PRESENT STATUS OF VEPP-2000*

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Abstract

VEPP-2000 electron-positron collider has been completed in the Budker INP in 2007. First beam was captured in a special lattice with switched off final focus solenoids. This regime is used for all machine subsystems test and calibration as well as vacuum chamber treatment by synchrotron radiation with electron beam current up to 150 mA. Another special low-beta lattice with solenoids switched on partially was used for the first test of the round beam option at the energy of 508 MeV. Studies of the beam-beam interaction were done in “weak-strong” and “strong-strong” regimes. Measurements of the beam sizes in both cases have indicated beam behaviour similar to expectations for the round colliding beams. Also the first collider energy calibration at the phi-meson resonance was performed with SND detector. Since the end of 2009 VEPP-2000 started first experimental work with both particle detectors SND and CMD-3 at the energies of 500-950 MeV range with the lattice mode close to project. The precise energy calibration via resonant depolarization method is in progress.

INTRODUCTION

At BINP for more than quarter of century the electron-positron collider VEPP-2M has been operated in the energy range of 0.4 ÷ 1.4 GeV. For a long time its results were the main source of information about hadrons production in this energy range. On the other hand, a whole number of events collected by different experimental groups in the energy span above VEPP-2M (up to 2 GeV) doesn’t exceed 10 % of the data accumulated by VEPP-2M. These motivations caused a decision to create instead of VEPP-2M collider a new machine with higher luminosity (up to 10^{32} $cm^{-2}s^{-1}$) and the beam energy up to 2×1 GeV.

To achieve the final goals (luminosity and energy), the Round Beam Concept was applied in design of the machine optics [1]. The main feature of this concept is rotational symmetry of the kick from the round opposite beam. Together with the x – z symmetry of the betatron transfer matrix between the collisions, it results in particle's angular momentum conservation ($M = xz' - zx' = const$). As a consequence, it yields an enhancement of dynamical stability, even with nonlinear effects from the beam-beam force taken into account.

Computer simulations of the beam-beam interaction in “weak-strong” and “strong-strong” situations confirmed these expectations [2, 3].

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COLLIDER OVERVIEW

The accelerator complex consists of VEPP-2000 collider itself and injection system including 900 MeV booster of electrons and positrons BEP and injection channels also designed for energy of 900 MeV.

Magnetic structure of VEPP-2000 [4] has the 2-fold symmetry. It includes two (3 m long) experimental straight sections, two straights (2.5 m) for beams injection and RF cavity and 4 short technical straights with 4 triplets of quadrupole magnets. Each triplet together with two 2.4 T bending magnets forms an 90° achromat.

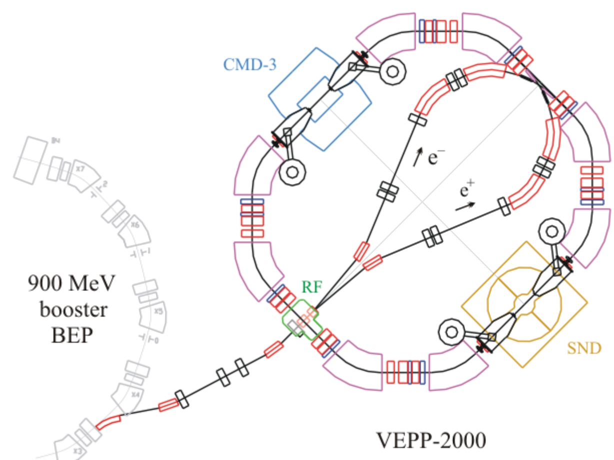

Figure 1: VEPP-2000 layout.

The RBC at VEPP-2000 was implemented by placing into Interaction Regions two pairs of superconducting solenoids symmetrically with respect to collision points.

