Nuclear Instruments and Methods in Physics Research A 405 (1998) 179–190

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

Synchrotron radiation and free electron laser activities at SSRC

V.A. Chernov, V.I. Kondratev, V.N. Korchuganov, G.N. Kulipanov, N.A. Mezentsev, A.D. Oreshkov, V.E. Panchenko, V.F. Pindyurin, A.N. Skrinsky, M.A. Sheromov, B.P. Tolochko, N.A. Vinokurov, K.V. Zolotarev*

Siberian Synchrotron Radiation Centre, Budker Institute of Nuclear Physics, Russian Academy of Science, 630090 Novosibirsk, Russia

Abstract

In the last decade the Siberian SR Centre has implemented a wide program of SR and FEL research in cooperation with various research centres and institutions in Russia and abroad. The report illustrates this program, including joint experiments with the use of SR and FEL sources available at the Budker Institute of Nuclear Physics (INP), the implementation of new joint projects in Novosibirsk and at other centres, as well as the delivery of equipment designed and fabricated at the Budker INP or in collaboration with the Russian industry. Some technical information about the SR storage rings, wigglers, undulators and free electron lasers which are being constructed, used or developed at Budker INP is given as well.

1. Introduction

At present the Siberian Synchrotron Radiation Centre (SSRC), which was established on the basis of the Budker Institute of Nuclear Physics (INP) Laboratories, is a major site for synchrotron radiation (SR) and free electron laser (FEL) research in Russia. The general lines of the SSRC scientific program are:

- performance of experiments and the development of new technologies using SR of the Budker INP sources: VEPP-2M, VEPP-3 and VEPP-4M storage rings;
- development of experimental SR equipment (beamlines, optics, monochromators and detectors);
- development of storage rings – dedicated SR sources, development of devices for SR generation – wigglers and undulators;
- development of free electron lasers.

The SSRC is financially supported by:

- the Russian State scientific-technical program "Synchrotron radiation, beam technologies";
- purposeful funding of FEL works;
- grants of Russian and international scientific and technological funds;
- contracts with various institutions in Russia and abroad;
- international cooperation.

2. SR sources of Budker INP

Three storage rings operate as synchrotron radiation sources at the Budker INP – VEPP-2M, VEPP-3, and VEPP-4M. The layout of these facilities is shown in Fig. 1 and their main parameters are given in Table 1. The experimental stations for all storage rings of the INP are listed in Table 2.

The VEPP-2M electron-positron storage ring is a main facility used for SR research in the VUV and soft X-ray ranges ($\lambda = 5 \cdot 10^3 \div 2$ Å) at the SSRC.

There are two special rooms and a hall for SR works. Their locations and the directions of SR beamlines are shown in Fig. 1. The radiation from a superconducting wiggler (beamlines 1E and 2E) and from a bending magnet (beamlines 3E and 4E) is extracted to the special rooms with total area 80 m^2 along the direction of the electron beam motion. In the direction of the positron beam motion, the radiation from a bending magnet (beamlines 1P to 4P) arrives at the hall whose total area is 48 m^2. The station for positron beam parameters measurements (beamline 5P) is housed in a separate room, and one of the stations for stimulated gas photodesorption (beamline 6P) is placed in the VEPP-2M hall.

At present, the VEPP-3 storage ring is a main SR source in the X-ray range. SR is generated by a dedicated 3-pole wiggler with a field of 2 T installed in the straight section of the storage ring. The magnetic field is approximately the same at each poles. The 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 to transmit photon beams with an angle of 8 mrad. Beamline

* Corresponding author. Tel.: +7 3832 359103; fax: +7 3832 352163; e-mail: Zolotarev@inp.nsk.su

