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PHYSICS AND TECHNIQUE OF ACCELERATORS

Recent Progress in the VEPP-2000 Collider

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Abstract—The VEPP-2000 is an electron–positron collider with round beams built and operating at the Budker Institute of Nuclear Physics (BINP). The collider luminosity was increased twofold last year. The integrated luminosity accumulated over the last year has exceeded 0.3 fb^{-1}, which almost doubled the total data collected since the collider operation began. The short description of the VEPP-2000 complex, current status, and the results are presented in this work.

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REVIEW OF THE VEPP-2000

The VEPP-2000 [1–3] is intended primarily for studying the physics of light mesons and precision measurements of the annihilation cross sections of electron–positron pairs into hadrons. The physical program assumes a set of integral luminosity of at least 1 fb^{-1} for each detector in the beam energy range of 0.2–1 GeV.

The VEPP-2000 complex (Fig. 1) was created on the site of its predecessor, the VEPP-2M, with the maximum preservation of the engineering infrastructure. As a result, the perimeter of the storage ring of the collider was only 24.4 m, which, at a high density of optical elements and equipment, does not allow beam separation and, accordingly, operation is only possible in the 1 by 1 bunch mode. To achieve the planned luminosity, the concept of round beams [4] is used, which implies the equality of transverse emittances and the fractional part of betatron frequencies, as well as axial symmetry and small transverse dimensions of the beams in the collision region. Thus, the transverse motion of particles becomes effectively one-dimensional, which increases the stability in the interaction of intense colliding beams.

The optical structure of the VEPP-2000 ring consists of four quadrants and four main gaps—two experimental ones and two technical ones. Each quadrant consists of two turning magnets separated by a small gap, where a triplet of quadrupole lenses is located to form an achromatic turn and radial and vertical sextupole lenses combined with skew quadrupole lenses to correct the chromatism and couple betatron frequencies. In the experimental gaps, the CMD-3 (Cryogenic Magnetic Detector) and SND (Spherical Neutral Detector) detectors are located, and superconducting solenoids are placed along the edges of both gaps for the final beam focusing, as well as rather weak quadrupole radial focusing lenses. Inlet magnets are located in one technical gap, an RF resonator is in the other, and doublets of quadrupole lenses and sextupole lenses combined with skew-quadrupole ones are placed along the cuts of both gaps.

All quadrupole lenses of the VEPP-2000 storage ring contain either radial or vertical dipole corrections, and the correction of the field of bending magnets is also provided. It is important to note that all elements of the optical structure and correctors are powered by personal power sources and, accordingly, can be controlled independently.

For beam diagnostics, four electrostatic pickups are provided, located one at a time in small gaps of squares, as well as 16 CCD cameras that record the visible part of the synchrotron radiation from the edges of the bending magnets. The absolute value of the beam current is measured by a ferroprobe–current transformer. Accurate measurement of the beam energy is carried out by the inverse Compton scattering of laser radiation.

In general, the optical structure of the VEPP-2000 ring can include beta functions at the meeting points

