ROUND BEAM COLLISIONS AT VEPP-2000*

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Abstract

The idea of round-beam collision was proposed more than 20 years ago for the Novosibirsk Phi-factory design. [1] It requires equal emittances, equal small fractional tunes, equal beta functions at the IP, no betatron coupling in the collider arcs. Such an approach results in conservation of the longitudinal component of 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 Round Beam Concept (RBC) was realized at the electron-positron collider VEPP-2000 and successfully tested at the energy of 510 MeV. [2] Despite the low energy, a high single-bunch luminosity of 10^{31} cm^{-2}s^{-1} was achieved together with a maximum tune shift as high as 0.1. At present the work is in progress to increase the energy of the collider to explore the range between 500 MeV and 1 GeV in collision.

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 825 MeV (see Figure 1). VEPP-2000 lattice has a two-fold symmetry with two experimental straight sections 3m long, where Cryogenic Magnetic Detector and Spherical Neutral Detector are located. Two other long straights (2.5 m) are designed for injection of beams and RF cavity, and 4 short technical straights accomodate triplets of quadrupole magnets (max. gradient 50 T/m). To avoid dispersion inside the detectors, RF cavity and injection straights, a couple 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.

Table 1: VEPP-2000 Main Parameters (at $E = 1$ GeV)

Parameter	Value
Circumference, Π	24.39 m
Betatron functions at IP, $\beta^*_{x,z}$	10 cm
Betatron tunes, $\nu_{x,z}$	4.1, 2.1
Beam emittance, ε	1.4×10^{-7} 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} cm^{-2}s^{-1}
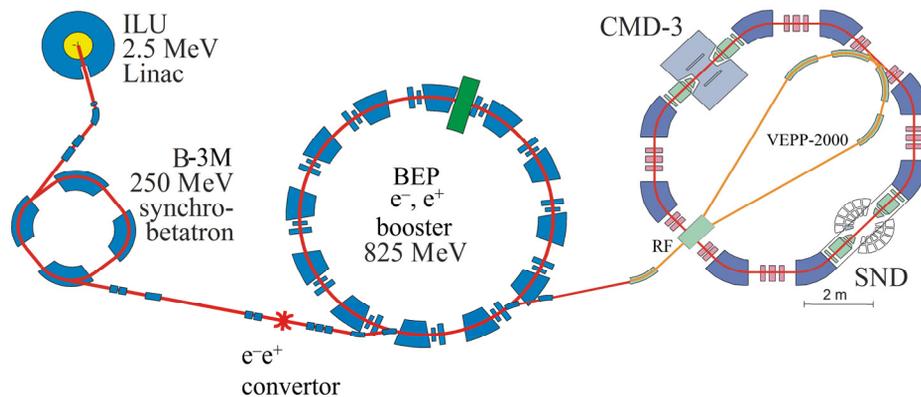
Figure 1: VEPP-2000 complex layout.

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

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

Beam diagnostic 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 Figure 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.

A density of magnet system components and detectors environment is so tight that it is impossible to arrange a 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 achieve the designed energy of 1 GeV in the constrained experimental hall area.
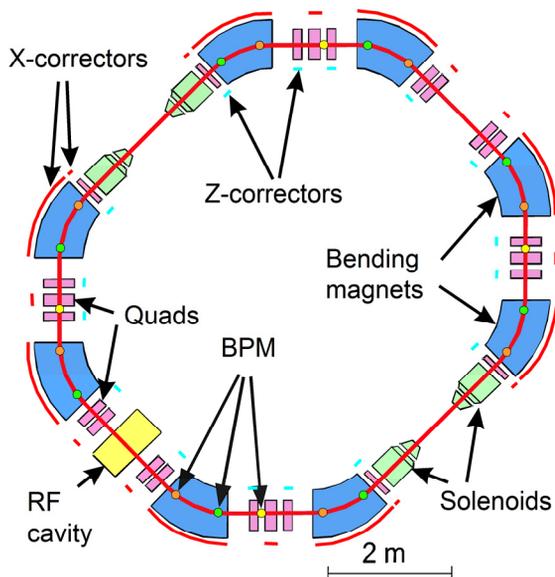

Figure 2: VEPP-2000 ring.

