COMPENSATION OF THE CHROMATIC EFFECTS IN THE NOVOSIBIRSK Φ-FACTORY LATTICE.

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ABSTRACT.

The chromatic effects of the ϕ-factory lattice are analyzed to optimize the location of the sextupolar correctors. Five families of sextupoles are envisaged to compensate for the tunes chromaticity as well as the chromatic dispersion and β-functions. The approximate π-relations in the betatron phase between the sextupoles are pursued to preserve the dynamic aperture, while the tolerance of breaking these relations is determined from the Hamiltonian treatment. The computer simulation results of the ϕ-factory lattice dynamic aperture taking into account the synchrotron motion are discussed.

1. INTRODUCTION.

The Novosibirsk ϕ-factory project is based on the concept of round colliding bunches [1]. To obtained equal and ultimately low β-functions (β_o~1cm) at the center of the interaction region (IR) the solenoidal focusing is proposed. The final focus is composed by two pairs of superconducting solenoids with the mirror-symmetric location on either side of the interaction point (IP). The opposite connection of the solenoids in each pair provides for $\int Hsds=\pi HR$ irrespectively of the focusing strength. This results in the rotation of the betatron oscillation planes at $\varphi=\pi/2$ for the direct passage and at $\varphi=-\pi/2$ for the reverse one. Thus, each normal betatron mode is directed vertically in one arc of the storage ring and horizontally in the other one, which provides for equal beam emittances. The layout of the ϕ-factory storage ring is shown in fig.1.

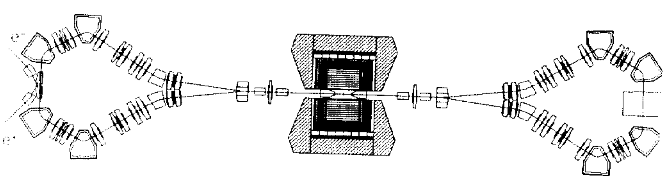

Fig.1.Layout of the Novosibirsk ϕ-factory.

The above features of the lattice impose severe restrictions on the options for the compensation of the chromatic effects. To reach the space charge parameter ξ>0.1 one has to aim the dynamic aperture at $15\cdot\sigma_{x,z}$, including the off-energy particles with $E=(8\div10)\sigma_E$. Moreover, the beam-beam effects limit the β-function chromaticity as well as the chromatic dispersion value at the IP.

2. CONCEPTUAL APROACH TO THE COMPENSATION OF THE LATTICE CHROMATICITY.

The high values of the β-functions (β_{max}~17m) in the focusing solenoids result from micro-β at the IP. This entails a strong chromatic perturbation in the lattice. As far as the dispersion is zero over the IR, the compensation of the betatron tune chromaticities $\gamma\cdot\partial\nu_{x,z}/\partial\gamma$ are possible only in the arcs by the appropriate sextupoles correction families S_x and S_z (fig.2). Compensation of the linear in $\Delta p/p$ part in

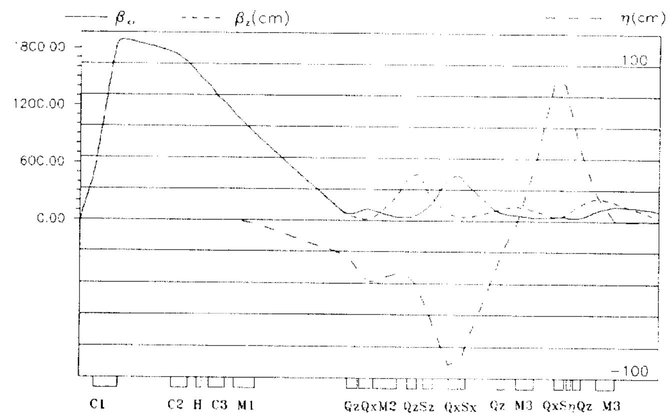

Fig.2. One quarter of ϕ-factory lattice period.

