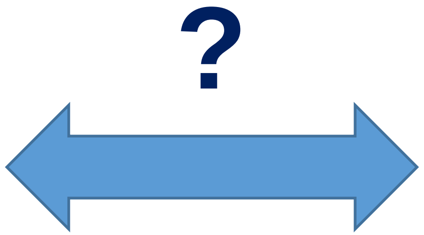
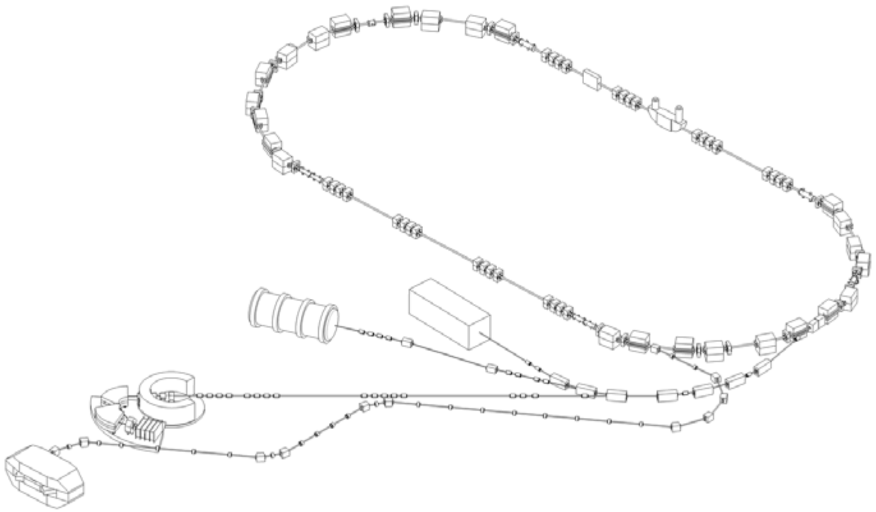
SIMULATION MODEL IMPROVEMENTS AT COSY USING THE LOCO ALGORITHM

31.03.2021 I 744. WE-HERAEUS-SEMINAR | VERA PONCZA

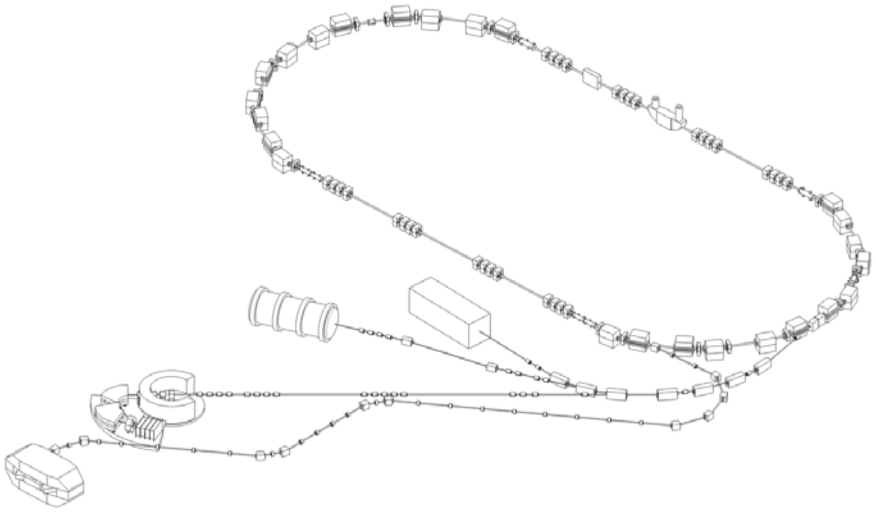
MOTIVATION





How to achieve a more realistic simulation model of COSY?

MOTIVATION



- Magnet misalignments
- Gradient errors
- Close standing magnets
- …

What effects influence the particle and spin motion?

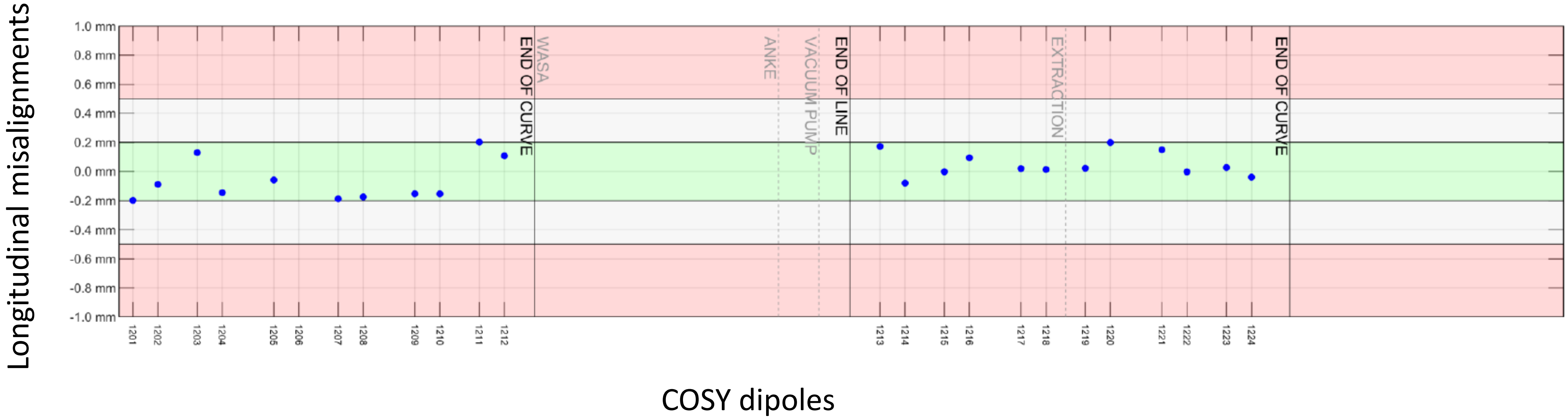
MOTIVATION

1. Stepwise approach: one effect at a time
2. Fitting several parameters at the same time

How to incorporate effects in a simulation model?

