Improvements in Optics Measurement Resolution for the LHC.

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Outline.

- Optics measurement improvements

- Beta-beat estimates at 7 TeV

- Improvements in correction techniques
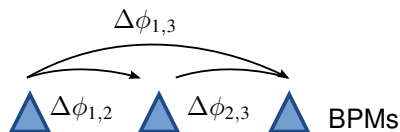
- Summary / Outlook

Optics measurement.

Optics measurement.

- Oscillation will be excited on the beam (Kicker, AC Dipole)

- Turn-by-turn data from the BPMs is recorded

$\rightarrow$ Harmonic analysis $\rightarrow$ phase advance of betatron oscillation

- Phase advance of 3 BPMs can be used to derive optical parameters

$\beta_{\text{BPM 1}} \propto \cot(\Phi_{1,2}) - \cot(\Phi_{1,3})$

$\beta_{\text{BPM 2}} \propto \cot(\Phi_{1,2}) + \cot(\Phi_{2,3})$
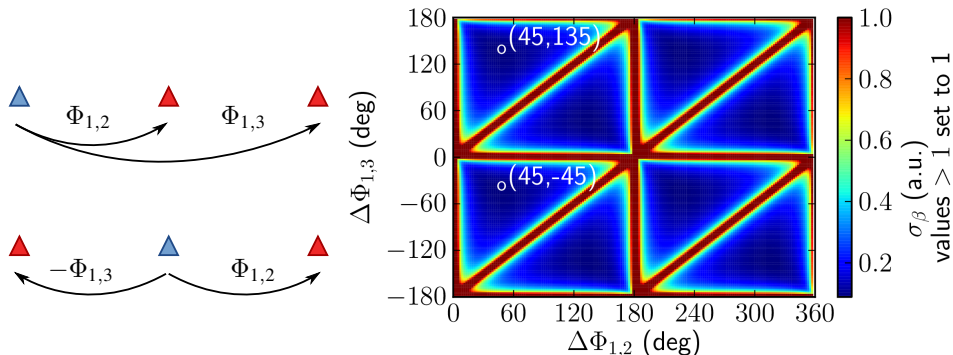
$\beta_{\text{BPM 3}} \propto \cot(\Phi_{2,3}) - \cot(\Phi_{1,3})$
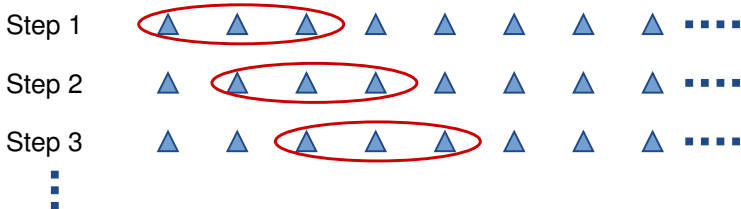

- Resolution depends on phase advances

Resolution dependency of the phase advances.

- Conditions on the phase advance for optimal resolution:

  - Phase advance from probed BPM to the two other BPMs should be close to $(45° + n \cdot 90°, n \in \mathbb{N})$

 - Avoid phase advances of $(n \cdot 180°, n \in \mathbb{N})$ in between BPM pairs

Implementation of the current algorithm.

△ Beam Position Monitors

Step 1   △ △ △ △ △ △ △ △ ....

Step 2   △ △ △ △ △ △ △ △ ....

Step 3   △ △ △ △ △ △ △ △ ....

- Algorithm goes step by step through all available BPMs

- Every set of three neighboring BPMs is used to calculate the optical functions at the three BPM positions

→ For every BPM position the optical functions are calculated 3 times and averaged

Situation in the arcs.
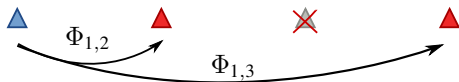

BPMs

$\sim 45°$ $\sim 45°$
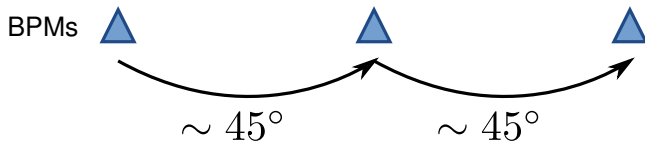
- In general the phase advance between BPM pairs is at about $45°$

- This is the optimum for the case that the probed BPM is in between the other two

- For the case that the probed BPM is left or right to the other two BPMs the phase advances are at about $45°$ and $90°$

$\rightarrow$ In the later case a phase advance of $45°$ and $135°$ with respect to the probed BPM would be better

Improvements for the arc.

