LATTICE OF NSC KIPT COMPACT INTENSE X-RAY GENERATOR NESTOR

A. Zelinsky*, P. Gladkikh, I. Karnaukhov, V. Markov, A. Mytsykov, A. Shcherbakov, National Science Center "Kharkov Institute of Physics and Technology", 61108, Academicheskaya 1, Kharkov, Ukraine

Abstract

The new generation of the intense X-rays sources based on low energy electron storage ring and Compton scattering (CS) of laser beam allows to produce X-rays with intensity up to 10^{14} phot/s. There are two basic problems in laser-electron storage rings (LESR) design. The first one is associated with strong effect of the intrabeam scattering at low electron beam energy. Because of this effect the beam size grows quickly and CS intensity decreases. The second problem is associated with large electron beam energy spread because of fluctuation of Compton generation. The value of the energy spread may run up to few percents and one needs to keep electron beam during long term in order to achieve the high Compton beam intensity.

The paper is devoted to the description of lattice of NSC KIPT Compact Intense X-ray generator NESTOR and the main principles are background for the LESR lattice design.

INTRODUCTION

The proposal of the LESR dedicated to hard X-ray generation by means of the CS of the laser light with low-energy electron beam of the storage ring was stated in 1997 [1]. Under scattering in head-on collision the quantum with maximal energy $\varepsilon_{max} = 4\gamma^2 \varepsilon_{las}$, is scattered towards the direction of electron velocity. Here ε_{las} is the laser photon energy, γ is the Lorentz factor. For example, in order to obtain X-rays energy $\varepsilon_\gamma \approx 33$ keV for angiographic studies under CS of laser photons with energy $\varepsilon_{las} = 1.164$ eV (neodymium laser) one needs electron beam energy $E_0 \approx 43$ MeV. To generate such X-rays in a synchrotron radiation (SR) source one needs electron beam energy $E_0 \approx 2.5$ GeV and superconducting wiggler with magnetic field value $B \approx 7.5$ T. It is clear that X-ray generators based on CS can become inexpensive, compact sources of the intensive X-rays.

Two basic schemes of LESR have been proposed. In the first scheme an electron beam with non-steady-state parameters is supposed to be used [2]. An intense electron beam is injected from linac into a storage ring and the beam is being used during short term within which beam size is not significantly increased. Then injection is repeated. For such experiments one needs very intense, low-emittance linac. At existed parameters of the laser systems designers expect average scattered beam intensity $n_\gamma \approx 10^{13}\text{-}10^{14}$ phot /s and spectral brightness $B \approx 10^{13}\text{-}10^{14}$ phot /(s mrad ^{2} mm ^{2} 0.1%BW). The main imperfection of such LESR scheme is the pulse nature of radiation whereas some experiments require long-term

stability of the X-rays intensity (for example, biological studies, laser cooling of electron beam etc.).

In this paper the second scheme of LESR with controlled momentum compaction factor designed at NSC KIPT is described [3]. In such storage ring one can achieve the large energy acceptance and keep the long-term stable motion of electron beam with large energy spread. The intensity of X-rays can be very stable due to using of electron beam with steady-state parameters. LESR NESTOR based on the scheme is under design and construction in NSC KIPT. This work is supported with NATO SfP Grant #977982.

MAIN REQUIREMENTS FOR RING LATTICE

Under intense CS when energy losses caused by CS are comparable to those ones because of SR the steady-state energy spread value reaches a few percents. To obtain the stable electron beam motion we need to solve several serious problems:

- to obtain the acceptable quantum life time one needs the large energy acceptance of the storage ring and unreasonable RF-voltage may be required. There is no room in a compact storage ring for a lot of RF-cavities.
- the transversal and longitudinal beam dynamics are specified in this case not only by linear on momentum deviation effects but also by quadratic and higher order ones. The aberrations do not allow to focus the electron beam at the interaction point (IP) that causes the decreasing of the CS intensity. Besides, the strong chromatic effects cause the beam diffusion because of synchrobetatron resonances at high RF-voltage. The quadratic on momentum deviation terms become apparent in longitudinal dynamics such as the distortion of separatrix shape and reducing of the RF-acceptance. Thus, one has to suppress the aberrations a ring lattice.
- the effects of the intrabeam scattering (IBS) become very strong at low electron beam energies. The emittances growth comparably to natural emittances may reach 2-3 orders that causes the essential increasing of the beam size and significant decreasing of the CS intensity.
- the sextupole lenses are used in a storage rings to correct the chromatic effects. The natural chromaticity of the storage ring is very large under condition of the strong focusing of the electron beam at the IP and the required sextupole strengths also become large (compact storage ring with low-β insertion). Dynamics aperture of a ring (DA) is reduced and the problem of the obtaining of the acceptable DA should also be solved at lattice design.

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*zelinsky@kipt.kharkov.ua

RING LATTICE

In order to meet above described requirements the LESR lattice with controlled momentum compaction factor is designed at NSC KIPT. Its layout is presented in [4].

Storage ring corresponds to racetrack. Long straight section with IP is dispersion free while dispersion at opposite long straight section is non-zero. Separated quadrupole lenses in ring arcs perform the control of momentum compaction factor. Quadrupole quadruplets on long straight section focus electron beam at IP. Only about of one third of ring orbit is dispersion free and long dispersion section allows placing the great number of sextupole lenses for correction of the chromatic effects. The strong sextupoles effect on beam dynamics similarly octupoles and to correct such affect four combined sextupole lenses with octupole field are incorporated in ring lattice. RF-cavity is placed on dispersion free IP drift. Injection system is placed on opposite drift. Bending radius and bending angle are equal to $\rho_{BM} = 0.5$ m, $\varphi_{BM} = 90°$, correspondingly. Field index is equal to $n = 0.6$. The maximal magnetic induction is equal to $B_{max} = 1.5$ T at the maximal electron beam energy $E_{0max} = 225$ MeV. The length of quadrupoles is equal to 150 mm, maximal quadrupole gradient is equal to $G_{max} \approx 25$ T/m. The length of all sextupole and combined lenses is equal to 100 mm. The maximal length of the drift spaces is approximately equal to 1.2 m what allows to place the 700 MHz RF-cavity and injection system elements. Ring circumference is equal to $C = 15.418$ m, harmonics number is $h = 36$ and one can store 1, 2, 3, 4, 6, 9, 12, 18 and 36 bunches on beam orbit.

The amplitude functions at a half of ring lattice are presented in Fig.1 (ring is dissymmetrical relatively the IP, curves begin from IP). Different focusing on IP-drift and opposite one (because dispersion functions on these drifts are different) causes insignificant asymmetry of the amplitude functions on arc and long straight sections. The less is the β-functions asymmetry the less are the amplitudes of the azimuthal perturbation harmonics and the more is the DA of the ring.

The first order dispersion function η_1 at a half of ring lattice is presented in Fig.2. We can obtain either both dispersion free long straight sections or one of them by controlling the separated quadrupole strength on ring arc. In the first case we obtain the operation mode with large linear momentum compaction factor $\alpha_1 = 0.078$ (BM-mode). In the second case dispersion function η_1 is negative in one of the arc bendings and we obtain operation mode with decreased momentum compaction factor (LM-mode). Dispersion function in Fig. 2 corresponds to $\alpha_1 = 0.019$. The maximal value of the dispersion function on arc is equal to $\eta_{1max} \approx 1.2$ m, its maximal value on long straight section is equal to 0.3 m. The lattice is very flexible and it allows us to change the momentum compaction factor over wide range without betatron detuning and without essential change of the amplitude functions (we can decrease α_1 down to zero and make it negative).

