VLEPP: BEAM-BEAM EFFECTS

V.E.Balakin and N.A.Solyak
Institute of Nuclear Physics, Novosibirsk, USSR

Getting a high luminosity at the VLEPP installation, wherein the frequency of collisions is not high, is inevitably connected with the use of dense bunches and with the skill to focus them into a small size (of the order of a quadratic micron). In this case, the forces, which appear at the interaction point, become significant so that namely these determine the transverse dynamics of particle motion in the bunches and most of the important characteristics of the accelerator, for example, luminosity, non-monochromaticity, final phase volume of the bunches, etc.

In collision of the bunches of the opposite sign (e^+e^-), their electric fields are compensated, and the magnetic ones are added. Therefore, the force is of attractive nature, and the particles will oscillate in the transverse direction. A clear parameter characterizing the force of a beam-beam interaction is the average number of plasma oscillations executed by the particles during their interaction. In each direction this parameter is equal to

$$\nu_x = \frac{\alpha}{2\pi}\left(\frac{r_e N\sigma_z}{\gamma\sigma_x^2}\,\frac{R}{R+1}\right)^{1/2}; \qquad \nu_y = \frac{\alpha}{2\pi}\left(\frac{r_e N\sigma_z}{\gamma\sigma_x\sigma_y}\,\frac{R}{R+1}\right)^{1/2}$$

where N is the number of particles in every bunch; σ_x, σ_y and σ_z are the r.m.s. sizes of a bunch in the transverse and longitudinal directions, $R=\sigma_x/\sigma_y$, and α is the factor of the order of unity, dependent on the charge distribution inside the bunch.

One can single out a few effects associated with a complex motion of the particles at the interaction point. Among them there is synchrotron radiation, which gives rise to the total energy losses from the bunch and to the appearance of an additional non-monochromaticity and the background of γ-quanta whose spectral and angular distribution is determined by the trajectories of particle motion in the bunches. The parameter of non-monochromaticity is equal, in order in magnitude, to

$$\Delta \simeq \frac{r_e^3 N^2 \gamma}{\sigma_z(\sigma_x+\sigma_y)^2}; \qquad r_e = \frac{e^2}{mc^2}$$

and should be sufficiently small. For the VLEPP, on the strength of all the effects leading to the non-monochromaticity, its required magnitude should be not larger than 1% and, as a consequence, this determines the parameter Δ.

The other important effect is a considerable difference of the luminosity obtained L from a geometrical one, $L_0 = N^2 f/4\pi\sigma_x\sigma_y$, where σ_x and σ_y are the unperturbed dimensions of the bunch at the interaction point and f is the frequency of collisions. The behaviour of the bunches depends on the number of plasma oscillations. At small values of ν_y, the pinch-effect is observed, which decreases the transverse dimensions of the bunches; this leads to an increase in luminosity. In case of $\nu_y > 2$, the beam-beam instability develops, which collapses the beam and degrades the luminosity.

An increase of the phase volume as a result of interaction is of significance from the point of view of further use of the bunches for regeneration. In work with polarized bunches /4/ the spin precession arises in the field of the colliding bunch, that results in a partial depolarization.

In our Institute these effects have been studied for the cylindrical and flat bunches in order that to choose their parameters necessary to achieve the luminosity $L = 10^{32}\ \mathrm{cm^{-2}s^{-1}}$ in the VLEPP installation. The major results of these studies have been briefly reported in /1,2/ and in detail in Ref. /3/. The analysis has shown that using the cylindrical bunches leads to large losses of radiation and to a non-monochromaticity close to 100%. The requirement for a decreased non-monochromaticity, to a level of about 1%, has led to the necessity to collide the flat bunches.

The self-consistent problem of particle motion at the interaction point has been solved numerically. In the case of flat bunches when $R=\sigma_x/\sigma_y \gg 1$, the motion occurs only in one of transverse directions y. The calculation has been made by the method of 'big' particles, 1600-3000 particles per each bunch. Among the characteristics being calculated there are luminosity, non-monochromaticity, spectrum of γ-radiation and final phase volume.

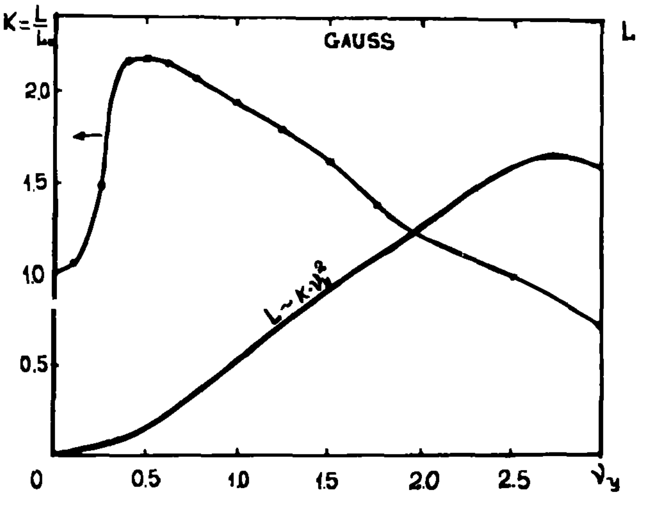

Fig. 1. Dependence of the relative and absolute luminosity on the parameter ν_y at the central beam-beam collision with Gaussian density distribution.

