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OPTIMIZATION OF PARAMETERS OF A DEDICATED SYNCHROTRON RADIATION SOURCE FOR TECHNOLOGY

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The problems of optimizing the parameters of a storage ring used as a source of synchrotron radiation (SR) for a multiplicity of sub-micron technology applications are considered. The storage ring lattice optimized for the minimum emittance of the electron beam provides for installation of undulators and wigglers to generate the high-power beams of ultra-violet (λ = 1200–2000 Å), soft X-ray (λ = 40–10 Å) and X-ray (λ = 4–2 Å) radiation. A number of design features are proposed, viz magnets with three different levels of magnetic field, a SR beam sweep for wigglers and undulators, quadrupole lenses made of two pieces, etc., which are optimal in the storage ring used as a dedicated SR source for technology.

1. Introduction

Historically the activities in synchrotron radiation (SR) applications can be conditionally divided into four periods. In the sixties the first research activities were launched using the SR from synchrotrons. At the same time, the development and construction of the first electron–positron storage rings for high energy physics with colliding beams began. In the seventies these storage rings became available for synchrotron radiation research in a parasitic mode with elementary particle physics. On the basis of the major storage rings, national centres for synchrotron radiation research were established. By the end of seventies a wide range of these research groups urged development and construction of the first specialized electron storage rings as dedicated SR sources for research centres. In the eighties SR research tends to be concentrated mainly at these storage rings which serve as dedicated SR sources. An extensive development of new technologies, based on SR applications is under way:
- fabrication of microelectronic devices with submicron dimensions;
- medical diagnostics of the human circulatory system;
- large-scale trace-elements express analysis;
- topography of crystals;
- metrology;
- radiation technology.

At present it is becoming clear that in the nineties the advent of a new type of storage rings is inevitable, namely dedicated SR sources developed for specific technologies. Each technology requires the development of a suitable storage ring as a SR source. Thus, the development of a storage ring has to account for the features of the technology in question.

The major part of the analysis in the present paper is relevant to a dedicated SR source for microelectronics, though the approach in general and some of the solutions can also be applied to considering storage rings for other technologies.

Two approaches seen natural in the development of storage rings for microelectronics. The first one is striving for a small-dimension compact SR source for X-ray lithography only. The second one is trying to construct a storage ring as the SR source not only for X-ray lithography but for a multiplicity of problems arising in the fabrication of devices with sub-micron structures. Apparently, the second approach is the most suitable one for the problem as a whole because it gives combined solutions to many particular problems of the submicron technology:
- X-ray lithography;
- large-scale express X-ray topography (checking crystal quality and the quality of produced epitaxial structures);
- X-ray fluorescent trace-element analysis of technological products;
- dry and low-temperature photochemical processes of depositing oxide and metallic films from gaseous phases by means of high-power ultra-violet radiation;
- sub-micron metrology;
- baking wafers by SR beams.

2. Requirements for a storage ring used as a SR source for technology

Choosing the electron storage ring parameters for a dedicated SR source, we start with the following conditions:

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1) the storage ring should provide for installation of X-ray lithography stations on the SR beam lines from the arc bending magnets ($\lambda_c \sim$ 10–20 Å);

2) the storage ring should provide for installation of X-ray lithography stations on the beam lines from "lithographic" wigglers and undulators ($\lambda_c \sim$ 10–20 Å). The use of quasi-monochromatic radiation from undulators is preferable because in this case the mask contrast attainable is higher while the mask heat loading is lower, etc.;

3) the storage ring should provide for installation of the superconducting wigglers for generating radiation in the range of $\lambda \sim 2$ Å for express topography and for trace-elements express analysis;

4) the storage ring should provide for VUV-technologies installation of VUV undulators generating an ultra-high brightness radiation beam in the VUV and soft X-ray ranges ($\lambda \sim$ 2000–20 Å);

5) all the special radiation sources (i.e. wigglers and undulators) should be capable of transforming the SR beam dimensions at the working places thus concentrating all the SR power either to a strip or to a rectangle of the area required.

