POSSIBILITY TO REACH THE DIFFRACTION LIMITED X-RAY SOURCE IN KURCHATOV CENTER OF SYNCHROTRON RADIATION

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Abstract

The creation of the diffraction limited radiation source (DLS) on the base of an in – vacuum mini-undulator with wavelength 6 Å is considered at a storage ring SIBERIA-2. Main parameters of undulator as a DLS are defined. Spectral characteristics of undulator radiation taking into account the electron beam parameters are obtained.

In addition method and possibility to obtain the minimal electron beam emittance in SIBERIA-2 storage ring, influence of insertion device (ID) on emittance, energy spread, linear and nonlinear motion of electron beam and dynamic aperture are the subjects of studying.

INTRODUCTION

The most important quality factor of synchrotron radiation for the users is its brilliance, which is mainly determined by the electron beam emittances and diffraction phase volume of the radiation. Even at zero emittances the phase space of the radiation from an undulator itself is finite due to diffraction effects. The corresponding emittance of the light beam is given by $\varepsilon_{ph}= \lambda/4\pi$, with λ being the wavelength at the peak flux. A light source is called diffraction - limited if the emittance of the electron beam is smaller than that of the photon beam.

To obtain diffraction limit in X-ray wave range (10^{-9}-10^{-11}m) it is necessary to have the electron beam emittance near 10^{-11} m·rad. Now obtaining such low emittances is impossible on storage ring SIBERIA-2 in both transverse phase planes simultaneously. But it can be obtained in vertical plane in new more brilliance structure on energy 1.3 GeV. The choice of such energy is a compromise between two competing processes: the emittance minimization and the instabilities arising at low energy (intra-beam scattering, small damping times et al). The emittance 50 pm·rad will correspond to wavelength of radiation 6 Å.

EMITTANCE MINIMIZATION

Nowadays a natural horizontal emittance of electron beam in SIBERIA-2 at 2.5 GeV is equal to 98 nm·rad [1]. Operating parameters of storage ring are listed in the Table 1. In addition to existing optical lattice new more brilliance lattice with horizontal emittance 18 nm·rad (on full energy) has been developed (Table 1), its optical functions are imaged in Fig.1. The new lattice allows to obtain the horizontal emittance of 4.9 nm·rad at 1.3 GeV. Vertical emittance of electron beam is 49 pm·rad taking into account a coupling factor of betatron oscillation k≈0.01 for SIBERIA-2. Thus, vertical emittance is equal to photon emittance with energy photons 2 keV. The feature of a new optical structure is an absence of the achromatic bends.

Table 1: KCSR Storage Ring Parameters

Lattice	"standard"	"brilliance"
Energy	2.5 GeV	1.3 GeV
Emittance	98 nm·rad	4.9 nm·rad
Beam size: σ_x/σ_y	1500/78	363/17
Circumference	124.128 m	
Coupling	0.01	
Momentum compaction	0.0103	4.2×10^{-3}
Betatron tunes: Q_x/Q_y	7.775/6.695	9.707/5.622
R.m.s. energy spread	9.5×10^{4}	5×10□
Damping times: τ_x, τ_y, τ_s	3.2; 3;1.5 ms	22;22;11 ms
Beam current	100-300 mA	

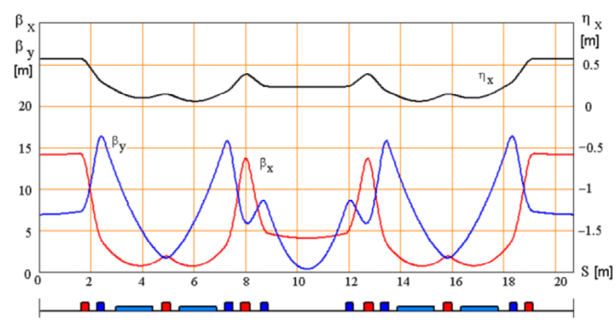

Figure1: Optical function of storage ring SIBERIA-2 with ε_{x0}=18 nm·rad at E=2.5 GeV.

In order to obtain the radiation with wavelength of 6 Å at 1.3 GeV electron beam energy a radiator of photons - undulator must meet the rigid requirements.

UNDULATOR

An expression for wavelength of radiation λ for planar undulator is given by [2]:

$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K_u^2}{2} + (\gamma\theta_x)^2 + (\gamma\theta_x)^2\right) \quad (1)$$

where *n=1,2,3…*- harmonic number, K_u - undulator parameter, λ_u – undulator period, θ_x,θ_z – horizontal and vertical observation angle with respect to the axis. PPM structure has been chosen from the two most popular magnet structures used to build undulators (Pure Permanent Magnet (PPM) and hybrid structure). 2D and 3D simulations of magnetic field have been carried out by using computer code ANSYS. Main parameters of undulator are summarized in the Table 2.

Table 2: Main undulator parameters.

