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PHI-FACTORY PROJECT IN NOVOSIBIRSK

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Abstract The project of a dedicated 510 MeV electron-positron storage ring with the luminosity above $10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ is proposed. Its energy corresponds to a maximum of the phi-meson resonance production (Phi-factory). An essential feature of the project is the solenoidal focusing used to obtain round beams at the interaction point.

INTRODUCTION

At the INP (Novosibirsk) a project for a set of facilities with colliding electron-positron beams is in progress[1].

The Phi-meson factory is a new generation facility with colliding e^+e^- beams in the Phi-meson resonance energy range (1020 MeV). In this project a single ring scheme is used to reach the very high luminosity. This seems to be preferable as compared with the idea of employing separate electron and positron storage rings with the electrostatic convergence of the two beams in the common interaction points[2].

The first stage envisages the Phi-factory operation in the single bunch mode with attainable luminosities in excess of $1\cdot10^{33}\,\text{cm}^{-2}\text{s}^{-1}$. With a view to attain higher luminosity, the lattice and the construction of the storage ring are capable to operate in the three-bunch mode using an electrostatic beam separation at the side interaction points. With the even number of bunches in each beam $e^{\mp}e^{\pm}$ colliding beams can be arranged with the simultaneous collision of four bunches. In case of exact coincidence of orbits in the interaction point the space charge compensation mode is realized.

The Phi-factory having a luminosity of $(1\div3)\cdot10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ offers the unique possibility to study the CP-parity violating interactions. Such a high luminosity makes it possible to attain the luminosity integrals of $3\cdot10^{40}-3\cdot10^{41}\,\text{cm}^{-2}$ in two to five years. Assuming that the efficiency of luminosity utilization is about 50 per cent, we will be able to obtain $5\cdot10^{10}$ to $5\cdot10^{11}$ monochromatic K_S and K_L mesons in the $e^+e^-\rightarrow\Phi\rightarrow K_SK_L$ reaction.

PHI-FACTORY LATTICE

In the lattice with 8-shaped orbit suggested for the Phi-factory, two opposite points of beam-beam collisions are geometrically superimposed due to reverse bend magnets, and hence the capacity of the facility is doubled (Figure 1). Taking into account the complexity of the detector and its sizes comparable with those of the storage ring, it is expedient to have a single interaction point for only one detector.

The Phi-factory project is based on the idea of round colliding beams, with the

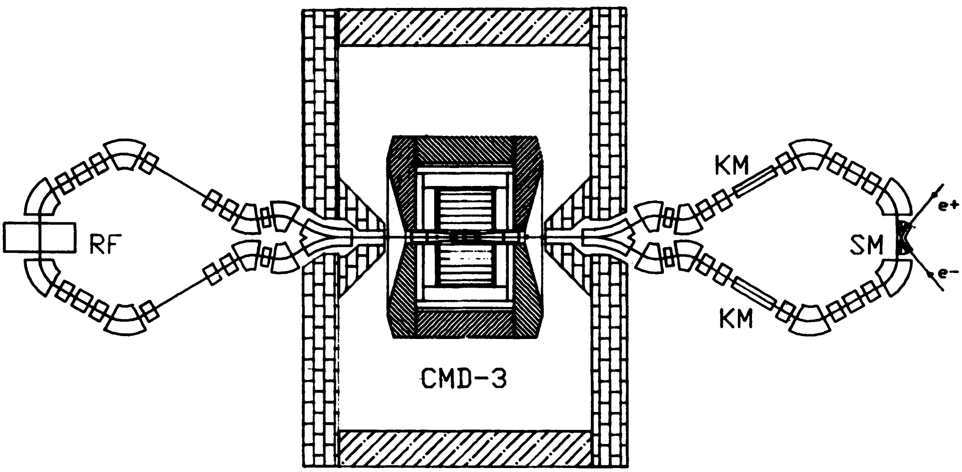

FIGURE 1. A schematic view of the Phi-meson factory.

operating point dwelling on the main coupling resonance near the integer one. The high-luminosity mode of operation is achieved with equal beta-functions at the interaction point taken as low as possible, and at equal transverse emittances of the beams.

