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VEPP-2000 COLLIDER OPERATION IN 2019–2021 RUNS: CHALLENGES AND RESULTS*

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Abstract

VEPP-2000 is the only electron-positron collider operating with a round beam that permits to increase the limit of beam-beam effects. VEPP-2000 is the compact collider with circumference of 24.39 m which has record design luminosity of 1×10^{32} cm^{-2} s^{-1} per bunch at energy up to 1 GeV and record achieved luminosity of 5×10^{31} cm^{-2} s^{-1} at energy of 500 MeV, magnetic fields in superconducting solenoids is 13 T and 2.4 T in the bending magnets. Collider complex experimental program of 2019–2021 was focused on several energy ranges. Energy range was (180–300) MeV in the second half of 2019, in the first half of 2020 we worked in (935–970) MeV, in the first half of 2021 that was (970–1003.5) MeV. Data taking was carried out by CMD-3 and SND detectors, the operation efficiency is compared with previous runs. Luminosity was limited by beam-beam effects. 2021 year was clouded by vacuum accident and subsequent intensive degassing using beam synchrotron radiation.

INTRODUCTION

We present in this paper an overview of VEPP-2000 electron-positron collider, operation chronology and statistics. In spite of problems connected with some vacuum accident and also with Anti COVID measures, luminosity records at operation energy ranges have been achieved. Data taking was also successful comparable to previous years level. This factor was provided by using several instruments for increasing peak luminosity such as Beam-shaker and lattice optimization. The analysis of operation time for data taking by collider detectors have been done and some solution for increasing the rate of collecting integral luminosity are in plans and have already been implementing.

VEPP-2000 OVERVIEW

VEPP-2000 is a compact electron-positron single rind collider [1] equipped with electron-positron booster ring [2] (Fig. 1) operating at bunch energy range (160–1000 MeV). Booster is feeded with particles by BINP Injection complex [3] at 430 MeV energy (until recently it was 390 MeV). Table 1 shows main parameters of the collider.

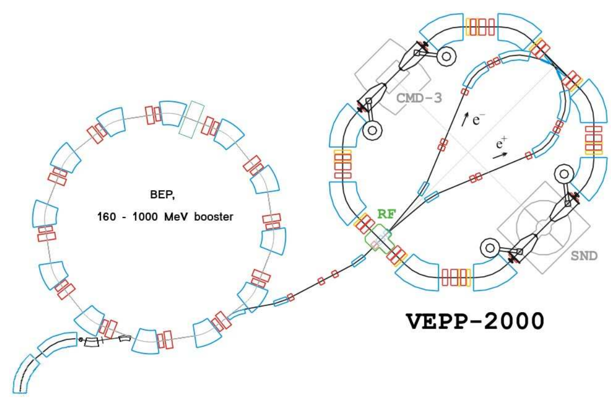

Figure 1: VEPP-2000 complex layout.

Table 1: VEPP-2000 Design Main Parameters at E= 1 GeV

Parameter	**Value**
Circumference, C	24.39 m
Energy range, E	160–1000 MeV
Number of bunches	1×1
Number of particles per bunch, N	1×10^{11}
Betatron functions at IP, $\beta^*_{x,y}$	8.5 cm
Betatron tunes, $\nu_{x,y}$	4.1; 2.1
Beam emittance, $\varepsilon_{x,y}$	1.4×10^{-7} m rad
Beam–beam parameters, $\xi_{x,z}$	0.1
Luminosity, L	1×10^{32} cm^{-2} s^{-1}

Round Beam Concept

Uniqueness and feature of VEPP-2000 collider is realization of Round Beam Concept [4, 5]. This factor allowed VEPP-2000 to have high luminosity and to make particles' dynamic one-dimensional although still non-linear. The concept applies several requirements to collider lattice:

- Head-on collisions (zero crossing angle)
- Small and equal β functions at IP ($\beta^*_x = \beta^*_y$).
- Equal beam emittances ($\varepsilon_x = \varepsilon_y$).
- Equal fractional parts of betatron tunes ($\nu_x = \nu_y$).

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Experimental Program

Collider hosts two particle detectors, Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector (CMD-3), placed into dispersion-free low-beta straights. Both detectors deals with measurement of cross section of annihilation of electron-positron pairs into hadrons, each detector has special experimental program [6, 7].

