CALIBRATION OF LINEAR OPTICS OF COSY BASED ON ORM DATA

C. Weidemann[*], M. Bai, Y. Dutheil, F. Hinder, and B. Lorentz
IKP, Forschungszentrum Juelich GmbH, 52425 Juelich, Germany

Abstract

In order to calibrate and correct linear optics of the COoler SYnchrotron(COSY) in Juelich and thereby overcome present disagreements between the COSY model and the machine a technique called Linear Optics from Closed Orbit (LOCO) [1], originally used at light sources, was implemented in a newly developed C++ program. After a careful benchmarking procedure, presented in [2], the algorithm was for the first time applied to a measured orbit response matrix (ORM). The achieved capabilities in calibrating linear optics as well as reconstructing machine imperfections, such as gradient errors of quadrupole magnets and calibration factors of BPMs and corrector magnets, are presented.

INTRODUCTION

The COoler SYnchrotron in Juelich is a well suited accelerator for a precursor experiment on the direct measurement of the Electric Dipole Moment (EDM) of the deuteron (see [3] and references within). It provides polarized and unpolarized proton and deuteron beams in the momentum range between 0.3 GeV/c and 3.65 GeV/c [4,5], allows for phase space cooling by means of electron and stochastic cooling and is highly flexible with respect to ion-optical settings [6].

So far the existing MAD-X model of COSY does not provide the agreement with the actual machine that is required by the EDM experiment. Significant deviations with respect to the working point and linear optics have been reported [7]. The newly developed LOCO program is supposed to improve the situation.

LOCO

The LOCO algorithm is based on the comparison of a measured orbit response matrix and a calculated one, which is derived using the existing COSY model and the MAD-X accelerator optics program (see Fig. 1). A typical ORM at COSY contains about 2400 entries, representing the orbit deviations caused by a change in the deflection strength of each of the approximately 40 correction-dipole magnets measured with about 60 beam position monitors (BPMs) (30 horizontal, 30 vertical) along the ring.

χ^2 is defined as the squared sum of the differences between the model and the measured ORM entries (M_{mod}, M_{meas}), weighted with the inverse of their measurement errors squared ($\sigma_{M_{\text{meas},ij}}$):

$$\chi^2 = \sum_{i,j} \frac{\left(M_{\text{mod},ij} - M_{\text{meas},ij}\right)^2}{\sigma^2_{M_{\text{meas},ij}}} = \sum_{k=i,j} E_k^2. \quad (1)$$

* c.weidemann@fz-juelich.de

Table 1: Machine Parameters Under Investigation

Parameter name	Number
BPM calibration	60
BPM roll (ψ), shift (s)	$2 \cdot 60$
Corrector calibration	40
Corrector magnet roll (ψ), position (s)	$2 \cdot 40$
Deflection angle (offset)	40
Gradient of quadrupole families	14
Gradient of individual quadrupoles	56
Quadrupole rotations (ϕ, θ, ψ) and misalignments (x, y, s)	$6 \cdot 56$
Dipole rotations (ϕ, θ, ψ) and misalignments (x, y, s)	$6 \cdot 24$
Quadrupole coefficient of dipoles (K1)	24
Sextupole coefficient of dipoles (K2)	24
Sextupole coefficient of quadrupoles (K2)	56

The indices i and j denote the BPM and the corrector magnet, respectively. Varying every single machine parameter (options can be found in Tab. 1) by several steps results in the individual error vectors $dE_k dK_l$, which represent the dependence of the full ORM to the particular parameter. Combining all vectors yields the Jacobian matrix $dE_k dK$. Applying a singular value decomposition (SVD) to this non-square Jacobian matrix allows the determination of its pseudoinverse and the direct recalculation of the corresponding parameter corrections

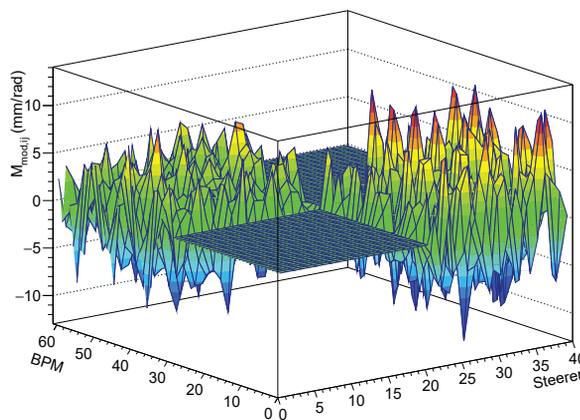$$\Delta K = -\frac{dK}{dE_k} \cdot E_k. \quad (2)$$

Figure 1: Calculated orbit response matrix of COSY. Horizontal corrector magnets (0-20) cause orbit responses in the horizontal plane (BPMs 30-60) but not in the vertical plane (BPMs 0-30). The opposite is true for the vertical corrector magnets (20-40).

Details of this procedure and its implementation are described in [2]. Due to non-linearities several iterations are required until convergence to the best set of parameters is reached. Effectively, a χ^2-minimization is performed by adjusting different model parameters until both ORMs are equal.