3. Requirements for the SR beam parameters in the design of a storage ring used as a SR source for technology

1) The productivity of an X-ray lithography station with an optimal X-ray lithography scheme and with an idealistic resist is basically determined by two parameters: the source brightness B and the required spatial resolution δa as the exposure time τ_{exp} is given by the equation [1]:

$$\tau_{exp} \sim \frac{1}{B \delta a^5}$$

Table 1 presents a comparison of various X-ray sources with respect to their brightness. Apparently the SR beams are capable of providing the productivity wanted in the fabrication of structures with $\delta a \sim 0.1$ mkm dimensions as this source brightness B comes to 10^{25}–10^{26} phot/cm$^2 \cdot$ sr $\cdot$ s.

2) The optimal radiation wavelength for X-ray lithography is determined by the situation where the diffraction broadening is equal to the photo- and Auger-electrons range. The specification of the spatial resolution puts the upper limit on the spacing between mask and resist provided that the wavelength is set at its optimum value. The spectral domain of interest is 20–4 Å.

3) The photochemical processes of depositing oxide and metallic films require the VUV radiation in the wavelength range of 1200–2000 Å [2]. The VUV lamps available yield a flux of ~ 100 mkW/cm^2 over this spectral domain, thus enabling a deposition rate of ~ 400 Å/min [2]. For large-scale production a flux enhancement up to 40 mW/cm^2 is needed over the full area of the wafer.

4) X-ray express topography and X-ray fluorescent trace element analysis require radiation with a wavelength $\lambda \sim 2$ Å.

Table 1

Type of source	Spectrum	Source spot size (cm^2)	Mean brightness [phot./s·cm^2·sr]	Mode of operation
X-ray tube, Si-target $P = 25$ kW [3]	Characteristic radiation = 7.13 Å	0.28	2×10^{16}	continuous
High-current discharge through a capillary [4]	Characteristic lines of hydrogen, hydrogen-like and helium-like ions of a capillary	0.08	$(10^{12}-10^{13}) \cdot f_{repeat.}$	pulse = 20 ns
Surface spark discharge in a capillary and with electron beam [5]	–"–	2.5×10^{-5}	$3 \times 10^{17} \cdot f_{repeat.}$	pulse = 120 ns
Blasting wires [6]	Characteristic radiation of wire material	4	$2 \times 10^{16} \cdot f_{repeat.}$	pulse = 60 ns
Laser plasma (100 J in the pulse of 1 ns duration [7]	Characteristic lines of hydrogen-like and helium-like ions of target	2×10^{-4}	$10^{20} \cdot f_{repeat.}$	pulse = 1 ns
Synchrotron radiation ($E = 1.5$ GeV, $I = 0.5$ A)	(3–20) Å	10^{-3}	2×10^{25}	continuous
Lithographic wiggler	(3–20) Å	10^{-3}	10^{26}	continuous

4. Storage ring energy option

To determine the storage ring energy needed we use the nomograph presented in fig. 1. In the nomograph the energy is plotted on the horizontal axis while the magnetic field strength at the radiation point is plotted on the vertical axis. The solid curves are the lines $\lambda_c = \text{const}$, where $\lambda_c\,[\text{Å}] = 186/E^2[\text{GeV}]\cdot B[\text{kG}]$ is the critical wavelength of the synchrotron radiation. The dashed curves are the lines $R = \text{const}$, where $R[\text{m}] = E[\text{GeV}]/0.03H[\text{kG}]$ is the radius of curvature of the electron trajectory in the magnetic field.

We take 45 kG as the maximum value of the magnetic field in a superconducting wiggler for this value is rather readily obtainable in superconducting systems of simple design. For the maximum field in lithographic wigglers we can take 12 kG that is feasible in multipole systems both with electromagnets and with SmCo permanent magnets [8].

The bending magnets field can be taken as high as 19.5 kG with magnetically soft steels such as ARMCO.

From the nomograph one can see that with a 45 kG superconducting wiggler the electron energy of 1.45 GeV is needed to obtain radiation with $\lambda_c = 2$ Å.

To generate the SR beams from the bending magnets for X-ray lithography with $\lambda_c = 10$ Å the field in the magnets must be $B = 9.5$ kG at this energy, that corresponds to the bend radius of $R \sim 5$ m in the magnets.

