SPS Optics Measurements with Closed Orbits

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- Motivation
- Introduction : optics measurements
  & corrections.
- Optics measurement using closed orbits
  at the SPS.
- Optics measurement for the TI8 transfer line.
- Conclusions.

Motivation

- A machine optics should match the model as closely as possible :
  orbit correction, knobs, aperture …

- To achieve this :
  - ✓ The beam optics must be measured.
  - ✓ Deviations must be corrected !

- So far we made lots of measurements but seldom corrections
  LEP : only low-beta quadrupoles were adjusted – was sufficient !

- For LHC the situation might be more critical than for LEP and SPS
  → we would like to have tools to correct a poor optics and identify the problems.

Optics measurements I : K-modulation

The local β-function is determined by measuring the tune change ΔQ due to a change or modulation ΔK of the quadrupole strength K :

$$\Delta Q \propto \int_{Quad} \beta(s)\Delta K(s)ds$$

K-modulation was for example used at LEP to measure and correct β^* (in fact the β @ low-beta quadrupoles)

Pro & contra :

- ✓ simple, ΔQ can be measured with high accuracy.
- ✓ ~ fast.
- ✓ parasitic measurements during 'physics' possible.
- ✘ requires individual power converters or special windings.
- ✘ must know precisely the transfer function $\Delta I \rightarrow \Delta K$!

Optics measurements II : phase advance

A (large) betatron oscillation is launched to measure the phase advance $\Delta\mu$ between each pair of beam position monitors (BPM). The β-function at the BPMs can then be reconstructed from the phase advance (provided some assumptions are made) .

Widely used everywhere….

Pro & contra :

- ✓ accurate (~ % on β).
- ✓ fast.
- ✘ requires large amplitude oscillations (not so nice with protons…).
- ✘ does not work with lines.

Optics measurements III : orbit response

The orbit or trajectory change (response) due to a steering magnet (corrector) kick θ is measured with BPMs. The position change Δu_i @ i[th] monitor is related to a kick θ_j @ j[th] corrector by :

$$\Delta u_i = R_{ij}\theta_j$$

***R* = response matrix**

$$R_{ij} = \frac{\sqrt{\beta_i\beta_j}\cos(|\mu_i - \mu_j| - \pi Q)}{2\sin(\pi Q)}$$

Closed orbit

$$R_{ij} = \begin{cases} \sqrt{\beta_i\beta_j}\sin(\mu_i - \mu_j) & \mu_i > \mu_j \\ 0 & \mu_i \le \mu_j \end{cases}$$

Trajectory

Pro & contra :

- ✓ simple & fast *qualitative* check.
- ✘ depends on BPM and corrector calibrations.
- ✘ de-convolution of β/μ is not straightforward.

Optics Corrections (I)

- **'Ideal' solution :**

Throw all information on the measured β-functions into your favorite matching program (MAD…) and rematch the optics…

→ Not guaranteed to work…

- **'Linearization' :**

Proceed by linearization of the model and iteration.

1) Evaluate the gradient :

Evaluate the local gradient of β/μ with respect to a set of strengths k_1 to k_n.
→ defines a matrix $\mathbf{G}$

$\mathbf{G} = \mathbf{G}(k_i)$ ↔ valid over a limited range !

$$\mathbf{G} = \begin{pmatrix} \frac{\partial \beta_1}{\partial k_1} & \cdots & \frac{\partial \beta_1}{\partial k_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial \beta_m}{\partial k_1} & \cdots & \frac{\partial \beta_m}{\partial k_n} \end{pmatrix}$$

Optics Correction (II)

2) <u>Least-square minimization :</u>

Solve the following equation for strength changes Δk

$$|| \left(\vec{\beta}^{meas} - \vec{\beta}^{model} \right) + \mathbf{G}\Delta\vec{k} \,||^2 = \text{minimum}$$

This type of equation is solved routinely for orbit correction with least-square algorithms : SVD, MICADO..

3) <u>Iterate until the minimum is stable :</u>

- Update model with new strengths $k_i \rightarrow k_i + \Delta k_i$
- Re-evaluate matrix **G**.
- Find new least-square solution.
- …

the problem is not linear !!!

Hopefully you can re-match to model to fit the data → know what's wrong !

Optics Correction : the LOCO program

A program named **LOCO** was developed at BNL by J. Safranek to check and correct machine models, BPMs, orbit corrector magnets… for synchrotron light sources.

- Input data : the orbit response matrix $\boldsymbol{R} = (\boldsymbol{R}_{ij})$
- LOCO proceeds by linearization and least-square minimization.
- It can handle BPM and corrector calibrations, corrector and BPM roll, coupling, … in fact everything that can be parametrized.
- LOCO is 'loosely' coupled to MAD (automatic script generation…).
- It has been used (apparently) with success in many US light sources.

LOCO was adapted and modified to run on the SPS and the LHC transfer lines → for evaluation…
First test of LOCO on a 'large' machine.

Optics corrections with LOCO (I)

1) <u>Measurements :</u>

A vector holding the weighted difference between the measured and modeled response is build from all matrix elements :

$$r_k = \frac{R_{ij}^{meas} - R_{ij}^{mod}}{\sigma_i} \quad \forall i, j$$

σ is the measurement error

2) <u>Local gradient :</u>

Evaluate the sensitivity wrt parameters c_1 to c_n (BPM and corrector calibrations, strengths…)

$$\mathbf{G} = \begin{pmatrix} \frac{\partial r_1}{\partial c_1} & \cdots & \frac{\partial r_1}{\partial c_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial r_m}{\partial c_1} & \cdots & \frac{\partial r_m}{\partial c_n} \end{pmatrix}$$

Optics Correction with LOCO (II)

3) <u>Least-square minimization :</u>

Solve the equation for parameter changes Δc

$$\| \vec{r} + \mathbf{G}\Delta\vec{c} \|^2 = \text{minimum}$$

4) <u>Iteration :</u>

Update c, update **G**, solve again… until the solution is stable.

$$\| \vec{r} \|^2 = \sum_{i=1}^{n} r_k^2 = \text{minimum} \approx \text{m - n}$$

m = # elements R_{ij}

For 'gaussian' errors (and provided there are correctly estimated) the minimum value that can be achieved is well determined.
Provides a statistical test of the fit quality.

Matrix sizes…

Consider a ring with **N** BPMs and **M** correctors per plane. The typical size of the gradient matrix **G** is :

$$(2 \times N \times M) \times (2 \times (N + M))$$

…with BPM and corrector calibration as parameters for c.

- **SPS** : N = 113 , M = 108 ~ 25000 x 221 → ~ 6 10^6 elements
- **LHC** : N = 500 , M = ~ 250 ~ 250000 x 1500 →375 10^6 elements !!!

- For LHC, one has to restrict to a fraction of the correctors / split the data. There is anyhow redundancy in the correctors (phases).
- Or one has to assume that the BPM & corrector calibrations are known …

Must be clever with large machines…

LOCO test @ the SPS

Orbit response measurements the SPS :

- LHC type beams @ 66 GeV/c (during the ramp).
- Corrector kicks : +20 & –20 μrad (→ ± 2 mm peak orbit changes).
- 18 (21) H (V) correctors were bumped in the sextants 1 & 2.
- Non-standard tunes (Q_x, Q_y) = **(26.76, 26.83)**.
- The phase advance between monitors in the SPS is (almost) 90°.

