Towards an Adaptive Orbit-Response-Matrix Model for Twiss-Parameter Diagnostics and Orbit Correction at DELTA

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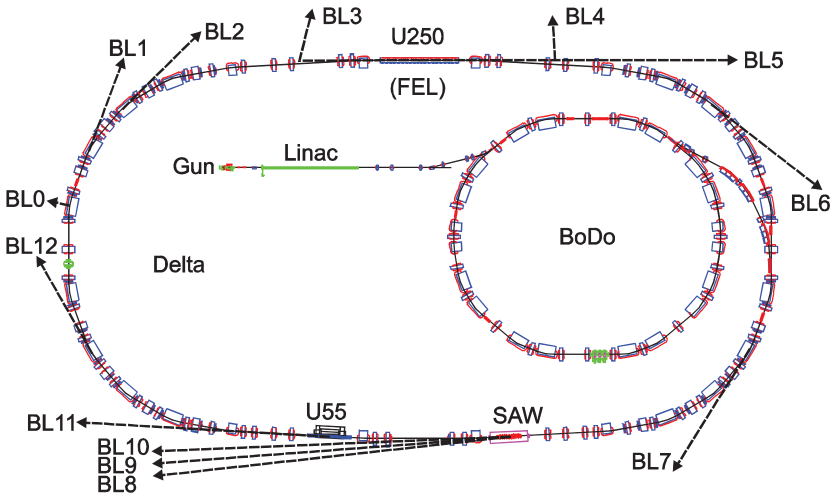
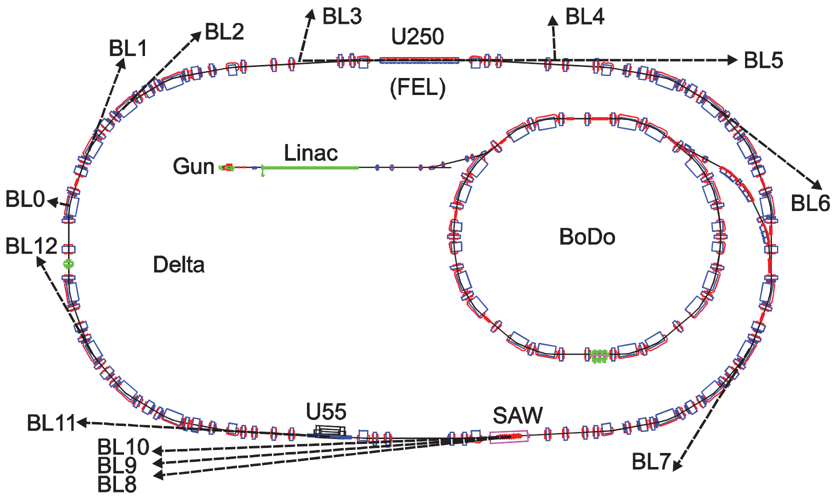
The DELTA Facility



- 1.5 GeV synchrotron radiation light source in Dortmund, Germany [1]
- Supplies radiation ranging from the THz to the hard X-ray regime

[1] “Vereinslogo des Fußballbundesligisten Borussia Dortmund”, Borussia Dortmund GmbH & Co. KgaA, Rheinlanddamm 207-209, 44137 Dortmund.

The DELTA Facility



Data acquisition: $10.0\,\mathrm{Hz}$

Orbit correction: $0.1\,\mathrm{Hz}$

- 1.5 GeV synchrotron radiation light source in Dortmund, Germany [1]
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My current research interests:

- Slow-orbit-feedback software
- Adaptive orbit-response matrix model
- Non-invasive measurements of optical functions
- Enhance orbit correction

[1] “Vereinslogo des Fußballbundesligisten Borussia Dortmund”, Borussia Dortmund GmbH & Co. KgaA, Rheinlanddamm 207-209, 44137 Dortmund.

