NOVOSIBIRSK Φ-FACTORY PROJECT

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Abstract

At Budker INP a project for a set of facilities VEPP-5 with colliding electron-positron beams is in progress. Inside this complex we consider a construction of a Φ-factory - the e^+e^- collider in the Φ-meson resonance energy range ($1020 MeV$). The Φ-factory having a luminosity of $1-3\cdot 10^{33} cm^{-2}sec^{-1}$ offers the unique possibility to study the CP-parity violating interactions. An essential feature of the project is the solenoidal focusing used to obtain round beams at the interaction point.

1 ROUND COLLIDING BEAMS

The basic parameter of a collider is its luminosity L which in the case of short bunches is determined by the formula:

$$L = \frac{\pi\gamma^2\xi_z\xi_x\epsilon_x f}{r_e^2\beta_z}\cdot\left(1+\frac{\sigma_z}{\sigma_x}\right)^2,$$

where ξ_z, ξ_x are the space charge parameters whose maximum values are limited by the beam-beam effects; ϵ_x is the horizontal emittance of the beams, σ_z, σ_x are their r.m.s. sizes at the interaction point (IP), and β_z is the vertical β-function at the IP; f is the frequency of collisions at this IP, r_e is the classical electron radius, γ is the relativistic factor. Colliding bunches with maximum values of $\xi_z \simeq 0.05$ and $\xi_x \simeq 0.02$ are experimentally obtained on the VEPP-2M collider.

In the Novosibirsk ϕ-factory project, for attaining the high luminosity it is proposed to use colliding beams with round transverse cross-sections (just "round beams" in what follows) [1]. In this case, the luminosity formula has the form:

$$L = \frac{4\pi\gamma^2\xi^2\epsilon f}{r_e^2\beta}.$$

Because of the X-Z symmetry, the space charge parameters are now the same in the two directions, so the horizontal parameter can be strongly enhanced. The evident advantage of round colliding beams is that with the fixed particle density, the tune shift from the opposite bunch becomes twice smaller than that in the case of flat colliding beams.

It's well known from the classical mechanic that a motion in the central field $U(r)$ is simplified due to the angular momentum conservation $M = [r\times p]$ to a motion in any effective potential $U_eff(r) = U(r) + \frac{M^2}{2r^2}$ with an additional so called centrifugal potential.

The field of the round counter beam does not change the longitudinal component of the angular momentum $M_y = zp_x - xp_z$ and in a case, when a machine optics conserves this quantity between two collisions, we have *an additional integral of the motion*. Thus the transverse particle motion in the round beams becomes equivalent to a one-dimensional motion. For the beam-beam effects, elimination of all betatron coupling resonances is of crucial importance, since they are believed to cause the beam lifetime degradation and blow-up.

Of course even in the one-dimensional situation the beam-beam force proceeds to depend on time and generaly saying the particle motion is not integrable. But it's easy to see that in a simplest model of the short opposite bunch the linear beam-beam tuneshift becomes already independent of the longitudinal position in the bunch thereby weakening the action of synchro-betatron resonances. Moreover, it is possible to make the motion in the field of "long" round bunch very close to integrable with strong suppression of the strengths of all transverse resonances [2].

1.1 Longitudinal motion

For correct study of the beam-beam effects it is important to consider kicks with both the longitudinal and transverse components, otherwise the transformation map will be non-symplectic.

Simulteneously with the transverse kick a witness particle is changed its energy in the field of the opposite beam, according to the following relation [5]:

$$\Delta E = \frac{Ne^2}{2\beta}\beta' - \frac{Ne^2}{r^2}\cdot[1-\exp(-\frac{r^2}{2\sigma^2})] \times\left[x(x'+\frac{\beta'}{2\beta}\cdot x) + z(z'+\frac{\beta'}{2\beta}\cdot z)\right]. \quad (1)$$

This kick depends on the coordinates and angles of the betatron motion x, x', z, z' ($r^2 = x^2 + z^2$) and thus we have a coupling of the transverse and longitudinal motions. An analitical consideration and simulations of the beam-beam effects [4] shown, that near the integer resonance and for the usual sign of the momentum compaction, it is possible for particles with a positive energy offset to slow down their relative motion so as their coordinates would not change between the consecutive collisions. Then their angles and energy offsets will rise together forming an outward phase space flow to large synchrotron and betatron amplitudes. For the negative momentum compaction $\alpha < 0$ this can never happen, such a flow does not occur.

