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Synchrotron-Radiation Technological Station at the VEPP-4M Storage Ring

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Abstract—On beam line no. 1 of the VEPP-4M storage ring located at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, a new technological station has been put into operation. First and foremost, the station is intended for conducting visual didactic experiments with an active beam for teaching university students of relevant specialities and novice users, developing and testing measuring instruments, as well as conducting preliminary or additional measurements. Such direct involvement of students in the design of the beamline components and the deployment of different synchrotron techniques increase their motivation towards professional and effective use of synchrotron-radiation techniques and instrumentation development, which is greatly required for the ongoing project of the Synchrotron Radiation Facility "Siberian Circular Photon Source". The modular design of the station enables the implementation of diverse techniques in development of the station. This work describes the optical scheme of the beamline and emphasizes the synchrotron-beam parameters therein with respect to other beamlines operating at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences. Selected examples of experimental results obtained by students using various techniques during training are given. In particular, the automized operation of a photodiode-based X-ray beam monitor is demonstrated, which is required for visualization of the incident X-ray beam, and for measuring its exact position and intensity. Implementation of the X-ray fluorescence analysis technique in a dedicated vacuum chamber enables the quantification of light elements, which is unattainable at other beamlines. The prospects for further development of the technological station are described.

Keywords: synchrotron radiation, experimental beamline, X-ray beam, monochromator, spectral measurements, X-ray fluorescence analysis, student training

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INTRODUCTION

Synchrotron radiation (SR) is an electromagnetic radiation that is emitted by charged particles moving in circular orbits at ultrarelativistic speeds [1]. It is a unique tool for studying the composition and structure of matter, as well as radiation technologies. There are about 50 research centers operating with synchrotron-radiation sources around the world. Research stations are designed to implement specific techniques. As an example, we can cite the station of Structural Materials Science [2] for studying the features of the spatial organization of functional materials, the Belok station [3] for the X-ray diffractometry of macromolecular single crystals at the Kurchatov synchrotron radiation source (Moscow, Russia) or the station on the ID02 ESRF channel (Grenoble, France) for studies of time-resolved small-angle X-ray scattering [4]. Such stations provide users with a high-tech precision tool to perform certain studies. In the world's leading research centers, much attention is paid to the popularization of high-tech research methods among high-school students and university students. In the US, there is a special National Academy of Sciences program called "Introducing Synchrotrons into the Classroom," or InSynC for short, designed to provide faculty and students with the opportunity to participate in original research conducted in state-of-the-art research labs at SR channels to see how they are assembled, and process and interpret data. Implementation of the program consisted in the introduction of remote access technologies both at SR stations and in schools. Thus, students can observe, discuss, and partially participate in conducting the experiment in real time [5]. Similar programs

