THE ELECTRON BEAM DYNAMICS SIMULATION IN THE LASER-ELECTRON STORAGE RING INVOLVING COMPTON AND INTRABEAM SCATTERING

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The feasibility of the development of intense X-ray sources based on Compton scattering in laser-electron storage rings is discussed. The results of the electron beam dynamics simulation involving Compton and intrabeam scattering are presented.

PACS: 29.20.Dh, 29.27.Bd

1. INTRODUCTION

In recent years several schemes of using the laser electron interaction for establishing the compact X-ray sources have been proposed [1-6]. The background for producing hard photons by scattering laser photons on relativistic electrons seems quite clear and efficient. It appears that for producing the X-ray beams with high intensity the increasing of the initial laser beam intensity will be enough. Abilities of the modern laser equipments with the laser flash energies up to 10 J allow the laser-electron storage rings (LESR) to have bright prospects. The experiments that have been carried out [7, 8] proved the applicability of the proposed schemes.

However, the electron beam dynamics in the LESR under conditions of interaction with the dense photon beam is essentially different from that in a commonly used storage rings. Such differences originate from increasing of the quantum fluctuation effects and, hence, from increasing of the energy spread in the beam. It leads to the increasing of the chromatic aberrations effect onto the particle motion. This effect is so crucial that leads to the beam blow-up and, finally, to its loss. On the other hand, in the case of total suppression of the chromatic effects in the ring, the effect of laser cooling leads to the decreasing of transverse beam size, and intrabeam scattering has to be taken into account.

Z.Huang has investigated the beam dynamics in the LESR analytically using undulator approach and has obtained expressions for the steady state beam parameters [9]. We carried out the numerical simulation of the longitudinal dynamics of the electron beam interacting with the dense laser target by using the Monte-Carlo method and the kinematic approach for description of the process of photon-electron interaction. The results of calculations for the steady state energy spread and bunch length in the LESR were in a good agreement with the estimations obtained by using Z.Huang's expressions [10,11]. But undulator approach doesn't permit to investigate the transverse beam dynamics taking into account chromatic aberrations in the beam with large value of the energy spread and intrabeam scattering.

In this paper the approach is described that allowed us to create the computer code for the full-scale 3-D simulation of particle motion in the storage ring taking into account photon-electron interactions and intrabeam scattering. The first results of calculations are shown and discussed. Algorithm had been realized within the pack of DeCA codes [12].

2. THE KINEMATIC APPROACH

The photon-electron interactions in the LESR can be described with the quantum theory where the Compton scattering is considered as a process of elastic collision of a photon with a free electron.

In a collision of a laser photon with energy $\varepsilon_{\gamma 0}$ and a relativistic electron with energy E_0 at a small collision angle α_0, the photon is scattered in a solid angle of about $1/\gamma$, where $\gamma = E_0 / mc^2$, mc^2 is the rest energy of the electron.

The energy spectrum of scattered photons is determined by differential cross section of Compton scattering [13]:

$$\frac{d\sigma_c}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda_e P_c r x (1-2r)(2-y)\right]; \quad (1)$$

where

$$y = \frac{\varepsilon_\gamma}{E_0} \le y_m = \frac{x}{x+1};$$

$$r = \frac{y}{x(1-y)} \le 1;$$

$$x = \frac{4E_0\varepsilon_{\gamma 0}\cos^2(\alpha_0/2)}{m_0^2 c^4};$$

$$\sigma_0 = \pi\left(\frac{e^2}{mc^2}\right) = 2.5*10^{-29} m^2;$$

λ_e, P_c - polarization direction of electron and photon beams ($|\lambda_e| \le \frac{1}{2}$; $|P_c| \le 1$);

$$\sigma_c = \sigma_c^+ + 2\lambda_e P_c \sigma_1;$$

$$\sigma_c^+ = \frac{2\sigma_0}{x}\left[\left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2}\right];$$

$$\sigma_1 = \frac{2\sigma_0}{x}\left[\left(1+\frac{2}{x}\right)\ln(x+1) - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right].$$

The differential cross-section for various electron energies and for the fixed photon energy has essential differences even if electron energy is changed within some percents. For this reason, for obtaining the accurate results in our calculations for electrons with different energies we have to use the various branches of curve (1).

