Analysis and correction of linear optics errors, and operational improvements in the Indus-2 storage ring

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Abstract: Estimation and correction of the optics errors in an operational storage ring is always vital to achieve the design performance. To achieve this task, the most suitable and widely used technique, called linear optics from closed orbit (LOCO) is used in almost all storage ring based synchrotron radiation sources. In this technique, based on the response matrix fit, errors in the quadrupole strengths, beam position monitor (BPM) gains, orbit corrector calibration factors etc. can be obtained. For correction of the optics, suitable changes in the quadrupole strengths can be applied through the driving currents of the quadrupole power supplies to achieve the desired optics. The LOCO code has been used at the Indus-2 storage ring for the first time. The estimation of linear beam optics errors and their correction to minimize the distortion of linear beam dynamical parameters by using the installed number of quadrupole power supplies is discussed. After the optics correction, the performance of the storage ring is improved in terms of better beam injection/accumulation, reduced beam loss during energy ramping, and improvement in beam lifetime. It is also useful in controlling the leakage in the orbit bump required for machine studies or for commissioning of new beamlines.

Keywords: LOCO code, beta-beat, betatron coupling, beam lifetime, Indus-2 storage ring

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1 Introduction

During the course of designing any storage ring based synchrotron radiation source, various parameters of the ring such as operating tunes, chromaticities, natural beam emittance, dynamic aperture (DA) etc. are optimized. An important design criterion is to achieve lower beam emittance to provide higher brightness for the users. Low emittance can be achieved by strongly focussing the beam with high field quadrupole magnets. As a result, a large negative chromaticity is generated, and, for its correction, strong field sextupole magnets are used. In the presence of sextupole magnets, the beam dynamics become nonlinear. This nonlinear behavior can lead to smaller DA. In general, the sextupole magnets in the lattice are placed at locations where the beta and dispersion functions are separated enough. This helps in minimizing the required strengths for the chromaticity correction. As far as possible, they should also be separated by a phase advance of $(n+1/2)\pi$, where n is an integer, for self-cancellation of the inevitably generated geometrical and chromatic aberrations. An important feature of the magnet lattice of storage rings is the high degree of periodicity. The periodicity can be addressed in terms of the distribution of lattice functions like beta function and dispersion function. However, in real operation, the periodicity is perturbed to some extent, almost in every storage ring, mainly due to quadrupole field errors. The main sources of quadrupole field errors are manufacturing errors and calibration errors of the power supplies driving the quadrupoles, and the orbit offsets in the sextupoles. As a result, the perturbation in the lattice functions, and most importantly the deviation in the phase relationship between the sextupole locations, lead to the non-cancellation of the geometrical and chromatic aberration of the sextupoles, and hence many nonlinear resonances are excited [1]. This has a non-vanishing adverse effect on the machine performance like the shrinkage of the DA, which leads to reduction in beam lifetime and injection efficiency. The beam optical parameters, like betatron tunes, corrected chromaticities, beam emittance etc., can also deviate from the optimized values. The broken periodicity is related to the deviation of the beta and dispersion functions from the design values. Thus, to identify the sources of the periodicity breaking and its beam dynamical effects on the storage ring

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performance, a good beam dynamical modelling of the storage ring is crucial. To restore the design periodicity and thereby improve the nonlinear behavior of the storage ring in operation, the measurement and correction of the lattice functions is essential.

For the measurement of linear lattice functions, particularly the beta function in a storage ring, there are various methods like quadrupole scan [2, 3], analysis of turn by turn BPM data [4] and linear optics from closed orbit (LOCO) [5–8]. The quadrupole scan method is the simplest and standard technique to measure beta function at the location of the quadrupole magnets. The change in betatron tune due to the variation of quadrupole strength is measured using a tune measurement system and then fitting is carried out to calculate the beta function. Though this method is simple, there are associated drawbacks like: (1) only average beta function over the quadrupoles can be measured, if the group of quadrupoles are driven by a single power supply, which is the case for the Indus-2 storage ring [9]; (2) it works in the linear field region of the quadrupole magnets, i.e. quadrupole magnetic field vs current transfer functions should be linear; (3) the drifts in tune due to hysteresis effects are to be restored to the nominal values after every measurement; and (4) it is time consuming.

The most advanced and fastest technique to measure the lattice functions is based on the analysis of the turn by turn (TBT) beam position data. Advanced storage ring facilities are equipped or being upgraded with TBT beam position measurement systems. In this technique, the TBT beam position data is gathered at the location of the BPMs for a few thousand turns, after exciting the betatron oscillations in the beam by a single shot pulsed dipole kicker. In addition, the TBT measurement is also very useful in understanding the nonlinear optics of the machine [10, 11]. In Indus-2, the present analog BPM electronics is being upgraded to advanced digital electronics to provide TBT beam position data in the near future.

Another very useful technique to measure the lattice functions is based on fitting of the measured closed orbit response matrix (ORM) [2, 5]. The ORM is a large set of data comprising the closed orbit changes measured at BPMs due to the change in the kick strength of the orbit correctors. These measurements are very helpful in modelling of the storage ring lattice or debugging the linear optics errors including the quadrupole field errors, which are the main contributors to the deviation in measured and model ORMs. Another key advantage of this method is that the calibration errors of the BPMs and the correctors, together with their tilts, and rotation errors of the quadrupole magnets can also be revealed.

In ORM modelling, the difference between the measured ORM data and the ORM derived from a theoretical model of the storage ring is minimized. The lattice of the operating storage ring can be reconstructed from the ORM data, and the magnet and diagnostic errors are corrected after comparing with the optimized values. Betatron coupling correction can be made by analyzing the off-diagonal components of the ORM by fitting the skew quadrupole strength in the ring. A computer code, LOCO in MATLAB [7] has been used to analyze the measured ORM and to control the linear lattice functions. The LOCO analysis is very robust and it provides full understanding of the lattice of the operational machine in a single measurement. Nevertheless, it is time consuming as the ORM measurement takes a few tens of minutes. The LOCO technique has been employed in several light sources worldwide, such as SLS [8], APS [12], SOLEIL [13], SSRF [14], ALBA [15], and NSLS2 [16], to name a few. The LOCO code has also been applied to calibrate the linear optics of the transport line [17] and correction of the optics at other accelerators like the COSY cooler synchrotron [18] and the Fermilab booster [19].