$\Phi_{1,2}$ $\Phi_{1,3}$
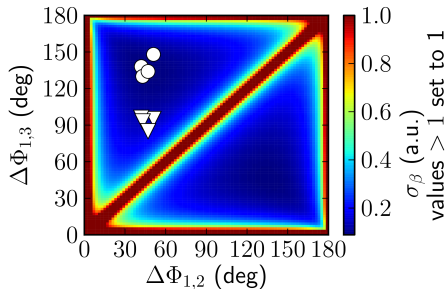
$\triangledown$ current algorithm
$\circ$ different BPM choice

BPM 15R4	Current Algorithm	Skip BPM for $135°$ in edge
β_x (m)	31.1	30.7
Error propagation from $\Delta\Phi$		
$\sigma_{\beta_x,1}$ (m)	0.21	0.17
Standard deviation (3 BPM sets)		
$\sigma_{\beta_x,2}$ (m)	0.22	0.43
β_y (m)	168.85	168.86
Error propagation from $\Delta\Phi$		
$\sigma_{\beta_y,1}$ (m)	1.69	1.03
Standard deviation (3 BPM sets)		
$\sigma_{\beta_y,2}$ (m)	1.93	2.04

- Propagated error from phase decreases, but standard deviation increases

- Model uncertainties contribute more if further away BPM are used

Situation in the IRs.

- In the interaction regions (IRs) the phase advances between BPM pairs differ from $45°$

- In many cases smaller phase advances, in some cases even just a few degree

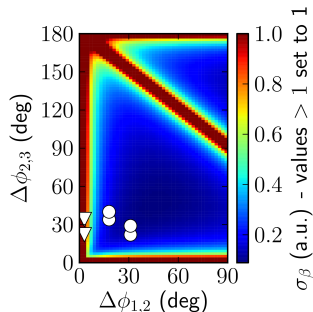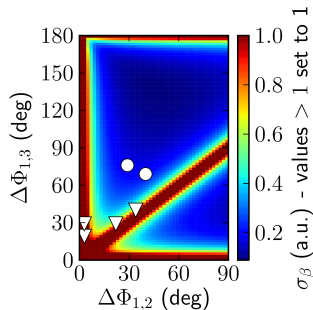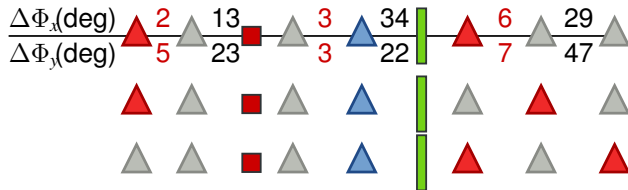- Sketch shows phase advances for BPMs close to IP4

$\Delta\Phi_x$ (deg) YA.5L4 17 WA.B5L4 2 WA.A5L4 13 IP4 WA.A5R4 3 WA.B5R4 34 BWS YB.5R4 6 YA.6R4 29 7R4 25 8R4

$\Delta\Phi_y$ (deg) 53 5 23 3 22 7 47 29
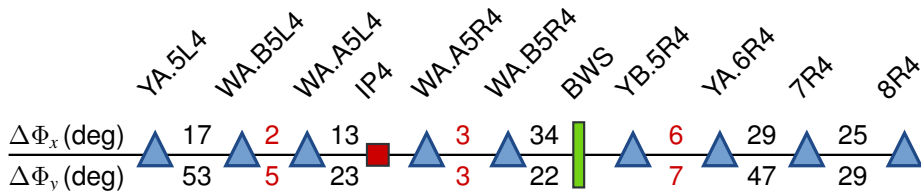
Improvements for IR4.

- Choice of BPMs in old algorithm ($\triangledown$ in right plot)

$\Delta\Phi_x$(deg) 2 13 3 34 6 29

$\Delta\Phi_y$(deg) 5 23 3 22 7 47
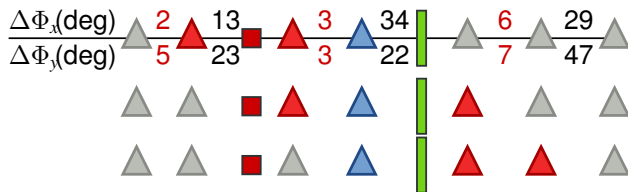
$\triangle$: probed BPMs $\triangle$: used BPMs $\triangle$: unused BPMs

- Better choice of BPMs ($\circ$ in right plot)

$\Delta\Phi_x$(deg) 2 13 3 34 6 29

$\Delta\Phi_y$(deg) 5 23 3 22 7 47

Improvements for IR4.

