Nuclear Instruments and Methods in Physics Research A 829 (2016) 383–385

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Generation of laser pulse trains for tests of multi-pulse laser wakefield acceleration

R.J. Shalloo *, L. Corner, C. Arran, J. Cowley, G. Cheung, C. Thornton, R. Walczak, S.M. Hooker

*Department of Physics and John Adams Institute for Accelerator Science, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*

ARTICLE INFO

*Article history:*
Received 15 November 2015
Received in revised form
8 January 2016
Accepted 14 February 2016
Available online 23 February 2016

*Keywords:*
Plasma accelerators
Laser wakefield
Pulse train

ABSTRACT

In multi-pulse laser wakefield acceleration (MP-LWFA) a plasma wave is driven by a train of low-energy laser pulses separated by the plasma period, an approach which offers a route to driving plasma accelerators with high efficiency and at high pulse repetition rates using emerging technologies such as fibre and thin-disk lasers. Whilst these laser technologies are in development, proof-of-principle tests of MP-LWFA require a pulse train to be generated from a single, high-energy ultrafast pulse. Here we demonstrate the generation of trains of up to 7 pulses with pulse separations in the range 150–170 fs from single 40 fs pulses produced by a Ti:sapphire laser.



## 1. Introduction

Laser-driven plasma accelerators can accelerate electrons to energies of several GeV in accelerator stages of only a few centimetres [1], and as such they have potential applications in driving compact light sources [2] and, in the longer term, new generations of particle colliders [3]. However, many of these applications will require the accelerator to operate at pulse repetition rates substantially above the few Hertz possible with today's driving lasers. A potential solution is the multi-pulse laser wakefield accelerator (MP-LWFA), in which the plasma wave is driven by a train of low-energy laser pulses separated by the plasma period [4]; this allows the use of new laser technologies which can generate low-energy pulses at multi-kilohertz repetition rates and with high wall-plug efficiency.

Whilst these laser technologies are being developed, proof-of-principle tests of MP-LWFA require a pulse train to be generated from a single, high-energy ultrafast pulse. Several methods of pulse train generation have been investigated including the use of stacked Michelson interferometers [5] and a linear array of birefringent plates [6]. Here we investigate pulse train generation by two methods based on spectral filtering of a chirped pulse by: (i) a combination of a multi-order wave plate and a linear polarizer [7–9]; and (ii) a single Michelson interferometer.

## 2. Pulse train generation with a spectral filter

Spectrally filtering a chirped pulse will generate a temporally-modulated pulse, or a pulse train, since the wavelength of a chirped pulse varies with time. If the spectral chirp is linear, i.e. the spectral phase is a quadratic function of the angular frequency $\omega$, then filtering will generate a train of pulses of constant spacing if the filter's pass-bands are identical and equally spaced in $\omega$.

### 2.1. Multi-order waveplate and linear polarizer

Previous work [7–9] using laser pulses with energies below 5 mJ has demonstrated the generation of pulse trains by passing a chirped pulse through a spectral filter formed by a combination of a multi-order wave plate (MWP) of thickness $\ell$ and a linear polarizer, as shown in Fig. 1(a). The retardance of the MWP is $\phi_{\text{ret}} = (2\pi/\lambda)\Delta n \ell$, where $\Delta n$ is the birefringence of the plate and $\lambda$ is the wavelength. If the transmission axis of the linear polarizer is parallel to the polarization of the incident chirped pulse, and at 45° to the axes of the MWP, then wavelengths for which $\phi_{\text{ret}} = 2\pi m$, ($m$, integer) will be transmitted with no loss; other wavelengths will leave the MWP elliptically polarized and hence their intensity will be reduced on passing through the polarizer. The temporal intensity profile of the resulting pulse train will be equal to that of the incident pulse, modulated by a cosine-squared function, if the input pulse is linearly-chirped and if the *differences* of second- and higher-order dispersion terms for the ordinary and extraordinary polarizations in the wave plate are small [8].

If a simple transmission polarizer is used in this arrangement then half of the incident energy is lost. Fig. 1(b) shows an extension of this idea which utilizes all of the incident energy to

* Corresponding author.
*E-mail address:* robert.shalloo@physics.ox.ac.uk (R.J. Shalloo).

