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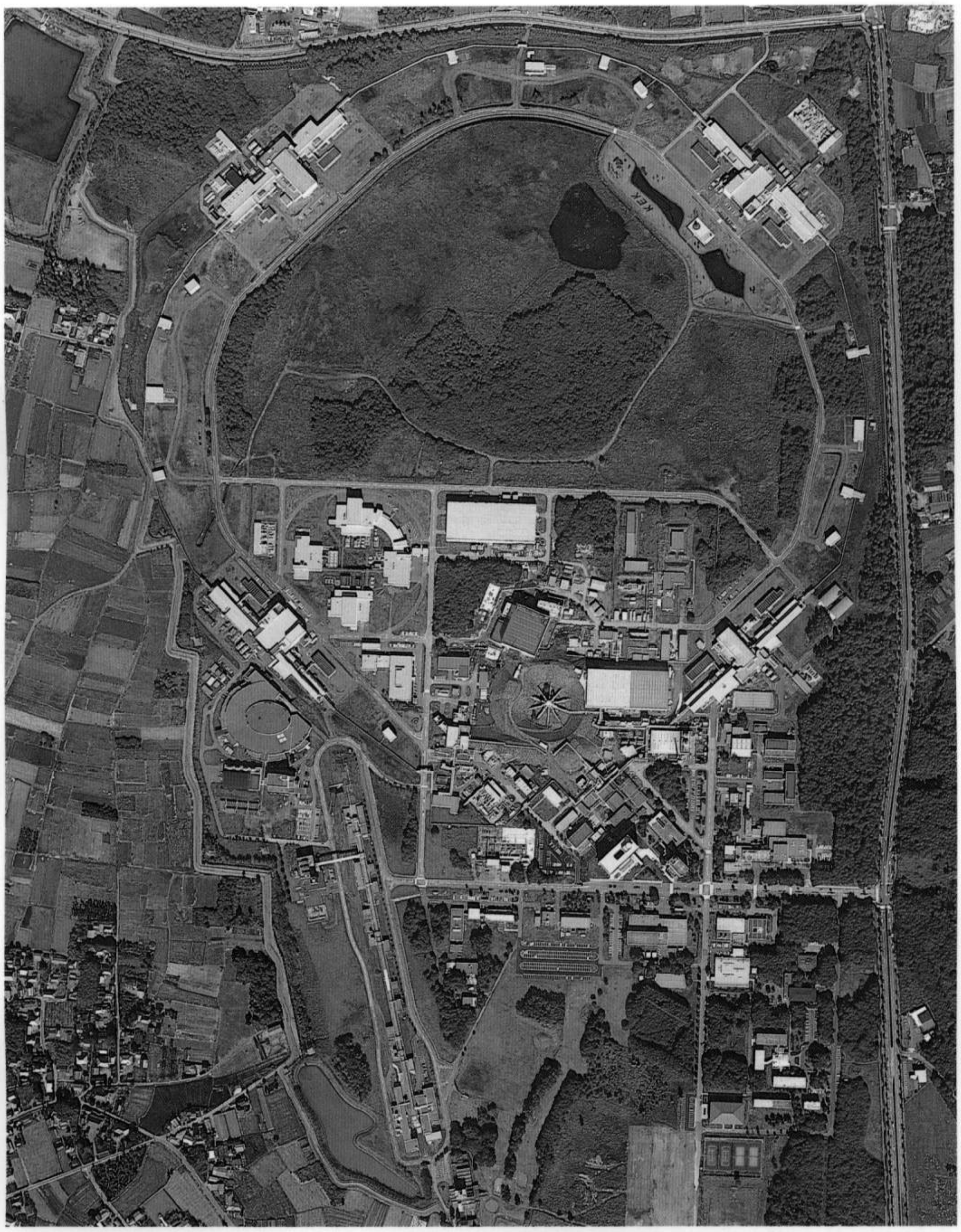

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PHI-FACTORY PROJECT IN NOVOSIBIRSK