Since the β-beating 'runs' twice as fast as the orbit :

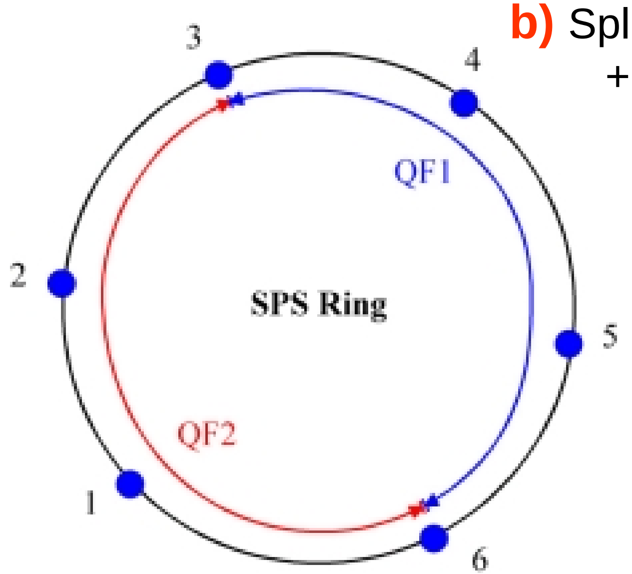
$$\Delta\beta(s) \propto \frac{\beta_0 \beta(s) \cos(2\,|\mu(s) - \mu_0| - 2\pi Q)}{2\sin(2\pi Q)}$$

- ≈180° change between BPMs → poor sampling !
- 90° lattices are not ***ideal*** for optics measurements (K-modulation is OK !).

SPS model and fit parameters

- Input model : nominal SPS model, (Q_x, Q_y) = **(26.62,26.58)**
  → deliberate model error !
- Fit parameters :
  - BPM and corrector calibrations.
  - Main quadrupole strengths :

a) Use normal strengths for QF1, QF2 and QD
→ 3 parameters, ~ simple tune adjustment.



b) Split the QF1, QF2 and QD chains into individual sextants
+ free the strength of the large aperture quadrupoles.

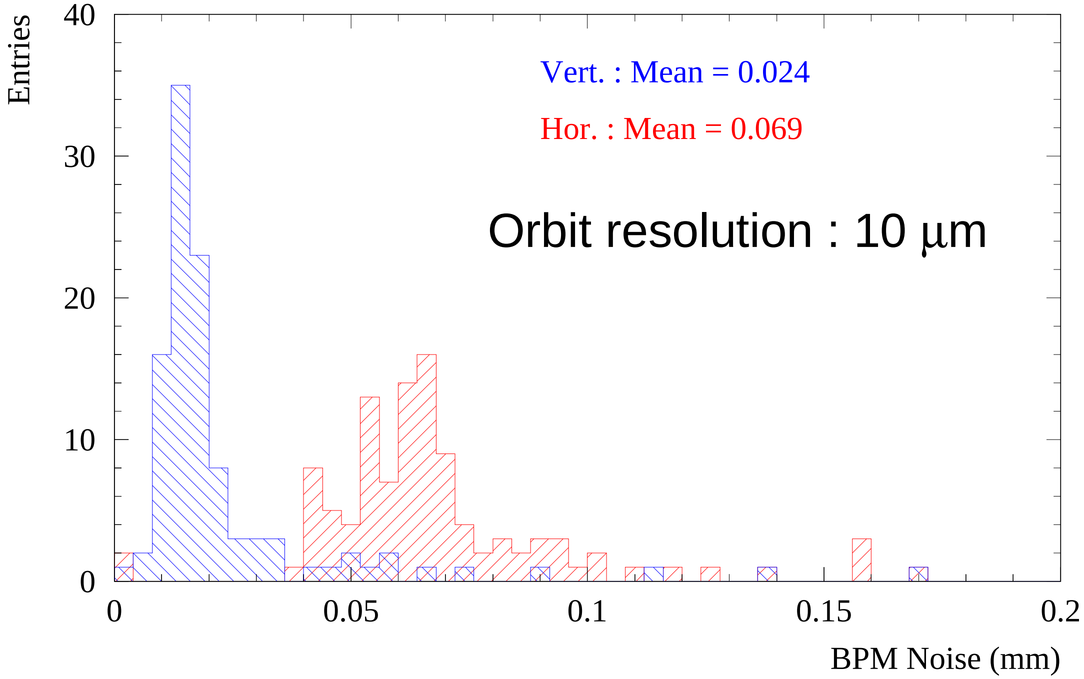
17 strength parameters

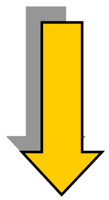
Measurement noise

The noise (electronics, SPS reproducibility...) is estimated from the RMS position change of reference orbits acquired during the measurements :

- vertical plane ~ **24 μm**
- horizontal plane ~ **70 μm**

A ratio ~ 2 is expected for pure BPM noise (aperture)





More ‘noise’ may be introduced into the measurements by BPM non-linearity !

Before fit : model versus data

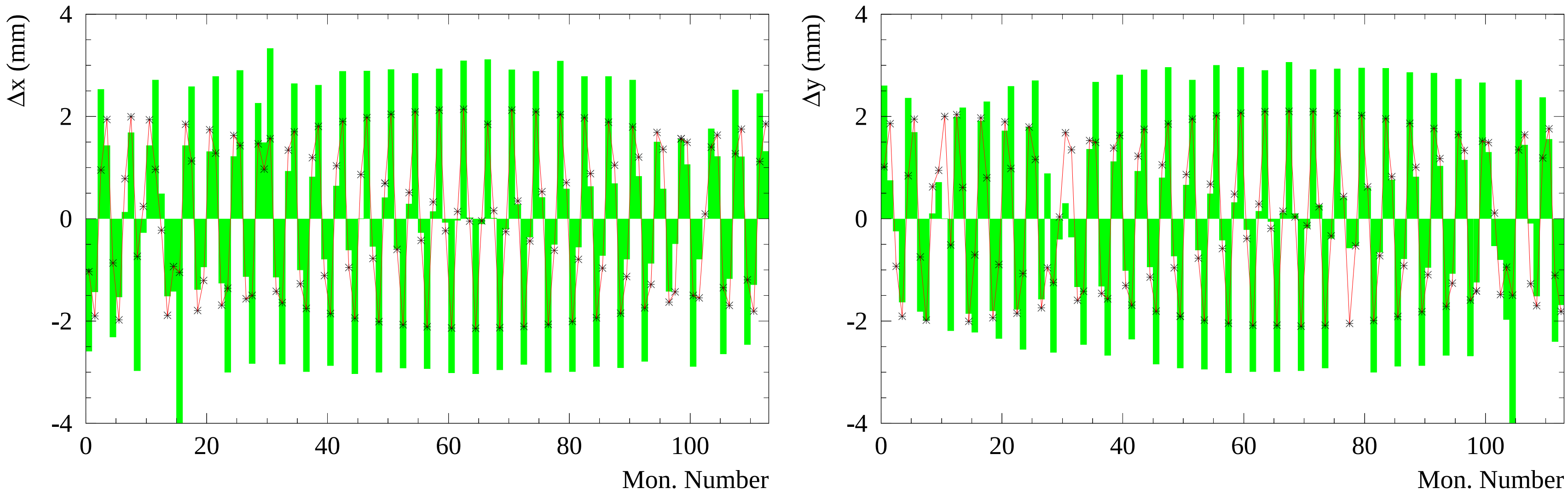
An amplitude error is visible, due to the tune error & orbit factor **sin(πQ)** :

$$\sin(26.6\,\pi)/\sin(26.8\,\pi) \sim 1.6$$

$$\Delta x \,/\, \Delta y = \text{response } \theta^{+} - \text{response } \theta^{-}$$

Histogram : raw data

(*) + line : model , tunes = (26.62,26.58)



