Control of Pulse Front Tilt and Curvature for Ultrafast Ponderomotive Electron Acceleration

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Abstract:
We explore an electron acceleration scheme which uses the ponderomotive force of a tilted ultrafast laser as the drive mechanism for acceleration. The effect of pulse front curvature on the acceleration process is also discussed. © 2022 The Author(s)

1. Tilted Pulse Ponderomotive Acceleration

The extremely high energy densities and field strengths of modern high power laser systems make them a promising driving source for particle acceleration. Recently, we proposed an acceleration method which utilizes the ponderomotive force of a tilted ultrafast laser pulse as the drive mechanism for acceleration of electrons in vacuum (i.e. without a background plasma) [1]. The relativistic ponderomotive force, given by $\mathbf{F}_P = -\overline{\gamma}^{-1}\nabla U_P$, is the cycle-averaged drift force experienced by a charged particle in an inhomogeneous oscillating electromagnetic field. Here, $\overline{\gamma} = \sqrt{1+(2/m_e c^2)((\overline{p}^2/2m_e)+U_P)}$ is the cycle-averaged relativistic factor [2]. In this expression m_e is the electron rest mass, c is the speed of light in vacuum, $\overline{p}$ is the cycle-averaged electron momentum, and U_P is the ponderomotive potential of the pulse. The ponderomotive potential, given by $U_P = (r_e\lambda_0^2 I)/(2\pi c)$, is the average quiver energy of an electron in the laser field, not accounting for the relativistic mass increase. Here, r_e is the classical electron radius, λ_0 is the laser wavelength, and I is the laser intensity.

Consider an ultrafast pulse propagating in vacuum whose pulse front is tilted relative to the propagation direction at an angle θ_{PF}. The velocity of the pulse front in this frame is $v_{PF} = c\cos(\theta_{PF})$. Now consider an electron at rest in the lab frame which interacts with the tilted pulse. In the co-moving frame of the pulse front, this electron is moving with a momentum of $p = \gamma m_e v_{PF} = \gamma m_e c\cos(\theta_{PF})$. Here, $\gamma = 1/\sqrt{1-v_{PF}^2/c^2}$ is the standard Lorentz factor. The kinetic energy of the electron is therefore $KE_{in} = p^2/(2m_e) = m_e c^2/(2\tan^2(\theta_{PF}))$. When the electron begins to interact with the tilted pulse, it will be captured and accelerated in a direction normal to the pulse front tilt (PFT) if the ponderomotive potential of the pulse is higher than the electron's kinetic energy in the moving frame: $U_P^{Cap} \geq KE_{in}$. If the potential is above the capture threshold U_P^{Cap}, the electron "reflects" off the ponderomotive potential of the laser for a net momentum change of $\Delta p = 2p$. Therefore, the final kinetic energy of an electron which is accelerated from rest in the lab frame is $KE_{out} = 4U_P^{Cap} = 2m_e c^2/\tan^2(\theta_{PF})$. From this, we can see that the acceleration direction, and final energy of accelerated electrons is determined solely by the PFT angle and not the height of the laser potential, although the pulse must be above threshold to fully capture electrons.

With modern ultrafast laser systems, it is relatively easy to generate pulses with ponderomotive potentials in the keV to MeV range. Therefore, with this ponderomotive acceleration scheme, we predict that we can accelerate electrons up MeV energies in vacuum without the use of a background plasma. For example, standard commercial titanium doped sapphire (Ti:Sapph) laser systems are capable of routinely producing 7mJ, 30fs pulses. Assuming a spot size of 10μm, this corresponds to a ponderomotive potential of 10.1 keV. To be above threshold, a PFT angle of greater than 78° is needed to capture and accelerate electrons to a maximum energy of 40.4 keV with such a laser system. As another example, the Advanced Laser for Extreme Photonics (ALEPH) laser is capable of producing 26J, 30fs pulses with a spot size of 33.8 μm which corresponds to a peak ponderomotive potential of 2.86MeV [3]. A PFT angle of at least 16.6° is then needed for this potential to be above the threshold and accelerate electrons to a maximum energy of 11.45MeV.

