PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 80, No. 2
February 2013
pp. 263–275

Measurement, analysis and correction of the closed orbit distortion in Indus-2 synchrotron radiation source

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MS received 4 June 2012; revised 8 August 2012; accepted 22 August 2012

Abstract. The paper presents the measurement, analysis and correction of closed orbit distortion (COD) in Indus-2 at 550 MeV injection energy and 2 GeV synchrotron radiation user run energy. The measured COD was analysed and fitted to understand major sources of errors in terms of the effective quadrupole misalignments. The rms COD was corrected down to less than 0.6 mm in both horizontal and vertical planes. A golden orbit was set for the operating synchrotron radiation beamlines. With COD correction, the injection efficiency at 550 MeV was improved by ∼50% and the beam lifetime at 2 GeV was increased by ∼8 h. In this paper, the method of global COD correction based on singular value decomposition (SVD) of the orbit response matrix is described. Results for the COD correction in both horizontal and vertical planes at 550 MeV injection energy and at 2 GeV synchrotron radiation user run energy are discussed.

Keywords. Indus-2; storage ring; closed orbit distortion; singular value decomposition; betatron tune; dispersion function.

PACS Nos **29.20.−c; 29.27.−a; 41.60.Ap**

1. Introduction

Synchrotron radiation (SR) sources are characterized by low emittance of the electron beam and high brightness of the photon beam radiated from dipoles and insertion devices. Indus-2 [1,2], a 2–2.5 GeV electron storage ring, is operational at Raja Ramanna Centre for Advanced Technology, Indore, India. The source comprises a large number of dipoles, focussing elements, i.e., quadrupoles and chromaticity correcting sextupoles. Indus-2 ring lattice consists of eight unit cells of a double bend achromat or expanded Chasman green lattice. Each unit cell accommodates two dipoles, nine quadrupoles and four sextupoles. The sources of the closed orbit distortion (COD) are the dipole field errors and the errors arising from magnetic element positioning. The most severe effects come from misalignment of quadrupole magnets, where the resulting dipole field is proportional to both field gradient and alignment errors. If the beam is going off centre in the strong sextupoles, this will lead to quadrupolar effect and can change the betatron tune and beta function. The beam offset in the sextupole should be minimized to make the storage ring optics near to linear. Large distorted orbit reduces the available aperture for the beam oscillations and results in poor injection efficiency and reduced beam lifetime. In addition, the radiated photon beam is not properly aligned to the SR beamlines. Initially, three beamlines were commissioned by making local adjustments in the vertical orbit using four orbit bumps. However in future, when as many as 27 beamlines are to be commissioned, then there is a need to correct and control the COD to a minimum possible residual satisfying the SR users. This will also improve the injection efficiency and beam lifetime.

Indus-2 is being operated in round-the-clock mode for SR users at 2 GeV with a stored beam current of 100 mA. Measurement of various beam dynamical parameters such as COD, betatron tune, beta function, dispersion function, chromaticity, central radio frequency (RF), linear coupling are being carried out. In this paper, we describe the COD measurement, analysis and its correction based on the orbit response matrix. Major sources of the COD are estimated in terms of effective quadrupole misalignments by fitting the measured COD. The fitted values of quadrupole misalignments are 100–150 μm, which are within the magnet alignment tolerances. The COD is corrected down to 0.6 mm rms in both the horizontal and vertical planes. With this corrected COD, the injection efficiency is increased by $\sim$50% and beam lifetime is improved by $\sim$8 h at 2 GeV user run energy.

In this paper, the global closed orbit correction algorithms based on the response matrix for minimizing and controlling the orbit are presented. Results for COD correction at 550 MeV and 2 GeV in both horizontal and vertical planes are reported. The golden orbit optimization to provide proper flux and aligned photon beam to SR users is also described.

2. Scheme and hardware for COD measurement and correction

The scheme for COD measurement and its correction in one unit cell, together with lattice functions for both horizontal and vertical planes are shown in figure 1. In a cell, there are seven beam position monitors (BPMs) for the COD measurement and for its correction, six horizontal and five vertical corrector magnets are installed. In the ring, there are 56 BPMs, 48 horizontal and 40 vertical corrector magnets. Out of these correctors, 32 are combined function correctors generating horizontal and vertical kicks. Each corrector is driven by an independent power supply of $\pm$10 A rating corresponding to $\pm$2 mrad kick at 2 GeV. Out of 56 BPMs, 16 are integrated with a dipole magnet chamber, while the remaining 40 are of individual type [3]. Each BPM consists of four button-type electrodes of 13.5 mm diameter and is mounted on a Bayonet Neill–Concelman (BNC) type feedthrough. The buttons in the BPMs are not placed on the symmetry axis of the vacuum chamber, rather they are placed diagonally to avoid the hitting of synchrotron radiation. This placement of the buttons in non-symmetric axis results in the nonlinear response of BPMs. Before installing the BPMs in the Indus-2 ring, they were calibrated on a test bench in the laboratory. The accuracy of beam position measurement was studied using