STEPWISE APPROACH: ONE EFFECT AT A TIME

MAGNET MISALIGNMENTS

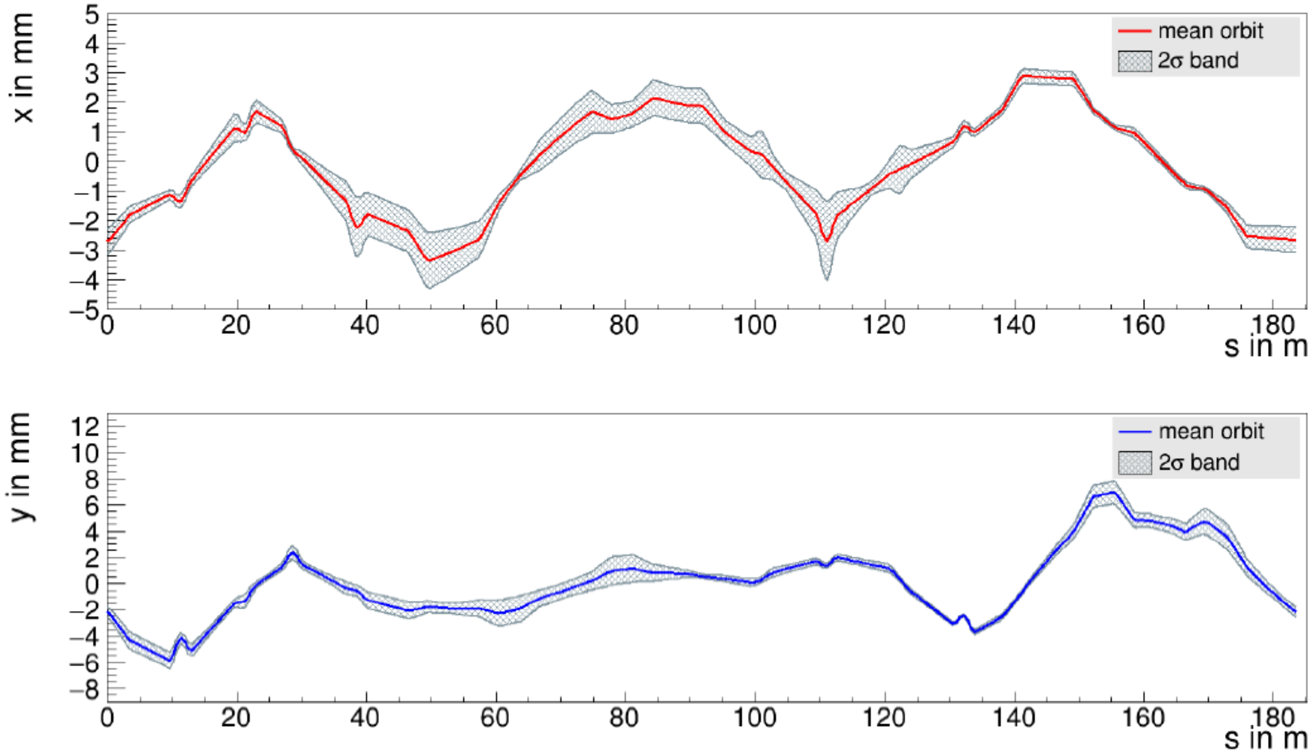


Dipole and quadrupole misalignments were measured in each direction

STEPWISE APPROACH: ONE EFFECT AT A TIME

MAGNET MISALIGNMENTS

Simulated closed orbits in horizontal and vertical direction



- Magnet misalignments lead to distortions of the closed orbits
- The uncertainties of the magnet positions measurement were taken into account:

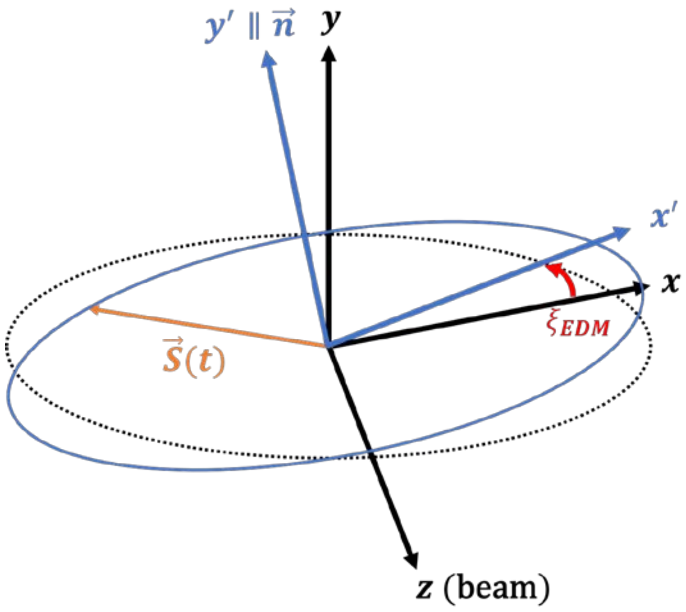
$$\Delta\tilde{x} = \Delta x_{\text{measured}} + \mathcal{N}(0, \sigma_{\Delta x})$$

STEPWISE APPROACH: ONE EFFECT AT A TIME

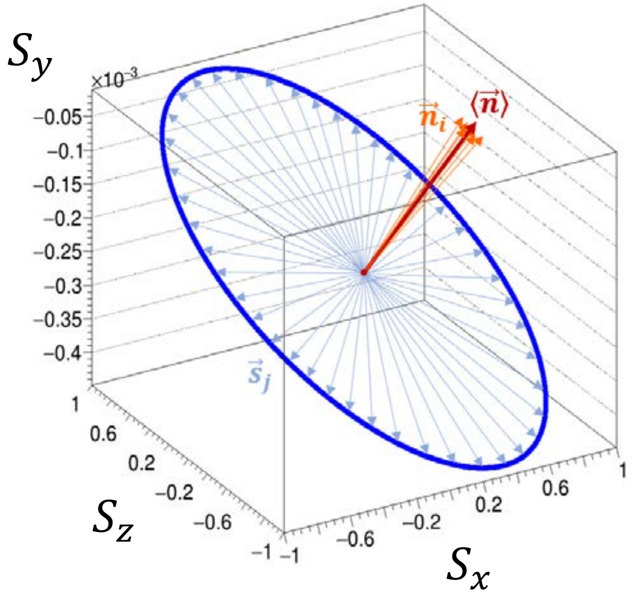
DETERMINATION OF INVARIANT SPIN AXIS

Invariant spin field $\hat{n}$: $\hat{n}(\vec{z}, \theta + 2\pi) = \hat{n}(\vec{z}, \theta)$

