Shape-Control of Ultrashort Laser Pulses for Optimal Electron Acceleration in Plasmas

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Abstract. The temporal shape of 50-100 femtosecond Ti:sapphire laser pulses has been controlled by appropriate choice of the higher order spectral phase coefficients, and used for optimization of a plasma wake-field electron accelerator.

INTRODUCTION

The specific pulse shape of ultrashort light pulses can play an important role in nonlinear processes. For example, two pulses with the same full-width-half-maximum (FWHM), but having different rising edge and tail characteristics or amplitude modulation, could lead to strongly different results in processes where the excitation in the medium depends on the ponderomotive force which is due to the gradient of the intensity profile. In laser wake-field acceleration [1], a driving pulse with a sharp leading edge will result in faster growth of the plasma wake-field, and consequently, higher energy electrons after acceleration.

There are several means of active control of the shape of ultrashort pulses, such as frequency-domain filtering and envelope transfer to the time-domain by using liquid crystal phase modulators [2] or acousto-optic phase and amplitude control [3]. In this report we investigate the intrinsic pulse shaping behavior of the most widely used optical pulse compressor, the grating pair – with special emphasis on the pulse skewness and its effect on a strongly nonlinear process, the laser wake-field generation. The future application of an acousto-optic phase and amplitude modulator (the DAZZLER [2]) will also be discussed.

PULSE SHAPING WITH GRATING COMPRESSOR

The properties of ultrashort optical pulses in the range of sub-100 fs duration strongly depend on the higher order phase characteristics. In addition to the simplest case of linear 'chirp' (when the phase of an optical pulse changes quadratically as a function of time or frequency), the presence of higher order components (such as 'cubic' third order, or 'quartic' fourth order) will modify the shape of the pulse,

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resulting in modulation, and even pre- or post pulses [4,5]. (Throughout this paper 'shape' means temporal envelope function of the propagating electromagnetic pulse, while transverse – spatial – variations are neglected.)

The description of the phase evolution and the related dispersive delay of each optical component in a CPA system is based on the Taylor's series expansion of the optical phase as

$$\phi(\omega) = \phi(\omega_0) + \left.\frac{\partial\phi}{\partial\omega}\right|_{\omega_0} (\omega - \omega_0) + \frac{1}{2!}\left.\frac{\partial^2\phi}{\partial\omega^2}\right|_{\omega_0} (\omega - \omega_0)^2 + \frac{1}{3!}\left.\frac{\partial^3\phi}{\partial\omega^3}\right|_{\omega_0} (\omega - \omega_0)^3 + \ldots \qquad (1)$$

Here ω is the angular frequency, and ω_0 is the center frequency of the expansion. While the first term is a constant and second term simply represents an overall time shift of the pulse, the remaining terms represent distortions to the shape of the pulse. The coefficient of the third term is the group velocity dispersion (GVD) or quadratic phase, representing linear chirp. The coefficient of the fourth term is the cubic phase. The coefficient of the fifth term is the quartic phase, and so on.

In a typical chirped pulse amplification (CPA) system, the final pulse-forming device is the grating pulse compressor. In contrast to the most simplistic view and practice, by scanning the grating separation the experimenter changes not only the linear chirp, but also modifies all the higher order terms [6]. This effect on the pulse shape becomes negligible at settings far from the shortest compression, i.e., where the pulse duration is much longer than the shortest possible. However, if the pulse duration is in the range of a few times the shortest one, and the compressor angle is set slightly differently from the optimum, or the pulse contains uncompensated higher order terms, then a typical scan around the shortest pulse will produce significant changes to the pulse shape. For example, when compressing stretched pulses with a positive bias third order phase component, the pulse shape in the course of a compressor separation scan initially will be skewed toward the head of the pulse ($s<1$), then flips to become a skewed pulse at the tail ($s>1$), and again flips back to the original asymmetric one ($s<1$). The skewness parameter (s) is conveniently defined here as the ratio of the 'head-width-half-max' (HWHM) and the 'tail-width-half-max' (TWHM), respectively. We note here, that these changes are fundamentally different from the well known and widely used mapping of the spectral amplitude to the time domain for strongly chirped pulses, where only the dominant, second order phase coefficient plays any role [2].

