COMPARISON OF LINEAR OPTICS CORRECTION MEANS AT THE SLS

M. Aiba, M. Böge, J. Chrin, N. Milas, T. Schilcher, A. Streun, PSI, Villigen, Switzerland

Abstract

The experimental determination of linear optics is a fundamental prerequisite to achieving a high performance storage ring. In order to further enhance SLS performance and to simultaneously reveal the limitations of the various experimental techniques, we have performed a systematic study of linear optics optimization using various independent methods. These include an analysis of the orbit response, turn-by-turn data, and the response of the tune to quadrupole variation.

INTRODUCTION

The Swiss Light Source (SLS) is a 3rd generation light source in its 10th year of operation, providing light of high brilliance to a current 20 beamlines. Its storage ring is equipped with a modern digital beam position monitor (BPM) system capable of measurements not only of the closed orbit but also as a function of turns. In addition, an optics measurement of tune response to variations in quadrupole strength has been implemented, which now acts as the standard optics setup procedure. The SLS is hence the ideal platform to perform a comparison of linear optics measurements and correction means. The study is motivated by several goals: 1) to confirm the linear optics correction of the standard procedure, 2) to establish precise control of the linear optics, which is the basis of both nonlinear optics manipulation and linear coupling correction and 3) to reveal the limitations of the various techniques as input for future accelerator R&D.

In this study, the nominal user operation optics is measured and corrected, but with insertion devices de-activated. The main parameters of the SLS storage ring are summarized in Table 1.

Table 1: SLS Storage Ring Parameters

Parameter	Value	Parameter	Value
Circ.	288 m	No. BPMs	73
E(Beam)	2.4 GeV	No. Correctors	73
Lattice	12 TBA	Betatron Tunes (H/V)	20.435 / 8.737

OPTICS MEASUREMETS AND CORRECTIONS

Quadrupole Variation (QV)

The average beta function over a quadrupole magnet can be measured from the response of the betatron tune to a small variation in the quadrupole strength. All 177 independently powered quadrupoles are available at the SLS for the measurement and correction [1].

It is worth mentioning that the fractional part of the horizontal tune is close to half integer and thus the tune response cannot be approximated by a linear function of the quadrupole variation. This is taken into account in the analysis [2].

Figure 1 shows the residual beta beat of the best optics correction to date. A residual beta beat of 4.0% rms and 3.2% rms in the horizontal and vertical planes, respectively, has been achieved. However, the average beta beat (red point in Fig. 1) was offset from the origin whereas the betatron tunes were set to the nominal values.

The transfer functions of quadrupole magnets are carefully treated, taking saturation effects into account. Furthermore, by restoring tune values to their original set-points after each QV response measurement, hysteresis effects are avoided. The remaining offset is not understood. This requires us to apply a high eigenvalue cut in the SVD matrix inversion to compute quadrupole corrections. Therefore the residual beta beat cannot be further reduced.

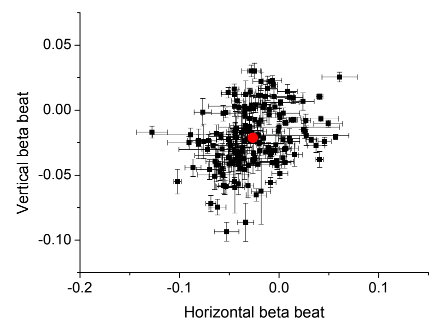

Figure 1: Residual beta beat with QV.

LOCO

LOCO (Linear Optics from Closed Orbit) [3] has been employed in many light sources and storage rings [4]. In the SLS, the correction of the betatron coupling is based on the off-diagonal orbit response matrix [5]; and we have extended it to the linear optics for this study.

When first applying the LOCO method, important calibration errors in BPMs and correctors were revealed, initiating their recalibration. A broken corrector power supply was also detected and fixed.

In order to facilitate comparison with other methods, the deviation of the orbit response matrix is converted to the beta beat. The closed orbit distortion due to dipole errors is represented by:

$$z(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi Q)} \sum_{i=1}^{N} \theta_i \sqrt{\beta(s_i)} \cos(|\phi(s) - \phi(s_i)| - \pi Q) \tag{1}$$

where z is the closed orbit distortion either in the horizontal or vertical plane at the longitudinal location s, θ is one of N dipole errors, ϕ is the betatron phase and Q is the betatron tune. For the orbit response matrix measurement, the reference orbit is subtracted from the orbit with an excited corrector. Hence only the i-th corrector kick θ_i is taken into account as the dipole error. Under the existence of the beta beat, we get:

$$\frac{z_i(s_j)}{\theta_i} = \frac{\sqrt{(\beta(s_j)+\Delta\beta(s_j))(\beta(s_i)+\Delta\beta(s_i))}}{2\sin(\pi Q)}\cos(|\phi(s_j)-\phi(s_i)|-\pi Q) \quad (2)$$