One turn spin map R : $R(\vec{z}_i, \theta)\hat{n}(\vec{z}_i, \theta) = \hat{n}\left(\vec{z}_f, \theta\right)$



$$\xi_{EDM} = \tan^{-1}\left(\frac{\eta_{EDM}\beta}{2G}\right)$$



- Perform spin tracking over several turns
- For each possible combination of 3 spin vectors:
  - Determine normal vector to the resulting plane
- Calculate the average invariant spin axis $\langle\vec{n}\rangle$ out of all normal vectors

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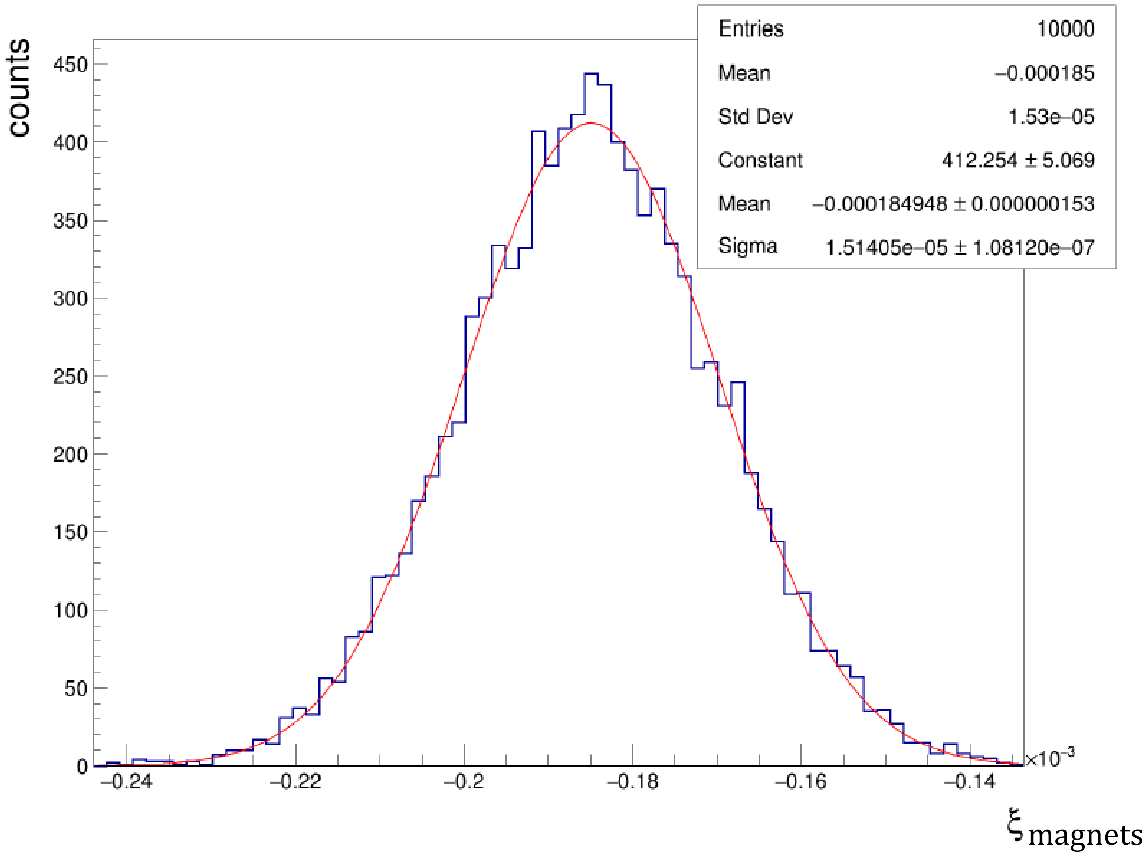
STEPWISE APPROACH: ONE EFFECT AT A TIME

MAGNET MISALIGNMENTS

Distribution of tilt angles of the invariant spin axis in the y-x-plan for 10000 random Gaussian magnet misalignments



Systematic limit of the EDM value due to measurement uncertainties

The EDM tilts the invariant spin axis by:

$$\xi_{\mathrm{EDM}} = \xi_{\mathrm{measured}} - \mu_{\xi_{\mathrm{magnets}}}$$

The threshold angle for the 3σ level

$$\xi_{EDM} = -0.0000454215\, rad$$

The threshold (minimal resolvable) EDM value:

$$d_{3\sigma} = 1.49 \cdot 10^{-19}\, e \cdot cm$$

FITTING SEVERAL PARAMETERS AT THE SAME TIME

Model parameters under investigation:

- magnet misalignments
- gradient errors
- steerer calibration

…

Random changes of one model parameter after the other and observation of the model behaviour

Unlikely to find the correct combination of model parameter changes that lead to a realistic description