The described qualitative behavior can be clearly seen in Figure 1, which shows the pulse shape dependence of a pulse with ~19 nm spectral bandwidth during a compressor scan around the shortest pulse. On the small graphs on the side, time flows from left to right. The grating parameters: groove density = 1480 1/mm, angle of incidence = 50.0 deg, grating separation at the shortest pulse = 323 mm, λ = 795 nm, third order bias = +20,000 fs^3.

In a real laser system, however, the situation is more complicated by the presence of even higher order components beyond third. The pulse shapes must be measured for both positive and negative chirped cases throughout a typical compressor scan.

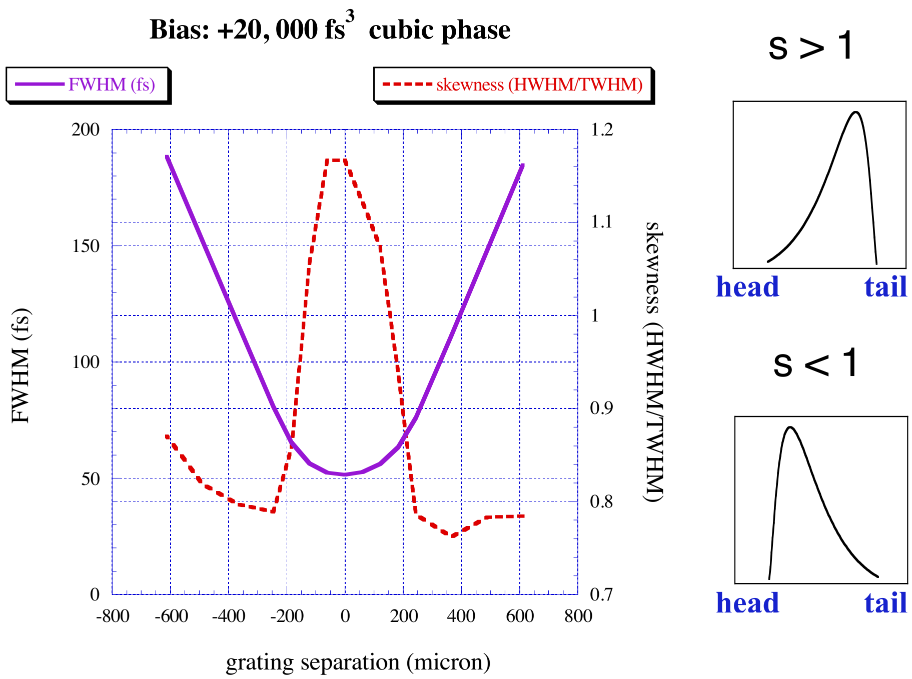

FIGURE 1. Pulse shape evolution in ideal grating scans with positive cubic bias.

In our experiments, in addition to the conventional autocorrelation measurement, which usually washes out the fine details of the pulse shape, we measured the actual pulse envelope and phase by using a PG-FROG device [8]. The measurements show similar pulse shape variations around the shortest pulse, in particular for pulses of 70-80 fs duration. Figure 2(a) shows a typical pulse at the *negative* chirp side, while Figure 2(b) shows the *positive* chirp side of the scan. The solid curves are the amplitude functions and the dashed curves are the phase functions in the time domain. A more detailed simulation of the pulse shape evolution using the experimentally retrieved parameters of the pulse can be seen in Figure 2(c). On the time-axis, time flows from the right to the left. The front region of the plot represents the positive chirp cases, while the back corresponds to negatively chirped pulses. The well-pronounced modulations at the negative chirp side provide a clear indication for the presence of unbalanced higher order terms (related to the phase properties of the laser amplifier chain). These terms are eventually responsible for the specific feature of 'positive chirp = sharper leading edge; negative chirp = sharper tail' observed in our CPA laser amplifier system with the described operating conditions. It should be noted, however, that for other experimental conditions that deviate from optimal (e.g. different mismatch of the stretcher/compressor or different stretcher/amplifier chain designs), balanced compression manifests itself differently at 'off-shortest' pulse durations (off-shortest compressor settings), which could lead to different 'chirp-shape' combinations.

