STATUS OF THE ELECTRON-POSITRON COLLIDER VEPP-2000 *

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Abstract

VEPP-2000 began high energy physics experiments in the end of 2010 and finished its third experimental season in July of 2013. The last season was dedicated to the energy range of 160-510 MeV per beam. Compton back-scattering based energy measurements were used for the regular energy calibration of the VEPP-2000 together with resonance depolarization and NMR based methods. The concept of the round colliding beams lattice along with the precise orbit and lattice correction yielded the high peak luminosity of $1.2\times10^{31} cm^{-2}s^{-1}$ at 505 MeV with average luminosity of $0.9 \times 10^{31} cm^{-2}s^{-1}$ per run. The total beam-beam tune shift up to 0.174 was achieved in the runs at 392.5 MeV. This corresponds to beam-beam parameter $\xi = 0.125$ per one interaction point. The injection system is currently being upgraded to allow for the injection of particles at the top energy of VEPP-2000 collider and to eliminate the present lack of positrons.

COLLIDER OVERVIEW

VEPP-2000 collider was designed for the refinement of the cross section of the e^+e^- annihilation to hadrons in the energy range $0.4 \div 2$ GeV [1]. The lattice design was aimed to fulfill the conditions of round colliding beams [2], which promised higher luminosity performance because of an additional integral of motion.

The main proposed collider parameters are given in Table 1. VEPP-2000 was designed for one-by-one bunch operation with two functional interaction points. The ring consists of four 90 degree achromatic bends with four straight sections (Fig. 1). Two of the straight sections are occupied by the CMD-3 and SND detectors along with final focus superconducting solenoids, the third is used for injection, and the RF cavity is placed in the fourth.

The focusing system consists of six quadrupole families, three focusing and three defocussing, and four final focus configurable solenoids. Three sextupole families are available for the chromaticity correction. All sextupoles have additional coils that form skew-quadrupole fields to correct the coupling. Due to dense element placement, the orbit steering fields are generated by additional coils in main dipoles and quadrupoles resulting in 20 horizontal and 16 vertical correctors.

The beam diagnostics system consists of 4 electrostatic pickups that are capable of taking turn-by-turn data; 16

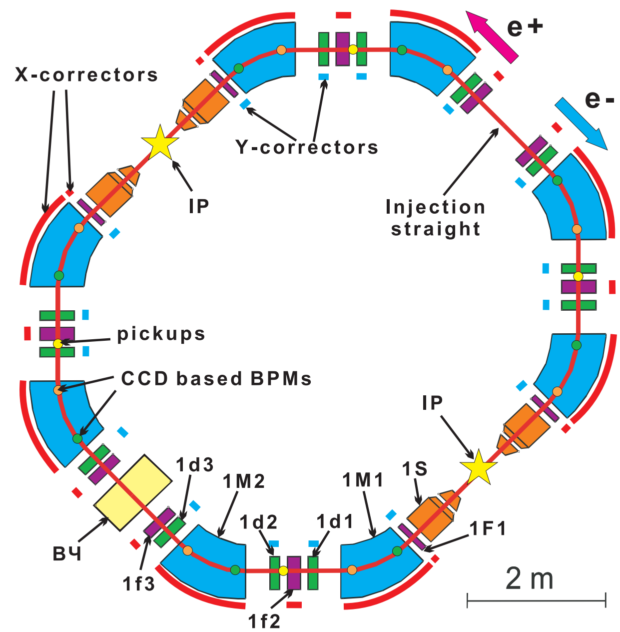

Figure 1: VEPP-2000 layout.