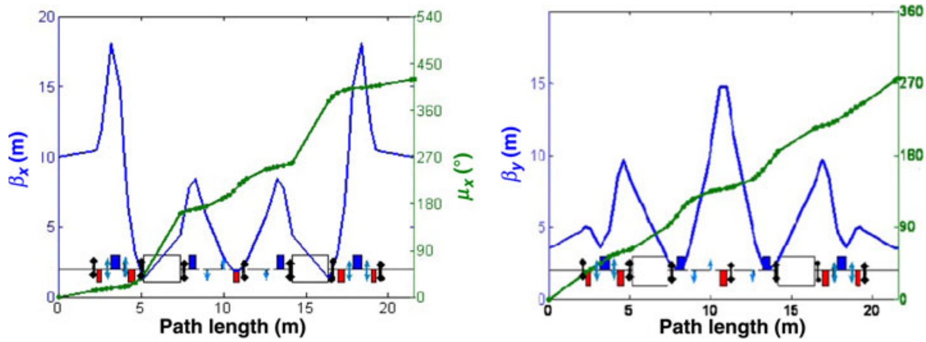

Figure 1. Scheme of COD correction in one unit cell of Indus-2 with beta function and phase advance in horizontal and vertical planes. In the figure, empty rectangles show the dipole magnet, upright rectangles show the focussing quadrupoles and downside rectangles show defocussing quadrupoles. Dot bars show the BPMs, up and down arrow shows combined function corrector magnets, down arrow shows the independent horizontal corrector magnet and up arrow shows the independent vertical corrector magnet.

the calibration of BPM with antenna. Mapping functions are identified for each BPM to provide accuracy of beam position measurement at higher orbit distortion. The accuracy of BPM is better than ± 100 μm. The resolution of BPM is measured with Indus-2 beam and found to be better than 50 μm.

3. COD correction algorithms

The measured orbit at BPM, the kick strengths of the corrector magnets for orbit correction and the response matrix are denoted by $\underset{\sim}{y}$, $\underset{\sim}{\theta}$ and $\underset{\approx}{R}$, respectively in both horizontal and vertical planes. Here, M and N are the numbers of BPMs and corrector magnets and $\underset{\approx}{R}$ is an $M \times N$ matrix. The objective of the optimization or correction is that the norm of $\underset{\sim}{r}$ defined by

$$\underset{\sim}{r} = \underset{\approx}{R}\,\underset{\sim}{\theta} + \underset{\sim}{y} \tag{1}$$

should be minimum.

The element R_{ij} of the orbit response matrix corresponding to the orbit shift at the ith BPM due to a unit kick from the jth corrector is given by [4,5]

$$R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi\nu)} \cos(|\varphi_i - \varphi_j| - \pi\nu), \tag{2}$$

where (β_i, φ_i) and (β_j, φ_j) are the beta function and phase advance at BPM and corrector magnet locations, ν is the betatron tune.

The norm of $\underset{\sim}{r}$ becomes minimum when its derivatives with respect to θj $(j = 1, 2, \ldots, N)$ are zero. The kick angle vector is then determined by

$$\underset{\approx}{R}\,\underset{\sim}{\theta} + \underset{\sim}{y} = 0. \tag{3}$$

Equation (3) represents the system of simultaneous linear equations between the reading at BPMs and corrector magnet strengths. Based on the response matrix, there are a number of methods for COD correction.

3.1 *Correction with MICADO method*

In principle, assuming that the response matrix is non-singular, the numbers of free parameters (corrector magnets) should be the same as the number of constraints (BPMs) for the linear problem to be exactly solvable. However, in general, a very good approximate solution can be achieved by using only a small subset of correctors. MICADO [4] is an algorithm that has been developed to choose such a subset. For a given subset of correctors, the optimal solution can be obtained as the least-square fit. The least-square fit suppresses all null-space corrections, that is, linear combinations of individual corrections that in total gives no effect at the monitors. The correction is computed using the pseudo-inverse of the response matrix. MICADO starts out by testing all the possible subsets containing only one corrector and finding the best one. Then, it tests all subsets that can be obtained by adding one more corrector to this subset. In iterations, every time, a corrector is thus added to the previously selected set of correctors to find the solution for the next best corrector. In this way, a subset p of the best correctors out of N orbit correctors is obtained. However, the required strengths of these best orbit correctors may go beyond the available maximum corrector strengths. Then, the method using single value decomposition (SVD) of the response matrix is applied to lower the strengths with a compromise on the level of orbit correction. The SVD method is described below.

