ROUND BEAM LATTICE CORRECTION USING RESPONSE MATRIX AT VEPP-2000*

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Abstract

Lattice correction based on orbit responses to dipole correctors and orbit correction based on orbit responses to field gradient variations in quads were successfully implemented on VEPP-2000 [1] for the flat-beam lattice. The round-beam lattice involves strong coupling of vertical and horizontal motions that require a full-coupling analysis in the orbit response technique. Programs used were modified to treat this task. Also, automation and speed enhancements were done that enable a routine use of this technique at VEPP-2000. New experimental results from VEPP-2000 are presented.

ORBIT CORRECTION

Introduction

The main task of the orbit correction in the VEPP-2000 is to shift the closed orbit as close to magnetic axes of elements as possible. After achieved the best orbit, one can store ideal positions of the beam at locations of the PBMs and use them for future orbit corrections.

The beam position monitoring system on VEPP-2000 consists of 16 CCD cameras and 4 picups [2]. CCD cameras are distorted from time to time, so to use them for direct orbit correction calibration should be performed on time. Orbit correction system of VEPP-2000 [3] consists of 20 horizontal correctors and 16 vertical correctors.

Orbit offset measurement

The first orbit correction (OC) method that was integrated in the control system [4] of VEPP-2000 was OC relative to the magnetic centers of the quadrupoles.

If a particle has an offset in the quadrupole lens $\delta\vec{l} = (\delta x, \delta y)$, then changing the gradient in this lens by δG will shift the closed orbit (CO) the same way as a dipole corrector with field $\delta\vec{H} = (\delta x \delta G, \delta y \delta G)$.

One can construct the response vectors $\delta\vec{X}_{\exp,i}$, by changing gradients in the lenses one by one and measuring the orbit shifts on BPMs. If the structure of the accelerator, is known then respective theoretical response vectors $\delta\vec{X}_{\mathrm{mod},i}$ for dipole correctors in tested lenses can be calculated. To find absolute shifts $\vec{X}_{\mathrm{err},i}$ of lenses relative to the ideal closed orbit, one should minimize the functional:

$$F(\lambda_i) = (\vec{\mathcal{X}}_{\mathrm{mod},in}\lambda_i - \vec{\mathcal{X}}_{\exp,in})^2 \to \min \tag{1}$$

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Here $\vec{\mathcal{X}}_{\mathrm{mod},in}$ and $\vec{\mathcal{X}}_{\exp,in}$ are measured and modeled response vectors normalized by the measurement precision σ_{in} (i is lens' number, n is BPM's number):

$$\begin{aligned}\vec{\mathcal{X}}_{\mathrm{mod},in} &= \left\{\frac{\delta x_{\mathrm{mod},i1}}{\sigma_{i1}}, \ldots, \frac{\delta x_{\mathrm{mod},iN}}{\sigma_{iN}}\right\}\\ \vec{\mathcal{X}}_{\exp,in} &= \left\{\frac{\delta x_{\exp,i1}}{\sigma_{i1}}, \ldots, \frac{\delta x_{\exp,iN}}{\sigma_{iN}}\right\}\end{aligned} \tag{2}$$

The functional (1) has a minimum if:

$$\lambda_{\min,i} = \frac{(\vec{\mathcal{X}}_{\mathrm{mod},i} \cdot \vec{\mathcal{X}}_{\exp,i})}{\vec{\mathcal{X}}^2_{\mathrm{mod},i}} \tag{3}$$

Now the absolute coordinates of the beam in the lenses can be obtained from the following formulas:

$$\delta x_{\mathrm{err},i} = \frac{\delta H_{y,i}\lambda_{\min,i}}{\delta G_i}, \quad \delta y_{\mathrm{err},i} = \frac{\delta H_{x,i}\lambda_{\min,i}}{\delta G_i} \tag{4}$$

To measure the accuracy of obtained displacements one can use functional (1). If the minimal value of this functional is $F_{\min,i} = F(\lambda_{\min,i}) = (\vec{\mathcal{X}}^2_{\exp,i} - (\vec{\mathcal{X}}_{\mathrm{mod},i} \cdot \vec{\mathcal{X}}_{\exp,i}))$, then let the accuracy $\delta\lambda_i$ of $\lambda_{\min,i}$ be defined by condition $F(\lambda_{\min,i} \pm \delta\lambda_i) = 2F_{min,i}$. Then:

$$\delta\lambda_i = \frac{\vec{\mathcal{X}}^2_{\exp,i} - (\vec{\mathcal{X}}_{\mathrm{mod},i} \cdot \vec{\mathcal{X}}_{\exp,i})}{\vec{\mathcal{X}}^2_{\mathrm{mod},i}} \tag{5}$$

Errors in the determined orbit can be obtained by combining (4) and (5).

For some elements, such as long solenoids of the final focus at VEPP-2000, it is necessary to know detailed information about orbit displacement relative to the magnetic axis of the element.