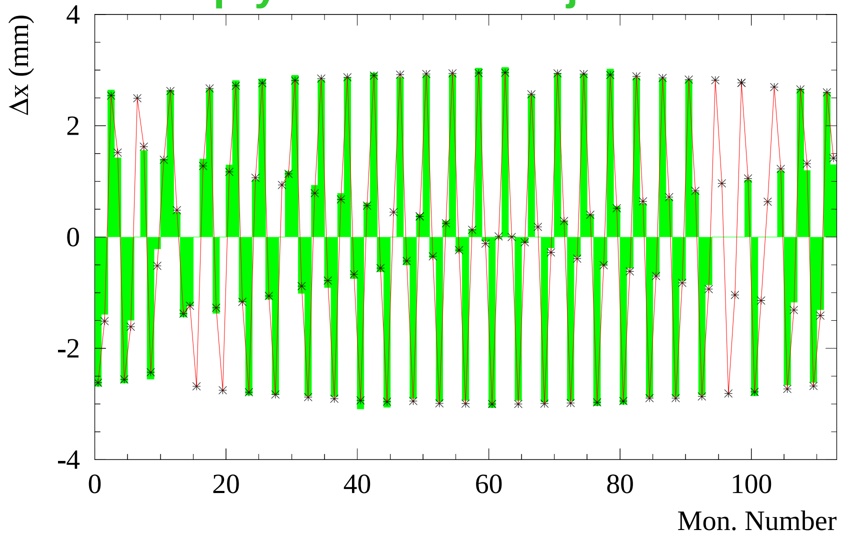
MDHD.118 **MDV.121**

A few fit iterations later…

- ✓ BPM and correctors are calibrated.
- ✓ Fit model tunes = (26.762, 26.826) , exactly as expected !
- ✓ At first sight – excellent agreement model-data.
- ✓ Sextant-to-sextant strength modulation ~ 0.1-0.2%.

Histogram : gain corrected data
Empty bin → BPM rejected

(*) + line : fit model (17 parameters) with calibrated kick



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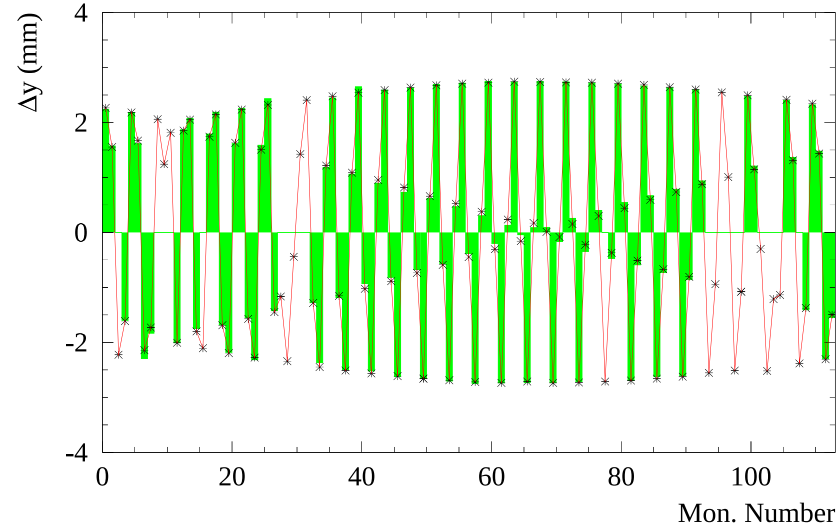


MDV.121

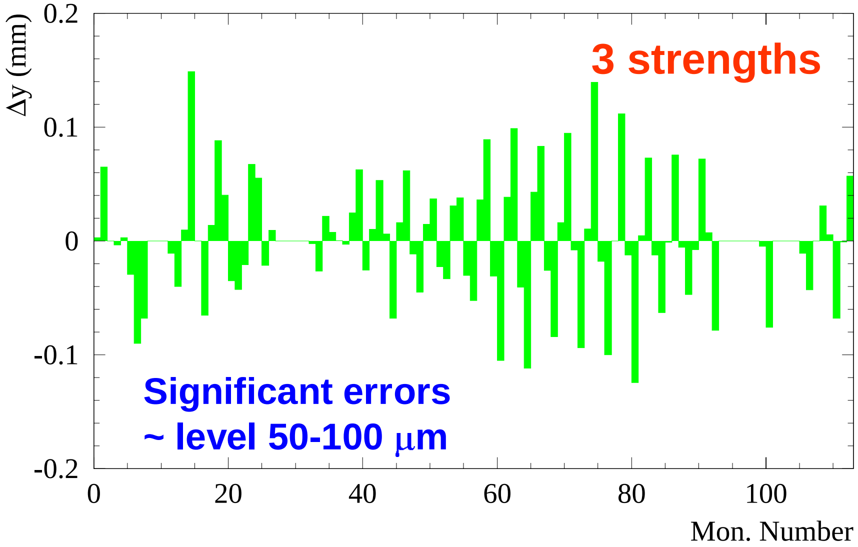
Difference data-model

RMS difference data-fit model with 17 strengths :

- H plane ~ 90 µm → expect 100 µm
- V plane ~ 44 µm → expect 35 µm

≈ at noise limit !

Histograms : calibrated data-fit model / V plane



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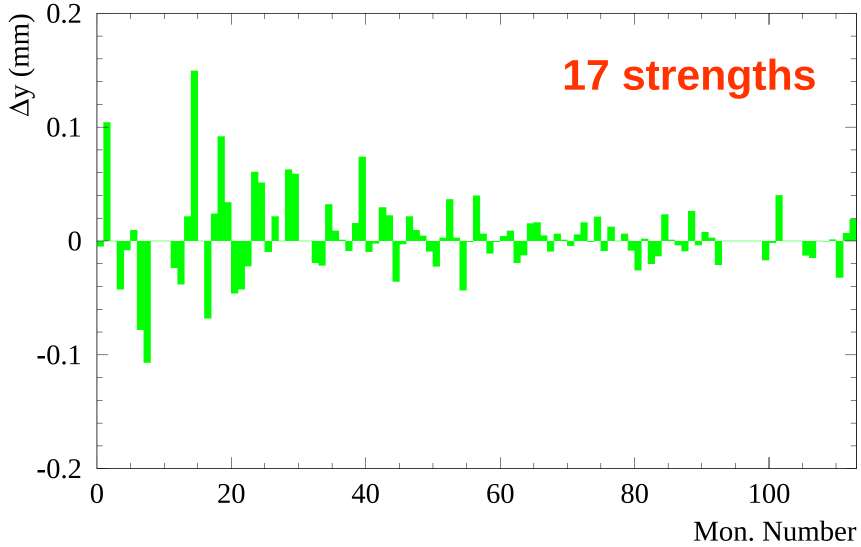
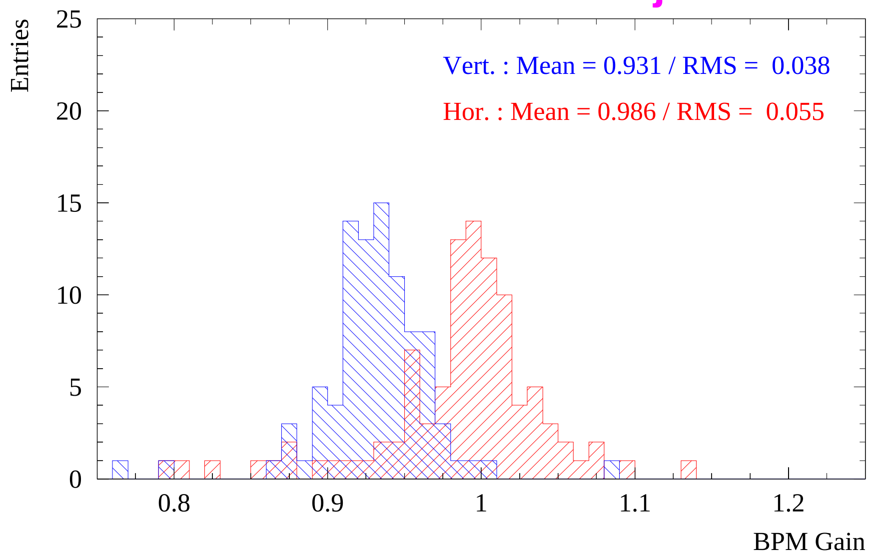


