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Electron–positron beam collision studies at the Budker Institute of Nuclear Physics

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Contents

Abstract. Beam-colliding facilities (colliders) are key to exploring the fundamental properties of matter and understanding elementary particles and their interactions. The Budker Institute of Nuclear Physics (BINP), Siberian Branch of the Russian Academy of Sciences, co-pioneered the development of the method of colliding beams and maintains the leading position in using it. This paper reviews the past, present, and future of research with colliding beams at the BINP.

Keywords: magnets, colliding beams, synchrotron, emittance, luminosity, electron, positron, detector, c-τ-factory, polarization

1. Introduction

Over recent years, the word 'collider' has become known not only among scientists but also among a wider audience not related to physics. After several decades, collider experiments have proven to be one of the primary sources of information about the fundamental properties of matter along with astrophysics. An advantage of colliders is the capacity to control the experimental conditions, which obviously cannot be done in astrophysics. The first facilities with colliding beams appeared more than 50 years ago (in 1964–1966) and the Institute of Nuclear Physics (INP) (currently, the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences) became one of the first research centers to build the foundation of this new field in elementary particle physics.

The idea of colliding beams was introduced by the Norwegian engineer Wideroe, who applied for a patent to use this method in 1943 and received it in 1953 [1]. The method was further developed by Kerst [2], who suggested colliding proton beams in a ring phasotron [3] (fixed field, alternative gradient, FFAG). In 1956, at the International Conference on High Energy Accelerators in Geneva, O'Neil proposed electron–positron colliding beams and, later the same year, proton–proton storage rings [4]. Kerst noted a huge energy benefit in the case of using relativistic colliding beams instead of the common method of hitting a fixed target with accelerated particles. This stems from the fact that if two particles move towards each other such that the center of inertia is at rest before and after the collision, then all energy of the colliding particles is spent on 'useful' action (for example, the production of new particles), while in the case of a fixed target a large amount of energy is spent on the excitation of the particles as a whole and only a small fraction on the investigated reaction. The gain in the equivalent energy of colliding particles essentially increases at relativistic energies, which is most strongly pronounced for electrons and positrons.

In the late 1950s, several physical laboratories around the world simultaneously started projects to develop colliding beam methods. In the USSR, this work was initiated by Gersh Itskovich Budker, the founder and first director of the INP, who was at that time the head of the Laboratory of New Acceleration Methods at the Institute of Atomic Energy (currently, the National Research Center 'Kurchatov Institute').

The first colliders that implemented colliding beams were the e^+e^- facility AdA (Italian: anello di accumulazione, storage ring) [5] with the maximum beam energy 250 MeV,

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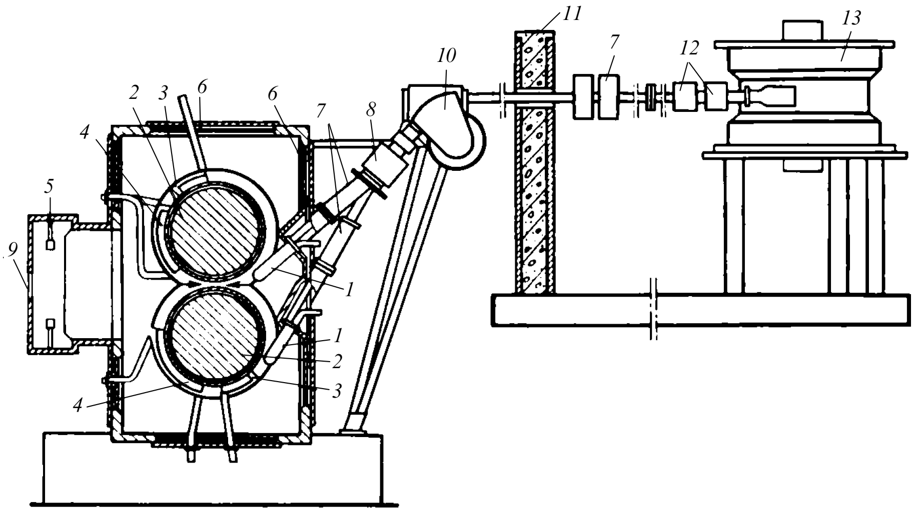

Figure 1. VEP-1 device schematic. *1* — compensating magnets (septum magnet analogue), *2* — magnet yoke, *3* — accelerating resonator, *4* — inflectors, *5* — vacuum pump (nitrogen), *6* — inner flanges, *7* — quadrupole lenses, *8* — switching magnet, *9* — synchrotron radiation output window, *10* — bending magnet, *11* — radiation shield, *12* — correcting magnets, *13* — B2-S synchrotron.

the LNF/INFN (Laboratori Nazionali di Frascati/Istituto Nazionale di Fisica Nucleare) (Frascati, Italy), VEP-1 (Russian: vstrechniye electronnye puchki, colliding electron beams) [6] (with the beam energy up to 160 MeV) (INP, Novosibirsk), and the e^+e^- project at the Princeton–Stanford Experimental Collider [7] with a beam energy of approximately 500 MeV (Stanford University, USA). Great interest in electron–electron scattering was connected with the results of Hofstadter's experiments on electron scattering on protons [8], which revealed the inner structure of the proton. Experimental tests of quantum electrodynamics at storage rings were continued until 1967, and these experiments proved the absence of the electron inner structure at scales down to 2.6×10^{-15} cm [9].

The positron intensity at AdA was small, and it was only possible to register the particle collision and perform studies in the field of accelerator physics. During the past 60 years, the colliding beam method has evolved in several directions. First of all, the number of accessible types of particles has increased. Storing electrons and positrons in rings became possible due to the damping of their phase volumes under the action of synchrotron radiation. The development of stochastic and electron cooling allowed storing protons and antiprotons. Facilities with colliding beams of these particles were successfully operating during the previous decade at CERN (Super Proton Synchrotron, SPS) and at the Fermi National Accelerator Laboratory in the USA (Tevatron). Nowadays, there are proton–proton and ion–ion colliders: RHIC (Relativistic Heavy Ion Collider) (Brookhaven National Laboratory, USA) and LHC (Large Hadron Collider) (CERN). Projects for muon–muon beams and colliding beams in linear accelerators are being discussed. The development of colliding beam physics inevitably led to the increase in both the particle energy and the luminosity of the devices.

The results obtained at the BINP, together with a large number of ideas, significantly influenced both the development of the colliding beam method and the research programs at electron–positron colliders. In this paper, we review BINP's history and describe its goals for the nearest future.

2. First colliding beam projects at the BINP

2.1 Colliding electron–electron beams (VEP-1)

The main task of the VEP-1 setup was to demonstrate the possibility of conducting high-energy physics experiments with colliding electron beams. The primary goal was to test quantum electrodynamics at small distances in electron–electron scattering at large angles for energies of several hundred MeV. For a fixed-target accelerator, the equivalent energy would be 100 GeV and the accelerator size would be several dozen kilometers (the size of the future Large Electron–Positron Collider, LEP).

The construction of VEP-1 started in 1958–1959 at the Institute of Atomic Energy in Moscow, but in 1962, with the foundation of the INP, the setup was moved to Novosibirsk.

The VEP-1 facility [10, 11] included the injector (electron synchrotron B2-S with betatron preacceleration B2-C), two coupled storage rings, which provided the collision of electron bunches at the intersection of the orbits, and an electron-optical channel to transfer the accelerated electrons from the synchrotron to the storage rings. A schematic of the device is shown in Fig. 1 and a photograph in Fig. 2. The VEP-1 collider parameters are shown in Table 1.

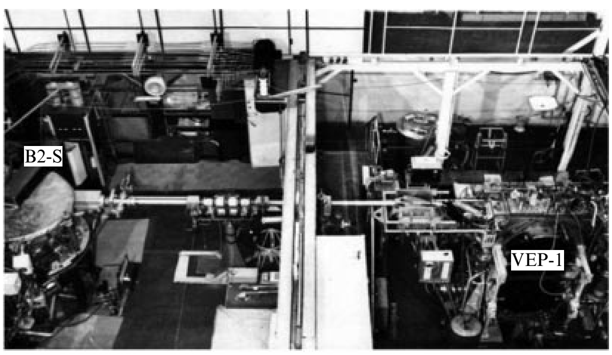

Figure 2. General view of the device. The photograph was taken from the opposite side with respect to the schematic in Fig. 1: on the left, the B2-S synchrotron; on the right, the upper ring of VEP-1.

Table 1. VEP-1 main parameters.

Injection energy, MeV	43
Maximum beam energy, MeV	160
Orbit radius, cm	43
Accelerating harmonic number	2
Maximum accelerating voltage, kV	6
Residual gas pressure, mm Hg	3×10^{-8}
Beam lifetime, s	$\sim 400-1200$
Damping time at injection energy, s	~ 1
Beam current, mA	$\leqslant 100$
Peak luminosity, $\mathrm{cm^{-2}\ s^{-1}}$	5×10^{27}

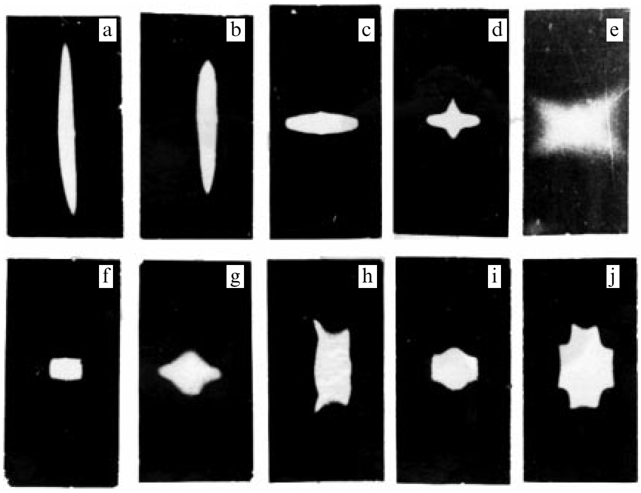

Figure 3. Beam cross section photographs near various resonances for betatron and synchrotron oscillations: (a) $\nu_x = 2/3$, (b) $\nu_x = 3/4$, (c) $\nu_z = 3/4$, (d) $\nu_z = 3/4$, $3\nu_x - 2\nu_s = 2$, (e) $2\nu_x + \nu_z = 2$, (f) $2\nu_x + \nu_z - \nu_s = 2$, (g) $\nu_z = 5/6$, (h) $\nu_z + 4\nu_x = 3$, (i) $4\nu_z + \nu_x = 4$, and (j) $4\nu_z + \nu_x = 4$, $\nu_z + 4\nu_x = 3$.

The circulating beam in the upper orbit of the storage ring was obtained on August 20, 1963, and the first luminosity was detected on May 19, 1964. From 1965 to 1968, the VEP-1 collider was regularly used for particle physics experiments, which confirmed the validity of quantum electrodynamics for energies up to 2×160 MeV, which implied that the electron is a point-like object at scales down to 4×10^{-14} cm and, unlike the proton, does not have an inner structure.

Besides high-energy physics research, VEP-1 was used to realize a number of projects in accelerator and charged particle beam physics, including the investigation of beam–beam effects, intra-bunch scattering, and nonlinear resonances [12–16].

Figure 3 shows the beam behavior during the study of nonlinear resonances using synchrotron radiation.

2.2 VEPP-2: first electron–positron collider at the INP

The discussion about colliding electron–positron beams started at the INP in 1959. Already during the first stage of the VEP-1 project, the researchers started the development of the VEPP-2 e^+e^- collider [17] with a 40,000 times larger luminosity than at AdA. In order to ensure K-meson production, the maximum energy of the setup was chosen to be 700 MeV.

