STATUS AND PERSPECTIVES OF THE VEPP-2000 COMPLEX*

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Abstract

The VEPP-2000 is a modern electron-positron collider at BINP. Last season in 2012–2013 was dedicated to the energy range of 160÷520 MeV per beam. The application of round colliding beams concept along with the accurate orbit and lattice correction yielded the high peak luminosity of $1.2\cdot10^{31}$ cm^{-2}s^{-1} at 500 MeV with average luminosity of $0.9\cdot10^{31}$ cm^{-2}s^{-1} per run. The peak luminosity limited only by beam-beam effects, while average luminosity – by present lack of positrons in whole energy range of 160÷1000 MeV. To perform high luminosity at high energies with small dead time the top-up injection is needed. At present new electron and positron injection complex at BINP is commissioned and ready to feed VEPP-2000 collider with intensive beams with energy of 450 MeV. Last calendar 2014 year was dedicated to the full/partial upgrade of complex's main parts.

VEPP-2000 OVERVIEW

The VEPP-2000 collider [1] exploits the round beam concept (RBC) [2]. This approach, in addition to the geometrical factor gain, should yield the significant beam–beam limit enhancement. An axial symmetry of the counter-beam force together with the *X–Y* symmetry of the transfer matrix between the two IPs provide an additional integral of motion, namely, the longitudinal component of angular momentum $M_z = x'y - xy'$. Although the particles' dynamics remains strongly nonlinear due to beam–beam interaction, it becomes effectively one-dimensional.

The RBC at VEPP-2000 was implemented by placing two pairs of 13 T superconducting final focusing solenoids into two interaction regions (IR) symmetrically with respect to collision points. There are several combinations of solenoid polarities that satisfy the RBC requirements, with different type of eigenmodes of betatron oscillations. Finally it was found that only 'flat' combinations (+− +− or +− −+) provide enough dynamic aperture (DA) for effective collider operation. This optics satisfies the RBC approach if the betatron tunes lie on the coupling resonance $\nu_1 - \nu_2 = 2$ to provide equal emittances via eigenmodes coupling.

The layout of the VEPP-2000 complex as it worked until 2013 is presented in Fig. 1. The complex consisted of the injection chain (including the old beam production system and Booster of Electrons and Positrons (BEP) with an energy limit of 800 MeV) and the collider itself with two particle detectors, Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector (CMD-3), placed into dispersion-free low-beta straights. The main design collider parameters are listed in Table 1.

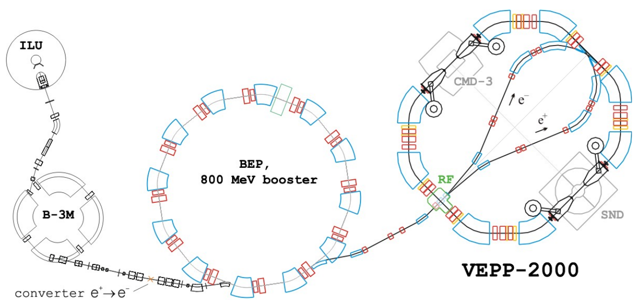

Figure 1: VEPP-2000 complex layout.

Table 1: VEPP-2000 main parameters @ *E* = 1 GeV.

Parameter	Value
Circumference (C)	24.3883 m
Energy range (E)	200÷1000 MeV
Number of bunches	1 × 1
Number of particles per bunch (N)	1×10^{11}
Betatron functions at IP ($\beta^*_{x,y}$)	8.5 cm
Betatron tunes ($\nu_{x,y}$)	4.1, 2.1
Beam emittance ($\varepsilon_{x,y}$)	1.4×10^{-7} m rad
Beam–beam parameters ($\xi_{x,y}$)	0.1
Luminosity (L)	1×10^{32} cm^{-2} s^{-1}

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

BEAM DIAGNOSTICS

Diagnostics is based on 16 optical CCD cameras that register the visible part of synchrotron light from either end of the bending magnets and give full information about beam positions, intensities and profiles. In addition to optical beam position monitors (BPM) there are also four electrostatic pickups in the technical straight sections, two photomultipliers for beam current measurements via the synchrotron light intensity, and one beam current transformer as an absolute current monitor.

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During last season VEPP-2000 was equipped with two phi-dissectors [3] – stroboscopic image dissector with electrostatic focusing and deflection, that gives information about e^+/e^- longitudinal distribution of particles and bunch length.