One can write the photon scattering angle in the interaction plane as a function of the photon energy as follows:

$$\theta_\gamma(y) = \theta_0\sqrt{\frac{y_m}{y} - 1}, \qquad (2)$$

where $\theta_0 = \frac{mc^2}{E_0}\sqrt{x+1}$. The electron scattering angle is given by:

$$\theta_e(y) = \theta_\gamma(y)\frac{y}{1-y}. \qquad (3)$$

3. THE MONTE-CARLO PROCEDURE

The simulation of the photon - electron interaction by the Monte-Carlo method, realized in the DeCA code is based on the follow theorem:

If the variate ξ is specified with the distribution function $F_\xi(x)$ and ξ satisfies the equation:

$$\int_{-\infty}^{\xi} \mathrm{d}F_\xi(t) = \alpha, \qquad (4)$$

where α is variate which is uniformly distributed within [0,1], then ξ is distributed according to $F_\xi(x)$.

So, by integrating $\frac{\mathrm{d}\sigma_c}{\mathrm{d}y}$ from -¥ to ε_l with fixed electron beam energy E_{0i} and normalizing this integral with total Compton cross section: σ_c, one receives the correspondence between the variate uniformly distributed within [0,1] and the scattered photon energy. By setting the electron beam energy and the scattered photon energy one can build a two-dimensional table of correspondence of these values to the number within interval [0,1]. Thus, if we know the recoiled electron energy it will be enough to generate the variate which uniformly distributed within [0,1] and to find in the correspondence table which scattered photon energy this one corresponds to.

We accepted the following model for simulation: an electron with coordinates ($x,x',z,z',s,\Delta E/E_0$) interacts with a laser flash, the laser flash is assumed to be a cylinder with the length L_{lf} and the radius R_{lf}, the photon density has uniform distribution along cylinder axes and Gaussian distribution in transverse directions:

$$I_{lf}(x_{lf}, z_{lf}, s_{lf}) = I_0 s_{lf} \exp\left[-\frac{1}{2}\left(\frac{x_{lf}^2 + z_{lf}^2}{R_{lf}^2}\right)\right], \qquad (5)$$

where I_0 is maximum value of laser intensity.

In the case of laser flash rotation around reference trajectory with the angles α_{lf}, β_{lf} in horizontal and vertical planes, correspondingly, one can express the photons coordinates in the laser flash by the matrix of rotary transformation:

$$\begin{pmatrix} x_{lf} \\ z_{lf} \\ s_{lf} \end{pmatrix} = \begin{pmatrix} \cos\alpha_{lf} & \sin\alpha_{lf} & 0 \\ -\cos\beta_{lf}\sin\alpha_{lf} & \cos\alpha_{lf}\cos\beta_{lf} & \sin\beta_{lf} \\ \sin\alpha_{lf}\sin\beta_{lf} & -\cos\alpha_{lf}\sin\beta_{lf} & \cos\beta_{lf} \end{pmatrix}\begin{pmatrix} x \\ z \\ s \end{pmatrix}$$

The algorithm of the interaction simulation includes the follow steps:

1. The electron free path length s_x, inside a photon flash is determined by the expression:

$$\int_{s_1}^{s_x} I(x_{lf}, z_{lf}, s_{lf})\mathrm{d}s = -\frac{\ln\alpha}{\sigma_c},$$

where α is variate distributed uniformly within [0,1].

If s_x is larger then flash length, an interaction takes no place and the electron coordinates don't change. The algorithm passes to the simulation of the particle motion in the next lattice element.

2. In another case, according to the procedure described above the process of photon scattering is simulated.
3. According to (3) the angle of the electron scattering is determined.

4. INTRABEAM SCATTERING SIMULATION

The formalism of intrabeam scattering was developed by J. Bjorken and S.K. Mtingwa [14]. We have used this formalism to calculate the emittance growth rate due to intrabeam scattering and emittance increment. Then matrix of emittance transformation is formed. Such procedure is repeated every several thousand turns for estimation of emittance growth rate.

