ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI083

# A FAST OPTICS CORRECTION FOR THE DIAMOND STORAGE RING

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## *Abstract*

Since March 2013, the Diamond storage ring has been operated with a target vertical emittance of 8 pm.rad. This condition is achieved by first applying a LOCO [1] optics correction with IDs set to their typical gaps, then offsetting the skew quadrupole magnets in order to increase the vertical emittance again to the desired value. Whilst a feedback application [2] is able to stabilise the vertical emittance during ID gap and phase changes in the short to medium term, regular applications of LOCO are still required to maintain good coupling control in the longer term. In this paper we describe measures taken to speed up the optics correction procedure, including a fast orbit response matrix measurement, a reduction of the number of magnets used to measure the data, and a distribution of the LOCO calculations to run in parallel.

## INTRODUCTION

Good control of the linear optics is a pre-requisite for successful operation of modern, 3rd generation light sources. Quadrupolar field errors can lead to tune-shifts and beta-beating, altering the characteristics of the electron beam at the source points. Similarly, skew quadrupole field errors affect the emittance coupling, altering the vertical beam size and hence the source brightness and transverse coherence. For both types of error source, users can also be impacted by any reduction in lifetime and injection efficiency that result from such errors.

To combat short term variations in the linear optics, several measures have been put in place at Diamond [2, 3]. These include local quadrupole feed-forward schemes, a tune feed-back application and a vertical emittance feedback. These have been demonstrated to be effective at stabilising the optics in the short to medium term; however, optimal operational performance still depends on a regular, global correction of the focussing. This is carried out routinely during machine start-up using LOCO [1].

The main limitation of LOCO relates to the fact it requires an orbit response matrix (ORM) measurement to be made, thus excluding the possibility to carry out a correction during user time. In the standard version of LOCO, each corrector magnet is stepped in turn over EPICS (or equivalent) via a Matlab-based script. Beam position data is acquired from the slow-acquisition (SA) data stream. For the Diamond storage ring, there are a total of 2×172 correctors magnets to cycle through, meaning the data acquisition time takes around 15 minutes to complete.

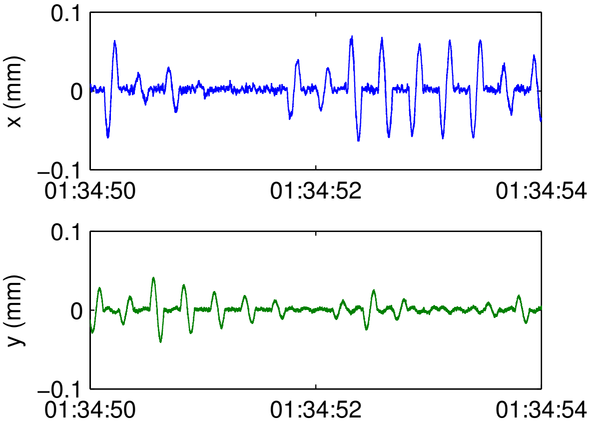

Figure 1: BPM readings during an ORM measurement.

Once the data have been acquired, several iterations of fitting need to be carried out to match the machine model to the measured data. At Diamond, the standard fit involves varying the gradients of 248 quadrupoles and 96 skew quadrupoles as well as fitting the gains and rolls of the 172 BPMs and correctors. Once penalty weights are included, the total fitting matrix therefore contains over $2{\times}10^8$ elements, making the fitting both memory-intensive and time consuming to perform. In all, a typical LOCO correction for the Diamond storage ring takes around 1 hour to complete, clearly limiting the occasions on which such a correction can be carried out.

In this paper we describe recent work carried out to reduce the total time required to perform an optics correction using a modified LOCO package. This reduction is achieved through a variety of measures, including a fast ORM measurement, a reduction in the number corrector magnets used, a parallelisation of the LOCO fit and an automation of the whole procedure.

## METHOD

### *Data Acquisition*

A LOCO fit requires three types of input data, namely the dispersion, an ORM and a BPM noise measurement. During this study, the dispersion measurement was left unchanged from the standard Middlelayer method [4].

The main improvement in acquisition time was achieved by making use of the fast orbit feedback (FOFB) network. Each feedback node is capable of producing sine wave excitations on each corrector with programmable amplitude, fre-

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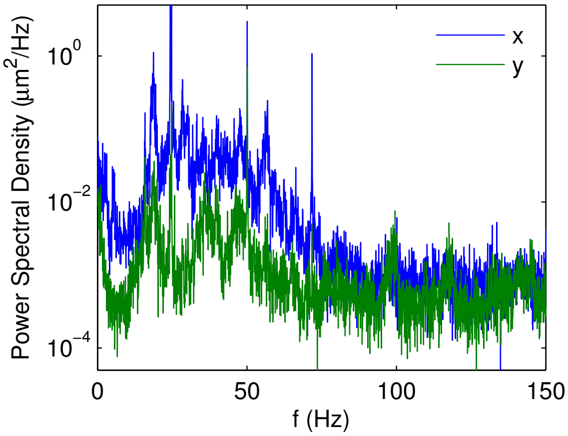

Figure 2: Beam spectrum in the horizontal and vertical planes (FOFB off).

