Linear Imperfections

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Introduction

Imperfection - sources

Orbit perturbations

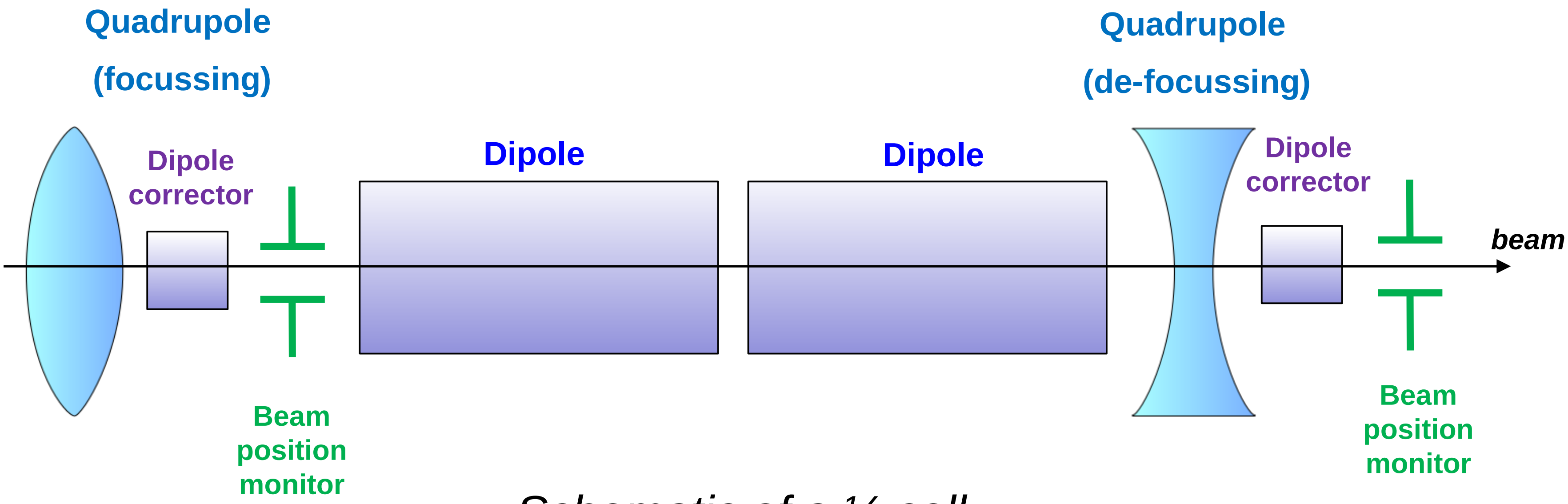
Optics perturbations

Coupling between planes

Summary

Accelerator lattice cell

- An accelerator is usually build using a number of basic 'cells'.
- The cell layouts of an accelerator come in many subtle variants.
- For today we consider a simple FODO cell containing:
  - **Dipole magnets** to bend the beams,
  - **Quadrupole magnets** to focus the beams,
  - **Beam position monitors** (BPM) to measure the beam position,
  - **Small dipole corrector magnets** for beam steering.



Schematic of a ½ cell

Dipole magnet

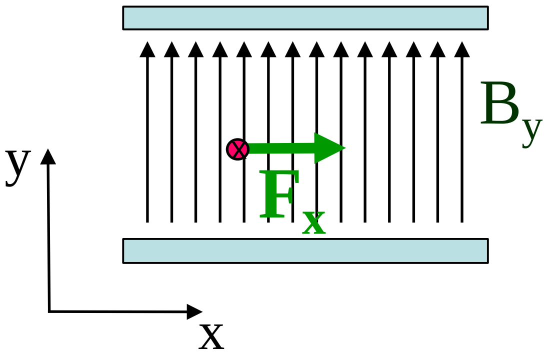
- The dipole has two magnetic poles and generates a **homogeneous field** providing a constant force on all beam particles – used to **deflect** the beam.
  - A dipole corrector is just a small version of such a magnet, dedicated to steer the beam as we will see later.

Lorentz force:

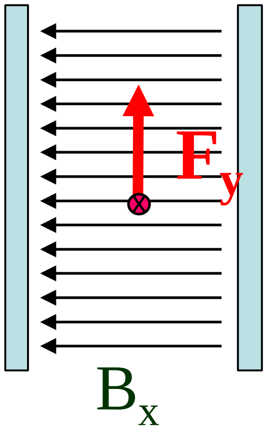
$$F = q\vec{v} \times \vec{B}$$

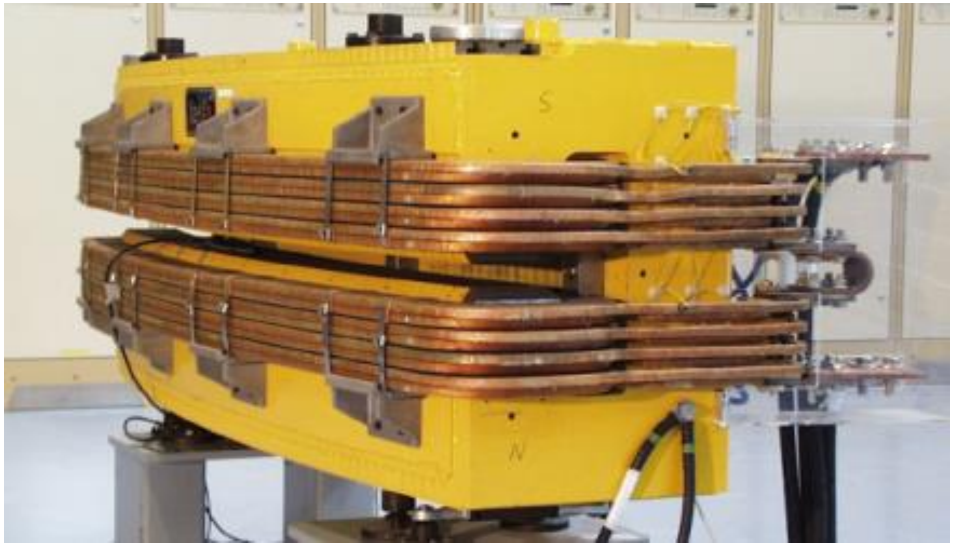
orthogonal to the speed and magnetic field directions

Horizontal deflection



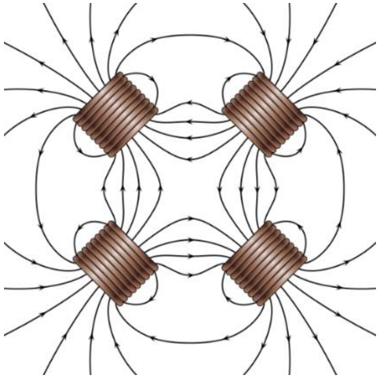
Vertical deflection

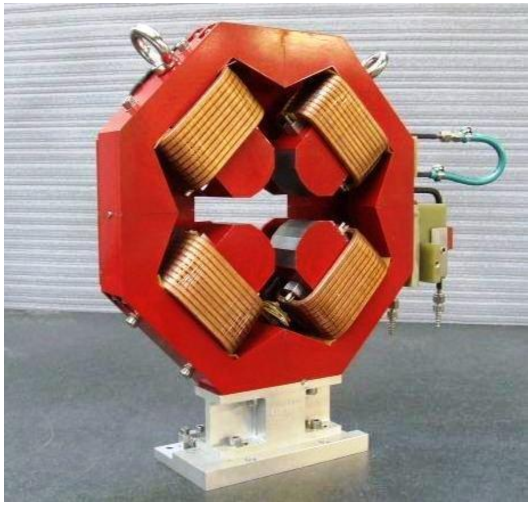


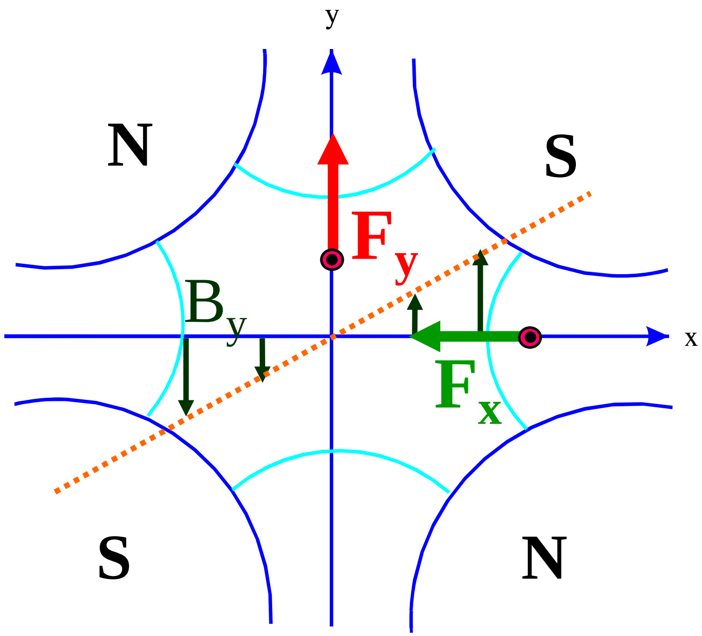


Quadrupole magnet

- A quadrupole has 4 magnetic poles.
- A quadrupole provides a field (force) that **increases linearly** with the distance to the quadrupole center – provides **focussing** of the beam.
  - Similar to an optical lens, except that a quadrupole is focussing in one plane, defocussing in the other plane.







$$F_y = k\,y$$

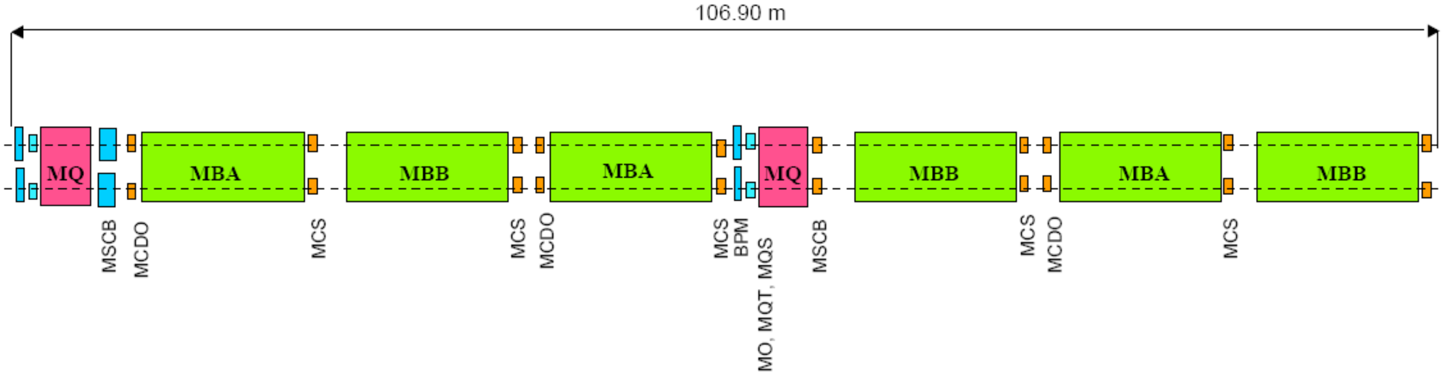
Force pushes the particle away from the center → **defocussing**