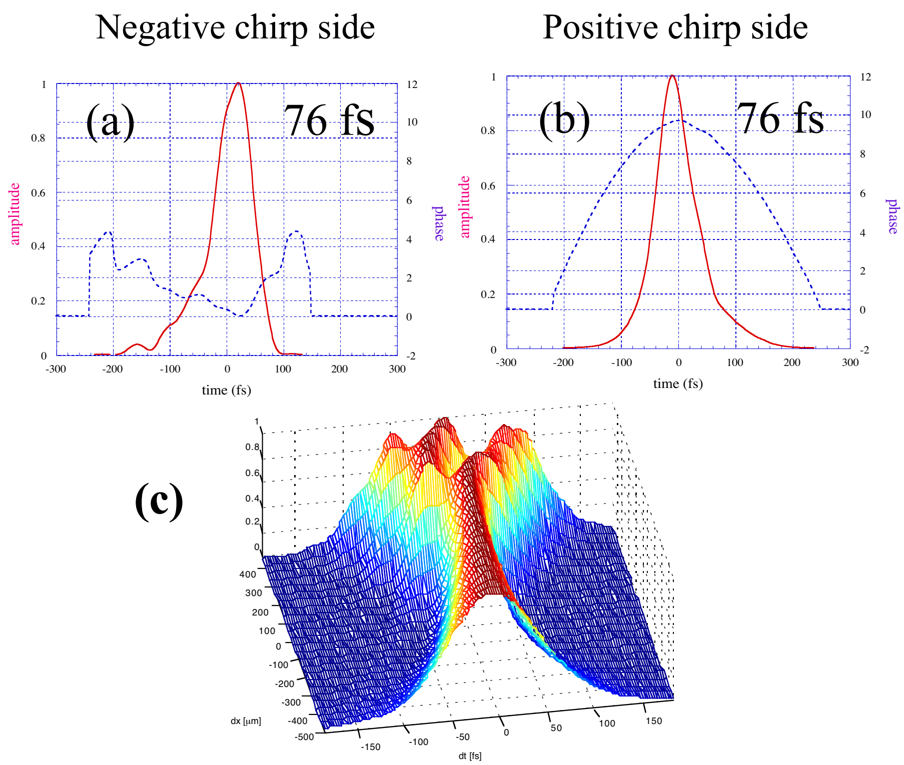

FIGURE 2. Retrieved pulse amplitude and phase function for the negative chirp side (a), and positive chirp side (b) of a typical compressor scan in a real experimental situation with not fully compensated 3rd, 4th & 5th order phases. The retrieved parameters of the system at several discrete positions of the grating pair were used afterward to simulate the continuous dependence of the pulse shape during a scan (c).

CONTROL OF WAKEFIELD ACCELERATORS

The analysis described in the previous paragraph shows the possibility of laser pulse shape control by the simple way of grating alignment. Here we describe the effects of these various pulse shapes in a particular experiment: the acceleration of electrons by laser produced plasma wakes.