LATTICE OPTIONS

The 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 collision points. That provides equal beta-functions of the horizontal and vertical betatron oscillations. There are several combinations of solenoid polarities that satisfy the round beams requirements (see Figure 3): "Normal Round" ($^{++--}$), "Moebius" ($^{++-+}$) and "Double Moebius" ($^{++++}$) options rotate the betatron oscillation plane by ± 90 degrees and give alternating horizontal orientation of the normal betatron modes outside of the solenoid insertions. Simplest "Flat"

combinations ($^{+-\ +-}$ or $^{+-\ -+}$) also satisfy the RBC approach if the betatron tunes lie on the coupling resonance $\nu_1 - \nu_2 = 2$. All combinations are equivalent in focusing and give the same optical functions. But the tunes for M and DM options are different due to additional clockwise and counter-clockwise circular mode rotations.
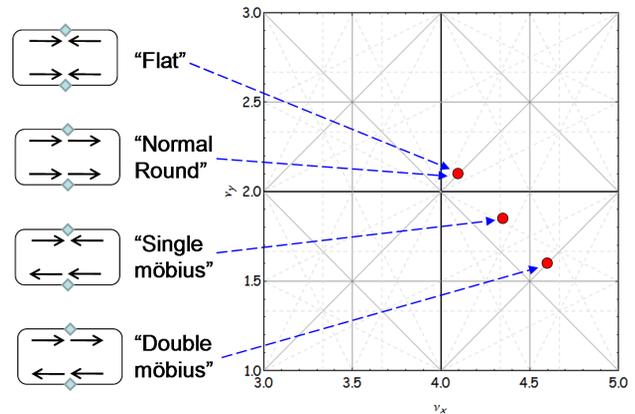

Figure 3: VEPP-2000 round beam options.

Preliminary data from computer simulations have shown serious troubles with the Dynamic Aperture (DA) for options with mode rotations. To improve the situation an additional third family of sextupole magnets was inserted in the quadrupole doublets with zero dispersion.

Till now, a full systematic experimental study of all round-beam options was not yet done. Only the Flat configuration has been studied in detail. DA in this case achieves about $(15-20)\sigma_{x,z}$ outside strong resonances. This value is two times less than the simulated one. Probably, it can be explained by the influence of lattice-asymmetry resonances. Figure 4 presents the positron beam lifetime dependence on the fractional tune along the coupling resonance for the beam current of $I^+ = 20$ mA.
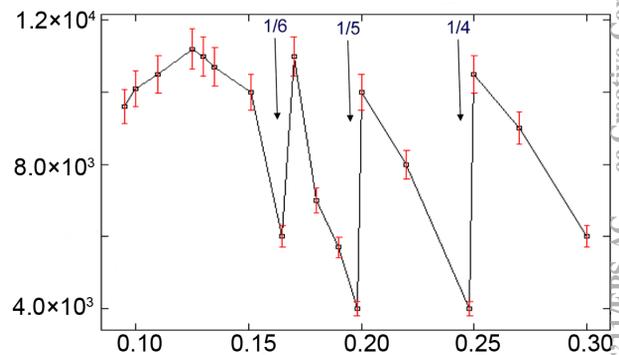

Figure 4: Positron beam lifetime vs. tune.

A similar study was briefly carried out for the DM option. At first glance, this case could be preferable, because the tune is a little above 0.5. However, both the simulation and measurement gave a DA of $\simeq 10\sigma_{x,z}$ only. Probably, such studies have to be continued for other

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options trying to pursue the similar experimental conditions as much as possible.

LATTICE CORRECTIONS

As seen from the above, the main part of machine and beam-beam studies have been performed in the "Flat" option, keeping betatron tunes on the coupling resonance.

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 (±0.2 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. This procedure as a rule is done in few steps in semi-automatic regime. By that, the final setting of the lattice has to approach designed tunes, dispersion and beta functions. Presently, measuring one 40×36 matrix takes one hour. It is necessary to make 3–4 iterations to achieve a desirable symmetry of the machine optics including perfect tuning of the 4 achromats. Figure 5 shows the beta functions behaviour along the machine before and after four steps of the adjustment procedure.
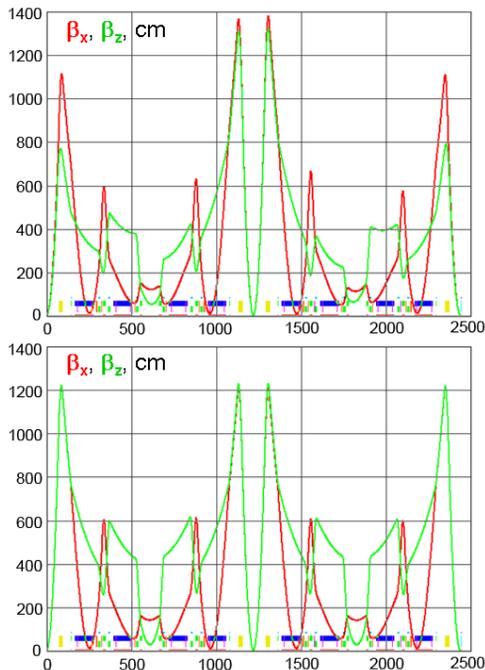

Figure 5: Lattice functions obtained by ORM analysis before and after lattice correction.