In LM-mode the first order dispersion is equal to zero only at IP-drift (approximately on one third of ring circumference), all other ring sections are not dispersion free. It allows us to place the required number of sextupoles at dispersion sections in order to suppress the second order dispersion η_2 at IP and to minimize it at whole ring. It is impossible to solve this problem in BM-mode. This statement is illustrated in Fig.3 where the trajectories of the particle with large momentum deviation in both operation modes are presented. In this figure one can see that particle trajectory in BM-mode depends essentially on momentum deviation and this effect causes growth of the effective emittance. Besides, in this mode electron beam may be slowly exited and may be lost on synchrobetatron resonances if the RF-cavity is placed at azimuth with non-zero dispersion. We observed this phenomenon in simulations.

Particle trajectory in LM-mode depends insignificantly on momentum deviation. The quadratic dispersion at IP is practically suppressed and the value of the second order momentum compaction factor is small, $\alpha_2 = 0.38$. Its critical value at electron beam energy $E_0 = 225$ MeV and RF-voltage $V_{RF} = 0.3$ MV is $\alpha_{2C} = 0.33$, consequently $|\alpha_2| > \alpha_{2C}$ [4,5].
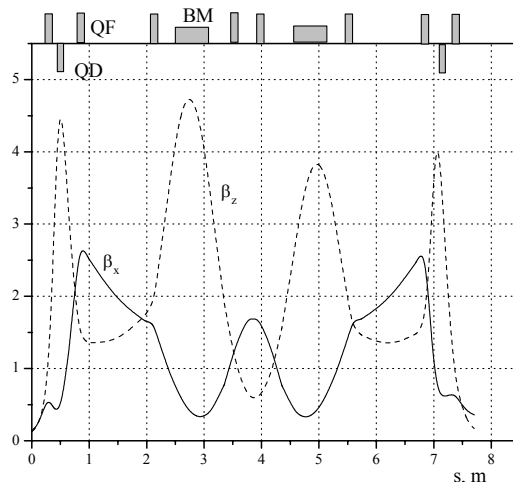

Figure 1. Horizontal β_x and vertical β_z amplitude functions at half ring lattice.
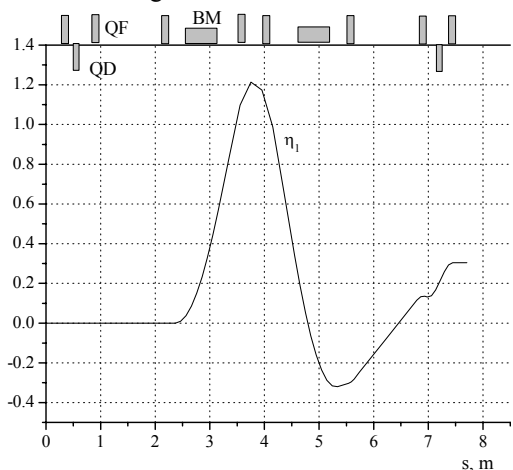

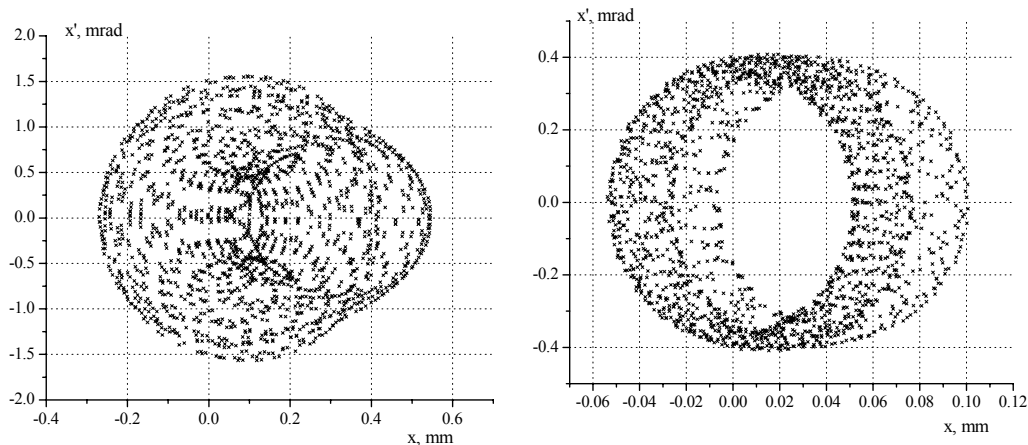Figure 2. First order dispersion function η_1 at a half of storage ring lattice

