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FINAL FOCUS SOLENOIDS BEAM-BASED POSITIONING TESTS

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Abstract

The final focusing at VEPP-2000 electron-positron collider is done by 13 T superconducting solenoids. The misalignment of solenoids not only provides the closed orbit distortions but also harmful for dynamic aperture reduction due to strong nonlinear fringe fields. The final beam-based alignment of solenoids was foreseen but turned out to be not a trivial procedure. Here we present the test study of solenoids positioning reconstruction procedure based on a circulating beam orbit responses.

INTRODUCTION

VEPP-2000 is a small one-ring electron-positron collider at Budker Institute of Nuclear Physics operating within beam energy range of 150÷1000 MeV [1]. Unusual feature of the machine is the final focusing realized by use of strong 13 T superconducting solenoids (see orange blocks in Fig. 1).

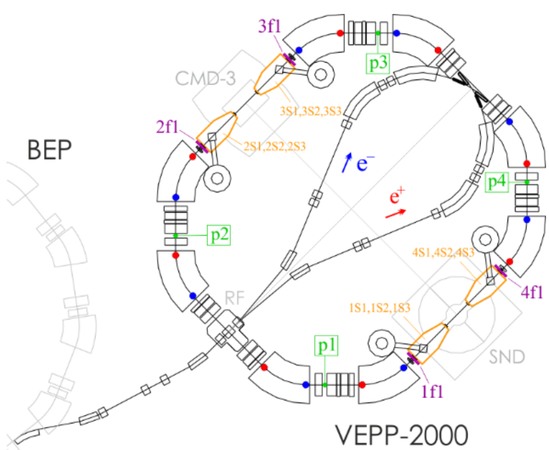

Figure 1: VEPP-2000 storage ring layout.

Final Focus Solenoids

Each solenoid block [2] in fact consists of several coils inside the iron flux return yoke which is also a part of cold mass (see Fig. 2). The main coils are divided in longitudinal direction into two parts powered in series. Inner Nb_3Sn coils and outer NbTi coils are powered by separate supplies S2 and S1 correspondingly. Short coil intended for compensation of CMD-3 detector longitudinal field has own power supply S3.

The vacuum chamber of the solenoidal module with the copper liner for synchrotron radiation absorption is a part of a cryosystem that makes a referencing of magnetic axis to external fiducials quite challenging at the test bench. The final alignment was supposed to be done by beam-based methods.

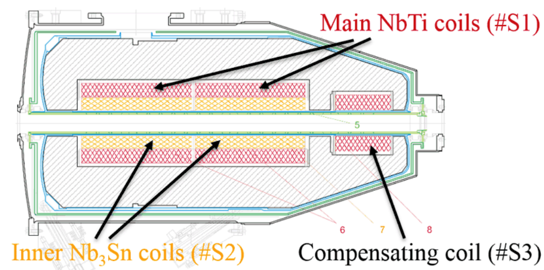

Figure 2: FF solenoid cross section. The effective length of main coil is 55.7 cm.

The first attempts to make this kind of alignment were carried out during commissioning phase [3] but for some reasons discussed below were not fairly successful. Later another approach was used: the solenoids are iteratively aligned in a way to minimize closed orbit (CO) distortions with switched off steerers.

The disadvantage of this method is nearly identity of CO distortions exited by different solenoids in regular lattice mode. Thus, even with non-disturbed CO the solenoids could be significantly misaligned, cancelling the distortions of each other. At the same time the dangerous for colliding beams are nonlinear fringe fields of solenoid. In addition the change of polarity crucially disturbs CO.

Beam Diagnostics

Beam diagnostics of the ring is based on 8+8 synchrotron light outputs forming the beam image at the CCDs from each side of each dipole (see dots in Fig. 1 at the reference orbit, blue for electrons, red for positrons) [4]. These images are used both for beam profiling and as a BPMs. Four pickups (see green dots) are used for continuous orbit measurements or in turn-by-turn regime.

