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Status of the Siberian synchrotron radiation center

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Abstract

Synchrotron radiation (SR) experiments at the Budker Institute of Nuclear Physics had been started in 1973, and from 1981 the Siberian Synchrotron Radiation Center (SSRC) had an official status as Research Center of the Russian Academy of Sciences. SSRC is the research center, which is open and free of tax for the research teams from Russia and abroad.

In this report some technical information about the storage rings—SR sources of the Budker INP, the main directions of activity of SSRC, experimental stations, experimental works and users—is given. Development of the free electron lasers, new SR sources and insertion devices is described.

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Keywords: Synchrotron radiation; X-ray experimental technique; Research center

1. Introduction

The Budker Institute of Nuclear Physics where the Siberian Synchrotron Radiation Center (SSRC) is located remains one of the major sites of synchrotron radiation and free electron laser investigations in Russia. Synchrotron radiation (SR) experiments at the Budker Institute had been started in 1973, and from 1981, the SSRC had an official status of Research Center. SSRC is the research center, which is open and free of tax for the research teams from Russia and abroad.

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The current research, development and education program of SSRC included the following directions [1,2]:

- research studies and development of new technologies using SR from the VEPP-3 and VEPP-4M storage rings;
- construction of experimental equipment for the works with SR as the beamlines, experimental stations, X-ray optics, monochromators, and detectors;
- development and construction of accelerators—dedicated sources of SR, wigglers and undulators for other Russian and foreign centers;
- development of free electron lasers and creation of the Siberian Center of Photochemistry;
- education and professional training of students and post-graduates.

2. SR sources of Budker INP

There are two operating storage rings—SR sources presently available at SSRC: VEPP-3 (2 GeV) and VEPP-4M (up to 6 GeV). Layout of accelerator complex VEPP-3/VEPP-4M and the basic parameters of these SR sources are shown in Fig. 1 and Table 1, correspondingly.

At present, the VEPP-3 storage ring is an important SR source in the X-ray range. The majority of SR beams in use are generated by a dedicated 3-pole wiggler with a field of 2 T installed in the straight section of the storage ring. SR passes through Be foils whose total thickness is 0.8 mm. These foils separate the storage ring vacuum from the vacuum of the beamlines. The total horizontal angle of the wiggler radiation, which is divided by 8 beamlines, is 120 mrad. Six beamlines transmit 5 mrad radiation angle each, and two others are capable of transmitting photon beams at an angle of 8 mrad.

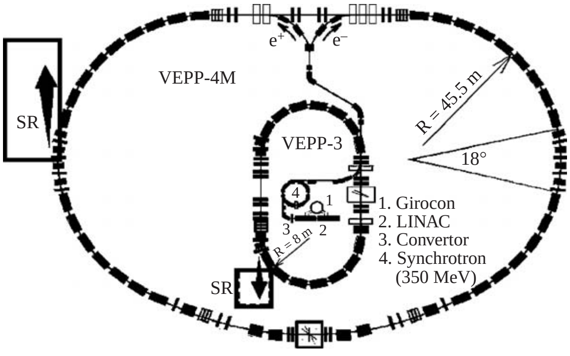

Fig. 1. Layout of accelerator complex VEPP-3/VEPP-4M. SR—synchrotron radiation experimental halls.

In 1996, the 11-pole wiggler was installed on the VEPP-3 storage ring. The wiggler is intended to supply intense and tunable photon beams for X-ray lithography and LIGA-technology station. This beam has an adjustable spectral band in the range 1–10 Å and a high uniformity of radiation power distribution over a sample.

The special foilless beamline 10 for soft X-ray and VUV experiments extracts radiation from a 1.76 T bending magnet into a ultrahigh vacuum channel with differential pumping. The basic parameters of VEPP-3 and VEPP-4M as SR sources are shown in Table 1.

Spectrum fluxes of photons from the wiggler at VEPP-3 and from the VEPP-4M bending magnet at the typical values of their parameters are given in Fig. 2.

3. SSRC experimental stations and users

At present, the use of SR in SSRC is concentrated at the storage ring VEPP-3 operating in the SR mode at 2 GeV with a typical electron current 100–150 mA. SR beams from the VEPP-3 storage ring are delivered to special hall (bunker) through nine SR extraction beamlines. Some of the 12 existing stations work in the mode of SR beam sharing.

Most experimental stations use the spectral range of X-ray photons from 4 to 35–45 keV, exceptions of which are the station of the soft X-ray and VUV metrology and radiation-induced gas desorption located at the foilless beamline where the energy of photons has no limitation from below and the LIGA-station with a 30 μm Be window where there is a possibility to work with photon energies starting with 1.5 keV and above. At present, nine beamlines for SR extraction and

