Photon Acceleration in a Flying Focus

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Theory and simulations demonstrate that the ionization front produced by a flying focus can upshift the frequency of an ultrashort optical pulse to the extreme ultraviolet (XUV) over a centimeter of propagation. An analytic model of the upshift predicts that this scheme could be scaled to a novel tabletop source of spatially coherent x rays.

A growing number of scientific fields rely critically on high-intensity, high-repetition-rate sources of XUV radiation (wavelengths <120 nm). These sources provide high-resolution imaging for high-energy-density physics and nanotechnology; fine-scale material ablation for nanomachining, spectrometry, and photolithography; and ultrafast pump/probe techniques for fundamental studies in atomic and molecular physics. While XUV sources have historically been challenging to produce, methods including nonlinear frequency mixing, high harmonic generation, and XUV lasing or line emission in metal-vapor and noble-gas plasmas have demonstrated promising results. Despite their successes, each of these methods introduces tradeoffs in terms of tunability, spatial coherence, divergence, or efficiency. Photon acceleration offers an alternative method for tunable XUV production that could lessen or even eliminate these tradeoffs.

Photon acceleration refers to the frequency upshift of light in response to a refractive index that decreases in time.[1] In analogy to charged-particle acceleration, the increase in photon energy, i.e., frequency, accompanies an increase in group velocity. In the context of an electromagnetic pulse, the leading phase fronts experience a higher index than adjacent, trailing phase fronts, which manifests as a local phase velocity that increases over the duration of the pulse. The trailing phase front, because of its higher phase velocity, gradually catches up with the leading front, compressing the wave period. In a medium with normal dispersion, the resulting frequency upshift translates to an increase in the local group velocity.

Plasmas, in particular, provide an ideal medium for photon acceleration: the refractive index depends on the density of free electrons, which can be rapidly increased or decreased over time through ionization and recombination or manipulated through electrostatic wave excitation. Specifically, a photon of frequency ω in an isotropic plasma experiences a refractive index $n\left(\omega = 1 - \omega_{\mathrm{p}}^2/\omega^2\right)^{1/2}$, where $\omega_{\mathrm{p}} = \left(e^2 n_{\mathrm{e}}/m\varepsilon_0\right)^{1/2}$ is the plasma frequency, n_{e} the free electron density, e the electron charge, m the electron mass, and ε_0 the permittivity of free space. An increase in the electron density over time—for example, by ionization—provides a decreasing refractive index that will accelerate the photons of a co-located pulse.

A prototypical scheme for photon acceleration involves propagating a witness pulse in an ionization front triggered by a co-propagating drive pulse. In spite of the impressive frequency shifts (>10×) predicted by theory and simulations,[1] experiments in the optical regime have met with limited success (~1.25×) (Ref. 2) as a result of witness pulse refraction and drive pulse diffraction. While these effects can be remedied by preforming a plasma or pre-shaping a gas to provide a guiding structure, two inherent limitations to the upshift remain. First, the drive pulse, and therefore the ionization front, travels at a subluminal group velocity. As the witness pulse accelerates, it quickly outpaces the ionization front, terminating the interaction. Second, the drive pulse refracts from the plasma it creates, limiting the formation of a continuous ionization front.

Here, we demonstrate, for the first time, a scheme for photon acceleration within a co-propagating ionization front that shifts an optical pulse to the XUV. The scheme utilizes a novel photonic technique known as the flying focus to overcome the afore-mentioned limitations.[3] An appropriately chirped drive pulse, focused through a chromatic lens, exhibits an intensity peak that counter-propagates at the speed of light in vacuum c with respect to its group velocity.[4] The peak intensity, in turn, triggers an ionization front traveling at c, which can continually accelerate the photons of a co-propagating witness pulse. A schematic is displayed in Fig. 1 for the case of a diffractive optic. The peak intensity of the drive pulse travels through the focal region $z_f = (\Delta\lambda/\lambda_c)f$ at the focal velocity $v_f = (1 + v_d T/z_f)^{-1} v_d$, where λ_c is the central wavelength of the drive pulse, $\Delta\lambda/\lambda_c$ is its fractional bandwidth, f is the focal length of the diffractive optic at λ_c, v_d is the group velocity, and T is the stretched pulse duration.
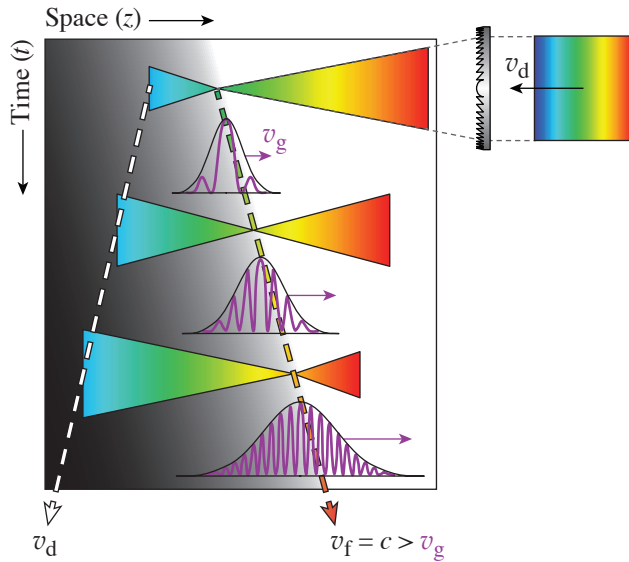

Figure 1

(a) A schematic demonstrating photon acceleration in the ionization front of a flying focus. A negatively chirped drive pulse propagating at its group velocity $v_d < 0$ forms a focus that counter-propagates at the velocity $v_f = c$, triggering an ionization front traveling at c. The resulting electron density is indicated by the gray shaded area. A witness pulse (purple curves) co-propagates with the ionization front at velocity and continually upshifts in frequency.