$$F_x = -k\,x$$

Force pushes the particle towards the center → **focussing**

A realistic lattice - LHC

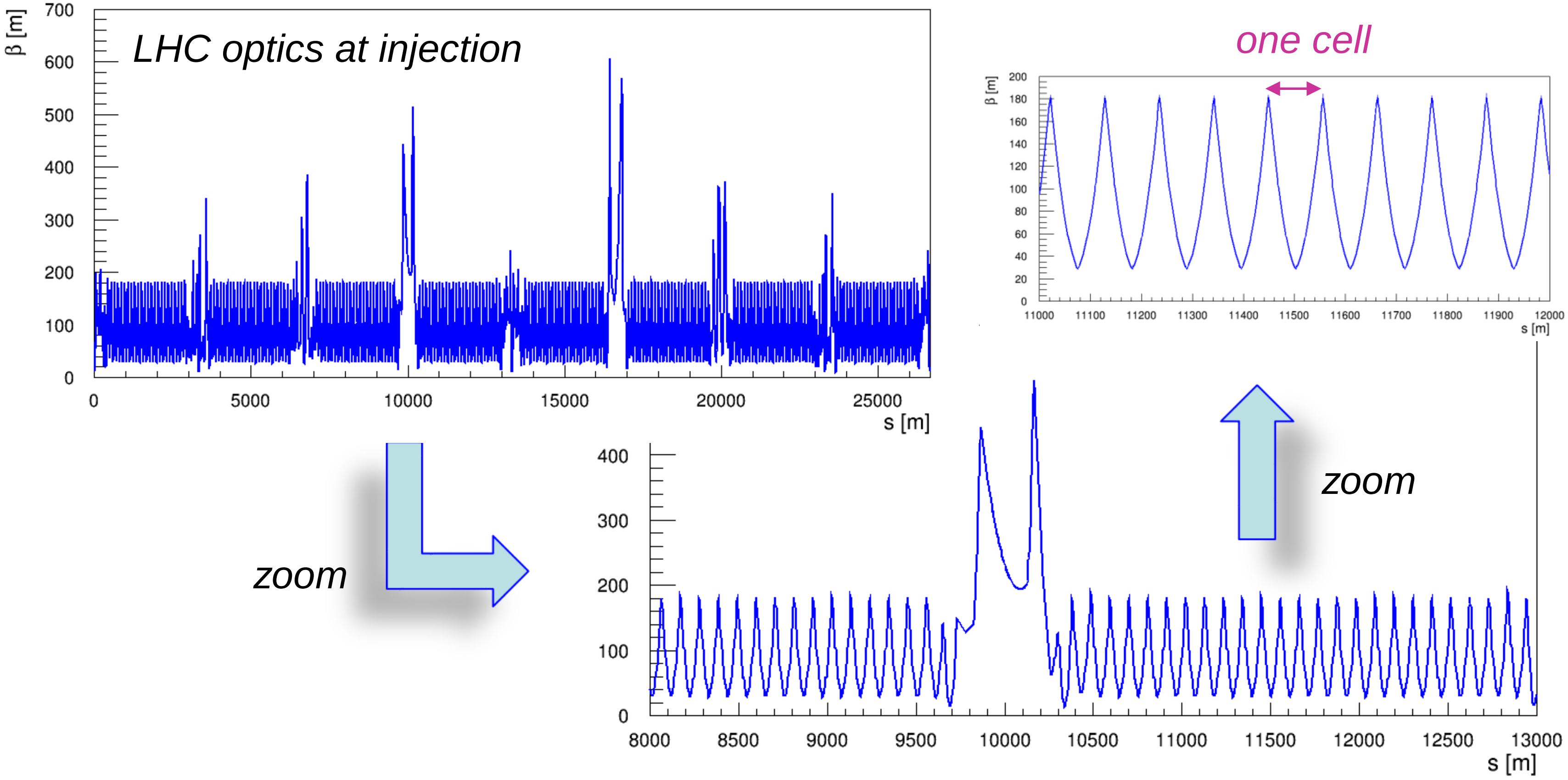
- The LHC arc section are equipped with 107 m long F0D0 cells. Besides our 3 main elements the LHC cell is equipped with other correction (trim) magnets.



- **MB: main dipole**
- **MQ: main quadrupole**
- MQT: trim quadrupole
- MQS: skew trim quadrupole
- MO: lattice octupole (Landau damping)
- **MSCB:** sextupole + **orbit corrector dipole**
- MCS: Spool piece sextupole
- MCDO: Spool piece 8 / 10 pole
- **BPM: Beam position monitor**

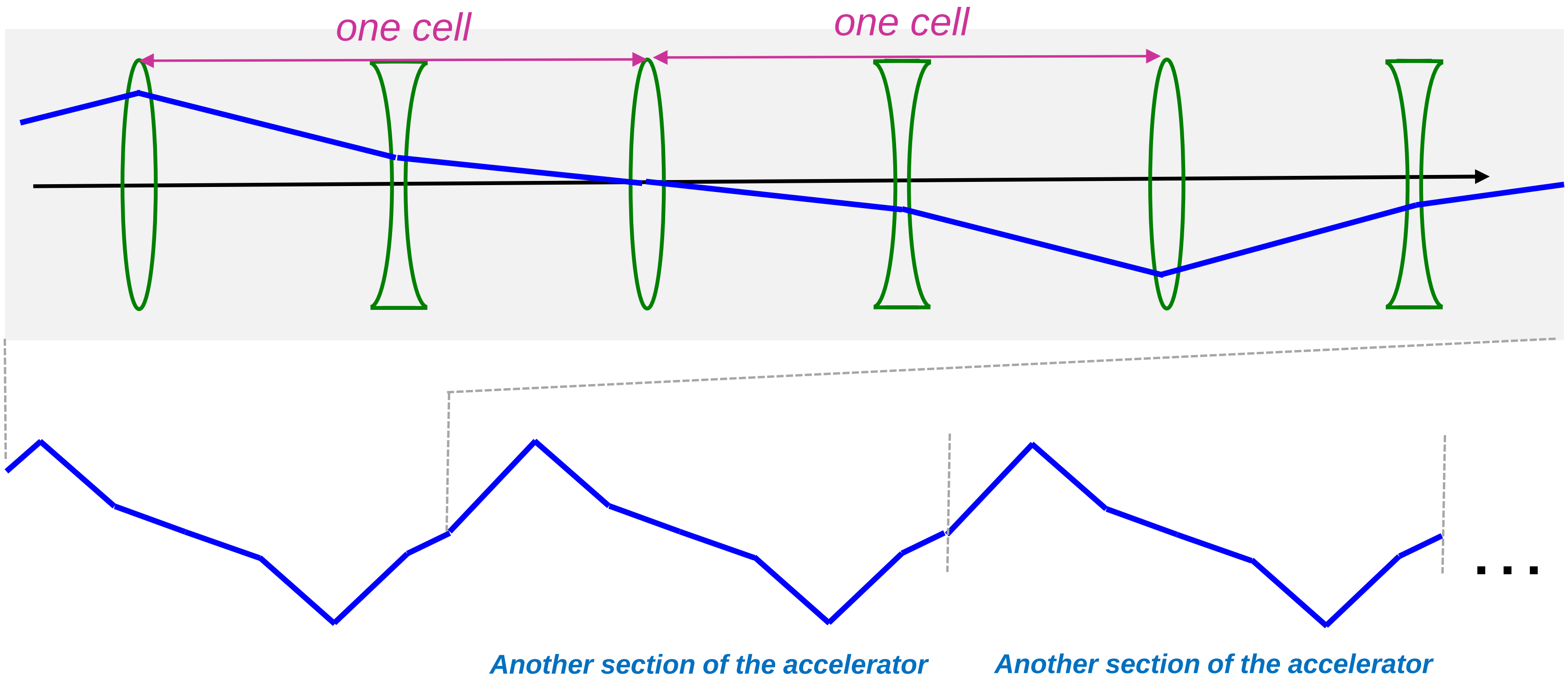
Recap on beam optics

- There are a few quantities related to a beam optics in a circular accelerator that we will need for the lecture:
  - The **betatron function** (**β**) that defines the beam envelope,
    - **Beam size / envelope is proportional to $\sqrt{\beta}$**
  - The **betatron phase advance** (**μ**) that defines the phase of an oscillation.



Recap on beam optics

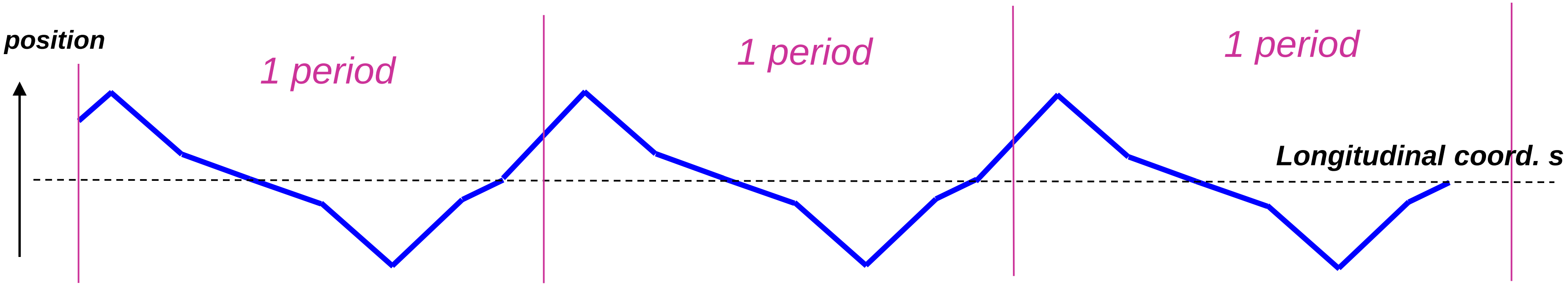
- Consider a particle moving in a section of the accelerator lattice. The focussing elements make it bounce back and forth.



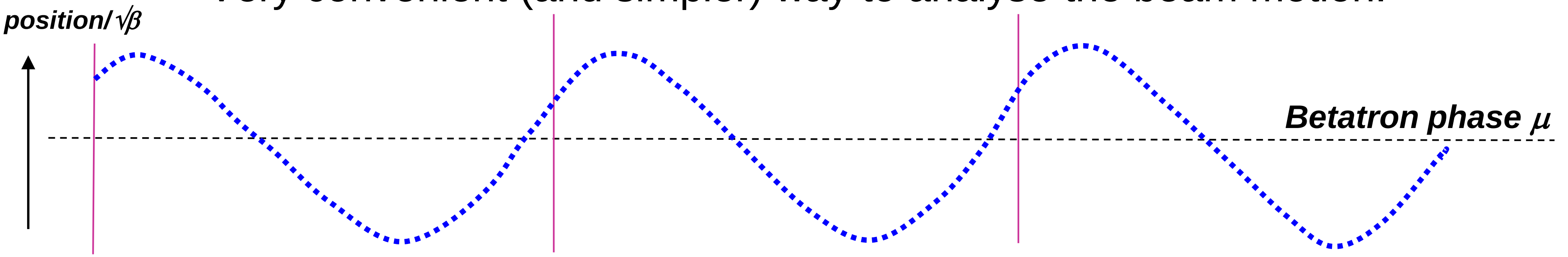
- Does this not look a bit like a periodic oscillation? This is called a betatron oscillation.

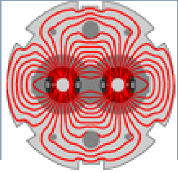
Recap on beam optics for pedestrians

- The number of oscillation periods for one turn of the machine is called the machine **tune** (**Q**) or **betatron tune**.
  - In this **example** Q is around 2.75 – 2 periods and ¾ of a period.



- It is possible to change the **coordinates** (from the longitudinal position in meters to the betatron phase advance in degrees) and transform this ‘rocky’ oscillation into a pure sinusoidal oscillation.
  - Very convenient (and simpler) way to analyse the beam motion.





