X-ray photon scattering at a focused high-intensity laser pulse

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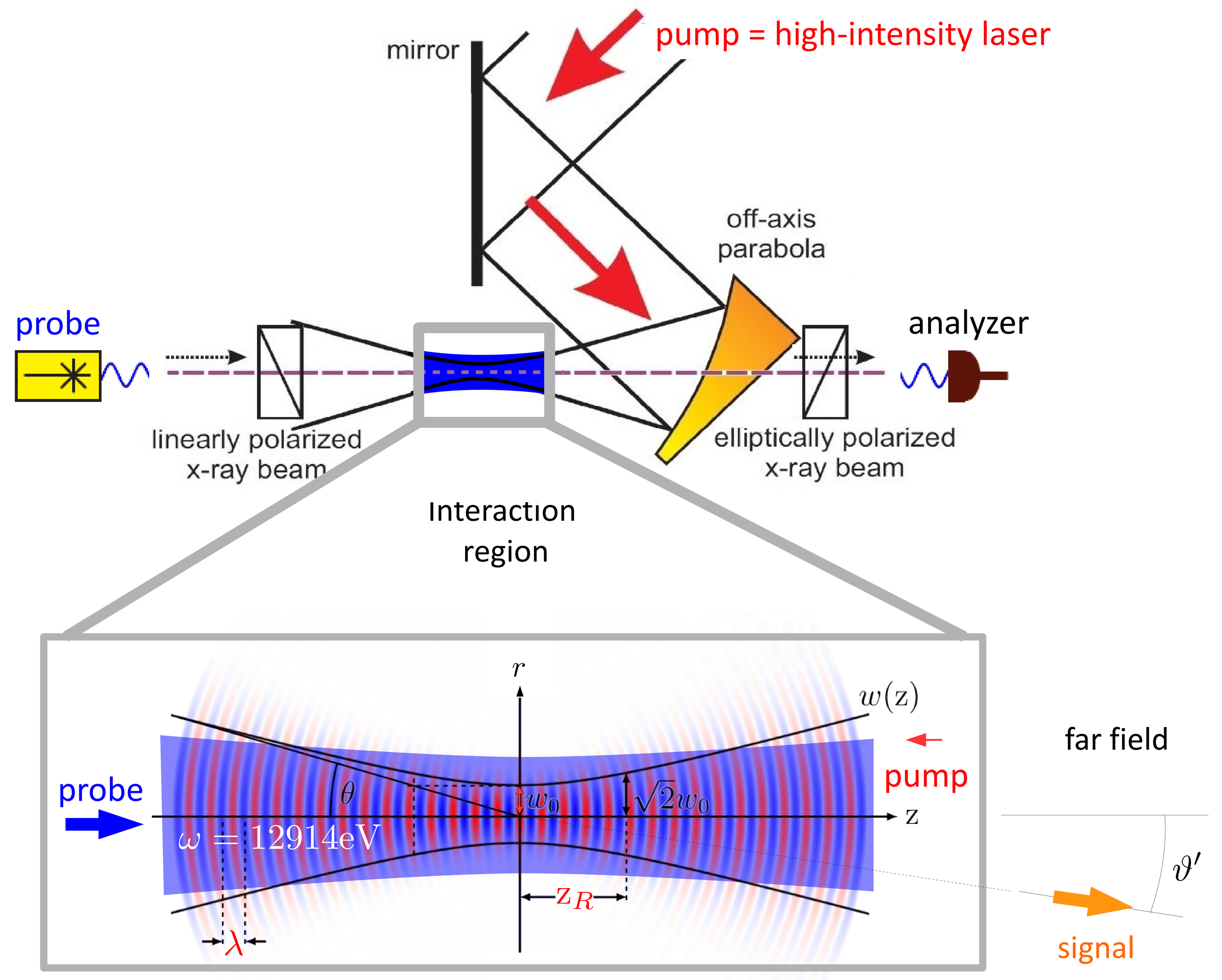
Abstract