3.2 *Correction with SVD method*

The solution of eq. (3) is used to effectively find out the inverse of the response matrix, i.e., $\underset{\approx}{R}^{-1}$. By SVD [5,6], the response matrix $\underset{\approx}{R}$ can be decomposed into $\underset{\approx}{U}$, $\underset{\approx}{W}$, $\underset{\approx}{V}$ matrices as

$$\underset{\approx}{R} = \underset{\approx}{U} \times \underset{\approx}{W} \times \underset{\approx}{V}^{T}, \tag{4}$$

where $\underset{\approx}{U}$ is an $M \times M$ unitary matrix $\left(\underset{\approx}{U}\,\underset{\approx}{U}^{T} = \underset{\approx}{U}^{T}\underset{\approx}{U} = \underset{\approx}{I}\right)$ and $\underset{\approx}{V}$ is an $N \times N$ unitary matrix $\left(\underset{\approx}{V}\,\underset{\approx}{V}^{T} = \underset{\approx}{V}^{T}\underset{\approx}{V} = \underset{\approx}{I}\right)$, $\underset{\approx}{W}$ is an $M \times N$ diagonal matrix with diagonal elements having positive or zero values. We call these diagonal elements, w_n (≥ 0 and $1 \leq n \leq \min(M, N)$), the eigenvalues, which represent the coupling efficiency between the BPMs and the correctors. The matrix $\underset{\approx}{R}$ is singular if any of the eigenvalues are equal to zero. The $\underset{\approx}{R}^{-1}$ can be calculated as

$$\underset{\approx}{R}^{-1} = \underset{\approx}{V} \times \underset{\approx}{W}^{\text{inv}} \times \underset{\approx}{U}^{T}. \tag{5}$$

Here, $\underset{\approx}{W}^{\text{inv}}$ is a diagonal matrix of dimension $N \times M$ and the elements are given by

$$W_{i,j}^{\text{inv}} = q_{\min}(i, j)\delta_{ij} \tag{6}$$

with

$$q_n = \begin{cases} 0, \; w_n \leq \varepsilon w_{\max} \\ \dfrac{1}{w_n}, \text{ otherwise} \end{cases} \qquad (1 \leq n \leq \min(M, N)), \tag{7}$$

where ε is the singularity rejection parameter in the range [0, 1]. This parameter is determined primarily by the orbit correction needs and the corrector strength limits. Zero q_n values correspond to the decoupled channels which do not contribute to orbit correction.

When $\varepsilon = 0$, all the non-zero eigenvalues are retained and the most accurate correction will result. However, this will lead to saturation of power supplies for the correctors. On the other hand, if $\varepsilon = 1$, $\underset{\approx}{R}^{-1}$ is a null matrix and there will be no orbit correction. Usually, ε is set to the smallest value such that none of the power supplies' current reaches its saturation limit.

The COD correction cannot guarantee that the SR users will get the aligned photon beam in their beamlines because the BPM readings may contain large offset errors. Then, the variant of SVD technique called as weighted (or constraint) SVD is used to set the golden orbit such that there should be global COD correction and simultaneously all beamlines should get proper flux with aligned photon beam in their beamlines. In this technique, BPM readings are constrained as per requirement to provide the aligned photon beam for beamlines and solution can be obtained by SVD algorithm [7,8]. This is equivalent to the global COD correction generating the desired local bumps.

3.3 *Correction with RF frequency method*

The corrector magnets can only correct the COD contribution from magnetic field errors and alignment errors. In synchrotron radiation sources, the dipole magnets are placed in horizontal plane which result in definite dispersion. In this plane, there is also a contribution from the path length effect which can be corrected by changing RF frequency. When RF frequency is changed, the electron beam moves horizontally onto a dispersive orbit given by

$$\underset{\sim}{x} = \underset{\sim}{\eta}\frac{\mathrm{d}p}{p}, \tag{8}$$

where $\underset{\sim}{\eta}$ is the dispersion function in horizontal plane, the energy shift $\mathrm{d}p/p$ (for ultra-relativistic energies: $\mathrm{d}p/p = \mathrm{d}E/E$) is related to momentum compaction factor (α) by

$$\frac{\mathrm{d}p}{p} = \frac{1}{\alpha}\frac{\mathrm{d}l}{L} = -\frac{1}{\alpha}\frac{\mathrm{d}f}{f}. \tag{9}$$

Combining eqs (8) and (9),

$$\underset{\sim}{x} = -\frac{\underset{\sim}{\eta}}{\alpha}\frac{\mathrm{d}f}{f}. \tag{10}$$