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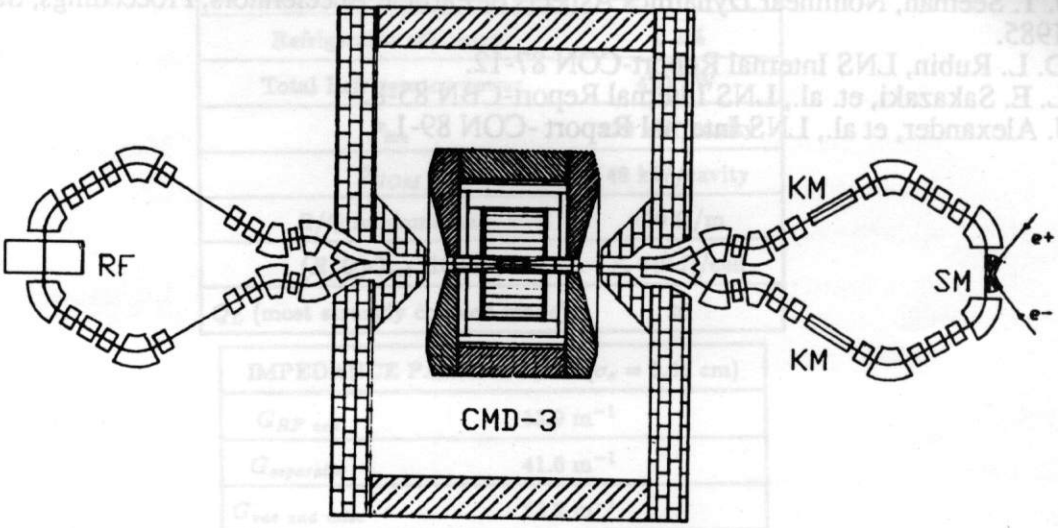

ABSTRACT

The project of a dedicated 510 MeV electron-positron storage ring with the luminosity above 10^{33} cm^{-2}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.

1. Introduction

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

It includes:

- a 2×6.5 GeV B-meson factory with the luminosity above $5 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$;
- a 2×510 MeV Phi-meson factory with the luminosity above $1 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$;
- an injector comprising the linacs and the damping ring to provide the factories with intense and perfect electron and positron beams.

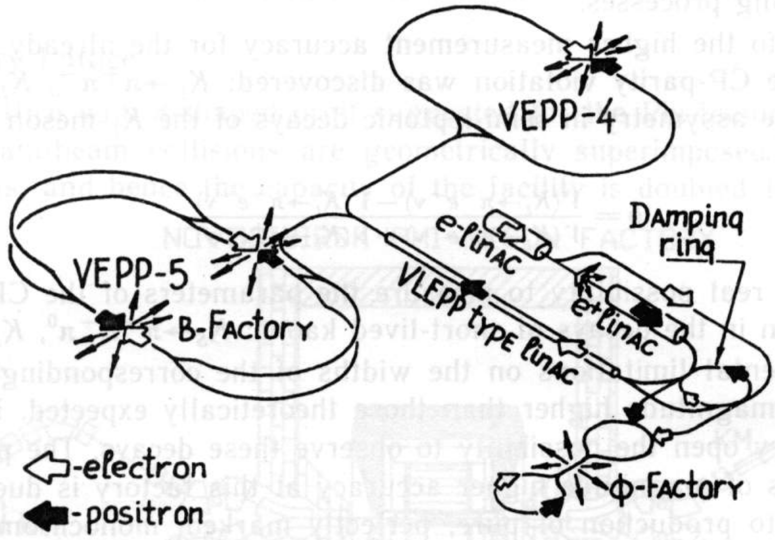

Fig. 1. Layout of VEPP-5, the facility with colliding electron-positron beams.

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 $1 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. 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 possibility to enhance the luminosity in this mode can be proved experimentally.

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

2. Physical Experiments on the Phi-Meson Factory

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

When using rather perfect universal detector, high monochromaticity permits an effective separation of various decay channels for both long- and short-lived kaons as well as a considerable advance in investigation of the CP-parity violating processes.

In addition to the higher measurement accuracy for the already known processes where the CP-parity violation was discovered: $K_L \rightarrow \pi^+\pi^-$, $K_L \rightarrow \pi^0\pi^0$, and where the charge assymetry in semi-leptonic decays of the K_L-meson was clearly demonstrated

$$\delta = \frac{\Gamma(K_L \rightarrow \pi^- e^+ \nu) - \Gamma(K_L \rightarrow \pi^+ e^- \nu)}{\Gamma(K_L \rightarrow \pi^- e^+ \nu) + \Gamma(K_L \rightarrow \pi^+ e^- \nu)}$$

there appears a real possibility to measure the parameters of the CP-parity violating interaction in the decays of short-lived kaons: $K_S \rightarrow \pi^+\pi^-\pi^0$, $K_S \rightarrow \pi^0\pi^0\pi^0$.