TECHNIQUE

Beam-based techniques are widely used for different applications worldwide. At VEPP-2000 the CO response matrix SVD analysis is used for lattice correction. The responses to quads variation are used routinely for closed orbit measurement and correction [5]. High precision of the CO control allowed even to measure the weak pulsed stray field map of injection septum magnet [6].

There are two fundamental differences of solenoids' responses with respect to usual steerer's or quads' ones: 1) solenoid is never "thin", x/y-shift and longitudinal x'/y' tilts both produce non-zero response; 2) responses to any shift/tilt are two-dimensional.

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In design lattice the solenoids are strong axial-symmetric final focus components, thus their misalignments are primary source of orbit distortions. In addition, as VEPP-2000 is a collider with deep β-function crossover at IP and total betatron tune is close to integer all 4 solenoids' responses can be hardly distinguished.

For solenoids positioning study the special "warm" lattice mode at the energy of 700 MeV was chosen with solenoids switched-off initially [7]. Once the closed orbit in nearby f1-quads (see Fig. 1) is measured, or set to zero, the needed solenoidal coil can be switched on to a given (relatively low) level, and the circulating beam CO response is measured by BPMs. In Fig. 3 the example of calculated response to vertical shift of 1S1 coil by 1 mm is shown.

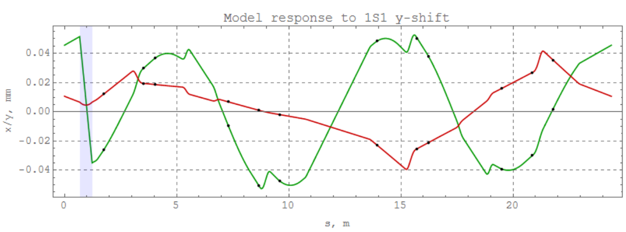

Figure 3: Horizontal (green) and vertical (red) response to the shift by 1 mm of 1S1 coil (position is marked with bluish stripe) powered to the 19.6 kGs field level.

The solenoid position can be described in terms of four offsets at the entry and exit $\{\Delta x_1, \Delta y_1, \Delta x_2, \Delta y_2\}$ that is convenient for CO calculation within linear map approach: one just use coordinate transformation. Nevertheless, we prefer to use another set of "elementary misalignments": the parallel shifts {dx, dy}, and the tilts with on-axis centroid {dx', dy'}.

The responses are linear to the misalignments, but has different dependence on longitudinal field value. The horizontal response (projection of the full 2D-response on horizontal plane) to the vertical shift/tilt (dy/dy') is linear with H_s, while the x-response to dx/dx' are quadratic $\propto H_s^2$.

In a case when solenoid is a relatively weak perturbation, the dominating effect is it's tilt: it produce transverse field component (with important kicks at the edges). This kind of response is proportional to field integral. The solenoid's focusing is proportional to squared field integral, thus this kind of responses are more evident for strong fields as it is in design lattice with final focusing.

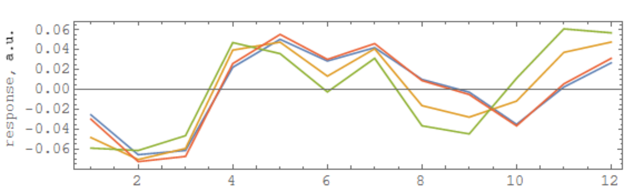

Figure 4: Normalized x-responses to {dx,dx',dy,dy'} misalignments of 2S1 coil.

Some of the elementary misalignments (dx, dx', dy, dy') responses projections being normalized are very similar to each other (see example in Fig. 4), that could lead to the response matrix (RM) degeneration. Fortunately if one will take full 2D response in a form of {x1, … xn, y1, …yn}, where n is a number of BPMs, the singularity disappears (see Figs. 5 and 6).

Although the responses amplitude changes with solenoid strength in a different way the singular values ratio remains more or less the same (see Fig. 6). It means that the choice of the field is important only in sense of detection ability by BPMs.