We note that in the late 1950s–early 1960s, the construction of such a device seemed impossible. The first plan of the setup was introduced to I V Kurchatov, who sent the colliding electron–positron beam project for review to three leading specialists. The reviews were different, but all strictly negative. With a laugh, Kurchatov said: "Looks like this task has something nontrivial about it. We should give it a try."

From the beginning, it was clear to Budker that the institute was not able to use a linear accelerator as an injector of high-energy electrons and positrons. The institute did not have complex technology for the assembly of such an accelerator, and there were no reliable and efficient klystrons around the country. As current experience shows, many years would be needed to build this kind of injector. However, the INP experience in accelerator construction suggested that the positron problem could be solved by accelerating electrons in a fast-cycling synchrotron. Budker suggested a design in which the magnetic field was formed by single-turn bus bars and magnetic poles, which should provide a small value of scattered fields and the possibility of reaching a short acceleration time. This idea was realized in the B-3M synchrotron, on which the injection part of the VEPP-2 setup was based.

A schematic and a photograph of the setup are shown in Fig. 4. The injection part consists of a pulsed linear accelerator (ILU), electron-optical beam transport system, B-3M electron synchrotron, injection–extraction systems, power supplies for the setup elements, and control and monitoring units. ILU was a high-frequency resonator operating at a frequency of 2.5 MHz with a maximal voltage of 2.5 MV, which accelerated a 30 ns long electron bunch with a 30 A current. The energy of the beam injected in the B-3M synchrotron was insufficient for the synchrotron regime, and therefore the beam was preliminarily accelerated to 7 MeV using a betatron core. Then the high-frequency accelerating system and the leading magnetic field were turned on. The injection and extraction from B-3M were single-turn. The maximal energy of B-3M reached 250 MeV [18]. The number of accelerated electrons was $3 \times 10^{11}\ \mathrm{s}^{-1}$ for the 1 Hz repetition rate. The synchrotron turned out to be a very reliable device and operated for more than 50 years, providing the operation of three generations of electron–positron colliders: VEPP-2, VEPP-2M, and VEPP-2000. During these years, there were multiple upgrades of the injector, the injection–extraction systems, the high-frequency (HF) system, power supplies, and the electron systems.

VEPP-2 (see Fig. 4) is a weak-focusing storage ring with four magnetic sectors and four straight gaps: two were used for electron and positron injection, the third one hosted the accelerating cavity, and the fourth was used for the detection systems. The beam lifetime was 10 hours at a small current and about 4 hours at a 100 mA current.

The main parameter of a storage ring with colliding beams is its luminosity, which defines the number of events per unit time $\dot{n} = L\sigma$ for some process with a cross section σ. If the colliding beams contain N_1 and N_2 particles, then the luminosity can be expressed as

$$L = \frac{N_1 N_2}{S} f , \tag{1}$$

where S is the cross-section area of the bunch and f is the collision frequency, which in the case of two bunches equals the revolution frequency f_0.

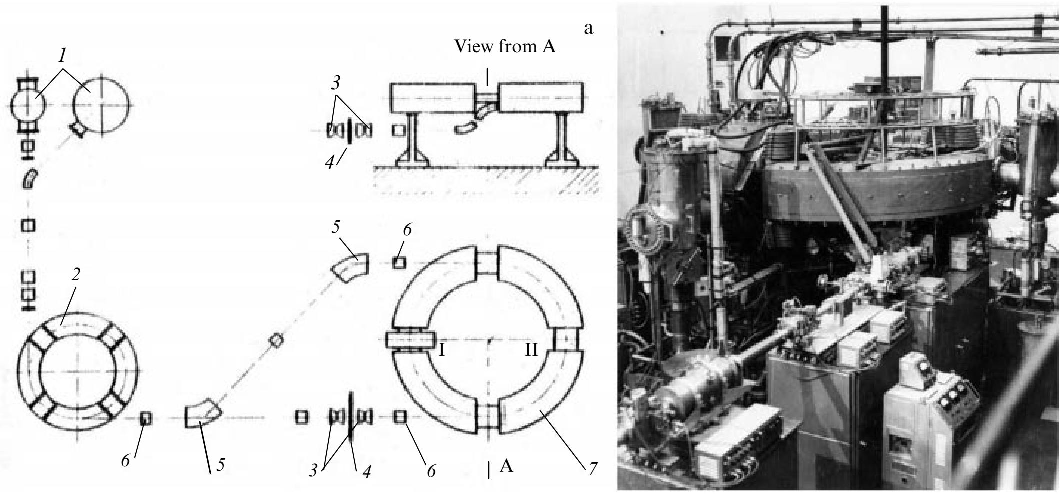

Figure 4. (a) VEPP-2 system schematic: *1* — ILU injector, *2* — B-3M synchrotron, *3* and *4* — parabolic lenses and a convertor, *5* — bending magnets, *6* — quadrupole lenses, *7* — VEPP-2 storage ring. VEPP-2 gaps: I — resonator, II — interaction region. (b) VEPP-2 photograph.

Table 2. VEPP-2 parameters.

Injection energy e^+/e^-, MeV	120/250
Maximum beam energy, MeV	670
Bending magnet radius, cm	150
Straight gap length, cm	60
Maximum accelerating voltage, kV	200
Revolution frequency f_0, Hz	2.5×10^7
Bunch length, cm	80 – 20 *
Beam current (at 510 MeV), mA	40
Peak luminosity, $cm^{-2}\ s^{-1}$	3×10^{28}
* The bunch was shortened after a system upgrade.	

Design parameters of the VEPP-2 storage ring are given in Table 2. Positrons were produced by electron conversion via gamma quanta on a target about one radiation unit in thickness. The positrons were efficiently collected from the converter by using a short-focus lens that consisted of two adjoined beryllium paraboloids of revolution. The lens was fed by a 1 μs current pulse above 100 kA [19].

The first injection of the electron beam in VEPP-2 was realized in June 1964 and the first positrons were obtained in May 1965 [20].

The first experiments with colliding e^+e^- beams started in June 1966 at the energy of 2×380 MeV. The positron current was around 5 mA and the electron current was several dozen milliamperes. In 1966, the optical spark chamber system registered the first π mesons. This was the beginning of electron–positron colliding beam physics [21].

In 1968, the VEPP-2 system was upgraded. The new cavity with a frequency of 75 MHz allowed shortening the particle bunches to 6 cm. The correction coils on magnetic poles broadened the range of betatron frequencies and made it possible to control the coupling of oscillations and their chromaticity. The installation of distributed magnetic discharge pumps in the vacuum chamber of magnetic sectors improved the vacuum in the ring to $\sim 10^{-9}$ Torr, which allowed stored beam currents up to 50 mA. The upgrade resulted in a luminosity enhancement to the design value $L = 3 \times 10^{28}\ cm^{-2}\ s^{-1}$.

The experiments at VEPP-2 continued until November 1970. Besides investigations of the already known meson resonances ρ, ω, and φ, the scientists observed many-hadron events at higher energies [22–24]. These results initiated the development of a new collider, VEPP-2M, with a significantly higher luminosity. The VEPP-2 ring was reconfigured into a booster.

Just like VEP-1, VEPP-2 was used to perform many experiments in accelerator physics. For the first time, researchers observed and investigated many collective effects and coherent instabilities of intense beams. The luminosity was optimized by studying collision effects and nonlinear dynamics. Using this system, researchers discovered and measured the radiative polarization of electrons [25] and suggested and experimentally realized the method of precise energy calibration of the circulating particle beam using resonant depolarization. This method was further developed at the new storage ring VEPP-2M, and it later became an important tool in high-energy physics, with applications at many storage rings around the world. The most impressive application of this method was the study of the Z boson at CERN on LEP, where the researchers measured not only its mass but also the width of the peak, which helped to identify the number of particle generations in the Standard Model: three.

2.3 High-efficiency electron–positron collider VEPP-2M

After the observation of many-hadron events in electron–positron collisions at VEPP-2 (as well as at the French ACO collider (Anneau de Collision d'Orsay) and the Italian system with colliding beams Adone), interest in high-energy physics at lepton colliders dramatically increased. At the same time, particle accelerator specialists gathered extensive practical experience, which deepened the understanding of colliding beam physics and allowed developing new technological systems and increasing their efficiency. This led to a decision in 1970 in Novosibirsk to build a new e^+e^- collider for the VEPP-2 energy range, but with a much higher efficiency. The system was named VEPP-2M [26], but this was a completely new storage ring and not an upgraded version of VEPP-2. Later on, at Stanford, the construction of the electron–

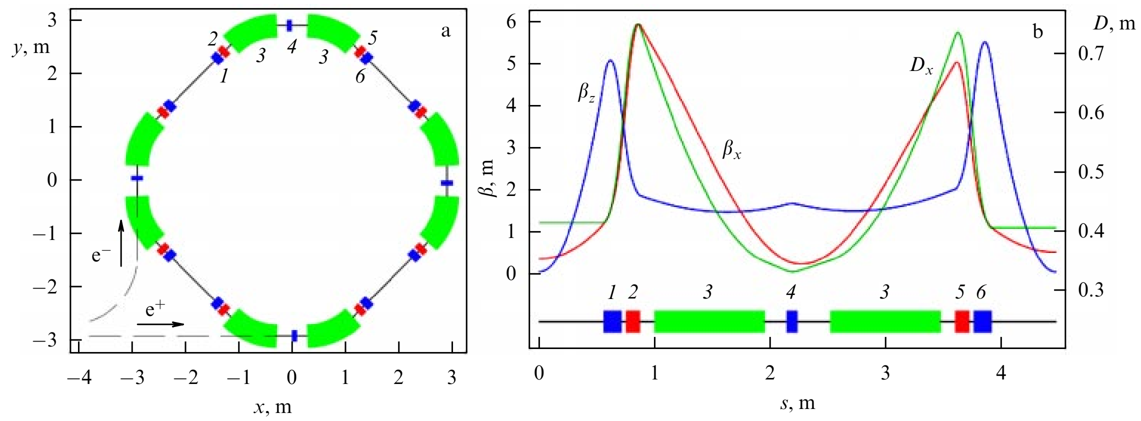

Figure 5. (Color online.) (a) VEPP-2M collider: *1*, *2*, *4–6* — quadrupole lenses, *3* — bending magnets. (b) Optical functions β_z, β_x, and D_x in one period of the storage ring.

positron storage ring SPEAR (Stanford Positron–Electron Asymmetric Rings) designed for the 3 GeV energy began based on the SLAC (Stanford Linear Accelerator Center) linear accelerator and [27].

The storage ring luminosity is known to be limited by the effects of the electromagnetic interaction between the bunches. In the case of a planar beam, this interaction leads to a shift in the vertical oscillation frequency, which for the Gaussian particle density distribution and a short bunch can be expressed as

$$\xi_z = \frac{N r_0 \beta_z}{2\pi\gamma\sigma_z(\sigma_x + \sigma_z)}\,, \tag{2}$$

where $\sigma_{x,z}$ are the standard deviations of particles in the bunch, r_0 is the classical radius of the electron, and β_z is the storage ring optical function, which is the vertical oscillation amplitude envelope. Substituting ξ_z in Eqn (1), we can express the luminosity as

$$L = \frac{N^+ N^-}{4\pi\sigma_x\sigma_z}\, f = \frac{N^+ \xi_z^+ \gamma}{2 r_0 \beta_z^*}\, f\,. \tag{3}$$

Because the frequency shift is always bounded, the main improvement that allows luminosity enhancement is beam focusing at the collision point due to a small vertical betatron function β_z^*. The magnetic structure designed for VEPP-2M was simple and reliable: it consisted of four mirror-symmetric elements of periodicity. Each period contained two bending magnets with a homogeneous field, two quadrupole lens doublets providing beam focusing at the collision point, and an additional lens between the magnets in order to increase the number of degrees of freedom in the optics alignment. Three of the four long straight gaps with small β_z^* were used to install the detectors, and the fourth gap for the accelerating resonator. The chosen positioning of the magnetic elements and the structure of the periodicity element are shown in Fig. 5.

