THE CONCEPT OF ROUND COLLIDING BEAMS

V.V.Danilov, P.M.Ivanov, I.A.Koop, I.N.Nesterenko, E.A.Perevedentsev, D.N.Shatilov,
Yu.M.Shatunov and A.N.Skrinsky, BINP, Novosibirsk, Russia

Abstract

This paper presents the theoretical view and summary of the simulation results on the proposed use of round beams for increasing the luminosity in e$^+$e$^-$ colliders. Some other effects, related with the particle's energy change in the fields of opposite beam, are taken into account. The interesting consequence of the longitudinal kick from opposite beam, i.e. dependence of the beam-beam effects on the sign of momentum compaction factor, is discussed.

All the presented simulation results are obtained with the modified VEPP-2M optics adapted for the round beam operation.

1 ROUND COLLIDING BEAMS

The basic parameter of a collider is its luminosity L which in the case of short bunches is determined by the formula:

$$L = \frac{\pi\gamma^2\xi_z\xi_x\epsilon_x f}{r_e^2\beta_z}\cdot\big(1+\frac{\sigma_z}{\sigma_x}\big)^2,$$

where ξ_z, ξ_x are the space charge parameters whose maximum values are limited by the beam-beam effects; ϵ_x is the horizontal emittance of the beams, σ_z, σ_x are their r.m.s. sizes at the interaction point (IP), and β_z is the vertical β-function at the IP; f is the frequency of collisions at this IP, r_e is the classical electron radius, γ is the relativistic factor.

The space charge parameter per interaction is:

$$\xi_{x,z} = \frac{Nr_e}{2\pi\gamma}\frac{\beta_{x,z}}{(\sigma_x+\sigma_z)\sigma_{x,z}},$$

where N is the number of particles in the opposite bunch. Colliding bunches with maximum values of $\xi_z \simeq 0.05$ and $\xi_x \simeq 0.02$ are experimentally obtained on the VEPP-2M collider.

In the Novosibirsk ϕ-factory project, for attaining the high luminosity it is proposed to use colliding beams with round transverse cross-sections (just “round beams” in what follows) [1, 2]. In this case, the luminosity formula has the form:

$$L = \frac{4\pi\gamma^2\xi^2\epsilon f}{r_e^2\beta}.$$

Because of the X-Z symmetry, the space charge parameters are now the same in the two directions, so the horizontal parameter can be strongly enhanced. The evident advantage of round colliding beams is that with the fixed particle density, the tune shift from the opposite bunch becomes twice smaller than that in the case of flat colliding beams. Also well-known feature of round beams is that the linear beam-beam tuneshift becomes independent of the longitudinal position in the bunch thereby weakening the action of synchro-betatron resonances.

What does the round beam mean in practice?

1. Small and equal β-functions $\beta_0 = \beta_x, \beta_z$ at the IP.
2. Equal beam emittances ϵ_x, ϵ_z.
3. Equal betatron tunes ν_x, ν_z and no betatron coupling in the arcs.
4. Small and positive fractional tunes.

Requirements 1–3 are satisfied by the use of a strong solenoidal beam focusing in the interaction straight. At each passage, the longitudinal field H_l, with an integral along the straight section $H_l l = \pi HR$, rotates the transverse oscillation plane over $90°$, exchanges rôles of the two betatron modes, and thereby provides their full symmetry. Besides, the rotational symmetry of both the solenoidal focusing and the kick from the round opposite beam, complemented with the X-Z symmetry of the betatron transfer matrix between the collisions, result in *an additional integral of motion*. Namely, the longitudinal component of the angular momentum is conserved, provided that conditions 1–3 are met. Thus the transverse motion becomes equivalent to a one-dimensional motion. For the beam-beam effects, elimination of all betatron coupling resonances is of crucial importance, since they are believed to cause the beam lifetime degradation and blow-up. Moreover, it is possible to make the motion in the field of round opposite bunch very close to integrable with strong suppression of the strengths of all transverse resonances [3].

Item 4 is also important for the attainment of large values of the space charge parameter ξ_{max}.

The luminosity value required $L = 2\div3\cdot10^{33}$ cm^{-2}s^{-1} is attained at $\xi_{max} \simeq 0.1$ in an 11×11 multi-bunch mode ($f \simeq 140$ MHz) at presently available values of $\beta_0 \simeq 1$ cm, emittances $\epsilon \simeq 1.25\cdot10^{-5}$ cm · rad and a “moderate” bunch intensity of $N \simeq 5\cdot10^{10}$.