Another argument in favour of $\alpha < 0$ is that both the coherent and incoherent synchrotron oscillations can no more become unstable, because in this case the opposite beam action adds to the longitudinal focusing [5].

1.2 *Simulation of the beam-beam effects for round colliding beams*

The computer simulation of the beam-beam effects is performed with a special code [6] where, in particular, the particle distributions over their 6D phase space are obtained as a function of the opposite bunch intensity. The bunch is represented by a set of thin nonlinear lenses, each changing both transverse angles of a witness particle and its energy, according to (1). The collision-to-collision map is formed by this multi-slice beam-beam kick followed by linear transformations and sextupole kicks according to the collider lattice. In addition, the smaller changes of particle coordinates and angles caused by the synchrotron radiation are included to provide for the radiative damping and quantum excitation of the synchrotron and betatron oscillations. All the parameters are first tuned so as to form the correct equilibrium distribution of particles as it is in the single beam mode. Then the distribution with the collisions on is built from the statistics collected over many damping times, so that one can expect reliable results at not too large amplitudes.

The main results of the simulations are presented in fig. 1 the beam size are plotted versus the space charge parameter ξ. One can see that the beam blow-up for the round beam option is much weaker than what is simulated by the same code for flat colliding beams (dashed line).

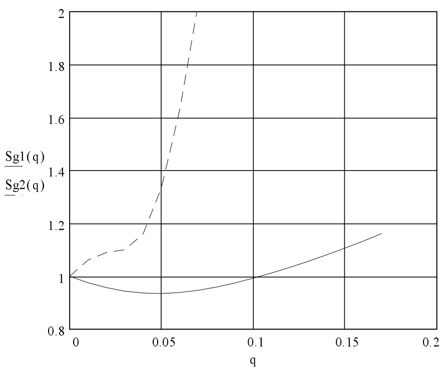

Figure 1: Variation of the weak beam size vs. the the space charge parameter ξ.

2 FOUR WINGS Φ-FACTORY

What does the round beam mean in practice?

In general case it's possible to show that the angular momentum is conserved by a transformation whose a 4×4 matrix is similar to the matrix of a solenoid. Apparently the transfer matrix between two collision points with $\beta_x = \beta_z$ conserves M_y along the main coupling resonance $\nu_x - \nu_z = 0$. So we can formulate main optical requirements for the ϕ-factory with the round beams:

1. Small and equal β-functions $\beta_0 = \beta_x, \beta_z$ at the IP.
2. Equal beam emittances ϵ_x, ϵ_z.
3. Equal betatron tunes ν_x, ν_z and no betatron coupling in the arcs.
4. Small and positive fractional tunes.

Requirements 1–3 are satisfied by the use of a strong solenoidal beam focusing in the interaction straight. At each passage, the longitudinal field H_l, with an integral along the straight section $H_l l = \pi HR$, rotates the transverse oscillation plane over $90°$, exchanges rôles of the two betatron modes, and thereby provides their full symmetry. Besides, the rotational symmetry of both the solenoidal focusing and the kick from the round opposite beam, complemented with the X-Z symmetry of the betatron transfer matrix between the collisions, result in the longitudinal component of the angular momentum conservation.

Item 4 is also important for the attainment of large values of the space charge parameter ξ_{max}.

All these ideas have been implanted into the first Novosibirsk ϕ-factory project [1]. Two last years resulted in a serious revision of the project: we switched to the double-ring machine with the electrostatic orbit separation. The 50 kV/cm electrostatic separator plates are 2 meters in length and provide ± 2 cm aperture. Similarly to the previous "Sibirian Butterfly" scheme, the interaction region is a common straight section with the axi-symmetric solenoidal focusing, envisaged for direct and reversed passages of colliding bunches (*i.e.* the bunches are in two-way head-on collision, see fig. 2).