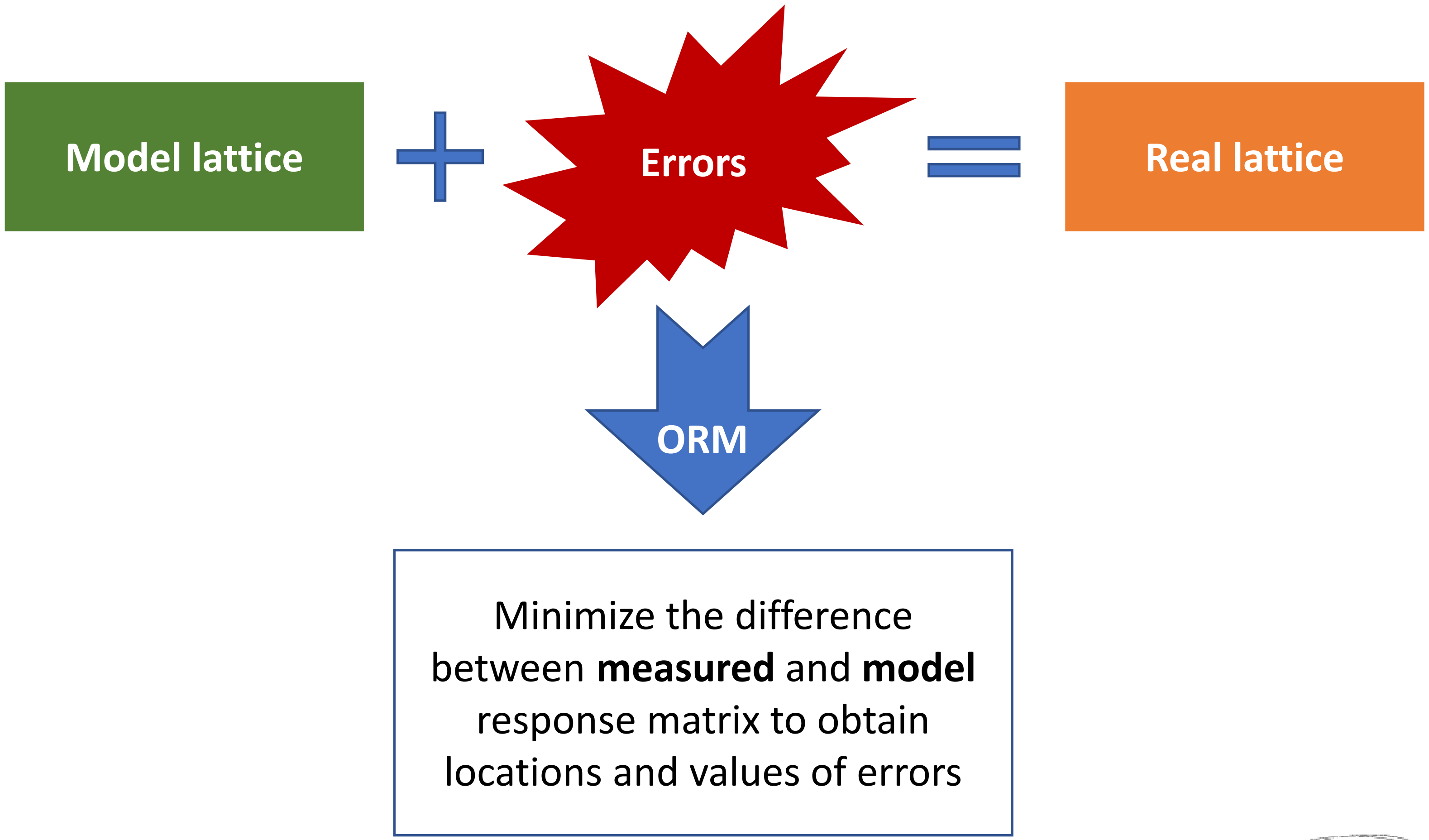
Systematic study of model parameters including simultaneous investigation of different parameters

Orbit Response Matrix analysis

LOCO ALGORITHM

Linear Optics from Closed Orbit

Proceeding IPAC 2016: *"Model driven machine improvement of COSY based on ORM data"* *(C. Weidemann, M. Bai, F. Hinder, B. Lorentz)*



ORBIT RESPONSE MATRIX (ORM)

$$\boxed{\begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix} = M_{ORM} \times \begin{pmatrix} \vec{\theta}_x \\ \vec{\theta}_y \end{pmatrix}}$$

m BPMs
n steerers

orbit vector (BPMs)

steerer kicks

$\boldsymbol{V}$: model parameter

$\boldsymbol{R} = \boldsymbol{f}(\boldsymbol{V})$: orbit response vector

$$\boldsymbol{R}(\boldsymbol{V}) \approx \boldsymbol{R}(\boldsymbol{V_0}) + \boldsymbol{R}'(\boldsymbol{V_0})(\boldsymbol{V} - \boldsymbol{V_0}) \quad \text{where} \quad \boldsymbol{R}'(\boldsymbol{V_0}) = \boldsymbol{J} = \begin{bmatrix} \frac{\partial \boldsymbol{R_1}}{\partial \boldsymbol{V_1}} & \cdots & \frac{\partial \boldsymbol{R_1}}{\partial \boldsymbol{V_k}} \\ \vdots & \ddots & \vdots \\ \frac{\partial \boldsymbol{R_{mn}}}{\partial \boldsymbol{V_1}} & \cdots & \frac{\partial \boldsymbol{R_{mn}}}{\partial \boldsymbol{V_k}} \end{bmatrix}$$

