Applying LOCO analysis to COSY

JEDI collaboration meeting @ Tbilisi State University

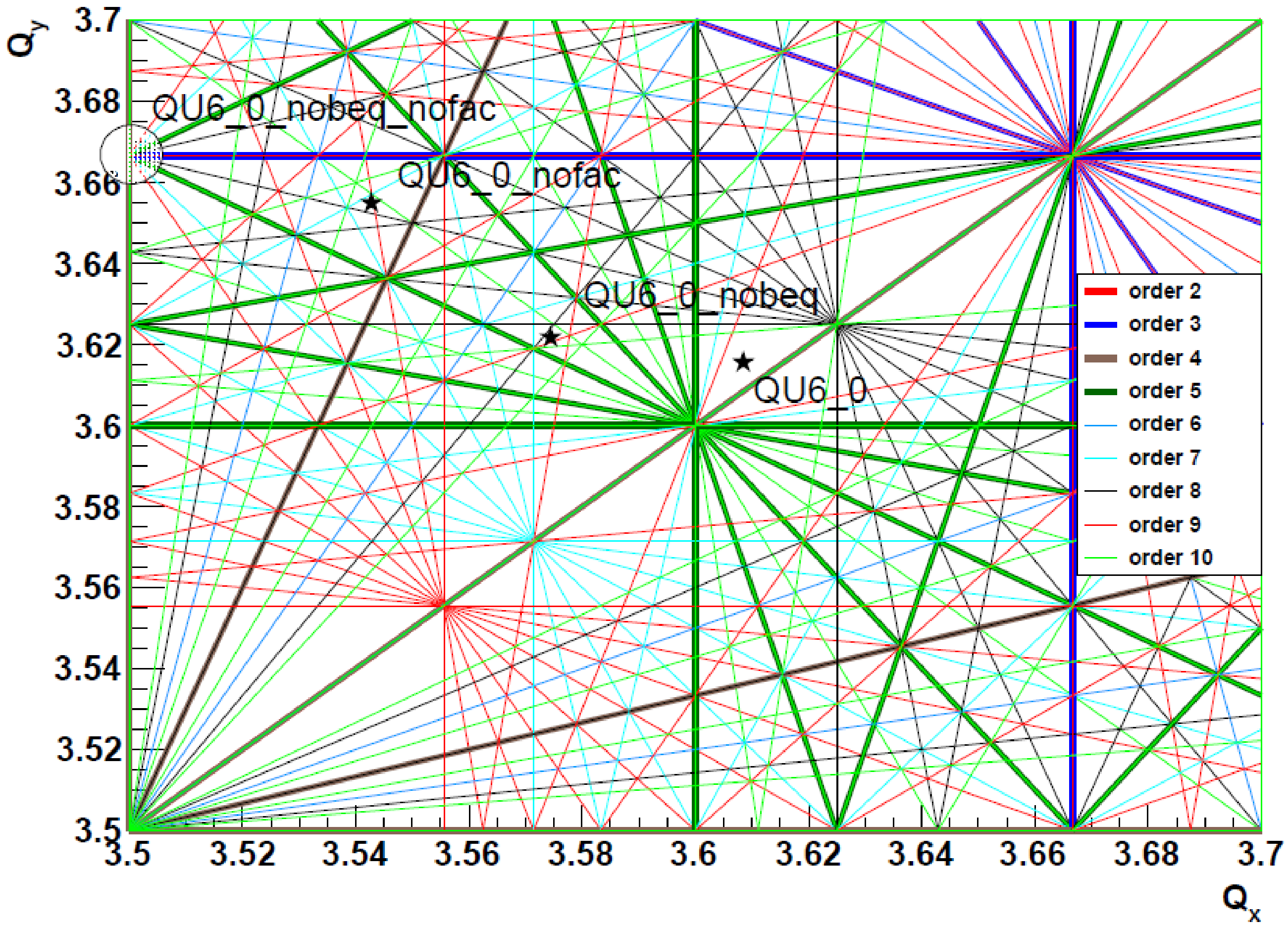
September 1, 2016 | Christian Weidemann

Status of COSY model

<u>Working point</u>

- Significant difference between calculated and measured tune
- Model adjustment to measured working points required

