STATUS OF THE NOVOSIBIRSK PHI-FACTORY PROJECT.

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I. Introduction.

The Novosibirsk Institute of Nuclear Physics develops the project of a complex electron-positron colliding beam facility$^{1)}$, which comprises:

a 4x7 GeV B-factory with a luminosity of $5\cdot10^{33}cm^{-2}s^{-1}$;

a φ-factory with a luminosity of over $10^{33}cm^{-2}s^{-1}$;

an injector consisting of a linear accelerator and a cooling storage ring for providing the factories with intense electron and positron beams.

The φ-factory is a new generation facility with colliding e^+e^- beams in the energy range of the φ-meson resonance (1020 MeV). The first stage of the project$^{2)}$ envisages the φ-factory performance in a single bunch mode on the basis of one storage ring with an attainable luminosity of $L_{max}\sim1\cdot10^{33}cm^{-2}s^{-1}$. This level of luminosity is a threshold one for experiments on measuring constants of CP violating interactions. Besides, the scope of experiments on the study of exotic decay modes of ρ-, ω-, φ-mesons becomes practically unlimited.

After investigating the relevant problems of accelerator physics and running the first cycle of experiments with the CMD-3 detector the second stage of the project will come into force. It will be devoted to increasing the luminosity. To attain this the magnetic structure and the storage ring design provide for a 3-bunched beam regime applying the electrostatic beam separation at the side interaction points(IP). Besides, an alternative scheme of multi-bunch regime is considered based on two independent electron and positron storage rings with electrostatic convergence of the beams at one IP. The luminosity can attain the values $L\sim3\cdot10^{33}-1\cdot10^{34}cm^{-2}s^{-1}$ dependent on the particular scheme under use.

II. Basic Features of the Accelerator Project.

The φ-meson factory project is based on the use of round colliding beams with the operating point (ν_x,ν_z) placed on the main coupling resonance line $(\nu_x-\nu_z=0)$ close to the integer resonance;

the regime of ultrahigh luminosity is attained at equal and minimum possible β-functions at the IP;

equal transverse emittances of the beams are formed independently due to the quantum fluctuations of synchrotron radiation without of betatron mode coupling;

to provide round beams at the IP the solenoidal focusing is used with a maximum longitudinal field of 11 T;

superconducting bending magnets with a field of 6.5 T are suggested to be used;

the lattice properties and beam parameters provide for an increase in the limiting values of the space charge parameter up to $\xi_0\geq0.1$.

III. Lattice.

In the proposed type of the storage ring lattice (Fig. 1) two opposite interaction regions are united in one by introducing negative curvature sections into arcs. 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 IP for one detector.

To obtain low beta-functions in both planes simultaneously, the solenoidal magnetic focusing has been chosen. The optical scheme consists of two pairs of superconducting solenoids C_1 and C_2 with a maximum field of 11.0 T, which are placed symmetrically with respect to the centre of the straight section. As construction components, the focusing solenoids C_1 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 for direct and reverse passages of beams due to $f_s^{-1}=(\int H_s^2ds)/(2HR)^2$. In each pair, the solenoids are connected in opposition. This enables to keep the longitudinal field integral over the straight equal to $\int H_sds=\pi HR$, regardless of variation of the required focusing parameters. As a result, the betatron oscillation planes are rotated by angles $\varphi=+\pi/2$ and $\varphi=-\pi/2$ during direct and reverse passages of the beam, respectively.

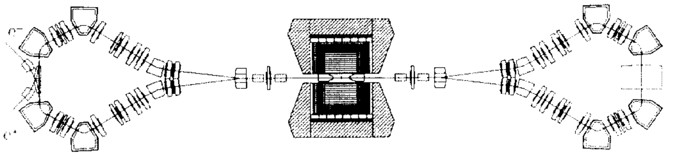

Fig.1. Layout of the Novosibirsk φ-factory.

It is easy to see that the eigenvectors of the transport matrix for the complete turn are "flat" in the arcs and dwell in the X or Z planes, and they are inclined at $\varphi=\pi/4$ at the IP. The betatron oscillation normal mode is thus vertical in one arc and horizontal in the other. Optical functions are shown in Fig. 2,3. The beam and the lattice parameters were calculated in terms of the formalism usually applied to the systems with strongly-coupled linear betatron oscillations$^{3)}$.

