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A b s t r a c t

The possibilities of increase the beam current limited by beam-beam effects are discussed. Both the experimental data on the VEPP-2M and the computer simulation results are used.

A study of beam-beam effects, with the aim to increase luminosity, is of great importance in regard to improving the efficiency of the machines already in operation and also those under design. As usually, the space charge parameter ξ is taken as a characteristic of the current density. In order to increase the critical value ξ_c, the series of experiments was performed at the storage ring VEPP-2M. In all our experiments the "strong-weak" beam scheme was used. As experience shows, this regime, as compared to the "strong-strong" beam scheme, does not practically influence the dependence of incoherent beam-beam effects on various parameters (see, for example, Ref. /1/) but simplifies the experiments and their analysis. In this paper some results of computer simulation of the space charge effects are presented. Computer simulation was used to study the possibility of operation on the main coupling resonance with equal β - functions at the crossing point and also the influence of different modulations on the quantity ξ_c. Below, we discuss some possibilities of increasing the quantity ξ_c in colliding beam machines.

1. The dependence of ξ_c on the vicinity to an integer resonance

As known, the maximum luminosity is determined by the product $\xi_{xc} \cdot \xi_{zc}$. Computer simulation /2/ shows that the value of ξ_c increases sharply approaching an integer resonance for which the condition is $\mu/\pi = k$. Here μ - the phase advance between the interaction points ($\mu = \frac{2\pi\nu}{m_0}$, ν - betatron frequency. m_0 - number of interaction points at the ring) and k - any integer. The operation near an integer resonance (above - for opposite charges and below - for the same charges) seems to be preferable also due to the fact that near the integer resonance there are no low order nonlinear resonances. At the storage ring VEPP-2M there is the possibility to change the interaction points. This makes it possible to carry out the beam-beam effect experiments for the cases when either the horizontal or vertical tune shifts are determining ones.

1.1. The plot of the quantity ξ_c against the working point in the vicinity of integer resonance, when the horizontal motion is a determining one, is presented in Fig. 1 (curve 1) for $\sigma_x/\sigma_z \approx 15$ and $\beta_x/\beta_z = 6.7$. Curve 2 shows the dependence of the calculated value of $\Delta\nu_c$, derived from the curve 1 data, on the working point. As seen in Fig. 1, near the integer resonance not only ξ_c but also $\Delta\nu_c$ increase. In this case, determining is the radial tune shift, although $\xi_x/\xi_z \approx 0.4$. This may be caused both by the dispersion function η_x at the interaction point and by different character of nonlinearity in both directions.

1.2. The results of a similar experiment for the case when the conditions of x - and z - motion are the same ($\xi_x = \xi_z$), are given in Fig. 1 (curves 3 and 4). In this case, the crossing point has the equal β - functions and $\nu_x = \nu_z$ (round beam, $\sigma_x = \sigma_z$). The coupling was kept in the limits $|\Delta\nu|_{min} < 3\cdot 10^{-3}$. Here, the motion is practically one-dimensional /2/. From the qualitative point of view, the dependence of the vicinity to the integer resonance is of the same character as that in section 1.1. There exist some explanations concerning a small magnitude of ξ_c in this case. One of them is connected to the modulations due to the azimuthal dependence of β - functions and also to the existence of a radial dispersion function at the interaction point /2,4/. The second factor which can decrease a value of ξ_c is a small ratio of vertical aperture to vertical beam size (see section 2).

1.3. Essentially different becomes the dependence $\xi_c = f(\nu_z)$ when the vertical motion is determining ($\xi_z \gg \xi_x$). In this case, numerous coupling resonances $m\nu_x + n\nu_z = K$ seem to work, and the dependence $\xi_c = f(\nu)$ becomes irregular even in the region without strong one-dimensional resonances. It becomes hard, or even impossible, to use the effect of vicinity to an integer resonance under such conditions. Comparison of the variants discussed in sections 1.1 and 1.3 enables the following conclusion to be made: for $\sigma_x \gg \sigma_z$ a more favourable variant is that where the determining direction is the radial one. In this case it is possible to use the effect of vicinity to the resonance. Moreover, as experimental results at VEPP-2M show,

the maximum value of ξ_{zc} is achieved in this case.

2. The dependence of ξ_c on aperture and beam shape

Particle losses in beam-beam interactions results from the increase of the betatron oscillation amplitude up to the aperture boundaries. The particle density at the centre nevertheless can vary insignificantly, and particle losses are due to the distribution "tails" only. Therefore, a study of the dependence of ξ_c on aperture seems to be useful.

In the experiment, a probe located in the chamber, limits the vertical aperture, and the value of ξ_c corresponding to a given position of the probe was measured. Measurements were carried out for several values of the coupling coefficient: $\varkappa \equiv \sqrt{\varepsilon_z/\varepsilon_x}$ where $\varepsilon_{x,z}$ is the beam emittance for the corresponding direction.

