COBEA

a method to obtain optical parameters from closed orbits without knowledge of magnet strengths[1]

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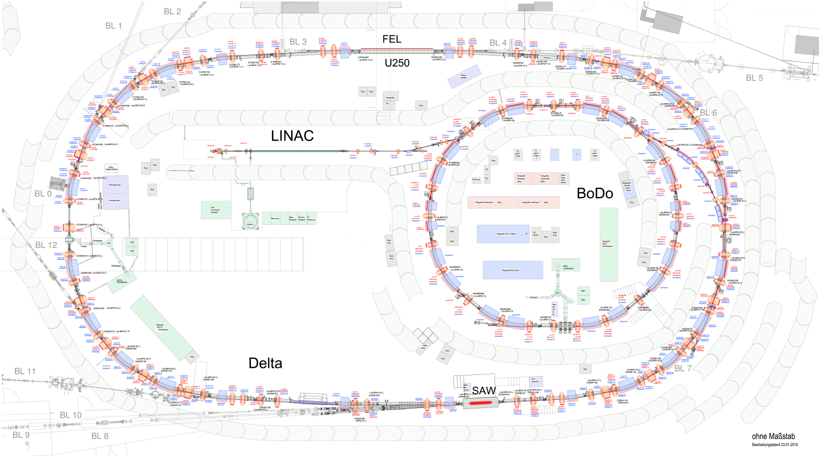
24th ESLS workshop — Lund — 2016-11-30

[1] Thanks to the whole DELTA and HZB staff for making this possible!

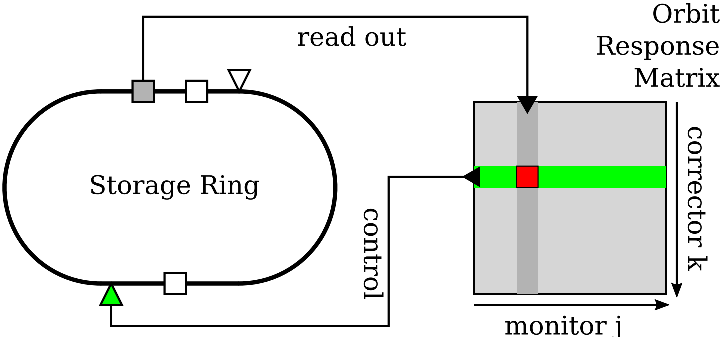
DELTA facility

✠ drawing by T. Schulte-Eickhoff (TU Dortmund University, 2015-05)



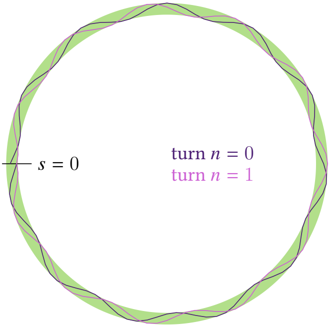
Response matrix

✠ sketch based on: T. Weis, Lecture script 2013, orig. by G. Schünemann



- necessary for orbit correction.
- can be recorded at almost every storage ring with standard hardware.

Betatron oscillation / Turn-by-Turn data



ring	length L	max(f_β)
LHC	27 km	5.55 kHz
SPS	6.9 km	20 kHz
MAX IV 3 GeV	528 m	284 kHz
BESSY II	240 m	625 MHz
DELTA	115 m	1.3 MHz
ANKA	110 m	1.36 MHz
MAX IV 1.5 GeV	96 m	1.55 MHz
MLS	48 m	3.12 MHz
ASTRID2	45.7 m	3.28 MHz

- observable frequency $f_\beta \leq f_\circ/2$ (but same magnitude)
- Recording of betatron oscillations with correct phases requires fast synchronization.
- High-resolution and high-frequency sampling requires special hardware.

Problem statement

[2] H. Wiedemann, *Particle Accelerator Physics*, 3rd ed. (Springer, 2007)

[3] lead to development of 'direct observation' methods (TbT analysis, AC dipole)

[4] A. Tarantola, *Inverse Problem Theory and Methods for Model Parameter Estimation*, 1st ed. (SIAM, 2005)

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☺ Beam optics → ⌨→ Response matrix: Elementary![2]

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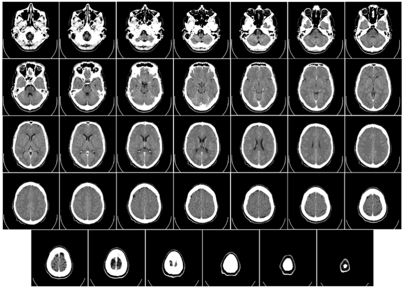
⇒ This is characteristic for an inverse problem.[4]

Examples: tomography, gravitational waves, particle collisions...