One way to correct the RF frequency is to measure the COD and project it onto a known dispersion orbit. In general, the horizontal COD contains both a 'betatron' component ($\underset{\sim}{x}^{\beta}$) and an RF component ($\underset{\sim}{x}^{\mathrm{rf}}$):

$$\underset{\sim}{x} = \underset{\sim}{x}^{\beta} + \underset{\sim}{x}^{\mathrm{rf}}. \tag{11}$$

To extract the RF component [9], one can project the orbit perturbation onto a measurement of the orbit response to a known RF frequency change, the vector: $\Delta \underset{\sim}{x}^{\mathrm{rf}}$. The projection generates a scalar proportional to the required RF frequency change which is given by

$$f = \frac{\underset{\sim}{x} \cdot \Delta \underset{\sim}{x}^{\mathrm{rf}}}{\Delta \underset{\sim}{x}^{\mathrm{rf}} \cdot \Delta \underset{\sim}{x}^{\mathrm{rf}}}. \tag{12}$$

Note that if $\underset{\sim}{x} = \Delta \underset{\sim}{x}^{\mathrm{rf}}$, then $f = 1$, i.e., the entire orbit perturbation is due to a change in RF frequency. Furthermore, we assume $\underset{\sim}{x}^{\beta} \cdot \Delta \underset{\sim}{x}^{\mathrm{rf}} = 0$, which is a good approximation since betatron orbits tend to be oscillatory with the betatron period, and the RF orbit is predominantly constant. The RF frequency shift required to correct the dispersive orbit is given by

$$\delta f_{\mathrm{rf}} = -f(\Delta f_{\mathrm{rf}}), \tag{13}$$

where Δf_{rf} is the change in frequency used to generate the measured dispersion orbit, $\Delta \underset{\sim}{x}^{\mathrm{rf}}$. The residual betatron component $\underset{\sim}{x}^{\beta} = \underset{\sim}{x} - \Delta \underset{\sim}{x}^{\mathrm{rf}}$ is corrected with standard methods of orbit correction.

4. Graphical user interface (GUI) for COD measurement and correction

The control architecture for the data acquisition of Indus-2 machine is implemented with a three-layer control architecture [10,11]. Out of the three layers, Layer-1 (L1) of the control architecture basically constitutes supervisory control and data acquisition (SCADA) functionality with application programming interface (API) managers, event managers, database managers and GUI applications. Layer-2 (L2) of the control architecture is composed of Motorola 68040 processor-based VME station which polls data from various Layer-3 (L3) stations through profi bus protocol over RS-485-based communication link. Communication link between L1 and L2 is Ethernet (100 Mbps). PVSS SCADA is used at L1 which polls data from L2. L3 stations are equipment controllers and they directly control the field devices. For COD correction, L3 stations directly interact with two types of elementary devices: BPM analogue front-end and corrector magnet power supply.

Taking advantage of matrix manipulation and extensive list of toolboxes, MATLAB [12] is chosen as the main platform for the implementation of COD correction algorithms. Its guide tool is used to develop GUI for COD correction software. In addition, Java platform is used to add functionality to communicate with PVSS SCADA over Ethernet using TCP/IP socket protocol. Java API client is developed to establish TCP/IP socket connection with PVSS-SCADA server API (for COD correction). This API provides all the required methods to retrieve data: BPMs position, corrector magnet power supply currents or their status and write data: corrector magnet currents. In addition to this, COD correction software also has a feature to save all the parameters such as predicted/measured orbit and kick strengths into central database for future reference. For this purpose, Java API is developed to establish connection with SQL Server database (Indus-2 database) using JDBC API of Java.

5. Measurement and analysis of COD

During orbit measurement, it was observed that a few BPMs are not providing proper COD data. To use the measured COD data for analysis and correction, a self-consistency test of the BPMs was carried out using three-electrode-based algorithm for each BPM. LMR-240 coaxial cables convey pick-up signals of each monitor to the equipment gallery located outside the tunnel where the signal processing electronics is located. The length of the cables between monitor and electronics unit varies from 25 to 50 m depending on the location of the monitors in the ring. Relative attenuations of the four cables of each monitor are measured carefully and used for beam position estimates. There are possibilities of fault occurring in the measurement because of attenuation of any of the signal due to loose connections or noise superimposed on the pickup signals. For measuring the position using three electrodes, a polynomial fit is performed using available calibration data. In this way, four sets of beam positions are calculated for each BPM. The accuracy of the calculated position using this polynomial is $\sim$100 μm up to the beam position of 5 mm from the centre of the BPM. Same exercise is repeated for all 56 BPMs and polynomial coefficients are fitted and stored in the files. For a given BPM, if four beam positions do not match within a given limit, the software treats this as inconsistent. Fifty-three BPMs are found consistent and provided authenticated measured COD data for analysis and correction.

