Plasma wakefield acceleration of light

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Abstract

Bright, coherent extreme ultraviolet (XUV) light has many important applications across the sciences. Frequency upshifting of an optical laser pulse in the co-moving refractive index gradient of a relativistic phase-velocity plasma wave is one method for producing short wavelengths at high intensity. Beam-driven plasma wakefields can generate arbitrarily high frequency-upshifts of `relativistically intense' light pulses and preserve their spatio-polarization structure. We present some recent theoretical advancements in understanding photon kinetics in plasma wakes. Ab-initio quasi-3D, boosted-frame electromagnetic particle-in-cell simulations show the formation of attosecond duration XUV light with 30-nm wavelengths, nearly flat phase fronts and high pulse-energy. The use of such XUV laser light in laser-beam collisions at 50 GeV energies would enable studies of the most extreme regimes of strong field QED at the onset of the fully non-perturbative regime. Beam-driven wakefield acceleration of light may provide new applications for intermediate level (~100 GeV) plasma accelerators.

Plasma wakefield acceleration of light

The many applications of bright, coherent XUV light have motivated substantial interest in source development, such as the construction of XUV wavelength Free Electron Lasers such as FLASH [1] as well as nonlinear frequency mixing [2], high harmonic generation [3], relativistic flying mirrors [4–6], and XUV lasing [7], to name a few. Another method for generating short wavelengths has been named ‘photon acceleration’ [8, 9], referring to frequency upshifting in the space-time varying refractive index of a plasma wave. As shown in Fig. 1, a sizable gap exists between the intensities available at optical frequencies and those available in the XUV. Bridging this intensity gap would improve the availability of XUV sources.

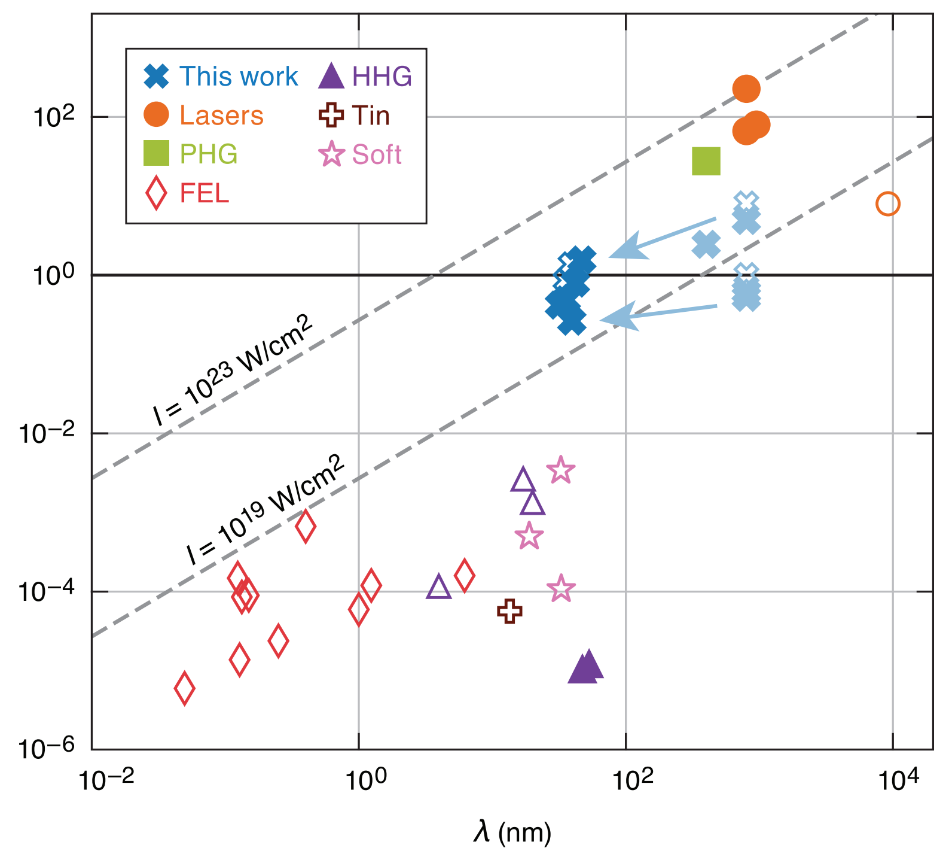

Fig. 1. Amplitude of available sources from the XUV to the long-wave IR [20].