The experimental limitations on the widths of the corresponding decays are 4—5 orders of magnitude higher than those theoretically expected. Experiments at the Phi-factory open the possibility to observe these decays. The possibility to reach a 5 orders of magnitude higher accuracy at this factory is due to its high luminosity and to production of pure, perfectly marked, monochromatic K_S-mesons. Note that on hadron accelerators all the studies on CP-violation can practically have been performed using the extracted beams of K_L-mesons, and therefore the K_S-mesons decay channels remain insufficiently studied.

In experiments at the Phi-factory the measurement accuracy for the relative amplitudes of the K_L decay into $\pi^+\pi^-$ and $\pi^0\pi^0$

$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = |\eta_{+-}|\, e^{i\Phi_{+-}},$$

$$\eta_{00} = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = |\eta_{00}|\, e^{i\Phi_{00}}$$

and for the phase differences $\Delta\Phi = \Phi_{+-} - \Phi_{00}$ is expected to be improved by about one order of magnitude. This will make it possible to check the Bell—Steinberger relation and the validity of the CPT-theorem at quite a new level of accuracy.

Thus, the possibility to improve nearly by an order of magnitude the measurement accuracy of such known parameters for the CP-violating interaction in decays of K_L-mesons as $|\eta_{+-}|$, $|\eta_{00}|$, $\varepsilon'/\varepsilon = 1/6\,[1 - |\eta_{00}/\eta_{+-}|^2]$, $\Delta\Phi$, and by five orders for $|\eta_{+-0}|^2$, $|\eta_{000}|^2$ in K_S-meson decay channels will considerably contribute to our understanding of the fundamental laws of nature, and current theoretical ideas will be tested at a qualitatively new level.

Besides measurement of the constants of the CP-violating interaction, the high luminosity Phi-factory will also enable a considerable advance in the search for the exotic decay modes of ρ-, ω- and φ-mesons. In addition, the monochromatic K^0 and $K^{\pm}$ meson intensity ($\approx 10^3$ per sec, $\Delta W = 300$ keV, at kinetic energy of $W=3-30$ MeV) may be of great interest for investigation of their interaction with nuclei.

In experiments with colliding e^+e^- beams on the Phi-factory the background must be extremely low. For events identification the detector should possess a high detection efficiency in all e^+e^- interaction channels, high measurement accuracy for the characteristics of charged and neutral particles. These properties are inherent in a CMD-type detector with a liquid xenon calorimeter [3]. The possibility is considered of using localized-charge counters which provide high spatial accuracy in detection of charged and neutral particles and their flighttime characteristics measurement at a level of tens of picoseconds.

3. 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 (Fig. 2). 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.

