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Section I. SR sources

THE DEDICATED SYNCHROTRON RADIATION SOURCE SIBERIA-2

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A general presentation on the main storage ring of the SRS complex SIBERIA is given. The facility will consist of the 2.5 GeV electron ring SIBERIA-2 with 12 straight sections to accommodate insertion devices. The magnetic lattice is optimized to achieve high brightness of SR. A low horizontal emittance of 7.65×10^{-6} cm rad is obtained.

1. Introduction

At present, in the Institute of Nuclear Physics, Novosibirsk, USSR the dedicated synchrotron radiation (SR) source electron storage ring Siberia-2 [1] is created for the Institute of Atomic Energy (Kurchatov Institute, Moscow, USSR). The facility is intended for experiments with SR in atomic and molecular spectroscopy, in the field of solid-state physics, in crystallography, biology researches, EXAFS spectroscopy of amorphous materials, trace-element analysis, Mössbauer experiments, high-time-resolution experiments, Compton and nuclear spectroscopy.

2. General description

The facility (fig. 1) includes a small storage ring, Siberia-1 (450 MeV), for works in the soft-X-ray and VUV ranges [2] and a main storage ring, Siberia-2 (2.5 GeV), for researches in the hard-X-ray range. The small ring is also used as an injector in the main ring. The injection system consists of a linac (80–100 MeV) and two transport lines for electron beams.

Siberia-2 is optimized to achieve high flux and brightness of synchrotron radiation. The lattice provides:

- installation of high-field superconducting wigglers to produce hard X-radiation;
- installation of undulators to emit bright SR in the soft-X-ray and VUV regions;
- optimization of the parameters of radiation from insertion devices without disturbing operation of the storage ring.

Synchrotron radiation is taken out of the bending magnets and insertion devices of Siberia-1 and Siberia-2. Of the twelve straight sections of the main ring, each about 3 m long, three are occupied by a septum magnet and rf-cavities. The other nine are available for insertion devices.

Minimization of the horizontal electron beam emittance is the most important condition for increasing the spectral brightness. The achievement of low emittance and the optimal betatron and dispersion functions at the source points determines the lattice quite definitely.

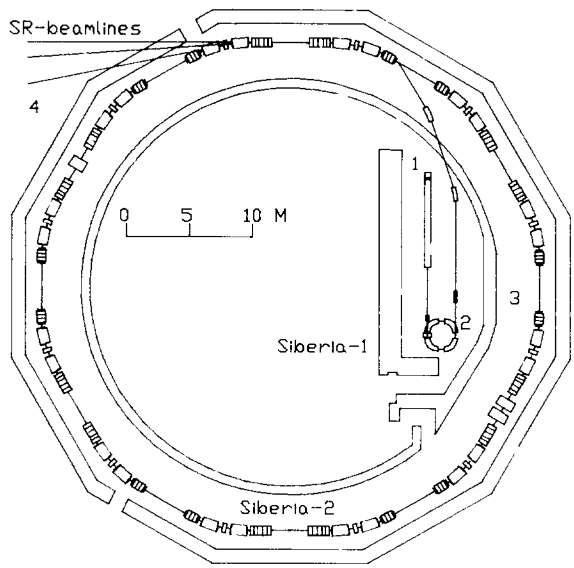

Fig. 1. Schematic of the SR source Siberia-2, showing the injection system (100 MeV linac (1) and 450 MeV booster storage ring Siberia-1 (2)), transport lines, storage ring lattice (3) and SR beam lines (4)

3. Main ring

The magnetic system of Siberia-2 is designed with separate functions. The lattice of the Siberia-2 consists of six mirror-symmetrical superperiods, each containing an achromat bend, and two 3 m long straight sections. As has been shown in ref. [3], for a storage ring with achromats the minimum horizontal emittance determined by quantum fluctuations can be estimated as

$$\epsilon_{x\,\min} = kE^2\phi_m^3,$$

where E is the energy of the electrons, $\phi_m = \pi/N$ the bending angle, N the number of superperiods and k a constant depending on the lattice.