EXPERIMENTAL RUNS

VEPP-2000 started data-taking with both detectors installed in 2009 [4]. The first runs were dedicated to experiments in the high-energy range, while during the last 2012 to 2013 run the scan to the lowest energy limit was done. Apart from partial integrability in beam-beam interaction the RBC gives a significant benefit in the Touschek lifetime when compared to traditional flat beams. This results in the ability of VEPP-2000 to operate at an energy as low as 160 MeV — the lowest energy ever obtained in e^+e^- colliders.

The averaged over 10% of best runs luminosity obtained by CMD-3 detector during the last three seasons is shown in Fig. 2 with red points. The red lines overestimate the hypothetically achievable peak luminosity. The blue dashed line shows the beam–beam limited luminosity for a fixed machine lattice (energy scaling law $L \propto \gamma^4$). It was successfully exceeded due to β^* reduction to 4÷5 cm available at low energies.

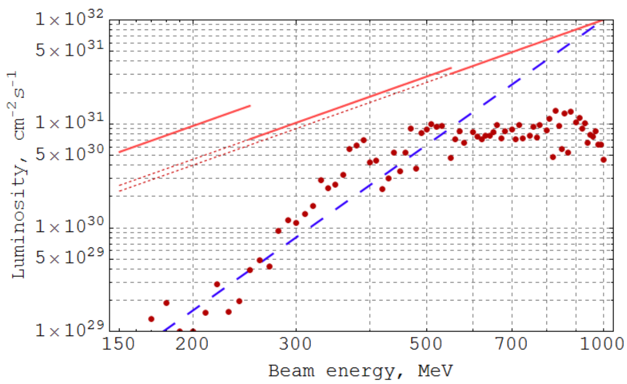

Figure 2: VEPP-2000 luminosity.

At high energies (>500 MeV) luminosity was limited mostly by an insufficient positron production rate. At energies over 800 MeV the necessity of energy ramping in the collider storage ring additionally restricts the luminosity. Only for middle energy range 300÷500 MeV the luminosity is really limited by the beam–beam effects, especially by the flip-flop [5]. At the lowest energies the main limiting factors are the small DA, IBS, and low beam lifetime.

BEAM–BEAM PARAMETER

We can define the 'achieved' beam–beam parameter as:

$$\xi_{\mathrm{lumi}} = \frac{N^- r_e \beta^*_{\mathrm{nom}}}{4\pi\gamma\sigma^{*2}_{\mathrm{lumi}}}, \qquad (1)$$

where the beta function is nominal while the beam size is extracted from the fairly measured luminosity.

In Fig. 3 the correlation between achieved and nominal beam-beam parameters is shown for the full data at the given energy $E = 392.5$ MeV. 'Nominal' parameter defined as (1) but with unperturbed nominal beam size, thus being the measure of beam current. After thorough machine tuning the beam–beam parameter achieves the maximal value of $\xi \sim 0.09$ during regular work (magenta dots in Fig. 3).

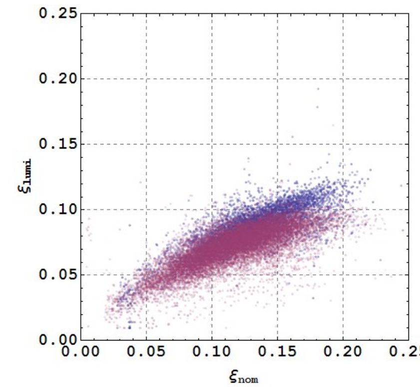

Figure 3: Achieved beam–beam parameter at 392.5 MeV.

LONG BUNCH

While studying the dependence of beam–beam threshold on bunch length at relatively low energy of 392.5 MeV it was found that the RF voltage decrease from 30 kV to 17 kV gives a significant benefit in the maximal value of ξ (blue dots in Fig. 3) up to ξ ~ 0.12 per IP. The cross-check for beam–beam parameter measurement is the analysis of the coherent beam oscillation spectrum.

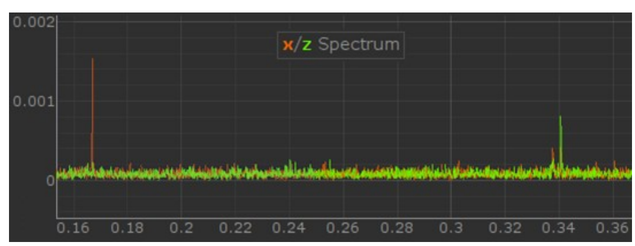

Figure 4: Beam-beam tune-shift @ 392.5 MeV.

