Dephasingless Laser Wakefield Acceleration

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Forty years ago, Tajima and Dawson recognized that the axial electric fields of ponderomotively driven plasma waves far surpass those of conventional radio-frequency accelerators,[1] launching the field of "advanced accelerators"—disruptive concepts that promise smaller-scale, cheaper accelerators for high-energy-physics experiments and advanced light sources. Since their seminal paper, a number of theoretical breakthroughs and experimental demonstrations of laser wakefield acceleration (LWFA) have made rapid progress toward that goal. In spite of the impressive progress, traditional LWFA faces a key design limitation of electrons outrunning the accelerating phase of the wakefield or dephasing.

In traditional LWFA, a near-collimated laser pulse, either through channel or self-guiding, produces a ponderomotive force that travels subluminally at the group velocity ($v_g < c$). The phase velocity of the resulting wakefield equals the velocity of the ponderomotive force. As a result, high-energy electrons traveling at near the vacuum speed of light ($v_e \simeq c$) escape the accelerating phase of wakefield after a dephasing length $L_d \propto n_0^{-3/2}$, where n_0 is the plasma density. Because the maximum accelerating field scales as $E_{max} \propto n_0^{1/2}$, a lower plasma density will increase the maximum energy gain of electrons, $\Delta\gamma \propto n_0^{-1}$, but will greatly increase the length of the accelerator.[2] As an example, a single-stage 1-TeV accelerator would require at least 200 m of uniform, low-density plasma, the creation of which would represent a technical feat unto itself. Instead, the current paradigm within the LWFA community envisions a TeV LWFA composed of multiple ~10-GeV stages. This approach, however, comes with its own set of challenges, such as precisely timing the injection of the electron beam and laser pulses into each of the stages.

We envision something different: a dephasingless laser wakefield accelerator (DLWFA) enabled by a novel optical technique for spatiotemporal pulse shaping that provides control over the phase velocity of the wakefield while preserving the ultrashort duration of the ponderomotive force. In the nonlinear regime ($a_0 > 1$, where $a_0 = eA/m_e c$ is the normalized vector potential of the laser), a DLWFA can achieve TeV energy gains in only 4.5 m—40× shorter than traditional LWFA. Simulations in the linear regime ($a_0 < 1$) demonstrate a 1.3-GeV energy gain in *~3.5× less distance* than a traditional LWFA (8 cm versus 28 cm). The optical technique combines the recently described axiparabola[3] with a novel echelon optic. The axiparabola creates an extended focal region, while the echelon adjusts the temporal delay to provide the desired ponderomotive velocity. This concept improves upon the chromatic flying focus[4] by providing the original features of a small focal spot that can propagate at any velocity over any distance while using an achromatic focusing system to maintain a transform-limited pulse duration ideal for LWFA. Further, by adjusting the profile of the echelon, the ponderomotive force can be made to follow a dynamic trajectory, with either accelerations or decelerations to control trapping and reduce dark current.

Figure 1(a) highlights the advantage of the DLWFA in the linear regime by comparing the energy gains as a function of accelerator length for a DLWFA, a traditional LWFA, and a conventional radio-frequency accelerator. The advantage of the DLWFA increases with the energy gain or accelerator length, i.e., the DLWFA achieves the same energy as a traditional LWFA with an increasingly smaller distance. Scaling laws in the linear regime illustrate this behavior. The energy gain of a DLWFA scales as $W_D = (\pi/8)(k_{pl}L)a_0^2$, where L is the accelerator length, $k_{pl} = \pi/c\tau_l$, τ_l is the transform-limited pulse duration of the laser, and energies are normalized by $m_e c^2$ throughout. Maximizing the energy gain requires operating at the highest possible

