BENCHMARKING OF THE NTRM METHOD ON OCTUPOLAR NONLINEAR COMPONENTS AT THE CERN-SPS SYNCHROTRON

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Abstract

The knowledge of the distribution of the nonlinear components in a ring is important for the resonance compensation. A method to measure the lattice nonlinear components based on the nonlinear tune response to a controlled closed orbit deformation (NTRM) was suggested in [1]. First benchmarking of this method was carried out with controlled sextupolar errors in the SIS18 synchrotron at GSI. We present here a further benchmarking of NTRM by using controlled octupolar errors at CERN SPS.

INTRODUCTION

The nonlinear field errors in the magnets excite unwanted resonances, which cause beam loss and dynamic aperture reduction. An approach to retrieve nonlinear field components is based on the measurement of the tune dependence on the momentum spread (called the nonlinear chromaticity) [2]. Varying the strengths of the nonlinear elements (fitting parameters) of the lattice model the fitted polynomial is reproduced. Another approach for measuring nonlinear components and compensating resonances is based on the resonance driving term (RDT) [3]. If the lattice is not free from nonlinearities, the spectrum of the betatron oscillations contains the betatron tune line and secondary spectral lines from the resonance driving term in the Hamiltonian to the first perturbative order. In general, a given spectral line is fed by different multipoles at different orders. A technique to diagnose nonlinear field components based on the *tune response* to the deformed CO was developed at BNL [4]. There the closed orbit was deformed via a local bump. At GSI this technique was extended with the NTRM [1]: The approach used is similar to the orbit response matrix (ORM) method, where the CO response to the steering angle change provides information on the linear field errors. This method extends the ORM analogy to the nonlinear errors with the difference that the tune response to the steering angle change is measured. The method is therefore referred to nonlinear tune response matrix (NTRM). This technique is useful for resonance compensation in project as FAIR [5], where the resonance compensation is required for mitigating space charge effects.

Benchmarking of NTRM at GSI

The NTRM method was experimentally benchmarked at GSI by reconstructing two controlled normal sextupolar errors with strength of the order of natural errors in the SIS18 [1]. The accuracy reached in the reconstruction of the controlled sextupolar errors is better than 10% for sufficiently large errors. The benchmarking of NTRM continues by attempts to reconstruct from six to twelve controlled sextupololar errors. The status this investigation is reported in [6]. Presently the benchmarking in the SIS18 is limited by the lack of higher order magnets as octupoles.

THE EXPERIMENT IN THE SPS

The benchmarking of NTRM with octupolar error was performed at the CERN SPS (SIS18 has no octupoles). The contribution to the machine tunes of several octupolar errors when the CO is distorted by one steerer is [1]

$$\Delta Q_x = \sum_{t=1}^{N_t} {}_xQ_{tt}^{xx} \theta_{xt}^2, \tag{1}$$

where

$${}_xQ_{tt}^{xx} = \frac{1}{2}\frac{1}{4\pi}\sum_{l=1}^{N_l} \beta_{x\,l} K_{3l} M_{lt}^x M_{lt}^x + O(2)\,, \tag{2}$$

and, θ_{xt} is steering angle, M_{lt}^x is the orbit response matrix at the location of the steerer and location of the octupolar error, $\beta_{x\,l}$ is taken at the location of the octupolar error, K_{3l} is the integrated strength of the octupolar error, and $O(2)$ is the quadratic contribution of sextupoles (see Eq. (20) in Ref. [1]). The NTRM method requires the measurement of ΔQ_x vs. θ_{xt} so to determine ${}_xQ_{tt}^{xx}$. If the number of steerers θ_{xt} is equal to the number of errors, then Eq. (2) form a linear system which can be solved in K_{3l}.