We have applied the LOCO technique at the Indus-2 storage ring for the following two purposes: (1) to generate the machine model or debug linear optics errors like quadrupole field errors, calibrate the BPMs and correctors, find out the rotation errors of the quadrupole magnets etc., and (2) apply correction through changes in quadrupole power supply currents to restore the design lattice functions and hence the periodicity. Based on the analysis of the measured ORM, the linear optics errors, which are responsible for the excitation of the nonlinear resonances in the storage ring, are identified. The correction of the linear optics errors will result in global improvements of the nonlinear dynamics of the storage ring. Simulation studies are carried out, through particle tracking and frequency map analysis, to understand the effects of periodicity breaking on the nonlinear beam dynamics of the lattice. The periodicity breaking results in reduction of the DA, which in turn leads to reduction in the beam lifetime and poor injection efficiency. For periodicity restoration, the corrections in the operating machine are applied by changing the power supply currents driving the quadrupole magnets. As a result, an improvement in the injection efficiency of $\sim 20\%$, and enhancement in the beam lifetime of ~ 2 hrs are observed.

The paper is organised as follows. In Section 2, the Indus-2 storage ring is briefly described together with the design parameters and details of diagnostics and magnet system relevant to this study. A brief introduction to the LOCO code is given in Section 3, and the measurement of the ORM is described in Section 4. In Section 5, the analysis of the measured ORM is presented. Here, the fitted results for calibration factors of the BPMs and correctors, and the deviations in the quadrupole magnetic fields, responsible for the periodicity breaking, are described in detail. A simulation study based on the particle tracking and frequency map analysis is also performed to understand the beam dynamics with perturbed periodicity. In Section 6, the correction of the lattice functions to restore the design periodicity and resulting improvements in the operational performance of the Indus-2 machine are discussed. Finally, in Section 7, conclusions and future prospects are given.

2 Description of the Indus-2 storage ring

Indus-2 [20, 21], a 2.5 GeV electron storage ring for generating synchrotron radiation, is located at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India. It is operated in the energy range from 0.55 GeV at injection to 2.5 GeV for user operation. There are eight super-periods in Indus-2. Figure 1 shows one super-period of the storage ring. Some of the relevant design and measured parameters are summarized in Table 1. Each super-period is composed of 2 main dipole magnets and 9 quadrupole magnets, divided into five families: Q1D, Q2F, Q3D, Q4F, and Q5D, for optics tuning. Many of the quadrupoles are powered in series. For the total number of 72 quadrupole magnets, there are 26 independent quadrupole-power supplies distributed around the ring. These 26 power supplies are the available knobs for the restoration of the perturbed beta functions, dispersion function and betatron tunes. Four sextupole magnets in a super-period are used for chromaticity correction and are grouped in two families: SF and SD. In Indus-2, a double view BPM system is used to measure the closed orbit distortion (COD) at 56 locations distributed all around the circumference. For COD correction, 48 horizontal and 40 vertical corrector magnets are installed. In addition, there are 4 skew windings on the sextupole magnets for the correction of spurious vertical dispersion and linear betatron coupling.

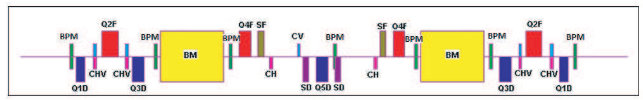

Fig. 1. (color online) One DBA cell of the Indus-2 ring. The yellow rectangles are the bending magnets; blue and red rectangles are the quadrupole magnets; SF & SD are the sextupole magnets; CH, CV & CHV are the independent horizontal, independent vertical and combined horizontal and vertical correctors; BPMs are the beam position monitors.

Table 1. List of important parameters of the Indus-2 storage ring.

parameter	design	measured value	
		before LOCO correction	after LOCO correction
beam energy: injection	0.55 GeV		
operating	2.5 GeV		
circumference	172.47 m		
lattice type	DBA		
No. of super-periods	8		
harmonic number	291		
betatron tune(H/V)	9.28/6.21	9.265/6.185	9.2801/6.208
corrected Chromaticity @ 2.5 GeV	1, 1	0.78/1.1	0.9/1.05
RMS beta beat (H/V)(%)	–	9/6	<1.0/0.5
RMS vertical dispersion	–	∼23 mm	∼20 mm
beam emittance	135 nm.rad	143 nm.rad	135.5 nm.rad
linear coupling(%)	–	∼0.23	∼0.2

Indus-2 is currently operating at 2.5 GeV with stored beam current up to 200 mA and providing synchrotron light to 14 beamlines. Recently, three undulators have been installed in the ring, and commissioned. The design and construction of the associated beamlines are underway.

3 LOCO code

The LOCO algorithm is described elsewhere [5, 7] in detail. A brief introduction of the LOCO algorithm is given here.

The ORM is defined as:

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = R \begin{bmatrix} \Delta\theta_x \\ \Delta\theta_y \end{bmatrix}, \tag{1}$$

where $\Delta\theta_x$ and $\Delta\theta_y$ are the changes in strengths of horizontal and vertical orbit correctors, respectively, and $\Delta x$and Δy are orbit perturbations at the BPMs. R is an $M\times N$ matrix, where M is the number of BPMs, and N is the number of horizontal and vertical orbit correctors.

The elements of the ORM are given by

$$R_{ij}=\frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu}\cos(|\varphi_i-\varphi_j|-\pi\nu)+\frac{\eta_i\eta_j}{\alpha_c L_0};\quad \text{in the horizontal plane} \tag{2a}$$

$$R_{ij}=\frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu}\cos(|\varphi_i-\varphi_j|-\pi\nu);\quad \text{in the vertical plane} \tag{2b}$$

where (β_i, β_j), (ϕ_i, ϕ_j) and (η_i, η_j) are the beta functions, betatron phase advances and the dispersion functions at the location of the $i^{\rm th}$ BPM and $j^{\rm th}$ corrector magnet; α_c, ν and L_0 are the momentum compaction factor, the betatron tune and the circumference of the ring, respectively.

In the optimized magnetic lattice, in which the locations and strengths of the magnetic elements are fixed, the lattice functions are uniquely defined. The β function is related to the normalised strength, K, of the quadrupole magnet by the following nonlinear differential equation:

$$\frac{1}{2}\beta(s)\beta''(s)-\frac{1}{4}\beta'(s)+K(s)\beta^2(s)=1. \tag{3}$$

As described by Eq. (2), the elements of the ORM only depend on the β functions and betatron phases at the BPMs and at the correctors, and the β function is connected through Eq. (3) with the quadrupole strengths. Thus, the elements of the ORM are related to the strengths of the quadrupole magnet. Based on this analogy, one can obtain the quadrupole gradients, though unevenly as a large number of parameters are to be fitted, to get a close representation of machine lattice. The LOCO analysis calculates the quadrupole gradients if the ORM is known. It is expected that the model and the measured ORM will be the same. If there is a disagreement, one can iteratively minimize the difference by changing the model parameters, mainly the quadrupole gradients. In addition to the quadrupole gradients, other parameters, including tilt errors of the magnets, longitudinal positions of the BPMs and correctors, BPM gains and couplings, etc., are also used to minimize the difference. The modelling is carried out using the method of least squares fitting to minimize the difference between the model ORM and the measured ORM data. This difference is characterized by a merit function χ^2, defined by Eq. (4), given below. By iteratively tuning the parameters of the model, a stable point is reached and the merit function attains its minimum value. At this juncture, the generated model is very close to the operational accelerator optics.