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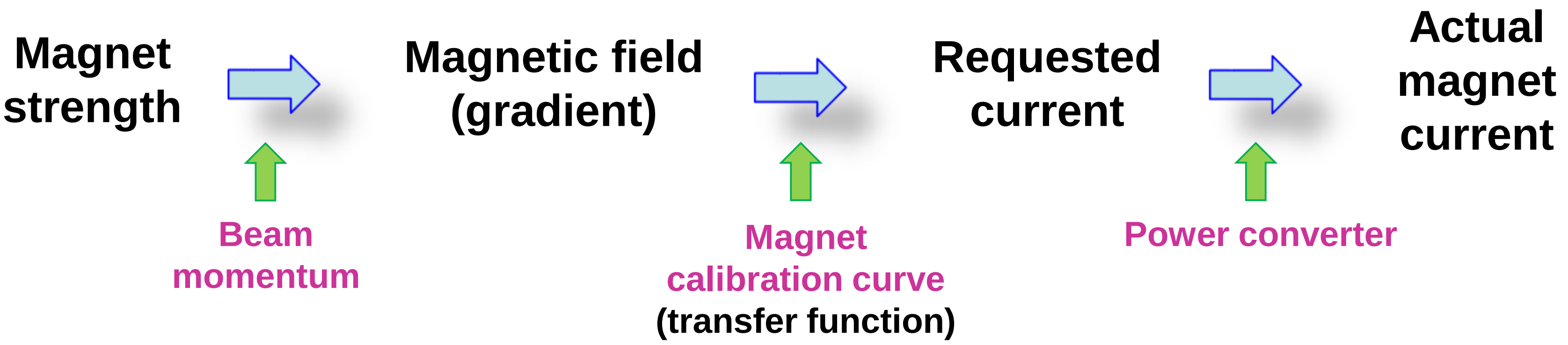
From model to reality - fields

- The **physical units** of the machine model defined by the accelerator physicist must be converted into **magnetic fields** and eventually into **currents** for the power converters that feed the magnet circuits.
- **Imperfections** (= errors) in the real accelerator optics can be introduced by **uncertainties** or **errors** on:
  - Beam momentum, magnet calibrations and power converter regulation.



Magnet strength

Magnetic field (gradient)

Requested current

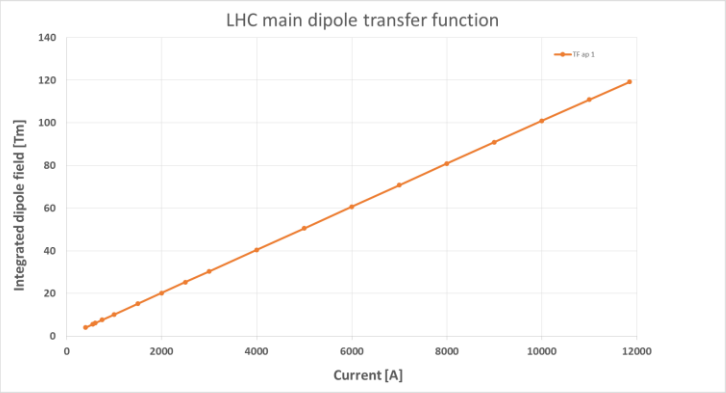
Actual magnet current

Beam momentum

Magnet calibration curve (transfer function)

Power converter

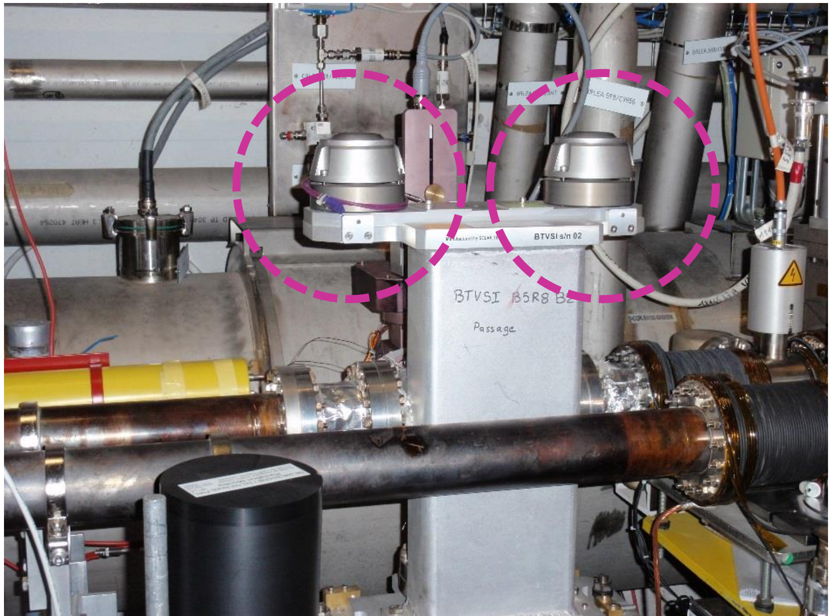
Example of the LHC main dipole calibration curve

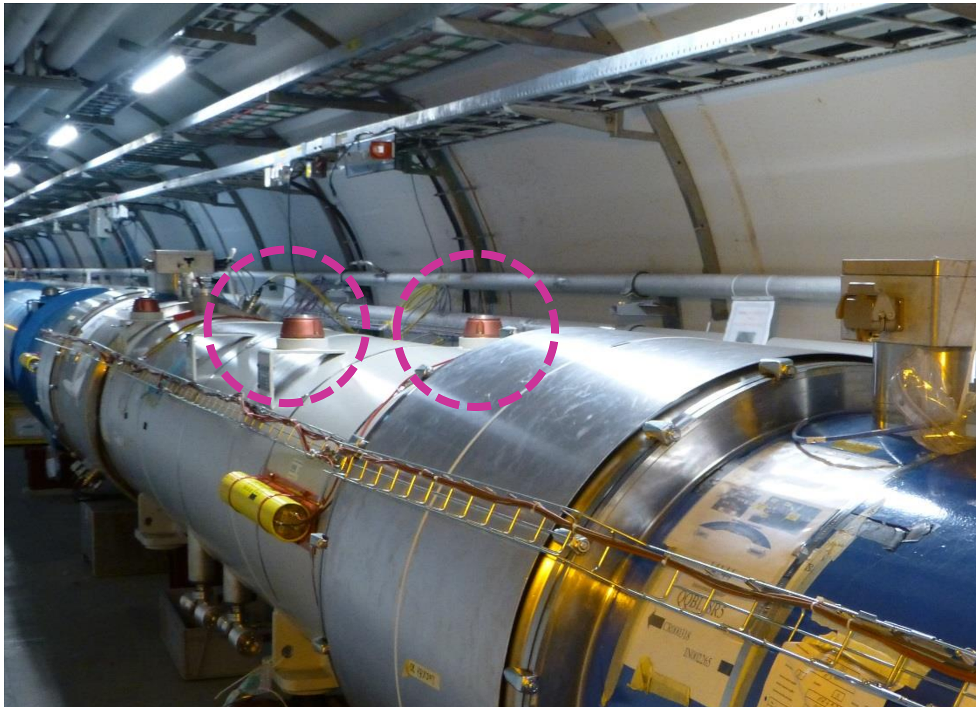


From the lab to the tunnel

From model to reality - alignment

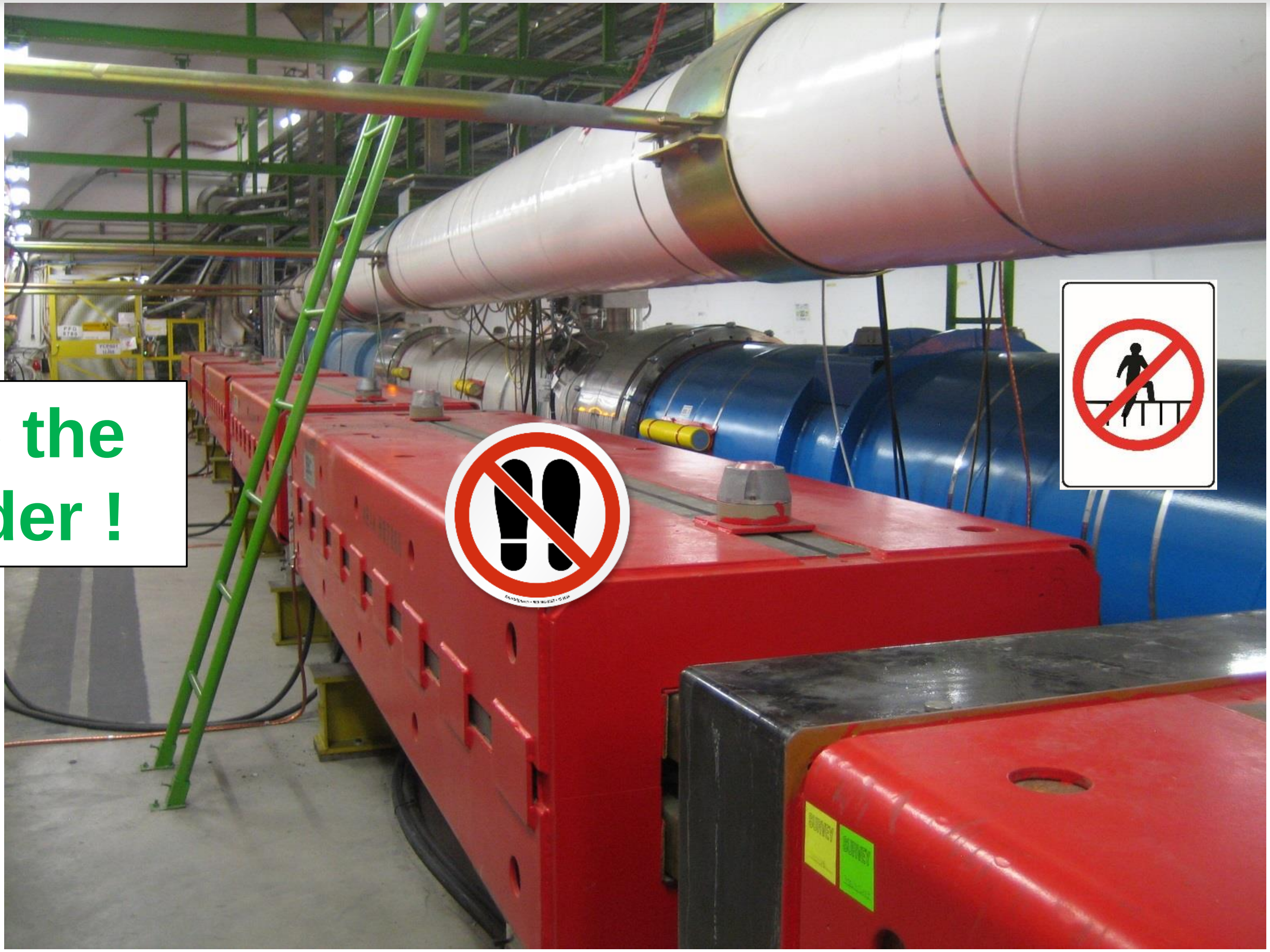
- To ensure that the accelerator elements are in the correct position the alignment must be precise – to the level of micrometres for CLIC !
  - At the CERN hadron machines we aim for accuracies of around **0.1 mm**.
- The alignment process implies:
  - Precise measurements of the magnetic axis in the laboratory with reference to the element alignment markers used by the survey group.
  - Precise in-situ alignment (position and angle) of the element in the tunnel.
- **Alignment errors** are a common source of **imperfections**.



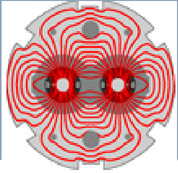


A good attitude in the tunnel

Please remember that accelerator components in the CERN tunnels are carefully aligned – please treat with respect !



Use the ladder !