measured **model**

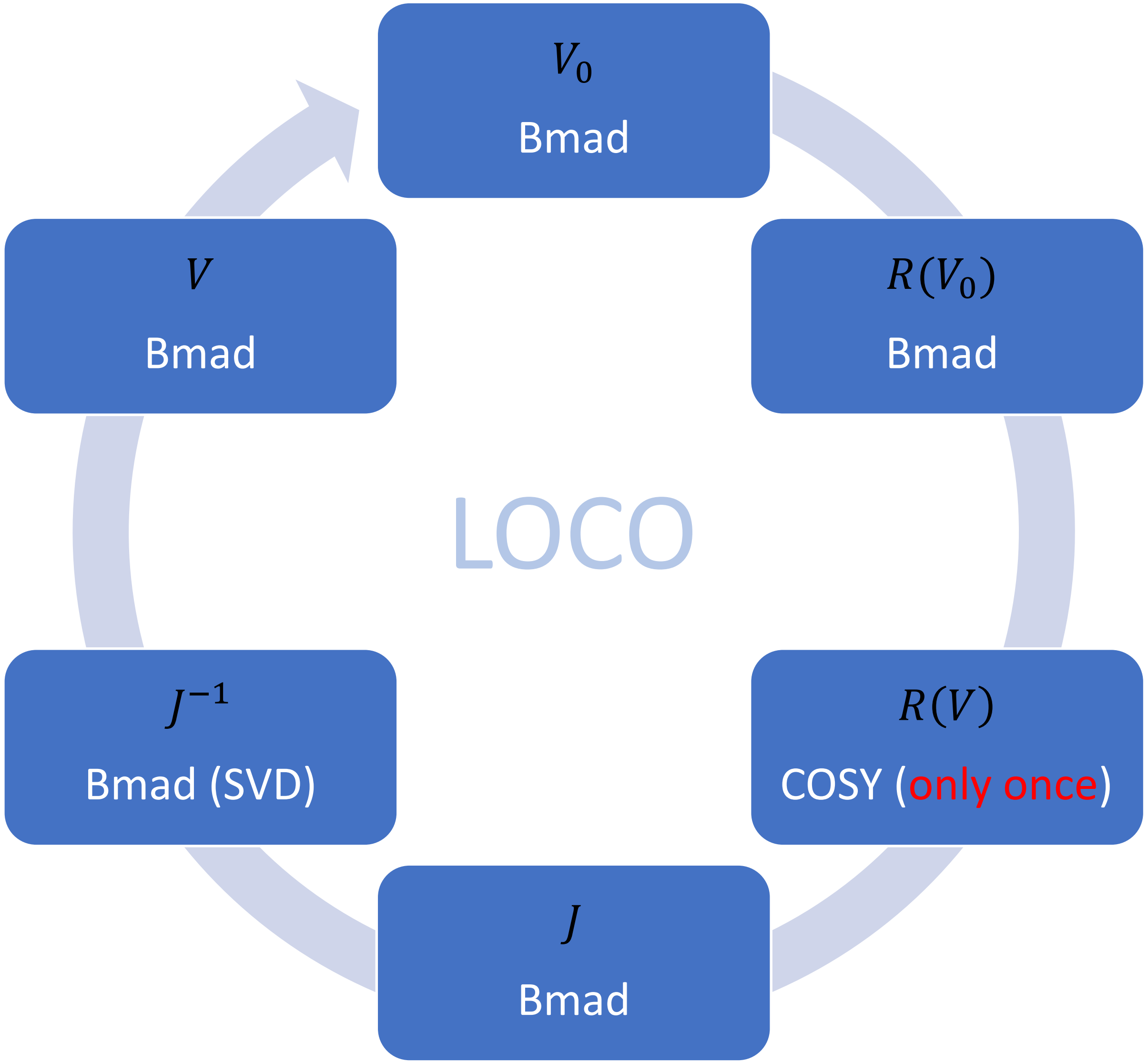
$$\boxed{\boldsymbol{\Delta V} = \boldsymbol{V} - \boldsymbol{V_0} = \boldsymbol{J}^{-1}(\boldsymbol{R}(\boldsymbol{V}) - \boldsymbol{R}(\boldsymbol{V_0}))}$$

ITERATION PROCESS

Minimize χ^2 + penalty weights ω_k:

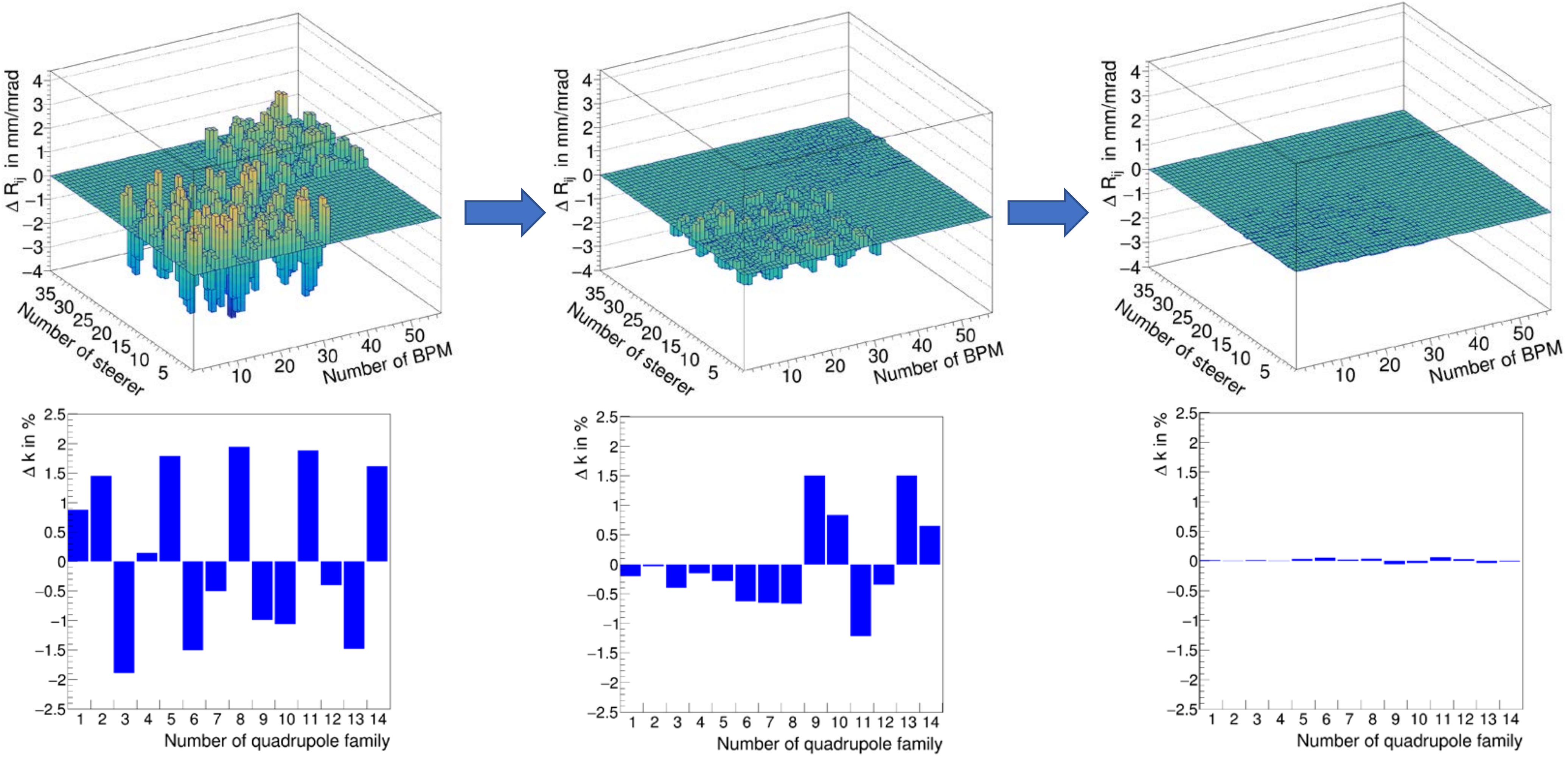
$$\chi^2 = \sum_{i,j} \frac{\left(M_{i,j}^{COSY} - M_{i,j}^{model}\right)^2}{\sigma_{COSY\ i,j}^2} + \frac{1}{\sigma_0^2} \sum_{k}^{N_V} \omega_k^2 \Delta V_k$$