1.1 Longitudinal motion

For an increase in the ϕ-factory luminosity, a lattice is envisaged with values of β_0 almost as small as the bunch length σ_s. In this case, the particle energy change over the IP passage becomes important. If $\sigma_s \le \beta_0$, for particles with small amplitudes the longitudinally defocusing action excerted by the opposite beam is equivalent to a reduction ΔU in the accelerating voltage amplitude [4]:

$$\Delta U = \frac{NeR}{2q{\beta_0}^2}.$$

Here R is the average radius of the machine and q is the RF harmonic number. Therefore, the incoherent longitudinal motion will be unstable if this value becomes equal to the cavity voltage.

For computer simulations of the beam-beam effects it is important to use correct kicks with both the longitudinal and transverse components, otherwise the iterated map will be nonsymplectic.

There is another important issue, related with the particle energy change in the fields of opposite beam. For a small positive betatron phase advance (near the integer resonance), and for the usual sign of the momentum compaction, it is possible for particles with a positive energy offset to slow down their relative motion so as their coordinates would not change between the consecutive collisions. Then their angles and energy offsets will rise together forming an outward phase space flow to large synchrotron and betatron amplitudes. For the negative momentum compaction $\alpha < 0$ this can never happen, such a flow does not occur.

A more detailed study of this effect is presented in Ref.[5], the simulation there confirms arguments in favour of the negative momentum compaction.

Another argument in favour of $\alpha < 0$ is that both the coherent and incoherent synchrotron oscillations can no more become unstable, because in this case the opposite beam action adds to the longitudinal focusing [6].

The Novosibirsk ϕ-factory lattice envisages an option to vary the momentum compaction factor between -0.02 and 0.06 thus enabling an optimization of the longitudinal motion parameters for the realistic collider performance.

2 SIMULATION FOR VEPP-2M WITH ROUND BEAMS

The computer simulation of the beam-beam effects is performed with a special code [7] where, in particular, the particle distributions over their 6D phase space are obtained as a function of the opposite bunch intensity. The bunch is represented by a set of thin nonlinear lenses, each changing both transverse angles of a witness particle and its energy, according to the following relation [6]:

$$\Delta E = \frac{Ne^2}{2\beta}\beta' - \frac{Ne^2}{r^2} \cdot [1 - \exp(-\frac{r^2}{2\sigma^2})] \times \left[x(x' + \frac{\beta'}{2\beta} \cdot x) + z(z' + \frac{\beta'}{2\beta} \cdot z) \right]. \quad (1)$$

Here x, x', z, z' are the coordinates and angles of the betatron motion, $r^2 = x^2 + z^2$. The collision-to-collision map is formed by this multi-slice beam-beam kick followed by linear transformations and sextupole kicks according to the collider lattice. The smaller changes of particle coordinates and angles caused by the synchrotron radiation are included to provide for the radiative damping and quantum excitation of the synchrotron and betatron oscillations. All the parameters are first tuned so as to form the correct equilibrium distribution of particles as it is in the single beam mode. Then the distribution with the collisions on is built from the statistics collected over many damping times, so that one can expect reliable results at not too large amplitudes.

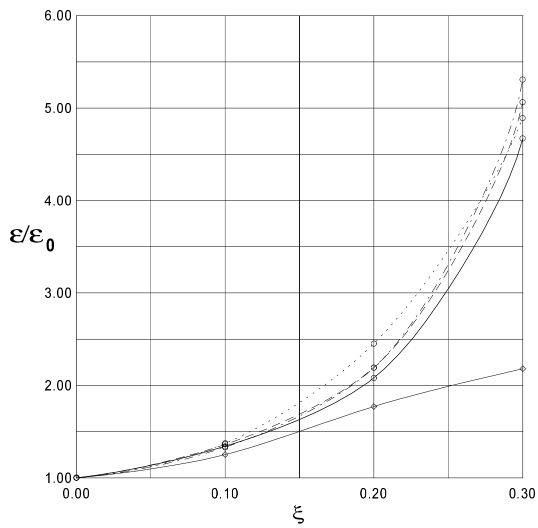

Figure 1: Emittance of the weak beam versus the space charge parameter ξ. The lower curve corresponds to an ideal and linear optics in the arcs. Upper curves include the effect of the arc sextupoles: solid line — the sextupoles only; dash line — plus slightly different x and z tunes; dash-dot line — plus a realistic x-z coupling in the arcs; dot line — plus the betatron tunes separated at 1/2 the synchrotron tune and with the solenoid rotation angle of $1.001 \cdot 90°$.

2.1 *Beam dimensions in the "weak-strong" model*

All the main results of the simulations are presented in Fig. 1. The lower solid line shows the round beam emittance in the case where the only nonlinearity present in the machine is the nonlinear field of the round opposite bunch. One can see that the beam blow-up here is much weaker than what is common for flat colliding beams.

