ISSN 1063-7761, Journal of Experimental and Theoretical Physics, 2011, Vol. 113, No. 2, pp. 213–220. © Pleiades Publishing, Inc., 2011.
Original Russian Text © D.E. Berkaev, D.B. Shwartz, P.Yu. Shatunov, Yu.A. Rogovskii, A.L. Romanov, I.A. Koop, Yu.M. Shatunov, I.M. Zemlyanskii, A.P. Lysenko, E.A. Perevedentsev, A.S. Stankevich, A.I. Senchenko, B.I. Khazin, A.V. Anisenkov, S.E. Gayazov, A.N. Kozyrev, A.E. Ryzhenenkov, D.N. Shemyakin, L.B. Epshtein, S.I. Serednyakov, P.M. Astigeevich, D.P. Kovrizhin, K.A. Martin, A.E. Obrazovskii, I.K. Surin, L.V. Kardapoltsev, O.V. Belikov, K.M. Gorchakov, A.N. Kirpotin, A.N. Skrinskii, 2011, published in Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2011, Vol. 140, No. 2, pp. 247–255.

The VEPP-2000 Electron–Positron Collider: First Experiments

D. E. Berkaev[a,b,*], D. B. Shwartz[a,b], P. Yu. Shatunov[a], Yu. A. Rogovskii[a,b], A. L. Romanov[a], I. A. Koop[a,b], Yu. M. Shatunov[a,b], I. M. Zemlyanskii[a], A. P. Lysenko[a], E. A. Perevedentsev[a,b], A. S. Stankevich[a], A. I. Senchenko[a], B. I. Khazin[a], A. V. Anisenkov[a], S. E. Gayazov[a], A. N. Kozyrev[a], A. E. Ryzhenenkov[a], D. N. Shemyakin[a], L. B. Epshtein[a], S. I. Serednyakov[a], P. M. Astigeevich[a], D. P. Kovrizhin[a], K. A. Martin[a], A. E. Obrazovskii[a], I. K. Surin[a], L. V. Kardapoltsev[a], O. V. Belikov[a,b], K. M. Gorchakov[a], A. N. Kirpotin[a], and A. N. Skrinskii[a]

[a] *Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Science, pr. Akademika Lavrent'eva 11, Novosibirsk, 630090 Russia*

[b] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia*

* *e-mail: D.E.Berkaev@inp.nsk.su*

Received November 12, 2010

Abstract—In 2007, at the Institute of Nuclear Physics (Novosibirsk), the construction of the VEPP-2000 electron–positron collider was completed. The first electron beam was injected into the accelerator structure with turned-off solenoids of the final focus. This mode was used to tune all subsystems of the facility and to train the vacuum chamber using synchrotron radiation at electron currents of up to 150 mA. The VEPP-2000 structure with small beta functions and partially turned-on solenoids was used for the first testing of the "round beams" scheme at an energy of 508 MeV. Beam–beam effects were studied in strong–weak and strong–strong modes. Measurements of the beam sizes in both cases showed a dependence corresponding to model predictions for round colliding beams. Using a modernized SND (spherical neutral detector), the first energy calibration of the VEPP-2000 collider was performed by measuring the excitation curve of the phi-meson resonance; the phi-meson mass is known with high accuracy from previous experiments at VEEP-2M. In October 2009, a KMD-3 (cryogenic magnetic detector) was installed at the VEPP-2000 facility, and the physics program with both the SND and LMD-3 particle detectors was started in the energy range of 1–1.9 GeV. This first experimental season was completed in summer 2010 with precision energy calibration by resonant depolarization.

DOI: 10.1134/S1063776111060136

1. INTRODUCTION

Since 1974, the VEPP-2M electron–positron collider at Novosibirsk has successfully operated in the energy range from the hadron production threshold to 1.4 GeV in the center-of-mass system (CMS). A luminosity integral of ~74 pb^{-1} was collected by the SND (spherical neutral detector) and CMD-2 (cryogenic magnetic detector). This allowed detailed study of most hadron e^+e^- annihilation channels. At the same time, the total number of events obtained in other experiments at energies of up to 2 GeV, where excited states of ordinary and strange quarks occur, did not exceed 10% of the data obtained using the VEPP-2M. Therefore, in spring 2000, at the Institute of Nuclear Physics, Siberian Branch, Russian Academy of Science, it was decided to modernize the VEPP-2M accelerator facility to increase the luminosity to 10^{32} cm^{-2} s^{-1} and to increase the maximum energy to 2×1 GeV, which makes it possible to significantly increase the potential of experiments at the facility. The new project was called VEPP-2000 [1].

The physics program of the VEPP-2000 collider is as follows.

(i) Precision measurement of the value of $R = \sigma(e^+e^- \longrightarrow \text{hadron})/\sigma(e^+e^- \longrightarrow \mu^+\mu^-)$.

(ii) Study of hadron channels of $e^+e^- \longrightarrow 2h, 3h, 4h, \ldots, h = \pi, K, \eta$ annihilation.

(iii) Study of excited states of vector mesons $\rho', \rho'', \omega', \varphi', \ldots$.

(iv) Testing of the hypothesis of conservation of the vector current (CVC test), i.e., comparison of the cross section of $e^+e^- \longrightarrow$ hadron ($T = 1$) annihilation with the τ decay spectrum.