Consequences of the SPS Symmetry

The CERN-SPS has two families of octupoles located symmetrically in all periods. The octupoles of the each family are powered by a common power supply. The horizontal steerers of SPS are placed symmetrically over the rings's circumference with respect to the octupoles of the two families. The symmetrical placement of the steerers and octupoles respect each other, and the powering octupoles in families (i.e. with the same strength) builds a symmetry of the SPS with respect to the steerers and the sequence of octupoles encountered in the machine. This symmetry leads to the linear dependence of the rows of the linear system Eqs. (2). A different type of information is needed to avoid this linear dependence in Eqs. (2), which can be obtained by breaking up the steerer-octupole symmetry using a combination of two steerers, called here 1, and 2. We create then a "virtual" steerer, $S^+ = (S1, S2) = (\theta_1, \theta_2) = (\theta_+)$, where $\theta_1 = \theta_2 = \theta_+$. Therefore Eq. (20) in Ref. [1], for this steerer configuration, yields ${}_xQ_+^{xx} = {}_x Q_{11}^{xx} + {}_x Q_{22}^{xx} + {}_x Q_{12}^{xx} + {}_x Q_{21}^{xx}$, that is

$$\Delta Q_x = {}_xQ_+^{xx}\theta_+^2 = 2({}_xQ_{11}^{xx} + {}_xQ_{12}^{xx})\theta_+^2. \quad (3)$$

The term ${}_xQ_{12}^{xx}$ is responsible for breaking the symmetry allowing the reconstruction.

The Experimental Procedure

For measuring the tune response, a small emittance beam is created and kicked for exciting transverse betatron oscillations. In order to prevent fast beam oscillation decoherence, the machine chromaticity is corrected. This causes additional 3d order resonances and quadratic nonlinear components in SPS. Therefore any controlled octupolar error would be simply added to the existing know and unknown nonlinearities. We have considered the case of two controlled normal octupolar errors (the two families of SPS octupoles) to be reconstructed by deforming the CO by means of two horizontal steerers. As we excite normal errors, only horizontal deformation of the CO can reveal them. First, we measure the tune response for the machine set for normal operation with chromaticity compensated (referred to the setting `S0`), then we add on the SPS lattice the two families of octupoles and re-measure the tune response for the same deformation of the CO (referred as `S0+O`). By subtracting the two response curves, the resulting differential tune response depends solely from extra octupolar error added to the lattice. As the octupolar errors are folded linearly into the terms ${}_xQ_{11}^{xx}$ and ${}_xQ_+^{xx}$, the experimental task is of measuring the differential tune response and obtaining ${}_xQ_{11}^{xx}$ and ${}_xQ_+^{xx}$.

A Numerical Example

Fig. 1a shows the horizontal tune response of SPS vs. horizontal steerers S (`MHD10207`) and S^+ (combination of the two steerers `MHD10207` and `MHD20407`) over the maximum possible steering range of [-150μrad;150μrad]. The setting `S0` is referred to chromaticity sextupoles of the five families switched on: K_2(`LSDA.F`)=-0.1672 m^{-2}, K_2(`LSDB.F`)=-0.0964 m^{-2}, K_2(`LSFA.F`)=0.0416 m^{-2}, K_2(`LSFB.F`)=0.1619 m^{-2}, and K_2(`LSFC.F`)=0.0416 m^{-2}. The setting `S0+O` refers to the same chromaticity sextupoles and octupoles of the two families switched on: K_3(`LOD`)=4.0 m^{-3} and K_3(`LOF`)=2.0 m^{-3}. In this simulation the CO is initially deformed of about 2 mm. Fig. 1b shows the differential tune response, and fitting a quadratic polynom to the each of the parabolic curves we obtain ${}_xQ_1^{xx}$ and ${}_xQ_+^{xx}$. On Fig. 1c a simulation of the difference in CO for the settings `S0+O` and `S0` is presented: for the large steering angles a quadratic-cubic behavior is obtained. If we take the data on the small steerer range (grey region in Fig. 1b and c) to fit the quadratic polynom, in the perturbative condition of the linear CO regime, then solving the system of Eqs. (2) gives the reconstructed solution

