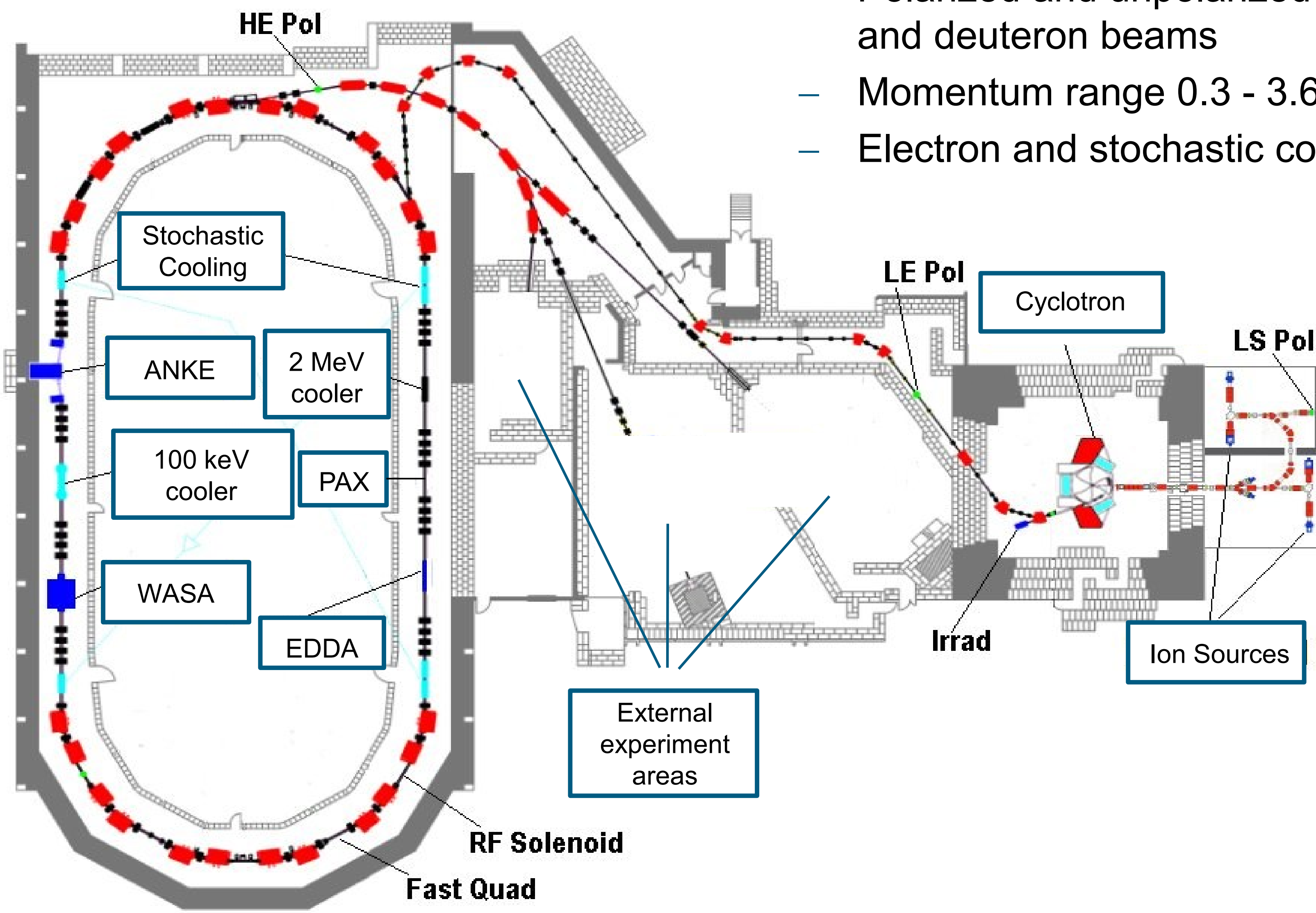
COSY optics

Workshop on Beam Dynamics and Control studies at COSY

November 18, 2016 | Christian Weidemann

COSY facility



- Polarized and unpolarized proton and deuteron beams
- Momentum range 0.3 - 3.65 GeV/c
- Electron and stochastic cooling

COSY - Parameters

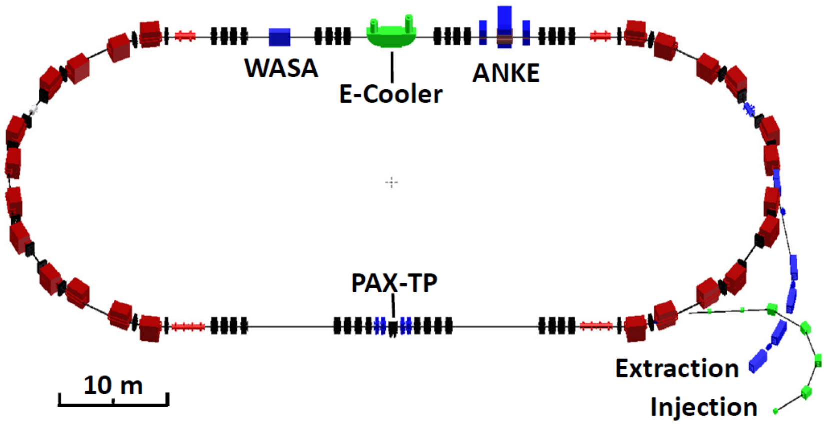
COSY	
Circumference	183.47 m
Particles	(Un)polarized p and d
Type of injection	H^-, D^- stripping injection
Current at source exit	Polarized: 15 μA Unpolarized: 100–200 μA
Momentum range	0.3–3.65 GeV/c
Betatron tune range	3.55–3.7 in both planes
Phase-space cooling	Electron and stochastic
Beam position monitors	31 (horizontal and vertical)
Steerers	23 (horizontal), 21 (vertical)
Straight sections	Length: 40 m 4×4 quadrupole magnets 4 sextupole magnets Beam pipe diameter: 0.15 m
Arc sections	Length: 52 m 3×4 dipole magnets 3×4 quadrupole magnets 5 sextupole magnets Beam pipe in dipole magnets: height: 0.06 m, width: 0.15 m

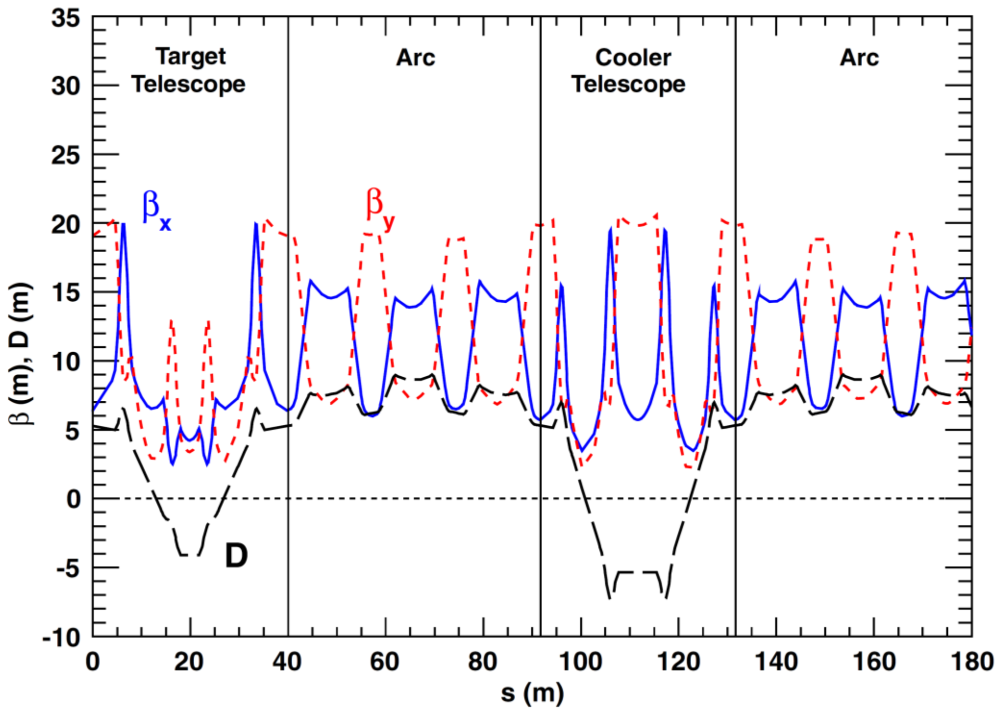
- $1.5 \cdot 10^{11}$ protons per injection (unpolarized beam)
- Internal targets: ANKE, WASA, EDDA, and the PAX interaction point
- Beam extraction to 3 target locations
- Beam cooling is realized by:
  - 100 keV electron cooling up to proton momenta of 0.6 GeV/c
  - 2 MeV electron cooling up to max. COSY momentum
  - stochastic cooling for proton momenta above 1.5 GeV/c
- Stacking injection for intensity increase

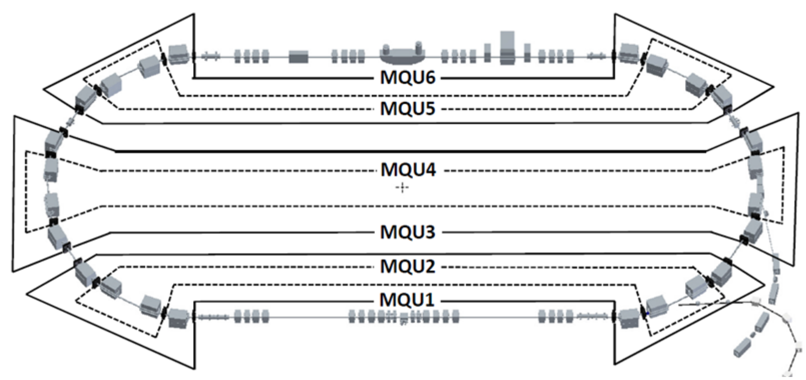
COSY - Lattice

Arcs:

- 3 mirror-symmetric unit cells with a DOFO-OFOD structure in the arcs
- Powered in groups resulting in 6 families
- Symmetric operation of all cells leads to a sixfold symmetry of the β-functions







COSY - Lattice

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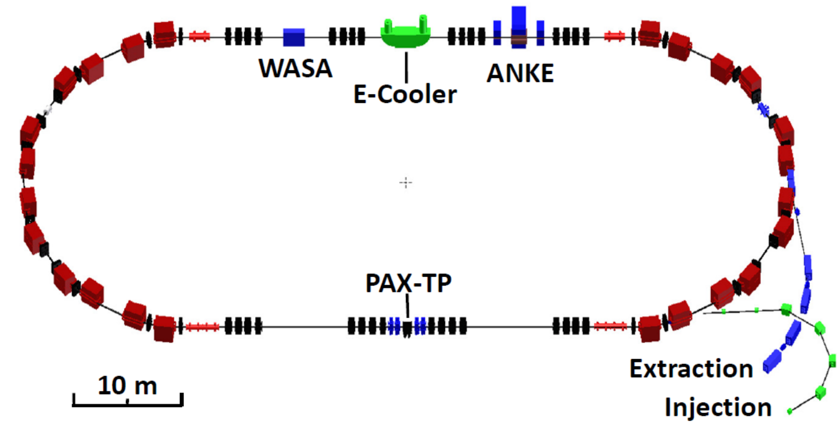
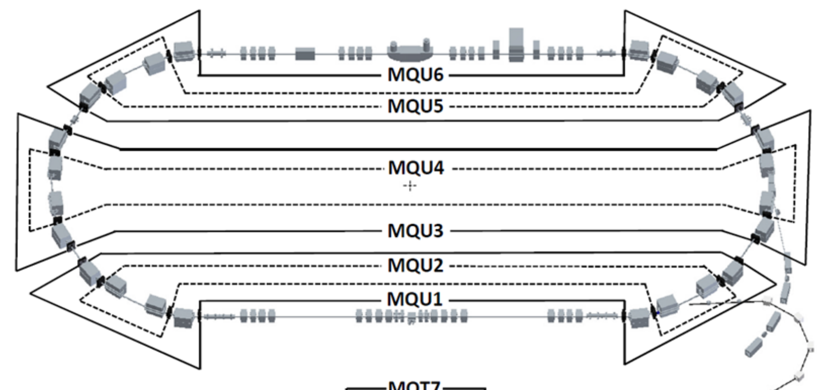
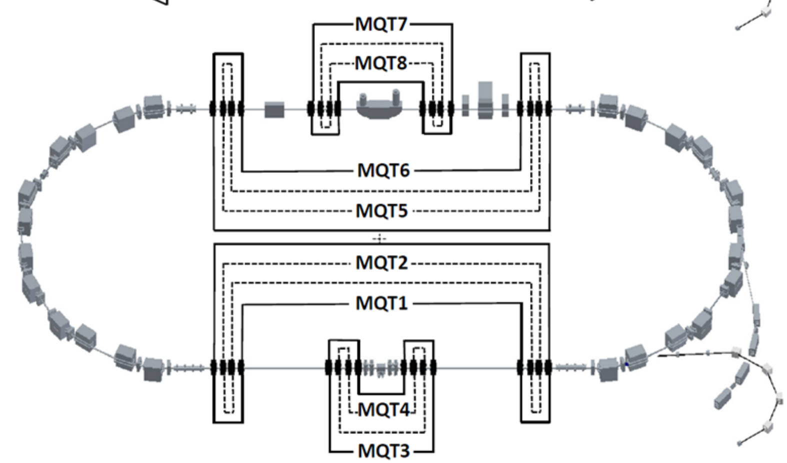
Straights:

- 2 mirror-symmetric telescopic arrangements with two quadrupole triplets
- A 2π phase advance and 1:1 imaging over the complete straight section
- Decoupling to first order the arcs from the straight sections
- Providing 3 possible locations per straight section for internal target experiments with adjustable β-functions in the center of the triplets







COSY - Lattice

Sextupole magnets:

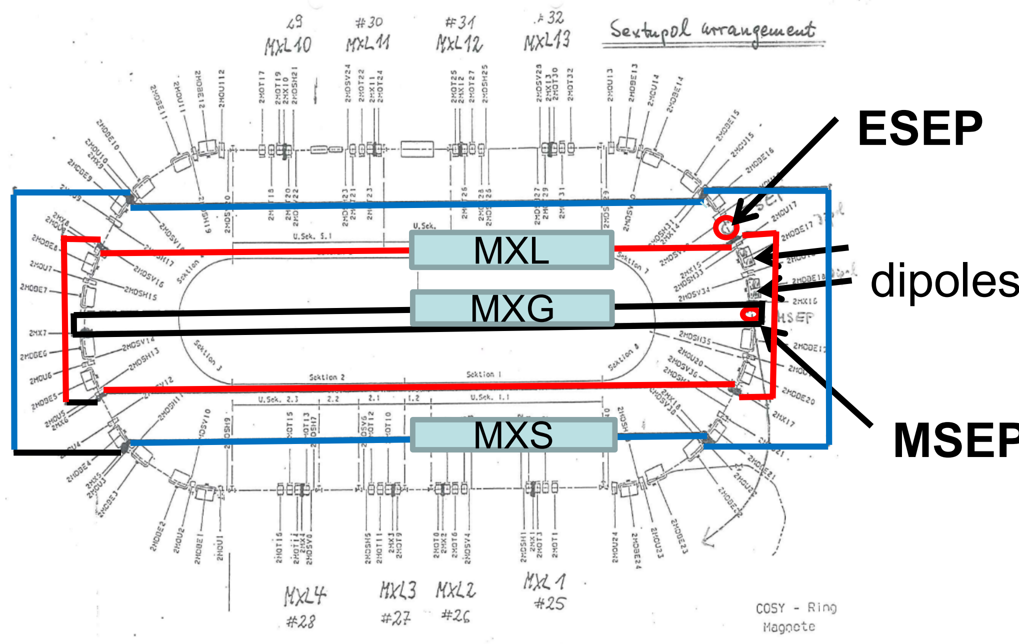
- 18 sextupoles
- Grouped into 11 families,
- 3 of them are placed in the arc for chromatic corrections
- 8 reside in the telescopes to form the separatrix for the outgoing particles

Dispersion = 0 in the straights:

- Modification of arc quadrupole families
- 2-fold symmetry

Low-βsection:

- Additional quadrupole magnets
- Increase of geometrical acceptance
- $\beta_{x,y} \approx 0.3\ m$



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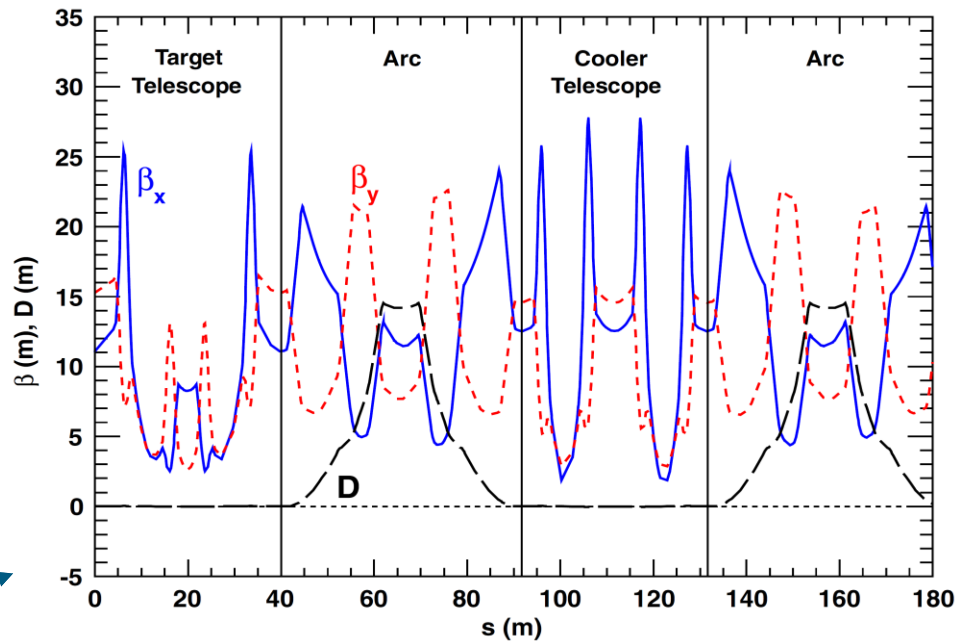

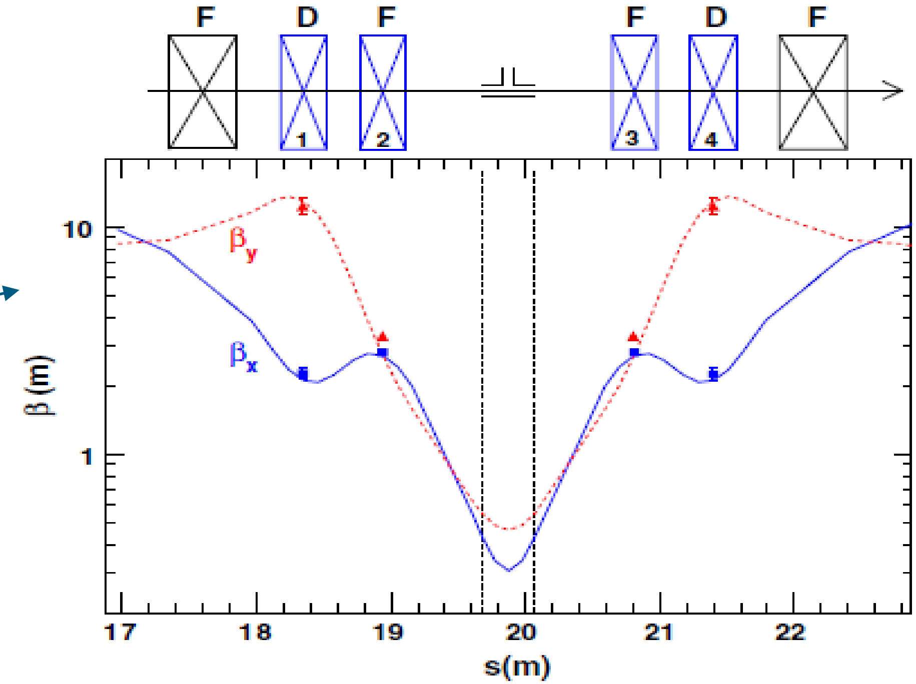

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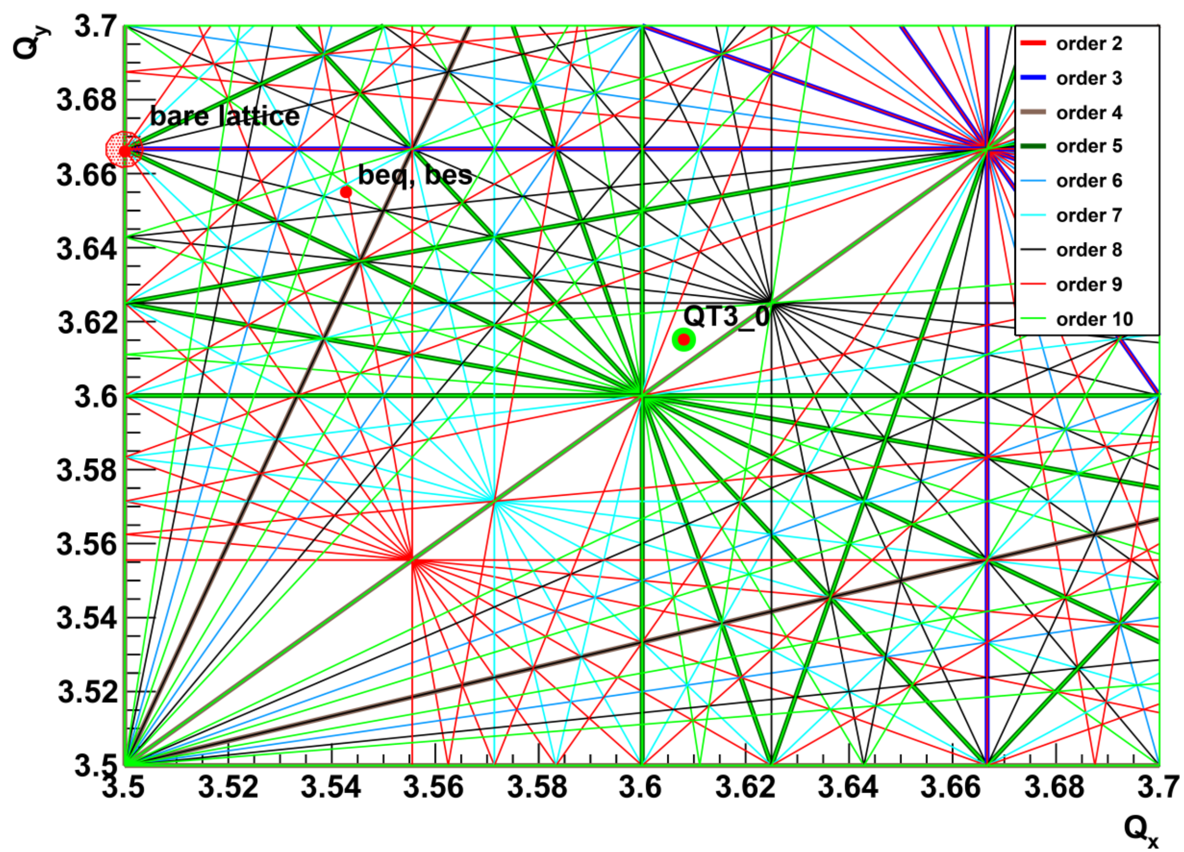
Status of COSY model

Working point

- Significant difference between calculated and measured tune
- Up to now: empiric adjustment of quadrupole calibration factors
- Model adjustment to measured working points required

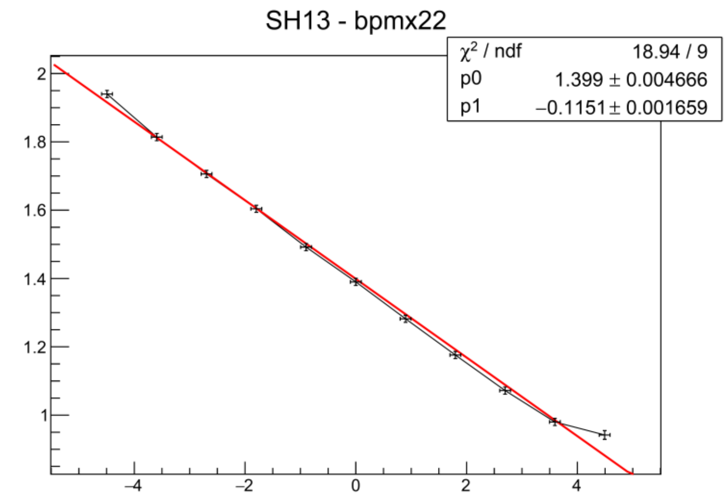
  $Q_x = 3.608;\ Q_y = 3.615$



- Model
- Measurement

LOCO *(linear optics from closed orbit)*

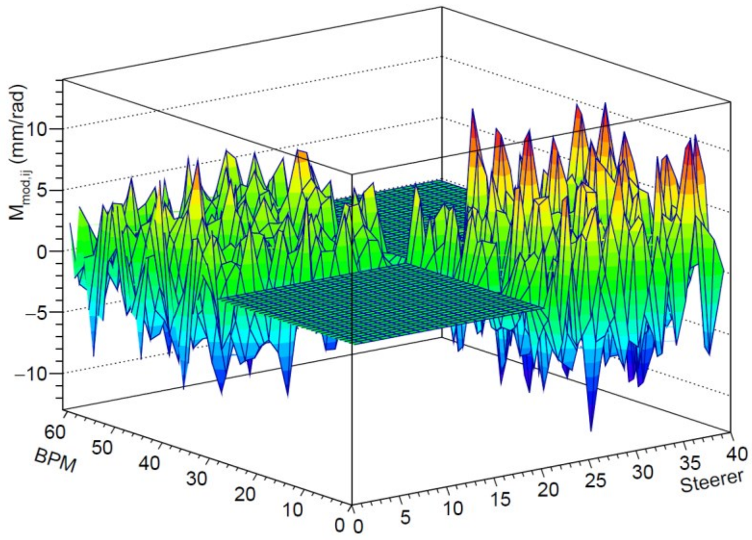
Orbit response matrix



- 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**

LOCO

– 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 · Steerer = 2400 data points
- Not all can be fitted simultaneously
- ORM is not sensitive to all parameters

