Linear-Field Particle Acceleration in Free Space by Spatiotemporally Structured Laser Pulses

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Abstract: We show that net energy transfer via linear-field forces, between a pulsed laser beam and multiple interacting electrons, is possible in unbounded free space by engineering the spatiotemporal structure of light.

OCIS codes (140.7090) Ultrafast lasers; (140.3300) Laser beam shaping; (350.4990) Particles

Linear-field particle acceleration refers to the net acceleration of charged particles subject only (or primarily) to the $q\mathbf{E}$ term of the Lorentz force $\mathbf{F} = q\mathbf{E} + q\mathbf{v}\times\mathbf{B}$, where q is the particle's charge, **v** the particle's velocity, and **E** and **B** respectively the electric and magnetic field which the particle experiences. The question of whether net linear-field particle acceleration is possible in the absence of nearby structures and media has attracted interest for more than 20 years [1-6], with many of such proposals investigated using approximate treatments. Serious concerns, however, have been raised about the validity of these approximate treatments [7-9]. Additionally, particle acceleration phenomena are governed by the Lawson-Woodward theorem [10-12], which forbids laser-driven linear-field acceleration in free space due to the fact that net energy gain in free space is possible only via higher-order interactions in perturbation theory, and first-order electron-photon interactions are forbidden in free space [13].