In Fig. 4 one can find two pairs of σ- and π-modes tunes equal to 0.165 and 0.34, respectively. The total tune shift of $\Delta\nu = 0.175$ corresponds to ξ per one IP equal to:

$$\xi = \frac{\cos(\pi\nu_\sigma) - \cos(\pi\nu_\pi)}{2\pi\sin(\pi\nu_\sigma)} = 0.124. \qquad (2)$$

The Yokoya factor here is taken to be equal to 1 due to the fact that oscillations with very small amplitude (~5 μm = 0.1 σ*) were excited by a fast kick and the spectrum was investigated for only 8000 turns. During this short time beam distribution is not deformed by an oscillating counter beam and remains Gaussian [6].

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The observed beam-beam limit enhancement correlated with bunch lengthening firstly believed to be an experimental evidence of predictions [7] of beam-beam interaction mitigation for the bunch slightly longer than β^* due to second integral of motion arrival. The bunch lengthening in our particular case comes not only from the RF voltage decrease itself, but also from microwave instability, which was observed at low energies with a low RF voltage above a certain bunch intensity. Later it was shown in simulations [8] that finite synchrotron oscillations should demolish full integrability of beam-beam interaction.

Bunch lengthening

The length of an electron bunch in a storage ring depends on the peak current of the bunch. The two effects which alter the length are potential well distortion and microwave instability. For potential well distortion the bunch length varies due to the electro-magnetic fields induced by the electrons modify the RF voltage as seen by the bunch. This effect is present even at very low currents. The second effect, microwave instability, is only observed after a certain threshold current has been reached. Above this threshold the energy spread of the beam increases until the peak current of the bunch reduces to equal the threshold current again.

Direct observation of the onset of microwave instability in the VEPP-2000 was possible at an intermediate energy. Measurements have been carried out for electrons with intensities up to 50 mA at energy equal to 478 MeV with different values of RF voltages in presence of positrons with infinitesimal intensity. In these experiments all three beam dimensions were recorded as a function of bunch current. A subsequent experiments for positrons shows the same dependencies as for electrons.

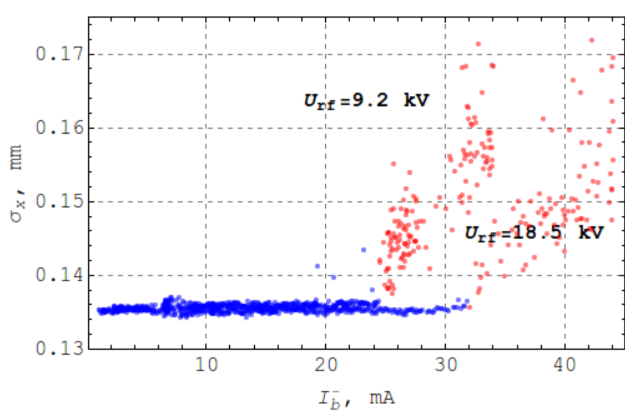

Figure 5: Horizontal beam size on 4M1L CCD (in place with non zero dispersion) as a function of beam current @ E=480 MeV.

Throughout the experiment σ_x remained constant below certain threshold (see Fig. 5, where blue dots show bunch size below threshold, red ones – above), confirming that the beam was indeed below the threshold of microwave instability. The variation of the bunch length with the beam current is given in Fig. 6. The microwave instability threshold appears at around 24.5 mA and 32 mA for RF voltages equal 9.2 kV and 18.5 kV respectively.

The bunch length data below threshold has been fitted to the model [9] described by equation:

$$\sigma_z^3 - \sigma_{z0}^2\sigma_z = \frac{\alpha_p |Z/n|_{eff} R^3}{\sqrt{2\pi}(E/e)\nu_s^2} I_b, \qquad (3)$$

where I_b is the average beam current, e is the electron's charge, R is the ring average radius, E is the beam energy and ν_s is the synchrotron tune. The magnitude of the effect depends on the reactive part of the effective longitudinal coupling impedance |Z/n|. The dashed lines on the figure is a curve derived using (3) for |Z/n| = 2.32 Ohm.

