

TARGET LUMINOSITY AND LUMINOSITY INTEGRAL ACHIEVEMENT AT VEPP-2000 COLLIDER

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Abstract

VEPP-2000 electron-positron collider operating in the beam energy range of 150-1000 MeV is the only machine originally designed to exploit Round Beams Concept which results in significant beam-beam limit enhancement. After long shutdown for injection chain upgrade VEPP-2000 resumed data taking with luminosity limited only by beam-beam effects. Thanks to extensive and thorough machine tuning the luminosity achieved $L = 9 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at $E = 900 \text{ MeV}$ that is above the design value. The stable operation resulted as well in high average data taking rate of 2-4 $\text{pb}^{-1}/\text{day}$ at top energies.

In 2024 VEPP-2000 achieved the symbolic long-term milestone: integrated luminosity recorded by each of two detectors, SND and CMD-3, exceeded 1 fb^{-1} . This value was the target data volume written in the project physical program. Recorded data allows to study physics of light quarks with unprecedented precision. Recently published by CMD-3 collaboration $e^+e^- \rightarrow \pi^+\pi^-$ cross-section measurement already changed the vision of muon anomalous magnetic dipole moment mystery – possible window to physics beyond the SM.

ROUND COLLIDING BEAMS

The luminosity of any collider is restricted by beam-beam effects. In order to increase beam-beam threshold the Round Colliding Beam (RCB) concept was introduced [1] firstly proposed for the Novosibirsk Phi-factory project [2]. This approach suggests an axial symmetry of the disruptive nonlinear counter-beam force together with the X–Y symmetry of the transfer matrix between IPs that results in additional integral of motion, namely, the longitudinal component of angular momentum $M_z = x'y - xy'$. The reduction of degrees of freedom thins out the resonance grid and suppress the diffusion rate resulting finally in a beam-beam limit enhancement [3].

The demands upon the storage ring lattice suitable for the RCB: 1) Head-on collisions (zero crossing angle); 2) Small and equal β functions at IP ($\beta_x^* = \beta_y^*$); 3) Equal beam emittances ($\varepsilon_x = \varepsilon_y$); 4) Equal fractional parts of betatron tunes ($\nu_x = \nu_y$).

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VEPP-2000 OVERVIEW

VEPP-2000 is a small 24 m perimeter single-ring collider operating in one-by-one bunch regime in the energy range below 1 GeV per beam [4-6]. Its layout is presented in Fig. 1. The collider hosts two particle detectors [7, 8], Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector (CMD-3), placed into dispersion-free low-beta straights. The final focusing (FF) is realized using superconducting 13 T solenoids [9]. The main design collider parameters are listed in Table 1.

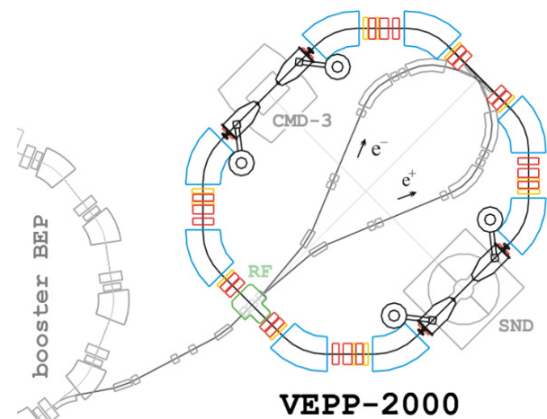


Figure 1: VEPP-2000 storage ring layout.

Table 1: VEPP-2000 Design Parameters (at $E = 1 \text{ GeV}$)

Circumference, C	24.39 m
Energy range, E	150–1000 MeV
Number of bunches	1×1
Particles per bunch, N	1×10^{11}
Beta-functions at IP, $\beta_{x,y}^*$	8.5 cm
Betatron tunes, $\nu_{x,y}$	4.1, 2.1
Beam emittance, $\varepsilon_{x,y}$	$1.4 \times 10^{-7} \text{ m rad}$
Beam–beam parameters, $\xi_{x,z}$	0.1
Luminosity, L	$1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

VEPP-2000 is served by booster BEP upgraded to perform top-up injection, which in turn was linked to the new BINP injection complex (IC) [10] via transfer channel.

Operation and Machine Tuning

Several operation modes satisfying RCB are available with different combinations of relative solenoids polarities.

Only "flat" mode (+ +) was found to have acceptable dynamic aperture (DA) with betatron tunes placed at the coupling resonance $\nu_x - \nu_y = 2$ to provide equal emittances via small X-Y coupling. Below 600 MeV beam energy, only the forward sections are used, helping move the final focus closer to the IP. Switching solenoid configurations ("long" to "short") causes significant closed orbit distortion, requiring beam-based realignment [11].

