STATUS OF THE DEVELOPMENT OF A BE-MODEL-BASED PROGRAM FOR ORBIT CORRECTION AT THE ELECTRON STORAGE RING DELTA

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Abstract

A new program for orbit correction is currently being developed at the electron storage ring DELTA. Based upon the standard approach of utilizing the linear response of a closed orbit to dipole-field-strength variations, proposed features include a live-updated orbit-response-matrix model and the integration of the Closed-Orbit-Bilinear-Exponential-Analysis algorithm (COBEA) to clean measured orbit-response matrices from noise. This work focuses on the current status of development of the aforementioned program. After an assessment of the situation at DELTA, first measurements are shown along with numerical convergence studies.

INTRODUCTION

The electron storage ring DELTA is a third-generation synchrotron light source operated by the TU Dortmund University running at 1.5 GeV nominal energy. It supplies synchrotron radiation in the VUV, soft and hard X-ray regime for experiments in condensed matter and chemistry physics. Due to difficulties modeling magnetic fields in the injection area of DELTA and a misalignment of magnet-optical elements in the eastern and western curve of the storage ring [1], existing lattice models do not match the optics of the storage ring well enough to use particle tracking codes like MAD-X for correction. Any orbit-correction program at DELTA has to rely on a measured orbit-response matrix to correct the orbit of the storage ring which limits the quality of orbit corrections. The transverse orbit position is currently controlled via a SVD-based approach in service since 2005 [2]. The program lacks a simultaneous correction of both planes and correction steps are slow at times. There are also some unknown software issues causing the program to freeze from time to time. Based on these facts, it was concluded that the quality and reliability of orbit correction at DELTA could benefit from a new program for orbit correction.

ORBIT CORRECTION VIA LINEAR ORBIT RESPONSE

The quality of the correction of a closed orbit refers to the deviation $\Delta\vec{\kappa}_d$ of this orbit from the reference orbit which can be expressed as a scalar quantity

$$\chi^2 = \sum_{d=1}^{2} ||\mathbf{W}_d \cdot \Delta\vec{\kappa}_d||^2$$

using the Euclidean norm $||...||$. $\mathbf{W}_d$ is a diagonal matrix of weights which increases the impact of the orbit deviation in critical positions of the storage ring (insertion devices, injection septum) on χ^2. d indexes the horizontal and vertical plane. A program attempting an orbit correction then has to minimize

$$\chi^2 = \sum_{d=1}^{2} \left\| \mathbf{W}_d \cdot (\Delta\vec{\kappa}_d + \mathbf{R}_d\vec{\theta}) \right\|^2$$

by variation of the deflection angles $\vec{\theta}$. The resulting vector translates into a set of currents for the correction magnets of the storage ring. The linear response $\mathbf{R}_d\Delta\vec{\theta}$ of the closed orbit then minimizes the orbit deviation $\Delta\vec{\kappa}$ where $\mathbf{R}_d$ is the orbit-response matrix in plane d.

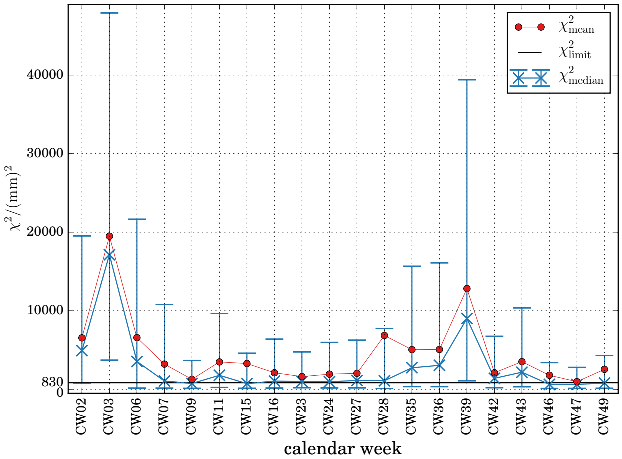

Figure 1: Median (blue) and mean (red) of χ^2-distributions at DELTA per week for all weeks in 2016 where the storage ring was solely used to generate synchrotron radiation for experimental use (standard operation). The error margins given correspond to the 95 %-confidence interval around the median. The displayed analysis results were created from parameters automatically logged by the orbit-correction program of DELTA. To receive a representative data set, data points were excluded from analysis if the beam current dropped below 60 mA or an injection was in progress.

