BEAM DYNAMICS SYMULATIONS IN THE STORAGE RING N-100 WITH ELECTRON PHOTON INTERACTION

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Abstract

In this paper we present the results of numerical simulations of longitudinal dynamics of the electron beam in the laser-electron storage ring (LESR). The effect of electron-photon interactions on the electron beam parameters is studied by Monte-Carlo method for beam energies in the range of 40-200 MeV. The analytical estimates and the numerical results are compared and discussed.

1 INTRODUCTION

Telnov has shown [1], that the transverse beam emittance in a high energy electron accelerator can be reduced by 1 to 3 orders of magnitude by interaction of the electron beam with the laser light (electron-laser cooling - ELC). Huang and Ruth proposed to use ELC for compensating the intrabeam scattering effects in low energy laser-electron storage ring (LESR) [2,3] in order to reduce the transverse beam emittance and produce intense beams of X-rays. The electron storage ring is equipped with a high - *Q*-factor optical resonator (*OR*) and the length of the resonator is chosen so as to provide electron-photon collisions at each turn in the resonator focus. The laser pulse in the LESR acts on the electron beam much like a strong undulator or a wiggler, thus decreasing beam emittance even at moderate (10-100 *MeV*) energies.

Feasibility studies of X-ray generator technologies based on Compton back-scattering are presently being pursued at several leading laboratories around the world (e.g., SLAC-USA, BNL-USA, SRS-Great Britain, KEK-Japan). We propose to develop the LESR facility at KIPT by reconstructing the first generation electron storage ring N100 [4] with top beam energy of 160 MeV. In order to estimate feasibility of the proposed scheme we started the extensive simulation studies of beam dynamics in LESR–N100. The first step is the simulation of the longitudinal motion of the electron bunch in the storage ring. The essential feature of LESR facility is the large beam energy spread σ_E/E_0 due to electron-photon interaction, and it seems important to study the effect the ring and laser beam parameters on the value of σ_E/E_0.

2 LESR-N100 PARAMETERS

The design of the upgraded N-100 facility is discussed elsewhere [5,6]. The main parameters of the LESR-N100 facility are presented in table 1.

For the electron beam energy E_0=100 *MeV*, the maximum scattered photon energy is $\varepsilon_{\gamma max}$=175 k*eV* and the average photon energy is $\varepsilon_\gamma \approx 100$ *keV*. For the given laser pulse energy E_L and power accumulation coefficient in the optical resonator k_{ph} the number of photons in the stored pulse will be $N_{ph}=2.4\cdot 10^{17}$.

Table 1. Main parameters of the LESR-N100 facility

Parameter	Value
Operating energy range, E_0, *MeV*	40-250
Circumference, *C*, *m*	13.72
Bending radius, ρ_0, *m*	0.5
Beam current, *A*	0.01
Number of bunches	1
Mean energy losses per turn (at E_e=100 *MeV*), *eV*:	
in bending magnets, $(\Delta E)_M$	17,7
at *IP*, $(\Delta E)_L$	410
Synchrotron damping time, *s*	0.226
RF voltage amplitude, V_c, *MV*	0.4
RF frequency, f_{RF} , *MHz*	699.4
Harmonic number, *h*	32
Momentum compaction factor, α	0.0037
Synchrotron oscillation tune, Q_s	0.0045
Radiation emittance, ε_x , *nm*	14.0
Laser and *OR* parameters:	
wavelength, μm	1.06
pulse energy, E_L , *J*	0.01
pulse duration, *ps*	50
accumulation factor, k_{ph}	4.5

The number of scattered quanta and the energy loss per turn is inversely proportional to the intersection area of the laser beam with the electron one. The minimal transverse size of the photon beam σ_{ph} is limited by an optical system and for considered configuration σ_{ph}~35 μm.

The horizontal size of the electron beam σ_x at the interaction point *IP* is about 20 μm for zero current. It is increased up to ~120 μm due to intrabeam scattering. The interaction of electron beam with the photon one leads to increase in energy spread of the beam. The electron bunch length is increased, thus decreasing bunch density and attenuating the intrabeam scattering. For ease of estimation we assume equal sizes of the electron and photon beams.

The mean energy loss by the electron per turn due to Compton scattering, averaged over large number of turns, is given by:

$$\left(\Delta E\right)_L = \varepsilon_\gamma \frac{n_\gamma \sigma_c}{s} = \varepsilon_\gamma \frac{n_\gamma \sigma_c}{\pi \sigma_x^2} \approx 410\ eV, \qquad (1)$$

where σ_c – Compton scattering cross-section, σ_x – transverse size of interaction area. The synchrotron radiation losses make up 17.7 *eV* at the stored beam energy E_0 =100 *MeV*. This will permit experimental verification of laser cooling effects.