Table 1
Basic parameters of the VEPP-3 and VEPP-4 M storage rings

	VEPP-3	VEPP-4M
Energy (GeV)	2.0	up to 6.0
Circumference (m)	74.4	366
Kind of particles	e^-	e^-, e^+
Operation mode	Single or two-bunch	Single- or multi-bunch
Emittance (m rad)	2.7×10^{-7}	1.2×10^{-6}
Max. stored current (mA)		
Total	250	
Single-bunch		40
Multi-bunch		80
Lifetime (h)	4–6	4–6
Magnetic field in bending magnets (T)	1.76 (for 2 GeV)	0.642 (for 5 GeV)
Revolution period (ns)	248	1200
Bunch length $2\sigma_s$ (cm)	30	5
Insertion devices	2 T 3-pole wiggler, 1 T 11-pole wiggler	1.5 T wiggler (planned)
Transverse beam dimensions at emission points		
$2\sigma_x$ (mm)	1.8	3
$2\sigma_z$ (mm)	0.42	0.8
Critical radiation wavelength (Å)	(for 2 GeV)	(for 5 GeV)
From bending magnet	2.64	1.16
From wigglers	2.32 (for 2 T) 4.64 (for 1 T)	0.5
Number of beamlines:	9	2 existent + 12 planned
From bending magnet	1	2 existent + 11 planned
From wiggler	8	1 planned
Mode of operation for SR works	Dedicated	Parasitic and dedicated

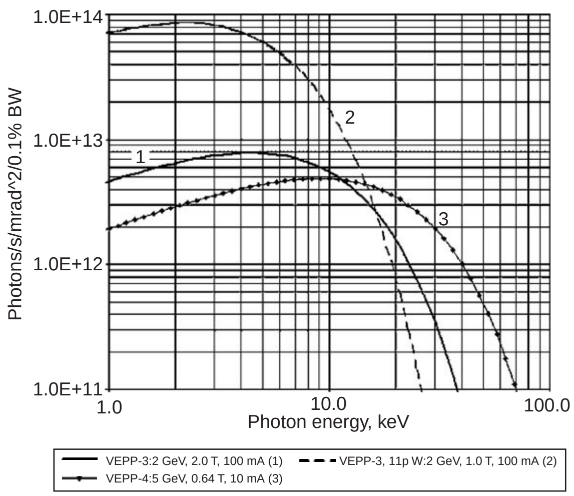

Fig. 2. Spectrum fluxes of photons from the storage rings VEPP-3 and VEPP-4M at some typical values of their parameters.

12 experimental stations are located in the SR experimental hall at VEPP-3 (Fig. 3).

In the above scheme, the following experimental stations are shown:

0a. LIGA-technology and X-ray lithography;
0b. "Explosion"—submicrosecond range time-resolved diffractometry;
2. Precision diffractometry and anomalous scattering;
3. Scanning and ordinary X-ray fluorescent analysis;
4. Diffractometry at high and superhigh pressure;
5a. X-ray microscopy and microtomography;
5b. Diffractometry with time resolution;
5c. Macromolecular crystallography;
5d. Small-angle scattering;

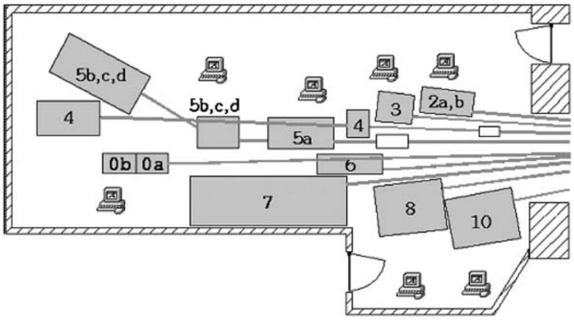

Fig. 3. Layout of the beamlines and experimental stations at VEPP-3.

6. Fluorescence with time resolution;
7. SR beam position stabilization (technical station);
8. EXAFS spectroscopy;
10. Soft X-ray and VUV metrology, radiation-induced gas desorption.

The Siberian SR Center team is based on the staff of the SR Laboratory and a number of other BINP laboratories jointly with SSRC staff of other institutes SB RAS located in Novosibirsk (Institute of Solid State Chemistry and Mechanochemistry, Institute of Hydrodynamics, Institute of Chemical Kinetics and Combustion, Institute of Catalysis). Namely, this personnel of about 120 persons provides the development and functioning of the SR experimental beamlines, development of the free electron lasers and creation of the Siberian Center of Photochemistry, and work on other SSRC Projects (construction of experimental equipment for the works with SR, and development and construction of the accelerators—dedicated sources of synchrotron radiation, wigglers and undulators for other Russian and foreign SR centers).

A rather larger number of researchers use SSRC for carrying out their experiments both individually and with the help of their partners on grants, contracts, and research agreements. These kinds of works are carried out periodically within the limits of the allocated time up to six 12-hour shifts per week for the staff of SB RAS or temporary visits from one to a few weeks for researchers from other cities. One of the collaboration forms is a study of various subjects and samples given by some organizations to the "hosts" of experimental stations for carrying out the joint studies. One more component of the use of the SSRC experimental stations is the apprentice work of students and post-graduate students and researchers.

In 2003, 2874 hours of the VEPP-3 operation time were allocated for SR experiments. The research team of about 60 research organizations and industrial firms including 14 Institutes of the Siberian Branch of Russian Academy of Science, 30 other Russian organizations and 16 from abroad took part in the works with SR beams.

