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A double FEL oscillator: A possible scheme for a photon–photon collider

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ABSTRACT

Exploration of the mutual scattering of photons in vacuum is considered as a fundamental test of the quantum electrodynamics theory. In this connection, we propose a "double" free-electron laser oscillator as a possible device for head-on photon–photon collisions. The device is conceived to comprise two undulator sections within the same cavity, where then two laser beams are produced by two counterpropagating electron beams. The latter are in turn exploited to produce gamma photons by backward Compton scattering of the intracavity FEL radiation itself. A preliminary analysis of the collision rate of the backscattered photons is presented specifically at the maximum of the relevant cross section.

1. Introduction

In contrast with the principle of superposition of the classical electromagnetic theory and the strict linearity of Maxwell's equations for a free electromagnetic field, quantum electrodynamics (QED) predicts the direct scattering of two photons mediated by the fluctuating electron–positron pairs of the quantum vacuum [1–8]. Accordingly, the exploration of the mutual scattering of photons in vacuum is considered as fundamental within the general context of the quantum vacuum investigations [9]. However, it may be experimentally practicable only in the high-intensity regime owing to the small cross section of the process.

The total cross section for unpolarized initial photons σ_{unp} in the center-of-mass frame, where photons of equal energy collide, has different trends in the low-energy and high-energy regions with the photon energy $E_{ph} = \hbar\omega_{ph}$ being measured in units of the electron rest energy $E_0 = m_e c^2 = 0.511$ MeV [5–8]. In the low-energy region, roughly identified by the limit $\mathcal{E}_{ph} \equiv E_{ph}/E_0 \simeq 0.5, \sigma_{unp}$ increases with the photon energy/frequency through a sixth-power dependence according to $\sigma_{unp}^{(\text{low-energy})} \simeq 0.13\mathcal{E}_{ph}^6\ \mu b$, whilst in the high-energy region, for which $\mathcal{E}_{ph} > 10, \sigma_{unp}$ decreases as $\sigma_{unp}^{(\text{high-energy})} \simeq 20\mathcal{E}_{ph}^{-2}\ \mu b$. Finally, σ_{unp} reaches its maximum value $\sigma_{unp}^{(\max)} \simeq 1.6 \cdot 10^{-30}$ cm^2 at $\mathcal{E}_{ph}^{(\max)} \simeq 1.5$.

As a consequence of the small value of the scattering cross section, the photon–photon collider strategy grounds on the use of high-power lasers (see [10,11] for a review), among which the free-electron lasers (FELs) offer outstanding, if not unique, potential advantages [12]. In fact, as stated in [13,14], "modetarely upscaled versions of existing FELs would provide optimal conditions for the detection of scattering of light by light." In the quoted papers, a possible experimental detection scheme was suggested to exploit the UV photon-beam provided by an FEL-amplifier; such a beam should be split into two pulses, each of which through a Compton back-scattering by the FEL driving electron-beam would produce γ-photons for the desired head-on collision.

As an alternative to the configuration, proposed in [13,14], we will propose here a possible FEL oscillator-based scheme for a photon–photon collider and investigate its feasibility at a primary level. The proposed scheme resorts to a compact structure, which, comprising two undulator sections within a single resonator, would allow for the production of two counterpropagating γ-photon beams by backward Compton scattering of the intracavity FEL photons by the electron beams, which so will drive both the FEL oscillation and the photon–photon scattering. The head-on γ–γ collisions would occur inside the resonator as well. Notably, instead of taking advantage of the high peak power radiation, potentially deliverable by an FEL device (possibly through a multi-stage configuration as well), which is in contrast central to other FEL-based photon collider schemes [15], the device we propose resorts to the availability of electron-beam delivery systems, that could both operate at high-repetition rate and deliver "long" e-bunches, to produce photons in such a way that detection of their collision be experimentally accessible.

Thus, in Section 2 we will briefly describe the double-undulator FEL oscillator, essentially highlighting the basic parameters that characterize the inherent performance. In Section 3 we will investigate the detectability of the photon–photon scattering, providing an estimate of the relevant collision rate for suitable ranges and/or

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specific values of the pertinent FEL parameters. Indeed, detection of the photon–photon scattering will be shown feasible even with a "comfortable" design of the proposed double FEL oscillator (and relevant electron-beam delivery system). Concluding remarks will be given in Section 4.

2. A double FEL oscillator as a photon–photon collider: scheme and basic parameters

The central part of the setup we propose for a photon–photon collider consists of a double-undulator based FEL oscillator, as schematized in Fig. 1.

It is composed of two identical linear-undulator sections closed within an optical cavity, and driven by two independent counter-propagating, but perfectly synchronized, electron beams. In each undulator section, an e-beam is injected with a twofold objective: (i) to produce FEL radiation in the cavity within a suitable frequency range, and (ii)) to scatter FEL photons (through Compton back-scattering) into higher-energy photons (possibly γ-photons) to facilitate the detection of photon–photon collisions, on account of the behavior of $\sigma(\mathcal{E}_{ph})$, as previously recalled.

Evidently, the device is structured to have two conversion regions, conveniently located at the exit (relatively to the travelling electrons) of the undulators. There, through backward Compton-scattering of FEL photons by the incoming electrons, higher-frequency photons are produced for the desired head-on collision, that should occur centrally in the cavity.