The fine lattice functions correction including X-Y coupling is made routinely at VEPP-2000 using Orbit Response Matrix (ORM) analysis [12]. Very important it turned out to minimize the dipole correctors' currents that done with help of ORM as well. The reason is poor quality of the steering coils being embedded into quadrupoles due to lack of space that affects the DA.

One of the recent studies conducted at the VEPP-2000 collider involved measuring the Resonance Driving Terms (RDTs) [13] shows how combinations of chromatic (SX and SZ) and dynamic SD sextupoles allows for a trade-off between maximizing the dynamic aperture and selectively mitigating specific high-order resonances.

BEAM-BEAM EFFECTS

Although the RCB performs well and the beam-beam parameter has been significantly enhanced, the beam intensity remains limited by the flip-flop effect across a wide range of operating energies.

It was reported earlier that implementation of the beam shaking technique at low and medium energies significantly increased both beam intensities and luminosity (comparison between 2013 and 2018 runs demonstrate a four-fold improvement at the same energy range) [14].

The significant luminosity enhancement in the high-energy regime was driven by a combination of technical upgrades and meticulous machine optimization. As shown in Fig. 2, luminosity in the 850–940 MeV range improved four-fold between 2017 and 2022.

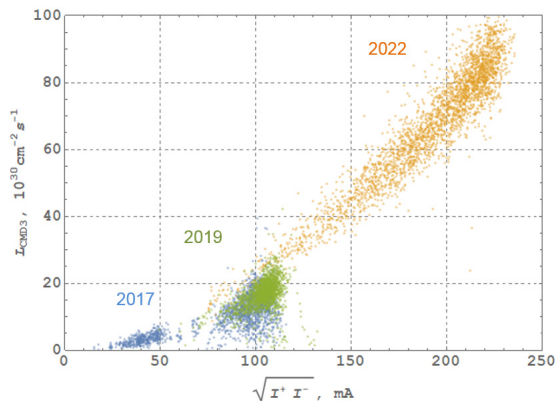


Figure 2: The CMD-3 recorded luminosity vs. beam currents. Blue and Green dots correspond to machine performance in 2017 and 2019 with long solenoids. Yellow dots corresponds to 2022.

Furthermore, the extracted beam-beam parameter (see Fig. 3) reached a record value exceeding $\xi > 0.1$, and even at this high value it is not saturated, the beams intensity is limited by detectors background.

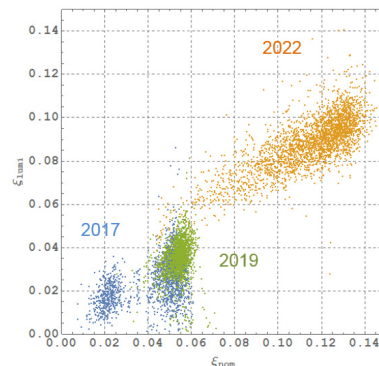


Figure 3: Beam-beam parameter extracted from CMD-3 luminosity. Notation is the same as in Fig. 2.

DATA COLLECTION

The 2016/17 run was the first data taking VEPP-2000 run with new injector [15, 16]. It was dedicated to energy range from 640 MeV to 1003.5 MeV per beam. The run 2017/18 was dedicated to the data collection at medium beam energies: 274 – 600 MeV per beam. The highest luminosity achieved is $L_{\text{peak}} = 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at 550 MeV.

The run 2019/20 was dedicated to the low energy above 900 MeV per beam. The highest luminosity achieved is $L_{\text{peak}} = 7.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at 950 MeV. Due to COVID-19 pandemic the run of 2020 lasted only for two months.

The achieved luminosity in comparison to 2010–2021 performance is shown in Fig. 4. With the mentioned above tricks with flip-flop additional suppression the achieved luminosity was well above expectations at the middle energies. At the same time at energy range from 600 MeV to 900 MeV luminosity was lower than design value in a factor of two.

The run 2021/22 was dedicated to the high energy in range from 800 MeV to 950 MeV. The highest luminosity achieved is $L_{\text{peak}} = 0.9 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ at 890 MeV.

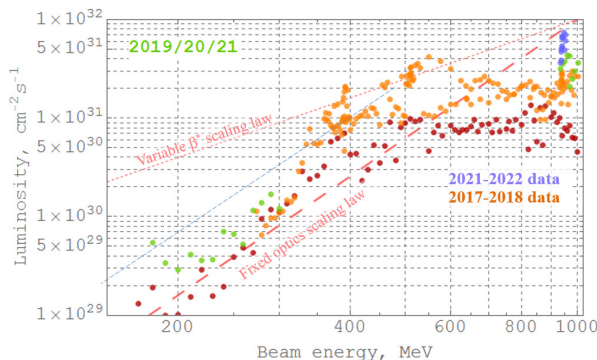


Figure 4: CMD-3 recorded in 2010–2013 (crimson), in 2017–2018 (orange) and in 2019–2022 (green and blue) luminosity averaged over 10% of best runs. Pink lines show scaling laws with fixed and variable β^* .