the chromatic functions $\gamma\partial\nu_{x,z}/\partial\gamma$ may enhance terms quadratic in $\Delta p/p$. In the perfect case location of the S_x and S_z sextupole families should have the corresponding chromatic betatron functions $\gamma/\beta_{x,z}(\partial\beta_{x,z}/\partial\gamma)$ close to zero. To meet the above conditions together with minimization of the chromatic betatron functions $\beta_{x1,z1}=\gamma/\beta_{x,z}(\partial\beta_{x,z}/\partial\gamma)$ and compensation of the chromatic dispersion $\eta_1=\gamma\partial\eta/\partial\gamma$ at the IP (fig.3), the

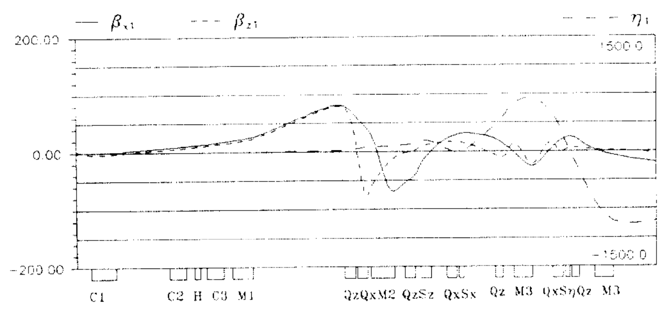

Fig.3. The chromatic betatron and dispersion functions.

transport matrix between the IP and the corresponding family should have the certain optical properties. To this end the transport matrix for this section of the lattice is optimized by including the quadrupole doublet Qz1, Qx1. At the location of the S_x, S_z sextupoles at specified values of $\int(\partial^2 H_z/dx^2)\cdot\beta\cdot\eta\cdot ds$ the high values of η and low β-functions are useful for enlargement of the dynamic aperture. Apparently, the strong sextupoles would cause a chromatic perturbation of the dispersion. To control the behaviour and the value of $\gamma\cdot\partial\eta/\partial\gamma$ function the third sextupole family $S\eta$ is needed. The effective correction of the

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chromatic dispersion $\gamma\cdot\partial\eta/\partial\gamma$ is governed by the following conditions (fig.2):

$$\beta(S_\eta) \ll \beta(S_{x,z}), \quad \eta(S_\eta) \approx \eta(S_{x,z})$$

and besides, the correction of the chromatic betatron functions $(\gamma/\beta_{x,z})\cdot\partial\beta_{x,z}/\partial\gamma$ necessitates two additional sextupole correctors which are realized in the pole-tip profiles of the quadrupoles Qx1,Qx3 (fig.2).

3. CONDITIONS OF COMPENSATION OF THE SEXTUPOLAR INFLUENCE ON THE DYNAMIC APERTURE.

Non-linear effects of the sextupole correctors in the particle motion may impose an intolerable limitation on the betatron dynamic aperture. On the other hand, the optimal relations of the betatron phase advances between the sextupoles in each family and between the families moderates the undesirable effects of the sextupolar fields. Having in mind the alternating orientation of the normal betatron modes in the arcs of the machine one can see that the placement of the sextupole lenses over $(2n+1)\cdot\pi$ of the betatron phase within each arc is optimal. This tactics results in a significant enlargement of the dynamic aperture.

In the one-dimensional case a simple description of the particle motion is available for a lattice with 2 sextupoles spaced approximately at $(2n+1)\cdot\pi$ in the phase and the betatron tune close to an integer (fig.4). Using the normalized variables $X/\sqrt{\beta}$ and the normalized sextupole strength in the form:

$$\int\beta_x^{3/2}\cdot(\partial^2 H_z/\partial x^2)\cdot ds=1,$$

we can obtain for such a lattice one-turn mapping of the particle's coordinate to the first order in μ_1 and μ_2:

$$\Delta x=\Delta\mu\cdot x'$$

$$\Delta x'=-\Delta\mu\cdot x-2\cdot\mu_1\cdot x\cdot x'-2\cdot\mu_1\cdot x^3 \qquad (1)$$

here:

M_1, M_2 are the betatron phase advances between the sextupoles,

$\mu_1+\mu_2=\Delta\mu$ ($\Delta\mu$ is module 2π).