Fig. 1 presents the results of the numerical simulation of the central collision of the oppositely-charged bunches with the

Gaussian density distribution. It is seen that in the 0.3÷1.5 region of the parameter ν_y the pinch-effect resulting in an increase in luminosity by a factor 2 takes place ((Fig. 2). The region $\nu_y > 2$ is the region of instability wherein the sizes of the bunches are considerably increased, and the luminosity degrades (Fig. 3) (similar effects take place for round bunches /5/). Thus, the admissible range for the parameter is $\nu \lesssim 2$ for the VLEPP.

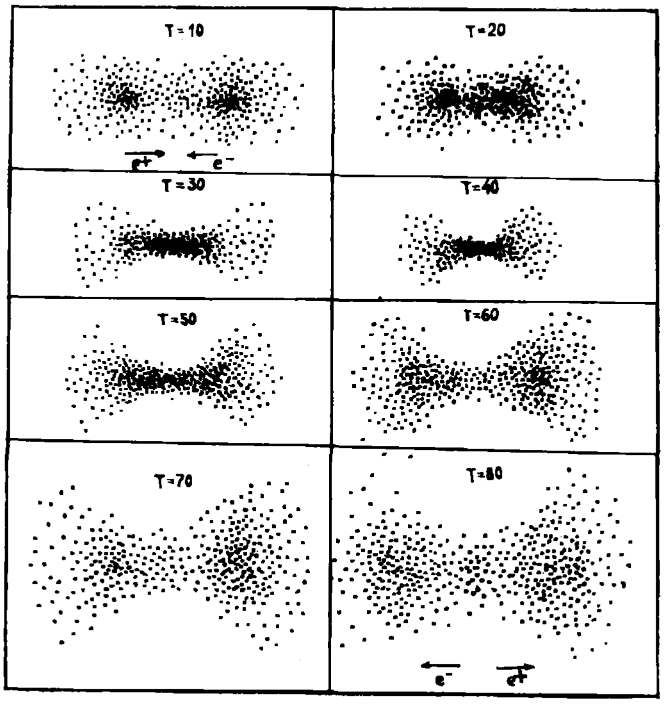

Fig. 2. Central collision of the oppositely-charged bunches.

The calculations have been made for a non-central collision as well. The behaviour of the relative luminosity and radiation losses have been studied as a function of the displacement parameter $\varkappa = \Delta y / 2\sigma_y$, where Δy is the initial off-centering of the bunches. The results obtained at different values of the parameter ν_y are given in Fig. 4. These data show that the luminosity decreases considerably slower, than in the case of non-interacting bunches ($\nu_y = 0$). Therefore, even at large initial displacement when the bunches overlap, i.e. $\varkappa > 1$, the luminosity is not equal to zero. It is equal to zero, when $\varkappa > \sqrt{3} r_e N \sigma_z / (4\sigma_x \sigma_y \gamma) \sim 10$. Attraction of the bunches simplifies the superposition of them. In the case of considerable displacement the beam as a whole acquires the angle $\theta \sim r_e N/(\gamma\sigma_x)$ towards the counterbunch. With the energy 100 GeV the acquired angle amount to $\sim 10^{-3}$. On the 1-m length this results in the 1-mm deflection, and the location of the bunches can be readily corrected. In the off-central collision, as well as in the case of a central one at $\nu_y > 2$, the dipole mode of oscillations of the bunches relative to each other proves to be unstable, and the amplitude of oscillations grows (see Fig. 3). The other specific feature characteristic of the off-central collision is an increase in the radiation losses when $\varkappa$ becomes more significant. It is rather evident since the bunch as a whole moves in the stronger field.