In electron storage rings, various sources of errors contribute to COD and, as discussed, the transverse quadrupole magnet misalignments generally have the strongest effect. By using the model of the lattice, one can estimate the effect of misalignment of the individual magnet around the ring. We have estimated the magnet misalignments [13,14] based on the linear machine model using accelerator simulation code accelerator toolbox (AT) [15]. The transverse coupling is not considered. Different configurations of the lattice are chosen to compare the results. If the linearity is good and the coupling negligible, the misalignment values should agree, with some reasonable accuracy, as misalignments are common to any lattice tuning of the machine. Amplitude of the fitted quadrupole misalignments to reproduce the measured COD at injection energy and 2 GeV with various betatron tunes are shown in figure 2. Here, the SVD of the response matrix generated between quadrupole misalignments and the COD change at BPMs per unit change of misalignments is used. Misalignments are estimated in one lattice at 550 MeV injection energy and in two different lattices at 2 GeV. Since the quadrupole misalignments are fixed during installation or realignment of magnets, they are independent of the lattice tune and beam energy. The misalignments obtained are found to be repeating for the various tunes and confirm the magnitude of estimated misalignments. The rms misalignment errors are of the order of 100–150 μm which are within the alignment accuracy which confirms that

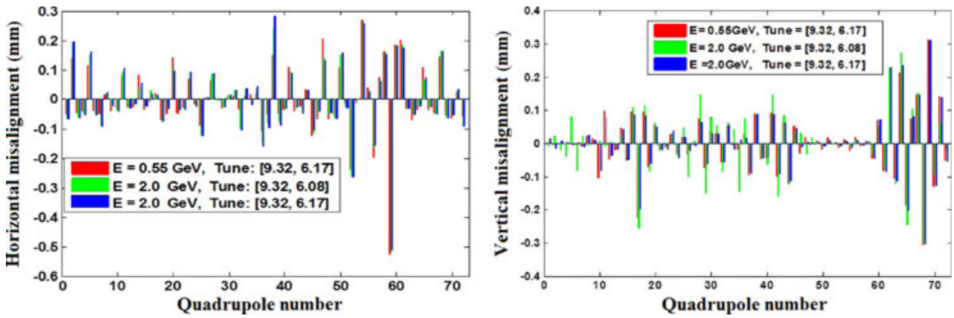

Figure 2. Effective misalignments of the quadrupoles in horizontal and vertical planes calculated by fitting the measured COD at 550 MeV injection energy and at final energy 2 GeV for various betatron tunes.

the elements of the machine are reasonably well-aligned. However, as different lattice configurations also give reasonably similar estimates of the magnet misalignments, they should not immediately be taken as the real misalignments, because SVD is used to invert the response matrix with some limited subset of eigenvectors. Nevertheless, the estimated misalignments are sufficient inputs to understand the effect on orbit distortion.

During beam energy ramp [16], the measured rms and maximum COD change due to change in betatron tune. As the vertical betatron tune gets drifted from 6.17 at injection to 6.08 at 2 GeV, the lattice becomes more sensitive to misalignment errors of the quadrupoles, i.e., amplification factors become large. As a result, the maximum and rms vertical COD increase from injection to final energy during normal ramp from (5 mm, 1.8 mm) to (7 mm, 2.9 mm) at 2 GeV. After correcting the vertical tune on the ramp, the COD becomes almost constant all along the ramp in the vertical plane. The horizontal tune remains almost constant; there is not much variation in horizontal COD during the ramp.

6. Results of COD correction

In the horizontal plane at 550 MeV injection energy, based on the model response matrix and measured orbit data from working BPMs, the MICADO method is used to identify a few best orbit correctors. Corrector no. 36 shows the most effective correction and next 36 & 3 show further correction and so on. In total, four numbers of correctors are energized and as a result, uncorrected rms value was reduced from 4.68 mm to 1.4 mm. It works well for small number of correctors, but the strengths as expected were large. Similarly, a few correctors are identified by MICADO algorithm to correct vertical COD. At this corrected orbit by MICADO method, the BPMs are in the linear zone and response matrix measurement can be performed. As the strong chromaticity correcting sextupole magnets are also ON, the closed orbit should be changed by a small value to reduce the feed-down effect of the sextupoles on optics and improve the accuracy of the response matrix measurement. The measurement was performed by applying 0.1 mrad kick in the correctors producing maximum change in orbit: 2.5 mm in horizontal and 3 mm in vertical planes. A lattice model was generated in AT by considering operating magnetic fields of the dipole, quadrupoles and sextupoles as per their set currents. The response matrix is generated with this model and compared with the measured response. Figure 3 shows the SVD analysis or the diagonal elements of matrix W (eq. (6)) of the model and measured response matrices for both horizontal and vertical planes. The number of singular values in horizontal and vertical planes is 48 and 40, i.e., it equals the number of corrector magnets. It can be observed that the behaviour of the model and the measured response matrix are almost similar. In order to correct the COD, one can use either the model response matrix or the measured response matrix.