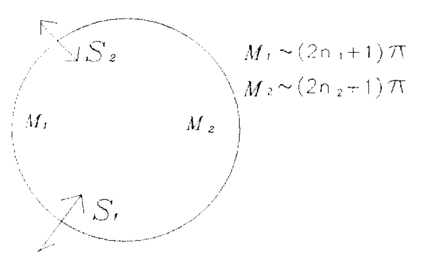

Fig.4. Lattice with the sextupole family.

For this mapping we put down an approximate Hamiltonian:

$$H^*=\Delta\mu\cdot(x^2+x'^2)/2+\mu_1\cdot x^2\cdot x'+\mu_2\cdot x^3/2 \qquad (2)$$

The canonical transformation $X=x$, $X'=x'+x^2\cdot\mu_1/\Delta\mu$ yields:

$$H^{**}=\Delta\mu\cdot(x^2+x'^2)/2+\mu_1\cdot\mu_2\cdot x^4/(2\cdot\Delta\mu). \qquad (3)$$

The amplitude-dependent betatron tune shift in this lattice is either negative or positive according to the sign of $\mu_1\cdot\mu_2$ (fig.5). The accuracy of the linear approximation in derivation of the Hamiltonian (2) was checked by comparison between its level lines on the phase plane and the numerical tracing of the precise mapping of this lattice. Within the required dynamic aperture one can see a very good agreement.

In the 2-dimensional case the influence of two identical sextupoles on the dynamic aperture is compensated under the following conditions:

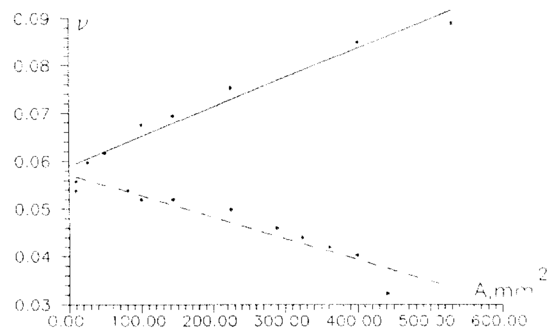

Fig.5. Amplitude dependence of the betatron tune shift for 1D motion:
a) solid line: $\mu_1\cdot\mu_2 > 0$,
b) dashed line: $\mu_1\cdot\mu_2 < 0$.

$$\mu_x(S_1\to S_2)=(2n_x+1)\cdot\pi, \quad \mu_z(S_1\to S_2)=(2n_z+1)\cdot\pi, \qquad (4)$$

$$\beta_x(S_1)=\beta_x(S_2), \quad \beta_z(S_1)=\beta_z(S_2). \qquad (5)$$

This relation (4) are approximately fulfilled by optimization of the realistic the ϕ-factory lattice, while condition (5) are satisfied due to the mirror-symmetric location of the sextupoles in their families. Similar to the one-dimensional motion we can write the Hamiltonian of the one-turn mapping for the ϕ-factory lattice in the form:

$$H^*=A_1\cdot(x^2+x'^2+z^2+z'^2)/2+A_2\cdot(x^2\cdot x'-z^2\cdot z')+$$

$$+A_3\cdot(x^2\cdot z'-z^2\cdot x')+A_4\cdot(x^4+z^4)/4-2\cdot\Delta_0\cdot A_2\cdot x^2\cdot z^2 \qquad (6)$$

The canonical substitution:

$$X'=x'+x^2\cdot A_2/A_1 \; ; \; X=x$$

$$Z'=z'+z^2\cdot A_2/A_1 \; ; \; Z=z$$

transforms the Hamiltonian into:

$$H^*=A_1\cdot(X^2+X'^2+Z^2+Z'^2)/2+A_3\cdot(X^2\cdot Z'-Z^2\cdot X')+$$

$$+(A_4-A_2^2/A_1)\cdot(X^4+Z^4)/4-(2\cdot\Delta_0\cdot A_2-A_3\cdot A_2/A_1)\cdot X^2\cdot Z^2 \qquad (7)$$

here:

$\mu_1=2\cdot(\Delta\mu-\mu_x(S_x\to S_x))$, $\mu_2=2\cdot(\Delta\mu-\mu_z(S_z\to S_z))$,

