COMPARISON OF OPTICS MEASUREMENT METHODS IN ESRF

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Abstract

The N-BPM and the Amplitude methods, which are used in the LHC for beam optics measurement, were applied to the ESRF storage ring. We compare the results to the Orbit Response Matrix (ORM) method that is routinely used in the ESRF. These techniques are conceptually different since the ORM is based on the orbit response upon strength variation of steering magnets while the LHC techniques rely on the harmonic analysis of turn-by-turn position excited by a kicker or an AC dipole.

Finally, we compare these methods and show the differences in their performance in the ESRF environment.

INTRODUCTION

We compare different optics measurement methods performed in the ESRF storage ring assessing the agreement of results and highlighting the effects that distort the agreement. The N-BPM method [1], where BPM stands for Beam Position Monitor, and the Amplitude method [2] rely on harmonic analysis of turn-by-turn position from all BPMs. The beam has to be excited by AC dipoles or kickers. As the amplitude method uses the amplitude of the transverse beam motion, it is biased by BPM calibration errors as discussed for example in [3]. The N-BPM method first decodes the phase of each tune line. Then phase advances between consecutive BPMs are obtained and used as described in [1]. The Orbit Response Matrix (ORM) is a closed orbit response to a unit change of single corrector strength [4], which depends on β-functions, betatron phases at BPM locations and corrector positions. It is obtained by successively changing corrector strengths one by one and measuring the closed orbit.

SYSTEMATIC ERRORS

The β-function from N-BPM method is a weighted average of β-functions obtained from various combination of BPM pairs. Ten thousand lattices were simulated, to estimate the resulting systematic error of β-function calculated from phase advances between given combination of BPMs. To account for the effects of unknown error sources the estimated misalignments and uncertainties of magnetic properties were added to simulated lattices. The added uncertainties are assumed to be normally distributed and are shown in Table 1.

Table 1: Estimated Gaussian Uncertainties of the Lattice

Uncertainty	σ
longitudinal quadrupole misalignment	1.8 mm
longitudinal BPMs misalignment	2.0 mm
transverse sextupole misalignment	0.1 mm
quadrupole gradient	0.6%
BPM resolution (horizontal plane)	12 µm
BPM resolution (vertical plane)	10 µm

ANALYSIS LIMITATIONS

We studied the measured accuracy with simulations in order to obtain optimal parameters for measurement i.e. number of turns acquired and kick amplitude. Due to particularly strong lattice sextupoles the amplitude detuning is very pronounced and it is at the level of $2.5 \cdot 10^{-3}$ and $1.0 \cdot 10^{-3}$ for the largest kicks that were applied in horizontal and vertical planes, respectively. The performance of harmonic analysis strongly depends on the number of analyzed turns. Single particles with various initial transverse displacements were tracked through the nominal lattice. The BPM white noise affecting the resolution shown in Table 1 was then added to the turn-by-turn data. Tracked-particles data were analysed using different number of turns. The harmonic analysis resolution as a function of number of turns degrades more rapidly below 500 turns, nevertheless it could be partially cured by imposing the same tune for each BPM (the average measured tune) [5]. Large transverse beam excitation spoils the optics linearity, due to "additional" focusing from sextupoles [6]. In Figure 1 the β-beating of single particles tracked through nominal lattice obtained by N-BPM method is shown. The particle initial displacements match the range of beam excitations during the measurement. Up to 10% peak β-beating is observed due to the kick amplitude. To achieve 1% accuracy in the β-function a kick below 2 mm at β = 36 m in horizontal plane is needed. The best setting for the measurement is the longest acquisition with the smallest possible beam oscillation, which still should be an order of magnitude higher than the BPM white noise, which can not be achieved due to kicker instability at low amplitudes.

OPTICS

A special optics was set-up to allow for precise measurements with all the methods under consideration. The choice of sextupole settings is of critical importance in the

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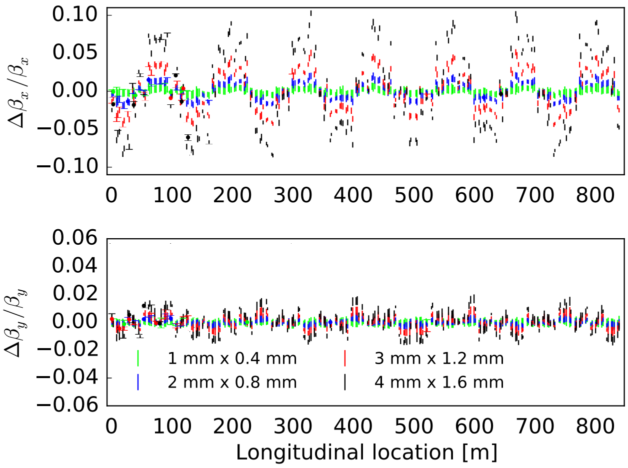

Figure 1: Simulated β-beating of single particles tracked through the nominal lattice with the nominal model used for reconstruction by N-BPM method, with transverse displacement at β_x = 36 m and β_y = 6 m as shown in the legend (notation: horizontal x vertical).

