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SYNCHROTRON RADIATION IN NOVOSIBIRSK: THE FIRST 13 YEARS

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We describe the development of activity at the Siberian Center for Synchrotron and Terahertz Radiation at Budker Institute of Nuclear Physics (BINP), SB RAS, since 1974, when the history of experiments with synchrotron radiation (SR) in the world was just beginning – there were no dedicated sources of radiation and works can be carried out at several nuclear centers in the world. BINP made a significant contribution to the development of synchrotron radiation sources, and SB RAS institutes did their part for development of SR application to problems of chemistry, catalysis, biology, geology and materials science. The experiments were made at VEPP-3/VEPP-4 installation.

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INTRODUCTION

Generated synchrotron radiation (SR) was first discovered by accident in 1947 in the optical range on a 70 MeV synchrotron made by General Electric. The practical discovery of SR stimulated the further development of the theory of synchrotron radiation (bremsstrahlung) and marked the beginning of systematic experimental study of the SR properties, which later on showed good agreement between the theory and experiment. Theoretical works suggested the SR created by ultra-relativistic particles in cyclic accelerators to have unusual properties: high intensity, orders of magnitude exceeding the intensity of conventional sources of radiation in the vacuum ultraviolet (VUV) and soft and hard X-ray regions of the spectrum; continuous (“white”) spectrum; small angular divergence of the radiation beams; high degree of polarization; and determinate temporal structure. Due to these properties, in the 50s and the 70s of the last century there outlined an apparent interest in the SR application to various scientific problems.

At that time, the real SR sources were synchrotrons, either already constructed or being built, for high-energy physics and nuclear physics. Since the end of the 50s, a number of synchrotrons have been equipped with special beamlines for SR output, primarily for the purposes of spectroscopy in the vacuum ultraviolet region. These electron facilities included the 320 MeV Cornell synchrotron (USA), 180 MeV SURF synchrotron (USA), 1.15 GeV synchrotron at Frascati (Italy), 750 MeV INS-SOR synchrotron in Tokyo (Japan), 6 GeV Synchrotron at DESY in Hamburg (Germany), 680 MeV synchrotron S-60 at LPI (USSR), 6 GeV synchrotron ARUS in Yerevan (USSR), 1.5 GeV synchrotron Sirius in Tomsk (USSR) and several others. However, works on the SR application were carried out either simultaneously with high-energy physics (HEP) experiments or in a specially allocated and quite limited time.

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The next stage, which further encouraged the SR use, was the creation of various synchrotron storage rings of charged particles in the 60s. In synchrotrons, charged particle beams are periodically injected at a relatively low energy, accelerated to a maximum energy, then dumped, and so on with repetition frequencies of up to 50 Hz. Due to the ultra-high vacuum in the storage rings, particle beams injected and accelerated to a maximum energy keep on circulating with a constant energy for hours and tens of hours. This greatly increases the average current of the particles in the storage ring and, consequently, raises the average SR flux, making the SR beam available at any time, not at a certain time, as in the acceleration cycles of synchrotrons. That also retains the emission spectrum, improves the spatial stability of the emitting particle beams and dramatically reduces the radiation hazard near the storage ring. Although synchrotrons are still used as SR sources, all the new centers on SR application have since been based on storage rings.

The situation in the USSR was unique in that context. Almost all the storage rings were concentrated at the Institute of Nuclear Physics, Siberian Branch of the USSR Academy of Sciences (the INP, USSR AS SB), Novosibirsk. There was also a small 100 MeV storage ring H-100 at the Kharkov Physical-Technical Institute of the Academy of Sciences of the Ukrainian SSR.

The INP, USSR AS SB was one of the world's pioneers in the method of colliding beams. Under the leadership of the first director of the Institute Academician G. I. Budker, the first electron-electron collider VEP-1 (160 MeV) was created in 1963, followed by the electron-positron collider VEPP-2 (670 MeV, 1967). Later on the electron-positron collider VEPP-3 (2 GeV, 1973) was commissioned, and VEPP-2M (670 MeV, 1974) was constructed instead of VEPP-2 and put into operation The spectrum of the SR of these storage rings covered the entire range from ultraviolet radiation to hard X-rays. All these facilities were intended for experiments in high-energy physics. So, from 1963 to 1973, synchrotron radiation in the visible range of these plants was used only as a tool for diagnostics of electron and positron beams in storage rings.

BEGINNING AND DEVELOPMENT OF SR APPLICATION IN NOVOSIBIRSK

Given the growing interest in the world in the SR application, in December 1972 it was decided to create a beamline for extraction of the X-ray part of synchrotron radiation from the newly commissioned storage ring VEPP-3 with a particle energy of up to 2.2 GeV. The first SR extraction beamline was installed in July 1973, and the X-ray beam was brought out into the atmosphere in the hall of the storage ring VEPP-3. The SR beam was coupled out of the bending magnet of VEPP-3 into the atmosphere through two vacuum-tight beryllium foils 150 µm thick; the distance from the point of emission to the output of the beamline was 2.5 m [1, 2].