Consider element A that has small displacement described by the vector $\vec{S}^t_A = (x_A, x'_A, y_A, y'_A, 0, 0)$. Here (x_A, y_A) is the displacement of the magnetic axis of A at its start, and (x'_A, y'_A) describes the tilt of the element. To get coordinates of the particles with zero initial condition after passing A, several steps should be done. First, before entering A, one should transit from the laboratory reference frame to the one where A is undistorted, then pass the element and, finally, switch back to the laboratory reference frame:

$$\delta V_A = M_A(-S_A) + L_A S_A, \tag{6}$$

where L_A is the transport matrix of a gap with length equivalent to the length of A. The closed orbit distortion at the exit point of A is $\delta V_{CO,A} = (I - T)^{-1}\delta V_A$, where T is the turn matrix with start at the end of the element A.

Shift S_A of element A will cause the orbit displacements X_i in the ith BPM:

$$X_i = M(p)S_A, \tag{7}$$

where $M(p)$ is response matrix of the CO for shift S_A, that depends on parameters p of the element A. The response of the CO on variation Δp will be:

$$\Delta X_i = (M(p+\Delta p) - M(p))S_A = \Delta M(p)S_A, \tag{8}$$

If the responses of the CO on variation Δp is measured and matrix $M(p)$ is known from a theoretical model, then the hypothetical shift of the element can be obtained by inversion of rectangular matrix $\Delta M(p)$ with help of the SVD method:

$$S_A = (\Delta M(p))^{-1}_{SVD}\,\Delta X_i, \tag{9}$$

The CO shift δV_{CO} from S_A at the start of element A can be calculated to get the relative orbit displacement in A:

$$V_{COrel.A} = \delta V_{CO} - S_A. \tag{10}$$

CO shifts in elements are generated by all imperfections of the accelerator. The shift calculated with eq.(9) does not describes real displacement of the element and is calculated for supplementary purposes.

Figure 1 shows reconstructed orbit offsets inside the solenoids of final focuses of the VEPP-2000 relative to its magnetic axes. Solenoids xS1 and xS2 are two coils of one solenoid and should be coaxial. Strong forces and some manufacturing faults probably caused asynchronisms of the measured shifts. Coherent shifts of the orbit in the solenoids are result of the intended bump that minimizes the background in the detectors.

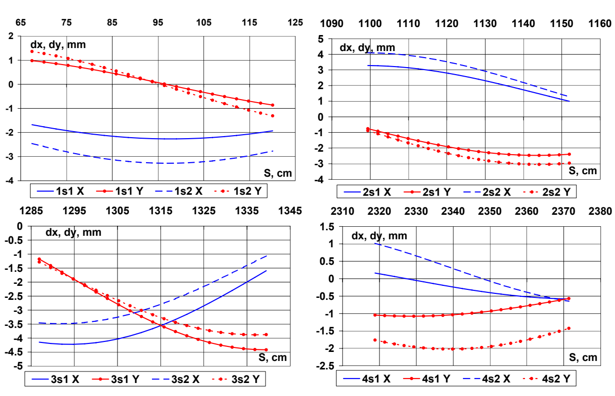

Figure 1: Example of the relative orbit measurement.

Orbit correction

To correct displacements of the closed orbit X_i, one should calculate the response matrix M_{ij} that contains responses of the closed orbit for unit current variation in each corrector from the selected group. Afterward, one should find the currents I_j that will minimize $\|F\|$:

$$F_i = \frac{X_i}{\sigma_i} - \frac{M_{ij}}{\sigma_i}I_j; \quad \sigma_i^2 = \sigma_{stat,i}^2 + \sigma_{syst,i}^2. \tag{11}$$

The software used at VEPP-2000 to optimize the correctors involves a method that uses SVD decomposition to invert the rectangular matrix:

$$I_j = \left(\frac{M_{ij}}{\sigma_i}\right)^{-1}_{SVD} \frac{X_i}{\sigma_i}. \tag{12}$$

Uncertainties in the theoretical model cause the errors in correction of the orbit, so several iterations are commonly needed to get the corrected orbit.

Table 1: Adjustment of the correctors

	before optimization	after optimization	after tuning
$\sum_{corrs} I/N_{corrs}$	0.52 A	0.22 A	0.28 A

Orbit correction results

Figure 2 shows the improvement of the closed orbit position relative to the magnet centers of quadrupoles.

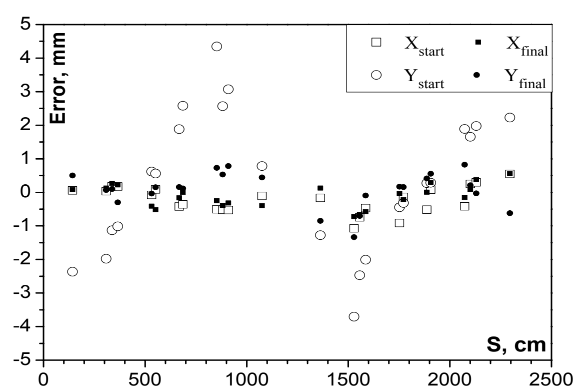

Figure 2: Example of orbit correction.