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)

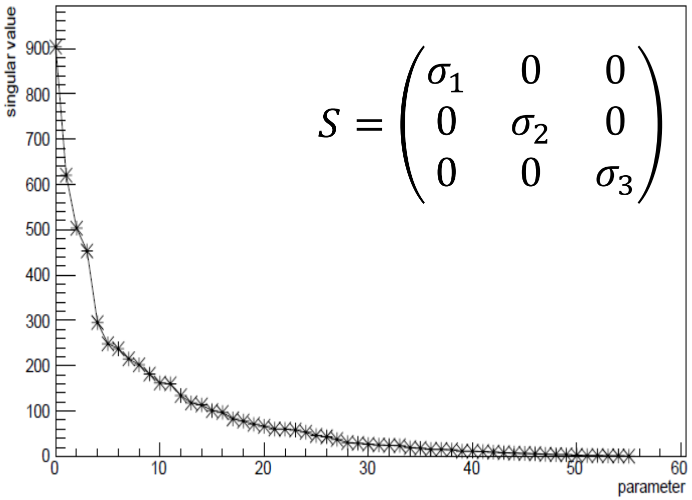
$$-E_k = \frac{dE_k}{dK_l} \cdot \Delta K_l$$

- 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

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



$$S = \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix}$$

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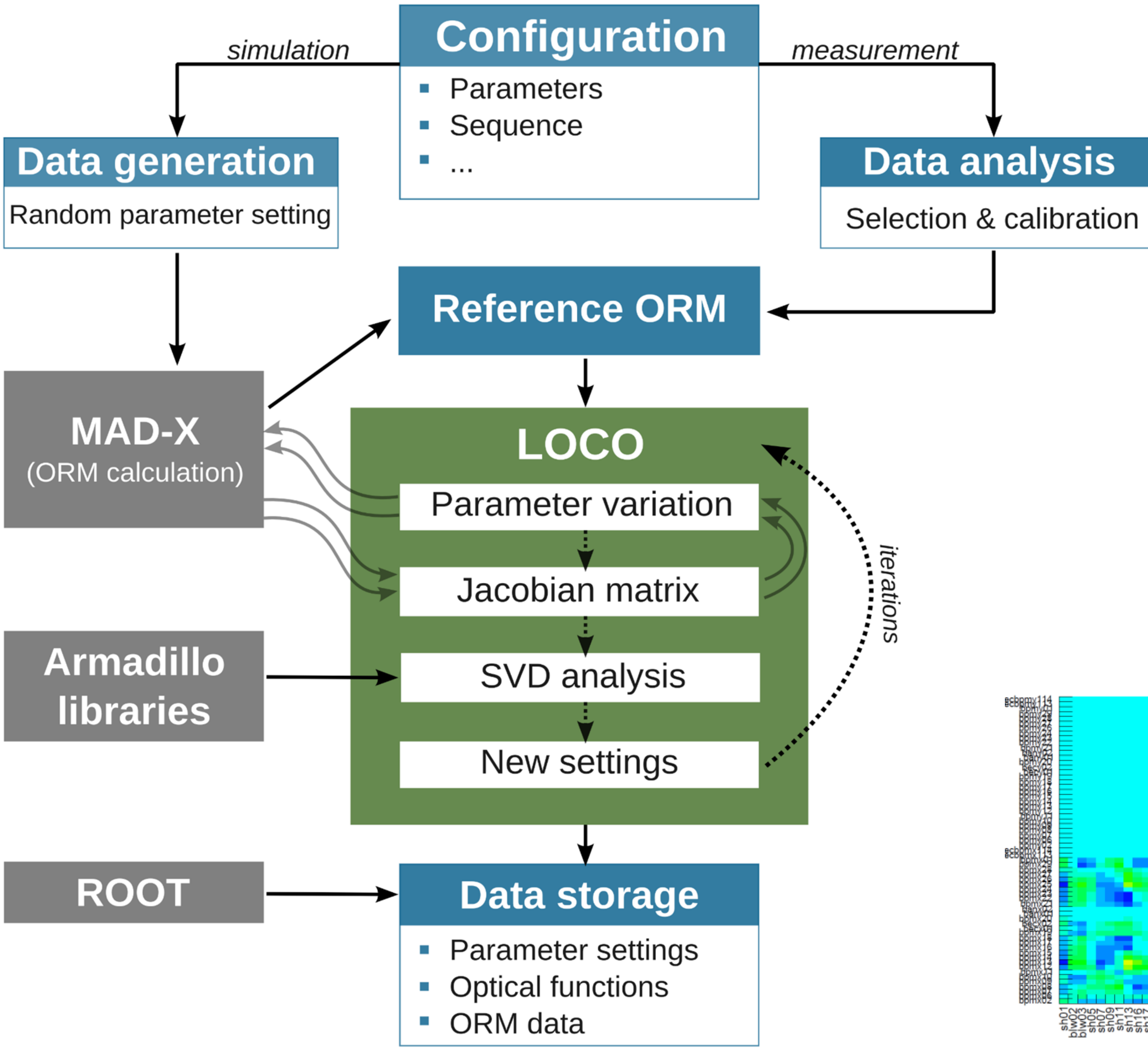
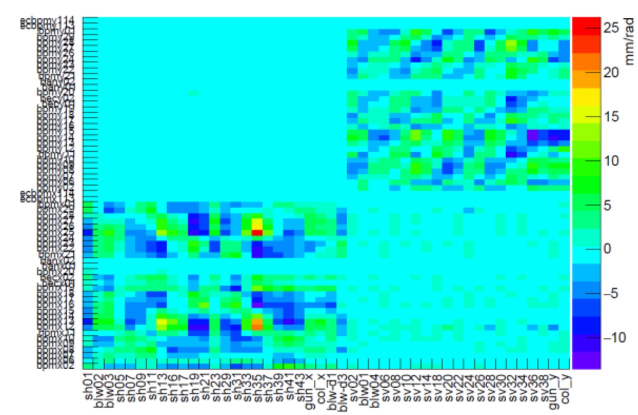
Loco - Program