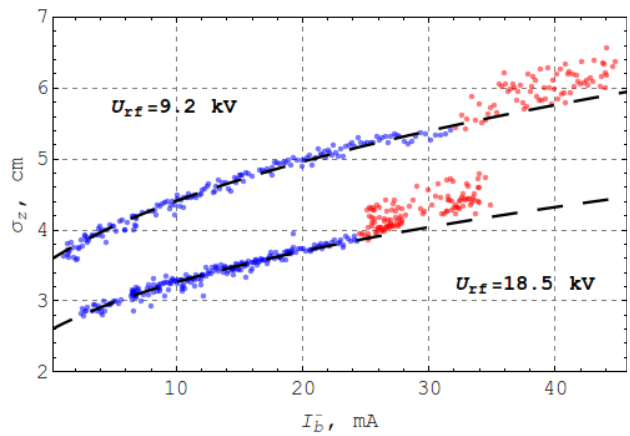

Figure 6: Bunch length as a function of beam current @ E=480 MeV.

Our capabilities do not allow to measure the energy spread directly, but estimation can be done by methods developed [10] during VEPP-2000 operations. This methods based on measurements of beam transverse sizes along the ring with further fitting the emittances end effective beta functions to known optical model of the ring assuming that there is no focusing perturbations other than those caused by collisions. In Fig. 7 one can find beam energy spread is estimated in such a way.

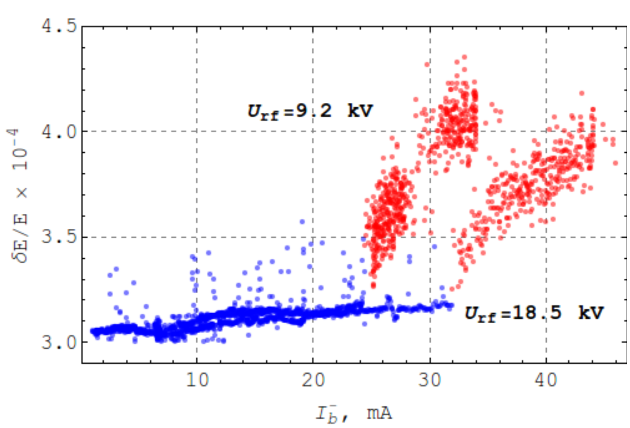

Figure 7: Beam energy spread as a function of beam current @ E=480 MeV.

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The synchronous phase shift is being determined as a difference between phase of beam longitudinal distribution centre of mass and phase of RF system reference signal. Dependence of synchronous phase on beam current allow to determine a value of a bunch coherent energy loss. Results are shown in Fig. 8, where dashed line corresponds to coherent energy loss caused only by RF cavity HOM frequencies. As one can see from the pictures the contribution of the RF cavity is comparable (or slightly less) with the contribution of all the vacuum chamber in the ring.

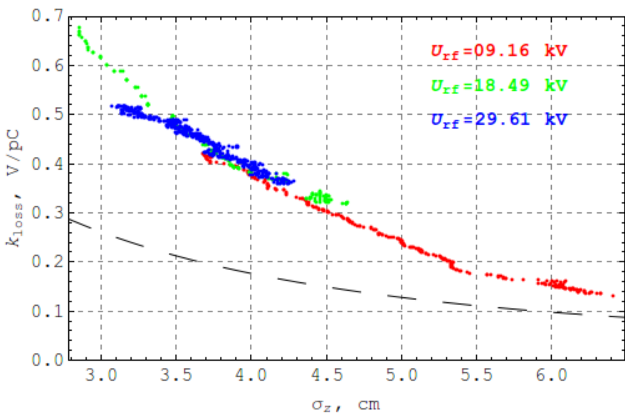

Figure 8: Longitudinal loss factor @ E=480 MeV.

UPGRADE MOTIVATION

VEPP-2000 electron positron collider was commissioned and spent three successful runs 2010-2013 collecting data at whole energy range of 160÷1000 MeV per beam [10]. During this work VEPP-2000 used the injection chain of its predecessor VEPP-2M [11]. That machine worked at lower energy (< 700 MeV) and showed luminosity 30 time lower than designed value of 10^{32} cm^{-2}s^{-1} for VEPP-2000 at 1 GeV. As a result the positron production rate was not enough to achieve beams intensity limited only by beam-beam threshold. This restriction will be cured by link up via 250 m beamline K–500 [12] to the new injection complex VEPP-5 [13] capable to produce intensive electron and positron high quality beams at energy of 450 MeV (see Fig. 9).

