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ROUND COLLIDING BEAMS: SUCCESSFUL OPERATION EXPERIENCE

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Abstract

VEPP-2000 electron-positron collider operating in the beam energy range of 150-1000 MeV is the only machine originally designed for and successfully exploiting Round Beams Concept. After injection chain upgrade including link to the new BINP injection complex VEPP-2000 proceeded with data taking since 2017 with luminosity limited only by beam-beam effects. At the low energies (300-600 MeV/beam) the novel technique of effective emittance controlled increase by weak coherent beam shaking allowed to suppress the limiting flip-flop effect and resulted in additional luminosity gain factor of 4. The averaged delivered luminosity at the omega-meson production energy (2×391 MeV) achieved $L = 2\times10^{31}$ cm^{-2}s^{-1}/IP. At the top energies above nucleon-antinucleon production threshold the stable operation with luminosity of $L = 5\times10^{31}$ cm^{-2}s^{-1}/IP resulted in high average data taking rate of 2 pb^{-1}/day in 2020.

INTRODUCTION

The luminosity of any collider is restricted by beam-beam effects. In order to increase beam-beam threshold the Round Colliding Beam (RCB) concept was introduced [1]. This approach suggests an axial symmetry of the disruptive nonlinear counter-beam force together with the *X–Y* symmetry of the transfer matrix between IPs that results in 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 reduction of degrees of freedom thins out the resonance grid and suppress the diffusion rate resulting finally in a beam-beam limit enhancement.

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 ($\nu_x = \nu_y$).

VEPP-2000 OVERVIEW

VEPP-2000 is a small 24 m perimeter single-ring collider operating in one-by-one bunch regime in the energy range below 1 GeV per beam [2]. Its layout is presented in Fig. 1. The collider hosts two particle detectors [3, 4], Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector (CMD-3), placed into dispersion-free low-beta straights. The final focusing (FF) is realized using superconducting 13 T solenoids. The main design collider parameters are listed in Table 1.

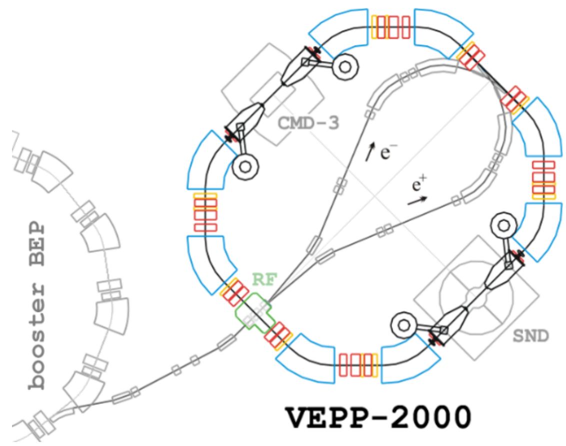

Figure 1: VEPP-2000 storage ring layout.

Table 1: VEPP-2000 Design Parameters (at E = 1 GeV)

Circumference, C	24.39 m
Energy range, E	150–1000 MeV
Number of bunches	1 × 1
Particles per bunch, N	1×10^{11}
Beta-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, $\xi_{x,z}$	0.1
Luminosity, L	1×10^{32} cm^{-2} s^{-1}

VEPP-2000 is served by booster BEP upgraded to perform top-up injection [5], which in turn was linked to the new BINP injection complex (IC) [6] via transfer channel.

Operation Modes

Several operation modes satisfying RCB are available at VEPP-2000 with different combinations of relative solenoids polarities. Only "flat" mode (+− +−) was found to have acceptable dynamic aperture (DA) with betatron tunes placed at the coupling resonance $\nu_x - \nu_y = 2$ to provide equal emittances via small X-Y coupling.

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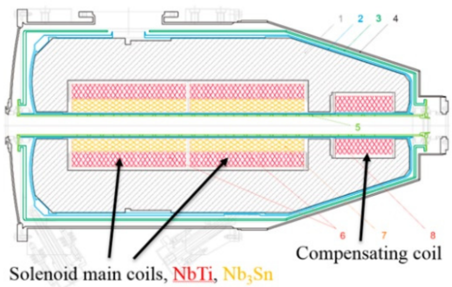

Figure 2: FF solenoid cross section.

