Bundesministerium
für Bildung
und Forschung

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

LHC optics measurements and corrections

A local observable for linear imperfections in circular accelerators

Andreas Wegscheider

Introduction

About Me

- Gentner Doctoral Student since Aug. 2017
- **PhD topic:** *Development of measurement methods for circular accelerators*
- **finished projects**
  - analytical N-BPM method (more precise and faster calculation of β function)
  - local observable
- **open project**
  - forced coupling

About Me

- Gentner Doctoral Student since Aug. 2017
- **PhD topic:** *Development of measurement methods for circular accelerators*
- **finished projects** **both published**
    - analytical N-BPM method (more precise and faster calculation of β function)
    - local observable
- **open project**
    - forced coupling

About Me

- Gentner Doctoral Student since Aug. 2017
- **PhD topic:** *Development of measurement methods for circular accelerators*
- **finished projects** **both published**
    - analytical N-BPM method (more precise and faster calculation of β function)
    - local observable $\leftarrow$ **this presentation**
- **open project**
    - forced coupling

This presentation

Overview of LHC Optics Measurement and Correction

- why is optics correction important?
- how do we perform optics measurements?
- how do we correct imperfections?

Local Observable

- why do we need a local observable?
- how is it constructed?
- which information do we get?

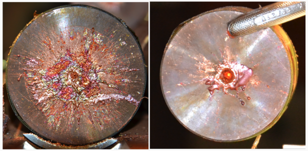
LHC Optics Measurement and Correction

LHC Optics Measurement and Correction

LHC Optics Commissioning

Importance of Optics Commissioning

- Machine protection



Beam hitting solid copper target [a]

[a] PhD thesis of F. Burkhart, former Gentner student

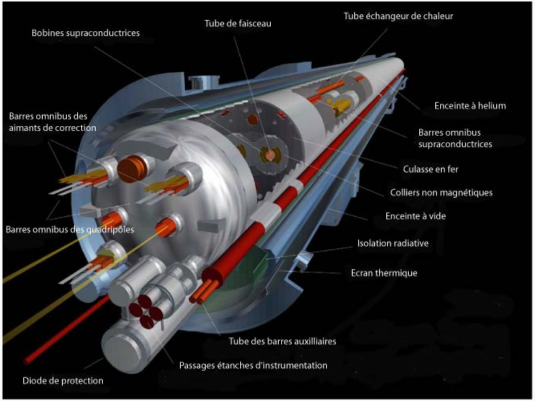
- Machine performance
  - Optics errors can reduce delivered luminosity
  - Optics errors can create luminosity imbalance between experiments

    critical for ATLAS and CMS

    aim for 1% level control of β^*
  - High quality optics improves operational control

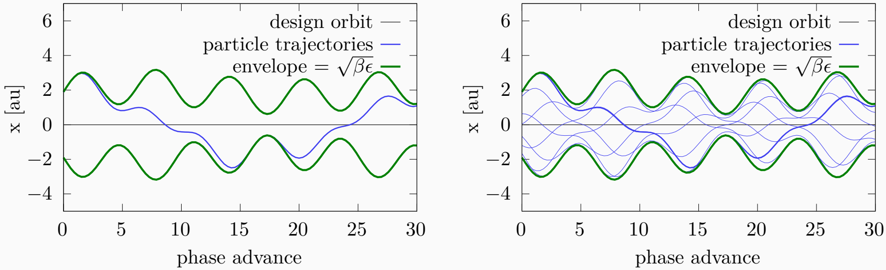
Importance of Optics Commissioning

- the LHC is a superconducting collider
- during one run of operation of the accelerator complex, access to the magnets for measurement is not possible
- to measure and correct lattice imperfections we need to use beam based measurements



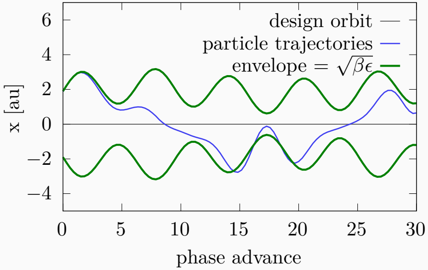
Betatron Oscillation

- particles in bunch perform betatron oscillation about the bunch center
- bunch center moves on closed orbit



