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INVERSE ORBIT RESPONSE MATRIX MEASUREMENTS: A POSSIBLE ON-LINE TOOL FOR OPTICS CONTROL IN STORAGE RINGS

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Abstract

We propose a novel technique to measure the linear optics in storage rings based on the acquisition of the inverse orbit response matrix (iORM). The iORM consists in the orbit correctors magnets (OCM) strength changes needed to produce a local orbit variation in each beam position monitor (BPM). This measurement can be implemented by introducing sequentially small changes in the BPM offsets and logging the OCM setting variations when the orbit correction is running. Very high precision and accuracy in the OCM set-points is required which poses a considerable challenge. Since the orbit feedback (FOFB) is kept running, the iORM could potentially be acquired in parallel to users storage ring operation. Since the iORM is very linear and local, optics perturbations could be easily diagnosed online. This paper introduces the iORM measurement concept and presents the progress of these studies at ALBA, where the implementation of this technique is limited by hysteresis effects in the OCM and the FOFB performance.

INTRODUCTION

Among other methods, the orbit response matrix (ORM) **R** observable is commonly used to characterize circular accelerator beam optics [1]. In the simplest case, it is measured varying each OCM j set-point by an small amount ΔI_j and storing the beam orbit change Δx_i at each BPM i. Every element of **R** is defined as:

$$R_{i,j} = \Delta x_i / \Delta I_j. \tag{1}$$

Other measurement techniques consist in using AC signals for the OCM while retrieving the values $R_{i,j}$ through spectral analysis of the BPM readings [2, 3].

Apart from being used to infer local optics information, the primary use of **R** is the orbit correction. The orbit feedback uses the inverse or pseudo-inverse of **R**. The matrix inversion is prone to amplify the noise contribution. To avoid that, at ALBA, the 5 kHz FOFB uses the standard approach of a pseudo-inverse matrix calculated via SVD and Tikhonov regularization, which we name it **S** to distinguish it from the measured iORM.

While the FOFB is active any attempt to measure **R** will be altered. At ALBA attempts have been done in order to use the “zero dB” crossing frequency of the FOFB for each OCM. The result was that in any case, the FOFB reacts noticeably to the excitation. We suspect that the fact that different OCM have slightly different dynamical properties prevents to achieve the desired accuracy.

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The FOFB being active allows to measure the inverse response matrix **T** directly. It is measured varying each BPM i objective position (usually called golden orbit) by an small amount Δx_i and storing how the FOFB modifies each OCM j set-point by ΔI_j. The elements of **T** can be defined as follows:

$$T_{i,j} = \Delta I_j / \Delta x_i. \tag{2}$$

Each column of **T** can be thought of as the OCM setpoints need to produce an small single BPM bump. In the vertical plane, in the limit of the linear case, with ideal OCM and BPM and without measurement errors and without any regularization, **T** and **S** are identical. In the horizontal plane, since the FOFB also changes the RF to correct energy drifts, that relation is not fully accomplished.

If the iORM technique was to be used in operation the interaction with the FOFB correcting insertion devices (ID) movements, the ID quadrupole correction feed froward tables or the RF correction should be considered. Also the BPM next to the ID should probably not be used. These complications are not taken into account at the level of this proof of principle study. In the present state the main limitations are the OCM hysteresis and the FOFB speed. An AC version of the iORM would potentially solve many of the issues but at the same time requires profound changes in the FOFB which can not be foreseen in the near future at ALBA.

iORM IN THE THE ALBA LAYOUT

The ALBA layout contains pairs of BPM without an OCM in between after and before each cell. There are 120 BPM at ALBA, but only 88 are used for the orbit correction, as much as OCM. When considering the square response matrix of the FOFB, the layout contains pairs of OCM without used BPM in between at each cell. Such feature is quite common in synchrotron light-sources where straight sections are used to install insertion devices. A consequence of this configuration for an square response matrix is that its inverse has only few non zero elements close to the diagonal. Each single BPM bump closes after few OCM. Two consecutive BPM lock angle and position and prevent the orbit bump to leak further. Also, two consecutive OCM can restore position and angle to the next BPM preventing the orbit bump to leak any further. To illustrate this, Fig. 1 shows the grey-scale map of the inverse 88 × 88 response matrix used by the ALBA FOFB.

In the ALBA case, the inverse response matrix has 432 non zero elements out of 7744 elements (88 × 88). In the horizontal plane due to the energy change of the bumped orbit and the dispersion function, the single BPM bump is not

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completely local. In the ALBA case this small contribution of the rest of the OCM is around a factor 10^{-3} smaller. In our approach it is not taken into account.

