INTENSE X-RAY SOURCES BASED ON COMPTON SCATTERING IN LASER ELECTRON STORAGE RINGS

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The main problem of the designing of intense X-ray sources based on Compton scattering in laser-electron storage ring is associated with large steady-state electron beam energy spread. In paper the principles of the development of compact storage ring lattice with large RF-acceptance and negligible chromatic effects at interaction point are considered. The storage ring with electron beam energy over the range 100-400 MeV that allows generating intense VUV from bending magnets, X-ray up to 280 keV with rate up to 10^{14} photons /s and γ-beam up to 2.8 MeV for neutron generation on beryllium target is proposed.

PACS: 29.20.Dh, 29.27.Bd

1. INTRODUCTION

It seems that the X-rays generators based on Compton scattering of intensive laser light on the relativistic electron beam stored in the low energy storage ring (laser-electron storage ring) offer the cheapest radiation in the energy range from several keV to several hundred keV, and they can become a powerful tool for fundamental studies and new technologies.

The main problem in the LESR development ensues from the large energy spread of the stored electron beam. The steady-state energy spread that takes into account both synchrotron and Compton radiation is given by:

$$\delta_{tot} = \left[\left(\frac{\tau_{tot}}{\tau_{CS}} \right) \delta_{CS}^{\ 2} + \left(\frac{\tau_{tot}}{\tau_{SR}} \right) \delta_{SR}^{\ 2} \right]^{1/2}, \qquad (1)$$

where $\tau_{tot}=1/(\tau_{CS}^{-1}+\tau_{SR}^{-1})$ is the total damping time; $\tau_{CS}\approx E_0T_{rev}/\Delta E_{CS}$, $\tau_{SR}\approx E_0T_{rev}/\Delta E_{SR}$ are the partial damping times, associated, with Compton and synchrotron radiation (SR) accordingly, E_0, ΔE_{CS}, ΔE_{SR} are the electron beam energy, mean energy losses per turn via Compton and synchrotron radiation, respectively; $\delta_{CS} = \sqrt{\frac{7}{10}\frac{\lambda_C}{\lambda_L}\gamma}$ is the energy spread due to Compton scattering [1]; δ_{SR} is the energy spread associated with SR, T_{rev} is the rotation period; λ_C, λ_L are the electron Compton wavelength and laser photon wavelength; γ is the relativistic factor.

The estimates and simulation studies presented at this conference [2] show that the steady-state beam energy spread in the LESR for high intensities of the laser beam can reach up to several percents. To ensure the stable beam motion in the ring one has to solve two essential problems. *Firstly*, one has to ensure the ring energy acceptance of 5–10 % in order to provide the reasonable beam quantum lifetime. One needs the RF-voltage of several MV to meet this requirement. In a compact storage ring there is no place to accommodate a large number of RF-cavities. *Secondly*, both longitudinal and transverse beam dynamics for the large energy spread is stipulated not only by the first order effects on momentum deviation, but higher order effects too. The aberrations hinder to focus the electron beam at interaction point (IP) properly. Hence, it decreases the intensity of the scattered photon beam. Besides, the chromatic effects can result in beam diffusion on synchrobetatron resonances for high RF-voltages (for high synchrotron oscillation frequency).

2. THE LESR LATTICES

Taking these considerations into account we proposed the compact storage ring lattice for the intensive X-ray source LESR-N100 [3]. This versatile lattice allows us to vary the momentum compaction factor α for different operation modes. Its layout is shown in Fig. 1.

In the normal operation mode (N) the long straight sections B1-B2 and B3-B4 are dispersion-free. In the low α operation mode (LA) the dispersion function is negative along the part of beam trajectory in the dipoles B3 and B4, and the straight section B3-B4 acquires the non-zero dispersion while the straight section with IP is still achromatic in the first order. The momentum compaction factor in LA mode decreases of about factor 4 against that one in the N mode. It allows to ensure the energy acceptance of about 5 % for the electron beam energy E_0 = 225 MeV with the accelerating voltage V_0 = 0.5 MV. The required voltage can be provided by the single-cell 500 MHz cavity.