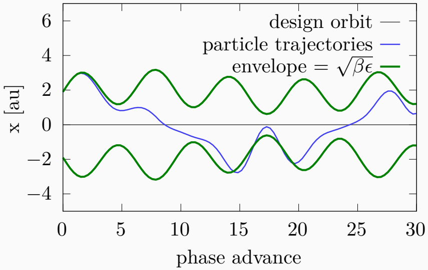
Betatron Oscillation

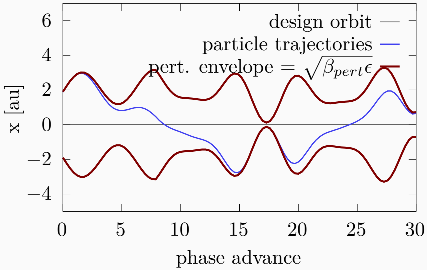
- particles in bunch perform betatron oscillation about the bunch center
- bunch center moves on closed orbit
- focusing errors change β function



Betatron Oscillation

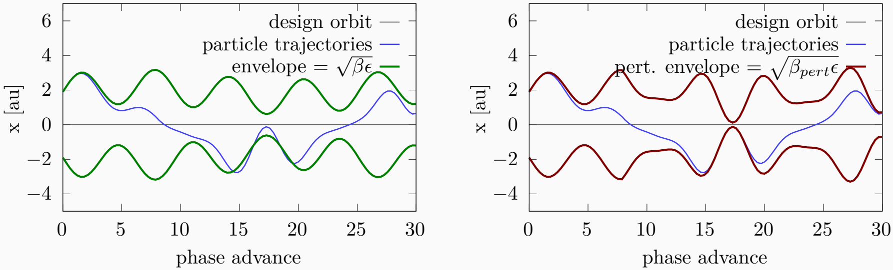
- particles in bunch perform betatron oscillation about the bunch center
- bunch center moves on closed orbit
- focusing errors change β function





Betatron Oscillation

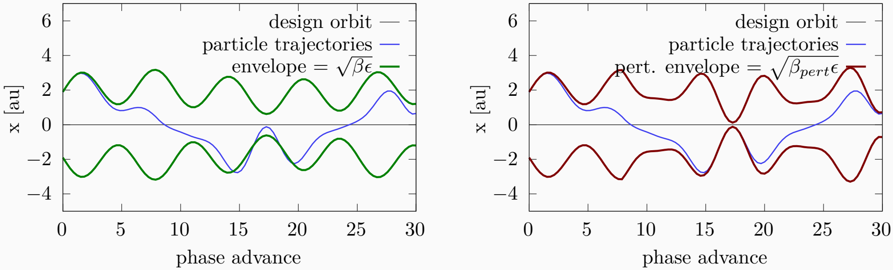
- particles in bunch perform betatron oscillation about the bunch center
- bunch center moves on closed orbit
- focusing errors change β function



- excitation: beam center performs betatron oscillation (if free kick)

Betatron Oscillation

- particles in bunch perform betatron oscillation about the bunch center
- bunch center moves on closed orbit
- focusing errors change β function



- excitation: beam center performs betatron oscillation (if free kick)
- need sufficiently strong amplitude to get good signal

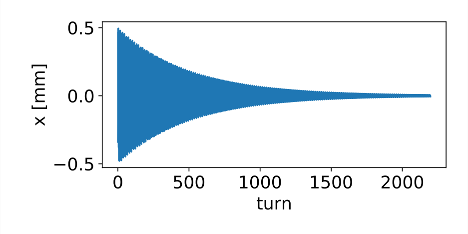
LHC Optics Measurement and Correction

Devices and Tools

Optics measurements via AC-Dipole

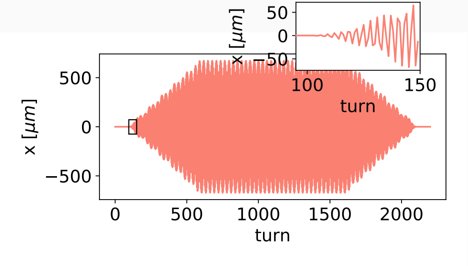
Free kick

- triggers free oscillation of beam
- amplitude of signal decreases fast
- easy to blow up emittance



