RADIO ENGINEERING, ELECTRONICS AND ELECTRICAL ENGINEERING

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RESPONSE MATRIX BASED CORRECTION OF THE MAGNETIC OPTICAL SYSTEM OF THE VEPP-4M COLLIDER

The VEPP-4M accelerating-storage complex is the electron-positron collider operating at the 2-11 GeV energy range. The target item of any collider's performance is known to be luminosity. It depends on many things of both beam characteristics and collider structure parameters. Therefore, it is mandatory to have precise structure's settings and correct them as well as possible. It's crucial to develop and increase performance of the collider since there are many users from different fields of physics and high precision experiments are required. In this case, luminosity of the VEPP-4M should and can be increased significantly. That's why, one of the VEPP-4M laboratory problems is to implement structure correction methods for high-luminosity experiments.

The VEPP-4M complex is 366m long. It imposes using of high amount of elements of both beam steering and observing. In this case, the amount of potential sources of errors increases. But this is the cost of large accelerator machines operation. The lattice of the VEPP-4M complex includes 26 quadrupole magnets, 108 combined-function magnets, 22 correctors and 54 BPMs (Beam Position Monitors). In fact, it is preferable to have as many BPMs as possible and to use all magnetic elements for smooth corrections.

The beam-based optics correction technique implemented in this work is Linear Optics from Closed Orbits (LOCO) [1]. This correction technique identifies imperfections in the machine lattice, and discrepancies between the machine and model. The LOCO method relies on the measurement of the ORM (Orbit Response Matrix). This is measured by recording the beam position response at all BPMs for a change in current applied to each individual magnet. The linear equation describes the method:

$$R_{ij} = \frac{dx_i}{d\theta_j}, \tag{1}$$

where x_i is the response at i monitor and θ_j is the kick of j corrector.

The main idea of the correction methods is to minimize chi-square index or discrepancy between experimental and model response matrices, by varying a set of parameters $\boldsymbol{p}$, so called knobs [2]:

$$\chi^2 = \sum_{ij} \frac{1}{\sigma_i^2} (R_{ij}^{exp} - R_{ij}^{model})^2 = \boldsymbol{r}^T \boldsymbol{r} = f(\boldsymbol{p}), \tag{2}$$

where σ_i is the rms noise level of i's BPM measurement. Since the fitting is finished, all modifications are reversed and applied on the machine to bring it to the design state.

In this work, Gauss-Newton and Levenberg-Markquardt optimization algorithms were used as described in [2]. Considering that the matrices are not square, SVD algorithm has to be used as well. It is a generic operation applicable to any rectangular matrix A. This algorithm has become the favourite tool for lattice correction. So the solution that minimizes the chi-square index in case of the Gauss-Newton minimization is:

$$\boldsymbol{r} = \boldsymbol{r_0} + J\Delta\boldsymbol{p}, \text{ with } J_{ij} = \frac{\partial r_i}{\partial p_j}, \tag{3}$$

$$f(\boldsymbol{p}) \approx f(\boldsymbol{p_0}) + 2\boldsymbol{r_0}J\Delta\boldsymbol{p} + \Delta\boldsymbol{p}^T J^T J \Delta\boldsymbol{p}, \tag{4}$$

$$\Delta\boldsymbol{p} = -(J^T J)^{-1}_{SVD} J^T \boldsymbol{r_0}. \tag{5}$$

In order to implement the correction procedure, the computer program should be written, which is aimed to optimize the structure of the collider and to automatize the correction procedure. Before the program implementing on the machine, one should test it on the models. In this work, the code was written in Python to have a possibility to implement the program on multiple computing platforms. It also allowed working with large arrays of data quickly and efficiently. Fast calculations and high accuracy are achieved due to using of MAD-X [3] accelerator tool inside the program. All calculations and correction procedure take 10 minutes, so if the lattice correction is needed for specific experiments, one can apply the correction in-situ in online mode. The program has a GUI (Graphical User Interface) for convenient operations.

The nominal fitting parameters used in the ORM (Orbit Response Matrix) lattice modeling are the quadrupole strengths, gradients of combined-function magnets, BPM and corrector gains which gives a total of 286 parameters. In order to test the linear lattice correction, the following errors have been introduced and applied to the model lattice of the VEPP-4M: 1% error of the strength of 3 quadrupoles. Gradients of quadrupoles and combined-function magnets were chosen as the fitting parameters (134 in total). The fitting algorithm was then applied to the simulated erroneous ORM generated by the MAD-X and simulated data set including the effects of the errors in gradients.