The equilibrium energy spread through Compton scattering is given by [2, 3]:

$$\sigma_{EL} = \sqrt{\frac{7}{10}\frac{\lambda_C}{\lambda_L}\gamma} \approx 1.8\ \% \qquad (2)$$

The total energy spread taking into account the radiation damping in bending magnets can be evaluated by using the following expression:

$$\sigma_E = \left[\left(\frac{\tau_d}{\tau_{dL}}\right)\sigma_{EL}{}^2 + \left(\frac{\tau_d}{\tau_{dM}}\right)\sigma_{EM}{}^2\right]^{1/2} \approx 1.76\ \%, \qquad (3)$$

where:

$\tau_d \approx \dfrac{E_0 T_{rev}}{\left[(\Delta E)_L + (\Delta E)_M\right]} = \dfrac{1}{\left(\tau_{dL}^{-1} + \tau_{dM}^{-1}\right)} \approx 9.3\ ms$ - total damping time; T_{rev} – revolution period of the electron beam in the ring;

$\tau_{dL} \approx \dfrac{E_0 T_{rev}}{(\Delta E)_L} = 9.7\ ms$– damping time by laser damping;

$\tau_{dM} \approx \dfrac{E_0 T_{rev}}{(\Delta E)_M} = 226$ ms – damping time by synchrotron radiation.

3 SIMULATION RESULTS

The scheme of the ring used in simulations is given in fig.1. Two identical high-quality mirrors *M1* and *M2* with the reflectance coefficient ~1 form the resonator. The straight section of the storage ring and the axis of the optical resonator are aligned and the center of the resonator coincides with the *IP*. The photon beam is focused so that its minimum transverse size is achieved at the *IP*.

The optical resonator length is chosen from the consideration of matching the paths of the laser and the electron beams between two successive collisions at the *IP*. This length is determined by the circumference *C* of the storage ring and by the number of electron bunches n_b in the storage ring: $L = C/2n_b$. For the case of single electron bunch in the ring $L = C/2$.

For simplicity we assumed that the ring accommodates a single *RF*-cavity. The simulation consisted in turn-by-turn running the electron bunch containing 1000 particles through the system shown in fig.1. The probability of the interaction of each particle with the laser bunch was calculated at each turn. The electron free path length in the photon bunch was obtained by using the standard technique of calculating the particle free path length in matter. The photon bunch was simulated with a thin 'disk' having thickness t_0 in its center and Gaussian radial density distribution in the transverse plane. If the free path length exceeded the bunch thickness, it was assumed that no interaction took place. Otherwise the scattered photon energy and the recoiled electron parameters were determined by using the differential cross section for Compton scattering of laser photons by moving electrons, obtained by Ginzburg et al [7]. Multiple scattering was also taken into account.

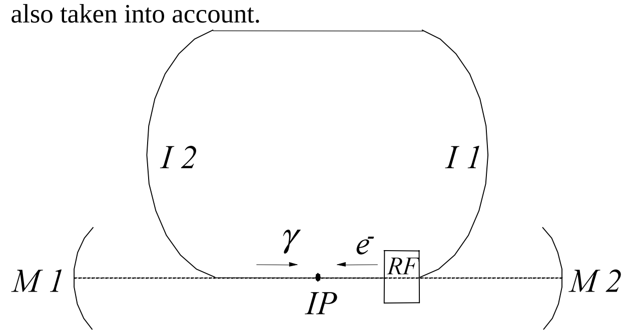

Figure 1. The scheme of the ring used in simulations. Figure captions: *RF* – the *RF*-cavity; *IP* – the interaction point for the electron and laser beams; *M1*, *M2* – the mirrors of the optical resonator.

The set of simultaneous equations for the synchrotron oscillations was solved:

$$\phi_{n+1}^{(i)} = \phi_n^{(i)} + \frac{\alpha \cdot \omega_{RF} \cdot T_{rev}}{E_0}\left(\varepsilon_n^{(i)} - U_{IP}^{(i)}\right) \qquad (4)$$

$$\varepsilon_{n+1}^{(i)} = \varepsilon_n^{(i)} + V_c \cdot \cos\phi_{n+1}^{(i)} - U_{rad}^{(i)} - U_{IP}^{(i)} \qquad (5)$$

where indices *i* and *n* denote the particle number and the turn number, respectively; $\varepsilon_n^{(i)}=E_n^{(i)}-E_0$ is the deviation of the energy of the *i*-th particle on the n-th turn, $E_n^{(i)}$, from the synchronous energy E_0; $\omega_{RF} = 2\pi\ f_{RF}$ is the RF-frequency; $U^{(i)}_{rad}$ is the particle energy loss per turn by synchrotron radiation given by:

$$U_{rad}^{(i)} = \frac{4\pi}{3} \cdot \frac{e^2}{\rho_0} \cdot \left(\frac{E_0 + \varepsilon_n^{(i)}}{m_e c^2}\right)^4 \qquad (6)$$

where *e* and m_e are the electron charge and electron mass, respectively.