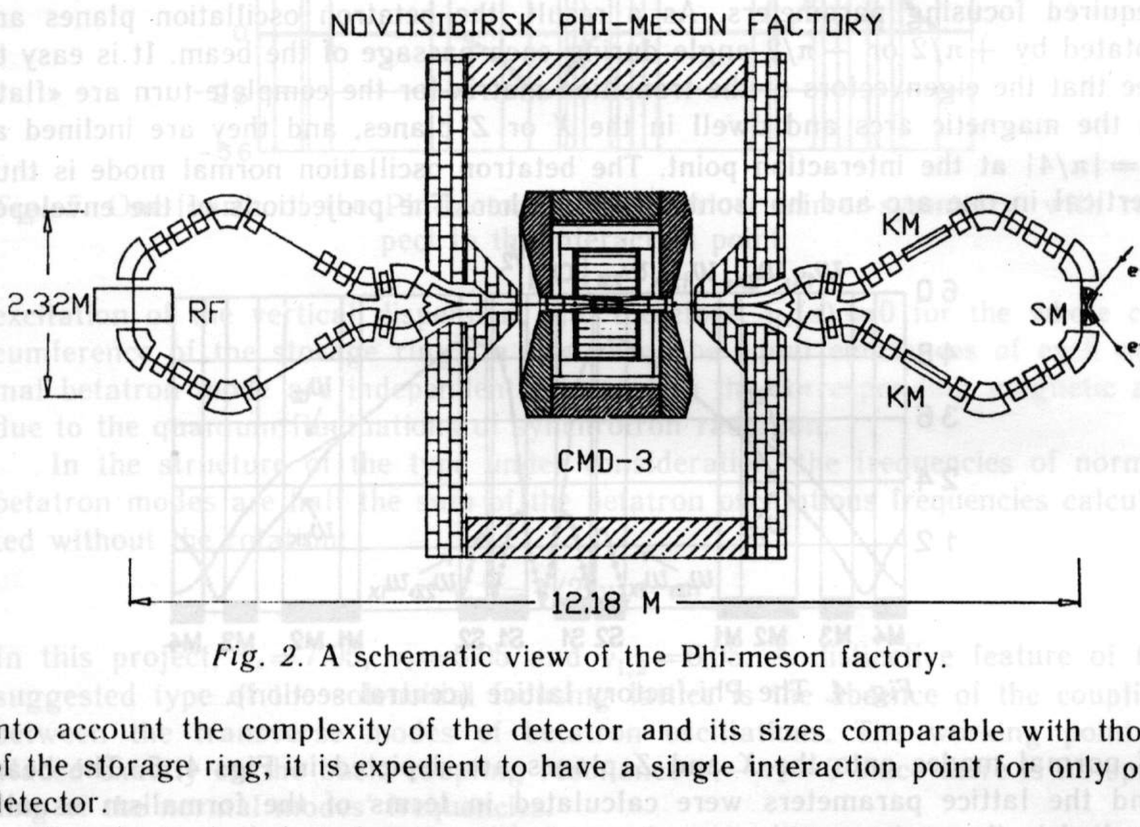

Fig. 2. A schematic view of the Phi-meson factory.

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 a 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 the quadrupole focusing, the use of solenoids in the common straight section provides quite symmetric focusing properties during forward and reverse passages of beams. The azimuthal dependence of the longitudinal magnetic field throughout the experimental straight section is given in Fig. 3. In each pair, the solenoids are connected in opposition. This enables one to keep the longitudinal

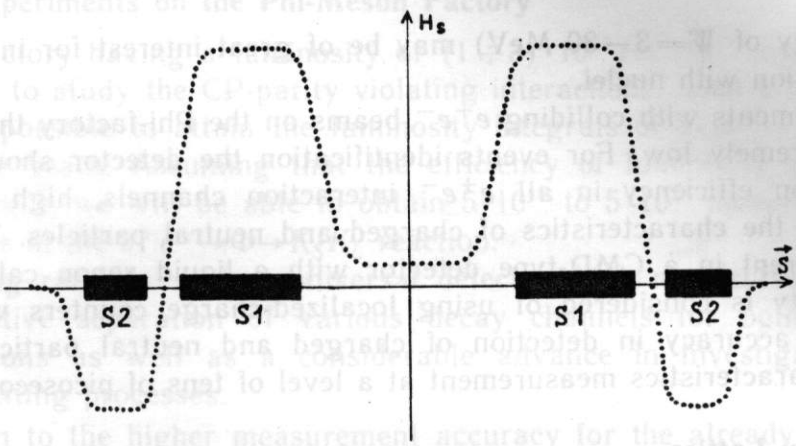

Fig. 3. Azimuthal distribution of the longitudinal magnetic field in the experimental straight section of the Phi-factory.

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 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

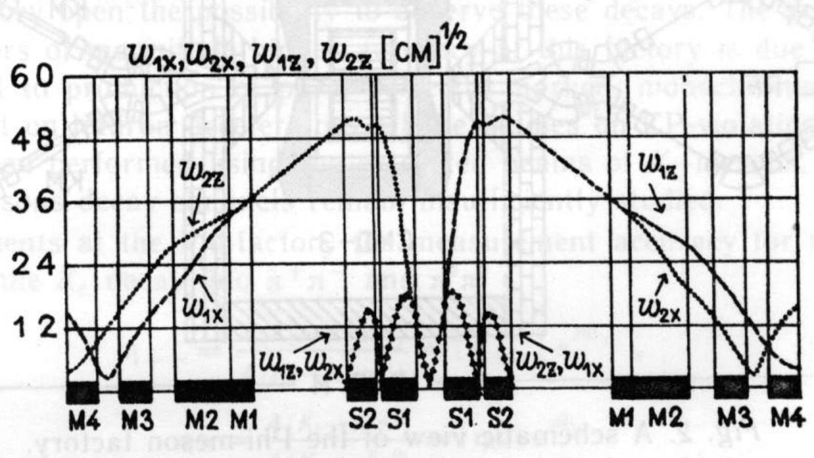

Fig. 4. The Phi-factory lattice (central section).

of normal modes onto the X and Z planes are depicted in Figs 4, 5. The beam and the lattice parameters were calculated in terms of the formalism usually applied to the systems with strongly-coupled linear betatron oscillations [4].

