Narrowband inverse Compton scattering x-ray sources at high laser intensities

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Bright narrowband x- and gamma-ray sources based on the inverse Compton scattering of laser light on high-energy electron beams rely on the Doppler upshift of the laser frequency $\omega' = 4\gamma^2\omega_0$.However, these sources suffer from a limitation of the maximum laser intensity because the longitudinal ponderomotive force in a high-intensity laser pulse will effectively slow-down the electrons, reducing their γ-factor. This gradual slow-down of the electrons as the intensity ramps up leads to a reduced Doppler upshift causing spectral broadening of the generated x- or gamma-rays. Recent results [1, 2, 3] suggest that this ponderomotive broadening could be compensated by suitably chirped laser pulses. This compensation would allow to reduce the bandwidth of the generated x- and gamma-rays and to operate narrowband Compton sources in the high-intensity regime. Here we report on our recent findings on the determination of the optimal frequency modulation and its properties.

Let us assume a high-energy electron with asymptotic four-momentum p (and $\gamma \gg 1$) collides head-on with an intense short laser pulse propagating along the direction $n = (1, 0, 0, -1)$, described by the normalized vector potential $a^\mu = a_0\varepsilon^\mu g(x^+)\cos\Phi(x^+)$. The laser is assumed to be chirped with a local frequency $\omega(x^+) = \partial\Phi/\partial x^+$, with the light-front time $x^+ = t + z$, and where g denotes the laser's envelope function that changes slowly on the time-scale $1/\omega$. When the electron enters the laser pulse, its momentum has to be supplemented by the pondermotive four-potential

$$p^\mu \to p^\mu + U^\mu\,, \quad U^\mu = \frac{m a_0^2 g^2(x^+)}{4\gamma} n^\mu\,, \tag{1}$$

that describes the longitudinal slow-down.

From the analysis of the scattering amplitude of nonlinear Compton scattering within the framework of strong-field QED in the Furry picture [3] we find the *local* frequency of the ℓ-th harmonic of the scattered x-rays as

$$\omega'_\ell = \frac{4\gamma^2\ell\omega(x^+)}{1+\gamma^2\vartheta^2+\frac{a_0^2 g^2(x^+)}{2}+\chi(x^+)}\,, \tag{2}$$

where $\chi = 2\ell\omega\gamma/m$ denotes the electron recoil, and ϑ is the scattering angle. From Eq. (2) we can determine the optimal laser chirp via the condition $\mathrm{d}\omega'_\ell/\mathrm{d}x^+ = 0$. In other words: The optimal chirping prescription

$$\frac{\omega(x^+)}{\omega_0} = 1 + \frac{1}{1+\gamma^2\vartheta^2}\frac{a_0^2}{2}g^2(x^+) \tag{3}$$

describes how the laser frequency needs to increase during the time of high laser intensity in order to exactly balance the ponderomotive red-shift due to the slow-down of the electrons. Eq. (3) shows that the ponderomotive broadening can be compensated only for just one particular scattering angle ϑ. Moreover, the form of the optimal frequency modulation, Eq. (3), does not depend on the electron recoil during the scattering (no dependence on χ) and it removes the ponderomotive broadening from all higher harmonics in addition to the fundamental line (no dependence on ℓ). A numerical simulation of the compensated nonlinear Compton spectrum taking into account realistic laser focus geometries and electron bunches shows a reduction of the bandwidth from 80% to less than 5%, see Fig. 1.

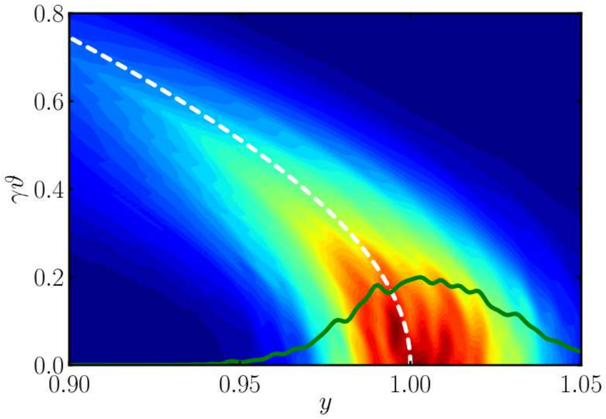

Figure 1: Simulated energy and angular radiation spectrum of a realistic electron beam interacting with a focused laser pulse with peak intensity $a_0 = 2.83$. The solid green line depicts the on-axis line-out of the radiation spectrum ($y = \omega'/4\gamma^2\omega_0$). For simulation parameters cf. Ref. [3].

To summarize, our analysis shows that the compensation of ponderomotive broadening by chirped laser pulses is a promising route towards operating narrowband Compton scattering x- and gamma-ray sources at high laser intensity.

References

[1] I. Ghebregziabher, B. A. Shadwick, and D. Umstadter, Phys. Rev. ST Accel. Beams **16**, 030705 (2013),

[2] B. Terzić, K. Deitrick, A. S. Hofler, and G. A. Krafft, Phys. Rev. Lett. **112**, 074801 (2014).

[3] D. Seipt, S. G. Rykovanov, A. Surzhykov and S. Fritzsche, arXiv:1412.2659.

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