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, $\varepsilon_{x,z}$	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}
RF frequency	172 MHz
RF harmonic number, q	14

RF voltage	100 kV
Number of particles per bunch, N	10^{11}
Beam-beam parameters, $\xi_{x,z}$	0.075
Luminosity, L	10^{32} cm^{-2}s^{-1}

The strong solenoid focusing provides equal beta-functions of the horizontal and vertical betatron oscillations. There are two combinations of solenoid polarities (+ + − −) and (+ + + +), that rotate the betatron oscillation plane by ±90 degrees and give alternating horizontal orientation of the normal betatron modes. It results in equal tunes and equal radiation emittances of the betatron oscillations. But the simplest case (+ − + −) with an additional small decompensation of solenoid fields also gives round colliding beams and satisfies the RBC requirements.

Superconducting Solenoids

Each solenoid is designed in two sections: main 13 T solenoid 50 cm in length, and 10 cm anti-solenoid (8 T). In part, the main solenoid consists of two identical units each of these has an inner coil wound with Nb_3Sn wire and an outer coil wound with NbTi wire. To feed the solenoid, we use separate power supplies for the outer and inner coils and for the anti-solenoid. All coils are embedded in the iron yoke located in a common LHe cryostat. During first run 2007/2008 the LHe consumption appeared to be surprisingly high. After the modernization of all solenoids in 2008 consumption decreased from 6 to 4 l/h. The investigations for further consumption decrease are in progress.

LATTICE OPTIONS

Several lattice schemes are available at VEPP-2000 all of them being useful for operation.

Switched off Solenoids

At the first stage the optics of VEPP-2000 was simplified to the conventional option without solenoids. This "soft" optics ($\nu_x = 2.4$; $\nu_z = 1.4$) is quite different from the round beam lattice (see Fig. 2, 4). But a part of the lattice near injection is preserved similar to the project one to produce proper betatron phase advance between injection and kicker. Optics without solenoids is available only at energy range below 600 MeV due to gradient limitation in weak F-lenses situated in IR.

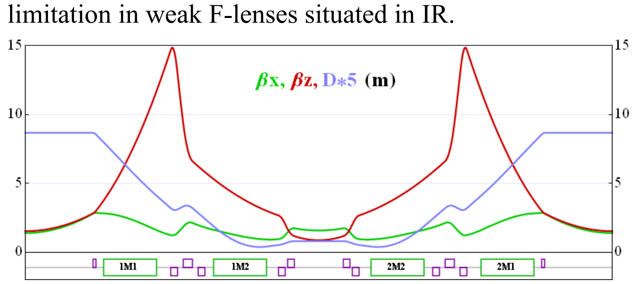

Figure 2: Half period lattice functions. "Soft" optics.

"Soft" lattice was used for the first beam capture, beam transfer efficiency tuning, calibration of the beam diagnostic system, etc. The procedure of vacuum chamber treatment by the synchrotron radiation was also done in this optics scheme, with electron beam in both directions, with several RF-buckets being populated. Beam current, while few days training, raised up to 150 mA and the beam lifetime achieved 1000 sec. At that condition, the lifetime of low beam current (about 1mA) exceeds 10 hours.

To start the round beam operation, first of all, we had to align the cooled solenoids. It was done in the same "weak focusing" regime by the CO deviation measurements as a response to the solenoids coils excitation (see Fig. 3). Each section of all 4 solenoids has been tested with magnetic field level up to 4 T. So, coordinates of each i-th solenoid section center (x_i, z_i, x'_i, z'_i) have been obtained from the Orbit Response Matrix analysis, and necessary mechanical adjustments of the solenoids have been done.

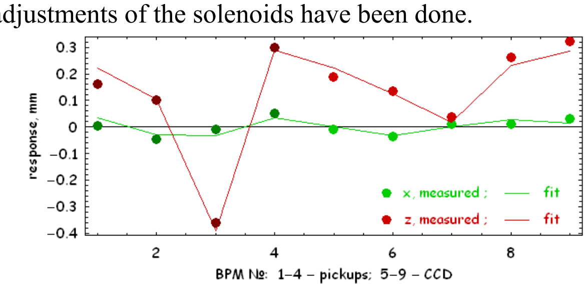

Figure 3: An example of fitted CO response exited by solenoid's coil field.