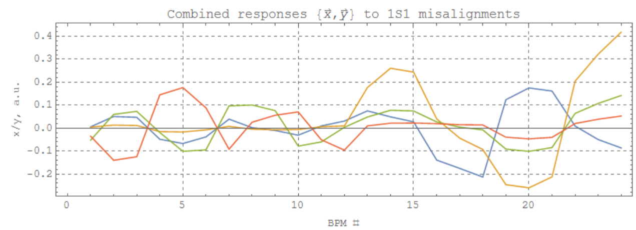

Figure 5: Combined x + y responses to {dx,dx',dy,dy'} misalignments.

$$\begin{pmatrix} 0.421473 & 0. & 0. & 0. & 0. & \cdots & 0. \\ 0. & 0.219664 & 0. & 0. & 0. & \cdots & 0. \\ 0. & 0. & 0.179973 & 0. & 0. & \cdots & 0. \\ 0. & 0. & 0. & 0.096416 & 0. & \cdots & 0. \end{pmatrix}$$

$$\begin{pmatrix} 0.882480 & 0. & 0. & 0. & 0. & \cdots & 0. \\ 0. & 0.481477 & 0. & 0. & 0. & \cdots & 0. \\ 0. & 0. & 0.324369 & 0. & 0. & \cdots & 0. \\ 0. & 0. & 0. & 0.185256 & 0. & \cdots & 0. \end{pmatrix}$$

Figure 6: The singular values of response matrix SVD . The RM is calculated for 1S1 coil excitation current of 20 A (above) and 40 A (below).

All the measurements discussed below consisted of two responses for two values of excitation current. Mainly the fitted misalignments were in very good agreement for each pair.

MEASUREMENTS

Measurements were done with circulating e^- beam at 700 MeV, thus 4 pickup and 8 CCD-type BPMs were in charge. Hence, each response consists of 12+12 coordinate readings. In addition most of the measurements were accompanied with weak counter positron beam providing extra 8 points of observation (see hollow points in the figures below) which were not used for fit. The example of the fitted response is given in Fig. 7.

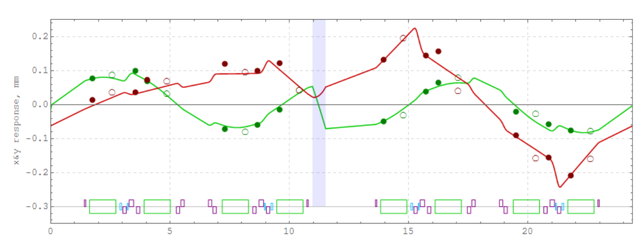

Figure 7: Horizontal (green) and vertical (red) response example for 2S2 coil (position is marked by bluish stripe). Filled circles for BPM readings of e^- beam, hollow circles for e^+ beam, solid lines show the fit result.

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The important point is the accuracy of the technique. As the method measures the CO with respect to the magnetic axis first of all the reference orbit should be well known. To estimate the accuracy of the fitted misalignments we use the growth of the difference between model and measured response while varying the parameters starting from the best fit values.

All the solenoidal coils were measured, 3×4 in total. The results for one solenoidal assembly is presented in the Table 1. Surprisingly it was found that coils are effectively misaligned to each other, even inner and outer coils in the single solenoid. By now we have no clear explanation of this phenomena since these huge shifts can be hardly tolerated by mechanical assembly. It also couldn't be explained with winding inaccuracy since the coils consists of thousands turns. At the same time, this observation probably can shed the light on confusion of early magnets alignment attempts at the commissioning stage.

