

STATUS OF ELECTRON-POSITRON COLLIDER VEPP-2000*

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Abstract

The main goal of VEPP-2000 construction is to measure the cross sections of hadron production in e^+e^- annihilations and to collect an integral luminosity about few inverse femtobarns in the energy range 0.4 – 2 GeV. To reach these goals, the Round Beam Concept (RBC) was realized at VEPP-2000 collider. RBC requires equal emittances, equal small fractional tunes, equal beta functions at the IP, no betatron coupling in the arcs [1]. Such an approach results in conservation of the longitudinal component of particle's angular momentum. As a consequence, it yields an enhancement of dynamical stability, even with nonlinear effects from the beam-beam force taken into account.

The first beam was injected in VEPP-2000 machine 5 years ago and RBC was successfully tested at VEPP-2000 in 2008 [2]. Two experimental seasons in 2010-2012 were performed with two detectors SND and CMD3 in the energy range between 500 and 1000 MeV. Now, the total luminosity accumulated at VEPP-2000 is near to the final result of the VEPP-2M collider. The single bunch luminosity of $3 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ was achieved together with a maximum beam-beam tunes shift as high as 0.15. At present, the work is in progress to increase the rate of positron delivery and upgrade the booster ring BEP for the beam transfer up to the top collider energy of 1 GeV.

COLLIDER OVERVIEW

The VEPP-2000 electron-positron collider has to operate in the beam energy range 0.2 – 1 GeV. It was constructed at the place of its predecessor VEPP-2M, using the existing beam production chain of accelerators: ILU – a pulsed RF cavity with a voltage of 2.5 MeV, a 250 MeV synchrotron B-3M and a booster storage ring BEP with the maximum beam energy of 800 MeV (see Fig. 1). The lattice of VEPP-2000 has a two-fold symmetry with two experimental straight sections of 3m length, where Cryogenic Magnetic Detector and Spherical Neutral Detector are located. Two other long straights (2.5m) are designed for injection of beams and RF cavity, and 4 short technical straight sections accommodate triplets of quadrupole magnets (max. gradient 50 T/m). To avoid dispersion in the detectors, RF cavity and injection straights, a pair of dipoles together with the triplet in between constitute 4 achromats. Chromaticity corrections are performed by two families of sextupole magnets located in the technical straight section, where the dispersion is high.

Design parameters of the collider are given in Table 1.