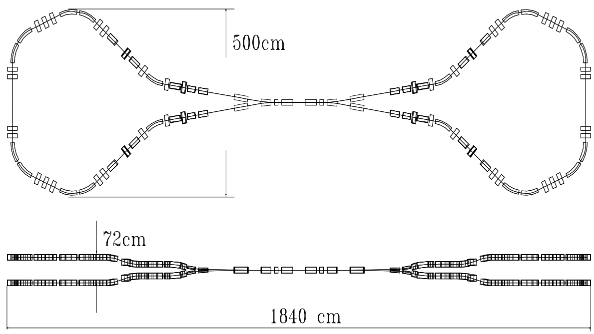

Figure 2: The ϕ-factory design.

With the design RF harmonic number h = 110 ($\lambda = 42.8cm$) two modes are possible for head-on collision of N bunches:

- At N = 11 (*i.e.* the bunches are spaced by 9 empty RF buckets) we will collide only electrons with positrons. The closest parasitic collision of e^+e^+, e^-e^- occurs at a distance of 2.5λ from the interaction point, and the orbits are horizontally separated with magnetic field. The parasitic e^+e^- collisions is 5λ apart from the interaction point, it is electrostatically separated in the vertical plane.

  At emittance about $1.25 \cdot 10^{-5} cm \cdot rad$ the luminosity should reach $2.5 \cdot 10^{33} cm^{-2} s^{-1}$.

Table 1: *The main parameters of ϕ-factory.*

Circumference, m	C	47.08
RF frequency, MHz	f_0	700.4
RF harmonic number	q	110
Momentum compaction	α	-0.02...0.06
Synhrotrone tunes	ν_s	0.012 ($\alpha = 0.04$)
Emittances, $cm \cdot rad$	ε_x ε_z	$1.25 \cdot 10^{-5}$ $1.25 \cdot 10^{-5}$
β_x at interaction point, cm β_z at interaction point, cm	β_x β_z	1.0 1.0
Betatrone tunes	ν_x, ν_z	8.1 , 6.1
Particles / bunch	e^-, e^+	$5.0 \cdot 10^{10}$
Bunches / beam		11
Tune shifts	ξ_x, ξ_z	0.1 , 0.1
Luminosity, $cm^{-2} \cdot s^{-1}$	L_{max}	$2.5 \cdot 10^{33}$

- At N = 10 (10 empty RF buckets between the bunches) the e^+e^- collisions at the interaction point (half of luminosity) are simultaneous with the e^+e^+ and e^-e^- collisions (another half). Here we have certain hopes for attaining a higher effective beam-beam parameter ξ as a result of overlapping of uni-directional e^+e^+ bunches prior collisions and of consequent space charge compensation at collision.

  At reduced emittances and/or higher bunch intensity, this option should give several times higher useful luminosity then the previous one.

Tunable optics of the rings is designed for controlling both the beam emittance values in the range of $(0.5 \div 2) \cdot 10^{-5} cm \cdot rad$ and the momentum compaction in the range of $-0.02 \div 0.06$. The latter option may be important in taming coherent longitudinal instabilities and longitudinal beam-beam effects.

The optical functions of the ring(s) are shown in fig. 3. Note that the negative contribution to the momentum compaction comes from the vertical bends. Their purpose is to compensate for the (unwanted) vertical dispersion which originates from the electrostatic separator. The main parameters of the ϕ-factory are presented in tab. 1.

3 CONCLUSION

The ϕ-factory will be built in a frame of the VEPP-5 complex which is under construction now. A civil engineering for the ϕ-factory is completed. We are going on with R@D of main elements of the machine and detector. But the crucial question of a reliability of the extra luminosity which is required for the ϕ-factory will be experimentally studied at the existing collider VEPP-2M.

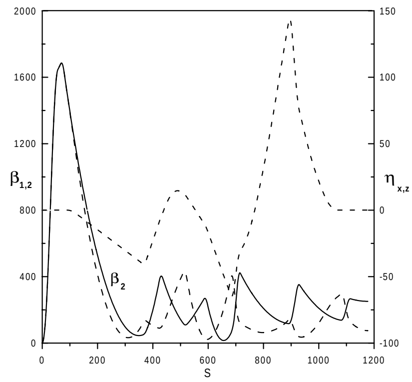

Figure 3: Optical function of ϕ-factory.

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