From the linear, unmagnetized plasma dispersion relation $\omega^2 = k^2c^2 + \omega_p^2$ where $\omega_p^2 = e^2 n_0 / m_e \varepsilon_0$ for a plasma of number density n_0, if we identify a localized electromagnetic energy wavepacket with central frequency ω as a ‘quasi-photon’, and consider its quasi-photon wave packet central energy and momentum $E = \hbar\omega$ and $\mathbf{p} = \hbar\mathbf{k}$, when propagating in the background plasma it will gain an effective “mass” $\hbar\omega_p^2/c$. In the presence of co-propagating density gradients, the ‘quasi-photons’ experience local frequency shifts due to spatiotemporal variations in the phase velocity [10], and are therefore accelerated. The resulting quasi-photon phase space trajectories in plasma wakefields are similar to those of leptons [11]. This mechanism can arise as a result of plasma wakefields [8], ionization fronts [12, 13] and even using metamaterials [14]. ‘Photon acceleration’ was measured in ionization front [15] and LWFA experiments [16, 17, 18].

Frequency shifting to XUV

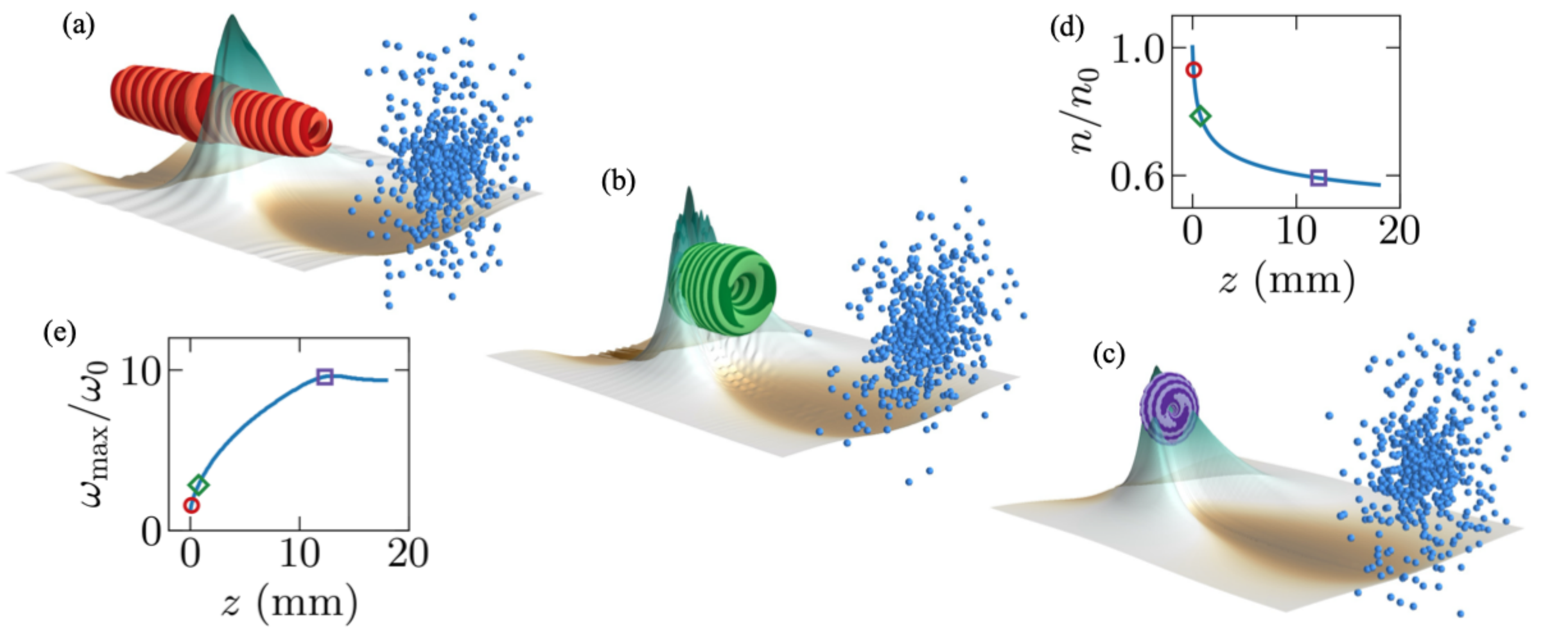

Fig. 2. Frequency upshifting of Vector Vortex up to XUV in plasma waves [20]

We have recently shown [19] that by using a beam driver and a density down ramp to achieve phase matching, extremely large (in principle, unlimited) frequency shifts can be obtained. In quasi-3D ab-initio simulations (Fig. 2.), we have shown that 30x frequency shifts with amplification of the light, maintaining initial amplitude a_0 to within a factor of 2, is achievable in a cm scale single stage with a 50 GeV beam driver [20]. Since the plasma wakefield frequency shifting process is linear, unlike many other frequency conversion processes, it preserves the structure of the light. In particular, we showed by direct simulation that vector vortex light can be frequency upshifted while preserving the vector structure.

Reaching high χ with XUV light

The interaction of charged particles and photons with extremely strong electromagnetic fields is believed to be at the heart of many extreme environments both in the universe and in terrestrial laboratories. However, the conditions necessary to observe such phenomena are prohibitively hard to access with optical lasers, which are one of the most widely used tools for the study of these interactions. A typical experimental configuration involves the collision of an ultra-relativistic (multi-GeV class) electron beam and a high-intensity (PW-class) laser pulse. The strength of such interaction is characterized by a parameter χ_e.