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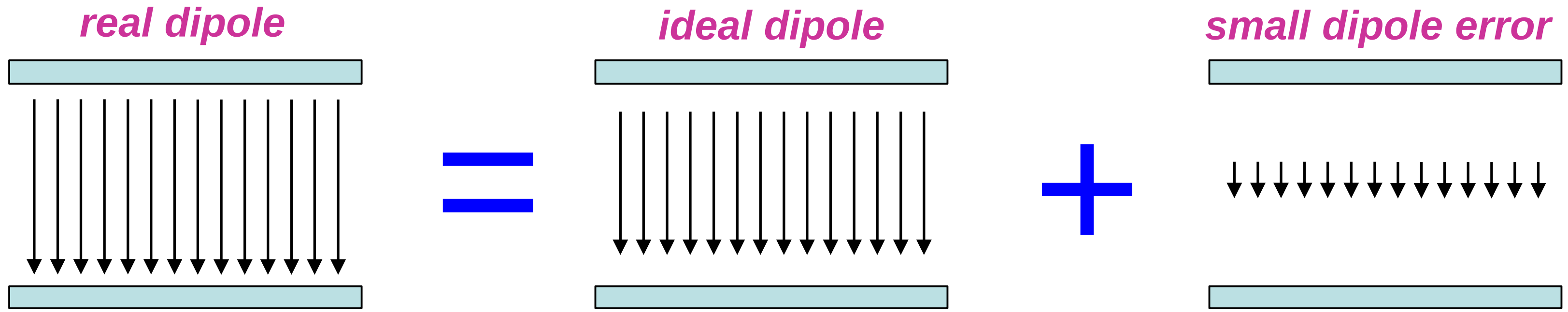
Imperfection – undesired deflection

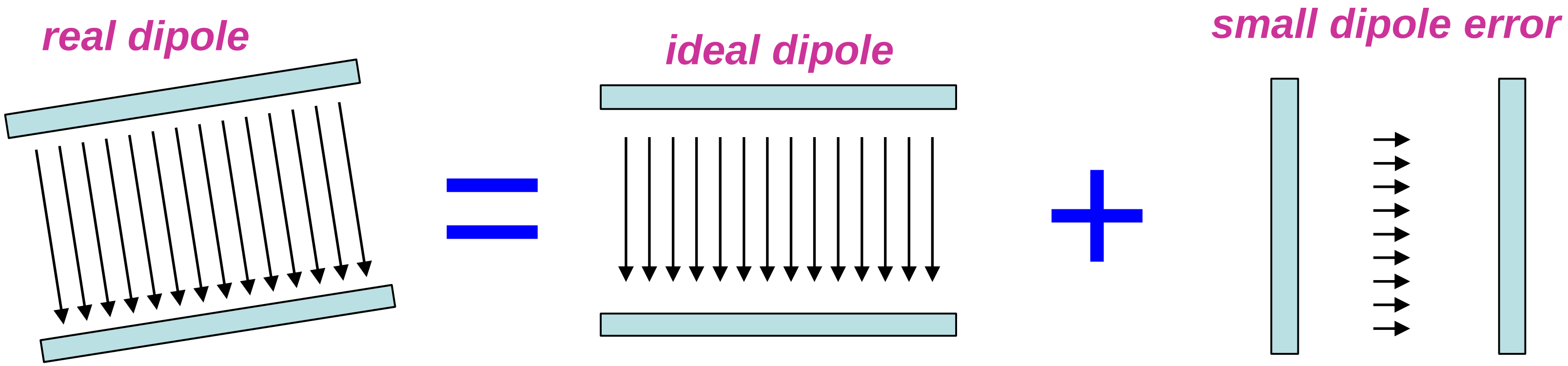
- The presence of an **unintended deflection** along the path of the beam is a first category of imperfections.
- This case is also in general the first one that is encountered when beam is first injected…
- The **dipole orbit corrector** is added to the cell to **compensate** the effect of **unintended deflections**.
  - With the orbit corrector we can generate a deflection of opposite sign and amplitude that compensates locally the imperfection.
- How can an **unintended deflection** appear?

Unintended deflection

- The first source is a field error (deflection error) of a dipole magnet.
- This can be due to an **error** in the **magnet current** or in the **calibration table** (measurement accuracy etc).
  - The imperfect dipole can be expressed as a perfect one + a small error.



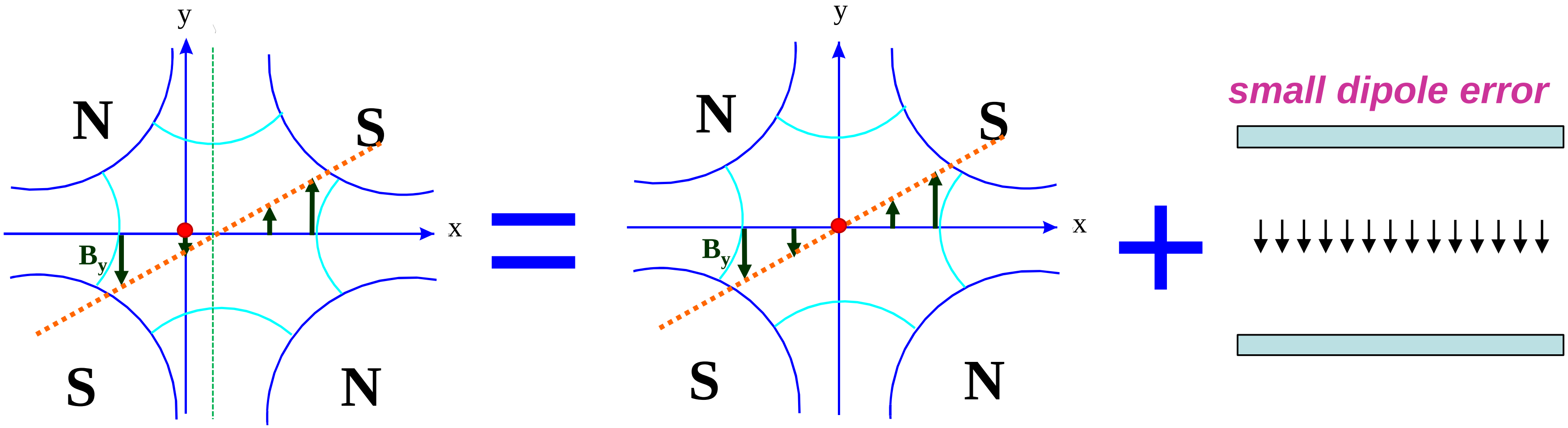
- A small rotation (misalignment) of a dipole magnet has the same effect, but in the other plane.



Unintended deflection

- The second source is a misalignment of a quadupole magnet.
  - The misaligned quadrupole can be represented as a perfectly aligned quadrupole plus a small deflection.

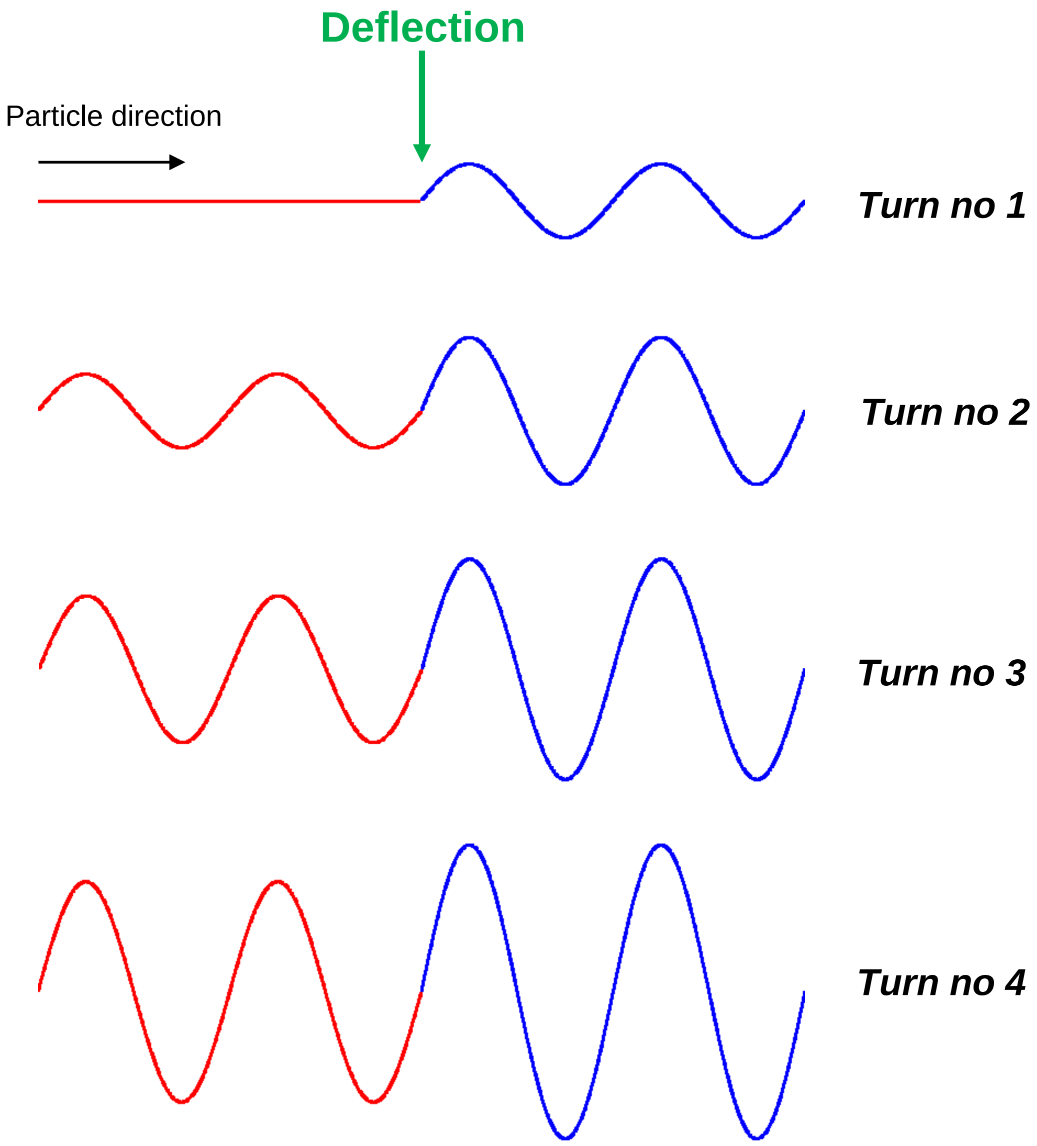
real quadrupole *ideal quadrupole* *small dipole error*



Non-zero magnetic field on the beam axis !