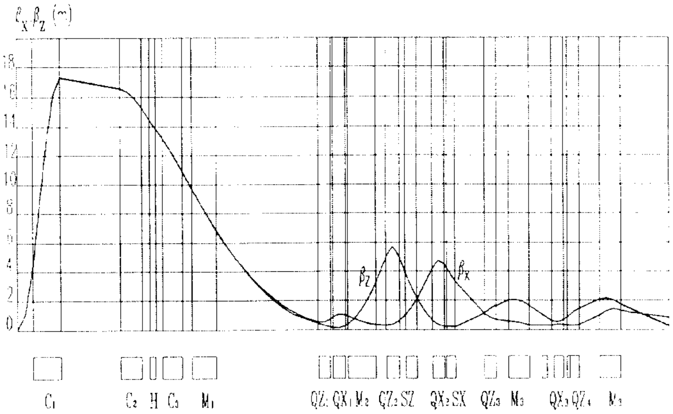

Fig.2. One-quarter of the φ-factory lattice period.

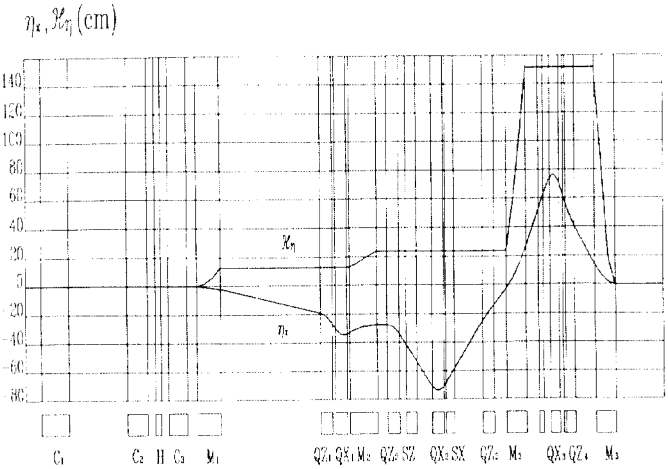

Fig.3. Dispersion function η_x and Courant-Snyders invariant for η_x.

The dispersion function η_x always lies in the median plane of magnetic arcs and is zero in the experimental straight section. In this case, the equal emittances of each normal betatron mode are independently excited in the corresponding magnetic arc due to the quantum fluctuations of synchrotron radiation.

The important feature of the suggested lattice type with a solenoidal focusing is the absence of coupling between the transverse betatron oscillation modes. The operating point is placed exactly on the line $\nu_1-\nu_2=0$, since of the normal modes' tunes are not split.

The φ-factory lattice is optimized to compensate the betatron tune chromatism, chromatic betatron and dispersion functions by minimizing the possible effect of sextupole correctors on the dynamic aperture. The sextupoles are grouped in three independent families. In each family they are placed in pairs over $(2n+1)\cdot\pi$ betatron phase advance in the arc of the machine:

$$S_z(\gamma\cdot\partial\nu_z/\partial\gamma,\ \gamma/\beta_z\cdot\partial\beta_z/\partial\gamma)$$

$$S_x(\gamma\cdot\partial\nu_x/\partial\gamma,\ \gamma/\beta_x\cdot\partial\beta_x/\partial\gamma)$$

$$S_\eta(\gamma\cdot\partial\eta_x/\partial\gamma)$$

The natural chromatism of betatron tunes $\gamma\cdot\partial\nu_{x,z}/\partial\gamma=-34$. The optimal arrangement of sextupole families S_z, S_x, S_η has resulted in minimizing the functions $\gamma/\beta_{z,x}\cdot\partial\beta_{z,x}/\partial\gamma$ and compensating $\gamma\cdot\partial\eta/\partial\gamma$ in the experimental straight section without a noticeable excitation of the betatron tunes chromatism quadratic in $\Delta p/p$. The dynamic aperture is limited mainly by nonlinearity of end-fields of focusing solenoids[4)] and, to some extent, by the nonlinear effect of sextupoles (Fig. 4).