The Bilinear-Exponential Model with Dispersion

Orbit-response matrix element

The BE+d Model

Not relevant for us today!

$$\frac{\Delta\kappa_{wj}}{\Delta\theta_k} = \sum_m^{M=2} \Re\left\{\sqrt{I_m\beta_{mwj}}\,e^{i\Phi_{mwj}}E^*_{mjk}(q_m)A^*_{mk}\right\} + d_{wj}b_k$$ [1]

j	BPM
k	Steering magnet
m	Mode
w	Plane

Fit to obtain:

- Beta function
- Betatron phase
- Tunes
- Unnormalized dispersion

Machine model :
Only ordering of BPMs and steering magnets along the beam path

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

Data Source: Slow-Orbit-Feedback Software

- Measurement after orbit correction

$$\begin{pmatrix} \Delta\vec{\kappa}_n \\ \Delta\vec{\theta}_n \end{pmatrix}$$

Orbit ($\Delta\vec{\kappa}_n$)

Steering angles ($\Delta\vec{\theta}_n$)

- Fill ring buffer of length N

$$\left[\begin{pmatrix} \Delta\vec{\kappa}_0 \\ \Delta\vec{\theta}_0 \end{pmatrix}, \begin{pmatrix} \Delta\vec{\kappa}_1 \\ \Delta\vec{\theta}_1 \end{pmatrix} \cdots \begin{pmatrix} \Delta\vec{\kappa}_N \\ \Delta\vec{\theta}_N \end{pmatrix}\right]$$

Fit orbit-response:

$$\chi^2 = \sum_n^N \left| \Delta\vec{\kappa}_n - \mathbf{R}_{\mathrm{meas}} \Delta\vec{\theta}_n \right|^2 \to \min$$

Orbit-response matrix ($\mathbf{R}_{\mathrm{meas}}$)

Closed-Orbit Bilinear-Exponential Analysis [1]

(Short: COBEA)

- Fits the the BE+d model on orbit-response matrix $\mathbf{R}_{\mathrm{meas}}$
- Output: βs, Φs, qs and ds
- Validated with LOCO[2]-based machine models

Cobaea Scandens [3]

[1] B. Riemann, S. Kötter, S. Khan, and T. Weis, "COBEA - optical parameters from response matrices without knowledge of magnet strengths", in Proc. IPAC'17, paper MOPIK066, Copenhagen, Denmark, May 2017
[2] J. Safranek, "Experimental determination of storage ring optics using orbit response measurements", Nucl. Instr. Meth. Phys. Res. A 388 (1–2), pp. 27–36, Mar. 1997.
[3] Buendia22, "Picture of cobea scandens", https://commons.wikimedia.org/wiki/File:Cobaea_scandens_4259.jpg, license CC-BY-SA-4.0, Sep. 2019.

Proposed Approach

Ring buffer:

$$\left[\begin{pmatrix}\Delta\vec{\kappa}_0\\ \Delta\vec{\theta}_0\end{pmatrix},\begin{pmatrix}\Delta\vec{\kappa}_1\\ \Delta\vec{\theta}_1\end{pmatrix}\cdots\begin{pmatrix}\Delta\vec{\kappa}_N\\ \Delta\vec{\theta}_N\end{pmatrix}\right] \xrightarrow{Linear\,fit} \mathbf{R}_{\text{meas}}$$

$$\mathbf{R}_{\text{meas}} \xrightarrow{COBEA} \mathbf{R}_{\text{BE+d}}$$

$$(\beta\text{s},\ \Phi\text{s},\ q\text{s and } d\text{s})$$

Proposed Approach

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(6048 fit parameters)

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(817 fit parameters)

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$$\mathbf{R}_{\mathrm{meas}} \xrightarrow{COBEA} \mathbf{R}_{\mathrm{BE+d}}$$

?

$\mathbf{R}_{\mathrm{BE+d}}$

$(\beta\mathrm{s},\ \Phi\mathrm{s},\ q\mathrm{s}\ \mathrm{and}\ d\mathrm{s})$

(817 fit parameters)

Direct fit:

- More data per fit parameter
- BE+d model is complex to fit
- Problem: COBEA's method of generating start values cannot be generalized easily!

New Fitting Recipe

- Requires measured tunes
- Otherwise random start values
- Increase model complexity in three steps
- Treat plane coupling and dispersion as perturbation

The Adam optimization method[1]:

➔ Evolution of stochastic gradient descent
➔ Leverages momentum and fit-parameter-specific learning rates

[1] D. Kingma and J. Ba, “Adam: A method for stochastic optimization”, in Proc. ICLR’15, San Diego, USA, May 2015.

Validation Measurement

250 orbit displacements $\Delta\vec{\kappa}$ with random steering angles $\Delta\vec{\theta}$.