ORBIT CORRECTION AT DELTA

The majority of read-out electronics of beam position monitors used at DELTA are Multiplexed Beam Position Monitors (MX-BPMs) manufactered by Bergoz Instrumentation with an error of ±2 μm [3, 4]. Their analogous signal

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is digitized by CAN modules which add an error of a least significant bit ($\approx 1\,\mu$m) [5]. The combined error was estimated using a monte carlo method to be $\pm 7.9\,\mu$m which confined 95 % of simulated measurements. This results in any χ^2 value below a threshold of

$$\sum_d ||\mathbf{W}_d \cdot \vec{7.9}\,\mu\mathrm{m}||^2 \approx 830\,(\mathrm{mm})^2$$

to have no meaning in terms of indicating a better quality of orbit correction. It is noted that this value represents a very conservative estimation deduced from minimum specifications given in the data sheets of both electronics. It is additionally noted that an upgrade of read-out electronics is currently being commissioned [5]. This upgrade will increase the resolution of the measured transverse orbit position and will hence decrease the hardware limit χ^2_{limit} yielding more potential for improvement.

The median of the distributions of χ^2 per calendar week during standard operation of the storage ring DELTA matches the previously determined hardware limit in most weeks (Fig. 1). The spreads of the distributions and their means however suggest a less stable orbit. During weeks of standard operation where the storage ring is solely used to generate synchrotron radiation for experimental use, the orbit drifts due to slightly decreasing currents in the coils of a superconducting wiggler. This requires the orbit to be corrected in short intervals. A separate tune correction program [6] adjusts the quadrupole currents at the same time which affects the orbit, as well. Specific hardware problems might also add systematic errors in certain weeks. The displayed analysis results therefore do not reveal instabilities of the orbit-correction program in use. During experimental operation of DELTA there were nights where SAW was turned off and the upper margin of the 0.95-confidence interval of the χ^2-distribution dropped below the estimated threshold.

New Orbit Correction Program

A new orbit-correction program will have to reliably match or increase the current quality of orbit corrections. The latter may only be achieved by using an orbit-response matrix which matches the optics of DELTA better than a simple measurement. Three options to achieve this are currently investigated. The first is the deployment of a coupled-optimization approach since the horizontal correctors at Delta evidently affect the vertical orbit position. A basic python implementation was already shown to converge (Fig. 2) but still used an orbit-response matrix normalized to corrector currents and therefore might suffer from non-linearities due to yoke saturation. Another option is the utilization of a machine-learning algorithm to live-update the orbit-response matrix based on orbit feedback via supervised learning. This would incorporate changes of the optical functions of the storage ring during operation caused by thermal drifts and non-linearities into the matrix without being forced to conduct an invasive measurement. Finally, the utilization of the BE+d model (BE model including dispersion) poses a third option to increase the quality of the orbit-response matrix which has the additional benefit of providing information about the beam optics of the storage ring. This is explained in the following using the simplified BE model as an example.

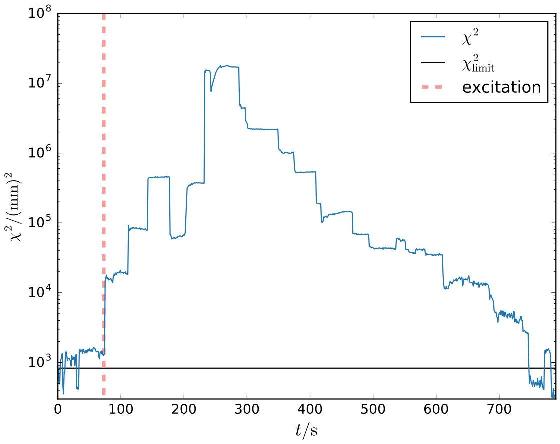

Figure 2: Convergence of a coupled orbit correction algorithm in python in April 2017 at the storage ring DELTA.

