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PHYSICS AND TECHNIQUE OF ACCELERATORS

Superconducting Wigglers and Undulators for Synchrotron Radiation Generation at the SKIF Storage Ring

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Abstract—The main devices for generating synchrotron radiation at the SKIF synchrotron light facility under construction will be superconducting wigglers and undulators created at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences. This report presents the rationale for the choice of operating parameters, the main characteristics and design features of these devices, and their current development status.

Keywords: wiggler, undulator, superconducting magnet, cryostat, synchrotron radiation

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INTRODUCTION

The main photon generation devices at the SKIF [1] synchrotron radiation source with an energy of 3 GeV are superconducting multipole insertion devices with a sign-alternating magnetic field: wigglers [2] and undulators [3]. Thanks to the use of superconducting technologies, such devices make it possible to obtain a higher level of magnetic field with a minimum period of the magnetic structure than similar devices based on permanent magnets. This makes it possible to place a larger number of magnetic poles over the available length of the straight section in order to increase the intensity of the generated radiation. In this case, the intensity of radiation from wigglers increases proportionally and, from undulators, quadratically to the number of poles. The use of superconducting insertion devices makes it possible to obtain radiation characteristics on relatively small storage rings such as SKIF with an energy of 3 GeV that are not inferior in brightness to radiation from bending magnets on machines with high energy up to 6 GeV. In the first stage of construction of the SKIF source, it is planned to put into operation five experimental stations that use superconducting multipole insertion devices to generate radiation, including two wigglers and three undulators, the main characteristics of which are presented in Table 1. The main magnetic parameters of each of these devices have been optimized for a specific user task.

1. SUPERCONDUCTING WIGGLERS

The use of multipole wigglers with a high field level, under the action of which the electron beam trajectory deviates by angles much larger than the angle of natural divergence of the photon beam $1/\gamma$ (where γ is the relativistic factor), is due to the requirements of experiments requiring a large geometric region of sample illumination. Also, due to the high field level, it becomes possible to generate photons in the high-energy X-ray range (up to ~150 keV). In this case, it is necessary to isolate from a wide continuous spectrum of high-power radiation the spectral range that is required for the experiment using X-ray optics. In this case, a significant part of the unused power has to be absorbed by the optical elements of the radiation output channel.

1.1. Superconducting Wiggler with a Period of 48 mm and a Field of 4.5 T for Station 1–5

Experimental station 1–5, called High-Energy X-Ray Diagnostics, was designed to study samples in the field of materials science, geology, archeology, and biomedicine using X-ray diffraction and X-ray fluorescence analysis in the hard photon range from 25 to 150 keV. The main parameters of the wiggler's magnetic structure were optimized to obtain the maximum possible photon flux in the required energy range. Since the main contribution to the thermal load on the elements of X-ray optics comes from the absorption of

Table 1. Basic parameters of superconducting wigglers and undulators

Parameters	Wiggler 1-5	Wiggler 1-3	Undulator 1-1 (1-2)	Undulator 1-4
Magnetic field, T	4.5	2.7	1.25	1.6
Period, mm	48	27	15.6	18
Pole gap, mm	7	7	7	7
Vertical/horizontal camera aperture, mm	5/40	5/40	5/40	5/40
Number of periods	18	74	128	111
Magnetic length, mm	~950	~2000	~2000	~2000
Length between flanges, mm	~2700	~2700	~2700	~2700
Radiation power, kW	39	33	7.7	11.7
Radiation angle, mrad	±3.5	±1.2	±0.32	±0.46
Deviation parameter K	~20	~6.8	~1.8	~2.7

the soft part of the spectrum and the hardness of the spectrum is proportional to the magnitude of the magnetic field, the radiation spectrum was shifted to the hard region by obtaining the maximum possible level of the magnetic field. At the minimum technologically possible magnetic gap of 7 mm, which is limited by the conditions of the dynamics of the electron beam along the vertical aperture of the vacuum chamber of 5 mm, the optimal level of the magnetic field was 4.5 T at a period of 48 mm and the number of main periods was 18. The windings were fabricated using a Nb–Ti/Cu superconducting wire 0.9 mm in diameter with a critical current of ~380 A in a field of 7 T. An additional condition was the limitation of the radiation power at a level of ~35 kW in order to avoid the thermal destruction of the diamond windows of the radiation output channel. In this case, the total radiation power is generated into a horizontal angle of ±3.5 mrad. Figure 1a shows the spectral-angular distribution of the photon flux for this wiggler. A short 10-pole wiggler prototype was successfully tested in a liquid helium cryostat, where a maximum field of 5.12 T was reached during training. The launch of a full-size 40-pole wiggler is planned for 2022.