Test setups for fitting recipe:

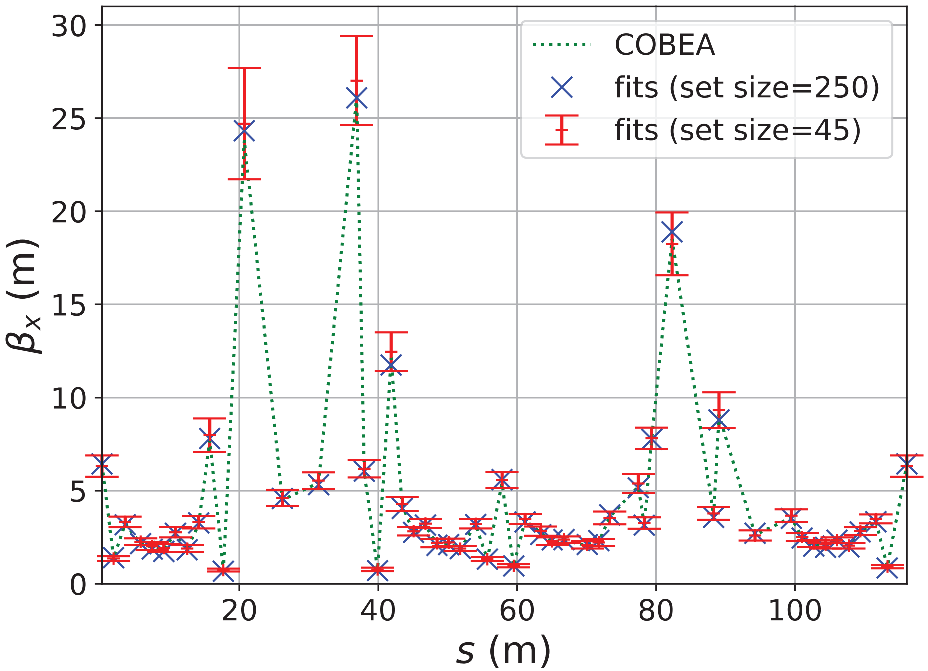
1. Apply to all samples 100 times (set size = 250)
2. Apply to random subset 300 times (set size = 45)

Fitting $\mathbf{R}_{\mathrm{meas}}$ and using COBEA only possible for set size > 56!

COBEA reference:

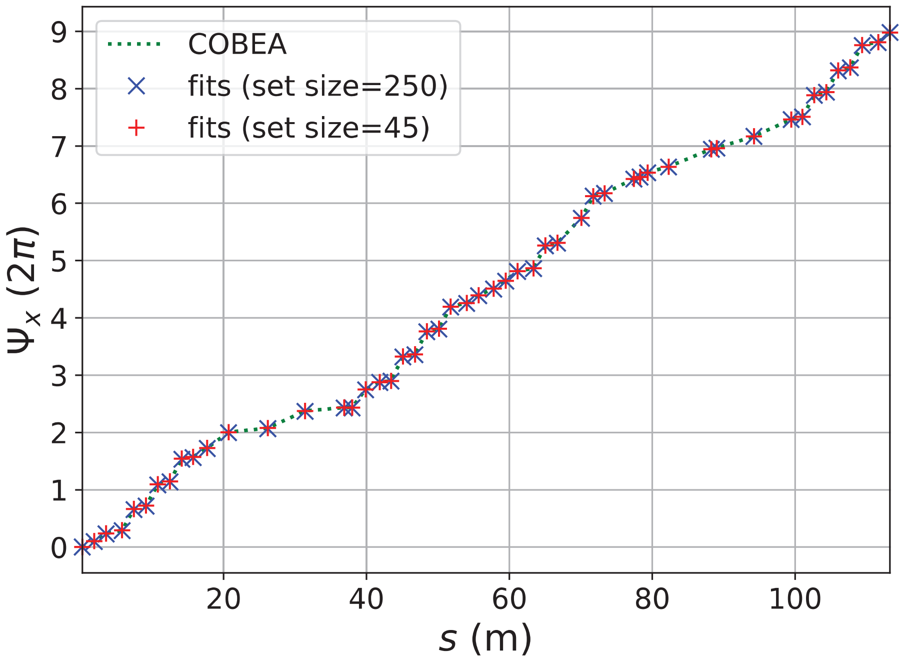
1. Fitted $\mathbf{R}_{\mathrm{meas}}$ on all samples
2. Used COBEA on $\mathbf{R}_{\mathrm{meas}}$

Validation of Fitting Recipe I: Beta Function



- Set size = 250:
  Very similar to COBEA results $(\sigma \approx 0\,\%)$
- Set size = 45 (10 % of fits diverged):
  Very decent results $(\sigma \approx \pm 10\,\%)$
- Results for the vertical plane support these statements

Validation of Fitting Recipe I: Betatron Phase



- Results of new fitting recipe match COBEA results exactly
- Standard deviations basically zero
- Results for the vertical plane support these statements

New fitting recipe:

1. Very robust
2. Produces decent results on set sizes where you cannot do the linear fit and subsequently cannot use COBEA!