The lattice symmetry and zero dispersion in the Interaction Points are crucially important for the round beam collision. A residual coupling has not to exceed $(2–3)\times10^{-3}$. A main source of the 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 3 families.

BEAM-BEAM STUDY

The result of machine tuning is demonstrated in Figure 6 showing the design *X–Z* beam envelopes (curves) and the measured *X–Z* beam sizes (points).
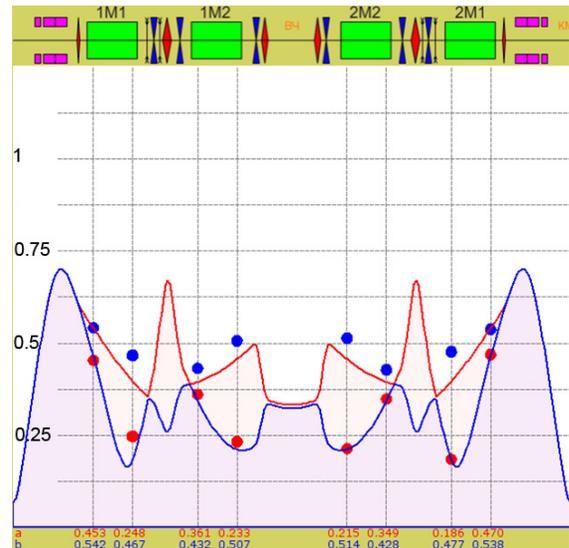

Figure 6: Beam sizes (mm) around the lattice.

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 behaviour for both colliding round beams up to the same critical currents I_{CR}. [4]

Experimentally, a study of these threshold currents was at first done in a "week-strong" mode for different tunes along the coupling resonance. One result of such scan is presented in Figure 7 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 that in the similar picture in Figure 4. For a few intervals of the tune, the threshold current I_{CR} exceeds a level of $I^- = 48$ mA, that corresponds to a value of the beam-beam parameter

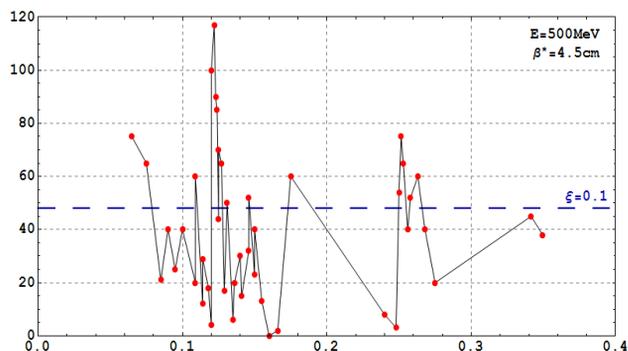$$\xi = \frac{Nr_e}{4\pi\gamma\varepsilon} = 0.1 .$$

Figure 7: "Week-strong" threshold current vs. tune.

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. It can be explained by non-identical machine tuning and unavoidable temperature dependence of magnet alignment.

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 $L_S = \dfrac{L}{I^+ \times I^-}$. 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 $\xi \simeq 0.05$ (see Figure 10). There is a reduction of the specific luminosity for higher currents, but it is not as dramatic as for the flat beams. [2]

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 measurements 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 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 evaluate the dynamic beta-functions and dynamic emittances of the modes. The accuracy of the method (10–20%) degrades at high beam intensities close to beam-beam threshold, where the beam distribution deviates from the Gaussian. Data from this luminometer, routinely taken during 1.25 hour at the

energy $E = 888.25$ MeV, is presented in Figure 8. In this run the beta-function was 8.5 cm at the IP, and the luminosity achieved $2.4 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$.
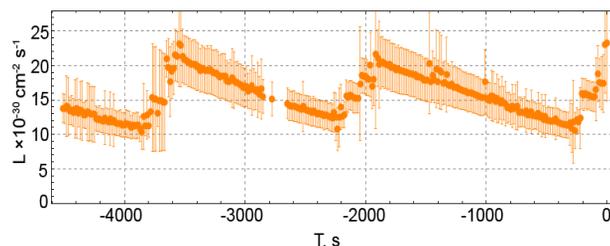

Figure 8: Luminosity at the energy $E = 888.25$ MeV.

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 detector's data. On the other hand, the new technique is not sensitive to possible focusing difference in two IPs. Generally, all those three meters give results coinciding within a 30% accuracy.

EXPERIMENTAL RUNS 2010–2011

Construction of the SND and CMD detectors has been completed by the beginning of 2010. The first measurement of the φ-meson and a short scan in the energy range of 500–950 MeV were done aiming at calibration of detecting systems and studying the ring problems at higher energies. 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 825 MeV. The strong head-tail instability arises and limits the positron beam intensity (20 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 Figure 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 $\xi \le 0.06$. It succeeds in a few-minutes ramping, 10 times shorter than the time between refills (see Figure 8). By the way, the luminosity lifetime in Figure 8 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 the positron production rate.