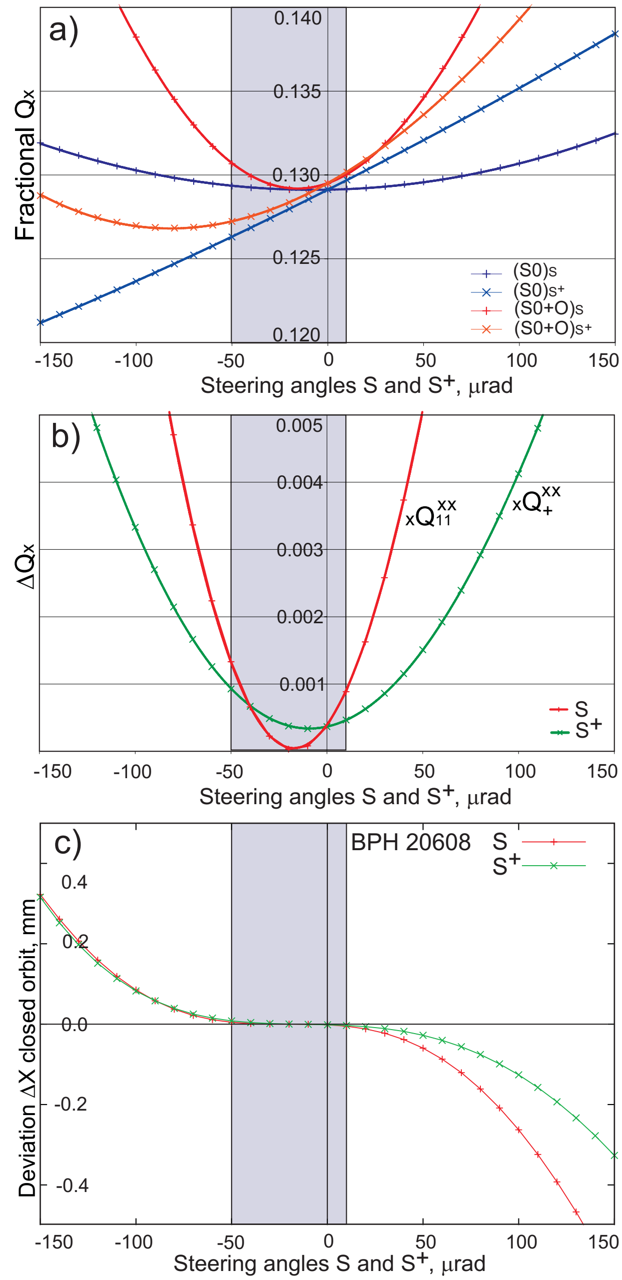

Figure 1: Simulated a) fractional part of the SPS horizontal tune vs. horizontal steering angles for only chromaticity sextupoles (blue and light blue) and with octupoles (red and orange). b) The correspondent differential tune response. c) Deviation of CO from linear response.

for K_3(`LOD`)=4.01 m^{-3} and K_3(`LOF`)=1.99 m^{-3}. However, taking the full range of the nonlinearly responded CO to the deformation, the reconstructed solution is away from the set values: K_3(`LOD`)=18.24 m^{-3} and K_3(`LOF`)=0.86 m^{-3}.

RESULTS

The coherent betatron oscillations of a bunched beam were excited by a fast kick at injection energy of about 26 `GeV/u` and an intensity level of approximately 5.5×10^{11}

particles. The kick was given in both x- and y-planes simultaneously with $\theta_x = 3$ kV and $\theta_y = 2$ kV over all 12 bunches. The chromaticity was corrected and 1024 turns were measured. The fractional part of tunes were retrieved using FFT with averaging over the number of BPMs and over the number of measurements.

