Towards high intensity few-cycle pulses using plasma wakefield self-compression effect

A. Pipahl¹, E.A. Anashkina², M. Toncian¹, T. Toncian¹, S.A. Skobelev², A.V. Bashinov², A.A. Gonoskov², O. Willi¹, A.V. Kim²

¹ Institut für Laser- and Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany
² Institute of Applied Physics, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia
E-mail: kim@ufp.appl.sci-nnov.ru

Abstract. We present experimental results for laser pulse compression due to wakefield excitation in the relativistic regime using the SPIDER technique for complete pulse characterization. The results indicate that the pulse was compressed to 10 fs duration which has been verified by 3D PIC simulations showing the possibility of getting laser pulses of few-cycle duration. These results were also verified by using a hydrodynamic code. The scalability of the latter allows to extend the wakefield compression scheme to the petawatt level, thus making it a route to PW-class few-cycle pulse generation.

1. Introduction

Tremendous progress has recently been made in laser technology primarily based on the chirped pulse amplification (CPA) [1] allowing ultrashort laser pulse generation with a duration as short as 30 fs and peak power up to one petawatt (PW) [2]. Now several projects worldwide are towards the 10 PW level in progress. However, the generation of high power few-cycle pulses, particularly below 10 fs for a Ti:sapphire laser at a wavelength of about 800 nm, is still a formidable task. The great demand of high intensity few-cycle pulses for various applications ranging from attosecond pulse production [3] to particle acceleration make [4] it challenging for present day laser physics. One of the ways relies on the optical-parametric chirped-pulse amplification (OPCPA) technology [5, 6, 7], however the progress of this technique has relative been slowly in obtaining high energy pulses. It possesses however a high potential, including ultrabroad amplification along with high gain. An alternative way is a recently proposed method for high energy few-cycle pulse generation using the ionization-induced self-compression effect [8] however this method has not been verified experimentally at high energy yet.

In this Letter, we propose to use the plasma wakefield self-compression effect for high power ultrashort laser pulses produced by conventional laser systems, e.g., such as based on Ti:sapphire laser technology, in order to obtain high intensity pulses with a duration of a few-cycles. We first carefully look at the temporal characteristics of the pulses compressed to 10 fs duration by using the SPIDER technique after passing a 100 TW, 30 fs pulse through a two millimeter gas jet. Then, these experimental data will be directly compared to 3D particle-in-cell (PIC) modeling showing that self-compression of the driver pulse takes place along with the self-focusing effect.
and is actually based on plasma wave excitation. To get a deeper insight into the underlying physics we developed a simplified 3D hydrodynamic model based on a quasi-one-dimensional description of the plasma waves and showed its qualitative agreement with PIC modeling and experiments as well. Finally, of particular interest is the extension of the wakefield compression scheme to the PW pulse level using the simplified model, since 3D PIC simulations for PW pulses cannot be done on presently available supercomputers.

Previous experiments in the relativistic regime [9, 10] have confirmed the general predictions [11, 12, 13] for pulse shortening in a plasma wave excited by the pulse. Going one step further towards few-cycle duration we employed a SPIDER (spectral phase interferometry for direct electric-field reconstruction) technique for complete pulse characterization, which is proven to be a perfect characterization method to the 10 fs temporal range [14]. However, it is worth noting that its application can become challenging when the spectrum is highly modulated or ultra-broadband [15].

2. Experiment
The experiment was conducted with the table-top Ti:Sa laser system (ARCTURUS facility; 100 TW, 30 fs, 800 nm, 10 Hz). The linearly polarized laser pulse with an energy of 1.8J was focused by an f/7 off-axis parabola onto a helium gas jet to a focal spot with a diameter of about 10 µm that leads to an intensity of $4 \times 10^{19}$ W cm$^{-2}$ in vacuum, corresponding to a normalized vector amplitude of $a_0 = 4$. The gas jet length is about 2 mm and the electron densities vary in the range of $n_e = (3 \div 15) \times 10^{18}$ cm$^{-3}$ obtained by changing the gas pressure.

The transmitted pulse was measured by collimating the central part of the laser beam. Figure 1 shows SPIDER interferograms, pulse spectra (right graphs), retrieved pulse intensity profiles and phases (central graphs) in the time domain for the electron densities of $6.6 \times 10^{18}$ cm$^{-3}$ (a) and $1.3 \times 10^{19}$ cm$^{-3}$ (b), respectively.