Figure3. Horizontal phase trajectories of a particle with large momentum deviation at IP azimuth in operation modes with large and low momentum compaction factor ($\alpha_1 = 0.078$ and $\alpha_1 = 0.019$). Initial particle coordinates are $x_{ini} = z_{ini} = 0.1$ mm, $x'_{ini} = z'_{ini} = s_{ini} = 0$, $\delta_{ini} = 0.01$

The separatrix of the longitudinal motion in these conditions is presented in Fig.4. One can see in this figure that separatrix shape is distorted because for even such small second order momentum compaction factor the quadratic on momentum deviation terms strongly disturb electron beam dynamics. Nevertheless, the value of the RF-acceptance is more than 7% at maximal electron beam energy for such relations between linear and quadratic momentum compaction factors.

The DA of the storage ring at IP azimuth for linear momentum compaction factors $\alpha_1 = 0.01$ is equal to $\pm 2 \times 3$ mm and for $\alpha_1 = 0.02$ is equal to $\pm 4 \times 3$ mm. Along with large energy acceptance such DA will allow the storing of the intense electron beam and, consequently, the obtaining of the intense X-rays.
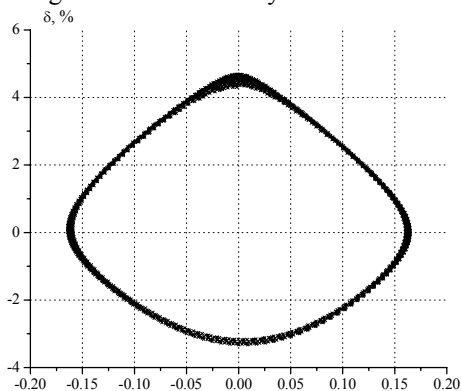

Figure 4. Separatrix of longitudinal motion at electron beam energy $E_0 = 225$ MeV and RF-voltage $V_{RF} = 0.3$ MV. Momentum compaction factor $\alpha_1 = 0.019$.

SUMMARY

The problems of the electron beam dynamics associated with large beam energy spread caused by intensive CS are solved in the proposed lattice of the laser-electron storage ring. X-rays over energy range 6 keV $\leq \varepsilon_\gamma \leq$ 900 keV with long-term stable intensity up to 10^{13} phot /s may be generated under realizable parameters of the injector, storage ring and laser system. Maximum allowed Compton beam intensity limited by energy acceptance of the storage ring is approximately 10^{15} phot /s over all energy range.

The main storage ring, electron and Compton beam parameters are presented in Table1.

Table 1. The main ring, electron and Compton beam parameters

Parameter	Value
Circumference, m	15.418
Energy range, MeV	40-225
Betatron tunes Q_x, Q_z	3.155; 2.082
Amplitude functions β_x, β_z at IP, m	0.14; 0.12
Momentum compaction factor α_1	0.01-0.078
RF acceptance, %	> 5
RF frequency, MHz	700
RF voltage, MV	0.3
Harmonics number	36
Number of circulating bunches	2;3;4;6;9;12;18;36
Electron bunch current, mA	10
Stacked laser flash energy, mJ	1
Collision angle, degrees	10; 150
Scattered photon energy, keV	6-900
Max. radiation intensity, phot /s	up to 10^{13}

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