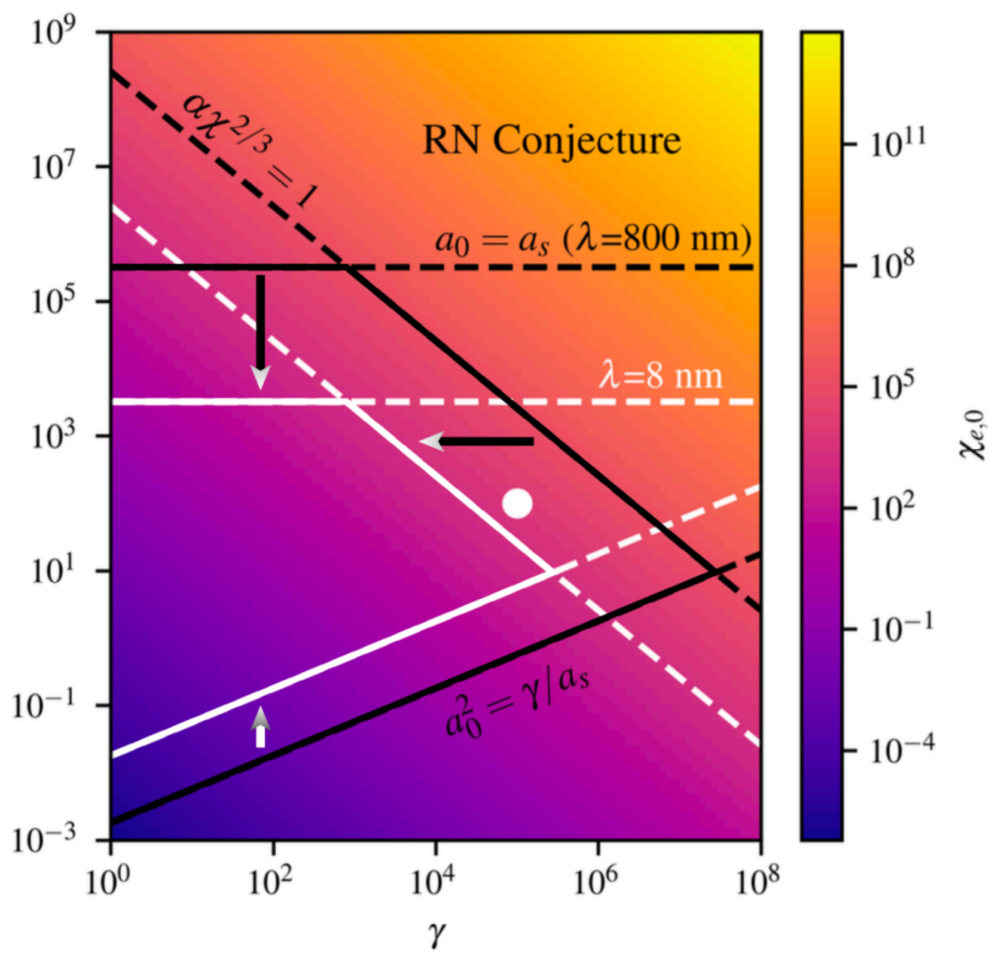

Fig. 3. Regimes of perturbative SFQED breakdown for different wavelengths.

To reach extreme regimes of particle interactions with electromagnetic fields this parameter needs to be boosted by many orders of magnitude. We have shown that this can be achieved by colliding a multi-GeV electron beam with the XUV light obtained via ‘photon acceleration’ of an optical laser pulse. This is not only because of the increased field strength due to pulse spatio-temporal compression but also quantum effects including enhanced "straggling". The photon spectra obtained from such an extreme interaction may be used to track the predicted breakdown of strong field quantum electrodynamics theory as it enters the fully non-perturbative regime.

Photon kinetics from first principles

We may derive photon kinetic transport equations from first principles. By doing so, we reveal high order corrections that may be used to correct transport. Starting from Wigner operator on the photon field [21]:

$$\hat{\rho}(x,k) = \int \frac{d^4y}{(2\pi)^4} e^{-ik\cdot y} A(x + \tfrac{1}{2}y) A(x - \tfrac{1}{2}y)$$

Introducing operators [22] $\kappa_{\pm} = k \mp \frac{1}{2} i\partial$ we obtain a transport equation:

$$k \cdot \partial_x \rho - \rho \cdot \sin(\overleftarrow{\partial}_x \cdot \overrightarrow{\partial}_k + \overleftarrow{\partial}_k \cdot \overrightarrow{\partial}_x)\sigma = 0$$

And a constraint equation:

$$\left(k^2 - \tfrac{1}{4}\partial_x^2\right)\rho - \rho \cdot \cos(\overleftarrow{\partial}_x \cdot \overrightarrow{\partial}_k + \overleftarrow{\partial}_k \cdot \overrightarrow{\partial}_x)\sigma = 0$$