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The response problem

beam optics at BPM and corrector positions are
encoded in response matrix – but how to obtain them?

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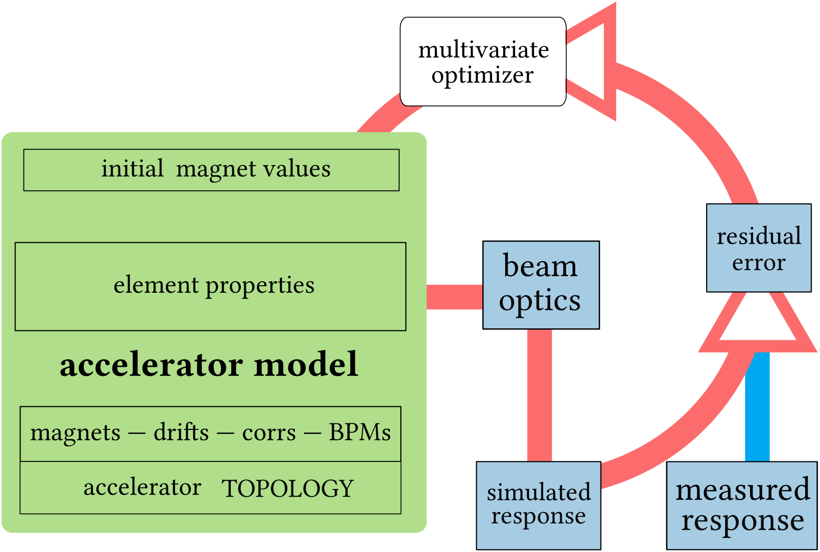
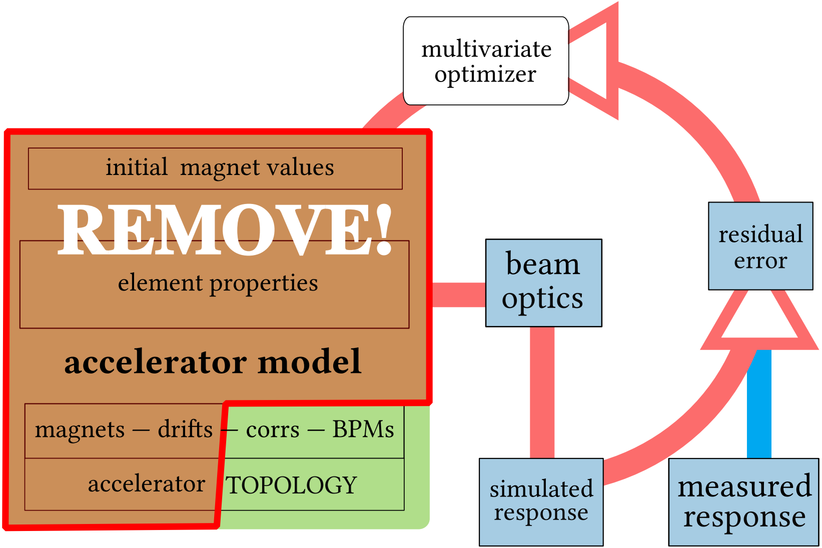
Linear Optics from Closed Orbits

✠ J. Safranek, Nucl. Instr. Meth. Phys. Res. A **388** (1–2), pp. 27–36 (Mar 1997)



- But LOCO does not converge for the present DELTA model…

reducing LOCO assumptions ✂

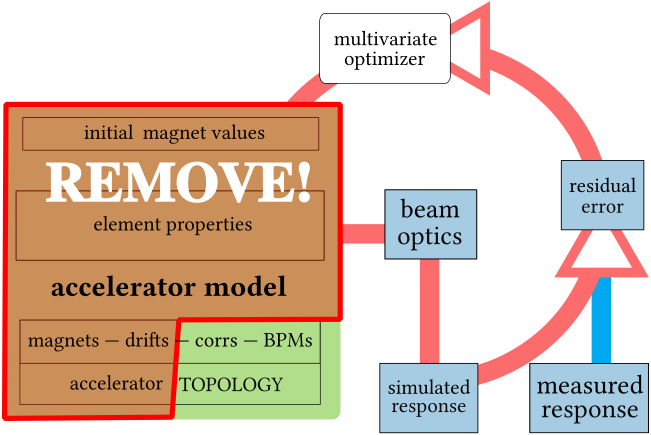


- only keep BPM-corrector order & **one** drift space (optional)

