in the radiation-pressure acceleration scheme might be deformed and, therefore, harmful for reflecting lasers. To depress these effects, a super-Gaussian laser pulse is employed in the simulation. One could also taper the foil to compensate the deformation [20]. Furthermore, we vary some of the parameters compared with 1D simulation, increasing the peak amplitude of the DR pulse to $a_0 = 60$ and reducing the foil density to $n_0 = 40n_c$. As the target hole-boring velocity scales as $a_0/n_0^{1/2}$ [17] and Rayleigh-Taylor instability develops much slower when the hole-boring velocity is larger, we choose the present parameters to offer a much larger velocity than that of 1D simulation. Figure 3(a) shows the laser field distribution after interacting. It is shown that a chirped pulse is well generated. After compensating second-order dispersion, a near single-cycle laser pulse is obtained, as seen in Fig. 3(b). Its duration is about $0.448T_0$, and the wavelength is shortened to 0.32 $\mu$m. It shows that this mechanism works very well in multidimensional geometry.

In conclusion, by combining Doppler shifting and a dispersion compensation technique, we have proposed a method to generate a relativistic single-cycled pulse with short wavelength by a laser-foil interaction. A driving pulse accelerates a foil to form a fast-moving layer and a counterpropagating SC pulse impinges on it. After being reflected from the layer, the SC pulse is Doppler shifted and strongly chirped. By applying dispersion compensation on the chirped pulse, it can be compressed to a nearly single-cycled relativistic pulse. This method has no intensity limit as it employs a laser-plasma interaction. The dimensionless amplitude of the generated pulse is greatly increased, and the wavelength is much shortened. Furthermore, the frequency characteristic can be determined by designing an appropriate DR laser form, which is very convenient for application. We also examined the conditions that should be fulfilled to make this method efficient. Two-dimensional simulations were performed to check the validity, and they showed that the proposal also works very well.

This work was supported by the 973 Program (Project No. 2006CB806004), the Program of Shanghai Subject Chief Scientist (09XD1404300), Shanghai Natural Science Foundation (10ZR1433800), and the National Natural Science Foundation of China (Projects No. 10675155, No. 10834008, and No. 10835003).

*To whom all correspondence should be addressed. bfshen@mail.shcnc.ac.cn

[1] T. Wittmann *et al.*, Rev. Sci. Instrum. **77**, 083109 (2006).
[2] A. Jullien *et al.*, Opt. Lett. **30**, 920 (2005); V. Chvykov *et al.*, Opt. Lett. **31**, 1456 (2006); D. Homoelle *et al.*, Opt. Lett. **27**, 1646 (2002); R. Shah *et al.*, Opt. Lett. **34**, 2273 (2009).
[3] A. Henig *et al.*, Phys. Rev. Lett. **103**, 245003 (2009).
[4] B. Shen *et al.*, Phys. Rev. E **64**, 056406 (2001).
[5] T. Esirkepov *et al.*, Phys. Rev. Lett. **92**, 175003 (2004).
[6] X. Zhang *et al.*, Phys. Plasmas **14**, 123108 (2007).
[7] X. Q. Yan *et al.*, Phys. Rev. Lett. **100**, 135003 (2008).
[8] L. Ji *et al.*, Phys. Rev. Lett. **101**, 164802 (2008).
[9] S. Gordienko *et al.*, Phys. Rev. Lett. **93**, 115002 (2004); T. Baeva *et al.*, Phys. Rev. E **74**, 046404 (2006); B. Dromey *et al.*, Nature Phys. **5**, 146 (2009).
[10] D. an der Brügge *et al.*, arXiv:1002.3576v1.
[11] B. Shen *et al.*, Phys. Rev. Lett. **89**, 275004 (2002).
[12] T. Zh. Esirkepov *et al.*, Phys. Rev. Lett. **103**, 025002 (2009); J. Meyer-ter-Vehn *et al.*, Eur. Phys. J. D **55**, 433 (2009); D. Habs *et al.*, Eur. Phys. J. D **55**, 253 (2009).
[13] L. Ji *et al.*, Phys. Rev. Lett. **103**, 215005 (2009).
[14] C. Nieter and J. R. Cary, J. Comput. Phys. **196**, 448 (2004).
[15] B. Shen *et al.*, Phys. Plasmas **8**, 1003 (2001).
[16] S. C. Wilks *et al.*, Phys. Rev. Lett. **69**, 1383 (1992).
[17] A. Macchi *et al.*, Phys. Rev. Lett. **94**, 165003 (2005).
[18] M. Chen *et al.*, Phys. Plasmas **15**, 113103 (2008).
[19] X. Q. Yan *et al.*, Phys. Rev. Lett. **103**, 135001 (2009).
[20] M. Chen *et al.*, Phys. Rev. Lett. **103**, 024801 (2009).