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RECENT BEAM–BEAM EFFECTS AND LUMINOSITY AT VEPP-2000*

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Abstract

VEPP-2000 electron-positron collider dedicated last season 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 $1.2{\cdot}10^{31}$ cm^{-2}s^{-1} at 500 MeV with average luminosity of $0.9{\cdot}10^{31}$ 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 [1] to allow for the injection at the top energy of VEPP-2000 collider and to eliminate the present lack of positrons.

VEPP-2000 OVERVIEW

The VEPP-2000 collider [2] exploits the round beam concept (RBC) [3]. 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. 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 ($\nu_x = \nu_y$).

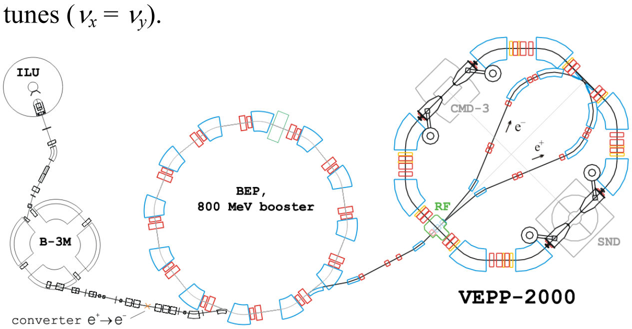

Figure 1: VEPP-2000 complex layout.

A series of beam–beam simulations in the weak-strong [4] and strong-strong [5] regimes showed the achievable values of beam-beam parameters as large as $\xi \sim 0.15$ without any significant blow-up of the beam emittances.

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.

Table 1: VEPP-2000 Main Parameters (at *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 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 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

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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.

EXPERIMENTAL RUNS

VEPP-2000 started data-taking with both detectors installed in 2009 [6]. 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.

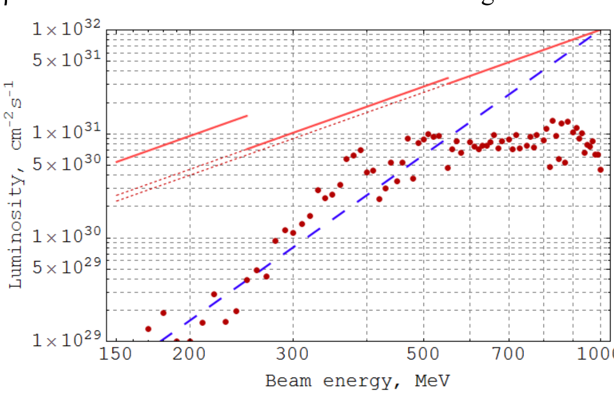

Figure 2: VEPP-2000 luminosity.

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 effect (see below). 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:

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

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).

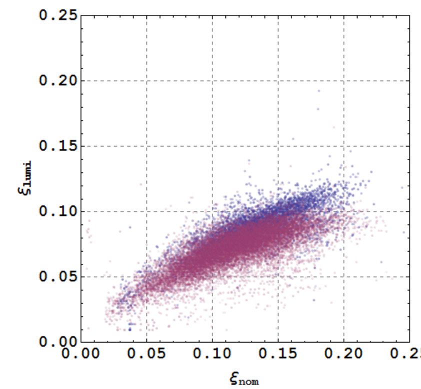

Figure 3: Achieved beam–beam parameter at 392.5 MeV.

FLIP-FLOP EFFECT

The beam–beam limit of $\xi_{lumi} \sim 0.1$ usually corresponds to the onset of a flip-flop effect: the self-consistent situation when one beam's sizes are blown-up while another beam's sizes are almost unperturbed. This flip-flop is probably caused by an interplay of beam-beam effects and nonlinear lattice resonances. One can see in the spectra of a slightly kicked bunch that the shifted tunes (π-mode) jumped to the 1/5 resonance in the case of a flip-flop (Fig. 4).