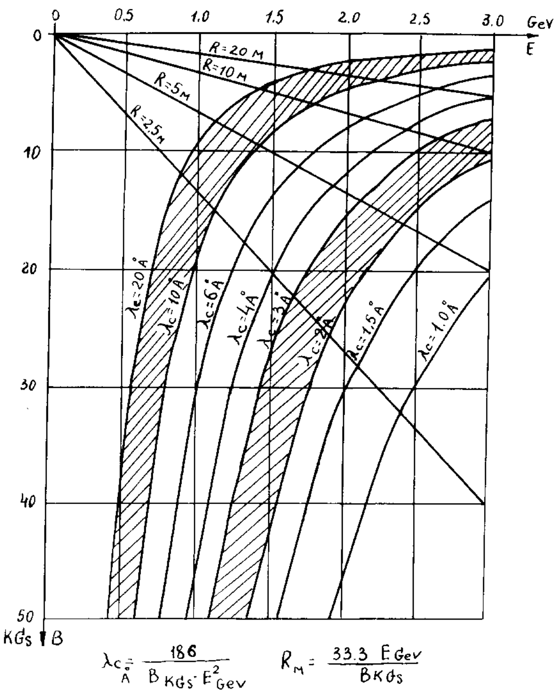

Fig. 1. Nomograph for choosing storage ring parameters.

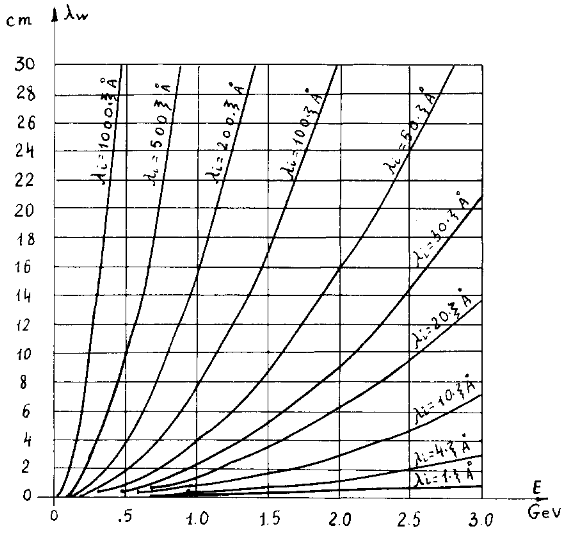

Fig. 2. Nomograph for choosing undulator parameters.

$$\lambda_i = \frac{\lambda_W}{2\gamma^2 i}(1 + K^2/2);$$

$$\frac{\lambda_i i}{1 + K^2/2} = \frac{\lambda_W}{2\gamma^2} = \text{const};$$

$$\zeta = i/(1 + K^2/2).$$

To produce SR beams from lithographic wigglers with $\lambda = (20\text{–}8)$ Å the wiggler field must range from 5 to 12 kG at the electron energy of 1.5 GeV.

To determine the possibility of installing VUV and lithographic undulators, we use the graph shown in fig. 2. Here the energy E and the undulator period λ_W are plotted on the horizontal and vertical axes respectively. The solid curves are the lines of constant:

$$\frac{\lambda_i i}{1 + K^2/2} = \frac{\lambda_W}{2\gamma^2}$$

where λ_i is the ith undulator harmonic wavelength, $\gamma = E/E_0$ is the relativistic factor, $K = \alpha\gamma$ is the deflection parameter and α is the maximum electron deflection angle in the undulator.

The analysis has shown that installation of hybrid structures with SmCo permanent magnets is reasonable with respect to reduction of the beam vertical aperture; hybrid undulators should be used with fixed gap and period $\lambda_w \gtrsim 3$ cm or with variable gap and the period $\lambda_W \gtrsim 2$ cm. In this case one can see from fig. 2 that the storage ring energy has to be in excess of 1.5 GeV to generate radiation in the range $\lambda \sim (10\text{–}20)$ Å.

The undulator for VUV technologies for the range $\lambda \sim (1000\text{–}2000)$ Å should be designed with the period $\lambda_W \sim 25\text{–}30$ cm and operated with $K = \alpha\gamma = 4\text{–}3$ at an energy of 1.5 GeV.

5. Storage ring current option

To provide illumination of a mask, $I \sim 2$ W/cm^2, at a distance $L \sim 20$ m from the radiation point, a storage ring current of ~ 300 mA is sufficient. The beam lifetime is expected to be in excess of 20 h in the multibunch operation mode at an energy of 1.5 GeV.