Merit function χ^2, which is to be minimized in LOCO code, is implemented as follows [5]:

$$\chi^2(p)=\sum_{i,j}\frac{(R_{\,\rm mod\,,\it ij}(p)-R_{{\rm meas},ij})^2}{\sigma_i^2}\equiv\sum_{ij}V_{ij}(p), \tag{4}$$

where σ_i is the measured noise level for the $i^{\rm th}$ BPM, and $V_{ij}(p)$is the function of the parameters, p_1,p_2,p_3 $\cdots$, varied in the model lattice. The accelerator modelling code Accelerator Toolbox (AT) [22] is used to calculate the model ORM, $R_{\rm mod}$.

4 The ORM measurement

For LOCO, the input parameters are the measured ORM, measured noise of the BPMs and the dispersive orbit. Before embarking on the measurement of the ORM, the COD was corrected to the minimum possible residual, which minimizes the feed down effects of the nonlinear magnetic elements such as strong chromaticity correcting sextupoles. This was carried out after integrating the BPM offsets obtained by applying the beam based alignment (BBA) technique into the BPM data base [23]. The RMS COD was corrected to a level of $\sim$300 μm in the horizontal plane and better than 200 μm in the vertical plane. However, for providing the photon beam to the beamlines, minor local adjustments in the electron beam path were performed, vertically, at the source points. This resulted in an increase in the vertical RMS orbit to $\sim$300 μm.

In actual measurement of the ORM, choosing a proper kick size is important to get measurable orbit response and at the same time, minimizing the nonlinearity due to sextupoles and magnetic multipoles is also important. For ORM measurement, kicks to the beam were such that the maximum change in the closed orbit was ~0.4 mm due to the chosen kick of 40 μrad when orbit corrector currents were changed by 0.25 A at 2.5 GeV. As discussed further in the next section, this kick size was chosen as it is large enough to give a significant change in the orbit to be detected by the BPMs, but not large enough to bring the beam into the nonlinear measurement region of the BPMs. The BPMs are known to have a beam current dependence with time. The ORM was therefore only noted for beam current within a range of 18–20 mA.

The ORM measurement was performed using software developed in LabVIEW. The total measurement time of the full ORM was $\sim$100 min. The RMS measured noise of the BPMs for 300 samples of the COD was less than 4 μm in both planes. To minimise the contribution of the BPM noise in the ORM measurement, the averaging of the change in orbit at all the BPMs was performed for 20 samples at each setting of the corrector kick. In order to take care of the slow orbit drift, a new orbit reference was made after measurement of the response of each corrector magnet. This is called the sliding orbit reference ORM measurement. This type of measurement has resulted in better fitting of the parameters. The dispersive orbit can be measured by changing the momentum of the charged particle and noting down the changes in the orbit at all BPMs. The change in RF frequency has the same effect as a change in momentum. For the dispersive orbit measurement, the RF generator frequency was changed by ±1 kHz.

5 Analysis of the measured ORM

The list of parameters which are varied in a LOCO fit are given in Table 2. Figure 2 shows the measured ORM and the difference between the model and the meassured ORMs at the 3rd iteration of the LOCO fit [24]. Initially, in the first LOCO analysis of the measured ORM, a large contribution of the systematic errors to the fit parameters were observed, and the solution converges to a higher χ^2-value. It is necessary to minimize the contribution of the systematic errors to get reasonable values of the fit parameters. Typical sources of systematic errors are the magnet model, with unknown multipole field effects, errors in the longitudinal positions of BPMs and corrector magnets, and nonlinearities in the BPMs. To understand the effect of systematic errors in the fit model, the number of measured ORMs with increasing kick strength of the corrector magnets was analysed. It was observed that selecting smaller strength of the corrector for ORM measurements is required to minimize the systematic error to the fit parameters. The corrector kick should however be large enough to generate the position shifts more than the BPM noise level. However, it was still difficult to get a smaller χ^2-value. It was doubtful that the longitudinal position errors of the correctors and BPMs, which are not included as LOCO fit parameters, could be the sources of such a result. Physical inspection of the longitudinal positions of the correctors and BPMs in the ring tunnel was done. It was found that the positioning of the eight BPMs in the arc section of the ring tunnel was different than the position in the model lattice file. The BPM at the centre of the arc was installed after family Q5D of the quadrupoles, while in the model lattice file it was wrongly placed before the Q5D quadrupole. This amounts to ~ 1 m longitudinal position error. The elements of the model and measured ORMs at these BPMs sampled different changes in positions for the same change in corrector strengths. In the LOCO fitting, these are responsible for the large χ^2-value. After placing the BPMs in the model lattice file as per the BPM location in the ring tunnel, the LOCO fitting converges to a smaller χ^2-value. In the following subsections, we discuss the results of the analysed ORM using the LOCO code in the Indus-2 storage ring after minimizing the systematic errors.

Table 2. List of parameters varied in LOCO to generate the real machine model.

BPMs	horizontal	gain	56
		roll	56
	vertical	gain	56
		roll	56
corrector magnets	horizontal	gain	48
		roll	48
	vertical	gain	40
		roll	40
quadrupole magnets		gradient	72
		roll	72
bending magnet		gradient	16
		roll	16
quadrupole compoent in sextupole magnets		normal	32
		skew	32
total parameters			640