To partially compensate beam–beam effects, the betatron oscillation frequencies were chosen to be near an integer resonance: $\nu_x = 3.06$, $\nu_z = 3.08$. VEPP-2M optics provided large horizontal emittance and control of the vertical emittance by suppressing the $x-z$ oscillation coupling. For storage ring compactness and radiative damping enhancement, the bending magnets had the maximum field of 1.8 T. All magnets and focusing doublets were connected in series to an 8 kA current source. The collider parameters are given in Table 3.

Table 3. VEPP-2M parameters.

Maximum beam energy, MeV	670
Bending magnet radius, cm	122
Straight gap length, cm	110.6
Maximum field, T	1.825
Betatron oscillation frequencies (horizontal/vertical)	3.06/3.08
Orbit compaction factor	0.167
Emittances (horizontal/vertical), cm rad	$2\times10^{-5}/2\times10^{-7}$
$\beta_{x,z}^*$ functions at the collision point (horizontal/vertical), cm	45/6.5
Maximum luminosity (for 510 MeV), cm^{-2} s^{-1}	5×10^{30}

A high-frequency resonator operating at 201 MHz provided an accelerating voltage up to 300 kV, which resulted in bunches less than 6 cm long as needed for high luminosity. To achieve beam lifetimes of several hours and normal background conditions for the experiment, an average vacuum of 10^{-9} Torr and 10^{-10} Torr in the experimental gaps under conditions of strong synchrotron radiation were needed. Such a vacuum was provided by a pumping system based on lumped and distributed magnetic discharge pumps, which were located in the magnetic field at the inner radius of the vacuum chamber. Synchrotron radiation was 'intercepted' using special receivers with water cooling.

The injection part of VEPP-2M included ILU, B-3M, and the VEPP-2 collider operating as a booster storage ring, in which electron and positron beams were alternately stored. In 1989, VEPP-2, which by that time was old and unreliable, was replaced with a new booster accelerator BEP [28] with a significantly larger acceptance. The conversion system was replaced with blocks of two lithium lenses [29], one of which focused the electrons on the convertor, while the other collected positrons. These improvements allowed an order-of-magnitude increase in the positron storage rate and an increase in the VEPP-2M luminosity at high energy.

Given VEPP-2M's low energy and sufficiently high bunch intensity, the decisive role in the particle dynamics was played by the intra-bunch scattering, which increases the transverse size and the energy deviation of the beams, depending on the current. To further increase the beam size and luminosity, one of the VEPP-2M gaps was equipped with a superconducting magnetic snake with a maximal field of 7.5 T, which significantly increased the peak luminosity (by five times at 510 MeV) [30].

The program of experiments at the collider included investigations of vector mesons ρ, ω, and φ, and their decay products: neutral and charged π and K mesons, etc. The integral luminosity produced by VEPP-2M over 25 years of its operation and collected by several generations of detectors provided approximately 70% of hadron production events for the Standard Model calculations of the hadron contribution to the muon anomalous magnetic moment [31].

The VEPP-2M storage ring was used to perform a large number of experiments with polarized beams, including pioneering work on the study of radiative polarization and spin resonances. The radiative polarization time $\tau_p \sim \gamma^5$ at a maximum energy of 670 MeV was 50 min, but the invention of the partial Siberian snake (1975) for the spin resonance crossing allowed obtaining polarized beams in virtually all of the energy range of the storage ring. The resonance depolarization method first used at VEPP-2 was further developed at VEPP-2M and allowed calibrating the beam energy with a relative accuracy of 2×10^{-6}. This gave life to a new field in elementary particle physics — precise measurements of the masses of particles produced in electron–positron annihilation. Masses of ω, φ, K^0, and $K^{\pm}$ mesons were measured with a record-high accuracy for that time [32]. Among the series of precise measurements with polarized beams, there is a distinguished one, in which the anomalous magnetic moments of the electron and positron were compared and these values were proved to be equal with an accuracy of 1×10^{-6} [33].

Besides investigations in the field of high-energy physics, VEPP-2M was also used for a broad program of experiments with synchrotron radiation (SR), which at that time was becoming popular as an instrument for multidisciplinary investigations in the fields of chemistry, biology, surface physics, material science, etc. VEPP-2M's energy and the value of the magnetic field in the bending magnets were enough to work in the ultraviolet and soft X-ray ranges from 2000 Å to 3 Å. The first absorption spectroscopy experiments were performed by a scientist from the Institute of Inorganic Chemistry, Siberian Branch of the USSR Academy of Sciences, in 1974. The installation of a superconducting snake with a large field in 1984 provided harder SR with a much greater power. Two radiation-protected halls with experimental setups could simultaneously host several experimental groups. Among the SR experiments, we note the investigations of SR-stimulated desorption in high vacuum. The beginning of this project in 1991 was connected with the Superconducting Super Collider (SSC) (Dallas, USA), but after the closure of that project the experiments were continued at the Large Hadron Collider (LHC) (CERN, Geneva). VEPP-2M was chosen for these experiments because the radiation spectrum of its electrons is close to the SR of the proton beam at these colliders. That is how experiments on a small collider helped create the LHC.

2.4 Electron–positron collider VEPP-4

Already when launching VEPP-2, there were discussions about building an e^+e^- collider for 3–3.5 GeV, which, naturally, was named VEPP-3. In 1967, the scientific community was introduced to the main characteristics of the VEPP-3 storage ring [34, 35]. A strong-focusing magnetic system consisted of two semicircles 8 m in radius separated by 12 m straight gaps. The operating point was chosen to be close to the center of the stability region, where the beam size was minimal. The betatron oscillation phase shift was chosen to be $\approx \pi/3$ per magnetic cell. The magnetic cell was designed to provide the largest average field. To reduce the price and simplify the construction, the cell was manufactured as a single block with short focusing and defocusing magnets, together with two long magnets with a zero gradient. The semicircle magnets were attached to the ceiling. This solution, suggested by Budker, allowed reducing the tunnel size and making its construction cheaper. Later on, the same technology was used for the VEPP-4 construction.

The role of injectors was played at VEPP-3 by the ELIT electron accelerator and B-4 synchrotron [36]. The development of the B-4 started in 1967, and it was launched in 1969. Electron injection in VEPP-3 was achieved in 1970, but the positron system started operating only in 1972. Its efficiency turned out to be low and the designed luminosity was not reached.

At almost the same time, the SPEAR storage ring was being built at Stanford (USA), and it was close to VEPP-3 in energy and dimensions. A powerful positron source based on the SLAC linear accelerator and small $\beta_z^* = 5$ cm quickly provided a luminosity of the order of 10^{30} cm^{-2} s^{-1} in the regime of one bunch in each beam. That luminosity was enough to make two fundamental discoveries. First, the J/ψ meson was observed in 1974 [37] simultaneously with its observation at the Alternating Gradient Synchrotron (AGS) in Brookhaven, and, second, the τ lepton was discovered in 1976 [38].

The misfortune of the VEPP-3 project led to the decision to make a new positron source at the INP and to use VEPP-3 as an SR source and a booster for the new VEPP-4 storage ring.

The VEPP-4 electron–positron collider became a successor of two projects with colliding beams: VEPP-3 and VAPP (Russian: vstrechnye antiproton-protonnye puchki, colliding antiproton–proton beams). VAPP was designed as a proton–antiproton collider with the energy up to 2×25 GeV. However, during the work on the VAPP project, it became clear that the proton–antiproton program at the INP could not compete with the CERN projects, where a high-energy proton source was already available. Therefore, it was decided to turn the VAPP ring into the VEPP-4 e^+e^- collider with an energy of 2×6 GeV and turn VEPP-3 into a booster–storage ring for positrons and electrons as part of the new collider (Fig. 6).

The positron deficiency was compensated by Budker's idea to use a pulsed gyrocon, which could provide an HF power supply at 430 MHz for the high-current linear electron accelerator. This accelerator was used to build a new positron injection system [39], launched in 1979. After the linear accelerator, the electron beam (up to 10^{13} particles per pulse) was focused on a tungsten convertor and the produced 7 MeV positrons were directed into the B-4 synchrotron, where they were accelerated to the energy of 350 MeV and were injected into VEPP-3.

The maximum intensity of the positron beam extracted from the synchrotron in VEPP-3 was 2×10^8 s^{-1}. This storage rate was enough to obtain accelerated currents of 10×10 mA in VEPP-4.

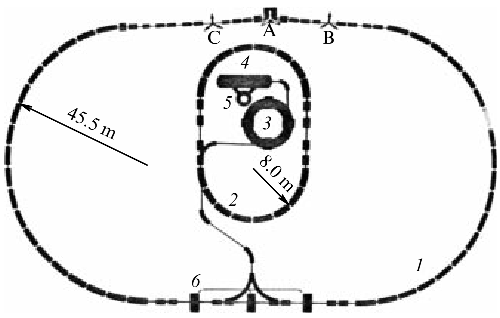

Figure 6. VEPP-4 system: *1* — VEPP-4 storage ring, *2* — VEPP-3, *3* — B-4 synchrotron injector, *4* — linear accelerator, *5* — Gyrocon pulsed high-frequency oscillator, *6* — VEPP-4 accelerating cavities, A, B, and C — collision points.

A significant difference between VEPP-4 and VAPP is the necessity to have a high-power accelerating HF system due to the intensive SR. By that time, the development of the gyrocon — a continuous HF oscillator with a circular sweep, suggested by Budker — had started. Synchrotron radiation of relativistic electrons and positrons required significant changes to be made in the vacuum chamber: the installation of effective SR absorbers and improvement (due to high desorption from the walls) in the system to pump out residual gas.

The semicircular magnetic structure, which was initially designed for the proton–antiproton program, did not provide the radiative damping of radial betatron oscillations; therefore, the circular structure was improved with a special magnetic element, a Robinson wiggler, which redistributed the radiative decrements. To install the detector with a transverse field, it was necessary to eliminate one periodicity element from each semicircle at the entrance to the experimental gap. The additional bending magnets were placed on both sides of the MD-1 detector, which increased the deflection of the particles that had lost their energy. The technological gap opposite the experimental one was used for accelerating cavities, the electron and positron injection system, and other equipment.

Preliminary estimates have shown that the VEPP-4 luminosity at a maximum energy must be 10^{30} cm^{-2} s^{-1} at 2×10 mA currents [40]. The feasibility of reaching such luminosity depended on the positron production efficiency and on the ability to obtain such large currents. An important role in the luminosity enhancement was played by the possibility of using a computer and accurately tuning the optics at the collision point after beam accumulation and acceleration in order to reduce the vertical β function from 46 cm to 12 cm. This design provided the experimental luminosity of 5×10^{30} cm^{-2} s^{-1}. An important question was the reduction in SR influence on the background conditions in the detector. A number of improvements in the vacuum pumping provided a good vacuum (of the order of 10^{-9} Torr), satisfactory background conditions, and several-hour lifetime at high energy (5.5 GeV) for operating currents of 2×10 mA.