BPMWA B5R4	Current Algorithm	Optimized BPM sets
β_x (m)	183.1	190.2
Error propagation from $\Delta\Phi$		
$\sigma_1\beta_x$ (m)	23.7	2.1
Standard deviation (3 BPM sets)		
$\sigma_2\beta_x$ (m)	2.4	0.2
β_y (m)	174.0	167.1
Error propagation from $\Delta\Phi$		
$\sigma_1\beta_y$ (m)	21.5	1.9
Standard deviation (3 BPM sets)		
$\sigma_2\beta_y$ (m)	4.6	0.2

BPMYB B5R4	Current Algorithm	Optimized BPM sets
β_x (m)	197.6	191.8
Error propagation from $\Delta\Phi$		
$\sigma_1\beta_x$ (m)	15.6	3.0
Standard deviation (3 BPM sets)		
$\sigma_2\beta_x$ (m)	1.7	0.7
β_y (m)	405.1	407.7
Error propagation from $\Delta\Phi$		
$\sigma_1\beta_y$ (m)	32.9	4.6
Standard deviation (3 BPM sets)		
$\sigma_2\beta_y$ (m)	9.1	3.3

Improvement of one order of magnitude on the error bar!

Implementation of a new algorithm.

Old algorithm
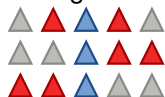
▲ ▲ ▲ ▲ ▲   ▲: probed BPMs
▲ ▲ ▲ ▲ ▲   ▲: used BPMs
▲ ▲ ▲ ▲ ▲   ▲: unused BPMs

- Old algorithm

  - 3 BPM sets of the nearest neighbors per BPM position

  - Final optical functions are the average from the 3 BPM sets
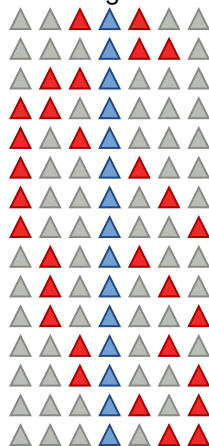
- New algorithm

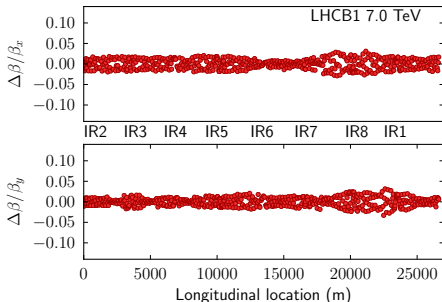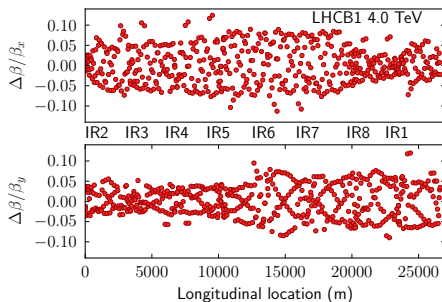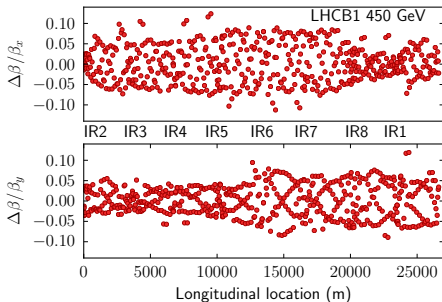 - One additional BPM right and left of the probed BPM are used

  → 15 combinations of BPM sets

  → The 3 BPM sets which feature the lowest errors are chosen and averaged

New algorithm

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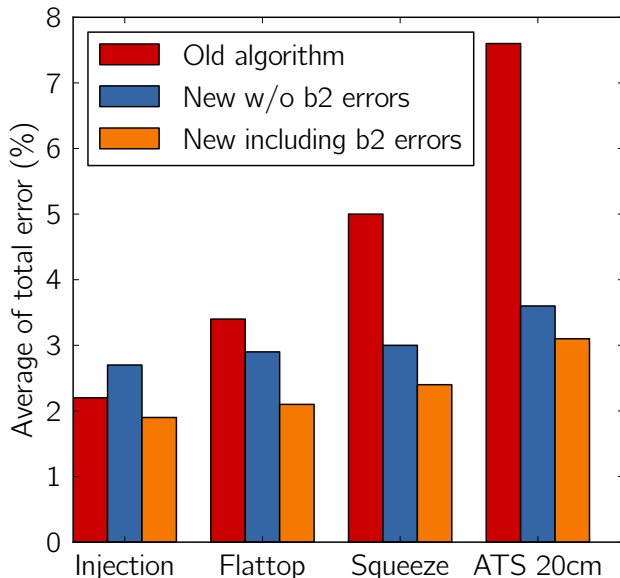▲ ▲ ▲ ▲ ▲ ▲ ▲
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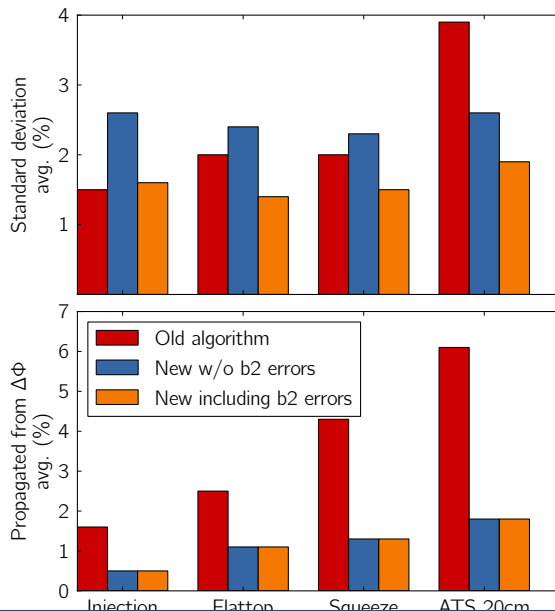# Including dipole b2 errors in the model.

