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Recommissioning and Perspectives of VEPP-2000 e^+e^- Collider*

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VEPP-2000 is electron-positron collider exploiting the novel concept of round colliding beams. After three seasons of data taking in the whole energy range of 160 ÷ 1000 MeV per beam it was stopped in 2013 for injection chain upgrade. The linking to the new BINP source of intensive beams together with booster synchrotron modernization provides the drastic luminosity gain at top energy of VEPP-2000.

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1. Introduction

The electron-positron collider VEPP-2M at Budker Institute of Nuclear Physics (BINP) was decommissioned in 2000 after 25 years of successful operation with several generations of particle detectors [1]. It was operating in the energy range of 180 ÷ 700 MeV per beam with maximal peak luminosity of 3×10^{30} cm^{-2}s^{-1}. The total integrated luminosity of about 100 pb^{-1} was collected that is more than one order of magnitude higher than about 6 pb^{-1} accumulated by various experimental groups in Frascati and Orsay in the c.m. energy range from 1.4 to 2 GeV. The decision to replace the existing collider with a new one, VEPP-2000 [2], was made in order to improve the luminosity and at the same time to increase the maximum attainable energy up to 1 GeV per beam. The luminosity increase comes from the implementation of novel concept of Round Beams while the energy range extension highly enriches the experimental program.

2. Round Colliding Beams

The VEPP-2000 collider exploits the round beam concept (RBC) [3]. This approach 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. Thus, there are several demands upon the storage ring lattice suitable for the RBC:

1) Head-on collisions (zero crossing angle);
2) Small and equal β functions at IP ($\beta^*_x = \beta^*_y$);
3) Equal beam emittances ($\varepsilon_x = \varepsilon_y$);
4) Equal fractional parts of betatron tunes ($\nu_x = \nu_y$).

The first three requirements provide the axial symmetry of collisions while requirements (2) and (4) are needed for *X-Y* symmetry preservation between the IPs.

A series of beam-beam simulations showed the achievable values of beam-beam parameters as large as $\xi \sim 0.15$ without any significant blow-up of the beam emittances.

3. VEPP-2000 overview

During commissioning and first phase of operation VEPP-2000 collider used the injection chain of it's predecessor VEPP-2M. It consisted of the old beam production system with limited rate of 2×10^7 e$^+$/sec, and Booster of Electrons and Positrons (BEP) with an energy limit of 800 MeV. Collider itself hosts 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. In Fig. 1 one can find the collider layout.

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. Several combinations of solenoid polarities satisfy the RBC requirements, with different type of eigenmodes of betatron oscillations. Finally it was found that only 'flat' combinations (+− +− or +− −+) provide dynamic aperture (DA) sufficient for stable operation. This optics satisfies the RBC approach if the betatron tunes lie on the coupling resonance $\nu_x - \nu_y = 2$ to provide equal emittances via X-Y coupling.

Table 1: VEPP-2000 main parameters (at $E = 1$ GeV).

Circumference, C	24.39 m	Energy range, E	150–1000 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–beam parameters, $\xi_{x,z}$	0.1	Luminosity, L	1×10^{32} cm^{-2} s^{-1}

