Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Coherent radiation characteristics of modulated electron bunch formed in stack of two plates

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A R T I C L E I N F O

Article history:
Received 4 December 2016
Received in revised form 31 January 2017
Accepted 27 February 2017
Available online xxxx

Keywords:
Transition
Stack of plates
Spontaneous radiation
XFEL
Modulated electron bunch
Form-factor
Medium polarization
Resonant frequency
Coherent X-ray radiation

A B S T R A C T

The present article is devoted to the radiation from the electron bunch with modulated density passes through the stack consisting of two plates with different thicknesses and electrodynamic properties. The new elegant expression for the frequency-angular distribution of transition radiation is obtained. Using the existence of resonant frequency at which the longitudinal form-factor of bunch not suppresses radiation coherence and choosing parameters for the stack of plates, one can also avoid suppression of the radiation coherence by transverse form-factor of bunch. The radiation from a bunch with modulated density in the process SASE (self-amplified spontaneous emission) FEL can be partially coherent at a resonant frequency. Then the intense sub monochromatic beam of X-ray photons is formed. On the other hand one can define an important parameter of the bunch density modulation depth which is unknown to this day.

1. Introduction

The phenomenon of short wavelength coherent radiation of asymmetric bunch is discovered in the article [1]. The radiation intensity is proportional to the second power of bunch's particle number. This phenomenon is universal and does not depend on the kind of radiation. The effect of coherence of diffraction radiation was observed in the Japanese experiment [2]. By radiation spectrum one can determine the real distribution of electrons in the bunch. The use of truncated electron bunch will significantly increase the free electron laser (FEL) efficiency [3] and will fulfill the coherence of diffractive [4] and Smith-Parcell [5] radiations.

In the article [6] the research target is the radiation problem of the bunch which density is modulated by laser beat waves (LBW). It was shown that the longitudinal form-factor of the bunch modulated at the resonant frequency does not suppress the coherence effect. The suppression of coherence may occur due to the transverse form-factor.

The electron bunch, interacting with LBW in a spiral undulator, coherently radiates in the submillimeter range [7]. In the article [8] the use of partially coherent radiation at a resonant frequency for definition of the modulation depth of LCLS (linac coherent light source) bunch was offered. The results of article [9] show that one can use X-ray crystalline undulator radiation in order to study the microbunching process in XFEL and the production of monochromatic intense beam. The review [10] is dedicated to the coherent X-ray radiation of various types produced by the microbunched beam in amorphous and crystalline radiators is given.

This article is devoted to the coherent X-ray radiation from a bunch of microbunched electrons produced in the stack of two plates at a given parameters.

2. Coherent radiation of electron bunch

The formula for frequency-angular average distribution of the photons' number of any nature that are emitted from freeform electron bunch is the following [1]

$$N_{tot}(\omega,\theta) = \overline{N}_{ph}(\omega,\theta) = N_{sp}(\omega,\theta)(N_b^2 F + N_b(1-F)), \quad (1)$$

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http://dx.doi.org/10.1016/j.nimb.2017.02.079
0168-583X/© 2017 Published by Elsevier B.V.

where $N_{sp}(\omega,\theta)$ is the frequency-angular distribution of photons number of single electron radiation, N_b is the number of electrons in the bunch, and the bunch form-factor F is defined with longitudinal $F_Z(\omega,\theta)$ and transverse $F_R(\omega,\theta)$ form-factors by the formulas

$$\begin{aligned} &F = F_Z(\omega,\theta)\times F_R(\omega,\theta),\\ &F_Z(\omega,\theta) = |\int f(Z)e^{-i\frac{\omega}{c}cos\theta}dZ|^2,\\ &F_R(\omega,\theta) = |\int f(R)e^{-i\frac{\omega}{c}sin\theta}dR|^2, \end{aligned} \tag{2}$$

where ω and θ are the radiation frequency and angle accordingly.