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 emittances 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

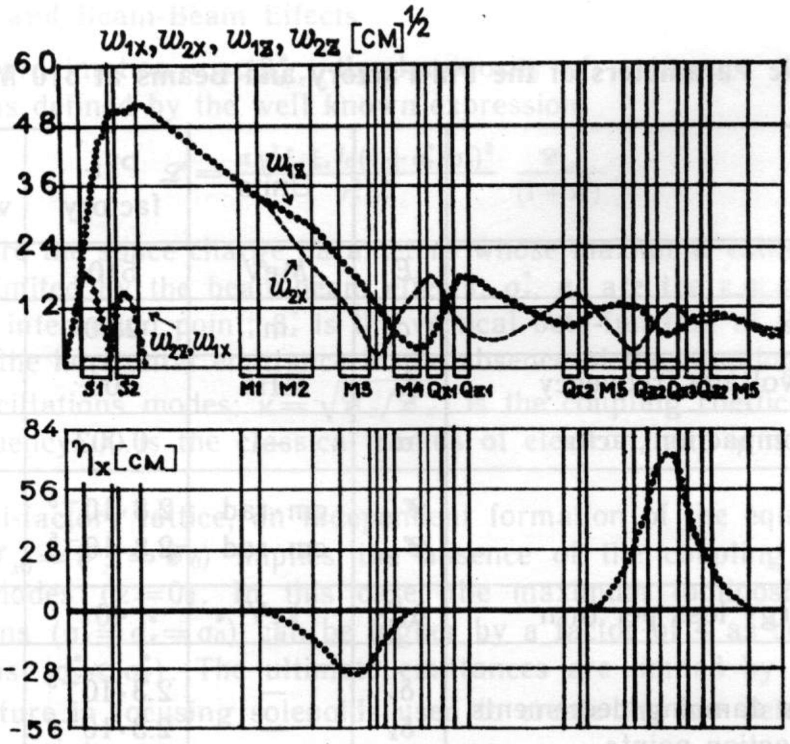

Fig. 5. One-fourth of the Phi-factory lattice period, mirror-symmetry with respect to the interaction point.

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. The working point is placed exactly on the basic coupling resonance $\nu_1-\nu_2=0$ since there is no splitting of the normal modes' frequencies.

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. The 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.

Table 1

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

Parameters		Units	Phi-factory	VEPP-2M with wiggler
Energy	E	MeV	510	510
Circumference	c	m	28.0	17.88
Accelerating voltage frequency	f_0	MHz	700	200
Momentum compaction factor	α	—	0.003	0.167
Emittances	$\mathscr{E}_{x0}$ $\mathscr{E}_{z0}$	cm·rad cm·rad	$2.8\cdot10^{-5}$ $2.8\cdot10^{-5}$	$4.6\cdot10^{-5}$ $5.5\cdot10^{-7}$
Radiative energy loss per turn	ΔE_0	keV	40	9.1
Dimensionless damping decrements between interaction points	δ_z δ_x δ_s	— — —	$2.3\cdot10^{-5}$ $2.3\cdot10^{-5}$ $4.7\cdot10^{-5}$	$0.44\cdot10^{-5}$ $0.38\cdot10^{-5}$ $0.94\cdot10^{-5}$
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^* β_x^*	cm cm	0.5 0.5	4.5 48
R.m.s. longitudinal bunch size	σ_s	cm	0.4	3.5
Betatron tunes	ν_z ν_x	— —	6.05 6.05	3.09 3.06
Number of particles per bunch	N	e^+, e^-	$8.9\cdot10^{10}$	$3.7\cdot10^{10}$
Space charge parameters	ξ_z ξ_x	— —	$\geqslant0.07$ $\geqslant0.07$	0.05 0.02
Luminosity in a single-bunch mode	$\mathscr{L}_{\max}$	$\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$	$\geqslant1\cdot10^{33}$	$\sim1\cdot10^{31}$
Luminosity in a three-bunch mode	$\mathscr{L}_{\max}$	$\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$	$\sim3\cdot10^{33}$	—

The basic parameters of the lattice and beams are given in Table 1. According to calculations the beam lifetime with ultimate parameters is limited by the effect of single intrabunch scattering and is 1000 s within the design aperture. At very high luminosity the lifetime is expected to degrade down to 300 s because of the losses, caused by the single bremsstrahlung on colliding beam. The injection frequency of the next portions of the beams is assumed to be ranged from 0.1 to 0.2 Hz, so that the average luminosity achieves as high value as possible.