The VEPP-4 HF system was designed for the 181 MHz frequency. At the first stage of operation at low energy, when measuring the ψ-meson mass, only one accelerating cavity was used, and it was powered by a lamp oscillator with an output stage of four GI-50A lamps (GI: Russian for generator impulsnyi, pulsed generator) with 130 kW power. The maximum voltage reached 1.1 MV, which was enough to obtain the energy of 3.8 GeV. Five more resonators provided the energy of 5.5 GeV. At the first stage, the gyrocon was used as an HF power supply [41], but this device turned out to be complicated and unreliable, and the program was temporarily suspended. In 1983, all cavities were connected to GI-50A lamp power supplies. The overall power of the HF power supplies was about 200 kW, which produced electron and positron currents of 2×10 mA for energies up to 5.3 GeV.

In order to make the experimental program at VEPP-4 unique, it was decided to focus the research on two-photon physics [42], which attracted more interest after the discovery of the e^+e^- pair production in the two-photon channel at VEPP-2. For this purpose, the magnetic field of the MD-1 magnetic detector was made transverse (vertical), which allowed registering electrons and positrons that had lost their energy in a two-photon interaction. Another unique characteristic of the VEPP-4 scientific program was the ability to precisely calibrate the beam energy using the radiative depolarization method. The electron beam was preliminarily polarized in VEPP-3 and was then injected into VEPP-4 at the required energy.

The first experiments with two beams at VEPP-4 started in November 1979 and used the Olya detector, which ended its program at VEPP-2M and was placed at collision point C (see Fig. 6). Together with the Olya detector, the energy calibration method using resonant depolarization was realized in VEPP-4. As a polarimeter, scintillation counters were used that registered particles leaving the beam due to intrabunch scattering [43]. In March 1980, the Olya detector performed precise measurements of J/ψ and ψ' meson masses, which improved the accuracy by one order of magnitude. Based on these results, the masses of D^+, D^-, and D^0 mesons were also calculated.

In spring 1982, preparations for Υ-meson mass measurements using the MD-1 detector were started. (The first upsilon meson $\Upsilon(1S)$ was discovered at Fermilab in 1977). As before, the absolute energy calibration was performed using the resonant beam depolarization method. The polarization measurement method is based on the asymmetry of Compton backscattering on an incoming polarized beam. A pulsed solid-state YAG laser was used as a source of circularly polarized photons in the first polarimeter [44] and in the second one, it was SR generated by the incoming beam [45]. The asymmetry value turned out to be large enough to perform reliable measurements for the precise determination of the Υ-meson mass [46]. During 1982–1985, several scanning cycles for various states of upsilon mesons were performed. As a result, the accuracy of mass determination was increased by almost two orders of magnitude for the Υ meson and by 20 times for Υ' and Υ'' [47]. This experiment attracted much attention in the scientific community, and similar measurements were repeated using the 'Novosibirsk method' at the Cornell Electron Storage Ring (CESR) (Cornell University, USA) [48] and at the Double Ring Store (DORIS) (Deutsches Elektronen Synchrotron (DESY), Germany) [49].

These systems, similar to VEPP-4, were its competitors. The DORIS storage ring was designed as a collider with two rings and the crossing of electrons and positrons at a vertical angle at the collision point. However, in reality, it turned out that the synchro-betatron resonances generally led to instabilities. As a result, the DORIS storage ring was reconfigured into a 'conventional' single-ring collider for the energy of

5.3 GeV with a PIA (positron intensity accumulator) high-power positron source and a luminosity of 5×10^{30} cm^{-2} s^{-1}.

The CESR electron–positron collider with the energy 1.75–6 GeV operated in 1979–2008 and was built in the same tunnel next to the electron synchrotron, which became the storage ring injector. In the '1 × 1-bunch' regime, CESR reached the luminosity of 3×10^{30} cm^{-2} s^{-1} at 5.5 GeV. CESR was the first collider where the crossing of a large number of bunches was realized. This was achieved by a special 'pretzel-like' distortion of the equilibrium orbit, which allowed avoiding beam crossings at 'parasitic' collision points. Reconfiguration of the focusing system to the regime with a small β function, the transition to multibunch operation (45 × 45 bunches), and crossing at an angle, as well as the development and introduction of superconducting HF cavities, resulted in the luminosity enhancement up to 1.25×10^{33} cm^{-2} s^{-1}. From 1990 until the moment when B-factories started their operation [50], CESR was the collider with the highest luminosity in the world.

The VEPP-4 system was already a quite large setup, at which there were several thousand control channels for complicated electro-physical equipment. It was obvious that the operation of such a system was impossible without an automated control system. To construct such a system, ODRA-1300 computers made in Poland with 16/32 kilobytes of RAM and 256 kilobytes of external storage performing 10^4 operations per second were used. Due to the uniqueness of the problem, the institute had to develop the rest of the elements: a full set of measuring and controlling devices, systems for fast synchronization (ns range), local network devices, and software (including the operating system, programming language, translators, and editors) [51]. In the late 1970s, the CAMAC (Computer Automated Measurement and Control) standard was introduced in the control systems, which allowed integrating different blocks in one crate and building local multifunctional control and measurement systems. This in turn required the development of an intellectual controller microcomputer, which was created at the beginning of the 1980s. This microcomputer had a performance similar to that of the IBM PC-XT 286 commercial personal computer, and it carried out multiple functions, both universal and dedicated ones, including a number of inter-device data exchange protocols and synchronization of the processes with the operation of the facility subsystems.

Besides high-energy physics experiments, the VEPP-4 system was used to perform many interesting and beautiful projects in the field of particle and accelerator physics. Below, we briefly review only some of them, and the details can be found in the references.

The scientists working at VEPP-4 succeeded in the first ever detection and investigation of relativistic electron radiation in a magnetic field, which is related to the electron spin ('spin effect') [52]. These experiments have not been repeated anywhere in the world. The spectrum and the cross section of a single bremsstrahlung of the incoming beam was measured, resulting in the discovery of the cross-section reduction effect associated with the limitation of the impact parameters by the bunch transverse size [53]. Many nuclear physics experiments based on the developed laser system were performed later [54]. The VEPP-3 storage ring was used for the first time to launch a unique source of coherent electromagnetic radiation designed at the INP — the 'optical klystron' [55], which is a free-electron laser modification with a high amplification factor. At the same setup, the scientists regularly performed experiments using SR from the world's first multipole superconducting snake [56] and investigated nuclear physics effects using an internal gas target (in some cases, polarized) [57]. Both storage rings (VEPP-3 and VEPP-4) were used to study various aspects of accelerator physics, including beam–beam effects, nonlinear beam dynamics, coherent instabilities, and the dynamics of polarized electrons.

Successful operation of VEPP-4 was interrupted by a fire that started on the night of August 16 1985. A short circuit caused the ignition of the power supply of the high-vacuum pump. The fire propagated along cable lines and reached almost all the rooms in the facility, destroying most of the equipment.

3. Current status of colliding beam projects at the BINP

3.1 VEPP-4 upgrade

The fire disaster disabled almost all of the systems of the VEPP-4 facility. Some of them were restored without changes, but most of the setup was significantly reconfigured. Even before the fire, various upgrade plans were considered, first of all, for problems such as monochromaticity of the interaction energy or generation of colliding beams with longitudinal polarization. Earlier, it had been planned to use the MD-1 detector for several more years, but work on the development of the detector with a longitudinal magnetic field had begun already. The fire changed everything. It had to be quickly decided what to do next. After long discussions, the decision was made: keep and improve the parts of the physical program related to two-photon physics experiments and significantly improve the luminosity [58]. Luminosity enhancement could also give opportunities to perform other experiments, including precise ones based on the use of polarized beams. First of all, significant changes were made in the magnetic structure of the collision gap, which could now register scattered electrons (positrons) and measure their energy without the necessity of a detector with a transverse magnetic field like MD-1 [59]. The Kedr detector with a longitudinal magnetic field allowed placing the focusing lenses closer to the collision point. These lenses and the bending magnets installed after them act as spectrometers, which use the detection systems inside to measure the spectrum of the electrons scattered in a two-photon process (Fig. 7).

The most important aspect of the upgrade was the symmetry of the VEPP-4M magnetic structure with respect to the gap centers. The new Kedr detector was installed in the center of the experimental gap, and the previous MD-1 detector was shifted 2.3 m from the center.

The installation of the final focus lenses closer to the crossing point allowed reducing the vertical betatron function to 5 cm, which increased the luminosity. Due to the magnets of the scattering electron spectrometer, the dispersion function at the collision azimuth was not zero, and the energy size there was higher than the betatron one, which also led to luminosity enhancement with the increase in the bunch intensity. In the semicircle centers, two periodicity elements were replaced with insets that consisted of four magnets and lenses with an increased aperture. The electrodes for the separation of electron and positron beams were

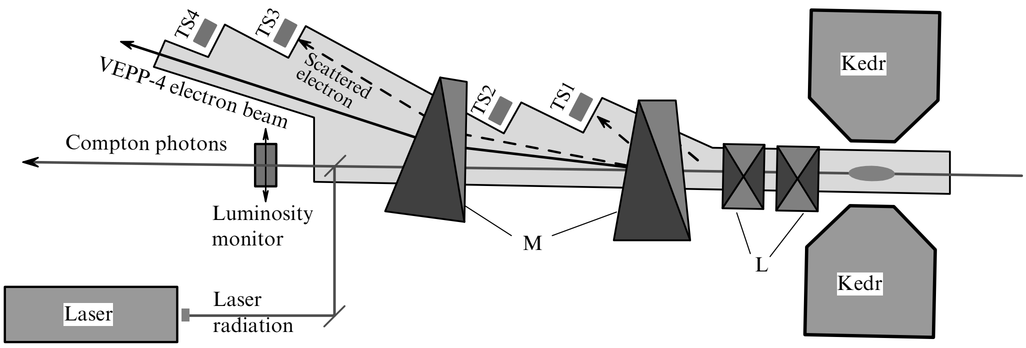

Figure 7. Schematic of the electron part of the spectrometer: L — final focus lenses, M — spectrometer magnets, TS1–TS4 — coordinate counters for scattered electron registration, Kedr — universal detector with the longitudinal field. The positron part of the spectrometer is mirror-symmetric with respect to the detector center (collision point).

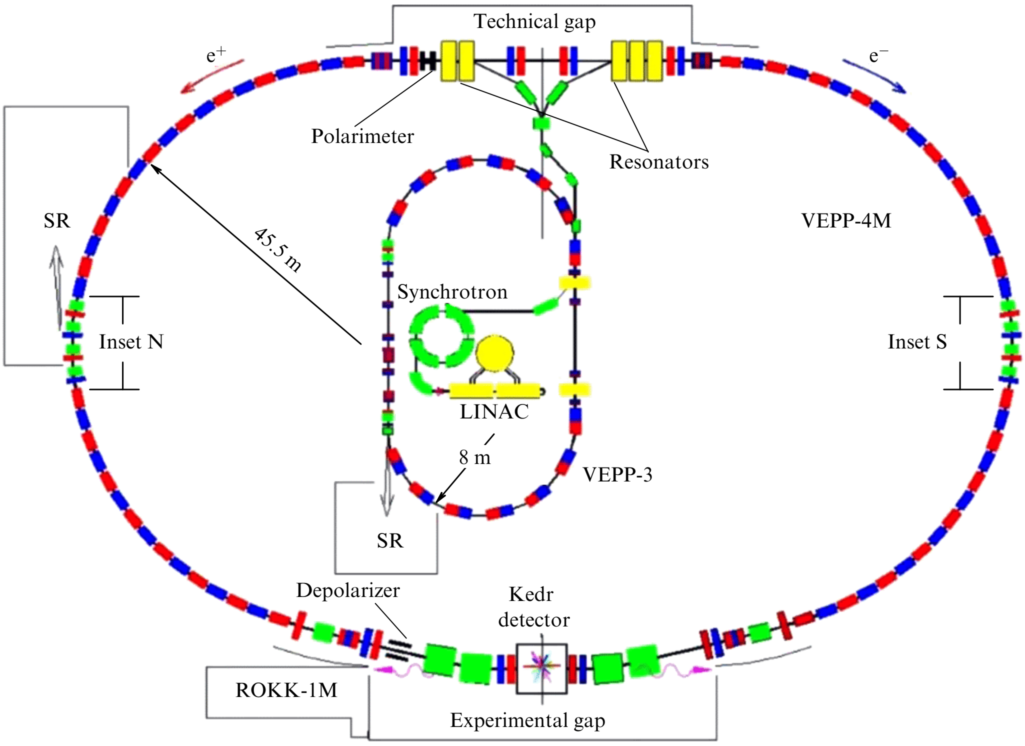

Figure 8. VEPP-4M facility schematic: SR — experimental rooms for measurements with SR, ROKK-1M — setup for operation with extracted beams and backscattered Compton gamma quanta, LINAC — linear accelerator.

also installed there, which allowed realizing the '2×2 bunch' collision regime. Unfortunately, due to the small aperture, it was not possible to achieve a multibunch regime at VEPP-4M as was realized at CESR.