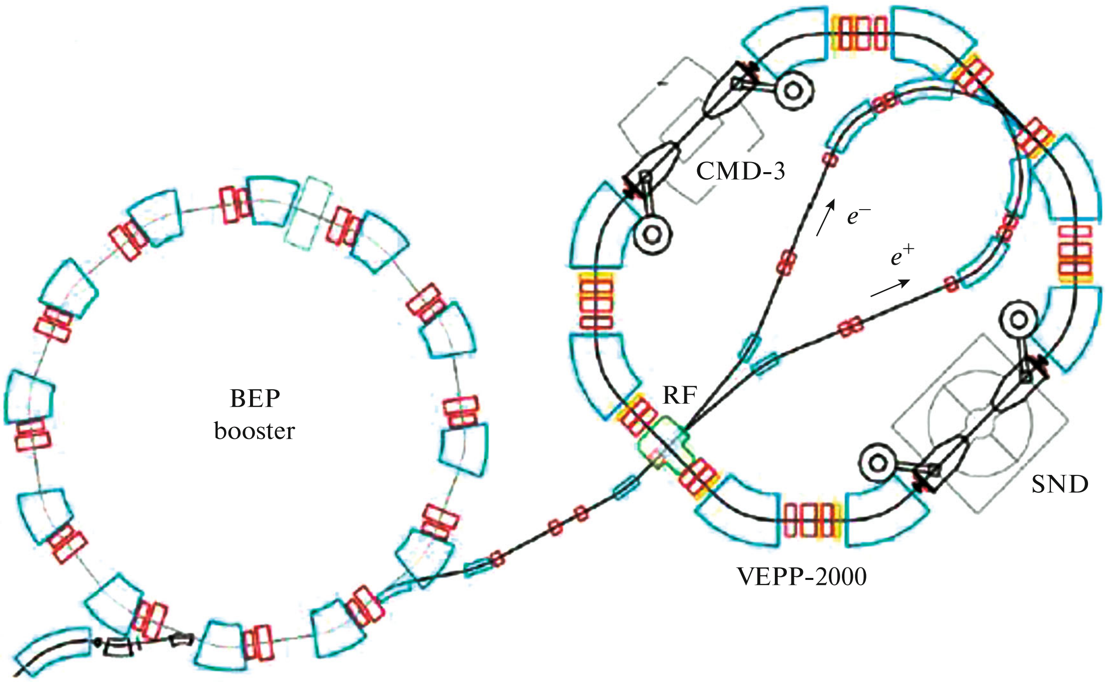

Fig. 1. VEPP-2000 complex.

in a range of about 5–10 cm; zero dispersion in the main free gaps; equal and small fractional parts of betatron frequencies at integer parts of 4 and 2 for radial and vertical oscillations, respectively; an encounter parameter exceeding 0.1; and luminosity at high energies of 10^{32} cm^{-2} s^{-1}.

WORKING WITH THE BEAM AND INCREASING LUMINOSITY

In the current configuration, the source of electrons and positrons for the VEPP-2000 complex is the injection complex (IC) [5]. Accumulated and cooled in the IC, the 430-MeV particles are delivered in turn to the VEPP-2000 complex in an automatic mode through a 250-m channel in accordance as needed. Incoming particles are injected, accumulated, and accelerated to the energy of the experiment in the Booster of Electrons and Positrons (BEP) [6]. Next, the particles are released from the BEP and injected through a branching channel into the storage ring of VEPP-2000. The injection in the BEP is adjusted according to the particle capture value, and the bypass channel from the BEP to VEPP-2000 is adjusted according to the readings of the beam position and size sensors in the channel and the percentage of particle bypass. The routine tuning of particle injection into the VEPP-2000 storage ring is primarily carried out according to the readings of the nearest peak. According to the coordinates of the first beam passage through the pickup, the beam entry is targeted according to the minimization of the amplitude of synchrotron oscillations; the adjustment of the beam energy and the accuracy of hitting the HF equilibrium phase; and the amplitudes of betatron oscillations, the adjustment of the forces, and moments of impacts of the traveling wave inflectors. It should be noted that, when intense beams collide, the particle capture coefficient during injection can greatly decrease and additional adjustment of the injection is required, but already almost "blindly," since the pickups measure the sum of the weak injected and intense circulating beams.

The collider is currently operating in the "flat" optics mode, when the solenoids located along the edges of the detectors are turned on in opposite directions. Thus, as a result of the passage of the experimental gap by the beam, there is no rotation of the plane of betatron oscillations. Therefore, the equality of the transverse emittances of the beam is ensured by the location of the operating point near the coupling resonance of the betatron frequencies.

Measurements of magnetic elements carried out at the stage of creation of the VEPP-2000 make it possible not only to reproduce the current optical structure of the ring in the simulation, but also iteratively, almost automatically, correct the equilibrium orbit and optical functions of the ring according to the calculated response matrices to dipole correctors [7]. This setting is effective as a basic one, but to obtain maximum luminosities, additional adjustment of the optics in manual mode is required.