The result of the procedure is a set of variables used in the fit that makes the model response matrix coincide with the erroneous response matrix within the accuracy of the simulated measurements (modeled BPMs noise). Of those variables, the most important are quadrupole gradient errors that define the betatron functions of the machine. Improvements done in the model lattice of the VEPP-4M resulted in the precise errors identification and proper optical functions recovery obtained in the 1.8 GeV mode. Since betatron functions (Figure 1) and dispersion are the representation of the accelerator lattice, they can be a metric of the program performance. The betatron beatings before and after correction are presented in the Figure 2. The beating is reduced significantly and chi-square equals decreased by a factor of $5 \cdot 10^7$ after 3 iterations. Introduced errors were found by the method with high precision.

The presented code can be effective in linear optics correction problems, which can save time during commissioning and increase reliability of existing machines.

However, the further investigations and studies of the influence of the several parameters such as coupling and chromaticity, type/value of the SVD cut, minimization methods, should be performed. Later the system of element control of the accelerator will be also engaged to adjust knobs of every correcting element. After all these stages, the program can be tested and implemented in the VEPP-4M for the real correction and experiments.

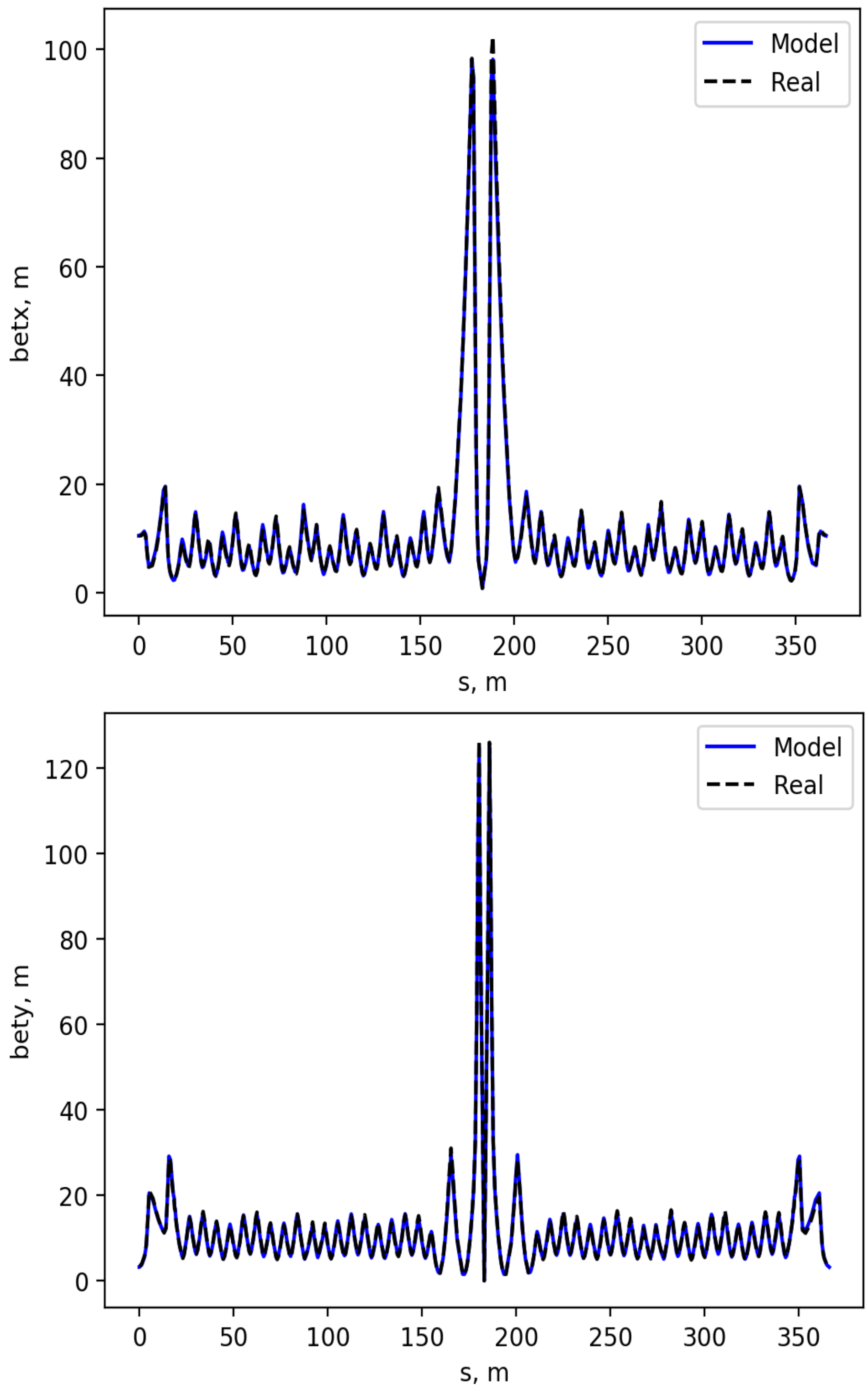
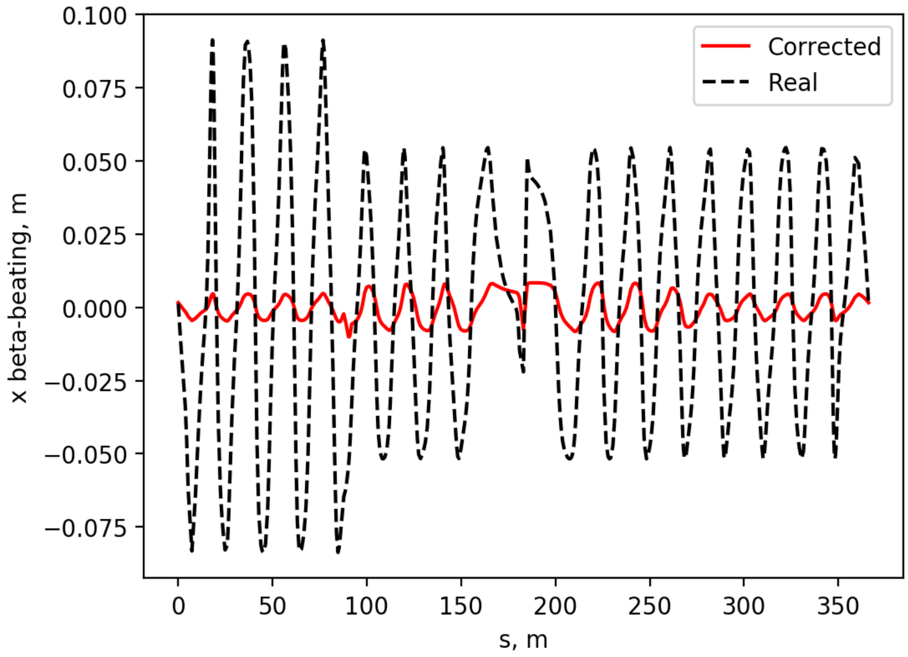