Besides the VEPP-4 storage ring magnetic system, major changes were made to the HF accelerating system, positron injection system, beam transport channel from VEPP-3 to VEPP-4, devices for particle injection/extraction, systems for monitoring and controlling the beams, etc. The first stage of the restoration was finished at the end of 1991 and on November 27, 1991 for the first time after the fire, an electron beam was captured in the VEPP-4M storage ring. A detailed description of the Kedr detector and the VEPP-4M accelerating system with many references is given in [60, 61], respectively.

A schematic of the VEPP-4M facility is shown in Fig. 8. Its main parameters are given in Table 4. Until 2016, the injection part consisted of the same systems as in VEPP-4: a linear accelerator powered by a pulsed gyrocon, the B-4 synchrotron, and the VEPP-3 storage-ring booster. Figure 9 shows the VEPP-4M tunnel with a storage ring fixed to the ceiling and the Kedr detector.

The main purpose of the VEPP-4M collider is the experimental investigation of elementary particle properties and studies of the resonant state parameters and electron–positron annihilation cross sections. The designed luminosity of VEPP-4M is in the range $(1-80) \times 10^{30}$ cm^{-2} s^{-1}, depending on the beam energies. At lower energy, the luminosity is limited by beam–beam effects and at higher energy by the positron production rate and the ability to obtain and accelerate large currents in an energy range from the injection energy (1.8 GeV) to the experiment energy.

Despite the quite low luminosity compared with that of modern colliders, VEPP-4M, together with the Kedr detector,

Figure 9. (a) VEPP-4M fixed to the tunnel ceiling. (b) Elements of the final focus and the Kedr detector.

Table 4. VEPP-4M main parameters.

Perimeter P, m	366.075
Revolution frequency f_0, kHz	818.924
HF system multiplicity	222
Revolution period T_0, ns	1221
Maximum energy E, GeV	5.5
Orbit compaction factor α	0.017
Betatron frequencies Q_x/Q_z	8.54/7.58
β and ψ functions at the collision point $\beta_x/\beta_z/\psi_x$, cm	75/5/80
Operating parameters at the energy of 1.8 GeV *	
Oscillation damping time $\tau_z/\tau_x/\tau_s$, ms	70/35/70
Horizontal emittance, nm rad	17
Energy spread σ_E/E	4×10^{-4}
Longitudinal size σ_L, cm	6
Number of e^+e^- bunches	2, 2
Multiplicity of the HF system	222
Luminosity, $cm^{-2}\ s^{-1}$	3×10^{30}

* Maximal time of statistics accumulation in the 2000–2010 season corresponded to the ψ-meson and τ-lepton production energy.

has a number of advantages, which allow performing unique experiments in high-energy physics:

- a broad energy range in the beam: from 0.9 GeV to 5.5 GeV;
- the capacity of measuring the beam energy using the resonant depolarization method with a record high absolute accuracy, 10^{-6};
- the possibility to continuously monitor the beam energy with a relative accuracy of 5×10^{-5} and the energy spread with an accuracy of 10% by measuring the Compton spectrum edge of backscattered monochromatic laser photons;
- a universal magnetic Kedr detector with the performance comparable to modern detectors for experiments at electron–positron colliders;
- a detection system for electrons scattered after the interaction of two beams with a high pulsed resolution of the 2γ state ($\sim 10^{-3}$), which allows conducting unique investigations of two-photon processes.

A system for particle energy measurement using the resonant depolarization method, together with a proven procedure of energy restoration between calibrations using the VEPP-4M measurable parameters, allows determining elementary particle masses with an extremely high accuracy. In the experiments conducted at VEPP-4M starting in 2000, the masses of the J/ψ, $\psi(2s)$, and $\psi(3770)$ mesons and the τ lepton were measured with a record-high accuracy. The J/ψ and $\psi(2s)$ meson masses, which were measured at VEPP-4M with an accuracy 3–4 times higher than the world average, are among the ten most accurately known elementary particle masses throughout the whole history of physics. At present, only the electron, proton, neutron, muon, and $\pi^{\pm}$-meson masses are measured more accurately. In 2008, an experiment on the τ-lepton mass measurement was finished, and it made a significant contribution to the determination of the applicability limit of the Standard Model — the theory that currently most fully describes the fundamental properties of matter and elementary particles.

The scientific program for the VEPP-4M collider for the coming years is devoted to increasing the colliding beam energy in order to measure the cross section of electron–positron pair annihilation into hadrons in the range $2E = 4-11$ GeV, investigating two-photon processes (such as $\gamma\gamma \to$ hadrons), measuring the lepton width, refining the Υ-meson masses, etc. To obtain a luminosity corresponding to high energy, the intensity of the colliding bunches had to be increased, which was a hard task (especially for positrons) for the previous positron injection system. Therefore, in 2016, VEPP-4M was reconfigured to the electron and positron feed from a new injection facility (IF), which was launched in 2013 [62]. The IF consists of two linear accelerators (with a planned energy of 300 and 510 MeV) with a positron convertor between them and a storage-cooling device with a maximal energy of 510 MeV. Currently, the electron and positron beams from the new IF are transported through a long (≈ 300 m) electron-optical channel into VEPP-3. The positron storage rate at VEPP-3 was increased by 10 times with the new IF. This will allow reaching the luminosity at an energy of 5.5 GeV close to the limiting one due to beam–beam effects.

VEPP-4M is a multifunctional multidisciplinary accelerating facility. Synchrotron radiation beams are used here to perform many experiments (15 experimental stations with SR from the VEPP-3 and VEPP-4M storage rings) [63]. The main research topics are: LIGA technology,[1] nanosecond diagnostics of fast processes, precise diffractometry and anomalous scattering, local and scanning X-ray-fluorescent element analysis, diffractometry at high pressure, X-ray microscopy and tomography, time-resolved diffractometry, small-angle scattering, extended X-ray absorption fine structure (EXAFS), and metrology in the vacuum ultraviolet and soft-X-ray ranges.

For several years, scientists also used VEPP-3 to perform investigations of the deuteron electromagnetic structure in experiments with a tensor-polarized internal gas target [64]. Such investigations play a key role in nuclear physics because the experimental results with this simplest nuclear system can be directly described by modern concepts of nucleon–nucleon interactions, meson exchange currents, and other non-nucleon degrees of freedom; in other words, these results can verify modern theories. The quite large VEPP-3 storage ring current (≈ 100 mA) and dense target provide high luminosity in experiments.

To conduct methodological work on the development of new detectors for high-energy physics and nuclear research, an experimental setup was assembled on the basis of the test electron beam extracted from the VEPP-4M vacuum chamber. The test beam is obtained by placing a mobile convertor in the halo of the collider beam and creating bremsstrahlung gamma quanta. Reverse conversion of the bremsstrahlung gamma quanta into electron–positron pairs is performed in the experimental room with the conversion target setup. For the selection of electrons with a specific momentum, a dipole bending magnet is used. The test electron beam has the following parameters: energy range 100–3500 MeV, energy spread of 7.8% at 100 MeV and 2.6% at 3000 MeV, average counting rate 50 Hz. The setup is equipped with all the necessary devices for trigger signal realization and measurement of the track coordinates and the test beam energy. The data acquisition system used in this experiment also collects data from the tested detector prototypes. Starting in 2011, the test electron beam has been used to gauge detectors for Chernekov ring detection (a promising setup for particle identification in the super-charm-tau factory project), devices based on microchannel plates for a time-of-flight system with limit time resolution, coordinate detectors based on a gas electron multiplier, etc.

3.2 Round colliding beams, VEPP-2000

By the end of the 1990s, the VEPP-2M collider had completed its physical program. In the beam energy range from 180 to 700 MeV. several generations of detectors collected an integral luminosity of ~ 100 pb^{-1}, which provided approximately 70% of the calculation accuracy for the hadron contribution to the anomalous magnetic moment of the muon. The setup was successful and had operated for a quarter of a century, but obtaining new interesting results either significantly improving the luminosity or setting out new physical problems.

At that time, the Double Annular Φ-Factory for Nice Experiments (DAΦNE) was launched in Italy. This facility used all modern approaches to the assembly of high-efficiency colliders (two rings, tilted crossing, multibunch regime, $\sim 1-2$ A beam currents) and had a planned luminosity higher than 10^{32} cm^{-2}. In the USA and Japan, the construction of B-factories was being finished, and these facilities were designed for a different energy range but had a super-high luminosity. In this situation, it was pointless to use the outdated VEPP-2M.

At the same time, it became clear that the financial economic model of the country had changed forever, and the realization of large and expensive projects was unlikely in the nearest future. From the late 1980s, a daring project of the Φ-factory was being developed at the BINP [65], and it included various nonstandard solutions: a figure-eight 'ring' with one colliding point ('Siberian butterfly'), strong superconducting dipoles for the radiative damping enhancement, final focusing with solenoids, etc. The cornerstone of the project was the round colliding beams concept [66].

In a planar storage ring, the electron bunch generates SR, and its vertical size is much smaller than the horizontal one, which is in turn much smaller than the longitudinal one. The collider luminosity is limited by beam–beam effects: the interaction of particles with the collective electromagnetic field of the upcoming bunch. Being nonlinear, this field gives rise to both a dense two-dimensional grid of nonlinear resonances and a betatron frequency spread in the beam, which overlaps the grid. The particle motion in such a field becomes stochastic. As we have seen, the attainable beam–beam parameter does not exceed $\xi_z \approx 0.06$ and weakly grows with the energy increase due to the damping enhancement, reaching the value $\xi \approx 0.083$ for an energy of 100 GeV at the LEP.

The use of a round beam for the suppression of beam–beam effects was first considered at the INP in 1979 [67]. To achieve maximal luminosity at VEPP-2000, the round beam concept was included in the facility optics project [68]. The symmetry of the $x-z$ transfer matrix for betatron motion between the collision points led to the conservation of the angular momentum ($M = xz' - zx' = \text{const}$). This established the requirements for the magnetic system of a collider with round beams: (a) equal transverse beam emittances; (b) the equality of the vertical and horizontal beta functions at the collision point, (c) equal noninteger parts of the betatron frequencies [69]. As a consequence, this increases the particle motion stability, even with nonlinear bunch–bunch interaction effects taken into account [70].