![Figure 1. SPIDER interferograms, pulse spectra (right graphs), retrieved pulse intensity profiles and phases (central graphs) in the time domain for the electron densities of $6.6 \times 10^{18}$ cm$^{-3}$ (a) and $1.3 \times 10^{19}$ cm$^{-3}$ (b), respectively.](image)

In the low density case of Fig. 1(a) the corresponding plasma wavelength $\lambda_p = 2\pi c/\omega_p = 13$ µm [$\omega_p = (4\pi e^2 n_e / m)^{1/2}$ is the plasma frequency] exceeds the pulse length $c\tau = 9$ µm. The retrieved output pulse duration is about 10 fs, i.e., the compression factor is $\sim 3$ after the pulse has propagated about 2 mm. Indeed, as shown below, this is also confirmed by simulations indicating that optimal compression takes place exactly at the distance of 2 mm. However, to increase the compression factor and get sub-10 fs pulses we can use higher plasma densities, since the interaction efficiency length is inversely proportional to the plasma density. Indeed, in the higher density case of Fig. 1(b), the pulse spectrum is essentially broader, which corresponds to
a transform-limited pulse duration of 5 fs, but the retrieved experimental output pulse consists of three subpulses with pulse durations between 7 and 10 fs. But, it is important to note that the temporal resolution of the SPIDER technique we used was about 10 fs. In order to properly treat these results it is natural to assume that either an optimal compression length is less than 2 mm or the Raman instability destroys the pulse compression for the input pulse length comparable to the plasma wavelength which is 9.3 µm.

3. 3D PIC modeling

First, to understand the specific features of relativistic pulse compression we use 3D particle-in-cell (PIC) modeling for the parameters relevant to the experiment. The fully relativistic PIC code, developed earlier and applied to proton acceleration [16], accounts exactly for electromagnetic dispersion as it uses a fast Fourier transformation for field calculations. This allows in some cases even a fair quantitative comparison with experimental data. The simulation box co-moving with the speed of light is $125\lambda \times 125\lambda \times 100\lambda$ and contains $512 \times 512 \times 1024$ cells. Each cell is filled with 8 quasiparticles. A linearly polarized laser pulse with a Gaussian envelope $a = a_0\exp[-(x^2 + y^2)/b^2]\exp[-t^2/\tau^2]$ is in both transverse (x, y) and longitudinal (z) directions is focused normally onto the front edge of the plasma slab from the left side ($z = 0$ µm). Since in the experiment the length of the gas jet was comparable with the beam Rayleigh length, we set the following parameters: $a_0 = 4$, $b = 20$ µm, $\tau = 30$ fs, and a uniform helium plasma slab of 2 mm in length, to mimic the experiment. The initial temperature of the electrons and protons is 20 keV.