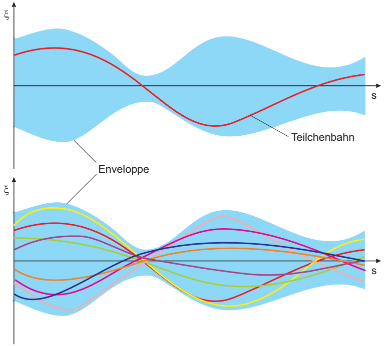
Repair the optimization

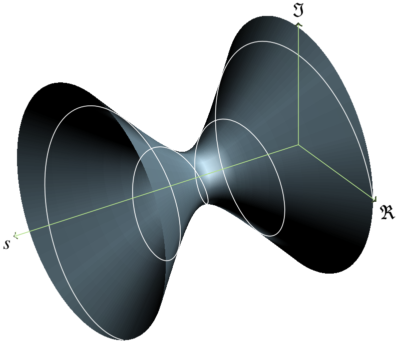
Task 1 Connect optimizer to beam optics.

Task 2 Find appropriate start values. → later



Beam optics by eigenorbits



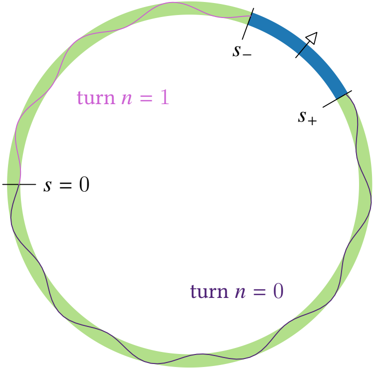


Real particle trajectories at turn n are described by

$$\vec{r}_n(s) = \Re\{\vec{R}_m(s)e^{i\mu_m n}\}$$

Outside of any local perturbation, a closed orbit is a betatron oscillation.

- This is *independent* of the perturbation type! (not decoupled, thin-lens or else...)
- This is also independent of the kick angle.
- With no further assumptions, one can create a general closed orbit model based on eigenorbits.



Bilinear-Exponential model with dispersion (BE+d model)

$$\vec{r}_{jk} = \Re\left\{\sum_m \vec{R}_{jm}\, A_{km}\, \mathrm{e}^{-iS_{jk}\mu_m/2}\right\} + \vec{d}_j\, b_k$$

- $\vec{r}_{jk}$: response matrix elements (BPM j, corrector k)
- $S_{jk} = \pm 1$: depend only on BPM-corrector order (topology)

BE+d optical parameters

- $\vec{R}_{jm} = \vec{R}_m(s_j)$: eigenorbit at BPM j (relation to β, ϕ)
- $A_{km} \propto \vec{R}_m(\tilde{s}_k)$: depends on β, ϕ at corrector k
- μ_m: angular betatron tunes ($2\pi Q_m$)
- $\vec{d}_j$, b_k: dispersion coefficients

Closed Orbit Bilinear-Exponential Analysis

Bilinear-Exponential model with dispersion (BE+d model)

$$\vec{r}_{jk}^{\,\text{model}} = \Re\left\{\sum_m \vec{R}_{jm}\, A_{km}\, \mathrm{e}^{-iS_{jk}\mu_m/2}\right\} + \vec{d}_j\, b_k$$

One can now rephrase the inverse problem:

The response problem

Find all BE+d optical parameters $\vec{R}_{jm}$, A_{km}, μ_m, $\vec{d}_j$, b_k

so that $\quad \chi^2 = \sum_{jk} \left|\vec{r}_{jk}^{\,\text{model}} - \vec{r}_{jk}\right|^2 \quad$ is minimal.

Closed Orbit Bilinear-Exponential Analysis

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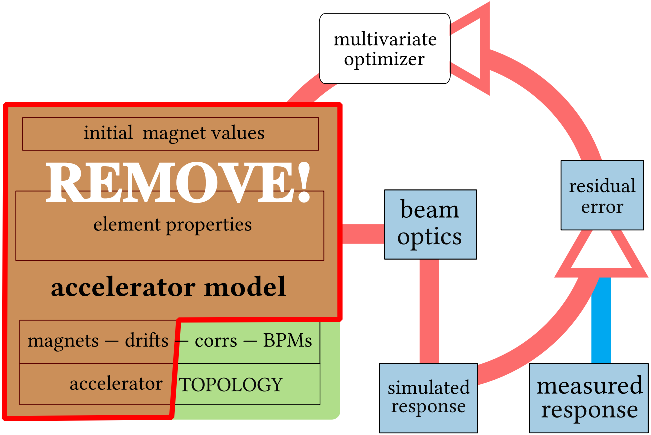
- Compute gradients *analytically*, e.g.