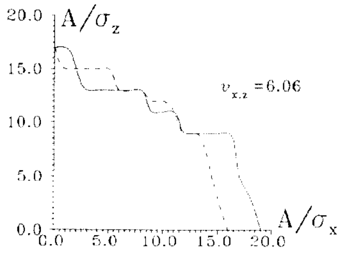

Fig.4. Dynamic aperture for φ-factory lattice with 3 sextupole families, end-fields of focusing solenoids and 16-pole lenses. Tracking simulation over 512 turns and with averaging over initial betatron phases. a) betatron dynamic aperture for synchronous particle (solid line); b) with energy deviation $|\Delta E/E|=8\sigma_E$ (dashed line).

IV. Design of Basic Elements of Storage Ring.

In order to increase the thresholds of various instabilities developments, including also the colliding beam coherent instabilities, it is necessary to have large enough decrements of radiation damping. For this purpose superconducting bending magnets with a 6.5 T field are envisaged in magnetic arcs. The schematic of a C-shaped SC magnet is shown in Fig 5. It provides:

- a field index in the magnetic gap close to 0.5;
- for end-fields slightly differing from the those of dipole magnets with unsaturated iron;
- against stray fields outside the magnet.

A pair of dipole magnets together with a quadrupole doublet forms a 122° achromatic bend for canceling the dispersion function in the technical straight sections. In one of them a superconducting RF cavity is positioned, in the opposite one septum magnets, designed for injecting e^+e^- beams in opposite directions, are placed.

The RF cavity should provide the required accelerating voltage (1 MV) without exciting beam instabilities and bunch lengthening. A schematic of the 700 MHz cavity under development is given in Fig.6. The coaxial power input with a capacitive coupling is placed close to the cavity body. Three waveguides are located on the opposite side and are placed at an angle of 120° to one another to provide for the HOM power extraction. The coherent losses of a bunch with $N=2\cdot10^{11}$ particles make 9.7 kW.

An important factor determining the shape and the design of the cavity is the high synchrotron radiation power from SC bending magnets. The direct radiation onto the cryogenic surface is eliminated due to the large aperture and the SR absorbers situated on both the sides.

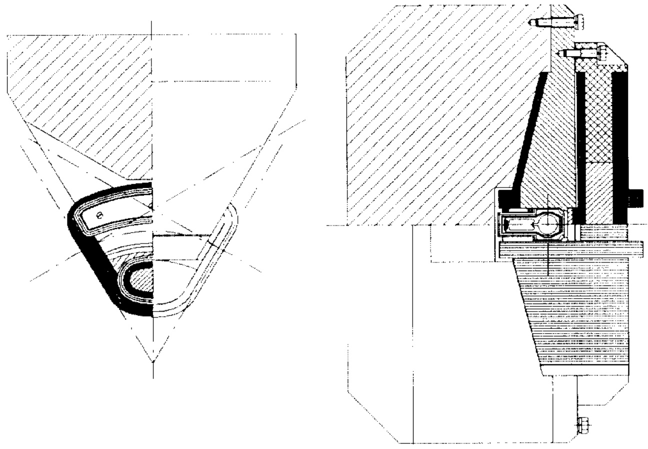

Fig.5. The 6.5 T superconducting bending magnet.

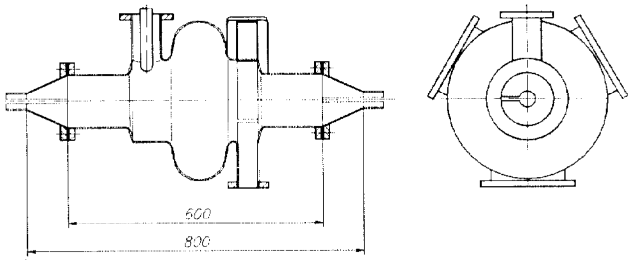

Fig.6. The 700 MHz superconducting RF cavity.

There are two symmetric kickers in the neighboring straight sections providing in turns the injection of both the beams. The basic parameters of the lattice and beams of the φ-factory are listed in Table 1. For comparison we have also included the corresponding parameters of the VEPP-2M, providing at present the best recorded luminosity within the range of the φ-resonance.

Table 1. Basic parameters of the φ-factory.