In Fig. 2(a,b) we present the simulation results for a plasma density of $6.6 \times 10^{18}$ cm$^{-3}$ which agrees qualitatively and quantitatively with the experimental data shown in Fig. 1(a). Indeed, the laser pulse is continuously shortened during its propagation in the plasma, reaching 10 fs at a distance of 2 mm. Since the pulse compression is accompanied with relativistic self-focusing, the laser beam diameter shrinks from 20 µm to 10.6 µm and the output intensity increases to $5.7 \times 10^{19}$ Wcm$^{-2}$. The most important feature of the compression is that it occurs so that the plasma wave is excited in a quasi-one-dimensional manner, i.e., unlike in the blowout or bubble regime [17]. This is very consistent with the weakly relativistic theory [18] and assures that the electron density immediately behind the laser pulse is controlled. Indeed, at the beginning of the pulse propagation the maximum excited plasma wave density is about $0.5n_c$, which is consistent with the 1D excitation in the relativistic regime. However, during propagation it decreases but not less than to $0.23n_c$, i.e., the electrons under the action of the ponderomotive force do not go around the laser pulse as in the bubble regime but mostly pass through it. At higher plasma densities we can expect more efficient pulse compression, if it is not destroyed by the Raman or self-focusing instabilities [13]. Although there are no systematic studies of the role of these instabilities at $a > 1$ for pulse compression, however from a general point of view it is obvious that in the strongly relativistic regime these obstacles maybe overcome by properly choosing the laser parameters, specifically its amplitude, beam diameter and pulse duration. In fact, for higher amplitudes, the effective plasma frequency becomes lower due to relativistic mass correction, which decreases the nonlinear interaction efficiency and may restrain the development of the instabilities. This is seen in Fig. 2(c) clearly demonstrating, on the one hand, pulse compression to 6.1 fs at a distance of 1.28 mm for a plasma density of $1.3 \times 10^{19}$ cm$^{-3}$ and, on the other hand, suppression of laser distortions due to relativistic self-focusing or Raman type instabilities. It is important to note that at a distance of 1.64 mm the pulse becomes broader (about 8.5 fs) and structured, both these factors increasing with further propagation. Thus, comparing this simulation with the experiment shown in Fig. 1(b) we can conclude that the pulse compression occurs at shorter distances of about 1 mm. The ultrabroad pulse spectrum actually reflects the possibility of such compression.
Figure 2. (a) Snapshot of the electron density distribution (green scale) and laser field (red scale) at the time of the pulse leaving the 2 mm long plasma with a density of $6.6 \times 10^{18} \text{ cm}^{-3}$ and (b) pulse profiles corresponding to this case: input (black line), in the middle $z = 1.2$ mm (blue-dotted line), and output (red line). (c,d) The result of modeling for a 2 mm long plasma with a density of $1.3 \times 10^{19} \text{ cm}^{-3}$: input (black), in the middle $z = 1.28$ mm (red) and at $z = 1.642$ mm (light blue) pulse spectra, and the corresponding pulse profiles (additionally: green line at $z = 628 \text{ µm}$), respectively. In the insets: the corresponding beam profiles of 10.6 µm (b) and 6.5 µm (d) in diameter (FWHM).

4. Hydrodynamic modeling

Despite the satisfactory agreement of the PIC simulations with the experiment it should be noted that 3D simulations, which are necessary for our case, cannot provide an exact description of the real laser-plasma interaction because of the high fluctuation level caused by the small number of quasiparticles in the cells, limited by present day supercomputers. Moreover, as we are interested in PW-class lasers it is impermissible to make any quantitative prediction from such comparison. To get one step further we have developed a simplified hydrodynamic code which allows, first, to assess the ultimate potential of the wakefield compression scheme and, second, to apply it to PW lasers. To do so we have employed the well-proven slowly evolving wave approach (SEWA) [19]. As the plasma density $n_e$ is much less than the critical value $n_c = m\omega^2/(4\pi e^2)$ ($n_e \ll n_c$) [$\omega$ is the pulse carrier frequency], assuming that the field changes only slightly on the wavelength scale and the transverse size of the beam is large compared to the characteristic longitudinal scale of the field (quasi-optical beam), the Maxwell equations and plasma hydrodynamic equations can be reduced to the following set of self-consistent equations in the corresponding reference frame.
\[ \tau = t - z/c \]

\[ \frac{2}{c} \frac{\partial^2 \mathbf{a}}{\partial z \partial \tau} - \Delta a \frac{a}{c^2} + \frac{\omega_p^2}{1 + \Phi} = 0, \tag{1} \]

\[ \frac{\partial^2 \Phi}{\partial r^2} + \omega_p^2 (1 + \Phi)^2 - \frac{(1 + |a|^2)}{2(1 + \Phi)^2} = 0, \tag{2} \]

where \( \omega_p = (4\pi e^2 n_e/m)^{1/2} \) is the plasma frequency, \( c \) is the speed of light in vacuum, \( \Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} \) which are dimensionless vector and scalar potentials: \( a = eA/mc^2, \Phi = e\varphi/mc^2 \). Equation (2) is the usual equation of state for a plasma wave [18, 20] when the electrons evolve mainly in the longitudinal direction (see also [21]). This occurs for laser pulses with a longitudinal dimension much smaller than the transverse one, which is especially true when the group velocity is close to the speed of light, i.e. for low density plasmas.

