Laser-Plasma Acceleration Beyond Wave Breaking

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Laser wakefield accelerators rely on the extremely high electric fields of nonlinear plasma waves to trap and accelerate electrons to relativistic energies over short distances. When driven strongly enough, plasma waves break, trapping a large population of the background electrons that support their motion. This limits the maximum electric field. We have discovered a novel regime of plasma wave excitation and wakefield acceleration that removes this limit, allowing for arbitrarily high electric fields. The regime, enabled by spatiotemporal shaping of laser pulses, exploits the property that nonlinear plasma waves with superluminal phase velocities cannot trap charged particles and are therefore immune to wave breaking. A laser wakefield accelerator operating in this regime provides energy tunability independent of the plasma density and can accommodate the large laser amplitudes delivered by modern and planned high-power, short-pulse laser systems.

Armed with a vision of smaller-scale, less-expensive accelerators and empowered by advances in laser technology, the field of "advanced accelerators" has achieved rapid breakthroughs in both electron and ion acceleration.[1] In laser wakefield acceleration (LWFA), in particular, a high-intensity laser pulse drives a plasma wave that can trap and accelerate electrons with a field nearly 1000× larger than the damage-limited field of a conventional radio-frequency accelerator.[2] Progress in the field of LWFA exploded with the advent of high-power, broadband amplifiers, which delivered ultrashort pulses with durations less than the plasma period. While advances in laser technology continue to deliver ever-shorter and more-powerful pulses, the current path to higher electron energies calls for longer pulses to match the plasma period at lower densities.

The substantial bandwidth provided by modern laser systems offers an alternative approach to designing LWFA's and increasing the maximum electron energy—spatiotemporal pulse shaping.[3,4] Spatiotemporal pulse shaping provides the flexibility to structure the pulse with advantageous space–time correlations that can be tailored to an application. As an example, stretching the region over which a laser pulse focuses and adjusting the relative timing at which those foci occur provides control over the velocity of an intensity peak independent of the group velocity.[5] In LWFA, because the phase velocity of the plasma wave (v_p) equals the velocity of the ponderomotive potential, a typical pulse, with an intensity peak that travels at the group velocity (v_g), will drive a subluminal wake ($v_\mathrm{p} = v_\mathrm{g} < c$). The intensity peak of a shaped pulse, on the other hand, can travel at or faster than the vacuum speed of light, such that $v_\mathrm{p} \geq c$ (Ref. 5).

The phase velocity of a subluminal plasma wave determines the maximum electric field that the plasma wave can support. A laser pulse propagating in a plasma with a peak normalized vector potential $a_0 = eA_0 / m_\mathrm{e}c$ expels electrons from its path and leaves behind a region of net positive charge. The resulting electrostatic field accelerates the expelled electrons back into this region in an attempt to neutralize that charge. When driven by a pulse with a sufficiently large peak amplitude ($a_0 = a_\mathrm{wb}$), the electrostatic field will accelerate the electrons up to the phase velocity of the wave. At this point, the wave breaks, trapping a significant fraction of the electrons that supported its motion. For a 1-D, cold plasma wave, the wave-breaking field depends only on the phase velocity, $E_\mathrm{wb} = [2(\gamma_\mathrm{p}-1)]^{1/2}$, where $\gamma_\mathrm{p} = \left(1 - \beta_\mathrm{p}^2\right)^{-1/2}$, $\beta_\mathrm{p} = v_\mathrm{p} / c$, the field has been normalized by $em_\mathrm{e}c/\omega_\mathrm{p}$,

$\omega_p = (en_0/m_e\varepsilon_0)^{1/2}$ is the plasma frequency, and n_0 is the ambient electron density. The unwanted injection and trapping of charge, or dark current, resulting from wave breaking reduces the accelerating field and increases the energy spread of the accelerated electron bunch.

The intensity peak of a spatiotemporally shaped pulse can drive a plasma wave with a superluminal phase velocity ($\beta_p > 1$), precluding wave breaking altogether: the electrostatic field of the plasma wave can never accelerate electrons up to its phase velocity ($\beta_e < \beta_p$). This property enables a novel regime of LWFA that (1) can have arbitrarily high accelerating fields and (2) avoids unwanted, continuous injection and trapping of electrons. The idea is to accelerate electrons with a large, unbounded electric field over half a dephasing length—the distance over which a highly relativistic electron experiences one-half period of the wake.

Figure 1 illustrates the design space for superluminal LWFA. When $\beta_p \geq 1$, wave breaking does not occur, and both the phase velocity (i.e., the driver velocity) and the vector potential can be used to tune the energy gain independent of the plasma density. This density-independent tunability of superluminal LWFA allows for operation at higher plasma densities with shorter matched pulses. As a result, this new regime can (1) take advantage of the high-intensity, ultrashort pulses delivered by modern and planned high-power laser systems and (2) avoid the experimental complication of having to create long, low-density plasmas to increase the energy gain.