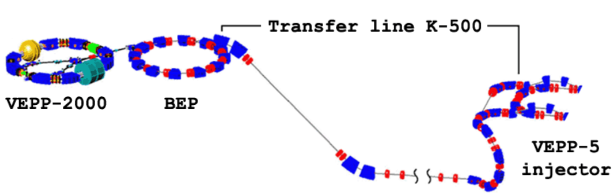

Figure 9: VEPP-2000 accelerator complex after upgrade.

Another VEPP-2000 efficiency limitation comes from maximal energy of the booster ring BEP [14] limited at the value of 800 MeV. Even with unlimited beams production rate beam-beam parameter being at the threshold after injection inevitably decrease after acceleration in the collider ring $\xi \propto 1/\gamma^2$. In addition dead time during acceleration process and the complexity of acceleration of colliding beams close to the threshold mean the necessity of the top-up injection.

BEP OVERVIEW

Booster synchrotron BEP dedicated to capture, cooling and storage of hot 125 MeV positrons from conversion system operated since 1991. It consists of 12 FODO cells. Each cell houses 30° sector dipole, two quads and straight, used for RF-cavity, kickers, injection/extraction septum, diagnostics, vacuum pumping. Booster layout is presented in Fig. 10, main parameters of BEP after upgrade are listed in Table 2.

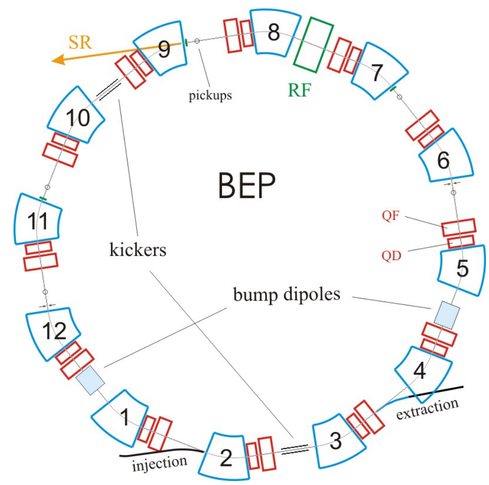

Figure 10: Booster synchrotron BEP layout.

Table 2: Modified BEP Main Parameters @ E = 1 GeV.

Parameter	Value
Perimeter, Π	22.35 m
Revolution frequency, f_0	13.414 MHz
Bending radius, r_0	128 cm
RF harmonic, q	13
Synchrotron radiation loss	70 KeV/turn
Emittances, ε_x, ε_y	$8.6{\cdot}10^{-6}$, 10^{-8} cm
Betatron tunes, ν_x, ν_y	3.4, 2.4
Momentum compaction, α_p	0.06

BEP UPGRADE STATUS

Magnetic system

To achieve the target beam energy all magnetic elements should be significantly strengthened [15]. The main idea of magnets upgrade is the use of existing coils, power supplies and whole infrastructure. Fields increase arises both from iron reshaping with aperture reduction and feeding current boost up to 10 kA.

Prototype dipole magnet was produced at the end of 2013. It's measured field distribution is shown in Fig. 11. Main efforts of quadrupole modification were

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aimed to reproduce strongly non-linear saturation curve of dipole.

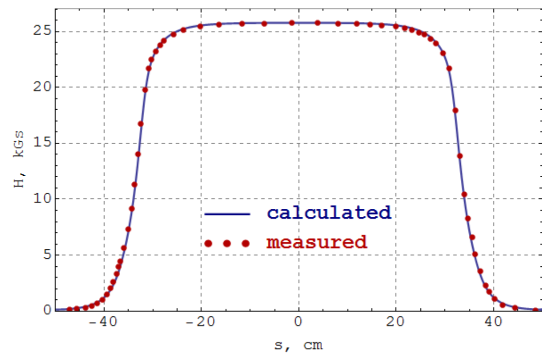

Figure 11: Field longitudinal distribution $B_y(s)$ at 9.9 kA.

Vacuum system

One cell vacuum chamber consists of extruded aluminium segment inside dipole and focusing doublet and stainless steel chamber with pumping equipment port. To use the old system after components modernization aluminium chamber (a) deformed locally inside dipole magnet (b) and small quad QD (c) (see Fig. 12). In order to decrease QD strength and reduce deformation the BEP working point was moved from (3.46, 2.85) to (3.4, 2.4).