Short Solenoids

Round beams optics introduces solenoid focusing, but at low energy of two main solenoid's units it is possible to use only one, closest to IP. It requires 10 T field at 500 MeV and allow to produce β-function at IP as small as $\beta^* = 4.5\ cm$. This optics in the simplest round beam regime (+ − + −) was used for the first round colliding beam tests in 2008. The colliding beam sizes measurements vs. beam current in "strong-weak" and "strong-strong" cases showed the behavior close to simulations results [5]. The space charge parameter defined by expression

$$\xi = \frac{N r_e \beta^*}{4\pi\gamma\sigma_0^2} \qquad (1)$$

achieved the value of ~0.1 and the corresponding maximum peak luminosity expressed as

$$L = \frac{f_0 N^2}{4\pi\sigma^2} \qquad (2)$$

or

$$L = \frac{4\pi\gamma^2 f_0}{r_e} \frac{\varepsilon}{\beta^*} \xi^2 \qquad (3)$$

was equal to $L = 1\times10^{31}\ cm^{-2}s^{-1}$. In the end of 2008/2009 run VEPP-2000 worked in this optics with collecting the data SND detector that allowed to make first absolute energy calibration at the φ-meson resonance.

Full Solenoids

Operation at higher energy requires the full solenoid use. Lattice functions for this option are presented at Fig. 4. This optics corresponds to almost twice larger $\beta^* = 8.5\ cm$, while the beam emittance is almost the same. That means that for the same beam currents the luminosity (2, 3) should be near twice lower.

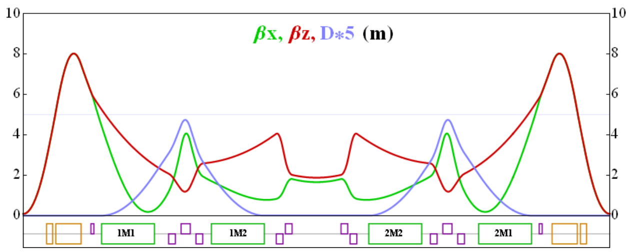

Figure 4: Half period lattice functions. Regular optics with full solenoids.

In the beginning of 2009/2010 run CMD-3 detector became ready for operation. After it's installation together with VEPP-2000 final focus solenoids into the IR of the ring, to compensate longitudinal field of the detector ($B = 1\ T$, $L = 1\ m$) anti-solenoids' coils were switched on.

Up to now round beams at VEPP-2000 were always carried out in simple mode where solenoids in each IR have opposite polarity (+ – + –). This corresponds to usual betatron modes, horizontal and vertical elsewhere except IR, where they are rotated on the large angle (roughly π/4). Equal beam emittances required for RBC are produced by finite betatron coupling and betatron tunes being at the coupling resonance $\nu_x - \nu_z = 2$. We plan to try another optic schemes (+ + – –) and (+ + + +) during the next experimental run 2010/2011, but expect difficulties with smaller dynamic aperture.

RESPONSE MATRIX TECHNIQUES

The ORM analysis is widely applied at VEPP-2000 complex. It was used in "soft" optics for rough alignment of cooled solenoids. The precision of coils' position and tilt restored from measured CO response at BPMs does not exceed 0.1 mm and 1 mrad correspondingly. More precise experiments of solenoid position determination with respect to CO was done in regular "round beam" optics also with use of ORM measurements [7].

Another ORM routine application is the measurement and correction of CO distortions at BEP and VEPP-2000 rings. Varying the gradient strength of each quadrupole one can get the CO distortion value there by comparison of measured CO response to model one. This technique is the only one for BEP, where the number of BPMs is poor, but it is also necessary for VEPP-2000 since 16 CCD cameras registering beam synchrotron radiation have high precision of 1 μm but haven't absolute calibration.

The use of SVD technique for ORM inversion also allows us to minimize steering coils currents for given CO. This is important for dynamic aperture optimization since many dipole correctors being embedded in quadrupole lenses have strong nonlinear field components.

Finally, the analysis of orbit responses to dipole correctors variation became a routine but powerful instrument for lattice correction at VEPP-2000 [6, 7]. In Fig. 5 the lattice functions for low-beta optics are presented before lattice correction and after 4-th iteration of the procedure.