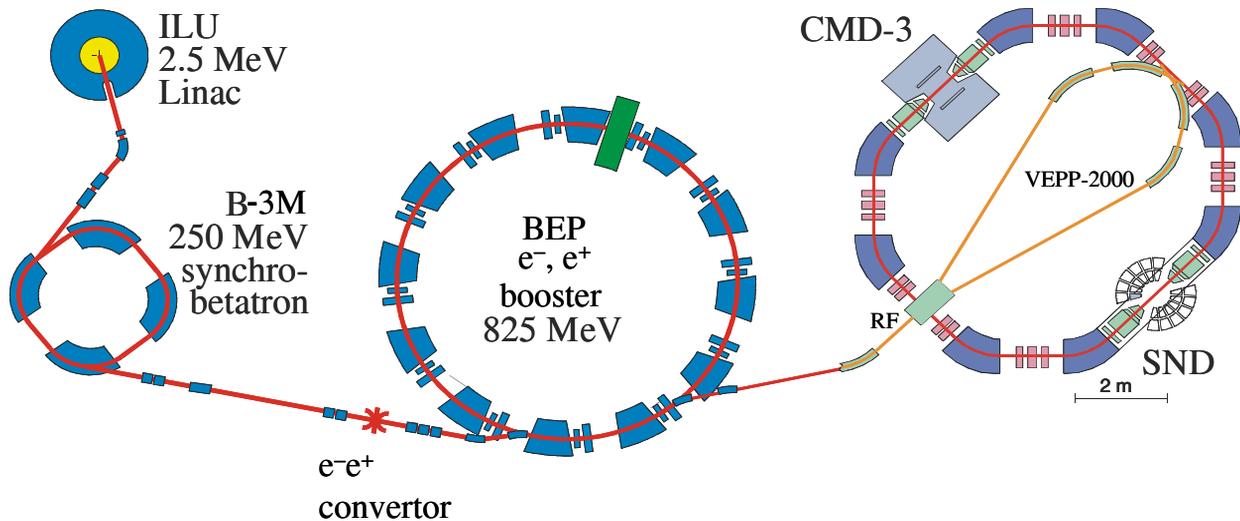


Figure 1: VEPP-2000 complex layout

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

Parameter	Value
Circumference, \mathcal{H}	24.39 m
Betatron functions at IP, $\beta_{x,z}^*$	10 cm
Betatron tunes, $\nu_{x,z}$	4.1, 2.1
Beam emittance, ε	$1.4 \times 10^{-7} \text{ m rad}$
Momentum compaction, α	0.036
Synchrotron tune, ν_s	0.0035
Energy spread, $\sigma_{\Delta E/E}$	6.4×10^{-4}
Beam-beam parameters, ξ	0.075
Luminosity, L	$10^{32} \text{ cm}^{-2}\text{s}^{-1}$

The closed orbit steering and gradient corrections are done with 1-2% coils placed in the dipole and quadrupole magnets.

The accelerating HOM-damping RF cavity operates at the 14-th harmonic of the revolution frequency (172.0 MHz)[6]. It provides for a bunch length of about 3 cm at the top energy and stability of design bunch current of 200 mA.

Beam diagnostics is based on 16 optical CCD cameras that register the synchrotron light from either end of the bending magnets and give the full information about beam positions, intensities and profiles (see Fig. 2). In addition to optical BPMs, there are also 4 pick-up stations in the technical straight sections and one current transformer as an absolute current monitor.

The density of magnet system components and detectors environment is so tight that it is impossible to arrange the beam separation in the arcs. As a result, only one-by-one bunch collision mode is allowed at VEPP-2000.

The magnetic field of 2.4 T in the bends is required to reach the design energy of 1 GeV in the constrained area of the experimental hall.

LATTICE CORRECTIONS

RBC at VEPP-2000 was implemented by placing two pairs of superconducting focusing solenoids (max. field 13 T) in the two Interaction Regions symmetrically with respect to the collision points. This provides equal beta-functions of the horizontal and vertical betatron oscillations. There are several combinations of solenoid polarities that satisfy the round beams requirements. The simplest combinations (+- +- or +- -+) have been chosen which satisfied the RBC constrains with the betatron tunes lying on the coupling resonance $\nu_1 - \nu_2 = 2$. The Dynamic Aperture (DA) in this case achieves about $15\text{-}20 \sigma_{x,z}$ apart strong resonances. This value is two times less than the simulated one. Probably, it can be

explained by the influence of lattice-asymmetry resonances: $\nu = 1/k$, where $k = 3, 4, 5, 6$.

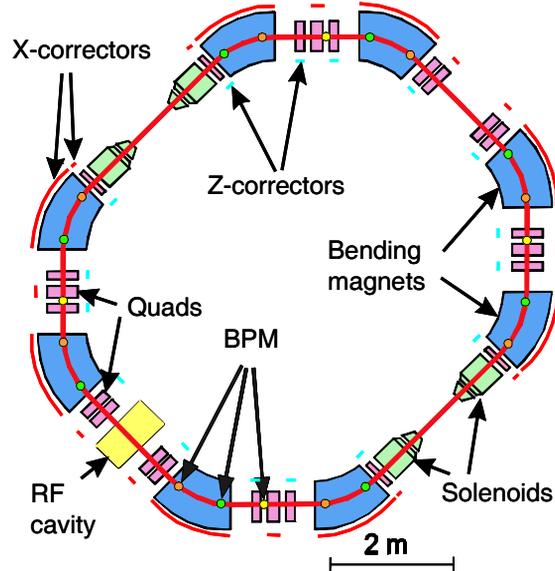


Figure 2: VEPP-2000 ring

To adjust the Closed Orbit (CO) and machine lattice to the design regime, an Orbit Response Matrix (ORM) method is applied. ORM measured from BPM response to small offsets given to the focusing elements (quads and solenoids) provides for control and corrections of the CO. Routinely, a sufficient accuracy ($\pm 0.2 \text{ mm}$) is obtained after 2-3 iterations with a Single Value Decomposition analysis of the taken ORM. In addition, steering coil currents are minimized. This is important for a DA optimization, because many dipole correctors, being embedded in quadrupoles, give rise to strong nonlinear field components.