For the chosen magnetic structure of the Siberia-2 we have

$$\epsilon_{x\,\min}[\text{cm rad}] \simeq 10^{-5}(E[\text{GeV}])^2(\phi_m[\text{rad}])^3$$
$$\simeq 7.8 \times 10^{-6}\ \text{cm rad}.$$

From the functional point of view, the half of the superperiod consists of two parts (fig. 2). The first, comprising the quadrupoles F_1, D_1, F_2 and bending magnets, is responsible for achromat bend and high β_x, β_z functions in the undulator straight section. The second part, comprising quadrupoles D_2, F_3, D_3 and a dispersion-free straight section, allows to change the betatron tunes, not disturbing the achromat bend, and to compensate locally for the betatron tune shifts due to the wigglers, preventing rise to noticeable beating in the structural functions on the ring.

Optimization of the behaviour of the horizontal betatron and dispersion functions in bending magnets permits to obtain the minimum emittance. In all magnets $\beta_x \leqslant 3.5$ m, and at the source points it is equal to 2.5 and 0.6 m.

In the undulator straight section the betatron functions are large enough to obtain a low divergent electron beam: $\beta_x = 17$ m, $\beta_z = 6$ m. The dispersion function is small here: $\eta_x = 80$ cm.

High-field superconducting wigglers are located in the dispersion-free straight sections and can be used for reducing the emittance.

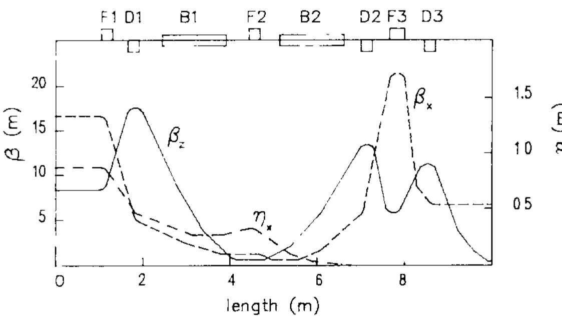

Fig. 2 Lattice functions through one unit cell of a half superperiod.

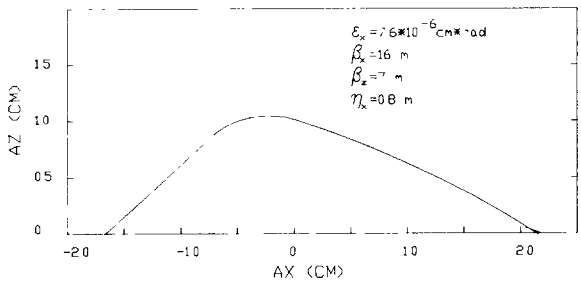

Fig 3. Dynamic aperture of the magnetic structure of Siberia-2.

The vertical β_z-function in the centre of the wiggler section is small (~ 0.5 m). This guarantees a small shift in the vertical betatron tune when installing strong-field wigglers. The horizontal β_x-function is equal to 6 m.

The designed lattice has a relatively small natural chromaticity. To compensate the chromaticity, there are two families of sextupole lenses (in vertical and horizontal directions) in the undulator sections. The necessity of using a large number of sextupoles leads to a limit of the dynamic aperture because of the nonlinear dependence of the betatron tunes on the oscillation amplitudes and the excitation quite power resonances of the third order. The dynamic aperture due to these sextupoles is shown in fig. 3.

The chamber aperture, free for the beam, has been chosen to be equal to ± 30 mm in horizontal and ± 16 mm in vertical planes.

Siberia-2 has a harmonic number $q = 75$ and a momentum compaction factor $\alpha = 0.0076$. This guarantees producing of very short electron bunches ($2.35\sigma_s = 4.4$ cm) necessary for high-time-resolution spectroscopy experiments.