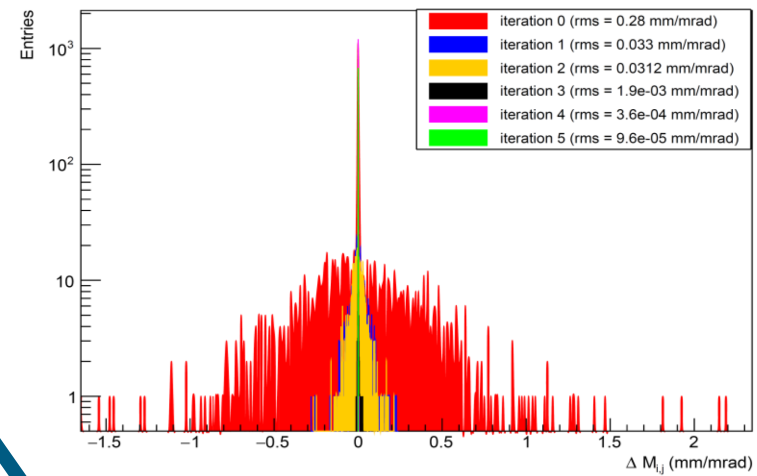


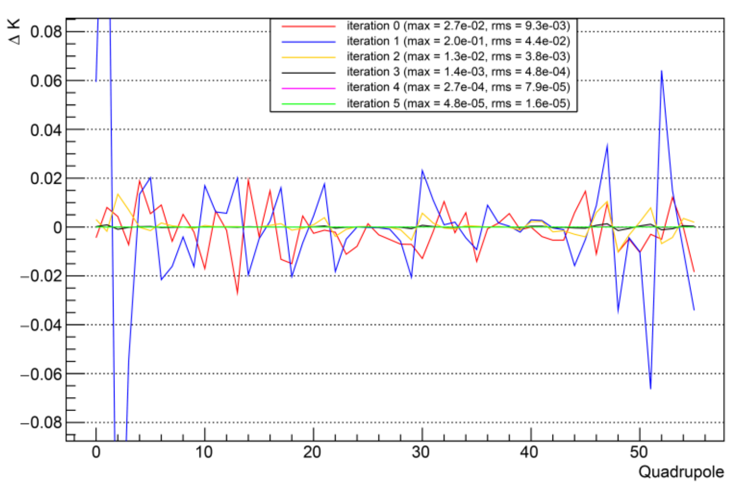
Loco - Program

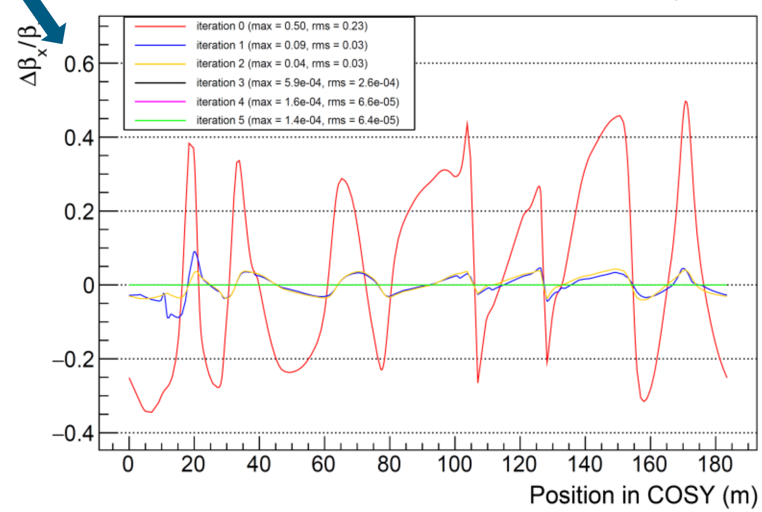
Benchmarking

- 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

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



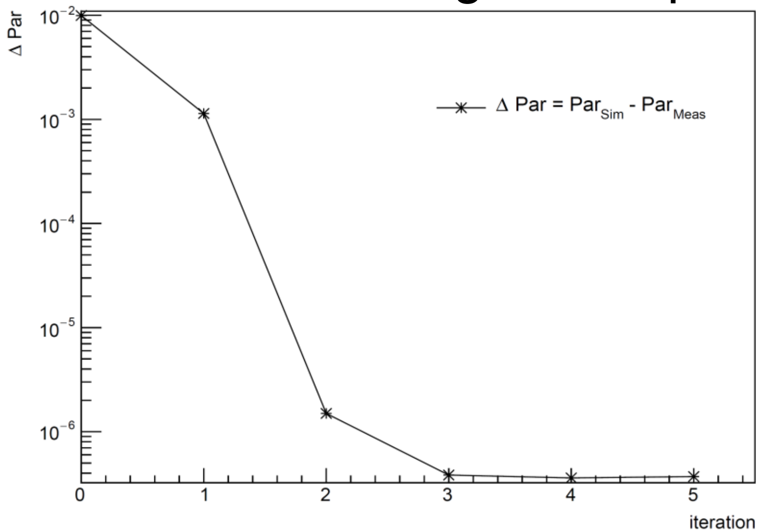


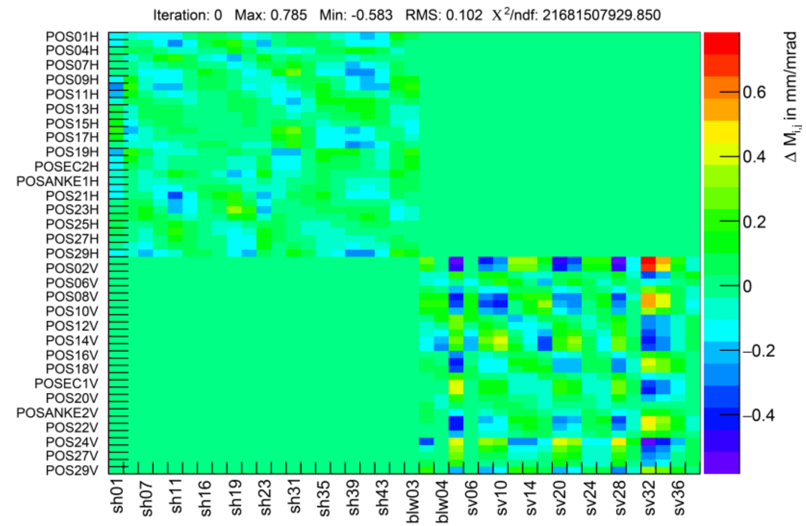


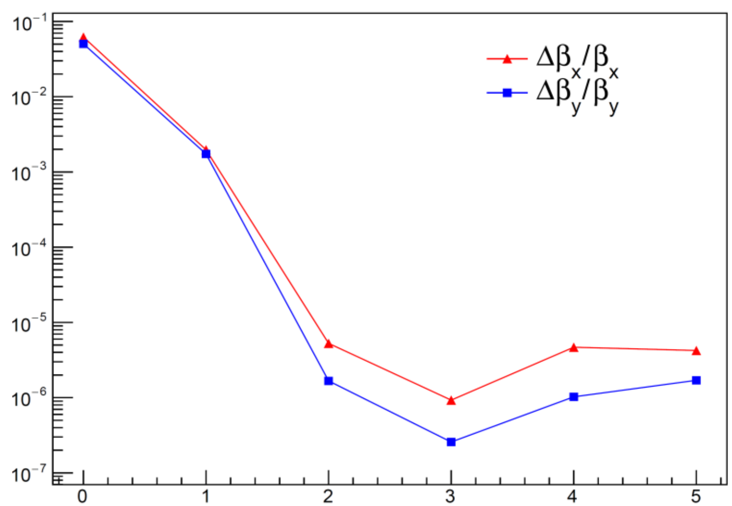
Loco - Program

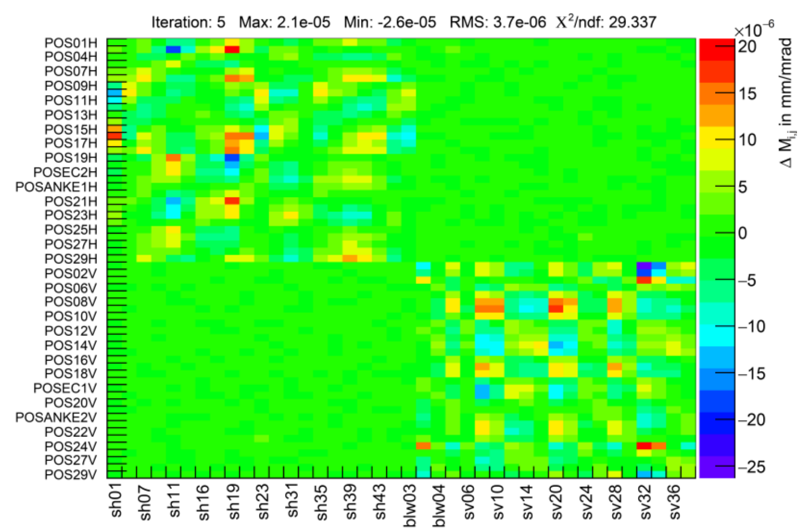
Benchmarking (good reconstruction):

Longitudinal position of quadrupoles





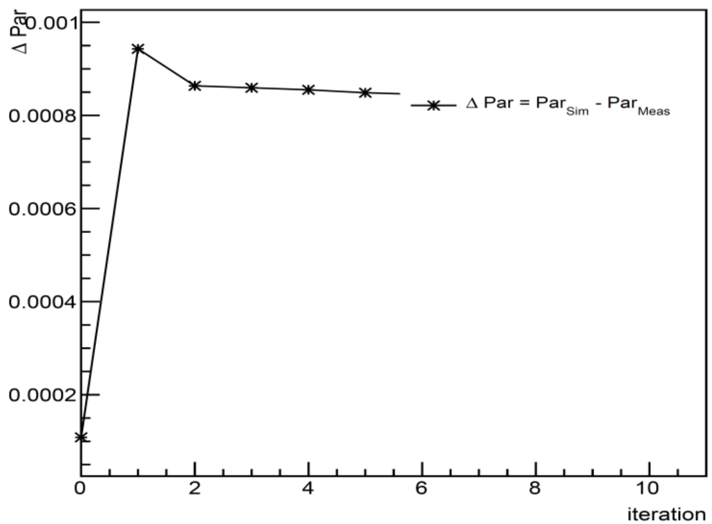


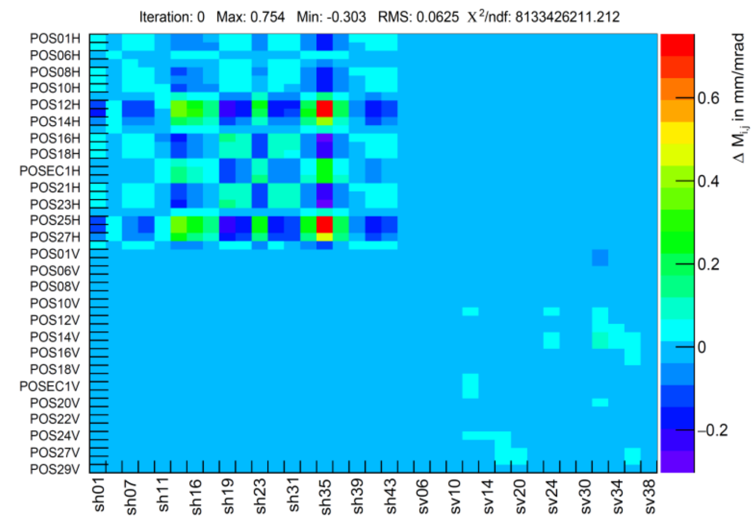


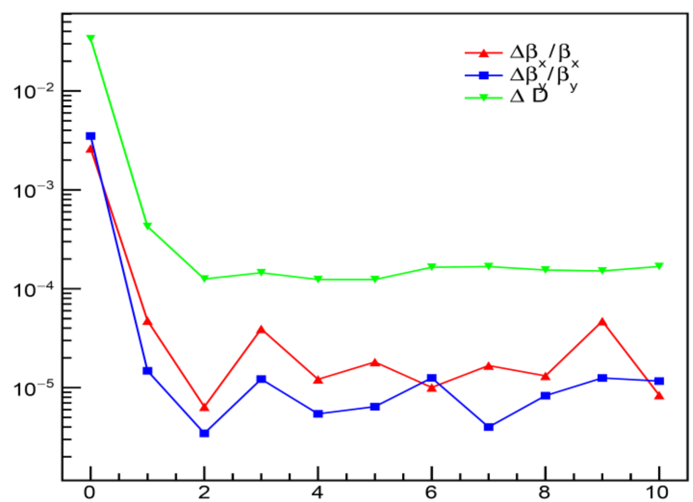
Loco - Program

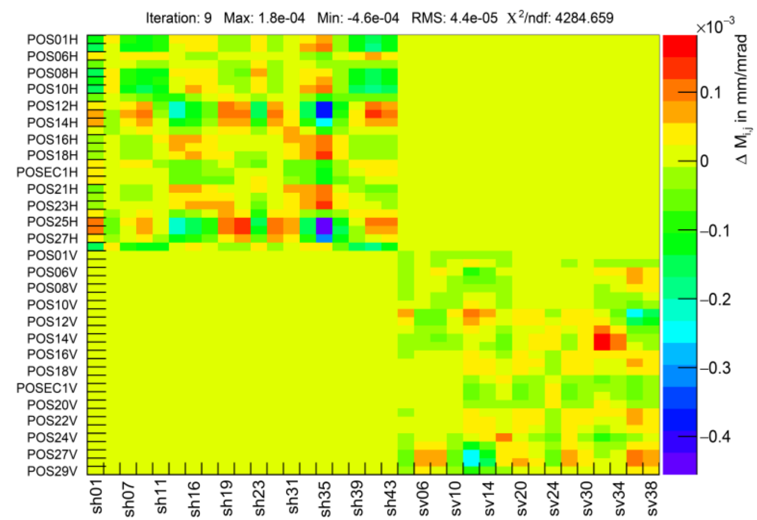
Benchmarking (only optics improvement):

Transverse position of quadrupoles









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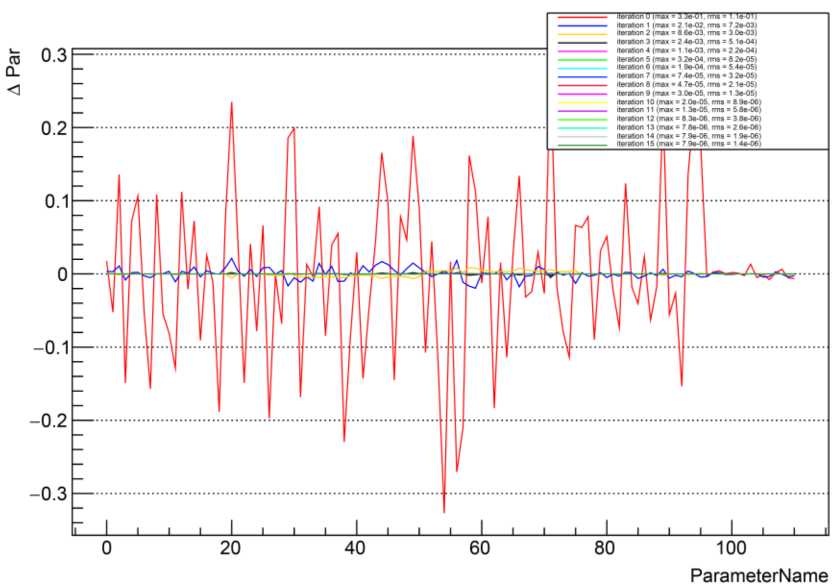
Loco - Program

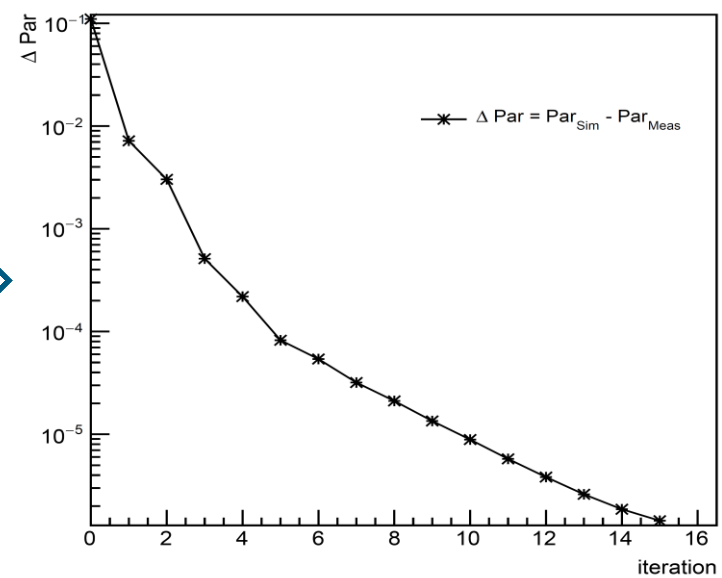
Benchmarking

- 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)

Benchmarking – fitting multiple parameters

- Quadrupole K1, Quadrupole ds





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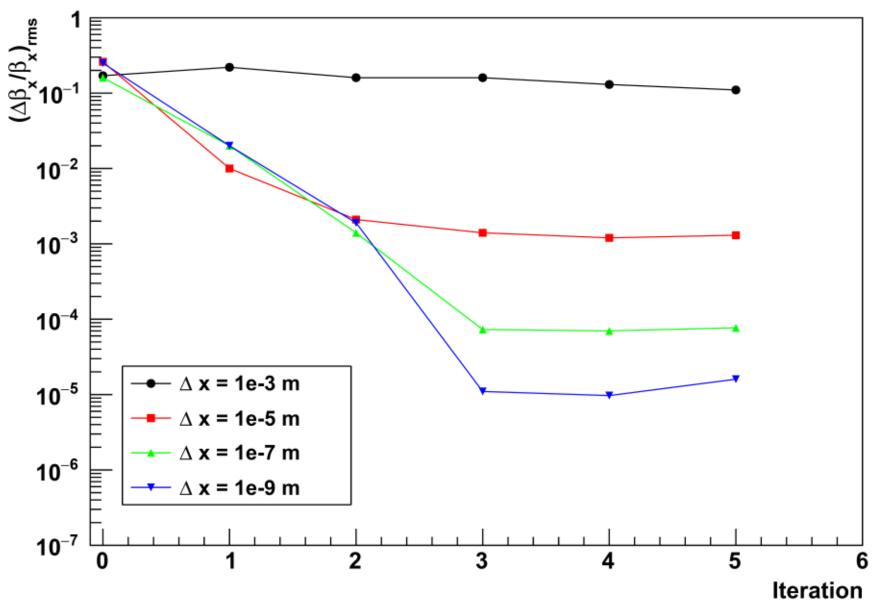
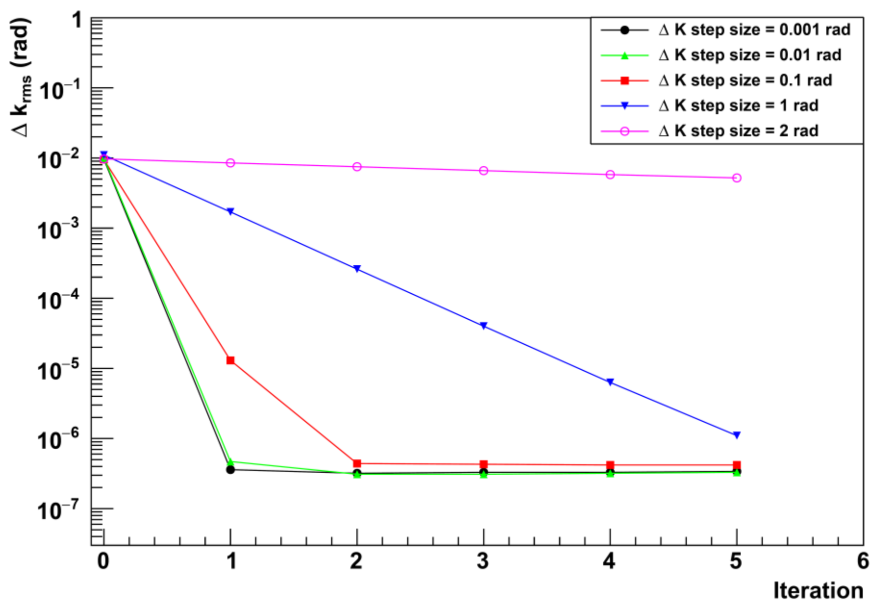
Loco - Program

