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STUDY OF TRANSVERSE OSCILLATION COUPLING AND POSSIBILITY OF ITS MINIMIZATION IN SKIF (NOVOSIBIRSK)

D. Leshenok†[1], G. N. Baranov[1], E. B. Levichev[1], S. A. Nikitin§,
Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
[1]also at Boreskov Institute of Catalysis, 630090, Novosibirsk, Russia

Abstract

The vertical emittance and, in general, the vertical beam size and angular divergence are of paramount importance in the SKIF (Russian acronym for Siberian Circular Photon Source) project developed in Novosibirsk. Therefore, a detailed simulation of the corresponding influence of possible errors in the storage ring was carried out with cross validation by different methods. Variants of transverse coupling correction are proposed and modeled to obtain a vertical emittance of the order of one picometer simultaneously with minimizing vertical dispersion.

INTRODUCTION

One of the main requirements for the SKIF synchrotron radiation (SR) source is a short period of manufacturing. With such a small emittance (ε_x = 73 pm), the selected energy of 3 GeV allows to make the storage ring less than 500 m. During the design and creation of the SKIF storage ring, it is necessary to know how accurately the magnetic elements must be aligned to maintain the vertical emittance below a certain limit. Because ultra-low vertical emittance (coupling coefficient) is critical in achieving high brilliance. Thereby, the accuracy of the alignment of the magnetic elements determines the necessary correction system: the strength of the correctors, the number of correctors and BPMs (beam position monitors).

ALIGNMENT REQUIREMENTS AND CORRECTION SYSTEM

The accuracy of modern geodetic laser trackers reaches about 10 μm per meter during routine work. If consider that the largest distance between elements will be 6 m, it may be found that the minimum positioning capability is 80 μm with a small margin (see Table 1).

Table 1: Requirements for the Alignment of Elements

Type of element	σ_x, μm	σ_y, μm	σ_s, μm	σ_ψ, μm
Girders	80	80	150	200
Elements on girder	45	45	150	200

Also, it should be noted the elements of the storage ring will be installed on the girders. Girders will significantly speed up the process of aligning the elements in the storage ring due to the preliminary alignment of the elements on them. Thus, assembled girders will be brought into the storage ring tunnel and set up against each other.

† dariya210612@gmail.com
§ S.A.Nikitin@inp.nsk.su

The SKIF storage ring consists of 16 arcs (see Fig. 1). There are 14 BPMs in each arc (224 BPMs in whole ring). This number of BPMs was determined so that there were at least 4 BPMs for the period of the beta function, this gives detailed information about the beta functions, considering that the horizontal and vertical frequencies are 50.806 and 18.84, respectively.

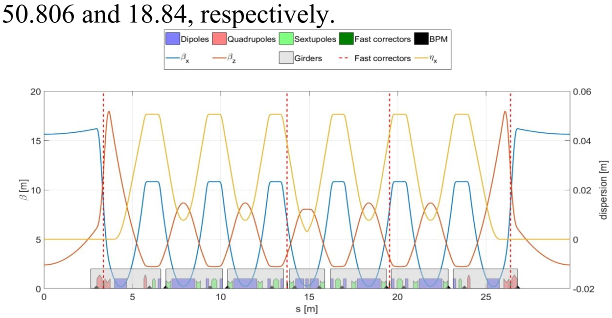

Figure 1: The arc of the SKIF storage ring.

Each sextupole magnet (16 in arc and 256 in whole ring) is equipped with additional correction coils, which can create dipole horizontal and vertical correction, normal quadrupole and skew quadrupole component. In addition, there are 4 free-standing correctors, which will be used both in the fast orbit correction system and in the slow orbit correction system. These correctors have a dipole correction in both coordinates, as well as a skew component.

SKEW QUADRUPOLE CORRECTORS SELECTION CRITERIA

To effectively minimize betatron coupling and reduce the excited vertical dispersion (η_y), it is necessary to determine the skew quadrupole correctors that best affect these parameters according to Table 2 [1].

