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Compact storage rings Siberia-AS and Siberia-SM synchrotron radiation sources for lithography

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The paper deals with two projects of compact superconducting storage rings for industrial production of integrated circuits (IC) using x-ray lithography within the 8- to 20-Å wavelengths range. The azimuthally symmetric superconducting storage ring Siberia-AS at an energy of 600 MeV is a superconducting analog of VEP-1, one of the earliest storage rings in the world intended for the purposes of high-energy physics. Unlike the conventional design, no iron yoke is used in the storage ring under consideration to form the magnetic field at the equilibrium orbit and to close the return magnetic flux—this is performed by some inner and outer superconducting windings. Such a scheme enables the size of the storage ring to be substantially reduced (a cylinder of 2 m in diameter and 2 m long), and as a result, its weight decreases, too (about 10 tons). The eight-magnet storage ring Siberia-SM is of four-order symmetry so that the periodicity element comprises two rectangular magnets and three lenses. Its basic component is a superconducting bending rectangular magnet at a 6-T magnetic field. Two variants of such magnets have been proposed: in the first, the iron yoke is utilized to form the magnetic field and to close the return flux, while the second is an ironless C-shaped magnet manufactured on the basis of original wedgelike coils.

INTRODUCTION

The basic criterion for comparison of the quality of x-ray sources is the brightness determining the exposure time:

$$\tau \sim 1/B_\lambda \delta^5. \quad (1)$$

Here B_λ is the brightness of a source and δ is the minimal size of the structure.

In this parameter, dedicated storage rings—the sources of synchrotron radiation—have no equal.[1]

Electron storage rings with conventional bending magnets made of room-temperature iron and designed for the optimal range of wavelengths are rather bulky and, as a result, have a great weight and a great power consumption. The changeover to superconducting bending magnets with a field of 4–6 T enables the storage ring circumference to be reduced by a factor of 2–3, the power consumption by the same factor, and the working and injection energy by a factor of 3–4.[2]

I. AZIMUTHALLY SYMMETRIC RING SIBERIA-AS

The azimuthally symmetric storage ring (Fig. 1) is analogous to the storage ring VEP-1, one of the earliest storage rings in the world that operated at the Institute of Nuclear Physics (Novosibirsk) in the 1960s.[3]

For the given spectral range, the parameters of the storage ring may be conveniently optimized by expressing the basic acceleration formula in terms of λ_c and B, the spectral characteristics of radiation and the value of the guiding magnetic field. So the energy and the equilibrium radius of an orbit may be expressed as follows:

$$E\ (\text{MeV}) \approx 4316 \lambda_c^{-1/2} B^{-1/2}, \quad (2)$$

$$R_0\ (\text{cm}) \approx 1439 \lambda_c^{-1/2} B^{-3/2}. \quad (3)$$

Here and below λ_c is measured in angstroms and B in Tesla.

The injection energy is determined by the damping time of residual oscillations of the injected electrons. For this pur-

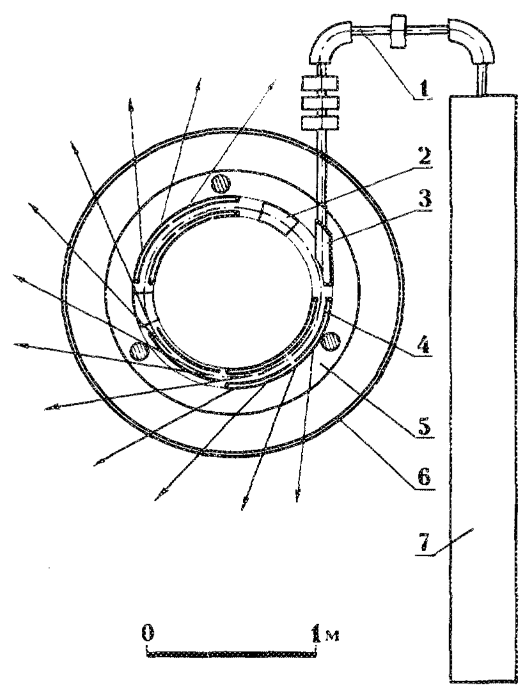

FIG. 1. The general view of the azimuthally symmetric storage ring Siberia-AS: 1, electron-beam transfer line; 2, magnetic field correction windings; 3, compensating magnet for injection; 4, rf resonator; 5, cryostat; 6, magnetic screen; and 7, linac.