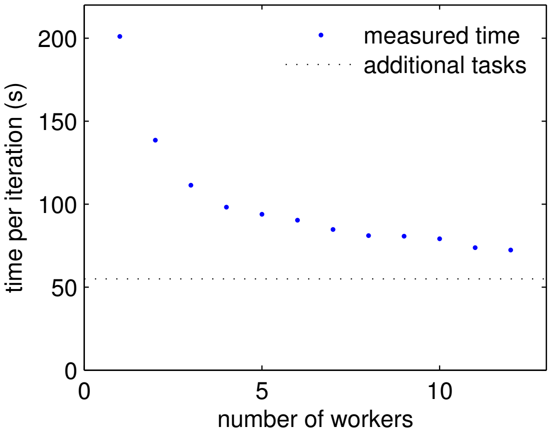

Figure 3: Time per iteration for the LOCO fit. The base time to perform the SVD, etc. is shown as a dashed line.

quency, duration and (synchronised) start time. This functionality allows the use of a Python script to configure the excitation for each corrector, then to open a connection to the fast-acquisition (FA) BPM data stream at 1 kHz data rate to record the resulting orbit distortions. From this data, each element in the ORM can then be calculated using

$$\begin{aligned} A_{m,n} &= < 2 \times z_m(t) \times sin(2\pi f t) > \\ R_{m,n} &= A_{m,n}/\Delta\theta_n \end{aligned} \qquad (1)$$

where $z_m(t)$ is the reading from the $m^{th}$ BPM during each corrector cycle in either the $x$ or $y$ plane, $A_{m,n}$ is the amplitude of the orbit distortion, $\Delta\theta_n$ is the amplitude of the sinusoid applied to the $n^{th}$ corrector magnet, $f$ is the excitation frequency and $R_{m,n}$ is the ORM element. A typical BPM reading during the measurement is shown in Fig. 1.

The BPM noise is assessed along similar lines. Once the ORM measurement is complete, an additional period of FA data is recorded equal to the length of each corrector cycle. The noise on each measurement is then processed in the same way as for the ORM, i.e.

$$\sigma_{z,m} =< 2 \times z_m(t) \times sin(2\pi f t) > \qquad (2)$$

### *Choice of Excitation Frequency*

The optimum choice of corrector excitation frequency is a trade-off between the desire to reduce the total measurement time and the need for accuracy. Increasing the frequency reduces the total measurement time at the expense of an increase in the measurement noise and an increase in the attenuation and phase delay of the corrector magnetic field through the stainless steel vacuum chamber. Lowering the frequency reduces the measurement noise and attenuation, but increases measurement time. After processing ORM measurements made at a variety of frequencies, and making an assessment of the BPM noise spectrum (see Fig. 2), the optimum frequency for Diamond was found to be a single-cycle 8 Hz excitation.

### *Increasing the Number of Processors*

Fitting of the machine model using LOCO is presently performed on a Dell PowerEdge R620 server with Intel Xeon E5-260 2.6 GHz processors, operating Red Hat Enterprise Linux 6. This machine has a total of 128 GB of RAM, sufficient to handle the large matrix manipulations carried out by LOCO.

In this work the standard Matlab version of LOCO is used to process the data, with minor modifications made to the code to allow it to run using Matlab's Parallel Computing Toolbox [5]. Using this, up to 12 workers can be used in parallel to construct the main ORM-to-fit-parameter Jacobian matrix. This leads to a significant reduction in time to perform the calculation, as shown in Fig. 3. A further increase in the number of workers would be of limited use, as the majority of the time is spent performing the matrix SVD and carrying out initialisation and post-processing tasks.

### *Automation of Process*

The final step taken to reduce the total time to perform a LOCO-based optics correction is to automate the entire procedure. In the standard form, LOCO is an interactive process, requiring user intervention to at each stage to begin the measurement, select filenames and directories, select fit parameters, initiate the fitting and so on. In the modified version, all parameters are defined in a configuration file, and the different steps in the process are triggered from within a bash shell script. All stages that execute Matlab scripts are launched in batch mode.

## PERFORMANCE

Using the modified code, the time to acquire the data (including dispersion and BPM noise measurements) was reduced to ~55 seconds from ~18 minutes using the standard scripts. The entire optics correction process from initiating the measurement to applying magnet corrections was ~5 minutes 30 seconds.