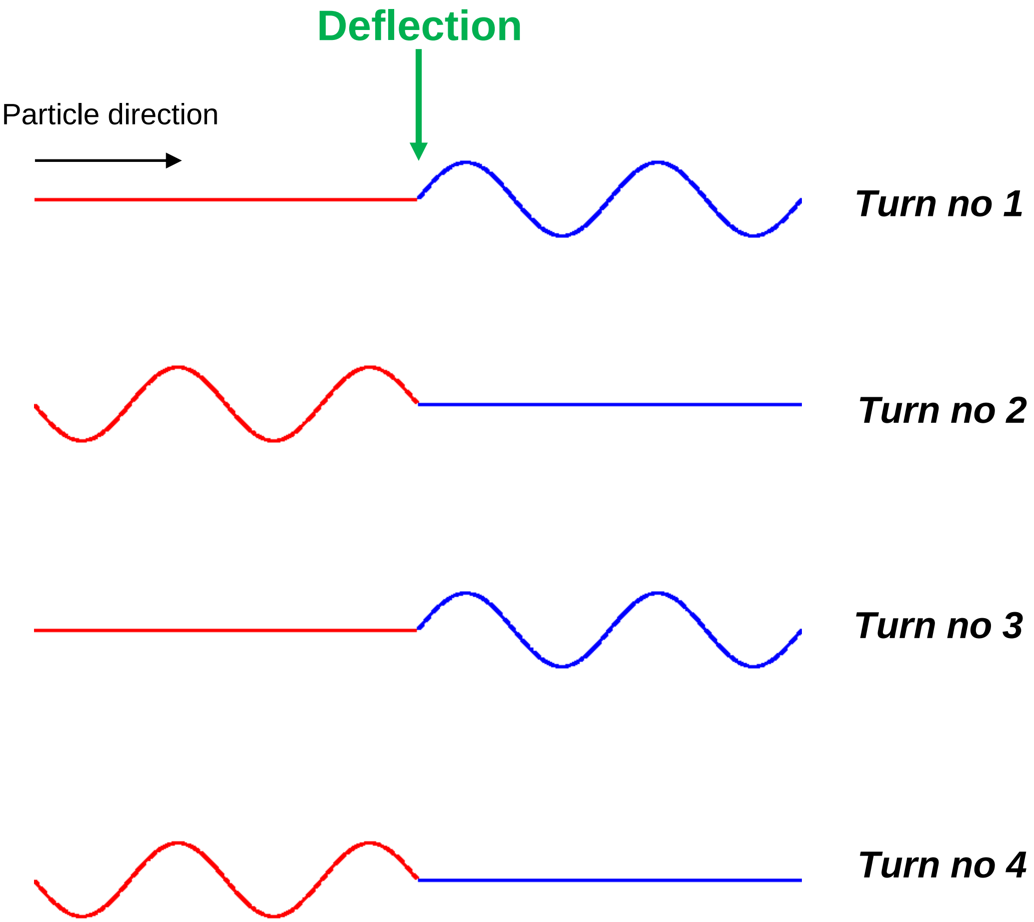
No magnetic field on the beam axis

Effect of a deflection



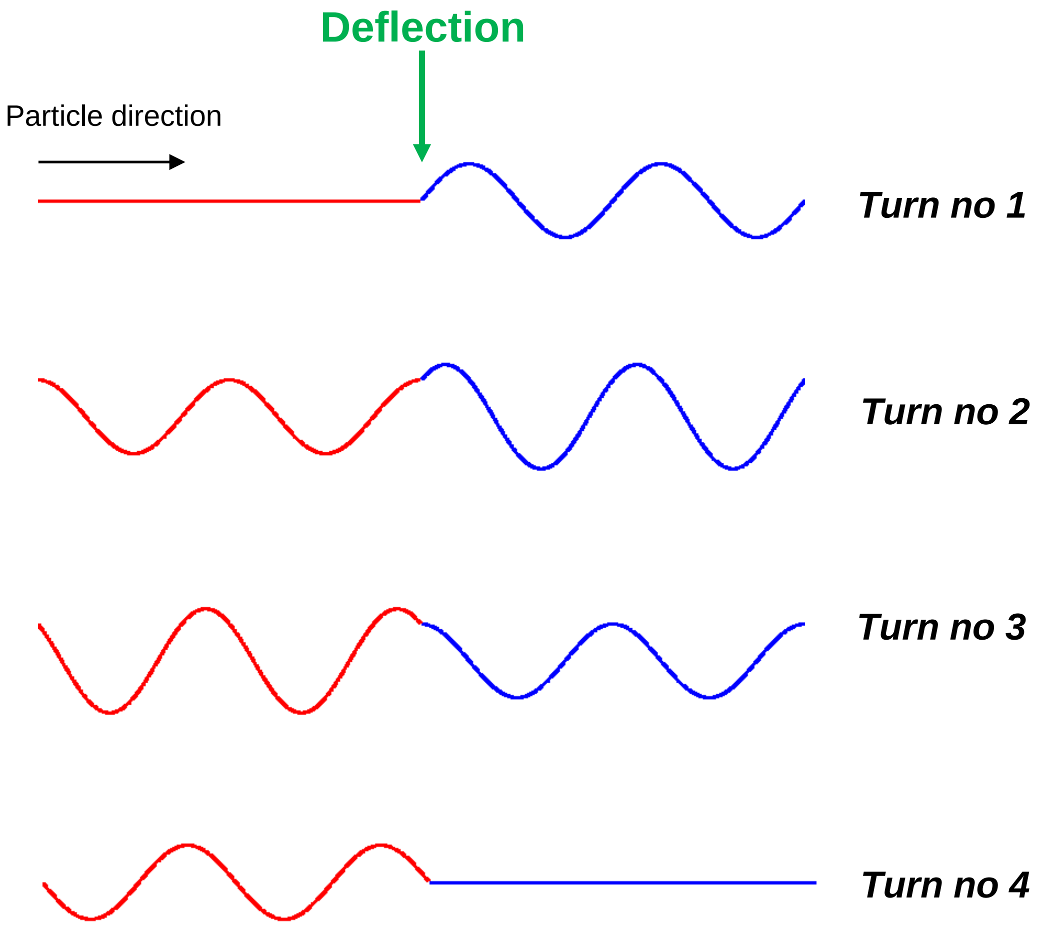
- We set the machine tune to an integer value:
  - Q = n ∈N
- When the tune is an integer number, **the deflections add up on every turn** !
  - The amplitudes diverge, the particles do not stay within the accelerator vacuum chamber.
- We just encountered our first **resonance** – the integer resonance that occurs when Q = n ∈N

Effect of a deflection



- We set the machine tune to a half integer value:
  - Q = n+0.5, n ∈N
- For half integer tune values, **the deflections compensate on every other turn** !
  - The amplitudes are stable.
- This looks like a much better working point for Q!

Effect of a deflection

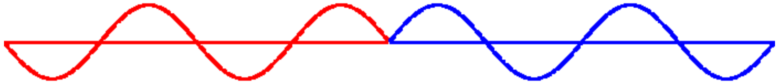


- We set the machine tune to a quarter integer value:
  - Q = n+0.25, n ∈N
- For quarter tune values, **the deflections compensate every four turns** !
  - The amplitudes are stable.
- Also a reasonable working point for Q!

Many turns reveal something

- Let's plot the 50 first turns on top of each other and change Q.
  - All plots are on the same scale

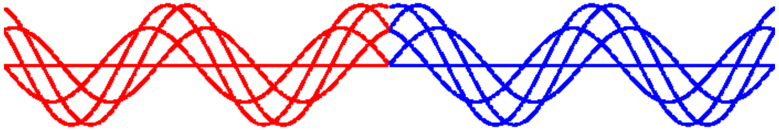
$Q = n + 0.5$



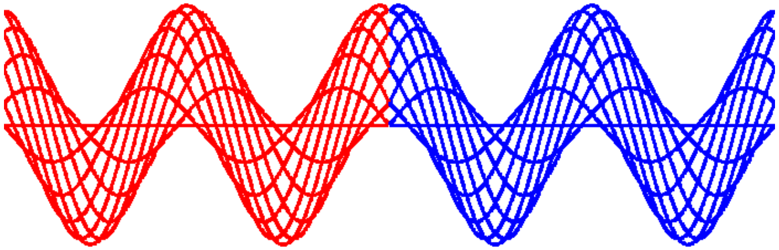
$Q = n + 0.4$

$Q = n + 0.3$

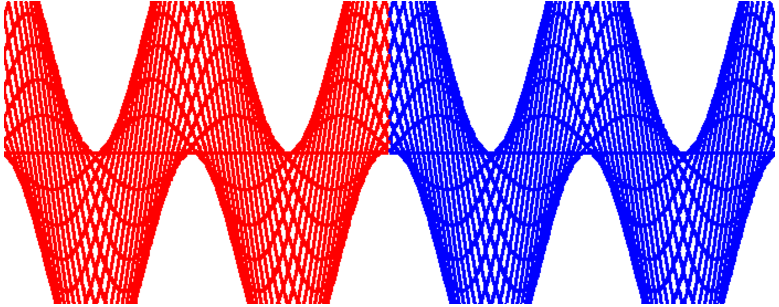
$Q = n + 0.2$



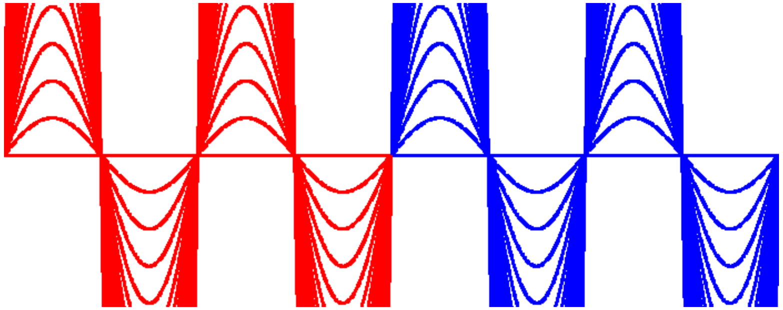
$Q = n + 0.1$



$Q = n + 0.05$



$Q = n$



- The particles **oscillate around a stable mean value** ($Q \neq n$)!
- The amplitude diverges as we approach Q = n → integer resonance

The closed orbit

- The stable mean value around which the particles oscillate is called the **closed orbit**.
  - Every particle in the beam oscillates around the closed orbit.
  - As we have seen the closed orbit ‘does not exist’ when the tune is an integer value.
- The general expression of the **closed orbit x(s)** in the presence of a **deflection θ** is:

amplitude modulated by the envelope β

oscillating term

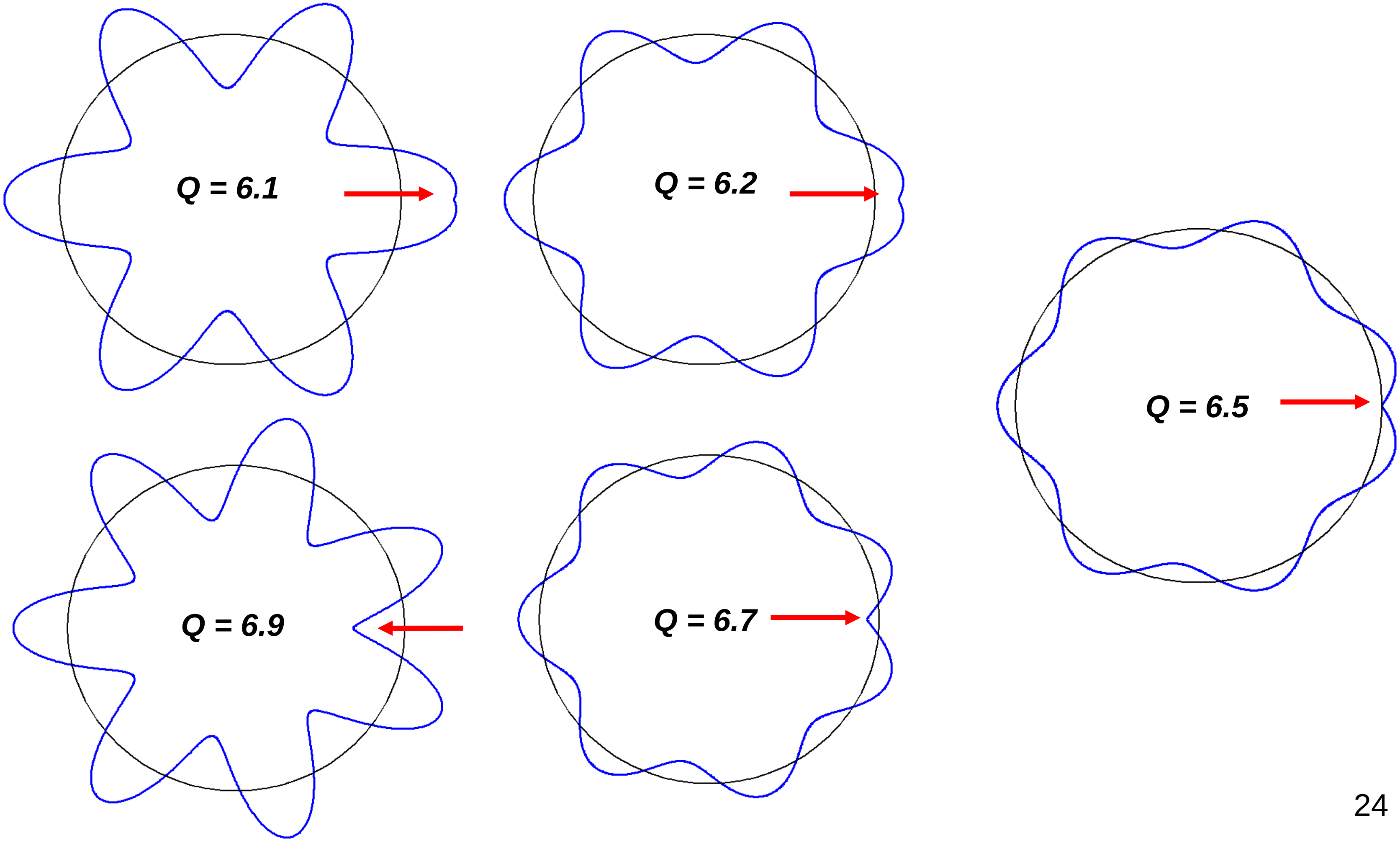
kink at the location of the deflection

$$x(s) = \frac{\sqrt{\beta(s)\beta_\theta}\cos(|\mu(s)-\mu_\theta|-\pi Q)}{2\sin(\pi Q)}\theta$$