(v) Study of electromagnetic form factors of nucleon–antinucleon pair production and the search for $n\bar{n}$ resonances.

(vi) Hadron production during "radiative return."

(vii) Two-photon physics.

(viii) Testing of quantum electrodynamics theory for higher orders $2 \longrightarrow 4, 5$.

To achieve the design parameters (energy and luminosity), the concept of round beams was pro-

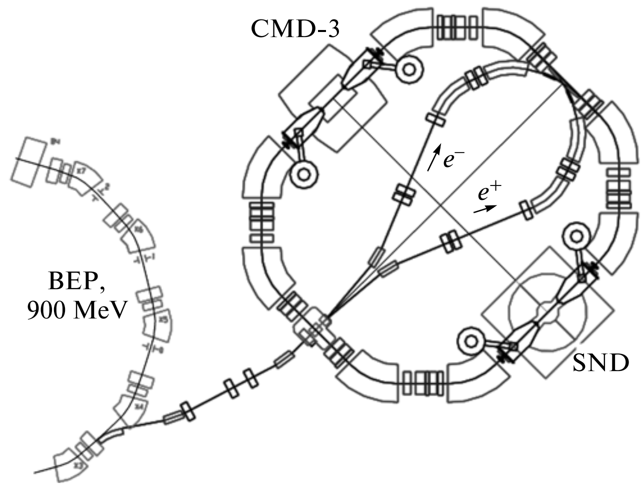

Fig. 1. Schematic representation of the VEPP-2000.

posed [2]. The main feature of this concept is the axial symmetry of the impact of the round colliding beam. Along with the x–z symmetry of the matrix of betatron motion between collision points, this leads to conservation of the angular momentum of particles ($M = xz' - zx' = \text{const}$). As a result, this leads to an increase in particle motion stability even with allowance for the nonlinear fields of the colliding beam.

Numerical simulation of the collision effects in the strong–weak mode (the intensity of the first beam is much higher than that of the second beam; hence, the effect of the second beam can be neglected) and strong–strong (the intensities of both beams are approximately equal and their interference cannot be ignored) approximations confirmed these assumptions [2, 3].

Main parameters of the VEPP-2000 collider at an energy of 1000 MeV

Parameter	Value
Perimeter P	24.39 m
Betatron functions at collision points $\beta^*_{x,z}$	10 cm
Betatron frequencies $\nu_{x,z}$	4.1, 2.1
Emissions $\varepsilon_{x,z}$	1.4×10^{-7} m rad
Orbit compaction factor α	0.036
Synchrotron frequency ν_s	0.0035
Energy spread $\sigma_{\Delta E/E}$	6.4×10^{-4}
HF frequency	172 MHz
HF harmonic number q	14
HF voltage U	100 kV
Number of beam particles N	10^{11}
Space charge parameter $\xi_{x,z}$	0.075
Luminosity L	10^{32} cm^{-2} s^{-1}

2. VEPP-2000 FACILITY

The VEPP-2000 accelerator facility consists of the VEPP-2000 collider and a beam storage and injection system, including a BEP (electron–positron buster) storage cooler and injection channels for an energy of up to 900 MeV.

2.1. Storage and Injection System

The system for beam injection into the VEPP-2000 collider makes it possible to store electron and positron beams of up to 200 mA (~10^{11} particles) with an energy of up to 900 MeV in the BEP ring. Experiments at an energy of 900–1000 MeV require increasing the beam energy directly in the VEPP-2000 collider.

The VEPP-2000 beam is injected into the straight section far from the BEP, with zero dispersion in the horizontal plane. Injection channels [4] allow transport of 10^8–10^{11} particles at energies of 200–900 MeV.

The inflector system consists of two inflector plates and four switched generators (two for electrons and two for positrons) and implies beam storage using the preimpact of the beam stored in the VEPP-2000. The transport efficiency in experiments has reached 95%.

2.2. VEPP-2000 Collider

The magnetic structure of the VEPP-2000 collider [5] consists of two superperiods with mirror symmetry (see Fig. 1). It includes two experimental sections for installation of detectors (3 m), two straight sections (2.5 m) for injection and an HF resonator, and four short technical sections with four triplets of quadrupole lenses in them. Each triplet with two bending magnets with a field of 24 kG represents an achromatic bend by 90°.

Final beam focusing in the VEPP-2000 ring is performed using a pair of superconducting solenoids with a field of 130 kG, which are symmetrized around either collision point and ensure equal and small transverse beam sizes.

The main parameters of the collider are listed in the table.

As solenoids are turned on, several combinations of their polarities are possible, e.g., (++ – –) and (++ ++), which provide rotation of the betatron oscillation plane by 90° as it passes through the collision section. In this case, the radiation emissions of two normal betatron modes, being excited in two identical ring arches, will be equal ($\varepsilon_x = \varepsilon_z$), which, along with the equal betatron frequencies of the modes, will satisfy all requirements of the round beam concept. However, the simplest version of the optics (+– +–) does not contradict the concept requirements either if the operating point is chosen at the betatron oscillation coupling resonance.