In the same year, the group headed by Mark Mokulsky with the Department of Biology of Kurchatov Institute of Atomic Energy (Moscow) recorded first SR diffraction patterns of sodium and cesium salts of DNA on the SR X-ray beam extracted from VEPP-3. Next year, 1974, the group headed by Alvina Vazina with the Institute of Biophysics, USSR AS (Pushchino) began the research on the structures of long-period biopolymers, in particular, the muscle structure. Starting with recording small-angle diffraction on X-ray films, they proceeded to using the one-coordinate X-ray detector OD-1 developed at BINP for the technique of X-ray diffraction "movies", first with a 100-ms resolution and later on with a 2-ms resolution. After many years of systematic studies of muscle in contraction, the team of A. Vazina managed to build a structural model of muscles and show how it worked.

That same year, the group of M. Mokulsky recorded the first SR diffraction patterns (Figs. 1-3) of a number of samples on the SR X-ray beam extracted from VEPP-3. They used the specially created diffractometer SRD-1 [1, 2]. The diffractometer included a single-crystal monochromator for monochromatic beam deflection in the vertical plane, an X-ray camera for recording X-ray diffraction patterns on the film and a number of auxiliary devices. Diffraction patterns from samples of different nature were recorded: the Laue diffraction patterns of single KBr crystals, mica and aluminum foils, different-wavelength monochromatic-radiation X-ray patterns from oriented polyethylene, wood and DNA with axial texture, and antinoksantin protein single crystals. The very first publications on SR X-ray examination were appearing in the world at that time. Much attention in these early works was given to the exposure time and the quality of diffraction patterns. It was

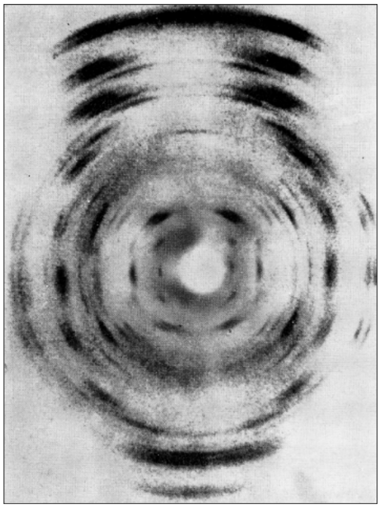

Fig. 1. X-ray diffraction of Na in calf thymus DNA, λ = 2 Å, A form. Registration time: 9 min at a storage ring current of 25 mA [2].

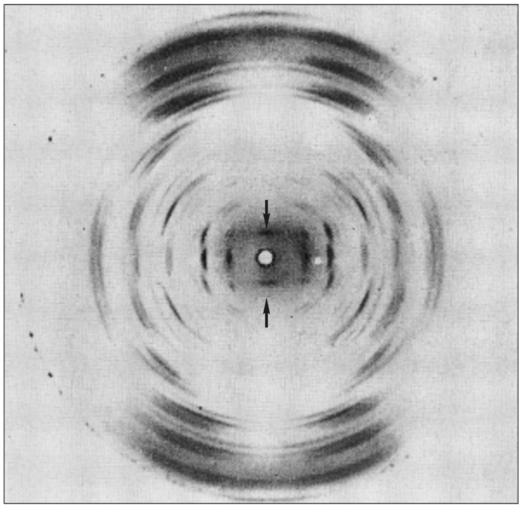

Fig. 2. X-ray diffraction of Cs in calf thymus DNA, λ = 1.2 Å, A conformation [3]. The meridional reflection on the first layer line (indicated by arrows) is absent in similar X-ray pictures of "light" Na of DNA in the A form. Exposure time: 19 min at a storage ring current of 55 mA.

shown that as compared with X-ray tubes (λ = 1.54 Å CuK_α), the time of recording diffraction patterns was significantly (~50-100 times) less, without use of any focusing device.

The very encouraging results of the first experiments made it possible to proceed to the problem of the determination of coordinates of metals in the structure of DNA molecules. These molecules are often associated with atoms of metals, e.g. sodium, which is important for their biological function. But light metal atoms give no significant contribution to the diffraction pattern, whereas atoms of a suitable heavy metal, e.g. cesium, greatly increase absorption in a sample and the recording time is as large as hundreds of hours, in which time the sample is destroyed by the radiation, and no good shot can be made.

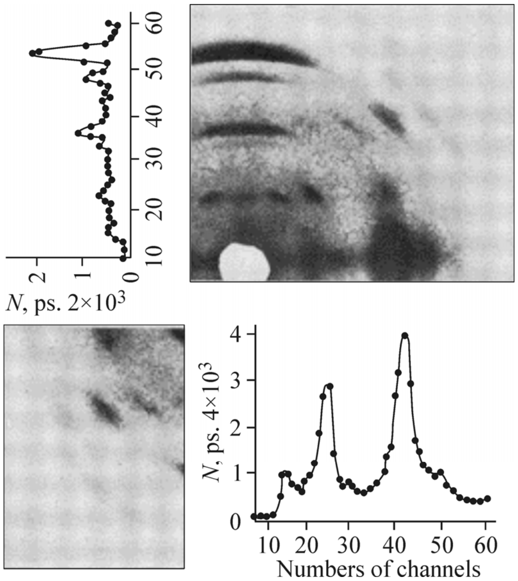

Fig. 3. X-ray diffraction pattern of chitin plates (crab) recorded on film and graphs of cross sections of intensity matrices (equatorial and meridional), obtained with detector [5].