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pose, it is convenient to use the relation

$$E_{inj}\ (\text{MeV}) \approx 3.62\tau^{-1/3}\ (\text{s}) R_0^{2/3}\ (\text{cm}). \qquad (4)$$

The required voltage at the accelerating gap of a rf resonator, and the power dissipated in the resonator are determined by the energy losses per turn, expressed as

$$\Delta W\ (\text{keV/turn}) \approx 2138\lambda_c^{3/2} B^{-1/2}. \qquad (5)$$

The horizontal emittance of the beam is found from the relation

$$\epsilon_x\ (\text{cm rad}) \approx \frac{2.74\times 10^{-3}}{\lambda_c B n \sqrt{1-n}}, \qquad (6)$$

where n is the field index.

The total radial size of the electron beam may be estimated by the formula

$$\sigma_x\ (\text{cm}) \approx \frac{3.43\lambda_c^{-3/4} B^{-5/4}}{\sqrt{n(3-4n)}}. \qquad (7)$$

In this scheme, the storage ring is an azimuthally symmetric magnet in which the return magnetic flux is closed through the inner parts of the ring without the use of an iron yoke and this is realized at the expense of an optimal arrangement of superconducting coils. The inner and outer coils are switched on in such a way that the magnetic flux outside the windings is small and is completely trapped by an iron screen 2 cm thick at a distance of about 1 m from the center of the storage ring (Fig. 2).

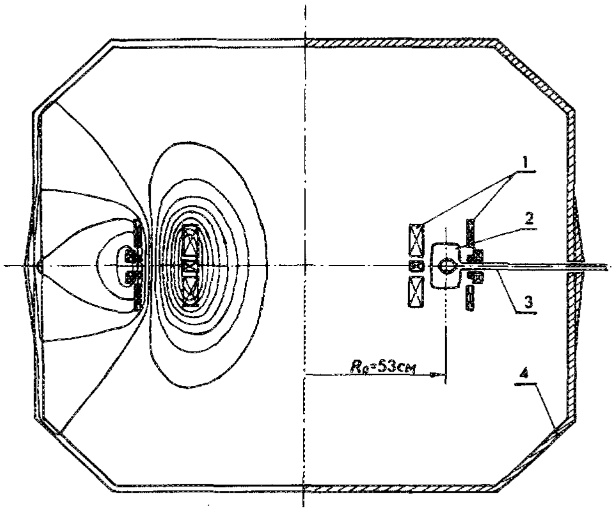

FIG. 2. Location of the windings and the magnetic field configuration in the azimuthally symmetric storage ring: 1, superconducting windings; 2, vacuum chamber; 3, SR extraction chamber; and 4, magnetic screen.

Despite a smooth decrease of E, R_0, E_{inj}, ΔW, ϵ_x, and σ_x as the field increases [see expressions (2)–(7)], there exists an optimal value of B at which the magnetic induction at the