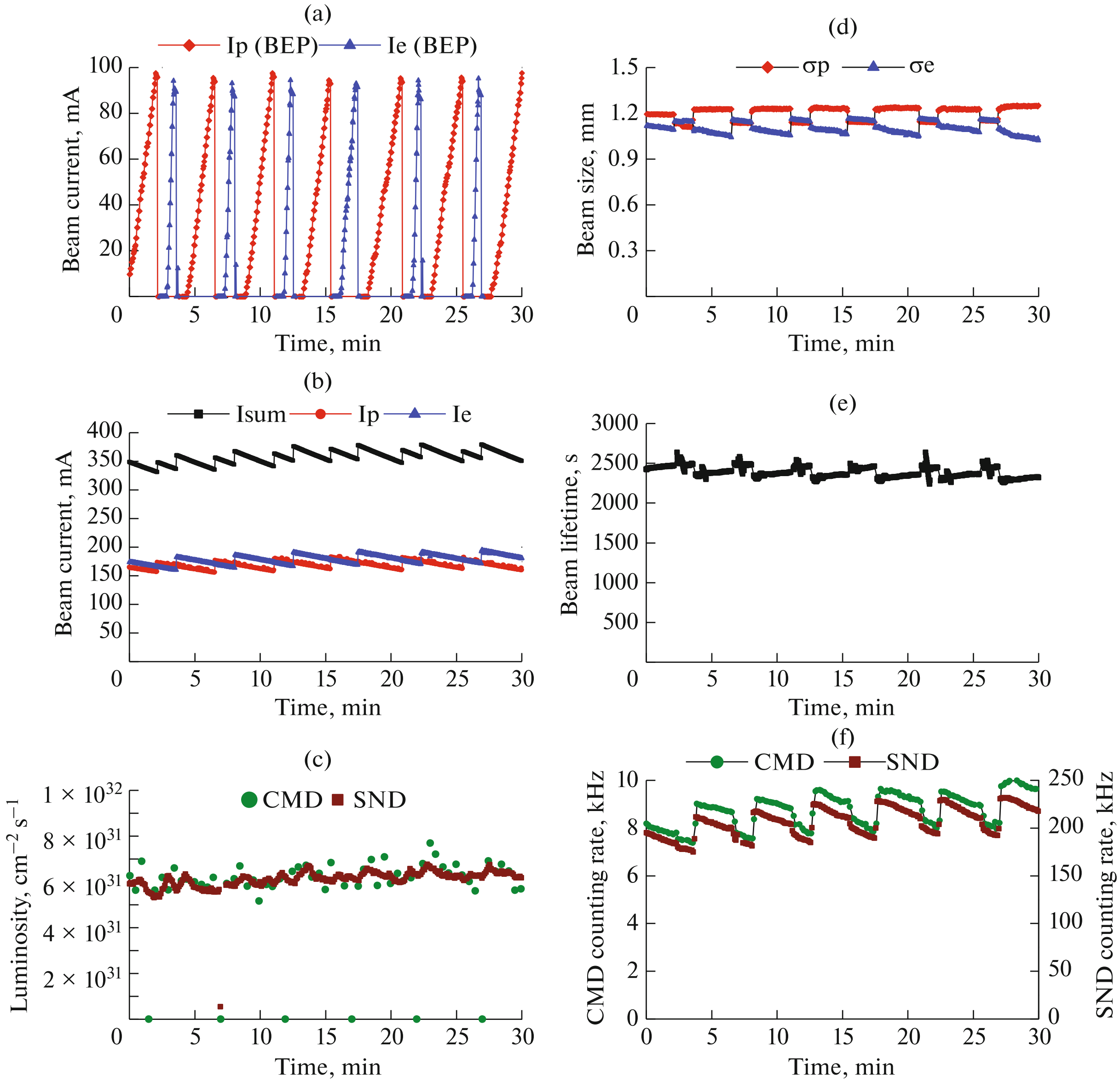

Fig. 2. Example of the operation of the VEPP-2000 complex at an experimental energy of 790 MeV. The time dependence of the beam current in the BEP booster is given (a), as well as for the VEPP-2000 collider, the time dependences of the beam currents (b), luminosities recorded by the detectors (c), vertical dimensions of the beams (d), lifetime by the total beam current (e), and counts of drift chambers at the inner radius of the detectors (f).

