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Compact hard X-ray synchrotron radiation source based on superconducting bending magnets

E.I. Antokhin, A.A. Gvozdev, G.N. Kulipanov, P.V. Logachev, N.A. Mezentsev, V.E. Panchenko, A.V. Philipchenko, Y.V. Rakshun, A.V. Utkin, N.A. Vinokurov, K.V. Zolotarev*

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

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Abstract

The unique properties of synchrotron radiation (SR) account for its wide usage into fundamental, applied and technological investigations. Large growth of the number of SR applications in technological processes and medical diagnostics has been observed recently, which makes the problem of developing compact and relatively cheap SR sources very actual.

A good progress of Budker Institute of Nuclear Physics (BINP) in the field of fabrication of different superconductive devices for SR generation may give rise to a new tendency in the design of compact SR sources. Indeed, the 9 T superconducting bending magnet fabricated at BINP for the BESSY-2 storage ring is a good candidate for the main element of the magnetic structure of a compact SR machine.

The development of compact hard X-ray SR source started at BINP. This work involves analysis of possible implementation of compact SR sources in industry, medicine and education. Main SR parameters meet the requirements of most popular research application methods. These parameters became a basis for determination of main parameters of storage ring and allowed us to propose a possible scheme of storage ring.

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1. Introduction

Development of compact and low-cost SR sources of hard (up to 50 keV) X-rays is an actual task for further application of the advanced X-ray methods in industry, medical centers, hospitals, small scientific centers and universities. Application of superconductive bending magnets allows solving this task with relatively small electron beam energies in a storage ring. Economically, a high cost of the magnetic system of such a storage ring can be compensated by cheaper injector, RF and protection systems and abrupt decrease of expenses for construction of the infrastructure of the complex. Low beam energy simplifies reduction of the emittance value and permits increasing spectral brightness of the source as compared with a high-energy storage ring with a magnetic system of a similar type.

The concept of compact SR source using superconducting magnets has been realized in different projects (AURORA, NIJI-3, SXLS, Helios, Super-ALIS, etc.) (see Refs. [1,2]) in the 1990s. However, these projects were aimed at generation of VUV and soft X-rays, which did not allow using such installations for research in the hard X-ray region.

In 1992, a prototype of superconducting bending magnet with a working field of 6 T was fabricated and successfully tested at Budker INP. It was decided to organize manufacture of such bending magnets for future creation of compact SR sources consisting of superconducting and

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*Corresponding author. Tel.: +7 383 339 4103; fax: +7 383 330 7163.
E-mail address: zolotarev@inp.nsk.su (K.V. Zolotarev).

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conventional bending magnets [3,4]. Unfortunately, these projects were not realized because of serious problems in Russian economics at that time.

In 2001, a project for design and fabrication of a 9 T superconductive bending magnet (Superbend) was started in the framework of collaboration between Budker INP and BESSY. In 2003, the Superbend was successfully tested and a field of 9.37 T was obtained. After some work to minimize heat inleak in the cryostat and reduce liquid helium consumption, the magnet was successfully commissioned at the BESSY site. The maximal field value of 9.6 T was achieved in 2004 during site acceptance tests at BESSY [5].

The successful commissioning of the superconducting bending magnet confirmed reliability of the BINP technology and allowed creation of a compact SR source of hard X-rays on the basis of such magnets. This project was started at Budker INP in 2006.

Besides, Siberian Synchrotron Radiation Center (SSRC) at Budker INP unites a lot of SR users from Siberian Branch of Russian Academy of Science and other organizations. SSRC has good experience in organization of large user communities, and has the infrastructure required for research [6]. But the main problem of SSRC is the absence of a specialized SR source. This project can be considered as a way of noticeable up-grade of this center. Thus, development of such compact and bright SR source is really a very actual task.

2. Required SR source parameters

To meet most SR users' requirements and select main machine parameters, the most popular SR methods have been specially analyzed. Then, the main storage ring parameters were correspondingly optimized. Some basic ideas of parameter selection are described in this chapter.

Hardness of the SR spectrum is an important feature of such a system. The world experience in SR application at different SR centers demonstrates that the most popular research methods use X-radiation with photon energy as high as 50 keV. Harder X-rays, as a rule, are not required in popular research techniques.