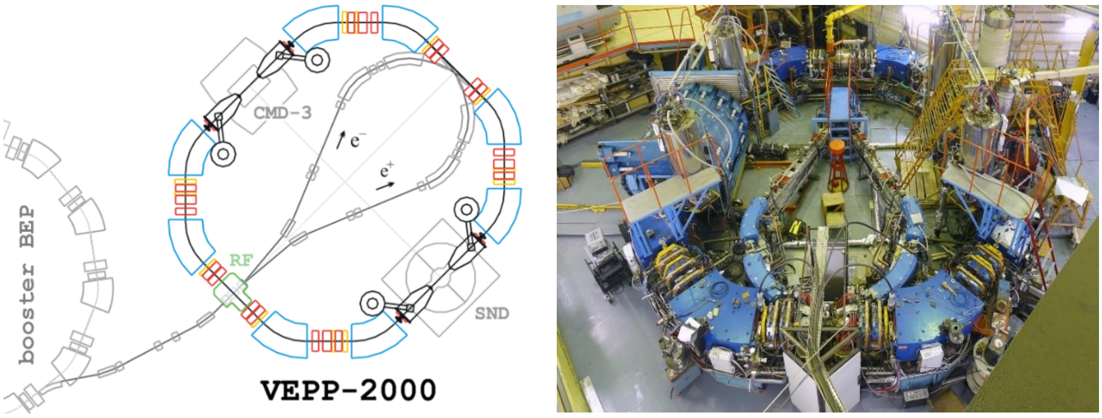

Figure 1: VEPP-2000 layout (left) and photo (right).

Beam diagnostics [4] is based on 16 optical CCD cameras that give full information about beam positions, intensities, and profiles (see Fig. 2). Additionally we use four electrostatic BPMs in the technical straight sections, two photomultipliers for beam current measurements from the synchrotron light intensity, and one beam current transformer as an absolute current monitor.

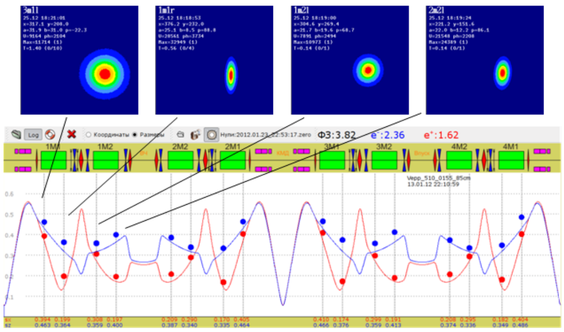

Figure 2: Beam profile measurements.

In addition, VEPP-2000 is equipped with two phi-dissectors for measurements of longitudinal distribution in e^+/e^- bunches. Beam energy is measured online by the Compton backscattering system [5].

4. Data taking during phase 1

VEPP-2000 started data-taking with both detectors installed in 2009. The first runs were dedicated to experiments in the high-energy range, 500 ÷ 1000 MeV [6, 7], while during the last 2012/2013 run the scan to the lowest energy limit was done (see Fig. 3). 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.

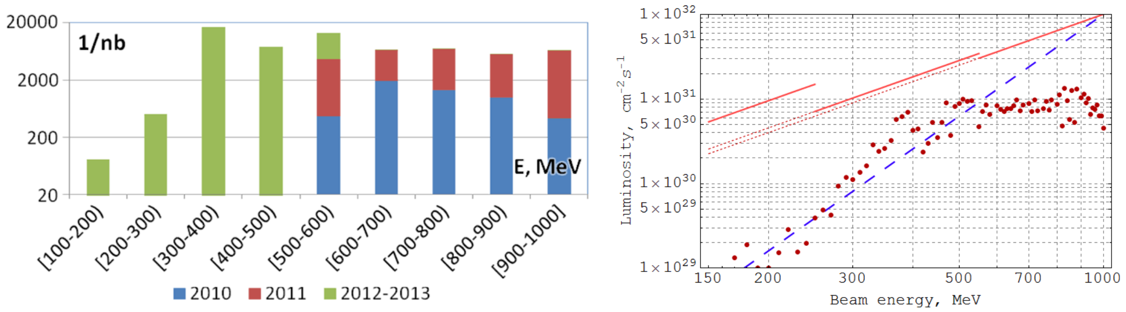

Figure 3: Delivered luminosity (left). Achieved luminosity at CMD-3 (right).

The averaged over 10% of best runs luminosity logged by CMD-3 detector during the last three seasons is shown in Fig. 3 (right) with red points. 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. At middle energies after thorough machine tuning the beam-beam parameter achieved the maximal value of $\xi \sim 0.12$ per one IP during regular work breaking a world record [8].

5. Complex upgrade and recommissioning

During first phase of operation, the luminosity of VEPP-2000 at top energies (see Fig. 3, left) was limited by: 1) insufficient e^+ production rate and 2) necessity of acceleration at VEPP-2000 ring. In order to achieve the design luminosity the machine was stopped in 2013 for upgrade of the whole injection chain. Firstly, the complex was linked up via a 250 m beamline K-500 [9] to the new BINP Injection Complex (IC) providing e^+,e^- beams at energy of 400 MeV (see Fig. 5). In addition, BEP was upgraded to provide top-up injection up to 1 GeV [10]. The transfer channels to VEPP-2000 ring were also reconstructed in order to cope with 1 GeV beam.