When collecting the luminosity integral, it is necessary that the noise of the detectors does not exceed a certain value; otherwise, the live time of the detectors decreases sharply and the quality of the collected statistics deteriorates due to the increased background. To control the noise of the detectors, the counting data of the drift chambers located on the inner radius of the detectors are used. The setting of the VEPP-2000 ring mode is carried out iteratively, by gradually increasing the beam currents with an acceptable detector background. When adjusting the beta functions at the meeting point with the preservation or violation of the roundness of the beams and tuning the betatron frequencies along or across the coupling resonance, software "knobs" are used to achieve the desired result with a minimum change in other parameters by means of a calculated change in the settings of many optical elements at once. The adjustment of the coupling and chromatism of the betatron frequencies, as well as the achromaticity of the turns, is carried out by the corresponding families of lenses, while an additional slight correction of the first and second harmonics of the action is also quite effective for increasing the currents of the circulating beams. When adjusting the equilibrium orbit with dipole correctors, various combinations of the second harmonics of the

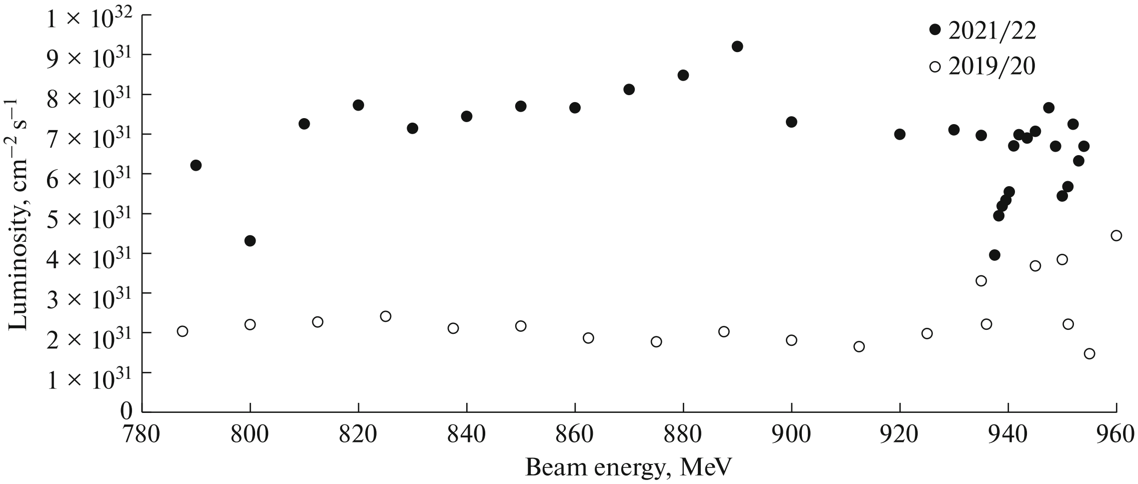

Fig. 3. Comparison of the average luminosities for the best 10% of entries of the last season and the results obtained in the same beam energy range in 2019–2020.

action are most effective. All elements and correctors can be controlled independently, but the nonideality of the elements, especially in the region of saturation of magnetic fields, leads to a distinct cross influence, so the tuning process is carried out iteratively. It is important to note that, when VEPP-2000 is tuned at maximum beam currents, at lower beam currents, the detector noise is always within the normal range, but not optimal for lower beam currents, although retuning to minimum detector noise at medium beam currents leads to the deterioration of the regime for high currents and, as a consequence, a decrease in the luminosity of the collider.