MDV.205

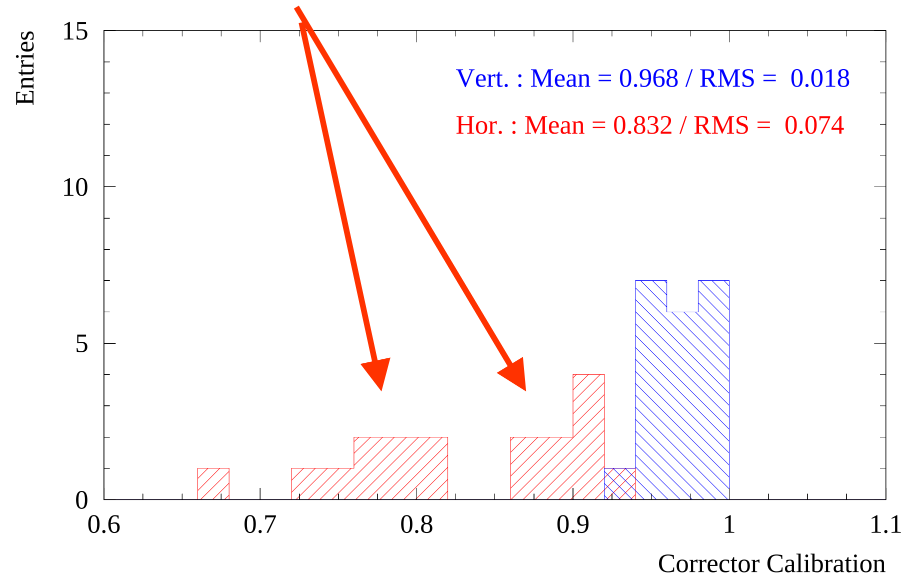
Calibration factors

- H plane : **BPM gains (re)normalized to dispersion !**
  Corrector gains : very low.
  double peak ↔ correctors 90° out of phase.
- V plane : calibrations ~ OK.

36 out of 226 monitors rejected !!



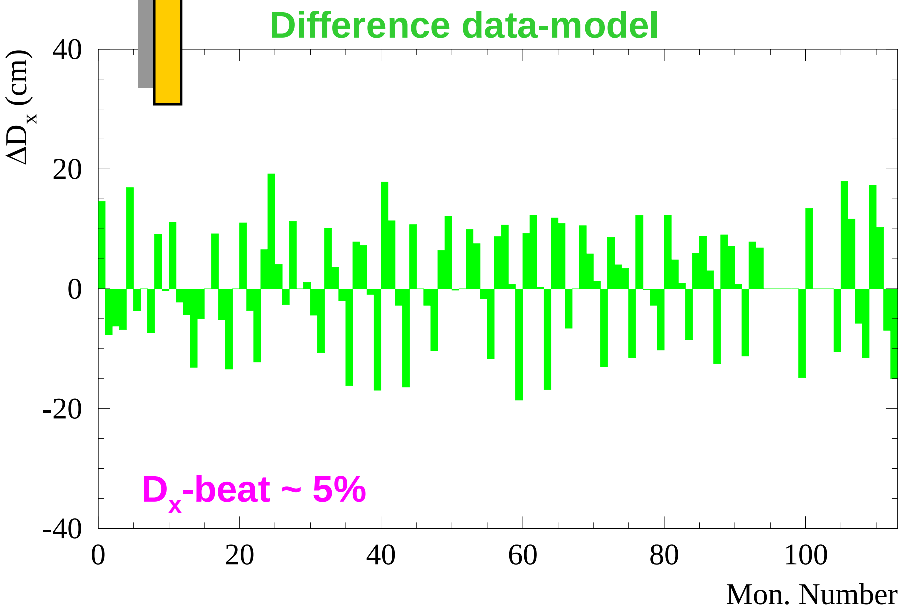
Suspicious double peak !

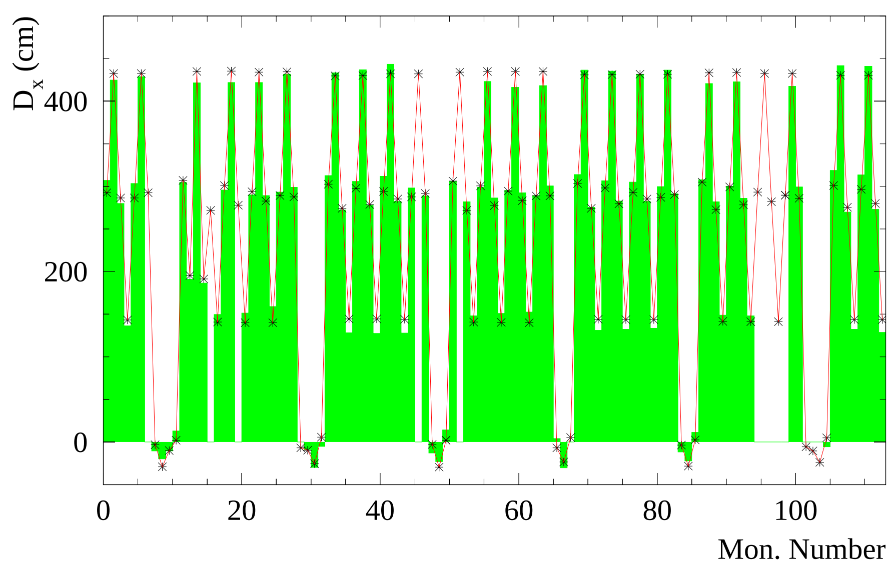


Horizontal Dispersion

- Not included in the fit, since it also depends on the bending (errors).
- Can be used to check the model and set the BPM scale.

Can be explained by a horizontal β-beat of ~ 5 to 10%.