4. Review of the new experimental works

4.1. Rapid time-resolved diffractometry

At SSRC, traditionally for a long period of time we have developed the X-ray diffraction cinema technique on the basis of the Budker INP fast coordinate detectors and studies "in situ" with this technique: a number of processes such as the deformation and brake of materials, changes in the structure of live muscles in the process of contraction, high-temperature synthesis, and various phase transitions. The time-resolved diffractometry technique, which is based on the use of one-coordinate X-ray detectors, enables one to obtain the diffractogram in $\sim$100 ms. However, for a study of mechanisms of some very fast processes, as, for example, the reaction self-propagating high-temperature synthesis (SPHTS) in heterogeneous systems (mixtures of powders and multiplayer structures), the time resolution should be increased by 1–2 orders. So, the reaction rate in multiplayer nanofilms achieves 10–20 m/s. In addition, as a rule, such films are texturized, i.e. they have the given orientation of the reflecting planes. For obtaining the kinetic data (consumption rate or formation of reagents), it was suggested to use the fast two-coordinate X-ray detector DED-5 developed at BINP. Its basic advantage is the data collection from the major part of the diffraction cone (up to 360°, whereas for the one-coordinate detector, it is by 1–2 orders

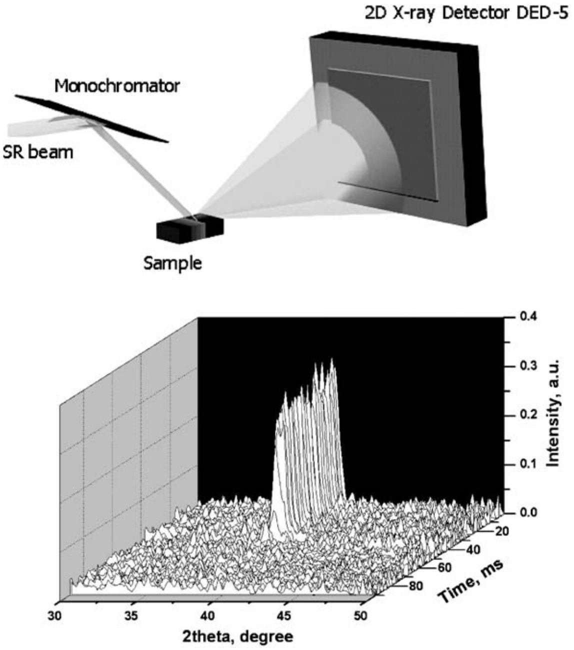

Fig. 4. Above—conceptual layout of the rapid time-resolved diffractometry at VEPP-3; below—X-ray diffraction movie with the resolution of 2 ms which shows an amount of nonreacted metallic Ti (a peak at diffractograms) in the process of SPHTS reaction $Ti+3Al>TiAl_3$. The initial sample is a laminated structure of 20 μm in thickness, which consists of ~200 alternating layers of metallic Ti and Al.

lower). Integration over the ring enabled reduction of time for obtaining diffractogram down to 1 ms. Fig. 4 shows an example of the diffraction "cinema" with the time resolution of 2 ms obtained in the process of SPHTS of $TiAl_3$.

4.2. Submicrosecond range time-resolved diffractometry

The next step in new developments was a unique submicrosecond diffractometry technique recently developed at SSRC [3,4], which allows the study of the processes of detonation and behavior of matter in the detonation front. The first experimental studies in substance under extreme conditions caused by action of the shock and detonation waves was carried out in the model of the experimental device at the VEPP-3 storage ring in 1999–2002 with the time resolution equal to the interval between bunches in VEPP-3 (124 or 248 ns).

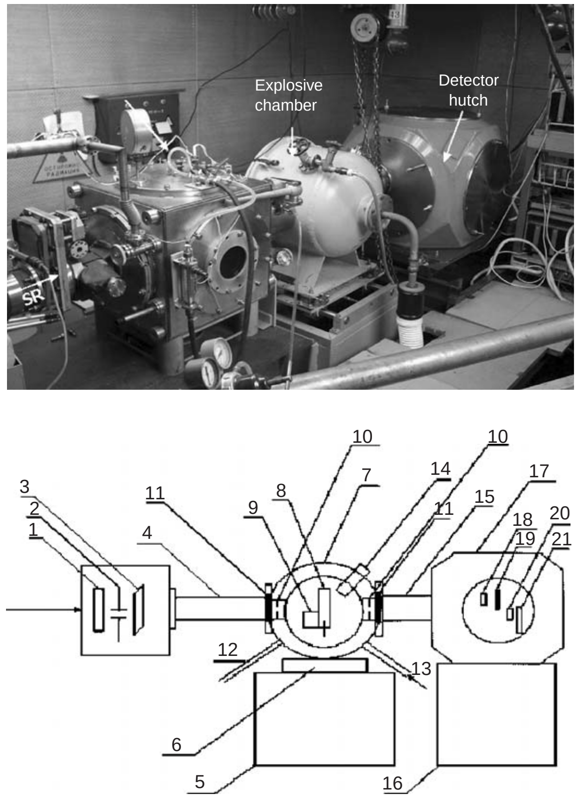

Fig. 5. General view (above) and layout (below) of experimental station "Explosion" at VEPP-3. 1—fast shutter; 2—*X*-*Y* collimator; 3—luminescent screen; 4—SR input beamline with the beryllium foils; 5—support with sand; 6—adjusting device; 7—explosion chamber; 8—explosive substance; 9—device for alinment of explosive substance; 10—shock wave suppressors; 11—beryllium ports of the explosion chamber; 12—gas exhaust of the explosion chamber; 13—filling with a gas; 14—current lead; 15—SR output beamline; 16—supports; 17—unit of detectors; 18—SR passing beam monitor; 19—absorber; 20—small-angle scattering monitor; 21—DIMEX detector.