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By decoupling the ionization-front velocity from the group velocity of the drive pulse, this scheme removes both of the inherent limitations of the prototypical photon accelerator. Most notably, the interaction distance is no longer limited by outpacing since the accelerated photons can never outpace a luminal (traveling at c) ionization front. Second, counter-propagating the drive pulse with respect to the ionization front mitigates ionization refraction since the focus of the drive pulse encounters only the un-ionized medium.

Figure 2 demonstrates that photon acceleration in the ionization front formed by the flying focus can upshift the frequency of an 87-fs witness pulse from the optical ($\lambda = 400$ nm) to the XUV ($\lambda = 91$ nm). The figure shows four snapshots from a photon kinetics simulation in the moving frame $\xi = ct - z$, where t is the time elapsed after injecting the witness pulse. The photons of the witness pulse enter the ionization front in Fig. 2(a), each with an initial vacuum wavelength of 400 nm. The photons continually upshift in frequency as they co-propagate with a temporal gradient in electron density as seen in Figs. 2(b) and 2(c). After ~1 cm, the photons—now upshifted to a minimum vacuum wavelength of 91 nm—approach the end of the focal region and encounter a decelerating ionization front, terminating their upshift.

Assuming an electron density profile with a constant gradient moving at c, the vacuum wavelength evolves according to $\lambda(z) = \left(1 + \omega_{p0}^2 z \big/ \omega_0^2 L_T\right)^{-1/2} \lambda_0$, where λ_0 is the initial wavelength of a photon in the witness pulse, $\omega_0 = 2\pi c/\lambda_0$, and ω_{p0} is the value of the plasma frequency at $\xi = L_T$. This analytic model is in good agreement with the simulation and reveals several paths to shorter wavelengths. The interaction length can be extended by increasing the bandwidth of the drive pulse or the focal length; the peak electron density can be increased by propagating within higher-density media, such as solid density targets (~10^{22} cm^{-3}); and the scale length can be decreased by increasing the intensity of the drive pulse or decreasing the effective duration of the
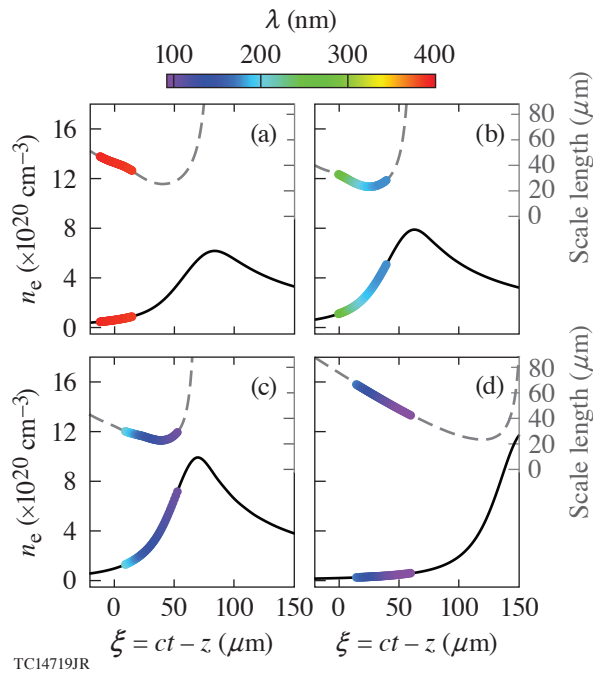
λ (nm)

Figure 2
[(a)–(d)] A series of snapshots of an 87-fs witness pulse with an initial wavelength $\lambda = 400$ nm co-propagating with a temporal gradient in the electron density. The snapshots are taken at propagation distances of (a) 0.10, (b) 0.30, (c) 0.85, and (d) 1.05 cm and plotted in the moving frame ξ. The pulse is modeled by photons initially spaced evenly in time over 87 fs. Each photon is represented by a circle colored to correspond to its vacuum wavelength (color bar). The electron density and scale length $L = n_e / \partial_\xi n_e$ are shown as solid black and dashed gray lines, respectively.

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flying focus intensity peak such that ionization occurs more rapidly. As a result, this scheme represents a promising method for the production of spatially coherent x rays at the tabletop scale.

1. S. C. Wilks *et al.*, Phys. Rev. Lett. **62**, 2600 (1989).

2. J. M. Dias *et al.*, Phys. Rev. Lett. **78**, 4773 (1997).

3. D. H. Froula *et al.*, Nat. Photonics **12**, 262 (2018).

4. J. P. Palastro *et al.*, Phys. Rev. A **97**, 033835 (2018).