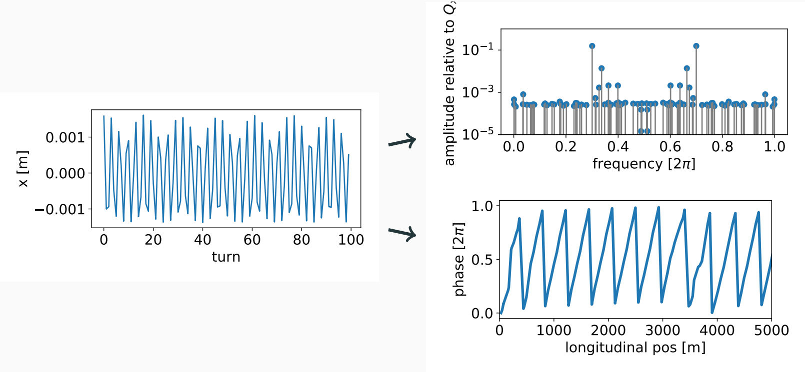
AC-Dipole

- No decoherence
- many turns for analysis
- No blow up due to adiabatic ramp-up/down
- driven oscillation ⇒ compensation



BPMs

- More than 500 dual plane **beam position monitors** (BPMs) record turn-by-turn betatron oscillation data during kicks
- Spectral analysis to obtain **phase advances** between BPMs
- Reconstruct β functions via N-BPM method



LHC Optics Measurement and Correction

Measurement and Correction steps

Measurement of Beta Function

Beta from phase

The β function can be calculated from the measured phase advances via:

$$\beta_i = \frac{\cot\varphi_{ij} - \cot\varphi_{ik}}{\cot\varphi_{ij}^{\mathrm{mod}} - \cot\varphi_{ik}^{\mathrm{mod}}} \beta_i^{\mathrm{mod}} \tag{1}$$

Improvements in β calculation

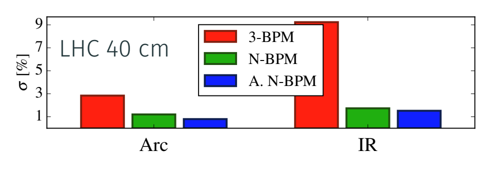
- Traditionally neighbouring BPMs
- improvement through averaging over several combinations, using error propagation to get correlations
- further improvement using analytical formula for error propagation

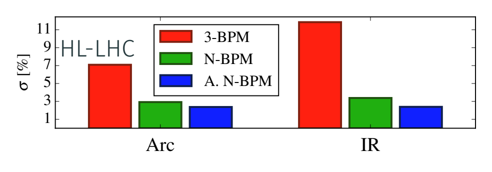
Beta from phase

The β function can be calculated from the measured phase advances via:

$$\beta_i = \frac{\cot\varphi_{ij} - \cot\varphi_{ik}}{\cot\varphi_{ij}^{\text{mod}} - \cot\varphi_{ik}^{\text{mod}}}\beta_i^{\text{mod}} \quad (1)$$

Improvements in β calculation

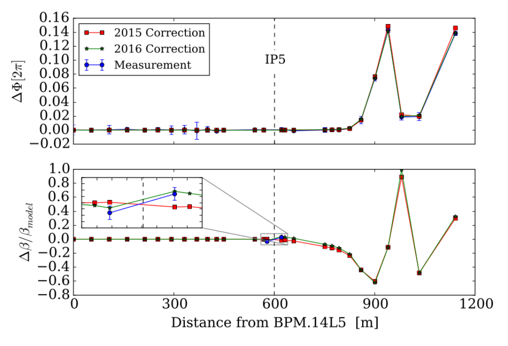




Local Corrections

First: apply corrections of large local errors

using phase beating = $\varphi_{\mathrm{meas}} - \varphi_{\mathrm{model}}$



Phase beating corrected by 2015 and 2016 optics, but only 2016 also reproduces β beating.