Parameters		Units	φ-factory	VEPP-2M*
Circumference	C	m	35.155	17.88
Accelerating voltage frequency	f_o	MHz	700	200
Momentum compaction factor	α	-	0.03-0.06	0.167
Emittances	ε_{xo}	cm·rad	$4.7\cdot10^{-5}$	$4.6\cdot10^{-5}$
	ε_{zo}	cm·rad	$4.7\cdot10^{-5}$	$5.5\cdot10^{-7}$
Radiative energy loss per turn	ΔE_o	keV	32.1	9.1
Dimensionless damping decrements between IP	δ_z	-	$1.6\cdot10^{-5}$	$0.44\cdot10^{-5}$
	δ_x	-	$1.6\cdot10^{-5}$	$0.38\cdot10^{-5}$
	δ_s	-	$3.4\cdot10^{-5}$	$0.94\cdot10^{-5}$
R.m.s. energy spread in the beam	σ_E	-	$8.2\cdot10^{-4}$	$6\cdot10^{-4}$
Beta-function at the IP	β_z	cm	1.0	4.5
	β_x	cm	1.0	48
Betatron tunes	ν_z	-	6.06-6.1	3.09
	ν_x	-	6.06-6.1	3.06
Number of particles per bunch	N	e^+,e^-	$2\cdot10^{11}$	$3.7\cdot10^{10}$
Space charge parameters	ξ_z	-	≥0.1	0.05
	ξ_x	-	≥0.1	0.02
Luminosity in a single-bunch mode	L_{max}	$cm^{-2}s^{-1}$	$\geq1\cdot10^{33}$	$\sim1\cdot10^{31}$

* - with 7.5 T superconducting wiggler.

V. Luminosity and Beam-Beam Effects.

The luminosity of a storage ring with colliding beams is defined by the well known expression:

$$L = \frac{\pi\gamma^2}{r_e^2}\,\frac{\xi_x\xi_z f_c}{\beta_z^*}\,(1+\sigma_z^*/\sigma_x^*)^2\,\frac{\varepsilon_o}{1+\varkappa^2}. \qquad (\sigma_s << \beta^*_{x,z})$$

The luminosity limit due to beam-beam effects is phenomenologically described by attainable values of the space charge parameters $(\xi_{x,z})_{max}$.

In the case of fixed parameters $(\xi_{x,z})_{max}=(\xi_*)_{max}$, $\beta_z^*=\beta_o^*$, $\varepsilon_{zo}=\varepsilon_{xo}=\varepsilon_o$ the luminosity for round beams ($\sigma_z=\sigma_x$) will 4 times exceed that for $\sigma_z<<\sigma_x$, with a 2-fold growth of currents. Moreover, if the use of round beams provides a 2-fold increase in $(\xi_o)_{max}$, then the maximum luminosity will increase 16 times. At the same time, it will also provide a 4-fold magnitude of the current density at the IP. The realization of the dependence $L_{max}\propto I^2$ is apparently the most plausible way in attaining the ultrahigh luminosity.

Coherent Beam-Beam Effects. For the majority of existing colliders the value of the space charge parameter $(\xi_z)_{max}\leq 0.05$ in the regime of maximum luminosity ($N^+=N^-$) seems to be determined by the condition of colliding beams' coherent instability[9]. On the whole, the beam-beam interaction results in the appearance of stop-bands with a coherent oscillation instability near the machine resonance lines[6]. Since the band widths (or the instability increments) die out only according to the power law with the oscillation multipole number growth, they may result not only in a spontaneous beam separation, but also in the increase in their vertical size with a corresponding drop in luminosity. Unlike in other colliders, the operating point of the φ-factory is chosen on the main coupling resonance line $\nu_x-\nu_z=0$. For round beams the vicinity of this resonance is free of both betatron and synchrobetatron forbidden bands. With the growth of colliding currents intensity the betatron tunes are shifted along the line $\nu_x=\nu_z$ and do not trespass on the bands of powerful two-dimensional coupling sidebands. Besides, it is supposed, that the interaction of colliding bunches with a longitudinal size of $\sigma_s\approx\beta_o^*$ will lead to a powerful suppression of coherent betatron instabilities in the stop bands along the lines of higher-order one-dimensional resonances[8].