Table 2: Selection Criteria for Skew Quadrupole Correctors

Coefficient	Betatron coupling	η_y	Requirements
$\sqrt{\beta_x \beta_y}$	Large	Small	$\mu_{x,j+1} \pm \mu_{y,j+1} - (\mu_{x,j} \pm \mu_{y,j}) \neq n\pi$
$\left\lvert \eta_x \sqrt{\beta_y} \right\rvert$	Small	Large	$\mu_{x,j+1} \pm \mu_{y,j+1} - (\mu_{x,j} \pm \mu_{y,j}) \neq n\pi$

The effective minimization of coupling may be carried out by skew quadrupole correctors, in which the coefficient $\sqrt{\beta_x \beta_y}$ has the greatest value. To reduce the η_y,

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skew quadrupole correctors with maximum $|\eta_x\sqrt{\beta_y}|$ are needed.

Table 3: Coefficients for Skew Quadrupole Correctors

Skew quadrupole corrector	$\sqrt{\beta_x\beta_y}$	$\lvert\eta_x\sqrt{\beta_y}\rvert$
SFA1; SFA2	4.905	0.075531
CFB1	4.8396	0.0712
CFB2	4.9865	0.0756
SFC; SFC2	4.902	0.075487

Table 3 shows the correctors that satisfy the conditions for minimization linear coupling (SFA1, SFA2, CFB1, CFB2) and reduction η_y (SFC1, SFC2, CFB1, CFB2). Figure 2 shows the location of the skew quadrupole correctors.

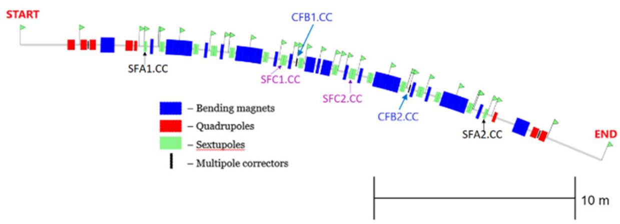

Figure 2: Skew quadrupole correctors for coupling minimization and η_y reduction in one arc of SKIF.

ERROR MODELING AND CORRECTION

The alignment errors were randomly assigned to the magnetic elements according to the Gaussian distribution cut off by 2σ.

During the orbit correction, the corrector strengths are calculated so that, firstly, there is a stable closed orbit, and, secondly, the new closed orbit is as close to an ideal orbit as possible. The calculation was carried out using the MADX program [2], that allows to correct and find a closed orbit by various methods (MICADO, SVD, LSQ). After finding a new closed orbit, optical functions and betatron coupling were corrected. Also, EVD-Based Generalized Coupling Minimization Method [3, 4] (Eigen Vector decomposition) as an additional correction method was used. Then the comparison with the calculation according to the theory of linear differential coupling resonance was carried out.

Correction using SVD Method [5]

Table 4: Required Strengths of Correctors

Correctors in sextupoles	
$G_{max,\ skew}$,Gs/cm	90
G_{max} ,Gs/cm	70
B_{max} (Horizontal), Gs	60
B_{max} (Vertical), Gs	55
Free-standing correctors	
B_{max} (Horisontal), Gs	390
B_{max} (Vertical), Gs	350

It was determined that to satisfy the required conditions for the dynamic aperture (DA), betatron coupling, as well as for the correction of optical functions and random orbital disturbances the gradients and corrector fields presented in Table 4 are required. It should be noted that the indicated maximum gradients of the correctors satisfy the required limitations: 100 Gs/cm – for correctors situated in sextupoles; and 200 Gs/cm – for free-standing correctors.

After correction on-momentum DA (see Fig. 3) with δ=0% remains sufficient for top-up injection, since the required aperture must be 7 mm.

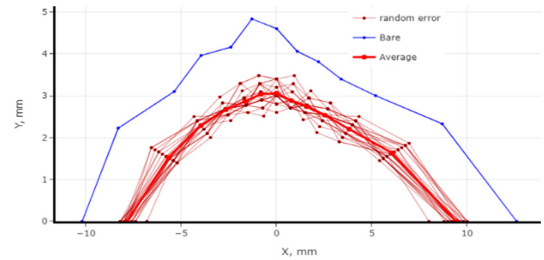

Figure 3: On-momentum DA (δ=0%) after correction of random alignment errors.