2.3. Superconducting Solenoids

Each solenoid consists of two parts, i.e., the main one, which is 50 cm long with a field of 130 kG, and the so-called antisolenoid, which is 10 cm long with a field of 80 kG. In turn, the main part consists of two identical halves, each including an inner section with Nb_3Sn wire winding and an outer section with NbTi wire winding. Each solenoid is supplied with three independent current sources for the inner and outer sections and with an antisolenoid section. All three superconducting coils are enclosed in a magnetic yoke in a common cryostat with liquid helium.

3. COLLIDER STRUCTURE CAPABILITIES

The VEPP-2000 magnetic system, despite the extreme compactness of its elements, is characterized by sufficient versatility to implement several electrooptical focusing schemes. All of them appeared very efficient during tuning and further activity within the physics program.

3.1. Mode with Turned-off Solenoids

At the first stage of activation, the VEPP-2000 optical system was significantly simplified and reduced to an ordinary structure without solenoids. Such a so-called “soft” optical system (betatron oscillation frequencies normalized to the revolution frequency are $\nu_x = 2.4$ and $\nu_z = 1.4$) differs significantly from the optical scheme with round beams. Nevertheless, the behavior of betatron oscillation envelopes (β_x and β_z) in the injection section is very close to the design parameters and exhibits appropriate betatron phase increments between the injection point and inflector. The optical system can be used in the mode without solenoids only below 600 MeV due to the limitations of the gradients of weak focusing lenses in the experimental sections.

The soft optical system was used for the first beam trapping into the ring, tuning of the particle bypass factor, calibration of the beam observation system, and training (degassing) of the vacuum chamber by electron synchrotron radiation.

To begin operation with round beams, first of all, superconducting solenoids suspended within cryostats and cooled to liquid-helium temperature should be mechanically aligned. This was also done in the mode of “soft optical system” by measuring distortions of the equilibrium beam orbit as the solenoid was turned on as a weak perturbation.

3.2. Mode with Short Solenoids

The structural separation of focusing solenoids into three sections allows optimum selection of the longitudinal field distribution depending on the beam energy. For example, at an energy of 500 MeV (phi-meson resonance), only one of two halves of the main solenoid part which is closer to the collision point, but induces a stronger field, can be used. In this case, beta functions at both collision points are $\beta_x = \beta_z = \beta^* =$ 4.5 cm. Such an optical system in the simplest mode of round beams (+– +–) was used in the first experiments with round beams in 2008. Size measurements of the colliding round beams as a function of the colliding beam current in the strong–weak and strong–strong modes showed results very close to numerical simulation data [6]. Figure 2 shows the experimentally measured dependences of the transverse size of the weak positron beam on the colliding electron beam current at various azimuths of the VEPP-2000 ring. The lower curve shows the horizontal size at the point where the horizontal beta function has a minimum in the bending magnet; i.e., it behaves similarly to the beta function at the collision point. This curve demonstrates that the beam size is almost independent of the countercurrent, which confirms the theoretical calculations and simulation data.

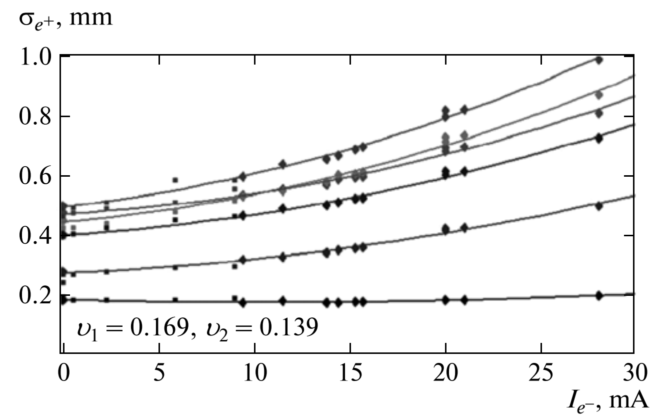

Fig. 2. Experimental dependences of beam sizes on the counter current.

The luminosity given by the formula

$$L = \frac{4\pi\gamma^2 f_0}{r_e}\frac{\varepsilon}{\beta^*}\xi^2, \quad (1)$$

where f_0 is the collision frequency; $r_e = 2.81794 \times 10^{-13}$ is the classical electron radius; ξ is the space charge parameter expressing the strength of the electromagnetic interaction of colliding beames, which reached 1×10^{31} cm^{-2} s^{-1} (see Fig. 3); and the space charge parameter defined by the expression

$$\xi = \frac{N r_e \beta^*}{4\pi\gamma\sigma_0^2}, \quad (2)$$

reached ~0.1 in this case.

3.3. Mode with Complete Solenoids

High-energy operation requires the use of the complete solenoid length. Such an optical system corresponds to a twice larger beta function at the collision

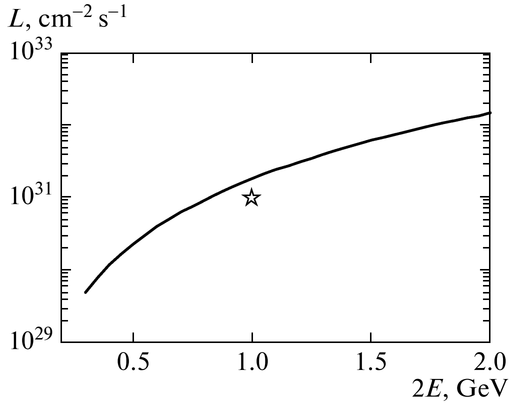

Fig. 3. Energy dependence of the luminosity and the achieved value.

point, i.e., 8.5 cm, while beam emissions are almost the same. This means that the luminosity for the same beam currents (see formula (1)) should be approximately twice as low.