For example, the most popular EXAFS spectroscopy technique (and its numerous modifications) does not use photons with energy more than 40 keV. The reason is that the natural width of the core levels of atoms with electron-bonding energy more than 40 keV becomes compatible with the period of EXAFS oscillations, which leads to abrupt reduction of the amplitude of oscillations and makes their registration in experiments much more difficult.

The same conclusions can be made for the X-ray diffraction methods. The typical dimensions of elementary cells of most crystalline materials are several Angstrom units (Å). Therefore, these structures can be studied with quanta with a wavelength of the order of 0.5 Å, i.e. with energy less than 25 keV (even for reflexes with high Muller indexes).

Availability of quanta with energy about 50 keV allows one to perform X-ray fluorescent element analysis of practically all elements of the periodic table. This non-destructive method of analysis is very popular in the study of composition and spatial distribution of elements in technology, biology and environmental samples.

It would be fair to note that there are a number of introscopy methods that require X-ray quanta energy of 120 keV and higher. Such requirements arise in the medical and engineering X-ray introscopy and tomography. However, no simple and cheap methods to generate a high-power photon flux have been found yet; as a result, these techniques have to be excluded from the list of methods realizable at such storage rings.

It should also be noted that, in spite of the increasing interest of users in the hard X-ray range, research and technological methods in the soft X-ray range are still developing. For instance, a relatively new method of mass micromanufacturing (the LIGA technology) is based on application of SR of a typical energy about 2 keV. Therefore, a right strategy to choose the scheme of compact storage ring should provide the possibility of arranging beamlines for extraction of SR both with the hard X-ray and soft X-ray spectrum.

It seems that the most adequate facility meeting these requirements should include a combined structure of magnetic system, with both superconductive and normal magnets. An advantage of such a scheme is the possibility to avoid excessive "compactness" of the storage ring, which gives sufficient freedom in designing beamlines for SR extraction.

Taking into account previous considerations, it is possible to define the optimal number of superconductive magnets in the structure. A large number of such magnets will significantly increase the cost of the facility, while few magnets will worsen the symmetry of the ring and create beam dynamics problems because of rise of dangerous resonances. It will also decrease the total cost efficiency, because of fewer hard X-ray beamlines, which is still a figure of merit of this project. Thus, the optimal number of superconductive magnets in the ring is four or six.

Electron energy in the storage ring may be 1–1.5 GeV, i.e. also close to the optimum for arrangement of the system for injection and biological protection shield. In so doing, in superconductive magnets with a field of 8.5 T the critical energy of SR quanta will be about 10 keV, which provides a photon flux sufficient to realize the above-mentioned methods in the spectrum range up to 50 keV. Besides, with the application of "warm magnets" to generate SR in the soft X-ray range it is also possible to meet users' requirements in this spectral region.

If electron energy is 1.2 GeV, and the efficient magnetic length of a superconductive magnet with a field of 8.5 T is 20 cm, the beam-bending angle in a magnet is about 20°. That means that three or four channels can be extended from the magnet without any difficulties in designing.

Table 1
Main parameters of a compact storage ring—SR source (requirements)

Parameter	Value
Electron energy	1.2 GeV
Critical energy of SR quanta	8.16 keV for SR from superconductive magnets (8.5 T) 1.6 keV for SR beams from normal magnets (1.65 T)
Number of bending magnets	6 superconductive magnets 12 conventional magnets
Number of SR beamline	18 with hard X-ray spectrum 6–10 with soft X-ray and VUV spectrum
Beam phase-space volume	10 nm rad
Beam current	800–1000 mA
Beam lifetime	8–10 h
Orbit perimeter	<60 m
Size of a hall for the storage ring facility	20 × 20 m (without the space required for users' stations)