The lattice corrections at VEPP-2000 appear a more complicated task, especially for high energies, taking into account different saturation of magnetic elements. All the BPMs are used to measure ORM by the orbit steering deviations. As a rule, this procedure is done in a few steps in semi-automatic regime. The resulting setting of the lattice has to approach designed tunes, dispersion and beta functions. It is necessary to make 3-4 iterations to achieve a desirable symmetry of the machine optics including perfect tuning of the 4 achromats.

The lattice symmetry and zero dispersion in the Interaction Points are crucially important for the round beam collision. The residual coupling has not to exceed $2\text{-}3 \times 10^{-3}$. The main source of coupling and symmetry violations is the CMD detector solenoid (1.5 Tm). To compensate for its influence on the optics, special coils in two nearest solenoids are used. Finally, the coupling is suppressed by a set of skew quadrupole coils which are embedded in each sextupole magnet of all the 3 families.

BEAM-BEAM STUDY

The result of machine tuning is demonstrated in Fig. 3 showing the design X-Z beam envelopes (curves) and the measured X-Z beam sizes (points). The beam sizes for this plot have been measured with e^+ and e^- beam currents below 1 mA. At these currents, a mutual influence of the colliding beams is negligible. But, already at a few mA the beam-beam focusing causes a visible perturbation of the beam sizes. This effect (“dynamical beta-function”) at VEPP-2000 leads to squeeze of $\beta_{x,z}^*$ and at the same time to an increase in the equilibrium beam emittances [3]. However, the resulting beam size at the IP is left practically unchanged. The simulation shows such a behaviour for both colliding round beams [4] up to the same critical currents I_{CR} .

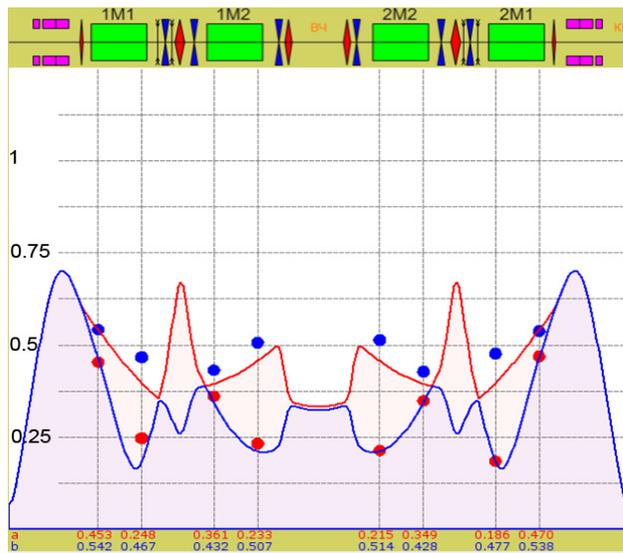


Figure 3. Beam sizes (mm) around the lattice.

Experimentally, a study of the beam-beam threshold currents was at first done in the “week-strong” mode for different tunes along the coupling resonance. A result of such a scan is presented in Fig. 4 at the beam energy of 510 MeV. We can see a resonance dependence of the I_{CR} on the tunes which is much stronger than mentioned above machine imperfection resonances $\nu = 1/k$. For a few intervals of the tune, the threshold current I_{CR} exceeds a level of $\bar{I} = 48$ mA, that corresponds to a value of the beam-beam parameter $\xi = \frac{N r_e}{4\pi\gamma\epsilon} = 0.1$.