PII S0168-9002(98)00003-5

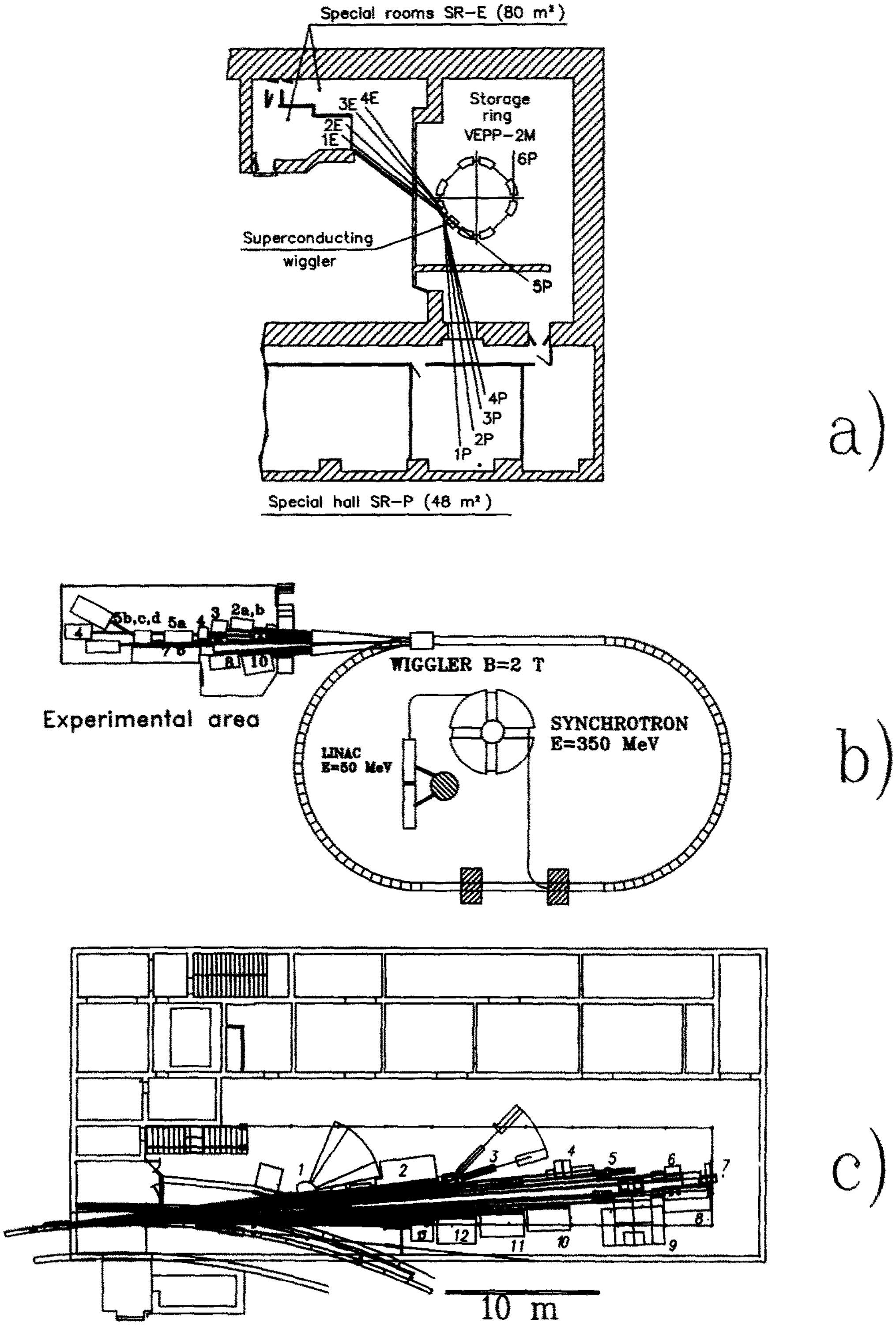

Fig. 1. Layout of the VEPP-2M (a), VEPP-3 (b), VEPP-4M (c) facilities.

Table 1
Basic parameters of the VEPP-2M, VEPP-3 and VEPP-4M storage rings

	VEPP-2M	VEPP-3	VEPP-4M
Energy, GeV	0.7	2.0	6.0
Circumference, m	17.88	74.4	366
Kind of particles	e^-, e^+	e	e^-, e^+
Operation mode	single- or multi-bunch	one- or two-bunch	single- or multi-bunch
Emittance, cm · rad	$4.6 \cdot 10^{-5}$	$2.7 \cdot 10^{-5}$	$1.2 \cdot 10^{-4}$
Stored current, mA:			
total	300 (150 e^- and 150 e^+)	250	
single-bunch	200 (e^- or e^+)		40
multi-bunch	300 (e^- or e^+)		80
Lifetime, h	1 ÷ 2	3 ÷ 4	4 ÷ 6
Magnetic field in bending magnets, T	1.91	1.08	1.3
Revolution period, ns	59.6	248	1200
Bunch length $2\sigma_s$, cm	8	30	5
insertion devices	superconducting wiggler (see Table 5)	3-pole wiggler, 11-pole wiggler (see Table 6)	wiggler (see Table 6)
Transverse beam dimensions at emission points			
$2\sigma_x$, mm	2.7 in bending magnet 1.0 in wiggler	1.8	3
$2\sigma_z$, mm	0.17 in bending magnet 0.03 in wiggler	0.12	0.8
Critical radiation wavelength, Å			
from bending magnet	19.9	4.31	0.51
from wiggler	5.1	2.3	0.4
Number of beamlines:	10	9	14
from bending magnet	7 ($2-e^-, 5-e^+$)	1	13
from wiggler	3 ($2-e^-, 1-e^+$)	8	1
Mode of operation for SR works	*parasitic & dedicated*	*shared & dedicated*	*parasitic & dedicated*

9 extracts radiation from a 1.7 T bending magnet through a 30 μm-thick Be foil into a superhigh vacuum tube with differential pumping.

In 1996 the 11-pole wiggler was installed on the VEPP-3 storage ring. The wiggler is intended to supply intense photon beam for a new LIGA station. This beam has an adjustable spectral band in the range of 1–10 Å and a high uniformity of radiation power distribution over a sample. The parameters of this wiggler are presented in Table 6.

In recent years, the project for VEPP-4M updating has been implemented. This project envisaged, in particular, the replacement of two periodicity components in the middle of each semi-ring by equivalent insertion devices consisting of C-shaped bending magnets and lenses. The design of these magnets enabled us to easily arrange radiation extraction from them using a special vacuum chamber of the storage ring at this location. Since the magnetic field in the C-shaped magnets was increased, their length was shortened, thus making it possible to provide 1.8 m long straight sections for installation of dedicated SR generators – wigglers and undulators. A 1.5 T electromagnetic seven-pole wiggler is suggested to be positioned in one of the straight sections.

The construction of a radiation-protected experimental bunker with a total area of about 1200 m^2 near the tunnel of the VEPP-4M northern semi-ring comes to completion. The SR beamlines and about 20 experimental stations and special laboratory rooms for experimental teams will be housed in this bunker (see Fig. 1c). Experimental works with SR beams in the new bunker are expected to start in 1998. Most of the SR experiments will be carried out simultaneously with high energy physics experiments. Some of SR experiments that need special operation modes will be performed during the runs intended for SR works. The components of front-end parts of all the 14 beamlines have already been designed, manufactured and prepared for mounting at the storage ring.

3. Application of SR sources of SSRC

The SSRC activities cover a wide spectrum of scientific and technological tasks. They were reported in more than 1400 publications in Russian and foreign journals and books [1].