It can also be inferred from figure 3 that singular values of more than 32 in horizontal and 24 in vertical planes are redundant and do not affect the level of orbit correction and may produce larger strengths of corrector magnets. For COD correction in horizontal plane, 10 singular values ($\varepsilon = 0.5$) are utilized, while for vertical plane, 23 singular values ($\varepsilon = 0.3$) are considered. These singular values are selected based on the correction needed and the optimization of the corrector strengths. For COD correction, consistent 53 BPMs, all 48 horizontal and 40 vertical corrector magnets are utilized. The fast Fourier transform (FFT) analysis of the measured COD in horizontal and vertical planes show the peak at 9th and 6th harmonics, which confirm the integer part of the operating betatron tune [2].

6.1 *Correction in the horizontal plane*

The COD correction is performed first in the horizontal plane at 550 MeV injection energy using model response matrix of size 53×48. Since the sextupoles are ON, the convergence is achieved iteratively. The result for the measured uncorrected and corrected horizontal COD is shown in figure 4a. The rms COD is reduced from 4.68 mm to 1.0 mm with

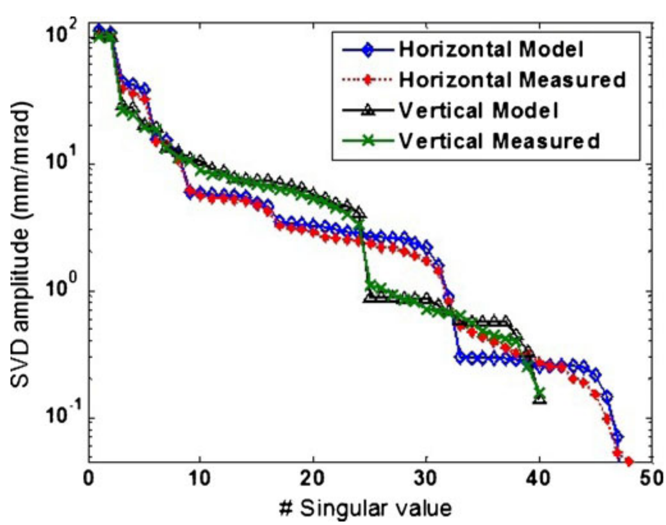

Figure 3. Singular value decomposition of the model and measured response matrices in the horizontal and vertical planes at 2 GeV.

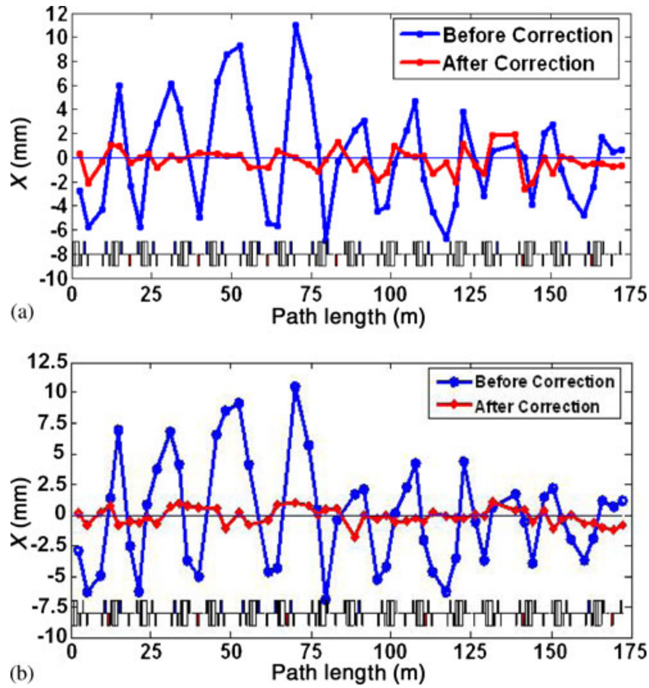

Figure 4. (**a**) Horizontal COD before and after correction at 550 MeV injection energy and (**b**) at 2 GeV.