- More precise model

- Better accuracy for the beta calculation expected

- Higher effect at lower energy
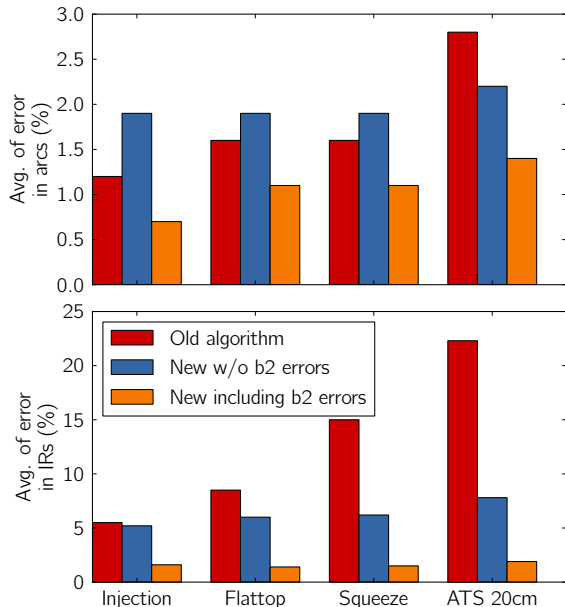
Errors bars of measured betas.

- Averaged $\Delta\beta$

- Errors larger than 200% were removed

- b2 dipole errors increase precision of the measurement

Two contributions to the error bar.

- New algorithm improves significantly errors propagated from $\Delta\Phi$

- Standard deviation is more sensitive to the model
  $\rightarrow$ improves when using b2 errors

# Error bars in arcs and IRs.

- Largest errors are in general in the IRs

- Here the algorithm shows the strongest improvements

- Errors in the arcs already on a low level

- Can be slightly improved with the new algorithm in combination with b2 errors

Beta-beat estimates.

Missing MQT magnets.

- MQT 18.L1 is broken

- The disabled magnet can be compensated by increasing the strength of the other MQTs in this arc

- Switching off 4 MQTs is a favored solution for keeping low beta-beat and low dispersion-beat

Beta-beat supression

14   16   18   20

Dispersion-beat supression
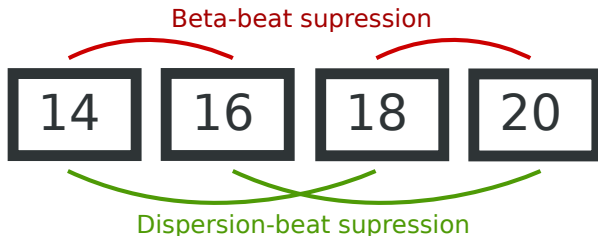
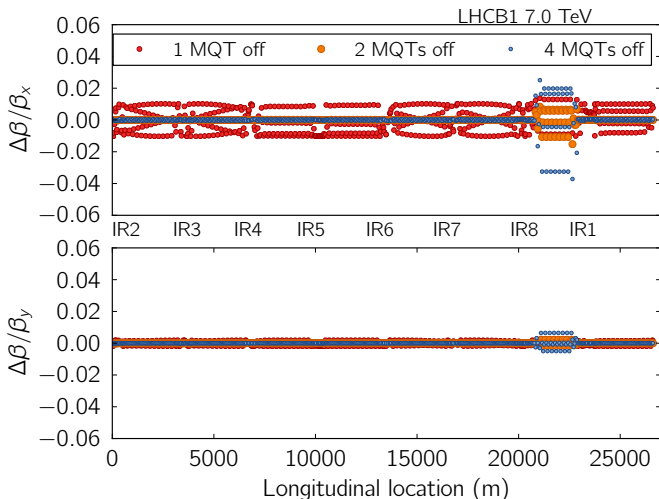# Injection optics at 7 TeV - Missing MQT magnets.