$$Q_x = 3.608;\ Q_y = 3.615$$



Status of COSY model

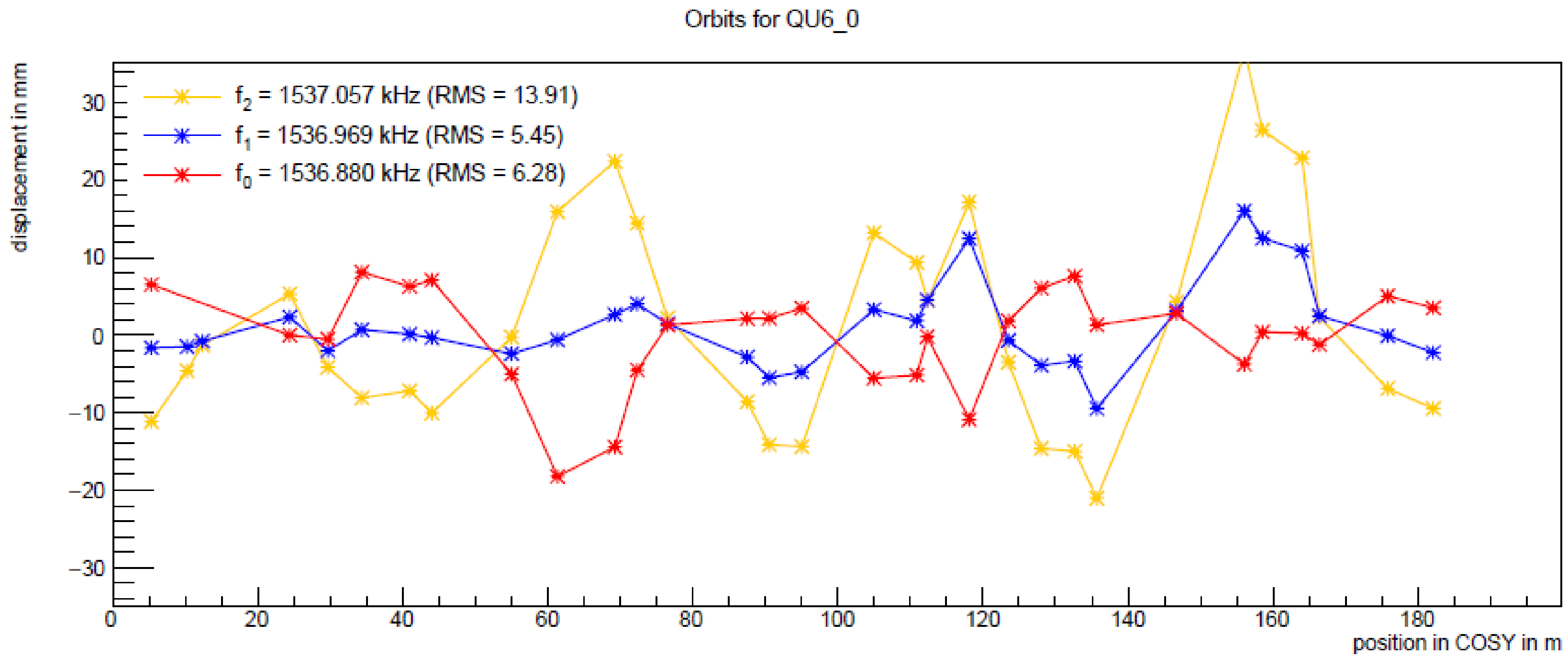
Dispersion

– Measure orbit for different rf-frequencies

$$x(s) = x_0(s) + D(s)\frac{\Delta p}{p}$$

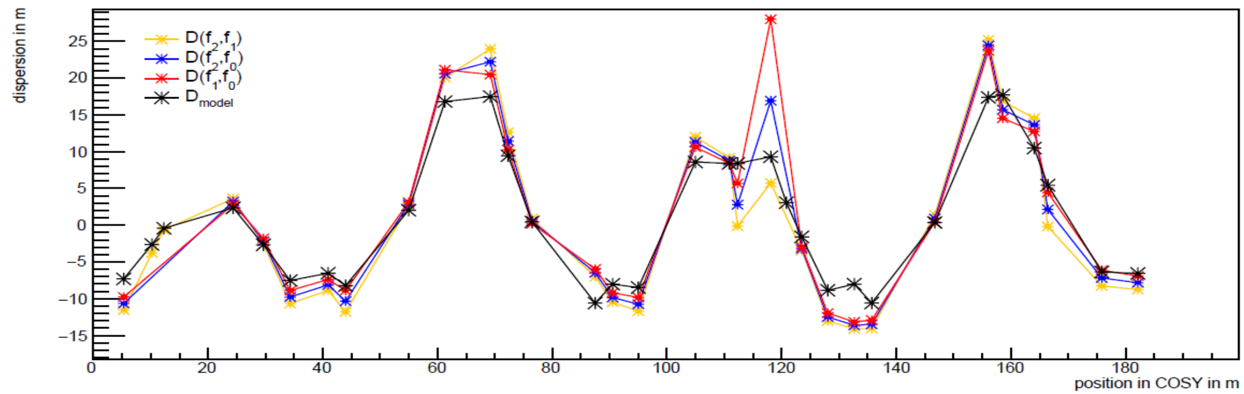
$$\Delta x(s) = D(s)\frac{\Delta E}{E} = \frac{D(s)}{\eta}\frac{\Delta C}{C} = -\frac{D(s)}{\eta}\frac{\Delta f_{rf}}{f}$$

D…dispersion,
η … phase slip factor,
C …length of accelerator

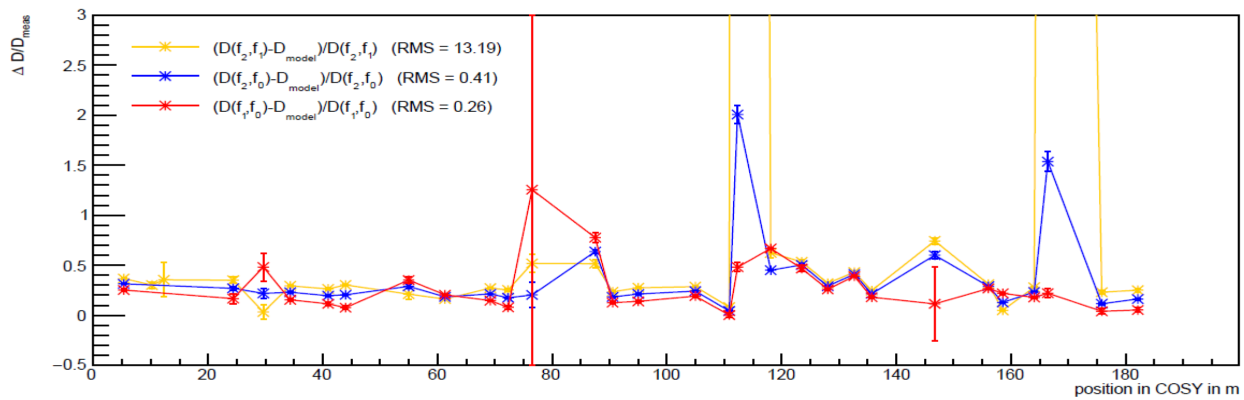


Status of COSY model

Dispersion



$\Delta D/D_{meas} \approx 0.4$



- $\frac{\Delta\beta}{\beta} \approx 30 - 50$ % [1]
- High demands on beam control and beam based measurements, e.g. $\Delta x_{rms} < 0.1$ mm [2]

➢ Improvement of COSY model required!

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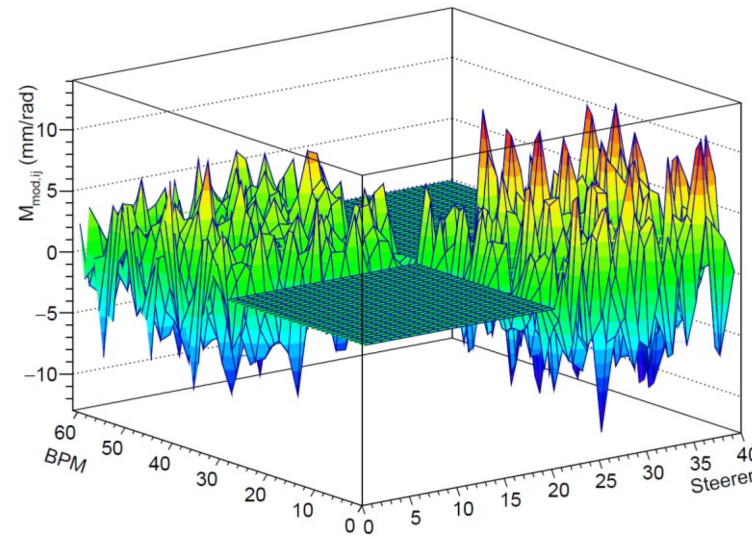
Introduction

Orbit response matrix

– ORM entries contain the response of the beam position at the BPMs(i) to changes of corrector magnets (j)

- $$\begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix} = \boldsymbol{M} \begin{pmatrix} \overrightarrow{\theta_x} \\ \overrightarrow{\theta_y} \end{pmatrix}$$

- $$M_{ij} = \frac{\sqrt{\beta_i \cdot \beta_j}}{2\sin(\pi\nu)} \cdot \cos\left(\left|\varphi_i - \varphi_j\right| - \pi\nu\right)$$



– ORM can be used for orbit correction

– … and to **calibrate and correct linear optics**

Introduction

<u>Loco *(linear optics from closed orbit)* *[3]*</u>

- LOCO was succesfully applied at several electron storage rings

Idea:

- Calculate orbit response matrix using the existing COSY model (MAD-X)
- Vary parameters of the lattice model to minimize difference between M^{mod} and M^{meas}

$$\chi^2 = \sum_{i,j} \frac{(M_{i,j}^{mod} - M_{i,j}^{meas})^2}{\sigma^2_{M_{meas,i,j}}} = \sum_{k=i,j} E_k^2$$

$\sigma_{M_{\mathrm{meas},ij}}$: errors of linear fit to the beam displacment at each BPM(*i*) as function of the current in each steerer magnet(*j*)

Goal:

- Determination of correct lattice parameter settings to improve model
- Correct unacceptable misalignments or calibration factors

Loco - Theory

Possible fit parameters @ COSY

Parameter	No.
BPM calibration	60
BPM roll (ψ), shift (s)	$2 \cdot 60$
Steerer calibration	40
Steerer roll (ψ), shift (s)	$2 \cdot 40$
Gradient of quadrupoles	56
Gradient of quad families	14
Quadrupole rotations (φ, θ, ψ), shifts (x, y, s)	$6 \cdot 56$

Parameter	No.
Dipole rotations (φ, θ, ψ), shifts (x, y, s)	$6 \cdot 24$
K1 of dipole magnets	24
K2 of dipole magnets	24
Deflection angle (offset)	40
K2 of sextupoles	14
Sum	**952**

- Typical COSY ORM contains BPM $\cdot$ Steerer = 2400 data points
- Not all can be fitted simultaneously
- ORM is not sensitive to all parameters

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Loco - Theory

Algorithm

$$\chi^2 = \sum_{i,j} \frac{(M_{i,j}^{mod} - M_{i,j}^{meas})^2}{\sigma_{i,j}^2} = \sum_{k=i,j} E_k^2$$

– Determine dE_k / dK_l by varying model parameters
  (number of entries = 2400 · parameter)

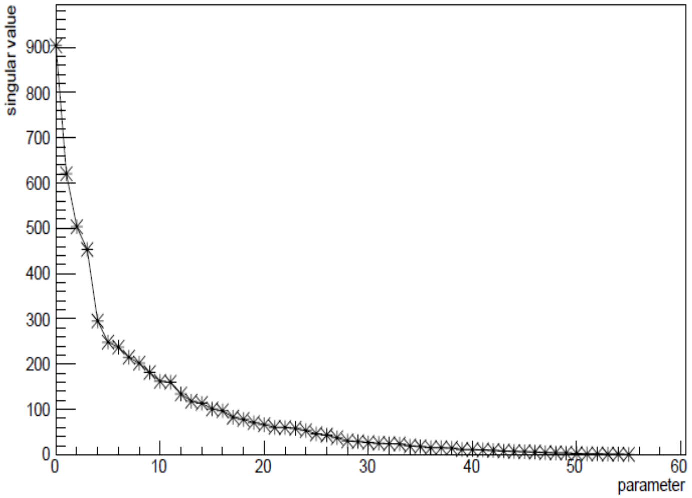
$$-E_k = \frac{dE_k}{dK_l} \cdot \Delta K_l$$

– Invert dE_k / dK_l using SVD analysis

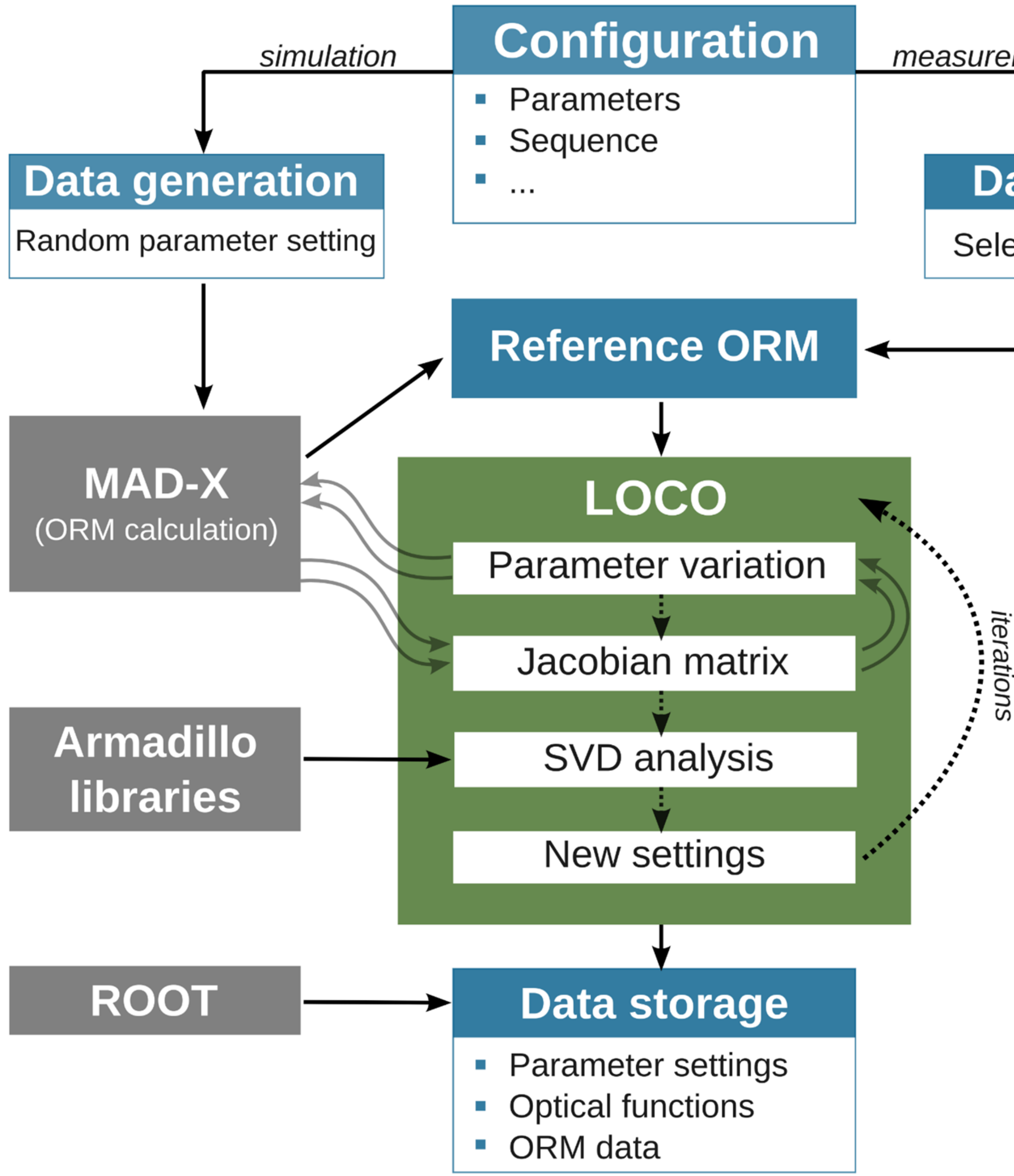
$$\frac{dE_k}{dK_l} = USV^T = \sum \vec{u}_l w_l \vec{v}_l^{\,T}$$