In 2003, we realized the experimental scheme that takes into account the spatial self-scanning of a process under study (the detonation, shock wave) and obtained the time resolution within 15 ns, which is by an order of magnitude shorter than the time interval between SR bunches from VEPP-3. The general view and layout of the new constantly operated experimental station "Explosion" is shown in Fig. 5.

The following experimental techniques with a nanosecond resolution have been realized at the station: (1) defining a three-dimensional distribution of a substance density in the axial-symmetric case (by the data of measurements of a two-dimensional picture of the X-ray radiation absorption coefficient); (2) measurements of the detonation wave front profile with resolution of 15 ns; (3) a study of the development dynamics of the electron density fluctuations in a substance (measurements of a small-angle X-ray scattering) during rapid chemical conversions.

In the period 2000–2004, a number of "in situ" studies have been carried out: a study with a time resolution of 124 and 248 ns of structural behavior of various substances under action of the shock and detonation waves; a study of dynamics of the formation and growth of the diamond particles behind the detonation front from the initial mean size of the order of 30 Å up to 100 Å during 6 μs and a study of dynamics of metallic nanoparticle formation in metal-organic composition under action of detonation waves [5]; a structural study of the gas and cumulative jets study both in free pass and during their passage through a substance; a study of dynamics of the occurrence and growth of microcracks under the action of shock waves; the behavior of the nanoparticles and nanomaterials under the action of shock waves; a study of the structure and relaxation process in the "new" and "free" nanoparticles, i.e. the newly formed and having no contacts, either with other particles or with a substrate.

In the course of the station construction, a number of fast one-coordinate detectors were tested as (1) a silicon microstrip detector; (2) a AsGa-based microstrip detector; (3) the Germanium and silicon detectors; (4) CCD-based detector; (5) DIMEX—the one-coordinate gas detector.

DIMEX proved to be the most promising detector for studies of the detonation and shock wave processes, which enabled measurements of the coordinate distribution of the X-ray flux density in times shorter than the interval between the neighboring bunches in the storage ring. For the SR source VEPP-3, in a two-bunch regime, this time is 124 ns.

The detector can store the results of 32 successive measurements (shots) and has the coordinate resolution of ~0.1 mm with the detection efficiency of ~50% for 30 keV photons. The detector aperture in the direction of the measured coordinate will finally be ~100 mm (1024 shots) and in the perpendicular direction ~1 mm. The detector prototype with a horizontal aperture of 25.6 mm (256 channels) is manufactured, and now, it is under the beam tests [6].

4.3. Scanning X-ray fluorescent analysis

Another novel technique under development at SSRC is the scanning fluorescent analysis of the lake sediments for the reconstruction of the environment state in the far past. In particular, with the use of this technique, we obtained the data on the climatic condition in the past within the intervals from hundreds to millions of years [7,8]. The general view of the station for scanning X-ray fluorescent analysis at VEPP-3 and an example of data obtained are shown in Fig. 6.

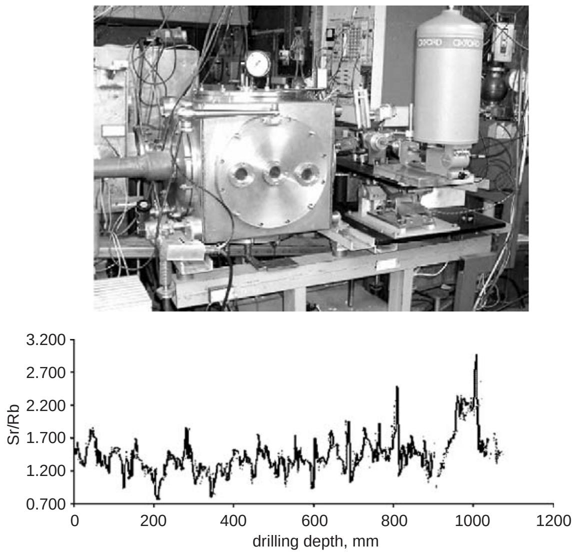

Fig. 6. At the top—general view of the station for scanning X-ray fluorescent analysis at VEPP-3; below—an example of data obtained: Sr/Rb ratio in a core of the Baikal lake sediments showing the climatic oscillations with a quasiperiod of 1–2 thousand years.

4.4. Soft X-ray and VUV metrology

Works on metrology using SR at BINP were started since the seventies of last century and were related to the calibration of radiation sources (various gas-discharge tubes), various kinds of detectors (solar blind PEM, semiconductor and scintillation detectors, X-ray films, coordinate resolved detectors), optical elements as mirrors, diffraction gratings, filters and spectrum devices (compact spectrometers). Works of this kind have been carried out at various times at the BINP with the SR sources available: VEPP-2M, VEPP-3, VEPP-4M. The spectrum range used for metrological measurements was ranged from 2.5 eV (5000 Å) up to 34 keV (0.36 Å).

In 1990–2000, the main metrological studies using SR were mainly carried out in the soft X-ray radiation range 0.1–1.5 keV at the VEPP-2 M storage ring at a special metrology station [9]. In December, 2000, VEPP-2 M was disassembled for making a new storage ring VEPP-2000 and SR beam studies ceased.

Since there is a necessity in metrological studies in soft X-rays a new metrology station was developed for the same spectrum range at VEPP-3. At present, the main components of the station are manufactured and its assembly has begun. The station commissioning and the beginning of experiments with SR beams at the station is planned for the beginning of 2005.

