THE PROJECT OF MODERNIZATION OF THE VEPP-4 STORAGE RING FOR MONOCHROMATIC EXPERIMENTS IN THE ENERGY RANGE OF Ψ AND Υ MESONS

Avdienko A.A., Kornyukhin G.A., Protopopov I.Ya., Skrinsky A.N., Temnykh A.B., Tumaikin G.M., and Zholents A.A.

Institute of Nuclear Physics, 630090, Novosibirsk

Summary

A thorough study of the Ψ and Υ mesons, which manifest themselves in the e^+e^- - annihilation of colliding beams in the form of narrow resonance peaks, is the urgent problem in elementary particle physics. The rate of generation of these mesons is dependent on two parameters: the luminosity and the energy interval within which the total energies of a particle interaction lie. If the e^+e^- collisions are arranged in a standard way, the magnitude of this interval is determined by the energy spread of particles inside the beam and is tens, hundreds times larger compared with the energy widths of the resonances. As a result, only a very small part of the events of the e^+e^- interaction is accompanied by the resonance production of mesons, and the remaining events give the nonresonance background. Monochromatization of the total energy of the particle interaction in a storage ring, suggested at the Novosibirsk Institute of Nuclear Physics, permits one to increase, to a considerable extent, the meson yield and to simultaneously increase the ratio of the resonance effect to the nonresonance background.

Monochromatization Method

In order to carry out the monochromatization of the total energy of the particle interaction in a storage ring, it is necessary to make a large spatial energy expansion of the beams at the collision point, as this is schematically shown in Fig. 1, and to arrange the beam collisions in such a way so as the electrons with an energy higher that the equilibrium one interact with the positrons with an energy lower than the equilibrium and vice versa[1,2]. It is essential that the location of the instantaneous orbits of the particles at the collision point is strongly connected with their energy and, hence, the total energy of an interaction of each pair of particles E_t is equal to $2\cdot E_0$ with an accuracy up to $(E-E_0)^2/E_0 \sim 10^{-6}E_0$ (E and E_0 are the current and equilibrium energy, respectively). Such an arrangement of an electron-positron interaction is referred to as the monochromatization, and the experiments with use of its properties are referred to as the monochromatic experiments.

Let us describe the monochromatization principle indicated above from a quantitative point of view. To do this, let us find the differential luminosity[2] $\frac{dL}{d\mathcal{E}_t}$:

$$\frac{dL}{d\mathcal{E}_t} = 2f_0 \iiint \rho_+(x,z,2\mathcal{E}_t-\mathcal{E})\,\rho_-(x,z,\mathcal{E})\,dx\,dz\,d\mathcal{E} \qquad (1)$$

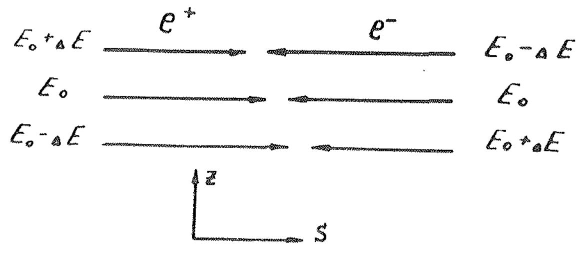

Fig. 1.

where f_0 is the revolution frequency, $\mathcal{E}_t = E_t - 2E_0$, $\mathcal{E} = E - E_0$, $\rho_\pm$ is the distribution function:

$$\rho_\pm = \frac{N^\pm}{(2\pi)^3 \sigma_{x\beta}\sigma_{z\beta}\sigma_\mathcal{E}} \cdot e^{-\frac{\left(x-\Psi_x\frac{\mathcal{E}}{E_0}\right)^2}{2\sigma_{x\beta}^2}} \cdot e^{-\frac{\left(z\pm|\Psi_z|\frac{\mathcal{E}}{E_0}\right)^2}{2\sigma_{z\beta}^2}} \cdot e^{-\frac{\mathcal{E}^2}{2\sigma_\mathcal{E}^2}}$$

Here the signs (+) and the (-) are referred to the positron and electron beams, respectively; N stands for the number of particles, $\sigma_\mathcal{E}$ is the rms energy spread, $\sigma_{x\beta}$ ($\sigma_{z\beta}$) is the r m s horizontal (vertical) betatron size at the collision point, Ψ_x (Ψ_z) denotes the horizontal (vertical) dispersion function at the collision point. In the expression for ρ , the fact is taken into account that the energy expansion of the electron and positron beams is made in the vertical direction and in the opposite sides. As a result of the integration of (1), we obtain

$$\frac{dL}{d\mathcal{E}_t} = \frac{L_0}{\sqrt{2\pi}\,\sigma_t} \cdot e^{-\frac{\mathcal{E}_t^2}{2\sigma_t^2}}$$