We study x-ray photon scattering in the head-on collision of an XFEL pulse and a focused high-intensity laser pulse, described as paraxial Laguerre-Gaussian beam of arbitrary mode composition. For adequately chosen relative orientations of the polarization vectors of the colliding laser fields, this gives rise to a vacuum birefringence effect manifesting itself in polarization flipped signal photons. The XFEL is assumed to be mildly focused to a waist larger than that of the high-intensity laser beam. This scenario is generically accompanied by a scattering phenomenon of x-ray energy signal photons outside the forward cone of the XFEL beam, potentially assisting the detection of the effect in experiment. Here, we demonstrate the fate of the x-ray scattering signal under exemplary deformations of the transverse focus profile of the high-intensity pump.

Studied experimental scenario

Polarization flip and photon scattering in an XFEL/high-intensity laser scenario:

[Heinzl, Liesfeld, Amthor, Schwoerer, Sauerbrey, Wipf: Opt. Comm. **267** 318 (2006)]
[Schlenvoigt, Heinzl, Schramm, Cowan, Sauerbrey: Phys. Scr. **91** 023010 (2016)]



We assume the XFEL to deliver pulses of duration $T{=}10\,\mathrm{fs} \simeq 15.20\,\mathrm{eV}^{-1}$, comprising $N_{\rm in} = 10^{12}$ photons at an energy of $\omega = 12914\,\mathrm{eV}$. The polarization purity of x-ray photons of this energy can be measured to the level of $P{=}5.7{\times}10^{-10}$. The counter-propagating high-intensity laser field is assumed to be provided by a petawatt class intensity system, delivering pulses of energy $W{=}30\,\mathrm{J}{\simeq}\, 1.87\times10^{20}\,\mathrm{eV}$, duration $\tau = 30\,\mathrm{fs} \simeq 45.60\,\mathrm{eV}^{-1}$ and wavelength $\lambda = 800\,\mathrm{nm} \simeq 4.06\,\mathrm{eV}^{-1}$. As a realistic estimate for the beam waist of the fundamental mode we choose $w_0 = 1000\,\mathrm{nm} \simeq 5.07\,\mathrm{eV}^{-1}$. The corresponding Rayleigh range is $z_R \simeq 19.89\,\mathrm{eV}^{-1}$. The radius of the probe is assumed to be given by $w_{\rm probe} = 3w_0$.

[Marx et al., Opt. Comm.**284**, 915 (2011)]
[Marx et al., Phys. Rev. Lett.**110**, 254801 (2013)]

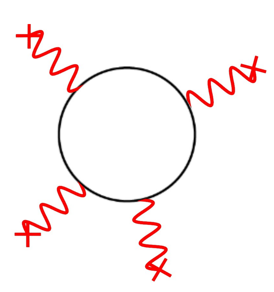
Theoretical setting

We use in our calculation:

[Euler and Kockel, Naturwiss. **23**, 246 (1935)]
[Heisenberg and Euler, Z. Phys. **98**, 714 (1936)]

→ Weak field limit of the 1-loop Heisenberg-Euler effective Lagrangian:

$$\mathcal{L}^{\text{1-loop}}_{\rm HE} \simeq \frac{m_e^4}{(8\pi)^2}\frac{1}{90}\left(\frac{e}{m_e^2}\right)^4\Big[4(F_{\mu\nu}F^{\mu\nu})^2+7(F_{\mu\nu}{}^\star F^{\mu\nu})^2\Big]$$



→ Generic paraxial solutions of the wave equation in vacuum describing focused beams with rotational symmetry around the beam axis. These can be represented by the superposition of Laguerre-Gaussian modes $\mathrm{LG}_{l,p}$:

[Siegman, Lasers, (1986)]
[Saleh, Teich, Fundamentals of Photonics, (1991)]

$$E(x) = \sum_{l,p} E_{l,p}(x)$$

$$\vec{E}(x)\perp\vec{B}(x),\ \vec{E}(x)\perp\vec{k},\ \vec{B}(x)\perp\vec{k}$$
$$|\vec{E}(x)| = |\vec{B}(x)| = E(x)$$

Results

We consider two different quantities:

- the number of signal photons $N^{\rm tot}$ attainable in polarization insensitive measurement, and
- the number of polarization-flipped signal photons $N^{\perp}$.