http://dx.doi.org/10.1016/j.nima.2016.02.044
0168-9002/

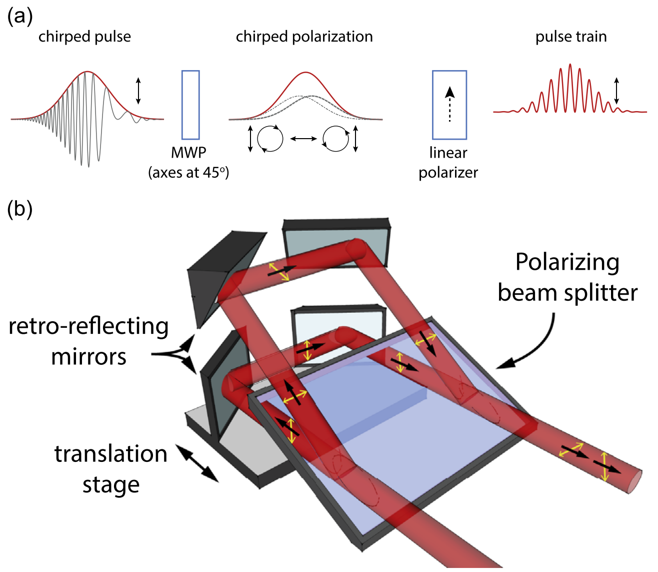


**Fig. 1.** (a) Schematic diagram of the generation of a train of laser pulses from a chirped input pulse and a multi-order wave plate (MWP) and linear polarizer. If the linear polarizer is replaced by the arrangement shown in (b), then two co-propagating pulse trains are generated, with orthogonal polarization and with a temporal delay which depends on the difference in optical path between the upper and lower arms.

generate two, co-propagating pulse trains with a controllable spacing between them. A chirped, horizontally-polarized pulse from the detuned compressor is passed through a MWP with its axes at 45° to a vertical axis. The transmitted pulse is then directed to a thin-film polarizing beam-splitter (PBS), which reflects (transmits) the horizontally (vertically) polarized components of the pulse. The transmitted and reflected components are retro-reflected by a pair of mirrors located in each arm and returned to the PBS. This arrangement yields two, orthogonally-polarized pulse trains which contain (apart from small optical losses) all the energy in the incident pulse; the retro-reflecting mirrors in the transmitted arm are mounted on a translation stage, which allows the spacing between the pulse trains to be controlled.

### 2.2. *Michelson interferometer*

Spectral filtering can also be achieved using a conventional Michelson interferometer with an optical path difference of $\Delta x$ (Fig. 2). This path difference causes a phase delay of $\phi = (2\pi/\lambda)\Delta x$. When the two pulses recombine at the beamsplitter, wavelengths for which the total phase difference (allowing for any constant phase-shift at the beamsplitter) is an even integer multiple times $\pi$ will be transmitted to the output with zero loss; it will therefore convert a linearly-chirped pulse to a pulse train containing half of the incident energy, with a temporal profile equal to that of the incident pulse modulated by a cosine-squared function. The wavelength spacing between successive pulses in the train can be described by the free spectral range of the system $\Delta\lambda_{FSR} = \lambda^2/\Delta x$.

## 3. Results

Pulse trains were generated with both methods using the Astra-Gemini Ti:sapphire chirped-pulse-amplification laser system at the Rutherford Appleton Laboratory. This system generates fully compressed laser pulses with an energy of approximately 0.5 J and 40 fs full-width at half maximum (FWHM) duration. Positively or negatively chirped pulses could be generated by detuning the spacing of the gratings from optimum in the final

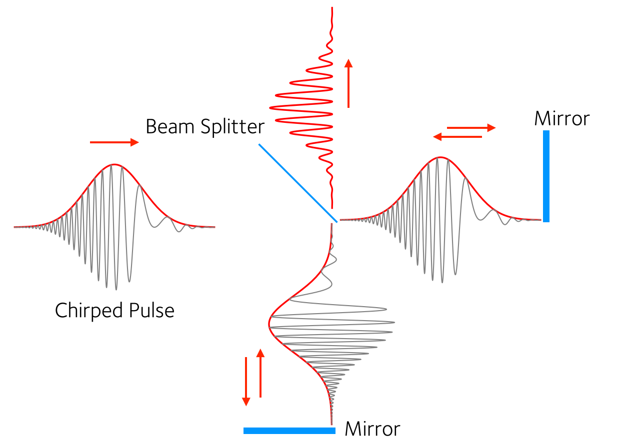


**Fig. 2.** Michelson interferometer setup used to convert a linearly chirped pulse into a pulse train by introducing an optical path length difference between the arms.

compression stage of the CPA system. For the measurements reported here the compressor gratings were moved 1.287 mm from the position of optimum compression, to yield a negatively chirped pulse of approximately 1 ps FWHM. For the MWP method the optical set-up shown in Fig. 1(b) was employed, but with the lower arm blocked so that only a single pulse train was generated.

The generated pulse trains were measured using a single-shot autocorrelator. An acousto-optic programmable dispersive filter (AOPDF) [10] was used to compensate for additional third-order phase introduced by the detuned compressor and, to a lesser extent, the materials of the pulse train optics. This was done by adjusting the third-order phase introduced by the AOPDF to maximize the number of peaks observed in the autocorrelation trace. The additional third-order AOPDF phase which was required to generate the optimum pulse trains was typically of order $-10,000\ \mathrm{fs}^3$; however, it is difficult to relate this figure to the third-order phase introduced by the detuned compressor and pulse train optics since the AOPDF was located before the last amplifier stage.

The pulse trains generated by both methods were simulated numerically by: calculating, as a function of frequency (and, for the MWP method, each polarization), the amplitude transmission of the grating compressor and the spectral filter; combining the measured laser spectrum with the calculated filter transmission; and taking the Fourier transform of the deduced spectral amplitude and phase to give the temporal amplitude, and hence the intensity, profile of the pulse train. The second- and higher-order spectral phases introduced by the detuned compressor and the pulse train optics were included in these calculations, but the AOPDF phase was not since it is not known how the amplifier stages modify these phase terms.