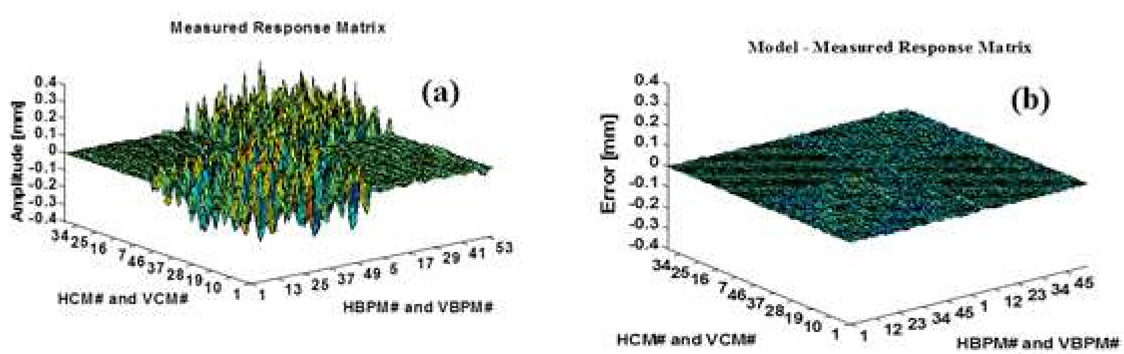

Fig. 2. (color online) (a) Measured response matrix at 2.5 GeV, and (b) the difference between model and measured response matrices at 3rd iteration of LOCO fit to the parameters. The HCM#, VCM#, HBPM# and VBPM# represent the number of the horizontal correctors, vertical correctors, horizontal BPMs and vertical BPMs. The amplitude is the numerical value of each element of the measured response matrix for the applied kick of 40 μrad in the corrector magnet.

5.1 BPM gains and coupling

The sources responsible for the linear optics errors are the quadrupole gradient errors and the orbit offsets in the sextupoles, which can be varied as independent variables in the LOCO fit. The BPM gains and couplings directly affect the measured ORM. The BPM gains and their cross couplings are included as fit variables. The fit results are shown in Fig. 3. The fitted BPM gains are in the range of 0.4–1.2. In Indus-2, the processing electronics of the BPMs are divided into two catagories, namely analog and Libera digital electronics. The gain factors are less than one mainly in the BPMs connected with analog electronics. The measurement of the gain of BPMs connected with digital electronics was carried out at the calibration stage in laboratory. It was found that their gain factors are very close to one. The fitted coupling are within 2% in the horizontal and 6% in the vertical plane. BPM number 19, which was excluded after the first LOCO analysis, shows a coupling of more than 15%. One of the electrodes of this BPM was faulty, and to get the orbit measurement a three electrode based beam position calculation algorithm was implemented. The detected high value of the coupling may be due to the algorithm used. Thus, the LOCO analysis of the measured ORM serves as a diagnostic tool for identifying abnormalities in the BPM system.

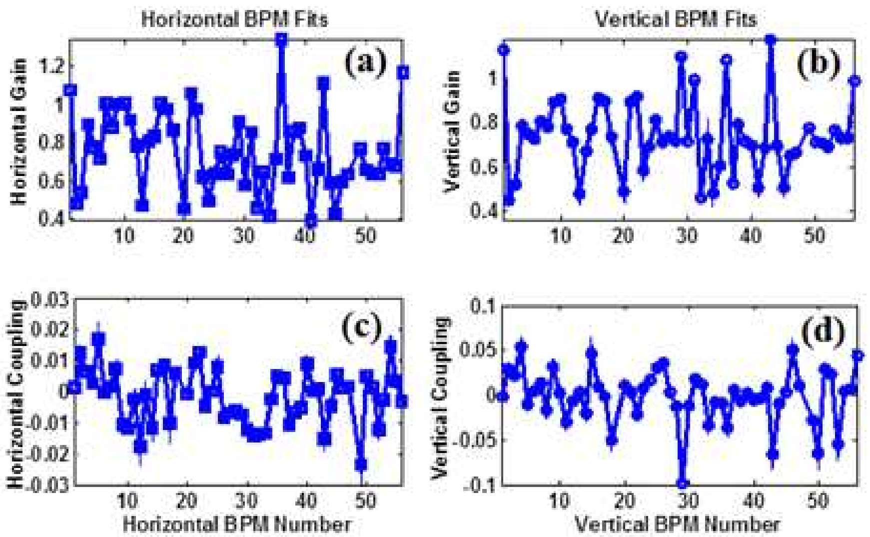

Fig. 3. (a) and (b) the fitted values of gain factors; and (c) and (d) the fitted values of the coupling factors of the BPMs in the horizontal and vertical planes at 2.5 GeV.

5.2 Corrector magnet calibration and coupling

The results of the LOCO fit for the corrector magnet calibration and coupling are shown in Fig. 4. In the horizontal plane, the corrector magnet calibration factors are mostly close to the expected values of 40 μrad at 2.5 GeV for a change in current of 0.25 A, but corrector number 20 shows only half of the calibration factor. After an investigation and survey of the ring tunnel, an M8 brass bolt, which connects the power supply cable to the corrector magnet coil, was found to be broken. Due to this, half of the winding of this corrector magnet was shorted. In the case of the vertical correctors, unexpected results were obtained. There are 40 vertical correctors, out of which 32 are combined function and 8 are independent. The vertical corrector magnets in the long straight sections show strengths as per their step change in current of 0.25 A (corresponding to 40 μrad at 2.5 GeV), but 8 correctors in the arc section show kick strengths ∼10% higher (∼45 μrad). Vertical corrector magnet number 36 also shows a fit strength (∼35 μrad) less than the calibrated value. The fitted corrector magnet couplings are different and the coupling is mainly observed in the combined function magnets (total 32 in number). Based on these fitted results, re-calibration of the corrector magnets was performed. Re-calibration of the corrector magnets and the BPMs helped immensely in achieving better orbit stability by slow orbit feedback.

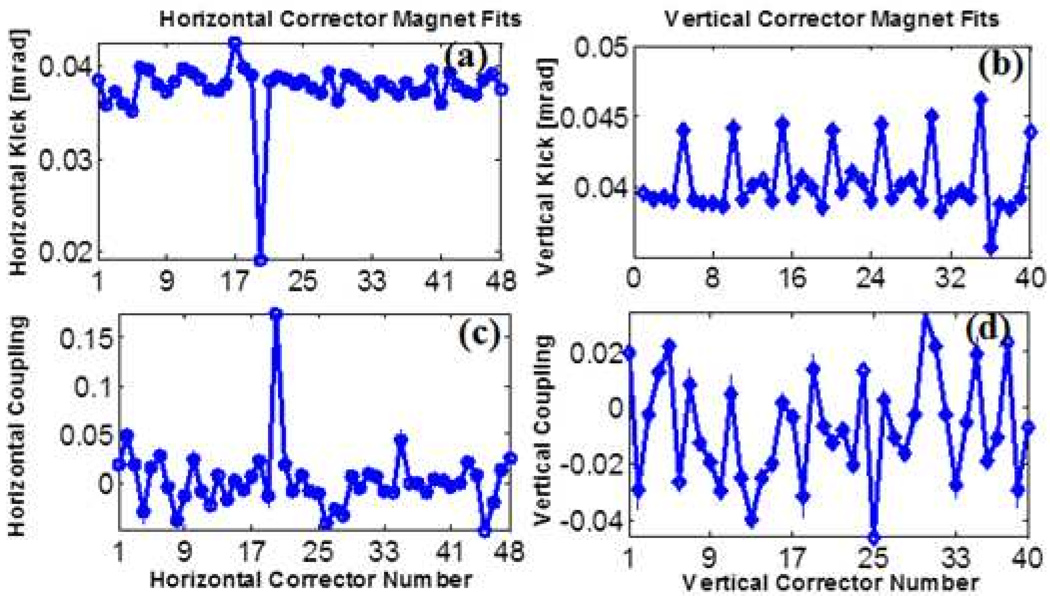

Fig. 4. (a) and (b) the calibration factors; and (c) and (d) the coupling factors of the horizontal and vertical corrector magnets at 2.5 GeV.