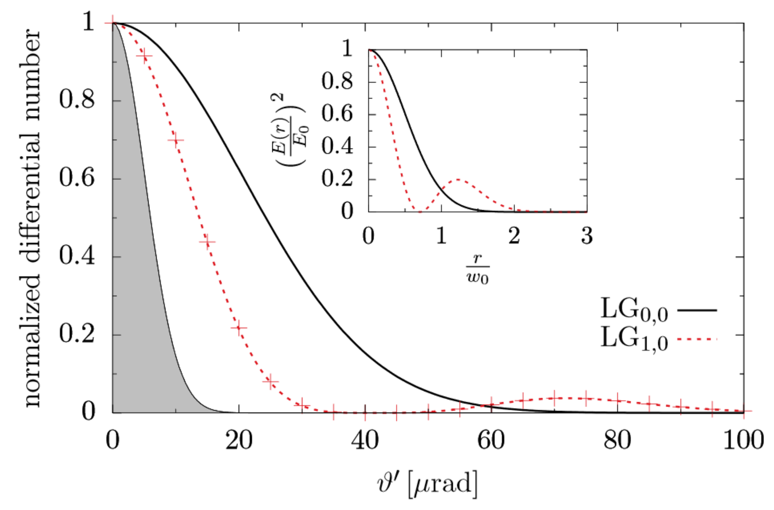
The latter are discernible from the background of the probe photons $N_{\rm in}$, traversing the interaction region unaltered if they fulfill

$$\frac{N^{\perp}}{N_{\rm in}} > \mathcal{P}.$$

A. Pure Laguerre-Gaussian modes

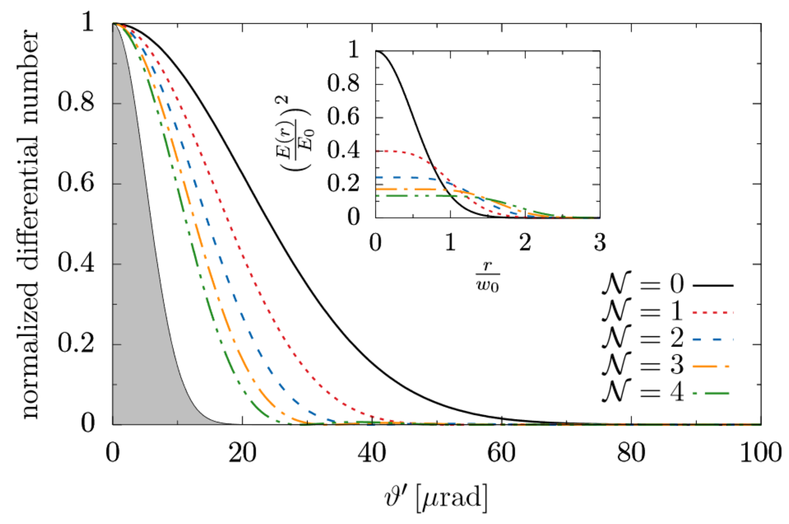
The total numbers of signal photons are $N^{\rm tot} \simeq 23.77$ $(N^{\rm tot} \simeq 11.57)$ per shot for the case of the $\mathrm{LG}_{0,0}$ $(\mathrm{LG}_{1,0})$ pump. The number of signal photons contained within a ring around the beam axis delimited by $\vartheta'_{\rm min} = 50\,\mu\mathrm{rad}$ and $\vartheta'_{\rm max} = 100\,\mu\mathrm{rad}$ is $N^{\rm tot}_{\circ} \simeq 1.31$ $(N^{\rm tot}_{\circ} \simeq 4.50)$, which is to be compared with the negligible number of probe photons $N_{\rm in,\circ} \simeq 1.14\times10^{-9}$ contained in the same angular interval.