Table 1: Measured Misalignments

	dx, mm	dx', mrad	dy, mm	dy', mrad
1S1	**+0.98** ± 0.30	**+0.17** ± 0.18	**+1.21** ± 0.40	**-2.33** ± 0.36
1S2	**+0.89** ± 0.25	**+1.26** ± 0.15	**+0.93** ± 0.38	**-0.40** ± 0.30
1S3	**+2.66** ± 0.40	**-2.20** ± 0.23	**+1.45** ± 0.42	**+0.94** ± 0.56

VERIFICATION TESTS

To ensure that all the polarities and calibrations are properly taken into account several tests were carried out with well-controlled large closed orbit distortions (see Fig. 8). For beam-based technique it is an equivalent to solenoid misalignment with respect to the orbit.

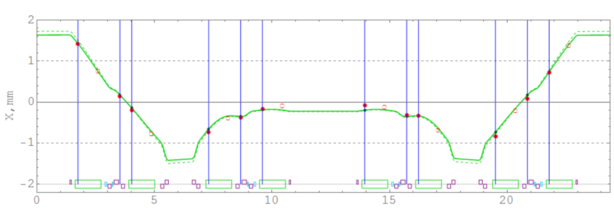

Figure 8: Measured (circles) and fitted (line) horizontal CO distortion with parallel shift in the 1S and 4S solenoidal blocks position. Dashed line shows the fit inaccuracy.

In the following Table 2 the measurement results are presented for one of the coils with regular and distorted orbit. The predicted shift is reproduced within estimated accuracy. Important is that other misalignments remained unchanged, that indicates absence of the mixing during response fit.

Although all the coils in one solenoidal unit have their own misalignments with respect to regular CO the change of the orbit is reconstructed almost identically (see Table 3). This fact gives an indication that discrepancies in coils relative alignment are reliable.

Table 2: Misalignments Change with CO Shift

1S1	dx, mm	dx', mrad	dy, mm	dy', mrad
initial	**+0.98** ± 0.30	**+0.17** ± 0.18	**+1.21** ± 0.40	**-2.33** ± 0.36
shifted	**-0.82** ± 0.27	**+0.11** ± 0.17	**+1.23** ± 0.36	**-2.40** ± 0.33
diff	**-1.80** ± 0.40			
predict	**-1.64** ± 0.09			

Table 3: Measured Shift (mm)

	@1S1	@1S2	@1S3	Predict
diff	**-1.80** ± 0.40	**-1.86** ± 0.38	**-1.82** ± 0.58	**-1.64** ± 0.09

In Fig. 9 the CO distortion of another type is shown. It gives us the possibility to test quality of tilt value fitted from solenoidal responses.

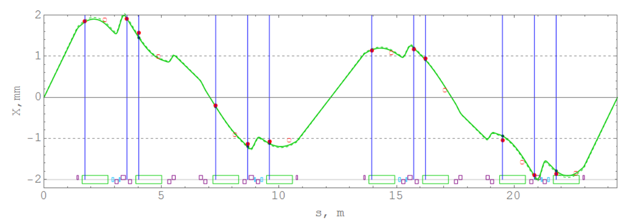

Figure 9: Horizontal CO distortion with tilt in the 1S and 4S solenoidal blocks position.

The results of this test are shown in Table 4. The orbit shift/tilt reproduced within the estimated accuracy.

Table 4: Misalignments Change with CO Tilt

1S1	dx, mm	dx', mrad	dy, mm	dy', mrad
initial	**+0.98** ± 0.30	**+0.17** ± 0.18	**+1.21** ± 0.40	**-2.33** ± 0.36
shifted	**+0.17** ± 0.24	**-0.96** ± 0.15	**+1.12** ± 0.32	**-2.29** ± 0.29
diff	**-0.81** ± 0.38	**-1.13** ± 0.23		
predict	**-1.18** ± 0.04	**-1.12** ± 0.04		

Another similar tests with different coils and with vertical CO distortions were done as well. All of them were consistent with the expectations.

CONCLUSION

The proposed beam-based method of solenoid positioning works well and can be used for alignment of single solenoidal coil. However the desired precision of ~0.1 mm remains challenging. In addition solenoidal block with several coils alignment is still under consideration due to significant discrepancy between the reconstructed magnetic axis of different coils.

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