SND:

- Measurements of ω, ρ and ϕ (782, 770 and 1020 MeV)
- Looking for $e^+e^- \to \eta$ (547.853 ± 0.024 MeV)

CMD-3:

- Birth nucleon-antinucleon pairs $e^+e^- \to N\bar{N}$
- Processes: $e^+e^- \to \eta'$, $e^+e^- \to \pi^0$, $e^+e^- \to D^{*0}$

Luminosity integral depending on bunch energy is depicted on Fig. 2.

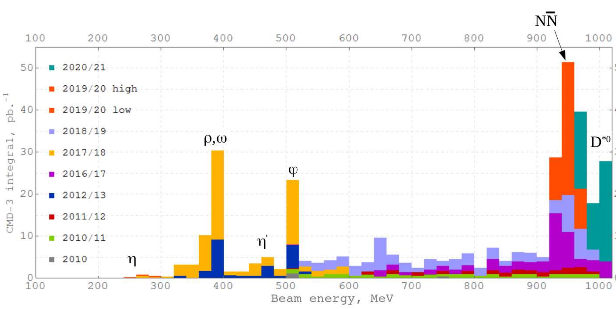

Figure 2: Luminosity integral for all the time.

OPERATION CHRONOLOGY

Run usually continues from 1st of September to 1st of July of the next year. In the "turning on" period of VEPP-2000 collider complex the power, control and beam diagnostic systems are tuned, soft is upgraded and operating mode of BINP Injection Complex is set up for work with two colliders (VEPP-2000 and VEPP-4 [8]). In the "luminosity" period bunches permanently (in perfect case) circulate in collider and data taking by detectors is carried out. Lets look at two operating run chronology separately. Hereinafter analysis is carried out using CMD-3 data.

2019–2020 Run

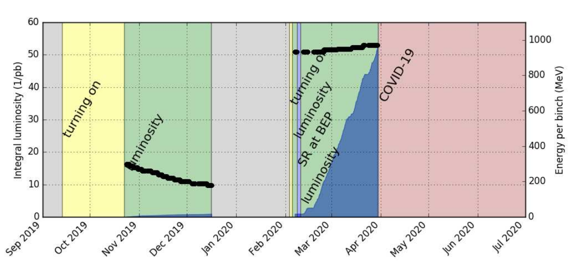

Figure 3: Chronology 2019–2020.

This operation run started at September 2019 and, after a month of tuning, collider has been operating for data taking by detectors ("luminosity") at low bunch energy range (180–300 MeV per bunch) from mid October to mid December. After that and further technical shut down in beginning of March the collider continued operation at high energy range (935–970 MeV per bunch) before shut down in connection with Anti COVID measure (see Fig. 3).

In addition to routine data taking, during this run several days were spent on serving the synchrotron radiation (SR) material science experiments at the BEP storage ring. The experiments are dedicated the sudy of in-vacuum properties (desorption, secondary electron emission) of the vacuum chamber wall covering under the SR treatment for HL-LHC research and development program [9]. In this regime BEP operates exclusively as SR source being unable to supply beams to VEPP-2000 collider.

2020–2021 Run

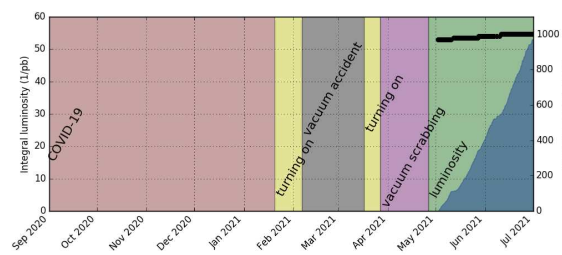

Figure 4: Chronology 2020–2021.

This run started in mid February 2020. In turning on process vacuum accident took place: hole in the vacuum chamber of BEP–VEPP positron transfer line has been burnt by arc discharge inside pre-injection pulse magnet. It resulted in collider vacuum volume depressurization. After pumping out beam lifetime was dramatically limited by gas photo stimulated desorption from vacuum volume surface [10]. Degassing (vacuum scrabbing by intensive beam synchrotron radiation) was required for decreasing coefficient of the desorption (see Fig. 4).

This process took almost month (beam energy was 700 MeV and dose achieved was 87 A h) and after that data taking was continued at previous run final energy point 970 MeV.