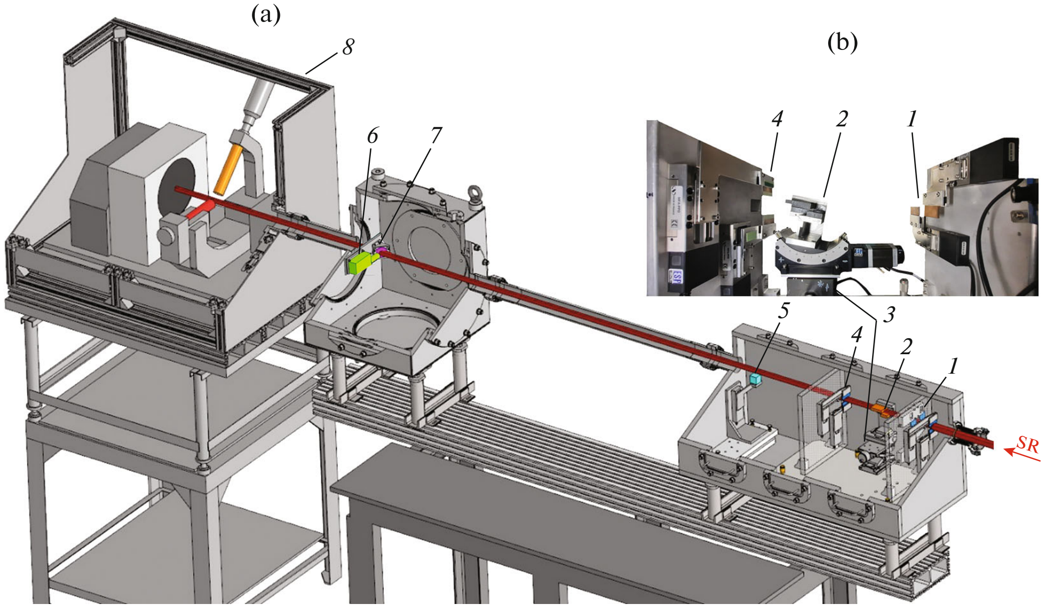

Fig. 1. (a) Schematic representation of the SR technological station: (*1*) block of entrance slits; (*2*) slit crystal-monochromator; (*3*) is the vertical displacement of the monochromator; (*4*) exit slits; (*5*) photodiode beam monitor; (*6*) Amptek energy-dispersive detector; (*7*) sample. The inset (b) shows the placement of a monochromator with a set of slits in the chamber.

aimed at involving high-school students in natural-science research through excursions and model laboratory work exist at the Australian Synchrotron [6] and the Canadian source of SR [7]. In France, there is a program of interaction between the Paris Central School and the ESRF synchrotron [8] covering excursions, virtual work, and direct participation in experiments on SR channels.

The project of the 4+-generation synchrotron-radiation source, Siberian Circular Photon Source "SKIF", is implemented in the Novosibirsk region. According to preliminary estimates, the operation of SKIF will require about 150 specialists working at SR experimental stations and developing new experimental methods [9]. In the Center for Collective Use "Siberian Center for Synchrotron and Terahertz Radiation" on the basis of the VEPP-3 and VEPP-4M storage rings at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences [10], there are SR experimental stations that implement methods of diffraction studies of the structure of matter [11, 12], X-ray spectral analysis of the elemental composition of objects [13, 14], extended X-ray absorption fine structure (EXAFS) spectroscopy [15], technological applications [16], and the like. Practical training of students is already being carried out at existing experimental stations. It should be noted that the equipment of stations at which routine experiments are carried out is adjusted to solve a specific problem, and its disassembly or reconfiguration for training purposes is not allowed, since this will significantly reduce the time available for ongoing experiments. Thus, it is possible for students to participate in conducting experiments and processing results, but not in setting up station equipment. The need to train not only users, but also specialists for the creation and operation of experimental stations at the SKIF source motivated the creation of an additional special station.

The SR technological station is a stand for teaching future specialists the basics of experimental work using SR. In the process of assembling and adjusting the equipment of the station, students will be able to get a visual representation of the principles of operation of the entire system and real experience in preparing and conducting experiments with SR [17]. Also, this stand is convenient for testing new elements of equipment for synchrotron experiments, for example, X-ray detectors.

INSTALLATION COMPOSITION

The technological station has a set of relatively standard elements of user stations using SR: an SR output channel evacuated to a level of 10 Pa, a monochromator module and a measurement module, which contain sliders, a monochromator, detectors, and other equipment. Variability in the layout of the station equipment opens up the possibility of carrying out demonstration and training work using various research methods with synchrotron radiation.

Figure 1 shows the layout of the technological station. The first chamber contains a slit monochromator [18] made of a Si(111) crystal and blocks of X-ray slits for shaping the SR-beam dimensions and cutting off the direct beam and scattered radiation. All elements are equipped with motorized sliders, which allows

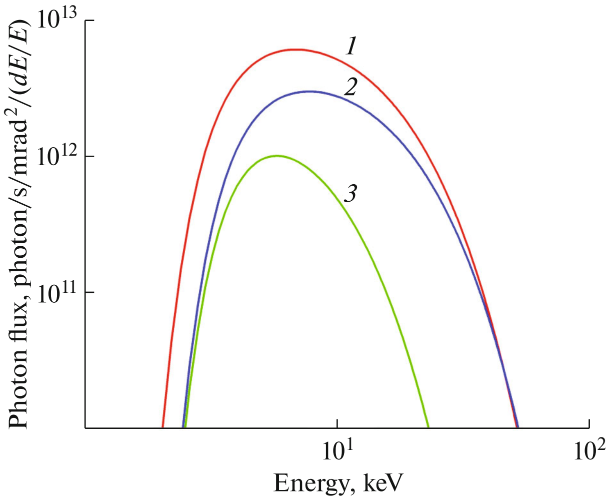

Fig. 2. Comparison of SR fluxes in the typical operating mode at the SR stations of the VEPP-3 (*1*) and at the SR technological station of the VEPP-4M at an electron energy of 4.5 (*2*) and 3.5 GeV (*3*); $dE/E = 0.001$.