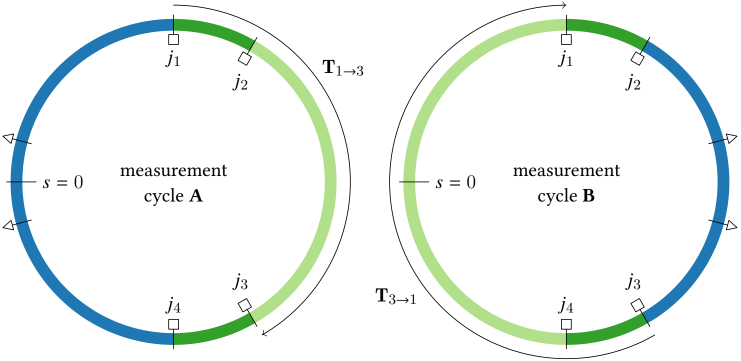
$$\frac{\mathrm{d}}{\mathrm{d}d_{j,x}}\chi^2 = 2\sum_k \left|x_{jk}^{\text{model}} - x_{jk}\right| b_k$$

Task 1 ☑ Connect optimizer to beam optics. → Optimize BE+d model.

Task 2 ▶ Find appropriate start values.



Monitor-Corrector Subset algorithm



- compute one-turn $\mathbf{T}_\circ = \mathbf{T}_{3\to1}\mathbf{T}_{1\to3}$ at *one* position in the ring.
  although technically possible, this approach is uncommon
- knowledge of $\mathbf{T}_\circ \Leftrightarrow$ knowledge of transverse eigenmodes (amplitude & phase) at two BPMs.[5]

[5] By similarity transform, basic principle applies to eigenorbits $\vec{R}_{jm}$ at two monitors even for unknown segments.

Corrector-Monitor mapping (now part of MCS)

- B. Riemann et al., Proc. IPAC 2015, MOPWA035, Richmond, USA (2015-06)
- precursor: B. Riemann, P. Grete, T. Weis, Phys. Rev. ST Accel. Beams **14**, 062802 (2011-06)

From eigenorbit data at two BPMs, compute missing data at all other BPMs and correctors.

CM mapping consists of two subroutines

1. C subroutine: Compute all A_{km} from a subset of $\vec{R}_{jm}$.
2. M subroutine: Compute all $\vec{R}_{jm}$ from all A_{km}.
   This subroutine has predecessors which input depended on accelerator models.[a] [b]

[a] M. Harrison and S. Peggs, Proc. PAC 1987, pp. 1105–1107, Washington, USA

[b] H. Koiso et al., *Int. Workshop on Perf. Impr. of Electron-Positron Collider Particle Factories*, Tsukuba, Japan (1999-09)

Workflow of COBEA

MCS layer

Compute starting values from measured response.

Optimization layer

Minimize effects of noise, get more precise estimates of optics.

Postprocessing.

- optional normalization (invariant)
  by known segment (drift space)
- extraction of ϕ and β (drift) or const$\cdot\beta$ (no drift) at BPMs,
  tunes incl. integer and quadrant
  and unnormalized dispersion factors.

DELTA response matrices (2006-03 – 2016-01)

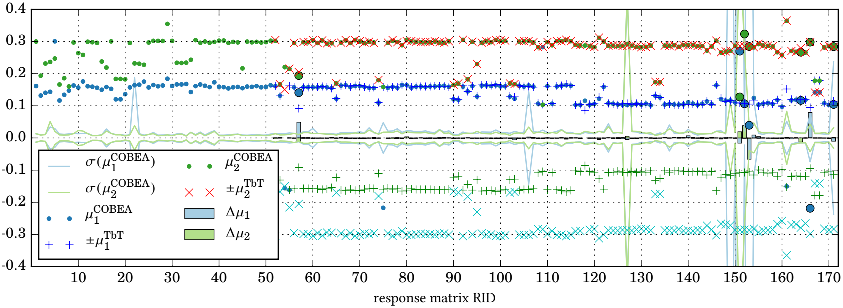
✠ M. Grewe, Ph.D. Dissertation (Dortmund University, 2005-01)

✠ P. Hartmann et al., Proc. DIPAC 2007, WEPB21, Venice, Italy

- LOCO not available for DELTA
  due to bad convergence (deviating standard operation mode)
- direct tune $|\mu_m|$ measurement (“Q-Pulser”) active during operation.

⇒ Possibility of validation:
compare Q-Pulser tunes with those obtained from COBEA
for 171 response matrices.