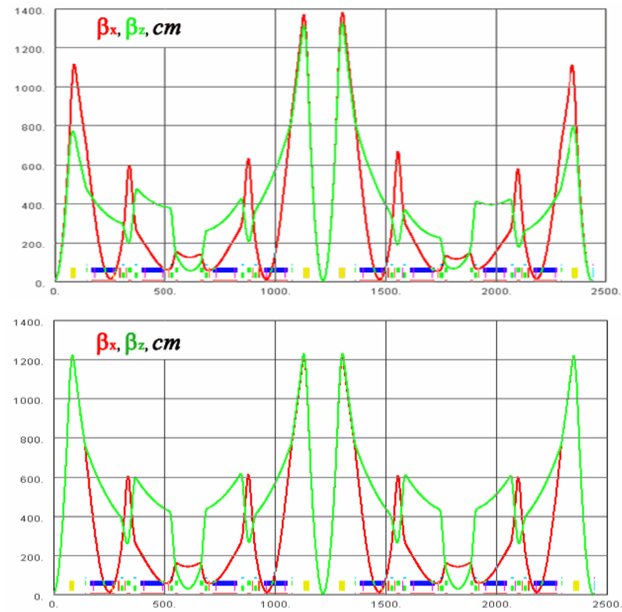

Figure 5: Lattice functions restored from ORM analysis before and after lattice correction.

LUMINOSITY INTEGRAL

In 2009/2010 first experimental run with both detectors SND and CMD-3 was carried out. Rude energy scan was done from 500 MeV to 950 MeV. The total luminosity integral collected by both detectors amounts to $\int L \sim 10\ pb^{-1}$. In Fig. 6 one can see the luminosity integral collected by SND at each point of energy scan. The integral collected by CMD-3 is ~1.6 times smaller.

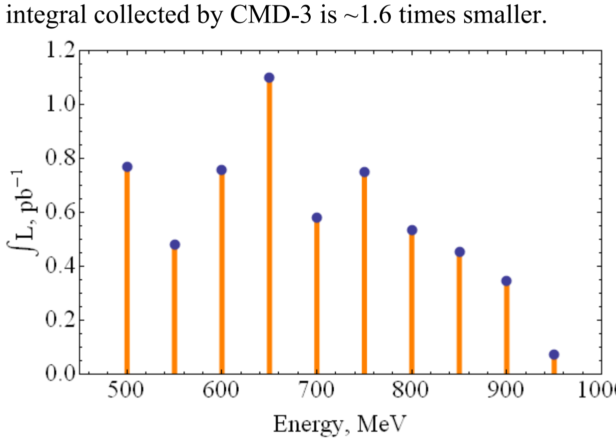

Figure 6: Integrated luminosity collected by SND.

Although the peak luminosity with given beam-beam parameter (3) should grow rapidly with energy ($L \propto \varepsilon\gamma^2$), at present several restrictions exists which do not allow us to provide maximum beam currents at high energy. First one is the insufficient positrons production by the old injection system (part of VEPP-2M complex). It would be fixed after the start up of new VEPP-5 injection complex at BINP. Another problem is low maximum energy of booster BEP and injection channels (900 MeV). In fact the energy ramping in VEPP-2000 was introduced for operation over 800 MeV due to head-tail instabilities in BEP at the higher energies. Firstly ramping inevitably causes large dead time. Moreover, even with enough positrons production the beam currents couldn't be on the beam-beam limit after ramping due to strong energy dependence of space charge parameter (1). In the case of ramping the luminosity dependence *L(E)* is defined by (2) but with fixed beam current *N* and thus degrade with energy. Due to mentioned restrictions together with β^* change the luminosity value decreased during 2009/2010 run from 1×10^{31} $cm^{-2}s^{-1}$ at 500 MeV to 1.5×10^{30} $cm^{-2}s^{-1}$ at 950 MeV. The project luminosity would be achieved only after BEP upgrade up to 1 GeV. The designing of upgrade is already in progress.