adjustment in a closed chamber with the SR beam turned on. The monochromator crystal is mounted on a precision goniometer with a sweep amplitude of 30°, a positioning accuracy of –0.05° ± 0.025°, and a minimum travel step of 0.0005°. The vertical position of the crystal can be adjusted in the range of 10 mm with an accuracy of ±1 μm using a vertical slider *3* (Fig. 1). X-ray blades *1* and *4* mounted on linear sliders with a positioning accuracy of 3 μm. Thus, the dimensions and spectrum of the SR beam are formed in the first chamber.

A photodiode beam monitor *5* is also installed in the monochromator chamber to control the SR intensity and automate adjustment of the position of the photon-beam size-forming elements. A silicon *p–i–n* photodiode is placed on a vertically mounted linear slider in a metal case. Optionally, a polished $CdWO_4$ scintillator crystal 0.4 mm thick can be installed in front of the diode. In front of the scintillator, there is an X-ray diaphragm made of tantalum 4 mm wide and 0.4 mm high, which determines the spatial sensitivity of the monitor.

The second chamber contains the test samples, an energy-dispersive detector, and auxiliary elements: a phosphor screen and CCD cameras for visual control of alignment. These elements are motorized for adjustment under the SR beam. In this configuration, the method of X-ray fluorescence analysis of the elemental composition of the sample is implemented.

EMISSION CHARACTERISTICS OF THE TECHNOLOGICAL STATION

Synchrotron radiation is output to the technological station from the bending magnet of the VEPP-4M storage ring; Table 1 shows the calculated radiation characteristics at the level of sample placement at the SR technological station in two main modes of operation of the VEPP-4M. For comparison, the characteristics of the radiation used in routine experiments at the stations "LIGA technology and X-ray lithography" [16] and "Local and scanning X-ray fluorescence elemental analysis" the VEPP-3 [19] are given. Figure 2 shows the calculated SR spectra at the technological station for two typical operating modes of the VEPP-4M (at an electron energy of 4.5 and 3.5 GeV, and at an average current of 10 mA). For comparison, the emission spectrum for the the VEPP-3 is shown in the typical mode used in most routine experiments implemented at the research center at an electron energy of 2 GeV and an average current of 100 mA. As can be seen, at an electron energy of 4.5 GeV in the VEPP-4M, the spectral distribution at the technological station is close to that of the VEPP-3, although less in intensity. This makes it possible to implement many of the techniques used at VEPP-3 stations.

At an electron energy of 3.5 GeV in the VEPP-4M, the spectral flux shifts to a region with a longer radiation wavelength and becomes noticeably weaker, which, however, does not interfere with training and demonstration work. This mode of operation of the VEPP-4M is interesting in that it is similar to the mode of operation of the collider used in research in the field of elementary particle physics, when electron and positron beams are separated vertically in the storage ring by an electrostatic field; however, the orbit of

Table 1. Comparison of the main characteristics of the SR

Options	VEPP-4M		VEPP-3
Electron energy, GeV	4.5	3.5	2.0
Magnetic field at the radiation point, kgf	4.34	3.38	20
Average electron current, mA	8	8	80
Total thickness of the separating beryllium windows in the channel, μm	800	800	500
Critical photon energy E_c, keV	5.86	2.76	5.33
Distance from the radiation point, m	21	21	20

electrons in the storage ring differs from the SR-generation mode. Thus, simultaneously with experiments in elementary particle physics, it is impossible to carry out work with SR on other channels for outputting radiation from the VEPP-4M, except for the technological station. A feature of the technological station is that the source of radiation is a rotary magnet located before the electrostatic separation system; therefore, the orbit of electrons does not change at this point under different modes. In addition, the available time for conducting experiments at the technological station is significantly longer than at other stations of the research center.

