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

Diagram showing the layout of COSY facility with various labeled areas:
- HE Pol
- ANKE
- 2 MeV cooler
- 100 keV cooler
- PAX
- WASA
- EDDA
- RF Solenoid
- Fast Quad
- LE Pol
- Cyclotron
- LE Pol
- LS Pol
- Irrad
- External experiment areas
- Ion Sources
- Stochastic Cooling
- Ion Sources

Facility details:
- Polarized and unpolarized proton and deuteron beams
- Momentum range 0.3 - 3.65 GeV/c
- Electron and stochastic cooling
### COSY - Parameters

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

- $1.5 \cdot 10^{11}$ 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 $\beta$-functions
COSY - Lattice

Acrs:
- 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 $\beta$-functions

Straights:
- 2 mirror-symmetric telescopic arrangements with two quadrupole triplets
- A $2\pi$ 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 $\beta$-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-\(\beta\) section:
- Additional quadrupole magnets
- Increase of geometrical acceptance
- \(\beta_{x,y} \approx 0.3 \, m\)
COSY - Lattice

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Low-β section:
- Additional quadrupole magnets
- Increase of geometrical acceptance
- $\beta_{x,y} \approx 0.3 \text{ m}$
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

\[ Q_x = 3.608; \quad Q_y = 3.615 \]
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)

\[
\frac{\hat{x}}{\hat{y}} = M \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}
\]

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

- ORM can be used for orbit correction
- … and to **calibrate and correct linear optics**
LOCO

− LOCO was successfully 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 $M^{\text{mod}}$ and $M^{\text{meas}}$

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

$\sigma_{M_{\text{meas}},ij}$: errors of linear fit to the beam displacement 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM calibration</td>
<td>60</td>
</tr>
<tr>
<td>BPM roll ($\psi$), shift ($s$)</td>
<td>$2 \cdot 60$</td>
</tr>
<tr>
<td>Steerer calibration</td>
<td>40</td>
</tr>
<tr>
<td>Steerer roll ($\psi$), shift ($s$)</td>
<td>$2 \cdot 40$</td>
</tr>
<tr>
<td>Gradient of quadrupoles</td>
<td>56</td>
</tr>
<tr>
<td>Gradient of quad families</td>
<td>14</td>
</tr>
<tr>
<td>Quadrupole rotations ($\phi, \theta, \psi$), shifts ($x, y, s$)</td>
<td>$6 \cdot 56$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole rotations ($\phi, \theta, \psi$), shifts ($x, y, s$)</td>
<td>$6 \cdot 24$</td>
</tr>
<tr>
<td>K1 of dipole magnets</td>
<td>24</td>
</tr>
<tr>
<td>K2 of dipole magnets</td>
<td>24</td>
</tr>
<tr>
<td>Deflection angle (offset)</td>
<td>40</td>
</tr>
<tr>
<td>K2 of sextupoles</td>
<td>14</td>
</tr>
</tbody>
</table>

**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
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 \cdot parameter)

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

- Invert \(dE_k/dK_l\) using SVD analysis

\[
\frac{dE_k}{dK_l} = USV^T = \sum \tilde{u}_l w_l \tilde{v}_l^T
\]

- Calculate parameter settings

\[
\Delta K = -\sum \tilde{v}_l \frac{1}{w_l} \tilde{u}_l^T \cdot E_k
\]

\[
S = \begin{pmatrix}
\sigma_1 & 0 & 0 \\
0 & \sigma_2 & 0 \\
0 & 0 & \sigma_3
\end{pmatrix}
\]
Loco - Program

- **Configuration**
  - Parameters
  - Sequence
  - ...
- **Data analysis**
  - Selection & calibration
- **Data generation**
  - Random parameter setting
  - MAD-X (ORM calculation)
  - Armadillo libraries
- **Reference ORM**
- **LOCO**
  - Parameter variation
  - Jacobian matrix
  - SVD analysis
  - New settings
- **Data storage**
  - Parameter settings
  - Optical functions
  - ORM data
**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
    ($\Delta k = k_{\text{meas}} - k_{\text{mod}}$)
**Loco - Program**

**Benchmarking** *(good reconstruction):*

Longitudinal position of quadrupoles

\[
\Delta \text{Par} = \text{Par}_{\text{sim}} - \text{Par}_{\text{meas}}
\]

\[
\Delta \beta_x / \beta_x, \quad \Delta \beta_y / \beta_y
\]

Iteration 0: Max 0.785, Min -0.583, RMS 0.102, $\chi^2$/ndf 2168/1507929 850

Iteration 5: Max 2.1e-05, Min -2.8e-05, RMS 3.7e-06, $\chi^2$/ndf 29 337
**Loco - Program**

**Benchmarking (only optics improvement):**

Transverse position of quadrupoles
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
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

<table>
<thead>
<tr>
<th>Quadrupole family</th>
<th>$\Delta k$</th>
<th>date</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQU 6</td>
<td>0</td>
<td>2015 – 11 – 11.19 – 38 – 07</td>
</tr>
<tr>
<td>MQU 6</td>
<td>+20</td>
<td>2015 – 11 – 11.20 – 24 – 38</td>
</tr>
<tr>
<td>MQU 6</td>
<td>-20</td>
<td>2015 – 11 – 11.21 – 11 – 18</td>
</tr>
<tr>
<td>MQT 3</td>
<td>+20</td>
<td>2015 – 11 – 12.08 – 54 – 56</td>
</tr>
<tr>
<td>MQT 3</td>
<td>-20</td>
<td>2015 – 11 – 12.09 – 31 – 24</td>
</tr>
<tr>
<td>MQU 2, MQU 6</td>
<td>+10</td>
<td></td>
</tr>
<tr>
<td>MQU 4, MQU 5</td>
<td>+20</td>
<td>2015 – 11 – 12.11 – 49 – 47</td>
</tr>
<tr>
<td>MQU 4, MQU 5</td>
<td>-20</td>
<td>2015 – 11 – 12.13 – 19 – 31</td>
</tr>
</tbody>
</table>
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

