Frontiers in Optics + Laser Science 2023 (FiO/LS) © Optica Publishing Group 2023

Ponderomotive acceleration with high energy tilted ultrafast laser pulses

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Abstract: Using a novel pulse compressor for the CSU ALEPH facility, we demonstrate direct ponderomotive acceleration of electrons with 1.5J, tilted ultrafast pulses. The $<$ 500keV electrons are directed normal to the tilted pulse front as predicted. © 2023 The Author(s)

1. Introduction

The promise of using laser sources for compact electron accelerators has been the subject of intensive research in recent years. Laser wakefield acceleration uses the ponderomotive force of the focused pulse to create a charge separation in the plasma that accelerates electrons with much higher gradients than found in conventional RF waveguide accelerators. Since the plasma wakefield travels at close to the speed of light, a mechanism to accelerate electrons from rest with low emittance would improve the output beam parameters. In an approach that we proposed recently [1], electrons are accelerated directly with the ponderomotive force. Since electrons cannot be captured and accelerated by a pulse moving at the speed of light, we slow the group velocity of the pulse with spatio-temporal tilt. An alternate proposed scheme for group velocity control is the 'flying-focus' approach [2]. While ponderomotive acceleration gradients are not as large as in plasma-assisted wakefields or direct-field laser

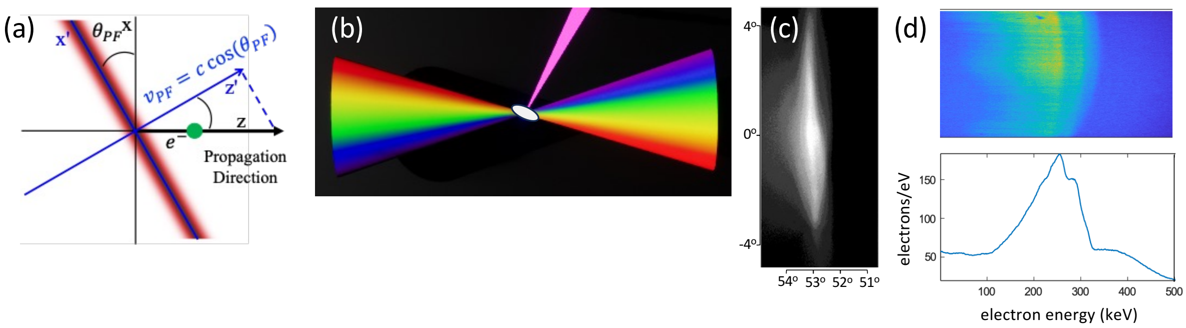

Fig. 1. (a) Schematic of tilted pulse geometry. (b) Focused beam with angular chirp accelerates electrons in the direction of the pink cone. (c) Experimental image of the electron distribution on the Lanex screen. Angles are referenced to the forward beam direction. (d) Image plate distribution with a calibrated average electron spectrum.

In this work, we demonstrate, for the first time to our knowledge, the laser acceleration of electrons directly with a shaped ponderomotive force. Referring to Fig 1(a), which illustrates the tilted pulse geometry with an idealized infinite width beam, the ponderomotive force vector is at an angle θ_{pf} relative to the overall beam propagation direction and the pulse front velocity is $v_{pf} = c\cos(\theta_{pf})$, where c is the speed of light in vacuum. In a rotated frame x',z', moving at v_{pf}, the electron (at rest in the lab frame) approaches the ponderomotive potential hill with a (classical) kinetic energy of $m_e v_{pf}^2/2$. It follows that the electron will be 'reflected' in this frame if the potential height U_{p0} is greater than this effective kinetic energy. In our theoretical work, we have extended this approach to calculate the capture intensity threshold accounting for relativistic effects. $U^R_{cap} = (1/2)m_e c^2 tan^{-2}(\theta_{pf})$. In this ideal situation, all electrons are captured and the output energies and angles are uniform, independent of the actual intensity, provided that $U_p > U^R_{cap}$. The maximum energy of the electrons accelerated from rest is $4 * U^R_{cap}$. The finite beam width and nominally Gaussian beam profile change the dynamics in two important ways. While an electron is being accelerated by the pulse, it translates along the pulse front (x' in Fig. 1). Therefore, the finite width of the beam reduces the acceleration time for some electrons. Second, just as the 'reflection' of the electrons from the potential is reminiscent of reflection of light from a mirror, the Gaussian intensity profile leads to a convex mirror shape that results in greater angular divergence. This will be especially pronounced in the vertical (non-tilted) direction, where the pulse front gradients are the steepest.

2. Experimental configuration and results

The tilted pulses are generated by focusing the laser beam with angular chirp (see Fig 1(b)). Since the frequency components are aligned to be completely overlapped at the focus, the pulse can reach the Fourier transform limited duration [3]. Upstream from the focusing parabola, the spatially-chirped beam is produced using a pulse compressor with a shorter distance between the first two parallel gratings than between the second grating pair. This novel compressor system, designed, constructed and aligned for this project, had the first two gratings outside vacuum with a motor-controlled separation, and the second grating pair inside a 0.5m x 1m vacuum chamber. The angular spatial chirp was measured using a spectrally-resolved knife-edge scan [4], and the at-focus pulse duration ($\sim$ 55fs) was characterized with dispersion scan (varying the separation of the gratings) . An off-axis parabola focused the beam to a radius of $16\mu m$ onto an continuous gas jet of nitrogen with a density of $2 * 10^{17} cm^{-3}$, measured by comparing the plasma emission in the jet to that of a backfilled chamber.

A Lanex scintillating screen was placed parallel to the overall beam direction so that the output electrons could be observed in the predicted direction, 53^o away from the central beam direction. The fluorescence from the screen was monitored with a digital camera positioned outside the target chamber. After working to optimize the focusing with the deformable mirror and alignment of the compressor angles and the focusing parabola, the compressed pulse duration using the grating separation and incident angle, and the positioning of the focus onto the gas jet, we were able to observe an electron beam on the scintillating screen (Fig 1(c)). The 53^o angle of the electrons in the plane of the table (which is the plane of the pulse front tilt), was less than 1^o different from the pulse front tilt angle inferred from the angular chirp measurements. The spread of the beam in the vertical direction was much larger, which was expected from the large intensity gradients in the vertical direction as mentioned above. To measure the electron energies, we placed a magnetic electron spectrometer built by the team [5]. The energy distribution (Fig 1(d)) shows a peak at 250keV, with a maximum output energy of 500keV. The peak ponderomotive energy at focus calculated from the measured energy, spot size and pulse duration is 381keV.

3. Discussion

This proof-of-principle work shows that electrons can be accelerated in an off-axis direction using tilted pulses at a facility scale. The good agreement of our theory with the observed output directions of the electrons is an encouraging confirmation of our theory. Our calculations show that by flattening the intensity profile of the focal spot, a dramatic improvement of the energy and angular distributions should be possible. The output energy can be tuned simply by adjusting the pulse front tilt angle; for larger θ_{pf} the capture intensity threshold can be reduced to scale to a table-top laser system, making this a practical source for applications.

Funding Acknowledgements: The CSM team gratefully acknowledges support from the National Science Foundation under award PHY-1903709. Work supported by DOE LaserNet US grant DE-SC0019076 and Vannevar Bush Faculty Fellowship ONR N00014212842.

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