Spatiotemporal Control of Laser Intensity for High Performance Plasma-based Accelerators

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Introduction: The substantial bandwidth of modern laser pulses combined with the creative use of optical elements presents a new paradigm for optimizing advanced accelerators—spatiotemporal pulse shaping. Spatiotemporal pulse shaping provides the flexibility to structure a laser 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 of the pulse in a plasma [1-3]. These controllable velocity intensity peaks have been demonstrated in proof-of-principle simulations to expand the design space of laser wakefield accelerators [1-3] and to enable a novel mechanism for vacuum laser acceleration [4] and in experiments to facilitate the formation of long plasma channels [5]—a critical component of both beam- and laser-driven wakefield accelerators. With respect to laser wakefield acceleration (LWFA), a spatiotemporally shaped pulse can decouple the phase velocity of a plasma wave from the plasma density and eliminate dephasing, i.e. electrons outrunning the accelerating phase of wakefield [1-3]. Furthermore, the stretched focal region obviates the need for external guiding structures or self-guiding. For plasma channel formation, a spatiotemporally shaped pulse can exhibit an intensity peak that counter-propagates with respect to the pulse, which mitigates ionization refraction and allows for the creation of long contiguous plasmas [5].

Dephasingless Laser Wakfield Acceleration: Laser wakefield accelerators feature electric fields nearly 1000 times those of conventional radiofrequency accelerators. The promise of a smaller-scale, cheaper electron accelerator for high energy physics experiments and advanced light sources has motivated rapid theoretical and experimental breakthroughs, highlighted by the recent observation of a 7.8 GeV energy gain in only 20 cm [6]. In spite of this impressive progress, traditional LWFA faces a key design limitation of electrons outrunning the accelerating phase of the wakefield or dephasing.

In traditional LWFA, high-energy electrons, travelling at near the vacuum speed of light, escape the accelerating phase of a 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. 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, which could be optimized by matching the dephasing length to the depletion length of the laser pulse. 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.

A novel electron acceleration concept based on the recently demonstrated achromatic "flying focus" technology offers a new paradigm for LWFA. A combined axiparabola-echelon optic can spatiotemporally structure a laser pulse with an ultrashort (transform limited) intensity peak that travels through meters of plasma at the speed of light in vacuum while maintaining a small focal spot and high-intensity. The axiparabola creates an extended focal region [7], eliminating the need for guiding, while the echelon adjusts the temporal delay to control the velocity of the intensity peak. In this dephasingless laser wakefield accelerator, the plasma density, and therefore the accelerating gradient, is decoupled from the speed of the intensity peak. By leveraging the horizon laser systems in development throughout the world, DLWFA can enable two critical experimental platforms: The kBELLA laser at Lawrence Berkeley National Laboratory, a kHz repetition rate system that delivers 30 fs, 3J laser pulses, could drive DLWFA in the linear regime, delivering ~2 GeV electron beams and the associated radiation sources every millisecond. Scaling laws for DLWFA in the nonlinear regime suggest that a 15 fs, 500 J laser, such as EP-OPAL planned at the University of Rochester Laboratory for Laser Energetics, could accelerate electrons to a 100 GeV in a single half-meter stage—a 20 times shorter distance than a traditional LWFA. Unlike traditional LWFA, where higher electron energy gains require longer laser pulses to match the plasma wavelength and increased laser energy to maintain high intensities, DLWFA is ideally suited for these high energy ultrashort pulses. These single-stage plasma accelerators could provide the compact particle and radiation sources needed (1) to probe high energy-density matter with unprecedented detail and repetition rate and (2) to access new frontiers of nonperturbative, collective strong field QED.

Formation of Long Plasma Channels: Meter-scale plasma channels are an essential component of both laser and beam driven wakefield accelerators. In the case of LWFA, maximizing the electron energy gain requires operating at lower plasma densities to mitigate dephasing, which increases the accelerator length. Beam-driven or plasma wakefield accelerators, on the other hand, are designed to maximize the transformer ratio by matching the length of the drive beam to the plasma period. Typically, this matching requires low plasma densities, which, in turn, requires a long plasma for efficient energy extraction. While several methods exist for creating long plasmas such as focusing with a large f-number lens, exotic optics such as axicons and axilenses, nonlinear self-focusing, and capillary discharges, each has a significant drawback that limits its effectiveness and tunability [8-11].

The recently realized chromatic "flying focus" avoids the compromises and challenges inherent to these approaches. In the chromatic flying focus, a chirped laser pulse focused by a hyperchromatic optic produces an intensity peak that can propagate at any velocity over distances much longer than the Rayleigh range [12]. When incident on a plasma, these pulses can create ionization waves at any velocity and plasma channels unconstrained by diffraction or ionization refraction. The length of the plasma channel is highly adjustable and is set by a combination of the laser bandwidth and the chromaticity of the focusing optic. The focal spot has a nearly diffraction-limited size, can be set independently of the plasma length, and like that of an axicon, is self-similar over the length of the focal region. Unlike axicons, however, the high-intensity region can be made to travel at any speed, including superluminal velocities or backwards with respect to the group velocity, thereby avoiding ionization refraction. Further, the uniformity of the peak intensity (and therefore plasma density profile) can be tailored by modifying the power spectrum of the pulse.

Summary: The bandwidth of modern, high-intensity lasers combined with the innovative use of optical elements offers unprecedented spatiotemporal control of laser intensity. Such detailed control of the spatiotemporal structure provides opportunities to tailor laser pulses for accelerator applications. Here we have presented three examples of how this control can enhance the performance of laser and plasma accelerators, enabling higher beam energies. Developing capabilities to control the space-time correlations of laser pulses will not only enable these examples, but will be critical for optimizing all laser-driven accelerator concepts.

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