It is necessary to remark that apparent strengths of the resonances in the beam-beam interaction differ day by day and, of course, vary at different energies. As a rule, the best working point found in the “week-strong” study, proves good for the “strong-strong” operation. Only a local tune scan is needed before starting the data-taking run with the detectors. A good parameter for quantitative assessment of the ring performance at collision is the

specific luminosity $L_s = \frac{L}{I^+ \times I^-}$. For the round beams we have found that this parameter is constant with equal beam currents as long as the beam-beam parameter does not exceed 0.05 (see Fig. 8). There is a reduction of the specific luminosity for higher currents, but it is not so dramatic as for the flat beams. [2]

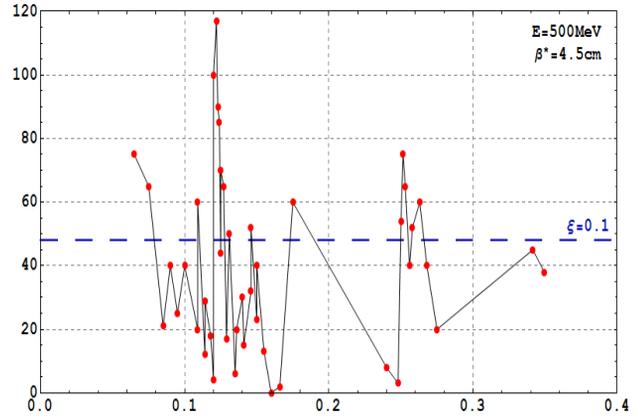


Figure 4: “Week-strong” threshold current vs. tune.

LUMINOSITY MEASUREMENTS

At VEPP-2000, the luminosity monitoring is available from both detectors. Electrons and positrons from elastic scattering are easily detected in coincidence by detector’s calorimeters with an efficiency near 100% and counting rates about 1 kHz at $L=1 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$.

For a “technical” usage, a method for the luminosity measurement was developed based on the beam size data from the optical diagnostics. To calculate the luminosity one should know only the beam currents and sizes at the IP. As we discussed above, due to the beam-beam effects the lattice functions and beam emittances show a significant current-dependent difference from their design values. Assuming no other focusing perturbations in the lattice other than those caused by the collision and thus located at the IP, one can use unperturbed transport matrices to evaluate beam sizes at the IP from the beam size measurements by CCD cameras placed around the ring. 8 measurements for each betatron mode of the both beams are more than enough to determine dynamic beta-function and dynamic emittance of the modes. The accuracy of the method degrades at high beam intensities close to beam-beam threshold, where the beam distribution deviates from the Gaussian. Data from this lumi-meter, routinely taken during 1.25 hour at the energy $E=888.25$ MeV, are presented in Fig.5. Beta-function in this run was 8.5 cm at the IP, and the luminosity reached $2.4 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$.

The advantages of this instrument over the SND and CMD luminosity monitors are the higher measurement speed and lower statistical jitter. Nominally, the accuracy of the new method is about 3-4% and it does not depend on the luminosity level in contrast to the detectors’ data.

On the other hand, the new technique is not sensitive to possible focusing difference in two IPs. Generally, all the three luminosity monitors give results coinciding within a 10% accuracy.

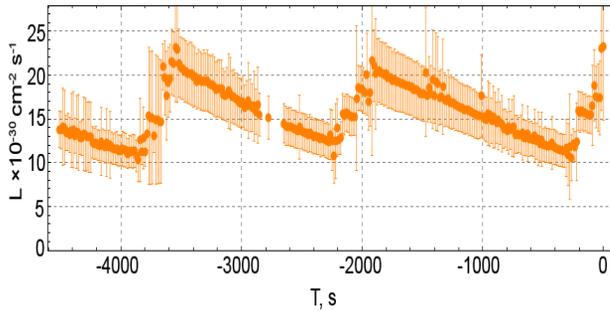


Figure 5: Luminosity log at the energy $E=888.25$ MeV.

EXPERIMENTAL RUNS 2010-2012

First of all, it is necessary to say that the existing beams production system is not able to provide enough positrons at the energies above 500 MeV. Besides that, a limitation of the booster ring BEP energy was found. It comes from insufficient chromaticity correction strength at the energies above 800 MeV. The strong head-tail instability arises and limits the positron beam intensity (50 mA). Another trouble appeared in ramping the VEPP-2000 ring up and down, between the injection and experiment energies, with non-separated colliding beams. A strict requirement to keep the betatron tunes equal to each other while ramping, and to stay within a narrow interval far enough from the resonances (see Fig. 7), leads to slowing the ramp speed down and thus to reduction of the average luminosity.