DELTA response matrices (2006-03 – 2016-01)



Tune comparison

- Most COBEA tunes do not show large deviations to Q-pulser tunes. Exceptions: 166,153,57,52,152,151,164,171
- Of the other tunes, some are in an unusual quadrant. 54, 55, 75, 161

DELTA response matrices (2006-03 – 2016-01)

Example: RID 151 – 154 Elog entries

responses were all recorded on 2014-09-24.

trying to repair DC1 — G. Schmidt, 19:21

…At that location, one could see that the isolation of the supply cable bursted at a constriction. After disassembly, one could measure current flow between magnet and this cable. …

Orbit problems — J. Friedl, 19:56

The orbit correction application (*running on RID 153*) cannot compensate the occurring deviations.

⇒ Fluctuating closed-orbit distortion impinged on measurement. Response matrix not properly recorded.

DELTA response matrices (2006-03 – 2016-01)

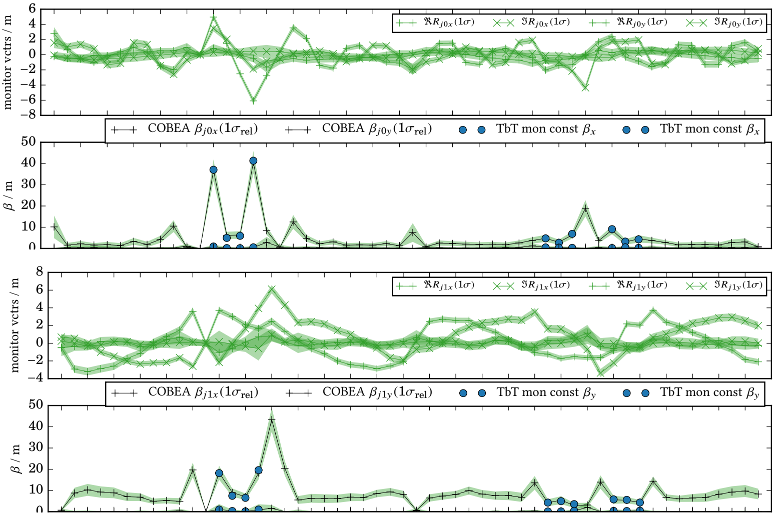
- 171 response matrices analyzed using COBEA.
  For 120 matrices, Q-Pulser tunes available.
- In 114 of 120 cases, COBEA and Tune feedback results matched up to $\approx 10^{-3}$.
- For the remaining cases, deviations were related to errors in measurement procedures, using DELTAs electronic log

Own TbT validation at DELTA

- ✠ correctors designed and described in:
  P. Towalski, Ph.D Dissertation in preparation (TU Dortmund University, 2016)
- ✠ control system integration of correctors: S. Kötter

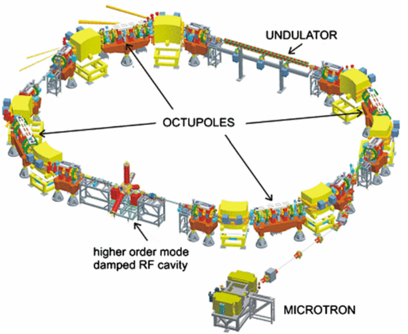
- Utilize an additional set of correctors (Towalski correctors) to measure alternative response matrices.
- 10 BPMs are equipped with hardware to sample the beam turn-by-turn (TbT).
- Comparison of TbT data with recording of response matrices allows to *validate COBEA tunes and monitor vectors* R_{jm}.

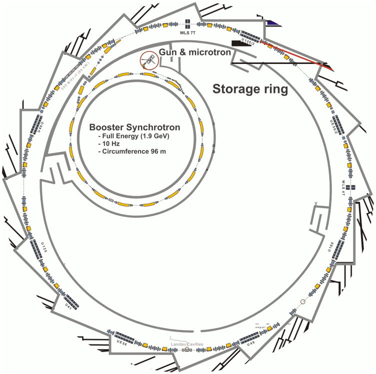
Own TbT validation at DELTA (TID 22)



Using HZB data from MLS and BESSY II

- D. Engel, A. Jankowiak, R. Müller, M. Ries, M. Ruprecht, J. Feikes et al., E-Mail communication (≥2015-06)
- J. Feikes, M. von Hartrott, M. Ries, P. Schmid and G. Wüstefeld, Phys. Rev. ST Accel. Beams **14**, 030705 (2011-03)



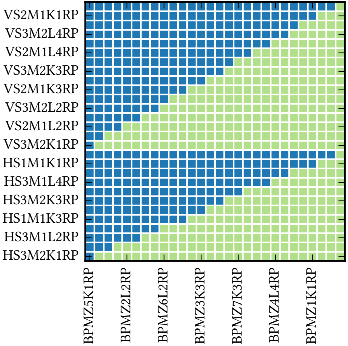


- Both accelerator models were unknown to me in detail.
- mail preliminary COBEA results ⇒ get back LOCO results.