Fig. 2 illustrates the annual number of SSRC publications.

The staff of the experimental teams involved in SSRC works is mainly from Novosibirsk Institutes of the Siberian Division of the Russian Academy of Sciences. These

Table 2
SR beamlines and experimental stations of the VEPP-2M, VEPP-3 and VEPP-4M storage rings

Beam line (emitting particles)	Emission point	Experimental station
VEPP-2 storage ring		
1E (e^-)	wiggler	Out of use
2E (e^-)	wiggler	Out of use
3E (e^-)	bending magnet	Photoelectron spectroscopy for chemical analysis (in operation)
4E (e^-)	bending magnet	Out of use
1P (e^+)	bending magnet	Out of use
2P (e^+)	bending magnet	Time-resolved luminescence (beamline ready, preparation of the station)
3P1 (e^+)	bending magnet	Soft X-ray metrology (station commissioning)
3P2 (e^+)	bending magnet	VUV spectroscopy & metrology
4P (e^+)	bending magnet	Stimulated gas photodesorption (SSC-1)
5P (e^+)	wiggler	Positron beam parameters measurements
6P (e^+)	bending magnet	Stimulated gas photodesorption (SSC-2)
VEPP-3 storage ring		
2	wiggler	High-resolution X-ray diffraction and anomalous scattering
3	wiggler	X-ray fluorescence element analysis
4	wiggler	Subtraction angiography
5	wiggler	a) X-ray microscopy and microtomography
		b) Time-resolved diffractometry
		c) Macromolecular crystallography
		d) Inelastic scattering
		e) Small-angle diffractometry
6	wiggler	Time resolved spectroscopy
7	wiggler	LIGA, X-ray topography and diffractometry
8	wiggler	EXAFS-spectroscopy
10	bending magnet	X-ray lithography
VEPP-4M storage ring		
1	Bending magnet (0.8 T)	Energy dispersive EXAFS
2	bending magnet (1.3 T)	EXAFS
3	bending magnet (1.3 T)	Diffraction cinema
4	bending magnet (1.3 T)	Elemental analysis
5	bending magnet (0.9 T)	Small angle diffractometry
6	bending magnet (0.9 T)	Anomalous scattering
7	bending magnet (1.3 T)	Energy dispersive diffractometry
8a	wiggler	Medicine
8b	wiggler	Microscopy
9	bending magnet (1.35 T)	Inelastic processes
10	bending magnet (1.35 T)	Metrology
11	bending magnet (0.95 T)	Calibration
12	bending magnet (0.95 T)	LIGA
13	bending magnet (1.35 T)	Reserve
14	bending magnet (1.35 T)	Technical beamline

teams are usually the hosts of the experimental stations. Besides, the teams from other cities from institutes of the Russian Academy of Sciences, universities and high education schools, technological institutes of industry both from Russia and abroad are involved in SSRC works. Fig. 3 illustrates the dynamics of the number of the experimental teams since 1973. The decreased number of the teams in 1986–87 was caused by the fire at the Institute, which happened in August of 1985. The second decrease after 1990 was due to the change in the political and economic situation in the countries of Eastern Europe and in the republics of the former Soviet Union. A drastic reduction of funds for science in Russia and the increased prices of flight tickets and hotel accommodation decreased the number of teams from cities of the European part of Russia.

The main recent SSRC activities in the field of SR application are briefly described below.

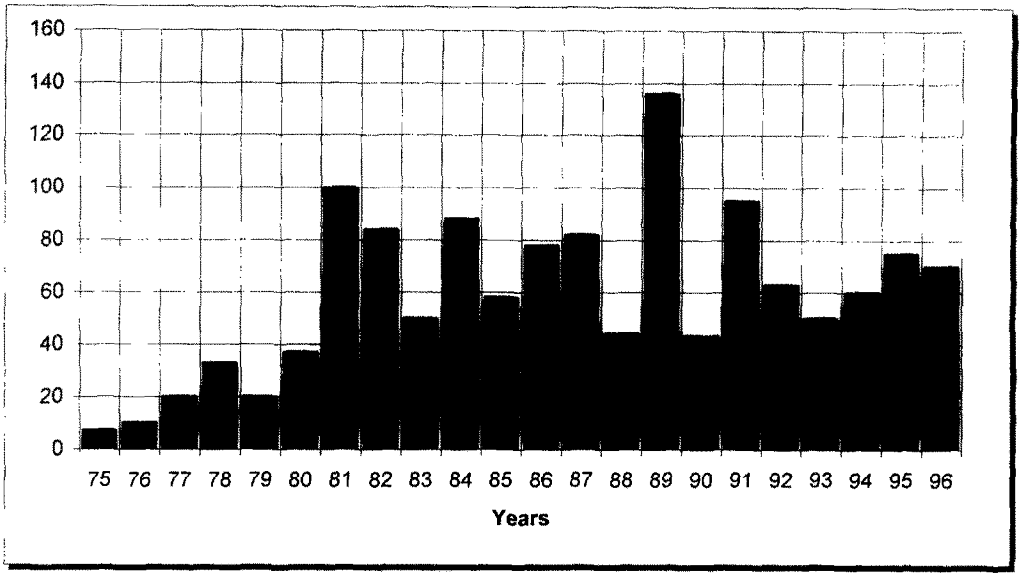

Fig. 2. Annual number of SSRC publications.

