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Production and properties of two-color radiation generated by using a Free-Electron Laser with two orthogonal undulators

N.S. Mirian [b,c,d], G. Dattoli [a], E. DiPalma [a], V. Petrillo [c,d,*]

[a] ENEA Centro Ricerche Frascati, via E. Fermi, 45, IT 00044 Frascati, Rome, Italy
[b] School of Particle and Accelerator Physics, Institute for Research in Fundamental Sciences (IPM), Post code 19395-5531, Tehran, Iran
[c] Università degli Studi di Milano, via Celoria 16, IT 20133 Milano, Italy
[d] INFN-Mi, via Celoria 16, IT 20133 Milano, Italy

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ABSTRACT

We present the analysis of the two-color Self Amplified Spontaneous Emission generated by a Free-Electron Laser amplifier constituted by two orthogonally polarized undulators with different periods and field intensities. Equations deduced in a non-averaged and in an averaged model have been integrated and compared. The two pulses have different frequencies, ruled by proper resonance conditions, and different polarizations, while the total length of the device does not change noticeably with respect to usual single color FELs. The wavelengths of two colors can be changed by choosing different periods, while variation in the magnetic strengths can be used to modify the gain lengths in view of various applications.

1. Introduction

Free Electron Lasers (FELs) sources [1–4] play a key role in several applications belonging to the most various scientific and technical fields. Among the different formats in which radiation can be proposed to users, one of the most required is where the pulse is composed of two distinct spectral lines with a variable time delay between them. Matter can be indeed probed on the atomic scale in space and time [5] by means of two color X-rays, extending in this way the knowledge about the fundamental properties of materials and living systems with respect to the Nobel Prize work on femtochemistry of Zewail [12]. Pairs of colored X-ray pulses are particularly suitable to perform pump and probe experiments of structural dynamics, which are designed to monitor the ultrafast evolution of atomic, electronic and magnetic structures [6–8]. In pump-probe experiments, the process under study – e.g. a chemical reaction, an excitation or a structural change on the surface of a solid – is activated by means of a first pulse with a fixed frequency and then, after a delay, a second one of another frequency, or a sequence of pulses, records the event. In this way, following its time evolution, information on pathways, barriers and transition states of the phenomenon can be accessed. As regards the time scales of the dynamics of these atomic events, they can range from 10 fs in ultrafast processes as the dissociative ionization [9], to hundred femtoseconds for less energetic chemical mechanisms [10,11]. In another important field, the future color X-ray technology, the color component contains extra information and allows us to distinguish the chemical composition of the absorbing tissues [13,14], permitting the development of the diagnostic clinical imaging.

Experiments on dual frequency production and use have been recently carried on with FELs [15–21] in many different ways. At the same time, several promising theoretical proposals aimed to generate two-color FEL emission in the X-ray wavelength regime [22–25] have been so far investigated.

The first schemes dated back to more than 20 years ago [26,27], in a period when the tunability at infrared and visible wavelengths was a unique feature of the FELs, since optical parametric amplifiers were not yet commercially available. The fact of reusing the same hardware for generating two frequencies constitutes the main advantages of a two-color FEL, with respect to two independent FEL beamlines, because minimizes the time jitter between the two pulses. Some of the initially proposed designs were based on staggered undulator magnets having different strength, to achieve lasing at two distinct wavelengths [28–31]. This idea has been recently reconsidered at LCLS and implemented in the X-ray range. The emittance-spoiler technique with a magnetic chicane in the undulator section was used to control the pulse duration and relative delay of a two-color intense X-ray pulse generated by using two separate canted pole undulators tuned at different resonances [15]. However, the undulator length is essentially doubled and saturation is reached at power levels comparable

* Corresponding author.
E-mail address: Petrillo@mi.infn.it (V. Petrillo).

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with the single color configuration by using a complex scheme. Another option, recently demonstrated at the FERMI soft X-ray FEL, involves the use of either a chirped or a two-color seed laser which initiates the FEL instability at two different wavelengths within the modulator gain bandwidth [18,17]. The different approach of injecting in the FEL undulator a multi-energy electron beam [32] resonating at two different wavelengths permits the control of the frequency and time separation ranges of the FEL radiation, while maintaining similar saturated power levels and minimal undulator length [16,19–21]. In this configuration, the SASE lasing occurs from separated and nearly independent electron distributions [33].

In the present paper, we analyze the operation with a further different scheme: the FEL emission is obtained by assembling in a unique structure two orthogonally polarized undulators with different periods and field intensities. In this case, the two radiations have not only different frequencies, but also different polarizations, while the total length of the device does not change substantially with respect to usual single color FELs [34]. Producing two waves with orthogonal polarizations with comparable intensities is very important because permits the selective excitation of the molecular fluorescence, opening various possibilities to control the internal organization and space orientation of molecules. In this way, the techniques based on fluorescence anisotropy [35] and dichroism [36] could be significantly improved. An undulator with crossed polarizations in a delta like magnetic structure has been already constructed and measured [37], and the extension to the configuration discussed in this paper is in progress. The wavelengths of two different colors can be changed by setting different periods, while variations in the magnetic strengths have the effect of modifying the gain lengths. In the first two sections, non-averaged FEL equations, similar to those described in [38] which are at the basis of the code MEDUSA, and averaged ones [39] have been extended in the case of presence of detuning and commented upon. Analytical and numerical data are presented in Section 4. Comments and conclusions close the paper.

