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I.Ya.Protopopov, A.N.Skrinsky,
A.A.Zholents

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I.Ya.Protopopov, A.N.Skrinsky, A.A.Zholents

Institute of Nuclear Physics
630090, Novosibirsk 90, USSR

## Abstract

The methods for improving the energy resolution in the colliding electron-positron beam experiments are considered. Some advantages of using the electrostatic skew-quadrupole lenses for this purpose, which produce the vertical energy dispersion of the beam particles in the interaction region, and additional radiation damping are shown. The operation principle of the experimental section and its possible scheme for VEPP-4 are described. This scheme enables one to attain the energy resolution in the $J/\psi$ - and $\psi'$ - mesons region much better than their widths, what, in particular, simplifies the observation of rare modes of decay of these particles. Compared with the standard technique of electron-positron collisions, much more clearly the resonance signals appear above the continuum background expected in the monochromatic experiments. This can simplify essentially the problem of studying the family of $\Upsilon$ -mesons. The questions concerning the achievement of maximum luminosity in monochromatic experiments are discussed.

## INTRODUCTION

A detail study of narrow resonances in colliding electron-positron beam experiments with the standard technique of electron-positron interactions faces excessive difficulties because of a large enough, as compared to the energy width of resonances, energy spread in the beams. So, on SPEAR, DORIS the beam energy spread is 0.5 MeV at the $J/\psi$ -meson energy, 0.7 MeV at the $\psi'$ -meson energy, and 6 MeV at the $\Upsilon$ -meson energy /1-3/. At the same time, the energy widths of these resonances are equal to 0.07, 0.23, 0.03* MeV, respectively. In storage rings VEPP-4, CESR, PETRA, PEP the energy spread in the beams will highly exceed the energy widths of the listed resonances as well.

High energy spread in the beams leads to a small probability of resonance production and to "thickening" of the resonant curves. In practice, the "useful" luminosity, that is the luminosity in the interaction energy range determined by a resonance width, was ~ 1/30 of the full luminosity for $J/\psi$ -meson at SPEAR and DORIS, and ~ 1/600 for $\Upsilon$ -meson at DORIS. Despite a low "useful" luminosity, the $J/\psi$ -meson manifested itself strikingly in the $e^+e^-$ collisions; the experimentally obtained ratio of the resonance effect to the non-resonant background in the hadron mode was 150, in the $\mu^+\mu^-$ mode - 25 (see /5/ ). From the experimental point of view, the situation concerning the $\Upsilon$ -meson is more complicated. In recent experiments on DORIS the effect-background ratio in the hadron mode was only 2 /2,3/ and

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* The last digit is taken from theoretical data.

in the $\mu^+\mu^-$ mode this ratio will, apparently, be 0.4 /4/ *. It is possible to obtain a high resonant peak and, correspondingly, to increase the ratio of the resonant effect to the non-resonant bachground only in the case of improving the energy resolution. At present, necessity of this, especially in the experiments concerning the observation of rare modes of particle decay, is very urgent.

## The Method

For reducing the full energy spread of particle interaction one can use the existing in storage rings correlation between the energy deflection of a particle from the equilibrium one and its orbit corresponding to instantaneous energy of this particle. The spatial energy dispersion of opposite signs for electrons and positrons at the collision point enables one to obtain, with a quite high accuracy, the same energy of interaction for the particles being on different instantaneous orbits.

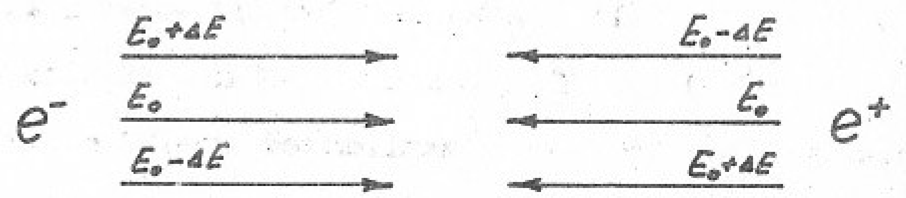

Fig.1

The betatron oscillations of electrons and positrons cause undesirable mixing of the particles with different energies inside the beam. Since in storage rings the vertical betatron size usually is much less than the horizontal one ($\sigma_{z\beta} \ll \sigma_{x\beta}$), most success may be achieved by energy dispersion in the vertical direction.