2. Generation of Tilted Ultrafast Pulses

A sophisticated and efficient method for generating PFT in a pulse that is fully compressed in the focus is through a process called simultaneous spatial and temporal focusing (SSTF). In SSTF, the standard grating compressor is altered so that the pulse has purely transverse spatial chirp exiting the compressor. When the pulse is focused, the individual spectral components spatially focus, and their spatial overlap and angled propagation lead to an axially dependent geometric dispersion which tends to compress the pulse on the way to focus. In SSTF, the pulse is only at its shortest possible duration in the focus and the pulse duration increases away from focus. Another consequence of the angular propagation of the spectral components is the development of PFT near the focus which approaches a maximum value of $\theta_{PF} = \tan^{-1}(\gamma_\theta \omega_0)$ at the focal plane. Here, γ_θ is the angular chirp rate and ω_0 is the central frequency of the pulse. In our lab, we have developed an SSTF pulse compressor which is capable of generating SSTF pulses with $0 \leq \theta_{PF} \leq 88^\circ$ when a short focusing optic is used.

As described above, the capture threshold and final energy of electrons ponderomotively accelerated by tilted pulses is solely dependent on the PFT angle. This is only fully true for an ideal pulse with a flat pulse front. Real laser pulses have pulse front *curvature* (PFC) which is due, in part, to their spatial envelope (Gaussian, super-Gaussian etc.). The PFC alters the acceleration process as the ponderomotive force is a *spatial* gradient of the laser potential at a given point in time. Therefore, curvature in the pulse front changes the direction of the ponderomotive force which can affect the acceleration direction and final energies of the accelerated electrons. This tends to increase the energy and angular spread of the accelerated bunch.

One important aspect of SSTF pulses is that they are intrinsically spatio-temporally coupled: the 4D (x,y,z,t) shape of the pulse changes as the pulse propagates even in vacuum. Typically, tilted ultrafast pulses are viewed as a function of their transverse coordinate, x, and time at a particular position along the optical axis. However, the ponderomotive force depends on the spatial shape of the ponderomotive potential as the potential evolves in time. It is therefore more appropriate for studying ponderomotive acceleration to view SSTF pulses as a function of their transverse and longitudinal spatial coordinates (x and z) at a given point in time. A consequence of the spatio-temporal couplings inherent in SSTF pulses is that the PFC can appear different in the (x,z) representation than it does in the (x,t) representation. The PFC near the optical axis can even be concave in the focus for an SSTF pulse with a nominally Gaussian spatial profile when viewed in the (x,z) domain. The net affect of a concave PFC on the acceleration process is the generation of a *focusing* electron bunch. The effective focal distance of the electron bunch is determined by the PFC and the Coulomb repulsion within the bunch. Figure 1 shows snapshots in time of a particle-in-cell (OSIRIS 4.0) simulation of an electron bunch being captured and accelerated from a localized neutral plasma by a $\theta_{PF} = 70^\circ$ SSTF pulse. The concavity of the pulse front can be seen in the focus (frame #2) and the focusing of the bunch can be seen as the spatial size decreases as the bunch moves away from the origin normal to the pulse front.

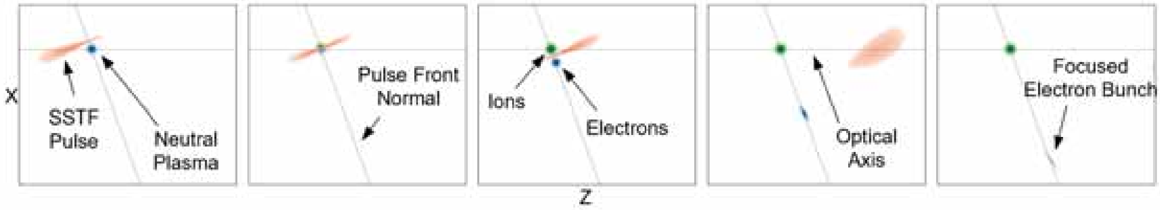

Fig. 1. Shapshots in time of an electron bunch (blue) being accelerated out of a localized neutral plasma. The laser pulse is shown in red and the ions are shown in green.

For longer duration pulses with lower PFT angles the PFC is convex and the accelerated bunch is always diverging. In a middle region, the PFC can be made to be nearly flat over a significant area of the focal spot which will tend to generate a nearly collimated electron bunch. While the affect of the local PFC is significant in the tilted pulse acceleration scheme, it will be important to understand in any ponderomotive acceleration scheme. Therefore, full knowledge and careful preparation of the 4D pulse shape is critical to understanding and optimizing laser driven acceleration schemes. In addition to presenting our analytic and computational results we will report on our experimental progress on this scheme.

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