Adaptive Orbit-Response Matrix Model

Ring buffer:

$$\left[\begin{pmatrix}\Delta\vec{\kappa}_0\\ \Delta\vec{\theta}_0\end{pmatrix},\begin{pmatrix}\Delta\vec{\kappa}_1\\ \Delta\vec{\theta}_1\end{pmatrix}\cdots\begin{pmatrix}\Delta\vec{\kappa}_N\\ \Delta\vec{\theta}_N\end{pmatrix}\right] \xrightarrow{\textit{Online fit}} \mathbf{R}_{\mathrm{BE+d}}$$

$(\beta\mathrm{s},\ \Phi\mathrm{s},\ q\mathrm{s}\ \text{and}\ d\mathrm{s})$

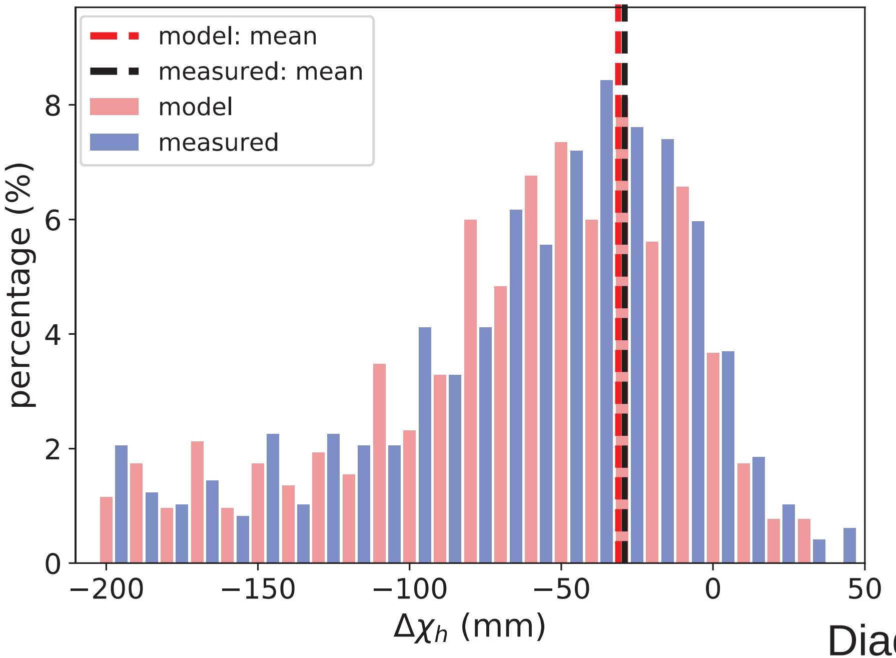
- After startup: online fitting-process keeps BE+d-model fit updated with every correction step made
- Optical functions can be accessed any time

BE+d-Model-Based Orbit Correction

Matrix-based orbit correction $\xleftarrow{\textit{Input}}$ $\mathbf{R}_{\mathrm{BE+d}}$

- Orbit response dependent on beam optics (beta function …)
- $\mathbf{R}_{\mathrm{BE+d}}$ adapts to changing beam optics

BE+d-Model-Based Orbit Correction



- Comparison of measured matrix and its BE+d-model representation for random perturbations
- Both work equally well

$\Delta\chi_\mathrm{h}$:

- ➔ Benchmarks quality of a correction step
- ➔ If smaller than zero, indicates better matching of orbit and orbit reference
- ➔ The more negative the better

$$\chi_\mathrm{h} = \left|\mathbf{W}\cdot(\vec{\kappa} - \vec{\kappa}_\mathrm{ref})\right|$$

Diagonal weight matrix — Orbit — Orbit reference

Summary

- Online orbit-response matrix model for twiss parameter diagnostics and orbit correction under development
- Achieved to fit the BE+d model directly on buffer
- Asserted BE+d model to work in matrix-based slow orbit feedback

Challenges & Outlook

- Determine good buffer size
- Validate dispersion output of new fitting recipe
- Dynamic simulations to check capabilities and limits of the online approach
- Implement & test the online model

Thank you for your attention!

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