Segment-by-segment technique

- Treat segment of ring as transfer line, propagate measured optics from entrance, then compare modelled phase propagation to measurement
- Use models to reproduce phase deviation and apply to real LHC

Global Corrections

Response matrix approach is used to calculate global corrections

$$(\Delta\varphi_x, \Delta\varphi_y, \beta_x^*, \beta_y^*, \Delta\beta_x, \Delta\beta_y, \Delta ND_x, \Delta ND_y, \Delta Q_x, \Delta Q_y)^T = \mathbf{R} \cdot \Delta\vec{k}$$

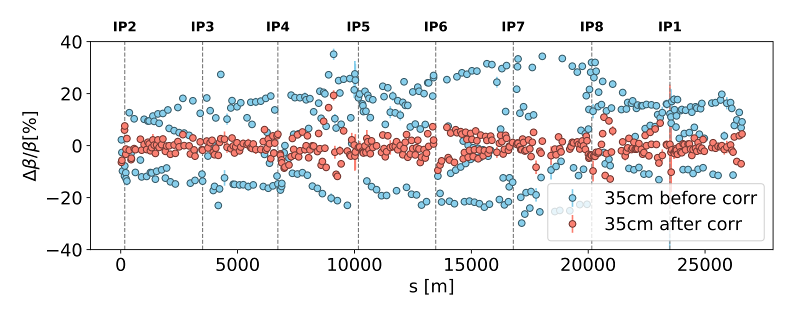


Figure 1: ATS optics MD. $\beta^* = 35\,\mathrm{cm}$

Other Measurement and Corrections Activities

Beyond the scope of this presentation:

- transverse linear coupling
- machine learning to preselect BPMs
- Non-linear optics

Local Observable

Local Observable

Theory

Phase beating due to focusing errors

Quadrupolar field errors alter the phase advance between elements i and j:

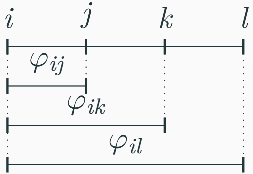


Figure 2: phase advances

Phase beating due to focusing errors

Quadrupolar field errors alter the phase advance between elements i and j:

$$\Delta\varphi_{ij} = \bar{h}_{ij} - 8\sin^2\varphi^{\mathrm{m}}_{ij}\mathcal{R}\{f_i\} - 8\sin\varphi^{\mathrm{m}}_{ij}\cos\varphi^{\mathrm{m}}_{ij}\mathcal{I}\{f_i\} + O(f^2) \tag{2}$$

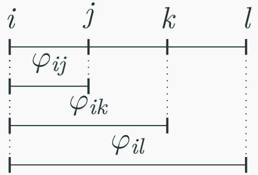


Figure 2: phase advances

Phase beating due to focusing errors

Quadrupolar field errors alter the phase advance between elements i and j:

$$\Delta\varphi_{ij} = \bar{h}_{ij} - 8\sin^2\varphi_{ij}^{\mathrm{m}}\mathcal{R}\left\{f_i\right\} - 8\sin\varphi_{ij}^{\mathrm{m}}\cos\varphi_{ij}^{\mathrm{m}}\mathcal{I}\left\{f_i\right\} + O(f^2) \tag{2}$$

- red: global terms
- blue: local terms

Phase beating due to focusing errors

Quadrupolar field errors alter the phase advance between elements i and j:

$$\Delta\varphi_{ij} = \bar{h}_{ij} - 8\sin^2\varphi^{\mathrm{m}}_{ij}\mathcal{R}\left\{f_i\right\} - 8\sin\varphi^{\mathrm{m}}_{ij}\cos\varphi^{\mathrm{m}}_{ij}\mathcal{I}\left\{f_i\right\} + O(f^2) \tag{2}$$