The station is planned for its use in the spectrum range 0.1–5 keV and in addition to metrological studies it is also designed for carrying out the fundamental and applied research in the field of catalysis (experimental techniques EXAFS, XANES), and material science (MCD and MLD magnetic dichroism techniques). The station will enable one to carry out the studies both with the "white" SR beam and with monochromatic radiation. For monochromatization of radiation, the monochromator based on two dispersing elements in a parallel geometry is used. As the dispersing elements used in the range 0.1–1.5 keV, the X-ray multilayer mirrors and in the photon energy range above 1.5 keV—crystals are planned to be used. The radiation spectrum available at the station is shown in Fig. 7 for two typical values of the electron energy at the storage ring VEPP-3: 2 and 1.2 GeV.

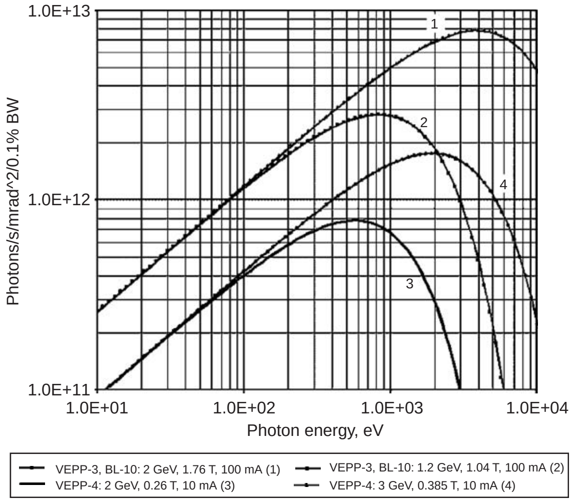

Fig. 7. The expected spectrum fluxes of photons at the metrology stations of storage rings VEPP-3 and VEPP-4M at some typical values of their parameters.

Recently, there is a necessity in calibration of rather large apparatuses, in particular, equipment of the "Space Solar Patrol" [10]. Due to the extended requirements to the calibration spectrum range as well as because of a large number of the experimental stations and a strongly limited area in the VEPP-3 SR bunker, there are no visible chances to place the large-scale equipment at the metrology station of SR beamline of the VEPP-3 storage ring. In this connection, we started the development of an additional metrology station at the VEPP-4 storage ring designed for an expanded spectrum range from 10 eV up to 10 keV. The areas available at the VEPP-4M SR bunker enable the location of large-scale equipment.

At the station, due to a broad spectrum range, it is planned to use several types of monochromators: on the basis of diffraction gratings (in a range 10–100 eV), on the basis of multilayer X-ray mirrors (100–1500 eV), and on the basis of crystals (>1.5 keV). The expected spectrum fluxes of photons at the station at an electron energy of 2 and 3 GeV of VEPP-4M are shown in Fig. 7.

4.5. X-ray lithography and LIGA-technology

The works on the use of SR beams for X-ray lithography were primarily aimed at the development of technology for producing microelectronic chips with the submicron dimensions of components. From the beginning of the 1990s, on the basis of the experimental results achieved in the field, the works on the deep X-ray lithography started with the aim of developing LIGA technology. The possibilities of applying deep X-ray lithography for producing a number of microproducts were demonstrated as for producing: regular micropore filters of high geometric transparency with the uniform pores of submicron sizes, optical microelements of the visible range with the new or improved properties (a bifocal artificial crystal of an eye, apochromatic diffraction lenses, gratings, mirrors), X-ray microstructured screen registrators of images of high efficiency with an improved spatial resolution [11].

The first stage of works on the X-ray lithography was, in practice, based on the experimental stations and "clean" rooms at the VEPP-2M storage ring and it was characterized by the used radiation spectrum range of 5–20 Å. Since 2001, because of the upgrade of VEPP-2M, the X-ray lithography station was arranged at the SR beamline #10 of the VEPP-3 storage ring, where it was used for several years in a special regime of the storage ring at reduced energy 1.2 GeV [12].

With the development of works on deep X-ray lithography and with the demand for harder X-ray radiation for the works on deep exposure, the "X-ray topography" station was used at VEPP-3. At the same time, we started the development and manufacture of a specialized LIGA station with the extended possibilities of X-ray lithographic works at the SR beamline #0 at VEPP-3, which replaced two stations used by this time.

The new LIGA station provides a possibility to exposure samples with dimensions up to $100 \times 100\,\mathrm{mm}^2$ with the scanning velocity of samples with respect to the beam of up to 20 cm/s. Exposure of samples can be done both in a vacuum and in the air or helium environment. The station can use radiation from both a 3-pole wiggler of the VEPP-3 storage ring ($H = 2.0\,\mathrm{T}$, $\lambda_c = 2.3\,\mathrm{\AA}$) and an 11-pole lithographic wiggler with the maximum field of up to 1.0 T ($\lambda_c \geqslant 4.6\,\mathrm{\AA}$). A feasibility of varying the magnetic field in the lithographic wiggler enables optimization of the radiation spectrum at the station for exposure of individual samples.

4.6. Precision diffractometry and anomalous scattering

The station is operated in the photon energy range from 5 to 20 keV with the detection of scattered radiation within the range of angles from $2\Theta = 0-140^\circ$. Radiographic pictures can be obtained both in the scanning regime by using a scintillation detector and a flat perfect crystal analyzer at a defragged beam (a high-resolution regime) and by using the one-coordinate detector OL-3-350 for the fast detection in the angle range.