APPLICATION TO MEASURED ORMS

As presented earlier the program was carefully benchmarked with regard to the reconstruction of various machine parameters and its sensitivity to different input parameters, such as for instance the BPM resolution and the sequence of reconstruction [2].

After completion of the benchmarking procedure the program was tested with measured data. For this purpose a set of orbit response matrices with only changed quadrupole gradients, was recorded in a dedicated beam time in November 2015. In addition, the dispersion D_x and the working points Q_x and Q_y were measured. Goal of the LOCO analysis is the determination of BPM and corrector magnet calibration factors, the detection of the applied quadrupole gradient changes and subsequently an improved reconstruction of the betatron tunes, which so far had to be calibrated empirically. Since the 56 quadrupole magnets along the ring are powered in groups of four, we end up with 14 so-called families [6] as displayed in Figure 2. The discussed data set contains two ORMs, where the only difference is the gradient of quadrupole family QT3, which was modified by 4 %.

Firstly, the data was preprocessed by means of advanced fitting of the beam position response to a change of the corrector strength. The analysis accounts for detected dipole drifts and known features of the BPM readout. Thereafter, the existing calibration factors of the corrector magnets are applied and a final validation check refuses data from non-working elements.

In the second step the ORMs are analyzed by LOCO using the quadrupole gradients and the BPM and corrector magnet calibration factors as fit parameter. As a consequence of the benchmarking one BPM per plane was always excluded from the fitting due to degeneracy issues. LOCO was set to execute eight iterations. For a better evaluation of the sensitivity of the LOCO procedure four different fitting sequences were executed and the resulting calibration factors were averaged, as plotted for one ORM in Figures 3 and 4. The corresponding errors are derived from the fluctuation of the results of the individual analyses. A brief look already reveals a wrongly oriented BPM (number 37 in Fig. 3) distinguishable by a calibration factor of -1. The derived calibration factors of the BPMs show a tendency towards values smaller than 1 with a mean value of 0.85 whereas the calibration factors of the corrector magnets fluctuate around 1 with a mean of 0.99. The deviation from 1 and the errors of the BPM and corrector magnet calibration

Figure 3: Reconstruction of BPM gain factors including the detection of a wrongly oriented BPM (number 37).
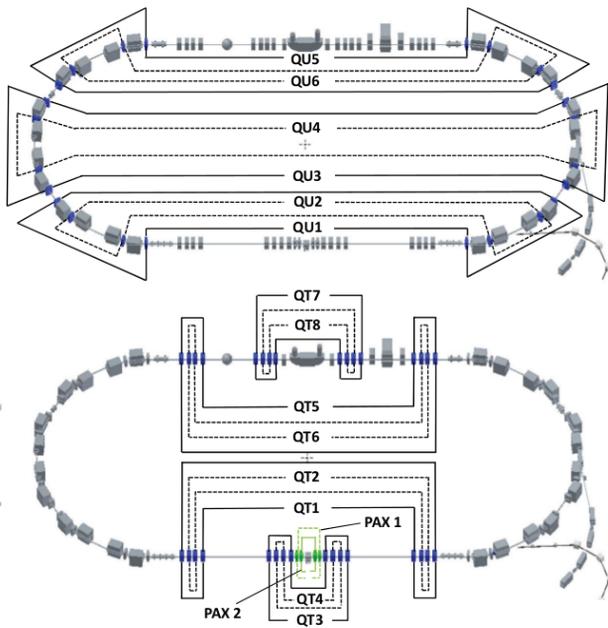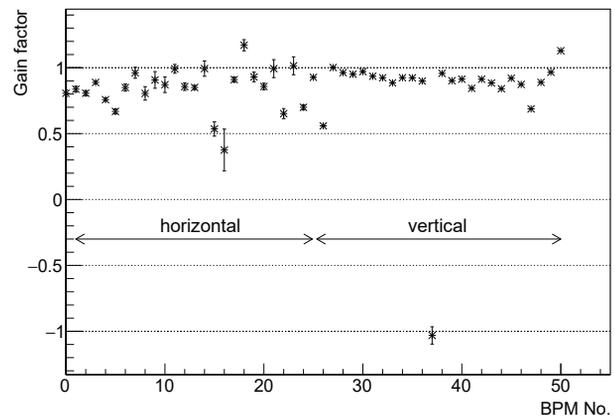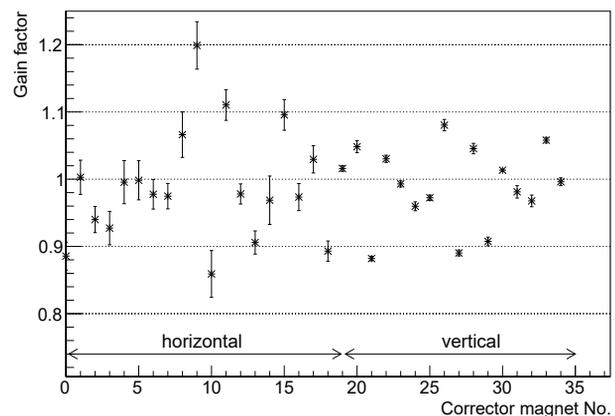

Figure 2: Floor plan of COSY showing the quadrupole families, each consisting of four magnets with a common current supply. There are eight families for the telescopic straight sections (QT1 to QT8, bottom panel) and six for the arcs (QU1 to QU6, top panel).