The methods of generating a necessary spatial energy dispersion by means of vertical orbit distortion having different directions for electrons and positrons have been earlier discussed in Novosibirsk and Frascati /6/ . This orbit distortion can be obtained both by the electric and magnetic fields. In the first case, the electrons and positrons circulate in one ring and special efforts are required to eliminate their orbit separation at the collision point with no essential decrease of spatial energy dispersion; in the second case - in two crossing rings.

Producing the orbit distortion in vertical direction by the electric and magnetic fields, we produce simultaneously the increment of the vertical beam emittance due to radiation processes occuring in these fields. The stronger distortion of the orbit and, correspondingly, the higher vertical energy dispersion are connected linearly with a growth of the fields. At the same time, additional increase of vertical emittance are proportional to the cube of these fields. Hence, from some orbit distortion the spread of the full energy of interacting particles, which decreases at first, will increase and the energy resolution will worsen.

In the present paper a scheme designed for the energy monochromatization of colliding beams interaction is considered wherein the vertical energy dispersion is produced by electrostatic skew-quadrupole lenses. The operation principle of this scheme is shown in Fig.2.

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* Due to smaller energy spread in the beams, on the facilities with a larger curvature radius in the bending magnets than that on DORIS the resonance signal should become more pronounced.

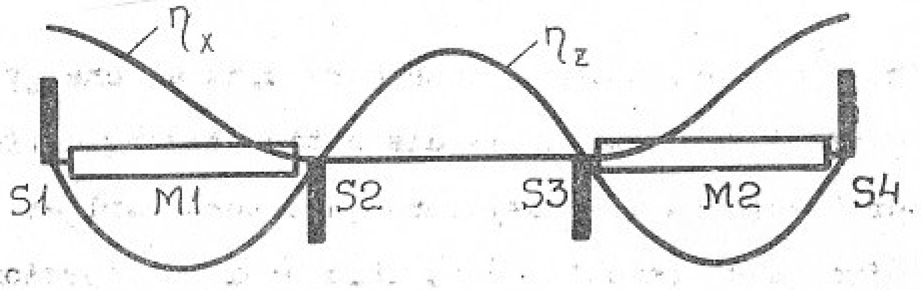

Fig.2

Skew-quadrupole lenses S1 and S4 placed in the odd number of the half-waves of betatron oscillations generate a necessary local excitation of the vertical dispersion function $\eta_z$ . As a result of their action, a coupling of oscillations appears in the storage ring, which is compensated by the lenses S2 and S3. These lenses have the opposite sign of the field with respect to that of the lenses S1 and S4 and they are placed in the half-wave of betatron oscillations relative to the latter. So, they eliminate the coupling of oscillations everywhere outside the experimental section and in its central part. The bending magnets M1 and M2 make the horizontal dispersion function $\eta_x$ to be equal to zero in front of the lenses S2 and S3 so that they do not influence $\eta_z$ . These magnets also determine a shape of the equilibrium orbit in the experimental section, which is certainly the same for electrons and positrons. The collision point should be organized in the central part of the section at the maximum $\eta_z$ .

In our scheme the vertical energy dispersion at the collision point is controlled by electrostatic skew-lenses. The dispersion increases as the focal length is shortened. Moreover, the vertical beam emittance also increases due to radiation processes occuring in the parts (involving magnetic fields) of the experimental section. If the initial vertical beam emittance is zero, dispersion and vertical betatron size at the collision point grow equally. In this case, the energy resolution is independent of the power of lenses. If the initial size differs from zero, for example, because of oscillation coupling, then with an increase of the lenses' power the energy resolution will gradually become better and attain the same limit $\sigma_E$ , when the contribution of the initial size can be neglected.