Function $U_{IP}^{(i)}$ has nonzero value only for the electrons colliding with a laser photon on this turn. In this case it equal the total energy of Compton photons scattered per one electron. Synchrotron radiation damping is treated using classic formulae, quantum fluctuations of the synchrotron radiation were not considered because a more powerful antidamping mechanism (Compton scattering) determines steady state electron bunch parameters.

The initial energy spread in the electron bunch was taken equal to the natural energy spread, defined by synchrotron radiation damping, the initial phase spread was taken equal zero for ease of interpretation of the results obtained. Because the photon beam damping time in the optical resonator essentially exceeds the laser flash repetition time, any fluctuations of the photon bunch density could be neglected. The parameter values used in simulations are given in the table.

The phase spread of electrons in the bunch is essentially increased due to interaction with the laser bunch, so the longitudinal coordinate of the interaction point for each electron and, consequently, the transverse dimensions and density of the laser ‘disk’ are dependent on the electron phase. Detailed considerations let us conclude that this effect leads to ~ 5% reduction of the effective density of the laser bunch .

The electron bunch length and energy spread as functions of the number of turns for a number of electron beam energies are presented in Fig.2 and Fig. 3. Both parameters show steep rises and level to their steady-state values after 10^6 turns. The steady-state value for σ. agrees with the estimate obtained by using formula (3).

The results of simulation show that the energy spread of the electron beam is increased due to electron-photon interactions as it was anticipated and thereby the intrabeam scattering effects will be reduce.

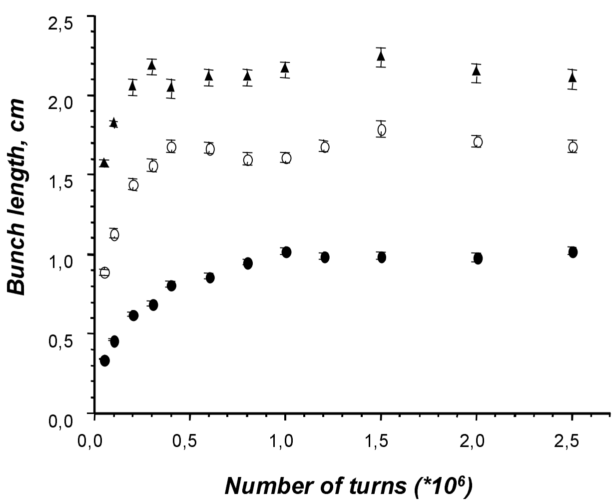

Figure 2. The electron bunch length versus turn number. Solid circles - E_0=40 MeV, open circles - E_0=100 MeV, triangles - E_0=200 MeV.

4 CONCLUSION

Computer simulation of the longitudinal motion of the electron beam in the proposed storage ring LESR-N100 with an optical resonator is performed. The calculated values of beam energy spread well agree with the estimates obtained within the framework of the model treating Compton back-scattering of laser photons on the electron beam as interaction of the electron beam with an undulator [2,3].

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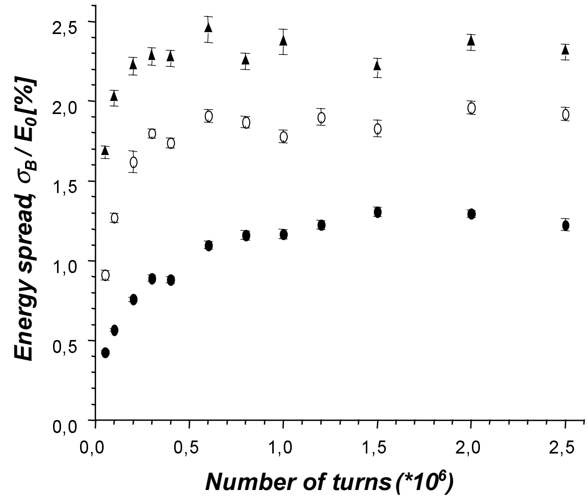

Figure 3. The electron beam energy spread versus turn number. Solid circles - E_0=40 MeV, open circles - E_0=100 MeV, triangles - E_0=200 MeV.

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