- red: global terms
- blue: local terms

Eliminate global terms by reshuffling:

$$\begin{aligned}\cot\varphi^{\mathrm{m}}_{jl}\Delta\varphi_{jl} - \cot\varphi^{\mathrm{m}}_{jk}\Delta\varphi_{jk} \\ +\cot\varphi^{\mathrm{m}}_{ik}\Delta\varphi_{ik} - \cot\varphi^{\mathrm{m}}_{il}\Delta\varphi_{il}\end{aligned} = \begin{aligned}\cot\varphi^{\mathrm{m}}_{jl}\left(\bar{h}_{il} - \bar{h}_{ij}\right)\cot\varphi^{\mathrm{m}}_{jk}\left(\bar{h}_{ij} - \bar{h}_{ik}\right) \\ +\cot\varphi^{\mathrm{m}}_{ik}\,\bar{h}_{ik} - \cot\varphi^{\mathrm{m}}_{il}\,\bar{h}_{il}\end{aligned}$$

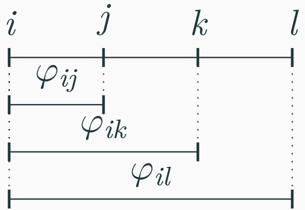


Figure 2: BPM combinations

$$\begin{matrix}\cot\varphi^{\mathrm{m}}_{jl}\Delta\varphi_{jl} - \cot\varphi^{\mathrm{m}}_{jk}\Delta\varphi_{jk} \\ +\cot\varphi^{\mathrm{m}}_{ik}\Delta\varphi_{ik} - \cot\varphi^{\mathrm{m}}_{il}\Delta\varphi_{il}\end{matrix} \equiv \begin{matrix}\cot\varphi^{\mathrm{m}}_{jl}\left(\bar{h}_{il} - \bar{h}_{ij}\right)\cot\varphi^{\mathrm{m}}_{jk}\left(\bar{h}_{ij} - \bar{h}_{ik}\right) \\ +\cot\varphi^{\mathrm{m}}_{ik}\bar{h}_{ik} - \cot\varphi^{\mathrm{m}}_{il}\bar{h}_{il}\end{matrix}$$

Local Observable from phase beating

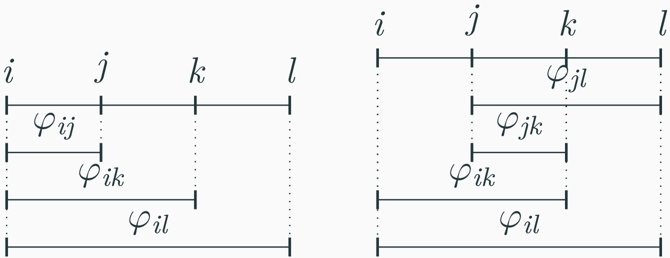


Figure 2: BPM combinations

$$\begin{matrix} \cot\varphi^{\mathrm{m}}_{jl}\Delta\varphi_{jl} - \cot\varphi^{\mathrm{m}}_{jk}\Delta\varphi_{jk} \\ +\cot\varphi^{\mathrm{m}}_{ik}\Delta\varphi_{ik} - \cot\varphi^{\mathrm{m}}_{il}\Delta\varphi_{il} \end{matrix} \equiv \begin{matrix} \cot\varphi^{\mathrm{m}}_{jl}\left(\bar{h}_{il} - \bar{h}_{ij}\right)\cot\varphi^{\mathrm{m}}_{jk}\left(\bar{h}_{ij} - \bar{h}_{ik}\right) \\ +\cot\varphi^{\mathrm{m}}_{ik}\bar{h}_{ik} - \cot\varphi^{\mathrm{m}}_{il}\bar{h}_{il} \end{matrix}$$

Local Observable

Simulations

Locality

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ.22R4	0.1

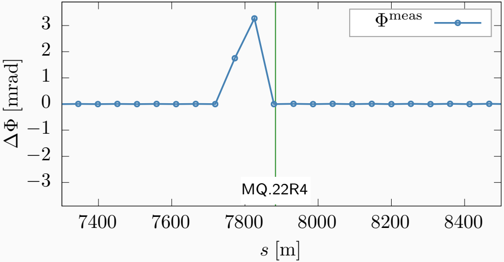
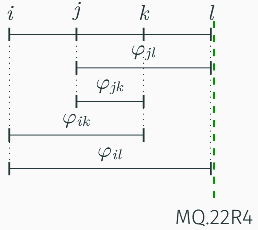