These problems have been (partly) resolved in operation. An appropriate matching of saturated magnets and solenoids was found, allowing a reasonably fast energy ramp with $\xi \leq 0.06$. It succeeds in a few-minutes ramping, 10 times shorter than the time between refills (see Fig. 5). By the way, the luminosity lifetime in Fig. 5 is determined by the luminosity effect: a cross-section of the single bremsstrahlung for VEPP-2000 conditions is equal to $2 \times 10^{-25} \text{ cm}^2$. So, particle losses in two interaction points approach to the positron production rate.

It is clear that the most interest of both detector teams was attracted to the beam energy above that of VEPP-2M. A few scans in the energy range 0.7- 1.0 GeV with a step 12.5 MeV were carried out during years 2010-2012. A summary of the whole run is presented in Fig.6, where all the luminosity measurements by CMD detector are given. The luminosity accumulated by two detectors at VEPP-2000 has already approached the VEPP-2M total obtained during 25 years of its operation.

It is necessary to say that VEPP-2000 experiments were twice interrupted for half a year shutdowns due to financial problems caused by a very low state funding.

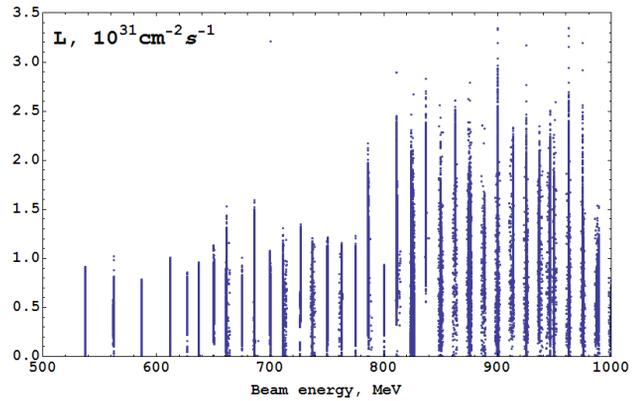


Figure 6: Luminosity measurements in the 2010-2012 runs.

Processing of the taken data is in progress at both detectors. A number of interesting events with multi π -meson productions are observed. But a more exciting result is measurement of the cross-section of $p\text{-}p_{\text{bar}}$ and $n\text{-}n_{\text{bar}}$ pairs production.

Simultaneously with data taking, a part of the machine time was spent for the beam-beam study. To demonstrate the luminosity dependence on the parameter ξ , an analysis of the SND luminosity data at the energy $E=537.5$ MeV has been done. One can see in Fig.7 that parameter ξ achieves a record value $\xi=0.15$ in the real “strong-strong” situation. This result coincides with our expectations based on the computer simulations for round beams [4].

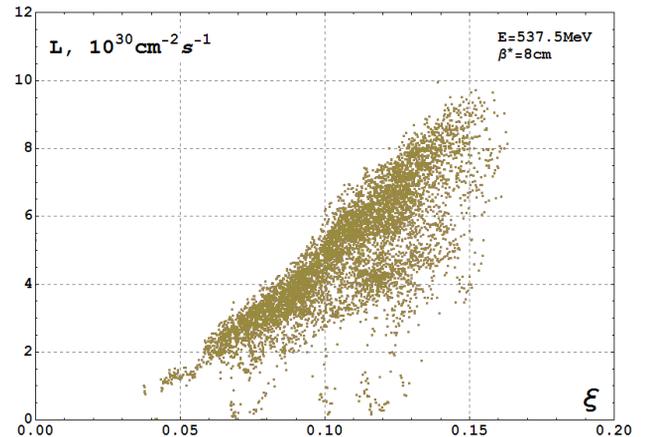


Figure 7. Luminosity vs the beam-beam parameter ξ .

BEAM ENERGY MEASUREMENTS

One goal of VEPP-2000 is an accurate measurement of hadron production cross sections in the whole energy range of 0.4 -2 GeV. This requires a knowledge of the beam energy with an accuracy of about 10^{-4} .