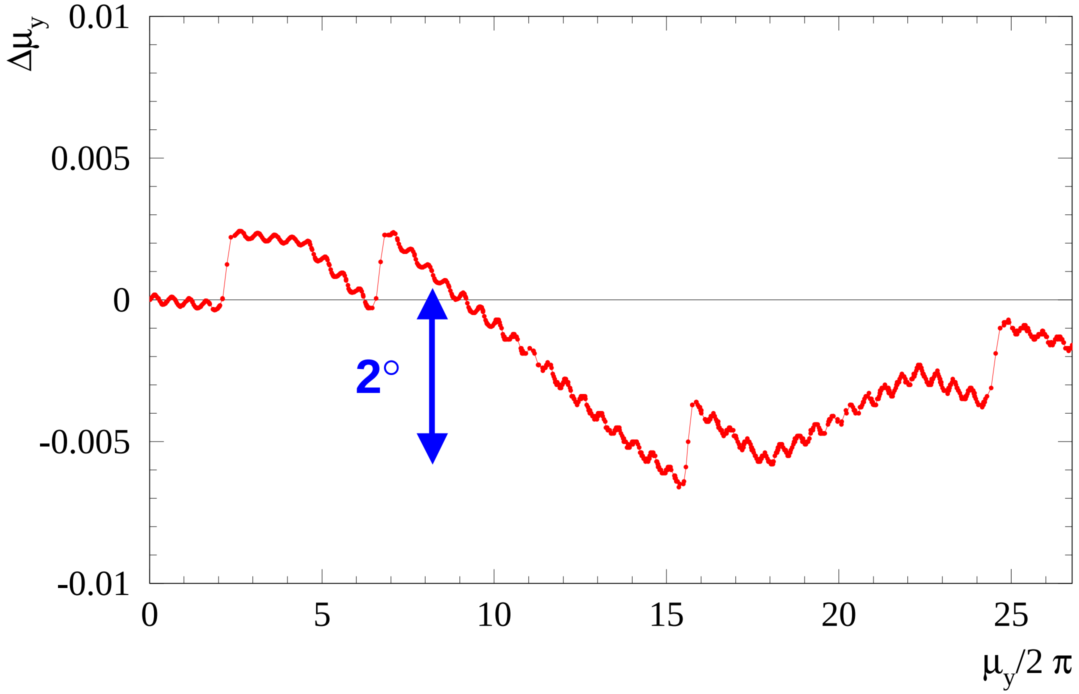




Model differences…

The main effect of the varying 17 strengths (versus 3) :

- A small phase advance 'modulation' over the ring.
- The associated β change is ~1-2 % !



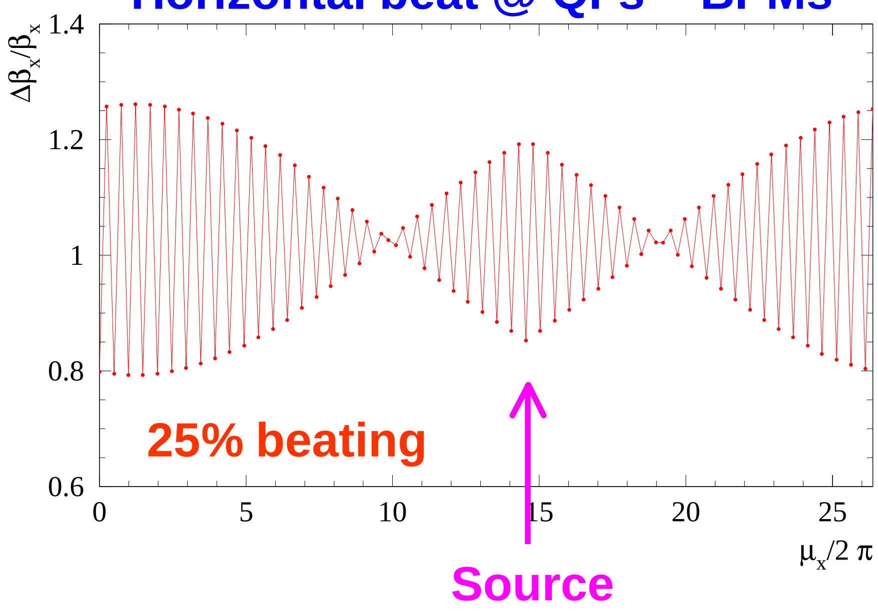
Simulation with β-beating

Can the fit **absorb** the *β*-beating signal in the BPM + corrector calibrations ?

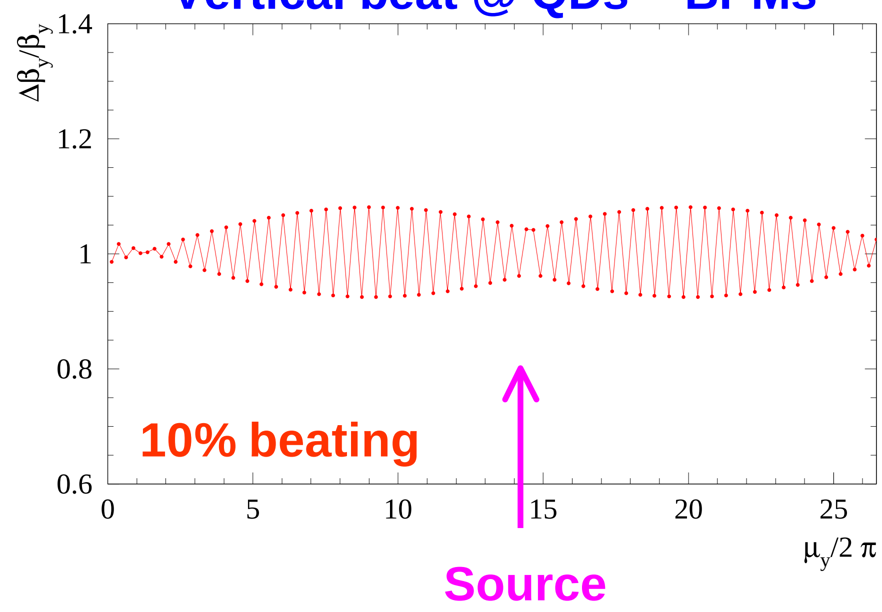
- 1 QF quadrupole mismatched.
- Fit with BPM & corr. calibrations, 17 strengths (same as for data) :
  ↔ the fit cannot properly correct the β-beat (no ‘access’ to individual quads !).

Amplitude modulation ↔ Sampling + Δμ/cell not exactly 90°

Horizontal beat @ QFs ~ BPMs



Vertical beat @ QDs ~ BPMs



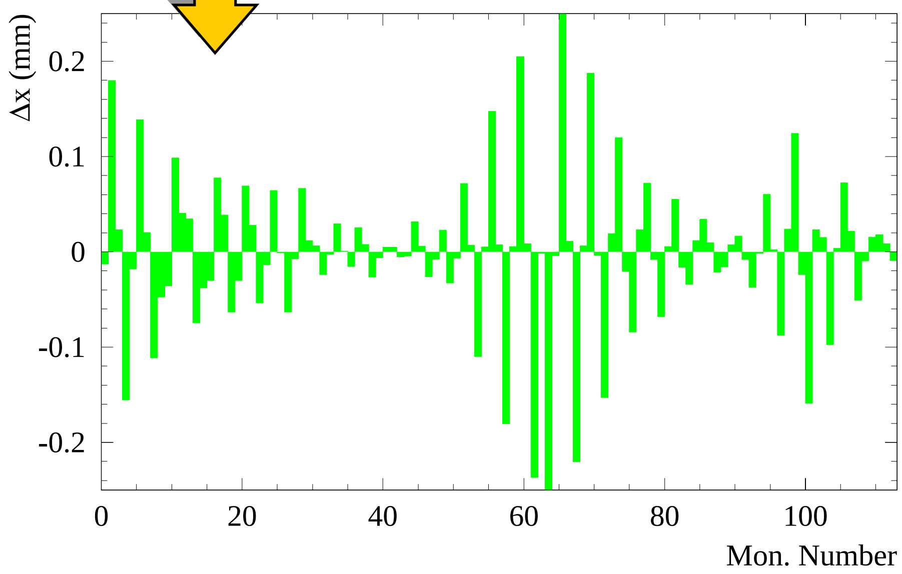
After fit with β-beating

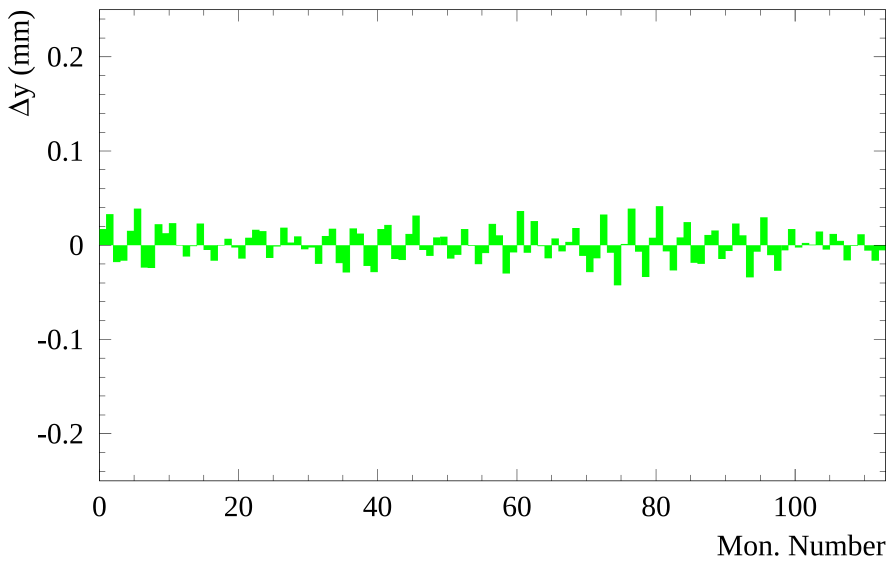
Residual difference data – model :