1. First guess $\boldsymbol{V_0}$
2. Calculate model response vector $\boldsymbol{R}(\boldsymbol{V_0})$
3. Measure response vector $\boldsymbol{R}(\boldsymbol{V})$ by varying steerers
4. Compute Jacobian $\boldsymbol{J}$ by varying model parameters
5. Pseudoinverse Jacobian $\boldsymbol{J}^{-1}$ calculated via SVD
6. Obtain new model parameter vector $\boldsymbol{V}$
7. Start new iteration with $\boldsymbol{V} = \boldsymbol{V_0}$



TESTING

Quadrupole gradient errors (assuming perfect BPMs)



Difference ORM (2 iterations)

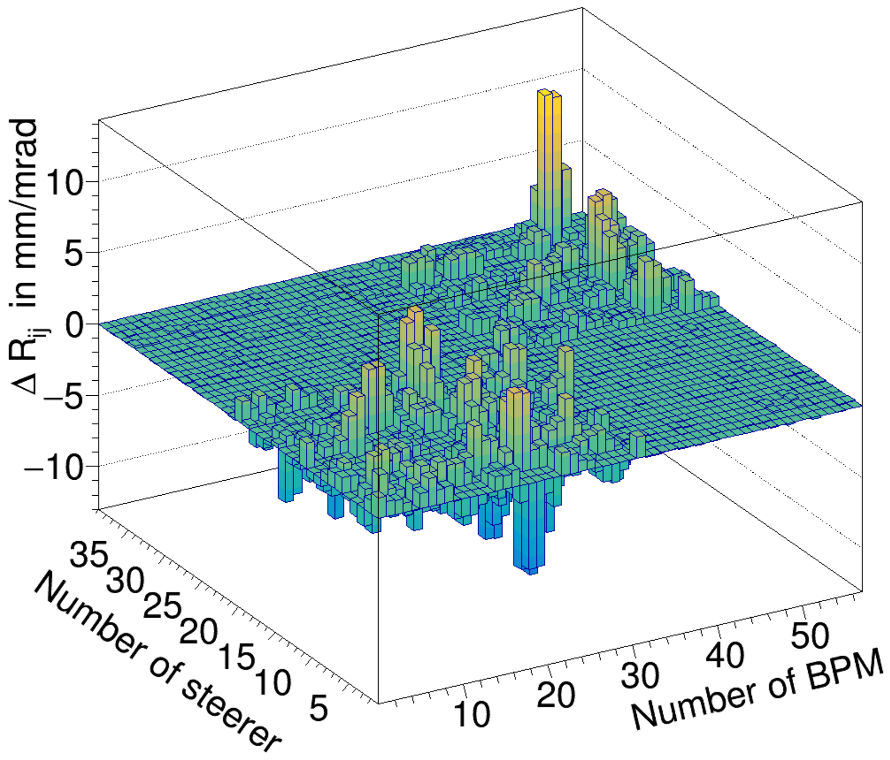
Remaining gradient error

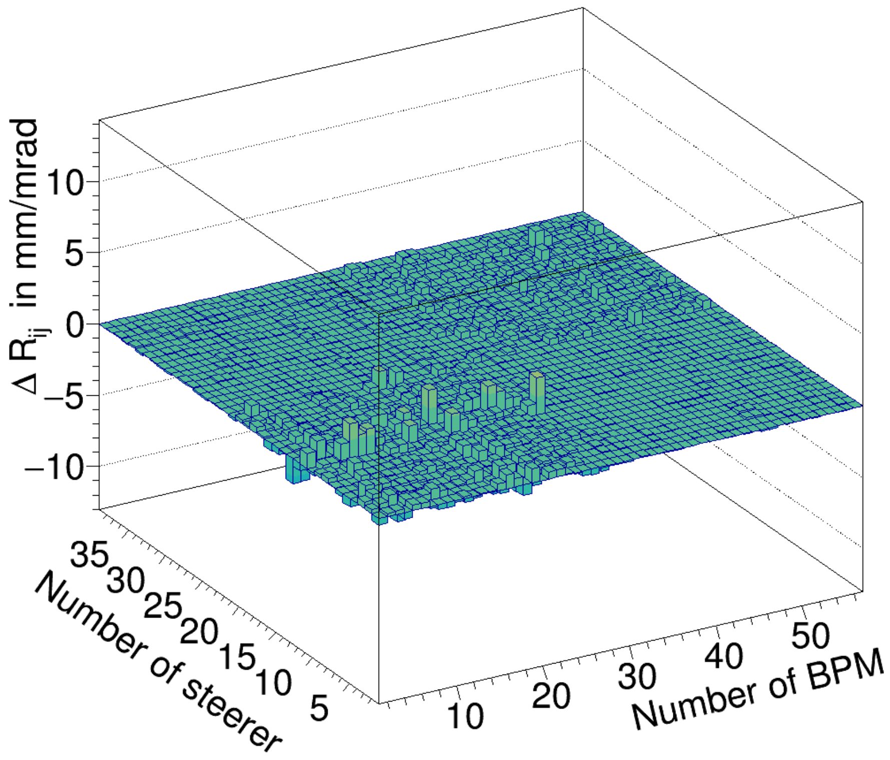
MEASUREMENTS (OCTOBER 2019)