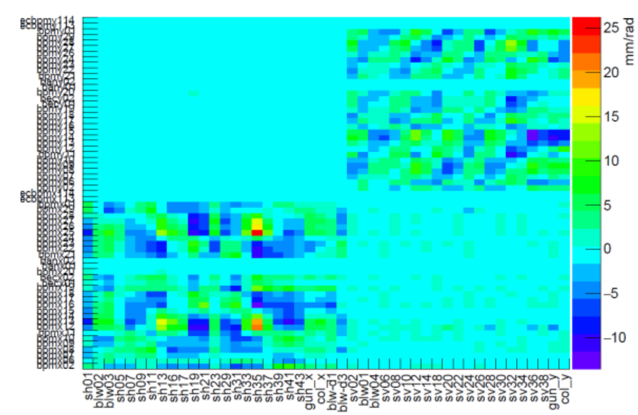
– Calculate parameter settings

$$\Delta K = -\sum \vec{v}_l \frac{1}{w_l} \vec{u}_l^{\,T} \cdot E_k$$



Loco - Program



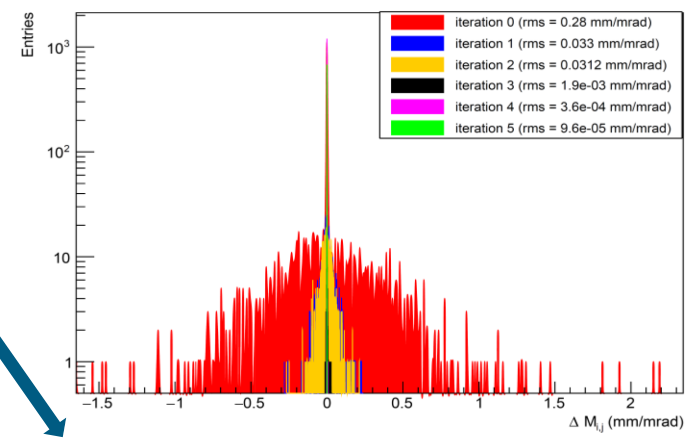


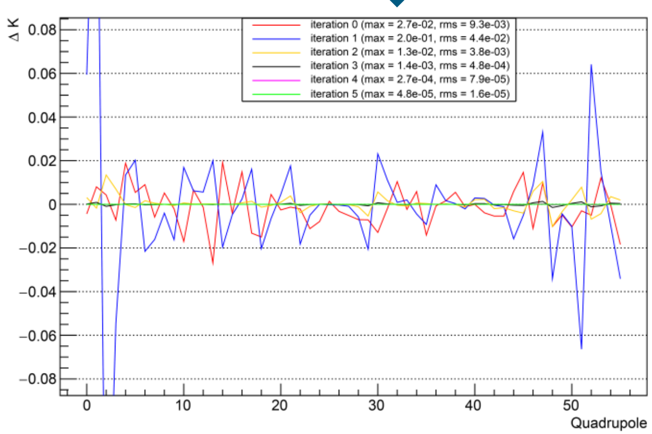
Loco - Program

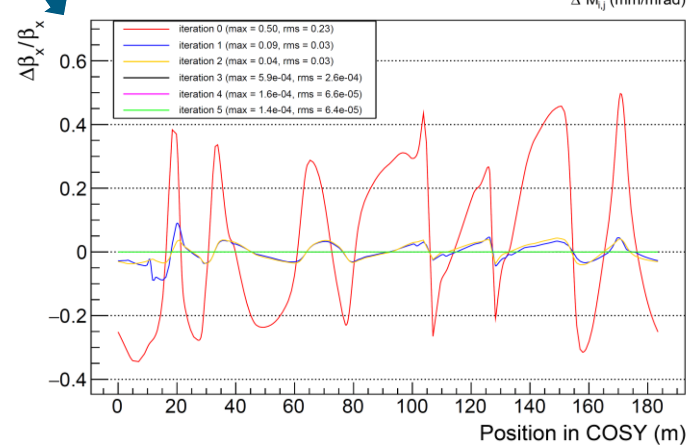
Benchmarking

– Simulation of ORM measurement with randomly generated parameter settings (Gaussian distributed)
– Evaluation of results by reconstruction of
  - Orbit response matrix
  - Beam optics ($\Delta\beta/\beta$)
  - Parameter settings