Aside from providing the required energy acceptance, the LA mode gives also the approach to solving the second problem–to ensure the independence of the electron trajectory parameters on the particle energy at the IP. To correct the chromatic effects 12 sextupole lenses are placed along the orbit in the points with non-zero values of the dispersion function. The

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2002, № 2.
Series: Nuclear Physics Investigations (40), p. 72-74.

lattice has been designed so that to provide the required phase advances of betatron oscillations between sextupoles and to compensate the second order dispersion and the dependence of radial and vertical amplitude functions on the particle energy at the IP. The location of the sextupole lenses along the ring is shown in Fig. 2. The next figure presents the phase-space trajectories of a particle at the IP for the N and LA operation modes. Particle tracking was simulated with MAD code. It is seen from Fig. 3 that in the LA mode the synchrotron oscillations do not practically affect the radial motion. In the N mode the effective beam size is stipulated by the chromatic effects, and it much exceeds the beam size in LA mode. Moreover, the simulations show that the beam with the high energy spread can be lost in the N mode.

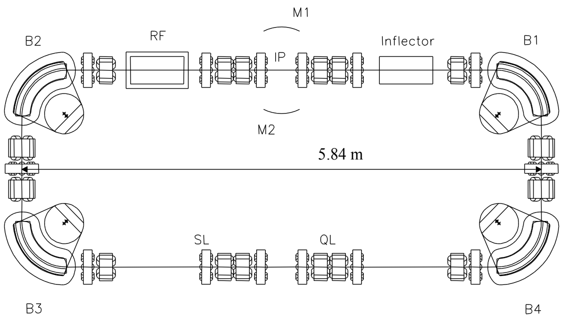

Fig. 1. *The layout of the storage ring LESR-N100M. B1-B4 are the dipole magnets; RF is the RF-cavity; QL, SL are quadrupole and sextupole lenses; IP is the interaction point; M1, M2 are the mirrors of the optical cavity*

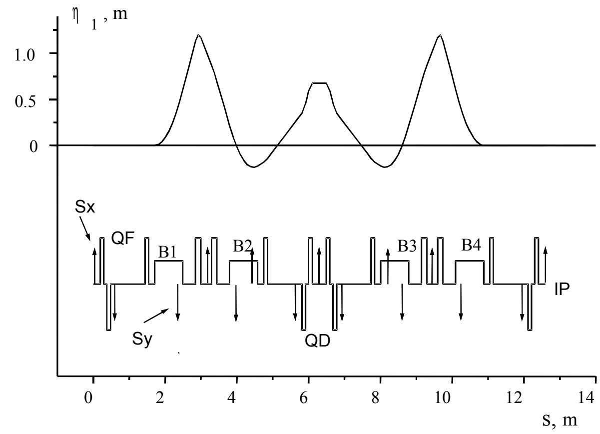

Fig. 2. *The dispersion function and the distribution of sextupoles for the correction of the chromatic effects. S_x, S_y are sextupoles, B1-B4 are bending magnets, QF and QD are quadrupoles*

One can not use the MAD code to simulate the beam dynamics in the ring taking into account the laser-electron beam interactions by two reasons. Firstly, the MAD code does not incorporate the proper algorithm, and, secondly, the calculation runtime is too long. So, we developed the proper algorithms and codes [2]. The developed code allows us to simulate the electron beam motion in the LESR through the period of time that exceeds the real damping times (millions of turns).

The results of simulation which was carried out for the LESR-N100M show that we can use a Nd:YAG laser for only high electron beam energies, when the SR losses become substantial. For low energies one can not obtain the X-ray beams of high intensity with the Nd:YAG laser. One has to use the laser with a higher wavelength or to look for the other ways to decrease the beam energy spread. One of the possible ways to decrease the electron beam energy spread is described below.