At a large current of stored beam the main effect limiting beam lifetime is the Touschek scattering. The bunch lengthening is likely to be the most effective method of increasing the lifetime. This is achieved by powering an additional rf voltage of a 225th harmonic of the revolution frequency. For this purpose a 541 MHz cavity is put into one of the Siberia-2 straight sections.

Table 1 summarizes the main parameters of Siberia-2.

4. Injection to Siberia-2

The electrons are injected to Siberia-2 at 450 MeV energy in a horizontal plane. The injected beam has an energy spread $\sigma_E/E = 0.39 \times 10^{-3}$ and its horizontal emittance is $\epsilon_x = 8.6 \times 10^{-5}$ cm rad, both being determined by quantum fluctuations of SR. The storage ring Siberia-2 is capable of operating in two regimes: single-bunch ($I = 100$ mA) and multibunch ($I = 300$ mA). The maximum possible bunch repetition rate in

Table 1
Main parameters of Siberia-1

Energy E [GeV]	2.5
Orbit circumference P [m]	124.13
Number of superperiods, N	6
Number of dipoles, N_d	24
Magnetic field in bending magnets, $B_{1,2}$ [T]	0.425; 1.7
Bending radii $R_{1,2}$ [cm]	1962.16; 490.54
Number of quadrupoles, N_q	72
Number of 3 m long sections ($\eta = 0$), N_w	6
Number of 3.18 m long sections ($\eta \neq 0$), N_u	6
Number of sextupoles, N_s	24
Betatron tunes ν_x, ν_z	7.731; 7.745
Momentum compaction factor α	7.6×10^{-3}
Chromaticity ξ_x, ξ_z	−25.3; −22.2
Horizontal emittance ϵ_x [cm rad]	7.65×10^{-6}
Damping times τ_z, τ_x, τ_s [ms]	3.04; 3.14, 1.5
Rms energy spread in the beam, σ_E/E	0.955×10^{-3}
Energy loss per turn (without the wigglers and undulators), ΔW [keV]	681.1
Revolution frequency f_0 [MHz]	2.4152
Rf harmonic number q	75
Rf voltage V_{rf} [kV]	1800
Rf frequency f_{rf} [MHz]	181.14
Current I [mA]	
(a) single-bunch mode of operation	100
(b) multibunch mode of operation	300
Energy aperture $(\Delta E/E)_{max}$	$\pm2\times10^{-2}$
Lifetime (single-bunch mode of operation: $I = 100$ mA and the coupling factor $\kappa \approx 0.2$) due to the Touschek effect, τ_T [h]	~10
Bunch length ($V_{rf} = 1800$ kV, 2 35σ_s) [cm]	4.4

the storage ring is determined by the rf frequency of a cavity, $f_{rf} = 181$ MHz, and the shortest repetition period is about 5.5 ns. Irrespective of the type of injection – to one separatrix or to many neighbouring ones – the beam is stored using the prekick. When designing the scheme of injection, the fact has been borne in mind that, with the achromatic bend incorporated in the superperiod, the betatron phase advance is exactly $\pi/2$, from the beginning of this superperiod to the centre of the lens F_2.

Small residual oscillations of the beam being injected decay with a damping time $\tau_x = 0.54$ s. At the injection energy, the equilibrium sizes of the electron beam are determined by the Touschek effect.

The injection procedure is repeated with a frequency given by the booster, the storage ring Siberia-1. The expected rate of current storage for a circulation of about 100 mA is roughly equal to 10–20 min.

5. Magnet system

5.1. Bending magnet

There are 24 dipole 15° bending magnets of an O-configuration (as shown in fig. 4) which are made of Armco magnetic steel. All magnets are electrically connected in series. The pole of each magnet is divided into two parts: a long one with the main field and a shorter one with a field that is equal to 1/4 of the main field. The shorter part of the magnetic pole adjoins to the long wiggler's or undulator's straight section. So there are 12 left and 12 right dipole magnets. This construction separates spatially the radiation of magnets from that of the wiggler, and also reduces the overheating of the superconducting system in the straight section due to radiation of the magnet edge. The bending magnet cross section and a plan view are shown in fig. 4.