ESRF storage ring. It strongly influences the decoherence of transverse beam motion and, of course, the chromaticity. There are two main drivers for the setting: performance of harmonic analysis requiring at least several hundred turns with longer damping times and chromaticity, which needs to be small in order to perform off-momentum measurements. The damping times were about 1000 turns and 2000 turns and measured chromaticities were -1.5 units and -0.1 units in horizontal and vertical planes, respectively.

Optics was corrected for the measurement using the ORM method. The fractional betatron tunes were at nominal values of 0.44 in horizontal plane and 0.39 in vertical plane.

OPTICS MEASUREMENT

The average BPM resolution was estimated by subtracting SVD-cleaned and raw data, which gave the resolution of 12 µm in horizontal plane and 10 µm in vertical plane. Once the optics was corrected the orbit response matrix was re-measured. Afterwards, turn-by-turn data of beam excited by kickers at transverse amplitudes varying in range from 1.25 mm to 4.5 mm were acquired. We performed ten kicks at each amplitude. For a given momentum both ORM and turn-by-turn data were taken with the same beam (no re-injection). The ORM was measured for 5 different beam energies (relative variation 0.25 %) and the turn-by-turn data were then taken even for 7 different beam energies.

COMPARISON OF THE RESULTS

Turn-by-turn data with the lowest amplitude of the oscillation were chosen for comparison studies since in this case the linear optics is the least disturbed by amplitude detuning and non-linearities. The β-beating obtained from turn-by-turn data with help of the nominal model and from ORM are shown in Table 2 and Figure 2. The two are in good agreement. The β-beating from the Amplitude method is systematically influenced by BPM calibration errors and non-linearity, which is why it is inferior to the N-BPM method. Moreover, the Amplitude method requires to rescale all β-functions according to the average β-function in the model. This in turn adds another systematic effect, because the average β-function depends on the rms β-beating [6, 7]. The systematic errors are not included in the average error unlike in the case of the N-BPM method. In Table 3 the rms relative difference between β-functions obtained by different methods is shown.

Table 2: Rms β-beating obtained by three different methods with respect to the nominal model using the nominal for the analysis and together with its average measurement error.

β-beating	N-BPM [%]	Amplitude [%]	ORM [%]
rms_x	5.0	5.0	5.2
rms_y	3.4	3.4	3.4
mean err_x	0.55	0.20	
mean err_y	0.37	0.16	

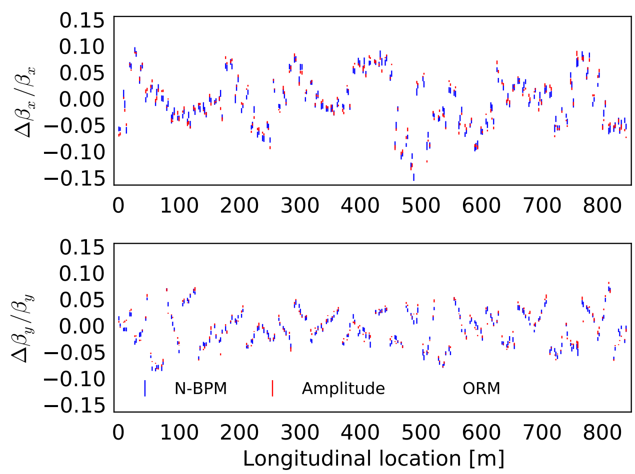

Figure 2: Measured β-beating with respect to the nominal model obtained by three different methods: N-BPM, Amplitude and ORM.

Table 3: Relative difference of βs (β-beating) between the results obtained by different methods using the nominal model for the analysis.

Relative difference of βs	N-BPM vs Amplitude [%]	Amplitude vs ORM [%]	N-BPM vs ORM [%]
rms_x	1.1	1.9	1.7
rms_y	0.8	1.9	1.8

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The agreement among the results of the all the three methods is significantly better, than their agreement with the nominal model. Therefore we use the model inferred from ORM instead of the nominal model as an input to the analysis as well as a reference. Table 4 and Figure 3 show the resulting relative difference of β-functions. The rms of the relative difference between the β-functions obtained from N-BPM and from ORM got significantly reduced. Moreover the average error, which is proportional to uncertainty of measurement, got reduced from 0.55 % to 0.41 % in horizontal plane and from 0.37 % to 0.32 % in vertical plane.