Here the averaging is done by the functions $f(Z)$ and $f(R)$ of the electron bunch density distribution in longitudinal Z and transverse R directions. In the case, when $f(Z)$ and $f(R)$ are Gaussian distribution functions with dispersions σ_Z^2 and σ_R^2 accordingly, form-factors are represented as

$$F_Z(\omega,\theta) = e^{-\left(\frac{\omega\sigma_Z cos\theta}{c}\right)^2},\ F_R(\omega,\theta) = e^{-\left(\frac{\omega\sigma_R sin\theta}{c}\right)^2}. \tag{3}$$

Then for $\theta \ll 1$ we have

$$F_Z(\lambda) = e^{-\left(\frac{2\pi\sigma_Z}{\lambda}\right)^2},\ F_R(\lambda,\theta) = e^{-\left(\frac{2\pi\sigma_R\theta}{\lambda}\right)^2}, \tag{4}$$

where λ is the radiation wavelength.

3. Generated X-ray radiation in stack of two plates

The problem of radiation when an electron passing through the stack consisted of two different plates with the thicknesses a, b, and the plasma frequencies of media ω_1, ω_2 accordingly, is considered. It was defined the average plasma frequency of stack and the parameter, characterizing the difference between electrodynamic properties in media as follows

$$\omega_p^2 = \frac{\omega_1^2+\omega_2^2}{2},\ 0 < \Delta = \frac{\omega_1^2-\omega_2^2}{\omega_1^2+\omega_2^2} \ll 1. \tag{5}$$

$x = \omega/(\omega_p\gamma) = \lambda_p/(\lambda\gamma)$ and $u = \theta\gamma$ (γ is the Lorentz factor)

$$\begin{aligned} &\frac{d^2N_e^{sp}}{dxdu^2} = \frac{32\alpha\Delta^2 nP}{\pi}\frac{u^2x^2\sin^2\left(\frac{\pi}{2}Z(x,u)\right)}{\left((x^2(u^2+1)+1)^2-\Delta^2\right)^2}\delta(u^2-\varphi(x)),\\ &Z(x,u) = \frac{a}{\lambda_p\gamma}\frac{x^2(1+u^2)+1-\Delta}{x},\ \varphi(x) = \frac{2P}{x}-1-\frac{1}{x^2},\\ &P = \frac{\gamma}{\gamma_{th}},\ \gamma_{th} = \frac{l}{l_p},\ n = \frac{L}{l}, l = a+b \end{aligned} \tag{6}$$

where $\alpha = 1/137$ is the fine structure constant, n is the number of pairs of plates, L is the stack length, λ_p is the average plasma wavelength of stack, γ_{th} is the energy threshold for formation of transition radiation, and $\delta(u^2-\varphi(x))$ is the Dirac's delta function.

The frequency distribution of number of radiated photons, with accuracy to small order of Δ^2, can be represented:

$$\begin{aligned} &N_e^{sp}(x) \equiv \frac{dN_e^{sp}}{dx} = \frac{32\alpha\Delta^2 nP}{\pi}\frac{(x-x_1)(x_2-x)}{(2Px)^4}sin^2\left(\frac{\pi}{2}Z(x)\right),\\ &Z(x) = 1-\xi+\frac{\Delta}{2Px}, \xi = \frac{b-a}{l}. \end{aligned} \tag{7}$$

Permissible interval of radiation frequencies is received from condition $u^2 \geqslant 0$ or $\varphi(x) \geqslant 0$. Note that the distribution is significantly different from zero at $P \gg 1$. Therefore the frequency interval can be represented as following forms (second form is given up to a small order of P^{-2})

$$\begin{aligned} &P\left(1-\sqrt{1-\frac{1}{P^2}}\right) = x_1 \leqslant x \leqslant x_2 = P\left(1+\sqrt{1-\frac{1}{P^2}}\right),\\ &\frac{1}{2P} = x_1 \leqslant x \leqslant x_2 = 2P. \end{aligned} \tag{8}$$

The radiation is formed when $\gamma > \gamma_{th}$. Therefore the radiation in the stack is constructively for all values of x if $Z(x) \approx 1$. Then we have

$$N_e^{sp}(x) = \frac{32\alpha\Delta^2 nP}{\pi}\frac{(x-x_1)(x_2-x)}{(2Px)^4}. \tag{9}$$