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



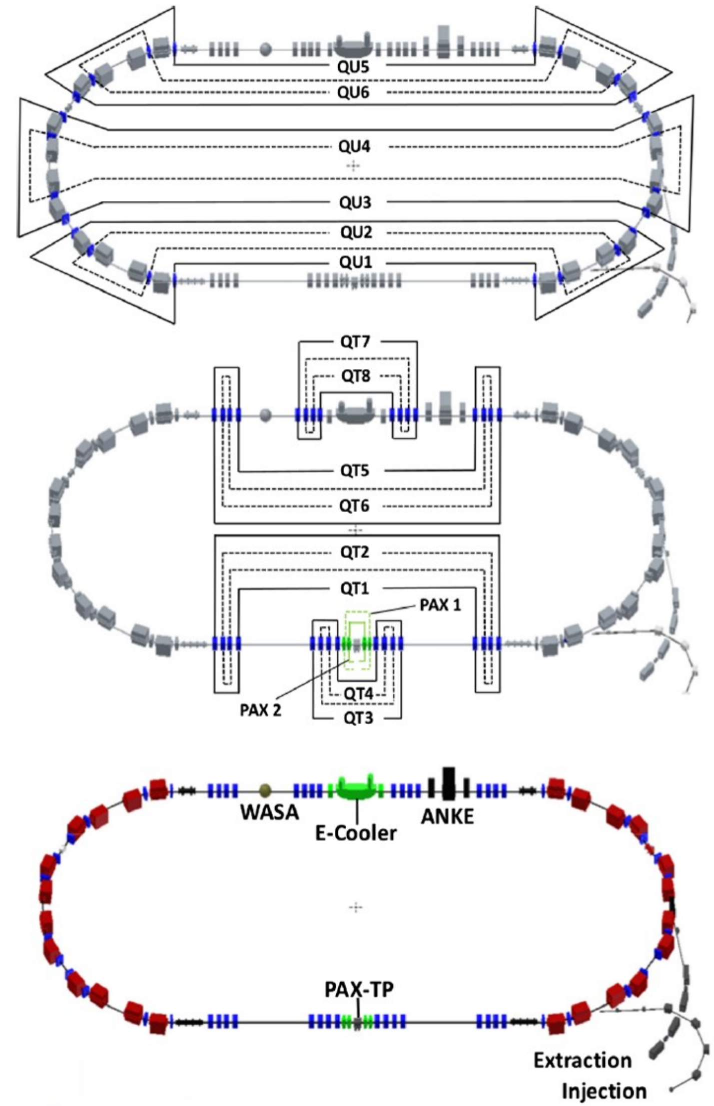


Beam optics studies

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



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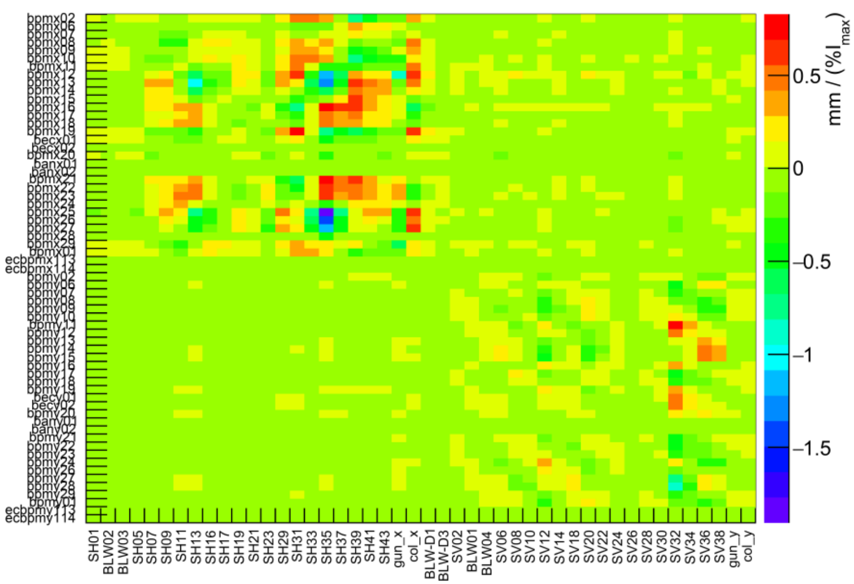
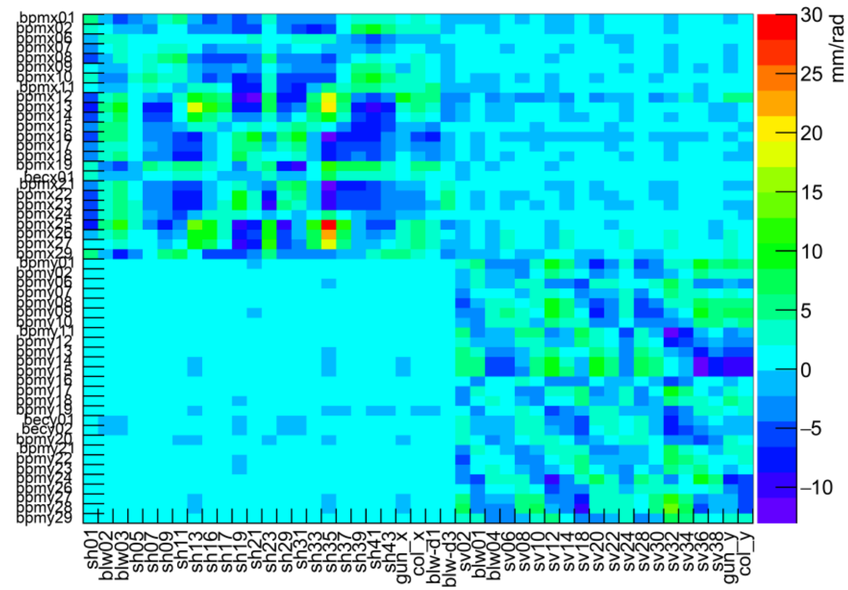
Applying LOCO to measured data

Procedure

- Analysis of measured ORM data with respect to LOCO analysis
  - Determine and exclude non-working components
  - Conversion of entries using calibration data of steerers



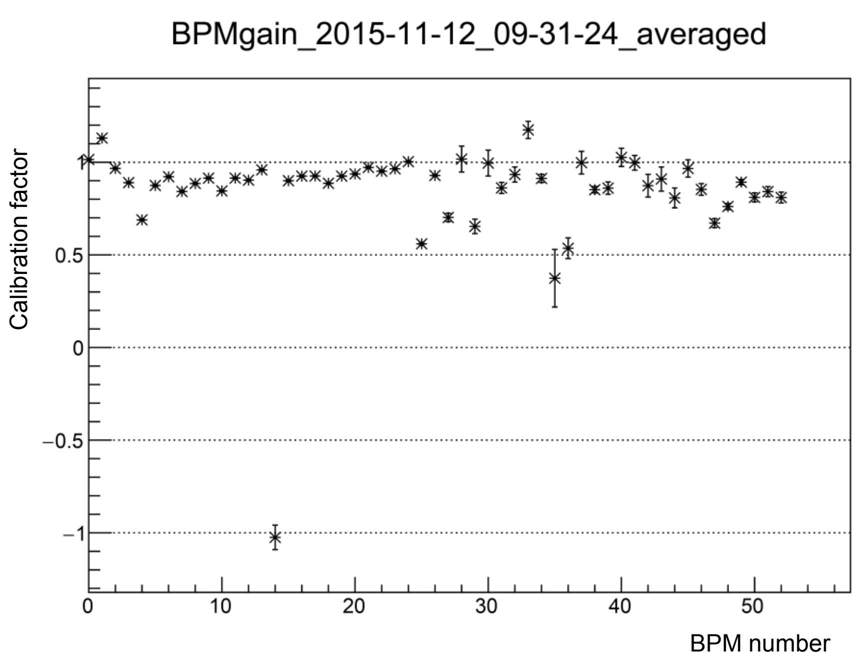


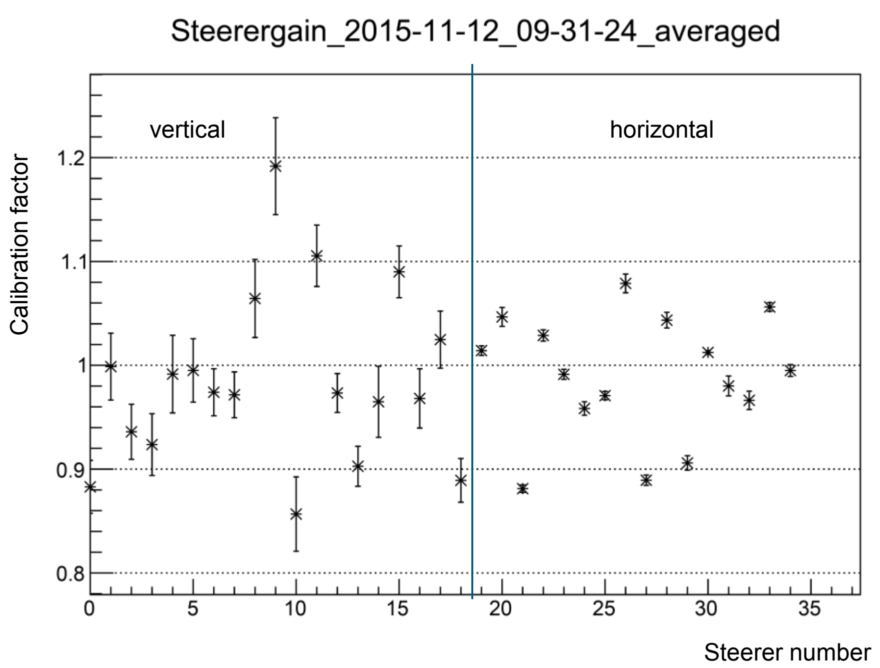
- Set LOCO configuration (different sequences)
- Averaging of resulting parameters and comparison for different measurements