Table 4: Relative difference of βs (β-beating) between the results obtained by different methods using the ORM model for the analysis

Relative difference of βs	N-BPM vs Amplitude [%]	Amplitude vs ORM [%]	N-BPM vs ORM [%]
rms_x	1.3	1.7	1.0
rms_y	0.9	1.3	0.9
mean err_x		0.20	0.41
mean err_y		0.16	0.32

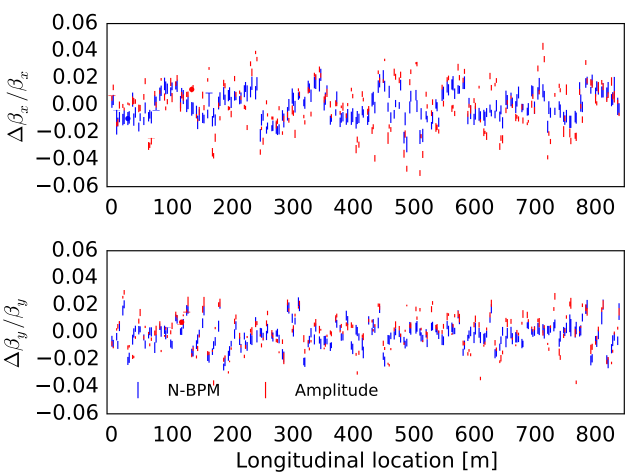

Figure 3: Measured β-beating with respect to the ORM model

Dispersion was measured using ORM and from turn-by-turn data. It is shown in Figure 4. Measurements are in very good agreement within the measurement errors.

The chromatic W-function, which describes how the β-function depends on momentum, is defined by:

$$W = \frac{1}{2} \cdot \sqrt{\left(\frac{\Delta\beta}{\beta \cdot \Delta p}\right)^2 + \left(\frac{\Delta\alpha}{\Delta p} - \frac{\alpha \cdot \Delta\beta}{\beta \cdot \Delta p}\right)^2}, \quad (1)$$

where α, β are Twiss parameters and Δp is relative changed of beam momentum. It was measured using turn-by-turn data and it is shown in Figure 5.

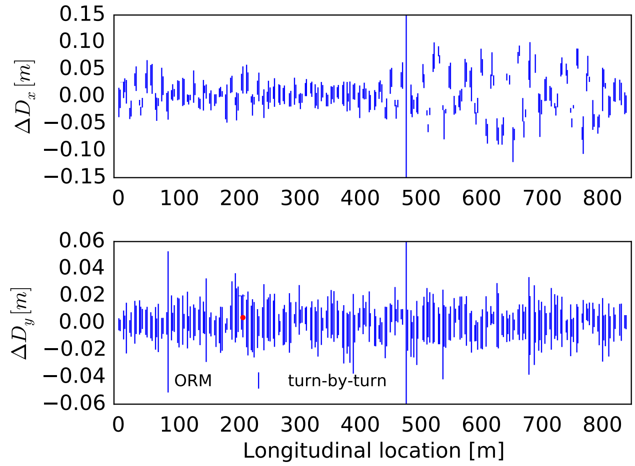

Figure 4: Dispersion deviation from the nominal model obtained from ORM and turn-by-turn data.

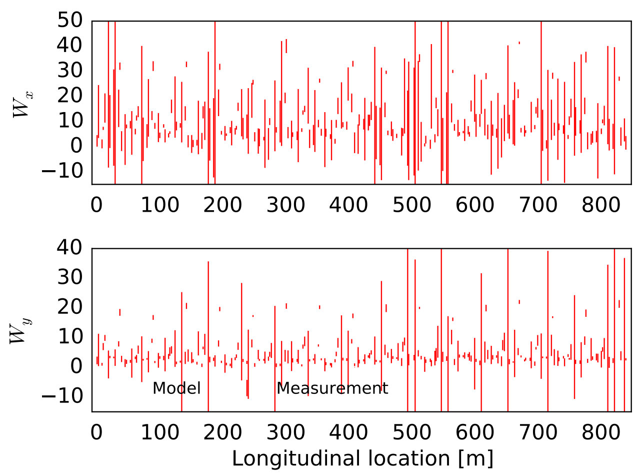

Figure 5: Measured W-function compared to nominal model

CONCLUSIONS AND OUTLOOK

Three optics measurement methods were used and their results compared for the ESRF storage ring. The β-beating measured by N-BPM method and ORM are in agreement to the 1% level, which is about 1σ. The agreement of the results obtained by the Amplitude method with the other two techniques is slightly worse, probably due to BPM calibration errors. The systematic effects on measurement can be further reduced, especially optics non-linearities, by lowering the beam excitation. This could be done by natural transverse oscillation damping, i.e., the turn-by-turn data could be acquired with a delay after the kick. To further improve the harmonic analysis the synchrotron motion could be subtracted from the transverse oscillations. Table 4 shows the resulting rms β-beating between the compared methods. More general analytical discussion is presented in [6].

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