At the station, the X-ray structural studies are carried out for new materials, in particular, the catalysts, sorbents, materials for microelectronics, products of the mechanochemical synthesis, nanomaterials, etc. A cycle of works was performed on a study of the formation mechanisms for the mesostructured silicate and element-silicate materials. The X-ray diffusion scattering technique was worked out for determining the roughness of the surfaces and interfaces in the multiplayer X-ray mirrors. In the time-resolution regime (time-resolution X-ray diffraction) by using the position-sensitive detector OD-3-350, the studies of the formation of the applied copper–cobalt oxide catalysts in the process of the surface thermal synthesis were performed.

The works are carried out on determining the structure and phase composition of the fine films obtained with the chemical vapor deposition technique under various conditions of the synthesis (as the pressure, chemical composition, etc.). The structure and phase composition of the detonation synthesis products were studied. The processes occurred during crystallization of the diffusion hardening alloys—the promising materials for cold soldering were studied.

4.7. High-pressure diffractometry

The station is operated in the photon energy range from 30 to 34 keV. The station is equipped with the high-pressure chamber by the "cylinder-piston" and "diamond-anvil" schemes. The novel patterns of experimental program are as follows: a study of the structure and properties of the gas hydrates—a promising source of the carbon fuel raw, a study of the structure and properties of the micropore framed aluminosilicates during compression in various media from the viewpoint of varying the ion exchange and other sorption properties of these compositions.

4.8. EXAFS spectroscopy

The experimental station is specialized at studies of the highly dispersed objects as catalysts and nanomaterials, i.e. the samples for which the radiographic and structural techniques are unacceptable. Some techniques were developed for preparation of samples for making shots of the reaction active compositions under inert conditions. Under conditions of the given gas environment, a study of samples at temperature range from 10 to 900 K is possible. The following techniques are realized: a traditional one—on absorption and also the X-ray fluorescence, complete external reflection, full photocurrent, X-ray stimulated optical luminescence. The structure of the local environment of atoms of the selected chemical element (the coordinate number, interatom distance, Debay factor, the kind of a neighboring atom) is studied by the experimental curves.

Depending on the technique used, the volume, surface or near-surface layers is analyzed.

Chemical elements studied	from $_{22}Ti$
Concentrations of the studied element	0.01–100%
Range of interatom distances measured	1.5–8 Å (±1%)
Error in defining the coordinate numbers	±10%
Error in defining the Debay factor	±40%.

As some examples of the new works performed in the last few years, one can mention the following:

A study of newly introduced compositions obtained by intercalation of the inserted molecules of ions between the salts of a monolayer MoS_2 [13]; a study of the ferrum ion state in atmospheric aerosols at an amount of the detected element of less than 1 mg; a study of a structure of the nickel nanoparticle surface with sizes exceeding 200 A with the technique of absorption of selenhydrogen as the probe molecule [14]; a study "in situ" of processes that occurred in the electrochemical cell during restoration of oxygen [15] and a study of a phase providing, in the cell, a superstrong stabilization of hydrogen in combination with a high inner mobility; a structural study of germanium "quantum points" at the silicon surface [16].

5. Development of the free electron lasers

The new kinds of the free electron lasers (FELs) had been developed at SSRC for over 25 years. In 1977, a fundamentally new type of FEL was proposed—an optical klystron (OK FEL) [17]. In 1987, with the OK installed at the VEPP-3 storage ring, we obtained the generation within the wavelength range of 2400–6900 Å, and the world's first FEL operated in the ultraviolet range of a spectrum [18].

In the middle of the 1990s, we started the development of a new direction of the research technological application of FEL, the generation and use of the intense beams of the terahertz radiation. The development of this rather promising direction was retarded by the absence of sources of such a radiation. In 1995–2000, in collaboration with the Research Institute of Atomic Energy of R. Korea (KAERI), a compact FEL of the terahertz radiation (FIR FEL) retunable in the wavelength range 100–360 μm (~3–1 THz) was developed and commissioned successfully by Budker INP [19]. The radiation power in a micropulse of 2–4 μs is up to 50 kW at a mean power of up to 0.1 W. At present, FEL is used at KAERI for studies in microscopy, molecular spectroscopy, solid body physics and other fields.

At the end of the 1980s, the Budker INP started the development of the powerful FELs of IR range for the research and technological applications. The FEL power at the electron storage rings is limited by the multiple interactions of electrons with radiation in the optical cavity, therefore, for the development of the powerful FELs, one has to use not the storage rings but the accelerator recuperators. The project of such a powerful FEL was first developed at the Budker INP (Novosibirsk) [20]. At present, at the Budker INP, a complex of three powerful FELs of the terahertz and IR ranges for the research and technological applications is under development and commissioning. The basic full-scale project of the complex will have a four-track accelerator recuperator at a maximum energy of 50 MeV (Fig. 8).

The expected total range of retuning the wavelengths of three FELs installed at the 1, 2 and 4 tracks of the full-scale FEL will amount from 3 to 200 μm. The first-stage FEL on the basis of the one-turn accelerator recuperator with an energy of up to 14 MeV was commissioned in April 2003. The first-stage FEL comprises the full RF system (all the cavities and generators) as well as an injector with the input channel but compared to the full-scale version, it has only one orbit.