Applying LOCO to measured data

Steer and BPM calibration

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

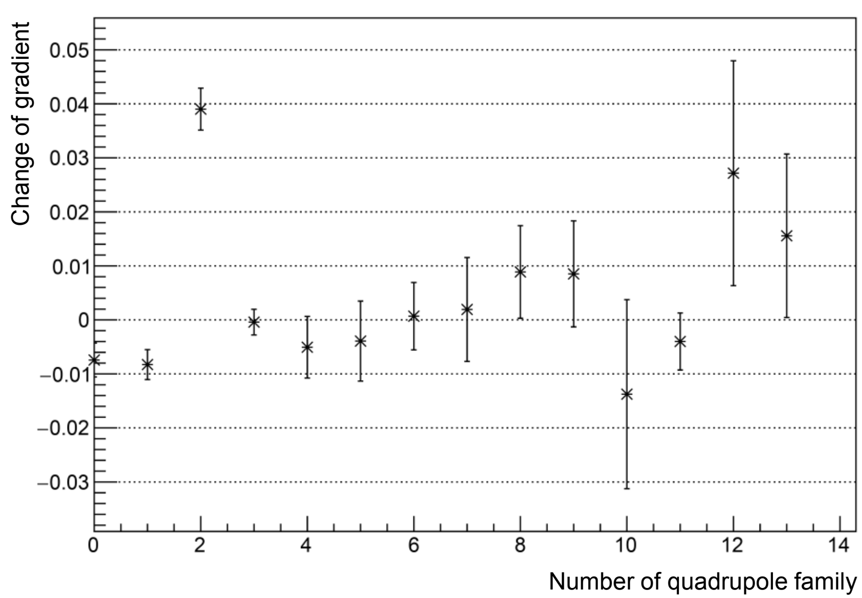


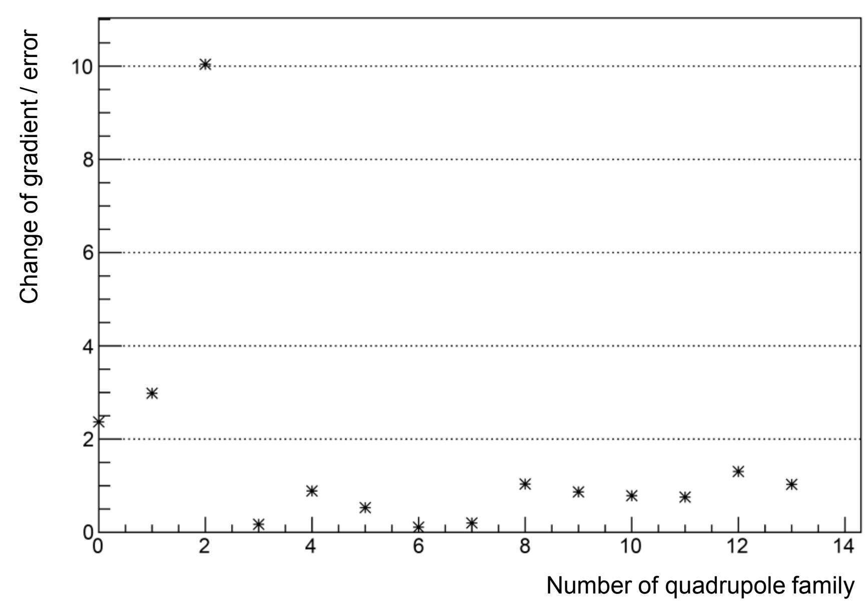


Applying LOCO to measured data

Quadrupole strength

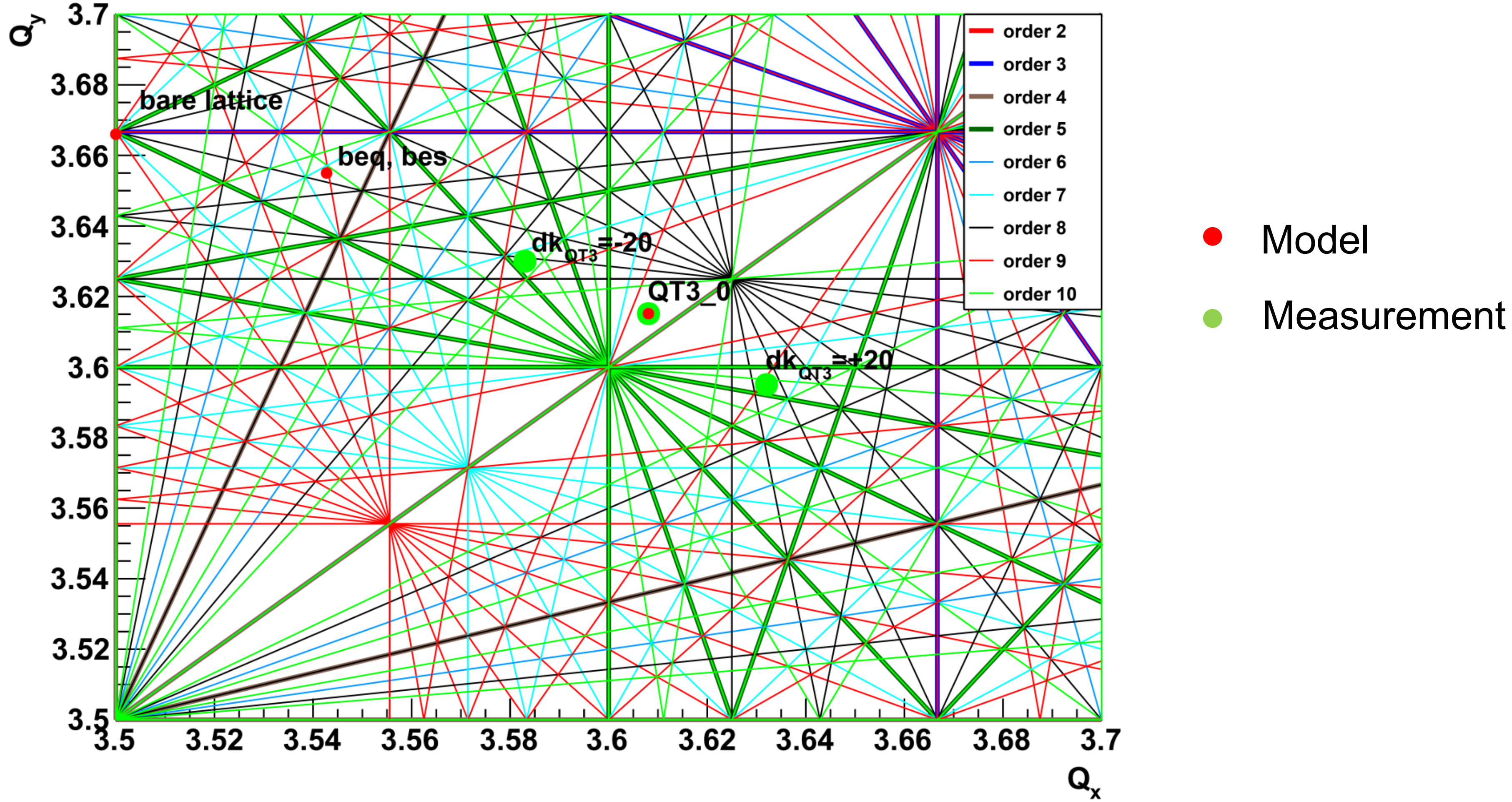
- Determination of individual gradients factors
- Absolute values are difficult to judge at this point
- Detection of changed gradient factors between individual measurements
- 4 % change was applied to quadrupole family MQT3 (number 2)





Applying LOCO to measured data

Tune reconstruction (empirically adjusted starting point)



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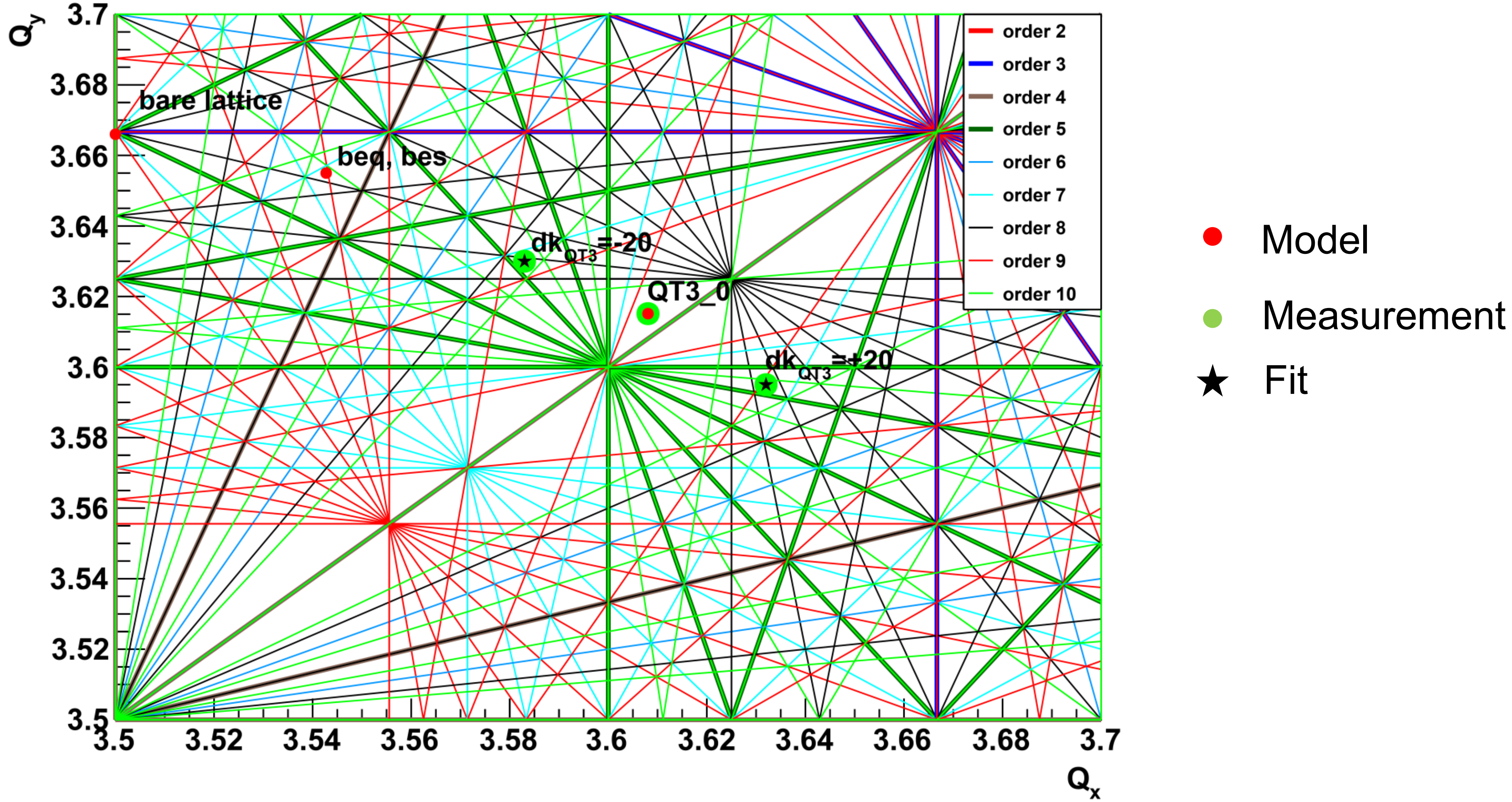


– Tune reconstruction works for arbitrary starting points

Summary

- Loco program was succesfully developed
- Benchmarking almost finished
- First test with measured data
  - Quadrupole change detected
  - Measured tunes perfectly reconstructed

Plan:

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

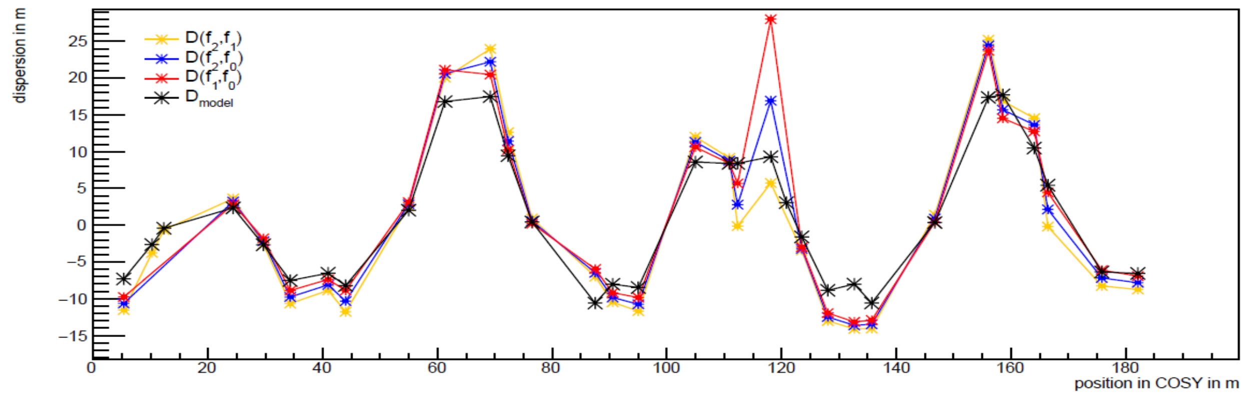
Literature

[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).

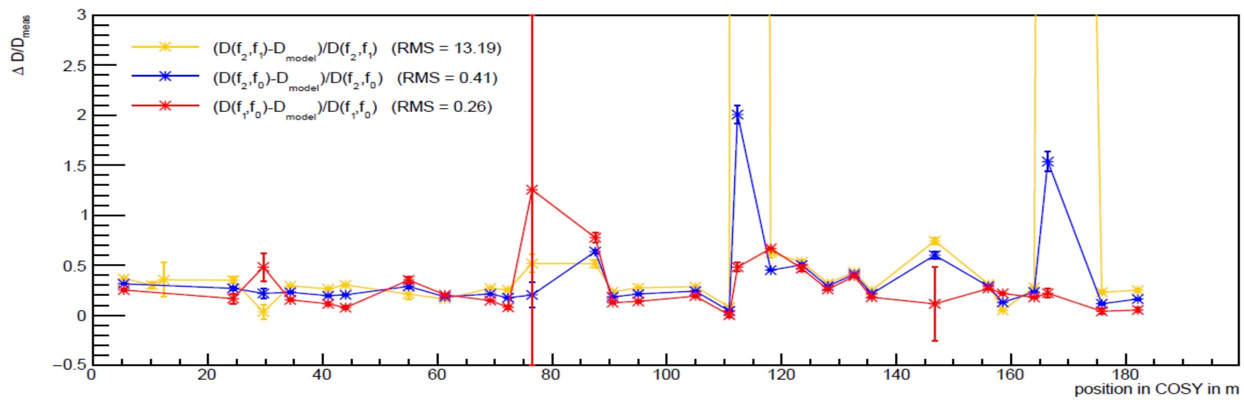
Additional slides

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!