The available spectral range is determined by the geometry of the slit monochromator. The width of the crystal lamellas is 40 mm, the length of the first lamella is 30 mm, the second one is 50 mm, the gap between the lamellas is 5 mm, respectively, and the available angles of the monochromator are limited from 4.8° up to 26.5°. The energy range is from 4.5 to 23.8 keV. The energy resolution of a monochromator is determined by the properties of the crystal used, the beam aperture, and the accuracy of goniometer movement. The energy resolution in the case of using a Si(111) crystal is $\Delta E/E = 1.4 \times 10^{-4}$ [20]. The angular aperture of the beam with an entrance slit size of 1 mm and a distance from the radiation source of 20 m is 2.5×10^{-5}, which gives a contribution to the energy resolution of $\Delta E/E = 1.1 \times 10^{-4}$, at an energy of 9 keV (the angle of the monochromator is 12.7°). The energy resolution of the monochromator is thus $\Delta E/E = 1.8 \times 10^{-4}$.

EXPERIMENTAL AND TRAINING WORKS AT THE TECHNOLOGICAL STATION

As can be seen from Fig. 2, the SR intensity at the technological station is weaker than at the VEPP-3 research stations, therefore, the time for conducting experiments increases, but this is sufficient for conducting training and demonstration works or testing new devices. The methods implemented at the station are based on the experience of work at the research stations of the Center for Collective Use “Siberian Center for Synchrotron and Terahertz Radiation” . Below are the types of educational and demonstration works implemented at the SR technological station.

Fundamentals of Safe Work with Synchrotron Radiation

In the course of introductory classes, the high penetrating power of SR into materials and dosimetry techniques, including measurement of the radiation dose in a chamber with an SR beam, are demonstrated. Hazards and ways to safely design experiments are considered.

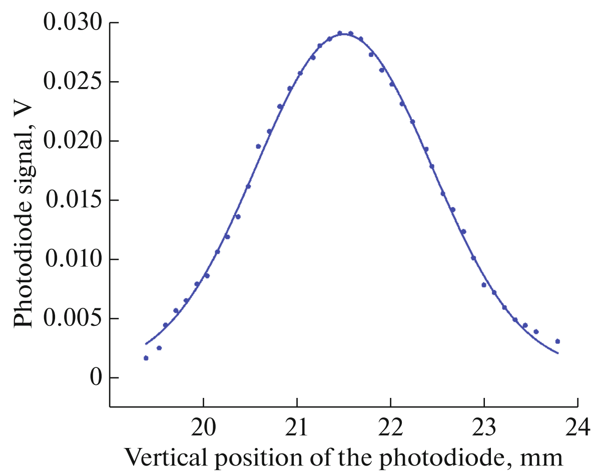

Fig. 3. Recorded SR vertical distribution profile.

Visualization and Control of the Position of the Synchrotron-Radiation Beam

This type of work makes it possible to demonstrate methods for visualizing radiation at the station and recording the spatial distribution of the beam. Consideration is given to controlling the size of the SR beam by means of motorized slits and to adjusting the beam for subsequent experiments. A compact photodiode beam monitor and a control program for measuring the SR flux have been developed. Scanning with a photodiode receiver using a coordinate slider *6* (Fig. 1) makes it possible to quickly obtain the vertical profile of the SR beam in the monochromator chamber and control the adjustment of the position of the monochromator and X-ray blades relative to the SR beam with an accuracy of no worse than 100 μm. Figure 3 shows an example of a recorded vertical SR profile.

Study of the Interaction of Synchrotron Radiation with Matter

During introductory classes, the interaction of SR with matter is considered using the example of studying the absorption of radiation in a material and recording absorption edges in transmission spectra. Figurre 4 shows the absorption spectrum of a copper–nickel alloy foil 10 μm thick recorded at the station. The position of the absorption jumps can be used to calibrate the goniometer of the monochromator. The resolving power of the monochromator makes it possible to implement the EXAFS spectroscopy technique. For example, the inset in Fig. 4 shows oscillations of the absorption coefficient near the absorption edges of copper and nickel.

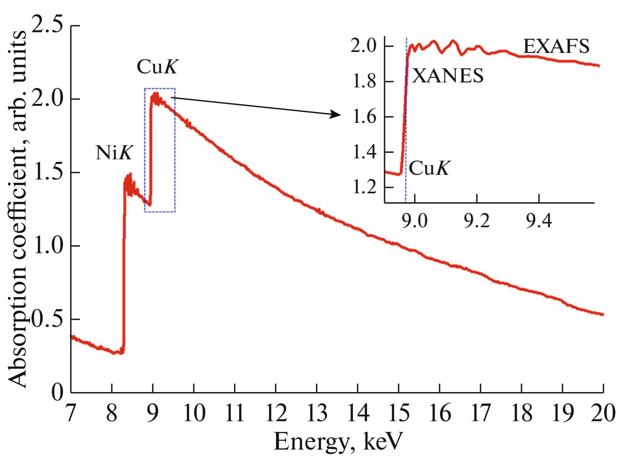

Fig. 4. Transmission spectrum of a copper–nickel alloy foil 10 μm thick.