divergence for Q = n

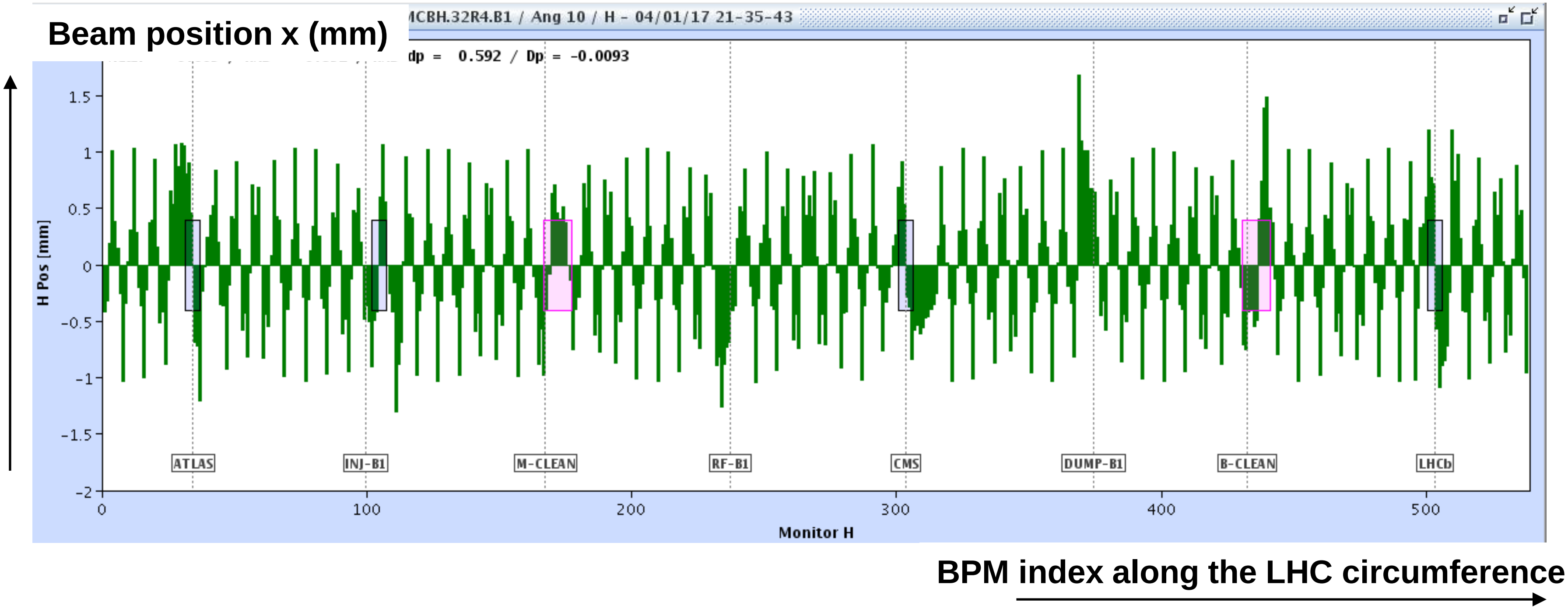
Closed orbit example

- ☐ Example of the horizontal closed orbit for a machine with tune Q = 6 + q.
- ☐ The **kink at the location of the deflection** (**→**) can be used to localize the deflection (if it is not known) → can be used for orbit correction.



A deflection at the LHC

- In the example below for the 26.7km long LHC, there is **one undesired deflection**, leading to a perturbed closed orbit.



Beam position x (mm)

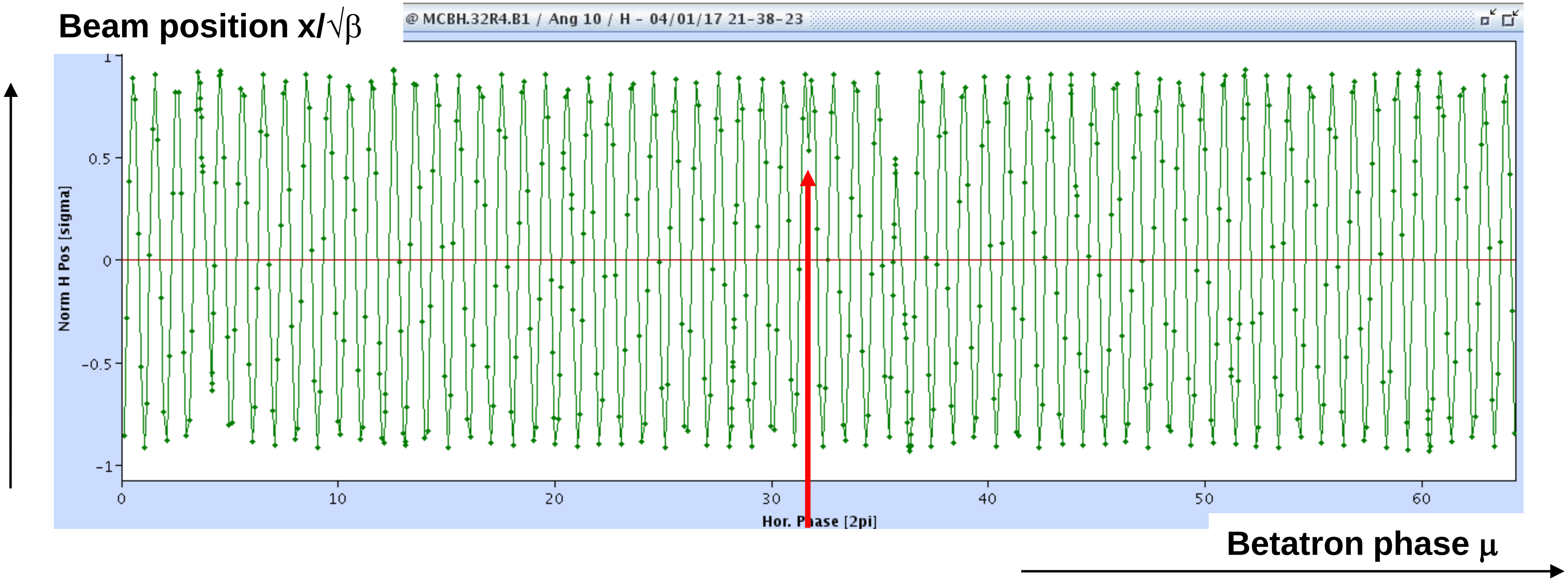
BPM index along the LHC circumference

Where is the location of the deflection?

A deflection at the LHC

- To make our life easier we divide the position by √β(s) and replace the BPM index by its phase μ(s).

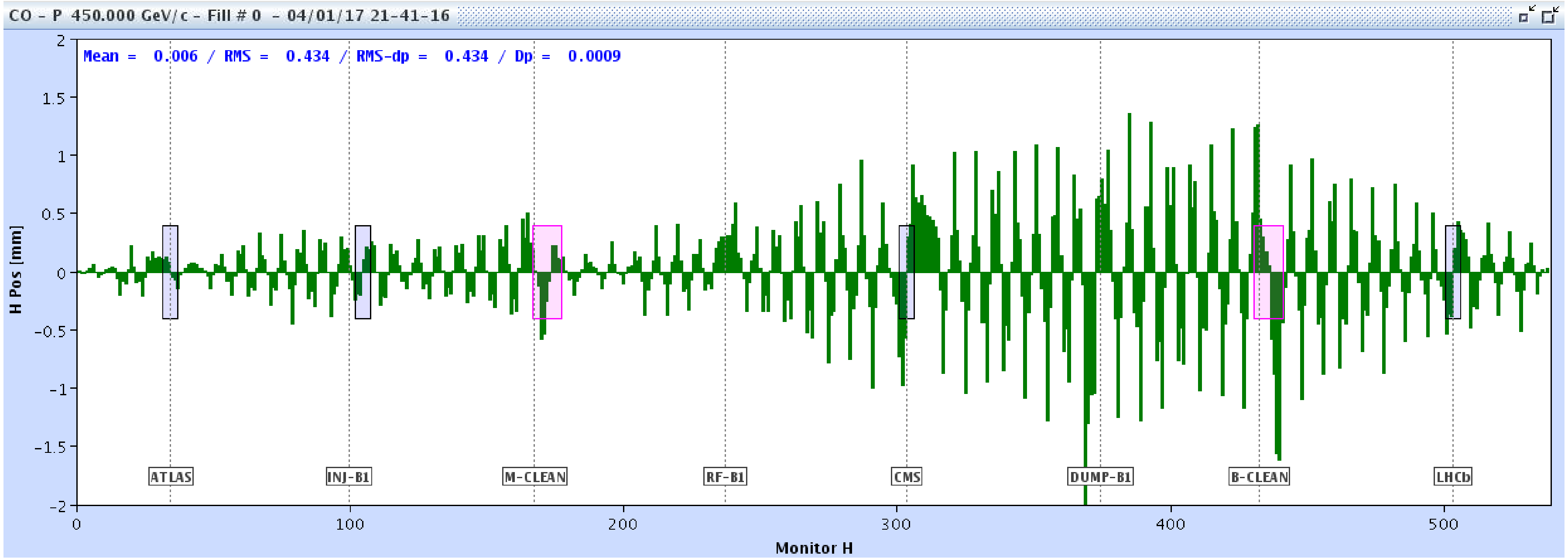
$$\frac{x(s)}{\sqrt{\beta(s)}} = \frac{\sqrt{\beta_\theta}\cos(|\mu(s)-\mu_\theta|-\pi Q)}{2\sin(\pi Q)}\theta \propto \cos(|\mu(s)-\mu_\theta|-\pi Q)$$



Can you localize the deflection now?

A more realistic case at LHC

- Now a more realistic orbit with 100’s of deflections.



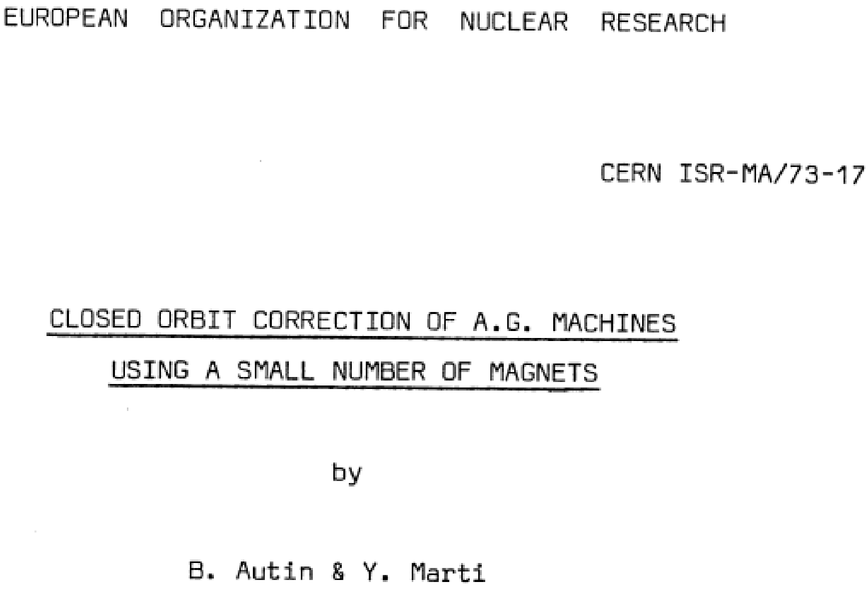
CO - P 450.000 GeV/c - Fill # 0 - 04/01/17 21-41-16

Mean = 0.006 / RMS = 0.434 / RMS-dp = 0.434 / Dp = 0.0009

How do we proceed to correct?

