# LINEAR OPTICS CALIBRATIONS FOR THE SSRF STORAGE RING BASED ON COD

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*Abstract*

The commissioning of the ssrf storage ring has progressed very well. The symmetry of the linear optics in a storage ring is important, however may be broken by errors. A distorted linear optics can excite stronger nonlinear resonances. Therefore, it is necessary to restore the designed symmetry of the linear optics based on measured closed orbit distortion. The calibrations can be done using LOCO. After fitting the measured response matrix by the model one, the linear optics of the storage ring is calibrated. And different operation modes have been also measured and calibrated.

## INTRODUCTION

SSRF is a third generation light source of 3.5 GeV in beam energy. Its storage ring is designed to reach low natural emittance of 3.9 nm.rad with a structure of 20 DBA cells into four super-periods[1-2]. The 200 quadrupoles are powered independently. 80 correctors in each plane and 140 BPMs are used for COD corrections.

Commissioning of the storage ring began on the evening of Dec. 21, 2007. Because of the delay of super-conducting cavities, the two KEK normal RF cavities were used to compensate the beam energy loss on the 3.0 GeV beam energy at that time [3]. A beam with 100 mA current was successfully obtained at 20:19 on Jan. 3, 2008.

The linear optics of real machine unfortunately suffered from serious aberration with respect to designed one due to the effective quadrupole errors. The effective quadrupole errors have two kinds of sources from sextupoles due to the larger COD, effective length difference in quadrupoles. During the commissioning, the BPM offsets with respect to the nearest quadrupoles were precisely measured using BBA[4]. After setting all the offsets in BPMs, the COD can be corrected to small values based on SVD[5] method. The quadrupole magnetic excitation is calibrated by the LOCO[6] method, i.e., by fitting the measured orbit response matrix with the model one quadrupole by quadrupole, then the symmetry of the linear optics can be restored. A number of beam orbit response matrix measurements and LOCO simulations were made, and linear optics corrections were done for four different operation modes[7-8]. Results show that LOCO has provided a powerful tool to control the symmetry of storage ring linear optics.

## LOCO METHOD

The response matrix *M*, defined by the difference of COD divided by kick angles of correctors. Using LOCO, we can obtain the twiss functions at BPMs and correctors locations, the BPMs and correctors gain factors, the quadrupole gradient errors. The model orbit response matrix is calculated from the given lattice by AT online code. This minimization process is done by several numeric methods[6]. The result is a model that best reproduces the measured response matrix, that is to say, this model can be considered as the real machine. Using this model, linear optics is calculated and then the correction is done

## RESULTS OF LOCO CALIBRATIONS

The LOCO simulations and linear optics corrections of the storage ring can be divided into two stages: tune correction and symmetry restoration of linear optics. The Matlab middle layer (MML) software tool-box provides a library of functions that access either the machine hardware via EPICS or the AT simulator. This software has been implemented in the SSRFstorage ring and plays an important role in the commissioning process and daily operation. MML is also widely used in many other accelerators, especially in the third generation light sources. MML is used to prepare data for LOCO, i.e. ORM, BPM noise levels and dispersion functions.

The fitting parameters used by the LOCO code to fit the model response matrix to the measured one at SSRF are 200 of quadrupole gradients, 140 of BPM gain factors in horizontal, 140 of BPM gain factors in vertical, 80 of horizontal correctors and 80 of vertical correctors, with total number of 640 parameters for the uncoupled matrix.

### *Tune Correction*

During the commissioning, due to the exist of the effective quadrupole errors, the actual tunes are far away from the designed ones, it's about 1.5 different in horizontal tune and about 0.4 different in vertical one. If the measured ORM and model are much different, the LOCO calibration cannot be effective. We firstly changed the quadrupoles family by family, and find the correct integer parts of the tunes in two planes. Finally the differences for horizontal and vertical tune were reduced down to about 0.2 compared to their designed ones. Figure 1 shows the dramatically difference between the measured orbit response matrix and model one. The x-axis is the model ORM and the y-axis is the measured one. If the integer parts of tunes are correct, then the measured ORM and the model one should be almost in a thick line, If the are the same, they must be in a very thin line with slope is a factor of unity. After the integer parts of tunes are correct, LOCO can work well in calibrations. Due to the BPM noise is large than 2 μm at that time, the LOCO fit only by family was carried out. The quadrupole

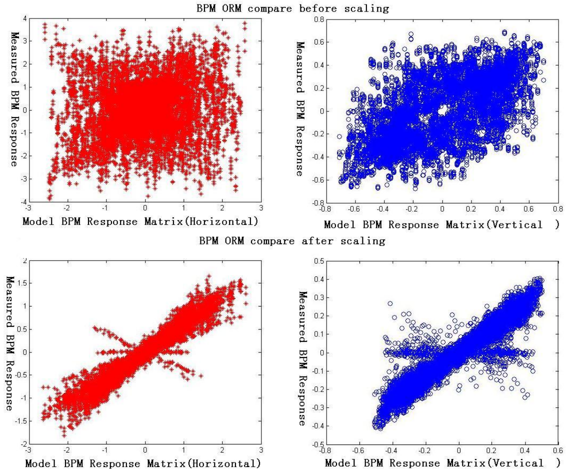


Figure 1: Similarity of the measured and model response matrix before (above) and after (below) integer tune corrections.

magnet excitation curves are modified according to the changing and fitted results.