- Global beta-beat is negligible if 4 MQTs are switched off

- Only around these MQT positions a larger beta-beat is observed
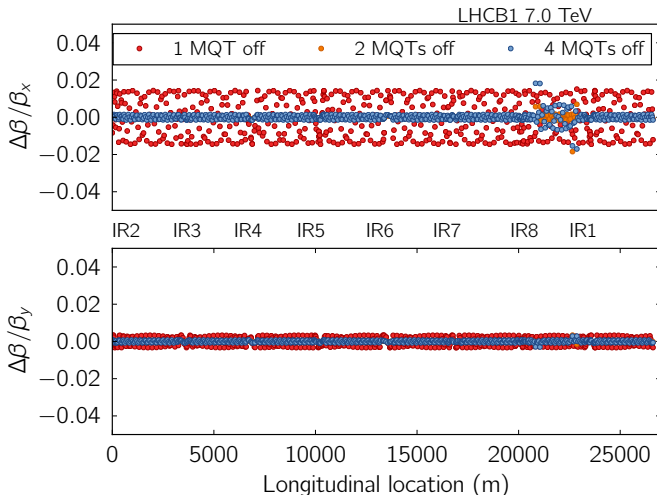
→ **2% peak beta-beat**

# ATS 20cm optics at 7 TeV - Missing MQT magnets.

- Global beta-beat is negligible if 4 MQTs are switched off

- Larger beta-beat in arc81

$\rightarrow$ **4% peak beta-beat**
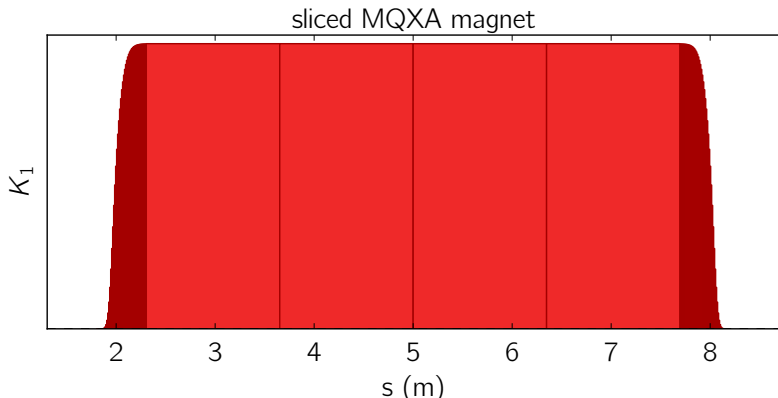
Fringe fields of triplet magnets.

- Hard edge model of a magnet does not take fringe fields into account
- Measured values of gradient versus longitudinal coordinate for MQXF magnets
- Applied on MQXA and MQXB by scaling with aperture (D)
- Fringe field fall off described by Enge function:
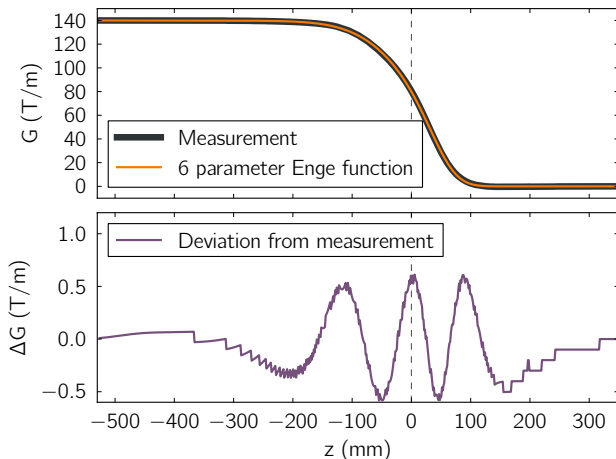
$$F(z) = \frac{1}{1+exp(a_1+a_2(z/D)+...+a_5(z/D)^6)}$$

Fringe fields of triplet magnets.

- 0.5m on each end of the magnet is modeled using the fringe field fit

- 50 slices of 10cm length on both ends

- the mid part of the magnet has the same k value as before but length is changed in order to achieve the same overall $k \cdot L$

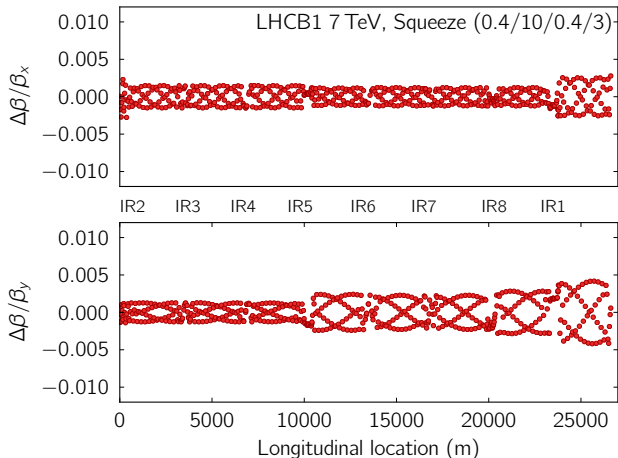sliced MQXA magnet

Fringe fields of triplet magnets.