1.2 .Superconducting Wiggler with a Period of 27 mm and a Field of 2.7 T for Station 1-3

When developing experimental station 1-3 (Fast Processes), designed to obtain “X-ray cinema” in the study of materials under conditions of pulsed shock loads with characteristic time scales from picoseconds to milliseconds, a device was required that provides the maximum number of photons per electron bunch in a wide spectral range from 20 to 70 keV. In this case, the use of a wiggler was justified, since the creation of an undulator that generates radiation at high harmonics with photon energies up to 70 keV is currently technically unavailable. A superconducting 152-pole wiggler with a period of 27 mm and a magnetic field of 2.7 T was developed as a plug-in device that is optimal for a given energy and has a wide beam for solving

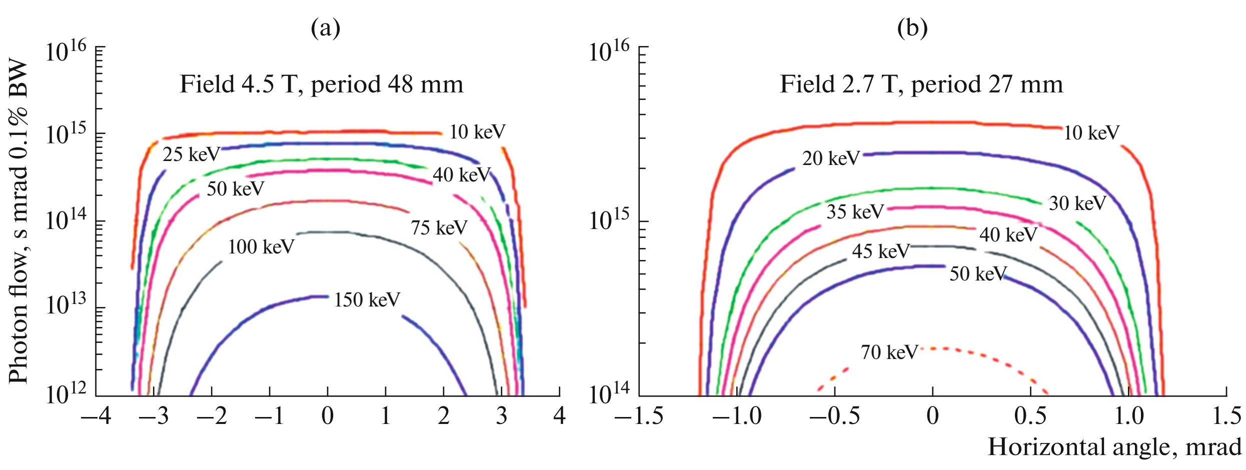

Fig. 1. Spectral-angular distribution of the photon flux from wigglers with a field: (a) 4.5 and (b) 2.7 T.

radiography problems. The total radiation power generated at a horizontal angle of ± 1.2 mrad was also limited to ~35 kW to protect the elements of the radiation extraction channel from a high thermal load. The spectral-angular distribution of the photon flux from this wiggler is shown in Fig. 1b. The main winding has one section and is made of Nb–Ti/Cu superconducting wire with a diameter of 0.9 mm, having a critical current of 570 A in a field of 7 T. At present, a short prototype of the magnetic structure of this wiggler is being manufactured for testing in liquid helium. The parameters of this device are currently record-breaking in terms of achieving the maximum possible field level with the minimum period. The closest in terms of these parameters is a 119-pole superconducting wiggler with a field of 2.1 T and a period of 30 mm, mounted on an ALBA storage ring [4].