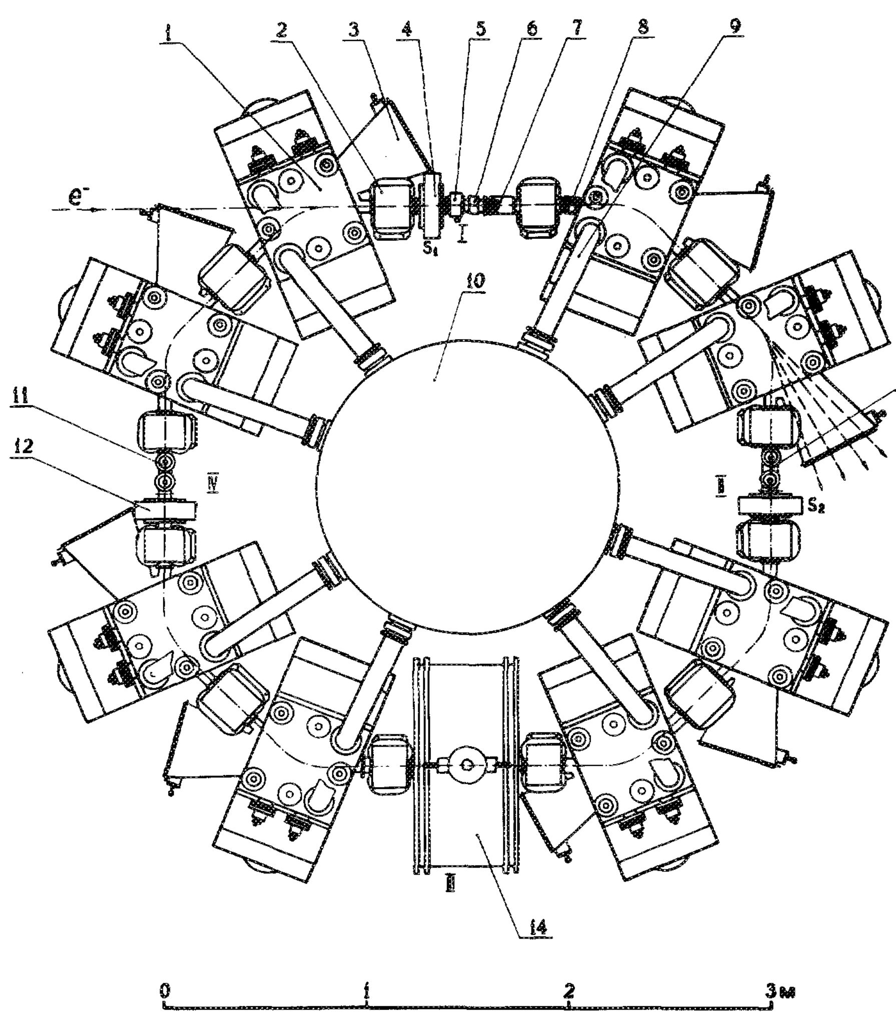

FIG. 3. The general view of the eight-magnet storage ring Siberia-SM: 1, superconducting magnet; 2, quadrupole lens; 3, SR extraction line; 4, sextupole lens; 5, monitor of the beam current; 6, meter of betatron oscillation frequencies; 7, 40° septum magnet; 8, 4° septum magnet; 9, helium pipeline; 10, cryodistributer; 11, preinflector; 12, octupole lens; 13, inflector; and 14, rf resonator.

windings does not exceed an admissible value of B_{max}.

The field index n does not vary in going from the regime of injection ($E_{inj} = 50$ MeV) to that with a maximum energy ($E = 600$ MeV) and equals 0.54. Such a value of n is convenient for injection.

The equilibrium orbit curvature radius $R_0 = 53$ cm and magnetic field $B = 3.8$ T have been chosen taking the restrictions on B_{max} into account. Location of the windings and the current distribution in them provides the required dependence of the vertical component B_z of the magnetic field on the radius within the 30×40-mm² vacuum chamber of the storage ring:

$$B_z \approx B_0 (R_0/R)^n.$$

The inner and outer windings are in separate cryostats with free space between them to place a vacuum chamber, correcting magnets, rf resonators, an inflector, and a compensating system for injection.

Injection is performed in the radial plane with the use of a pulse compensating system similar to the injection system of VEP-1. The working frequency of radial betatron oscillations is chosen near the resonance $\frac{2}{3}$, thereby offering the possibility of using a simple injection scheme, accumulation being carried out by means of one inflector with a pulse duration of three turns.

The injection energy has been taken equal to 50 MeV, and this corresponds to a 1-s damping time. The frequency of electron storing is 1 Hz.

The compensating system consists of a pulsed ironless septum magnet with a thin knife and a screening tube which traps the edge field of the magnetic system and thus eliminates its influence on the injected beam.

The rf system comprises two resonators operating at a frequency of 180 MHz, which corresponds to the second harmonic of electron revolution frequency in the storage ring. Each resonator consists of two quarter-wave coaxial sections. As has already been mentioned, formula (5) describes the energy losses per turn. It is seen from it that if the necessity arises to obtain harder radiation from the storage ring, the major difficulties will be caused by resonator cooling. The design voltage in the accelerating gaps of each resonator is about 35 kV for a dissipated power of about 3 kW.