Each solenoidal knob (see Fig. 2) in fact consists of several coils [7]. The small very forward coil S3 is intended to compensate the longitudinal field of CMD-3 detector. The main coil is split in longitudinal direction into two parts powered in series with middle point brought out to room-temperature commutation deck for quench control. At the beam energy range below 600 MeV usually only forward parts of main coils are used that helps effectively to move final focusing closer to IP.

All the solenoids configuration changes ("flat" to "möbius", "long" to "short") unfortunately results in strong closed orbit distortion and needs solenoids beam-based realignment [8].

Machine Tuning

VEPP-2000 operates in a wide energy range with strong saturation of magnetic elements at the top energy. At the same time, at low energies the fixed 1.3 T longitudinal field of CMD-3 detector (in contrast with SND detector which doesn't have magnetic field) significantly disturbs the focusing. Thus while energy scanning to achieve high machine performance of great importance is the machine tuning at each energy level.

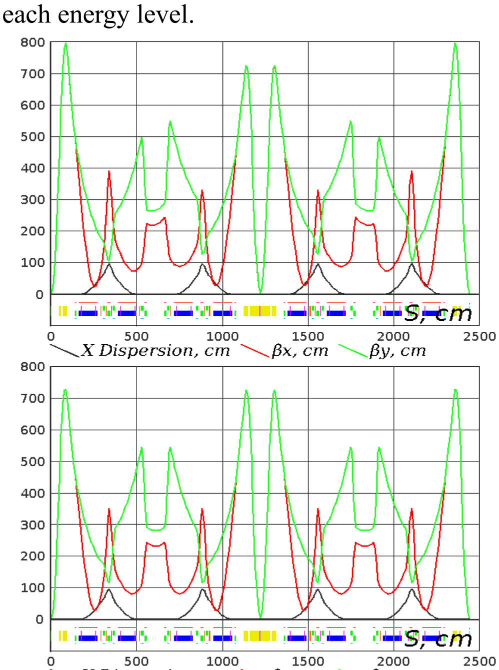

Figure 3: Lattice at 250 MeV distorted by CMD-3 detector's field. Tuned by S3 variation to keep equal β^* (up), and tuned with both S1, S3 (down).

To compensate the difference between two interaction regions (IR) at list to produce equal β^* values one can use different strength of S3 compensating coils in pairs. It finally results in the break of mirror symmetry (see Fig. 3). It was found that introduction of main S1 coils difference in addition can fix this drawback to almost ideal lattice.

The fine lattice functions correction including *X-Y* coupling is made routinely at VEPP-2000 using Orbit Response Matrix (ORM) analysis [9]. Very important it turned out to minimize the dipole correctors' currents that done with help of ORM as well. The reason is poor quality of the steering coils being embedded into quadrupoles due to lack of space that affects the DA.

BEAM-BEAM EFFECTS

Although the RCB works well and beam-beam parameter was significantly enhanced with total observed tuneshift over 0.2, the beams intensity is still limited by one of the beam-beam effects, namely flip-flop effect [10]. This "strong-strong" effect appears as additional meta-stable states of the two-beam system above given intensity threshold. Except the state with equal beams sizes there are two states with one of the beams being blown-up. The transverse distribution becomes strongly non-Gaussian, the coherent modes spectra indicates some interplay with machine non-linear resonances.

The flip-flop threshold is sensitive to several tuning knobs, in particularly to X-Y coupling and beta-functions misbalance at IP. In addition, the influence of bunch length on the threshold was observed.

Bunch Lengthening

While studying the dependence of beam-beam effects 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 beams intensity and luminosity threshold [10].

This enhancement comes from the bunch lengthening. In our particular case, this lengthening is the result of several effects. In addition to regular growth of radiative bunch length with voltage lowering two collective effects take place: potential well distortion and microwave instability. The latter one is observed at low energies with a low RF voltage above a certain bunch intensity [11].

The bunch lengthening close to the β^* value is believed to be helpful due to betatron phase averaging along the beam-beam interaction area [12].

Beam Shaking

At low energies where the radiative emittance is small but significant beta-squeeze is not allowed due to the DA shrinking thus leaving mechanical aperture not fully used the natural desire appears to increase the emittance. That allows with the same beam-beam parameter (counter beam particles density) to increase the beam current and, consequently, the luminosity.