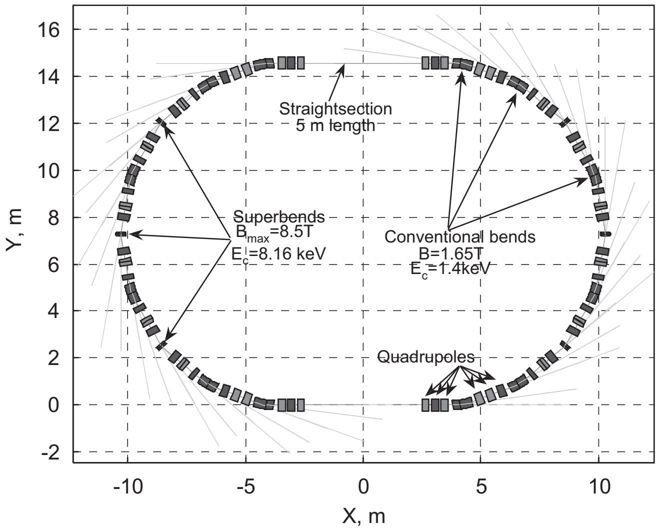

Fig. 1. Possible schemes of compact SR source.

Therefore, the efficiency of usage of the storage ring resources may be very high.

Of course, a typical list of users' requirements (or preferences) includes high source brightness and high stability of photon flux during the whole beam shift time. So, a top-energy beam injection system that allows keeping beam current on the same level with a few percent variations is also very desirable.

Though the main device for SR generation in this machine is the Superbend magnet, and the beam emittance value is not as important for source brightness maximization as in the case of undulator source, it would be desirable to analyze the ways of emittance minimization. Since the value of equilibrium horizontal emittance is proportional to the square of beam energy, a relatively low working energy provides a significant simplification of emittance reduction, and permits achieving a third generation SR source typical value of about 10 nm.

The storage ring perimeter cannot exceed 60 m. Thus, a room for such a center may be 20 × 20 m in size, though arrangement of users' stations requires some additional space.

All the above preferences or requirements to such storage ring are summarized in Table 1.

3. Possible scheme of compact storage ring

To show realizability of all the above-mentioned ideas, a scheme of such a system was suggested. A general view of the complex is presented in Fig. 1. The ring perimeter is 56 m, and a 17 m × 22 m hall can accommodate such storage ring. This variant allows organization of as many as 18 channels for hard-spectrum SR extraction and of a rather large amount of channels for the soft X-radiation.

Fig. 2 presents the optical functions of the suggested scheme. Magnets and quadrupole lenses are arranged in accordance with the theoretical minimal emittance (TME) lattice requirement, as far as it is possible for such compact lattice. The structure has a racetrack shape and consists of two arcs and two 5-m long straight sections. Each of the arcs includes three Superbends and six conventional bends. Bending angles in all the magnets are the same and equal 20°. The edge arc bends work as dispersion suspensors; they provide zero dispersion in the straight section. The Superbends are separated with conventional magnets, to prevent intersection of beamlines from a Superbend with the cryostat of next one.

The computed horizontal beam emittance is 11 nm rad. Thus, this facility can be classified like the most compact among the third generation SR sources.

Of course, this design is only a first proposal and covers only the stage of linear optimization of lattice optics. A lot of problems of non-linear beam dynamics are complicating implementation of this scheme. But this example shows the main direction for design optimization.

Since bending angles in the magnets are big enough, several beamlines can be extended from one magnet, three beamlines in this design. In this case, the central beamline takes SR from the center of the Superbend, where the magnetic field is maximal. The angle between neighbor beamlines is 5°, which provides enough space for users. Since the field at irradiation points in side channels is about 8 T, spectral parameters of SR of these beamlines do not differ much from those of the central one. The same angle was selected for beamlines from the normal conducting magnets.