To obtain low beta-functions in two planes simultaneously, the magnetic focusing of solenoidal type has been chosen. The optical scheme consists of two pairs of superconducting solenoids with maximum field of 11.0 T, which are placed symmetrically with respect to the centre of straight section. As construction components, the solenoids are incorporated in the detector housing. In contrast to quadrupole focusing, the use of solenoids in the common straight section provides quite symmetric focusing properties during forward and reverse passages of the beams. The azimuthal dependence of the longitudinal magnetic field throughout the experimental straight section is given in Figure 2. In each pair, the solenoids are connected in opposition. This enables one to keep the longitudinal field integral over the straight equal to $\pi \cdot HR$, regardless of variation of the required focusing parameters. As a result, the betatron oscillation planes

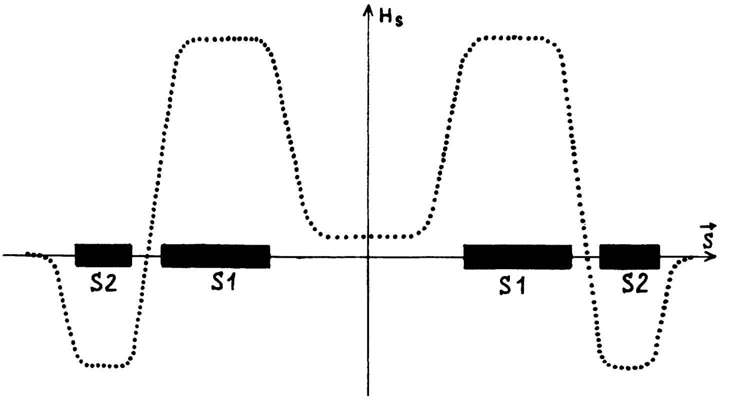

FIGURE 2. Azimuthal distribution of the longitudinal magnetic field in the experimental straight section of the Phi-factory.

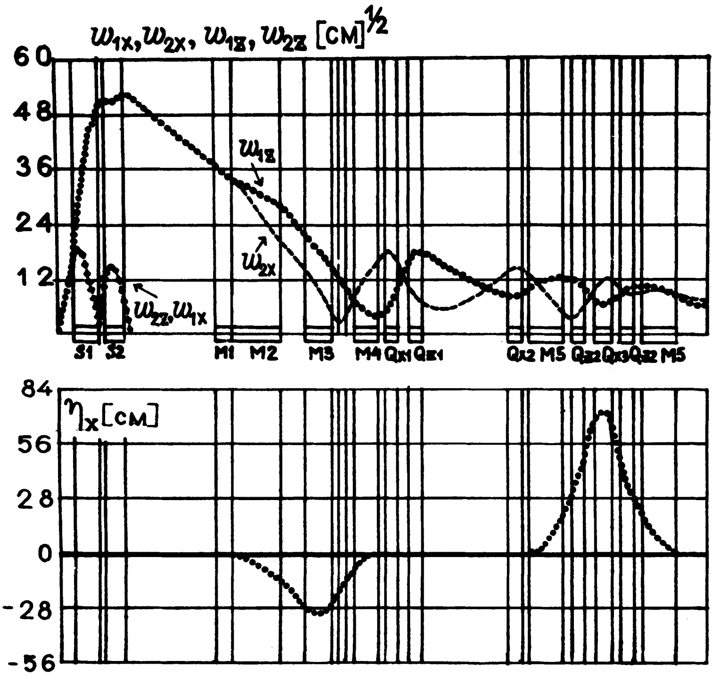

FIGURE 3. One-fourth of the Phi-factory lattice period, mirror-symmetry, with respect to the interaction point.

are rotated by $+\pi/2$ or $-\pi/2$ angle during each passage of the beam. It is easy to see that the eigenvectors of the transition matrix for the complete turn are «flat» in the magnetic arcs and dwell in the X or Z planes, and they are inclined at $\varphi = |\pi/4|$ at the interaction point. The betatron oscillation normal mode is thus vertical in one arc and horizontal in the other. The projections of the envelopes of normal modes onto the X and Z planes are depicted in Figure 3. The beam and the lattice parameters were calculated in terms of the formalism usually applied to the systems with strongly-coupled linear betatron oscillations[3].