6. General requirements for the storage ring lattice

Developing a storage ring as a dedicated SR source one has to provide a lattice that meets the conventional "machine" requirements (stability of betatron and synchrotron motion, compensation of the guide-field nonlinearities, proper conditions for injection of electrons, etc.). On the other hand, the lattice should be optimized for the requirements put upon the SR source by the specific technology. From the above consideration these are a high photon flux per unit spectral range and high spectral brightness of the radiation source in various domains of the spectrum.

Therefore, the storage ring lattice should satisfy the following requirement:

(1) The electron beam emittance should be a minimum. According to the smooth approximation, the emittance is expressed by the simple formula [9]:

$$\epsilon_x \simeq \frac{R}{\rho} \Lambda \frac{\gamma^2}{\nu_x^3},$$

where γ is the relativistic factor, $\Lambda = 3.86 \times 10^{-11}$ cm is the Compton wavelength for the electron; R and ρ are the average and the bending radii respectively, and ν_x is the betatron tune for horizontal oscillations.

(2) In the storage rings under discussion the synchrotron radiation will be generated in the arc bending magnets, therefore at the radiation azimuth the betatron function β_x should be a minimum.

(3) In view of installing VUV undulators there should be long enough straight sections in the lattice with

$$\beta_{x,z} \gg \gamma^2 \epsilon_{x,z}.$$

(4) In view of installing wigglers or undulators with high field and short spatial period (which results in a narrow gap) there should be straight sections with low β_z where the vacuum tube aperture can be made locally small.

(5) To minimize the effect of the high-field wigglers on the electron beam parameters there should be zero dispersion ($\eta = \eta' = 0$) in these straights. So, the storage ring structure should contain the parts of the orbit with an achromatic bend.

(6) To obtain a high degree of symmetry in the lattice all the superperiods should be identical.

Bearing all the above conditions in mind, one can easily obtain the analytic dependence of the minimum attainable emittance:

$$\epsilon_{x\,\min}\,[\mathrm{cm \cdot rad}] = \frac{1}{\sqrt{240}} \frac{C_q \gamma^2 \varphi_m^3}{J_x} \approx 10^{-5} \cdot E^2[\mathrm{GeV}] \cdot \varphi_m^3[\mathrm{rad}] \qquad (1)$$

where $\varphi_m = l_m/\rho$ is the bend angle in the magnet, l_m is the magnet length, $C_q = 3.84 \times 10^{-11}$ cm, $J_x \simeq 1$ is the damping partition of the horizontal betatron oscillations.

Thus, the minimum emittance in the storage ring including the achromatic bend superperiods depends on the only characteristic of their geometry, that is on the bending angle φ_m in each magnet.

Table 2 summarizes the design values of the beam emittances together with the estimates of the minimum emittances attainable based on eq. (1) for a number of storage rings that are presently being designed [10] or constructed [11] and are dedicated SR sources. One can see that their design emittances are twice as large as those minimally obtainable for their lattice geometry and their energies.

Table 2

Radiation source	ϵ_x [cm·mrad] (project)	ϵ_x [cm·mrad] (eq. (1))
NSLS X-Ring $E = 2.5$ GeV $\varphi_m = 22.5°$ [11]	8×10^{-6}	3.8×10^{-6}
NSLS VUV-RING $E = 0.7$ GeV $\varphi_m = 45°$ [11]	3.6×10^{-6}	2.4×10^{-6}
ESRF $E = 5$ GeV $\varphi_m = 7.5°$ [10]	1.1×10^{-6}	0.56×10^{-6}

7. Lattice design

Taking into account all the conditions for the storage ring as an optimized SR source for technology, the lattice has been designed consisting of six superperiods with central symmetry where the expected value of the emittance [from eq. (1)] is $\epsilon_x = 3.2 \times 10^{-6}$ cm · rad.

The superperiod endpoint are taken to be at the centre of straight sections designed for undulators (00 plane) while the centre of the superperiod (WW plane) is in the centre of the straight section designed for a high-field wiggler. Due to the central symmetry it is sufficient to consider one half of the superperiod.

Fig. 3 shows the lattice of one half of the centrosymmetric superperiod.