THE BE MODEL

The Bilinear-Exponential (BE) model without dispersion [7, 8] is a generalization of the well known model for closed-orbit distortions [9]

$$r_{jk} = \frac{\sqrt{\beta(s_j)}}{2\sin\frac{\mu}{2}}\theta_k\sqrt{\beta(s_k)}\cos\left(\Phi(s_j) - \Phi(s_k) \pm \frac{\mu}{2}\right)$$

at position s_j within the beam transport system of a storage ring caused by a dipole field kick at position s_k. The strength of the perturbing field is given as kick angle θ_k. The quantities $\beta(s)$ and $\Phi(s)$ correspond to the beta function and the betatron phase at their respective positions s_j and s_k. μ is the tune in rad. This model for closed-orbit distortions is limited to a single plane. The BE model describes coupled closed-orbit perturbations as a superposition of two modes m as

$$r_{jkd} = \sum_{m=1}^{2} \Re\left\{Z_{jmd}e^{i\frac{\mu_m}{2}\,sign(s_k - s_j)}A_{km}\right\}.$$

The complex quantity

$$Z_{jmd} \propto \sqrt{\beta_{jmd}}e^{i\Phi_{jmd}}$$

encodes the beta function β_{jmd} and the Φ_{jmd} betatron phase in mode m corresponding to beam position monitor j in plane d. A_{km} is a similar quantity depending on the beta function and the betatron phase of mode m at corrector k. It is possible to obtain all model quantities by fitting the BE model to a given orbit-response matrix via an implementation of the COBEA algorithm [8]. The obtained quantities can then be used to construct an orbit-response matrix which represents a noise-cleaned version of the input matrix (model reduction).

Noise Cleaning with COBEA

The noise-cleaning effect of the COBEA algorithm on a noised orbit-response matrix was tested in a set of simulations. The basis for these simulations was a matrix measured in April 2017. After analysis with COBEA, the resulting, noise-cleaned orbit-response matrix $\mathbf{R}_0$ was deliberately noised using gauss distributed noise values

$$\mathbf{R}_0 \xrightarrow[\text{noise}]{} \mathbf{R}_1 .$$

In a second step, this noised matrix was reanalyzed with COBEA

$$\mathbf{R}_1 \xrightarrow[\text{COBEA}]{} \mathbf{R}_2 .$$

The noise-cleaning effect of this process was then evaluated by comparing

$$\Delta r_{\text{noise}} = ||\mathbf{R}_1 - \mathbf{R}_0|| \quad \text{to} \quad \Delta r_{\text{COBEA}} = ||\mathbf{R}_2 - \mathbf{R}_0||.$$

This procedure was repeated >1000 times for four different noise levels ($\sigma = 0.5\,\%$, $1.0\,\%$, $1.5\,\%$ and $2.0\,\%$ of $||\mathbf{R}_0||$). The results are displayed in Fig. 3. The distribution of initial noise levels is printed in red (Δr_{noise}) and the distribution of noise levels after analysis with COBEA is printed in blue (Δr_{COBEA}). The results indicate that the noise level was reduced by a factor two on average and therefore assert the acclaimed noise-cleaning capabilities of COBEA.

CONCLUSION AND OUTLOOK

The assessment of the quality of orbit corrections at the storage ring DELTA in 2016 yielded a volatility of χ^2. Although being caused by systematic errors in parts, the dependency of orbit corrections at DELTA on measured orbit response matrices poses a bottle neck for the overall quality of orbit corrections. Three different methods to increase the reflection of the beam optics of the storage ring in an orbit-response-matrix model for use in a program for orbit correction were presented. A python implementation of a coupled optimization approach was shown to converge (Fig. 2) using a current-normalized orbit-response matrix. The noise-cleaning capabilities of the COBEA algorithm were asserted in a set of simulations but were not tested on DELTA, yet. In the upcoming months, the aforementioned python implementation will be upgraded to use orbit response matrices normalized on deflection angles based on [2] and the effect of noise-cleaned matrices on convergence will be tested.