2. Model equations in a non-averaged SVEA treatment

The FEL undulator shown in Fig. 1 is composed by two linear arrays of magnets orthogonally polarized and with periods given respectively by λ_{01} and λ_{02}. The undulator magnetic field, in the paraxial approximation, is described by the following expression:

$$\underline{B}_w = -B_{w2}\sin k_{02}z\underline{e}_x + B_{w1}\sin k_{01}z\underline{e}_y \quad (1)$$

where $k_{01,02} = 2\pi/\lambda_{01,02}$ and $K_{1,2} = |eB_{w1,2}\lambda_{1,2}/mc^2|$ are the deflecting parameters of the undulators.

2.1. Momentum equation

The complex radiation fields, in terms of the two orthogonal components, assume the form:

$$\underline{E} = [E_1 e^{i(k_1 z-\omega_1 t)}\underline{e}_x + E_2 e^{i(k_2 z-\omega_2 t)}\underline{e}_y]$$
$$\underline{B} = -B_2 e^{i(k_2 z-\omega_2 t)}\underline{e}_x + B_1 e^{i(k_1 z-\omega_1 t)}\underline{e}_y, \quad (2)$$

while the vector potential may be written as

$$\underline{A} = -i[A_1 e^{i(k_1 z-\omega_1 t)}\underline{e}_x + A_2 e^{i(k_2 z-\omega_2 t)}\underline{e}_y], \quad (3)$$

where $E_{1,2}$, $B_{1,2}$ and $A_{1,2}$ are slow complex amplitudes and the two radiation wavelengths are $\lambda_{1,2} = 2\pi/k_{1,2}$. The eventual presence of a frequency detuning $\delta_{1,2}$ for one of the two frequencies or both leads to the fact that the frequencies $\omega_{1,2}$ can be expressed as $\omega_{1,2} = \omega^R_{1,2} + \delta_{1,2}$, with $\omega^R_{1,2}$ the nominal resonance frequency.

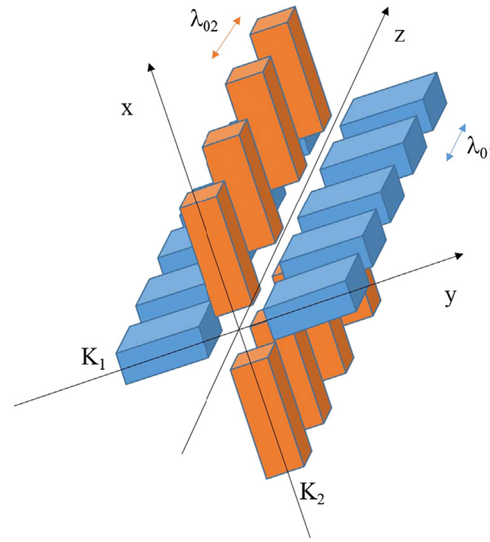

Fig. 1. Geometry of the undulator.

The momentum equations for each electron of the beam turn then out to be

$$\frac{dp_{xi}}{dt} = e\beta_{zi}B_{w1}\sin k_{01}z - ek_1(1-\beta_{zi})[A_1 e^{i\alpha_{1i}} + cc] \quad (4)$$

$$\frac{dp_{yi}}{dt} = e\beta_{zi}B_{w2}\sin k_{02}z - ek_2(1-\beta_z)[A_2 e^{i\alpha_{2i}} + cc] \quad (5)$$

$$\frac{dp_{zi}}{dt} = -e\beta_{yi}B_{w2}\sin k_{02}z - ek_2\beta_{yi}[A_2 e^{i\alpha_{2i}} + cc] - e\beta_{xi}B_{w1}\sin k_{01}z - ek_1\beta_{xi}[A_1 e^{i\alpha_{1i}} + cc] \quad (6)$$

where

$$\alpha_{1,2,i} = k_{1,2}z_i - \omega_{1,2}t. \quad (7)$$

and $\beta_{x,y,zj} = v_{x,y,zj}/c$ are the normalized velocity components, and cc represents the complex conjugate.

From Eq. (6) we obtain the following resonance conditions:

$$\lambda_{1,2} = \frac{\lambda_{01,02}}{2\gamma_0^2}(1 + K_1^2/2 + K_2^2/2) \quad (8)$$

with $\gamma_0 = \langle\gamma_i\rangle$, the average value of the Lorentz factor of the electrons.

2.2. Field equation

The wave equation can be written as

$$\frac{\partial^2}{\partial z^2}\underline{A} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\underline{A} = -\frac{4\pi}{c}\underline{J}_\perp. \quad (9)$$

By expressing the transverse currents in terms of the particle density $\overline{n}$:

$$J_{x,y} = -\sum ec\beta_{x,yj}\overline{n}\delta(z-z_j) = \sum ec\frac{K_{1,2}}{\gamma_j}\cos(\omega_{01,02}t)\overline{n}\delta(z-z_j) \quad (10)$$

and by using the Slowly Varying Envelope Approximation (SVEA), we obtain for the two polarizations the following independent differential equations:

$$\frac{\partial}{\partial z}A_1 + \frac{1}{c}\frac{\partial}{\partial t}A_1 - i\frac{\delta_1}{c}A_1 = \frac{2\pi e\overline{n}}{k_1}\sum\beta_{xj}\delta(z-z_j)e^{-i\alpha_{1j}}. \quad (11)$$

$$\frac{\partial}{\partial z}A_2 + \frac{1}{c}\frac{\partial}{\partial t}A_2 - i\frac{\delta_2}{c}A_2 = \frac{2\pi e\overline{n}}{k_2}\sum\beta_{yj}\delta(z-z_j)e^{-i\alpha_{2j}}. \quad (12)$$