In addition to conventional magnetic field measurements by NMR probes in each bending magnet, two methods of the absolute energy calibration are under development at VEPP-2000.

The first method is the resonance depolarization technique which originates from VEPP-2M [5]. At VEPP-

2000, the strong solenoids complicate obtaining a polarised beam. But the present solenoid option allows to get a polarization degree of about 60% with a polarization time about 10 minutes at the top energy [6]. This is enough for observation of a jump in the counting rate of the intra-beam scattered positrons, when a frequency of the RF depolarizer coincides with the spin precession frequency. Figure 8 summarizes data of three depolarization runs. All together it gives the energy calibration: $E = 750.67 \pm 0.03$ MeV.

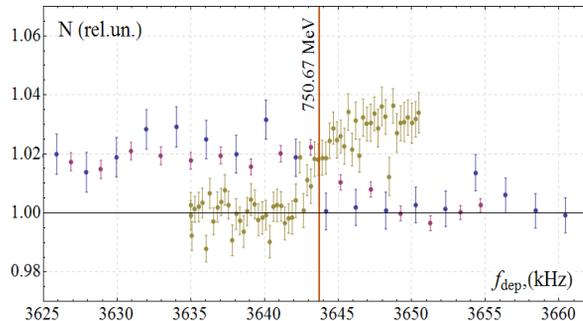


Figure 8. Resonant beam depolarization at VEPP-2000.

The second method which is in progress at VEPP-2000, is the Compton back-scattering of laser photons with the energy of $\hbar\omega_0$ on the counter electron beam. The energy of secondary γ -quanta $\hbar\omega_1=4\gamma^2\hbar\omega_0/(1+\gamma^2\theta^2)$ has a maximum at zero scattering angle ($\theta=0$). The γ -quanta are detected by a Ge crystal, which is energy-calibrated against reference isotope γ -sources [7]. It was only possible to arrange the electron-photon collision point inside the bending magnet.

The first test of this system was carried out last April. Figure 9 shows the recorded spectrum at the beam energy of $E=990$ MeV.

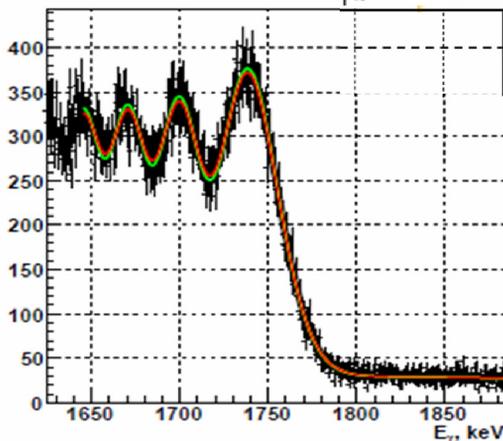


Figure 9. Compton back-scattering spectrum at VEPP-2000 at the energy of 990 MeV, $\hbar\omega_0=0.117$ eV.

Since the collision point in our case is in the magnetic field, the γ -quanta spectrum in addition to a sharp edge at $\omega_1=4\gamma^2\omega_0$ clearly indicates an interference of scattered radiation caused by the bend of electron trajectory [8].

Till now both methods of the energy calibration were tested separately in different conditions. Our nearest goal is to match all three methods and get the beam energy calibration accuracy of 10^{-4} in the whole energy span.

UPGRADE PLANS

The mentioned-above problems of the chronic positron deficit together with the collider ramping necessity will be solved soon after completion of the new positron injector at BINP. A transfer line (200 m long) is also under construction. It will deliver positron and electron beams from the damping ring of the positron source to the booster ring BEP at the energy of 500 MeV.

The booster and beam transfer lines BEP-VEPP will be upgraded to provide the beam injection into VEPP-2000 at any experiment energy. To do that, the bending fields of 2.6 T is required in the booster and transport line magnets.

CONCLUSION

VEPP-2000 is successfully running for data tacking with 2 detectors. A number of interesting results are observed. Round beams give the luminosity enhancement. The space charge parameter achieves value $\xi = 0.15$.

Beam energy calibration is in progress to achieve the accuracy of 10^{-4} .

To reach the target luminosity, more positrons and the upgrade of booster BEP are needed.

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