- H plane   85 µm
- V plane   30 µm

≈ similar to data
(10 µm noise in the simulation)

Residuals reflect β-beat,
but one needs sufficient resolution to see the structure !

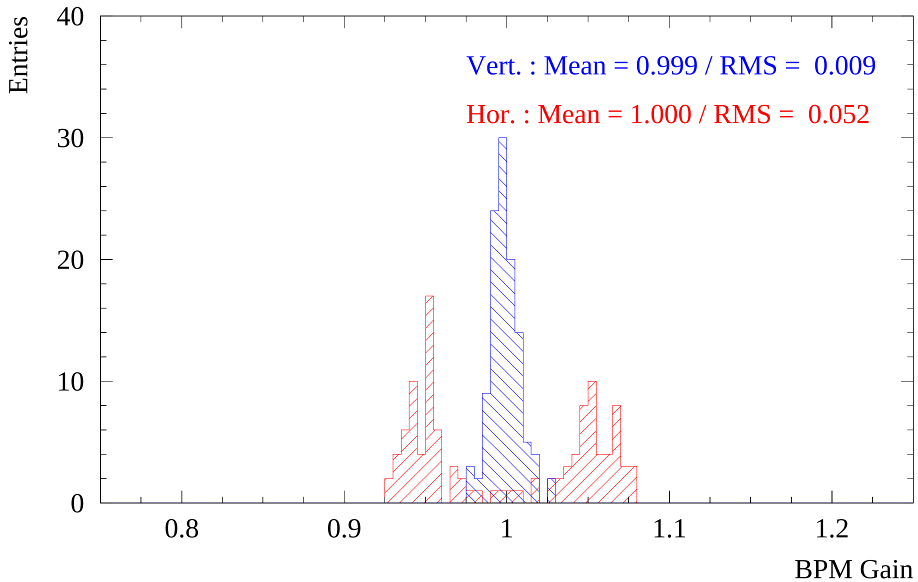


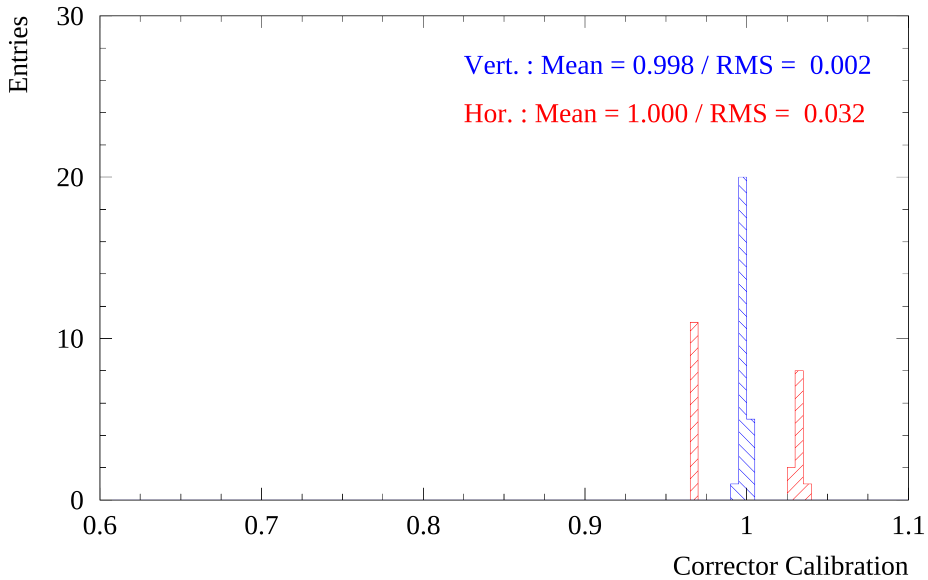


Calibration factors with β-beating

BPM & corrector calibrations :

- H plane distinct 2 peak structure – similar to data for correctors.
  → some beating 'absorbed' into calibration factors
- V plane ~ nothing visible





Beating or no beating ?

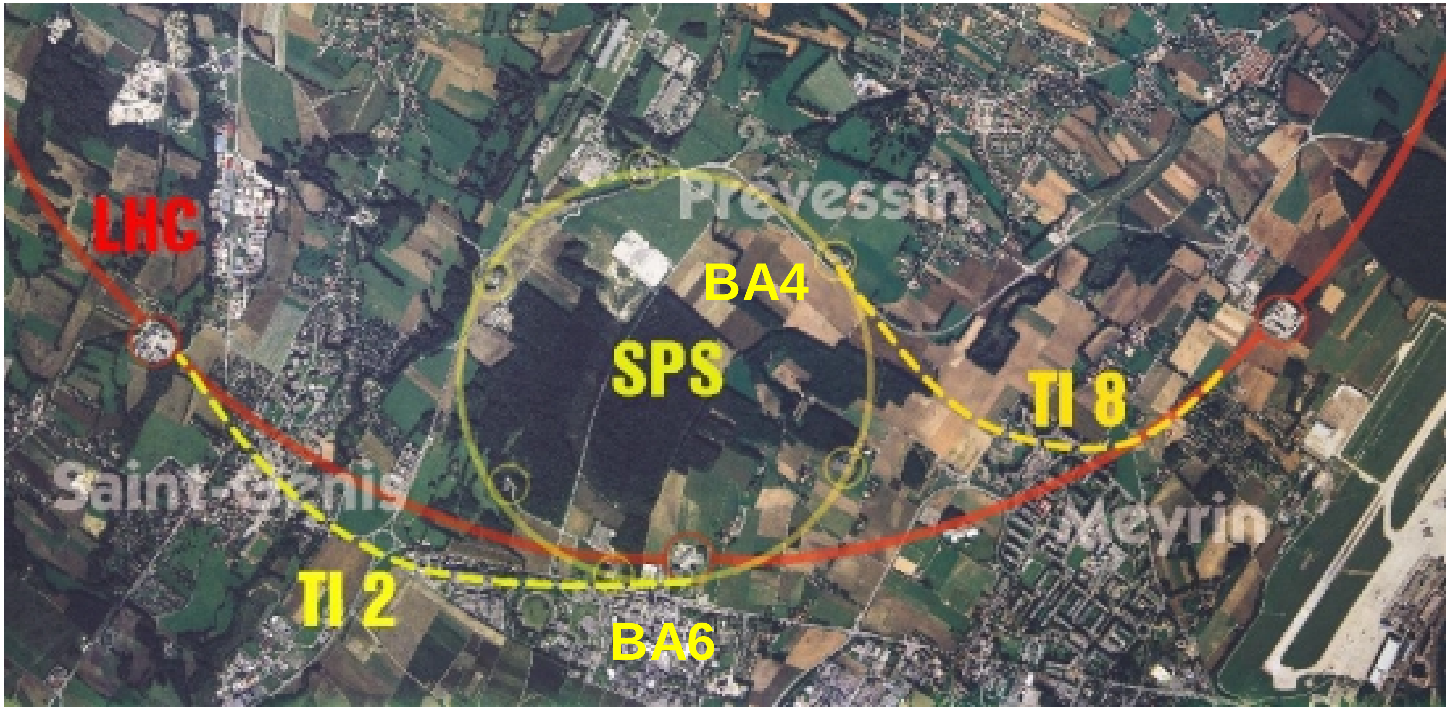
The previous example shows that :