The left hand side of Eq. (2) is now the orbit response at the j-th BPM to the i-th corrector kick. Assuming that the BPMs and correctors as well as quadrupole errors are rather randomly distributed over the ring, the deviation of the orbit response can be approximately connected to the beat beat:

$$\left[\Delta\left(\frac{z_{ij}}{\theta_i}\right)^2\frac{1}{\beta_i\beta_j}\right]_{RMS} \propto \left[\frac{\Delta\beta}{\beta}\right]_{RMS} \quad (3)$$

where the longitudinal location is also represented with subscript i or j for simplicity. The rms beta beat would be computed for the BPM locations, which must be close to the one for the corrector locations under the assumption we made. Figure 2 shows the beta beat versus the figure of merit (L.H.S. of Eq. (3)). The poor correlation in the horizontal plane is due to the half-integer proximity of the fractional tune.

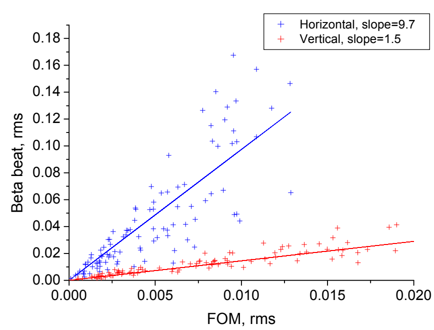

Figure 2: Beta beat vs. the figure of merit.

The measured orbit response matrix is fitted with the parameters: quadrupole strengths (177), BPM and corrector calibration and tilt (2*2*73 and 2*73), skew quadrupole component at sextupole (73) and the momentum shift due to the additional kick of corrector at dispersive section (2*73). The algorithm we use for the fitting is SVD.

The SVD cut is experimentally determined to minimize the effect of measurement noise as well as the degeneracy issue. Since the number of quadrupoles is much larger than the number of BPMs, correctors and betatron waves, neighbouring quadrupoles a few meters apart may serve as an "equivalent knob". The SVD algorithm then distributes the quadrupole strengths over a given "knob". Figure 3 shows the fitted quadrupole strengths for a large quadrupole error (ΔK=0.06 m^{-2} at s=10.8 m) intentionally introduced into the machine. An SVD cut of 0.001 would be optimum. It is confirmed with simulations that the residual beta beat due to the degeneracy issue is negligible.

An iteration of the LOCO optics correction procedure achieved a residual beta beat of about 2% rms in both planes according to the slopes shown in Fig. 2. The prediction from SVD fitting is roughly 2 and 10 times better in the horizontal and vertical plane, respectively.

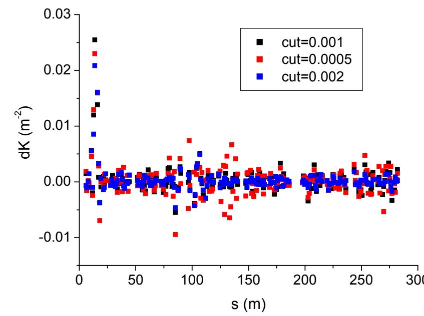

Figure 3: Quadrupole correction strengths corresponding to the single known error for various SVD cut.

Turn-by-Turn (TBT)

Turn-by-turn BPM data can be utilized to measure the linear optics by exciting betatron oscillation with a pulsed magnet. The phase advance between neighbouring BPMs is measured in terms of BPM calibration independent observables. The phase beat can be converted to the beta beat [6]. Figure 4 shows the beta beat versus the phase beat for the SLS lattice.

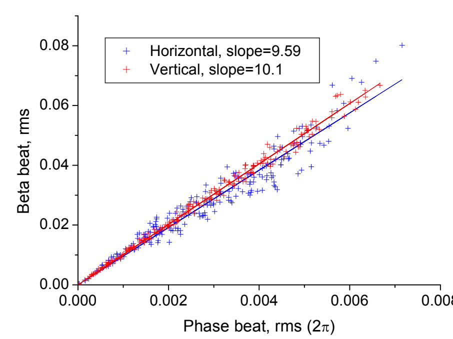

Figure 4: Beta beat vs. phase beat for the SLS lattice.

As soon as we began with the optics measurement with TBT BPM, we encountered serious BPM synchronization issues. This was solved by installing cable delays, which synchronized BPM triggers, taking into account the electron beam time of flight around the ring. Another issue in TBT BPM data is the signal mixture with the next and previous turns. In the present SLS BPM system, the mixture is about 20%, and we adjust the trigger timing to equalize the mixtures to the next turn and to the previous turn such that they cancel out in the phase measurement. Assuming that a linear sum is valid, BPM signal for turn n with mixture is represented as:

$$\begin{aligned} &A_n\sin(2\pi Qn)+A_{n+1}\sin[2\pi Q(n+1)]+A_{n-1}\sin[2\pi Q(n-1)] \\ &=[A_n+A_{n+1}\cos(2\pi Q)+A_{n-1}\cos(2\pi Q)]\sin(2\pi Qn) \\ &+[A_{n+1}\sin(2\pi Q)-A_{n-1}\sin(2\pi Q)]\cos(2\pi Qn) \end{aligned} \quad (4)$$

where A_n is the oscillation amplitude, Q is the betatron tune. The initial phase is assumed to be zero for simplicity. The amplitude A is almost constant for a few turns unless the chromaticity is extremely high. As we see, the second term will disappear when we equalize the mixture, $A_{n-1}=A_{n+1}$.