5.3 Gradient and roll errors of the magnetic elements

The ORM elements are proportional to the square root of betatron amplitude functions at the BPM and at the corrector locations (see Eq. (2)). The β-function depends on the distribution of quadrupoles and their gradients in the ring (see Eq. (3)). This makes it possible to analyse the gradient errors from the measured ORM data. In the LOCO fit for the real machine model, we varied the parameters tabulated in Table 2 and the fit results are shown in Fig. 5. The inset picture shows the quadrupolar components in bending magnets and sextupole magnets, the roll errors in the quadrupole and bending magnets and the skew quadrupole components in the sextupole magnets. The nominal normalized gradients and LOCO fitted range of normalized gradients of the individual quadrupoles for the five families are given in Table 3. The calculated values of maximum relative gradient deviations in each family are also given. The deviations in the gradients of the Q1D and Q3D families of quadrupoles are large, up to 3.5%. This may be due to non-availability of the BPM between them, which ultimately resulted into cross fight between the gradients. The bending magnets in the Indus-2 storage rings are parallel edge magnets without quadrupole gradient. The fitted gradient in the bending magnets may be due to manufacturing errors of the entrance and exit edges. We have also considered the quadrupole components in the sextupole magnets, which show the fitted quadrupole strengths in sextupoles larger than the bending magnets. However, the integrated quadrupole strengths are more for bending magnets than sextupoles, as the length of the bending magnet is longer. One important aspect of the fitted gradients of the quadrupoles is that the deviation in the model betatron tune is explained by the changes in the gradients. According to the operating lattice and for the set currents in the quadrupoles, the betatron tune is expected to be [9.28, 6.21]. However, the measured betatron tune in the operating machine is [9.265, 6.185]. After fitting, the measured betatron tune matches very closely to the calculated value of the betatron tune [9.267, 6.184] from the LOCO fit model based on the analysis of the measured ORM.

The offdiagonal elements of the measured ORM, which are generated due to coupling of the betatron motion, are fitted with the roll errors in the quadrupoles, bending magnets and the skew quadrupolar components in the sextupole magnets. The equivalent model of the Indus-2 machine was obtained. The measured linear betatron coupling of ~0.23 % (see Section 6.2) was found to be very close to the calculated value of 0.25% from the LOCO fit model in AT.

As discussed earlier, the linear optics errors lead to periodicity breaking. Periodicity breaking severely affects the nonlinear dynamics of the storage ring. Many higher order resonances become excited and hence DA is also reduced. The reduced DA directly affects the beam lifetime and injection efficiency. In order to understand the resonance excitation and hence the effect on DA due

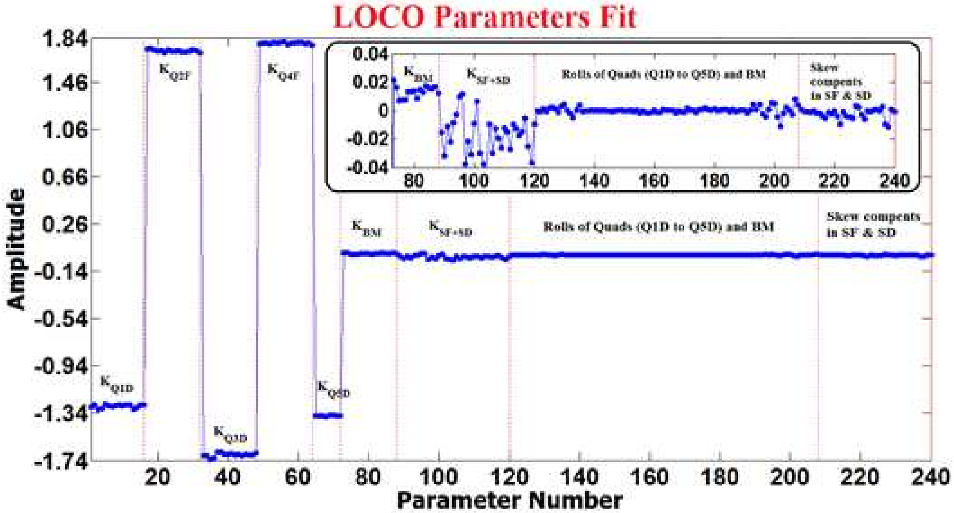

Fig. 5. Fitting results of the parameters in LOCO analysis of the measured ORM to generate the model of the operating storage ring lattice. The parameters varied are quadrupole magnet strengths (72); quadrupole components in the bending magnet (16) and sextupole magnets (32); roll errors in the quadrupole magnets (72) and bending magnets (16); and skew components in the sextupole magnets (32). The units of the gradients and rolls are m^{-2} and radian, respectively.

Table 3. Nominal normalized gradients, range of LOCO fitted normalized gradients and maximum relative change in gradients for the individual quadrupoles in the five families in Indus-2.

	quadrupole families				
	Q1D	Q2F	Q3D	Q4F	Q5D
model K/m^{-2}	−1.2579	1.7204	−1.6769	1.7884	−1.3608
LOCO fit range K/m^{-2}	−1.3050 −1.2617	1.7152 1.7451	−1.7304 −1.6681	1.7763 1.8057	−1.3672 −1.3579
absolute Max. $\Delta K/K(\%)$	3.5	1.4	3.1	0.9	0.5

K: normalised quadrupole gradient; +(−) sign for focussing (defocussing) quadrupole.

to periodicity breaking in the real machine, we have performed simulation studies. In simulation, we have performed single particle tracking, and compared the performance in terms of the DA in the ideal storage ring lattice, a realistic lattice obtained after the LOCO fitting, and a lattice with linear optics corrected using the 26 available quadrupole power supplies (see Section 6). The chromaticity correcting sextupoles are assumed to be ON for the corrected chromaticity [1, 1]. Based on single particle tracking for 1024 turns, the DA was estimated and frequency map analysis (FMA) [25] was performed. The results are shown in Fig. 6. The DA is well above the physical aperture (30 mm × 17 mm) of the storage ring for the case of ideal lattice and is reduced to ∼20 mm × 15 mm for the LOCO fit model of the operational lattice. After optics correction using 26 quadrupole power supplies, the DA is almost recovered. A vertical aperture has been measured in Indus-2 using a beam scraper installed in one of the long straight sections, and found to be well above 8 mm.