Using radiation with a wavelength λ = 1.2 Å, i.e. harder than the usually applied one, and thereby reducing the absorption in a sample, the authors managed to make good radiographs of Cs in calf thymus DNA and Cs in the DNA phage T2 on the film RT-1 in a time of about one hour at a current in the storage ring of 30-40 mA [3, 4]. These radiographs enabled completion of the determination of coordinates of metal atoms in a DNA molecule with due account of the SR polarization and large absorption in the sample [4].

These first SR works had another essentially aspect of the use of position-sensitive X-ray detectors and automation of experiments using computers. That was already widely used in experiments on high-energy physics and in the control of accelerator storage rings. A 4096-channel two-dimensional detector for soft X-rays on the basis of multi-wire proportional chamber with a mixture of argon and CO_2 as the working gas was created in 1975 at the INP [5]. It was the first such detector in the Soviet Union. The detector had 64×64 channels with a size of 2×2 mm and a total working area of 128×128 mm. The efficiency of detection of 6 keV X-ray quanta was 30%; the maximum operation speed of the detector was 130 kHz. The electronic registration unit of the detector, which determined the address of a quantum registered, was connected to the computer M-6000, where the information was stored and subjected to primary processing.

In 1975, the group of Isabella Ovsyannikova with the Institute of Catalysis of the USSR Academy of Sciences Siberian Branch began X-ray spectroscopy analysis of catalysts on the same SR extraction beamline. They obtained the *K* emission spectra of nickel in supported catalysts with a Ni concentration of up to 1%.

Almost simultaneously, in 1974, the first beamline for extraction of vacuum ultraviolet and soft X-rays was created on the VEPP-2M storage ring and a spectroscopy station for high-resolution ultrasoft X-ray absorption spectra was built. The first precision experiments on the spectroscopy of simple molecules were carried out in 1975 by the group of L. Mazalov with the Institute of Inorganic Chemistry (IIC), USSR AS SB. The group included E. Gluskin, A. Krasnoperova, and V. Kochubei.

Members of the IIC, USSR AS SB installed the RSM-500 spectrometer with a diffraction grating ($R = 2$ m; $p = 600$ strokes/mm; $S = 5$ μm) on VEPP-2 [6]. This spectrometer was involved in the examination of the photoabsorption of SO_2 molecule near the $L_{\text{II, III}}$ absorption edge of sulfur [7]. The main attention was paid to the analysis of quasi-stationary states beyond the threshold of the $L_{\text{II, III}}$ absorption of sulfur. A fine structure in the form of peaks and singularities *a*, *b*, *c*, *d*, *e*, and *f* (Fig. 4) was discovered for the first time in the first absorption bands. This fine structure was caused by the manifestation of electron-vibrational transitions and multiplet terms resulting from the interaction of an excited electron with an open sulfur *2p* shell. Moreover, an absorption peak at $E = 173$ eV was found; it was not observed earlier and did not fit into the Rydberg series.

When investigating the subthreshold region of the $L_{\text{II, III}}$ absorption spectrum of sulfur in SF_6, this group of authors again found a peak at $E = 177$ eV, which did not fit into the Rydberg series [8]. The authors explained the nature of this peak by a manifestation of dipole-forbidden transition to the molecular orbital of t_{1u} symmetry.

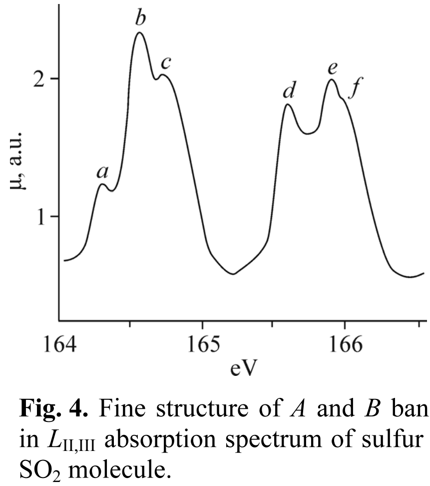

Fig. 4. Fine structure of *A* and *B* bands in $L_{\text{II,III}}$ absorption spectrum of sulfur in SO_2 molecule.

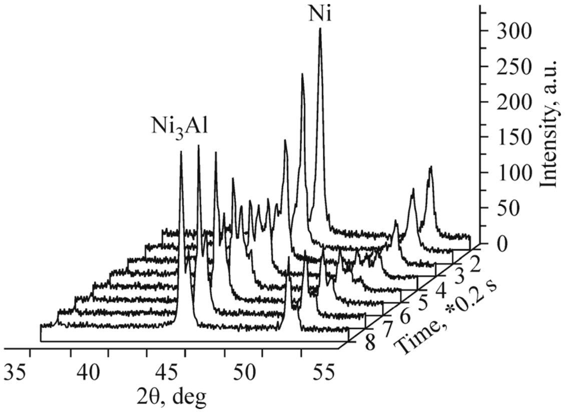

Fig. 5. Formation of the intermediate phase in the interaction of mechanically activated Ni + Al mixture during self-propagation high temperature synthesis (SHS). Time of reaction: about one second. An X-ray diffraction pattern of a mixture of nickel and aluminum can be seen in the first frame. The last frame shows the product, Ni_3Al. The intermediate phase, identified as NiAl, is clearly seen.