At the beginning of 2010, the CMD-3 detector was ready for experiments. After its installation at the VEPP-2000 ring together with final focus solenoids, it was necessary to turn on the antisolenoids to compensate for the longitudinal field of this detector (B = 10 kG, $L_B = 1$ m).

Since then, the VEPP-2000 has operated in the simple round beam mode, i.e., with solenoids turned on toward each other at each collision point (+– +–). This corresponds to ordinary modes of betatron motion, i.e., horizontal and vertical everywhere except for the experimental section, in which they are turned at a large angle ($\sim\pi/4$). The equal emissions necessary for the round beams concept are formed due to small but finite betatron oscillation coupling (frequency splitting is $\delta\nu = 0.001$–0.002) and the resonance $\nu_x - \nu_z = 2$ to which the VEPP-2000 operating point is tuned. Later, despite the expected problems associated with the small dynamic aperture, it is planned to use other solenoid polarity schemes, i.e., (++ ––) and (++ ++).

4. RESPONSE MATRIX ANALYSIS

The technique of orbit response matrix analysis is widely used in experiments on the VEPP-2000 collider. It has been used in the soft optical system to measure positions and align superconducting solenoids. However, the measurement accuracy of coordinates and angles was no better than 0.1 mm and 1 mrad, respectively. More accurate experiments for measuring and correcting the solenoid positions by response matrix analysis have been performed in the round beams mode [7].

Another typical application of response matrix analysis is measurement and correction of closed orbit distortions in the BEP and VEPP rings. When the gradients of all quadrupole lenses are sequentially varied, closed orbit distortions in them can be measured by comparison with model values.

The use of the singular value decomposition method for response matrix inversion also allows minimization of currents in the correction coils for an individual closed orbit. This is important for optimizing the dynamic aperture, since most dipole correctors are combined with quadrupole lenses and hence have strong nonlinear field components.

Finally, orbit response analysis for dipole correction variations has become a routine, but very powerful tool for correcting the VEPP-2000 structure itself [7, 8]. Figure 4 shows the collider optical system for the structure with small beta functions at the collision point before and after the fourth iteration of this procedure.

5. EXPERIMENTS WITH SND AND CMD-3 DETECTORS

The first experiment on collecting the luminosity integral with SND and CMD-3 detectors started at the end of 2009. The first rough energy scanning in the range from 500 to 950 MeV (energy of one beam) was performed. The total luminosity integral collected by both detectors was $\int L \sim 10\ \mathrm{pb}^{-1}$. Figure 5 shows the luminosity integral collected by the SND detector at each energy point. The integral collected by the CMD-3 detector is smaller by a factor of ~1.6.

Despite the fact that the peak luminosity for a given space charge parameter (3) should rapidly increase with energy ($L \propto \varepsilon\gamma^2$), currently there are several limitations that prevent achieving maximum currents at high energies. The main one is the insufficient rate of positron production by the old injection system (part of the VEPP-2M facility). This problem will be solved by putting the VEPP-5 facility at the Institute of Nuclear Physics into operation. As a result, the maximum luminosity will decrease with energy from 1×10^{31} cm^{-2} s^{-1} at 500 MeV to 1.5×10^{30} cm^{-2} s^{-1} at 950 MeV. The planned luminosity can be achieved only after BEP modernization to an energy of 1 GeV. Such modernization at the Institute of Nuclear Physics has already started.

One of the problems of the VEPP-2000 physics program is the study of nucleon–antinucleon pair production. It is expected that the VEPP-2000 experiments will result in improved measurement accuracy of the neutron form factor at the threshold; due to good angular resolution, the electric and magnetic form factors of the neutron will be individually measured; bound $n\bar{n}$ states near the threshold will be searched for.

During the experiment at a luminosity of L = 10^{32} cm^{-2} s^{-1}, collection of 10^5 events of this process is