As magnetic measurements have shown, the value of the relative dipole magnetic field strength is $|\Delta B/B| \leqslant 10^{-3}$ in the required radial aperture $2a_x = 60$ mm and sextupole component is less than 3 G/cm^2. To avoid a dependence of the effective length of the bending magnet on the magnetic field amplitude, there are 45° cutoffs having 41 mm for the external edge of the main pole and 38 mm for its enternal edge. With such cutoffs the effective length is equal to the geometrical one.

To compensate for a disbalance between the fields in the long and short parts of the pole due to their non-simultaneous magnetic saturation, there are correcting coils in every magnet on the short part of the pole. The geometrical aperture of the dipole magnet is large enough in the horizontal direction to extract synchrotron radiation both from the magnet itself and from the insertion device located in the straight section.

5.2. Lenses

In the magnetic structure of Siberia-2 there are 72 quadrupole lenses, series-connected in six families with 12 lenses in each family. The quadrupoles of the long straight sections have closed magnetic yokes and are combined in "doublet" and "triplet" magnetic blocks for higher accuracy in their manufacturing and convenience in the survey and alignment. Opposite to the single lenses located in between, the bending magnets have opened magnetic yokes having two C-shaped parts (upper and lower). These are necessary for extraction of the radiation from the superconducting wigglers. All quadrupoles have dipole and gradient correction windings.

According to magnetic measurements the nonlinear dependence of the field gradient on the excitation current arising from the magnetic saturation is less than 8% at a current of 0.8 kA; the relative field gradient is

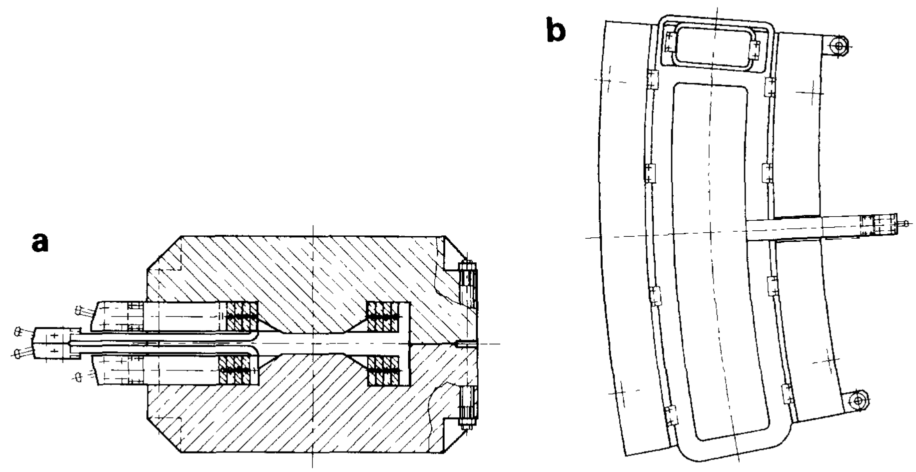

Fig. 4. (a) Storage ring bending magnet cross section. (b) Storage ring bending magnet plan view.

Tabel 2
Main work parameters of the magnetic elements at 2.5 GeV energy

Parameter	Bending magnet	Quadrupole lenses			Sextupole lenses
Number	24	48	12	12	24
Max. magnetic strength	1 7 T; 0.425 T	35 T/m	35 T/m	35 T/m	840 T/m^2
Effective length [cm]	124.3; 16.7	30	40	31.5	11
Aperture gap or diameter [mm]	42	56	56	56	59
Bending radius [m]	4.906, 19.626	–	–	–	–
Max. current [A]	7200	680	760	680	25
Power [kW]	22.8	4.36	6.51	4.36	0.545
Cooling	water	water	water	water	

$|\Delta G/G| \leqslant 10^{-3}$ within a circle aperture of 2 cm in radius at the maximum gradient value.