3.1. Accelerator physics

Some SR experimental stations of the SSRC are used for investigation of various phenomena in machine physics. For example, in 1996 gas photodesorption stimulated by SR from the walls of prototypes of vacuum chambers of supercolliders was studied on SSC-1 and SSC-2 stations (VEPP-2M). In the last years, this work has been carried out under the CERN contract. In addition, a measurement technique for ultrahigh vacuum ($10^{-11}-10^{-12}$ Torr) is being developed at VEPP-2M beamline 3P2, with the use of UV luminescence of the residual gas under SR irradiation.

3.2. X-ray metrology

Many experimental works were carried out for absolute calibration of X-ray detectors. The spectral sensitivity and

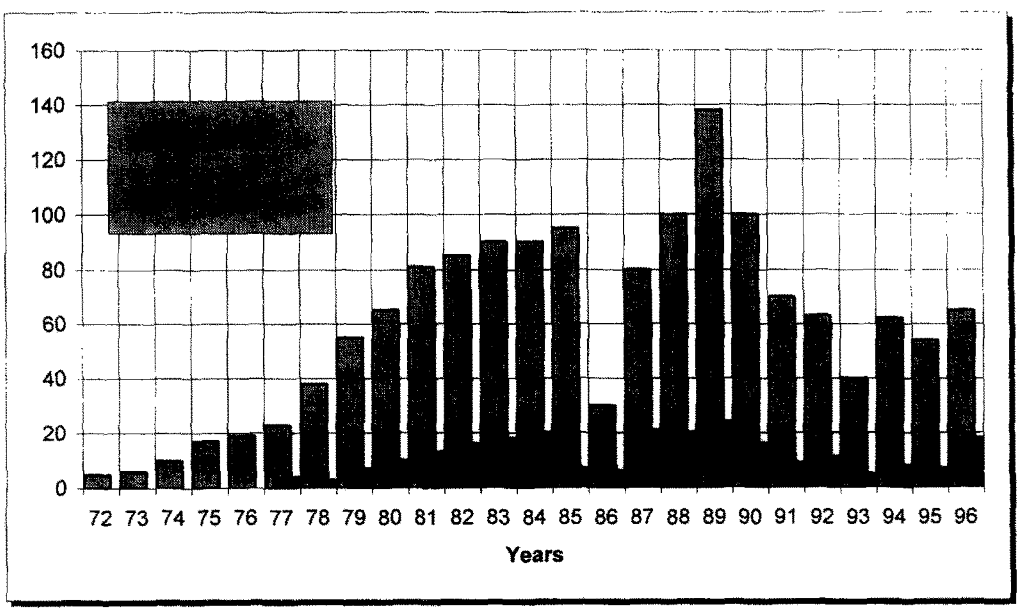

Fig. 3. The numbers of working teams in SSRC.

time response of X-ray detectors were studied in relatively hard X-rays (5–20 keV) on the VEPP-3 storage ring (X-ray microscopy and microtomography, and X-ray lithography stations), and in soft X-rays (0.1–1 keV) on the VEPP-2M (X-ray metrology station).

3.3. Materials science

These kinds of investigations cover the main part of SR activities. As a rule, materials research is carried out on the VEPP-3 experimental stations of EXAFS spectroscopy, anomalous scattering, small-angle scattering and diffraction cinema, time resolved spectroscopy, XRF analysis and X-ray miscroscopy and microtomography. The range of samples to be examined is very wide. Very often, the complex studies of materials are performed using a combination of different methods.

3.4. Medicine

In the last years, the station of subtraction angiography was constructed and commissioned at the VEPP-3 storage ring, and the possibility of visualizing lymph nodes in alive rats at the K-absorption edge of iodine was demonstrated.

A new trend in this field is the development of xenon bronchography of lungs. If a person inhales a mixture of oxygen and xenon in the proportion 1 : 4 (as when nitrogen is replaced with xenon in air), then a xenon distribution image can be obtained by subtracting X-ray images taken just above and below the xenon K-absorption edge. The preliminary results demonstrate that a 0.5 mm thickness of xenon in the test samples can be observed.

Another part of SR medical applications concerns the composition of different types of tissues, organs, blood, plasma, lymph and other medical samples, as well as the distribution of different elements in the samples. These kinds of investigations are performed at the XRF analysis station and X-ray microscopy and microtomography station of VEPP-3.

3.5. Biology

The main trend in SSRC biological research is time resolved X-ray diffraction for a study of the muscle structure during contraction and relaxation. This work is performed at the station for small angle scattering and diffraction cinema by the group from the Institute of Biophysics, Pushino. This station has begun to be used also for experiments on obtaining X-ray refraction (phase contrast) images of various biological objects.

3.6. Environmental research

The main part of SSRC environmental research is performed at the station for XRF analysis and concerns the examination of the contents of different elements in samples. The following subjects are covered:

- analysis of the atmospheric aerosol samples from various regions of Siberia, Baikal Lake and North Kazakhstan;
- analysis of bottom sediments and water suspensions from the Novosibirsk reservoir and also of the various organs of fishes for technogenic impurities;
- analysis and scanning microanalysis of insects (meadow moths) and their food plants for studying element migration along the food ways;
- analysis of agricultural grain plants;
- analysis of human hairs.

3.7. Geology and geochemistry

The station for XRF analysis using SR of SSRC is widely used for solving a number of fundamental and applied problems of geology and geochemistry. These problems include:

- analysis of bottom sediments and samples from bottom drilling bores from the Baikal Lake to reconstruct the variation in the Earth's paleoclimate and the geochemical history during the last 100 000 years;
- analysis of rock ore samples to reveal platinum deposits;
- complex analysis of moon and meteorite samples using the SRXRFA and instrumental neutron activation analysis (INAA) methods for geochemical characterization of the East Edge of the Moon;
- analysis and scanning microanalysis of the deep-water Fe-Mn pacific nodules and statistical analysis of the layered structure of these nodules.