For round colliding beams, the expression for luminosity in (3) can be rewritten as

$$L = \frac{4\pi\gamma^2 \xi_{\max}^2 \varepsilon f}{r_0^2 \beta^*}\,, \tag{4}$$

where ε is the beam emittance.

Computer modeling confirmed the expectations for both the 'weak–strong' and 'strong–strong' interaction types and provided an attainable value of the beam–beam parameter $\xi = 0.1$ [71].

Already the first measurements of beam–beam effects at VEPP-2000 have shown a high stability of round beams to the beam–beam effects and resulted in the parameter value $\xi = 0.1$ [72].

Because the Novosibirsk Φ-factory did not receive additional funding, only a minimal project of VEPP-M upgrade was originally considered, which corresponded to the final focus quadrupole replacement with superconducting solenoids creating an 8.5 T field. However, the experimenters insisted on a beam energy increase to 1 GeV, which would not

[1] LIGA: acronym from the German names for the main stages of this technology: X-ray lithography using SR (Lithographie), galvanoforming (Galvanoformung), and plastic moulding (Abformung).

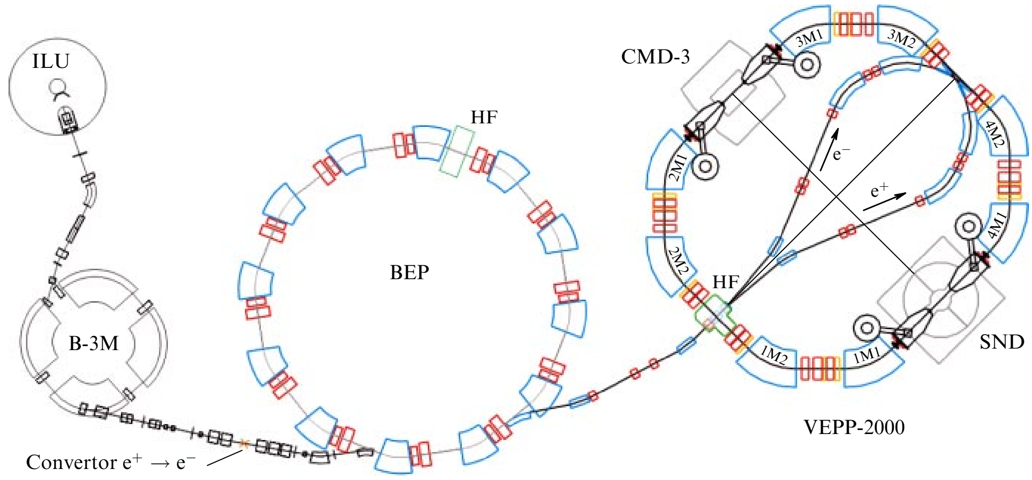

Figure 10. Schematic of the VEPP-2000 storage ring with an old injector.

only allow a 10-fold increase in the VEPP-2M performance in e^+e^- annihilation into hadrons, but also give an opportunity to study these processes in the energy range where only old Adone and DCI (Dispositif de Collisions dans l'Igloo) setups were operating with a very low luminosity modern standards, $\sim 3 \times 10^{29}$ cm^{-2} s^{-1}. Moreover, higher energy would lead to the possibility of proton–antiproton and neutron–antineutron pair production, and the energy range of the new collider would close in on the energy range of VEPP-4M. Finally, it was decided to completely disassemble the VEPP-2M storage ring and build a new one instead, VEPP-2000, with the maximal use of the old facility infrastructure [69]. At the end of 2000, the VEPP-2M operation was stopped.

To make the construction of the new collider cheaper and faster, it was planned to maximally use the existing rooms and the infrastructure, and, at least at the initial stage, use the VEPP-2M injection complex. A VEPP-2000 schematic is shown in Fig. 10 and the main parameters are given in Table 5.

During the planning and construction of the new collider, the main problem was the quite small available area. The magnetic structure of the ring is similar to the VEPP-2M structure: four quadrants, two experimental gaps (with CMD-3 [73] and SND [74] detectors[2]), and two technological ones. However, the bends are made achromatic in order to set the dispersion function to zero in the collision and HF-cavity gaps. Final focusing is realized using superconducting solenoids with the field of up to 13 T. The ring circumference is 24.39 m. Sector bending magnets are W-like with a 140 cm curvature radius and a large (for such a compact setup) value of the magnetic field, up to 2.4 T for a 40 mm gap between the poles. Special attention during the development was paid to the choice of the profile for the pole concentrator and the end chambers, and to various effects connected with high saturation of iron, for example, the dependence of the effective length of the magnet on the supply current.

The most complicated element of the magnetic system is the superconducting solenoid of the final focus. Each solenoid is a block of five coils, which are placed in one closed magnetic circuit. A field of 13 T, which is necessary for the operation at 1 GeV, was created by using inner coils with niobium–tin wire.

[2] CMD — cryogenic magnetic detector, SND — spherical neutral detector.

Table 5. Main parameters of VEPP-2000.

Energy, MeV	500	1000
Circumference, m	24.39	
Frequency (HF), MHz	172	
Harmonic number	14	
HF voltage, kV	100	
Revolution frequency, MHz	12.2915	
Beta function at the collision points, cm	5	10
Betatron frequencies	4.1; 2.1	
Emittances, cm rad	6.8×10^{-6}	1.4×10^{-5}
Transverse beam size at the collision point, mm	0.058	0.12
Orbit compaction factor	0.036	
Beam energy spread	3.5×10^{-4}	7.1×10^{-4}
Bunch length, cm	1.2	3.5
Energy loss per turn, keV	4	63
Radiative damping time, ms	21.8	2.7
	9.8	1.2
Beam current, mA	50	200
Number of particles in the beam	2.5×10^{10}	1×10^{11}
Beam–beam parameter	0.1	
Luminosity, cm^{-2} s^{-1}	1.8×10^{31}	1×10^{32}

A liquid-helium-cooled vacuum chamber for solenoids is a powerful cryopump, which implements the pumping of experimental gaps through a perforated liner. The water-cooled vacuum chamber for technological gaps and dipole magnets is made of stainless steel and is equipped with SR absorbers. All welded flanges and bellows are covered from inside with HF contacts that provide electromagnetic 'smoothness' in order to avoid collective instabilities. The pumping is realized using 16 PVIG-100 (post-vacuum ion-getter) pumps located at the dipole edges, together with titanium sublimators.

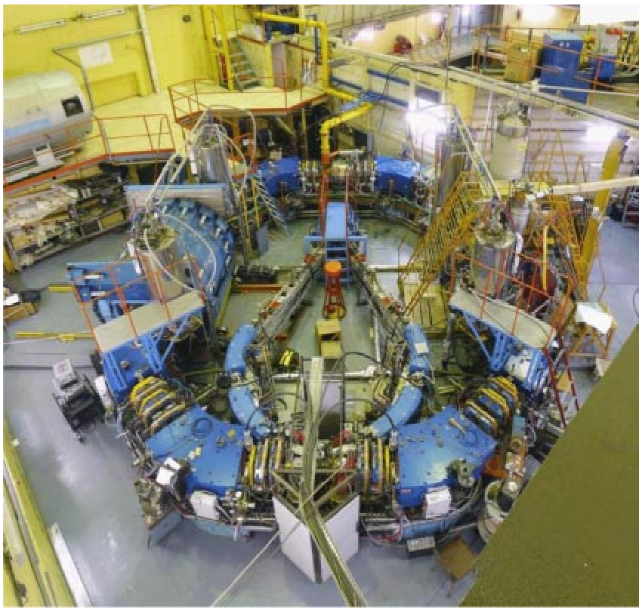

Figure 11. General view of VEPP-2000.

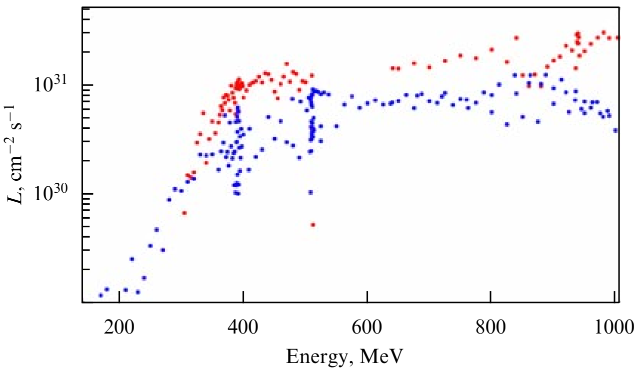

Figure 12. (Color online.) VEPP-2000 luminosity. Blue circles show the results obtained with an old injection system, and red ones, after the upgrade.

A general view of the VEPP-2000 storage ring is shown in Fig. 11. The beam transfer channels from the BEP (booster for electrons and positrons) pass below the VEPP-2000 median plane, enter the ring, separate, and bend to the further technological gap with 2.6 T magnets. These magnets are powered in series with the BEP magnetic elements. Pulsed entrance magnets are separated into a powerful bending magnet with the field higher than 3 T and a small-aperture septum magnet with a beam gap of 5.4 mm and the field higher than 2 T. The electron and positron injection in VEPP-2000 is realized using a single-turn scheme with radial inflector plates located in the bending magnets nearest to the injection gap. The resonator at VEPP-2000 with 120 kV voltage corresponds to the 14th harmonic of the revolution frequency (172.081 MHz), while the higher harmonics are suppressed with a load from weakly conducting ceramics.

The electron beam made its first turns at VEPP-2000 in September 2006 at an energy of 140 MeV, but the full operation in the special regime and without using the final focus solenoids took place on October 14, 2006. In June 2007, a positron beam was for the first time stored at VEPP-2000 and by the end of 2007 the SND detector calorimeter registered the luminosity [74].

In 2010–2013, VEPP-2000 accumulated statistics in the beam energy range 160–1000 MeV [75]. In the high-energy range (above 500 MeV), the luminosity was limited by the positron deficiency in the old injection complex. At moderate energies, the limitation was caused only by the beam–beam effects. At low energy, due to low damping, the problems of dynamic aperture and lifetime become more important. Record values of the beam–beam parameter per collision point were achieved in the long-bunch regime due to collective effects at a low voltage of the accelerating cavity.

After the beginning of the VEPP-2000 project, it was clear that the old injection facility based on the B-3M synchrotron could not provide enough positrons for the setup with a 30-times higher luminosity than that at VEPP-2M. In 2002, the BINP started the construction of a 250 m tunnel from the new injection facility (IF) and the planning of the corresponding electron-optical transport channel. To achieve the nominal luminosity at high energy, additional improvements in the injection part of the collider (mainly connected with the increase in the BEP energy range and top-up injection channel) had to be introduces, and, in 2013, VEPP-2000 was stopped for an upgrade. Because the IF provides well-shaped small-size damped beams, the aperture of the BEP bending magnets was decreased, which led to the generation of a record-high field of 2.6 T in the gap of the resistive magnets. Moreover, a new accelerating cavity with an increased gap voltage was built, the top-up channel magnets were upgraded, and the quadrupole lenses were optimized for the higher energy.

The year 2016 was devoted to the launch and tuning of the IF and VEPP-2000 cooperation [76]. In 2017, the operation of the detectors in the beam energy range 640–1003 MeV was restarted [77]. The positron storage rate at the BEP was 2×10^9 s^{-1}, which is one order of magnitude larger than that of the old injector. Luminosity in the high-energy range increased several-fold, and the peak luminosity reached 4×10^{31} cm^{-2} s^{-1}. The integral luminosity accumulated over the season exceeded the record-high value of 50 pb^{-1} per detector. At the end of 2017, luminosity integration was performed for the 300–500 MeV energy range.

Figure 12 gives the full picture of the luminosity measured in the whole VEPP-2000 energy range during 2010–2013 and 2016–2017 runs.