Status of COSY model

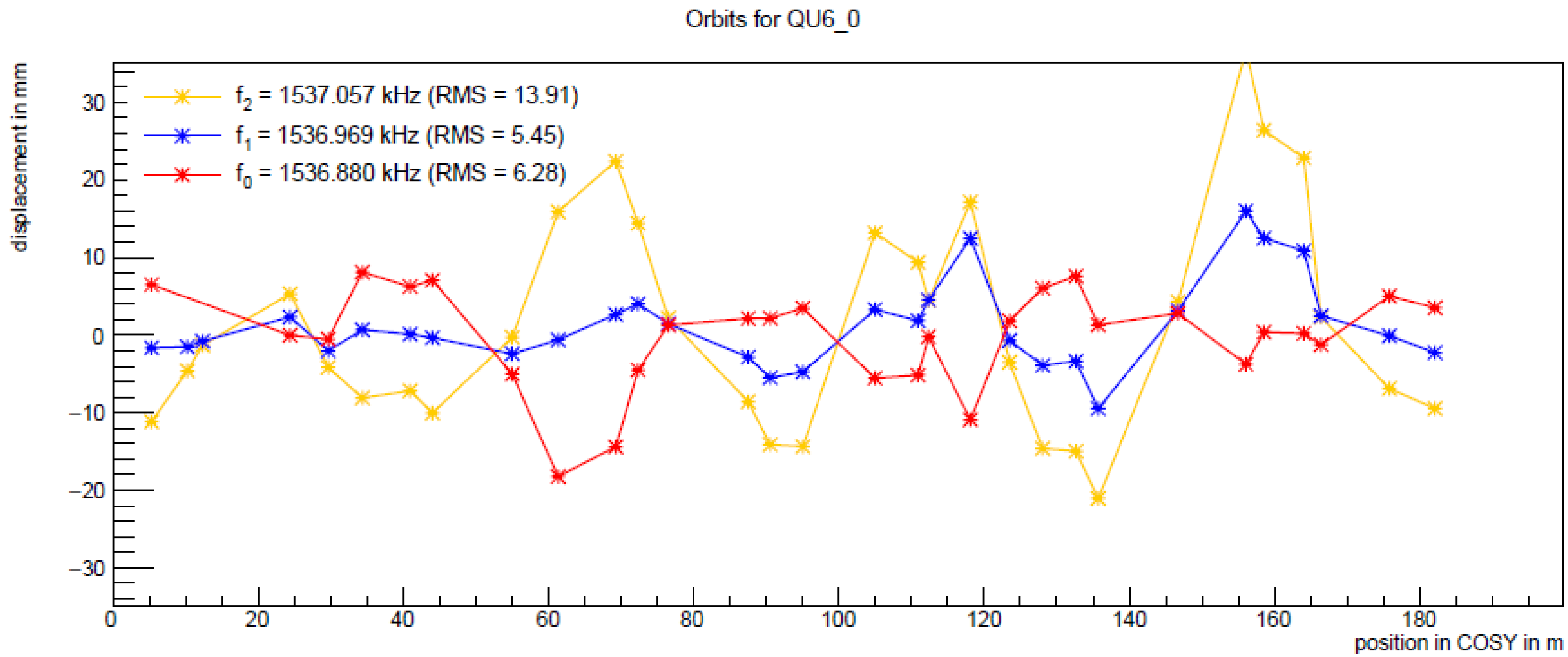
Dispersion

– Measure orbit for different rf-frequencies

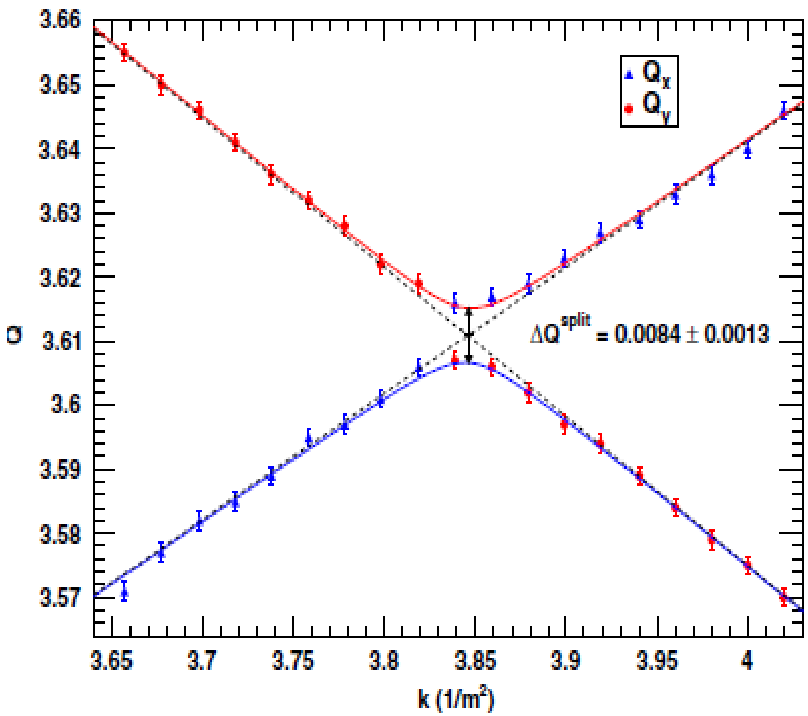
$$x(s) = x_0(s) + D(s)\frac{\Delta p}{p}$$

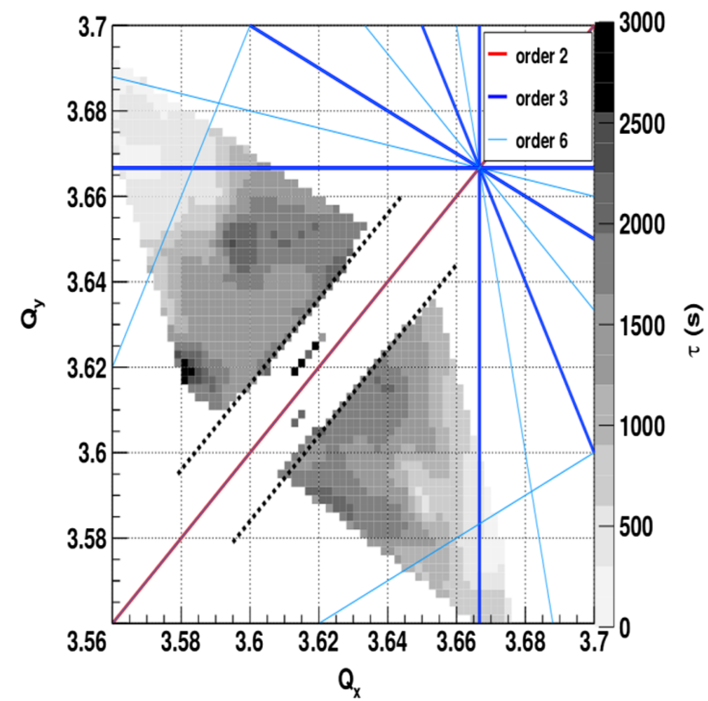
$$\Delta x(s) = D(s)\frac{\Delta E}{E} = \frac{D(s)}{\eta}\frac{\Delta C}{C} = -\frac{D(s)}{\eta}\frac{\Delta f_{rf}}{f}$$

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



- Acceptance
- Tune, tune adjustment





Loco - Program

Benchmarking – fitting multiple parameters

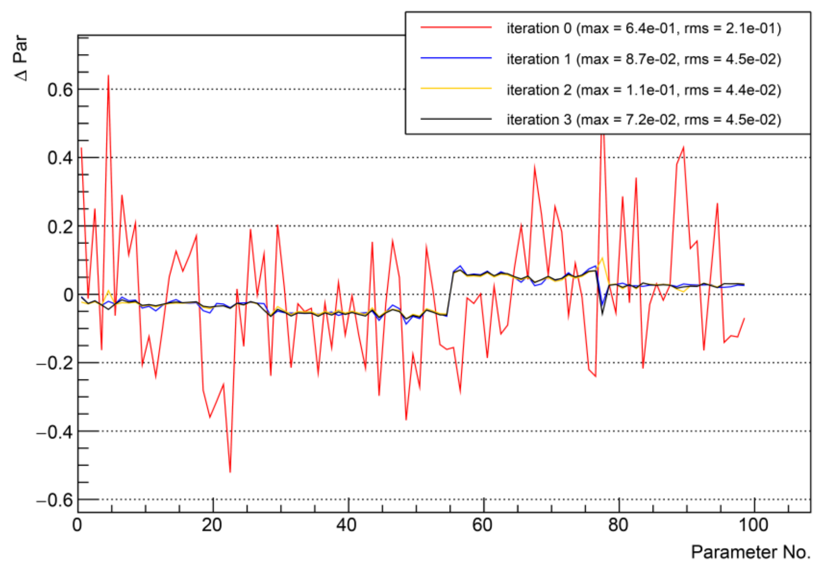
```
# LOCO config_file
# General Settings
generateMeasurement         1                               //0..Measurement,1..Simulation
iterations                  15                              //Number_of_iterations
nvariation                  3                               //Number_of_parameter_variations
nSteps                      3                               //Number_of_steerer_steps_for_ORM
errBPMMeasurement           1E-9                            //Measurement_error_of_BPMs


# Which parameters?
varyBPMgain                 1                               //Include_gain_factor_of_BPM
varySteerergain             1                               //Include_gain_factor_of_steerer
varyBPMPosition             0                               //Include_position_of_BPM
varySteererPosition         0                               //Include_position_of_Steerer
varyQuadFamilies            1                               //Include_gradient_of_quadrupole_families
varyQuadStrength            0                               //Include_gradient_of_quadrupoles
varyKickAngle               0                               //Include_error_of_kickangle
varyQuadPosition            0                               //Include_position_of_quadrupoles
varyBend_K1                 0                               //Include_K1_of_dipoles
varyBend_K2                 0                               make//Include_K2_of_dipoles
varySext_K2                 0                               //Include_K2_of_sextupoles
varyBendPosition            0                               //Include_position_of_dipoles

#Which parameter_when?  BPMgain//Steerergain//BPMposition//SteererPosition//QuadGradients(family)//
QuadGradients(all)//KickAngle//QuadPosition//DipolPosition
iteration1                  11001000000                     //Parameters_to_adjust_in_1st_iteration
iteration2                  11001000000                     //2nd_iteration
iteration3                  11001000000                     //3rd_iteration
iteration4                  11001000000                     //4th_iteration
iteration5                  11001000000                     //5th_iteration
iteration6                  11001000000                     //6th_iteration
iteration7                  11001000000                     //7th_iteration
iteration8                  11001000000                     //8th_iteration
iteration9                  11001000000                     //9th_iteration
iteration10                 11001000000                     //
10th_iteration(this_setting_is_used_for_every_following_iteration)


# Sigma_for_simulated measurements
sigmaGains                  0.1                             //Sigma_of_gain_variation(%/100)
sigmaKickAngle              0.01                            //Sigma_of_kick_angle_variation(rad)
sigmaQuadGradient           0.005                           //Sigma_of_quad_gradient_variation(%/100)
sigmaQuadDisplacement       0.001                           //Sigma_of_quad_displacement(m)
sigmaQuadAngle              0.01                            //Sigma_of_quad_angle_variation(rad)
sigmaDipQuad                0.0001                          //Sigma_of_quadcomp_of_dipoles(m^-2)
sigmaDipSext                0.05                            //Sigma_of_sextupole_comp_of_dipoles(m^-3)
sigmaSextSext               0.05                            //
Sigma_of_sextupole_comp_of_sextupoles(m^-3)
sigmaBendDisplacement       0.001                           //Sigma_of_dipole_displacement(m)
sigmaBendAngle              0.001                           //Sigma_of_dipole_angle_variation(rad)

#Choose Misalignment    dX/dY/dS/dPhi/dTheta/dPsi
misBPM                      000001                          //Details_of_misalignments(BPM)
misSteerer                  000001                          //Details_of_misalignments(Steerer)
misQuad                     001000                          //Details_of_misalignments(Quadrupoles)
misBend                     000001                          //Details_of_misalignments(Dipoles)


# Filenames !
filenameInputSteerers       config/steerer.dat                                  //
Name of steerers for ORM
```

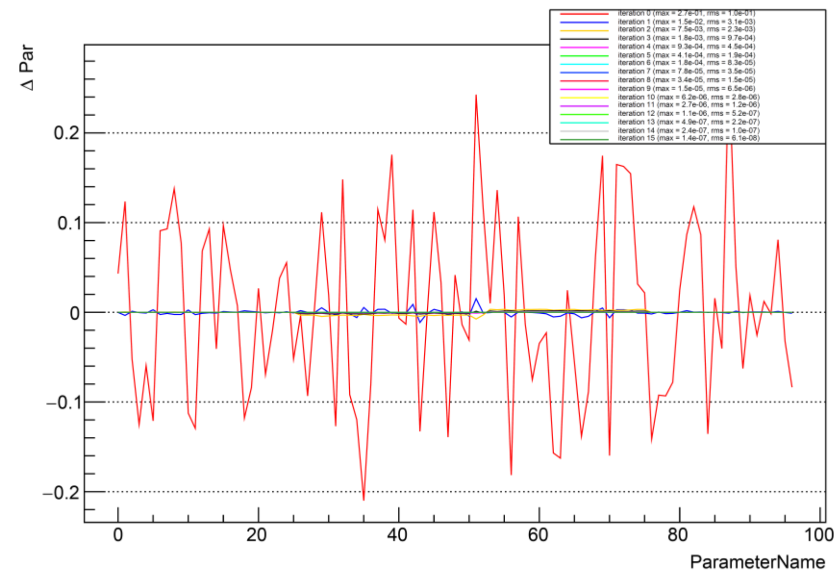
Exemplary config file:

- 15 iterations
- Number of variations
- BPM uncertainty (1E-9 m)
- Vary BPM gain, Steerer gain, quadrupole strength
- Fit parameters per iteration
- ….