LUMINOSITY TIME STATISTICS

If we look at the statistics of operating in the "luminosity" mode we met similar pictures. In 2019–2020 and 2020–2021 runs VEPP-2000 operated 2530 and 1440 hours for luminosity respectively, and the distribution of operating and dead time is depicted on Figs. 5 and 6.

"Smooth operation" work looks like the Fig. 7: BEP stores beams without interruption and almost constant intensity bunches circulate in VEPP-2000.

"Liquid He refill" corresponds to the replenishment of liquid helium (LHe) in four superconducting solenoids' cryostats. This process now is impossible without an access

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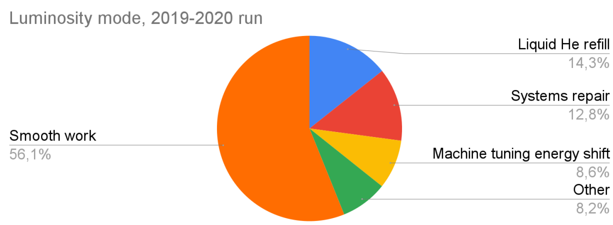

Figure 5: Luminosity mode, 2019–2020 run.

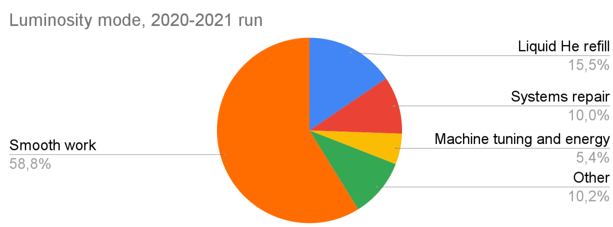

Figure 6: Luminosity mode, 2020–2021 run.

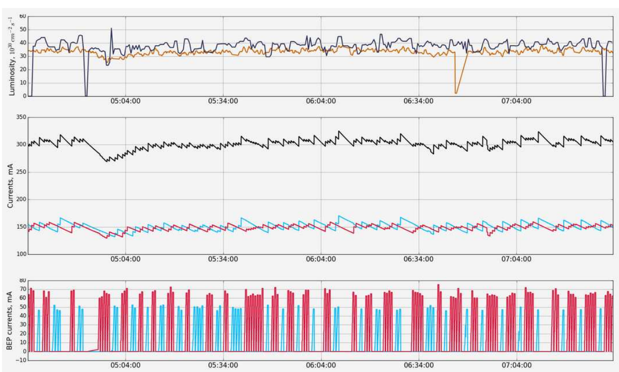

Figure 7: Smooth work.

to experimental hall that means beams abort and interruption of regular operation thus affecting the daily luminosity integral rate. This daily stop takes from 1 to 4 hours every morning, depending on logistics.

"Systems repair" is for time spent for removal of malfunctions of various accelerator complex subsystems. To mitigate this factor the modernization program is developed, for example for power supplies, and being implemented gradually.

"Machine tuning and energy" is the optimization machine lattice for luminosity and beam dynamics, and changing beam energy according to experimental program.

"Other" reasons of dead time is due to problems outside of VEPP-2000 complex. For example: Injection complex tuning, instabilities of water station work, power interruption. Also including here are quenches in solenoids:

- 5 times at 2019–2020 run
- 7 times at 2020–2021 run

Quenches occurred mostly at high bunch energies due to failed injection when beam dump took place. Quenches in the some solenoid usually resulted in almost total evaporation LHe from its cryostat. For reducing this factor which again demanded time-consuming LHe refill testing of the quench-protection system were carried out and stabilization measure of it was took.

According to the diagrams we can make rough estimation of operation and dead time due to main significant reasons: see Table 2.

Table 2: Smooth Luminosity Operation and Dead Time

Work	Persent
Smooth work	60
Liquid helium	15
System repair	12
Machine tuning and energy shift	8

For decreasing dead time some ways potentially are available.

INCREASING OPERATION EFFICIENCY

Project "Helium Outside"

To save data taking time there is an expensive concept of placing liquid helium volume inside the experimental hall which will be connected with solenoids cryostats and its input will be located outside the hall. Thus helium refill will take place without complex operation interruption saving about 15 % operation time. The concept is under consideration and its advisability is estimated now.