0.5 mrad maximum strength of the corrector magnet which is much smaller than the limiting strength of 2 mrad. During correction, the horizontal betatron tune changes. In the next iteration, corresponding to this change in tune, the new model response matrix is generated and used for COD correction. The correction did not improve further (less than 1 mm rms). This may be due to the larger offsets in the BPMs or the contribution from the RF frequency which could not be corrected by the corrector magnets. It was observed that the COD data pattern is shifted towards the negative side of the dataset. It indicates the contribution of RF frequency in the total orbit data. Using eqs (12) and (13), the contribution of the RF frequency is calculated and it is found to be 5 kHz less with respect to the set RF frequency 505.811 MHz. After reducing RF frequency by 5 kHz and further correcting the remaining orbit, rms COD was reduced to ∼0.6 mm. In figure 4a, the COD before and after correction at 550 MeV is shown. Further correction is limited by the BPM offsets which will be obtained after performing the beam-based alignment [17–19]. The results for the orbit correction in the horizontal plane at 2 GeV is shown in figure 4b.

6.2 *Correction in the vertical plane*

Similarly, in the vertical plane model response matrix of size 53 × 40 is used for COD correction. Based on this response matrix, orbit correction is performed with 23 singular values and convergence is achieved iteratively. The measured betatron tune is found

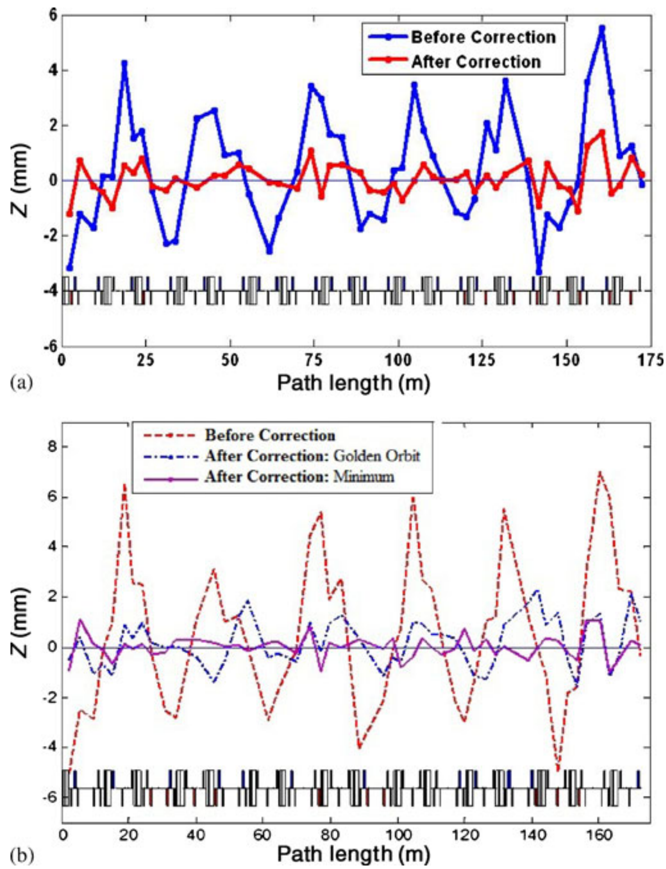

Figure 5. (**a**) Vertical COD before and after correction at 550 MeV. (**b**) Vertical COD before and after correction at 2 GeV. Dotted line shows the orbit before correction, dash–dotted line shows after correction for the beamline users (golden orbit) and solid line shows the minimum possible corrected orbit.

constant at different levels of orbit correction. In the iterations, same model response matrix is considered for correction. In figure 5a, the vertical uncorrected and corrected orbits in the last iteration at 550 MeV is shown. The corrector strengths are less than 0.8 mrad which are well below the saturation limit of the corrector strengths.

As discussed earlier, the vertical COD gets amplified at 2 GeV compared to COD at 550 MeV due to change in tune value from 6.17 at injection to 6.08 at 2 GeV. With the model response matrix for the tune 6.08, the correction was also performed. The vertical COD before and after correction at 2 GeV is shown in figure 5b. Here also, the corrector magnet strengths are below 1.2 mrad. The vertical COD has been reduced to 0.5 mm rms at both 550 MeV injection energy and at 2 GeV final energy. But what is more important is that the beamline users should obtain proper flux at right photon beam position in their respective beamlines. Presently, Indus-2 storage ring operates at 2 GeV in user mode. In the horizontal plane, the continuous fan of the synchrotron radiation is emitted and the orbit correction will not significantly change the condition in the beamlines. In the vertical plane, the radiation is emitted in a small cone which is decided by the energy of the electron beam. The direction of this emitted cone depends upon its position and angle in the electron orbit at the source point. It is crucial and important to satisfy all the beamline users simultaneously. A new orbit called golden orbit is optimized based on the feedback from the beamline users and beam position at BPMs around the source points. For this, the weighted SVD technique is used by optimizing proper weights to the BPMs and that provides the required corrected beam positions in the beamlines. Finally, at corrected rms vertical orbit of ∼0.8 mm, the photon beam is aligned in all the SR beamlines. This golden orbit with uncorrected orbit is shown in figure 5b.