Gap	mm	2.2
Permanent magnet material		NdFeB
Residual field, $\mu_0 H_c$	T	1.2
Undulator period, λ_u	mm	7
Poles width, w	mm	50
Field amplitude, B_0	T	0.75
Undulator parameter, K		0.492
Number of periods	N_p	300
Undulator length, L_{ID}	m	2.1
Wavelength radiation, λ_1, Photon energy, ε_1	Å, keV	6.06 2.045

From the Table 2 we can see that undulator has very short period 7 mm and high peak field 0.75 T. A production technology of the undulators was greatly advanced during the last years [3,4,5], it is allows us to hope that a realization of the undulator with such record parameters is possible.

UNDULATOR INFLUENCE ON ELECTRON BEAM

Our analysis of the beam dynamics in the ID begins from the following expressions of the magnetic field which are known to be a good approximation of the actual distribution inside the ID [6]:

$$\begin{aligned} B_x &= (k_x / k_z) B_0 \sinh(k_x x)\sinh(k_z z)\cos(k_s s) \\ B_z &= B_0 \cosh(k_x x)\cosh(k_z z)\cos(k_s s) \\ B_s &= -(k_s / k_z) B_0 \cosh(k_x x)\sinh(k_z z)\sin(k_s s) \\ k_s &= 2\pi / \lambda_u, k_x = 2\pi / \xi, k_x^2 + k_z^2 = k_s^2 = (2\pi / \lambda_u)^2 \end{aligned} \tag{2}$$

with x, z, s – horizontal, vertical и longitudinal coordinates respectively; B_0 – peak field; ξ – field decrease parameter in horizontal direction. In particular, damping of the field in the x-direction can be expressed by the replacement $k_x \rightarrow ik_x$.

To obtain a field components we shall pass to moving coordinate system – beam trajectory (x^*, z^*, s^*), by means of the replacement of variables:

$$x = x_0 + x^*; s = s_0 + x' s^*; z = z^* \tag{3}$$

Further we differentiate fields up to third order. With assumption - betatron oscillations wavelength much larger than ID length, and after some simplifications and averaging over ID period, we finally find the expression for the magnetic field expansion at the beam orbit in ID:

$$\begin{aligned} B_z &= B_{z10} x + B_{z30} x^3 + B_{z12} x z^2 \\ B_x &= B_{x01} z + B_{x03} z^3 + B_{x21} x^2 z \end{aligned} \tag{4}$$

Normalized expansion coefficients are presented in Table 3. We notice first that the linear effect of an ID is equivalent to that of a “pseudo” quadrupole which has different magnitude of focusing strength in two transverse directions. As rule, where $k_x \ll k_s$, an additional focusing in the x direction is weak, which can be interpreted as a result of cancellation between the focusing effect of the dipole and the defocusing effect of the magnetic edge. In our case focusing in the z direction is weak also. In fact, a vertical tune shift and a vertical beta function distortion are $\Delta\upsilon_y = 0.016$ and $(\Delta\beta_y/\beta_y)_{max} = 0.08$ respectively. Major nonlinear forces come from the octupole-like components. It should be noted that octupole-like components increase as k_s^2. These forces may seriously reduce the dynamic aperture.

It should be noted that radiation effects from undulator are negligible.

Table 3: Expansion coefficients of magnetic field in moving coordinate system.

$\frac{B_{z10}}{B_0\rho_0} = -\frac{k_x^2 + k_s^2}{2k_s^2\rho_0^2}$	$\frac{B_{x01}}{B_0\rho_0} = -\frac{k_x^2 + k_s^2}{2k_s^2\rho_0^2}$
$\frac{B_{z30}}{B_0\rho_0} = \frac{B_0 k_x^2}{12\rho_0^2}\left[3 + \frac{k_x^2}{k_s^2}\right]$	$\frac{B_{x03}}{B_0\rho_0} = -\frac{k_z^2\left[k_x^2 + k_s^2\right]}{12\rho_0^2 k_s^2}$
$\frac{B_{z12}}{B_0\rho_0} = -\frac{k_z^2\left[k_x^2 + k_s^2\right]}{4\rho_0^2 k_s^2}$	$\frac{B_{x21}}{B_0\rho_0} = \frac{k_x^2\left[k_x^2 + k_s^2\right]}{4\rho_0^2 k_s^2}$

Nonlinear effects

Introduction of nonlinear fields leads to the amplification of the amplitude-dependent tune shift, a distortion of phase space and a reduction of the dynamic aperture (DA).

Simulation of undulator field influence on DA was carried out for lattice structure with natural emittance of 18 nm·rad, Figure 2. We have introduced the ID as long quadrupole with a lumped nonlinear element at the center. Nonlinear elements are simulated as the kicks given by next expressions:

$$\begin{aligned} x' &= \frac{B_{z30}}{B\rho} L_{ID} x^3 + \frac{B_{z12}}{B\rho} L_{ID} x z^2 \\ z' &= \frac{B_{x03}}{B\rho} L_{ID} z^3 + \frac{B_{x21}}{B\rho} L_{ID} x^2 z \end{aligned} ; \tag{5}$$

Fig.2 shows significant reduction of DA in vertical direction to about ±1 mm, therefore we must compensate for the octupole components. Moreover, it is necessary to note that ±1 mm undulator gap is also small..