$$(\Delta k = k_{\mathrm{meas}} - k_{\mathrm{mod}})$$



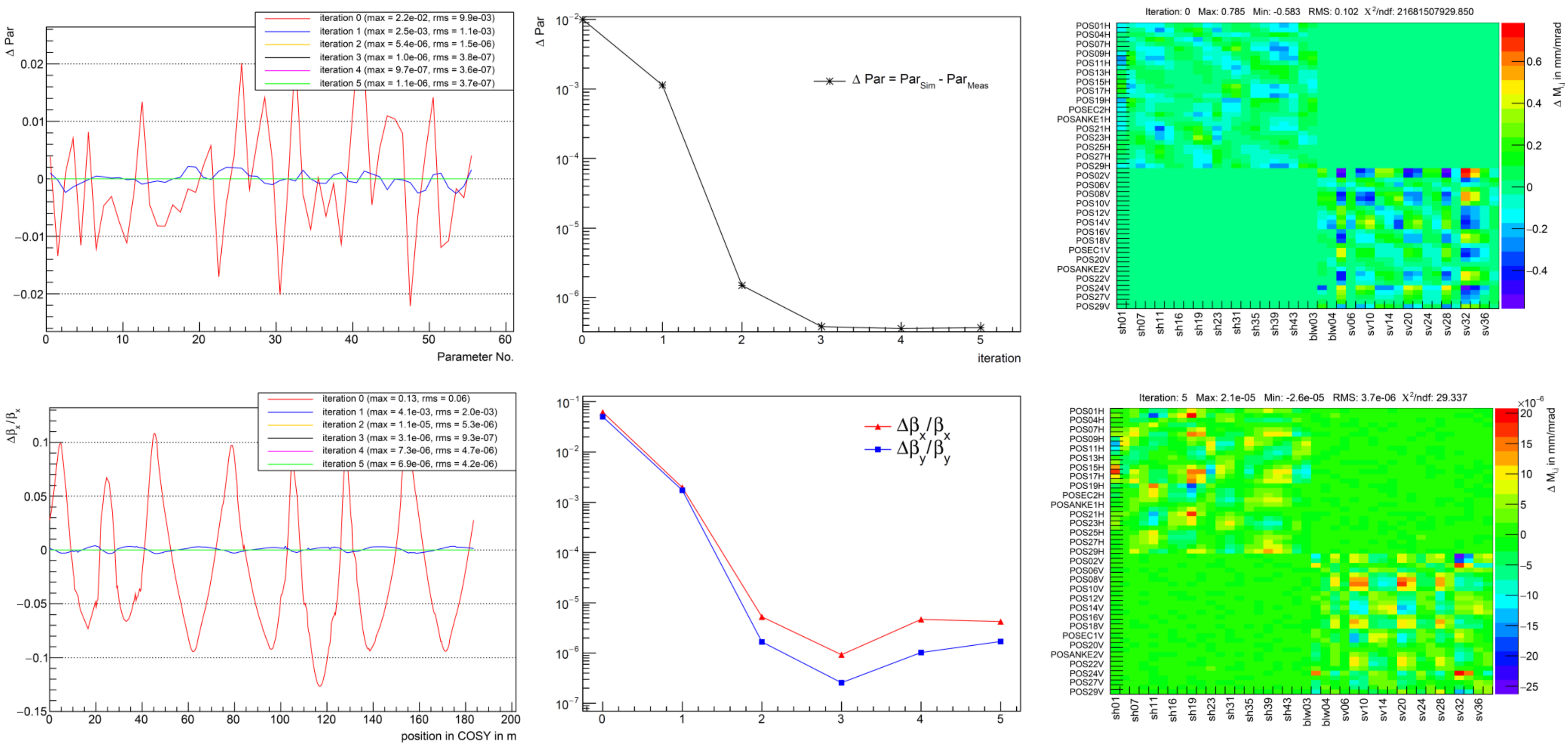




Loco - Program

<u>Benchmarking</u> (good reconstruction):

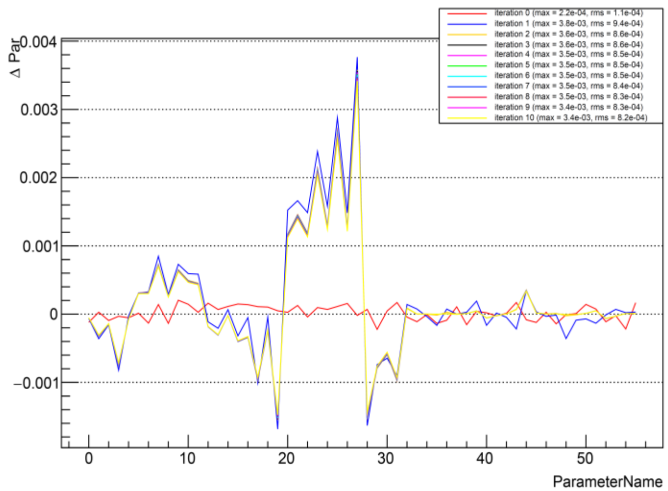
Longitudinal position of quadrupoles

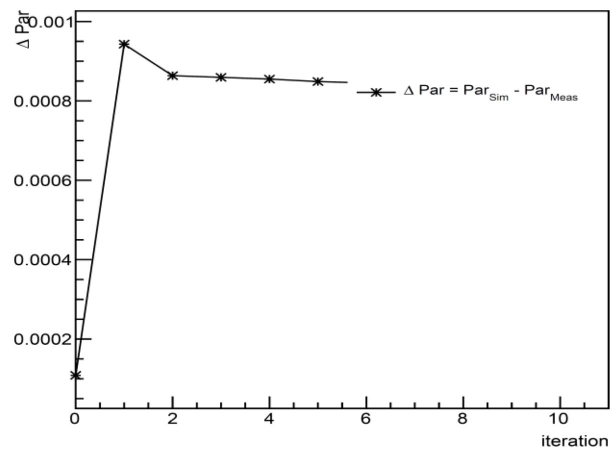


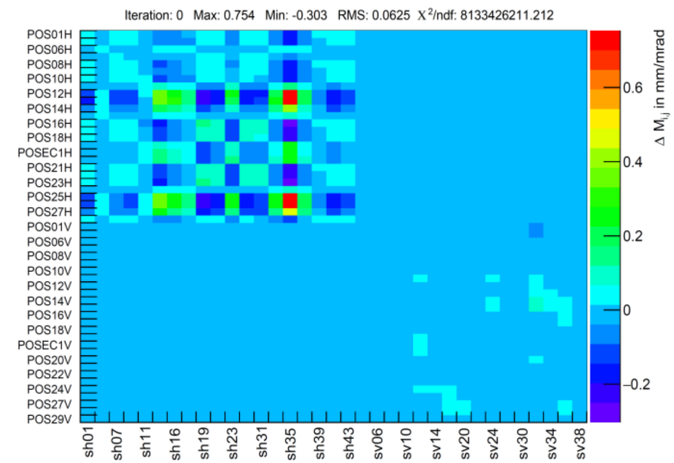
Loco - Program

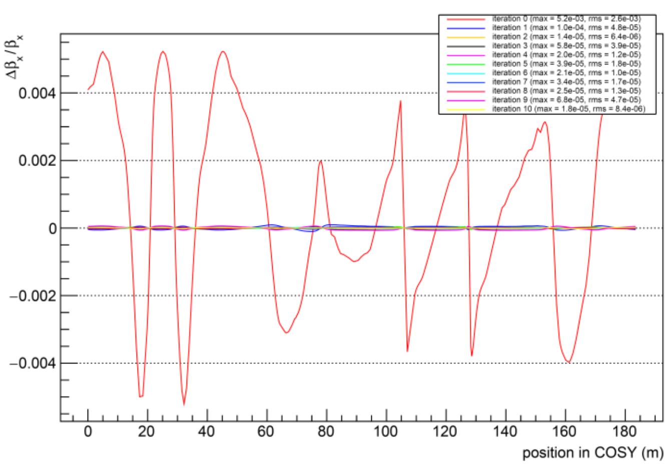
<u>Benchmarking</u> (only optics improvement)*:*