Initial difference ORM

LOCO

Final difference ORM

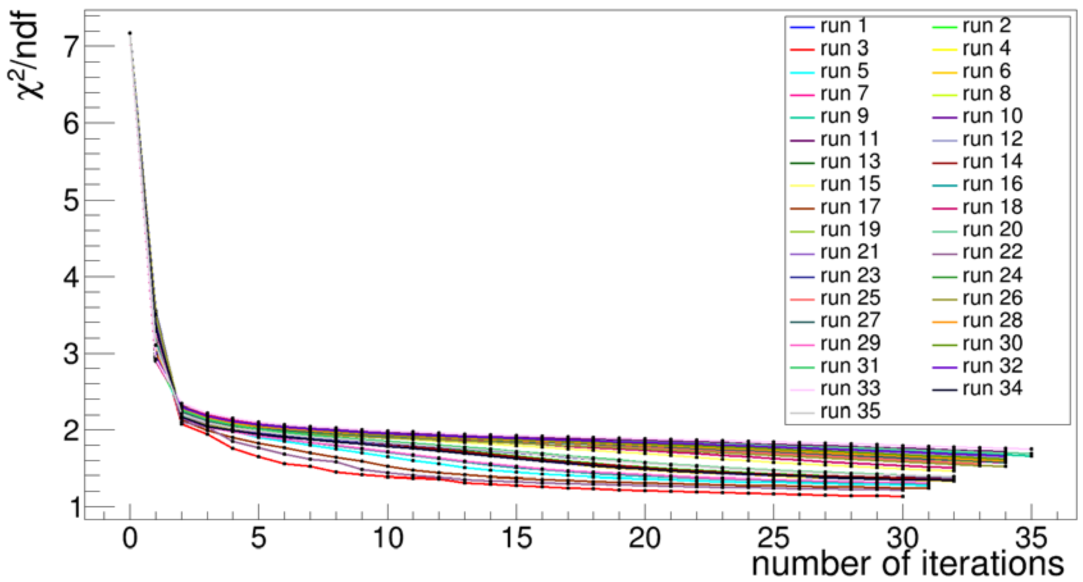


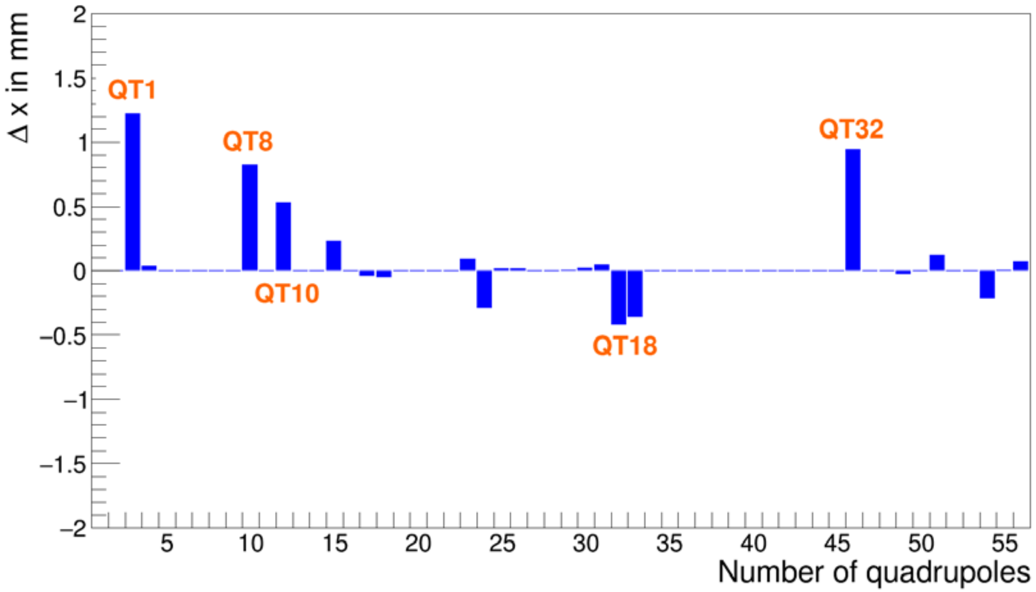


MEASUREMENTS (OCTOBER 2019)

- Weights prevent unrealistic path to global minimum.
- First estimate for weights are the χ^2 contributions of each fit parameter.
- The global minimum is reached independetly of the actual weights.

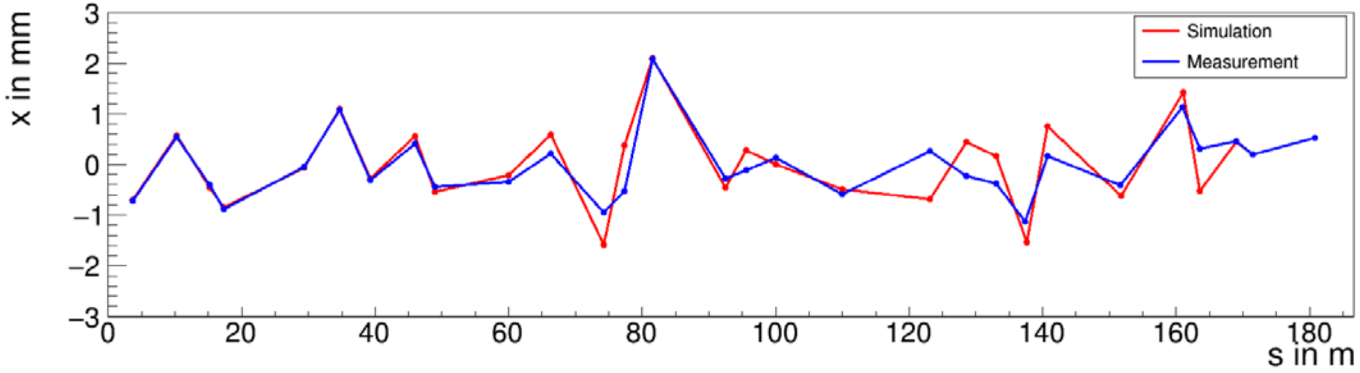
- All position changes are mostly within the 2σ range of the Stollenwerk accuracy of $\sigma = 0.2\ mm$.
- Some QPs have larger offsets in horizontal direction.
- The QPs are the same that Tim Wagner* found during his beam time and the offsets are similarly large.