Figure 3: local observable

Locality

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ.22R4	0.1



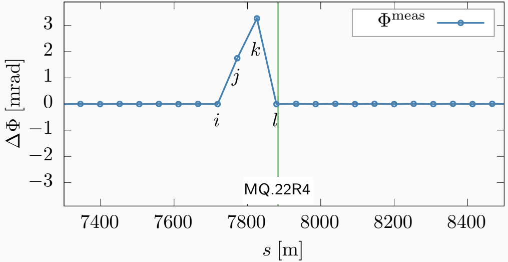
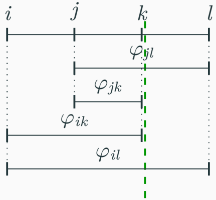


Figure 3: local observable

Locality

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ.22R4	0.1



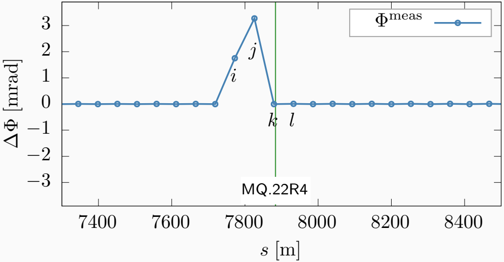
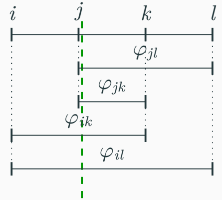


Figure 3: local observable

Locality

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ.22R4	0.1



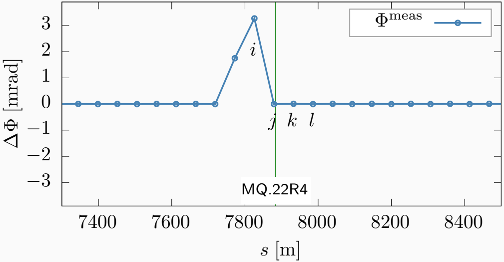
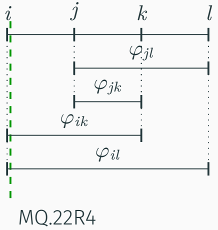


Figure 3: local observable

Locality

Element	σ_{K_1}/K [10^{-4}]
MQ.22R4	0.1



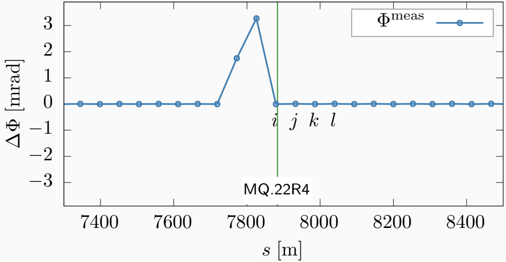
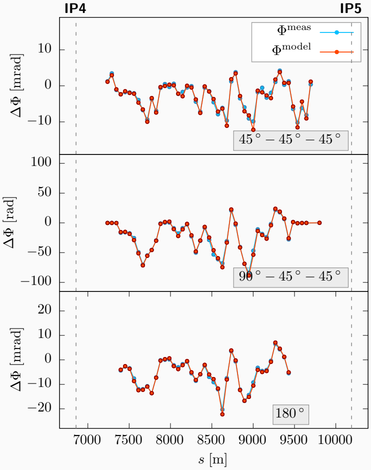


Figure 3: local observable

Design error distribution

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ	12
MQT	75
MQM	12
MQY	11
MQW	15
MQX	1
MB	40