The SUSSIX [7] algorithm is used to analyze turn-by-turn data but may not be optimum for finding the betatron phase since its phase accuracy is scaled proportionally to the inverse of the number of turns, 1/N. However, other algorithms, which in principle are able to find the phase with an accuracy scale of $1/N^2$ or even $1/N^3$, are also limited to 1/N due to the presence of noise [8]. The rms phase accuracy at the SLS is about 0.001 in units of 2π, which corresponds to a beta beat limit of 1% rms.

An iteration of TBT optics correction achieved a residual beta beat of 1.4% and 3.6% rms in the horizontal and vertical plane, respectively, as is apparent from the slopes of Fig. 4. The residual horizontal beta beat is agreeably close to the limit of phase accuracy. The asymmetry in the achieved beta beat implies that the signal mixture issue persists in the vertical plane since the second term tends to remain for a fractional tune of 0.74.

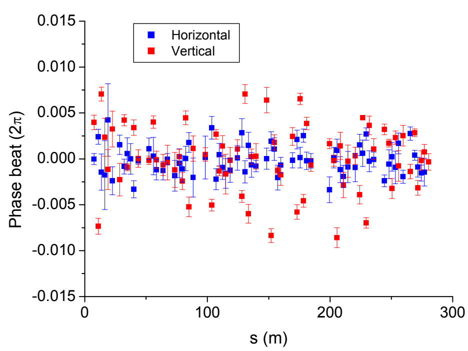

Figure 4: Residual phase beat.

Comparison

The best corrected optics with LOCO and TBT were measured with QV. Figure 5 shows the residual beta beat for these measurements together with the measurement from QV alone. The offset is subtracted for the comparison.

From the QV point of view, LOCO and QV result in similar optics correction quality. TBT generated some local beta beat which were not observed in the phase beat.

SUMMARY

We have performed a comparison of linear optics measurements and correction methods, namely QV, LOCO and TBT at the SLS. In order to compare the results from the three different techniques, the phase beat in TBT is converted into the beta beat, and we introduced the figure of merit in LOCO, which is approximately proportional to the beta beat. QV measures the beta beat itself through the tune response. With these self consistent measures, LOCO achieved the smallest residual beta beat (sum of both plane).

We have revealed the limitations of these techniques through the study. QV includes the beta beat offset of 2~3%, which is not well understood. The ultimate limit in LOCO, that is, the residual of fitting corresponds to a beta beat of ~1% rms and ~0.2 % rms in the horizontal and vertical planes, respectively. The higher limit in the horizontal plane is probably due to the fractional horizontal tune close to the half integer. Concerning TBT, the phase accuracy sets a limit of the beta beat of ~1% rms. The signal mixture may in practice still disturb the phase measurement.

A direct comparison between QV and LOCO showed consistent residual beta beats, confirming the validity of the standard linear optics correction procedure. The TBT performance approaches that of LOCO, such that in future a complete optics characterization may be performed on-line. LOCO and TBT have now been introduced into the SLS. Further studies will allow us to improve on the LOCO and TBT procedures.

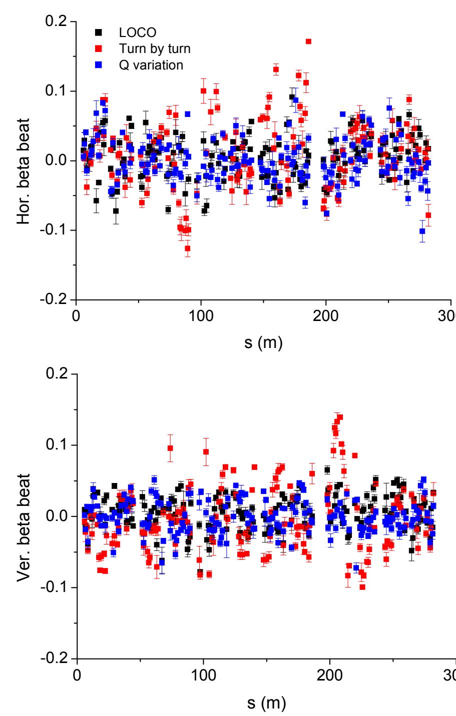

Figure 5: Comparison of residual beta beat.

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