- Fringe field was applied to triplets in IR1 and IR5
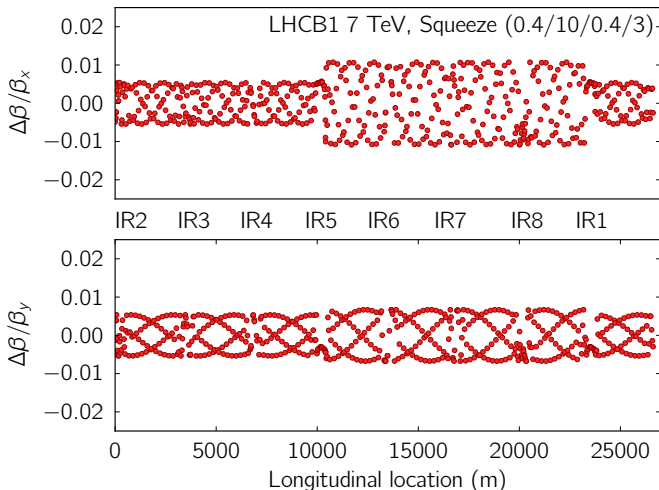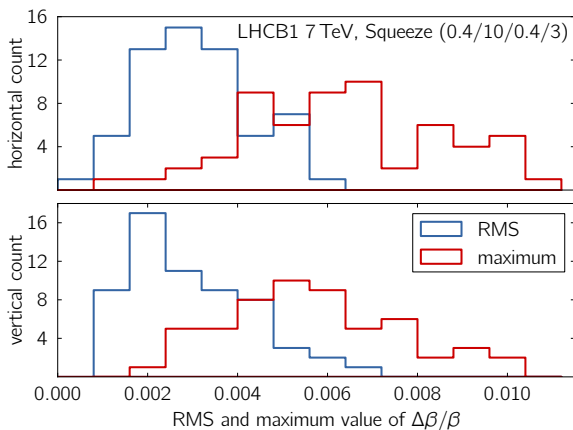
→ **1% beta-beat**

Hysteresis at 7 TeV.

- FiDeL model describes ramp up branch

- This causes an error for magnets which are ramped down, e.g. during the squeeze

- 30 magnets from the MQY, MQM and MQML family

→ **0.5% peak beta-beat**

# Saturation and hysteresis at 7 TeV (squeeze).

- Saturation uncertainties are treated statistically

- Simulation of 60 cases with random gradient errors following a Gaussian distribution within the saturation uncertainty

- Considered magnet types: MQ, MQY, MQM, MQML, MQMC and MQW

→ **1% peak beta-beat**

Saturation and hysteresis at 7 TeV (squeeze).

- Saturation uncertainty of triplet magnets MQXA and MQXB is now added to the simulation

- Strongest contribution to the beta-beat from these magnets

LHCB1 7 TeV, Squeeze (0.4/10/0.4/3)

RMS and maximum value of $\Delta\beta/\beta$

RMS

maximum
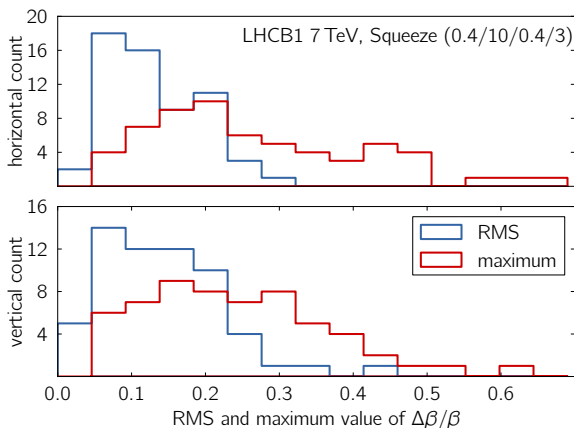
→ ≈ **50% peak beta-beat in worst case scenarios**

Summary from beta-beat estimates.

- Missing MQT magnets
  → **2-4% peak beta-beat** (in arc81, negligible elsewhere)

- Fringe fields of triplets
  → **1% peak beta-beat**

- Hysteresis
  → **0.5% peak beta-beat**

- Saturation (w/o triplets)
  → **1% peak beta-beat**

- Saturation (with triplets)
  → **≈ 50% peak beta-beat**

Improvements of correction techniques.

Segment-by-Segment.
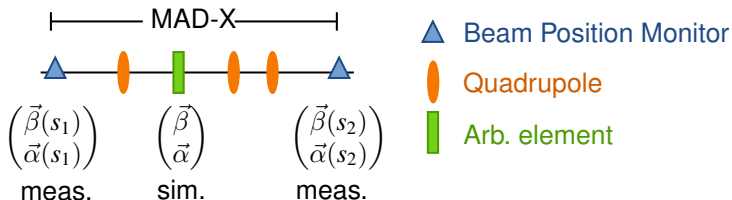
- Transport of optical functions from a BPM position

- Technique for investigating local corrections

- Calculation of optical functions at specific elements

- Uses measured optical function at starting point of simulation

Improvements in measured beta-function accuracy.