Fig. 3 compares the measured and simulated autocorrelations of pulse trains generated by both methods. For the simulations the parameters of the pulse train optics, such as the Michelson path length difference and the compressor grating separation, were allowed to vary within the experimental uncertainty. For both methods the measured and simulated autocorrelations are seen to be in good agreement. The lower panels in Fig. 3 show the simulated temporal intensity profile of the pulse train from which the autocorrelations were calculated; note that although the autocorrelations are symmetric, the direction of time in the pulse trains is known since the sign of the spectral chirp in the pulses leaving the compressor is known. The good agreement between the measured and calculated autocorrelations enable us to be confident that the pulse trains generated in practice are close to the calculated ones.

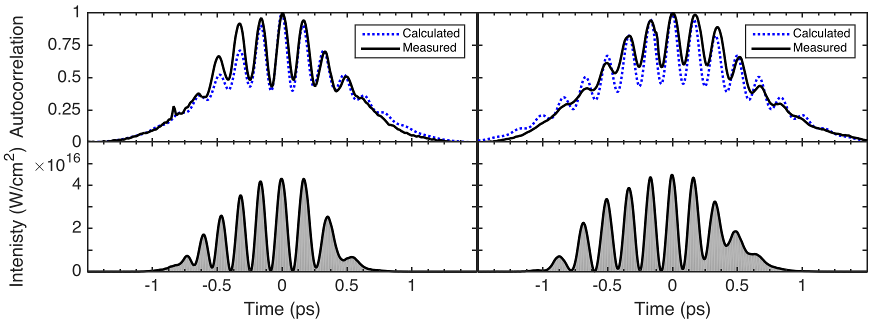


**Fig. 3.** Top: comparison of calculated and measured autocorrelations of pulse trains generated by the MWP (left) and Michelson (right) methods. Bottom: the simulated temporal intensity profiles of the pulse trains used to calculate the associated autocorrelations.

## 4. Conclusion

In conclusion we have demonstrated the generation of trains of laser pulses, with separations in the range 150–170 fs, by spectrally filtering a chirped laser pulse from a CPA laser system. For the results presented here the trains comprise approximately 7 pulses within the FWHM of the train. Pulse trains with these parameters are well suited for tests of multi-pulse laser wakefield acceleration.

## Acknowledgements

This work was supported by the UK Science and Technology Facilities Council (STFC UK) through grants ST/J002011/1; Helmholtz Association of German Research Centres [Grant number VH-VI-503]; and Air Force Office of Scientific Research, Air Force Material Command, USAF [Grant number FA8655-13-1-2141].

## References

[1] S.M. Hooker, Nat. Photon 7 (2013) 775, http://dx.doi.org/10.1038/nphoton.2013.234.
[2] F. Albert, A.G.R. Thomas, S.P.D. Mangles, S. Banerjee, S. Corde, A. Flacco, M. Litos, D. Neely, J. Vieira, Z. Najmudin, R. Bingham, C. Joshi, T. Katsouleas, Plasma Phys. Control. Fusion 56 (8) (2014) 084015.
[3] C.B. Schroeder, E. Esarey, C.G.R. Geddes, C. Benedetti, W.P. Leemans, Phys. Rev. STAB 13 (2010) 101301, http://dx.doi.org/10.1103/PhysRevSTAB.13.101301.
[4] S.M. Hooker, R. Bartolini, S.P.D. Mangles, A. Tuennermann, L. Corner, J. Limpert, A. Seryi, R. Walczak, J. Phys. B 47 (2014) 1, http://dx.doi.org/10.1088/0953-4075/47/23/234003.
[5] C.W. Siders, J.L.W. Siders, A.J. Taylor, S.-G. Park, A.M. Weiner, Appl. Opt. 37 (22) (1998) 5302, http://dx.doi.org/10.1364/AO.37.005302 ⟨http://ao.osa.org/abstract.cfm?URI=ao-37-22-5302⟩.
[6] B. Dromey, M. Zepf, M. Landreman, K. O'Keeffe, T. Robinson, S.M. Hooker, Appl. Opt. 46 (22) (2007) 5142 ⟨Go to ISI⟩://000249167100039.
[7] R. Yano, H. Gotoh, Jpn. J. Appl. Phys. 44 (12) (2005) 8470.
[8] T. Robinson, K. O'Keeffe, M. Landreman, S.M. Hooker, M. Zepf, B. Dromey, Opt. Lett. 32 (15) (2007) 2203 ⟨Go to ISI ⟩://000249087200045.
[9] T. Robinson, K. O'Keeffe, M. Zepf, B. Dromey, S.M. Hooker, J. Opt. Soc. Am. B-Opt. Phys. 27 (4) (2010) 763.
[10] F. Verluise, V. Laude, J.P. Huignard, P. Tournois, A. Migus, JOSA B 17 (1) (2000) 138.