Position 1 stands for the undulator straight section,

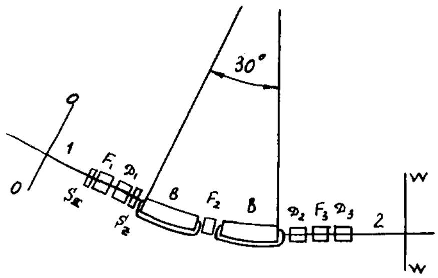

Fig. 3. Lattice of half of the centro-symmetric superperiod.

position 2 is that of a wiggler. There is the central symmetry in the lattice with respect to planes 00 and WW.

The lattice of one half of the superperiod comprises 6 quadrupole lenses and 2 bending magnets. Two lenses (F_1 and D_1) are placed in the undulator straight while the lenses D_2, F_3 and D_3 are located in the wiggler straight section.

The feature of the lattice is that the focusing lens F_2 is placed between two identical (and symmetric) 15° bending magnets which comprise the 30° bend. The quadrupole lens F_2 thus placed in the focal plane of the achromatic bending system (i.e. from the centre of the undulator straight to the centre of the lens F_2) makes it possible to easily control the position of β_x minimum (to the left or to the right of the lens F_2) and hence to obtain the needed value of the emittance. Note that the optimal position and the value of minimum β_x can also be reached in the achromatic bend version performed by the bending magnet and two lenses F_1 and D_1 only, without splitting the bend magnet into two. However, in this case the length of the undulator straight necessarily becomes rather long: $l_{und} \sim \beta_x^{und}$. Splitting the bending magnet into two and placing the lens in between has resulted in an undulator straight length compatible with the needed value. For the case in question $l_{und} = 250$ cm.

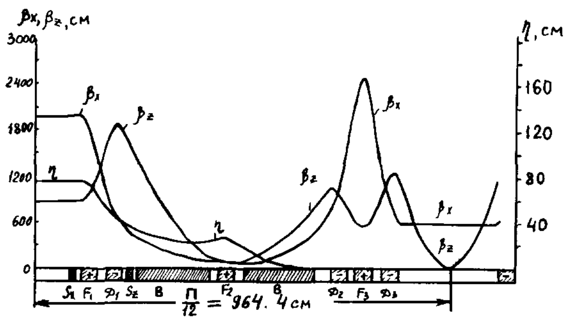

Fig. 4. Lattice functions β_x, β_z and η.

Table 3
The main parameters of the dedicated synchrotron radiation source for technology

Energy, E [GeV]	1.5
Circumference, P [cm]	11572.8
Main radius, R [cm]	1841.86
Dipole bending magnet, $R_{1,2,3}$ [cm]	490.64, 981.28, 1962.57
Bending magnet field, $B_{1,2,3}$ [kG]	10.2, 5.1, 2.55
Bending magnet angle, φ_m	$15° \times 2$
Revolution frequency, f_0 [MHz]	2.5905
Orbital period, T_0 [ns]	386.03
Number of superperiods, N	6
Nominal tunes, ν_x; ν_z	7.731; 7.745
"Undulator" straight section length, L_{ond} [m]	2.5
"Wiggler" straight section length, L_{wig} [m]	3
Momentum compaction, α	8.00×10^{-3}
Chromaticity, ξ_x; ξ_z	−27.5; −30.9
Horizontal emittance, ϵ_x [cm·rad]	2.8×10^{-6}
Vertical emittance (10% coupling), ϵ_z [cm·rad]	2.8×10^{-8}
Damping times τ_z, τ_x, t_s, [ms]	13.76, 14.17, 6.78
Energy spread, σ_E/E	5.66×10^{-4}
Radiation power (without undul. and wigglers), ΔW [keV]	84.2
Harmonic number, k	70
RF peak voltage, U_{RF} [kV]	300
With 2 superconducting wigglers ($B_0 = 45$ kG, $L = 1,5$ m) and lithographic wigglers and undulators:	
Horizontal emittance, ϵ_x [cm·rad]	1.1×10^{-6}
Vertical emittance (10% coupling), ϵ_z [cm·rad]	1.1×10^{-8}
Damping times, τ_z, τ_x, τ_s [ms]	10.07, 10.37, 4.96
Energy spread, σ_E/E	1.0×10^{-3}
Radiated power, ΔW [keV]	115
RF peak voltage, U_{RF} [kV]	400

To compensate the chromaticity for either directions, two sextupole lenses S_x and S_z are positioned in the undulator straight (where $\eta \neq 0$). At the sextupole lenses azimuths the values of betatron functions β_x and β_z are held in the correct relation (see fig. 4).