For a $\mathrm{LG}_{0,0}$ $(\mathrm{LG}_{1,0})$ pump, the signal photons scatter outside $\vartheta' = 22.36\,\mu\mathrm{rad}(\vartheta' = 24.38\,\mu\mathrm{rad})$. The corresponding number of discernible signal photons per shot is $N^{\perp}_{\rm dis} \simeq 0.61$ $(N^{\perp}_{\rm dis} \simeq 0.34)$.



Far-field angular decay of the signal as a function of the polar angle ϑ' measured from the forward beam axis of the probe for different transverse pump profiles. Here, we consider the pump to be prepared in a pure LG mode; see the inset for the radial intensity profiles in the focus. For comparison, in gray we also highlight the angular decay of a fundamental Gaussian probe of waist $w_{\rm probe} = 3w_0$; w_0 is the waist of the fundamental pump mode $\mathrm{LG}_{0,0}$. The data points marked by crosses follow from a direct numerical evaluation for the $\mathrm{LG}_{1,0}$ scenario. They are in good agreement with the red dashed line obtained from analytical approximation.

B. Flattened Gaussian beams

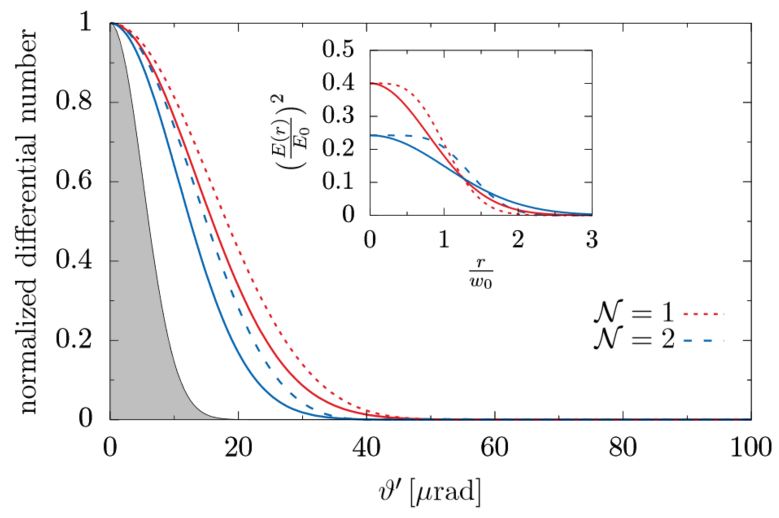


Far-field angular decay of the signal and probe (gray) for different transverse pump profiles. For the high-intensity pump we consider different order $\mathcal{N}$ flattened Gaussian beams of the same pulse energy; see the inset for the radial intensity profiles in the focus.

The corresponding numbers of signal photons are:

$\mathcal{N}$	0	1	2	3	4
$N^{\rm tot}$	23.77	12.68	8.51	6.37	5.09
$N^{\perp}_{\rm dis}$	0.61	0.17	0.05	0.01	0.005

Finally, we compare these findings with the results obtained for fundamental Gaussian pumps of similar waist:



Far-field angular decay of the signal and probe (gray) for different transverse pump profiles. Here, we compare the angular decay of the signal for flattened Gaussian pumps of order $\mathcal{N}\in\{1,2\}$ (dashed lines) with the analogous results for a fundamental Gaussian pump with rescaled waist $w_0 \to w_{\mathcal{N}}$ (solid lines); see the inset for the respective focus profiles.

The signal photon numbers associated with the rescaled Gaussian pump are $N^{\rm tot} \simeq 10.23$ $(N^{\rm tot} \simeq 6.26)$, $N^{\perp}_{\rm dis} \simeq 0.11$ $(N^{\perp}_{\rm dis} \simeq 0.02)$ for $\mathcal{N}=1 (\mathcal{N}=2)$.

Based on Phys. Rev. D **100**, 033002 (2019).