To begin with, we first compare the results of hydrodynamic modeling, as shown in Fig. 3, with the PIC simulations and experiment. We can definitely say that the results of the pulse compression dynamics for both plasma densities are in good qualitative agreement. For a lower plasma density of \( n_e = 6 \times 10^{18} \text{ cm}^{-3} \) and \( a_0 = 4 \) the pulse is compressed, being one-hump localized in all dimensions, to the duration comprising 1.5 optical oscillations, i.e. to 5 fs, at a distance of 2 mm. Whereas for the higher density of \( n_e = 1.3 \times 10^{19} \text{ cm}^{-3} \) and \( a_0 = 3 \) the minimum pulse duration is 1.2 optical periods, i.e. 4 fs, at a distance of 1.15 mm only. But in this case after passing the point of compression, at a distance of 2 mm the pulse splits into subpulses, as can clearly be seen in Fig. 3(b). For comparison we also present in Fig. 3(c,d) the temporal profiles of the input pulse and pulses with minimum durations along the axis, and their spectra. It is interesting that at the higher plasma density the quality of compression is better, i.e., the laser pulse (red line) is well localized and practically does not contain wings on the back side as compared to the blue line. It should also be mentioned that during propagation the pulse’s peak shifts forward and its leading edge becomes steeper, thus making the longitudinal dimension smaller than the transverse one. From this modeling we can state with confidence that the wakefield compression is capable of producing laser pulses with few-cycle durations. In fact, in both cases of Fig. 3 we actually obtained single-cycle pulses with an energy efficiency of about 20%.

A very intriguing question is that of producing few-cycle pulses with petawatt powers. The remarkable feature of Eqs. (1), (2) is that they contain scalable solutions. In fact, with the following transformations for spatial and temporal variables: \( \omega_p r \rightarrow \tau, \omega_p z/c \rightarrow z, \omega_p r/c \rightarrow r \), Eqs. (1), (2) can be written in dimensionless form. This means that the simulations presented, for example, in Fig. 3 are suitable for other laser-plasma parameters with the corresponding scalability, i.e., laser pulse parameters such as laser frequency \( \omega \), pulse duration and beam diameter which can be scaled by a factor of \( \omega_p/\omega \). But this scalability cannot help us if we have one type of laser, i.e., if \( \omega \) is fixed. However, to get an insight into the physics of interest we can employ an approximate scalability valid for comparatively long pulses, when the envelope approximation holds. In fact, to obtain compression we usually start from long pulses containing many optical cycles. Thus, assuming \( a \sim e^{i\omega \tau} \) and reducing Eq. (1) to the form \((2i\omega/c)\partial a/\partial z - \Delta a + (\omega_p^2/c^2)a/(1 + \Phi) = 0 \) [18] the following scalability

\[ n_0^{1/2} \omega \tau \rightarrow \tau, n_0 k z \rightarrow z, n_0^{1/2} k r \rightarrow r \tag{3} \]

(where \( k = \omega/c \) and \( n_0 = \omega_p^2/\omega^2 \)) can now be applied with respect to the envelope of the laser field; the difference is that the length of the compression is proportional to \( n_0 \), i.e. to the plasma density. For compression of PW-class laser pulses for an input amplitude \( a \sim 1 \) we have to use larger laser beams and therefore, as it follows from Eq. (3), lower plasma densities.
Figure 3. Spatial-temporal pulse dynamics along the propagation direction at plasma densities of $6.6 \times 10^{18}$ cm$^{-3}$ (a) and $1.5 \times 10^{19}$ cm$^{-3}$ (b) respectively; additionally input (dashed curve) and current (red) laser pulse profiles on the axis, and transverse (blue) beam profiles at the plane of maximum intensity are depicted. (c) Intensity profiles of the input pulse and compressed pulses with a minimum duration, and (d) corresponding spectra: blue line for $n_e = 6.6 \times 10^{18}$ cm$^{-3}$ - 5 fs at FWHM and red line for $n_e = 1.3 \times 10^{19}$ cm$^{-3}$ - 4 fs at FWHM.
As an example we make estimations for a 1 PW laser pulse with a duration of 500 fs (pulse energy of 500 J). Following the scalability given by Eq. (3) and the simulations presented in Fig. 3 we may suggest a two-stage wakefield compression scheme to get a few-cycle pulse. At the first stage, by using plasma densities of about $5 \times 10^{17}$ cm$^{-3}$ the pulse is compressed by a factor of 7, i.e., down to the duration of 70 fs at a plasma length of 4 cm with an energy efficiency of about 20%. At the second stage, this pulse should enter into the plasma jet with $(3 ÷ 4) \times 10^{18}$ cm$^{-3}$ density. After passing a length of about 4 mm the pulse will be compressed down to 10 fs. Thus, with the same efficiency of 20% at this stage, we obtain an output pulse with the energy of 20 J that corresponds to the pulse power of two petawatts, i.e., even more than the input power but for the shorter pulse.