In fig. 4 graphs are shown of the betatron functions β_x, β_z and of the dispersion η over one half of the superperiod.

The basic parameters of a storage ring for technology are summarized in table 3.

In conclusion of this section the appropriate data are presented revealing the "merit" of the lattices of several storage rings being operated or built. As a "factor of merit" the ratio $2\pi\epsilon_x/C_q\gamma^2$ is taken which does not depend on energy. For the summary see table 4. Part of the data here quoted is taken from ref. 12.

Table 4

Storage ring SR source	E [GeV]	P [m]	ϵ_x [cm·rad]	$2\pi\epsilon_x / C_q\gamma^2$	ν_x	ν_z	Number of superperiods
SPEAR	4	215.3	3.74×10^{-4}	0.2	5.2	5.2	
NSLS	2.5	170.08	8×10^{-6}	0.055	9.7	5.7	8
TSUKUBA	2.5	187.07	41×10^{-6}	0.28	7.25	5.28	
			17.2×10^{-6}	0.12	7.25	3.25	
ALADDIN	1	88.75	68×10^{-6}	2.9	7.15	7.15	
VEPP-3	2.2	74.6	40×10^{-6}	0.35	5.14	5.27	
Technology ring	1.5	115.72	2.8×10^{-6}	0.053	7.73	7.74	6

8. Design of the lattice components

8.1. The quadrupole lenses

These lenses are of C-shaped design and may be horizontally split in the design orbit plane. The design provides for an easy escape of the SR beam.

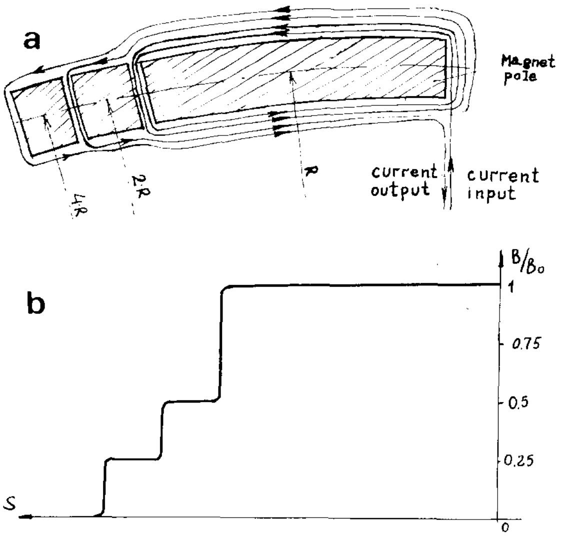

Fig. 5. (a) The scheme of the bending magnet winding which produces the magnetic field relation 1 : 1/2 : 1/4. (b) Magnetic field versus the azimuth.

8.2. The bending magnet

The storage ring lattice comprises 24 bending magnets with 15° bending angle, which are connected in series. The bending magnet design takes account of the following experimental requirements:

1) to provide for utilizing the long wavelength range of the SR spectrum emitted from the magnet so that the hard radiation be of no concern;

2) to provide for the spatial separation of hard photons emitted from the magnets, from the wiggler and undulator radiation;

3) to settle the problem of heat loading on the samples and crystals in soft X-ray performance;

4) to reduce the thermal radiation flux from the magnet edges, that is incident to the straight sections where the superconducting systems (e.g. the wigglers) are to be installed which demand cryogenic cooling.

Thus the magnetic field in the magnet gap varies with the azimuth so that at the magnet edge adjacent to a straight section occupied by a wiggler or an undulator, the field strength drops down to one half and then to one fourth of its maximum value (see fig. 5). This field pattern is created by the special design and positioning of the stir windings while the pole gap is uniform.