For a primary analysis of the collider performance, we ignore the detailed setup structure, reasoning as if we were considering a FEL oscillator composed of a single (linear) undulator, which as usual will be characterized by the relevant number of periods $N_{\rm U}$, the period length $\lambda_{\rm U}$, and the undulator strength parameter $K_{\rm U}$, explicitly given as [16]

$$K_{\rm U} = \frac{\lambda_{\rm U}[\rm cm] B_0[\rm kG]}{10.71},$$

B_0 being the on-axis undulator magnetic field. Then, as we know, the virtual undulator photons (with angular frequency $\omega_{\rm U} = \frac{2\pi c}{\lambda_{\rm U}}$) are back-scattered by the on-axis travelling electrons into the real FEL photons, whose central wavelength and angular frequency are

$$\lambda_{\rm FEL} = \frac{\lambda_{\rm U}}{2\gamma_e^2}\left(1 + \frac{K_{\rm U}^2}{2}\right), \qquad \omega_{\rm FEL} = \frac{2\gamma_e^2 \omega_{\rm U}}{(1 + K_{\rm U}^2/2)}, \tag{1}$$

where $\gamma_e = E_e/E_0$ is the electron relativistic factor, E_e being the electron energy.

Moreover, in accord with well-known scaling laws [17], the equilibrium intracavity FEL radiation intensity $I_{\rm FEL}$ can be given in the form

$$I_{\rm FEL}[W/{\rm cm}^2] = 2.41\left[\sqrt{\frac{1-\eta}{\eta}G_{\max}(g_0)} - 1\right] I_{\rm S}, \tag{2}$$

with η denoting the cavity losses, $G_{\max}(g_0)$ the FEL maximum gain in the small-signal small-gain regime (suitable to the oscillator operation), and $I_{\rm S}$ the FEL oscillator saturation intensity. The former depend on the specific cavity design, whereas, resorting to the aforementioned scaling laws [17], $G_{\max}(g_0)$ and $I_{\rm S}$ can be written as

$$G_{\max}(g_0) = 0.85 g_0 + 0.192 g_0^2 + 4.23\cdot 10^{-3} g_0^3 \qquad (g_0 \leqslant 10), \tag{3}$$

$$I_{\rm S}[{\rm W/cm^2}] = \frac{2.77\cdot 10^5}{R(g_0)}\left(\frac{\gamma_e}{N_{\rm U}}\right) J_e[A/{\rm cm}^2], \tag{4}$$

with

$$R(g_0) = g_0(1 + 0.19 g_0 - 8.7\cdot 10^{-3} g_0^2 + 2.7\cdot 10^{-4} g_0^3) \qquad (g_0 \leqslant 20).$$

Here, $J_e[{\rm A/cm^2}]$ is the electron-beam (peak) current density,

$$J_e[A/{\rm cm}^2] = \frac{I_e[A]}{2\pi\sigma_x[{\rm cm}]\sigma_y[{\rm cm}]} = \frac{I_e[A]}{2\Sigma_e[{\rm cm}^2]}, \tag{5}$$

which conforms to an inherent transverse dependence like

$$J(x, y) = J_e e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}},$$

σ_x, σ_y signifying the beam sizes, respectively in the horizontal and vertical directions, defined by the pertinent variances of the beam particle density, so that the electron beam current follows as $I_e[A] = \int J(x, y)dxdy$. Also, as signalized in (5), the cross sectional area of the electron beam is taken as $\Sigma_e[{\rm cm}^2] \equiv \pi\sigma_x\sigma_y$.

Finally, g_0 is the FEL small-signal gain coefficient [16,17],

$$g_0 = 3.7\cdot 10^{-4} J_e[{\rm A/cm^2}]\left(\frac{N_{\rm U}}{\gamma_e}\right)^3 [\lambda_{\rm U}[{\rm cm}] K_{\rm U} F_{\rm B}(\xi_{\rm U})]^2, \tag{6}$$

where $F_{\rm B}(\xi_{\rm U})$ is the Bessel function factor,

$$F_{\rm B}(\xi_{\rm U}) = J_0(\xi_{\rm U}) - J_1(\xi_{\rm U}), \qquad \xi_{\rm U} \equiv \frac{K_{\rm U}^2}{4(1 + 0.5K_{\rm U}^2)}$$

J_0, J_1 representing the Bessel functions of first order.

It is worth remarking that, in accord with the limitations specified in (3), the expression (2) for $I_{\rm FEL}$ holds for values of the gain

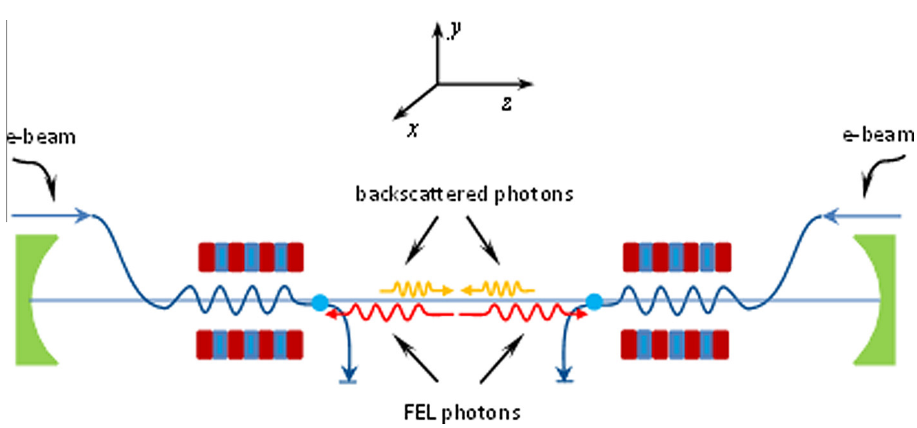

Fig. 1. "Double" FEL oscillator as a possible device for head-on photon–photon collisions. The device is structured to have two conversion regions, where, through Compton back-scattering of FEL photons by incoming electrons, higher-frequency photons are produced for the desired head-on collision, which should occur in the middle of the optical cavity.