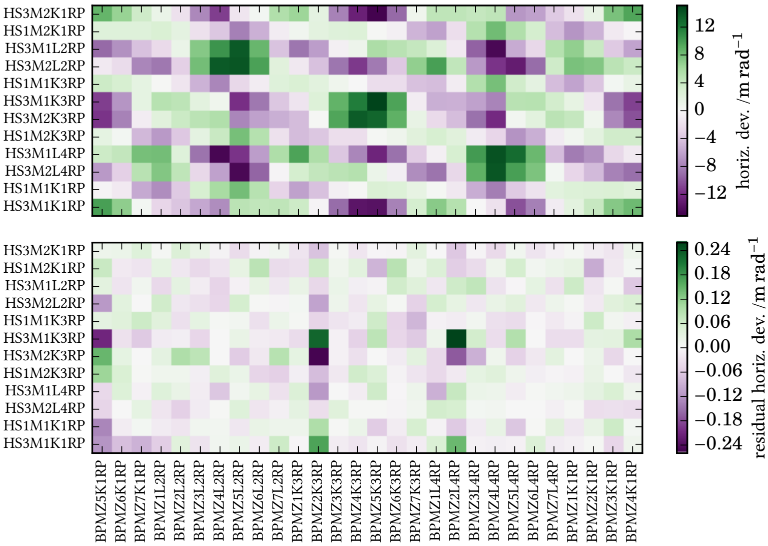
Using HZB data from MLS and BESSY II

COBEA input

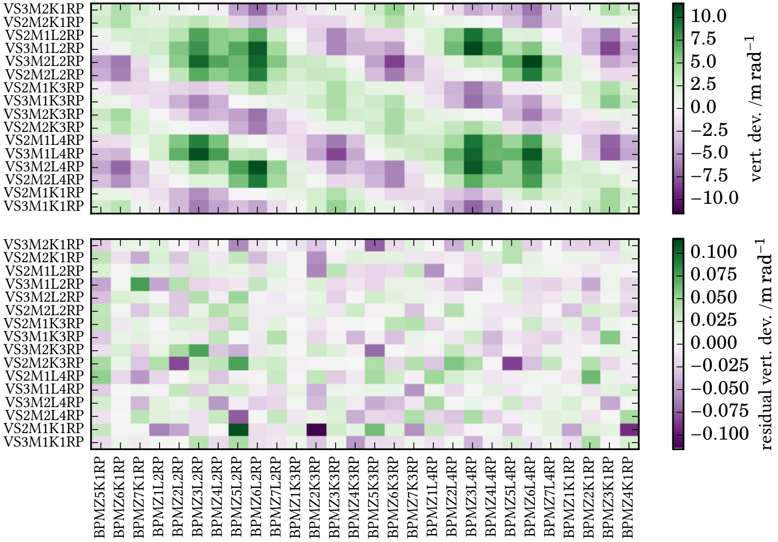
1. decoupled response matrices **x**, **y**
2. (column) labels for each corrector
3. (row) labels for each monitor
4. ordered list of all labels along the beam path (“downstream”)
5. optional: drift space of known length between two monitors



MLS → fit residuals (x mode)



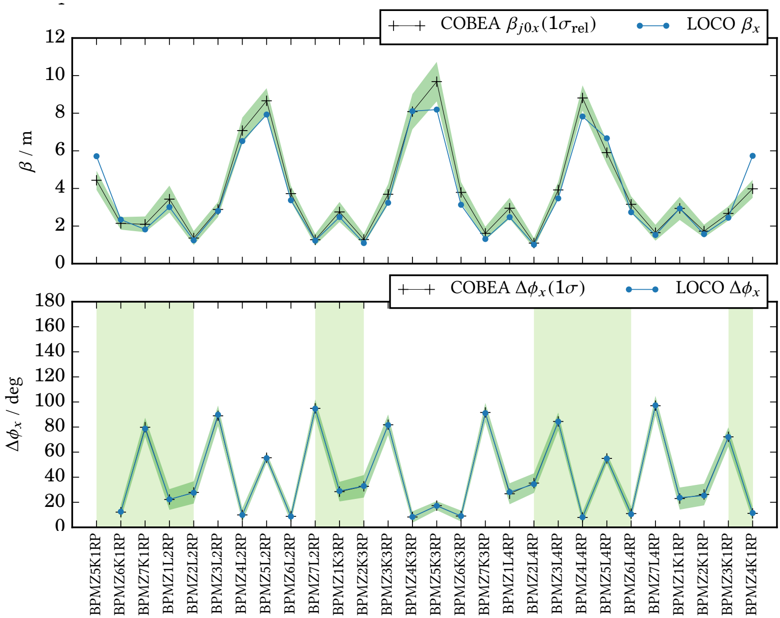
MLS → fit residuals (y mode)