3.8. X-ray lithography and LIGA-technology

The recent SSRC activities in the field of X-ray lithography clearly demonstrate the change of emphasis from low aspect ratio structures of microelectronics to rather high aspect ratio microstructures with micrometer and submicrometer features for different purposes.

The efforts in this field are devoted to the development of regular polymer microporous membranes with a graduated pore size and with a high transparency and also the study of the membranes for different applications. The membrane prototypes are fabricated of 3–10 μm thick mylar films and have 0.3–0.6 μm pores arranged at a two-dimensional grid with a 1-μm spacing. The working area of the fabricated prototypes ranges from 0.5 to 2.5 cm^2, and their transparency reaches 30%. Unlike the traditional track membranes, a geometrical transparency of regular membranes can be up to 50% or higher without degradation of the selective filtration properties. The high transparency and high uniformity of the pores do regular membranes attractive for applications in medicine, biotechnology, ecology monitoring, physical research, etc.

Another focus of the SSRC efforts concerns the development of microoptical elements with qualitatively new properties. X-ray lithography offers the possibility of creating deep diffractive profiles both on plane and curved surfaces. Using this fact, a number of prototypes of hybrid refractive-diffractive and completely diffractive microoptical elements were fabricated and investigated. They are a hybrid interocular lens (artificial eye) with multifocal properties, plane blazed diffraction lenses, gratings and mirrors with a profile depth of up to 10 μm and with apochromatic capabilities. The preliminary results obtained reveal good prospects of X-ray lithography employment in this field.

First experience was also acquired in fabrication of regular arrays of magnetic Ni/Cu multilayer nanowires on copper and semiconductor crystal substrates with a wire length of several micrometers and with a 0.3–0.5 μm wire diameter.

The works on development and construction of a new LIGA station on the VEPP-3 storage ring have been started. The station is based on radiation from a special 11-pole wiggler (see Table 6) which has recently been installed and commissioned on the VEPP-3. The station is expected to provide adjusting the exposure spectral band in the range of 1–10 Å by changing the magnetic field in the wiggler without disturbance of other SR users, as well as a 72 × 20 mm exposure area with 5% uniformity and high intensity.

4. Development of instrumentation for SR research

4.1. Detectors

4.1.1. OD family of one-coordinate gas detectors

The new generation of one-coordinate X-ray detectors at SSRC is presented now by the OD-3.1 and OD-3.2 (see Table 3) models. Both models are fast parallax-free, multiwires proportional detectors. The main difference from the previous family of one-coordinate detectors (OD-2) is a geometrical configuration of the cathodes planes. In these models, the planes of anode wires and cathode strips are parallel to the incoming X-rays. This gives the following advantages:

- a parallax-free scheme can be easily realized for any focal length;
- the detector quantum efficiency can be increased without loss of the spatial resolution.

The OD-3.1 model has a 350 mm focal length and, hence, covers 30° of arc. The minimum frame time is 1 μs. This detector is dedicated for X-ray powder diffraction experiments and was installed on beamline 5-b of the VEPP-3 storage ring.

The OD-3.2 detector is similar to the OD-3.1, but its focal length is 1500 mm, so it covers an angle of the arc corresponding to 9°. This detector was installed on the beamline 15A at Photon Factory (KEK, Japan) for small angle scattering experiments.

4.1.2. DED family of two-coordinate detectors

The new detector in this family is DED-5. This model has two coordinate MWPC with an aperture of 384 * 384 mm. Absorption of quanta in the chamber produces the avalanche near the nearest anode wire. Information is read out from the two cathode planes with mutually orthogonal wires. A signal amplifier and a shaper are connected to each wire. The fast digital processor determines both coordinates of the X-ray quantum.

The detector has two working modes: increment accumulation of data and frame-by-frame recording. In the first regime, the information after equalizing is stored in a special incremental memory. In the second mode, the data are recorded in the memory (event by event); moreover, in addition to the coordinates, the energy of quanta and the time of event are recorded as well. The memory volume in a frame-by-frame mode is 8 million events. The minimum frame time is limited to about 100 μs. The detector parameters are presented in Table 3.

Table 3
Parameters of SSRC detectors

Detector name	Entrance window (mm × mm)	Focal length (mm)	Channel size (mm)	Spatial resolution FWHM (mm)	Number of channels	Photo-absorption length (mm)	Working energy (keV)	Minimal frame time μs	Count rate (MHz)
OD-3.1	200 × 10	350	0.07	0.18	3328	50	5–20	1	10
OD-3.2	200 × 25	1500	0.07	0.15	3328	50	5–20	1	10
DED-5	384 × 384	no	1.5 × 1.5	1.5 × 1.5	65536	10	5–20	100	5
MSGC-100	10 × 20	no	0.2	0.2	100	5	5 – 20	100	100
MSGC-500*	100 × 10	500	0.2	0.2	500	50	5–70	1	1000
1D-160-L(H)*	2760 × 10	1350	1.2	1.2; 0.12**	6600	50	5–30; (30–70)	1	3300

* under construction or testing.
** in scanning mode.

4.1.3. Microstrip detectors

A prototype MSGC-100 of the microstrip detector (see Table 3) was mounted and tested at the SR beamline 7 of VEPP-3.

The spatial resolution depends strongly on a drift camera gas pressure. At 5 bar, a spatial resolution of about 200 μm FWHM was achieved. The energy resolution was equal to 8.7% at the 22 keV quanta.

The counting rate reaches a value of about 700 kHz per one strip, which permits one to investigate a fast process by powder diffraction technique with high accuracy.