4. Brief subsystems description

Other subsystems of this facility can be built in accordance with standard Budker INP approaches and

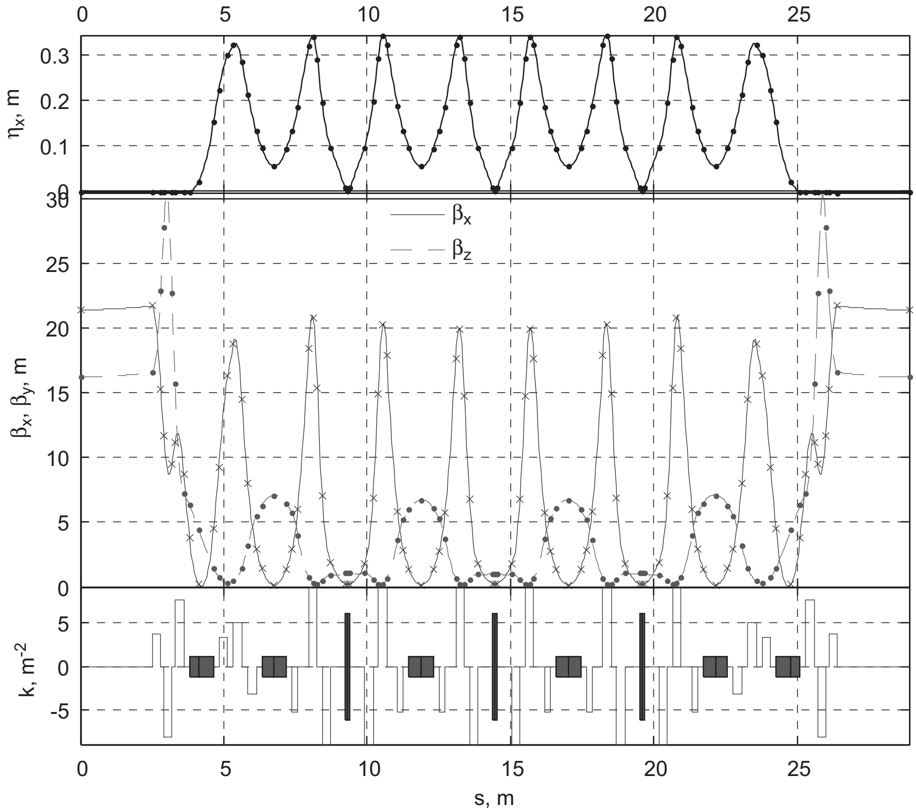

Fig. 2. Optical functions in one superperiod of a compact SR source.

technologies. Most of these components already have working prototypes and thus can be used after small modifications.

The injector system will include a 150 MeV linac and a booster synchrotron for full-energy (1.2 GeV) injection.

A special electron and positron source as a universal injector facility was created and commissioned at BINP [7]. The fist section of this facility can be used in the current project as an initial electron beam source. It contains two sections of the linear accelerator structure that can accelerate electron bunches up to 150 MeV. All parameters of this linac meet the booster injection requirement, so it was decided to use this system.

The booster takes the electron beam from the linac and accelerates it up to 1.2 GeV, for full-energy injection into the main ring. The booster will be similar in design to the booster produced at BINP for Duke University (North Carolina, USA) [8].

Standard RF cavities used at Budker INP, with high-order mode suppression and a frequency of 180 MHz, will be installed in the booster and main ring. In spite of big dimensions of the system, relatively long bunches formed by these cavities will help to decrease intrabeam scattering and increase the beam life time.

The facility will be located in an already existing building of Budker BINP. Fig. 3 shows a possible layout of the injector system, storage ring, beamlines and experimental stations for users. A median plane of booster synchrotron and linac will be located in 1 m lower than median plane of main ring. This building is being reconstructed now. Some stations will be placed in a building extension to be created later.

Altogether 18 experimental stations will be installed on beamlines from the Superbends. They will use SR in the hard X-ray region. The most popular X-ray research techniques will be presented, XAFS, XRD and XRF among them. Also six beamlines will use SR from the conventional bends. Thus, some research techniques in the soft X-ray and VUV regions will also be implemented.

5. Conclusions

Modern technology for fabrication of superconductive bending magnets can be effectively used to create a compact SR source with hard X-ray spectrum. The relatively small beam energy of such storage ring simplifies meeting a number of important requirements for biological protection, injection system and emittance minimization.