Experimental data are presented in Fig. 2. The magnitude of the vertical aperture, normalized over the r.m.s. beam size, is on the axis of abscissa. The dependence of ξ_c on the relative aperture size has nearly the linear character in the case when the vertical tune shift is determining (curve 2,3). Despite the fact that the dependence was measured for different values of $\varkappa$ the linearity is remain. This shows also the linear coupling, which change the vertical beam size and the beam shape, influence slightly the magnitude of ξ_c in this case. The dependence of ξ_c on aperture is fairly slight too. If the interaction points are used, where the horizontal tune shift is determining, the dependence of ξ_c on the vertical aperture is of another character, as could be expected (curve 1). There exists a large region in the aperture, which does not influence the lifetime of the "weak" beam. At the same time for $A/\sigma_z < 30$ the value of ξ_c drastically changes. It means the restriction of vertical diffusion (the distribution tails' don't extend far away).

Therefore the experimental data show us the additional restriction of the vertical aperture caused by the beam-beam effects. The lack of these requirements can lead to decreasing of the beam current.

3. Dependence on the ratio between colliding beam sizes

This problem has arisen in connection with the development of colliding proton-antiproton beam projects. If the transverse proton bunch dimensions are enlarged (compared to those of the antiproton bunch), the antiprotons seem mainly to be in the linear part of the proton beam field. Since the space-charge effects are associated with the nonlinear dependence of the colliding beam field on a coordinate, one can reasonably suggest that a decrease of nonlinearity must result in increasing ξ_c , and hence, in increasing the proton beam density. As a result, at a given number of antiprotons, the luminosity will grow.

The storage ring VEPP-2M makes it possible to verify whether the above considerations are valid or not, because at low energies the beam sizes are current-dependent. The experiment was carried out at low energies under condition that $J^- \gg J^+$, i.e. in the "strong-weak" beam approximation. The dependence of ξ_c on the "strong" to "weak" beam size ratio is plotted in Fig. 3. Such interaction points were chosen where the horizontal motion is determining. As seen in Fig. 3, the dependence $\xi_c = f(\sigma_x^- / \sigma_x^+)$ is quite strong, and the use of this effect may turn out to be very promising in order to increase luminosity in colliding proton-antiproton beam machines. We would like to mention that the increase of ξ_c with decreasing the proton beam sizes may be partly connected, in our experiment, with increase of the effective aperture and with decrease of the storage ring nonlinearities, whose influence depends on the beam size.

4. Operation on the main coupling resonance with equal β - functions at the crossing point

Such a variant is considered in Ref. /3/ on the basis of computer simulation results. It is shown that in this case, at a quite small value of the linear coupling ($|\Delta\nu|_{min} < 3\cdot 10^{-3}$),

the motion is close to a one-dimensional one with the corresponding values of ξ_c in both directions. The advantage of the variant under discussion is also the absence of modulations which appear due to the azimuthal dependence of the β - function at the interaction point. This is connected with the fact that, for a round beam $\xi_{x,z} \sim \frac{\beta_{x,z}}{\sigma^2}$, $\sigma \sim \sqrt{\beta}$ and if $\beta_z = \beta_x$, ξ becomes independent of longitudinal coordinate.

Moreover, this variant enables one to use the effect of vicinity to the integer resonance, as it follows from the results of section 1, and hence, to increase the quantity ξ_c . The difficulty in realization of this variant is due to the necessity to have equal and small β - functions at the crossing point and also to have the larger vertical aperture as compared to that of the ribbon beam for electron-positron storage rings.

5. Influence of different modulations

The possibility of increasing the limiting current density is also connected with decrease of different betatron motion modulations because of synchrotron oscillations. The modulation associated with the presence of an energy dispersion function at the interaction point is analyzed in Ref. /2/. It is shown that such a modulation can substantially decrease the quantity ξ_c. At the present time, most of the machines, those in operation and those under construction, have the zero η - function at the interaction point. However, there exist the other types of modulations which can decrease limiting currents, in particular:

1) betatron phase modulation between interaction points due to energy oscillations;

2) modulation of the quantity ξ by phase oscillations, which is associated with the azimuthal dependence of the β - function. This problem is discussed in some detail in Ref. /4/. As already mentioned, in operation with the round beam on the coupling resonance there is no modulation associated with the azimuthal dependence of the β - function.

Thus, as our analysis shows, there exist some possibilities of increasing ξ_c and, hence, the luminosity of colliding beam machines. Attention should be focused on the operation on the main coupling resonance with equal β - functions and also near the integer resonance. The problems connected with orbit distortions and synchrotron resonances appear to be solvable in the latter case.