Some obvious improvements can bring the performance of the detector at a considerably higher level. The MSGC-500 project (see Table 3) is under development now. This model will have a wedge shaped geometry and will be positioned parallel to the X-ray beam. A few 500 microstrips sections will connect with each other, and it will be possible to assemble a large detector. The present results promise that a rate capability can reach 1 MHz per strip.

4.1.4. Image plates

A prototype setup for photostimulated readout of X-ray image data was created and tested at SSRC. The diameter of the reading laser beam is 25 μm, the scanning step is 0.5 and 5 μm along two coordinates, and the scanning field area is $240 \times 150\ \mathrm{mm}^2$.

Recently, the successful preliminary results on the improvement of spatial resolution of X-ray phosphor and image plate screens have been obtained. This was achieved by microstructuring the screen surface with the regular array of deep (60–120 μm) wells filled in with both normal and photostimulatable storing X-ray phosphors. The 25×25 μm wells cover the screen surface with a 30 μm spacing, and the well walls were coated with copper for optical insulation of the screen cells. Another approach was to fabricate a spatial-angular optical microfilter installed between a normal fine grain phosphor screen and a photofilm during registration of X-ray pictures. The results obtained demonstrate that in all cases, a 30 μm spatial resolution (the cell size) is provided at X-ray imaging with the 30 keV photons. It allows us to hope that new types of X-ray screen detectors with improved parameters can be developed in these ways.

4.2. X-ray optics

The development of new high throughput dispersive elements for X-ray radiation is an important task. Multilayer gratings (MGs) are new promising dispersive optical elements for both ultrasoft and hard X-ray ranges.

In the ultrasoft X-ray (USX) range, MGs permit one to improve significantly the spectral and optical characteristics of conventional schemes based on grazing-incidence gratings. The conventional spectroscopy devices based on traditional dispersive elements (grazing incidence gratings or crystals) have very low efficiency in this range of the spectrum. Potentially, MGs extend the advantages of normal incidence designs to the SX range. Among advantages are stigmatic imaging, higher resolution power and throughput, and the replacement for large 2d-spacing crystals.

In the hard X-ray range, MGs are a promising alternative to overcome the monopoly of "monochromatic" crystal optics. Unlike crystals that are essentially monochromatic elements, MGs are polychromatic ones. Along with the application of wide-band synchrotron (undulator) radiation, this merit of MGs makes it possible to create new high-throughput X-ray optical schemes for non-monochromatic experimental techniques (Flash-XAFS spectroscopy, X-ray inelastic scattering, etc.).

A joint team of four Institutes of the Siberian Division of the Russian Academy of Sciences (Institute of Nuclear Physics, Institute of Catalysis, Institute of Automation and Electrometry, Institute of Solid State Chemistry) cooperate in the MG development. The work goes on in the following directions:

- Improvement of the technology of fabricating X-ray multilayers;
- Creation of small-period MGs;
- Theoretical computation and simulation of the diffraction properties of MGs;
- Investigation of the X-ray optical characteristics of MLs and MGs;
- Development of spectrometers for hard X-ray and XUV ranges on the basis of MGs.

To create MGs, a "grooved" technology was developed using holographic lithography and ion-beam etching. Now it is possible to fabricate MGs with a diameter of up to 50 mm and a grating period from 0.27 μm to 2.0 μm.

A new method of numerical simulation of MGs diffractional characteristics (called as "the eigenvector method") was devised out. This method allows one to significantly broaden the scopes for numerical simulation of MGs diffraction characteristics compared with the already existing (differential and modal) methods. Diffraction characteristics of the fabricated MGs were investigated in the soft and hard X-ray ranges of the spectrum. The measured maximum reflectivity into the $(-1, 1)$ diffraction order is about 8% ($\lambda = 0.154$ Å) and 4% ($\lambda = 4.47$ Å) and corresponds to approximately 70% of the calculated one.

The advantage of the MG used in the hard X-ray range is the possibility of concentrating practically all diffracted X-rays to any of the first orders by tuning the incident angle. For the incident angle corresponding to the reflection maximum of the $(-1, 1)$ order, the measured ratio of the $(0, 1)$ order to $(-1, 1)$ order peak reflectivity of about 1% is surprisingly small and can be considered as a figure of merit of the crystal-like behavior of the MG.

5. Development of dedicated SR sources and insertion devices

5.1. Design and creation of dedicated SR sources. Status of the Siberia-2 electron storage ring

In 1996 the joint group of the SSRC and of the Kurchatov Joint Institute of Atomic Energy (Moscow) achieved the design parameters of the dedicated SR source – Siberia-2 storage ring (Table 4).

The energy increase process at Siberia-2 (from 450 MeV up to 2.5 GeV) was adjusted by July, 1996. The energy increase time at Siberia-2 is slightly above 6 minutes. For 5 mA current, the beam lifetime at 2.5 GeV was registered to be about 1 hour.

At present, the maximum stored current value is limited by vacuum in the storage ring. The balance between the loss of particles due to scattering by the atoms of the residual gases and the current increase occurs at a 25–28 mA current in one bunch.

The linac injects a 75 MeV electron beam into the Siberia-1 storage ring with a repetition frequency of 1 Hz, a current pulse of 65 A with an energy spread of 1% and a duration of 18 ns. The electron beam emittance is 0.03 mrad · cm. The single-shut capture current during injection into Siberia-1 reaches 30 mA. The Siberia-1 storage ring is a booster for an energy of 450 MeV for the Siberia-2 storage ring. The parameters of the extracted beam are as follows: one bunch with a current of 100–200 mA and the longitudinal size $\sigma_s = 30$ cm. The time interval of electron beam extraction from Siberia-1 is slightly less than 30 s with a current of 100–140 mA.