2. SUPERCONDUCTING UNDULATORS

The creation of a fourth-generation SKIF synchrotron radiation source with an ultralow horizontal emittance (~75 pm rad), which approaches the diffraction limit in the most in-demand photon energy range, makes it possible to create high-brightness coherent photon beams with an energy of tens of keV. Such beams can be generated using multipole superconducting undulators with a short period of ~15–18 mm and an orbital magnetic field of ~1.2–1.6 T. The difference between the magnetic structure of an undulator and a wiggler is that the trajectory of the electron beam in the undulator deviates by small angles comparable to the angle of natural divergence of the $1/\gamma$ photon beam. As a result, radiation interference from all poles occurs, which leads to a discrete spectrum of undulator radiation in the form of harmonics. The quality criterion of the undulator is the value of the r.m.s. phase error, which characterizes the difference between the magnetic field of the real undulator and the ideal sinusoidal field, and which should not exceed ~3°. On modern storage rings with a low emittance and energy spread, the importance of this parameter especially increases, since a large phase error will limit the radiation brightness at high harmonics and will not allow the full use of storage ring capacity.

2.1 .Superconducting Undulator with a Period of 15.6 mm and a Field of 1.25 T for Stations 1-1 and 1-2

Two identical superconducting undulators with a period of 15.6 mm and a field of 1.25 T will be used as radiation sources for experimental stations called Microfocus (1-1) and Structural Diagnostics (1-2), designed to study a wide range of problems using microscopy methods and X-ray diffraction. It is supposed to use, among other things, high harmonics of undulator radiation with photon energies up to 35 keV, which imposes particularly stringent requirements on minimizing the phase error. The magnitude of the phase error increases with an increase in the difference in the field amplitudes between the poles, as well as with the instability of the period along the length of the undulator. According to estimates, the spread of the geometric dimensions of the magnetic poles should not exceed 10–20 μm.

As a prototype to study the technical feasibility of creating a device with the required characteristics, a full-size 119-pole undulator based on alternating active and neutral poles was designed and manufactured [3]. The main element of the magnetic structure is a superconducting coil wound on an iron core. We used a superconducting Nb-Ti/Cu wire 0.55 mm in diameter with a critical current of 260 A in a field of 7 T. The maximum field in the critical region of the winding at a current of 500 A is 4.25 T, which corresponds to a field level of 1.2 T on the undulator axis. The instability in the period value was minimized by milling grooves to fit the superconducting poles with the required accuracy. However, it is not possible to debug the manufacturing technology of the poles themselves, which provides the same repeatability in size. Therefore, the magnitude of the phase error of the undulator, calculated on the basis of magnetic measurements immediately after the manufacture of the undulator, turned out to be more than 5°. A series of permutations of individual poles between themselves based on measuring the amplitudes of the magnetic field did not allow to reduce the phase error to less than 4° due to the strong mutual influence of the fields of neighboring coils on each other. Therefore, a method was proposed for suppressing the phase error based on feeding individual groups of poles with independent corrective current sources at a level of ~1% of the main current with a value of ~500 A. Independent feeding of each group of coils made it possible to select corrective currents, which made it possible to simultaneously correct the level of the magnetic field and beam orbit over the entire length of the undulator. As a result of the correction, the value of the integral phase error calculated from measurements of the magnetic field along the undulator was 2.9°, and the local phase error decreased to 1.9°. Figure 2 shows the emission spectra calculated by the SPECTRA software [5] based on the uncorrected and corrected magnetic field of the undulator for an electron beam energy of 3 GeV, a current of 0.4 A, and an emittance of 75 pm rad. fields increased significantly at all harmonics.

2.2. Superconducting Undulator with a Period of 18 mm and a Field of 1.6 T for Station 1-4

As a source of radiation for the experimental station 1-4, called XAFS Spectroscopy and Magnetic Dichroism, using X-ray spectroscopy methods, a superconducting undulator with a period of 18 mm and a field of 1.6 T is the optimal choice. This will make it possible to carry out experiments in the range