Electron Acceleration Experiment

In laser plasma wake-field electron acceleration experiments in the L'OASIS Lab of LBNL we observed strong asymmetry in the yield of electrons and neutrons produced by these accelerated electrons of multiple-tens of MeV as a function of compressor scans [8,9]. The main features of the experimental setup are as follows: low energy pulses (laser wavelength λ= 800 nm) from a Ti:sapphire laser oscillator were first temporally stretched, than amplified to ~1 J/pulse level and then compressed

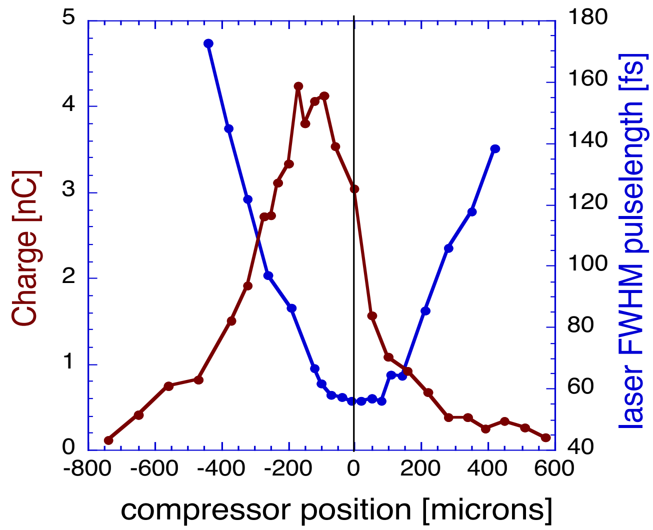

FIGURE 3. Electron yield versus compressor position in laser wakefield acceleration experiment.

using a grating based optical compressor to pulse widths as short as 45 fs. Following compression, the laser beam was focused to a size w = 6 μm with a 30 cm focal length (F/4) off-axis parabola (OAP) onto a pulsed gas jet. The peak power P of the laser was varied using both the pulse duration and laser energy. At optimum compression, P = 8.3 TW, resulting in a calculated peak intensity $I = 2P/\pi w^2 = 1.5\text{x}10^{19}$ W/cm^2 and a normalized laser strength $a_0 = 8.6\text{x}10^{-10}\lambda[\mu\text{m}]I^{1/2}[\text{W/cm}^2] = 2.6$. The laser pulse spectral bandwidth was typically 21-22 nm (FWHM). The total charge per bunch and spatial profile of the electron beam were measured using an integrating current transformer (ICT) and phosphor screen imaged onto a 16-bit CCD-camera, respectively.

The total charge of the emitted electrons depends strongly, and asymmetrically, on the position of the grating separation relative to the optimum pulse compression setting (Figure 3). Analytic modeling and simulation indicate that the effect of the intrinsic frequency chirp - meaning the enhancement related to the fact that the pulses are positively chirped on the left side and negatively on the right side for equal pulse durations - is much less important and itself can not explain the observed anomaly [10]. On the other hand, as we will see in the next section, taking into account the *shape* dependence instead, it is possible to explain the observed asymmetric enhancement seen in Figure 3.

Wakefield Simulations

Using the experimental temporal laser profiles, the plasma response was calculated using the 1-D non-linear fluid equations. Fast rising pulses generated significantly larger amplitude plasma wakes *underneath* the laser envelope than slow rising ones, as can be seen in Figure 4. It shows the plasma wave potential $\delta\phi_+$ ponderomotively excited by the positive $a_+(\zeta)$ and negative $a_-(\zeta)$ chirped experimental laser pulse profiles with τ_{FWHM} =76 fs. A larger wake is excited within the laser pulse for the case of the positively chirped (fast rise) laser pulse than for the negatively chirped (slow rise) laser pulse. The Raman forward scattering (RFS) instability is seeded by the density perturbations, which contain Fourier components at the relativistic plasma frequency ω_p, and therefore the positively skewed pulses will provide a larger seed for RFS than negatively skewed pulses. The consequence of larger accelerating fields is a more rapid onset of particle trapping and growth enhancement, eventually leading to more accelerated electrons observable in the experiments.