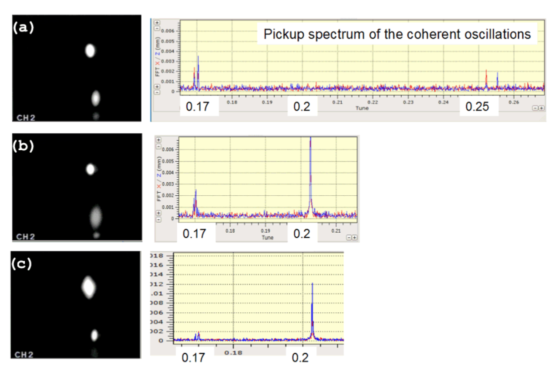

Figure 4: Coherent beam-beam oscillations spectra.

The type of flip-flop effect that has been observed seems to be avoidable by suppressing the resonance driving terms, as well as by tuning down the working point. Unexpected problems with DA prevent us from currently using the design working point. The acceptable bunch stacking rate and beam lifetime at collision is available only for the betatron tunes of $\{\nu\} \sim 0.13$–0.18.

In Fig. 4 the images from the online control TV camera are presented for the cases of regular beams (a), flipped

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electron beam (b) or positron beam (c). The corresponding spectra are shown on the right.

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 $\xi \sim 0.12$ per IP.

The cross-check for beam–beam parameter measurement is the analysis of the coherent beam oscillation spectrum. In Fig. 5 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 ($\sim 5\ \mu m = 0.1\ \sigma^*$) 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 [7].

Figure 5: Beam-beam tuneshift @ 392.5 MeV.

The observed beam-beam limit enhancement correlated with bunch lengthening firstly believed to be an experimental evidence of predictions [8] 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 [9]. Later it was shown in simulations [10] that finite synchrotron oscillations should demolish full integrability of beam-beam interaction.

The post-analysis of logged data was done after VEPP-2000 upgrade shutdown had started. At the energy of 392.5 MeV enough data was stored for short (a) and long (b) bunch cases. Only "strong-strong" data was selected, i.e. the beam currents difference does not exceed 10%. In Fig. 6 the measured horizontal sizes of electron (σ_{4M1Lx}) and positron (σ_{1M1Rx}) beams as a function of beam currents geometric average is shown. These particular sizes are chosen since these observation points are separated from IP by telescopic transformation matrix in horizontal plane and mirror-symmetric to each other. One can see from Fig.6 that in both cases flip-flop develops (unequal positron and electron beam sizes) for beams intensity higher than 15 mA that corresponds to $\xi_{nom} \sim 0.1$. But the long bunch tends to mitigate this troublesome due to specific luminosity degradation effect for higher intensities.

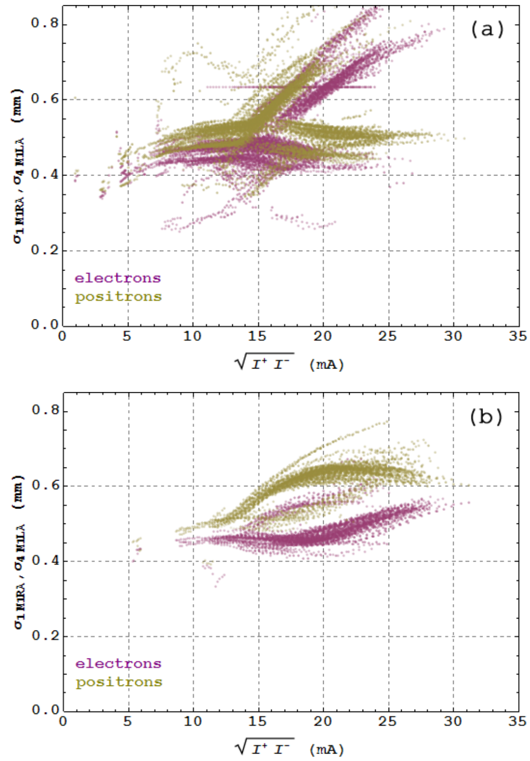

Figure 6: Beam sizes vs. beam current.

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 [11]. To reach the target luminosity, injection chain upgrade was started.

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