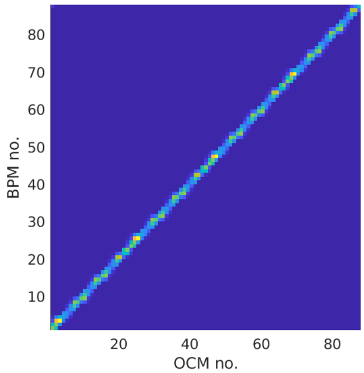

Figure 1: Color map of the square vertical plane iORM. The yellow color is associated with a high absolute value while the blue color represents the zero value.

COMPARISON WITH OTHER OBSERVABLES

Apart from the ORM, it is also common to use the betatron phase advance ϕ_i from each BPM i turn by turn (TbT) data to infer the local optics. Unlike R_{ij} and T_{ji}, ϕ_i have the advantage that do not require any calibration factor. As in the case of **R**, the $\boldsymbol{\phi}$ measurement requires a beam movement not compatible with operation.

The non zero **T** elements are far less than for **R** but more than for $\boldsymbol{\phi}$. However, since **T** is more local, the number of the fitting parameters describing the correlation between observables and knobs can be smaller. As a qualitative test, Table 1 shows the number of linear fitting parameters needed for the different observables mentioned previously at ALBA. Although it does not totally describes the fitting complexity, already the number of first order parameters gives a qualitative idea of which observable should be easier to fit, in this case the inverse response matrix **T**.

Table 1: Number of terms (first order) per plane to fit the dependency on the quadrupole strengths (knobs) using different observable in the ALBA case. Here we have considered the 112 quadrupoles plus the 32 combined function dipoles as knobs.

Method	Observables × Knobs	Linear Terms
R	10560×144	1520640
$\boldsymbol{\phi}$	120×144	17280
T	432×144	2608

To roughly evaluate the fitting complexity derived from the non-linearities, a single quadrupole strength k variation has been simulated up to 3% ($\Delta k/k = 0.03$). The relative variation of the observables was fitted as a function of $\Delta k/k$ with a second order polynomial ($a_0 + a_1 \Delta k/k + a_2(\Delta k/k)^2$). As shown in Table 2, the iORM responds to the quadrupole variation as strongly (a_1 coeficient) as the phase advance but not as much as the ORM. However the iORM non-linear effect (a_2/a_1 ratio) is up to a factor 80 smaller than for the rest of the compared observables.

Table 2: Simulated first and second order polynomial coefficients for different observables as a function of a single quadrupole strength variation. For each observable the element varying the most has been selected. The quadrupole strength has been varied up to 3%.

Observables	$\mathbf{a_1}$	$\mathbf{a_2}$
$\Delta\mathbf{R}/\mathbf{R}$	8.685493	1.002178
$\Delta\boldsymbol{\phi}$	0.538436	0.007941
$\Delta\mathbf{T}/\mathbf{T}$	0.574982	0.000119

In summary, the iORM should be easier to fit since it has less parameters and less non-linearly related than other observables.

This new technique is not free of new challenges. The OCM usually suffer from magnetic hysteresis. In the case of the ORM, to overcome this difficulty for every varied OCM all the BPM data can be used to fit the non repeatably of the OCM strength. In the case of the iORM when a BPM offset is varied every OCM will respond according to a different magnetic history since the FOFB is continuously changing their strength. This effect can be mitigated if the OCM changes are big enough and BPM offset change is repeated enough times. That makes the iORM more time consuming and less transparent fore the users unless the beamlines BPM are not affected. Regarding the systematic calibrations of BPMs and OCM, the ORM analysis since it has many more elements, is more robust. We believe that a complete online implementation of the iORM measurement should make use of the calibration established by the offline ORM analysis.

PROOF OF PRINCIPLE

To test the iORM method at ALBA, a single quadrupole (central quadrupole in a tripled with no BPM in between) was changed by −4A (3%). A complete measurement was not possible due to time constrains, only 3 BPM offsets were changed.

Changing a single quadrupole by an small amount allows to fit the iORM change and ignore the BPM and OCM systematic calibration errors. The ORM analysis is carried out by LOCO which fits the OCM and BPM calibrations but those were not used in the iORM analysis.

The iORM at ALBA is acquired using OCM set-points generated by the FOFB at a 2 Hz rate. The number of OCM measurements in this test was 20. The FOFB is actually sending write commands at 5 kHz but the software has not been prepared to make use of that data. That is a strong limitation in the precision (or speed) that we can get when measuring the iORM.

The RF correction loop was disabled for convenience. At ALBA the RF loop runs at 1Hz, stabilizes slower and when

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active occasionally the OCM readings changed considerably during the measurement.

The matrix **S** used by the ALBA FOFB has a considerable regularization. That causes the FOFB to react slowly after single BPM changes. The OCM readings are taken after that stabilization which can take up to 15 seconds. Considering adding and removing the BPM offset, the total measuring time after a BPM offset change was 40 seconds. Reducing the regularization is not an option at ALBA since this strongly increases the OCM noise.