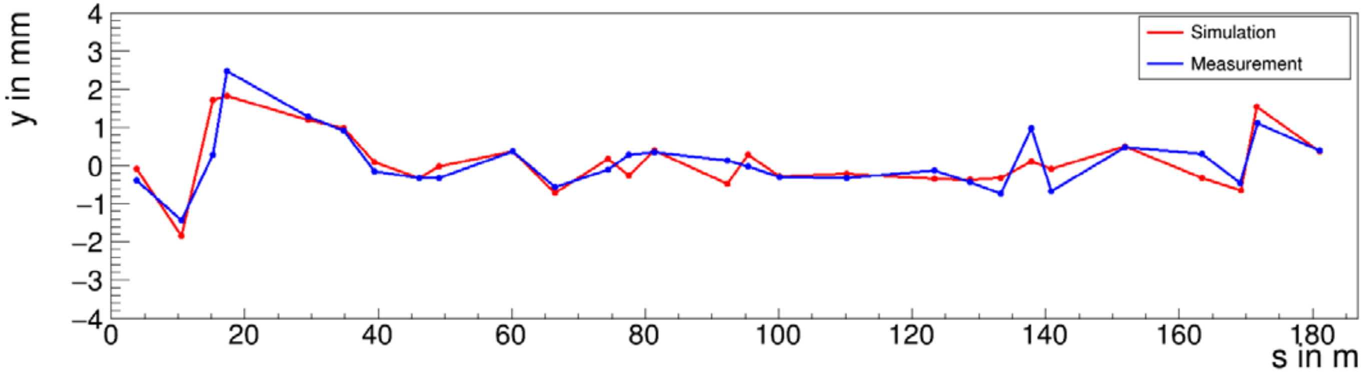




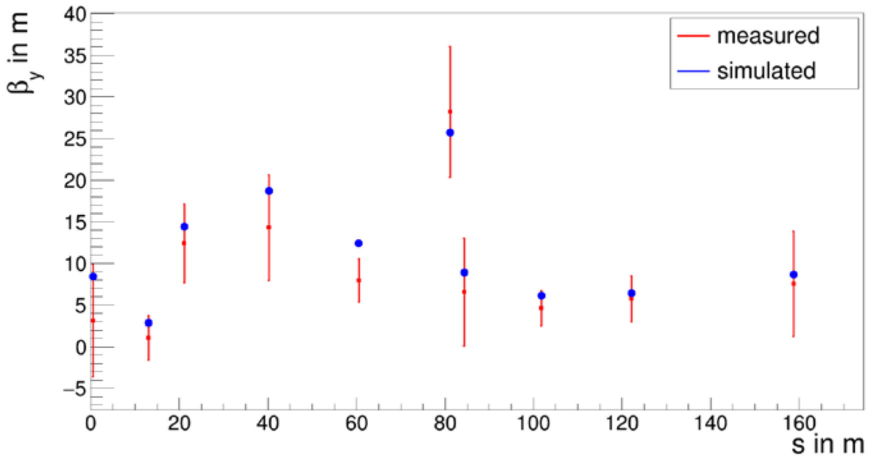
MATCHING THE ORBIT

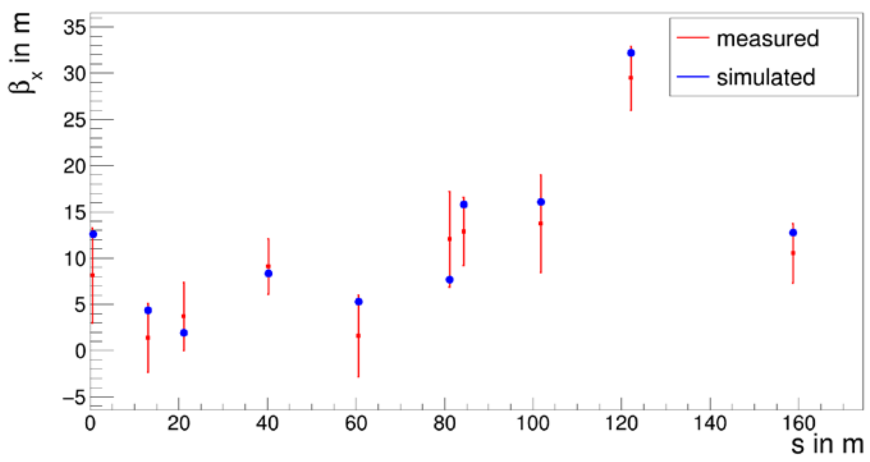
- Fitting the steerer strengths using the usual orbit correction algorithm.
- Target orbit = the measured orbit (October 2019)





FINAL MODEL VS. MEASUREMENT





	Simulation	Measurement
Q_x	3.58210	3.57119
Q_y	3.59430	3.58641
ν_s	0.16143665	0.16099023
n_x	-0.003122	-0.00348
n_s	0.0009970	0.00557

SUMMARY

- There is a systematic way of investigating the influence of different model parameters: LOCO algorithm.
- The algorithm was succesfully implemented into Bmad.
- A LOCO fit was performed using quadrupole gradients and positions to fit the model.
- An additional orbit matching was done by fitting the steerer strengths.
- The model could be clearly improved.
- The longitudinal component of the invariant spin axis is still not fully understood.

THANK YOU