4. 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:

$$\mathscr{L} = \frac{\pi\gamma^2 \xi_x \xi_z f_0 (1+\sigma^*_z/\sigma^*_x)^2}{r_e^2 \beta^*_z} \; \frac{\mathscr{E}_{x0}}{(1+\varkappa^2)},$$

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_0 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 the 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 the round beams as follows:

$$\xi_{z,x} = \xi_0 = \frac{N r_e \beta^*_0}{4\pi\gamma\sigma_0^{*2}}.$$

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 6—10.

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 $\xi_{z,x}$ 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. The enhancement of radiation damping can decrease the order of the effective resonance and thus allows to attain the larger values of the space charge parameters.

In our project the operating point was chosen in close proximity to the integer resonance with eqeal frequencies of normal betatron oscillations modes $\nu_1 = \nu_2$. In terms of the coherent beam-beam instability the operating point location on the main coupling resonance offers some advantages [9]. 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 $(\xi_{zx})_{\max}$ 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. This can contribute efficiently to the realization of the very high luminosity regime due to the quadratic dependence: $\mathscr{L}_{\max} \sim (\xi_0)^2_{\max}$.

The behaviour of incoherent beam-beam effects on the main coupling resonance has been numerically simulated in the «strong-weak» approximation in Ref. 11.

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:

$$\beta_0(s) = \beta_0^* + s^2/\beta_0^*,$$

$$\beta_0^* = w_{1z}^{*2} + w_{2z}^{*2} = w_{1x}^{*2} + w_{2x}^{*2}.$$

Here s is a longitudinal coordinate counted off from the interaction point. 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

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

where $\mathscr{L}_0 = \frac{N^+ N^- f_0}{4\pi\sigma_0^{*2}}$, $\operatorname{erf}(\beta_0^*/\sigma_s)$ is the probability integral of the parameter $\beta^*{}_0/\sigma_s$. The geometric factor is equal to 0.76 at $\beta_0^*/\sigma_s = 1$.

One should also notice one more important advantage of round colliding beams. In the case $\mathscr{E}_{x0} = \mathscr{E}_{z0}$ and $\beta_z^* = \beta^*{}_x$ the space charge parameters are no more dependent on the colliding bunch length. For flat beams, the modulation effect establishes the threshold value of $\beta^*{}_z/\sigma_s \approx 1.5$ starting with which the maximum attainable value of $(\xi_z)_{\max}$ begins falling off, and further decrease of β_z^* does not lead to better luminosity.

5. Radiative Polarization on the Phi-Factory

The lattice of this factory has some peculiarities which result in the electron and positron radiation polarization effects. Application of superconducting bending magnets with high magnetic fields leads to a characteristic polarization time [12]:

$$\tau_p^0 = \left[\frac{5\sqrt{3}}{8}\,\frac{me^2c}{\hbar^2}\,\gamma^2\,\frac{\langle H_z^3\rangle}{H_0^3}\right]^{-1},$$

$$H_0 = \frac{m^2c^3}{e\hbar^3} = 4.41 \cdot 10^{13}\,\text{Oe}; \quad \langle H_z^3 \rangle = \frac{1}{2\pi R} \int_0^{2\pi R} |H_z|^3\, ds$$

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 the depolarizing resonances approaches to $S_\infty \sim 70\%$. 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 in order to eliminate the angular deformations of cross-sections which are associated with the beam polarization.

The spin precession frequency in the Phi-factory lattice is proportional, just as in the usual «round» storage rings, to the particle energy, and the resonance depolarization method [13] is applicable to the absolute calibration of the mean energy in the beams.

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 [14]. In this case, the polarization direction at the interaction point changes from turn to turn, according to the known law. Thus, phase of coherent spin precession can be measured for each event.

It is probable that the luminosity of the Phi-factory with polarized beams will be somewhat lower as compared with the conventional regime because of a depolarizing influence of the colliding bunches. This problem and the problem of machine depolarizing resonances need further investigation.

Acknowledgements

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