Systems Upgrade

During all the VEPP-2000 complex lifetime both the software and hardware is upgraded gradually. For example new 300 A/20 V power supplies for all the collider quadrupole magnets are developed by BINP lab and in production now at BINP workshop. Four of them have been already installed and operates reliably. The power supplies for regular pulsed quadrupole magnets for transfer line between BEP and VEPP-2000 rings are planned to be changed in order to increase the beam injection stability. The prototype of pulse power supply developed for NICA project by BINP will be used for series production.

Machine Tuning and Beam Diagnostic Improvement

Machine Tuning Process of tuning collider lattice is realized by analysis of response matrix singular value decomposition (SVD) using data from 16 CCD-cameras and 4 electrostatic BMPs [11]. This process is needed when change of energy point takes place and now it takes much time. In plans there are:

- development more automated methods for doing lattice and orbit correction
- revealing diagnostic optics defects
- more close investigation of non-linear effects (including beam-beam) influencing the dynamic aperture

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Beam Diagnostic Improvement For better understanding beam injection processes and for studying beam dynamics and also beam-beam effects new optical diagnostic system based on beam synchrotron radiation detection is developed. The system includes avalanche photodiode array with low relaxation time [12] as sensible element that provides turn-by-turn measurements of one-dimensional section of beam transfer profile. Prototype of this system was tested with different scales of beam image and different conditions: at stationary beam circulation and synchronized with kicks of variable amplitude. Combination of two described orthogonal arrays is planned to be installed at the single VEPP-2000 SR output in order to carry out measurements in horizontal and vertical planes simultaneously.

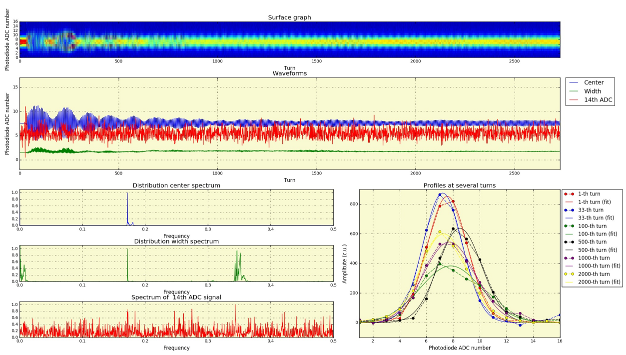

Figure 8: View of test application.

Test software application was developed for visualization measurements (Fig. 8). This soft can parse output file of signals from 16 arrays' photodiode during 2730 turns and makes graphs. Illustrating at the graphs are:

- Color two-dimentional diogram of turns history
- Oscillograms of center and weight of Gaussian distribution fit and also modulated signal from one of the 16 diodes
- Spectra of these oscillograms
- Profiles and their fit at several turns

Typical transverse VEPP-2000 beam size is 0.6–1.7 mm (standard deviation σ of Gaussian distribution) depending on operation energy and other factors. Thus optical table (Fig. 9) with wide movement range was designed allowing beam image to be scaled from 8 to 20 σ for full σ range. This factor provide ability of changing balance either to have high resolution or to observe high amplitude oscillation.

Current status of the optical table is under development.

BEAM-BASED POSITIONING TESTS

For example, mentioned above SVD method was applied to beam-based positioning tests of solenoids. VEPP-2000 solenoids consists of three different superconducting coils. The misalignment of solenoids not only provides the closed orbit distortions but also is harmful for dynamic aperture reduction due to strong nonlinear fringe fields.

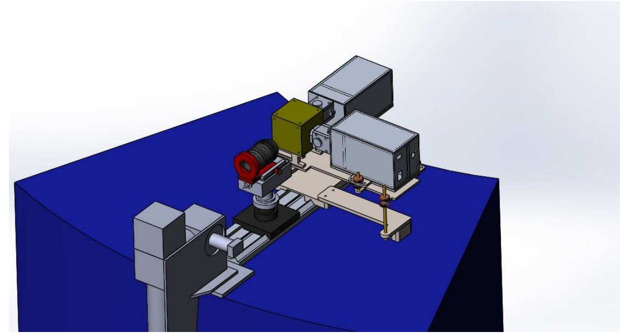

Figure 9: Optical table.

In the recent paper [13] the test study of solenoids positioning reconstruction procedure based on a circulating beam orbit responses was presented. Test measurement reveal that coils are effectively misaligned to each other, even inner and outer coils in the single solenoid. By now there is no clear explanation of this phenomena since huge shifts can be hardly tolerated by mechanical assembly. It also couldn't be explained with winding inaccuracy since the coils consists of thousands turns. At the same time, this observation probably can shed the light on confusion of early magnets alignment attempts at the commissioning stage.