To understand the beam dynamics at an injection energy of 0.55 GeV, measurement and analysis of the ORM was performed and an equivalent storage ring lattice model was generated. The reduced DA has important implications for the beam accumulation rate in Indus-2, in which an off-axis beam injection scheme is adopted. The particle motion in horizontal phase space for the ideal lattice and the model obtained with LOCO fit of the measured ORM were analysed. The tracking of 10 particles, with amplitude from 3 mm to 30 mm in steps of 3 mm, was performed for 10000 turns and the results are shown in Fig. 7. It was found that the contribution in DA reduction in the horizontal plane is due to the amplitude-dependent tune shift and the effect of the fourth order resonance: $4\nu_x = 37$. In the ideal lattice, no resonance excitation up to maximum amplitude could be seen, while a fourth-order resonance-island is clearly visible in the LOCO fit model of the real machine at horizontal amplitude of ∼20 mm. This may hamper the beam accumulation rate. At 2.5 GeV, as the COD is well corrected and oscillations are damped, this resonance will not affect the beam. Thus, using the errors found in the lattice model, numerical simulations indicate that a 4^{th} order resonance will be excited, which may be responsible for the DA reduction observed in the real machine.

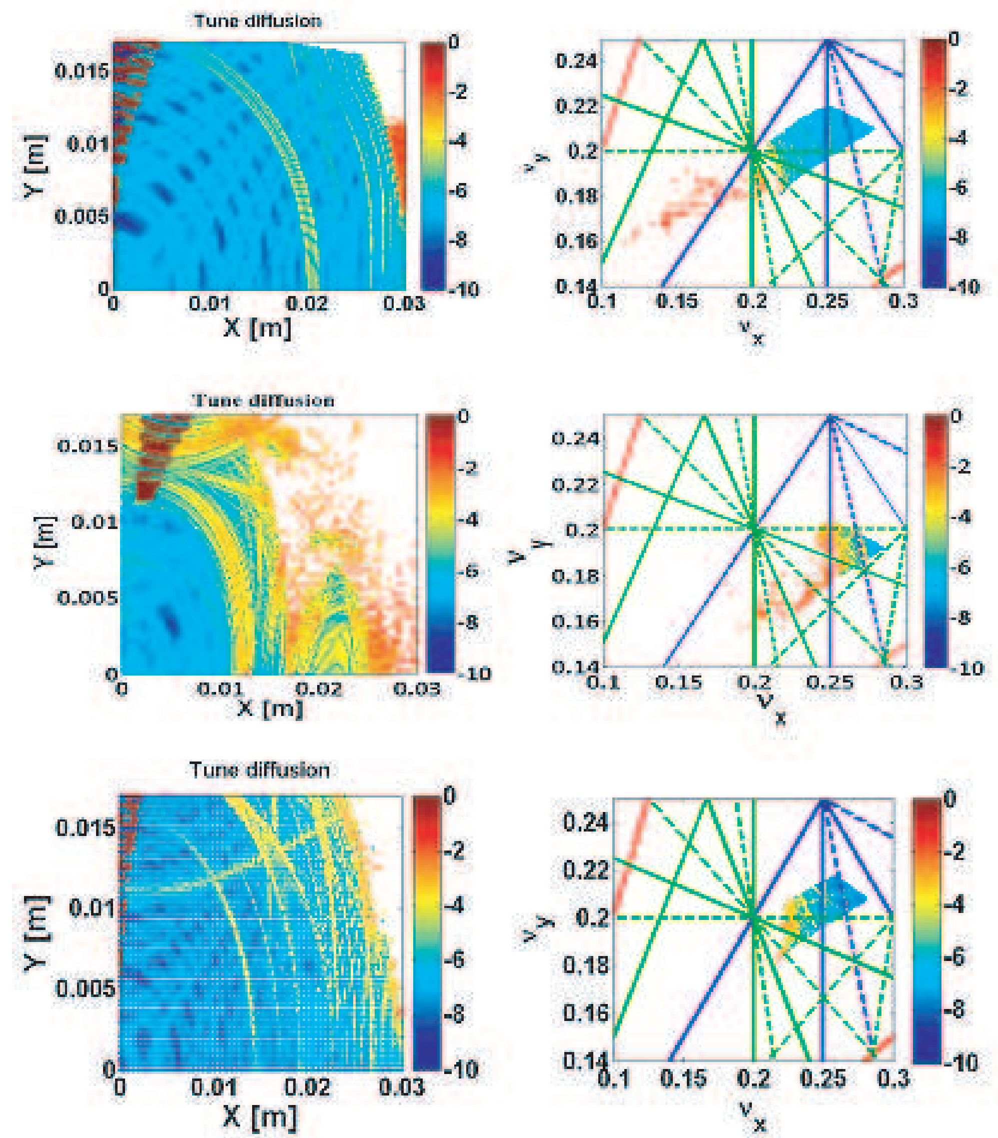

Fig. 6. (color online) The calculated frequency maps of the ideal lattice (top), lattice with LOCO fit to the operating storage machine (middle), and lattice with linear optics corrected (bottom).

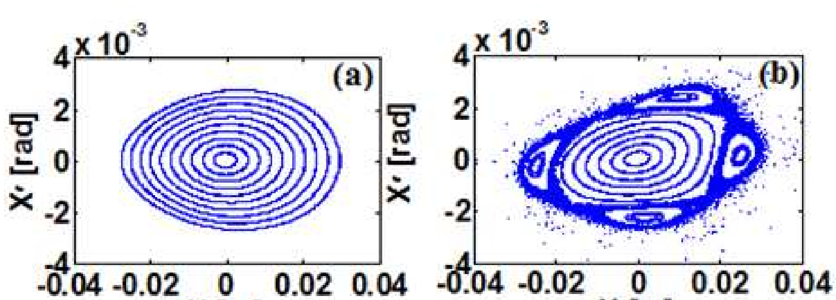

Fig. 7. (a) Particle motion in horizontal phase space in the ideal lattice, and (b) with model obtained with LOCO fit of the measured ORM, for tracking of ten particles for 10,000 turns with initial horizontal offset positions from 3-30 mm in steps of 3 mm. The sextupoles are on at corrected chromaticity of [1, 1].