Fig. 1. **Horizontal (upper) and vertical (lower) betatron functions**



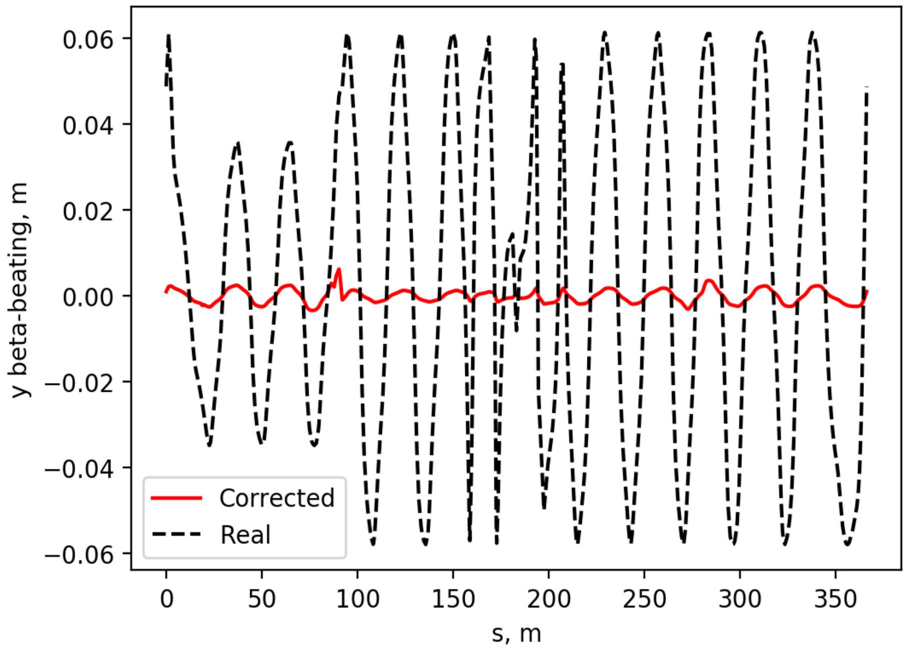


Fig. 2. **Horizontal (upper) and vertical (lower) betatron functions before and after correction**

References:

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