The best energy resolution achieved in the described-above experimental scheme can be estimated by the formula:

$$\sigma_E = \left\{ \frac{55\sqrt{3}}{48} \Lambda \frac{\eta_{x0}^3 \cdot R}{(L/2\pi)^5} \cdot \frac{3}{64} f(\varkappa) \right\}^{1/2} \cdot \frac{E_0^2}{mc^2}$$

Here $\sigma_E$ is the energy resolution, $E_0$ is the experimental energy, $mc^2$, $\Lambda$ are the rest energy and Compton wavelength of the electron, $R$ is the mean radius of curvature in the storage ring bending magnets, $L$ is the total length of the sections between the lenses S1, S2 and S3, S4; $\eta_{x0}$ is the initial value of $\eta_x$ at the monochromaticity scheme input, $\varkappa$ is the filling coefficient by a magnetic field ( $0 < \varkappa < 1$ ) for $L$ . The function $f(\varkappa)$ is equal to

$$f(\varkappa) = \frac{\varkappa\left(1 + 2\sin^2\frac{\pi\varkappa}{2}\right) - \frac{\sin\pi\varkappa}{\pi}}{3 \cdot \sin^5\frac{\pi\varkappa}{2}}$$

To derive this formula, the initial value of $\eta'_{x0}$ is taken to be equal to zero.

The choice of the focal length for skew-quadrupole lenses is conditioned by

$$F \ll \left\{ \frac{\eta_{x0}^5 \cdot R^2 \cdot \bar{\beta}_x}{(L/2\pi)^4 \cdot \bar{\eta}_x^2 \cdot K^2} \cdot \frac{3}{64} f(\varkappa) \right\}^{1/2}$$

where $F$ is the focal length of skew-quadrupole lenses, $\bar{\beta}_x$, $\bar{\eta}_x$ is the mean value of the horizontal beta-function and of the dispersion function in the storage ring, $K=\sqrt{\frac{\varepsilon_{z0}}{\varepsilon_{x0}}}$ , $\varepsilon_{z0}$ , $\varepsilon_{x0}$ are natural vertical and horizontal emittances of the beams.

As will be shown below, at VEPP-4 in the region of $J/\psi$ - and $\psi'$ -mesons the energy resolution of about 100 keV can be obtained by this method. But this is still somewhat worse compared to that required for studying a feasible internal structure of these mesons.

One can improve this resolution if one installs superconducting wigglers with high sign-varying vertical field to increase radiation damping in the storage ring. This leads to decreasing the vertical size of the beam appearing in the bending magnets M1 and M2 and, correspondingly, to attenuating the mixing of the particles with different energies. The gain will be proportional to the square root of the damping times ratio. If one supposes that the possibility to compensate radiation losses increasing with the wigglers is the only limitation, then the additional gain will be $\frac{E_{max}^2}{E_0^2}$ , where $E_{max}$ is the maximum energy of the electron-positron storage ring. Thus, this method will make it possible to obtain on VEPP-4 the energy resolution for $J/\psi$ - and $\psi'$ -mesons much better than their widths, and on the storage rings PETRA and PEP - to "resolve", perhaps, the internal structure of $\Upsilon$ -mesons.

## Luminosity

The distinctive characteristic of the collision of the beams with vertical energy dispersion exceeding severalfolds the amplitudes of betatron oscillations is a rather large modulation of the betatron oscillation frequencies by the synchrotron frequency of vertical-phase oscillations. As numerical experiments in Ref.7 have shown, for such amplitudes of synchrotron oscillations, the overlap of nonlinear resonances phase-spaces regions and the particle motion instability arise at much lower intensities in comparison to the case when modulation is absent. Following the results of these calculations, one might expect that in monochromatic experiments the maximum admissible tune shift by beam-beam effects $\Delta\nu_{max}$ will be by a factor of 3-5 less than the usual one. If one considers that the beam parameters at the collision point can be always chosen under variation of the magnetic structure of the central part of the experimental section so that the tune shifts of vertical and horizontal betatron oscillations be equal $(\Delta\nu_x = \Delta\nu_z = \Delta\nu_{max})$, then in the case of equal number of electrons and positrons the luminosity at one collision point, taking into account the additional radiation damping, can be written as follows:

$$L = \frac{\pi \cdot f_0 \cdot \Delta\nu_{max}^2 \cdot \varepsilon_{x\,max}}{r_0^2 \cdot (mc^2)^2} \cdot \frac{(1+\beta_z/\beta_x)^2}{\beta_z} \cdot E_0^2$$

where $r_0$ is the classical electron radius, $f_0$ is the rotation frequency, $\varepsilon_{x\,max}$ is the horizontal beam emittance at $E_{max}$ ; $\beta_z$ , $\beta_x$ are the vertical and horizontal beta-functions at the collision point. $\beta_z$ and $\beta_x$ are chosen to make vertical and horizontal betatron tune shifts equal:

$$\frac{\beta_z}{\beta_x} = M^2 \frac{\varepsilon_{z\,max}}{\varepsilon_{x\,max}} \cdot \frac{E_0}{E_{max}}$$

Here $\varepsilon_{z\,max}$ is the maximum vertical emittance of the beams at $E_{max}$ with taking into account the additions arising because of the monochromatization scheme, $M$ is the gain in energy resolution at $E_{max}$.

To derive a formula for luminosity, we have assumed that superconducting wigglers will be installed in the ring so that the horizontal emittance of the beams be constant when varying the storage ring working energy. Under this condition the number of electrons and positrons required for achieving maximum luminosity is

$$N = \frac{2\pi \cdot \Delta\nu_{max} \cdot \varepsilon_{x\,max}}{r_0 m c^2} \cdot \left(1 + \beta_z/\beta_x\right) \cdot E_0$$

The luminosity we may obtain at VEPP-4 in monochromatic experiments at different energies is shown in Fig.3. The electron and positron currents necessary for this are given in Fig.4. To plot the diagrams, we have chosen the following values: $M = 5$, $\Delta\nu_{max} = 0.01$, $\varepsilon_{x\,max} = 10^{-4}$ cm·rad, $\varepsilon_{z\,max}/\varepsilon_{x\,max} = 0.1$. Beta-functions at the collision points are given according to the last condition but not less than 10 cm.

It is likely that in the experiments with narrow resonances the notion of differential luminosity, i.e. the luminosity in a given interval of energy, is more convenient. In our case, the differential luminosity $L_{\Delta E}$ is related with the full luminosity $L$ by

$$L_{\Delta E} = L \cdot \Phi\left(\frac{\Delta E}{\sigma_E}\right)$$

where $\Delta E$ is the energy interval, $\Phi$ is the error function.

## Results

Fig.5 shows one of the possible variants for using the described above method of the energy monochromatization of colliding beam interaction at VEPP-4. It is an arrangement of the

