Nonlinear Spatiotemporal Control of Laser Intensity

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Spatiotemporal control over the intensity of a laser pulse has the potential to enable or revolutionize a wide range of laser-based applications that currently suffer from the poor flexibility offered by conventional optics. Specifically, these optics limit the region of high intensity to the Rayleigh range and provide little to no control over the trajectory of the peak intensity. In this summary, we introduce a nonlinear technique for spatiotemporal control—the "self-flying focus"—that produces an arbitrary trajectory intensity peak that can be sustained for distances comparable to the focal length.[1] The technique combines temporal pulse shaping and the inherent nonlinearity of a medium to customize the time and location at which each temporal slice within the pulse comes to its focus. As an example of its utility, simulations show that the self-flying focus can form a highly uniform, meter-scale plasma suitable for advanced plasma-based accelerators.

A wide range of laser-based applications share two requirements: (1) that the driving laser pulse maintain a high intensity over an extended distance, and (2) that the velocity of the peak intensity conform to some underlying process. Examples from across the fields of optics and plasma physics (such as THz and high-harmonic generation, photon acceleration, laser-wakefield and vacuum electron acceleration, Raman amplification, and plasma channel or filament formation) illustrate the ubiquity of these requirements. By providing unprecedented control over the trajectory of an intensity peak and the distance over which it can be sustained, spatiotemporal pulse shaping promises to expand the design space for these applications.[2,3]

Existing methods utilize linear optical elements in the near field to structure a pulse with advantageous space–time correlations, but nonlinear processes, such as self-focusing, can also give rise to these correlations. Self-focusing occurs when the nonlinear optical response of a medium, quantified by the nonlinear refractive index reduces the phase velocity in regions of high intensity. The ratio of the instantaneous pulse power P to the critical power P_c parameterizes the effect. For temporal slices within a pulse with $P > P_c$, self-focusing overcomes diffraction. These slices undergo transverse collapse until their intensity reaches a threshold for activating a mechanism that can arrest the collapse. Because the distance over which a slice collapses depends on its value of P/P_c, the temporal profile of the power correlates time within the pulse to a collapse location [Fig. 1(a)].

The self-flying focus technique combines temporal pulse shaping with the inherent nonlinearity of a medium to control the velocity of an intensity peak over distances comparable to the focal length. Specifically, the instantaneous power determines the collapse location for each temporal slice, with the minimum and maximum powers setting the collapse range, while the pulse shape determines the time at which the intensity peak moves through these locations. A self-focusing arrest mechanism with an intensity threshold, such as ionization refraction, ensures that the maximum intensity of the peak remains nearly constant throughout the collapse range.

Figure 1 illustrates that the trajectory of self-focusing collapse can be controlled with temporal pulse shaping. A Gaussian pulse with $P > P_c$ focused into a nonlinear medium by an ideal lens exhibits a U-shaped collapse trajectory over the collapse range (L_c) [Fig. 1(a)]. The lower-power temporal slices collapse closer to the linear focal point (f), while the higher-power slices collapse closer to the lens ($z = 0$). By shaping the pulse, the collapse point can move at a constant velocity through the collapse region [Fig. 1(b)]. In this example, the power decreases with time, ensuring that the higher-power temporal slices collapse earlier and closer to the lens, while the lower-power slices collapse later and farther from the lens. In both cases, the collapse velocity is decoupled from the group velocity of the pulse. Notably, because each temporal slice collapses to a different location, the duration of the resulting intensity peak can be substantially less than the overall pulse duration.