As it can be appreciated in Fig. 2 the iORM measurement suffers from repeatability issues. Up to 5 repetitions were necessary to get rid of the OCM hysteresis effects. The relative hysteresis effect is larger for smaller OCM changes. In order to avoid that the BPM offsets change was selected to produce a maximum OCM change of 1A, which for the BPMs corresponds to a maximum of 300 µm and 170 µm in the horizontal and vertical plane respectively. In terms of beam size it represents a factor 1.3 and 14 larger in the horizontal and vertical plane respectively. That is quite far from what would be acceptable for operation (at least for the BPM located in the beam-line straight sections) but ensured a good accuracy of our test.

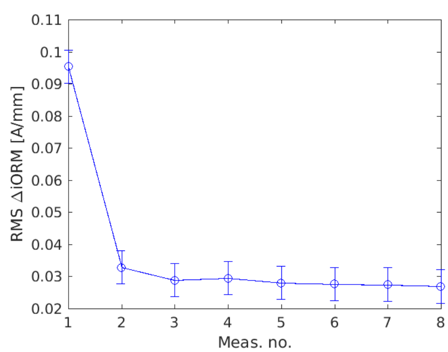

Figure 2: iORM RMS change among all the measured elements. Each BPM offset is varied 9 times consecutively.

As a consequence of the above mentioned limitations a measurement with the required precision would take 19 hours. For this reason the measurements were performed only varying 3 out of the 88 BPM. In this case the iORM has only 14 non-zero elements per plane. The change of the iORM matches quite well the expected value, this can be appreciated in Fig. 3. Using the iORM (blue line) the actual quadrupole change can be recovered with a quite good accuracy compared to the LOCO analysis (red line) which spreads the correction over the triplet as shown in Fig. 4. This comparison is not straightforward since LOCO fits the ORM (not the iORM), it takes only 1 minute to be measured, it uses the 1kHz fast archiver, it measures all OCM and BPM and it also fits their calibration factors. In order to understand LOCO's inaccuracy we performed an ORM fit with the same 4 quadrupoles (green line) used in the iORM fit. This is not realistic since the ORM is not local like the iORM but still the accuracy is not as nearly as good as with the iORM fit. The iORM was also fitted non-linearly using an artificial neural network (ANN) using Keras [4]. In this case the result improves only marginally but it could be helpful in the case of a complete iORM measurement. Using ANN provides a fast fitting mechanism that would be helpful if the method is ever implemented online.

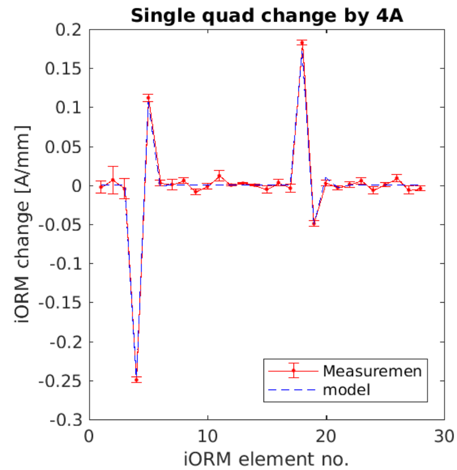

Figure 3: iORM change after changing a single quad by 4 A. The change according to the model is represented by a dashed line.

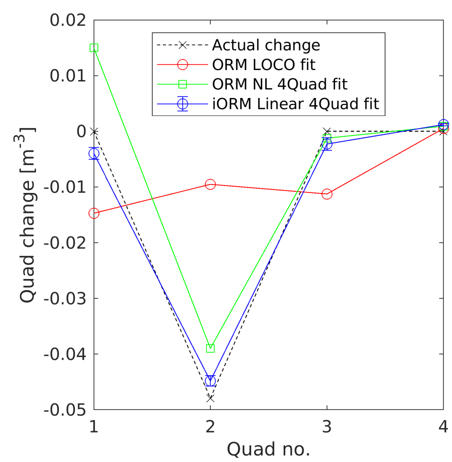

Figure 4: Quadrupole change reconstruction fitting the iORM data and a LOCO fit (ORM) compared with the actual quadrupole change. For comparison an unrealistic 4 quadrupole non linear ORM fit is added (green line).

CONCLUSION

The iORM technique has been presented together with a first promising test. This new technique makes it possible to accurately localize quadrupolar errors in a way that has never been possible before. On the long road to making the iORM usable during operation, many technical difficulties will have to be overcome. The main limitation at this point are the OCM hysteresis and reading speed and the FOFB correction speed. Other complications that can already be anticipated include the interaction with the orbit and optical correction systems.

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