Since the late 70s, chemists and materials scientists have been strongly interested in the application of synchrotron radiation to the study of changes in materials under different effects or in the course of chemical reactions by the method of X-ray diffraction “movies”. These methods have been successfully developed and used on SR beams from VEPP-3 at different institutes: the group headed by B. P. Tolochko (Institute of Solid State Chemistry and Mineral Resources, USSR AS SB) [9-11] – study of solid-phase reactions including SHS (Fig. 5), B. K. Barakhtin with colleagues (Ioffe Physical-Technical Institute, Leningrad) – research on the dynamics of dislocation structure in deformation of metals; P. Forgacs (Research Institute for Plastics, Budapest, Hungary) – investigation into phase transitions in plastics [12, 13]; U. Steinike (Central Institute of Physical Chemistry, Berlin, Germany) – chemical processes in mechanically activated systems [14, 15], U. Lembke (Rostok University, Rostok, Germany) – sol-gel processes [16], and others.

X-ray diffraction analysis has been widely applied to study reactions in solids. However, the main objective of members of the Institute of Solid State Chemistry and Mechanochemistry was to obtain information *in situ* [17]. Unfortunately, at the initial stage the work was hampered by the lack of necessary equipment adequate to the problems of solid state chemistry, e.g. there was no X-ray optics enabling obtaining information from micron-size regions in a time of about a microsecond or less. There were no reactors for X-ray diffraction studies *in situ* of chemical reactions in solids.

The lack of hardware and methodological support was most acute in the study of fast processes: self-propagating high-temperature synthesis (SHS), and chemical transformations under shock-wave loading (impact in mechano-chemical reactions). The SHS and the shock-wave processes required a resolution of about 1 ms and 1 ns, respectively.

An experiment station was designed for addressing solid state chemistry problems. It enabled experiments with a millisecond-range time resolution [17].

A series of works on the study of SHS [18, 19] changed the understanding of the mechanism of chemical transformations in the area of the SHS reaction. Prior to this experiment, it was believed that all the chemical transformations ended in a very narrow zone of the combustion wave front. It was found that the chemical processes lasted for hundreds of milliseconds, and some processes (recrystallization, re-orientation of crystallites, and annealing of structure) occured in a second-scale time range (Fig. 5). Further development of these studies together with the staff of the Institute of Structural Macrokinetics of RAS yielded data on the kinetics of the chemical process [20]. These works became a basis for the development of the diffraction experiment with nanosecond time resolution [20, 21]. In 2015, owing to the RSF support, the DIMEX-M detector was developed, and the experiment reached the following parameters: 73 ps exposition, the time of 100 ns between diffraction patterns, 1 ps accuracy of synchronization with the process under study.

Radiation from modern X-ray tubes penetrates into a sample to a depth of the order of a few micrometers (copper radiation, $\lambda = 1.54$ Å, penetrates into copper to a depth of 8 μm), and thus no information about processes inside the sample is available. The same applies to the investigation into the processes in the electrolyte – solid electrode interface. It was important to develop SR methods for research on processes both in the electrode and on the electrolyte – solid electrode boundary [22]. Works performed by ISSCM SB RAS [23] theoretically proved the possibility of recording X-ray patterns from samples under an electrolyte layer, which enabled selection of conditions for obtaining structural information about the electrode and electrochemical deposit directly in the electrolysis process. Experiments confirmed that the transition to the area of hard radiation – 30 keV and more – can solve this problem. Solving the problem of radiation scattering in an electrolyte enabled several studies of processes occurring on the electrolyte – solid boundary: 1) ultrafast relaxation processes in deformed metal electrodes in contact with the electrolyte; 2) hydrogen saturation of nickel; 3) formation and decomposition of nickel hydride [24].

The publication of the review on SR investigations by G. N. Kulipanov and A. N. Skrinsky [25] in 1978 facilitated the vigorous growth of the number of new research groups.

In 1975, researchers carrying out high-energy physics experiments on VEPP-3 faced the problem of on-line measurement of particle energy in the storage ring to better than 10^{-3}. Following a proposal from G. N. Kulipanov and A. N. Skrinsky, INP researchers developed and implemented a method of immediate energy measurement based on SR spectral characteristics (the exponential decrease in the intensity in the high-energy part of the spectrum), first with an accuracy of 10^{-3}, and then the accuracy of the method was improved to 10^{-4}.

Luminescence investigation methods were developed and samples of various substances were studied under excitation both by X-rays and vacuum ultraviolet synchrotron radiation, including research on fast luminescence with subnanosecond time resolution (V. V. Mihailin et al. (the Moscow State University), V. V. Shelkovnikov et al. (the Institute of Organic Chemistry, USSR AS SB), A. A. Obynochny (Institute of Chemical Kinetics and Combustion, USSR AS SB), V. A. Pustovarov et al. (the Urals Polytechnic Institute), E. S. Gluskin, E. I. Zinin (INP), and others).

Researchers from the Institute of Nuclear Physics and other organizations were developing a method of fast X-ray fluorescence elemental analysis with excitation by an SR beam (SR XRF analysis). Almost the first experiments showed good prospects for SR XRF application to quick multiple-element analysis of samples, as well as to analysis of very small samples. In particular, in the early 80s the group of L. S. Tarasov (Vernadsky Institute of Geochemistry and Analytical Chemistry, USSR AS, Moscow) used the SR XRF method at the INP to investigate the geochemical characteristics of the lunar soil, delivered to the Earth by the American space ship “Apollo” and Soviet automatic stations “Luna”.