The quadrupole is designed so that SR beam with the horizontal size being equal to ± 5 cm can pass through its vacuum cham[illegible]

Besides the main m[illegible]ents, there are four families each incorporat[illegible]les (the first two families compensate for na[illegible]ically and the second two families, located i[illegible] free area, increase the dynamic aperture), [illegible]tupole families for controlling the cubic [illegible]nd skew-quadrupole coils at octupole yokes [illegible] the vertical beam size.

Table 2 summarizes the main work parameters [illegible] magnetic elements at the energy of 2.5 GeV.

6. Vacuum system

Aluminium vacuum chambers in bending magnets and lenses are built by using extrusion techniques. A vacuum of 3×10^{-9} Torr (in nitrogen equivalence, $z \simeq 7$) is required to obtain a beam lifetime of ~ 10 hours with an electron current of ~ 0.3 A. The photon-induced desorption defines the pumping rate at 72 000 l/s. The radiated power at the energy of electrons, 2.5 GeV, and a current of 0.3 A is 34 W in 1 mrad of horizontal angle.

There are 62 complex pumps (pumping ~ 1000 l/s) that consist of a magnetic-discharged pump and a titanium sublimator pump and 12 separate titanium sublimator pumps which can pump 200 l/s.

To obtain the required pressure in rf-cavities, two special titanium sublimator pumps (pumping 3000 l/s [illegible]ch) and two magnetic-discharged (700 l/s each) are in [illegible]

[illegible]leaning of the surface of the vacuum chamber [illegible]ut at a temperature of 160 °C for the a[illegible]part and 300 °C for the steel parts during 24 hours. [illegible]ter that, only synchrotron radiation cleaning takes place. We hope that the total integral of electron beam current, ~ 50 A h, maintains a vacuum lifetime of

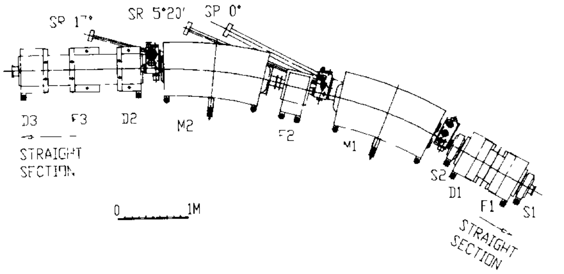

Fig. 5. Plan view of one sector of the storage ring, showing radiation transmitted to the beam lines.

~ 10 hours. The different parts of the vacuum chambers are separated from each other by 24 automatic shutters. The separation of the SR vacuum lines and the storage ring vacuum system is realized by means of analogous shutters.

7. Rf-system

The rf-system of Siberia-2 provides a 1.8 MV voltage on two accelerating cavities with 181 MHz frequency. The power for compensating radiation losses is ~ 300 kW at 2.5 GeV with a maximum beam current of 300 mA. The loss power in the cavity walls is 90 kW. So, the total output power of the rf-generator is 400 kW. In order to get high reliability, the rf-system has two channels with independent cooling, supply, safe and control. The total power consumed by rf installations is 1.2 MW.

Accelerating cavities are made of copper, cylindrical type. They are excited by E_{010} type oscillation. The tuning of the cavities is carried out by the bend of plain walls with the help of electric motors.