ENERGY CALIBRATION

The requirement on the beam energy measurement precision is $\Delta E/E \leq 10^{-4}$. All VEPP-2000 bending dipoles are equipped with 2 NMR probes each. Probes themselves have high accuracy and show good stability of magnetic field ($\sim10^{-5}$). At the same time they are situated in the dipole gap, but outside of the vacuum volume i.e. rather far from the CO. Rude calibration of the NMR probes was done through the maps of magnetic field obtained from the magnetic measurements. For higher accuracy we use two methods.

Phi-meson

The φ-meson mass is known with high precision $M_\varphi = 1019.455 \pm 0.020$ *MeV* (PDG). So, the first absolute VEPP-2000 energy calibration was done at the φ-meson resonance with SND detector. It showed an error of previous calibration as large as 3.5 MeV (see Fig.7).

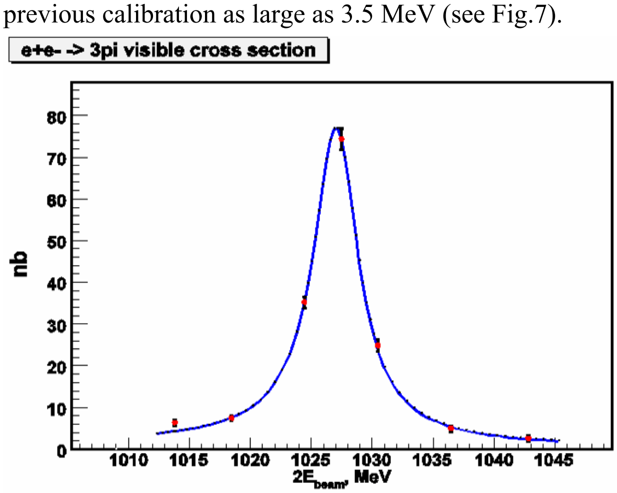

Figure 7: φ-meson resonance before energy calibration (SND data).

Resonant Depolarization

For more precise energy measurement in addition available at other energy values the method of resonance depolarization is assumed. At the end of 2009/2010 run two weeks were spent for polarization experiments at VEPP-2000. Two counters were installed into one of the technical straights to detect scattered particles. Counters are positioned in horizontal plane one from inner side and another from outer side at some distance from CO. At high energies the main contribution to counting rate is done by Intra Beam Scattering. By comparison of beam lifetime for the case of one bunch and two bunches with the same total beam current it was shown that IBS gives more than 80% of counting rate at 800 MeV. Moreover, to select precisely only good Touschek events only coincident data from two counters was taken. Since the Touschek effect depends on beam polarization the jump in the counting rate should happen during the polarization destruction. The special RF depolarizator was installed into center of injection straight.

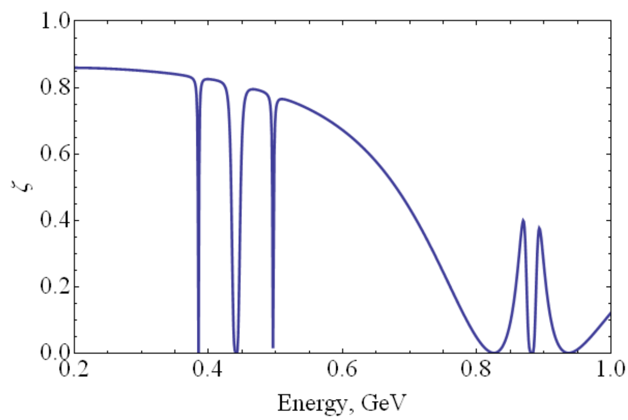

Figure 8: Calculated polarization degree vs. beam energy. Solenoids polarity scheme for low energy experiments.