O. P. Aleshko-Ozhevsky from the Institute of Crystallography, USSR Academy of Sciences (Moscow) studied the possibility of using SR for X-ray topography of crystals, including the observation of phase transitions, magnetic and electric domains, and recording topograms from highly disturbed and strongly absorbing crystals. Members of other organizations also conducted X-ray studies of the topography of various crystals on the SR from the VEPP-3 storage ring.

At that time many researchers were interested in the new method of EXAFS spectroscopy. INP members in collaboration with a team from the Institute of Catalysis, USSR AS SB (D. I. Kochubey with colleagues) created an experiment station on VEPP-3 to record the EXAFS spectra of various substances [26]. Scientists from the German Democratic Republic [27, 28] and Czechoslovakia were working actively at the station. Since then, the station has been the most popular among the users.

The methods of X-ray microscopy were also under development (Fig. 6). Members of the Institute of Automation and Electrometry, USSR AS SB (V. P. Koronkevich and V. I. Nalivaiko) participated in the research on the use of non-standard recording media – chalcogenide materials – for contact X-ray microscopy. The development of digital technology enabled the start of work on scanning X-ray microscopy, including differential microscopy on the edges of absorption of elements. This work was continued by a series of microscopy and micro-tomography studies of distributions of some contrasting elements in mediastinal lymph nodes in animals and humans in health and disease processes for understanding of the functioning of the lymphatic system (in cooperation with the members of the Institute of Physiology of the USSR Academy of Medical Sciences (Novosibirsk) G. N. Dragoon, Y. I. Borodin and others).

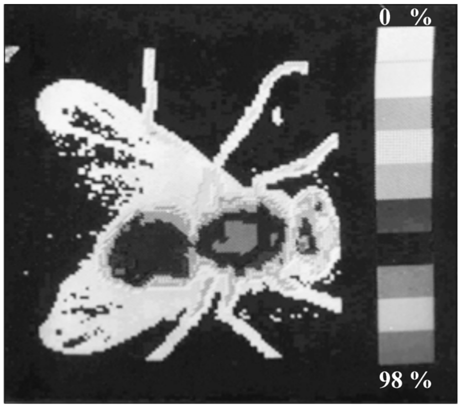

Fig. 6. X-ray scanning microscopy of the Siberian fly (SR beam from VEPP-3, spatial resolution 100 μm, 100×100 image points, quantum energy 13.5 keV).

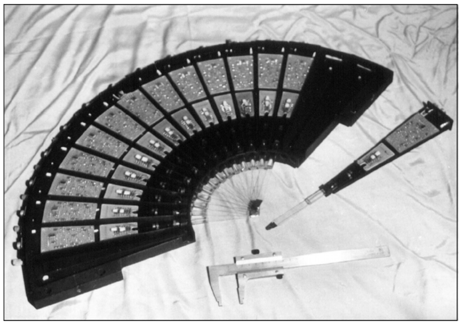

Fig. 7. The first fast one-coordinate scintillation X-ray detector for digital differential angiography on synchrotron radiation (spatial resolution: 1.5 mm, number of channels: 128, count rate: 128×1 MHz).

Together with doctors of the Novosibirsk regional hospital (A. P. Ogirenko, V. M. Omigov, and V. N. Roschupkin) INP scientists were also actively developing the technology of digital difference angiography for investigation into the human blood circulatory system. A fast specialized one-coordinate scintillation X-ray detector for recording angiograms on the *K*-edge of absorption of iodine was designed and developed (Fig. 7), and the first images of abdominal aorta in a live dog were obtained with the SR beam from VEPP-4 in 1985.

Members of the Moscow Institute of Atomic Energy (A. N. Artemyev, E. P. Stepanov, A. I. Chechin and others) and the INP (V. A. Kabannik and others) were developing works on the Mössbauer excitation of nuclei using synchrotron radiation. First encouraging results on the excitation of the Mössbauer level of ^{57m}Fe (14.4 keV) were obtained *via* monochromatization of SR beam due to reflection from a single crystal of hematite α-$^{57}Fe_2O_3$.

The VEPP-2M storage ring was involved in research in the field of vacuum ultraviolet radiation and soft X-rays. In addition to a wide range of spectroscopic works done by various Soviet and foreign researchers, the first metrology measurements of solar-blind PMTs, secondary electron multipliers, and spectral apparatus were initiated and carried out by E. S. Gluskin (the INP), V. A. Kochubey (the Novosibirsk State University), V. I. Nalivayko (the Institute of Automation and Electrometry, USSR AS SB), V. I. Ogurtsov (Vavilov State Optical Institute, Leningrad).

X-ray holography with nanometer-range resolution has long been an ambition of investigators. Works carried out on the SR beam from VEPP-3 in 1974 yielded the first diffraction patterns from a slit in the X-ray range. It was the first success, but it came together with understanding that even the intensity of SR from the bending magnet was not sufficient for high-resolution X-ray holographic microscopy because of the necessity to conduct experiments with highly monochromatic beams. For increase in the SR intensity in experiments on microscopy and holography, the world's first helical undulator was made in the early 80s. It had the following parameters: the period was 2.4 cm; the total number of periods was 10; the maximum on-axis magnetic field was 1.3 kG. E. Gluskin (the INP) and P. Ilyinsky (the NSU) performed a study of the radiation in the wavelength range of 100÷300 Å. The undulator radiation with its natural monochromatization was shown to be the best in the use in X-ray holography as compared with the radiation from the bending magnet, and thus the existing X-ray resists enabled a spatial resolution of holograms of ~50 Å. P. Des (LURE, Orsay, France) took part in the research on the polarization properties of the undulator radiation. For a long time, this undulator was the only world's source of quasi-monochromatic undulator radiation with circular polarization.