At present, it provides a continuously retunable radiation in a submillimeter (terahertz) wavelength range (120–180 μm) with a record mean power over 200 W. By 2007, it is planned to realize the second stage of the FEL whose power will be of the order of 10 kW in the IR range of 3–20 μm. The Siberian Center of Photochemistry Studies is based on these powerful FELs.

The Budker INP takes part in the project of high-power IR FEL on the basis of the superconducting linac at KAERI, Korea. In 2003, the RF system of the machine has been commissioned. It consists of two cryomodules with 352-MHz superconducting cavities from CERN in a common cryostat, and two 50-kW 352-MHz generator modules, produced at Budker INP. The total RF voltage 10 MV was obtained on the cavities. Also, the injection beamline from the injector to the cavities has been manufactured, assembled, and commissioned. A high-power 10-MeV SC linac, as an intermediate stage, has been commissioned.

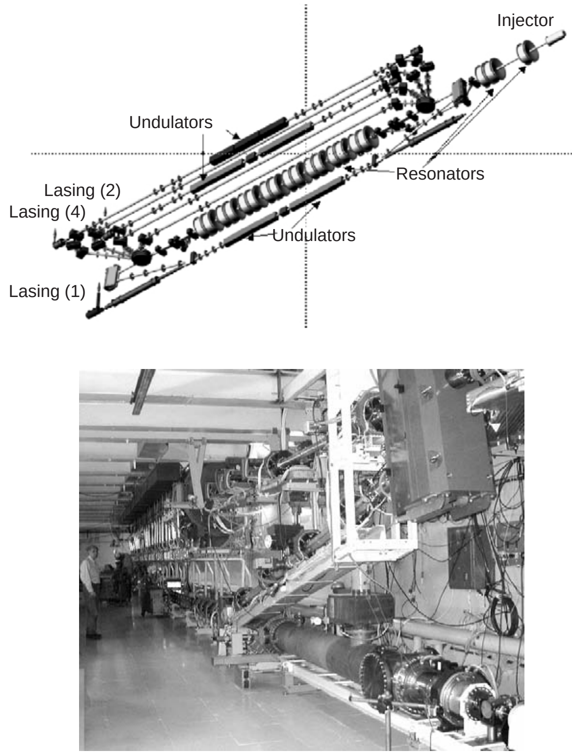

Fig. 8. At the top—layout of a complex of three powerful FELs of the terahertz and IR ranges for the Siberian Center of Photochemical Research on the basis of a multiturn accelerator recuperator; below—general view of the first-stage THz range FEL.

The full-scale project includes the second SC module, a backward track, and FEL installed on it. The scheme of the accelerator is energy-recovery linac. It is necessary to increase maximum RF voltage up to 20 MeV on each module. In this case, one can expect about 10 kW or more CW FEL emission in the 6–20 μm wavelength region.

6. Development of new SR sources and insertion devices

Twenty-five years ago, the development and creation of new SR sources and magnetic systems for SR generation (insertion devices) became an important field of the SSRC activity.

6.1. Kurchatov Synchrotron Radiation Source (KSRS)

KSRS is a specialized accelerator complex designed for generation of SR beams. The complex was completely developed and manufactured at the Budker Institute of Nuclear Physics and assembled by the BINP staff at the premises of the Russian Scientific Center "Kurchatov Institute", Moscow. In the course of development of the project, the conditions for minimum attainable horizontal emittance of the beam required for getting the radiation high brightness were first obtained. The obtained results enabled the development of the project of two dedicated SR sources: "Siberia-I" (with an electron energy of 450 MeV) and "Siberia-II" (at an energy of 2.5 GeV), which have been designed and manufactured at BINP and under operation at the Kurchatov Institute since 1983 and 1995, respectively.

6.2. Technological storage ring complex "Zelenograd"

The storage ring SR source for the Russian research-industrial center of microelectronics in Zelenograd (near Moscow) has been designed and manufactured at Budker INP in the period 1990–1996. The primary goal of the center is the production of micromechanic elements by X-ray lithography and LIGA-technology techniques. The design energy of the Zelenograd SR-source is 1.6 GeV with a possibility to increase it in the future up to 2.5 GeV. Unfortunately, in the period 1997–2001, the financing of the project was stopped. In 2002, the assembly and commissioning of all the systems of the project were renewed step by step. At present, the foreinjector is already assembled and commissioned and the current of 30 mA is obtained; the transfer channel to the small storage ring (booster) and the booster magnetic-vacuum system are assembled.

6.3. Magnetic systems for foreign SR sources

In 1999–2001, by the order of the Paul Scherer Institute, Willigen, (Switzerland) the magnetic system for the SR source of the third generation—the Swiss Light Source has been developed, manufactured and delivered to the customer. In total, 306 quadrupole and sextupole magnets with a mechanic tolerance for production of the magnetic pole profiles of $\pm 15\,\mu M$ and with the difference of the measured position of the lens magnetic axis no more than $\pm 30\,\mu M$ have been produced and installed at SLS. In 2003–2004, the Budker INP has designed, manufactured and delivered to customers the elements of the SAGA (Japan) SR source magnetic system, which consists of 16 dipole magnets, 40 quadrupole lenses, 32 sextupole lenses and 52 quadrupoles for SOLEIL (France).

