Vacuum Acceleration of Electrons in a Dynamic Laser Pulse

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Vacuum laser acceleration (VLA) exploits the large electromagnetic fields of high-intensity laser pulses to accelerate electrons to relativistic energies over short distances.[1] The field of an intense pulse can far surpass that in conventional radio-frequency (rf) or advanced plasma-based accelerators, and the underlying interaction—involving only an electron and the electromagnetic field—has an appealing simplicity.

In the strong electromagnetic fields characteristic of pulses delivered by modern laser systems, nonlinear forces become a predominant driver of electron motion. Accordingly, many VLA schemes utilize the ponderomotive force, which pushes electrons against the gradient of the local intensity. For planar pulses, however, the ponderomotive force is insufficient to achieve net energy gains: The rising edge of an intensity peak that travels at the vacuum speed of light (c) will accelerate an electron in the direction of propagation, but the falling edge will eventually overtake and decelerate the electron back to rest [Fig. 1(a)]. To overcome this symmetry and impart net energy to an electron, the speed of the intensity peak must be subluminal, i.e., $|v_I| < c$.

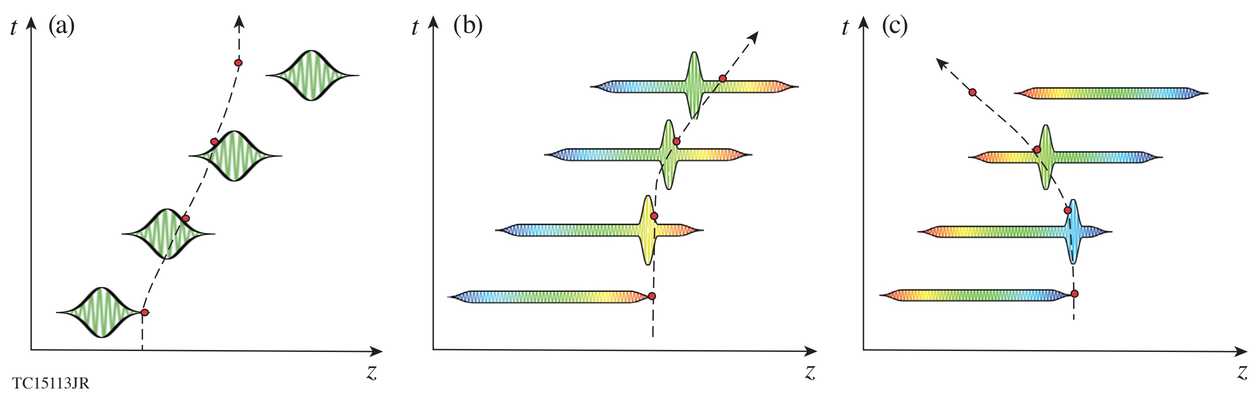

Figure 1
(a) A typical luminal intensity peak in vacuum. The electron, shown as a red dot, experiences equal and opposite ponderomotive accelerations on the leading and falling edges of the pulse, respectively, and gains no net energy. (b) A positively chirped flying focus with a subluminal intensity peak. After forward acceleration in the leading edge of the intensity peak, the electron outruns the peak and retains the energy it gained. (c) A negatively chirped flying focus with a subluminal intensity peak that travels in the opposite direction of the pulse. After backward acceleration in the leading edge, the electron outruns the intensity peak and retains the energy it gained.

We have demonstrated the first vacuum acceleration of electrons in a single planar-like laser pulse in either the forward or the backward direction. This novel mechanism for VLA utilizes the "flying focus"—a recently realized spatiotemporal pulse-shaping technique in which a chirped pulse focused by a hyperchromatic diffractive optic produces an intensity peak that can propagate at any velocity, including $|v_I| < c$, over distances much longer than the Rayleigh range.[2,3] When the peak normalized vector potential of the flying-focus pulse $\left(a_0 = eA_0/m_e c\right)$ exceeds a critical value $\left[a_c = 2^{1/2}\left|\beta_I\right|\gamma_I\right.$, where $\beta_I = v_I/c$ and $\left.\gamma_I = \left(\beta_I^2\right)^{-1/2}\right]$, it can accelerate electrons from rest to a final axial momentum that depends only on the velocity of the intensity peak: $p_f = 2m_e c\beta_I\gamma_I^2$. In principle, the spectral phase and power spectrum of a pulse can be adjusted to create an intensity peak with an arbitrary trajectory. Using this principle, we also show that matching the trajectory of an intensity peak to that of an electron enhances the momentum gain beyond $2m_e c\beta_I\gamma_I^2$.