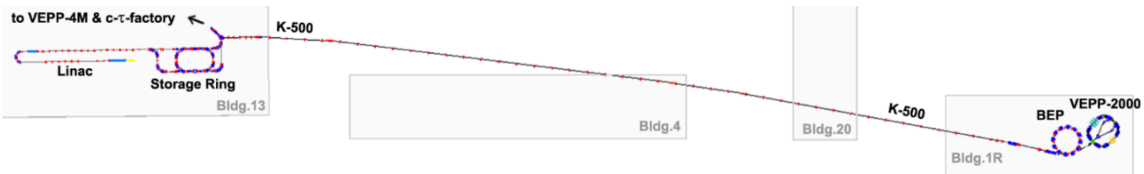

Figure 5: VEPP-2000 linked to the new Injection Complex.

IC consists of electron gun, 270 MeV driving electron linac, 510 MeV positron linac and damping ring (see Fig. 6). Damping ring stores and cools down both electron and positron beams for the next extraction to K-500 beam transfer line [11].

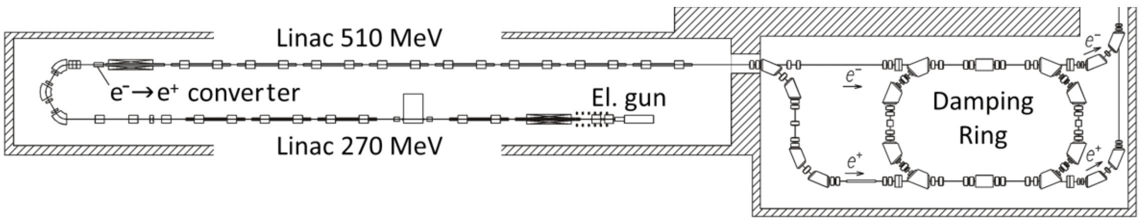

Figure 6: VEPP-5 Injection Complex Layout.

The K-500 beam transfer line was turned into operation in the end of 2015. This 250 m beamline consists of three parts: descent from DR to K-500 tunnel, regular FODO structure in the tunnel and ascent to the BEP hall. The fragment of the K-500 is shown in Fig. 7 (left).

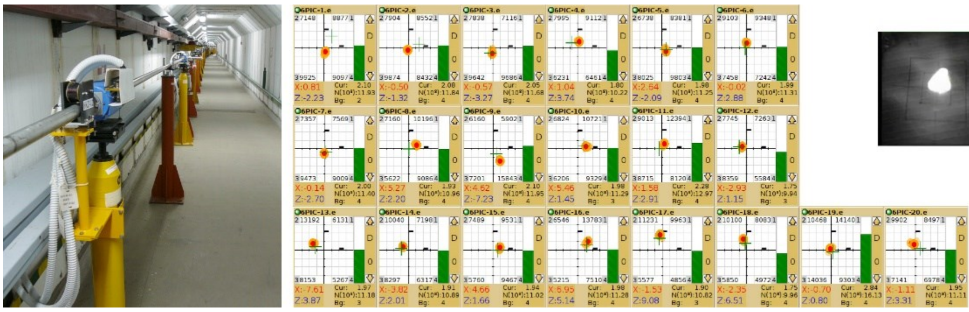

Figure 7: K-500 tunnel (left). Beam at BPMs along K-500 (center) and at scintillator screen (upright).

Booster BEP dedicated to capture, cooling and stacking of hot 125 MeV positrons from old 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 (see Fig. 8, right).

To achieve the 1 GeV all magnetic elements were strengthened during upgrade. The field of 2.6 T was achieved in the normal conducting dipole magnets [10] both by 20% reduction of gap and feeding current increase up to 10 kA. Due to feeding in series with dipoles by accurate return yoke profiling quads' excitation curve was fitted to the dipoles' one in whole energy range (see Fig. 9, left). The poles of quadrupoles also were remachined to increase the sextupole component needed for chromaticity compensation.