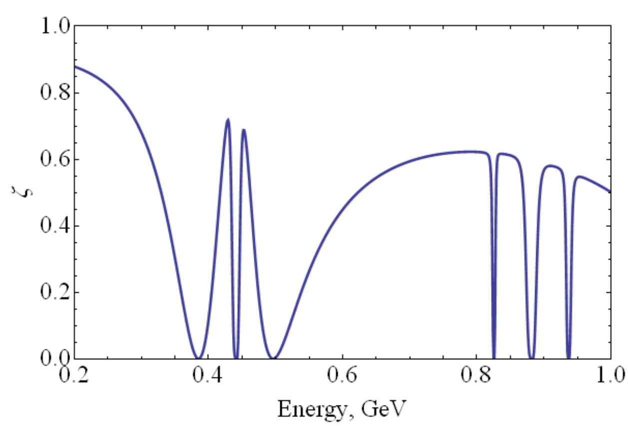

Figure 9: The case of solenoids polarity scheme for high energy polarization experiments.

According to theoretical calculations [8] the jump in Touschek scattering rate depends on the beam emittances ratio being suppressed for the round beam case comparatively to the flat one. So, experiments were held with flat beam: opposite solenoids polarity in each IR; betatron tunes away from coupling resonance; betatron coupling suppressed with skew quadrupole correctors family. To avoid problems with beam parameters drift due to ion cloud focusing the positron beam was chosen for experiments. Radiative polarization time at experiment energy of 750 MeV amounts to ~ 45 minutes according to calculations.

Simulations made with ASPIRRIN code [9] show the great difference for solenoids polarity schemes. In Fig. 8 the beam polarization degree is shown for the (+ –   + –) scheme. This scheme includes 2-nd harmonic of longitudinal field that provide strong integer spin resonance at 880 MeV that destroy the polarization at this energy. Thus, such a polarity is suitable for beam polarization only at low energy. Narrow resonance at 440 MeV with two betatron satellites appears in case of solenoids detuning ($\Delta B_s/B \sim 10^{-3}$ at Fig. 8, 9) that is inevitable for real operation. Another scheme (+ –   – +) generates the first longitudinal field harmonic, and provide ~60% polarization at 700-800 MeV energy span (see Fig. 9). This scheme was used in attempts of energy calibration at 750 MeV.

Experimental results were dramatically obtained only last night before the complex shut down in the end of July 2010. The first results for the counting rate jump are shown in Fig.10. One can see three scans with the 2.5 ÷ 3 % jump in counting rate. The energy obtained is 750.67 ± 0.03 MeV.

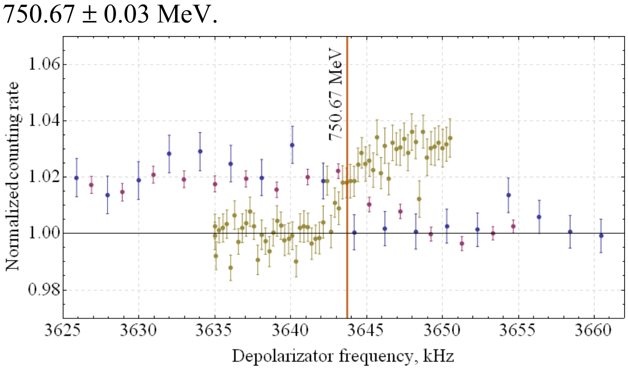

Figure 10: The jump in counting rate.

We plan to continue polarization activity at the beginning of the next run.

CONCLUSION

VEPP-2000 started up the data taking. First energy scan was done. All subsystems were tested at the energies up to 950 MeV. Different optics regimes were tried: technical solenoids-free option; regular round beam optics with $\beta^* = 8.5$ cm and CMD field switched on; low beta optics with higher luminosity; flat beam lattice for resonance depolarization method implementation.

The experimental results of the beam-beam study in the round beams mode have confirmed our expectations for the beam size behaviour in the “weak-strong” and “strong-strong” situations. In the “weak-strong” case the space charge parameter achieved the value of $\xi = 0.1$. The peak luminosity $L = 1\times10^{31}\ cm^{-2}s^{-1}$ has been achieved at energy of 500 MeV with beam currents $I^+ \times I^- = 40 \times 40\ mA^2$. To reach the target luminosity (1×10^{32}) at high energy (1 GeV) more positrons are required and booster BEP upgrade is need.

Energy calibration is in progress. NMR probes system was calibrated at the φ-meson resonance. First results of energy measurements via resonance depolarization method were obtained.

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