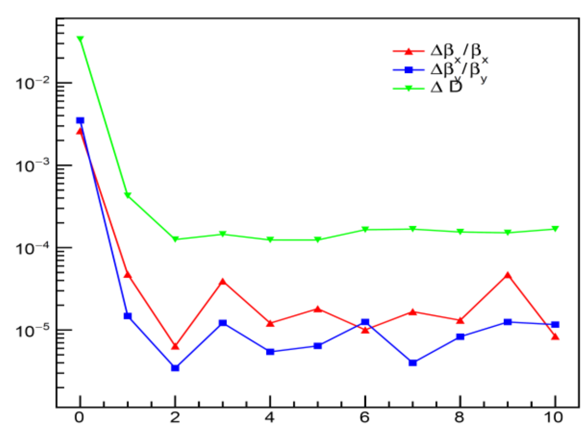
Transverse position of quadrupoles

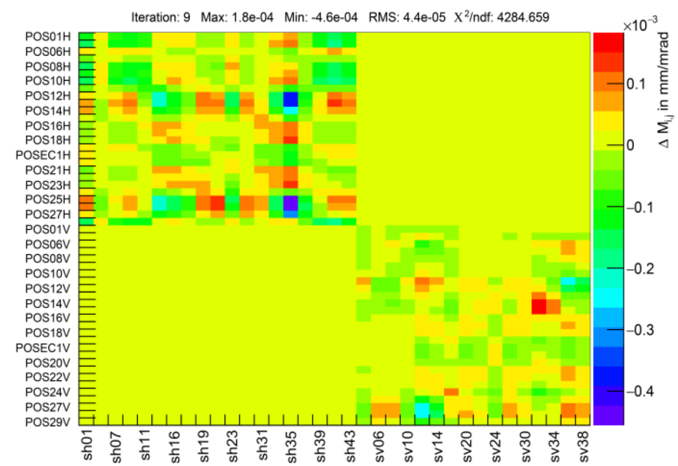








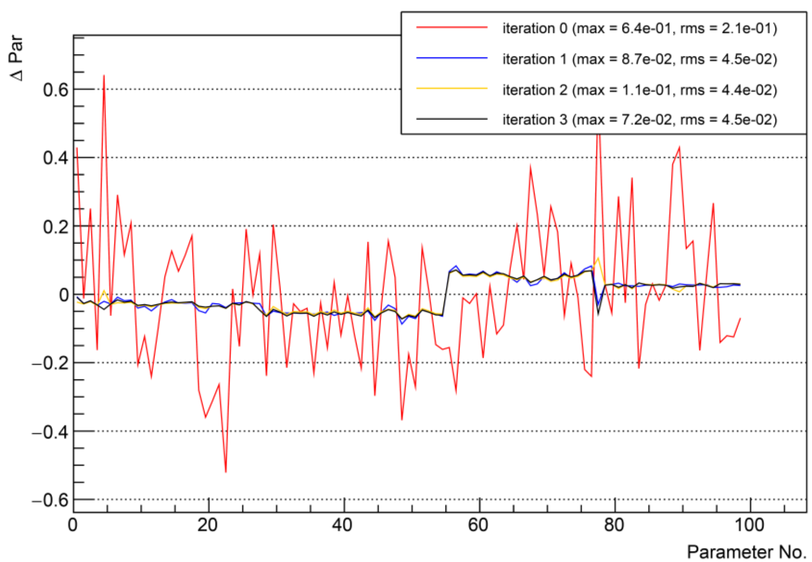


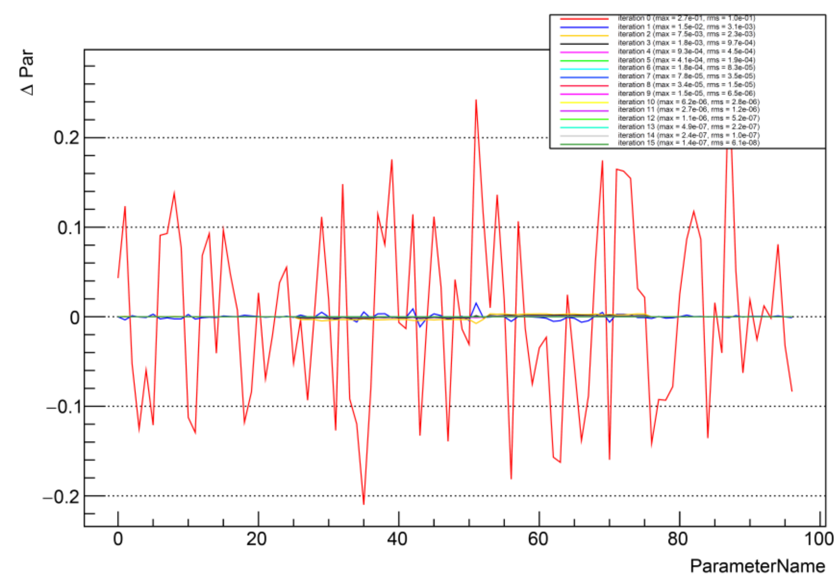


Loco - Program

Benchmarking

- Different combinations of parameter settings yield the same beam response (degeneracy)
- No unique result detectable
- Fixing parameters helps to overcome the degeneracy problem
- Requires calibration of fixed parameters