In the planes natural for the storage rings, i. e. in the X and Z planes, the r.m.s. sizes of the beams are:

$$\sigma_z^2(s) = w_{1z}^2(s)\, \mathscr{E}_1 + w_{2z}^2(s)\, \mathscr{E}_2,$$

$$\sigma_x^2(s) = w_{1x}^2(s)\, \mathscr{E}_1 + w_{2x}^2(s)\, \mathscr{E}_2 + \eta_x^2(s)\, (\sigma_{\Delta E/E})^2,$$

where $w_{1,z,x}$ and $w_{2,z,x}$ are the projections of the envelopes of normal modes onto the x, z planes; $\mathscr{E}_1$ and $\mathscr{E}_2$ are the emittance of the normal betatron modes.

The energy dispersion function $\eta_x(s)$ always lies in the median plane of magnetic arcs and is zero in the experimental straight section. There is no excitation of the vertical dispersion, and therefore, $\eta_z(s) \equiv 0$ for the whole circumference of the storage ring. In this case, the equal emittances of each normal betatron mode are independently formed in the corresponding magnetic arc due to the quantum fluctuations of synchrotron radiation.

In the structure of the type under consideration, the frequencies of normal betatron modes are half the sum of the betatron oscillations frequencies calculated without the rotation:

$$\nu_{1,2}=1/2(\nu_x+\nu_z)\,.$$

In this project, $\nu_x=7.05$, $\nu_z=5.05$ and $\nu_{1,2}=6.05$. A distinctive feature of the suggested type of the solenoidal focusing lattice is the absence of the coupling between the transverse modes of betatron oscillations.

To substantially increase the thresholds of different kinds of instabilities, including the coherent instability on the colliding beam, it is necessary to have large enough decrements of radiation damping. For this purpose, superconducting bending magnets with 6.0 T field are envisaged in magnetic arcs. A pair of dipole magnets with a quadrupole triplet in between form a 120° achromatic bend. An RF resonator is positioned in one of the straight sections between the achromats. Septum-magnets designed for the injection of electron and positron beams in opposite directions, are placed in the opposite straight section in another arc. There are two symmetric kicker-magnets in the straight sections on either side of the septum straight. The basic parameters of the lattice and beams are given in Table I.

Table I. Basic Parameters of the Phi-Factory and Beams at 510 MeV.

Parameters		Units	Phi-factory	VEPP-2M with wiggler
Circumference	c	m	28.0	17.88
Accelerating voltage frequency	f_0	MHz	700	200
Momentum compaction factor	α	—	0.003	0.167
Emittances	$\mathscr{E}_{x0}$	cm·rad	$2.8\cdot10^{-5}$	$4.6\cdot10^{-5}$
	$\mathscr{E}_{z0}$	cm·rad	$2.8\cdot10^{-5}$	$5.5\cdot10^{-7}$
Radiative energy loss per turn	ΔE_0	keV	40	9.1
Dimensionless damping decrements between interaction point	δ_z	—	$2.3\cdot10^{-5}$	$0.44\cdot10^{-5}$
	δ_x	—	$2.3\cdot10^{-5}$	$0.38\cdot10^{-5}$
R.m.s. energy spread in the beam	$\sigma_{\Delta E/E}$	—	$5\cdot10^{-4}$	$6\cdot10^{-4}$
Beta-functions at the I.P.	β_z^*	cm	0.5	4.5
	β_x^*	cm	0.5	48
R.m.s. longitudinal bunch size	σ_s	cm	0.4	3.5
Betatron tunes	ν_z	—	6.05	3.09
	ν_x	—	6.05	3.06
Number of particles per bunch	N	e^+, e^-	$8.9\cdot10^{10}$	$3.7\cdot10^{10}$
Space charge parameters	ξ_z	—	$\gtrsim0.07$	0.05
	ξ_x	—	$\gtrsim0.07$	0.02
Luminosity in single-bunch mode	$\mathscr{L}_{\max}$	$\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$	$\gtrsim1\cdot10^{33}$	$\sim1\cdot10^{31}$
Luminosity in three-bunch mode	$\mathscr{L}_{\max}$	$\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$	$\sim3\cdot10^{33}$	—