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)
Applying LOCO to measured data

Tune reconstruction (empirically adjusted starting point)
Applying LOCO to measured data

Tune reconstruction (empirically adjusted starting point)

- Tune reconstruction works for arbitrary starting points
Summary

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


Status of COSY model

Dispersion

\[ \frac{\Delta D}{D_{\text{meas}}} \approx 0.4 \]

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

➢ Improvement of COSY model required!
Dispersion

- Measure orbit for different rf-frequencies

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

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

\( D \) ... dispersion,
\( \eta \) ... phase slip factor,
\( C \) ... length of accelerator
• Acceptance
• Tune, tune adjustment
Exemplary config file:
- 15 iterations
- Number of variations
- BPM uncertainty (1E-9 m)
- Vary BPM gain, Steerer gain, quadrupole strength
- Fit parameters per iteration
- ....

```
# 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
varylsteerergain 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             //Include K1 of dipoles
varyBend K2             //Include K2 of sextupoles
varyBendPosition 0      //Include position of dipoles

#Which parameter when? BPMgain/Steerergain/BPMposition/Steererposition/QuadGradients(family)/QuadGradients(all)/KickAngle/KickPosition/DipolePosition
iteration1 11001080000  //Parameters to adjust in 1st iteration
iteration2 11001080000  //2nd iteration
iteration3 11001080000  //3rd iteration
iteration4 11001080000  //4th iteration
iteration5 11001080000  //5th iteration
iteration6 11001080000  //6th iteration
iteration7 11001080000  //7th iteration
iteration8 11001080000  //8th iteration
iteration9 11001080000  //9th iteration
iteration10 11001080000  //10th iteration

# Sigma for simulated measurements
sigmaGain 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
sigmaQuadAngle 0.01     //Sigma of quad Angle variation(rad)
sigmaDipolquad 0.0001   //Sigma of dipolquad of dipole(m^-2)
SigmaDipolQuad 0.05     //Sigma of dipolquad of dipole(m^-3)
SigmaQuad 0.05
SigmaOfSixtupole 0.001  //Sigma of sextupole comp of sextupole(m^-3)
SigmaOfSixtupoleCompOfSextupole 0.001

#Choose Misalignment dx/dy/dz/Phi/dTheta/dPsi
misBPM 0.00001         //Details of misalignments(BPM)
misSteerer 0.00001     //Details of misalignments(Steerer)
misQuad 0.00001        //Details of misalignments(Quadropoles)
misBend 0.00001        //Details of misalignments(Dipoles)

# Filenames
filenameInputSteerers  config/steerer.dat  //
```
Benchmarks

- 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
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 $(ds, d\psi)$, Quad $(ds, d\psi, K1)$, Dipole $(K1, K2, ds, d\psi)$, Sextupoles $(K2)$
- Only optics improvement: Quad $(dx, dy, d\theta)$
- Not sensitive: BPM and steerer $(dx, dy, d\varphi, d\theta)$, Quad $(d\varphi)$
- Fitting combinations of parameters has partly been studied
Loco - Program

Benchmarking – fitting multiple parameters

# Loco config file
# General Settings
# Number of iterations
iterations 15
nsteps 3
errBPMMeasurement 1e-9

# Which parameters?
# Include gain factor of BPM
varyBPMgain 1
# Include gain factor of steerer
varySteererGain 1
# Include position of BPM
varyBPMPosition 0
# Include position of Steerer
varySteererPosition 0
# Include gradient of quadrupole families
varyQuadFamilies 1
# Include gradient of quadrupoles
varyQuadStrength 0
# Include error of kickangle
varyKickAngle 0
# Include position of quadrupoles
varyQuadPosition 0
# Include K1 of dipoles
varyK1 0
# Include K2 of dipoles
varyK2 0
# Include K2 of sextupoles
varySext2 0
# Include position of dipoles
varyDipPosition 0

# Which parameter when? BPMgain/SteererGain/BPMPosition/SteererPosition/Quadfamilies
QuadGradients/all//KickAngle//QuadPosition//DipolePosition

iteration1 11001000000
iteration2 11001000000
iteration3 11001000000
iteration4 11001000000
iteration5 11001000000
iteration6 11001000000
iteration7 11001000000
iteration8 11001000000
iteration9 11001000000
iteration10 11001000000

10th iteration (this setting is used for every following iteration)

# Sigma for simulated measurements
# Sigma of gain variation
sigmaGain 0.1
# Sigma of kick angle variation
sigmaKickAngle 0.01
# Sigma of quadrupole displacement
sigmaQuadDisplacement 0.001
# Sigma of quadrupole angle variation
sigmaQuadAngle 0.01
# Sigma of sextupole displacement
sigmaSextDis 0.05
# Sigma of sextupole angle variation
sigmaSextAngle 0.05
# Sigma of sextupole of dipole displacement
sigmaDipDis 0.001
# Sigma of sextupole of dipole angle variation
sigmaDipAngle 0.001

# Choose Misalignment
dx/dy/dz/dphi/dtheta/dpsi

misBPM 0
misSteerer 0
misQuad 0
misDip 0

# Filenames
# Name of steere for ORM
config/steerer.dat
Applying LOCO to measured data

Tune reconstruction (arbitrary starting point)

- Model
- Measurement
- Fit
Applying LOCO to measured data

Tune reconstruction (arbitrary starting point)

- Model
- Measurement