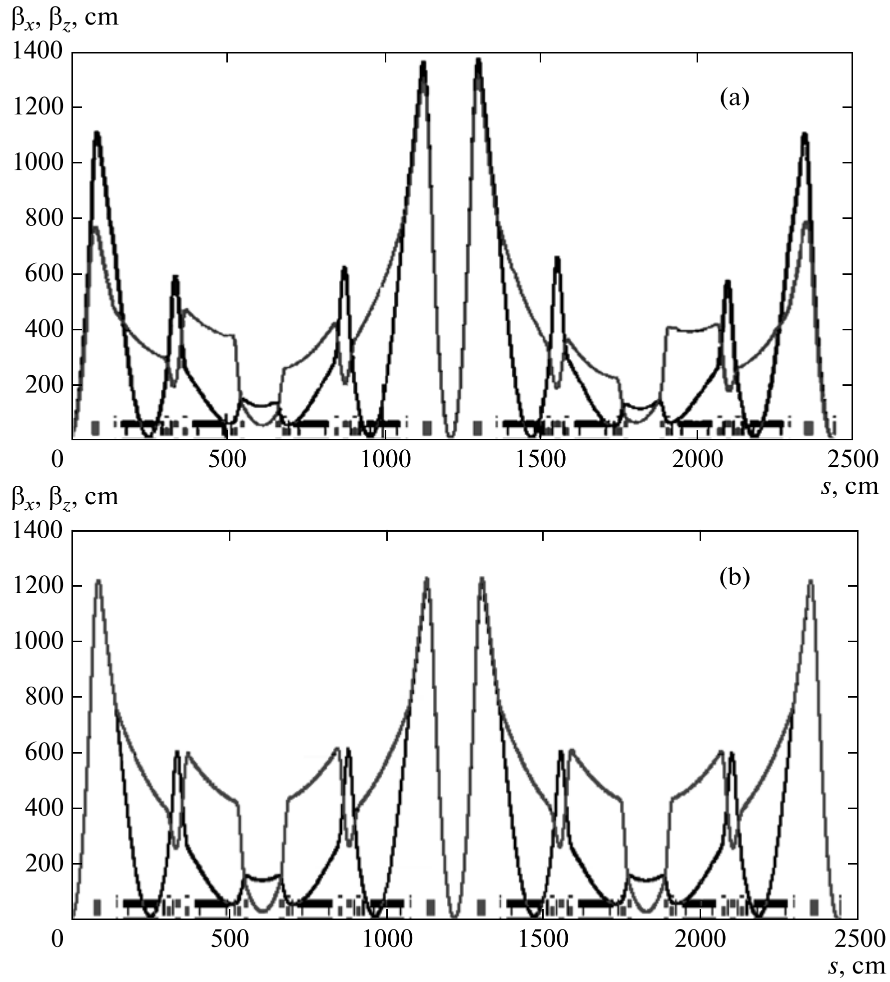

Fig. 4. Optical functions β_x (black curves) and β_z (gray curves), measured by the response matrix analysis method (a) before and (b) after the correction procedure as functions of the coordinate *s* along the ring.

expected at an expected cross section of 0.7 nbarn at the threshold, which approximately 100-fold exceeds the number of events currently available for this process.

Since produced neutron–antineutron pairs are nonrelativistic, the best method for suppressing the background is the use of the time-of-flight technique. The antineutron time of flight to the first calorimeter layer at its kinetic energy of 5 MeV is ~8 ns. At such a kinetic energy, almost all antineutrons annihilate in the first layer of the NaI crystal, since their effective annihilation length at this energy is 5 cm, i.e., about twice as small as the thickness of crystals of the first layer.

Part of the statistical data obtained in the VEPP-2000 experiments was recorded at energies above the threshold of proton–antiproton and neutron–antineutron pair production. Currently, the events collected by both the SND and CMD-3 have been processed. The first task of processing is measurement of the physical background formed by all events with the production of many particles.

Figure 6 shows one of the numerous “frames” recorded by the CMD-3. In the detector track chamber, we can see the trajectories of flying-apart particles produced in the detector magnetic field.

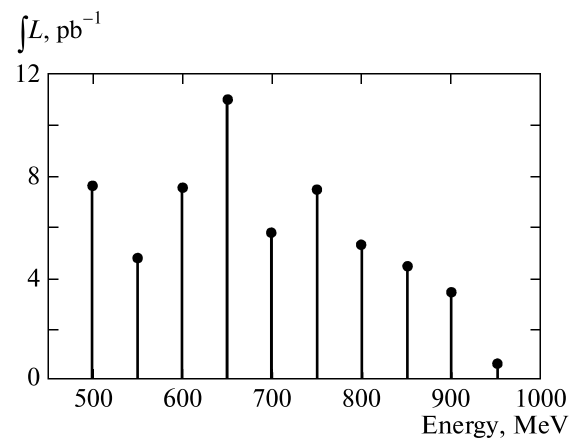

Fig. 5. Luminosity integral collected by the SND detector.

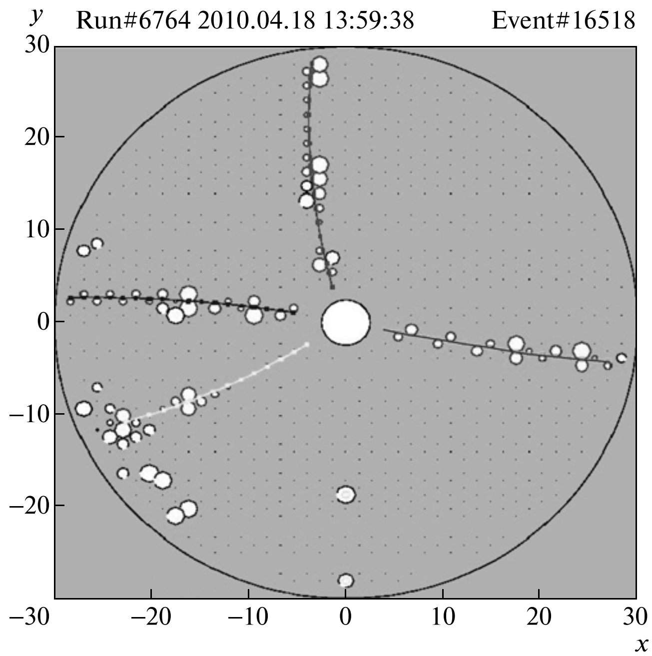

Fig. 6. Particle tracks in the central region of the CMD-3 detector.