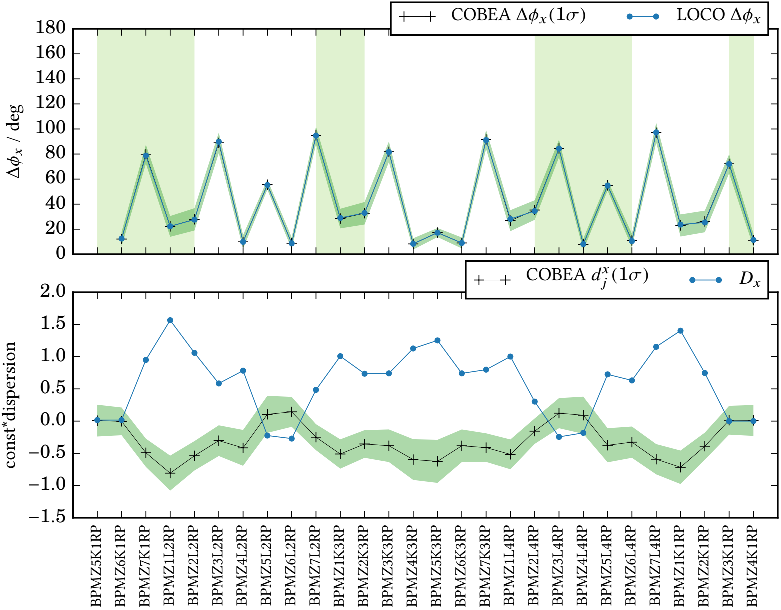
MLS $\rightarrow$ global results

	Quantity	Variable	Value	Error
COBEA tune	$-x$ mode	Q_x^{COBEA}	3.17766	7.21×10^{-3}
	$-y$ mode	Q_y^{COBEA}	2.23114	6.28×10^{-3}
LOCO tune	$-x$ mode	Q_x^{LOCO}	3.17762	
	$-y$ mode	Q_y^{LOCO}	2.23869	

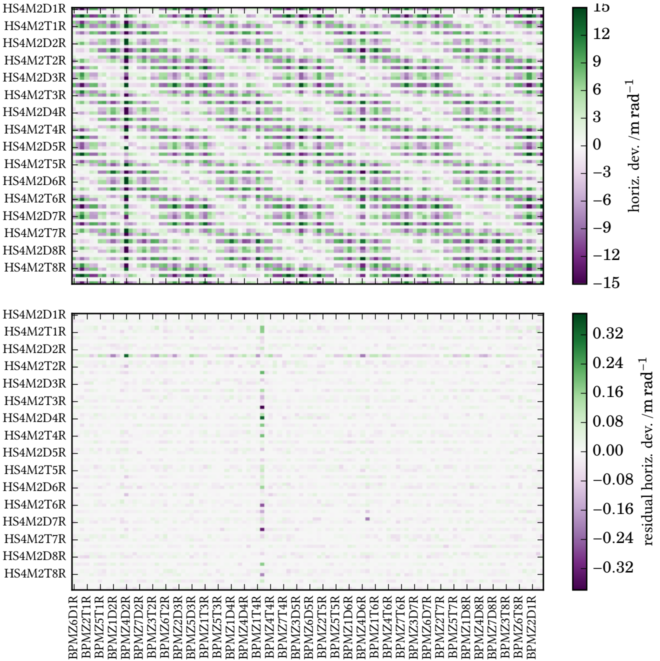
MLS → x mode (β and phase advance)



MLS → x mode (phase advance and dispersion)



BESSY II → fit residuals (x mode)