where L_0 is the luminosity:

$$L_0 = f_0 \frac{N^+N^-}{4\pi\left(\sigma_{x\beta}^2 + \Psi_x^2\frac{\sigma_\mathcal{E}^2}{E_0^2}\right)^{1/2}\left(\sigma_{z\beta}^2 + \Psi_z^2\frac{\sigma_\mathcal{E}^2}{E_0^2}\right)^{1/2}}$$

and σ_t is the rms spread of the total interaction energy during monochromatization:

$$\sigma_t = \frac{\sqrt{2}\,\sigma_\mathcal{E}}{\left(1 + \Psi_z^2\frac{\sigma_\mathcal{E}^2}{E_0^2}/\sigma_{z\beta}^2\right)^{1/2}} \qquad (2)$$

Thus, in monochromatic experiments the energy resolution is improved by a factor of

$$\lambda = \frac{\sqrt{2}\,\sigma_\varepsilon}{\sigma_t} = \sqrt{1 + \Psi_z^2 \frac{\sigma_\varepsilon^2}{E_o^2} / \sigma_{z\beta}^2}$$

compared with the conventional technique of electron-positron collisions. There is no difficulty in showing that for very narrow resonances the rate of their generation increases by the same number of times. The parameter λ will be referred to as the gain in energy resolution.

With $\lambda \gg 1$, the expression (2) can be reduced to the form

$$\sigma_t = \sqrt{2}\, \frac{\sigma_{z\beta}}{|\Psi_z|}\, E_o \qquad (3)$$

It is clear from the above expression that the monochromaticity is obtained the better the higher the energy dispersion, compared with the betatron size, at the collision point. This is connected with the fact that the betatron oscillations of particles mix the different energies inside the beam, thereby worthening the monochromaticity. Hence, to achieve a good monochromaticity, a large Ψ_z needs to be created at the collision point, not increasing substantially $\sigma_{z\beta}$. In view of this, the special insertion schematically depicted in Fig. 2.[1] This optical scheme will now be referred to as the 'monochromatization scheme'. The figure presents only the elements of the scheme, which are of importance for understanding of its operation: electrostatic skew-quadrupole lenses and magnets. The lenses which carry out the uniform vertical and horizontal focusing are not shown.

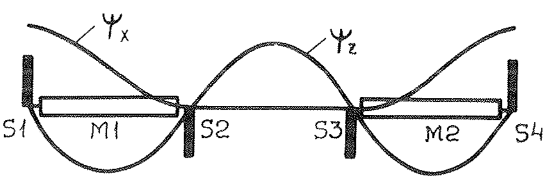

Fig. 2. Monochromatization scheme.

The operational principle of the monochromatization scheme is the following. Lenses S_1 and S_4 are located in an integer number of the half-waves of the vertical betatron oscillations and induce a local excitation of Ψ_z . The arising of Ψ_z on the section between S_1 and S_4 is, indeed, equivalent to the rotation of the plane of radially-phase oscillations from x - to z - direction. The angle of rotation grows with increasing Ψ_z and decreasing Ψ_x . Together with the phase oscillations, the betatron oscillations also change their directions in such a way that the betatron size is the largest at the maximum of Ψ_z over the vertical direction. To eliminate this, the lenses S_2 and S_3 are included in the scheme, which are placed exactly in one half-wave of the vertical and horizontal betatron oscillations with respect to the lenses S_1 and S_4 and compensate for their influence on the betatron motion. For this reason, the betatron motion remains non-perturbed throughout except the sections between the lenses S_1, S_2 and S_3, S_4. Lenses S_2 and S_3 have the switching on polarities opposite to those of lenses S_1 and S_4. In order that they have no influence on Ψ_z, the Ψ_x is made equal zero before the **lenses** S_2 and S_3 . Due to the insertion of additional lenses and magnets in the scheme, the appearance of a large Ψ_z at the collision point when keeping a small vertical betatron size becomes possible as a result. It is worth noting that it is the magnetic field that carries out the required energy expansion of the e^+e^- beams at the collision point.

Limiting Energy Resolution

In the monochromatization scheme the value of Ψ_z at the collision point is controlled by means of skew-quadrupole lenses. The Ψ_z increases as the focal distance F of the lenses decreases. However, the vertical betatron size $\sigma_{z\beta}$ increases, at the collision point, with a simultaneous increase of Ψ_z. This occurs because of the fact that on the sections with magnets M_1 and M_2 there are the Ψ_z -function and its derivative Ψ_z' , which are different from zero and the normal betatron-oscillation modes rotated with respect to the axes $\vec{e}_x$ and $\vec{e}_z$. Therefore, the quantum fluctuations of the radiation lead here to an additional excitation of the vertical emittance $\Delta\varepsilon_z$. If, for example, there would not be the initial vertical emittance ε_{zo} , then the $\sigma_{z\beta}$ and Ψ_z would grow, at the collision point, in an equal extent and the value of σ_t , according to equation (3), would not change with decreasing F . Under real conditions with the availability of ε_{zo}, the growth of $\sigma_{z\beta}$ occurs, at the beginning, more slowly than Ψ_z and, hence, the σ_t decreases. This continues until the contribution from the magnets M_1 and M_2 to the vertical emittance becomes dominant. After that, the σ_t becomes independent of the force of the lenses and achieves the same limiting value as in the case without ε_{zo} . This limiting value can be estimated according to the formula[1]:

$$\sigma_t = 0.3 \left\{ \Lambda \frac{\Psi_{xo}^3 R}{(L/2\pi)^5} \right\}^{1/2} \frac{E_o^2}{mc^2} \qquad (4)$$

where Λ, mc^2 is the Compton wavelength and rest energy of an electron, R is the mean radius of curvature, $L/2$ is the distances between the lenses S_1 and S_2 , and Ψ_{xo} is the value of Ψ_x at the entrance of the monochromatization scheme. The limiting value of σ_t is attained at a small focal distance of skew-quadrupole lenses, which satisfies the condition

$$F < 0.2 \left\{ \frac{\Psi_{xo}^5 R^2 \bar{\beta}_x \varepsilon_{xo}}{(\ell/2\pi)^4\, \bar{\Psi}_x\, \varepsilon_{zo}} \right\}^{1/2} \qquad (5)$$

where $\bar{\beta}_z$ and $\bar{\Psi}_x$ are the average values of the beta- and Ψ_x - functions, respectively, in the standart cell; and ε_{xo} is the horizontal emittance. The condition (5) is the simpler the less the initial vertical emittance ε_{zo}. In order that this emittance be small, it is necessary to eliminate the Ψ_z -function and the coupling of betatron oscillations in the main ring.

In principle, there is the possibility of further decreasing σ_ε compared with (4). In an analysis of the expression (3) it is easy to note that an additional improvement is possible to achieve, by increasing the decrement of the vertical betatron oscillations[1,3]:

$$\sigma_\varepsilon = \sqrt{2}\,\frac{\sqrt{\sigma_{z\beta}\,\frac{d_{z0}}{d_z}}}{|\Psi_z|}\,E_0 \qquad (6)$$

where d_z is the new, and d_{z0} the 'old' decrement of the vertical betatron oscillations. If one uses the wiggler with an alternating magnetic field B_0, it is possible to have

$$\frac{d_{z0}}{d_z} = \left(1 + \frac{B_0^2 \ell_w}{\langle B_z^2\rangle \cdot \Pi}\right)^{-1}$$

Here ℓ_w is the wiggler length, $\langle B_z^2\rangle$ is the mean square of the field in the storage ring, and Π is the perimeter.

It is very essential that the quantum fluctuations of the radiation in the wiggler would not lead to a direct increase of ε_{z0}. For this purpose, the Ψ_z and Ψ_z' functions have to be made exactly equal to zero in the wiggler. With equation (6) taken into account, the limiting energy resolution (4) can be rewritten as follows:

$$\sigma_\varepsilon = 0.3\left\{\Lambda\,\frac{\Psi_{x_0}^3\,R}{(\ell/2\pi)^5\left(1 + \frac{B_0^2\ell_w}{\langle B_z^2\rangle\,\Pi}\right)}\right\}^{1/2}\frac{E_0^2}{mc^2} \qquad (7)$$

For the VEPP-4 the estimates show that the wigglers will help to obtain σ_ε less than the widths of these resonances in the energy range of the ψ and ψ' mesons. It is probable that this will enable their internal structure to be resolved.

Beam-beam effects

The influence of the beam-beam effects on monochromatization is analysed in detail in [4]. As pointed out in this paper, a large vertical expansion of the beams over energy, corresponding to the arranged monochromatization, makes for a certain weakening of the nonlinear resonances occuring upon periodical motion of the particles of one beam through the nonlinear fields of the space charge of the particles of the other beam.

This is due to the fact that upon monochromatization the betatron size $\sigma_{z\beta}$ of the beam constitutes only a small fraction of the total size σ_z. As a result, the nonlinearity of the interaction 'force' on the size of the betatron oscillations of particleas is much less than in the usual case when $\sigma_{z\beta} \sim \sigma_z$. At the same time, for a good monochromatization to be kept, the perturbations caused even by the linear component of the field of the beam's space charge turn out to be dangerous. Indeed, upon acting the beam-beam effects, it is necessary that the perturbations of the electron Ψ_{z^-} and positron Ψ_{z^+} dispersion functions, which are initiated by a field of the colliding beam, be small. This is of importance both for the satisfaction of the basic condition $\Psi_{z^+} = -\Psi_{z^-}$ at the collision point and for the smallness of Ψ_z in the main ring. If $\Psi_{z^+} \neq \Psi_{z^-}$, then the instantaneous orbits of the particles with equal, in magnitude, and sign-opposite, deviation of the energy from the equilibrium, cease to coincide, and the vertical emittance of the beam raises when appearing Ψ_z in the main ring. Both these factors make the energy resolution to degrade. In the linear approximation of the colliding beam field, the loss in energy resolution can be estimated by means of the formula[4]