Table 1: VEPP-2000 Parameters at 900 MeV

Circumference, m	C	24.388
RF frequency, MHz	f_0	172
RF voltage, kV	V	100
RF harmonic number	q	14
Momentum compaction	α	0.036
Transverse emmitances, $cm \cdot rad$	ϵ_x, ϵ_y	$2.2 \cdot 10^{-5}$
Betatron tunes	ν_x, ν_y	4.1, 2.1
Twiss β at IP, cm	β_x, β_y	6.3
Particles/bunch	e^-, e^+	$1.0 \cdot 10^{11}$
Tune shifts	ξ_x, ξ_y	0.075
Luminosity/IP, $cm^{-2} \cdot s^{-1}$	L_{max}	$1.0 \cdot 10^{32}$

CCD cameras that take beam images using synchrotron light; two photomultipliers for bunch current measurements; one DCCT for measurements of full circulating current; two phi-dissectors [3] that give information about the longitudinal distributions of particles in both bunches.

The first beam was injected to the VEPP-2000 in the end of 2007 without final focus solenoids. This special “warm” configuration of lattice was used to test all vital systems of the collider. After installation of the final focus solenoids, the first luminosity runs were done in 2010. These runs were done only with SND detector, while the CMD-3 de-

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tector and its solenoidal field were off. The CMD-3 field of 8-13 kGs breaks the lattice symmetry with greater influence at lower energies.

ENERGY CALIBRATION

The requirement for the precise measurement of the hadron creation cross sections applies strict constraints on the precision of the energy measurement tools. The relative uncertainty of the beam energy should be within $\Delta E/E \leq 10^{-4}$. VEPP-2000 has a number of tools to solve this complex task.

The most precise absolute method is based on resonant depolarization of the beam [4]. The series of spin resonances of the experimental ring leaves only several energy points that could be used for this method, also non-ideal orbit inside the final focus solenoids affects the measurements in unpredictable way. Therefore the main goal of the resonant depolarization method is to calibrate and test faster techniques using special lattice without solenoid fields. The other, even longer, absolute method of energy calibration is measuring the cross sections of the well-known resonances, for example, of ϕ and ω mesons.

The fastest and the least precise method is based on power supplies readings and a complex calibration model. It gives the precision of about 1 MeV and is used for the preliminary energy adjustments. Another fast method is based on readings from the NMR probes installed in each main dipole. The data from the NMR should be calibrated and combined with readings from steering magnets located inside the achromatic bends to give the energy measurement. These measurements have very low statistical jitter of about $0.2 \cdot 10^{-4}$ but the systematic errors are still quite big $\sim 10^{-3}$.

The main energy measurement tool is based on the Compton backscattering [5]. The laser beam interacts with the electron bunch inside the main dipole and the germanium calorimeter detects spectra of the reflected photons. The short interaction length results in lower flux in comparison to the regular configurations where the interaction occurs in the straight section, but it also produces a non-trivial energy distribution of these photons that is used to compensate low statistics. Figure 2 shows the typical edge of the backscattered photons.

In January 2013, a detailed comparison of Compton, NMR and depolarization methods of energy measurements was done. During these tests the precise calibration coefficients for NMR based method have been worked out (Fig. 3).

LATTICE AND CLOSED ORBIT CORRECTION

Fast and reliable closed orbit and lattice correction algorithms are extremely important for successful operation of the VEPP-2000 because of regular energy change in very wide range.

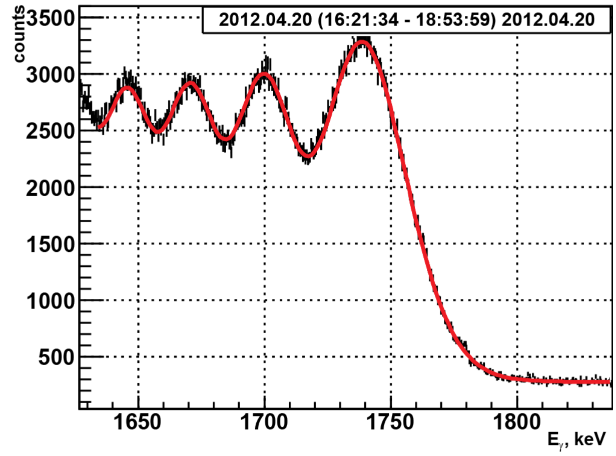

Figure 2: Compton backscattering spectrum at VEPP-2000. Reconstructed energy is $E = 993.662 \pm 0.016 MeV$.