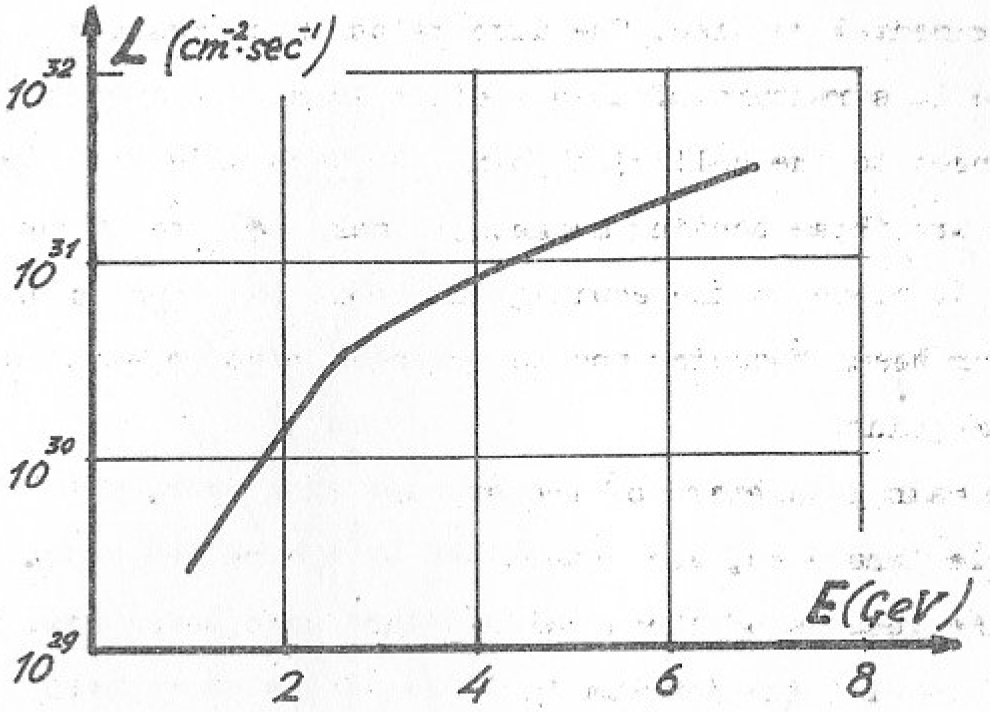

Fig.3

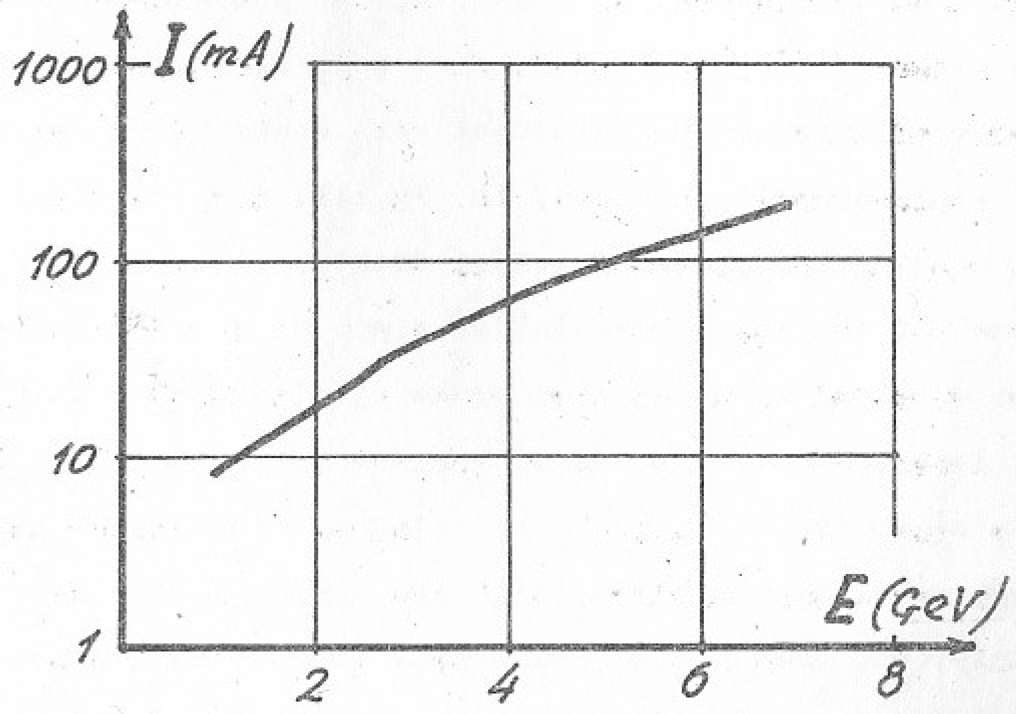

Fig.4

magnetic elements and the electrostatic quadrupole lenses in the experimental section. The dispersion functions are plotted. The magnetic structure of this section is mirror symmetrical with respect to the collision point. On each side from the centre there are three bending magnets to make $\eta_x$ to be equal to zero and to close to the equilibrium orbit and eight quandrupole lenses for beams focusing and to organize beam parameters at the collision point.

