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OPTICS MEASUREMENT USING THE *N*-BPM METHOD FOR THE ALBA SYNCHROTRON

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Abstract

The *N*-BPM method which was recently developed for the LHC has significantly improved the precision of optics measurements that are based on beam position monitor (BPM) turn-by-turn data. The main improvement is owed to the consideration of correlations for statistical and systematic error sources, as well as increasing the amount of BPM combinations for one measurement. We present how this technique can be applied at light sources like ALBA, and compare the results with other methods.

INTRODUCTION

Linear optics from closed orbit (LOCO) [1] is the standard method for optics measurements and corrections at the ALBA synchrotron [2]. Turn-by-turn measurements can provide faster optics measurements than LOCO and are of great interest also for other light sources [3–5]. Recently, efforts have been put in developing optics measurements based on BPM turn-by-turn data at ALBA. However, previous measurements showed discrepancies of the measured β-beating in comparison to LOCO of 4-10 % [6]. Also at SOLEIL significant discrepancies were observed when comparing the β-beating from turn-by-turn measurements to LOCO and an optics correction study at SLS found an inferior performance of turn-by-turn measurements compared to LOCO. Studies in ESRF [7] show that the model which arises from a fit to the phase advances from turn-by-turn data is superior to their standard orbit response matrix (ORM) based model. However, this approach could not become operational for technical reasons. One method to infer the β-function uses the phase advance of the betatron oscillation between three BPMs [8, 9]. The phase advance can be derived from the BPM turn-by-turn data while an oscillation has been excited on the beam.

Previous attempts of optics measurements from turn-by-turn data at LHC and SOLEIL used only neighboring BPMs for the analysis because the effect of systematic errors for larger ranges of BPMs would quickly deteriorate the results. The *N*-BPM method overcomes this limitation by performing a detailed analysis of systematic and statistical errors and their correlations [10]. This allows to consider more BPM combinations for the analysis and therefore to use more information when probing the β-function at one BPM position. This is especially useful if neighboring BPMs have phase advances which are not well suited for a measurement. Optimal phase advances in between two BPMs are $45° + n_1 \cdot 90°$, and phase advances of $n_2 \cdot 180°, (n_1, n_2) \in \mathbb{N}^2$ should be avoided. The phase advances of consecutive BPMs are shown in Fig. 1 for the nominal ALBA lattice. In the vertical plane there are many consecutive BPMs with small phase advance, and considering BPMs combinations within a larger range of BPMs would allow for better phase advances for the measurement.

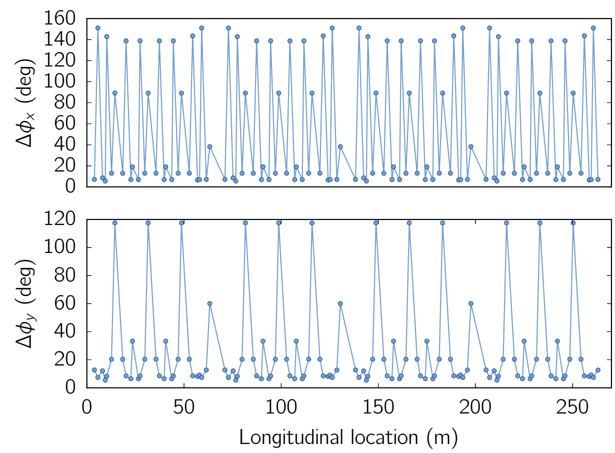

Figure 1: Phase advances of consecutive BPMs in the nominal model.

SYSTEMATIC ERRORS

For the *N*-BPM method it is crucial to consider model uncertainties and their correlations for the β-function measurement. They can be derived for example in a Monte-Carlo simulation where the error sources are varied within their uncertainty and the impact on the measurement is observed. The calculation of systematic errors is based on the uncertainties of magnetic measurements and alignment uncertainties, which can be found in Table 1. The Monte-Carlo simulation was performed for 1,000 iterations and the error sources were varied randomly following a Gaussian distribution.

We perform Monte-Carlo simulations separately for each contribution to study how much each error source is contributing to the total systematic error, cf. Fig 2. The dominant contribution comes from quadrupolar gradient errors (b_2), and transverse misalignment of sextupole magnets. For the horizontal plane the quadrupole b_2 errors have a larger effect than the dipole b_2, which is the opposite in the vertical plane. This is because β_y is much larger at the dipole magnets than β_x.