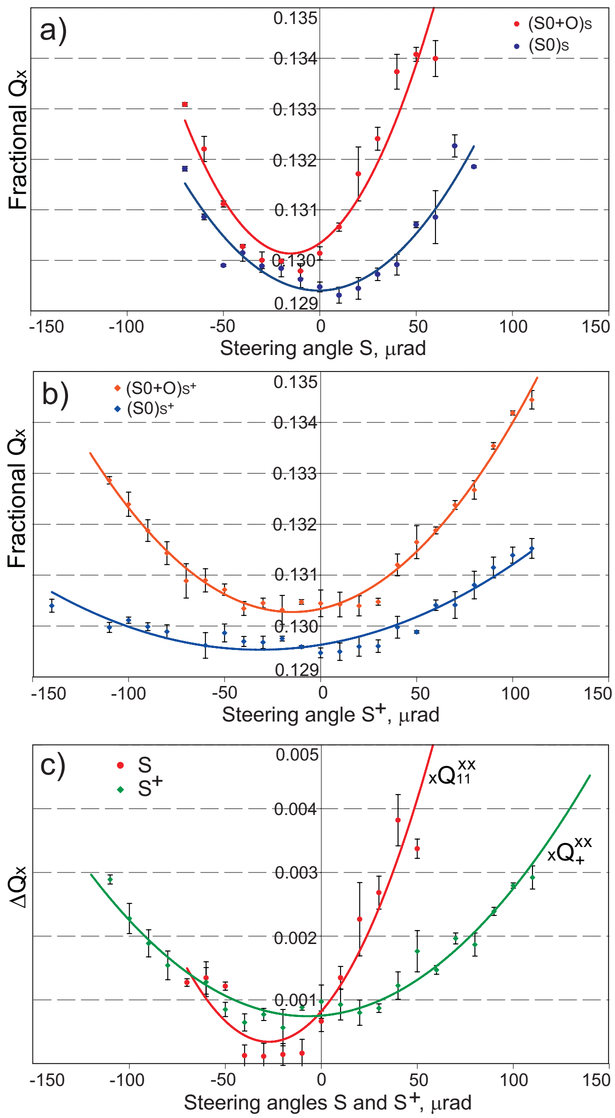

Figure 2: Measured fractional part of the SPS horizontal tune for chromaticity sextupoles switched on and octupoles on top of the chromaticity setting vs. horizontal steering angles S in a) and S^+ in b). c) Differential tune response.

Experimental Tunes and Limits of NTRM

Fig. 2 shows the experimentally measured absolute and differential horizontal tune response for the same steerer configuration as of the simulation in Fig. 1. The sextupoles and octupoles were excited to the same values as in the simulation. The octupole values $K_3(\mathtt{LOD}) = 4.0$ m^{-3} and $K_3(\mathtt{LOF}) = 2.0$ m^{-3} were chosen strong in order to make the differential response more resolvable (of the order 10^{-3}), since the precision of the tune measurement is of the order 10^{-4}. For the same reason, the steerers were varied almost to the maximum range of 150 μrad. The large range of the CO deformation (COD) interferes with the perturbative condition in which NTRM is valid. Hence, a fit of tunes with a quadratic polynom does not yield ${}_xQ_{11}^{xx}$ and ${}_xQ_{+}^{xx}$.

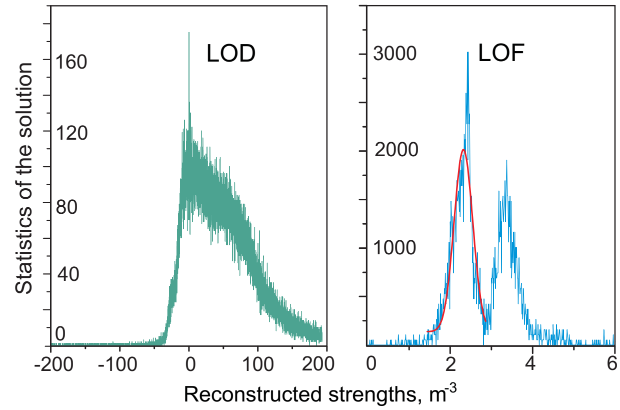

Figure 3: Distribution of the reconstructed $K_3(\mathtt{LOF})$ and $K_3(\mathtt{LOD})$ for several ranges of COD.

CONCLUSION

The result of the reconstruction of $K_3(\mathtt{LOF})$ and $K_3(\mathtt{LOD})$ depends on which range we select the tunes (or COD) in Fig. 2. In order to avoid arbitrariness in selecting the data range, we proceed with a statistical approach showing all the results, for arbitrary ranges, in an histogram (Fig. 3). We find that among all the reconstructed solutions, which include also the error bar on the fit parameters, the octupole strength $K_3(\mathtt{LOF}) = 2.35 \pm 0.32$ m^{-3} emerges with a distinct peak (Fig. 3 right). The other otcupolar error $K_3(\mathtt{LOD})$ is not retrieved with decent accuracy. We attribute this large spread to the deviation of the experimental conditions from the perturbative requirement to apply NTRM. That is, as here discussed (and also in Sec. III of Ref. [1]), we used too large COD, and large controlled octupolar errors.

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