All the other lines show the emittance growth with ξ affected by the sextupolar nonlinearities in the realistic machine and by different small perturbations of the perfect "round beam mode" optics (see the caption). It is evident, that the beam emittance growth is dominated by the sextupole effect in this case, and for $\xi \simeq 0.2$ the beam blow-up is related with the 1/3 resonance.

In Fig. 2 one can see the r.m.s. beam size for the case of round beam with the sextupoles (solid line) and the β-function (dashed line) at the IP, as reduced by the linear fields of the opposite beam. The squeeze in dimensions (notwithstanding the emittance growth) is due to the focusing action of the opposite round beam.

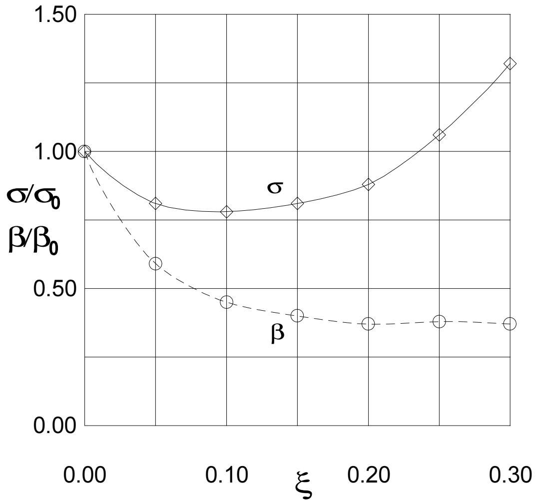

Figure 2: Variation of the weak beam size and relative β_0 vs. the strong beam current.

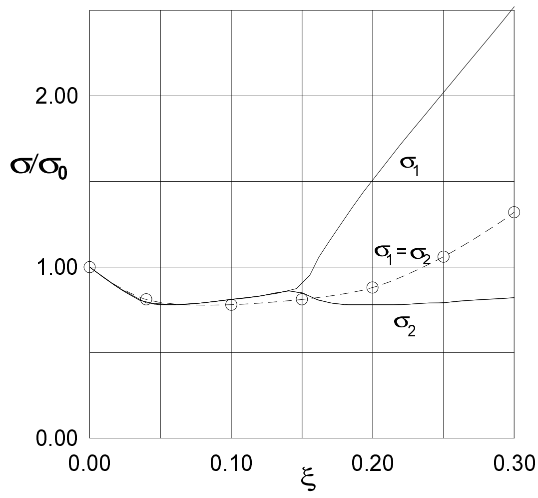

Figure 3: Branching of the beam sizes above the flip-flop threshold. (Dashed line shows the weak-strong size dependence from Fig.2, used as a starting point for the iterations).

2.2 *"Flip-flop" effect*

The next step we can do is to investigate the incoherent "stong-strong" effect with certain assumptions and using data on the beam size variation from the "weak-strong" simulation. The main assumption is that the beam dimension depends on the maximum density in the (center of) opposite beam. This is more or less validated by the simulation results and was exploited earlier (see [8]). Then we can numerically find the sizes of both strong colliding bunches by the iterative use of the weak-strong model results as summarized in Fig. 1 (see the upper solid line). The result of this calculation is presented in Fig. 3. One can see, that the beam size dependence on ξ for the two colliding bunches splits into two branches above $\xi \simeq 0.15$.

2.3 *Other "round beam operation" modes*

There are a few possibilities to modify the existing VEPP-2M optics for the round beam operation. All the above simulations are made with one pair of solenoids rotating the betatron oscillation planes over an angle of $\pi/2$ while the other pair rotates over $-\pi/2$. Taking into account the symmetry of the arcs we have equal betaron tunes on the main difference resonance line. We can reverse the fields in one pair of solenoids and we get the so-called "Möbius ring" [2, 9]: two twists per two collisions, and the betatron tunes here differ by 1. One more option comes from the possibility of switching the opposite fields in two solenoids of one pair, so as to have only one $\pm 90^\circ$ twist over the circumference with 2 IP's. The latter case showed much worse beam blow-up in simulation in comparision with the previous cases, and the reason is that the tune difference of 1/2 now disfavours the safe accomodation of the tune footprint between resonance lines on the tune diagram, so the action of resonances amplifies.

3 CONCLUSION

The results of simulations have strengthened the concept of round colliding beams. No beam-beam blow-up threshold is seen for round beams with the parameters close to the design ones. The beam emittance growth at $\xi > 0.1$ is mostly related with nonlinearities of the machine optics, so we hope that it will be possible to achieve a higher luminosity by reducing the action of nonlinear lattice resonances.

4 REFERENCES

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