The systematic errors can furthermore be assessed separately for different BPM combinations. In Table 2 the aver-

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Table 1: Uncertainties Which Are Considered in the Computation of Systematic Errors. Gradient errors are specified relative to their main field (quadrupoles), respectively relative to their quadrupole component (dipoles).

Gradient errors	**Uncertainty**
Dipole b_2 component	0.1 %
Quadrupole	0.2 %
Misalignments	
Quadrupole, longitudinal	300 µm
BPM, longitudinal	300 µm
Sextupole, transverse	150 µm

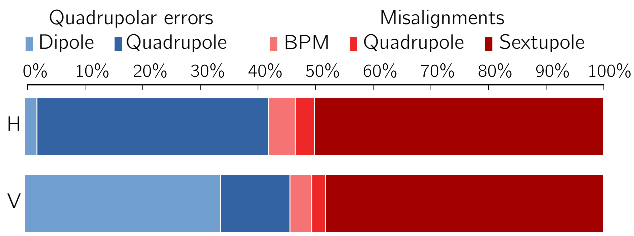

Figure 2: Contribution of different uncertainties to the average systematic errors. This is shown for probing the middle BPM of neighboring BPMs as it is the combination which has the smallest systematic error and is averaged over all BPMs. The top bar is for the horizontal plane (H) and the bottom one for the vertical plane (V). Quadrupolar errors are shown in blue and misalignment uncertainties in red.

age systematic error of the measured β-function is shown for different BPM combinations. The lowest error is in both planes achieved for neighboring BPMs, if the BPM in the middle is probed. For other BPM combinations the systematic errors are increasing more in the horizontal than in the vertical plane. The uncertainty of the measurement depends additionally on the statistical error of the phase measurement. Considering systematic errors and correlations allows to use more BPM combinations together to probe the β-function in order to minimize the measurement uncertainty [10].

MEASUREMENTS

The ALBA synchrotron is equipped with 120 BPMs, but acquiring reliable turn-by-turn data is not a straight-forward task, and requires a thorough understanding of the BPM electronics, accurate timing system setup and BPM synchronization. At ALBA, the setup of a reliable turn-by-turn data measurement took almost two years and has finally been carried out thanks to the successful implementation of the moving average filter acquisition mode (MAF) [11]. The value of the β-function at the BPM positions vary approximately between 4 m and 12 m. For the excitation of the betatron oscillation, a pinger magnet was used. The peak-to-peak value of the amplitude for the betatron oscillation was 1 mm in the horizontal plane and 1.4 mm in the vertical plane, for BPMs with a β-function of around 12 m. The turn-by-turn data was acquired for 1024 turns, and the measurement was repeated 40 times. From these 40 data sets only 31 were used in the analysis since some cases needed to be excluded due to BPM synchronization problems. A cleaning of the turn-by-turn data was performed using the singular value decomposition (SVD) technique and keeping only the 12 strongest modes [12, 13]. Figure 3 shows the β-beating as computed from the phase of the betatron oscillation with the N-BPM method in comparison with the results obtained with LOCO. The error bars for the N-BPM method contain systematic and statistical uncertainties whereas the error bars for LOCO account only for the reproducibility of the results.

Table 2: Systematic Error of the Measured β-function for Using Different BPM Combinations. The five best combinations are shown for each plane.

BPM combination (△: probed, ▲: used, △: unused)							**Average systematic error (%)**
horizontal plane							
unused	unused	used	probed	used	unused	unused	0.18
unused	used	used	probed	unused	unused	unused	0.49
unused	used	unused	probed	used	unused	unused	0.87
used	used	unused	probed	unused	unused	unused	0.99
used	unused	used	probed	unused	unused	unused	1.0
vertical plane							
unused	unused	used	probed	used	unused	unused	0.17
unused	used	unused	probed	used	unused	unused	0.27
used	unused	unused	probed	used	unused	unused	0.51
unused	used	unused	probed	unused	used	unused	0.63
unused	used	used	probed	unused	unused	unused	0.64

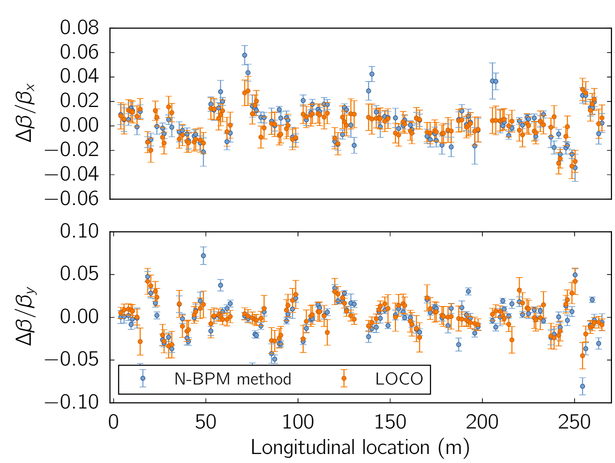

Figure 3: Comparison of β-beating as derived from BPM turn-by-turn data using the phase of the betatron oscillation (N-BPM method) to the β-beating from LOCO.