There is no room to install the wiggler for emittance excitation as it was done at VEPP-2M [13]. Instead the idea was proposed to kick the beam weakly (in comparison to

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beam size) and frequently (in comparison to damping time). In the presence of strong nonlinear forces of colliding beam after the single kick the excited coherent oscillation decoheres very quickly thus increasing effective beam emittance [10].

This beam shaking experimentally results in beams emittance growth. This growth depends on the controllable shaker parameters (pulse amplitude, pulse duration, repetition rate). The properly increased emittance prevents the flip-flop development during injection cycle: the "strong" beam can't shrink to unperturbed size when "weak" beam oscillates with large amplitudes. In addition the beam lifetime is improved since the Touschek scattering is suppressed with increased emittance.

DATA TAKING

With target luminosity of $10^{32}\,cm^{-2}s^{-1}$ at the top energy, the scaling low is proportional to γ^4 for the fixed lattice (see dashed line in Fig. 4). With given aperture one can vary β^* value in a way to fix the beamsize in the FF solenoids that gives γ^2 scaling (dotted line). Unfortunately, with β^* lower than 4 cm the DA decrease to unacceptable size that force us to freeze the lattice again at very low energy range (blue dashed line).

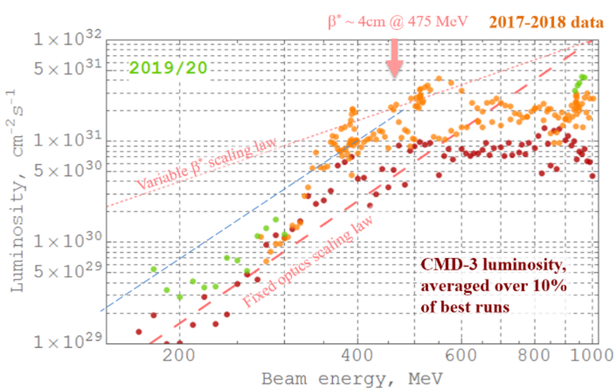

Figure 4: CMD-3 recorded luminosity averaged over 10% of best runs.

With the mentioned above tricks with flip-flop additional suppression the achieved luminosity already exceeds the discussed estimated limits at the middle energies. At the same time at top energy the achieved peak luminosity $L = 5\times10^{31}\,cm^{-2}s^{-1}$ is still lower than design value in a factor of two.

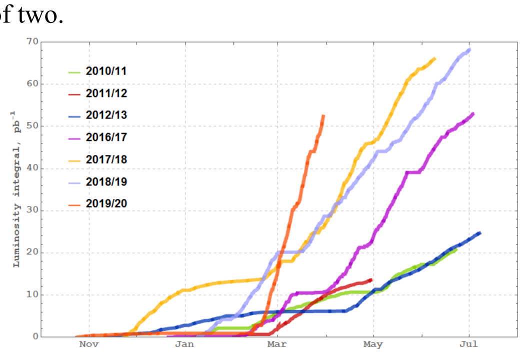

Figure 5: CMD-3 recorded luminosity integral.

The integrated luminosity as compared for several operating years is shown in Fig. 5. One should beware of direct comparison of integrals due to luminosity dependence on energy while different runs correspond to different experiments. However, the progress in data taking is clear.

Due to COVID-19 pandemic the run of 2020 lasted only for two months. Nevertheless, the record data taking rate of $2\,pb^{-1}$/day was achieved at the beam energies of 935-970 MeV (see Fig. 6).

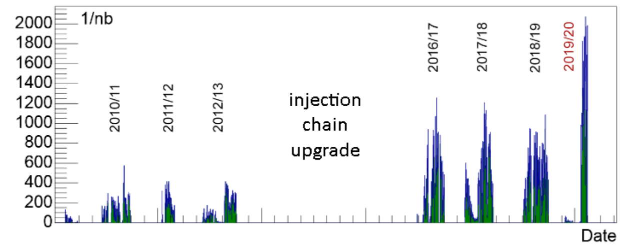

Figure 6: CMD-3 recorded luminosity integral/day.

CONCLUSION

Round beams give a serious luminosity benefit. VEPP-2000 with new BINP injector and upgraded booster is operating in all energy range of 150–1000 MeV with a luminosity progressing towards design value. Novel technique of "beam shaking" allows to suppress flip-flop effect and increase beams intensity at middle energies where the luminosity already exceeded design expectations.

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