Figure 8: BEP new RF-cavity (left). BEP after assembly (right).

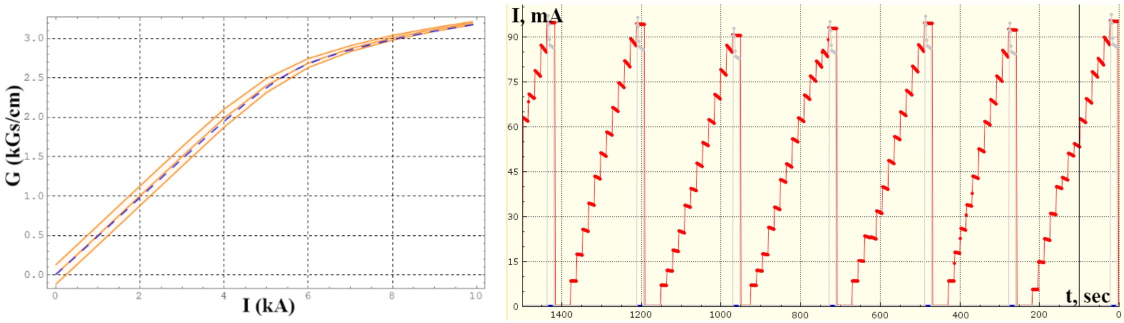

Figure 9: F-quad excitation curve compared to dipole's one (left). e^+ stacking @ BEP (right).

The aluminium vacuum chamber was deformed locally inside the dipoles and D-quads due to aperture reduction. In order to increase RF voltage up to 110 kV new 174.376 MHz cavity was installed (see Fig. 8, left). Beam diagnostic system based on six CCD-cameras and old-fashioned BPMs was improved with 2 new sensitive calibrated electrostatic pickups.

The upgrade was finished in the beginning of 2016. VEPP-2000 injection chain was successfully recommissioned [11]. The achieved positron stacking rate at BEP amounts to

$2{\times}10^8$ e^+/sec that exceeds corresponding value before upgrade in one order of magnitude (see Fig. 9, right).

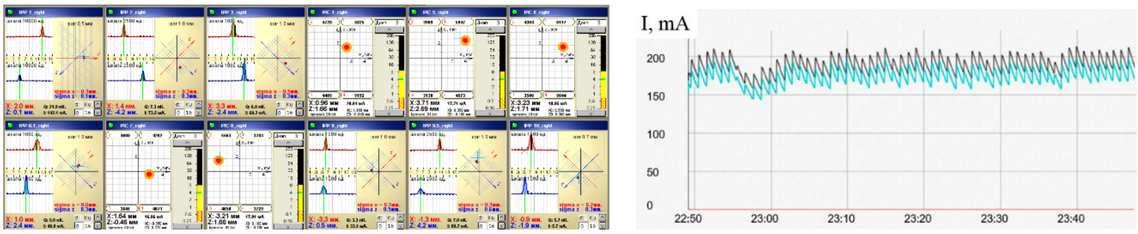

Figure 10: BEP-VEPP beam transfer (left). Beam scrubbing at VEPP-2000 (right).

Relatively small modifications were done in VEPP-2000 storage ring. Two additional kickers were installed to provide 1 GeV beam injection. All 8 two-sided copper mirrors used to extract the synchrotron light to CCD cameras were replaced. In 2016 the collider passed through the beam scrubbing procedure (see Fig. 10, right) working with switched-off SC solenoids. In addition, in this regime two beams e^+/e^- with low intensity were obtained to carry out the beam diagnostics alignment and tuning.

6. Conclusion

Round beam concept at VEPP-2000 proved to be powerful instrument for luminosity enhancement. To eliminate all the luminosity restrictions except for beam-beam effects VEPP-2000 injection chain was upgraded. During upcoming new run we intend to achieve the target luminosity and start it’s delivery to detectors with an ultimate goal to deliver at least 1 fb^{-1}.

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