6 Optics correction

6.1 Beta beat and dispersion function correction

Correction of the lattice function to restore the design periodicity is required to assure beam stability and efficient operation of any storage ring. For optics correction, the LOCO fit parameters are configured differently. The fit parameters are the 26 quadrupole power supplies for beta and dispersion function correction, and 4 skew quadrupole power supplies for coupling correction. To implement the correction in the storage ring, the current in the m^{th} quadrupole power supply is changed such that

$$\frac{\Delta I_m}{I_m}=-\frac{K_{\text{fit},m}-K_{\text{ideal},m}}{K_{\text{ideal},m}}, \tag{5}$$

where K_{fit} and K_{ideal} are the fitted and model values of the normalised strengths of the quadrupoles.

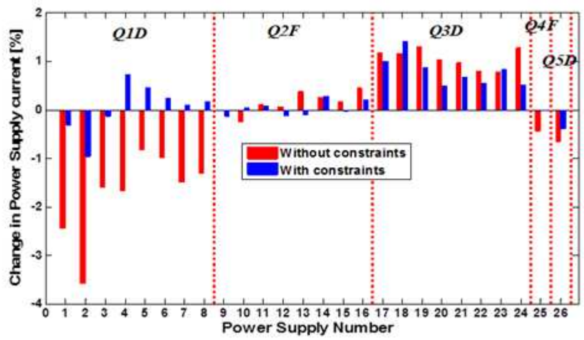

Fig. 8. (color online) Relative change in currents of 26 quadrupole power supplies to correct the beta-beat and restore the dispersion function. The two types of bars show the change in currents with (blue) and without (red) constraints on the quadrupole strengths.

A LOCO fit to 26 quadrupole power supplies driving 72 quadrupole magnets was performed to find out the correction factors. The required changes in the excitation currents (strengths) were obtained using Eq. (5), and are shown in Fig. 8. These values were applied back to correct the pre-set strengths of the quadrupoles, and periodicity of the linear optics is restored. The restored horizontal and vertical beta functions are shown in Fig. 9, and the dispersion function in Fig. 10. The beta function beating is defined as the relative difference between the measured and designed beta functions. The calculated beta-beat from the model generated by LOCO fit of the measured ORM by quadrupole power supplies are ∼ 9% and ∼6% RMS in the horizontal and vertical planes, respectively. After applying the correction, the ORM was re-measured and analysed. It was found that the beta beat went down to ∼1.0% and ∼0.5% in the horizontal and vertical planes, respectively. Figure 11 shows the measured betatron tunes before and after correction of the linear optics. The betatron tunes are restored to very near to the theoretical set values. Therefore, the linear optics of the storage ring is successfully restored and the beta functions are close to the design values and the design periodicity.

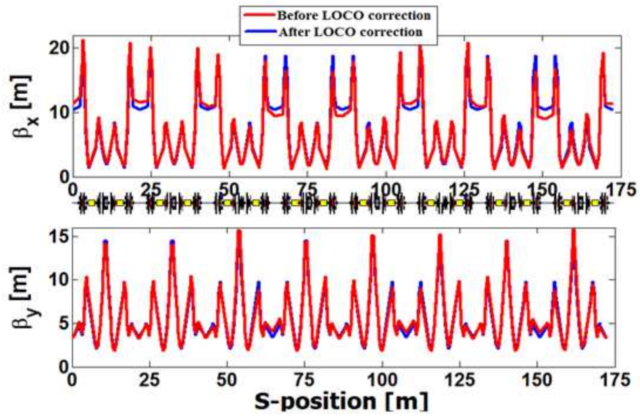

Fig. 9. (color online) Beta function in horizontal (top) and vertical (bottom) planes before and after LOCO correction with 26 quadrupole power supplies. After correction, the beta functions are very close to the design values.

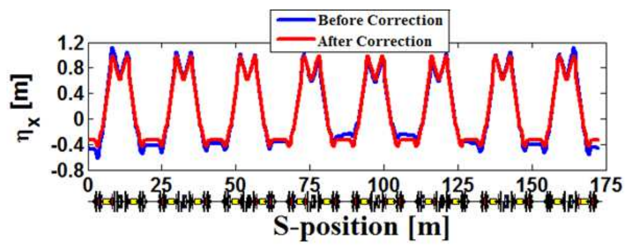

Fig. 10. (color online) Horizontal dispersion function before and after LOCO correction with 26 quadrupole power supplies. The corrected dispersion function is very close to the design value.

As shown in Fig. 8, the deviations in the fitted quadrupole strengths are large, up to 3.5% in the Q1D family of the power supplies compared to the deviations observed in other quadrupole power supplies. Another observation is that the Q1D and Q3D families show opposite behaviour in the change in driving currents for correction. As discussed earlier, this may be due to cross fight amongst the fitted values of strengths of these power supplies, as there is no BPM in between them. It means that in the region where BPMs between the quadrupole magnets are not available, quadrupole strengths have more freedom to vary and balance each other and still achieve the same magnitude of χ^2. In order to tackle this problem, we put constraints on the strengths by optimizing the weight factors of the Q1D, Q2F and Q3D families of the quadrupole power supplies. For the same level of beta beat correction, large reduction in strengths of the quadrupoles was observed. The required correction in the quadrupole strengths was reduced remarkably, from 3.5% to better than 1.5%, as shown in Fig. 8. However, the correction strengths of earlier obtained values, i.e. up to 3.5%, were also applied in the real machine successfully, without beam loss.

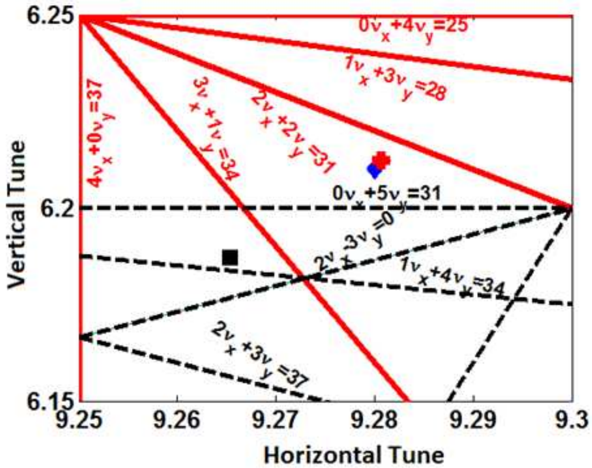

Fig. 11. (color online) Tune diagram up to the 5th order resonances. At 2.5 GeV, the theoretical betatron tune is shown by a plus symbol, and the square and the diamond symbols show the measured betatron tunes before and after optics correction, respectively, using 26 quadrupole power supplies. The corrected betatron tune matches very closely to the theoretical model value.