Optimization of the orbit correctors strengths

Sometimes a situation occurs when some correctors work against others, so that their strengthes are not ideally selected for current orbit configuration. Special software was developed at VEPP-2000 to help easily adjust correctors' strengths. First the program collects information about selected correctors and calculates orbit distortion that they generate:

$$X_{dist} = \sum_{corrs} X_i = M_{corr} I_{corr,i} \tag{13}$$

Then, the software calculates optimal strengthes of the correctors that will generate distortion that has acceptable deviation from the initial one.

$$\begin{aligned} I_{optimal,i} &= (M_{corr})^{-1}_{SVD}\, X_{dist} \\ \Delta X_{CO} &= M_{corr}\,(I_{corr,i} - I_{optimal,i}) \end{aligned} \tag{14}$$

An operator can control the difference between the closed orbit before and after the adjustment, by tuning the amount of singular values used to calculate $(M_{corr})^{-1}_{SVD}$. After the adjustment, additional orbit tuning should be done because of the deviations between the model and the real structure of the ring. Table 1 shows the result of the described procedure.

LATTICE CORRECTION

Introduction

One of the main problems during commissioning and running the circular accelerator is determining and eliminating the errors of the optical parameters in the real lattice. To correct the lattice of VEPP-2000, a program was written to implement algorithms discussed in [5, 6]. The main idea of the correction method is to minimize χ^2 by varying a set of parameters:

$$\chi^2 = \sum_{i,j} \frac{(M_{\mathrm{mod},ij} - M_{\mathrm{mes},ij})^2}{\sigma^2_{ij}} = \sum_{i,j} V^2_{k(i,j)} \tag{15}$$

where $M_{\mathrm{exp},ij}$ and $M_{\mathrm{mod},ij}$ are experimental and theoretical closed orbit responses on variation of j-th corrector at i-th BPM; σ_{ij} – precision of corresponding measurement.

The main feature of the written code is the usage of 6-d formalism for calculation of the theoretical responses on dipole correctors. In this formalism vector $X^t = (x, p_x/p_0, y, p_y/p_0, c\Delta t, \Delta p/p_0)$ is used for particle displacements and momenta.

Results

The software "sixdsimulation" was upgraded to perform the automated lattice correction procedure. Interaction with operator is organized through the sequence of dialogs. One iteration of the lattice correction takes about 60 minutes. Measurement of the orbit response matrix on dipole correctors, tunes and dispersion takes about 50 minutes. About 10 minutes is needed to get through the dialogs and adjust parameters of the correction.

Table 2 and figure 3 illustrate successful correction of the severe distortion of the lattice of VEPP-2000.

There is a strong degradation of the magnets at higher energies at VEPP-2000 due to the saturation of the iron poles of magnetic elements. This phenomenon results in unacceptably large distortions of lattice functions formed by theoretically calculated currents. Lattice correction procedures are performed at each level of energy that is used to accumulate luminosity.

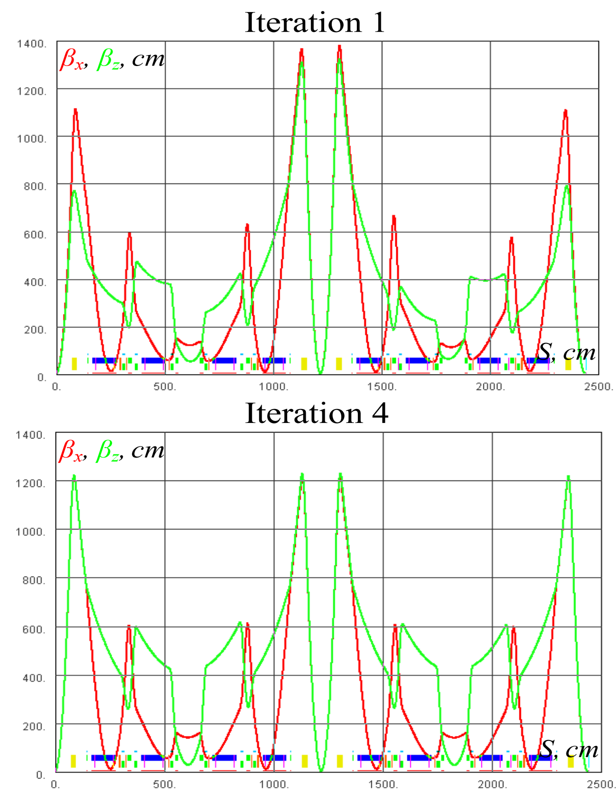

Figure 3: Example of lattice correction.

Table 2: Averaged errors of currents in quadrupoles in four consequent iterations.

Iteration	1	2	3	4
$100 \times \dfrac{\sum \Delta I_{quad}/I_{quad}}{N_{quads}}$	6.17	3.24	0.85	0.24

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