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 – 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

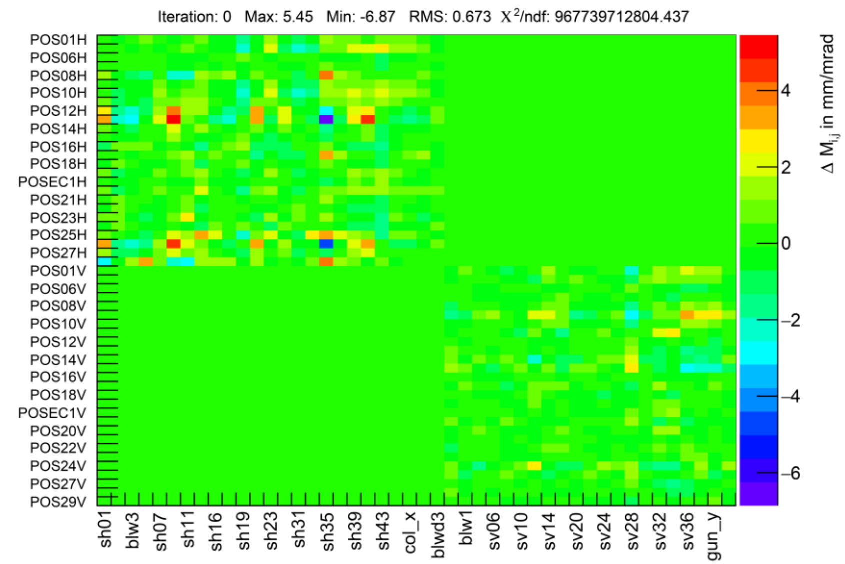
- BPM and steerer gains work perfect (degeneracy problem when fitting both simultaneously can be avoided by fixing one component)

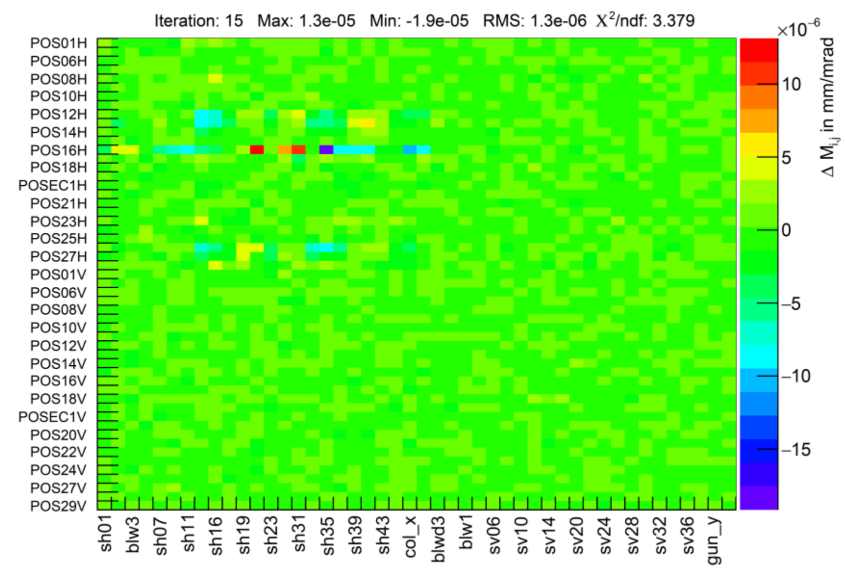
- Good reconstruction: BPM and steerer (ds, dψ), Quad (ds, dψ, K1),
  Dipole (K1, K2, ds, dψ), Sextupoles (K2)
- Only optics improvement: Quad (dx, dy, dθ)
- Not sensitive: BPM and steerer (dx, dy, dφ, dθ), Quad (dφ)

- Fitting combinations of parameters has partly been studied

Benchmarking – fitting multiple parameters

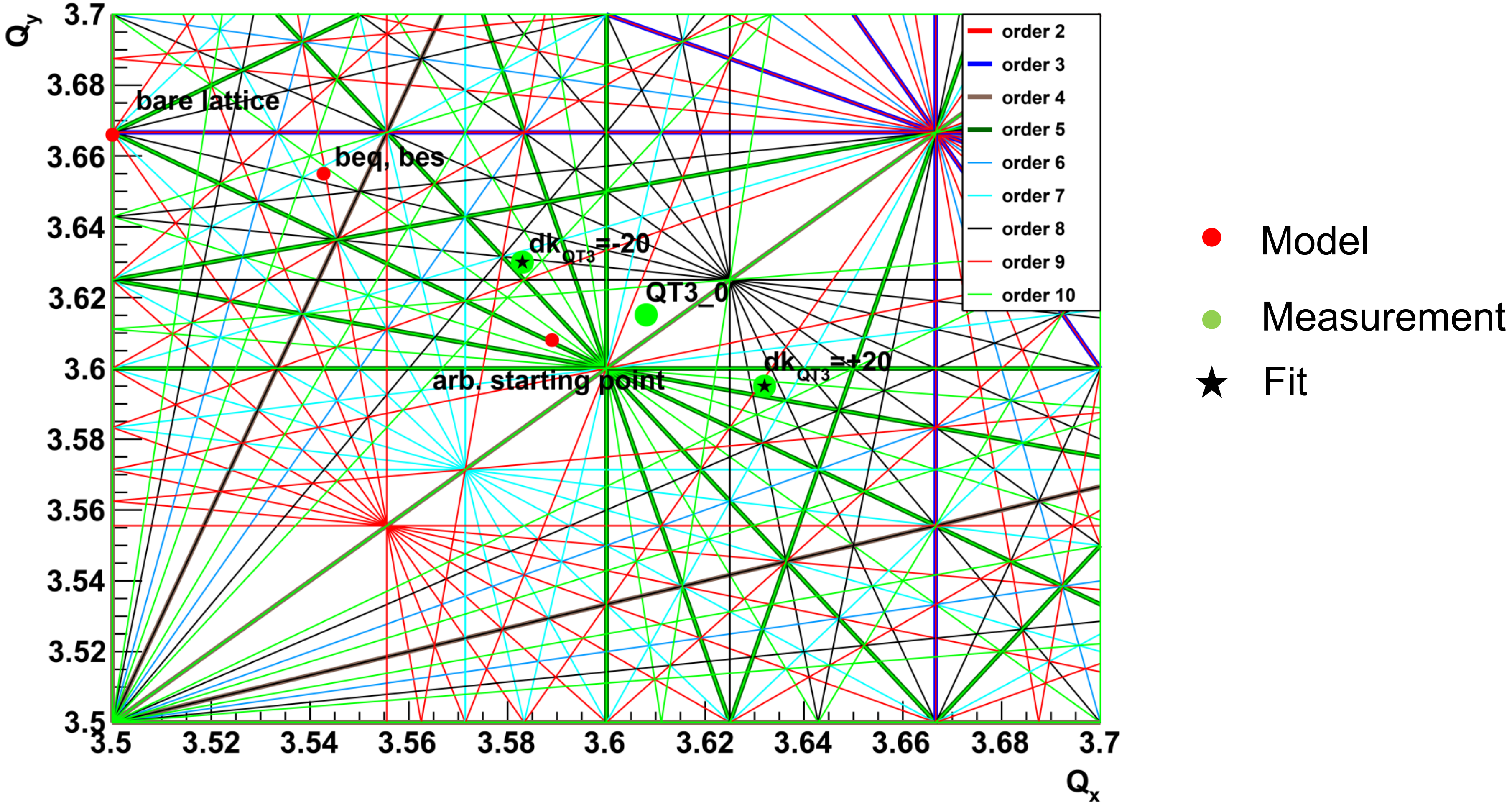
```
# LOCO config_file
# General Settings
generateMeasurement          1                 //0..Measurement,1..Simulation
iterations                   15                //Number_of_iterations
nvariation                   3                 //Number_of_parameter_variations
nSteps                       3                 //Number_of_steerer_steps_for_ORM
errBPMMeasurement            1E-9              //Measurement_error_of_BPMs


# Which parameters?
varyBPMgain                  1                 //Include_gain_factor_of_BPM
varySteerergain              1                 //Include_gain_factor_of_steerer
varyBPMPosition              0                 //Include_position_of_BPM
varySteererPosition          0                 //Include_position_of_Steerer
varyQuadFamilies             1                 //Include_gradient_of_quadrupole_families
varyQuadStrength             0                 //Include_gradient_of_quadrupoles
varyKickAngle                0                 //Include_error_of_kickangle
varyQuadPosition             0                 //Include_position_of_quadrupoles
varyBend_K1                  0                 //Include_K1_of_dipoles
varyBend_K2                  0                 make//Include_K2_of_dipoles
varySext_K2                  0                 //Include_K2_of_sextupoles
varyBendPosition             0                 //Include_position_of_dipoles

#Which parameter_when?  BPMgain//Steerergain//BPMposition//SteererPosition//QuadGradients(family)//
QuadGradients(all)//KickAngle//QuadPosition//DipolPosition
iteration1                   11001000000       //Parameters_to_adjust_in_1st_iteration
iteration2                   11001000000       //2nd_iteration
iteration3                   11001000000       //3rd_iteration
iteration4                   11001000000       //4th_iteration
iteration5                   11001000000       //5th_iteration
iteration6                   11001000000       //6th_iteration
iteration7                   11001000000       //7th_iteration
iteration8                   11001000000       //8th_iteration
iteration9                   11001000000       //9th_iteration
iteration10                  11001000000       //
10th_iteration(this_setting_is_used_for_every_following_iteration)


# Sigma_for_simulated measurements
sigmaGains                   0.1               //Sigma_of_gain_variation(%/100)
sigmaKickAngle               0.01              //Sigma_of_kick_angle_variation(rad)
sigmaQuadGradient            0.005             //Sigma_of_quad_gradient_variation(%/100)
sigmaQuadDisplacement        0.001             //Sigma_of_quad_displacement(m)
sigmaQuadAngle               0.01              //Sigma_of_quad_angle_variation(rad)
sigmaDipQuad                 0.0001            //Sigma_of_quadcomp_of_dipoles(m^-2)
sigmaDipSext                 0.05              //Sigma_of_sextupole_comp_of_dipoles(m^-3)
sigmaSextSext                0.05              //
Sigma_of_sextupole_comp_of_sextupoles(m^-3)
sigmaBendDisplacement        0.001             //Sigma_of_dipole_displacement(m)
sigmaBendAngle               0.001             //Sigma_of_dipole_angle_variation(rad)

#Choose Misalignment    dX/dY/dS/dPhi/dTheta/dPsi
misBPM                       000001            //Details_of_misalignments(BPM)
misSteerer                   000001            //Details_of_misalignments(Steerer)
misQuad                      001000            //Details_of_misalignments(Quadrupoles)
misBend                      000001            //Details_of_misalignments(Dipoles)


# Filenames !
filenameInputSteerers        config/steerer.dat                    //
Name of steerers for ORM
```





Applying LOCO to measured data

Tune reconstruction (arbitrary starting point)



Applying LOCO to measured data

Tune reconstruction (arbitrary starting point)