The preliminary processing results of the collected statistics are measurements of cross sections with multiple pion production. One of such measurements, i.e., the cross section of production of four π-mesons is shown in Fig. 7.

The study of the physical background already made it possible to begin the search for events satisfying selection criteria for proton–antiproton and neutron–antineutron pairs among useful frames. One of such events is shown in Fig. 8. The total number of frames with nucleon production in the collected statistics is expected to be several hundred. Certainly, this number is insufficient for accurate measurements of all parameters of these processes. However, this is sufficient to study detector parameters required to measure proton–antiproton and neutron–antineutron pair production processes.

6. ENERGY CALIBRATION

The requirements for the measurement accuracy of the beam energy in the experiments are such that $\Delta E/E \leq 10^{-4}$. All bending magnets of the VEPP-2000 are equipped with two magnetometers based on the nuclear magnetic resonance (NMR sensors). The sensors themselves are characterized by high accuracy, and their measurements show high stability of the magnetic field ($\sim 10^{-5}$). At the same time, they are placed in the magnetic gap, but outside the vacuum chamber and outside the beam orbit. Rough calibration of NMR sensors was based on magnetic measurements of dipoles of the VEPP-2000. More accurate energy calibration of the VEPP-2000 is performed using two methods.

6.1. Phi-Meson

The phi-meson mass is known with high accuracy, $M_\varphi = 1019.455 \pm 0.020$ MeV [9]. Thus, the first absolute energy calibration of the VEPP-2000 was performed in the experiment for measuring the peak position of the phi-meson resonance using the SND

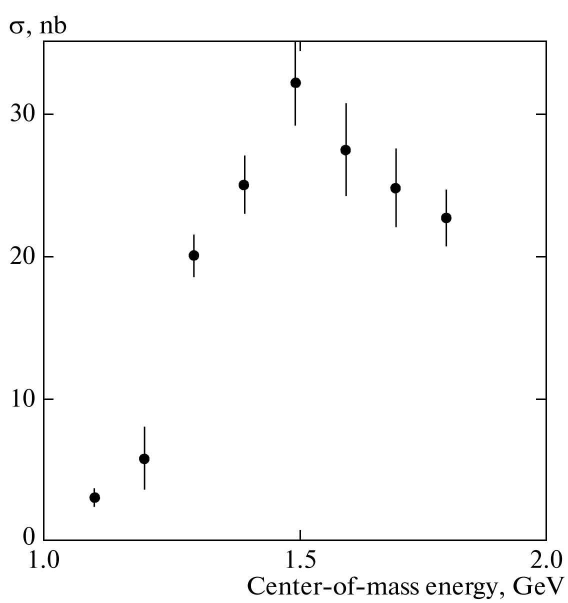

Fig. 7. Cross section of production of four π-mesons at various energies. Preliminary results using the SND detector.

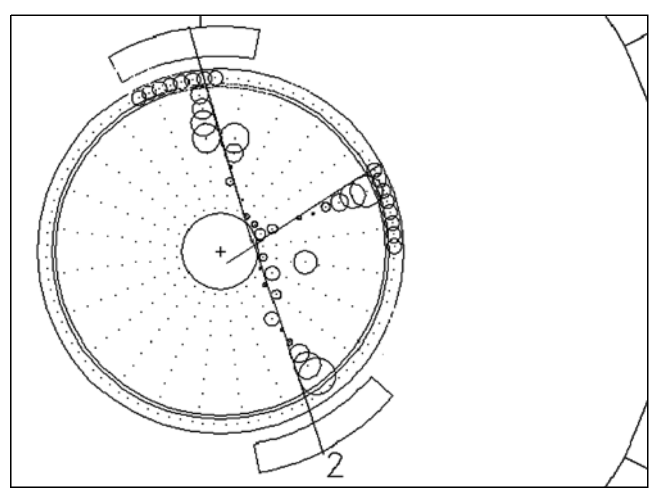

Fig. 8. One of the events of proton and antiproton production.

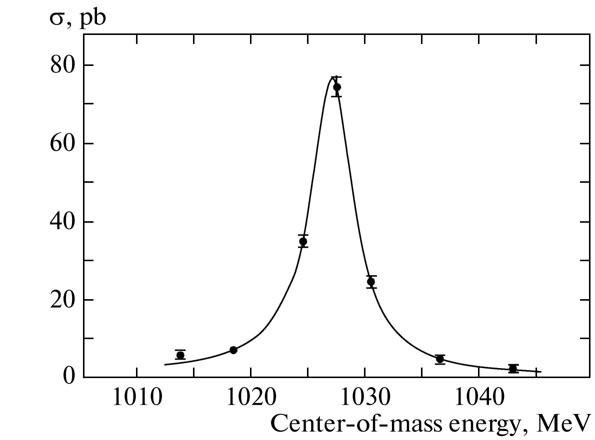

Fig. 9. Phi-meson resonance before energy calibration (data of an SND group). $e^+e^- \longrightarrow 3\pi$.

detector. This experiment showed that the error in the energy calibration using NMR sensors is 3.5 MeV (see Fig. 9).