$A_1=2\cdot\mu_x(S_z\to S_x)+\mu_x(S_x\to S_x)+\mu_1+\mu_2$,

$A_2=2\cdot\mu_x(S_x\to S_x)+\mu_x(S_x\to S_x)+\Delta_0\cdot\mu_x(S_x\to S_x)$,

$A_3=\Delta_0\cdot(2\cdot\mu_x(S_z\to S_x)+\mu_x(S_x\to S_x))$,

$A_4=((\Delta_0^2+1)\cdot(2\cdot\mu_x(S_z\to S_x)+\mu_x(S_x\to S_x)+\Delta_1\cdot\mu_x(S_x\to S_x))$,

$\Delta_0=\beta_z/\beta_x(S_z)$,

$\Delta_1=(\partial^2 H_z/\partial x^2)\cdot\beta_x^{3/2}(S_x)/(\partial^2 H_z/\partial x^2)\cdot\beta_x^{3/2}(S_z)$

In the case of $A_3=0$ the cubic terms in Hamiltonian (7) are cancelled and only the 4-th order terms reside, similarly to the one-dimensional problem. Fig.6 shows the tune dependence on the square of the betatron amplitude with the sextupole families S_x, S_z, S_η.

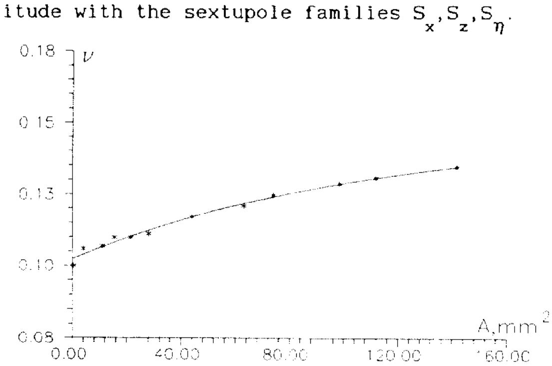

Fig.6. Amplitude dependence of the betatron tune shift for ϕ-factory lattice.

4. SIMULATION OF THE DYNAMIC APERTURE LIMITATION.

To widen the boundaries of the dynamic aperture the lattice was optimized to phase relations (4) for the following sextupole families S_x, S_z. To determine the dynamic aperture the particle motion was tracked in the lattice with averaging over initial betatron phases. The results are presented in fig.7.

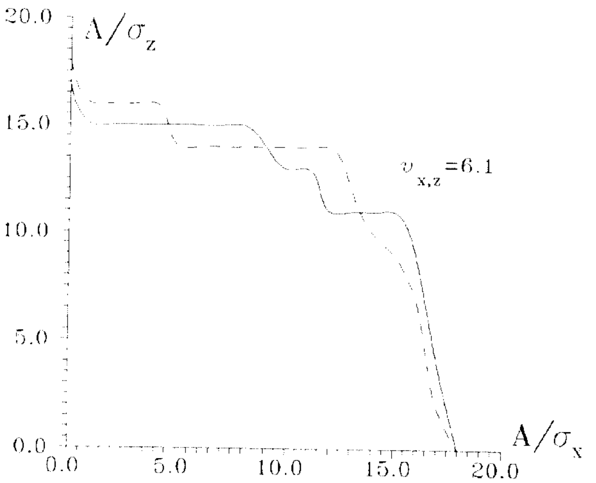

Fig.7. Dynamic aperture for ϕ-factory lattice with the 3 sextupole families from tracking simulation over 512 turns and with averaging over initial betatron phases.
a) betatron dynamic aperture for synchronous particle (solid line);
b) with energy deviation $|\Delta E/E|=8\sigma_E$ (dashed line).

The dynamic effect of the end-focusing solenoids in the ϕ-factory lattice has been studied in [2]. The combined effects from the solenoid end-fields and from the sextupole lenses, result in reducing the dynamic aperture, because the betatron tune shift from the oscillation amplitude squared is positive for both the cases. The simulation results for two operating points $\nu_{x,z}=6.1$, 6.06 are shown in fig.7,8.