LUMINOSITY AND BEAM-BEAM EFFECTS

In the approximation $\sigma_s\ll\beta_{z,x}^*$, the luminosity of a storage ring with colliding beams is defined by the well known expression:

$$\mathscr{L}=\frac{\pi\gamma^2\xi_x\xi_z f(1+\sigma_z^*/\sigma_x^*)^2}{r_e^2\beta_z^*}\;\frac{\mathscr{E}_{x0}}{(1+\varkappa^2)},$$

where ξ_z, ξ_x are the space charge parameters whose maximum value, $(\xi_z)_{\max}$ and $(\xi_x)_{\max}$, are limited by the beam-beam effects; σ_z^*, σ_x^* are the r.m.s. sizes of the beams at the interaction point; β_z^* is the vertical beta-function at the interaction point; $\mathscr{E}_{x0}$ is the horizontal emittance in the absence of the coupling between the transverse oscillations modes; $\varkappa=\sqrt{\mathscr{E}_z/\mathscr{E}_x}$ is the coupling coefficient; f is the collision frequency; r_e is the classical radius of electron, and γ is a relativistic factor.

In the Phi-factory lattice, an independent formation of the equal transverse emittances ($\mathscr{E}_{x0}=\mathscr{E}_{z0}=\mathscr{E}_0$) implies the absence of the coupling for betatron oscillations modes ($\varkappa=0$). In this case, the maximum luminosity for round colliding beams ($\sigma_z^*=\sigma_x^*=\sigma_0^*$) can be higher by a factor of 4 as compared with the flat beams ($\sigma_z^*\ll\sigma_x^*$). The ultimate emittances are limited by a permissible dynamic aperture in focusing solenoids used to create low beta-functions at the interaction point.

In general case the maximum luminosity is limited by the electromagnetic beam-beam interaction effects. The interaction force is characterized by the space charge parameters defined as follows for round beams:

$$\xi_{z,x}=\xi_0=\frac{N r_e\beta_0^*}{4\pi\gamma\sigma_0^{*2}}.$$

In the maximum luminosity regime, the threshold of the space charge parameter is likely to be determined by the coherent colliding beams instability conditions. This effect is theoretically treated in Refs 4—8.

The coherent shift of betatron tunes, which is caused by the colliding beam field, results in the appearance of the bands where coherent oscillations are unstable, near the machine resonance lines. The band width depends on the achieved value of of $\xi_{z,x}$ and on the order of the effective resonance. As the multipole number of the oscillation modes grows, the widths of the coherent betatron resonances and the instability increments die out according to the power law.

In terms of the coherent beam-beam instability the operating point location on the main coupling resonance offers some advantages . The tune shift for round beams, which is caused by the colliding beam, takes place along the line $\nu_1-\nu_2=0$; note that the coherent instability bands formed by powerful two-dimensional coupling satellite resonances are not trespassed. Exactly on the resonance $\nu_1-\nu_2=0$, no instability of coherent betatron and synchrobetatron oscillations appears provided that $\sigma_x^*=\sigma_z^*$ and $\xi_{x,z}=\xi_0$. On the other hand, sufficiently large radiation damping decrements are capable of suppressing the coherent instability near one-dimensional high-order betatron resonances which intersect the coupling resonance. On the existing electron-positron colliders the attainable $(\xi_{z,x})_{\max}$ usually is at a level of 0.03—0.06. The lattice properties and the choice of the operating point favour the attaining of the highest values of the space charge parameters.