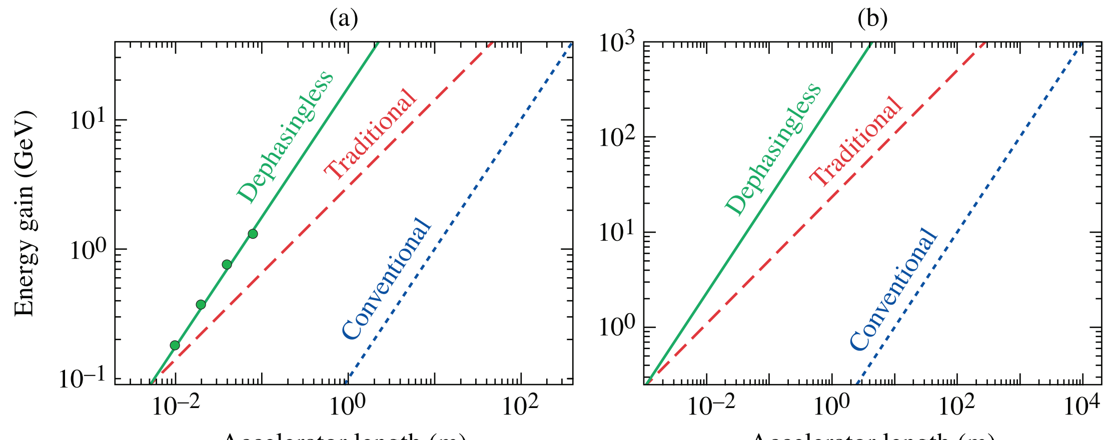

Figure 1
Energy gain of a DLWFA and traditional LWFA in the (a) linear ($a_0 = 0.5$) and (b) nonlinear ($a_0 = 4$) regimes as a function of accelerator length compared with a conventional radio-frequency accelerator. Simulations (green circles) show excellent agreement with the theoretical scaling. The nonlinear DLWFA reaches a TeV energy gain in 4.5 m—40× less distance than a traditional LWFA. The energy gain for the conventional accelerator is determined by the electric-field threshold for material damage, $W_c = E_{thr}L$, where $E_{thr} = 100$ MeV/m. The linear and nonlinear wakefields were driven by a 1-μm laser with $\tau_1 = 30$ fs and $\tau_1 = 15$ fs, respectively.

density, $n_{max} = \pi^2 \alpha_0 m_e / e^2 \tau_1^2$, and increasing the length of the plasma as much as possible. The promise of extending DLWFA to the nonlinear bubble regime—a TeV accelerator in 4.5 m—is illustrated by Fig. 1(b). For a nonlinear DLWFA, $W_D = 1/2\left(k_{pl}L\right)a_0^{1/2}$, where now $k_{pl} \sim a_0^{1/2}/c\tau_1$ in order to match (roughly) half the bubble radius to the transform-limited pulse duration. As before, operating at the highest possible density and increasing the plasma length maximize the energy gain.

The dephasingless wakefield can be excited by a ponderomotive force that travels through the plasma at the speed of light in vacuum over a distance greater than the dephasing length. The novel spatiotemporal technique employed here and depicted in Fig. 2 accomplishes this by using two optics: an axiparabola[3] and a cylindrically symmetric echelon. The axiparabola creates an extended focal region by focusing different radial locations in the near field to different axial locations in the far field. The echelon adjusts the temporal delay of radial locations in the near field to produce the desired ponderomotive or "focal" velocity.

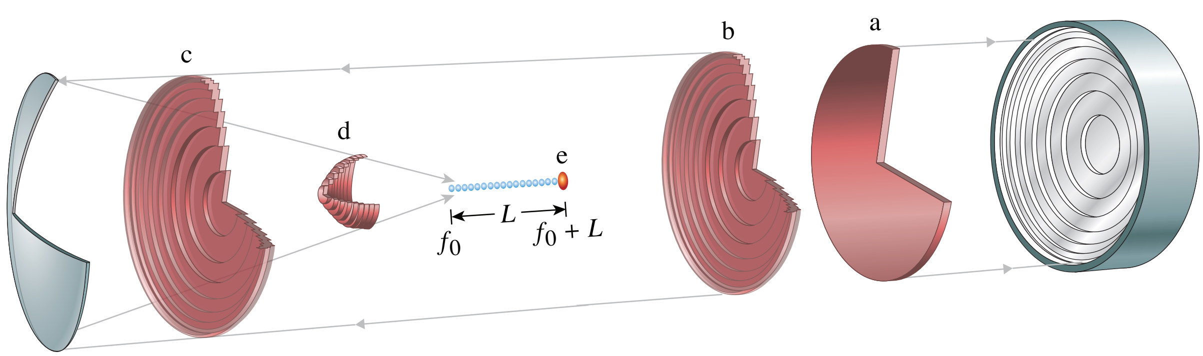

Figure 2
A schematic of the optical configuration enabling the DLWFA. [(a),(b)] The laser pulse first reflects off of a stepped echelon, which imparts the temporal delay required for a focal velocity equal to the speed of light in vacuum without introducing angular dispersion or aberrated focusing. [(c),(d)] After reflecting from the echelon, the pulse encounters the axiparabola, which focuses different rings in the near field to different axial locations in the far field, stretching the region over which the pulse can sustain a high intensity from the initial focus at f_0 to $f_0 + L$. (e) The pulse drives a wakefield at the speed of light in vacuum.

The combined axiparabola/echelon system delivers an ultrashort pulse to each axial location in the focal region without unwanted focusing aberrations and a duration equal to that of the incident pulse.

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