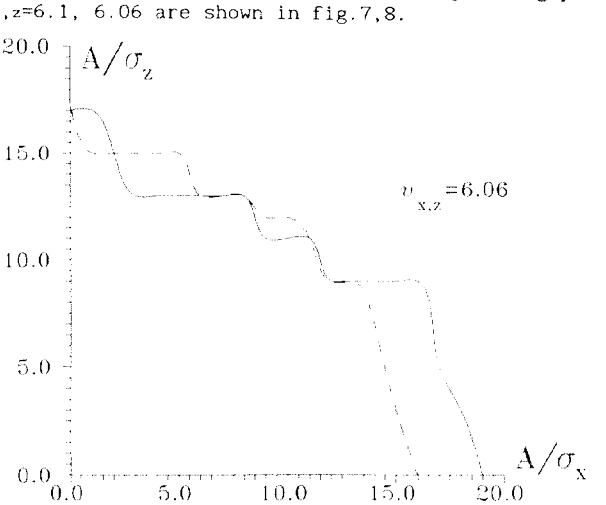

Fig.8. Dynamic aperture for ϕ-factory lattice with the 3 sextupole families, end-fields of focusing solenoids and 16-pole lenses. Tracking simulation over 512 turns and with averaging over initial betatron phases.
a) solid line: betatron dynamic aperture;
b) dashed line: with energy deviation $|\Delta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

5. PROTECTION OF THE DETECTOR AGAINST THE BEAM BACKGROUND.

An important problem in the ϕ-factory design arises from the beam background caused by the particle losses due to the intrabeam scattering effects (IBS) upstream the detector. The lattice has been especially optimized to suppress this background. First of all, there are remote driver scrapers in the arcs, which are to limit the machine admittance. This will localize the loss of particle belonging to the distribution tails in safe places. However the optics of the lattice would not permit one to overcome the IBS background only by these scrapers. The scattered particles from certain parts of the machine in the narrow energy range $\Delta E/E=(1.3\div1.85\%)$ are still not intercepted at a safe distance from the detector. The background countrate could approach 10^7Hz. This necessitates special optics to be installed in the experimental straight section. The background suppression optics comprises two superconducting solenoids C3 and two sqew 16-poles are oppositely connected in either side of the detector (fig.9). Hence $\int H_s(C3)ds=0$. The purpose of the 16-poles, as shown in fig.9, is to focus the particles scattered between the two SC dipoles in the energy range $\Delta E/E=\pm(1.3\div1.85\%)$ in order to provide for their first (and the last) passage through the detector within the physical aperture. The scattered particles' trajectories lie in the median plane upstream the solenoid C3. Then they are rotated at an 11.75° angle according to the sign of the charge to pass through the focusing sectors of the 16-pole field for each sign of the charge, on their way to the detector. The cancellation of the nonlinear effects of sqew 16-poles for the particle stability within the dynamical aperture is due to their opposite connection on either side of the IR together with the betatron phase advance close to $(2n+1)\pi$ between their locations. The high multipole order and the above specified location provide for the dynamic aperture in excess of $15\sigma_{x,z}$. The simulation results for the combined nonlinear actions are presented in fig.8.

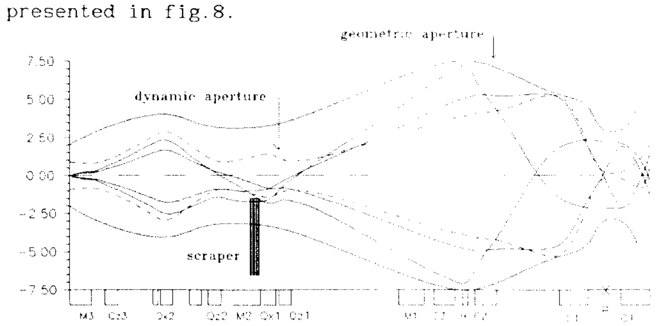

Fig.9. Cheme for the detector protection from beam bacground due to intrabunch scattering.

In conclusion we note that the optical properties of the ϕ-factory lattice provide for the operating fine tuning of the betatron phase relations (6) between the sextupole correctors.

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