The behaviour of incoherent beam-beam effects on the main coupling resonance has been numerically simulated in the «strong-weak» approximation in Ref. 9.

The lattice of a storage ring with very low beta-functions at the interaction point necessitates an obtaining of short intense bunches. A possible bunch lengthening can lead to a considerable degradation of luminosity because of an increased geometrical factor at the interaction point. For $\beta_0^*/\sigma_s\leqslant 1$ modulation of the beta-functions throughout the interaction region results in enlarging the effective interaction area. At the interaction point, these functions are characterized by the azimuthal dependence:

$$\beta_0(s)=\beta_0^*+s^2/\beta_0^*;\qquad \beta_0^*=w_{1z}^{*2}+w_{2z}^{*2}=w_{1x}^{*2}+w_{2x}^{*2}.$$

The luminosity of round colliding beams with a charge density of the form:

$$\rho_{\pm}(x, z, s, t) = \frac{N^{\pm}}{(2\pi)^{3/2}\sigma_0^{*2}\sigma_s} \exp\left(-\frac{x^2}{2\sigma_0^{*2}}\right) \exp\left(-\frac{z^2}{2\sigma_0^{*2}}\right) \exp\left[-\frac{(s \pm ct)^2}{2\sigma_s^2}\right]$$

can be determined by

$$\mathscr{L} = \mathscr{L}_0\sqrt{\pi}\,\left(\frac{\beta_0^*}{\sigma_s}\right)\,\exp\left(\frac{\beta_0^{*2}}{\sigma_s^2}\right)\left[1 - \mathrm{erf}\left(\frac{\beta_0^*}{\sigma_s}\right)\right],$$

where $\mathscr{L}_0 = N^+ N^- f/4\pi\sigma_0^{*2}$, erf (β_0^*/σ_s) is the probability integral of the parameter β_0^*/σ_s. The geometric factor is equal to 0.76 at $\beta_0^*/\sigma_s = 1$.

RADIATIVE POLARIZATION ON THE PHI-FACTORY

Application of superconducting bending magnets with high magnetic fields leads to a characteristic polarization time τ_p^0 equal to 9.5 mins for $E = 510$ MeV, and this can occur to be comparable with «luminosity life time». The attainable polarization degree outside depolarizing resonances approaches $S_\infty \sim 70\%$. It is evident that the radiative polarization should be taken into account since the angular deformations of the elastic e^+e^- scattering and cross-sections of secondary particles production are possible.

On passing the experimental straight with the longitudinal field integral $|\pi HR|$ the particle spin rotates around the velocity direction by $\varphi = \pi$. In this scheme, the equilibrium precession axis $\vec{n}_s(\theta)$ in the storage ring arcs is vertical and oppositely directed, while it is horizontal at the interaction point. If the directions of the guide fields are chosen to be symmetrically opposite in the opposite arcs, then the radiative polarization with τ_p^0 and S_∞ indicated above will occur. For uni-directed fields in the opposite arcs, the self-polarization degree is identically equal to zero. This can be useful in some physical experiments to eliminate the angular deformations of cross-sections which are associated with beam polarization.

The Phi-factory can also be employed for longitudinal polarization experiments. For these purposes, it is proposed to inject accelerated in the linac polarized e^-. After injection the direction of polarization can be rotated by the angle $\pi/2$ with a high frequency magnetic field whose frequency is resonant with the spin motion[10]. In this case, the polarization direction at the interaction point changes from turn to turn, according to the known law. Thus the phase of the coherent spin precession can be measured for each event.

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