Table 1: Error distribution at 6.5 TeV

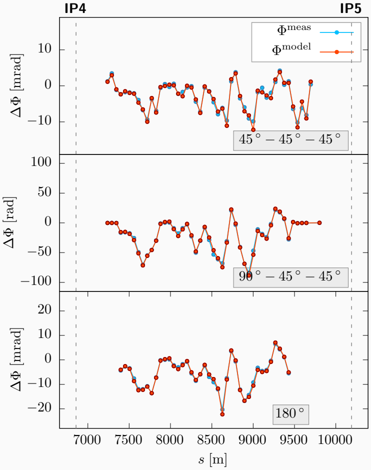


Design error distribution

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ	12
MQT	75
MQM	12
MQY	11
MQW	15
MQX	1
MB	40

Table 1: Error distribution at 6.5 TeV

good agreement between model and simulation

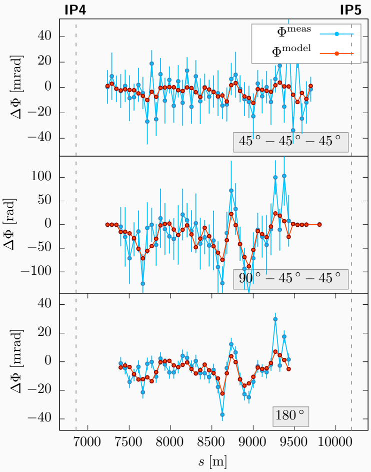


Design error distribution with noise

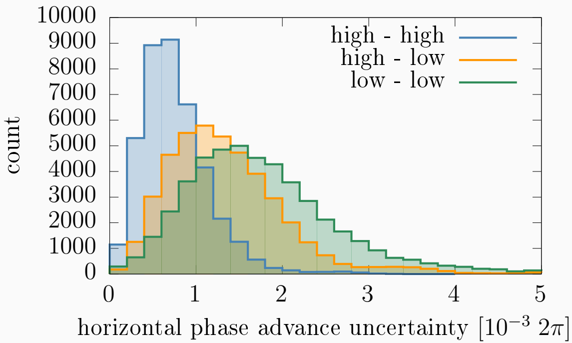
Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ	12
MQT	75
MQM	12
MQY	11
MQW	15
MQX	1
MB	40

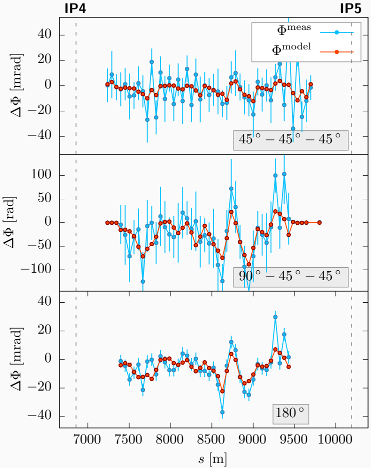
Table 1: Error distribution at 6.5 TeV

not so good agreement between model and simulation



Design error distribution with noise



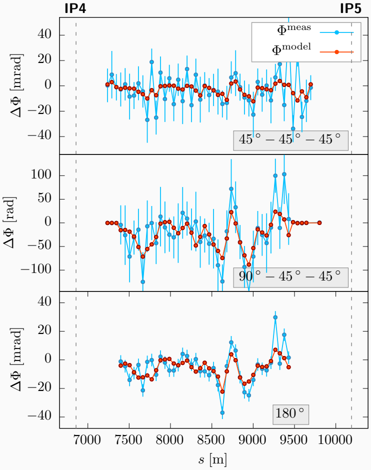


not so good agreement between model and simulation

Design error distribution with noise

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ	12
MQT	75
MQM	12
MQY	11
MQW	15
MQX	1
MB	40

Table 1: Error distribution at 6.5 TeV

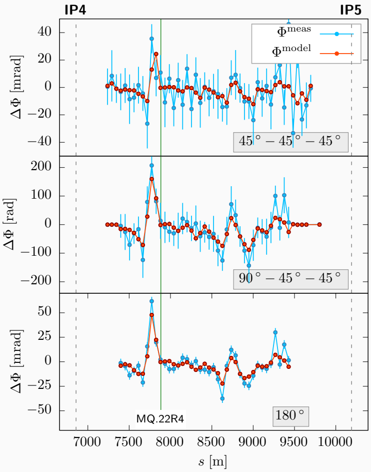


strong error source

Element	$\sigma_{K_1}/K\ [10^{-4}]$
MQ	12
MQ.22R4	100
MQT	75
MQM	12
MQY	11
MQW	15
MQX	1
MB	40