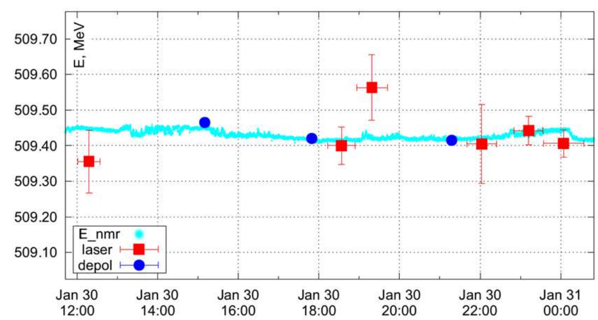

Figure 3: Comparison of three different method of energy measurements: blue circles – resonance depolarization; red squares Compton backscattering; light-blue curve – calibrated NMR.

The main task of the orbit correction in VEPP-2000 is to set the closed orbit as close to magnetic axes of elements as possible. After the best orbit is achieved, one can save and store ideal positions of the beam at locations of the BPMs and use them for future orbit corrections.

To correct the lattice of VEPP-2000, a program was written to implement expanded LOCO algorithms [6–8]. First, a model that best describes the experimental data is found. Second, based on this model, the corrections can be found that fix supposed distortions. The first task is usually performed by minimizing χ^2:

$$\chi^2 = \sum_i \frac{(M_{\text{mod},i} - M_{\text{mes},i})^2}{\sigma_i^2} = \sum_i V_i^2 \qquad (1)$$

where $M_{\text{exp},i}$ and $M_{\text{mod},i}$ are the experimental and theoretical sets of data points; σ_i is precision of corresponding measurement. If the model has the set of parameters p_j, then one can linearize the dependence $V_i(p_j)$:

$$\Delta V_i(\Delta p_j) \simeq \sum_j \frac{\partial V_i}{\partial p_j} \Delta p_j = -V_i, \qquad (2)$$

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Inverting the Eq. 2 with help of singular value decomposition (SVD) one can find the variation of the model parameters to reduce χ^2:

$$\Delta p_j = \sum_i \left(\frac{\partial V_i}{\partial p_j} \right) \Big|_{SVD}^{-1} (-V_i) \, . \tag{3}$$

Several iteration are needed because of nonlinear dependence of the model on the parameters.

Before the last season, one of the main drawbacks of the full lattice correction procedure was required time of 2-3 hours. During the shutdown in the summer of 2012, the replacement of the old CCD cameras with the new ones was performed. Additionally, the image treating software was rewritten so the overall time required for the correction decreased to 40-50 minutes.

LUMINOSITY PERFORMANCE

Last season started with unexpectedly small dynamic aperture in the collider ring. Investigations revealed that it was reduced by strongly nonlinear dipole correctors. Due to dense element placement, most steering magnets are located in the quadrupoles and create significant sextupole fields. To fix huge initial distortion of the uncorrected closed orbit, the superconducting final focus solenoids were slightly moved. This hardware orbit correction in combination with of other tuning tools allowed to reach very good results during the last season.

VEPP-2000 team steadily increases the luminosity production rate over the whole running period. Recently the careful lattice tuning with and the bunch length control resulted in world largest beam-beam parameter $\xi = 0.125$ per one IP that corresponds to the observed tune difference between frequencies of the π and σ modes of $\Delta\nu = 0.174$. This outstanding result was obtained during regular runs in the strong-strong regime at the energy level of $E = 392.5$ MeV per bunch.