Repeated measurements of the peak position of the phi-meson resonance showed a disagreement less than 0.2 MeV.

6.2. Resonant Depolarization

The so-called resonant depolarization method is used for precision energy measurements. Two counters of scattered particles are placed inside and outside the ring in the beam orbit plane in one of technical sections. At high energies, the main contribution to the rate of beam particle loss is made by the so-called intrabeam scattering (Touschek effect). A comparison of beam lifetimes for the cases of one and two beams, but with the same total number of particles, shows that intrabeam scattering yields 80% of the particle loss at an energy of 800 MeV. Furthermore, to improve accuracy, only "pure" scattering events were selected by detecting event coincidences in the inner and outer sensors. Since the Touschek effect depends on beam polarization, a jump in the counting rate should occur at the instant of polarization decay. A high-frequency strip-line depolarizer is intended for controlled polarization decay, which is placed in the VEPP-2000 injection section. The frequency at which depolarization occurs is uniquely related to the beam energy; therefore, the particle energy in the ring can be calculated with high accuracy by determining the instant of the jump in the counting rate of scattered particles during scanning by the depolarizer frequency.

According to the calculations [10], the jump in the counting rate depends on the ratio of emissions and is suppressed in the case of round beams in comparison with the case of planar beams. Thus, the energy calibration experiments were performed using a planar beam (opposite polarities of solenoids at each collision point; betatron frequencies are far from the coupling resonance; betatron coupling is suppressed by the system of skew-quadrupole corrections). For the experiments, the positron beam was chosen to avoid problems associated with beam parameter distortions due to focusing by ions accumulated at the equilibrium beam orbit during polarization. The time of radiative polarization at an energy of 750 MeV was ~45 min.

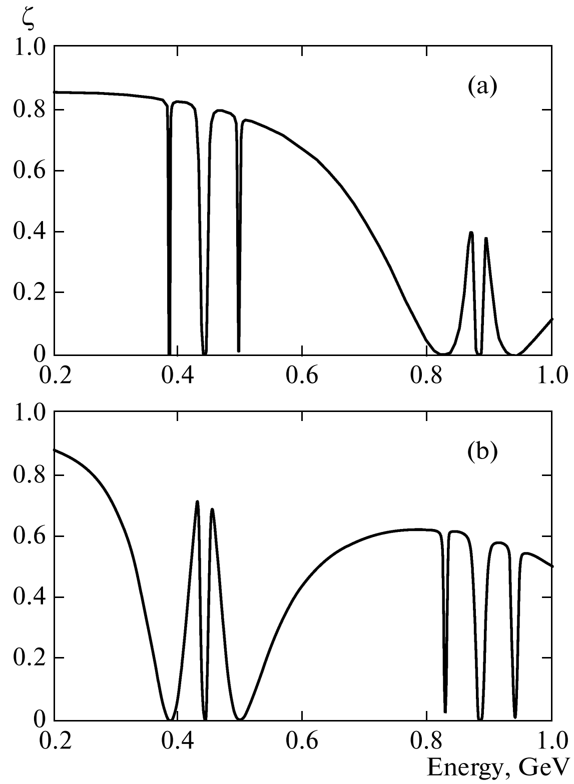

Fig. 10. Calculated dependences of the degree of polarization on the beam energy for solenoids tuned to (a) low and (b) high energies.

Numerical simulation using the ASPIRRIN software [11] showed significant differences in the degree of polarization for various solenoid polarities. Figure 10a shows the calculated degree of polarization for the scheme (+– +–).

This scheme implies the second harmonic of the longitudinal field, which leads to the strong integer spin resonance at an energy of 880 MeV, which causes polarization decay at this energy. Thus, this scheme is applicable only to polarization experiments at low energies. The narrow resonance at 440 MeV with two betatron satellites appears in the case of solenoid detuning ($\Delta B_s/B \sim 10^{-3}$, Fig. 10), which is inevitable in real experiments. Another scheme (+– –+) generates the first harmonic of the longitudinal field and makes it possible to achieve 60% polarization in the energy range of 700–800 MeV (see Fig. 10b). Exactly this scheme was used in experiments on calibration at an energy of 750 MeV.

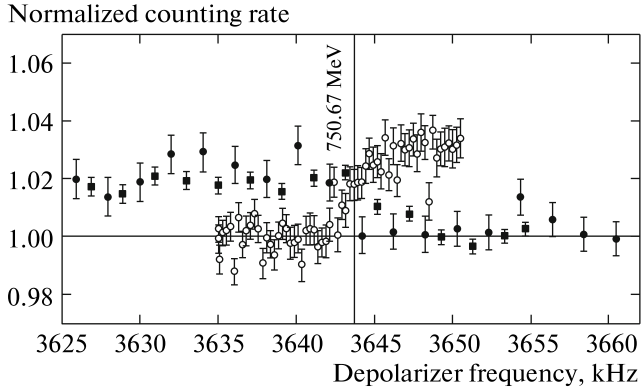

Fig. 11. Jump in counting rate.