Off-momentum DA with δ=±3% is sufficient to capture the beam from the booster with the calculated energy spread. In addition, such aperture will make it possible to obtain an about 10 hours Touschek beam lifetime.

Theory of the Linear Resonance Coupling

Complex coupling coefficient characterizing the strength of the linear differential coupling resonance is described by the Eq. (1) [6]:

$$k = \frac{1}{2\pi}\int_0^C K_s(s)\sqrt{\beta_x\beta_y}\, e^{i[\psi_x-\psi_y-(Q_x-Q_y-q)2\pi s/C]}ds, \quad (1)$$

where coefficient K_s describes perturbations caused by vertical orbit disturbances in sextupoles $K_s = \delta Y \cdot \frac{1}{H\rho}\frac{\partial^2 H_x}{\partial x^2}$; and $K_s = 2\varphi \cdot \frac{1}{H\rho}\frac{\partial H_y}{\partial x}$ for perturbations depending on the rotation of the quadrupole lenses round the longitudinal axis. In addition to affecting beam emittances, orbital distortions in sextupoles and uncontrolled rotations of quadrupoles lead to the increase of η_y, which increases the vertical size of the beam. Parameter $\Delta = Q_x - Q_y - q$ is resonance detuning. Here q is integer and found from the ratio $Q_x - Q_y - q = 0$; Q_x and Q_y are betatron frequencies.

In linear theory, the sum of the emittances is conserved:

$$\varepsilon_x + \varepsilon_y = \varepsilon_{x0}, \quad (2)$$

here ε_{x0} is the horizontal emittance in case without coupling (for SKIF ε_{x0} = 73 pm).

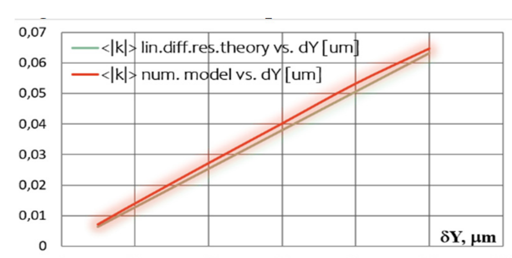

Figure 4: The |k| as a function of the vertical scatter of orbital distortions in sextupoles.

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Figures 4 and 5 show the dependences of the modulus of the coupling coefficient averaged over the 100 error sets ($|k| = \sqrt{(\{Q_1\} - \{Q_2\})^2 - \Delta^2}$, here $\{Q_{1,2}\}$ is non-integral part.) on the spread of the orbital deviation from the axis in sextupoles (Fig. 4) and on the angle of the quadrupole rotation round the longitudinal axis (Fig. 5).

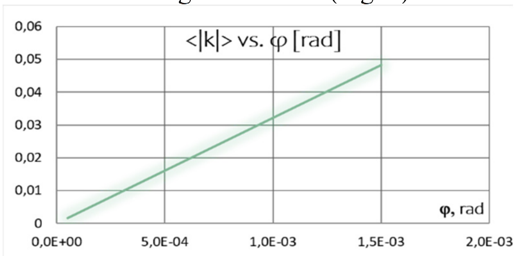

Figure 5: The |k| as a function of the scatter of the quadrupole rotation angles round the longitudinal axis.

The main contribution to the value of the vertical emittance will be introduce by vertical distortions of the closed orbit. The critical level of $|k|$~Δ~10^{-2} is reached at δY≈20 μm. This places quite high demands on the quality of the orbit correction. The same coupling occurs when the magnets are positioned along the rotation angle round the longitudinal axis with an accuracy of $\varphi \approx 3{\cdot}10^{-4}$ rad, that is much rougher than the design accuracy $\varphi<10^{-4}$.

EVD-Based Coupling Minimization Method

This method [3, 4] consists in finding a solution for a set of gradients of skew quadrupole correctors $\bar{G} = \{G_j\}$ from the condition of the minimum function equal to the sum of squares of the resulting vertical dispersion at the azimuths of its measurement. Also, the requirements for the real and imaginary parts of the coefficient k generated by this correction must be considered.