There is a good agreement for many data points between both methods, however in general the deviations from LOCO to the nominal model are smaller, cf. Table 3. Another

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method which can be used to obtain the β-function uses the amplitude information of the betatron oscillation. A prerequisite for this method is the knowledge of the kick action as well as the gain of the BPMs. Instead of assessing these values, a normalized β-function was computed [14]. The β-beating from the amplitude method is compared to the *N*-BPM method in Fig. 4 and the RMS β-beating are shown in Table 3.

Table 3: The First Part Shows the RMS Deviation of the β-function to the Nominal Model as Computed from the Different Methods. The second and third part shows the RMS deviation of the β-function between using two different methods.

Method vs. nominal model	**RMS β-beating (%)**	
	horizontal	vertical
N-BPM (phase)	1.5	2.2
From amplitude	2.0	2.7
LOCO	1.1	1.6
Method 1 vs. Method 2		
N-BPM (phase) vs. LOCO	1.0	1.5
N-BPM (phase) vs. amplitude	1.8	2.3
From amplitude vs. LOCO	1.4	1.7
N-BPM using LOCO model		
N-BPM (phase) vs. LOCO	1.1	1.2

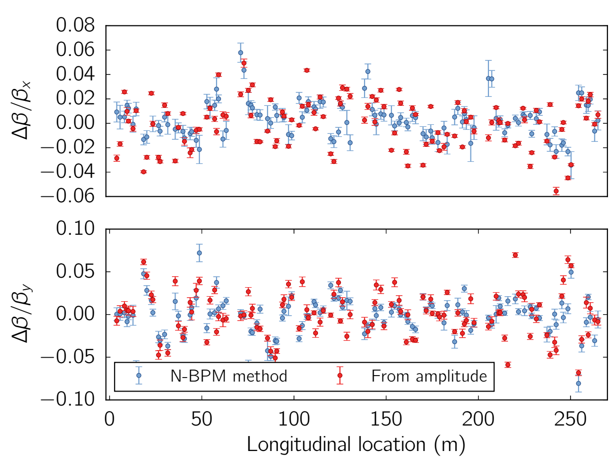

Figure 4: Comparison of β-beating as derived from BPM turn-by-turn data using either the amplitude information or phase of the betatron oscillation (*N*-BPM method).

The amplitude method shows the largest deviation from the nominal model. Using the normalized β-function on the one hand does not suffer from uncertainties of the computed kick action or BPM gains, but on the other hand introduces further systematic errors.

Since the *N*-BPM method uses model transfer matrix elements, it was also tested to run the analysis not with the ideal model, but the model that has been fitted with LOCO. The idea is that if the LOCO model is closer to the real machine, then using the LOCO model for the *N*-BPM method should also provide a result that is closer to the LOCO result. There is a slight increase of the RMS β-beating from the *N*-BPM method to LOCO of 10 % in the horizontal plane and an improvement of 20 % in the vertical plane. LOCO is not necessarily providing a model closer to the real machine than the nominal model, especially in the horizontal plane.

The maximum RMS β-beating between *N*-BPM method and LOCO of 1.5 % is still very good, especially since previous studies of LOCO measurements at ALBA concluded that only a value of ≈ 1 % for the accuracy of LOCO is possible [15].

CONCLUSION

Large efforts for optics measurements from turn-by-turn data at ALBA resulted in a great step forward in both cases of using either amplitude [14] or phase (*N*-BPM) of the betatron oscillation. Deriving systematic errors and correlations in the *N*-BPM method successfully increased the optics measurement precision. The agreement with LOCO is now at a level of ≈ 1 %. For the first time turn-by-turn data and LOCO show the same level of precision in the measurement of β-functions at light sources. Further studies should also evaluate the different performance for each method with respect to reconstruct optics errors, which could be applied to the machine on purpose before an optics measurements. Furthermore, comparisons to β-functions derived from quadrupole variation should be possible in the future [16].

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