Figure 4 illustrates comparison of the predicted luminosity and the one obtained in the best runs. Blue dashed line illustrates the case of constant lattice scaling with energy:

$$\beta^* = const; \; \epsilon \propto \gamma^2; \; L \propto \gamma^4. \tag{4}$$

The final focus solenoids could provide lower β^* at energies lower than 1000 MeV. Red dashed lines in Figure 4 represent the luminosity dependence in the case of variable final focus strength, so that:

$$\beta^* \propto \gamma; \; \epsilon \propto \gamma; \; L \propto \gamma^2. \tag{5}$$

Finally, there is another trick to boost the luminosity at lower energies. The final focus solenoids have complex inner structure with longitudinal and radial sectioning. At lower energies, it is possible to switch the current supplies to move the effective center of the final focus closer to the interaction point. Three solid lines on Fig. 4 illustrate the predicted limit of luminosity for three different configurations of the final focus fields. The tests of this approach revealed a dramatic decrease of dynamic aperture, probably because of increased influence of the solenoid fringe fields.

During the last season, VEPP-2000 collected data at energies down to 160 MeV per beam that is the world record for modern electron-positron colliders.

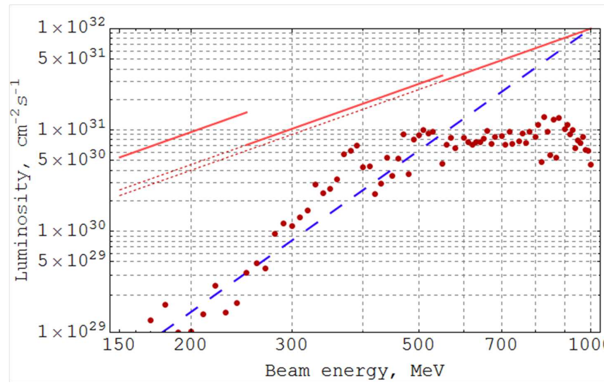

Figure 4: Luminosity dependence on energy. Lines – theoretical estimations; dots – performance in best runs over the entire VEPP-2000 operation time.

Figure 5 illustrates luminosity integrals in different energy ranges over the entire VEPP-2000 operation time. The last season was dedicated to the low energy range, but despite this the total integral is of the same order of magnitude as in the previous seasons aimed at higher energies.

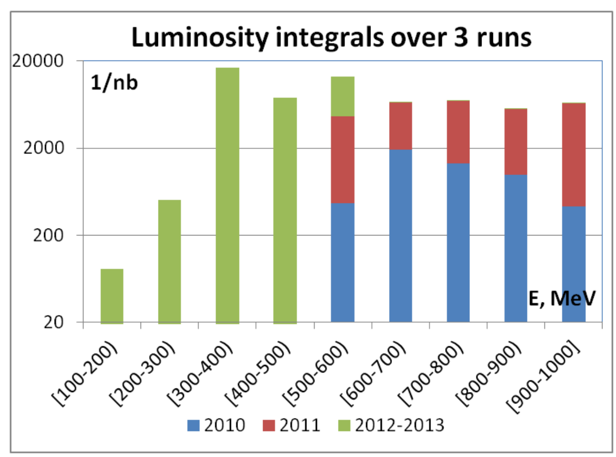

Figure 5: Luminosity integrals collected by SND in different energy ranges over the entire VEPP-2000 operation time.

LUMINOSITY MONITORING

There are a number of theoretical and empirical considerations regarding lattice configuration depending on the energy [8], but the last step of the final tuning is almost always unique and done manually. To optimixe the luminosity performance, the operator should fine tune parameters such as beta-functions at the IPs, closed orbit position, betatron tunes, chromaticity, betatron coupling and others.

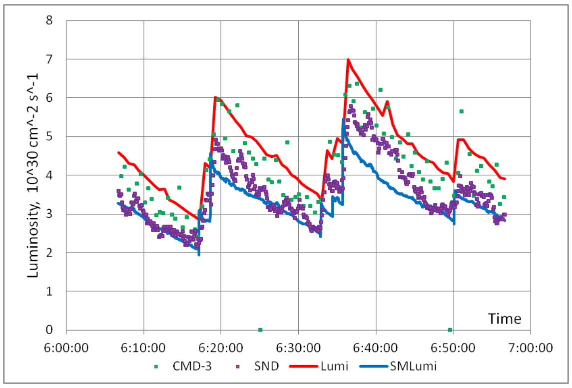

Figure 6: Comparison of the luminosity values from different measurements: green dots – CMD-3, purple dots – SND, red and blue lines – estimation methods.