8. Main parameters of the Siberia-2 source

Synchrotron radiation from Siberia-2 is taken out of the bending magnets (beams of 5°20′ and 17°, fig. 5), the wiggler straight section (section 1) and the undulator straight section (section 2) identically in each super-

Table 4
SR beam parameters of Siberia-2

Max. electron energy [GeV]	2.5
Max. stored current [mA]	
– single bunch mode	100
– multibunch mode	300
SR spectral range [Å]	2000–0.1
Characteristic wavelength of SR, λ_c [Å]	
– from bending magnet	1.75, 7
– from superconducting 3-pole wigglers	0.25–0.4
– from undulators	20
Pulse duration of SR [ns]	0 14
Time interval between SR-pulses [ns]	5 5–414
Number of beam lines	
– from bending magnets with horizontal angles of ±5 mrad	24
– from two superconducting 3-hole wigglers with horizontal angles +1°40′ – –1°20′	10
– from undulators	up to 5

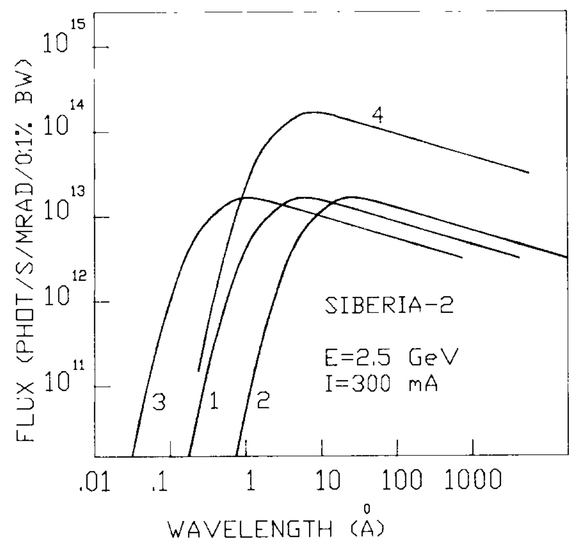

Fig. 6. Spectral flux as a function of the wavelength of photons for a bending magnet at a field of about 17 kG (1) and 4.5 kG (2) strength, for a 3-pole superconducting wiggler at a field strength of 120 kG (3) and for a 20-pole undulator at a field strength of 17 kG (4).

Table 3
Values of some parameters of the electron beam in radiation points ($E = 2.5$ GeV, $\nu_z = 7.745$, $\nu_x = 7.731$, $I = 300$ mA, $\kappa = 0.01$, $\epsilon_x = 8\times10^{-6}$ cm rad, $\epsilon_z = 8\times10^{-8}$ cm rad, $\sigma_E/E = 0.96\times10^{-3}$)

Radiation point	β_x [m]	β_z [m]	η_x [cm]	η' [mrad]	$\sigma_{x\beta}$ [mm]	σ_{xs} [mm]	$\sigma_{x\,tot}$ [mm]	$\sigma_{x'}$ [mrad]	$\sigma_{z'}$ [mrad]	$\sigma_{z\,tot}$ [mm]
Section 1	17.3	6	75	0	1.18	0.72	1.38	$\sigma_{z\,tot}$	0.017	0 070
5°20′	2.5	8.25	30	−40	0.45	0.29	0.53	0.18	0.010	0.08
17°	0.58	1.75	14	−230	0.22	0.13	0.26	0.44	0.021	0.037
Section 2	6.5	0.25	0	0	0 72	0	0.72	0.11	0.056	0.014

period (see fig. 5). The values of β- and η-functions, and the mean-square dimensions and angles of the electron beam in radiation points are shown in table 3. Parameters of the SR beams of Siberia-2 are shown in table 4.

There are two types of beam lines on Siberia-2: one type for hard X-rays and another for ultraviolet and soft X-rays. In fig. 6 one can see the dependence of the photon flux at the interval $\Delta\lambda/\lambda = 10^{-3}$ per 1 mrad of horizontal angle per second on wavelength for radiation from the bending magnet with 1.7 and 0.425 T fields (curves 1 and 2, respectively), from 3-pole superconducting wigglers with a 12 T field (curve 3) and from a 20-pole wiggler with a 1.7 T field (curve 4).

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