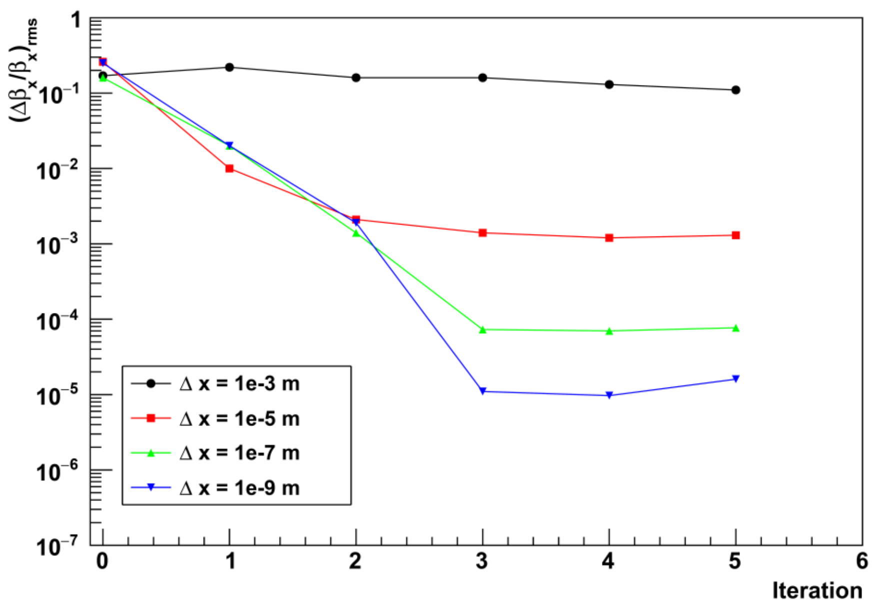


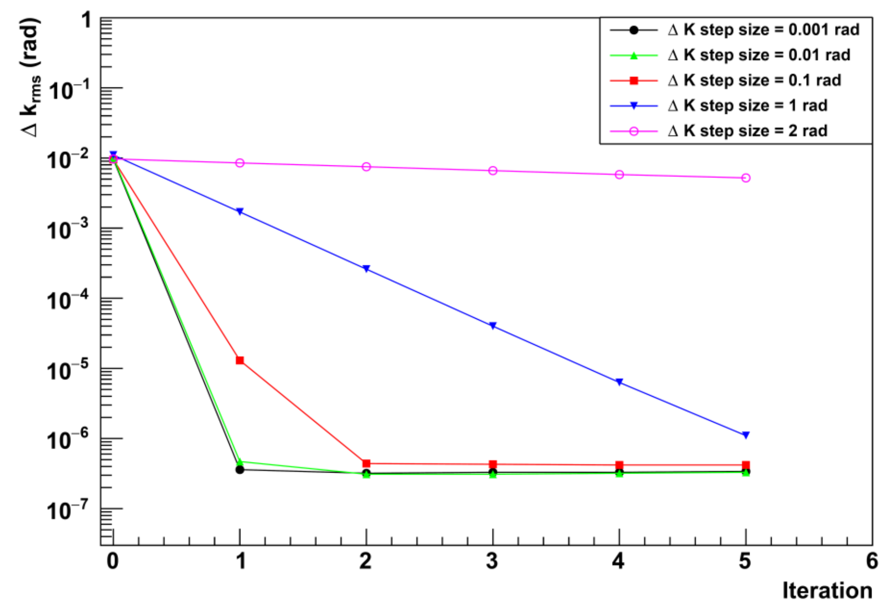


Loco - Program

Benchmarking

- Sensitivity to different parameters (e.g. quadrupole gradients)
- Influence of error of beam position measurement
- Sensitivity to truncated rank of matrix in SVD analysis
- Sequence of parameter adjustment
- Effect of step size of parameter variation





Loco - Program

Benchmarking – some results

- Performance of parameter reconstruction and optics determination depends significantly on BPM errors
- Sensitivity to step size depends on linearity of ORM to parameter change

- BPM and steerer gains work perfect (degeneracy problem when fitting both simultaneously can be avoided by fixing one component)

- Good reconstruction: BPM and steerer (ds, dψ), Quad (ds, dψ, K1),
  Dipole (K1, K2, ds, dψ), Sextupoles (K2)
- Only optics improvement: Quad (dx, dy, dθ)
- Not sensitive: BPM and steerer (dx, dy, dφ, dθ), Quad (dφ)

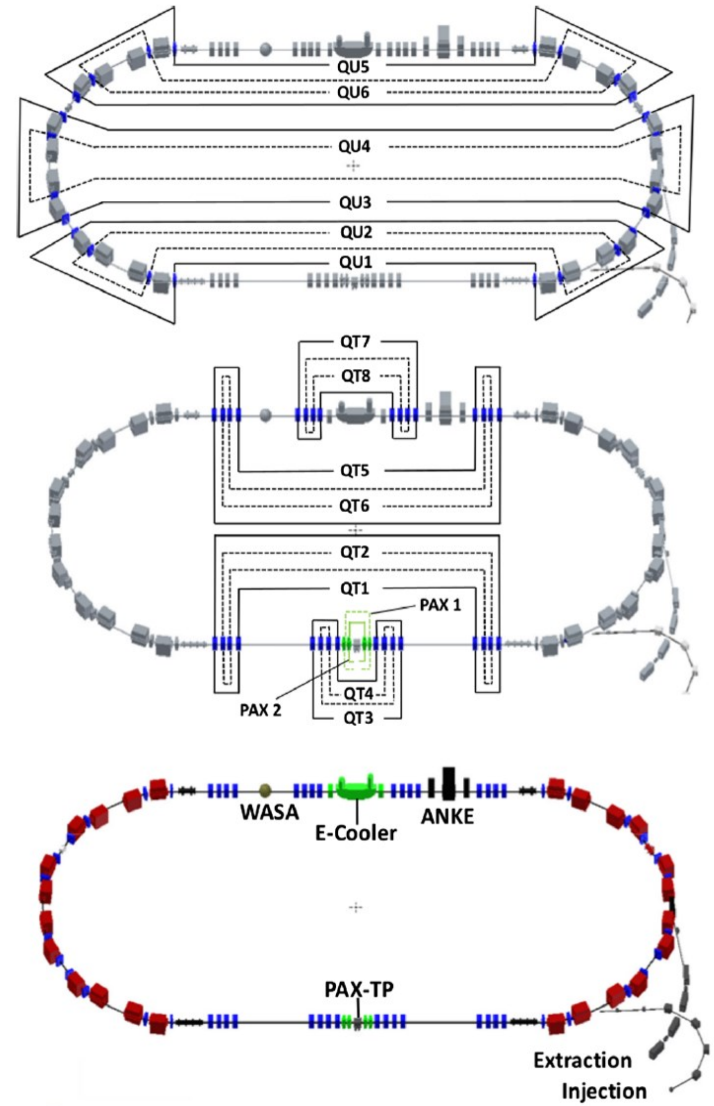
- Fitting combinations of parameters has to be studied

Beam optics studies

Machine parameters

- Proton beam of 2.6 GeV/c momentum
- Regular COSY optics (D≠0)
- ORM measured for different settings of quadrupole families

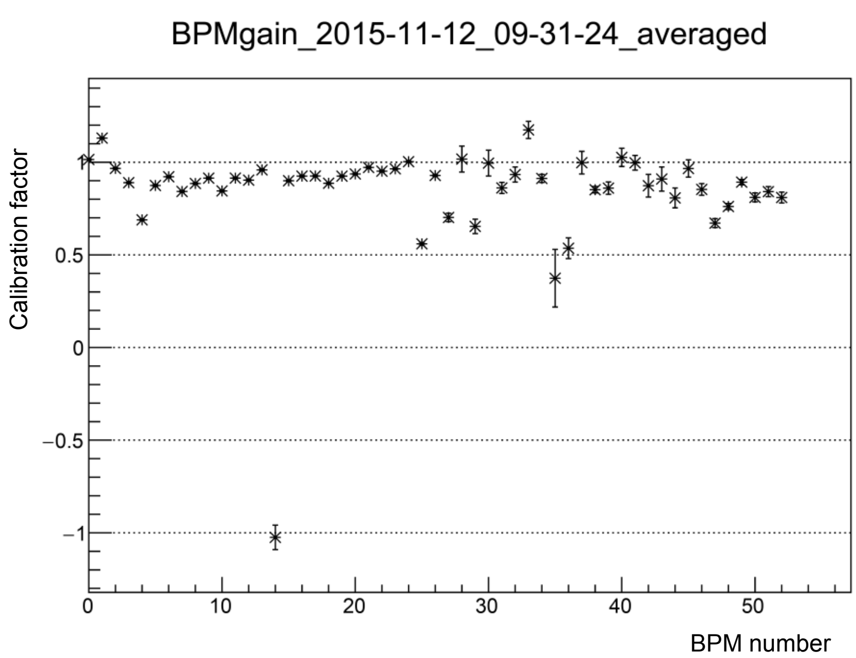
Quadrupole familie	Δk ‰	date
MQU 6	0	2015 – 11 – 11_19 – 38 – 07
MQU 6	+20	2015 – 11 – 11_20 – 24 – 38
MQU 6	-20	2015 – 11 – 11_21 – 11 – 18
MQT 3	+20	2015 – 11 – 12_08 – 54 – 56
MQT 3	-20	2015 – 11 – 12_09 – 31 – 24
MQU 2, MQU 6	+10	
MQU 4, MQU 5	+20	2015 – 11 – 12_11 – 49 – 47
MQU 4, MQU 5	-20	2015 – 11 – 12_13 – 19 – 31