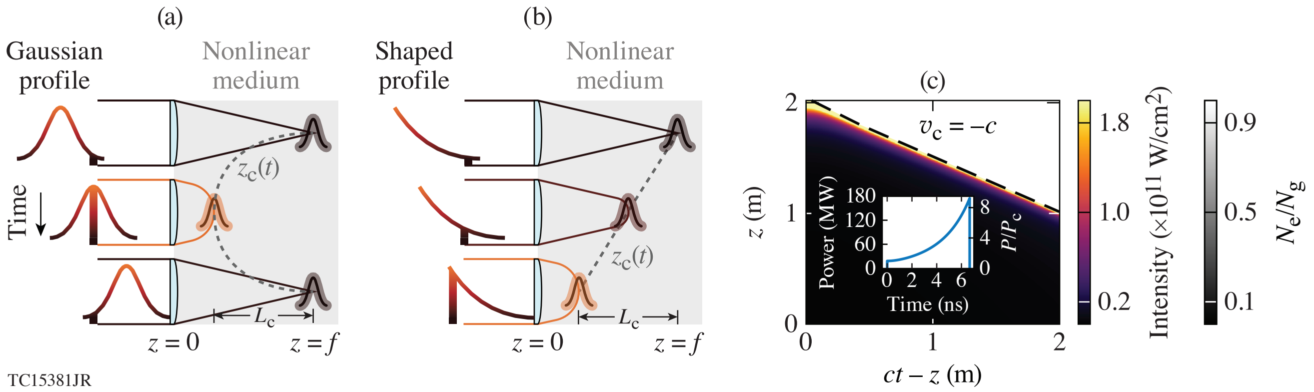

Figure 1
(a) Focusing a laser pulse with a Gaussian temporal profile with $P > P_c$ into a nonlinear medium creates a collapse point that traces out a U-shaped trajectory $z_c(t)$ over a distance L_c at a velocity v_c that is decoupled from the group velocity. (b) Focusing a temporally shaped pulse with $P > P_c$ can create a collapse point and intensity peak that follows any arbitrary trajectory—in this case, a constant, positive velocity—over a distance L_c. (c) On-axis intensity and electron density profiles from simulations of an $L_c = 1$ m self-flying focus pulse with $v_c = -c$ propagating through a lithium gas of density $N = 10^{19}/\text{cm}^3$ are shown. The incident power profile is plotted in the inset, with 20-ps exponential rise and fall times added to better represent a realistic shaped pulse. The intensity peak resulting from the collapse moves exactly at the desired trajectory and creates a smooth ionization front along that trajectory.

The ability to control the intensity trajectory over long distances makes the self-flying focus ideal for creating long plasma channels—a critical component in a number of applications, such as advanced laser-based accelerators and directed energy. Current techniques for creating long plasmas rely on filamentation through a dynamic balancing of self-focusing and plasma refraction, axicon focusing, variable wave front distortion, or the use of short wavelengths. Axicon focusing, for example, can suffer from significant pump depletion and ionization refraction by the end of the medium due to the forward propagation of the intensity peak. The self-flying focus has elements in common with filamentation but offers velocity control and does not necessarily require a short-pulse laser. Further, the ability to counter-propagate the intensity peak with respect to the pulse avoids ionization refraction, allowing for a wider range of focal geometries.

Here the self-flying focus is applied to the formation of a plasma channel necessary for the recently described "dephasingless" laser-wakefield accelerator.[3] Figure 1(c) displays simulation results of a self-flying focus pulse with $v_c = -c$ propagating through lithium gas and triggering a sharp ionization front that travels at the same velocity (i.e., $v_f = -c$) over a meter. The negative collapse velocity allows the intensity peak to propagate through the background gas rather than the ionized plasma, thereby mitigating ionization refraction. The specific velocity of $-c$ was chosen such that an injected, relativistic electron bunch would be velocity matched to the plasma creation and therefore experience constant plasma conditions throughout its acceleration.

The self-flying focus can accommodate a wide range of parameters facilitating their use on various laser systems and in diverse applications. Notably, the self-flying focus could take advantage of long-pulse, high-energy laser systems, such as the National Ignition Facility or the OMEGA laser, to create intensity peaks with durations comparable to short-pulse lasers. Further, the self-flying focus could improve the formation of long, uniform plasma channels in other media for filamentation and directed energy-based applications.

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