ACHIEVED LUMINOSITY

During discussed above experimental runs VEPP-2000 peak luminosity record breaking have been done in both operation energy ranges.

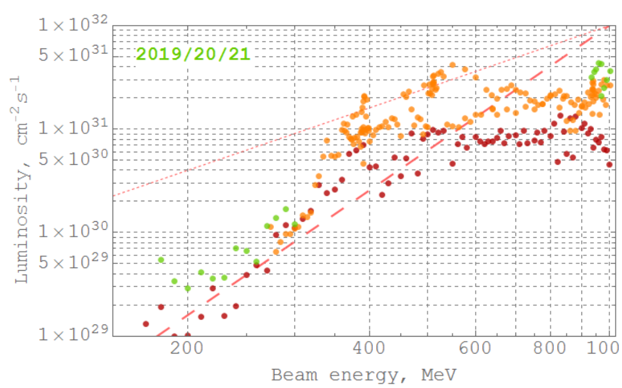

Figure 10: Peak luminosity. Red points correspond 2010–2013 run, orange points correspond 2017–2018 run after injection chain upgrade [14].

Dashed trend lines at the graph (Fig. 10) show two calculated luminosity dependencies on bunch energy. Short dashed line corresponds fixed β-function at IP (β^*), long dashed line corresponds variable β^* when its value was increased in such a way that bunch size takes as more aperture as possible.

Luminosity at low energy is limited by IBS (intra-beam scattering), small DA and low beam lifetime and also flip-flop effect which has threshold character depending on beam intensity. This device is a square pulse generator

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which applies amplified signals to additional kicker plates for shaking bunches increasing effectively emittance and suppressing flip-flop effect [15].

At high energy record values have been achieved only by precise lattice tuning.

The highest luminosity $L_{\text{max}} = 5 \times 10^{31}\,\text{cm}^{-2}\,\text{s}^{-1}$ in the VEPP-2000 history has been achieved at energy of 550 MeV in 2017–2018 run and at 950 MeV in 2019–2020 run (Fig. 10), while the design value is $L_{\text{proj}} = 1 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$.

RESULTS

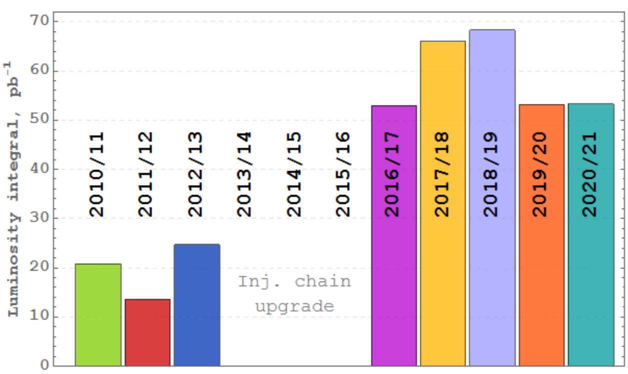

Figure 11: Total luminosity integral.

In spite of challenges and difficulties the luminosity integral comparable to previous runs has been collected (Fig. 11). It is worth noting that rates of data collection were higher (Fig. 12).

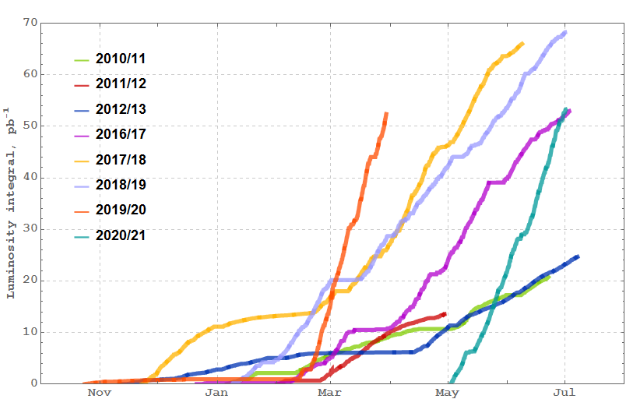

Figure 12: Data taking dynamics.

The total luminosity integral collected by each detector at VEPP-2000 achieved the value of $350\,\text{pb}^{-1}$ with a target of $1\,\text{fb}^{-1}$ foreseen for physical program completion.

ACKNOWLEDGEMENT

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