At present, BINP takes an active part in the development and creation of a new 1.2 GeV synchrotron—injector for FEL based on the electron storage ring at the Duke University (USA), and the development and manufacturing of sextupoles for magnetic system of SR source DIAMOND (England).

6.4. Insertion devices

Budker INP has major experience in the development and construction of insertion devices as the planar and elliptical wigglers, superbends, various types of undulators: electromagnetic undulators on the base of permanent magnets, hybrid ones with a tunable SR polarization, and others for the Russian and foreign SR and FEL centers.

6.5. Superconductive wigglers

Strong field wigglers or wavelength shifters (WLS) are installed in the straight section of the storage ring to enhance the performance of the machine for short-wavelength users and to provide new possibilities for SR experiments [21]. There are several reasons to install wigglers or shifters on a storage ring: (1) to shift the spectrum to the hard X-ray region by using a higher magnetic field of the wiggler (shifter); (2) to increase the photon flux due to many poles (multipole wiggler); (3) to obtain new features of radiation-like polarization; (4) to obtain a flexibility for experiments, due to the possibility of changing the wiggler field during the experiment; (5) to decrease or increase the emittance of the beam in the storage ring; (6) to decrease the polarization time of the electron (positron) beam; and (7) generation of the intensive SR beams with photon energy 0.1–0.10 MЭB and creation of the slow positron source of high brightness by conversion of gamma-ray into electron–positron pairs and positron moderation down to low energy (an example of realization is the installing of superconducting wiggler with magnetic field of 10 T at the SPring-8).

The first superconducting 20 pole wigglers in the world have been assembled in 1979 for the VEPP-3 storage ring. Over the last 10 years, Budker INP has constructed a new type of superconducting wiggler and shifter for the number of storage rings around the world. Some of them have record parameters among the same devises produced by other companies. Among them, there are strong field 3-pole wavelength shifters for PLS, Korea (7.6 T, 1995), LSU-CAMD, USA (7.5 T, 1998), SPring-8, Japan (10.3 T, 2000), BESSY-II, Germany (7.5 T, 2000), and BESSY-II PSF, Germany (7.5 T, 2001).

In 2002–2003, we have carried out work on the development and creation of the multipole superconducting wiggles for the foreign storage rings-SR sources. In particular, we have developed and manufactured the superconducting wigglers for generations of SR beams of high brightness: a 17-pole wiggler with a period of 14 cm and maximum field of 7.3 T for the storage ring BESSY-II by the order of the Hann–Meinter Institute (Berlin, Germany) and a 49-pole wiggler with a period of 6 cm and a magnetic field of 3.5 T for the ELETTRA storage ring (Triest, Italy), development and manufacturing of 63-pole 2 T wiggler for CLS (Canada).

6.6. Superbend

In 2002–2003, we have developed and, at the end of 2003, we have successfully tested at the stand a new type of the strong field superconducting SR—a superbend for BESSY-II (Germany), a bending magnet with the magnetic field up to 9.6 T (turn on 11.25°). On the basis of these magnets, it is possible to construct the compact and inexpensive dedicated SR sources for the Universities and industrial companies.

6.7. Elliptical wigglers and undulators for generation of radiation with tunable polarization

The elliptical wiggler and undulator designed for obtaining elliptically polarized synchrotron radiation/Kul-**4**/with rapid change of the polarization sign was manufactured and tested at Budker INP in 1996 and 1998. In 1997, the elliptical wiggler was installed at NSLS-II (BNL, USA) and the undulator was installed in 1999 at SR source APS (Argonne National Laboratory, USA). The time required for switching of the polarization sign is 5 ms. The four universal electromagnetic undulators ordered by the Duke University (Northern Carolina, USA) have the separate power supply of the windings allowing application of these undulators as planar, elliptic or spiral ones.

The examples of magnetic systems for the new SR sources developed and produced at Budker INP are shown in Fig. 9.

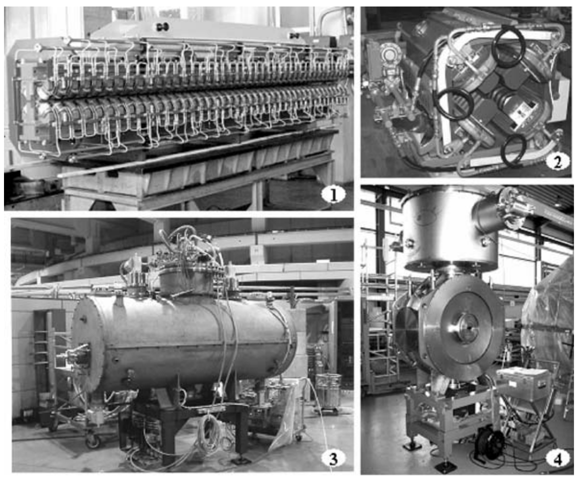

Fig. 9. Examples of magnetic systems for the new SR sources developed and produced at Budker INP. 1—elliptical undulator for the SR source SLS, Switzerland (2001); 2—quadrupoles for the SR source SOLEIL, France (2003–2004), 3—49-pole 3.5 T superconducting wiggler for ELETTRA, Italy (2003), 4—9.6 T superbend for BESSY-II, Germany (2004).

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Erratum

Erratum to: "Status of the Siberian Synchrotron Radiation Center" [Nucl. Instr. and Meth. A 543 (2005) 1]

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