During the 2016–2017 run, a new world record for the beam–beam parameter was registered: $\xi = 0.145$ at 350 MeV.

In the near future, VEPP-2000 will be the main accelerating facility at the BINP, to provide data for elementary particle physics. The goal is to accumulate an integral luminosity not less than 1 fb^{-1} in the energy range 0.35–2.0 GeV.

4. Super-charm-tau factory

The colliding beam method is one of the main instruments in high-energy physics, and just the colliding beam experiments have provided data for the development of the modern theory of subatomic world, the Standard Model (SM). Colliding beams were mostly used to verify this theory. The final confirmation of the SM was the Higgs boson discovery in 2012 at the LHC at CERN. Currently, there is no experiment with results deviating from the SM prediction. Despite the triumph of the Standard Model, there are a number of unsolved problems in fundamental physics: the particle mass hierarchy (less than 1 eV for the neutrino and almost 200 GeV for the t quark), the problem of baryon asymmetry in the Universe, the dark matter problem, etc. Traditionally, there has always been hope that deviations from the SM (the so-called 'new physics') would he observed at colliders at super-high energies (LHC), but there are no traces yet of 'new physics' in these experiments. There are also a number of fundamental problems that are being and will be solved on the colliding electron–positron beam setups at relatively low energies ($E = 0.3-10$ GeV), but with a high luminosity. Such facilities are called 'factories' (c-τ-, Φ-, and B-factories). At these setups, quark physics, *CP*-violation or, in other words, asymmetry between matter and antimatter properties, and other effects are being studied. It is possible that phenomena beyond the SM framework can be found here.

In the 1990s, various laboratories performing high-energy physics research discussed several plans for super-charm-tau-factories (also known as c-τ-factories) (including the BINP project using round beams [78, 79]). To study narrow resonances, researchers considered various options of particle collision monochromaticity and investigated the possibility of working with transverse-polarized beams for precise energy calibration. The only successful project of that era was the BEPC II collider (Beijing Electron–Positron Collider II), launched in 2009 at the Institute of High Energy Physics (IHEP) in Beijing [80]. The peak luminosity of BEPC II was 10^{33} cm^{-2} s^{-1}.

Renewed interest in the topic and the beginning of the c-τ-factory project at the BINP are due to, first, the outstanding results obtained at B-factories of the High Energy Accelerator Research Organization (KEK) (Japan) and the SLAC National Accelerator Laboratory (USA). The high luminosity of the B-factories provided interesting results using the radiative return method (suggested and developed at the BINP [81]). However, the development of a low-energy collider factory for studies of the charmed quark and tau-lepton physics is still a very topical task. Second, more interest in the c-τ-factory construction of the next generation was due to the appearance of a fundamentally new scheme for beam collision in e^+e^- colliders, which allows increasing the luminosity by one to two orders of magnitude without a significant increase in the beam energy, setup dimensions, or bunch compression. The idea was suggested by the Italian physicist Pantaleo Raimondi when investigating the possibility of creating a high-luminosity B-factory [82, 83].

In the new scheme, the beams collide under a quite large angle of several tens of milliradians. If the horizontal emittance and the beam size are small at the collision point, then the longitudinal size of the bunch–bunch interaction (overlap) region becomes significantly smaller than their bunch length. This allows decreasing the vertical beta function at the collision point to submillimeter values without influencing the so-called 'hourglass' effect, and thus increasing the luminosity by more than an order of magnitude. Collisions at small angles were used in the first generation of the factories (DAΦNE, PEP-II (Positron–Electron Project II), KEKB, and BEPC-II), which provided the capacity to operate in a multibunch regime. The vertical beta function in this case was of the order of the bunch length and the synchro-betatron coupling resonances enhanced due to the tilted collision [84] limited a further increase in luminosity. However, in the case of large-angle collision and a small beta function, the mechanism of the coupling resonance excitation changes, and the leading role is played by the modulation of the vertical betatron phase with horizontal betatron oscillations. This problem was elegantly solved using two sextupole lenses placed symmetrically on both sides of the collision point at certain azimuths. The idea of this step is to make the particle vertical betatron phase independent of its horizontal coordinate at the point where the particle crosses the upcoming beam axis. This leads to the suppression of betatron and synchro-betatron coupling resonances [85, 86], which provides very large values of the beam–beam parameter and further increases the luminosity by 2 to 3 times. It can be shown that after such a transformation, the vertical beta function minimum line (beam waist) is no longer perpendicular to the beam axis: it turns and becomes parallel to the upcoming bunch axis. This waist turn gave the name to the whole system, Crab Waist (CW), and the sextupoles used in the scheme were called 'crab sextupoles'. Figure 13 shows the numerical modeling results [87] that demonstrate the operation of crab sextupoles.

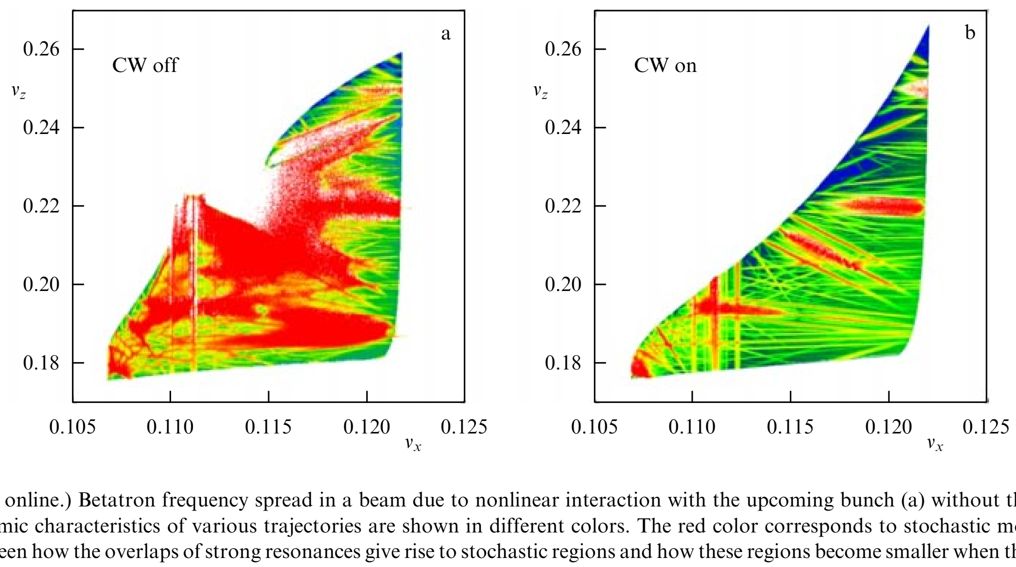

Figure 13. (Color online.) Betatron frequency spread in a beam due to nonlinear interaction with the upcoming bunch (a) without the crab waist and (b) with it. Dynamic characteristics of various trajectories are shown in different colors. The red color corresponds to stochastic motion, blue to the regular one. It is seen how the overlaps of strong resonances give rise to stochastic regions and how these regions become smaller when the crab sextupoles are turned on.

The new method eliminates the problem of parasitic collision points (because the beams quickly separate) and does not need short bunches (which reduces the danger of collective effects). The beam parameters needed for the new particle factories are within the limits already reached either at the SR sources (small emittance, small betatron coupling coefficient) or in previous-generation colliders (beam current of $\sim 1-2$ A). Starting from 2008, the CW has been successfully operating at the DAΦNE Φ-factory (Italy). The experimental results confirm the promising capabilities of this method and are in good agreement with the theory [88]. Besides the c-τ-factory in Novosibirsk, this new approach is also used at e^+e^--collider projects designed for super-high luminosity: the Future Circular Collider (FCC-ee) [89] at CERN and the Circular Electron–Positron Collider (CEPC) [90] in China.

The c-τ factory physical program has the following main requirements for the accelerating facility.

• The energy range in the center-of-mass system must be 2–5 GeV, which would allow conducting experiments at energies from the nucleon and antinucleon production threshold to the ranges of ψ-meson and charmed baryon families and using the VEPP-2000 and VEPP-4M results.

• The factory luminosity must be no lower than 10^{35} cm^{-2} s^{-1} in the high-energy range and no lower than $\sim 10^{34}$ cm^{-2} s^{-1} in the low-energy range.

• The electron beam must be polarized longitudinally at the collision point.

• The beams collide with equal energies, and energy asymmetry is not needed.

• Collision monochromaticity is not required because the corresponding schemes are complicated and significantly decrease the luminosity, while the higher luminosity provides opportunities to efficiently study narrow states without monochromaticity.

• Transverse polarization of the beams is not needed for energy calibration. The energy can be measured using the Compton backscattering of laser radiation on particles of the circulating beam [91]. This method was first applied to e^+e^- colliders at the BINP, and it gives a relative accuracy higher than 10^{-4}, which is enough for the c-τ-factory tasks.

The super-c-τ-factory is schematically shown in Fig. 14 together with other BINP facilities related to colliding beam experiments: VEPP-2000 with the BEP, VEPP-4M with the VEPP-3 storage ring, and the injection facility with a synchrotron for beam preparation for the new particle factory.

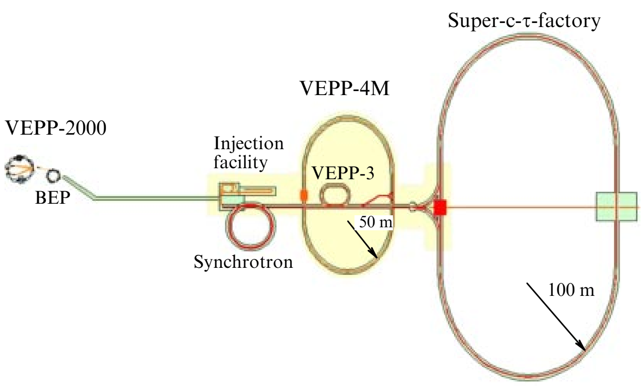

Figure 14. Super-c-τ-factory and other BINP facilities for colliding beam experiments.

Table 6. Main parameters of the c-τ-factory.

Energy, GeV	1.0	1.5	2.0	2.5
Circumference Π, m	766.6			
Orbit compaction factor α	9×10^{-4}			
Accelerating voltage V_{RF}, kV	310	900	990	1000
Energy loss per turn U_0, keV	170	256	343	434
Energy spread $\sigma_E \times 10^4$	1.009	9.953	8.435	7.378
Bunch length σ_s, cm	1.6	1.06	1	1
Damping time $\tau_x/\tau_z/\tau_s$, ms	30/30/15			
Coupling coefficient k, %	0.5			
Horizontal emittance ε_x, nm rad	8			
Vertical emittance ε_z, nm rad	40			
Number of particles in the bunch N_0	7×10^{10}			
Number of bunches N_{b}	390			
Full number of particles N	2.73×10^{13}			
Full current I, A	1.7			
Beta functions at the collision point, β_x/β_z, cm	4/0.08			
Collision angle 2θ, mrad	60			
Beam–beam parameter ξ_z	0.15	0.15	0.12	0.095
Luminosity L, 10^{35} cm^{-2} s^{-1}	0.63	0.95	1.00	1.00

The super-c-τ-factory collider [92] includes two independent storage rings, each approximately 800 m long, with a detector placed at the collision point (at the second collision point, the beams are displaced vertically). The beams cross at an angle of 60 mrad. The vertical betatron function at the collision point is 0.8 mm. The main parameters of the collider are given in Table 6, and the super-c-τ-factory collision gap with the detector is shown in Fig. 15.