- New algorithm for beta-function measurement

- Accuracy has been increased especially in the IRs

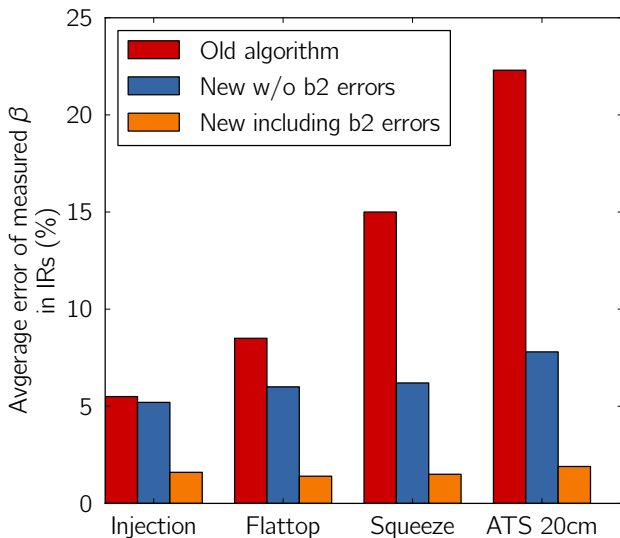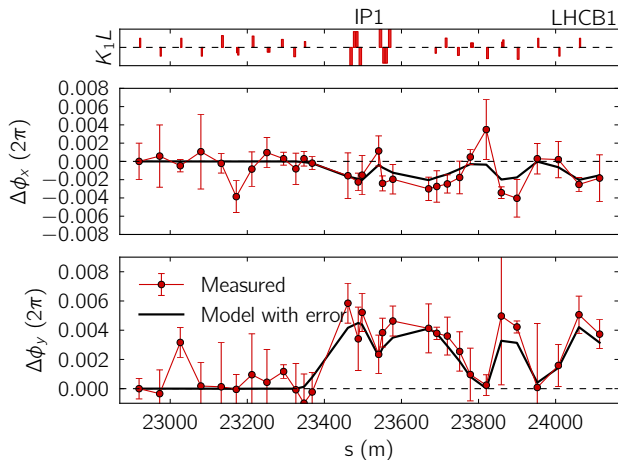→ Increased resolution for correction technique

# Illustration of Segment-by-Segment.

- Errors in the real machine cause deviation of the phase advance

- Searching for magnet errors that can reproduce the measured deviation

→ Correcting optics with this magnet errors

Systematic errors.

- Errors on the measured β- and α-functions propagate to an error of the phase advance → has not taken into account before

- Error on phase advance has minima which indicates higher sensitivity at specific locations

→ Local corrections might be better constrained by using 2 segments with starting location separated by $\approx 90°$
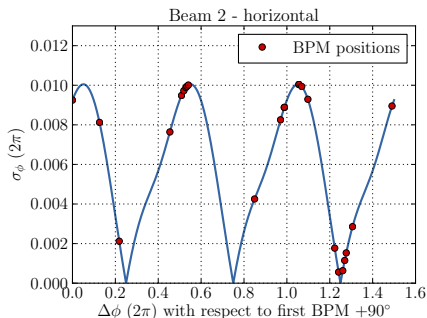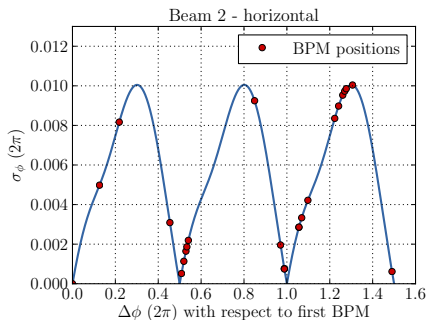
Systematic errors.