### *Symmetry Restore of Linear Optics*

Symmetry restoration of linear optics to the design periodicity assures beam performance in a ring. By doing so, the ring is under a well-controlled mode of operation. When a need to change the beam parameters occurs, one can then easily change the quadrupole currents to the desired values and modify the optics of the storage ring. As orbit correction and BPM calibration have been done for several rounds, therefore, the BPM noises become much smaller, from original 2 μm down to about 0.5 μm in horizontal plane and about 0.1 μm in vertical plane. So it is possible to do LOCO fit magnet by magnet and by using this calibration, the symmetry of linear optics is restored, especially beta functions are much close to the designed ones.

The SSRF storage ring has ten families of quadrupoles named as Q1, Q2, Q3, Q4, Q5, and Q1L, Q2L, Q3L, Q4L, Q5L. The first 5 families each consist of 32 quadrupole magnets, and others each consist of 8 quadrupole magnets [1], so there are total 200 quadrupole magnets distributed in the ring. Because the quadrupoles are powered individually, they are all included as free parameters in the LOCO fit. The following describes the

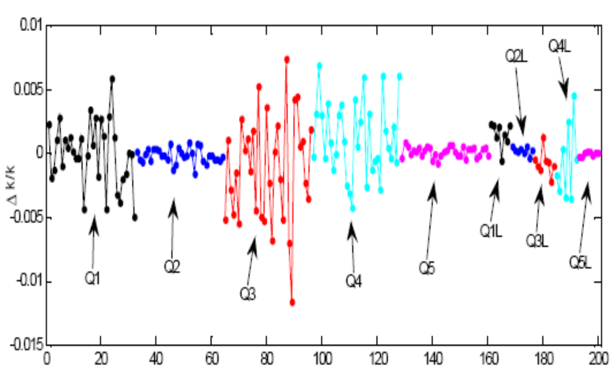


Figure 2: The calibrated quadrupole gradient errors.

results of a nominal mode. The resolution of each BPM was estimated by weighting the fit in the LOCO analysis. Dispersion functions were also measured. The orbit response matrix was measured with all sextupole magnets turned on because the SSRF storage ring could not be operated at more than 100 mA without sextupole magnets.

The focusing errors obtained from the LOCO fitting were applied back to correct the preset strengths of the quadrupoles. The current of quadrupole power supplies after several rounds LOCO fitting and application to the real machine are shown in Fig. 2. Figure 2 shows that the relative deviation of the power supply current for the 200 quadrupole magnets, defined as

$$\frac{\Delta k}{k} = \left(\frac{I_{fitted}}{I_{designed}} - 1\right)$$

where $I_{fitted}$ and $I_{designed}$ are the fitted quadrupole power supplies current and the designed one,resperctively. The beta function beating before and after LOCO calibration, defined as the difference between the designed beta functions and measured ones are shown in Fig. 3. The horizontal and the vertical differences of the beta functions from design values are around 10% before LOCO calibration and less than 1% after LOCO calibration. Therefore, the linear optics of the storage ring is successfully restored and the beta functions are almost close to the designed values and the designed periodicity.

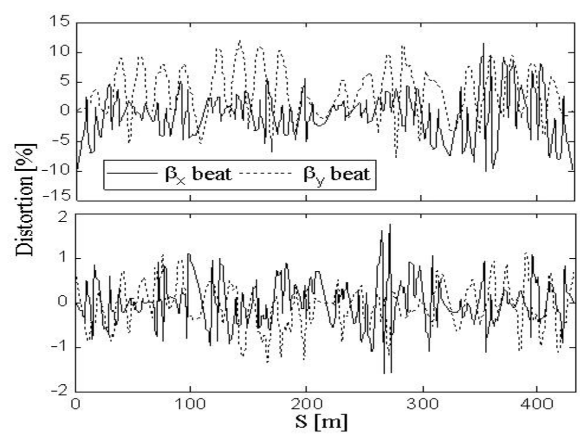


Figure 3: Beta beating of the real and designed machine before (top) and after (bottom) LOCO calibrations.

## VERIFICATIONS

In order to verify the LOCO calibration results, we also have done the same LOCO calibrations for other three operation modes of the storage ring, i.e., dispersion free mode with the same tunes, high horizontal tune mode with Qx=23.32 and low horizontal tune mode with Qx=19.22. From March 22 to 30, 2008, the other three operation modes were commissioned in the SSRF storage ring on the 3.0 GeV beam energy. When we set the quadrupole's power supply currents according to the calibrated values, the linear optics of the machine had a very few distortions. The periodicity or symmetry of the

Table 1: LOCO Calibrated Results for Four Operation Modes

| rms | Mode I | Mode II | Mode III | Mode IV |
|---|---|---|---|---|
| Beta function distortion before LOCO | 3.9~5.8% | 7.8~4.1% | 6.1~4.1% | 4.4~4.9% |
| Beta function distortion After LOCO | 0.50~0.52% | 0.52~0.87% | 0.48~0.71% | 0.81~0.36% |
| Calibrated dK/K | 0.29% | 0.43% | 0.33% | 0.23% |

linear optics was easily restored. The quadrupole gradient errors were within ±1.5% for different operation modes, and the beta beatings were within ±2% approximately. Some measured parameters, including the tunes, the natural emittance and the natural chromaticities, were in good agreement with the designed values. Table 1 summarizes the RMS beta beatings of the four operation modes, including the results before and after LOCO calibrations. These results verify that the LOCO calibrations are operation mode independent for the quadrupole gradients.

## CONCLUSIONS

We have described the analysis of the beam-optics distortion and subsequent correction in the SSRF storage ring. Although the measured beta functions did not significantly deviate from the design values, after optics correction, the Q3 and the Q4 quadrupoles were found to deviate significantly from the preset currents, probably because of the systematic errors, and will be considered. After optics correction, the beta functions became very close to the designed values. As a result of this study, the storage ring began to operate in a under well-controlled mode. There still are many works to do, for example, calibration of the BPM gain, coupling correction, and so on.

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