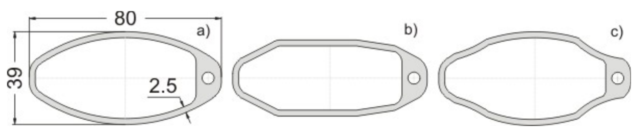

Figure 12: Vacuum chamber cross-section.

RF system

Since the energy loss increases at higher energy and achieves 70 KeV/turn new copper RF cavity was manufactured in BINP workshops. It will operate with 174.376 MHz frequency and 110 kV voltage.

Injection / extraction

New injection septum magnet is needed to receive 450 MeV beams from VEPP-5. 25° pulsed magnet with 10 mm aperture and field value of 34 kGs is completed and will be installed after magnetic measurements. Extraction system remains completely unchanged.

Slow-pulsed closed orbit distortion of ~25 mm in horizontal direction (so called "bump") is needed for beam extraction. Old system of additional windings in 4 dipoles becomes very ineffective at high energy due to strong iron saturation. Instead two 30 cm pulsed (2.5 ms) laminated C-shape magnets will be installed with 1.7 kGs field.

TRANSFER LINE BEP-VEPP

The transport of accelerated to 1 GeV bunches from BEP to VEPP-2000 collider needs significant modernization of transfer line. The most important one is the manufacturing of new bending magnets (17.2°, 41.2°) with the same radius and field as BEP dipoles but smaller gap of 12.8 mm and 2 turns/pole coil instead 5 turns/pole in BEP dipoles. Fed in series with BEP magnets channel's ones should have the same field-current dependence.

CONCLUSION

Round beams give a serious luminosity enhancement. The achieved beam-beam parameter value at middle energies amounts to $\xi \sim 0.1$–0.12. VEPP-2000 is successfully taking data with two detectors across the whole designed energy range of 160÷1000 MeV with a luminosity value two to five times higher than that achieved by its predecessor, VEPP-2M [10]. At present the VEPP-2000 booster BEP is disassembled and passing through deep modernization to achieve top energy of 1 GeV, provide top-up injection and designed luminosity of the electron-positron collider.

REFERENCES

[1] Yu. Shatunov et al., "Project of a New Electron-Positron Collider VEPP-2000", EPAC'2000, Vienna, Austria, p.439.
[2] V.V. Danilov et al. “The Concept of Round Colliding Beams”, Proc. EPAC’96, Sitges, p. 1149 (1996).
[3] E.I. Zinin, PhD Thesis, Budker Institute of Nuclear Physics, 1984 (un Russian)
[4] M.N. Achasov et al., “First Experience with SND Calorimeter at VEPP-2000 Collider”, Nucl. Instrum. Meth. A 598 (2009) 31–32.
[5] D.B. Shwartz et al., “Recent Beam–Beam Effects and luminosity at VEPP-2000”, Proc. IPAC’14, Dresden (2014)
[6] P.M. Ivanov et al. “Experimental Studies of Beam–Beam Effects at VEPP-2M”, Proc. Workshop on Beam–Beam Effects in Circular Colliders, Fermilab, p. 36 (2001).
[7] V.V. Danilov and E.A. Perevedentsev. “Two Examples of Integrable Systems with Round Colliding Beams”, Proc. PAC’1997, Vancouver, Canada, p. 1759 (1997).
[8] A. Valishev et al. “Beam-Beam Limit in an Integrable System”, Proc. NaPAC’13, Pasadena, p. 77 (2013).
[9] A. Hoffman and J.R. Maidment, “Current dependent phenomena in LEP”, CERN, LEP Note-168 (1979).
[10] A. Romanov et al. “Status of the Electron-Positron Collider VEPP-2000”, Proc. NaPAC’13, Pasadena, p. 14 (2013).
[11] G.M. Tumaikin et al., HEACC'1977, Serpukhov, USSR, p.443.
[12] I. Zemlyansky et al., "Electron and Positron Beams Transportation Channels to BINP Colliders", these proceedings (FRCA03).
[13] A. Starostenko et al., "Status of Injection Complex VEPP-5", these proceedings (TUY02).
[14] V.V. Anashin et al., "Damping Ring for Electrons and Positrons BEP", BINP preprint 84-114, Novosibirsk, 1984.
[15] D.B. Shwartz et al., “Booster of Electrons and Positrons (BEP) Upgrade to 1 GeV”, Proc. IPAC’14, Dresden (2014)

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