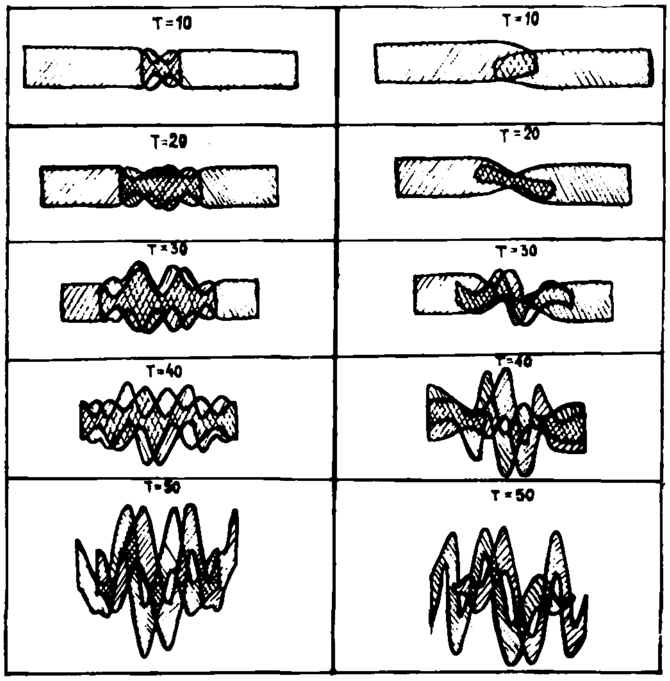

Fig. 3. a) central collision,
b) off-central collision, $\varkappa = 0.2$
Development of the instability in the collision of oppositely-charged bunches with the uniform charge density distribution, $\nu_y = 2.0$.

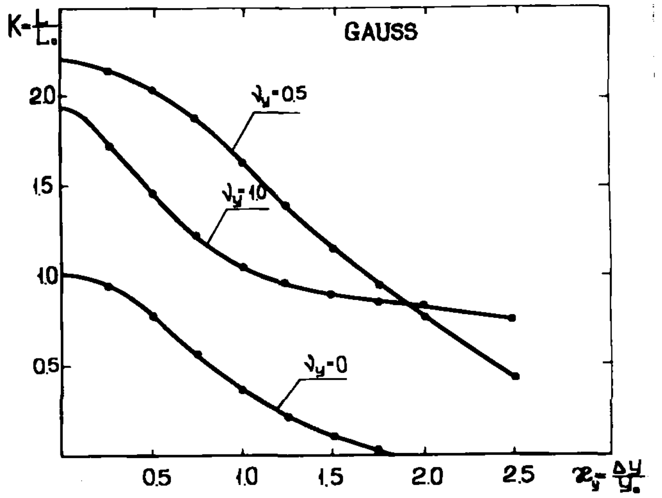

Fig. 4. Off-central collision. Dependence of the relative luminosity on the displacement $\varkappa$ for the bunches with Gaussian density distribution.

The results of the beam-beam effects for two equally-charged bunches (e^-e^-, e^+e^-) are presented in Fig. 5. The data show that the repulsion leads to a fast degradation of luminosity with increasing the parameter ν_y. For VLEPP ($\nu_y \sim 1$), even during the central collision the relative luminosity is decreased by a factor of 3 compared with its value for weakly-interacting bunches. In the case of inaccurate matching of the beams, the luminosity decreases so that the expected luminosity of the VLEPP facility during its operation with the equally-charged bunches will be less by one order of magnitude.

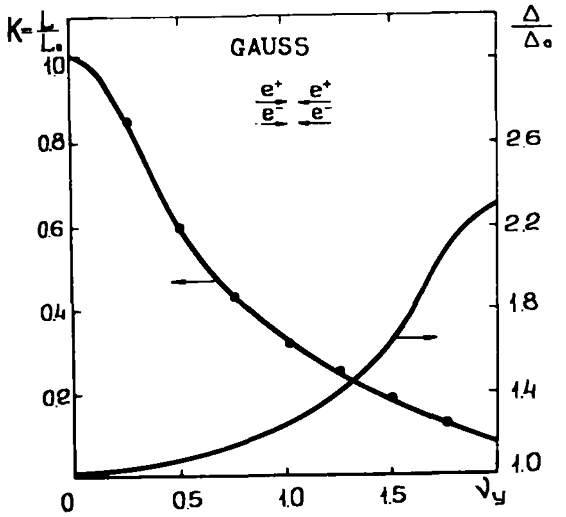

Fig. 5. Relative luminosity and radiation losses in the central collision of equally-charged bunches.

The analysis of the beam-beam effects for flat beams enables one to draw conclusion that at the VLEPP energies 100÷500 GeV the required luminosity, $L = 10^{32}$ cm^{-2}s^{-1}, can be achieved with a non-monochromaticity of about 1%. The necessary sizes of the bunches and the values of the parameters ν_x and ν_y, and of the final phase volume are listed in Table 1. For these calculations the following data have been used: $\mathcal{N} = 10^{12}$ particles, $2\sigma_z = 0.8$ cm and $f = 10$ Hz.

Table 1

Energy, GeV	100	200	300	500
$2\sigma_x$, micron	14	19	23	30
$2\sigma_y$, micron	0.25	0.18	0.15	0.11
$R = \sigma_x/\sigma_y$	56	105	160	270
ν_x	0.18	0.09	0.06	0.036
ν_y	1.32	0.94	0.76	0.59
$\delta\Omega_x \cdot 10^7$cm rad	1.2	0.67	0.45	0.26
$\delta\Omega_y \cdot 10^9$cm rad	3.1	1.1	0.56	0.31

References

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