- A fit will always do its best, but if you don't give him the correct parameters, it can artificially 'squeeze' the other parameters.
- It is important to find / guess the error source, in which case LOCO works extremely well.
- The 90° phase advance (BPMs, corr., cell) makes life difficult : poor sampling, beating can be absorbed in calibration factors.
- ~ 10% β-beating could be hidden in the data, even if the fit looks good ! Some features require further studies.

More studies and X-checks in 2002

The LHC transfer lines

- The total length of TI2 + TI8 is equivalent to one SPS.
- The aperture of the lines is small.
- We must deliver a well-matched beam to the LHC (ε budget).
  - The line optics is important (but not sufficient !).
  - Simulate LOCO on the TI8 line.



TT40 & TI8 line

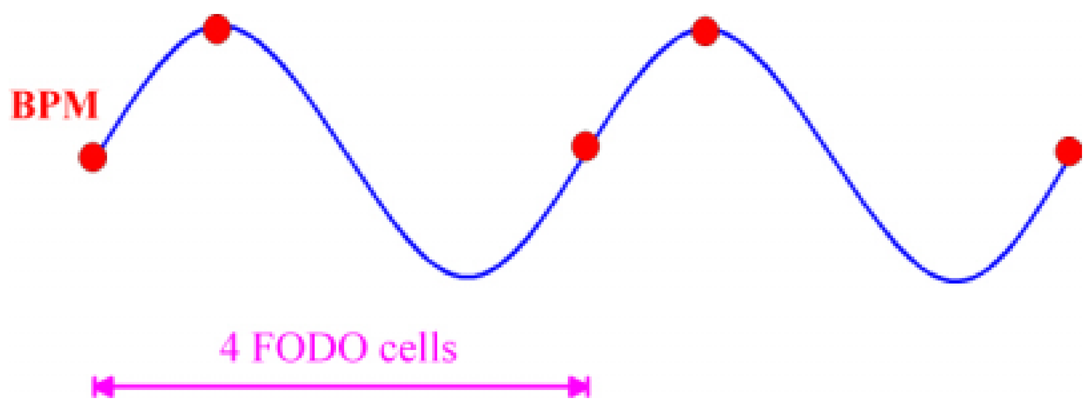
<u>Structure :</u>

- matching sections at either ends.
- 85 half cells.

Problem areas for LOCO fits : start & end of line

- First BPM and last corrector cannot be calibrated (both planes).
- First & last 2 quadrupole strengths cannot be properly determined.

insufficient sampling / too many degrees of freedom !

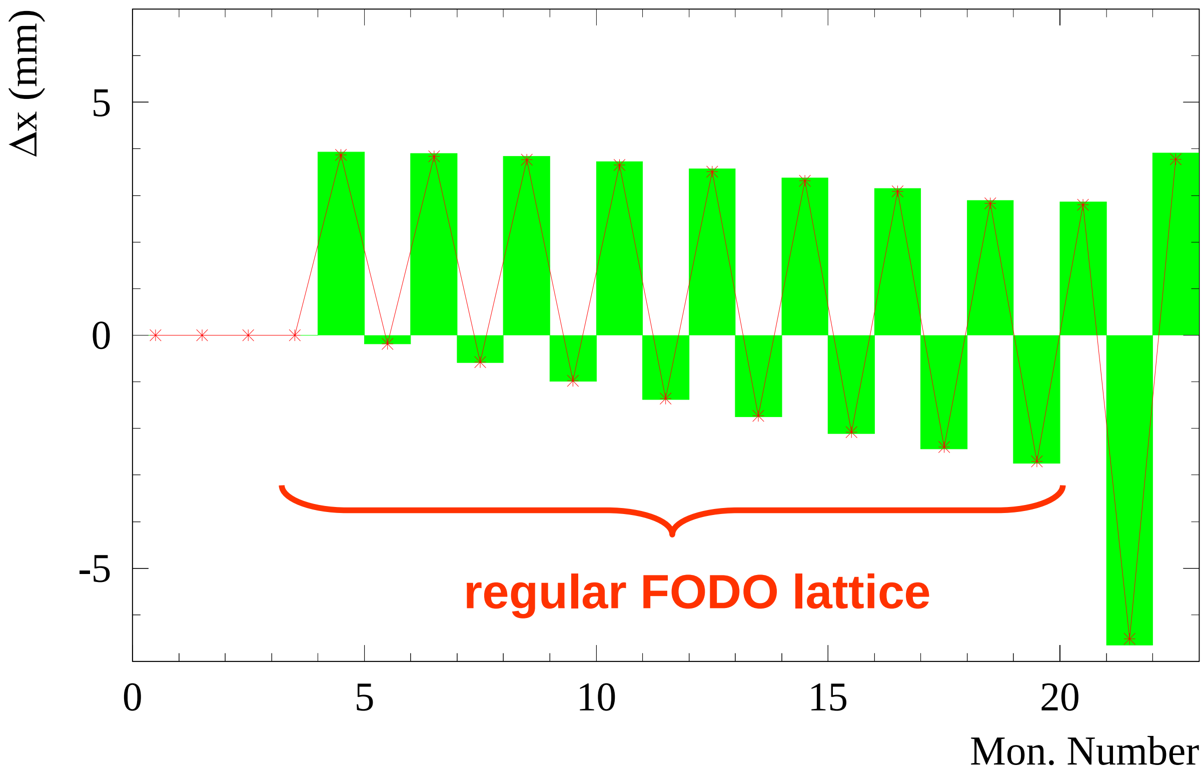


In the FODO cells, the BPM sampling is based on a 2-in-4cell layout (separate in each plane).

½ sampling of the SPS ring

Trajectory response TT40 & TI8

Response to an upstream horizontal corrector kick (+/- 20 μrad).



With a small phase advance error in the FODO lattice !

Sensitivity test on TT40 & TI8

A) Test conditions :

- nominal (perfect) optics.
- 5% BPM calibration errors.
- 1% corrector calibration errors.
- 50 μm monitor noise + 50 μm 'other' noise (ripple)
- to improve the sampling (+50%) the profile monitors were added to BPMs (same errors & noise).
- FIT : BPM & corr. calibrations and all possible quad strengths.

