Nonlinear Thomson Scattering of Spatiotemporally Shaped Laser Pulses

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Bright sources of high-energy photons lead to advancements in a range of disciplines including ultrafast biology and material science, nonlinear quantum electrodynamics, nuclear spectroscopy, and radiotherapy. The brightest sources currently reside at large accelerator facilities in the form of x-ray free-electron lasers or synchrotrons. While laser-driven sources promise a smaller-scale, widely accessible alternative, challenges in achieving the required photon number, energy, and coherence have held these sources back. Of the potential candidate laser-driven schemes, nonlinear Thomson scattering (NLTS) can produce extremely high energy, collimated radiation in a relatively controlled setting. NLTS, however, has inherent constraints that currently impede its realization as a practical light source.

In NLTS a relativistic electron collides with a laser pulse traveling in the opposite direction [Fig. 1(a)]. The electron rapidly oscillates in the fields of the pulse, reflecting and reradiating the incident photons. The properties of the radiation depend on the laser intensities and frequency of the pulse and the initial electron energy. Maximizing the radiated power requires large laser intensities. In these strong fields, the ponderomotive force of the pulse appreciably decelerates the electron and increases the amplitude of its oscillations along the direction of its initial motion. This red shifts the emitted frequencies and widens the emission angle.[1] The trade-off between the power, spectrum, and emission angle constrains the utility of NLTS.

Spatiotemporal pulse shaping provides control over the ponderomotive force, which can compensate for the ponderomotive deceleration in NLTS. As an example, the chromatic aberration from a diffractive optic and a chirp can be used to control the location and time at which each temporal slice within a pulse comes to its focus, respectively. By adjusting the chirp the resulting intensity peak, and therefore the ponderomotive force, can travel at any velocity with respect to the phase fronts (forward or backward) over distances much longer than a Rayleigh range.[2] Aside from extending the interaction length, a ponderomotive force that counter-propagates with respect to the phase fronts can *accelerate* an electron in NLTS.[3]

Here we describe novel regimes of nonlinear Thomson scattering that exploit the ponderomotive control afforded by spatiotemporal pulse shaping to substantially enhance the scaling of power, emission angle, and frequency with laser intensity. For high-intensity pulses, these regimes exhibit orders-of-magnitude-higher radiated powers and smaller emission angles than conventional NLTS. Further, the improved scaling with laser intensity allows for lower electron energies, relaxing the requirements on the electron accelerator.

Figure 1 contrasts backscattering configurations for conventional NLTS and NLTS with ponderomotive control (NPC). Conventional NLTS employs a standard laser pulse with an intensity peak and phase that counter-propagate at the vacuum speed of light with respect to a relativistic electron. NPC employs a spatiotemporally shaped pulse with an intensity peak that counter-propagates with respect to its phase fronts and co-propagates with respect to the electron. In both cases, as the electron enters the leading edge of the intensity peak, it begins oscillating in the polarization (transverse) and propagation (longitudinal) directions.

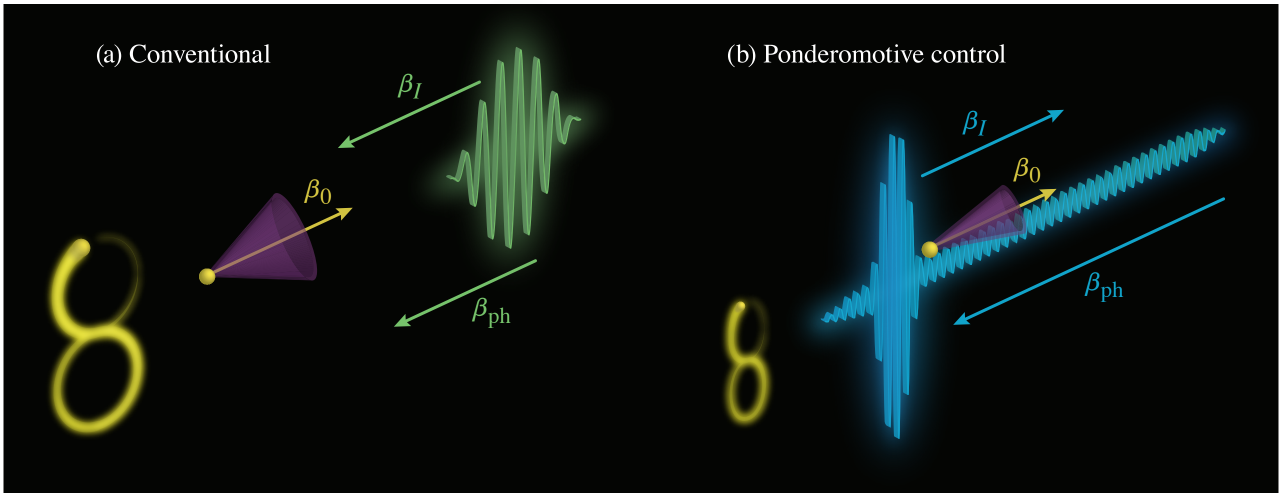

Figure 1
(a) A conventional NLTS configuration in which the intensity peak and phase fronts of a laser pulse travel in the opposite direction of the electron. At the rising edge of the intensity peak, the ponderomotive force decelerates the electron, red shifting the emitted frequencies and widening their emission angle (purple cone). (b) NLTS with ponderomotive control aligns the velocities of the intensity peak and the electron. Here the ponderomotive force of the intensity peak increases or maintains the electron velocity, allowing for higher-frequency emission into a smaller angle. The electron trajectory in its average rest frame (figure-eight motion) is depicted to the left of each case.

In NPC as the co-propagating intensity peak begins to overtake the initially slower moving electron, the electron is ponderomotively *accelerated* by the co-traveling intensity peak of the pulse—in the direction opposite to the phase velocity. The electron momentum increases as the electron enters regions of higher intensity. The acceleration enhances the overall radiation properties: emitted frequencies are now blue shifted and the radiation cone narrows. Ultimately, NPC switches the burden of accelerating electrons from an external source to the laser pulse itself—a situation ideal for existing and emerging high-energy, high-power laser facilities. Nonlinear Thomson scattering with ponderomotive control can produce extremely high energy photons with a spectrum that can be tuned through the initial electron energy, the laser amplitude, and, now, the ponderomotive velocity. The added flexibility enabled by ponderomotive control eliminates the tradeoffs inherent to conventional NLTS.

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1. E. Esarey, S. K. Ride, and P. Sprangle, Phys. Rev. E **48**, 3003 (1993).
2. D. H. Froula *et al.*, Nat. Photonics **12**, 262 (2018).
3. D. Ramsey *et al.*, Phys. Rev. E **102**, 043207 (2020).