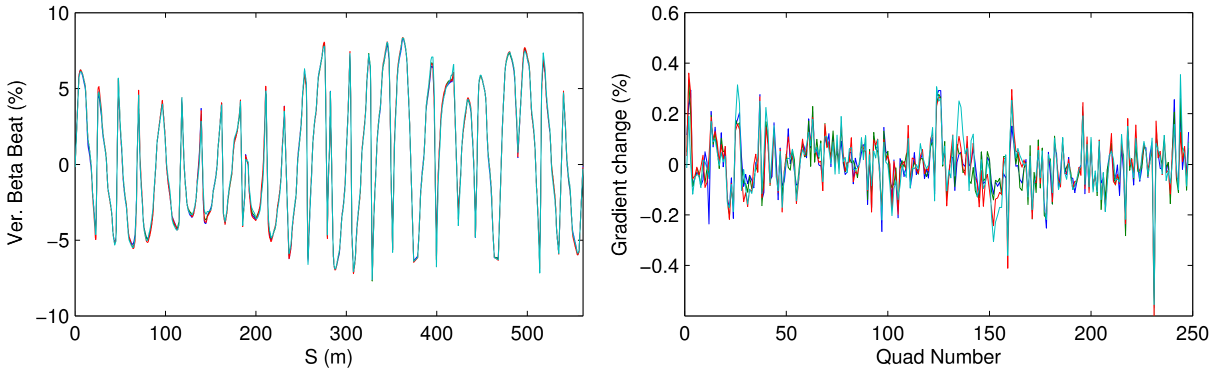

Figure 4: Reproducibility of measurements using the modified LOCO code. The blue lines shows data measured using standard LOCO scripts, with green, red and cyan taken with the modified LOCO.

### *Measurement Reproducibility*

The reliability of the modified LOCO process has been assessed by carrying out several measurements back to back and comparing these to a data set recorded using the standard LOCO scripts. The results of this are shown in Fig. 4. As can be seen, the calculated beta-beat extracted from the fitted machine model is near-identical for each data set, with differences in the individual quadrupole gradient changes less than 0.1%.

### *Convergence of Optics Correction*

A side benefit of reducing the time it takes to perform a complete optics correction cycle is that it allows the freedom to increase the number of correction cycles that are applied, or in the number of model-fitting iterations carried out each time. As such, the correction becomes more reliable at converging to a stable solution.

For Diamond, results show that three optics correction cycles, each with three model-fitting iterations per measurement, is sufficient for the correction to converge to stable results. In this case, the residual beta-beat is of the order 1% peak-to-peak in both planes, and the r.m.s. vertical dispersion is below 0.6 mm.

### *Reducing the Number of Correctors*

The inherent symmetry of the storage ring can be exploited by reducing the number of corrector magnets used to acquire the ORM. This follows from the fact that a single corrector will generate an orbit distortion in the entire ring, and in principle only a subset of correctors are required in order to sample the phase advance with sufficient detail. Increasing the number of correctors will still improve accuracy due to the finer sampling and the reduced sensitivity to BPM noise, individual corrector error and so on; however, given the large number of correctors in the Diamond storage ring, it is anticipated significant reductions in acquisition and processing times can be made without significant detriment to the accuracy of the final fit.

To investigate this possibility, several LOCO fits were made of the perturbed machine optics using a variety of corrector magnet combinations. Each cell of the Diamond storage ring contains 7 BPMs and correctors. Measurements were taken in the combinations [1], [1,4,7], [1,3,5,7], and for every other corrector magnet (i.e. [1,3,5,7] then [2,4,6] in alternating cells). Comparing the results of these fits to one acquired using all correctors demonstrated excellent agreement in beta-beat, dispersion, quadrupole and skew quadrupole gradient changes, with the main discrepancies appearing in the mean values for the BPM and corrector gains.

For the case with only 1 corrector magnet per cell, the ORM measurement time was reduced to 8 seconds, with the total time to apply an optics correction reduced to 2 minutes 20 seconds.

## CONCLUSIONS AND FUTURE WORK

Using a modified version of the LOCO package, the time to correct the storage ring optics has been reduced from around 1 hour to just over 5 minutes. This reduction has been achieved through a variety of measures, including a fast ORM measurement, a distribution of the LOCO fit to run in parallel and an automation of the entire procedure.

Future work aims to improve the accuracy of the fit via integrating an orbit correction into the ORM measurement, and to further reduce the time spent initialising and executing each stage of the process.

## ACKNOWLEDGEMENTS

The authors would like to thank Greg Portmann and Geoff Corbett for their interest in this work and suggestions for topics to pursue.

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