Where it has been assumed that the four current may be replaced by a linear scalar operator σ on the four potential, i.e. a linear conductivity. (This could be replaced by a tensor response at the expense of compactness of expression). Assuming that the distribution can be written as $\rho(k,x) = g(\mathbf{k},x)\delta^4(D)$, i.e. subject to the constraint $D\rho = 0$, integration over all frequencies k^0 with $k^0 = \omega$ being the solution to $D = 0$ yields the usual first order transport equation for photons, that may be shown to be equivalent to Fresnel diffraction,

$$\partial_t g + \frac{\nabla_{\mathbf{k}} D}{\partial_\omega D} \cdot \nabla g - \frac{1}{2\omega} \nabla\sigma \cdot \frac{\partial g}{\partial \mathbf{k}} = 0$$

NLO corrections can correct for instabilities in the first order transport owing to errors introduced by tight focusing in space and time.

Conclusions

Frequency upshifting in plasma waves — ‘photon acceleration’ — may provide a way of generating extremely intense light at wavelengths in the XUV and beyond. Phase matched beam driven acceleration is one solution, and may be a good application for stepping-stone 100 GeV class wakefield accelerators. Photon acceleration can be applied to structured light: vector vortex pulses with tunable frequency. We may be able to probe the limits of SF-QED (RN) in 50 GeV beam/XUV laser collisions, i.e. near term experimental tests of theory relevant to 10 TeV pCM interaction point. Photon kinetics may be derived from first principles, which yields useful corrections to the transport equations to account for tight focusing.

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