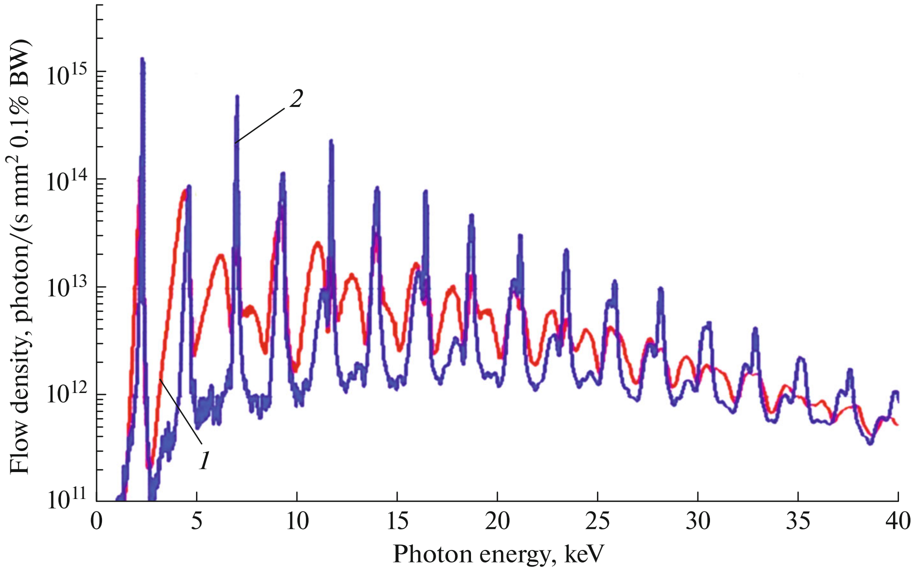

Fig. 2. Emission spectra calculated by the SPECTRA program based on the uncorrected (*1*) and corrected magnetic field (*2*) of the undulator.

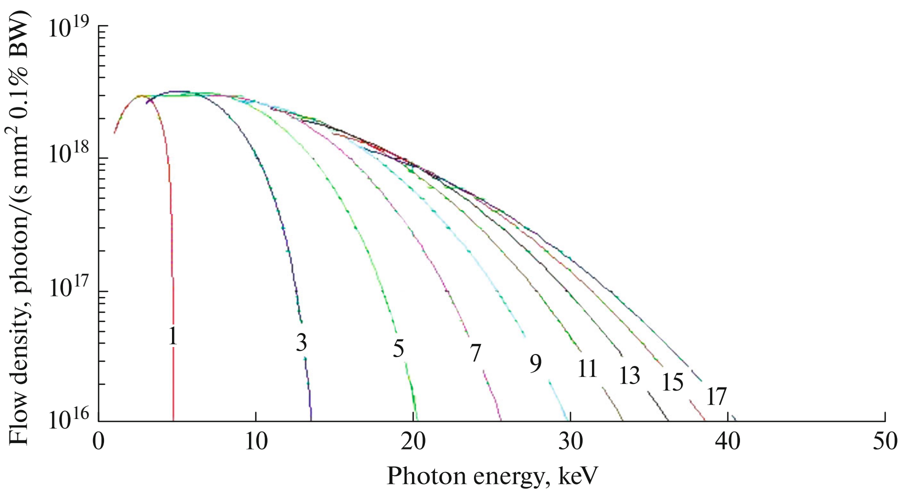

Fig. 3. Spectral flux of photons at harmonics from 1 to 17 when the field changes from 0 to 1.6 T.

from 4 to 35 keV. The design of this device, based on the same principles as the previous undulator, is under development. Figure 3 shows the spectral characteristics of this insertion device.

3. CRYOGENIC SYSTEM WITH INDIRECT COOLING

The cryogenic system of the presented insertion devices operates on the principle of indirect cooling, in which the magnet is located in a vacuum, and all heat inflows in the cryostat are intercepted by the corresponding stages of cryocoolers [2]. The temperature of the magnet at the level of ~3.5 K is maintained due to the circulation of liquid helium through the channels in the body of the magnet, and the helium itself is contained in a separate vessel located in a protective vacuum outside the magnet. The pre-cooling of the magnet to operating temperatures is carried out by means of nitrogen heat pipes, which provide heat removal for 60 K of the cryocooler head. When the freezing temperature of nitrogen reaches ~64 K, the thermal connection between the magnet and the cryocooler is automatically broken. Further cooling of the magnet occurs due to the circulation of helium. In this case, only gaseous helium is used for primary cooling, which is supplied from a cylinder. As the temperature decreases, the density of helium in the cryostat increases and, upon reaching the appropriate temperature, liquefaction begins and the working level of helium in the vessel begins to rise. Further, in this mode, the cryogenic system allows one to work autonomously inside the storage ring bio protection for several years.

4. CONCLUSIONS

Superconducting wigglers and undulators created at the BINP for the SKIF fourth-generation storage ring will become the main devices for synchrotron radiation generation and provide the required spectral characteristics for solving a wide range of research problems.

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