The operating energy of the storage ring is about 600 MeV, which corresponds to a SR wavelength from a bending magnet of about 13.6 Å. At 300 mA maximum current stored in the ring the total SR power along the circumference will be 6.5 kW.

II. EIGHT-MAGNET STORAGE RING SIBERIA-SM

This type of the storage ring[2] is larger in dimensions (10-m circumference) and weight (about 20 tons). However, the beam quality is considerably better, which is achieved by strong focusing using the lenses and the edge field of bending magnets.

The magnetic system of this storage ring comprises four superperiods, each having two superconducting 45° bending magnets, three quadrupole lenses placed mirror symmetrically, and a straight section (Fig. 3). Bending magnets are of the rectangular type with parallel edges and are designed for a maximum magnetic field of 6 T. Such magnets create a strong edge focusing in the vertical direction, and all the quadrupole lenses focus in the radial direction.

The magnetic structure was optimized by means of a computer with the aim at achieving a minimum emittance and circumference assuming the possibility of a single-turn injection in the vertical direction.

The superconducting magnet is referred to the most complicated elements of the storage ring since all the others have no fundamental difference from those used in room-temperature facilities. Two versions of the magnets are being designed. In the first magnet, the iron yoke is used to form the field of needed quality at the injection energy and to close the return magnetic flux. This magnet includes three superconducting windings. Figure 4 shows the cross section of its cold part placed into a cryostat. The slope angle of the pyramidal coil 1 is chosen such that the iron 5 does not saturate outside it and, hence, has no influence on the field configuration in the aperture.

The second version of the magnet has no iron components to form the magnetic field. The latter is generated by currents in five superconducting wedgelike coils forming a C-shaped closed magnet (Fig. 5). In fact, the magnet is a closed solenoid where the force lines of the magnetic field are refracted on the current surfaces sloped at an angle of 45°.

The values of betatron frequencies ν_x and ν_z are taken equal to 2.6 and 1.12, respectively. In this case, a minimum

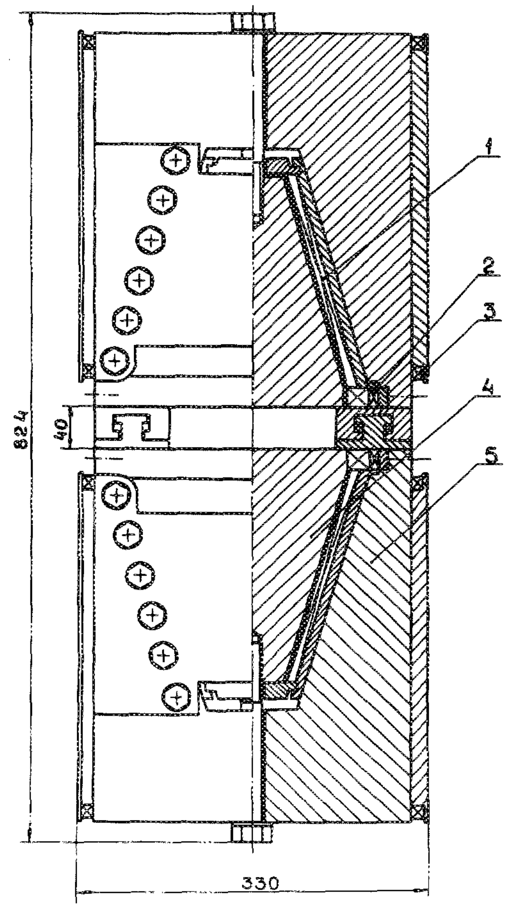

FIG. 4. The general view of an iron superconducting magnet (without the yoke closing the return magnetic flux): 1, basic winding; 2, additional winding; 3, compensating winding; and 4 and 5, iron yoke.