The main parameters of the storage ring beam, with skew-quadrupole lenses on, are determined by the method described in Ref.8. The results of these calculations have been used, in particular, to plot the diagram in Fig.6. It is shown here the energy resolution at an energy of 2 x 4.75 GeV attainable in such experimental scheme at VEPP-4 for different values of the electric field gradient and for different ratios of natural vertical and horizontal emittances. All the diagrams approach asymptotically the value of $\sigma_E$ = 0.86 MeV. Just such r.m.s. spread of the full energy of interacting particles will occur after switching on the skew-quadrupole lenses at the initial zero vertical beam size. Increasing the power of lenses does not lead to a further improvement of the energy resolution since at the collision point the vertical betatron size grows simultaneously with $\eta_z$ .

The dependence of the energy resolution on the storage ring energy is shown in Fig.7. The first diagram corresponds here to the energy resolution achieved with the monochromatization scheme only; the second - to the energy resolution achieved with taking into account the additional damping at low energies. It is seen that in the second case at VEPP-4 in the region of $J/\psi$ - and $\psi'$ -mesons the energy resolution can be achieved much better

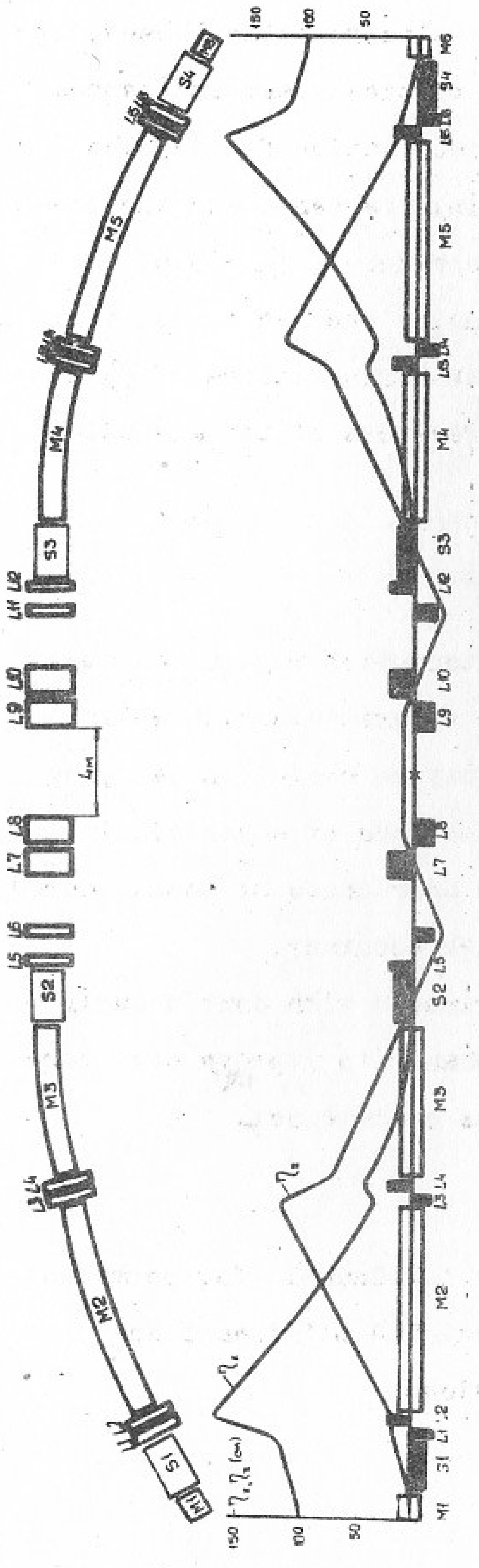

Fig.5 The experimental section of VEPP-4

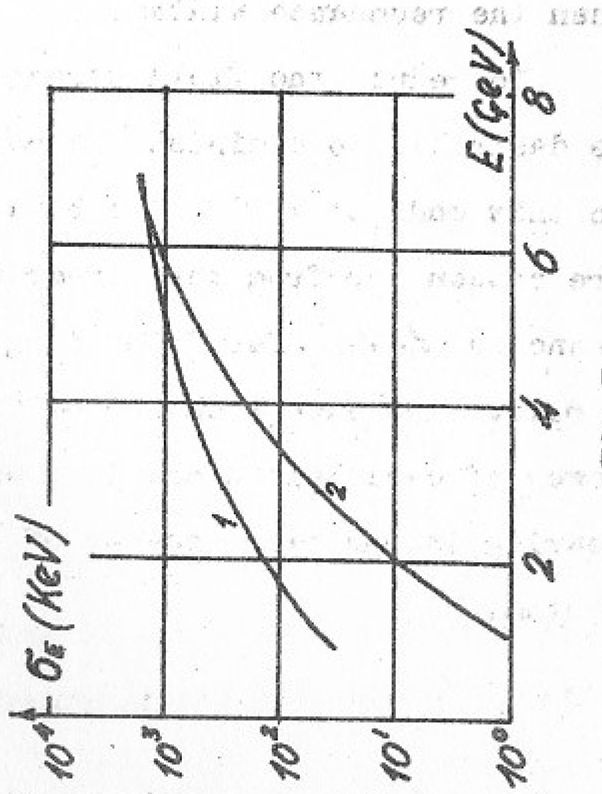

Fig.7

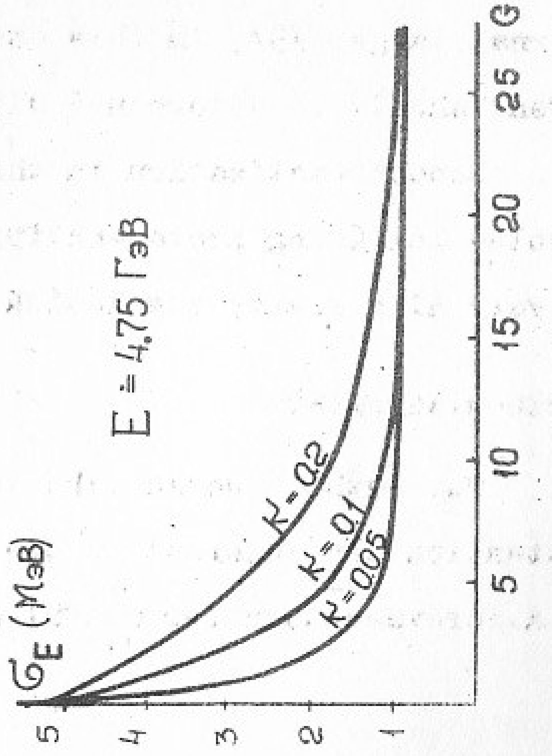

Fig.6

than the resonance widths.

To reduce the field strengths in electrostatic lenses, it is desirable to diminish the natural vertical beam emittance. To this end, at VEPP-4 the betatron oscillation frequencies are chosen far from the linear coupling resonance and the frequencies $\nu_x, \nu_z$ - far from integer resonances ( $\nu_z = 9.6$, $\nu_x = 8.1$). With such a choice of frequencies one can expect a small power of oscillation coupling and weak perturbations of $\nu_z$ appearing in the ring because of imperfectness of the magnetic system.

## Conclusion

The energy dispersion in the interaction region can improve the energy resolution in other experiments with well "cooled" beams. In particular, this may be useful in carrying out "spectrometric" experiments in the mode of superthin internal target /9/; in this case, the coordinate of each occured event should be determined with a high accuracy.

Monochromatization in the experiments with continuously cooled colliding proton-antiproton beams (to improve even more a very high energy resolution) may be of interest.

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