B) Test conditions : same as A) but

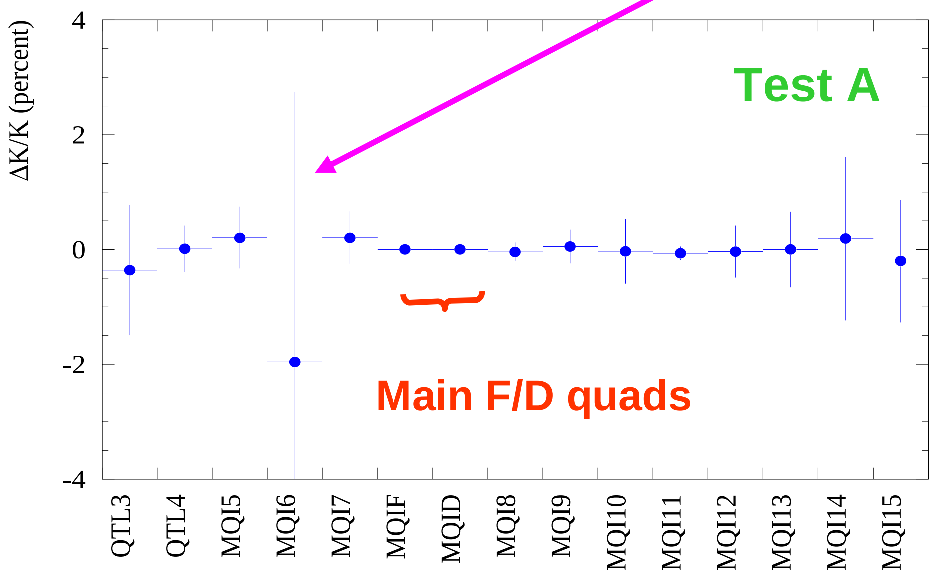
- 1% BPM calibration error, calibration fixed !
  - → adds a small error/noise of ~ 20 μm.
- 0.1% corrector error, calibration fixed !
  - → adds a negligible error !

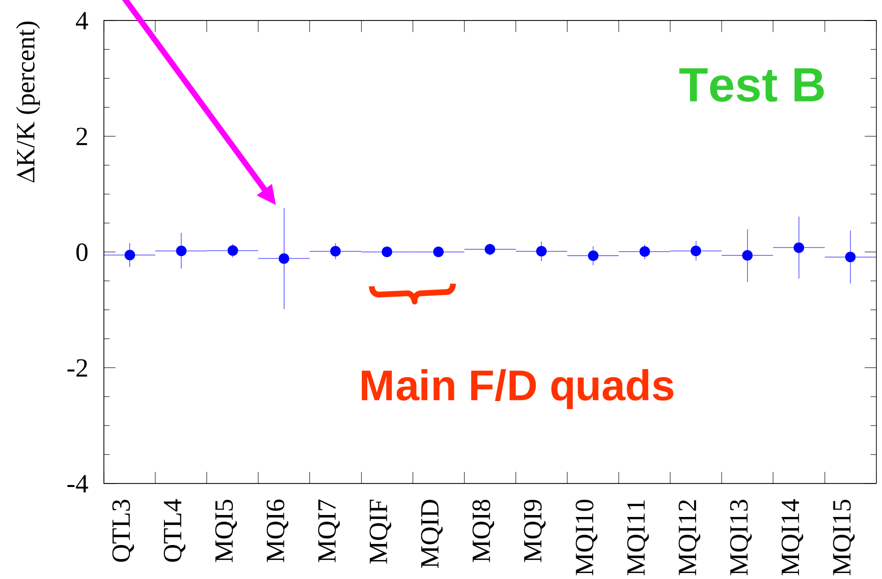
What are the reconstructed quadrupole gradient errors under such conditions ?

Reconstructed TT40/TI8 strengths

- ➢ Reconstructed strength errors → define the sensitivity !
- ➢ The errors are reduced significantly if the BPM scale is known…
  ↔ # of degrees of freedom versus sampling in fit !

Unfavorable $\Delta\mu$ with respect to upstream H corr.

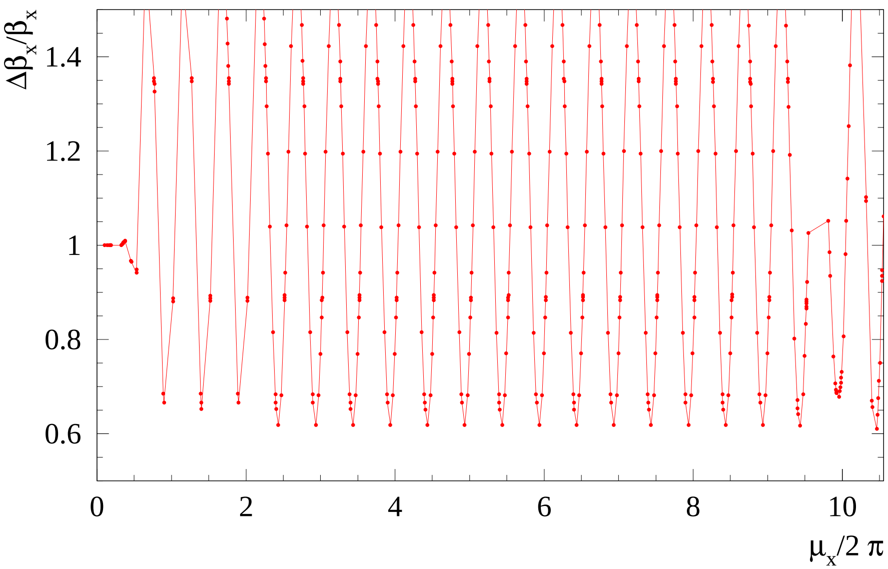




Corrected line optics

Careless correction :

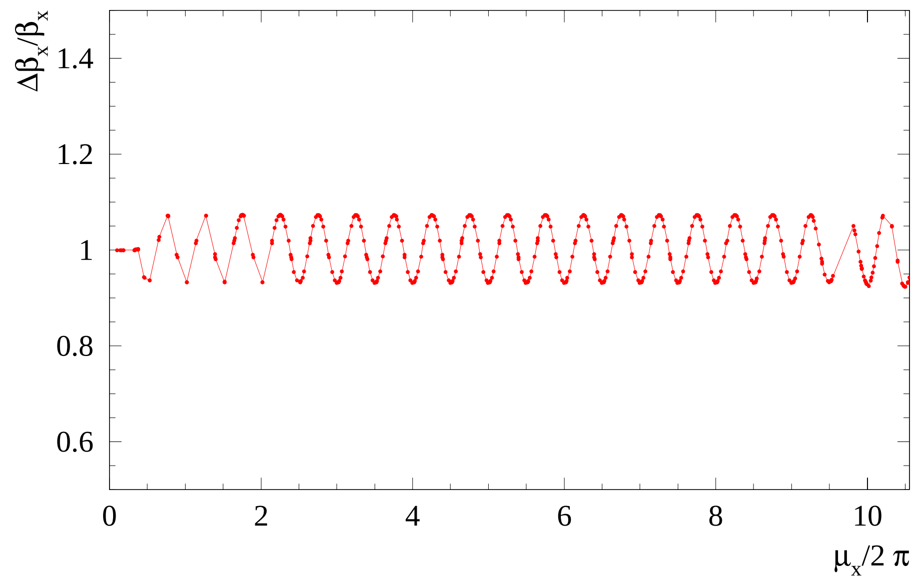
- MQI6 quad trimmed, ignoring the poor accuracy…
- Huge beating added (!!) to a perfect line optics !



Careful correction :

- Quads with poor accuracy ignored.
- Adds moderate beating ~ 5-10%

  ↔ limit on β-beat correction due to measurement accuracy…



Conclusions

- Orbit response - LOCO
  - program was adapted and works well,although matrix sizes become large for SPS and LHC.
  - provides calibration of monitors and correctors.
  - interpretation of results can be delicate – particularly with phase advances close to 90°.

- SPS tests in 2002
  - re-measure with more correctors, check stability of results.
  - measurements with controlled β-beating.
  - X-check with K-modulation (windings installed around some quads in point 5) and phase advance measurements.

- TI lines
  - LOCO is very good for main (FODO) quads.
  - At the limit for the matching quads with all parameters free !
    $\rightarrow$ good BPM & corrector calibrations are an asset !