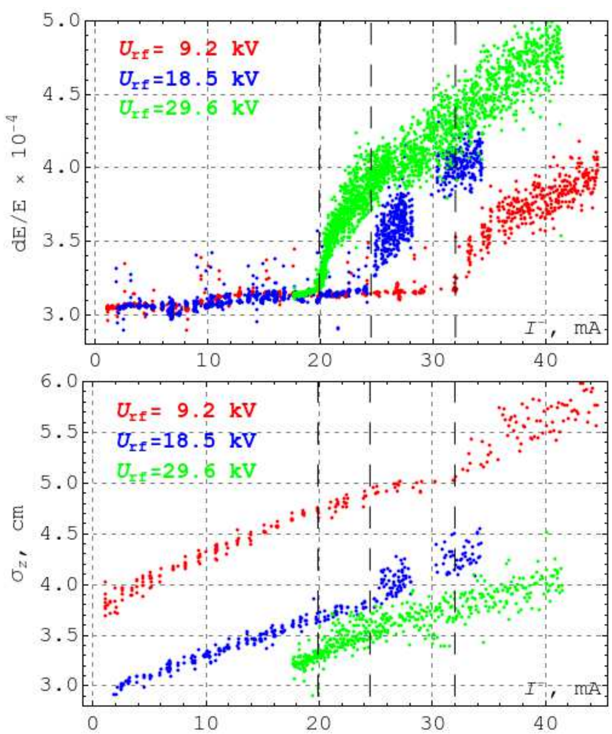

Figure 7: Correlation of the current dependence of the extracted energy spread and the measured bunch length.

To help the operator with this task both detectors provide luminosity measurements. Unfortunately, the time needed for one data point is too long and, in addition, at low energies statistics become to poor. To overcome these limitations, two luminosity estimation methods were developed based on machine diagnostics [9].

Both presented methods of luminosity estimation assume that the accurate optics model of the real accelerator ring is available. If there are no focusing perturbations in the lattice other than those caused by the collisions, and thus located at the IP, one can use known transport matrices to evaluate the beam sizes at the IPs from the beam size measurements by CCDs.

The first method was implemented in the software called "LumiMeter" and is based on the fitting of the emitances and effective beta functions for e^- and e^+ bunches and both IPs. The second method was implemented in Java code called "SMLumiMeter" and is based on fitting of the set of second moments for both bunches.

Bunch lengthening

At the end of the last experimental season, the e^- and e^+ phi-dissectors were installed at VEPP-2000, that can measure bunch length with the precision of about 2 mm [3]. The bunch length measurements combined with energy spread estimations produced by "SMLumiMeter" revealed the presence of microwave instability that could be controlled by RF voltage (Fig. 7).

UPGRADE STATUS

Starting from the first experimental season it became obvious that old injection complex strongly limits the operation of the VEPP-2000 at high energies. Last season also demonstrated insufficient positron production range at lower energies when the beam lifetime in the collider goes down.

To overcome the listed difficulties, a deep upgrade of the injection system was started in July 2013 at VEPP-2000. Booster BEP will be modified to be able to cover the full energy range of VEPP-2000. In the new configuration, particles will be transported to the BEP from the VEPP-5 injection system by about 200 meters channel. Table 2 shows comparison of the old and new injection systems. Figure 9 illustrates VEPP-2000 facility after upgrade.

Table 2: Comparison of the Old and New Injection Facilities

e^+ production rate, e^+/sec	2×10^7	3×10^8
e^- production rate	10^9	$1 \times 10^{1}1$
Max booster energy, MeV	825	1000
Booster accum. energy, MeV	125	500
Max pulses rate, Hz	0.7	12.5

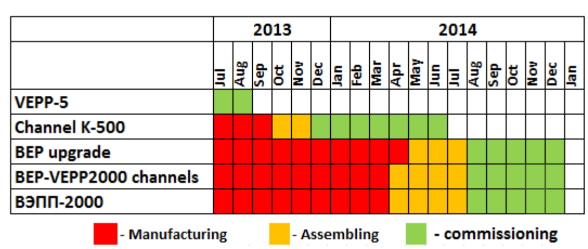

Figure 8: VEPP-2000 upgrade schedule.