- optics measurement simulated

- 0.5% error on Q5.L1 → segment-by-segment run

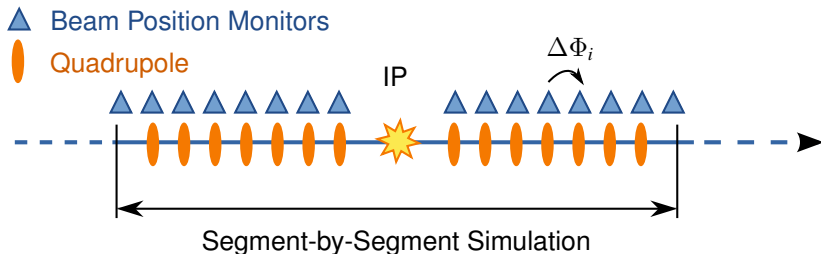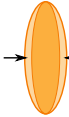- two starting positions separated by ≈ 90° phase advance
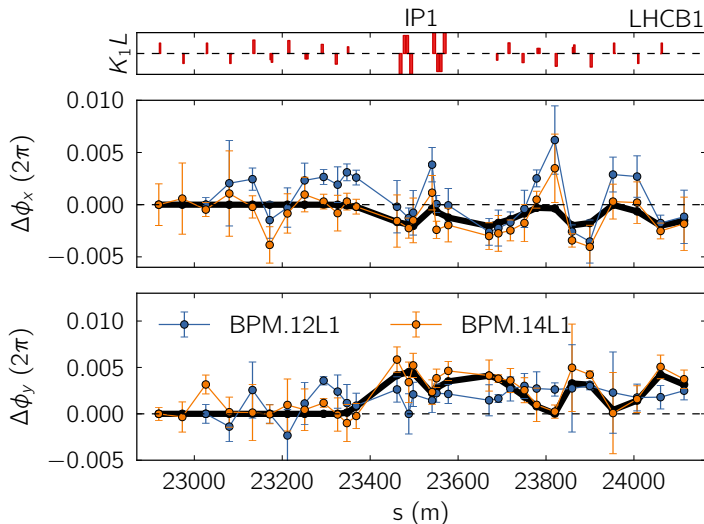
Impact of fringe fields on Segment-by-Segment.

- Fringe fields in the triplet cause also a phase advance

- Should be implemented in Segment-by-Segment for higher precision

Offline correction technique.

- **Beam Position Monitors**
- **Quadrupole**

IP

$\Delta\Phi_i$

Segment-by-Segment Simulation
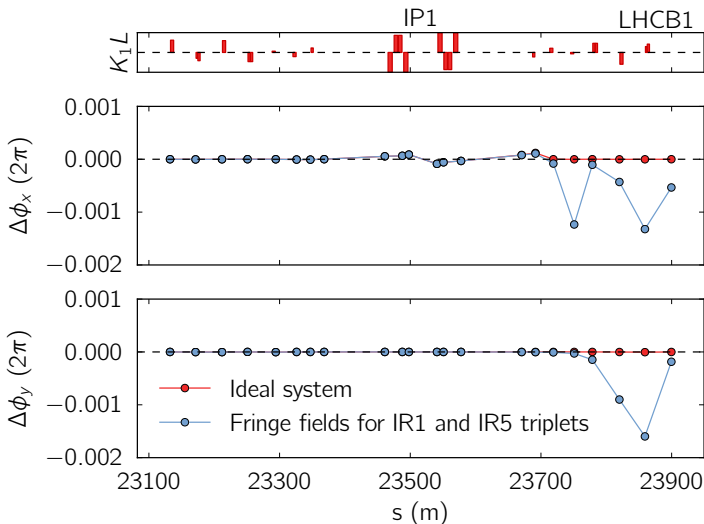
- Monte-Carlo Approach to fit optics to measured constraints

- Vary quadrupole strengths Δk and long. positions Δs

$\rightarrow$ Variation of simulated phase advances $\Delta\Phi_{i,Sim}$

- Minimize $\chi^2 = \sum_i \left(\dfrac{\Delta\Phi_{i,Meas} - \Delta\Phi_{i,Sim}}{\sigma(\Delta\Phi_i)} \right)^2$

Offline correction technique.

- Flexible technique
  → can be
  combined with
  other
  measurements
  (k-modulation)

- This method was
  tested in IR1 in
  combination with
  constraints from
  ALFA detector
  measurements
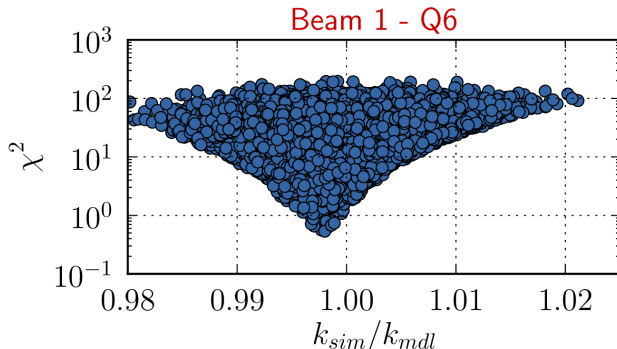
Summary.

- Improved algorithm for β-function calculation studied

  - Significant improvements on the error bars

  - Precise knowledge of the model (b2 errors) crucial

- beta-function measured with higher accuracy
  $\rightarrow$ Higher precision of Segment-by-Segment

- Code will be extended to use different start location for the simulation
  $\rightarrow$ Sensitivity for different error sources

- Fringe field impact will be included in the code

- Monte-Carlo approach for offline corrections

- More sophisticated error treatment $\rightarrow$ Propagation of β-function to specific elements will benefit from these improvements

Thank you for your attention.