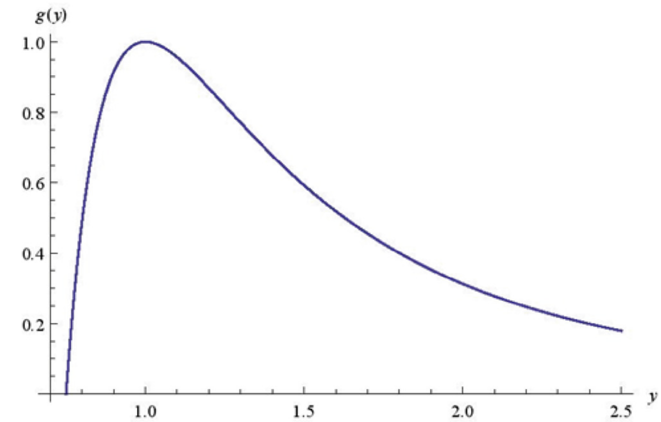

Fig. 1. The frequency distribution of radiation generated in the stack of two plates.

The maximum of distribution is at the frequency $x_m = 2/(3P)$. Herewith choice of values for the parameters a and b and follows from the condition $Z(x_m) = 1$ or $\xi = 3\Delta/4$, and therefore:

$$l = \frac{3}{2}\frac{\lambda_p^2}{\lambda_m},\ a = \frac{1}{2}\left(1-\frac{3}{4}\Delta\right),\ b = \frac{l}{2}\left(1+\frac{3}{4}\Delta\right). \tag{10}$$

If the parameters are chosen according to expression (10), then the radiation in stack will be constructively at the frequency $x_m = \lambda_p/(\lambda_m\gamma)$ and occurs at angle $\theta_m = 1/(\sqrt{3}x_m\gamma)$.

The frequency distribution is represented conveniently as a function from the variable $y = x/x_m$. On condition $\gamma \gg \gamma_{th}$ we have $x_1 \ll 1$ or $x_2 = 1/x_1 \gg 1$ and the frequency distribution has the following form

$$N_e^{sp}(y) = \frac{9\alpha\Delta^2 n}{4\pi}g(y), g(y) = \frac{1}{y^3}\left(4-\frac{3}{y}\right). \tag{11}$$

Consequently, $g(0.75) = 0, g(1) = 1$ and the distribution function $g(y)$ is presented in Fig. 1.

The total number of radiation photons is equal to

$$N_{tot}^{sp} = N_b N_e^{sp} = \frac{8\alpha}{3\pi}N_b\Delta^2 n. \tag{12}$$

4. Coherent radiation of bunch with modulated density at the resonant frequency

The case when the coherent part of radiation is dominated on spontaneous ($FN_b \gg 1$) is considered. The transverse form-factor (3) plays a minor role in the wavelength region $2\pi\sigma_R\theta \ll \lambda \ll 2\pi\sigma_Z$ and the coherence is suppressed due to the longitudinal form factor (3). In the region of shorter wavelengths the radiation coherence principle is violated due to transverse form-factor too. Depending on the new variables x and u, the longitudinal and transverse form-factors have the following form

$$\begin{aligned} &F_Z(x) = e^{-Ax^2}, F_R(x,u) = e^{-Bx^2u^2},\\ &A = \left(\frac{2\pi\sigma_Z\gamma}{\lambda_p}\right)^2,\ B = \left(\frac{2\pi\sigma_R}{\lambda_p}\right)^2. \end{aligned} \tag{13}$$

Now the factors A and B depend on the radiation wavelength λ_p but not on λ because $x = \lambda_p/(\lambda\gamma)$.

If we assume that the bunch density is modulated by law $2b_1cos(2\pi Z/\lambda_r)$, where $2b_1$ is the modulation depth and λ_r is the modulation period. In the mentioned article [6] it was shown that at condition $\lambda_r \ll \sigma_Z$ the bunch longitudinal form-factor is obtained by averaging the radiation field phase function depending on $x \mp x_r$. Leaving member containing $x - x_r$ is received the expression