The end of the 70s to the early 80s was a time of extraordinary efflorescence of works on the X-ray lithography with orientation towards the production of large and very large integrated circuits with submicron elements. Only SR, with a typical wavelength of ~10 Å, was seriously regarded to as a source of radiation. The INP together with the Novosibirsk Scientific-Production Enterprise "Vostok" created an X-ray lithography station on the VEPP-2M storage ring and launched research on physical and technological processes and improvement of specialized equipment.

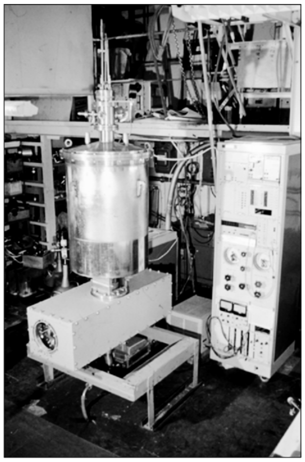

Fig. 8. The first 20-pole superconducting wiggler with magnetic field of 33 kG and period of 9 cm.

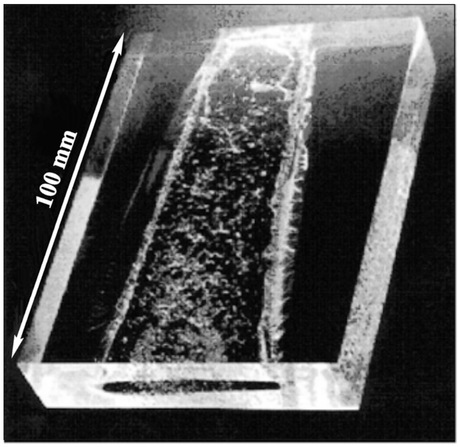

Fig. 9. Organic glass parallelepiped (10 cm length) burnt by high-power X-ray beam from the first superconducting wiggler on VEPP-3 (the first "ultradeep X-ray lithography").

A landmark event in those years was the creation of the world's first 20-pole superconductive wiggler with a magnetic field of 33 kG and a period of 9 cm. In 1979, the wiggler was mounted in the straight section of the VEPP-3 storage ring and an X-ray beam with a total power of ~1 kW was generated. The intensity of the SR from the wiggler in the wavelength range of ~1 Å increased about 200 times as compared with the radiation from the VEPP-3 bending magnet. Owing to that experience of creating and working with the first superconducting wiggler, now the team of Prof. N. A Mezentsev designs, creates and delivers superconducting wigglers and undulators to many SR centers all over the world.

In 1984, a superconducting wiggler with three central dipole magnets with a field of 75 kG and two side magnets with a field of 45 kG was set on VEPP-2M (Figs. 8 and 9). The radiation from the wiggler was used for works on X-ray lithography. In particular, an X-ray Bragg-Fresnel lens made at the Institute of Microelectronics Technology and High Purity Materials, USSR AS (Chernogolovka, Moscow Region) transferred the first image (at a wavelength of 1.7 Å) on the SR beam from the wiggler.

In 1977 N. A. Vinokurov and A. N. Skrinsky, developing the idea of the free electron laser, offered the optical klystron, which included a pair of undulators and a grouping magnet section between them. Since then, the INP has been developing the direction associated with the free electron lasers (FELs). The optical klystron was under experimental investigation on VEPP-3 since 1979. The spontaneous emission spectrum was examined and the gain per flight was measured. Several designs of permanent magnet undulators were created and studied. The works with the optical klystron that were carried out in those years made a basis for the world's first generation of radiation in the ultraviolet range in a storage ring (1988) and the subsequent creation of high-power free electron laser (1994).

The initial period of work with synchrotron radiation at the INP was also associated with significant expansion of the experimental premises for work with SR beams. The construction of a new dedicated room, the SR cave, was begun on VEPP-3 in the late 70s. In addition to professional workers, researchers also took part in this activity. Since 1981, all works with SR beams on VEPP-3 have been conducted in this cave, the radiation both from the bending magnet and the superconducting wiggler was delivered to. A "new X-ray lithography" SR cave was also built on VEPP-2M and accommodated the X-ray lithography and clean process rooms.

In connection with the development of works on the optical klystron, the radiation from which was also to be extracted into the SR cave on VEPP-3, all activity with X-ray SR beams was transferred in 1984 to the newly built SR experimental hall on the VEPP-4 storage ring (5.5 GeV). All these works were done there till August 1985.

In the second half of the 70s and the first half of the 80s, not only researchers from the former Soviet Union actively used SR beams at the INP; scientists from foreign countries were also eager to apply SR beams to their studies. Researchers from England (K. Bowen and S. Davies), France (P. Dhez), the former GDR (W. Blau, K.-H. Hallmeier, A. Meisel, H.-G. Eberle, E. Schnurer, and U. Steinike), Hungary (P. Forgacs), and Czechoslovakia (L. Pajasova, J. Hrdy, and E. Krousky) worked on SR beams from the VEPP-3 and VEPP-2M storage rings. Dr. Pierre Deux, one of the pioneers of work with synchrotron radiation in France, lived and worked in Novosibirsk for a year, doing research on X-ray multilayer mirrors and the polarization properties of undulator radiation.