6.2 Coupling correction

The contributions to the vertical beam size are due to betatron coupling and spurious vertical dispersion. The sources of the betatron coupling are quadrupole rotation errors and vertical orbit in sextupoles in the dispersive region. Vertical dispersion is produced by vertical bend error from bending rotation errors, vertical closed orbit errors in the quadrupoles and dispersion coupling due to skew quadrupole errors in the dispersive region. The separate coils generating skew quadrupole components are integrated on the chromaticity correcting sextupole magnets and are designed for the coupling and vertical dispersion correction. In regular operation of Indus-2, the skew quadrupole power supplies are kept off. In addition to the 26 quadrupole power supplies, 4 skew quadrupole power supplies are included to correct the coupling. The off-diagonal elements of the ORM are included in the LOCO fitting to find the required correction strengths of the skew quadrupoles. The fitted strengths of the 4 skew quadrupole power supplies are shown in Fig. 12. The strengths are very small for the coupling correction, which indicates that the amplitudes of the vertical dispersion function and the coupling are small.

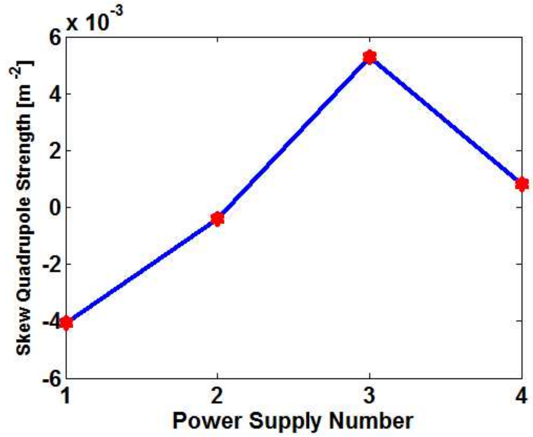

Fig. 12. The skew quadrupole strengths of the four power supplies to correct the vertical dispersion and betatron coupling at 2.5 GeV.

The tune split method [26] was used for betatron coupling measurement in the Indus-2 storage ring. In this method the betatron tunes are derived across the coupling resonance. By changing one of the quadrupole power supplies, the betatron tunes are changed and, as they get close to the coupling resonance, the horizontal motion is transferred to the vertical motion and vice versa. Figure 13 shows the measured horizontal and vertical betatron tunes as a function of the quadrupole current in the Q3D family of quadrupoles. The measured betatron coupling is <0.23% as against the earlier measurements [3] of ∼0.5%. This is mainly attributed to the small value of rotation errors of the quadrupoles and the well-controlled vertical orbit in the sextupole magnets. The measured RMS value of the vertical dispersion function is ∼ 20 mm.

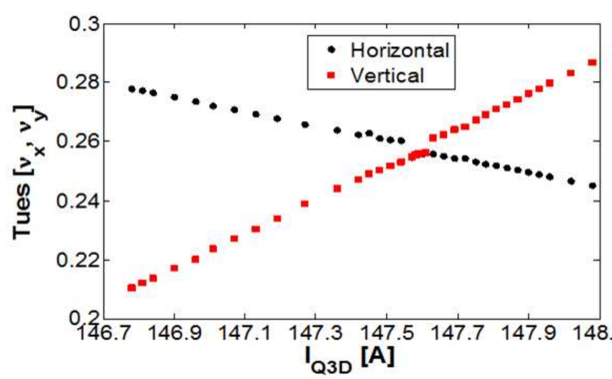

Fig. 13. (color online) The variation of betatron tunes with the change in power supply current in the Q3D family of quadrupoles at 2.5 GeV. The minimum tune split at coupling resonance is ∼0.008 and the resulting measured betatron coupling is ∼0.23%.

As discussed earlier, distortion breaks the periodicity of the beta functions and phase advance between sextupoles, which could lead to stronger sextupole resonances and reduce the DA. Studies were carried out to find the beneficial effects of the optics restoration on various beam parameters. In particular, we measured beam lifetime before and after optics restoration. The lifetime increased by approximately two hours after correction of the optics. In regular operation, the beam lifetime at ~150 mA improved from ~15 hrs to ~20 hrs, mainly due to optics correction and partially due to improvement in the vacuum. Another important benefit of the restored periodicity is the improvement in beam accumulation rate. After applying the optics correction at injection energy, the beam accumulation rate improved by ~20 %.

For commissioning of new beamlines or for machine experiments, sometimes a local four orbit bump needs to be applied, which requires more iterations to close the bump before the optics correction. After optics correction, and properly taking into account the calibration factors of the corrector magnets, the bump closure is easily achieved.

7 Conclusions and future perspectives

Analysis of the orbit response matrix, using LOCO code, helps in determining the quadrupole strength errors, BPM gains, corrector kicks, rotation errors of quadrupoles etc. The fitted quadrupole gradient errors are within 3.5% of the theoretical values. The fitted model accurately predicted the tune, beta and dispersion functions of the operating machine. The linear optics have been corrected in the real machine and the RMS beta-beat was then reduced to less than 1.0% and 0.5% from 9% and 6% in the horizontal and vertical planes, with an accompanying increase in beam lifetime of ~ 2 hrs. The horizontal dispersion is well restored, the measured vertical dispersion is ~20 mm RMS and the coupling is <0.23%. The beam accumulation rate is improved by ~20% and also beam lifetime improvement in user mode is observed.

LOCO is useful not only to restore lattice periodicity, but also to quickly identify problems with equipment. During maintenance and installation of new components such as insertion devices in the storage ring, parts of the connections of the correctors and BPMs are disconnected. Even with utmost care while reconnecting the cables, a recalibration error may occur. An analysis of the measured ORM can be used to identify the errors, which can then be corrected. In a long term, LOCO can also be used for analysing the deterioration in well-corrected optics on a shutdown to shutdown basis.

We are currently considering the use of LOCO as a diagnostic tool for identifying undesirable eventual changes in the machine equipment during its routine operation. In future, Indus-2 will be operated for low emittance optics, alternate low and high beta lattice and low alpha mode. These different modes of operation will be calibrated using LOCO code. The LOCO application will also be extended further to determine the sextupole offsets.

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