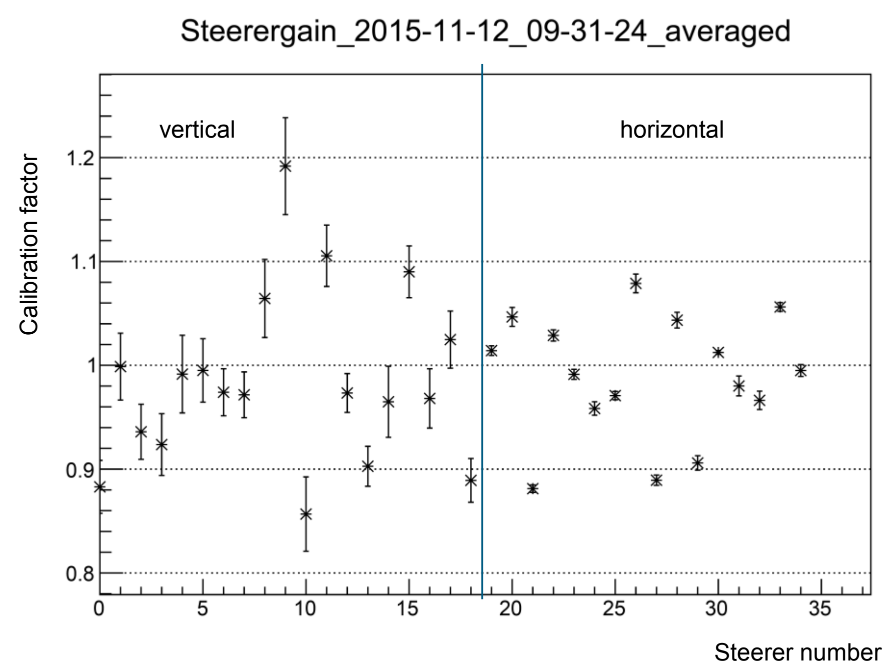


Applying LOCO to measured data

Steerer and BPM calibration

- Detection of wrongly oriented BPMs
- Detection of wrongly oriented steerer magnets
- Variation of vertical steerer calibration factors larger than horizontal

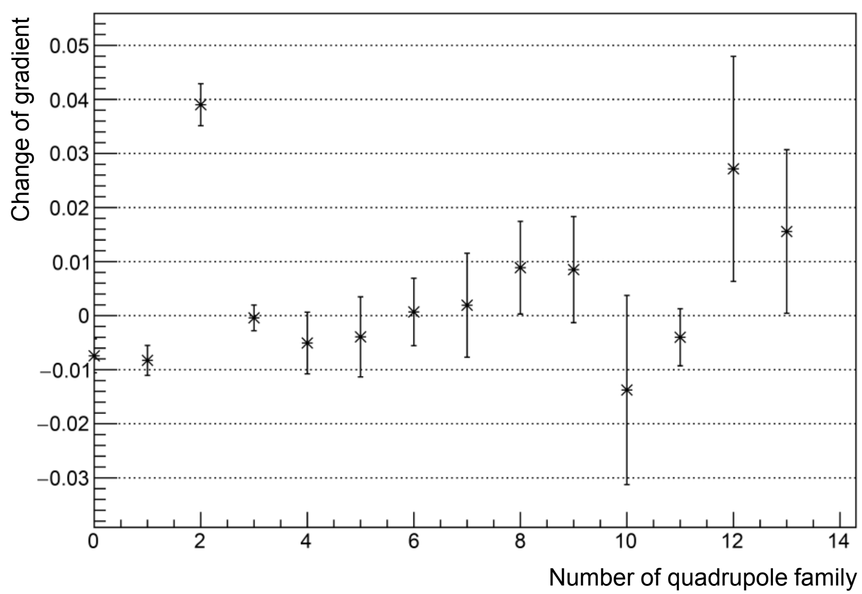


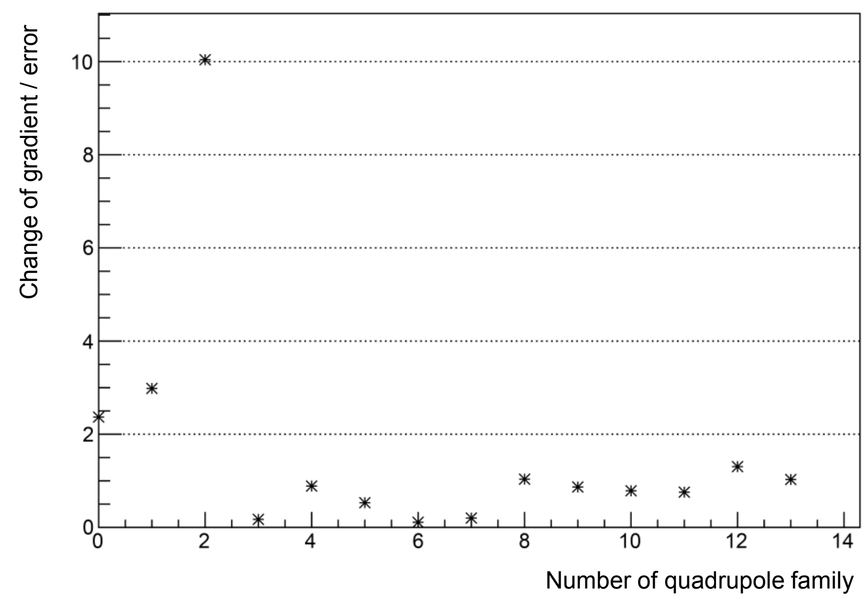


Applying LOCO to measured data

Quadrupole strength

- Determination of individual gradients factors
- Absolute values are difficult to judge at this point
- Detection of changed gradient factors between individual measurements
- 4 % change was applied to quadrupole family MQT3 (number 2)





Summary

- Loco program was succesfully developed
- Benchmarking almost finished
- First test with measured data

<u>Future plans:</u>

- Determine magnet displacements and compare with recent survey measurement
- Constrain with dispersion measurement
- Improved ORM measurement (more data points)
- Outlier data rejection
- Automatic step size finder
- Implementation of additional minimization algorithm
- Multi-core processing
- ….

Literature

[1] D. Ji, „First experience of applying LOCO for Optics measurement at COSY“, IPAC 16, Busan, South Korea, 2016.

[2] M. Rosenthal, “Experimental Benchmarking of Spin Tracking Algorithms for Electric Dipole Moment Searches at the Cooler Synchrotron COSY”, PhD thesis, 2016.

[3] J. Safranek, Nucl. Instrum. Meth. A 388, 27 (1997).