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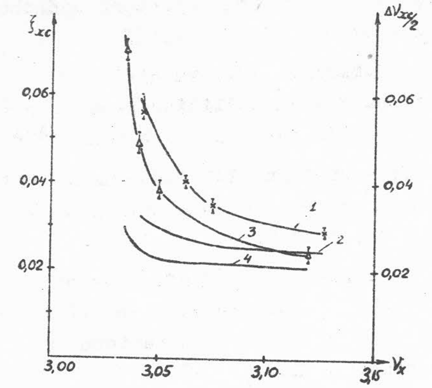

Fig. 1. The dependence of ξ_c and $\Delta\nu_c$ on a distance to the integer resonance, E - 510 MeV. There are two interaction points.
Curves 1 (ξ_c) and 2 ($\Delta\nu_c$) - for β_x = 40 cm; β_z = 6 cm, η_x = 40 cm; $\frac{\partial\beta_x}{\partial s}$ = 0.
Curves 3 (ξ_c) and 4 ($\Delta\nu_c$) - for $\beta_x = \beta_z$ = 350cm, η_x = 60 cm; $\frac{\partial\beta_x}{\partial s}$ = 40.

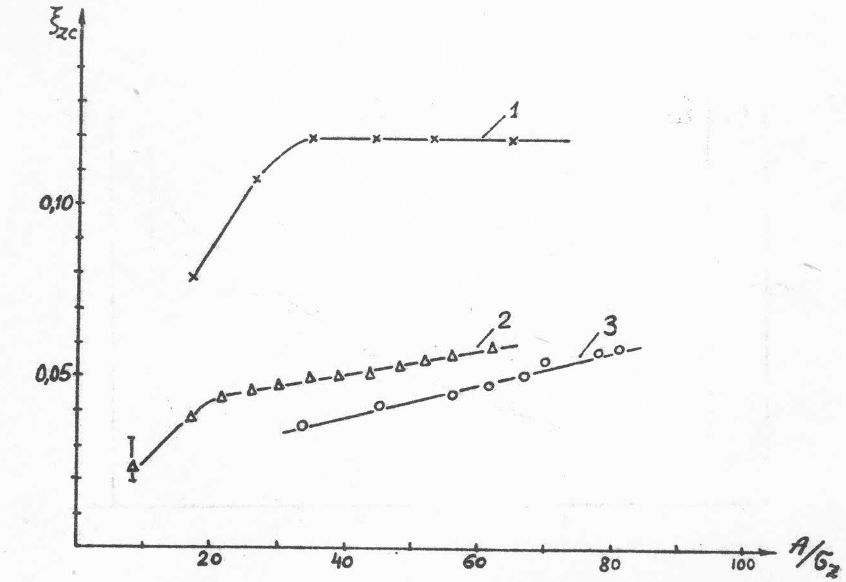

Fig. 2. The dependence ξ_{zc} on relative aperture.
E = 510 MeV; ν_x = 3.081; ν_z = 3.105
x — β_x = 40 cm, β_z = 6 cm, æ = 0.15
o — β_x = 25 cm, β_z = 150 cm; æ = 0.12
Δ – β_x = 25 cm, β_z = 150 cm; æ = 0.16.

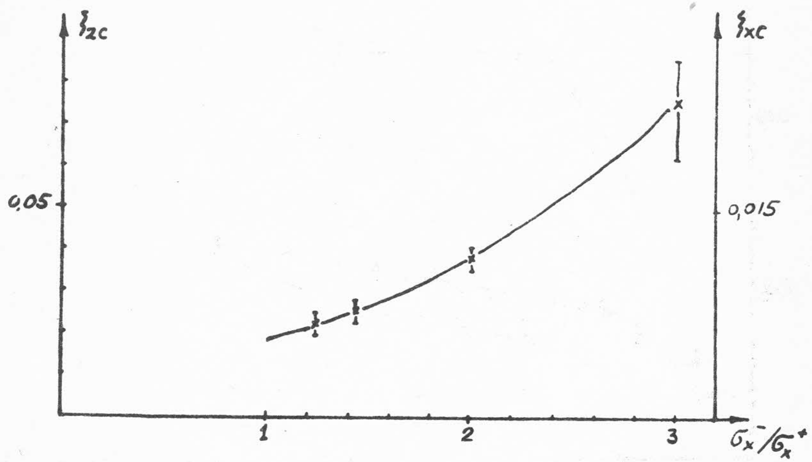

Fig. 3. The dependence of ξ_c on the ratio between the electron and positron beam sizes.
$\sigma^- >> \sigma^+$, E = 180 MeV, ν_x = 3.057; ν_z = 3.076;
β_x = 40 cm, β_z = 6 cm.

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