Another but more rigorous example we present by directly checking the possibility of compression of petawatt-class pulses to few-cycle durations. In Fig. 4 we present results for a plasma density of $10^{18}$ cm$^{-3}$, when the input pulse has the following parameters: pulse duration 70 fs, beam width 36 µm, and $a_0 = 4$, which correspond to 70 J pulse energy and 1 PW power, respectively. The pulse is smoothly compressed, reaching at a distance of 5 cm its minimal duration of 5 fs. As is clearly seen, the pulse temporal and beam profiles have good quality, the energy efficiency is about 18%, so that at the output we obtain a 5 fs, 2 PW pulse.

![Figure 4. Spatial-temporal pulse dynamics along the propagation direction for the PW-class laser pulse (70 fs, 70 J, $a_0 = 4$) in a plasma with a density of $1 \times 10^{18}$ cm$^{-3}$. Notations as in Fig. 3.](image)

5. Conclusion
We have examined wakefield pulse compression in a combined experimental and numerical study. It is shown that in the relativistic regime ($a_0 \sim 1 ÷ 5$) laser pulses can be effectively compressed to a duration of to few-cycles. Moreover, the scheme is scalable to the petawatt level, which means that for present day conventional laser systems delivering comparatively long pulses the wakefield compression opens up a new way of producing PW-class few-cycle pulses.

Acknowledgments
This research has been supported by the DFG SFB/TR 18 and the GRK 1203 programmes. Two of the authors (S.A.S. and E.A.A.) also acknowledges partially support from the RF President
Grant No. MK-4902.2011.2 and Dynasty Foundation.

References

[1] Strickland D and Mourou G 1985 Opt. Commun. 56 219
[2] Sung J H, Lee S K, Yu T J, Jeong T M and Lee J 2010 Opt. Lett. 35 3021
[3] Krausz F and Ivanov M 2009 Rev. Mod. Phys. 81 163
[4] Schmid K et al. 2009 Phys. Rev. Lett. 102 124801
[5] Chekhlov O V et al. 2006 Opt. Lett. 31 3665
[6] Lozhkarev V V et al. 2007 Laser Phys. Lett. 4 421
[7] Herrmann D, Veisz L, Tautz R, Tavella F, Schmid K, Pervak V and Krausz F 2009 Opt. Lett. 34 2459
[8] Skobelev S A, Kim A V and Willi O 2012 Phys. Rev. Lett. 108 123904
[9] Faure J, Glinec Y, Santos J J, Ewald F, Rousseau J-P, Kiselev S, Pukhov A, Hosokai T and Malka V 2005 Phys. Rev. Lett. 95 265003
[10] Schreiber J, Bellei C, Mangles S P D, Kamperidis C, Kneip S, Nagel S R, Palmer C A J, Rajeev P P, Streeter M J V and Najmudin Z 2010 Phys. Rev. Lett. 105 235003
[11] Ren C, Duda B J, Hemker R G, Mori W B, Katsouleas T, Antonsen T M Jr. and Mora P 2001 Phys. Rev. E 63 026411
[12] Lontano M and Murusidze I G 2003 Opt. Express 11 248
[13] Gordon D F, Hafizi B, Hubbard R F, Penano J R, Sprangle P and Ting A 2003 Phys. Rev. Lett. 90 215001
[14] Gallmann L, Sutter D H, Matuschek N, Steinmeyer G, Keller U, Iaconis C and Walmsley I A 1999 Opt. Lett. 24 1314
[15] Wyatt A S and Walmsley I A 2006 Opt. Lett. 31 1914
[16] Gonoskov A A, Korzhimanov A V, Eremin V I, Kim A V and Sergeev A M 2009 Phys. Rev. Lett. 102 184801
[17] Pukhov A and Meyer-ter-Vehn J 2002 Appl. Phys. B 74 355
[18] Abramyan I A, Litvak A G, Mironov V A and Sergeev A M 1992 JETP 75 978
[19] Geissler M, Tempea G, Scrinzi A, Schnurer M, Krausz F and Brabec T 1999 Phys. Rev. Lett. 83 2930
[20] Sprangle P, Esarey E, Krall J and Joyce G 1992 Phys. Rev. Lett. 69 2200
[21] Esarey E, Schroeder C B and Leemans W P 2009 Rev. Mod. Phys. 81 1229