Incoherent Beam-Beam Effects. The behaviour of beam-beam effects on the main coupling resonance line has earlier been numerically simulated in the "strong-weak" beam model with a thin lens approximation $\sigma_s \ll \beta^*$ [7]. The suggested idea of exciting equal transverse emittances without coupling of betatron oscillation normal modes, as well as the use of a micro-β with a bunch length $\sigma_s\sim\beta_o^*$ has clearly shown the advantage of round beams. According to the theoretical study and numerical simulation[8] one can predict the following behaviour of the incoherent round beam interaction. In the "strong-weak" beam model (the beams length is $\sigma_s\sim\beta_o^*$) a powerful suppression of betatron resonances is observed for the particles with a small longitudinal amplitude $A_s \ll \sigma_s$, while for $A_s\geq 5\sigma_s$ this effect is essentially weakened. As a result, the space charge parameter can achieve the value $\xi_o\sim 0.2$ with no noticeable growth of the transverse beam sizes. Nevertheless, in practice the limitation may happen to be lower than $\xi_o=0.2$ due to a considerable shortening of the life time ($\tau<200$s). In this case the leading role will belong to synchrobetatron resonances.

Longitudinal Beam-Beam Effects. The effect of longitudinal electric field of the opposing bunch was originally studied for non-axis particles[9]. For the φ-factory design parameters this effect results in a serious reduction of longitudinal focusing thus necessitating the RF overvoltage well above 400 kV to exceed the longitudinal instability onset and to oppose the incoherent synchrotron tune shift. The topic was recently revised[10] and even a more serious effect for off-axis particles has been revealed: the may gain ~±0.5 MeV energy over one IP passage. The gain is not completely averaged out due to strong modulation of the betatron phases by the synchrotron motion across the micro-β IP. The analysis of this dynamics may explain the new simulation of the beam-beam interaction which now involves this effect: the transverse beam size blows up without noticeable changes in the longitudinal degree of freedom and this limits the attainable space charge parameter $\xi_o\sim 0.2$.

VI. Beam Life Times. Background conditions.

In the ultrahigh luminosity regime the single bremsstrahlung on the colliding beam determines the beam life time:

$$(\tau_\gamma)_{min} = N_{max}/(L_{max}\cdot\sigma_\gamma)$$

where σ_γ is the bremsstrahlung cross section

For $N^\pm_{max}=2\cdot 10^{11}$, $L_{max}=1\cdot 10^{33}$ $(\tau_\gamma)_{min}=0.67\cdot 10^3$s.

The fluxes of e^+,e^-, which have lost a considerable portion of their energy, and the bremsstrahlung photons are concentrated mainly in the angles of the order of $1/\gamma$ and can easily leave the experimental section without loss. In order to suppress the backward scattering from the vacuum chamber, absorbers will be installed at the detector exit.

In the absence of a colliding beam the life time is limited by a single intrabunch scattering (IBS). In the case of other conditions being equal, for round beams the loss rate $\dot N_{IBS}$ for the particle producing the probable background in the detector will be $\varkappa/\sqrt{2}$ times lower as compared to the case of $\dot N_{IBS}$ for a flat beam ($\varkappa\sim 0.1$). Besides, the advantage of round beams may show in the relation $L_{max}/\dot N_{IBS}$:

$$(L_{max}/\dot N_{IBS})_{round}=\frac{4\sqrt{2}}{\varkappa}\cdot(L_{max}/\dot N_{IBS})_{flat}$$

provided $\varepsilon_x(fl.)=\varepsilon_{x,z}(rd)$, $(\xi_o)_{max}=2\cdot(\xi_{x,z})_{max}$, $\beta_z^*=\beta_o^*$, $\sigma_s(rd)=\sigma_s(fl.)$.

Within the dynamic aperture range $(\Delta E/E)_{max}=\pm 1\%$ at the designed parameters the life time is $\tau(\text{IBS})\approx 5\cdot 10^3$s. With the luminosity growth ($\xi_o>0.1$), due to the losses of particles which were involved in the intrabunch scattering and now have the energy deviation $|\Delta E/E|\geq 5\sigma_E$ from the equilibrium one, the life time may dramatically decrease. The injection rate for the new portions e^+e^- currents (less than 10 per cent of stored currents) is 0.1 Hz. Hence the time average luminosity will tend to its maximum value. On the other hand, the φ-factory lattice is specially optimized to reduce the background in the detector region due the particle losses. Besides, the storage ring admittance in the bending arcs will be adjusted with the help of controlled scrapers. It will help to confine the losses of the particles in scattering "tails" at designed spots.

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