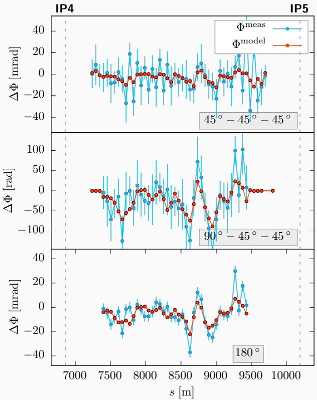
Table 2: introduced strong error in MQ.22R4

error peak clearly visible



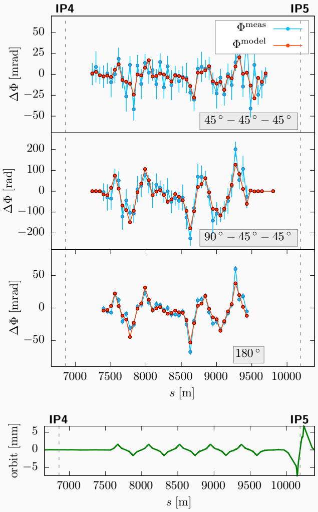
orbit offsets

- orbit offset feeds down to quadrupolar errors in sextupoles



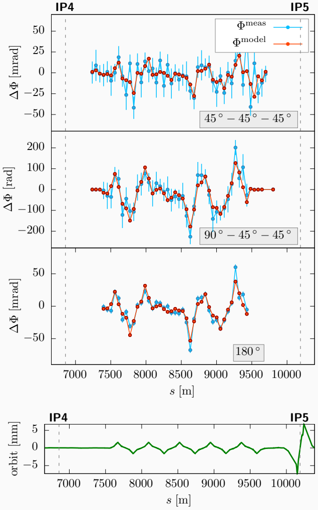
orbit offsets

- orbit offset feeds down to quadrupolar errors in sextupoles
- add orbit offsets



orbit offsets

- orbit offset feeds down to quadrupolar errors in sextupoles
- add orbit offsets
- red line: model values with dispersion bumps and no errors
- blue line: measured (simulated) values with disp. bumps and errors



Local Observable

Measurements

measurements

- simulations with dispersion bumps on
- red line: model values with dispersion bumps and no errors
- blue line: measured (simulated) values with disp. bumps and errors

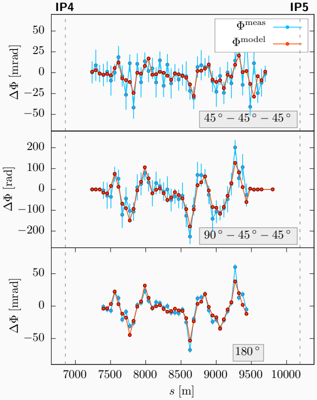


Figure 4: simulation

measurements

- measurement data from 02.04.2018
- LHC beam commissioning, $\beta^* = 30\,\text{cm}$
- dispersion bumps were on
- red line: model values with dispersion bumps and no errors
- blue line: actual measurement

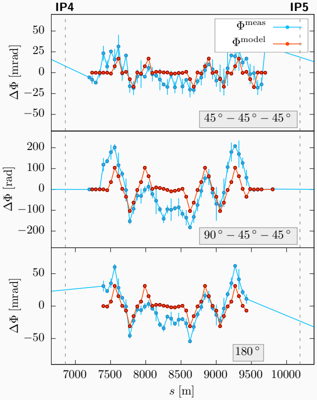


Figure 4: measurement

Local Observable

Conclusion

Conlusion

- LHC design errors can not be seen in the local observable

Conlusion

- LHC design errors can not be seen in the local observable
- strong error sources ($\gtrapprox 1\%$) are clearly visible

Conlusion

- LHC design errors can not be seen in the local observable
- strong error sources ($\gtrapprox 1\%$) are clearly visible
- presence of dispersion bumps can be seen and reproduced in simulations