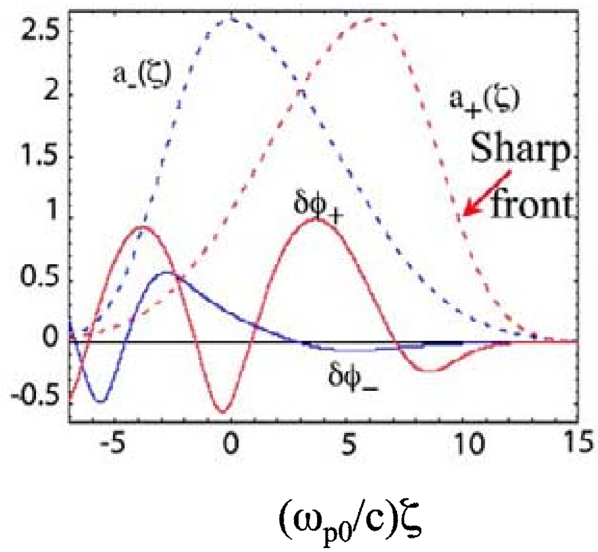

FIGURE 4. Analytically calculated wakefield amplitudes ($\delta\phi_+$, $\delta\phi_-$, solid lines) excited by laser pulse envelopes (dashed lines) for positively ($a_+(\zeta)$) and negatively ($a_-(\zeta)$) skewed pulses, corresponding to s<1, and s>1, respectively. Note: the horizontal axis is the transformed and normalized axial coordinate in the frame moving with the propagating laser pulse, ζ=z-ct.

SUMMARY

We have discussed experiments supporting the concept that the interplay of pulse shapes and higher order phase components leads to enhanced growth of the plasma wake in the standard wake-field accelerator regime early in the interaction. This process eventually results in optimal acceleration conditions, different from the shortest, highest intensity pulse, favoring slightly longer pulses with sharp rise time. The detailed knowledge of the evolution of the pulse shapes provides us an additional path to control the parameters of plasma wake-field accelerators even in a conventional grating compressor scan by intentionally biasing the higher order phase components. The presented method of higher order phase control is a simple alternative to the recently developed acousto-optic phase modulation devices such as the DAZZLER [3], and can conveniently be used at arbitrarily high power and energy levels limited only by the damage threshold of the compressor gratings.

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REFERENCES

1. Leemans, W. P., Siders, C. W., Esarey, E., Andreev, N. E., Shvets, G, and Mori, W. B., *IEEE Transactions on Plasma Science* **24,** 331-342 (1996).
2. Weiner, A. M., Leaird, D. E., Patel, J. S., and Wullert, J.R., *IEEE Journal of Quantum Electronics* **28,** 908-920 (1992).
3. Verluise, F., Laude, V., Cheng, Z., Spielmann, C., and Tournois, P., *Optics Letters* **25**, 575-577 (2000).
4. Fittinghoff, D. N., Walker, B. C., Squier, J. A., Tóth, Cs., Rose-Petruck, C., and Barty, C. P. J., *IEEE J. Sel. Top. Quant. Elec.* **JSTQE-4**, 430-440 (1998).
5. Backus, S., Durfee, III, C. G., Murnane, M.M., and Kapteyn, H. C., *Rev. Sci. Inst.* **69**, 1207-1223 (1998).
6. Tóth, Cs., Fittinghoff, D. N., Walker, B. C., Squier, J. A., and Barty, C. P. J., in *Ultrafast Phenomena XI,* edited by T. Elsaesser, et al., Berlin: Springer, 1998, pp. 109-111.
7. Kane, D. J., and Trebino, R., *Optics Letters* **18**, 823-825 (1993).
8. Leemans, W. P., Rodgers, D., Catravas, P. E., Geddes, C. G. R., Fubiani, G., Esarey, E., Shadwick, B. A., Donahue, R., and A. Smith, A., *Physics of Plasmas* **8**, 2510-2516 (2001).
9. Leemans, W. P., Catravas, P. E., Esarey, E., Geddes, C. G. R., Tóth, C., Trines, R., Schroeder, C. B., Shadwick, B. A., van Tilborg, J., and Faure, J., submitted to *Phys. Rev. Lett.*, (2002).
10. Schroeder, C. B., Esarey, E., Shadwick, B. A., and Leemans, W. P., submitted to *Phys. Plasmas* (2002).