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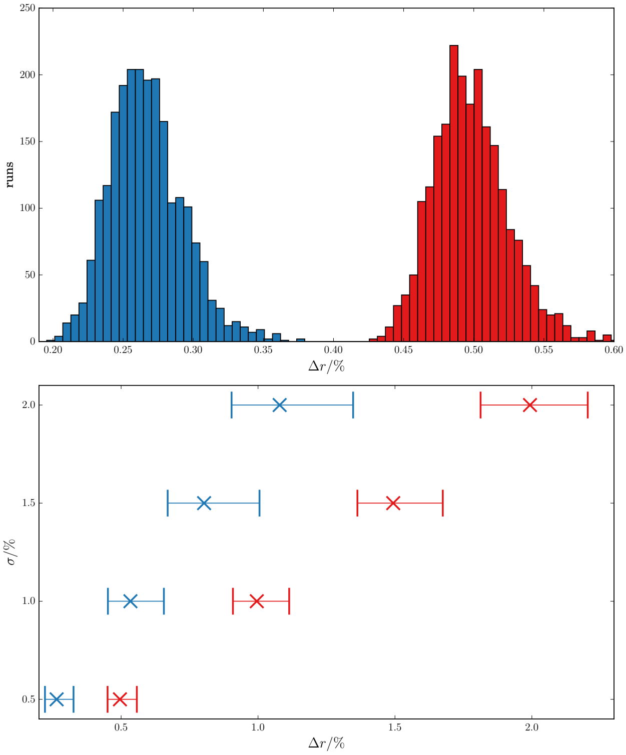

Figure 3: Benchmark of the cleaning capabilities of the COBEA algorithm regarding the noise level of a orbit-response matrix. The top plot displays the distributions of Δr_1 (red) and Δr_2 (blue) in percent of $||\mathbf{R}_0||$ for gauss distributed noise with $\sigma = 0.5\%$ of $||\mathbf{R}_0||$. The bottom plot displays the median and the 0.95 confidence interval of the noise distributions of Δr_1 (red) and Δr_2 (blue) in percent of $||\mathbf{R}_0||$ for all four tested, initial noise levels.

REFERENCES

[1] S. Hilbrich, “Studies of the delta lattice in view of a future short-pulse facility based on echo-enabled harmonic generation”, Master’s thesis, TU Dortmund University, Mar. 2015.

[2] M. Grewe, “Orbitkorrektur am speicherring delta”, PhD thesis, TU Dortmund University, Jan. 2005.

[3] *Multiplexed beam position monitor user’s manual*, Rev. 1.5.4., Bergoz Instrumentation, Espace Allondon Ouest, 01630 Saint Genis Pouilly, France.

[4] A. Jankowiak, “Strahldiagnose und closed-orbit-charakterisierung mit hf-strahllagemonitoren am beispiel der synchrotronstrahlungsquelle delta”, PhD thesis, TU Dortmund University, Nov. 1999.

[5] *Can-cai812 hardware-handbuch*, CAN-CAI812 Hardware Rev. 2.0, esd-electronics system design gmbh, Vahrenwalder Straße 205, W-3000 Hannover 1, 1993.

[6] P. Hartmann *et al.*, “Frequency map analysis and particle accelerators”, ser. Proc. PCAPAC 2016, THPOPRPO23, Campinas, Brazil, 2016.

[7] B. Riemann *et al.*, “COBEA - optical parameters from response matrices without knowledge of magnet strengths.”, ser. Proc. IPAC17, MOPIK066, Copenhagen, Denmark, 2017.

[8] B. Riemann, “The bilinear-exponential closed-orbit model and its application to storage ring beam diagnostics”, PhD thesis, TU Dortmund University, Apr. 2016.

[9] H. Wiedemann, *Particle Accelerator Physics*, 3rd ed. Berlin/Heidelberg: Springer-Verlag, 2007, ISBN: 978-3-540-49043-2.