The run 2022-24 was dedicated to medium beam energies: 400 – 800 MeV. The achieved luminosity is shown in Fig. 5. Luminosity at 400–500 MeV noticeable falls below design values, most likely caused due to dynamic aperture shrinkage from strong dipole correctors (needed to correct orbit errors from quads misalignments).

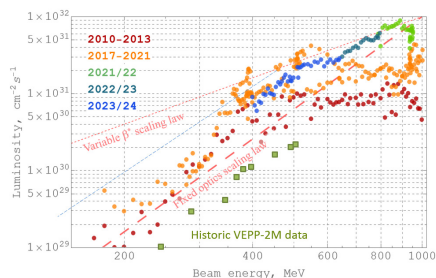


Figure 5: CMD-3 recorded in 2010-2013 (crimson), in 2017-2021 (orange) and in 2021-2024 (green and blue) luminosity averaged over 10% of best runs.

The Fig. 6 shows the integrated luminosity across several operating years. Note that direct comparison of the integrals requires caution due to the energy dependence of luminosity. However, the last three runs (2022–2024) mark a major breakthrough in data collection: their contribution to the total integral above 500 MeV is dominant.

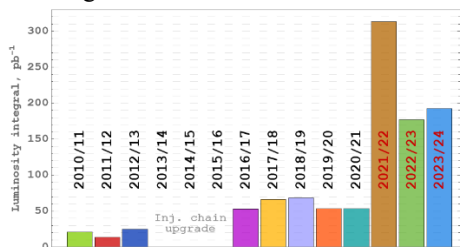


Figure 6: CMD-3 recorded luminosity integral.

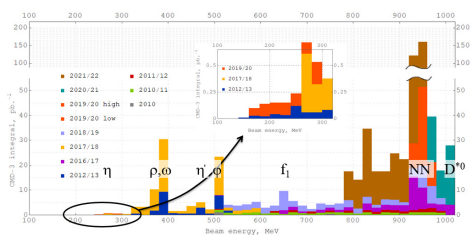


Figure 7: CMD-3 recorded luminosity integral.

The energy dependence of the integrated luminosity (Fig. 7) shows non-uniform accumulation, with ~80% of statistics concentrated at particular energies corresponding to $\phi/\omega/\rho$ meson resonances and the NN production threshold [17, 18].

Finally, the VEPP-2000 collider just hit 1 fb^{-1} integrated luminosity per each of two detectors (CMD-3 and SND), meeting its original performance target, in 2024.

One of the key results from the CMD-3 experiment at the VEPP-2000 collider is the precise measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section in the centre-of-mass energy range of 0.32 to 1.2 GeV [19]. This measurement is particularly significant for testing the Standard Model's prediction of the hadronic contribution to the muon's anomalous magnetic moment (a_μ).

EXPERIMENTAL SEASON 2024-2025

One method used to cross-validate the CMD-3 results involved reversing the beam direction in VEPP-2000. This reversal is operationally equivalent to flipping the detector's orientation, enabling an independent assessment of potential systematic effects caused by detection efficiency non-uniformities across the detector subsystems.

The most sensitive observable for this test is the charge asymmetry in the $e^+e^- \rightarrow \pi^+\pi^-$ process. The predicted asymmetry is below 1%, and its sign should invert upon beam direction reversal, providing a clear signature for verification.

To implement the beam direction reversal, we had to completely reverse the polarity of the collider's magnetic structure (except for the superconducting FF solenoids), modify the beam transfer channels, and upgrade the control software. The collider operated in this reversed configuration from January to June 2025, accumulating 40 nb^{-1} of integrated luminosity for each detector in 350-400 MeV energy range.

CONCLUSION

The RBC concept demonstrates compelling advantages for electron-positron physics, delivering superior beam quality. While offering significant luminosity gains, this approach demands exceptional control of beam dynamics and sophisticated optics optimization – challenges successfully addressed at VEPP-2000.

Operating across its full range VEPP-2000 has not only achieved but exceeded its design luminosity at top energies (with beam-beam parameter $\xi > 0.1$ which is not saturated yet). A breakthrough "beam shaking" technique has further enhanced performance at medium energies, suppressing the limiting flip-flop instability to push luminosities beyond original specifications.

As a unique facility for low-energy QCD precision physics, VEPP-2000 continues to deliver critical data for studying strong interactions and probing potential new physics. Its results are integral to global analyses, such as those by the Muon $g-2$ Theory Initiative, helping to resolve discrepancies between experimental measurements and theoretical predictions.

Ambitious upgrade plans are being developed to further enhance VEPP-2000's capabilities:

- Detector system modernization for improved precision;
- Collider optimization to reach higher luminosities;
- New instrumentation for expanded physics reach;

These improvements will secure the facility's leading position in precision QCD studies for the coming decade.

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