The works with the linac will be continued to increase the extracted beam energy up to 90 MeV. It is expected to increase the one-time capture current in Siberia-1 up to 90–100 mA.

At Siberia-1, degassing of the vacuum chamber is continued to increase the beam lifetime at high current. The decrease of the injection cycle duration down to 20–25 s and the increase of the extracted current up to 200 mA are connected with the promotion of tuning of the RF-cavity at Siberia-1 with energy rise up to 450 MeV.

At the Siberia-2 storage ring, it is planned to improve vacuum conditions in the chamber of the storage ring using, as usual, pumping-out devices and subsequent degassing by an SR beam.

5.2. Construction of wigglers and undulators

The INP designed and fabricated many dedicated SR generators – wigglers and undulators – on the basis of superconducting magnets (Table 5), permanent magnets (Table 7), and conventional electromagnets (Table 6).

In recent years, SSRC is involving in the following insertion device projects:

- Superconducting wiggler with a maximum field of 7 T for the Centre of Microstructures of Louisiana University. The wiggler will be installed at the CAMD storage ring with a maximum electron energy of 1.5 GeV at the end of 1997. The main feature of this wiggler is that the orbit of an electron beam passes through the geometrical centre of the wiggler at any field in the central pole. This is achieved by means of two additional warm magnets located at both ends of the wiggler. The main task to be solved with the help of this wiggler is the creation of new microstructures with the use of LIGA-technology.
- Superconducting wiggler for Spring-8 storage ring for a high brightness source of slow positrons. This wiggler is designed for a magnetic field of 8–10 T, and, hence, it will be a unique source for generation of hard X-rays and slow positron beams in combination with the Spring-8 high electron beam energy.

Table 4
General design parameters of Siberia-2

Energy	E	2.5 GeV
Perimeter	C	124.13 m
Number of superperiods	N	6
Betatron numbers	ν_x, ν_y	7.77, 6.70
Horizontal emittance	ε	$9.0 \cdot 10^{-8}$ m · rad
Chromaticity	ξ_x, ξ_y	16.7 – 12.9
Momentum compaction	α	0.0104
Magnetic field in the bending magnets at 2.5 GeV		1.7 T
Gradient of the field in the quadrupole lenses at 2.5 GeV		up to 35 T/m
Radiation damping times	τ_x, τ_y, τ_s	2.92 ms, 3.04 ms, 1.55 ms
RF harmonic number	q	75
RF frequency	F	181.14 MHz
Maximum current (the multi-bunch regime)	I	300 mA
Lifetime	τ	5 hours

Table 5
Superconducting insertion devices of INP

	Year	Energy, GeV	Maximum magnetic field, T	Period, cm	Number of poles	Total length, cm	Gap, cm	Vertical aperture, cm
Wiggler VEPP-3	1979	2.1	3.4	9	20	90	1.1	0.8
Helical undulator VEPP-2M	1984	0.65	0.47	2.4	16	25	1.8	1.3
Wiggler VEPP-2M	1984	0.65	8	24	5	60	2.65	1.5
Wiggler Siberia-1	1985	0.45	5.8		3	35	3.2	2.2
Wiggler PLS (Pohang)	1994	2	7.5		3	90	4.8	2.4
Wiggler CAMD	1997	1.5	7.4		3	90	5.1	3.2
Wiggler Spring-8	1998	8	10		3	100	4	2

Table 6
Electromagnetic insertion devices of INP

	Year	Energy, GeV	Maximum magnetic field, T	Period, cm	Number of periods	Total length, cm	Gap, cm	Radiation wavelength, Å
Helical undulator VEPP-2M	1980	0.7	0.21	2.5	10	25	1.8	100
Wiggler VEPP-4M	1985	5.5	1.6	22	5	110	2.2	0.4
Wiggler VEPP-3	1986	2	2.2	15 and 30	3	70	3	2.1
Undulator OK VEPP-3	1987	0.34	0.56	10	68	680	2.2	$2400 \div 7200$
Undulator TNK (2)	1992	1.6	0.65	11	12	130	3.2	$100 \div 1500$
Wiggler TNK (4)	1992	1.6	1	24	8	210	3.2	$8 \div 40$
Elliptical wiggler for NSLS	1994	2.5	0.8	16	7	120	2.8	$2.5 \div 10$
Elliptical wiggler for APS	1995	7	1.2	16	36	340	2	$0.3 \div 4$
LIGA wiggler for VEPP-3	1996	2	1	24	5	133	3.2	4.6
Wiggler VEPP-4	1997	$3 \div 5.5$	1.5	20	7	128	3.8	$0.4 \div 1.3$
Helical undulator APS	1997	7	0.15	12.8	17	230	1.1×1.8	3

Table 7
Permanent magnet insertion devices of INP

	Year	Maximum magnetic field, T	Period, cm	Number of periods	Total length, cm	Gap, cm
VEPP-3 OK-1	1979	$0 \div 0.3$	10	6	70	$1.1 \div 2$
VEPP-3 OK-2	1981	0.7	6.5	9	60	1.1
VEPP-3 OK-3	1983	0.64	6.9	22	160	1.3
KAERI U-1	1996	$0.6 \pm 10\%$	1.25	160	200	0.5
TESLA U-1	1997	0.5	2.73	33	90	1.2

• Elliptic multi-pole wiggler for the APS SR source of Argonne National Laboratory. The aim of the project was to create a source of X-rays with control circular polarization. The elliptical multipole wiggler consists of a permanent magnet hybrid wiggler which ensures a strong vertical magnetic field and an electromagnetic structure which is also a wiggler with low horizontal field. The period of wigglers is 0.16 m, and the total length is 3.4 m. The electromagnetic part of the wiggler is energized with trapeze-shaped alternating current. It allows one to change the direction of the horizontal magnetic field and, as a consequence, the sign of circular polarization of radiation with a frequency up to 10 Hz. In the summer of 1996, the electromagnetic structure and its power supply were delivered to ANL, tested, and prepared for operation. The wiggler was installed at the storage APS ring and the first runs with a beam were conducted. Since early beginning of operation no orbit distortion was observed outside the wiggler in the rest part of the perimeter of the storage ring. The accuracy of observation was 4 micrometer, as determined by the APS measurement system. The measured parameters of the wiggler radiation are in agreement with calculations. The wiggler will be used in experiments where circularly polarized X-ray radiation with switchable helicity is required.