It is vital to get a repeatable performance of the Indus-2 storage ring for the beamline users. The vertical position and angle at the 10-degree port of all the dipole chambers are calculated at the golden orbit. The angle is simply calculated based on the geometry, assuming 2.4 m separation between upstream and downstream BPMs at each dipole magnet. At a vertical tune of 6.08, SR users reported that the beam position is not repeatable in their beamlines from one filling of the beam to another in the machine. However, no noticeable change in betatron tune is observed. On comparing the COD data for fill-to-fill of the beam, a difference in orbit data of the order of 200 μm is observed because the machine is more prone to any variation as the tune is very close to integer value. When the tune was changed from 6.08 to 6.2, the machine became less sensitive and users obtained repeatable beam position and flux. Still there are variations in the beam positions due to perturbations coming from the flow of cooling water, temperature variations, P/S fluctuations, etc. It is important now to provide proper feedback to control the beam positions and the machine parameters so that no beamline users should get affected. In the near future, we are planning to implement global slow and fast orbit feedback in Indus-2 to stabilize the orbit movements.

The COD correction at injection energy has improved the injection efficiency by 50%. The lifetime at 2 GeV in user mode has improved from 10 h to 18 h at 100 mA stored beam current. The machine is being operated in user mode with corrected COD and lifetime will improve further with improvement in vacuum.

7. Conclusions

The closed orbit response matrix was measured and found to be in agreement with the model response matrix in Indus-2. The measured COD was analysed in both horizontal and vertical planes and effective quadrupole misalignments were calculated by fitting the COD data. The rms misalignment errors obtained were 100–150 μm, which are within the alignment accuracy. The COD correction was performed using model response matrix and golden orbit was set at which all SR users could obtain proper flux and photon beam position in their beamlines. The vertical tune was changed to a point where the lattice becomes less prone to any perturbation to ensure the orbit repeatability in day to day operation. With orbit correction, the injection efficiency was improved by 50% and the lifetime was increased by ∼8 h. For further reduction in the COD, the offset determination by beam-based alignment technique is required and being considered. For orbit stability, the global orbit feedback is being implemented.

Acknowledgements

Authors thank Gurnam Singh for fruitful discussions and suggestions and P D Gupta for his support and keen interest to complete this work. Authors also like to thank Indus accelerator complex shift crew members for their help during the experiments conducted in Indus-2 storage ring.

References

[1] G Singh *et al*, *Indian J. Appl. Phys.* **35**, 183 (1997)
[2] A D Ghodke *et al*, ICFA, *Beam Dynamics Newsletter*, **41**, 77 (2006)
[3] T A Puntambekar *et al*, *Asian Particle Accelerator Conference* (*APAC*) (Indore, India, 2007) p. 413
[4] B Autin and Y Marty, CERN ISR-MA/73-17, Geneva (1973)
[5] Y Chung, G Decker and K Evans, Jr., *Particle Accelerator Conference* (1993) p. 2263
[6] W H Press *et al*, *Numerical recipes in C* (Cambridge University Press, 1992)
[7] N Nakamura *et al*, *Nucl. Instrum. Methods* **A556**, 421 (2006)
[8] K Harada *et al*, *Nucl. Instrum. Methods* **A604**, 481 (2009)
[9] Anze Zupanc, Igor Kriznar and Mark Plesko, *International Workshop on Personal Computers and Particle Accelerator Controls* (Frascati, Italy, 2002), http://www.lnf.infn.it/conference/pcapac2002/TALK/TU-P13/TU-P13.pdf
[10] R K Agrawal *et al*, *International Conference on Accelerator and Large Experimental Physics Control Systems* (Geneva, 2005), http://accelconf.web.cern.ch/accelconf/ica05/proceedings/pdf/o3_014.pdf
[11] N Lulalni *et al*, *Indian Particle Accelerator Conference* (New Delhi, India, 2011)
[12] MATLAB, the Mathworks.com
[13] Hiroshi Nishimura and Tom Scarvie, *Particle Accelerator Conference* (Knoxville, Tennessee, USA, 2005) p. 3559
[14] A Terebilo, SLAC-PUB-8732 (2001), http://www-ssrl.slac.stanford.edu/at/
[15] R K Agrawal *et al*, *Asian Particle Accelerator Conference* (Indore, India, 2007) p. 443
[16] Riyasat Husain, A D Ghodke and Gurnam Singh, *Asian Particle Accelerator Conference*, (Indore, India, 2007) p. 351
[17] W J Corbett and V Ziemann, SLAC-PUB-6112 (1993)
[18] Igor Pinayev, *Nucl. Instrum. Methods* **A570**, 351 (2007)
[19] Saroj Jena, A D Ghodke and Gurnam Singh, *Asian Particle Accelerator Conference* (Indore, India, 2007)