As an example, Fig. 2 shows the mode of operation of the VEPP-2000 complex for the last point in terms of the beam energy of the season, 790 MeV. Figure 2a shows the process of accumulation of electrons and positrons in the BEP. It can be seen that positrons accumulate more slowly than electrons, which is associated with different rates of arrival of particles from the IC. Figure 2b shows the dependence of the positron and electron currents and the total beam current in the VEPP-2000 storage ring. With a total current of beams within 380 mA, the luminosities in each of the meeting points are approximately equal to 0.6×10^{32} cm^{-2} s^{-1} (Fig. 2c). Since the beam intensities are sufficiently high, each injection of particles causes a significant change in the transverse dimensions of the circulating beams (Fig. 2d). The more intense beam is compressed, while the weak beam increases in transverse size, which affects the lifetime of the total beam current (Fig. 2e). In this case, the background loading of the detectors increases (Fig. 2f), which is the main reference point when acquiring the luminosity integral. In the mode shown in Fig. 2, with a total beam current of 380 mA, the measured frequencies of the σ mode and π mode of coherent oscillations are 0.14 and 0.33, respectively, which corresponds to the estimated value of the meeting parameter: 0.15.

The values of the average luminosities for the 10% of the best runs for all the energies of the experiment of the last season are shown in Fig. 3. For comparison, Fig. 3 also shows the best results obtained in this energy range in previous years. We can see significant progress in increasing the luminosity over the entire energy range of the last season. Maximum luminosity 0.9×10^{32} cm^{-2} s^{-1} was obtained at a beam energy of 890 MeV at a total beam current of almost 0.5 A.

RESULTS OF WORK ON THE COLLECTION OF THE LUMINOSITY INTEGRAL

The last season for the collection of statistics took place from December 2021 to June 2022. During the season, the beam energy varied within 790–954 MeV; the dependence of the energy on the day of operation is shown in Fig. 4a (curve). The daily integral of luminosity depending on the day of work is shown in Fig. 4a (histogram). It can be seen that, during the season as a whole, there was an increase in the daily set of statistics. Dips to zero in daily statistics are associated with repair work, both at VEPP-2000 and at the IC. Figure 4b shows the energy distribution of the luminosity integral collected over the last season and over all previous years. The peak of the luminosity integral is located in the region of the threshold of nucleon production during the annihilation of electron–positron pairs.

The average luminosities for the best 10% approaches for all energies of the experiment for the entire time of operation of the VEPP-2000 complex are shown in Fig. 5a. Also, for clarity, analytical curves