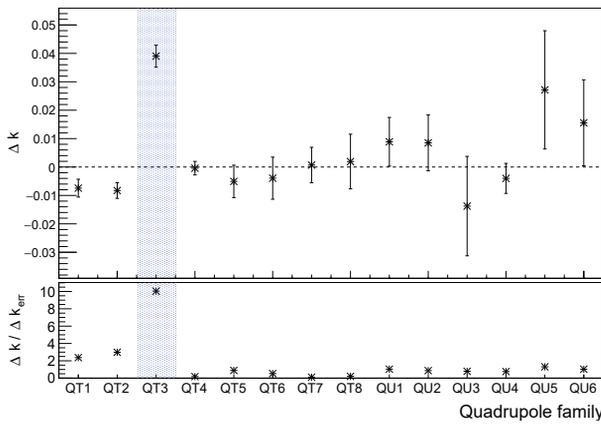Figure 4: Reconstruction of corrector magnet gain factors.

Figure 5: Change of the quadrupole gradient Δk for all 14 quadrupole families (top panel). The ratio of the determined Δk and it's uncertainty is plotted in the lower panel to allow for an improved judgment of significant changes. As visible, the gradient of family 3 (QT3) was changed by 4%.

factors in the horizontal plane are larger than those of the vertical ones. This feature is still under investigation.

The determined gradient change Δk between the two measured ORMs and the corresponding uncertainty for all 14 quadrupole families is displayed in the top panel of Figure 5. As visible, family QT3 shows a difference of $4 \pm 0.15\%$, which is in perfect agreement with the applied change.

Deviations from zero can also be observed for family QU5 and QU6. Considering the large error bars the values are still in agreement with zero. An explanation for the behavior of these comparably large differences and errors is a degeneracy effect, which allows to compensate changes of one quadrupole gradient by another one. Exe-
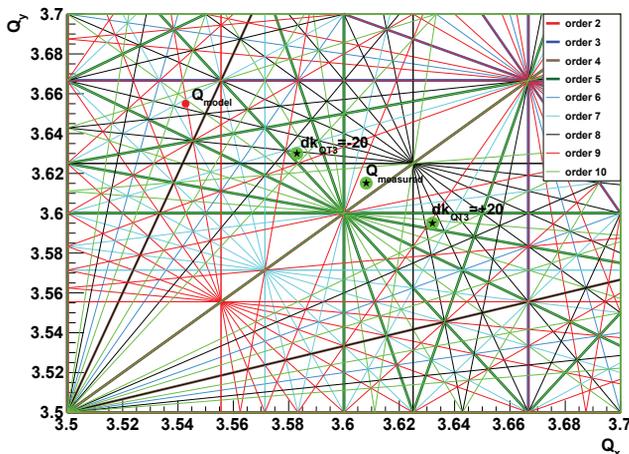

Figure 6: Reconstruction of the measured working points $Q_{measured}$ (green) for three different quadrupole settings using the LOCO algorithm. In red the working point of the uncorrected model Q_{model} is shown and the black stars indicate the tunes after applying the parameter adjustments determined by LOCO.

cuting the LOCO analysis with modified fitting sequences

thus results in different setting combinations for these families and consequently large errors. Dividing the detected gradient change by the corresponding uncertainty (lower plot in Fig. 5) enables a clear identification of significant changes. This is the case for QT3, which agrees with the applied modifications, but also for QT1 and QT2 $\Delta k \Delta k_{err}$ differs from zero. The reason might also be a degeneracy between these two, but with a reduced degree of degeneracy compared to QU5 and QU6.

Finally, the machine parameters determined by LOCO are used to calibrate the model, which is then again utilized to calculate the working point. In Fig. 6 the working point calculated by the initial model Q_{model} (red dot) is in clear discrepancy from the measured tune $Q_{measured}$ (green dot). After applying the corrections to the mentioned machine parameters in the model, the measured working points of the initial setting and the two modified ones ($dk_{QT3} = -20\overset{o}{oo}$, $dk_{QT3} = +20\overset{o}{oo}$) are perfectly reconstructed as indicated by the black stars.

SUMMARY AND OUTLOOK

A first application to measured ORM data allowed for a determination of BPM and corrector magnet calibration factors, accompanied with the detection of a wrongly oriented BPM and a perfect reconstruction of the measured working points. Furthermore an intentional change of the strength of one quadrupole family could be nicely detected.

Current investigations are addressing misalignments of dipole and quadrupole magnets. A recent survey measurement indicated misalignments of up to several mm for a small number of elements. Whether the LOCO program is capable of detecting these misalignments is an exciting question. It might also help to judge by how much an improved beam position measurement or a larger number of measurement points can improve the determination of these parameters.

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