In general, there are five major parts of the started upgrade. First of all VEPP-5 injection system should be fully commissioned and become a reliable source of high quality beams. Next, some elements of new channel K-500

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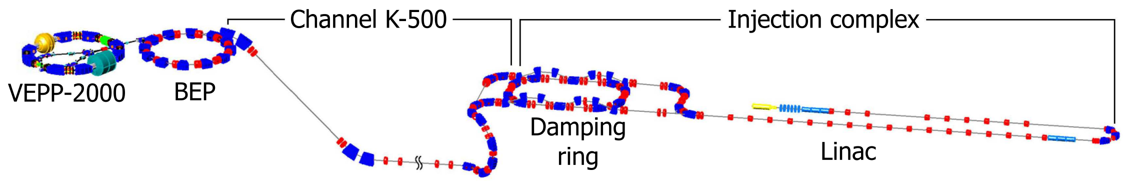

Figure 9: Layout of the facilities related to the VEPP-2000 collider after upgrade.

should be manufactured, installed and tested. The third part is aimed at booster BEP upgrade. Some subsystems of VEPP-2000 will be modified for better beam control. In addition, the old transport lines between BEP and VEPP-2000 were designed for the old BEP energy and, therefore, must be significantly modified. Figure 8 illustrates a timetable for the listed activities.

Due to funding limitations it was decided to upgrade the BEP booster rather than to build a completely new ring. The main dipoles and quadrupoles will be manufactured by reshaping existing yokes. The preserved bending radius and cross section of conductors apply extreme requirements to the design. At 1GeV, it will be possible to operate BEP only in rapid-cycling mode with fast ramping up and down with top guiding field almost 26 kGs. The first prototype of the upgraded main dipole was recently tested and demonstrated all necessary parameters (Fig. 10). Quadrupole prototype manufacturing is in progress. The vacuum chamber will be also re-shaped by compressing and milling the old one.

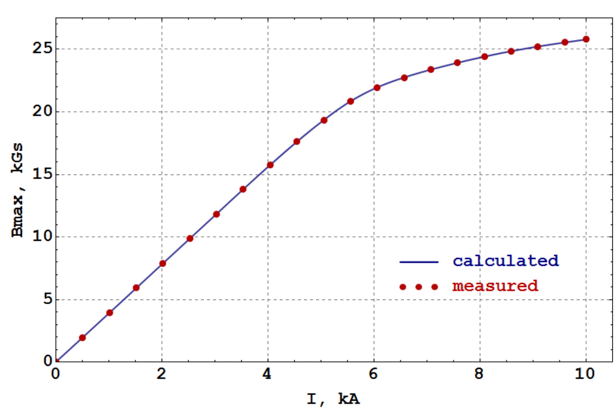

Figure 10: Comparison of the calculated and measured magnetic field vs current for the upgraded BEP dipole.

CONCLUSION

Correction techniques from precise magnet alignment to versatile beam-based algorithms, as well as bunch length adjustments and manual fine tuning, based on computer control, allowed to reach the limits of the VEPP-2000. It became obvious that main limitations come from the obsolete injection facility, therefore its upgrade will be necessary for the long term, high luminosity performance of the VEPP-2000. The long shutdown for the serious upgrade was stared in July of 2013.

Among the main VEPP-2000 achievements over the past years are:

- The total integral in the energy range $160 \div 1000$MeV is about $64pb^{-1}$.
- The world record of the beam-beam parameter $\xi = 0.125$ obtained during the regular run.
- Data collection in lowest energy range for the e^+e^- colliders down to 160 MeV per bunch.

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