It seems very promising to use the LESR for producing the intensive neutron beams from beryllium target by using the reaction $Be^9+\gamma\rightarrow n+2\alpha$ with the negligible residual activity of the target. For beryllium Q - value is equal Q_n = - 1.66 MeV. If the maximum energy of scattered photons $\varepsilon_{\gamma max} << E_0$ it can be obtained from the following relation:

$$\varepsilon_{\gamma max} \approx 4\,\gamma^2\,\varepsilon_{las}\,cos^2\,(\theta/2),$$

where ε_{las} is the laser photon energy; θ is the angle between colliding electron and photon beams.

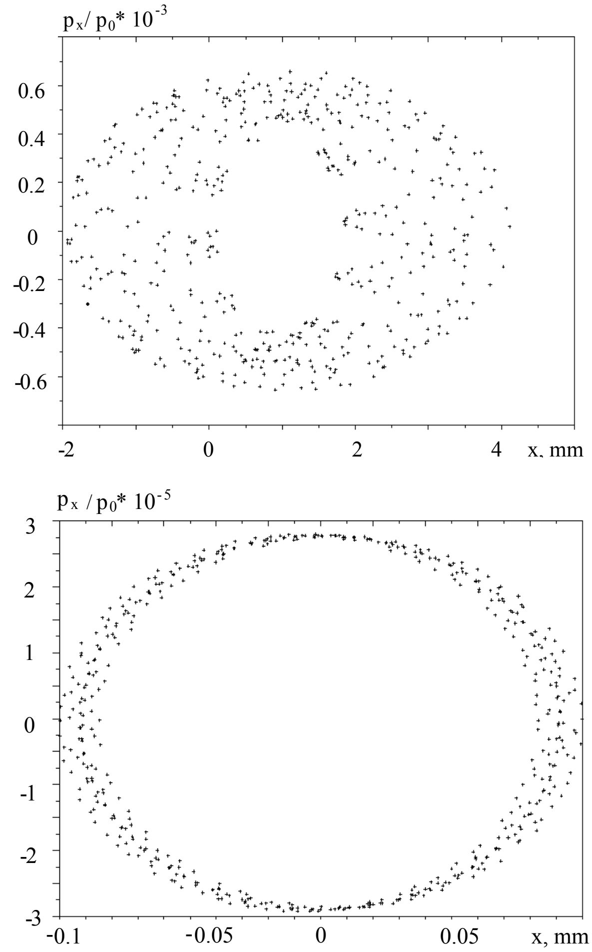

Fig. 3. *The phase-space trajectories of the particle at the azimuth of the IP in N and LA modes. Initial coordinates of the particle are: x=100 μ; x'=0; y=100 μ; y'=0; δ=1%*

In our estimates we assume $\varepsilon_{\gamma max}$ is 2 MeV. To obtain ε_γ = 2 MeV for θ = 0 and Nd:YAG laser one needs to use the electron beam with the energy E_0 = 335 MeV. But one has to bear in mind that the realization of the beam collision at θ = 0 is a complicated task because of difficulties with the extraction of the produced γ-beam and with the protection of the optical cavity mirrors from the hard radiation. Besides, it is impossible to obtain the small laser beam spot at the IP for large distance between the mirrors. For the collision angle $\theta = 90^\circ$ the required electron energy E_0 is 475 MeV and for $\theta = 60^\circ$ $E_0 = 390$ MeV. We consider using the Compton scattering at small collision angles in order to achieve a high intensity of the scattered photons. In order to decrease the steady-state energy spread we propose to increase the synchrotron damping rates by using the second laser with the larger wavelength (for example, the CO_2 laser). The steady-state beam energy spread in this ring can be estimated by using the expression:

$$\delta_{tot} \approx \sqrt{\frac{\Delta E_{SR}}{\Delta E_{tot}}\delta_{SR}^2 + \frac{\Delta E_{CO_2}}{\Delta E_{tot}}\delta_{CO_2}^2 + \frac{\Delta E_{Nd}}{\Delta E_{tot}}\delta_{Nd}^2} \qquad (2)$$

where ΔE_{SR}, ΔE_{CO2}, ΔE_{Nd} are mean energy losses per turn due to SR and Compton scattering of the photons of the CO_2 and Nd:YAG lasers, accordingly; ΔE_{tot} are the total energy losses, δ_{SR}, δ_{CO2}, δ_{Nd} are partial energy spreads due to the correspondent energy losses. The layout of the proposed storage ring with maximum electron beam energy up to 400 MeV is presented in Fig. 4.