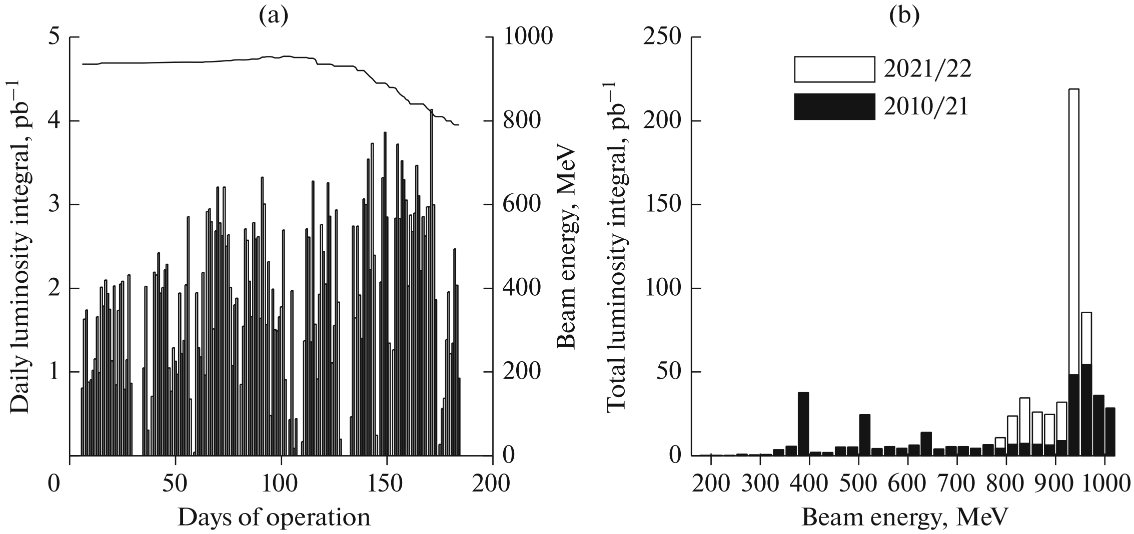

Fig. 4. Daily luminosity integral (histogram) and beam energy (curve) during the last season (a), as well as the energy distribution of the luminosity integral accumulated over the last season and for all previous years (b).

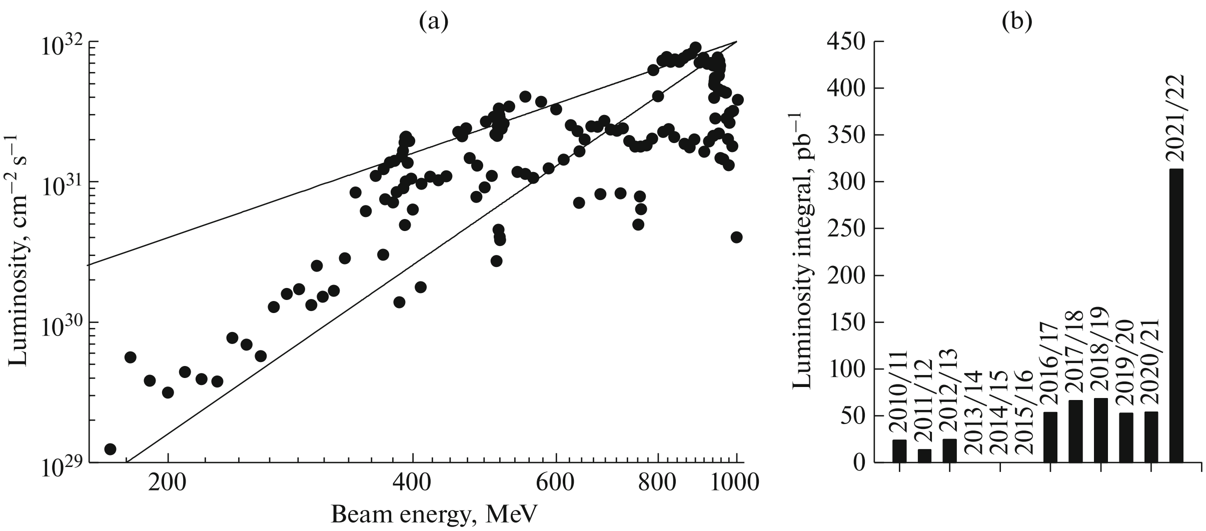

Fig. 5. Average luminosities for 10% of the best runs depending on the beam energy for the entire period of operation of the VEPP-2000 complex (a) and the seasonal distribution of the accumulated luminosity integrals (b).

of the dependence of luminosity on energy are presented in Fig. 5a with the preservation of the optics of the ring and with a decrease in the beta functions at the meeting point in proportion to the beam energy. Figure 5b shows the seasonal distribution of the accumulated luminosity integrals. In general, luminosity integrals of 0.31 fb^{-1} (CMD-3) and 0.36 fb^{-1} (SND) were accumulated over the last season, which almost doubled the luminosity integrals over the entire period of operation of the VEPP-2000: 0.67 fb^{-1} (CMD-3) and 0.74 fb^{-1} (SND).

CONCLUSIONS

Working with the beam made it possible to significantly increase the luminosity in the high-energy range of VEPP-2000. The luminosity integral accumulated over the entire period of operation of the VEPP-2000 increased over the last season from about 1/3 to 2/3 of the target level of 1 fb^{-1} for each detector. The results demonstrate a sufficiently high level of efficiency of the VEPP-2000 collider with the achievement of round beams for the physics program.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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