$$\lambda(\xi_+,\xi_-) = \lambda_0\left\{1 + \frac{4\pi^2\lambda_0^2}{\sin^2\pi\nu_z}(\xi_+^2 + \xi_-^2) + \pi^2(\xi_- - \xi_+)^2\lambda_0^2\,\mathrm{ctg}^2\pi\nu_z\right\}^{-1/2} \qquad (8)$$

where λ_0 is the gain in the absence of the beam-beam effects, ξ_+,ξ_- is the parameter of the space charge of the positron (electron) beam, and ν_z is the vertical betatron tune. The λ dependence of the ξ, calculated according to formula (8) at $\lambda_0 = 11.5$, $\xi_+ = \xi_-$, and $\nu_z = 0.6$, is demonstrated by graph 1 in Fig. 3. Graph 2 on this figure shows the dependence found numerically with allowance for the nonlinear nature of the force of the colliding beam. As it is clear from the figure, the linear approximation describes the realistic situation in a proper manner. On the other hand, this means that, having compensated only the linear component of the 'force' of the colliding beam, we can substantially weaken the influence of the beam-beam effects on monochromatization.

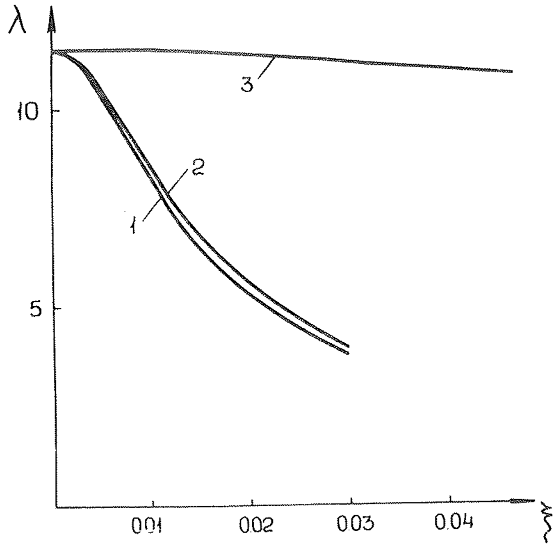

Fig. 3.

Such a compensation is possible to make with the help of a quadrupole lens with the focal distance $f = -\beta_z/4\pi\xi$ (β_z is the beta-function at the location of the lens), which is placed exactly in one half-wave of the vertical betatron oscillations from the collision point[3]. The optimal compensation is achieved when the 'force' of the lens constitutes 95% of the 'force' of the colliding beam. This case is demonstrated by graph 3.

Project of a 'monochromatic' VEPP-4

The project of modernization of VEPP-4 with the aim at performing monochromatic experiments covers a few major aspects. Let us indicate some of them:

a) Complete reconstruction of the experimental straight section of the storage ring with the change of its geometry and the installation of new elements of the magnetic structure, including the optics of the monochromatization scheme.

b) Replacement of the MD-1 detector with a vertical magnetic field by a detector with a longitudinal field. This is connected with that the quantum fluctuations of the radiation in the MD-1 magnetic field will result, during monochromatization, in raising the vertical emittance of the beam and, hence, in worthening the monochromaticity.

c) Remounting of the cells in the main ring, in order to obtain the small vertical beam size. In the course of monochromatization, the correction system, based on the skew-quadrupole lenses, which are placed in the standard cells, is planned to be used. To this end, the magnetic blocks of the cells are assumed to be moved apart, by removing some cells and placing the correction lenses on the sites available. The new sextupole lenses can be installed here, as well.

The design parameters of the 'monochromatic' VEPP-4 are listed in Table 1. The table presents the approximate experimental energy E_0, the gain λ with the beam-beam effects and the possibility of their partial compensation, the r m s spread of the total interaction energy σ_t, the vertical beta-function β_z at the collision point, the luminosity L, the beam currents I required for this luminosity, and the linear tune shift ξ at these currents.

Table 1.

E_0 GeV	Gain	σ_t keV	β_z cm	ξ	I (mA)	L cm^{-2}, s^{-1}
1,5	10	45	7	0.01	0.5	10^{28}
1.5*)	23	20	7	0.01	1.5	$5\cdot 10^{28}$
5	10	500	7	0.03	20	10^{31}

*) with wigglers

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