Figures 1(b) and 1(c) illustrate the ponderomotive acceleration of an electron in either a subluminal forward or backward flying-focus intensity peak. In both cases, when $a_0 > a_c$, the electron can reach a velocity sufficient to outrun the intensity peak and retain its axial momentum, $2m_e c\beta_I\gamma_I^2$. The laser pulse propagates from left to right at the vacuum speed of light, while the flying-focus intensity peak moves independently at a velocity determined by the chirp and chromaticity of the diffractive optic (not shown). The chromatic aberration and chirp control the location and time at which each frequency comes to focus, respectively. Specifically, the intensity peak travels a distance $z_I = (\Delta\omega/\omega)f$ at a velocity $\beta_I = (1 \pm cT/z_I)^{-1}$, where ω is the central frequency of the pulse, $\Delta\omega/\omega$ is its fractional bandwidth, f is the focal length of the diffractive optic at ω, T is the stretched pulse duration, and $\pm$ takes the sign of the chirp.

Figure 2 displays the final momentum as a function of the maximum vector potential and velocity of the intensity peak. The final momentum increases with the velocity of the intensity peak and diverges as $\beta_I \longrightarrow 1$, but the required vector potential increases as well. Operating at the lowest-possible vector potential ($a_0 = a_c$) provides the scaling $\left|p_f\right| = m_e c a_0\left(2 + a_0^2\right)^{1/2}$.

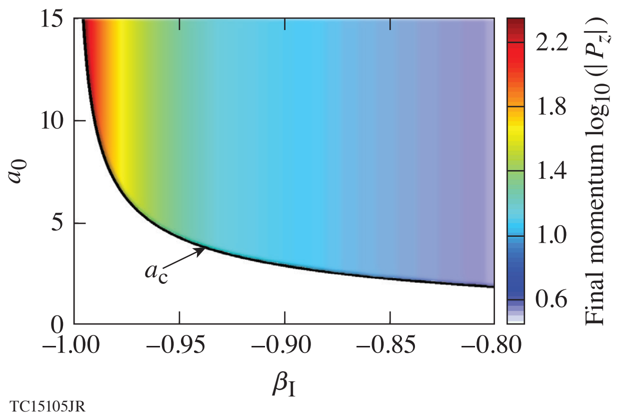

Figure 2
Final momentum of an electron accelerated in a backward propagating flying focus intensity peak. Below the cutoff vector potential (a_c), an electron acquires a velocity insufficient to outrun the intensity peak. Above the cutoff, an accelerated electron can outrun the intensity peak, and the final momentum is independent of a_0.

Accelerating the intensity peak to match the ponderomotive acceleration of an electron, i.e., "trajectory locking," can substantially increase the momentum gain. Constant velocity intensity peaks limit the interaction distance and the momentum gain to a value determined by the maximum vector potential. By limiting the interaction distance, the constant velocity scheme wastes any length that the intensity peak has yet to travel. Trajectory locking, on the other hand, keeps the electron in the ponderomotive potential and can utilize the entire distance, z_I, to increase the final momentum.

In the trajectory-locked scheme, the intensity peak initially moves at a constant velocity, β_{I0}. Once the electron has accelerated from rest to the velocity of the intensity peak, which occurs at the location $a = a_c$, the intensity peak accelerates to keep the electron at this location (i.e., at $a = a_c$). In the trajectory locked peak, the cycle-averaged axial momentum of the electron evolves according to

$$\left\langle p_z\left(t > t_c\right)\right\rangle \approx m_e c\sqrt{\left(\beta_{I0}\gamma_{I0}^2\right)^2 + \frac{1}{2}\left(t - t_c\right)\frac{\partial a^2}{\partial z}\bigg|_{a=a_c}}, \tag{1}$$

where $\beta_{\mathrm{I0}}\gamma_{\mathrm{I0}}^{2}$ is the cycle-averaged electron momentum upon reaching a_{c} at time t_{c}. Equation (1) predicts that optimizing the momentum gain requires co-locating a_{c} with the maximum intensity gradient of the peak. Asymptotically, the momentum gain has a relatively weak scaling with time, $\langle P_z \rangle \propto t^{1/2}$. This results from the diminished ponderomotive force as $\langle \gamma \rangle$ increases. Achieving a momentum gain greater than the constant velocity peak requires that the peak remains trajectory locked for a time $\Delta t > 2\tau a_{\mathrm{c}}^{-2}\beta_{\mathrm{I0}}^{3}\gamma_{\mathrm{I0}}^{4}$.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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