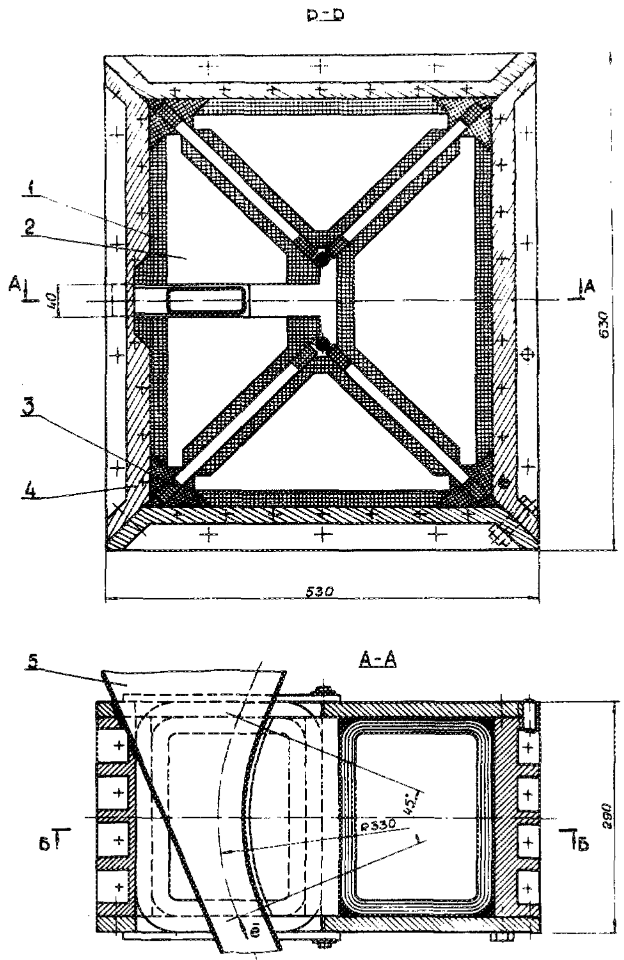

FIG. 5. The general view of an ironless superconducting magnet: 1, basic winding; 2, frame of the winding (glass-cloth-base laminate); 3, compensating winding; 4, bandage; and 5; vacuum chamber.

horizontal emittance of $\epsilon_x = 8.5\times10^{-6}$ cm rad is provided at 600 MeV of energy, and optimal conditions for a one-turn injection in the vertical direction are created.

The excited oscillations of the stored beam by preinflector are completely compensated in an inflector. The injection frequency of electrons is 0.5–1 Hz at the 60-MeV.

The rf system of the storage ring operates at a frequency of 30 MHz, which corresponds to the first harmonic of the revolution frequency. The resonator is of the coaxial type, vacuum, quarter-wave; its accelerating voltage is up to 100 kV and the maximum power fed from a rf generator is 40 kW. The full radiated power at a current of 300 mA is 10.3 kW.

TABLE I. Main characteristics of the storage rings.

Type of a storage ring	Azimuthally symmetric	Eight-magnet
Energy (MeV)	600	600
Circumference (m)	3.33	10
Magnetic field (T)	3.8	6
Betatron frequencies: ν_x	0.678	2.6
ν_z	0.753	1.12
Horizontal emittance: ϵ_x (cm$\times$rad$\times10^{-6}$)	146	8.5
Horizontal size of the beam σ_x (mm)	1.3	0.4
Losses per turn (keV)	22	31.6
Revolution frequency (MHz)	90	30
Current (mA)	300	300
Life time at 300 mA (h)	6	4.4
Critical wavelength (Å)	13.6	8.6

III. CONCLUSION

For comparison, Table I lists the parameters of both versions of the storage ring.

In recent years the construction of technological SR centers for solution of applied problems in microelectronics is in progress.

The projects of medical SR centers where dedicated compact medical storage rings for 1.2–1.8 GeV of energy will be employed are being discussed as well. It seems promising to use in such storage rings superconducting rectangular magnets which have been designed for lithographic purposes. After they are put into production their cost will be substantially reduced.

[1]G. N. Kulipanov and A. N. Skrinsky, Usp. Fiz. Nauk **122**, 369 (1977).
[2]V. V. Anashin, *et al.*, Project of the storage ring Siberia-SM, Preprint INP 88-96, Novosibirsk, 1988.
[3]International Conference on High Energy Accelerators, p. 389, 5th, Frascati, 1965.