CONFERENCES ON APPLICATION OF SYNCHROTRON RADIATION

In December 1975, Novosibirsk hosted the first workshop on synchrotron radiation, SR-75 (the official name is "The 1st Meeting on Using Electron Storage Rings SR Sources for Experiments in Biology, Chemistry and Physics"). Only four reports on experimental results on SR beams from the VEPP-2M and VEPP-3 storage rings were presented at SR-75: by M. Mokulsky, on X-ray analysis of DNA; by A. Vasina, on research on the structure of long-period biopolymers, in particular, the muscle structure; by I. Ovsyannikova, on X-ray spectral study of catalysts; by E. Gluskin, on the study of X-ray absorption spectrum of chemical compounds in supersoft X-rays. I. Coop (the INP) also made a report on the first version of the conceptual design of the future storage ring to be an SR source for the Moscow region.

Then the first workshop was followed by regular meeting and conferences on the use of synchrotron radiation: SR-77, SR-78, SR-79, SR-80, and further on every two years. With the exception of SR-90, held in Moscow, all the rest conferences took place in Novosibirsk. Since 1986 (SR-86), the Conference Proceedings have been published in a special issue of the journal *Nuclear Instruments and Methods in Physics Research*. The number of participants grew rapidly and exceeded two hundreds, including dozens of foreign scientists.

Given the new direction, associated with synchrotron radiation, and its importance for basic research in physics, chemistry, biology, materials science, and development of new technologies for solving various applications, the Presidium of the Siberian Branch of the USSR AS in a regulation of 1981 established on the basis of the SR sources on VEPP-2, VEPP-3 and VEPP-4 and INP laboratories the Siberian Center for Synchrotron Radiation, which operates till now. For many years, this center is still a major one in the Soviet Union and then in Russia for research on SR beams.

The first bibliography "Synchrotron radiation at the INP, USSR AS SB" included publications on the generation and use of synchrotron radiation performed at the Institute of Nuclear Physics of the USSR AS SB from the beginning of the SR development to May 1986 [29].

CONCLUSIONS

Academician G. I. Budker, the first INP director, and Academician A. N. Skrinsky were initiators and inspirers of the work with synchrotron radiation at the INP. They were integral to a number of works.

The first decade of work with synchrotron radiation at the INP is characterized by an abrupt increase in the number of experimental groups from the Soviet Union and other countries that used this radiation (5 teams in 1975 and 87 teams in 1984) and rapid expansion of the scope of work with SR beams for research, technological purposes, and formation of a qualified community of SR users.

The researchers really felt cramped on the SR beams from the INP storage rings, initially created for high-energy physics. The researchers' requirements to the SR beams were also increasing. Therefore, storage rings specialized as SR sources were developed and created in the world, at the INP too: the "Sibir" storage rings for the Institute of Atomic Energy (Moscow) and the technological storage complex in the city of Zelenograd.

This article describes the beginning and development of works on the use of synchrotron radiation from the storage rings at the Institute of Nuclear Physics, USSR AS SB, basically covering the time range from 1973 to 1985.

Because of the large volume and diversity of the works, the article is inevitably focused on some fragments, although the authors have tried to reflect or at least mention the main works carried out on the SR beams. At the same time, the authors deliberately avoided considering the works carried out that time on the development and creation of specialized storage rings ("Sibir" for the Institute of Atomic Energy in Moscow and the technological storage in the city of Zelenograd) and works on free electron lasers.