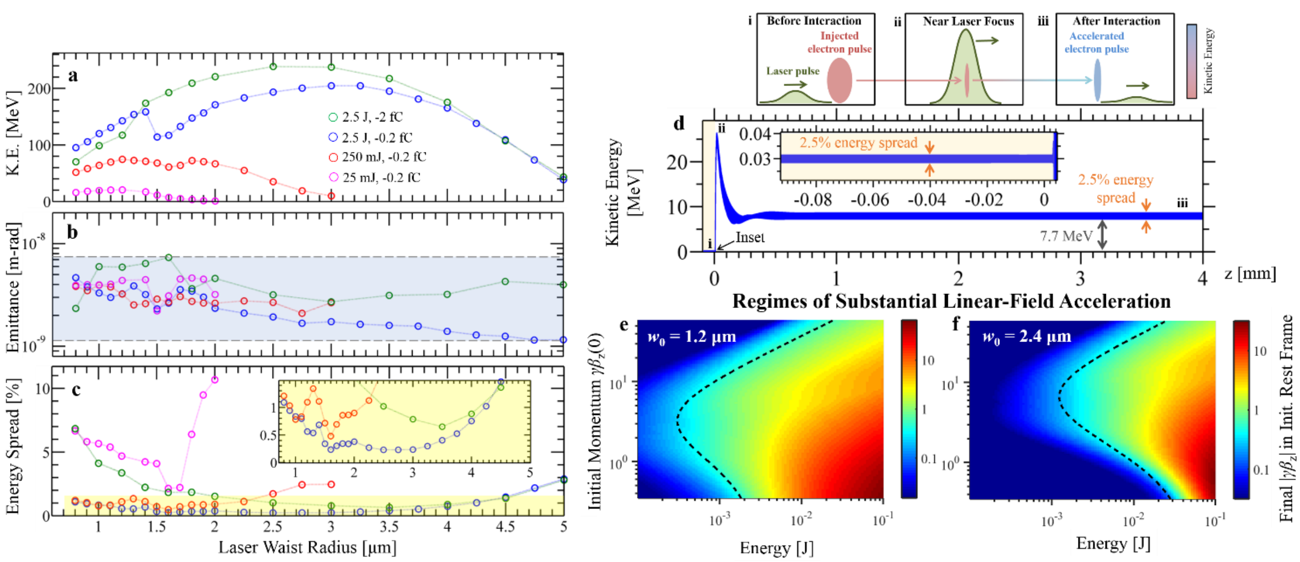

Figure 1. Properties of laser-driven linear-field acceleration in free space. The final mean kinetic energy (K.E.) (a), normalized trace-space emittance (b), and energy spread (c) are shown as a function of waist radius for different laser pulse energy and electron pulse charge values. The initial electron bunch is of K.E. 30 keV with a 2.5 % energy spread. The shaded region between the dashed lines in (b) is to highlight the fact that for a wide range of parameters, the final emittance falls in the nm-rad range. (Dotted lines are included only as a visual guide). (d) shows the electron dynamics of linear-field acceleration where a 0.2 fC (1250 particles), 30 keV electron bunch is accelerated to 7.7 MeV using a 25 mJ, 3 fs radially-polarized laser pulse of waist radius 1.6 μm, with panels i, ii and iii illustrating different portions of the process schematically. (e) and (f) show the regimes of substantial linear-field acceleration for the case of a 10 mJ, 6 fs radially-polarized laser pulse of waist radius 1.2 μm (e) and 2.4 μm (f). Note that $\gamma\beta_z$ refers to the normalized longitudinal momentum of an on-axis electron. Dashed lines in (e) and (f) are results of the analytical formula for the acceleration threshold derived in Ref. [6] (also elucidated in the Supplementary Information of Ref. [14]), showing excellent agreement with our *ab initio* numerical simulations. In all cases here, the central wavelength of the laser pulse is 0.8 μm.

Here, we present *ab-initio*, exact. many-body simulations showing that the Lawson-Woodward theorem can be bypassed to accelerate a multi-electron bunch monoenergetic ally in free space, by relying largely on the longitudinal field of an ultrafast laser pulse. It is noteworthy that multi-electron nature of the problem necessitates a treatment in which inter-electron interactions are taken into account, and our model provides this exactly. In spite of the interaction occurring in free space, where first-order interactions are forbidden, we find that net energy gain purely via the $q\mathbf{E}$ term of the Lorentz force equation is possible, and the energy gain can scale linearly in the laser field amplitude. As examples, 30 keV electrons (2.5% energy spread) are accelerated to 205 MeV (0.25% spread) and 7.7 MeV (2.5% spread) and using 2.5 J and 25 mJ radially-polarized laser pulses respectively (Fig. 1) [14]. More specifically, significant net linear-field acceleration is possible if the laser pulse is powerful enough to significantly perturb the particle and take it to the relativistic regime, in the initial particle's rest frame [6].

The possibility of linear-field particle acceleration has a significance beyond the possible ability of such a scheme to miniaturize practical particle acceleration, as it illuminates an important point on light-matter interactions. A major reason why the concept of linear-field particle acceleration is counterintuitive is due to the fundamental reason that energy-momentum conservation considerations forbid first-order electron-photon interactions. As a result, any acceleration scheme in free-space must include second-order or higher interaction terms of perturbation theory. At the same time, a higher-order interaction is expected to lead to an energy gain proportional to a higher power of field amplitude [13]. The confirmation our results give on the possibility of linear-field particle acceleration implies the existence of higher-order interactions that lead to an energy gain which scales linearly with field amplitude. This reveals an intriguing aspect of high-order processes in electrodynamical interactions and shows us the ability of intense, few-cycle laser fields to excite non-perturbative physics governed by very different scaling laws from the perturbative scenario.

Our results strongly suggest that is possible to accelerate other types of charged particles in this way. Examples include protons and ions, for applications lithography by ion beam milling and hadron therapy in cancer treatment. In general, the charged particles enter from the output of a previous external stage, and do not have to be introduced by methods like ionization [15] that require the presence of material structures or media near the laser focus. The weaker inter-particle interactions that charged particles of greater mass experience is also beneficial in terms of the higher currents they allow, and could enhance the performance of the acceleration scheme. Note that the linear-field acceleration gradient is given by electric field amplitude E, whereas the ponderomotive acceleration gradient is given by $qE^2/(2\omega\gamma m\mathrm{c})$, where q and m are respectively the particle's charge and rest mass, ω is the central angular frequency of the laser, γ is the relativistic Lorentz factor, and c is the speed of light in free space. As a result, we expect charged particles with larger mass to experience a stronger accelerating force in a linear-field acceleration scheme.

Why have experiments on laser-driven acceleration never led to direct observations of linear-field acceleration, although this is possible over a wide range of parameters? The reason can be traced to an important requirement in this scheme that our results highlight, which is the use of few-cycle pulses that are also of significant intensities (it is noteworthy that this requirement falls within the reach of current experimental capabilities, e.g., [16]). Our findings thus strongly motivate the development of few-cycle -- even sub-cycle – high intensity laser pulses, as well as better phase and polarization control of such pulses. Additionally, advances in spatiotemporal beam shaping continue to give us new ways of achieving high-intensity hotspots, abruptly-focusing characteristics and subluminal beam propagation behavior [17,18] that could be the key to achieving even higher energy gains via linear-field acceleration in free space. Our findings suggest many exciting opportunities in developing compact ultra-relativistic electron sources that sidestep conventional limits imposed by structural constraints or material breakdown.

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