BINP has great experience in development and creation of different accelerators. All necessary technologies for

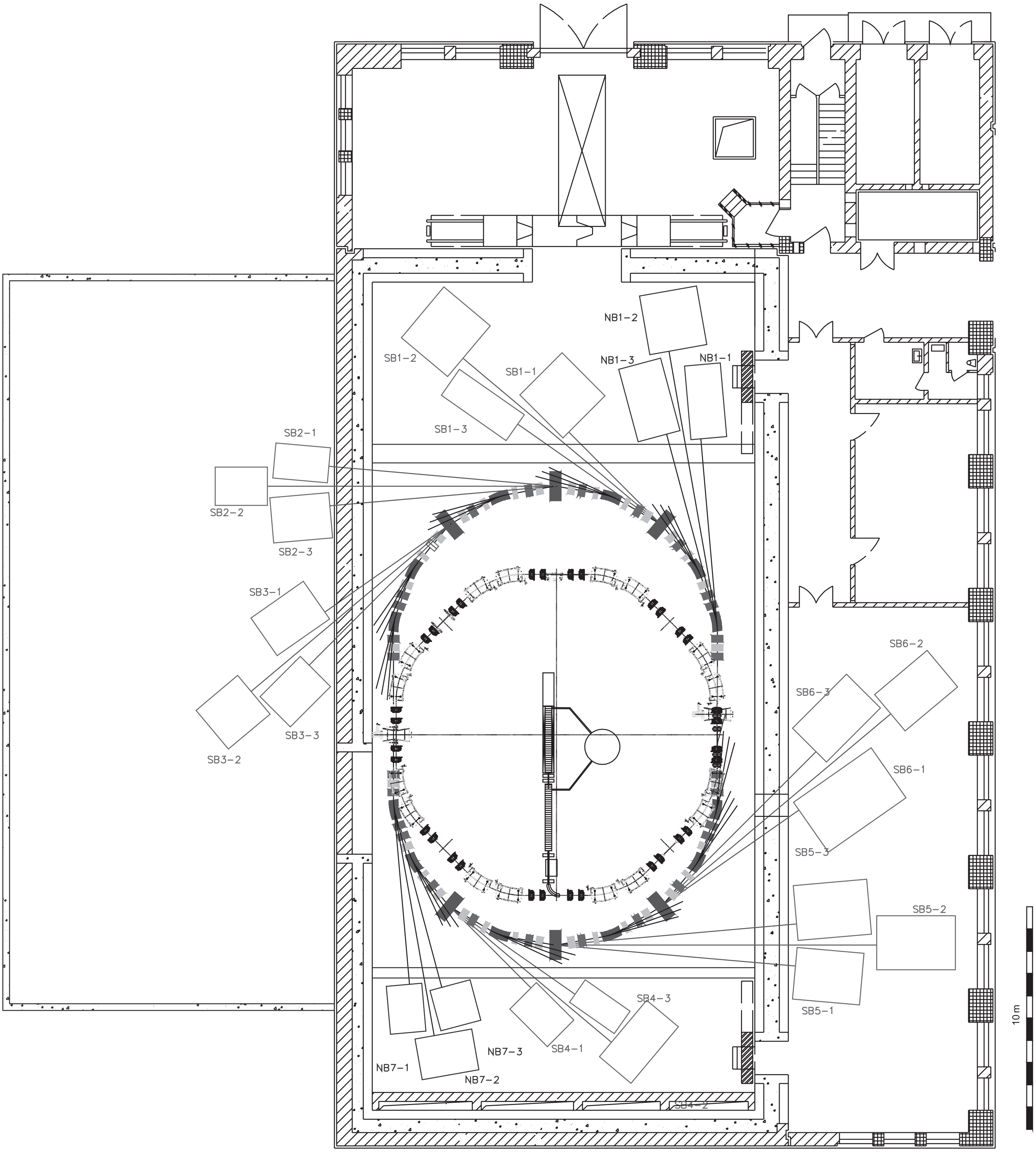

Fig. 3. General layout of compact SR source facility, SR beamlines and experimental stations.

fabrication of this facility and all components are also available. Thus, such compact SR source really can be created.

Since SSRC really needs a specialized SR source, the decision for development of such source was taken at BINP. This source should cover large part of SR user needs in the hard and soft X-ray ranges.

A detailed project of this source is under development now. Prototypes of some critical components can be fabricated next year.

It is possible to suppose that the facility will be commissioned in the end of 2010.

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