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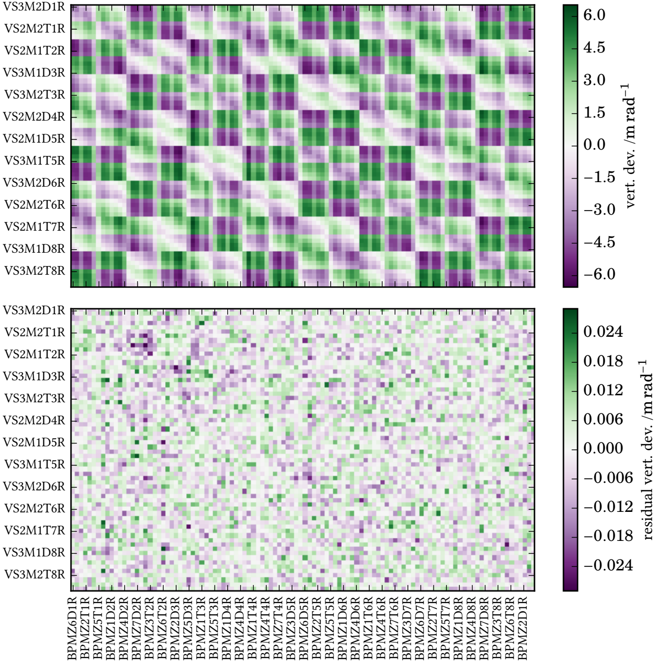
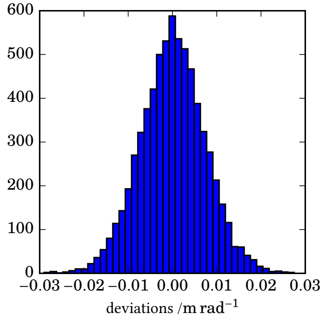
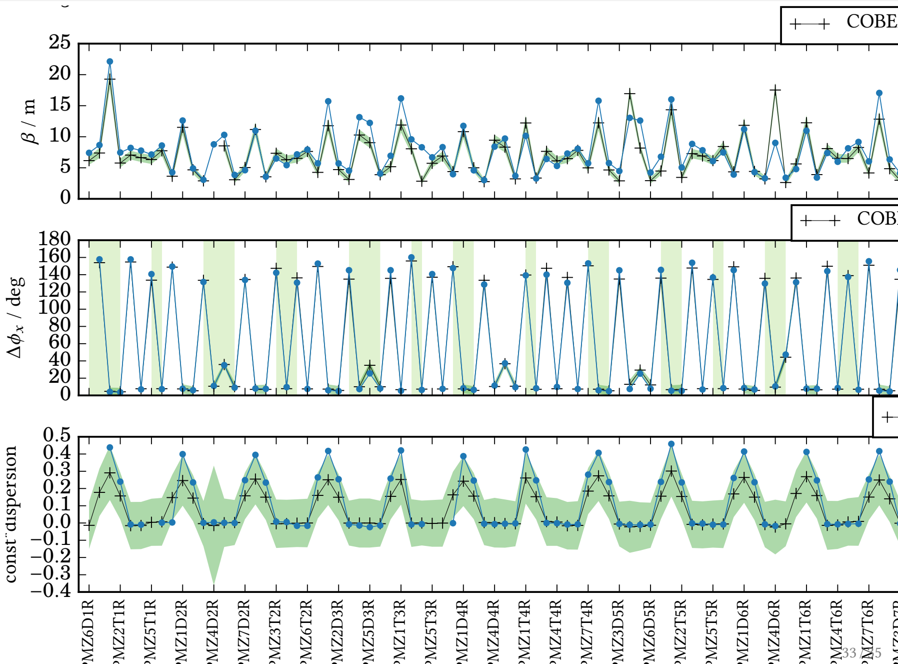




y mode deviation histogram

Global results	Quantity	Variable	Value	Error
COBEA tune	$-x$ mode	Q_x^{COBEA}	17.84740	2.87×10^{-3}
	$-y$ mode	Q_y^{COBEA}	6.74054	3.55×10^{-3}
LOCO tune	$-x$ mode	Q_x^{LOCO}	17.84690	
	$-y$ mode	Q_y^{LOCO}	6.74484	

BESSY II → x mode



Summary

COBEA

- able to decompose properly recorded response matrices into optical parameters.
- only order of BPMs and correctors in a storage ring and optional drift space required.
- No symmetries or similar assumptions placed on the accelerator.
- has been applied to BESSY II, MLS and DELTA storage rings. Results seem to be overall consistent with existing measurement procedures.

$\Rightarrow$ should be applicable to a considerable fraction of existing storage rings.

Thank you for your attention!

Send me your response (matrix)!

Contact:
bernard.riemann@tu-dortmund.de

Find my PhD thesis about COBEA at
http://dx.doi.org/10.17877/DE290R-17221

or lookup at DELTA Homepage ("Mitarbeiter / Staff")
www.delta.tu-dortmund.de