Table 5 presents the characteristics of the three sections of the magnet: magnetic fields, bend radii and lengths together with the SR critical wavelengths in these three sections. The scheme of the SR ejection from the bending magnet, the undulator, and of the wiggler is shown in fig. 6. Table 6 presents the values of β_x, β_z,

Table 5
Experimental parameters (E = 1.5 geV, I = 0.3 A)

Section	B [kG]	R [cm]	Length [cm]	λ_c [Å]	$\dot{N}$ [ph/s·mrad·1% $\Delta\lambda/\lambda$]
1	10.2	490.54	111.2	8.12	7.2×10^{13}
2	5.1	981.08	23	16.24	7.2×10^{13}
3	2.55	1962.16	23	32.48	7.2×10^{13}

Table 6

	β_x [m]	β_z [m]	η [cm]	η'	$\sigma_{x\beta}$ [mm]	σ_{xs} [mm]	σ_x [mm]	σ_z [mm]	$\sigma_{x'}$ [mrad]	$\sigma_{z'}$ [mrad]	l [cm]
1	19.26	10.82	75.1	0	0.74	0.43	0.86	0.055	3.8×10^{-2}	5×10^{-3}	250
2	0.50	1.20	12.3	0.22	0.12	0.07	0.14	0.019	0.3	1.7×10^{-2}	
3	5.7	0.10	0	0	0.41	0	0.41	5×10^{-3}	7.2×10^{-2}	5.6×10^{-2}	300

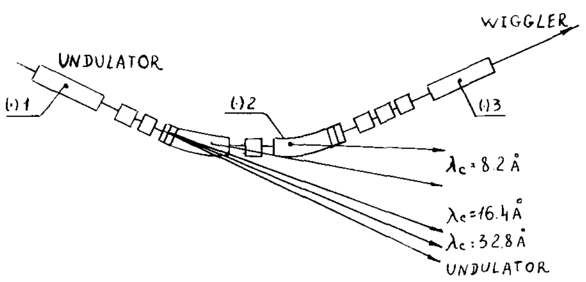

Fig. 6. One half of superperiod. The extraction scheme of SR from the magnet, undulator, wiggler.

η-functions, the standard dimensions σ_x, σ_z and angles $\sigma_{x'}$, $\sigma_{z'}$ of the electron beam in the main SR ejection points.

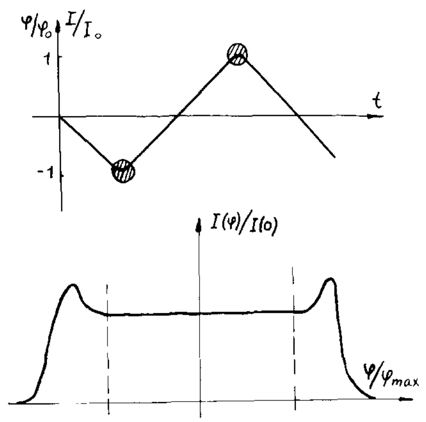

Fig. 8. Illumination distribution over sample area.

9. Sweep system for SR beams emitted from wigglers and undulators

Installation of special sources of synchrotron radiation, namely lithographic wigglers and lithographic undulators, urges the designing of a special SR beam sweeep system capable of transforming the SR beam dimensions at the lithography station to concentrate all the SR beam power in a strip or to distribute it over a rectangle of the desired area. An optimum sweep design which does not reduce the source brightness is shown in fig. 7.

X-ray lithography puts strict requirements on the uniformity of the wafer illumination. To obtain a fairly uniform illumination a linear time dependence of the deflection angle is the best one, and the sweep angle amplitude should be slightly larger than that necessary ($\varphi_{max} > \varphi = a/L$, where a is the sample dimension and L is the distance between the source and the sample), thus avoiding the problems with non-uniform illumination near to the sweep return points. The illumination distribution over the sample area is shown in fig. 8.

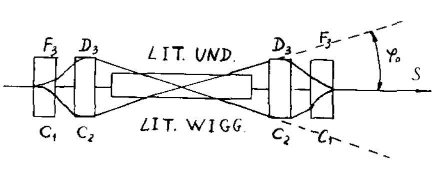

Fig. 7. Sweep system for SR beams emitted from wigglers and undulators.

10. Conclusion

In this report the problems of optimizing the parameters of a storage ring used as a source of SR for a big technological centre of the electronics industry are considered. Perhaps, at individual plants with some specific technology the less universal but compact storage ring is preferable. For X-ray lithography, for example, one can consider, as a possibility, a certain small superconducting storage ring at an energy of 0.5 GeV. The superconducting storage ring at an energy of 3.5–4 GeV may also be optimized for other technologies (medical diagnostics, trace element express analysis).

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