Undulator influence on beam life time

The small aperture undulator (g=2.2 mm) will essentially reduce lifetime of electron beam. Main contribution to the reduction of lifetime will give an elastic scattering of the electrons on the atoms of residual gas. Nowadays average pressure of residual gas over the storage ring 1 nTorr. At such pressure lifetime of electron beam will be τ=2 hours. That is sufficient at Top Up injection [7]

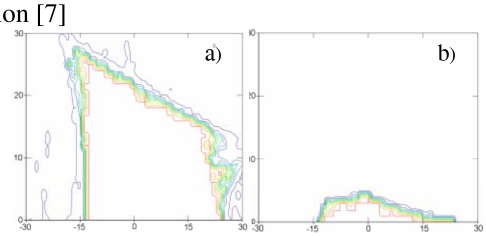

Figure 2: DA in mm: a) without undulator; b) with undulator.

UNDULATOR RADIATION

A simulation of undulator radiation with the help of SRW code [8] has been made. The point of radiation observation is placed in 15 meters from undulator. Parameters of undulator and electron beam are listed in Table 1 and Table 2.

Distributions of flux density for first and second harmonic are shown in Fig.3 and Fig.4. for two cases: a) horizontal and vertical emittances and energy spread of electron beam are equal to zero: $\varepsilon_{x0}=\varepsilon_{z0}=0$, $\Delta E/E=0$; b) ε_{x0}=4.9 nm·rad, ε_{z0}=49 pm·rad, $\Delta E/E=5\cdot10^{-4}$. From Fig.3, 4 one can see that emittance and energy spread of an electron beam essentially influence on characteristics of radiation.

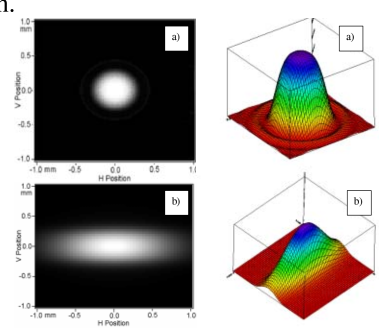

Figure 3: Distribution of flux density for first harmonic a) $\varepsilon_{x0}=\varepsilon_{z0}=0$, $\Delta E/E=0$; b) ε_{x0}=4.9 nm·rad, $\Delta E/E=5\cdot10^{-4}$.

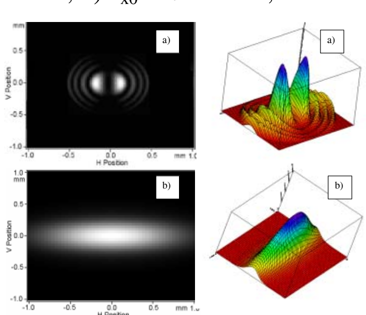

Figure 4: Distribution of flux density for second harmonic a) $\varepsilon_{x0}=\varepsilon_{z0}=0$, $\Delta E/E=0$; b) ε_{x0}=4.9 nm·rad, $\Delta E/E=5\cdot10^{-4}$.

Distributions of flux density of first harmonic for horizontal and vertical planes in view of different parameters of electron beam such as the emittance and the energy spread are shown in Fig. 5. In horizontal plane, when taking into account the electron beam finite emittance and energy spread, maximal flux density essentially decrease. Moreover significant broadening of the glowing area occurs. In a vertical plane the glowing area practically does not vary, and decreasing of intensity is about 40%. Thereby it is possible to assume, that in a vertical plane we can partially achieve the diffraction limit.

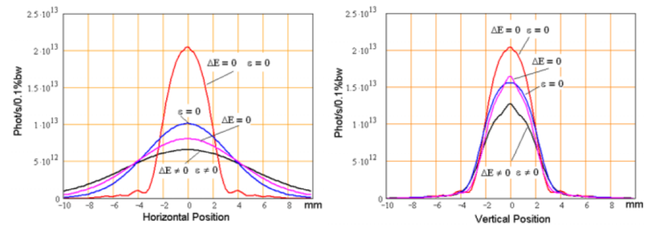

Figure 5: Distributions of flux density for first harmonic In view of different parameters of electron beam

CONCLUSIONS

Possibility to obtain the diffraction limited x-ray radiation source on base of storage ring SIBERIA-2 is considered. Main undulator parameters as a DLS are obtained. Installation in-vacuum mini-undulator with a variable pole gap and a very short period of a magnetic field will be expedient and effective only after realization of modernization of optics of the storage ring SIBIRIA-2 and reception in the modernized structure natural emittance to ~ 5 nm-rad at an energy ~1.3 GeV. In this case one could say about a possibility of work with a very bright diffraction-limited source in vertical plane in the range of 6 Å fundamental harmonics. A preliminary study of the influence of insertion device on beam dynamics is presented also. We found that undulator with very short period introduces the octupole components which essentially reduces dynamical aperture. Linear tune shifts and beta-function distortions are negligibly small. Simulations of undulator radiation are shown that we may achieve the diffraction limit in vertical plane.

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