In contrast to subluminal wakes, the energy gain for a superluminal wake ($\beta_p \geq 1$) increases indefinitely with a_0. A subluminal plasma wave driven with an $a_0 > a_{wb}$ will break, trapping a significant fraction of the background electrons. The electrostatic field of the trapped electrons cancels that of the wakefield and diminishes the energy gain. Figure 2 shows the results of 1-D *OSIRIS* particle-in-cell simulations[6] that demonstrate this for $a_0 = 15$ after ~0.7 of a dephasing length. For nearly the same value of $|\gamma_p^2|$, the superluminal wake [Fig. 2(a)] has maintained its accelerating field, while injection and trapping have significantly reduced the field of the subluminal wake [Fig. 2(b)].

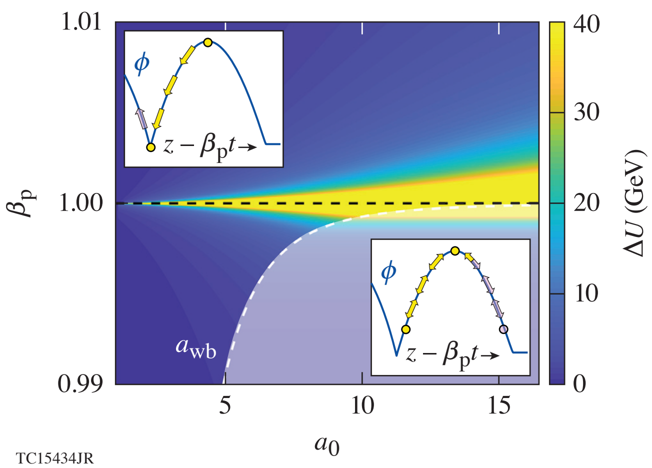

Figure 1
Design space for superluminal ($\beta_p \geq 1$) and subluminal ($\beta_p < 1$) LWFA. Wave breaking limits the design space for subluminal LWFA when the amplitude of the driving laser pulse exceeds a threshold value ($a_0 > a_{wb}$). A superluminal LWFA can take advantage of arbitrarily high intensity, preserving the structure of the wakefield and its peak accelerating field. The top and bottom insets illustrate the differences in the dynamics of an electron that achieves the maximum energy gain injected at rest into the potential of a super and subluminal wake, respectively. The solid (yellow) arrows mark the path over which the electron gains energy.

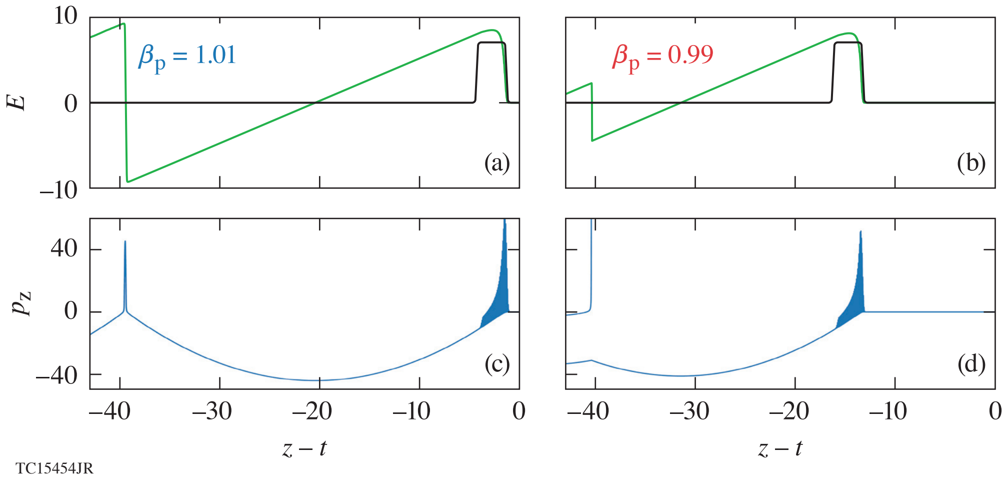

Figure 2
A comparison of the electric field of the wake and electron phase space for [(a),(c)] a superluminal and [(b),(d)] a subluminal wake with $\beta_p = 1.01$ and $\beta_p = 0.99$, respectively. The phase velocities were chosen to make the distinction between the two cases clear throughout the summary. The driver intensity, shown in black for reference, has $a_0 = 15$ and a square pulse shape with duration $\tau = \pi$. The superluminal wake maintains its structure and maximum electric field. Wave breaking of the subluminal wake leads to the injection and trapping of a large population of electrons, which load the wake and diminish its maximum field.

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