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The next 7 months long data tacking session took place in the end of 2010 and first half of 2011 year. The energy scan from 500 up to 1000 MeV with a step of 12.5 MeV was carried out. A summary of the whole run is presented in Figure 9, where all luminosity measurements by the CMD detector are given.
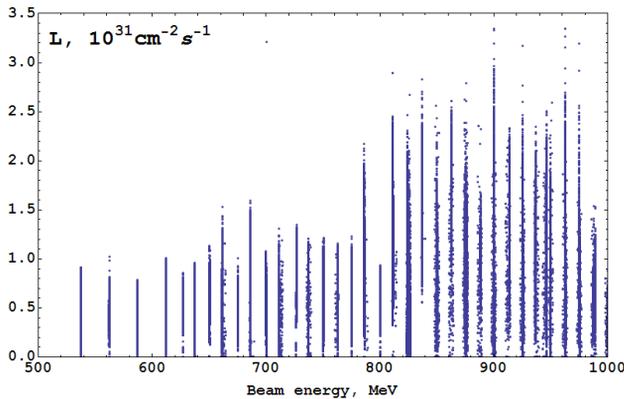

Figure 9: Luminosity measurements in the 2011 run.

The luminosity accumulated at each energy point was taken about 0.5 pb^{-1} per detector. To demonstrate the luminosity dependence on the parameter ξ, an analysis of the data at the energy point 537.5 MeV was done, using the results of all three lumimeters (see Figure 10).
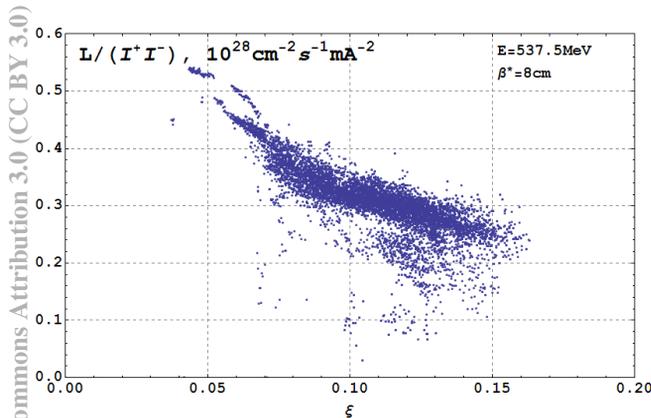

Figure 10: Specific luminosity vs. the beam-beam parameter ξ.

Full integral luminosity per 2011 run slightly exceeds 40 pb^{-1}. Together with the previous run data, a whole sum amounts to a one-half of theVEPP-2M luminosity accumulated during 25 years of its operation.

RADIATIVE POLARIZATION

One goal of VEPP-2000 is an accurate measurement of hadron production cross sections in the energy range of 0.4–2 GeV. By that, knowledge of the beam energy with an accuracy of about 10^{-4} is required.

For the absolute energy calibration at VEPP-2000, a resonance depolarization technique has been applied. [5] The usage of the strong solenoids caused complications in obtaining a polarized beam. But the "flat" option of the ring lattice allows the polarization degree about of 60%.

[6] It is enough for observation of a jump in the counting rate of the Intra-Beam Scattered positrons, when the frequency of RF depolarizer coincides with the spin precession frequency. Figure 11 summarizes data of three depolarization runs. Together they give the following energy calibration result: $E = 750.67 \pm 0.03$ MeV.
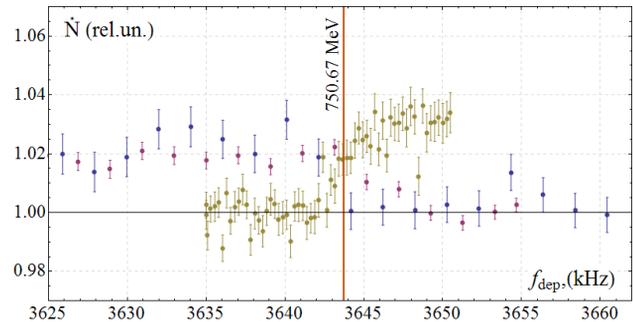

Figure 11: Resonant beam depolarization at VEPP-2000.

UPGRADE PLANS

Above-mentioned problems of the chronic positron deficit together with the necessity of ramping will be solved soon, after completion of the new positron injector that is under construction at BINP. A 200-meter long transfer line is under construction that will be used for delivering of 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 will be also upgraded in the next year to provide for the beam injection to VEPP-2000 at the energy of experiment in the whole energy range.

CONCLUSION

Round beams give a serious luminosity enhancement. The beam-beam parameter achieves a value $\xi = 0.13$.

VEPP-2000 started the data-tacking with 2 detectors.

Beam energy calibration is in progress.

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

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