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REFERENCES

1. T. D. Mokulskaya, M. A. Mokulsky, A. A. Nikitin, V. V. Anashin, G. N. Kulipanov, V. A. Lukashov, and A. N. Skrinsky, *Using Synchrotron Radiation of VEPP-3 Storage Ring for X-Ray Diffraction Studies*, IAE preprint, 2385 (1974).
2. T. D. Mokulskaya, M. A. Mokulsky, A. A. Nikitin, V. V. Anashin, G. N. Kulipanov, V. A. Lukashov, and A. N. Skrinsky, *Proc. USSR Acad. Sci.*, **218**, No. 4, 824-827 (1974).
3. T. D. Mokulskaya, M. A. Mokulsky, A. A. Nikitin, I. Ya. Skuratovsky, S. E. Baru, G. N. Kulipanov, V. A. Sidorov, A. N. Skrinsky, and A. G. Khabakhpashev, *Crystallography*, **22**, No. 4, 744-752 (1977).
4. M. A. Mokulsky, *Bull. USSR Acad. Sci.*, No. 8, 8-14 (1978).
5. S. E. Baru, T. D. Mokulskaya, M. A. Mokulsky, V. A. Sidorov, and A. G. Khabakhpashev, *Proc. USSR Acad. Sci.*, **227**, No. 1, 82-84 (1976).
6. E. S. Gluskin, L. N. Mazalov, A. A. Krasnoperova, V. A. Kochubey, S. A. Mishnev, A. N. Skrinsky, E. M. Trachtenberg, and G. M. Tumaikin, *Bull. USSR Acad. Sci.: Phys.*, **40**, 225 (1976).
7. A. A. Krasnoperova, E. S. Gluskin, L. N. Mazalov, and V. A. Kochubey, *J. Struct. Chem.*, **17**, No. 6, 947-950 (1976).
8. E. S. Gluskin, A. A. Krasnoperova, and L. N. Mazalov, *J. Struct. Chem.*, **18**, No. 1, 156-158 (1977).
9. V. V. Boldyrev, Y. A. Gaponov, N. Z. Lyakhov, A. A. Politov, B. P. Tolochko, T. P. Shakhtshneider, and M. A. Sheromov, *Nucl. Instrum. Methods Phys. Res., Sect. A*, **261**, Nos. 1/2, 192-199 (1987).
10. V. V. Aleksandrov, M. A. Korchagin, B. P. Tolochko, and M. A. Sheromov, *Combust., Explos. Shock Waves*, **19**, No. 4, 430/431 (1983).
11. N. Z. Lyakhov, S. V. Mytnichenko, M. A. Sheromov, V. V. Smirnykh, and B. P. Tolochko, *Nucl. Instrum. Methods Phys. Res., A*, **246**, Nos. 1-3, 776-778 (1986).
12. P. Forgacs, M. A. Mezentsev, V. F. Pindiurin, M. A. Sheromov, and B. P. Tolochko, *J. Polym. Sci., Polym. Phys. Ed.*, **18**, 2155-2168 (1980).
13. P. Forgacs, M. A. Sheromov, and B. P. Tolochko, *Polym. Bull.*, **6**, 127-133 (1981).
14. F. Neissendorfer, U. Steinike, B. P. Tolochko, and M. A. Sheromov, *Nucl. Instrum. Methods Phys. Res., A*, **261**, Nos. 1/2, 216-218 (1987).
15. F. Neissendorfer, U. Steinike, B. P. Tolochko, and M. A. Sheromov, *Nucl. Instrum. Methods Phys. Res., A*, **261**, Nos. 1/2, 219/220 (1987).
16. Yu. A. Gaponov, L. G. Karakchiev, N. Z. Lyakhov, B. P. Tolochko, U. Lembke, K. Bohlmann, and I. P. Dolbnya, *Nucl. Instrum. Methods Phys. Res., A*, **359**, Nos. 1/2, 170-174 (1995).
17. N. A. Mesentsev, M. A. Sheromov, V. V. Smirnykh, A. S. Sokolov, A. V. Sukhorukov, B. P. Tolochko, V. A. Ushakov, and A. M. Vlasov, *Nucl. Instrum. Methods Phys. Res., A*, **246**, Nos. 1-3, 604-608 (1986).
18. V. V. Aleksandrov, M. A. Korchagin, B. P. Tolochko, and M. A. Sheromov, *Combust., Explos. Shock Waves*, **19**, No. 4, 430/431 (1983).
19. V. V. Boldyrev, V. V. Alexandrov, M. A. Korchagin, B. P. Tolochko, S. N. Gusenko, A. S. Solokov, M. A. Sheromov, and N. Z. Lyakhov, *Dokl. Phys. Chem.*, **259**, No. 5, 722 (1981).
20. M. Sharafutdinov, O. Evdokov, D. Naumov, B. Pirogov, B. Tolochko, V. Alexandrov, E. Pismenskaya, and A. Rogachev, *J. Synchrotron Radiat.*, **10**, No. 5, 384-386 (2003).
21. B. P. Tolochko, A. N. Aleshaev, M. G. Fedotov, G. N. Kulipanov, N. Z. Lyakhov, L. A. Luk′yanchikov, S. I. Mishnev, M. A. Sheromov, K. A. Ten, V. M. Titov, and P. I. Zubkov, *Nucl. Instrum. Methods Phys. Res., A*, **467/468**, Part 2, 990-993 (2001).

22. B. P. Tolochko, A. I. Masly, and N. Z. Lyakhov, *Bull. USSR Acad. Sci.: Chem.*, **1**, No. 2, 54 (1985).
23. B. P. Tolochko, A. I. Masly, and M. A. Sheromov, *Bull. USSR Acad. Sci.: Chem.*, **1**, 48-54 (1985).
24. N. Z. Lyakhov, A. I. Maslii, B. P. Tolochko, and M. A. Sheromov, *Nucl. Instrum. Methods Phys. Res., A*, **261**, No. 1/2, 209-215 (1987).
25. G. N. Kulipanov and A. N. Skrinsky, *Usp. Fiz. Nauk*, **122**, No. 3, 369-418 (1977).
26. A. M. Vlasov, K. I. Zamaraev, D. I. Kochubei, M. A. Kozlov, and M. A. Shedrov, *Khim. Fiz.*, **6**, 793 (1983).
27. E. Zschech, W. Blau, H. Vega, K. Kleinstrueck, S. Mager, M. A. Kozlov, and M. A. Sheromov, *Phys. Status Solidi A*, **86**, No. 1, 117-124 (1984).
28. E. Zschech, W. Blau, K. Kleinstück, H. Hermann, N. Mattern, M. A. Kozlov, and M. A. Sheromov, *J. Non-Cryst. Solids*, **86**, No. 3, 336-349 (1986).
29. *Synchrotron Radiation at the INP, USSR AS SB: Bibliography*, Institute of Nuclear Physics, USSR AS SB, Novosibirsk (1986).