Back to the early days of CERN

- The problem of correcting the orbit deterministically came up a long time ago in the first CERN machines.
- B. Autin and Y. Marti published a note in 1973 describing an algorithm that is still in use today (but in JAVA/C/C++ instead of FORTRAN) at ALL CERN machines:
  - **MICADO***


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN ISR-MA/73-17

CLOSED ORBIT CORRECTION OF A.G. MACHINES
USING A SMALL NUMBER OF MAGNETS

by

B. Autin & Y. Marti

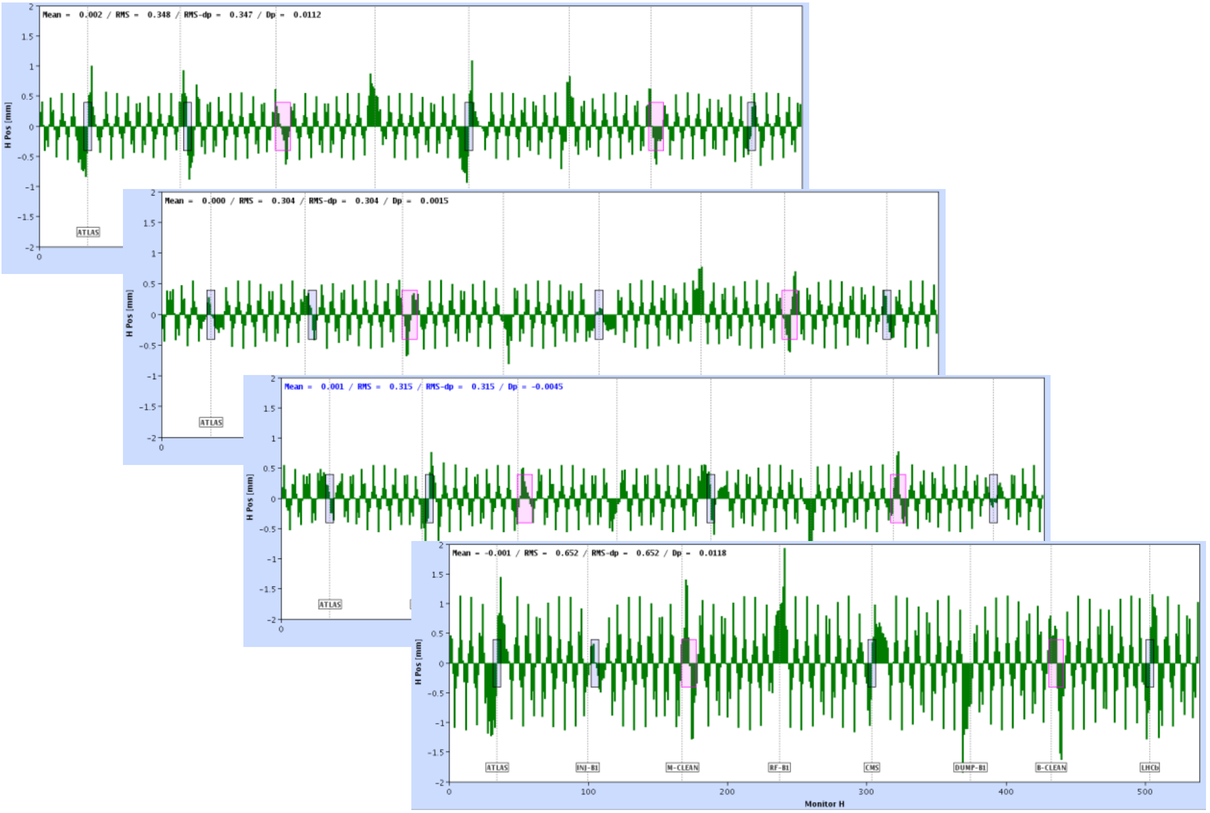

```
CALL MICADO (A, B, NDIM, M, N, AP, XA, NA, NB, NC, EPS, ITER, DP, X, NX, R, RHO).
```


* MInimisation des CArrés des Distortions d'Orbite.

(Minimization of the quadratic orbit distortions)

MICADO - how does it work?

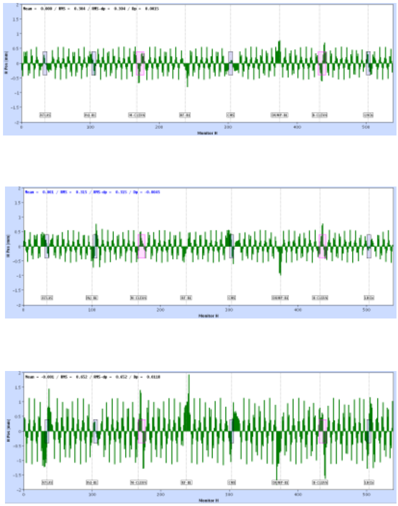
- The intuitive principle of MICADO is rather simple.
- Preparation:
  - You need a model of your machine,
  - You compute for each orbit corrector what the effect (response) is expected to be on the orbit.

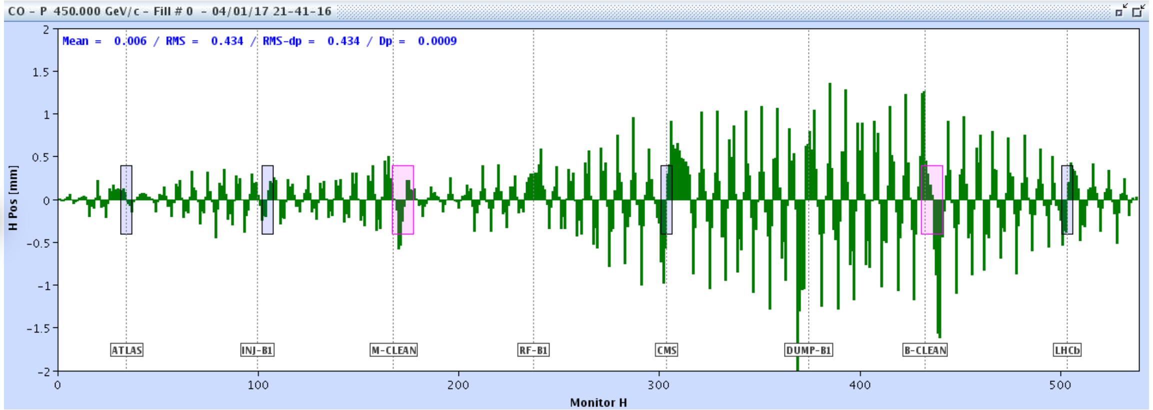


. . .

MICADO - how does it work?

- MICADO compares the response of every corrector with the raw orbit.

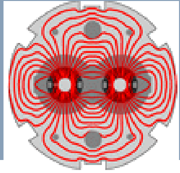




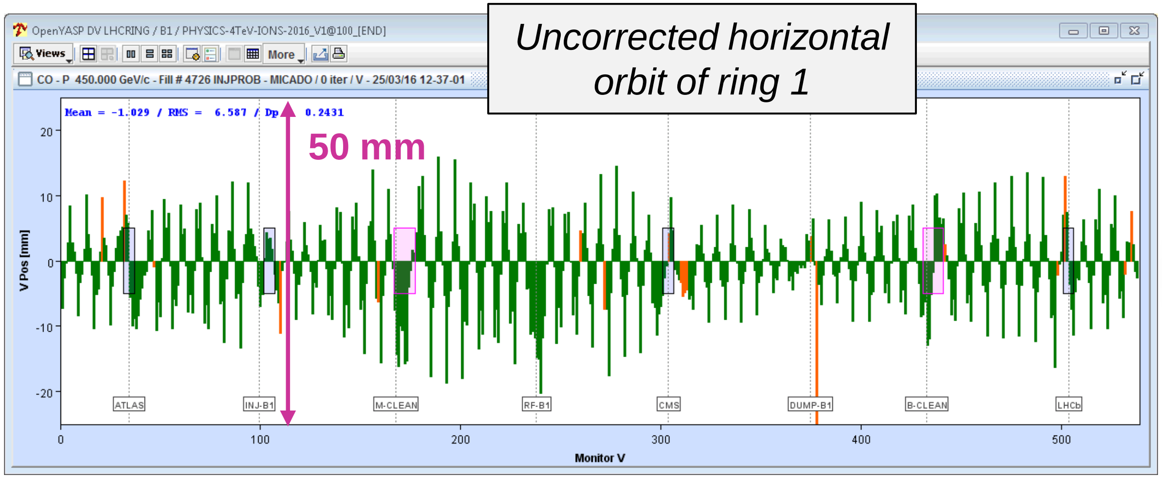
…

- MICADO then picks out the corrector that hast the **best match** with the orbit, and that will give the largest improvement to the orbit deviation rms.
- The procedure can be **iterated** until the orbit is good enough (or as good as it can be).

LHC orbit correction example



- The raw orbit at the LHC can have huge errors, but the correction (based partly on MICADO) brings the deviations down by more than a factor 20.



OpenYASP DV LHCRING / B1 / PHYSICS-4TeV-IONS-2016_V1@100_[END]

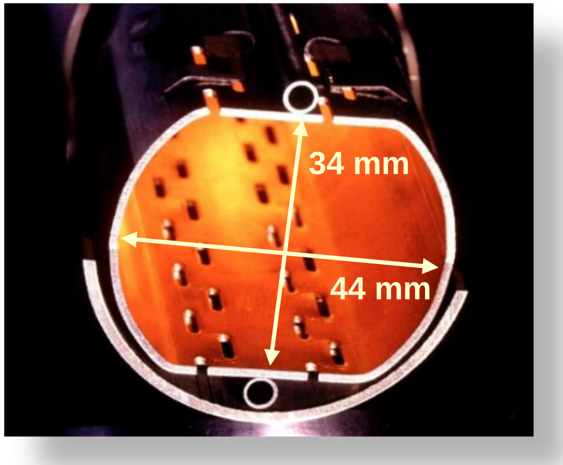
CO - P 450.000 GeV/c - Fill # 4726 INJPROB - MICADO / 0 iter / V - 25/03/16 12-37-01

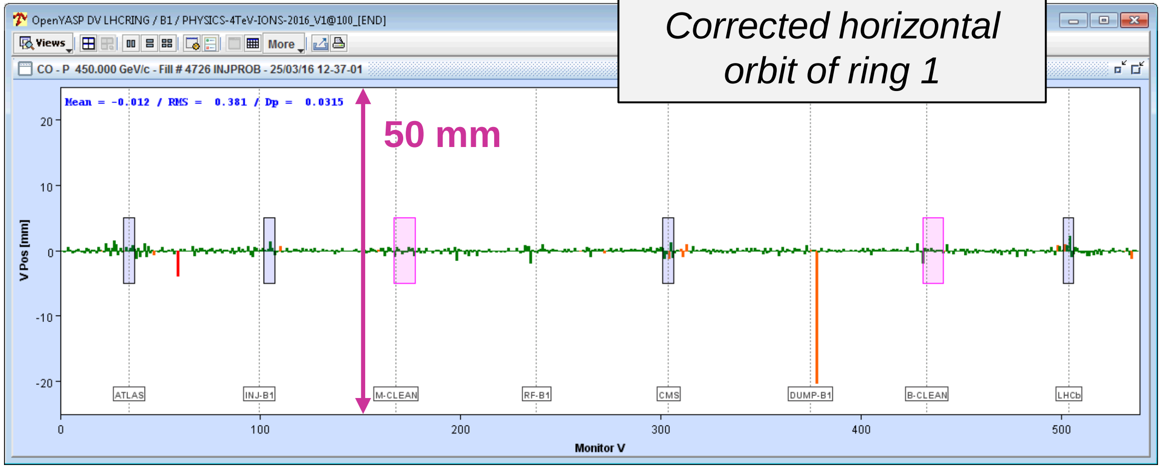
Mean = -1.029 / RMS = 6.587 / Dp = 0.2431

Uncorrected horizontal orbit of ring 1

MICADO & Co

LHC vacuum chamber





OpenYASP DV LHCRING / B1 / PHYSICS-4TeV-IONS-2016_V1@100_[END]

CO - P 450.000 GeV/c - Fill # 4726 INJPROB - 25/03/16 12-37-01

Mean = -0.012 / RMS = 0.381 / Dp = 0.0315

Corrected horizontal orbit of ring 1

At the LHC a good orbit correction is vital !