The results combining three such experiments are shown in Fig. 11. We can see that the 2.5–3% jump in the counting rate occurs at an energy of 750.67 ± 0.03 MeV.

It is planned to continue the experiments on the VEPP-2000 collider energy calibration by the resonant depolarization method.

7. CONCLUSIONS

The VEPP-2000 collider modernized at the Institute of Nuclear Physics started the physics program and data collection using two modern detectors, i.e., the SND and CMD-3. All systems of the facility were tested in experiments at energies to 950 MeV.

Various versions of collider optical systems were experimentally tested: the technical soft optical system; a round beam with $\beta^* = 8.5$ cm and with introduced magnetic field of the CMD-3; small beta functions for higher luminosity; and the planar beam for using the resonant depolarization method.

The experimental results on the study of the effects of round colliding beams confirmed the predictions of the behavior of beam sizes in weak–strong and strong–strong operation modes. In the former, a space charge parameter of $\xi = 0.1$ was achieved. A peak luminosity of $L = 1 \times 10^{31}$ cm^{-2} s^{-1} was achieved at an energy of 500 MeV and currents of $I^+ \times I^- = 40 \times 40$ mA^2. To achieve the planned luminosity at 1 GeV, a new positron injector is required and the BEP ring should be modernized. Currently, these works are in progress at the Institute of Nuclear Physics.

Precision calibration of the VEPP-2000 energy measurement system was performed. NMR sensors were calibrated by the peak position of the phi-meson resonance and by the data of the first experiments on resonant depolarization.

The SND and CMD-3 began experimental data collection at the VEPP-2000 collider.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 09-02-01060-a.

REFERENCES

1. Yu. M. Shatunov, A. V. Evstigneev, D. I. Ganyushin, P. M. Ivanov, I. A. Koop, V. S. Kuzminykh, A. P. Lysenko, N. A. Mezentsev, N. V. Mityanina, I. N. Nesterenko, A. V. Otboev, E. A. Perevedentsev, V. M. Petrov, D. B. Schwartz, P. Yu. Shatunov, A. N. Skrinsky, A. A. Valishev, and V. N. Volkov, in *Proceedings of the Seventh European Particle Accelerator Conference (EPAC 2000), Vienna, Austria, June 26–30, 2000* (Vienna, 2000), p. 439.
2. V. V. Danilov and E. A. Perevedentsev, in *Proceedings of the European Particle Accelerator Conference EPAC 1996, Sitges, Barcelona, Spain, June 10–14, 1996* (Barcelona, 1996), Vol. 2, p. 1149.
3. A. A. Valishev, E. Perevedentsev, and K. Ohmi, in *Proceedings of the Particle Accelerator Conference (PAC 2003), Portland, Oregon, United States, May 12–16, 2003* (Portland, 2003), p. 3398.
4. D. E. Berkaev, V. V. Druzhinin, I. Koop, A. P. Lysenko, F. V. Podgorny, V. P. Prosvetov, P. Yu. Shatunov, Y. M. Shatunov, and D. B. Shwartz, in *Proceedings of the European Particle Accelerator Conference (EPAC 2006), Edinburgh, Scotland, June 26–30, 2006* (Edinburgh, 2006), p. 622.
5. P. Yu. Shatunov, D. E. Berkaev, A. A. Borisov, I. Koop, N. A. Mezentsev, E. Perevedentsev, Y. M. Shatunov, D. B. Shwartz, and A. Valishev, in *Proceedings of the European Particle Accelerator Conference (EPAC 2006), Edinburgh, Scotland, June 26–30, 2006* (Edinburgh, 2006), p. 628.
6. Y. M. Shatunov, D. E. Berkaev, I. Koop, A. P. Lysenko, E. Perevedentsev, A. L. Romanov, P. Yu. Shatunov, D. B. Shwartz, and A. N. Skrinsky, in *Proceedings of the 11th European Particle Accelerator Conference (EPAC 2008), Genoa, Italy, June 23–27, 2008* (Genoa, 2008), p. 956.
7. A. L. Romanov, D. E. Berkaev, I. Koop, A. N. Kyrpotin, E. Perevedentsev, Yu. A. Rogovsky, P. Yu. Shatunov, and D. B. Shwartz, in *Proceedings of the First International Particle Accelerator Conference (IPAC 2010), Kyoto, Japan, May 23–28, 2010* (Kyoto, 2010), p. 4542.
8. A. L. Romanov, D. E. Berkaev, A. N. Kirpotin, I. A. Koop, E. A. Perevedentsev, Yu. A. Rogovsky, P. Yu. Shatunov, and D. B. Shwartz, in *Proceedings of the XXI Russian Particle Accelerators Conference (RuPAC 2008), Zvenigorod, Moscow region, Russia, September 28–October 3, 2008* (Zvenigorod, 2008), p. 64.
9. Particle Data Group (PDG Collab.), http://pdg.lbl.gov/.
10. V. M. Strakhovenko, arXiv:0912.5429 [physics.acc-ph].
11. E. A. Perevedentsev, Yu. M. Shatunov, and V. Ptitsin, AIP Conf. Proc. **675**, 761 (2003).

Translated by A. Kazantsev