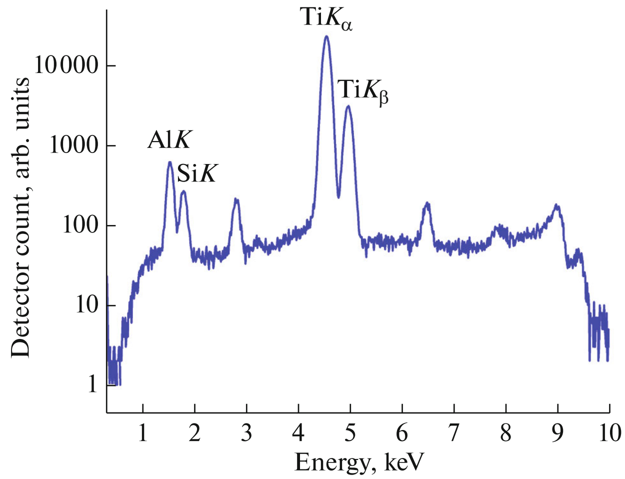

Fig. 5. X-ray fluorescence spectrum of the test sample.

Studying the Fundamentals of X-ray Fluorescence Elemental Analysis Using Synchrotron Radiation

This type of activity makes it possible to study the operation of an energy-dispersive detector, and methods for recording X-ray fluorescence spectra and determining the elemental composition of a substance. Figure 5 shows the X-ray fluorescence spectrum of a test sample recorded at the technological station (layers of aluminum and titanium deposited onto a silicon substrate with a thickness of 1 μm). This spectrum is of interest for training novice users since it can be clearly interpreted. The luminescence lines of aluminum (1.49 keV) and silicon (1.74 keV), the lines of titanium (4.51 and 4.93 keV), the elastic scattering line corresponding to the excitation energy in this experiment (6.50 keV), and two-photon excitation lines (9.02 and 9.44 keV) are clearly visible here, as well as the emission peak from the detector material (silicon) (2.77 keV). This spectrum was recorded at a pressure of 30 Pa; it demonstrates the advantages of the station for studying the elemental composition in the low-energy region (light elements), which is inaccessible to X-ray fluorescence analysis stations operating at the Siberian Center for Synchrotron and Terahertz Radiation [13, 14] intended for studying relatively heavy elements without vacuuming.

Experiment Automation

During introductory classes, students are given the opportunity to independently write experiment control programs that integrate the operation of the equipment used: sliders, a detector, an analog-to-digital converter, etc. In the course of graduate work on the station software for automating the operation of the station, which passed state registration [21], was developed. The software controls all movements at the station and the analog-to-digital converter for the implementation of tuning algorithms and experiments.

The development of the station continues. The installation of a compact fully functional Mardtb diffractometer (manufactured by the German company MarXperts) with a 2D hybrid-pixel detector Pilatus 1M (Dectris, Switzerland) is planned after the second experimental chamber (Fig. 1, position *7*). This will make it possible to effectively implement a set of diffraction methods at the station, namely powder diffraction and the X-ray diffraction analysis of single crystals, including macromolecular crystallography. The possibility of a monochromator included in the station will allow one to choose the optimal photon energy for the experiment in the range of 7–25 keV. The expanded capabilities of the station will make it a very attractive educational site for students enrolled in programs related to the use of SR.

CONCLUSIONS

A specialized synchrotron radiation station operates at the Center for Collective Use "Siberian Center for Synchrotron and Terahertz Radiation" for conducting educational and demonstration work to train future users, including the synchrotron-radiation source being created at the Siberian Circular Photon Source "SKIF". Students of Novosibirsk State Technical University and Novosibirsk State University were directly involved in the creation and commissioning of the station in the format of graduate theses in terms of designing and assembling station elements, and developing software for controlling station equipment and conducting test measurements. A photodiode of the SR monitor has been developed for real-time monitoring of the position of the station elements relative to the synchrotron-radiation beam. Expansion of the possibilities of the technique of X-ray fluorescence elemental analysis of light chemical elements is demonstrated.

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