5. RESULTS OF CALCULATION

We have carried out the simulation of electron-photon interaction for the variant of LESR-N100 storage ring lattice. The simulations were performed with following parameters: electron energy E_0=225 *MeV*, number of electrons per bunch $3*10^9$, incident photon energy 1.17 *eV*, (Nd:YAG laser), laser flash energy – 10 *mJ*, laser flash waist – 50 μ.. We simulated electron – photon interactions with zero collision angle. Such parameters provide the scattered radiation intensity up to 10^{14} phot/s. The main results are shown in Fig. 1-4. One can see that electron motion is stable. The steady state horizontal size of the electron beam, in our opinion, is caused by the chromatic effects (Fig. 1). The vertical size decreases due to both synchrotron radiation damping and laser cooling (Fig. 2). The steady state energy spread is about 1.2 % (Fig. 3), and it is in a good agreement with the analytical estimates [11].

The obtained spectrum of the scattered photons is shown in Fig. 4.

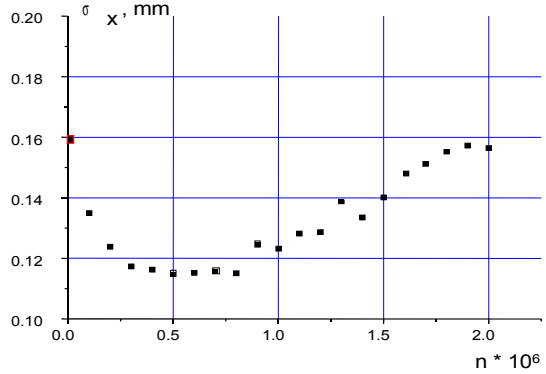

Fig. 1. *Horizontal electron beam size versus turn number*

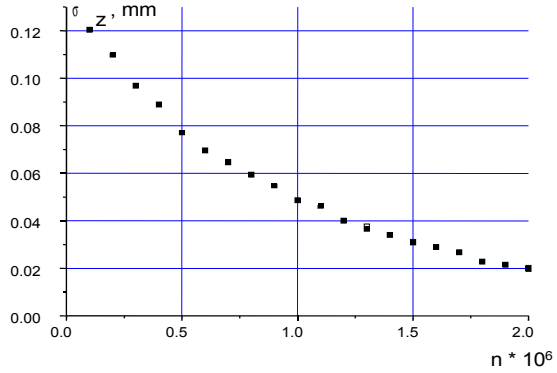

Fig. 2. *Vertical electron beam size versus turn number*

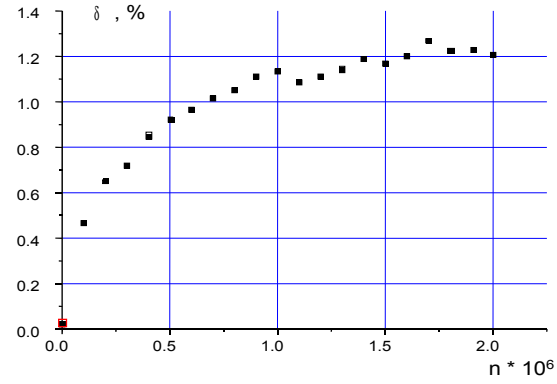

Fig. 3. *Energy spread versus turn number*

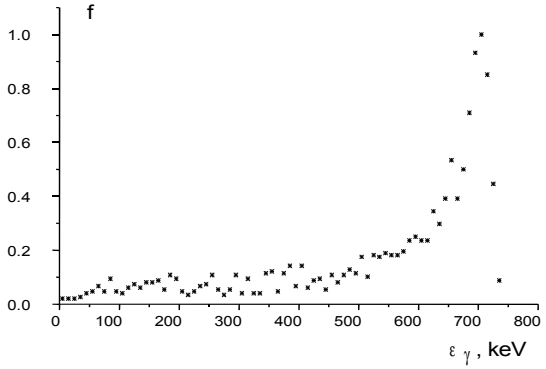

Fig. 4. *Normalized scattered photon spectrum for electron beam energy 200 MeV*

6. CONCLUSION

The code for 3-D simulation of laser-electron interaction by the Monte-Carlo method was developed. The algorithm of the intrabeam scattering calculation in single-particle tracking was developed too. These algorithms were realized in the DeCA code and permit to investigate the beam dynamics in the LESR through the periods of time that exceed the real damping times (millions of turns).

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