Table 5: Examples of Using EVD-Based Correction Method

Initial $\varepsilon_y/\varepsilon_x$	Initial $|k|$	Result $\varepsilon_y/\varepsilon_x$
42.64/69.42	0.0285	3.07/75.50
23.52/66.38	0.0349	5.85/76.12
32.02/63.18	0.0463	5.28/75.39
22.20/70.68	0.0244	3.06/75.57
21.33/72.78	0.0152	1.86/75.39

$A = \{a_{ij}\}$, $i = 1, 2, \dots N$, $j = 1, 2, \dots M$ – response matrix of vertical dispersion at N measurement points to the applied force of M skew quadrupoles $\bar{\eta}_c = \{\eta_i\}_c = A\bar{G}$, $i = 1, 2, \dots N$. Matrix $B = \{b_{ij}\}$, $i = 1, 2$, $j = 1, 2, \dots M$ describes the contribution of the correction to the width of the coupling linear resonance: $\bar{k}_c = \begin{Bmatrix}\mathrm{Re}\,k\\ \mathrm{Im}\,k\end{Bmatrix}_c = B\bar{G}$. The solution for $\bar{G}$ is found using the expansion in eigenvectors $\bar{U}_j$ of the symmetric matrix A^TA (EVD): $\bar{G} = \sum_{j=1}^{M} c_j \bar{U}_j$.

Table 5 shows examples of using the EVD-based method for different sets of disturbances with a scatter of the residual vertical orbit in sextupoles δY = 40 μm.

In all cases, the linear coupling resonance is completely minimized. The latter refers to the definition of this parameter with respect to the ideal (without perturbations) structure. In fact, minimization is expressed in mutual convergence of normal modes frequencies Q_1 and Q_2 [3, 4].

Betatron Coupling Control

To meet the demands of SR users, it is necessary to be able to effectively control coupling. Therefor skew quadrupole correctors located in the gaps where $\eta_x = 0$, were chosen for this purpose (see Fig. 6).

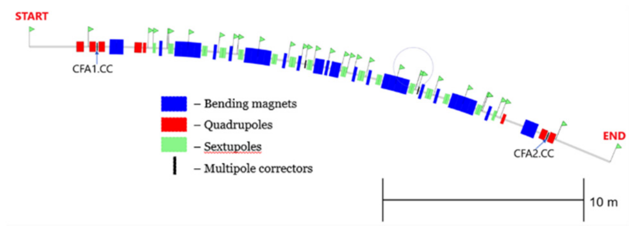

Figure 6: Skew quadrupole correctors for coupling control in one arc of SKIF.

These correctors were divided into two families: the first family consist of CFA1 type correctors, and the second – CFA2 type correctors. Using the selected correctors, it is possible to excite a coupling from 1% to 100% without significant distortion of optical functions (that is easily corrected by neighboring quadrupole lenses) and excitation of η_y. It is important that the DA remains unchanged up to 100% coupling (see Fig. 7). Also, gradients of skew quadrupole correctors do not exceed 185 Gs/cm; this means that the strengths of the correctors are within the required limitations.

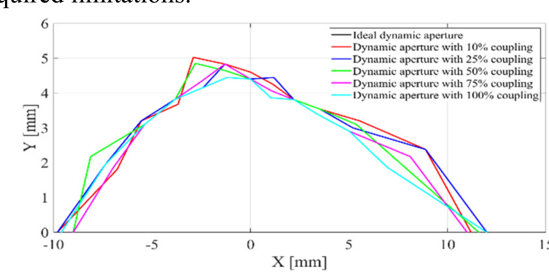

Figure 7: The DA in cases of different betatron coupling.

CONCLUSION

Sets of skew quadrupole correctors to effectively minimize coupling and reduce vertical dispersion were determined. After correction off-momentum and on-momentum dynamic aperture is sufficient for work and satisfy the necessary requirements. Maximum gradients of the correctors do not exceed the required limitations. It was found that the main source of coupling in SKIF will be residual vertical displacements of the orbit in sextupoles. EVD-based method can be an effective addition to the SVD method. And to control the coupling without distortion optics and exciting vertical dispersion it is necessary to use skew correctors in gaps with zero horizontal dispersion.

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