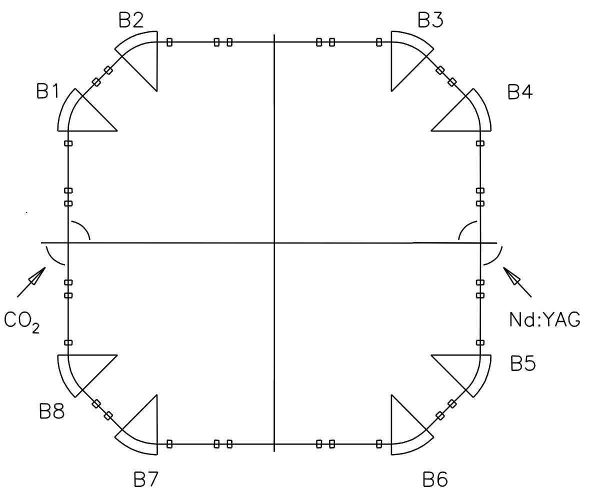

Fig. 4. *The layout of the storage ring with two laser beams*

The straight sections with interaction points are achromatic in the first and the second order on momentum deviation, and in the long straight sections B2-B3 and B6-B7 the dispersion function has non-zero value. One can vary the momentum compaction factor in this lattice. The sextupole lenses placed in the long straight sections ensure achromaticity of both IP.

The energy spread in such ring versus electron beam energy is shown in Fig. 5.

The estimates are obtained for the following parameters of the electron and photon beams:

- stored beam current I_{stor}=500 mA (number of electrons $n_e = 1.5 \cdot 10^{11}$);
- bending radius $\rho = 1$ m;
- intensity of the scattered photons of the Nd:YAG laser $n_\gamma = 10^{14}$ photons /s;
- intensity of the scattered photons of the CO_2 laser $n_\gamma = 10^{15}$ photons /s ($\Delta E_{CO2} = \Delta E_{Nd}$).

We estimated the intensity of neutron beam by integration of the $\gamma-$quanta spectrum, obtained in the simulation studies. The evaluation shows that for $\varepsilon_{\gamma\,max} = 2$ MeV and $n_\gamma = 10^{14}$ photons /s we can obtain more than 10^{11} n /s.

The proposed LESR facility with electron beam energies ranging from 100 MeV to 400 MeV allows producing the beams of electromagnetic radiation with the following parameters:

- the beams of VUV radiation from the bending magnets;
- X-rays with the energies in the range of 18–280 keV with intensities up to 10^{15} photons /s obtained through the Compton scattering of photons from the CO_2 laser;
- X-rays in the range of 180–2800 keV with intensities up to 10^{14} photons /s obtained through the Compton scattering of photons from Nd:YAG laser;
- the neutron beam with intensity up to 10^{11} n /s.

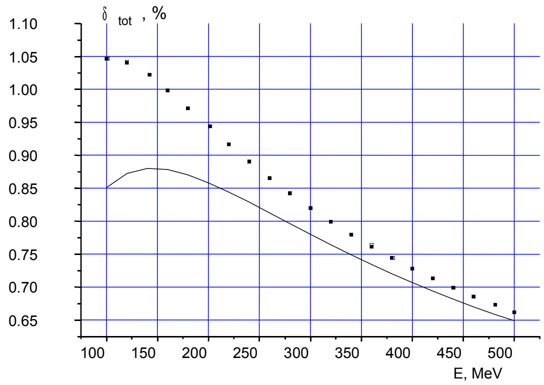

Fig. 5. *The total energy spread versus electron energy. The solid line – CO_2&Nd:YAG lasers, symbols –Nd:YAG laser only*

3. CONCLUSION

The proposed low-α schemes of the LESR with compensation of chromatic aberrations at the interaction point enable to develop the sources of intensive X-ray beams based on compact storage rings.

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