6. Free electron laser activities at the Budker INP

6.1. Activities on creation of the Center of photochemical research

In 1996 the main efforts on the creation of the Center of photochemical research were concentrated on the RF-system of the microtron-recuperator [2]. Construction and maintenance were conducted in the hall of the RF-generators and in the hall of power supply of the RF-system; the waveguide-feeder tracts were designed. The main modifications of RF-generators were tested at full power: a two-tube module with a power of 300 kW and a four-tube one with power of 500 kW.

The FEL project was updated to extend the short-wave region of the IR range down to 1 μm. The number of tracks in the microtron-recuperator was increased up to eight, and the energy was increased up to 90 MeV. The FEL radiation will consist of $10 \div 30$ ps pulses with repetition frequency $2 \div 22.5$ MHz at a wavelength of $2 \div 10$ μm.

6.2. A compact free electron laser for KAERI

In accordance with the contract between Budker INP and Korean Atomic Energy Research Institute (KAERI), Budker INP developed, designed and fabricated equipment for a compact free electron laser. The electron source is a microtron, the total electron energy is 8 MeV, the average current is up to 75 mA, the pulse duration is up to 6 μs, and the repetition frequency is up to 10 Hz. The original two-meter electromagnetic undulator with permanent magnetic plates between the poles allowed one to obtain a field on the axis of up to 0.48 T with a 5 mm gap and a 12.5 mm period. It will permit one to obtain radiation in the far IR range (25–30 μm). A long undulator with short period, small emittance and energy spread of the electron beam from the microtron give a hope of getting considerable intensification per passage and radiation power up to 1 W. Matching the output parameters of the electron beam from the microtron with the optimal parameters of an electron beam for FEL work is provided by the electron beamline consisting of four bending magnets and six quadrupole lenses.

The microtron-based FEL is space saving (it is placed in a protected room of 3×5 m in size) and easy in operation.

At this stage, all the main FEL elements, except the mirrors of the optical cavity, were fabricated. The output parameters of the electron beam from the microtron were measured. The FEL-optimal regime of the electron beam line was calculated and an electron beam was conducted through the undulator. The measurements of spontaneous radiation and production of generation are being prepared.

6.3. Experiments at the optical klystron at the storage ring of Duke University

At the laboratory of free electron lasers of Duke University a specialized storage ring for a FEL was designed. In the framework of cooperation, in 1996 Budker INP delivered to Duke University an optical klystron, used earlier for work with the FEL at the VEPP-3 bypass. Detecting apparatus on the basis of monochromator MDR-23 with a set of photomultipliers and a CCD-meter, and also a dissector, developed at INP and having a time resolution of about 10 ps were delivered. In 1996, in Duke University generation in the blue region with electron beam threshold currents of about 100 μA was obtained, the experiments on backward Compton scattering of light stored in the optical cavity were conducted, and 12.6 MeV gamma-quanta were obtained. The storage ring parameters and the construction of the optical klystron give a hope of obtaining generation within the range from 0.5 to 0.05 μm.

6.4. Experiments with one electron circulating in the VEPP-3 storage ring

Several experiments devoted to the investigation of single quantum objects in macroscopic traps had already been done. However, investigation of the characteristics of an electron in a storage ring is of great interest. For several years the experiments on investigation of localization length of a single electron circulating in the storage ring VEPP-3 have been performed at INP with the use of SR generated by an electron.

In the quasi-classical model for a beam of charged particles in a storage ring, the longitudinal dimension of the beam appears due to joint action of radiation friction and fluctuation drive forces on an ensemble of single point electrons. According to the quantum theory, there is a correspondence between a particle and some batch which determines space localization of the particle and depends on the shape of the potential holding the particle, and also on the structure of the "thermostat" which with the particle interacts. The arising issue of exhibition of quantum properties of the particle captured in the potential of longitudinal motion of the particle in the storage ring was studied in the first experiments. Based on an experimental system with a classical Brawn-Twiss interferometer, the time distribution of the intervals between the photons induced by undulator radiation of one electron circulating in the storage ring VEPP-3 was investigated.

The purpose of the second stage of the experiments was to observe a random process of synchrotron oscillations of one electron in the storage ring. The use of high-sensitive photomultipliers with good time characteristics allowed one to detect separate quanta of SR, the moments of registration of which gave information on the longitudinal positions of the electron at the moment of emission.

After digital processing, the data obtained gave full enough information on details of the longitudinal dynamics of an electron in the storage ring.

References

[1] Synchrotron radiation in the INP of the Siberian Division of the USSR Academy of Sciences (bibliography): Part 1 (1986), Part 2 (1988), Part 3 (1990), Part 4 (1992) and Part 5 (1996).

[2] N.G. Gavrilov, E.I. Gorniker, et al. Project of a race-track microtron-recuperator for free electron laser. IEEE J. Quant. Electron 27(12) (1991) 2626.