Changes in the beam energy will lead to changes in its parameters, which influence the luminosity (emittance, damping time, bunch length, etc.). To optimize the luminosity, it is planned to install several superconducting magnetic snakes on both rings and maintain the horizontal emittance and the damping factors constant throughout the whole energy range of the collider.

One of the key advantages of the c-τ-factory is the possibility of longitudinally polarizing the electron beam at the collision point. This will be realized by using a polarized electron source that can produce electrons with any spin direction, such that with all the subsequent turns taken into account, the injected beam has the correct spin direction. Longitudinal polarization at the collision point will be achieved by using the scheme with five 'Siberian snakes' [93], which would provide a high polarization rate ($\geqslant 80\%$) in the entire energy range.

A serious problem for any collider with a nonzero crossing angle is the complicated magneto-vacuum final-focus system. For the CW collision scheme, this problem becomes even more complicated: due to the extremely small vertical betatron function at the collision point (less than 1 mm), the final lenses should have an extremely short focus and large

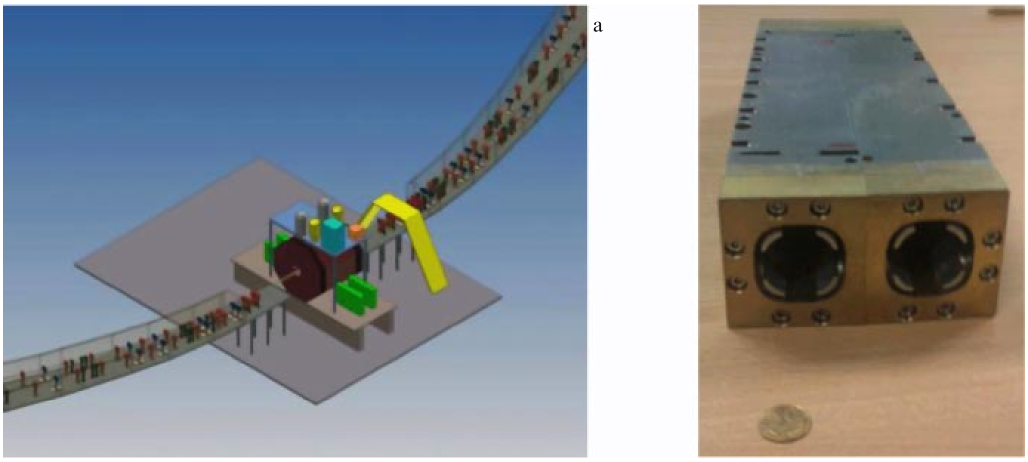

Figure 15. (a) Schematic of the c-τ-factory collision gap with the detector. (b) Yoke of the final-focus two-aperture superconducting lens.

gradient and should be located close to the collision point inside the detector [94]. At the same time, the receiving angle of the detector should have the maximum width, and because numerous other equipment located are located quite close to the collision point (solenoids for detector field compensation, luminosity monitors, monitors and correctors of the beam position, etc.), the final-focus lens construction has to be very compact.

For the c-τ-factory project, the BINP has developed a unique two-aperture superconducting lens [95], which can be installed at a distance of 0.6 mm from the collision point, creating a field gradient of 100 T m^{-1} and having an aperture of 26 mm. The lens yoke (Fig. 15b) is made of magnetically soft iron, which provides a high quality field on the beam axis, prevents the interaction of the adjacent lenses, and 'captures' the field scattered outside the lens. The lens prototype had successfully passed testing at the cryogenic temperature.

The performance of the existing injection complex is not enough to provide the high luminosity of the factory. The planned c-τ-factory injection complex (not shown in Fig. 14) consists of several high-intensity electron sources (including polarized ones), a storage cooler with a short damping time, and several linear accelerators for electron and positron beams. The injection is planned only at experimental energies without top-up injection.

Electron–positron annihilation in the c-τ-factory energy range leads to the creation of c-quark and c-antiquark bound states (charmonia), charmed mesons consisting of a c quark and one of light (u, d, or s) antiquarks, as well as charmed baryons that include two light quarks and a c quark. For the center-of-mass energies more than 3.6 GeV, the τ-lepton pairs start to appear. The main goal of the experiments at the super-c-τ-factory is to study processes involving c quarks and τ leptons with statistics several orders of magnitude higher than both those already accumulated in this energy range and those currently being integrated at the Chinese c-τ-factory BEPC II (we note that the Novosibirsk planned luminosity is 100 times larger than that of the Chinese collider). After six months, the super-c-τ-factory will accumulate an integral luminosity of ~ 1 ab^{-1} and will produce approximately 3×10^9 τ leptons, 7×10^9 D mesons, and an incredibly large number of J/ψ mesons, 3×10^{12}. Such statistics will allow systematically studying almost all the states formed by first-generation quarks, including the exotic ones. A large number of D mesons and τ leptons will allow paving the way to investigations of fundamentally new phenomena like *CP* violation in the charmed hadron and τ-lepton decays and the lepton number nonconservation.

To realize all the potential of the proposed super-c-τ-factory project, a universal magnetic detector is needed. This detector should demonstrate a number of unique characteristics and have the following parameters:

• a large pulsed resolution for charged particles and a good energy resolution for photons;

• record parameters of the particle identification system compared with the corresponding parameters of already existing detectors or ones being developed;

• digitalizing electric equipment and data acquisition systems capable of recording events with a frequency of 300–400 kHz and average event duration of 30 kB;

• digitalizing electric equipment to be located inside the detector and optical links with a speed of 10 gigabytes per second for data transmission;

• detector construction that allows quick access to the inner systems for their repair or replacement: the time needed for the disassemble–repair–assemble procedure should not be longer than 12–24 hours;

• activation (shut down) of the detector magnetic field should not take more than 2–3 hours.

A detector schematic is shown in Fig. 16. It has a classical layout for colliding beam experiments.

We note that almost all the methods and approaches needed for the super-c-τ-factory detector realization were already tested in other detectors that are already built or are currently being developed for experiments in high-energy physics around the world.

The major difficulties are expected in the development and construction of the unique identification system with record parameters. This system will be based on Cherenkov ring detector with a multilayer focusing aerogel radiator and silicon photomultiplier tubes (SMPTs) for photon registration. This method has not yet been used at large detectors, and therefore large-scale methodological investigations of system prototypes need to be conducted. Moreover, currently, SPMTs are very expensive, while their fabrication technology is at a stage of fast development [96]. For example, over the last five years, the SMPT's own noise at room temperature (25 °C) was reduced by one

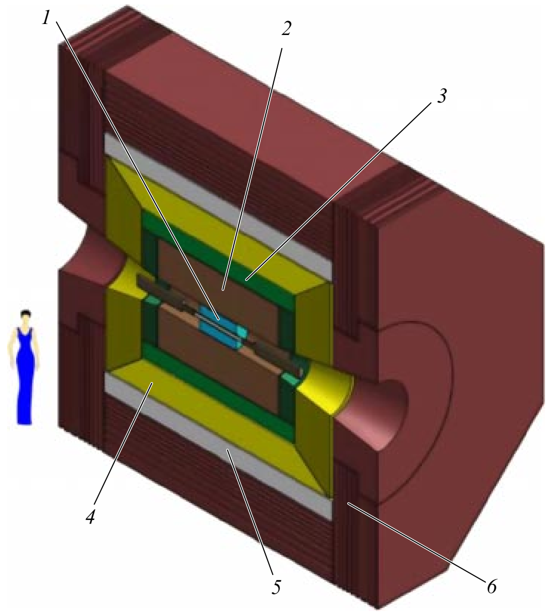

Figure 16. Universal magnetic detector: *1* — vertex chamber, *2* — drift chamber, *3* — identification system based on aerogel Cherenkov counters (Focusing Aerogel Ring Imaging Cherenkov, FARICH), *4* — Calorimeter based on CsI crystals, *5* — superconducting solenoid, *6* — magnet yoke and muon system.

order of magnitude, reaching the photon registration efficiency of more than 40% in a broad optical range (300–700 nm) [97, 98].

Here, we note that the BINP has extensive experience in the use of aerogels for identification purposes. The Boreskov Institute of Catalysis, SB RAS, in cooperation with the BINP, produces aerogel with the world's best quality. Aerogel made in Novosibirsk is used in the LHC Beauty Experiment (LHCb), in the Alpha Magnetic Spectrometer (AMS) recently installed at the International Space Station, and in many other experiments both inside the institute (Kedr and SND detectors) and across the border [99]. The aerogel was used at the BINP to build a prototype of the Cherenkov ring detector for the identification system. This prototype has shown the excellent quality of μ/π separation for the test beam of charged particles with 1 GeV/c momentum. The achieved performance is higher than in any other particle identification method developed for colliding beam experiments [100].

Construction of such a unique facility as the super-c-τ-factory is a complicated many-year task, and the BINP started preparing for the realization of this project already in Soviet times. Starting in 1992, the project received government funding: up to 2002, this project was devoted to the construction of linear colliding electron–positron beams (VLEPP-100), and starting from 2007 it is a project of the VEPP-5 facility. In 2015, the funding of this project came to an end, and the BINP significantly improved the engineering and scientific infrastructure. A number of expensive real estate projects (major construction sites) and infrastructure projects (electro-physical setups: the injection facility with electron and positron beam transport channels, VEPP-2000 collider with CMD-3 and SND detectors, SR stations at the VEPP-4 storage ring) were developed and commissioned, and registered as Russian Federation property. Currently, the overall price of operating objects that were built within the federal targeted investment program, is approximately 700 million rubles (at current exchange rates).

The new BINP injection complex with high positron production rates was launched in 2015. The integration of the complex in the BINP accelerating infrastructure led to improvements in the parameters and to an increase in the effectiveness of the experiments at the operating colliders — VEPP-4 and VEPP-2000 — including experiments with SR. The parameters and the reliability of the injection facility are constantly being improved.

5. Conclusions

The super-c-τ-factory project is a major challenge for the BINP. Over the 55 years of the colliding beam method development, the BINP has gained a large scientific and technological potential, which allows solving many problems of accelerator and elementary particle physics. The BINP stuff, including the authors of this review, have participated in many projects in various scientific centers around the world. Based on this experience, we believe that the number of tasks that we will need to solve during the construction of the super-c-τ-factory exceeds the scope of one institute, and therefore the project can be realized only in a collaboration with Russian and foreign laboratories.

In the summer 2011, a government committee selected six projects of the *Megascience* class for realization on the Russian Federation territory: the Research Nuclear Reactor PIK, the Nuclotron-based Ion Collider Facility (NICA), the IGNITOR, the fourth-generation specialized SR source (ISSI-4), the Exawatt Center for Extreme Light Studies (XCELS), and the super-c-τ-factory. The super-c-τ-factory project of the BINP has been approved by the European Committee for Future Accelerators and received a high score from many important experts in the field of elementary particle physics.

On December 1, 2016, the Russian Federation president approved the Russian Federation Scientific and Technological Development Strategy. An important point of this strategy is support for the construction and development of unique scientific setups of the megascience class, as well as support for large-scale research infrastructure on Russian territory. According to the plan for this strategy realization, the preparations for the decision about the super-c-τ-factory project realization should be completed by the end of 2019. Formation of the international collaboration for the super-c-τ-factory project is one of the most important and complicated tasks, which should be completed in order to facilitate a positive decision regarding the project realization.

The possibility of raising funding for the realization of certain stages of the super-c-τ-factory project, as well as the acceptance of the project by the Russian Federation government, mostly depends on factors such as our own conviction in the importance of this project, confidence in its feasibility, and the ability to correctly prioritize, concentrate, and consolidate the work inside the BINP and to organize fruitful collaboration with partners and potential participants in the project.

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