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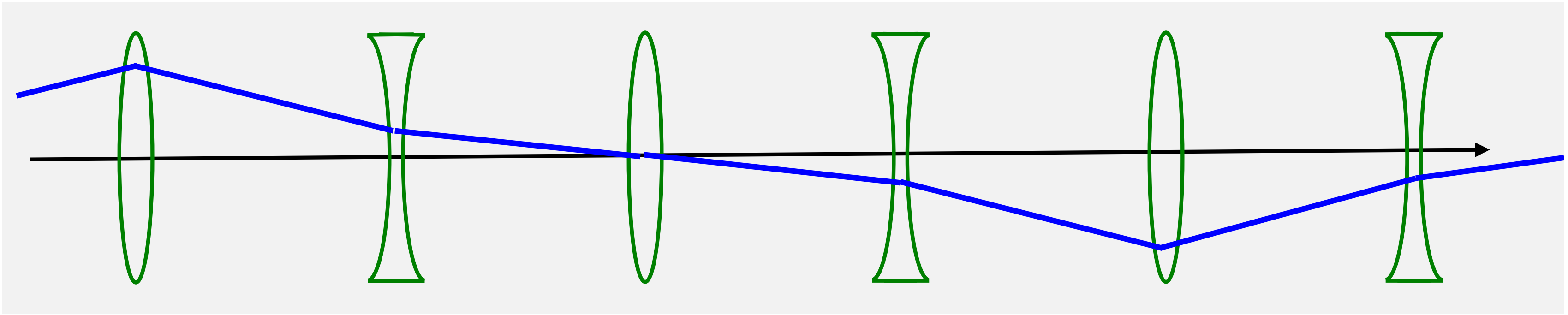
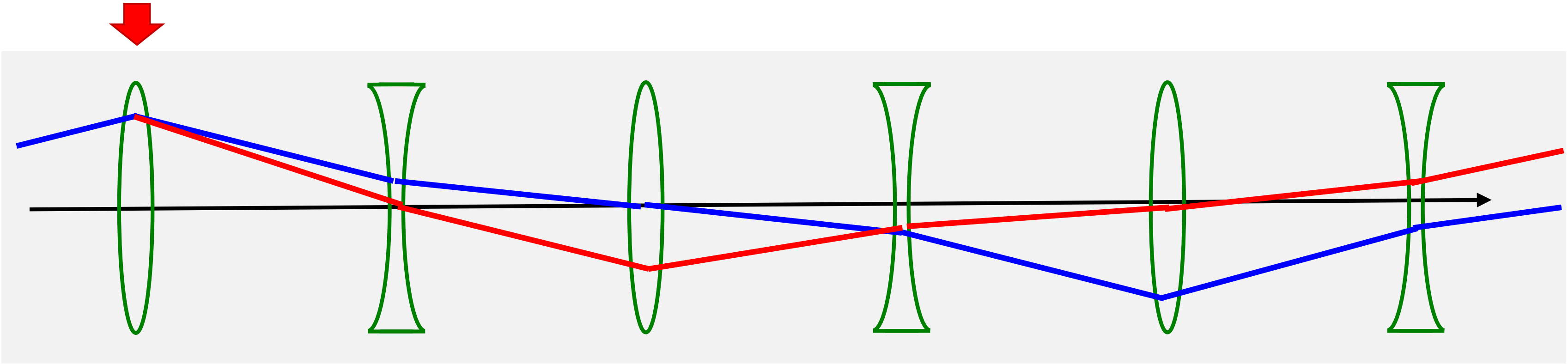
Quadrupole gradient errors

- What is the impact of a quadrupole gradient error?
  - Let us consider a particle oscillating in the lattice.



Too strong gradient / lens

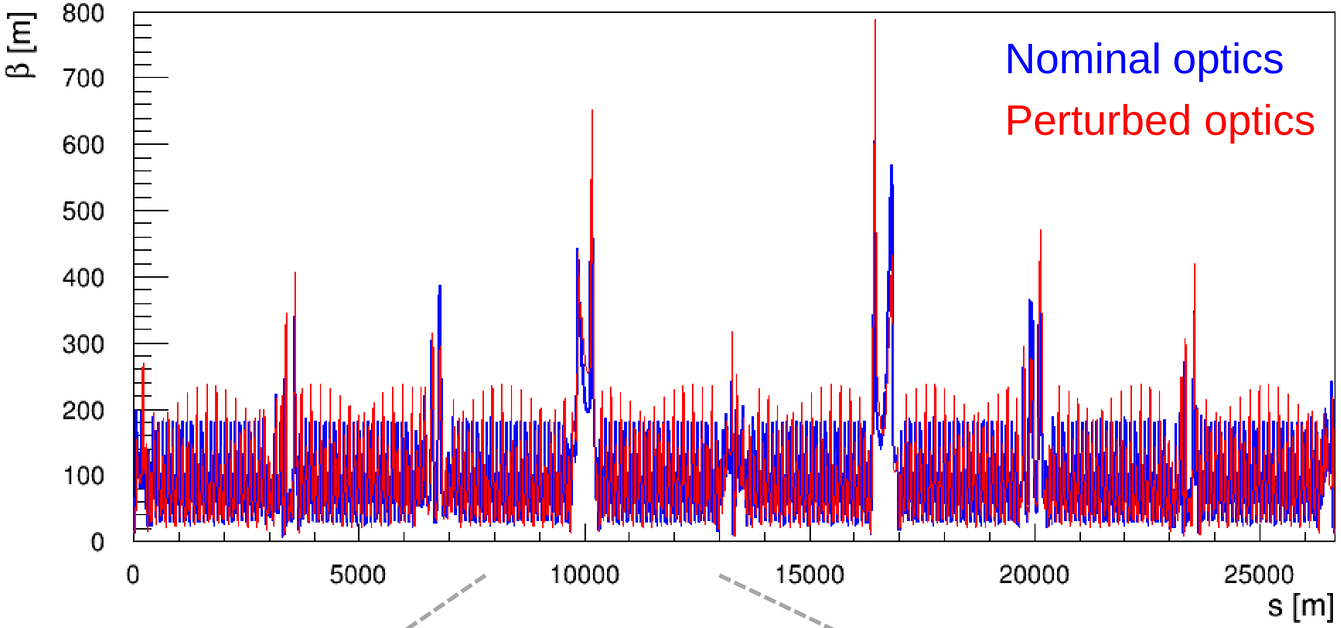


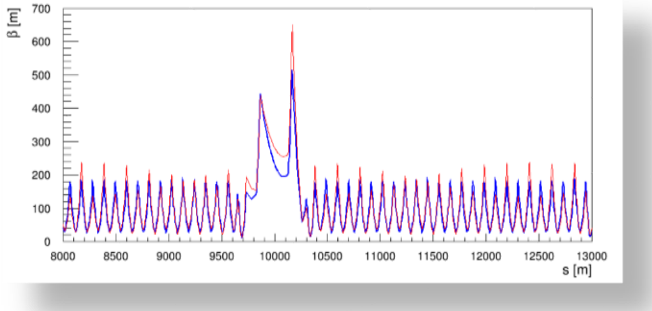
*The oscillation period is affected → **change of tune**, here Q increases !*

Optics perturbation

- In a ring a focussing error affects the beam optics and envelope (size) over the entire ring ! It also changes the tune.

Example for LHC: one quadrupole gradient is incorrect

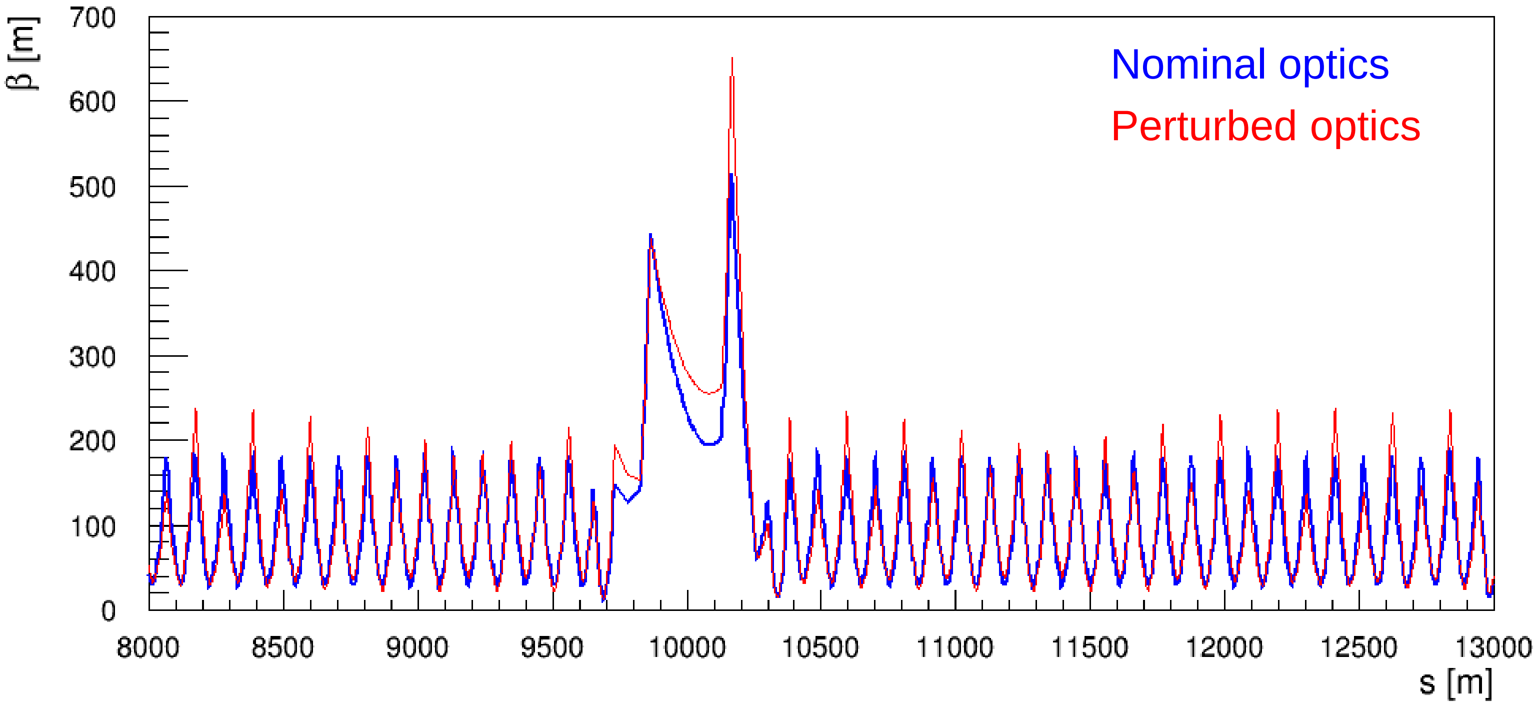




Zoom into a subsection

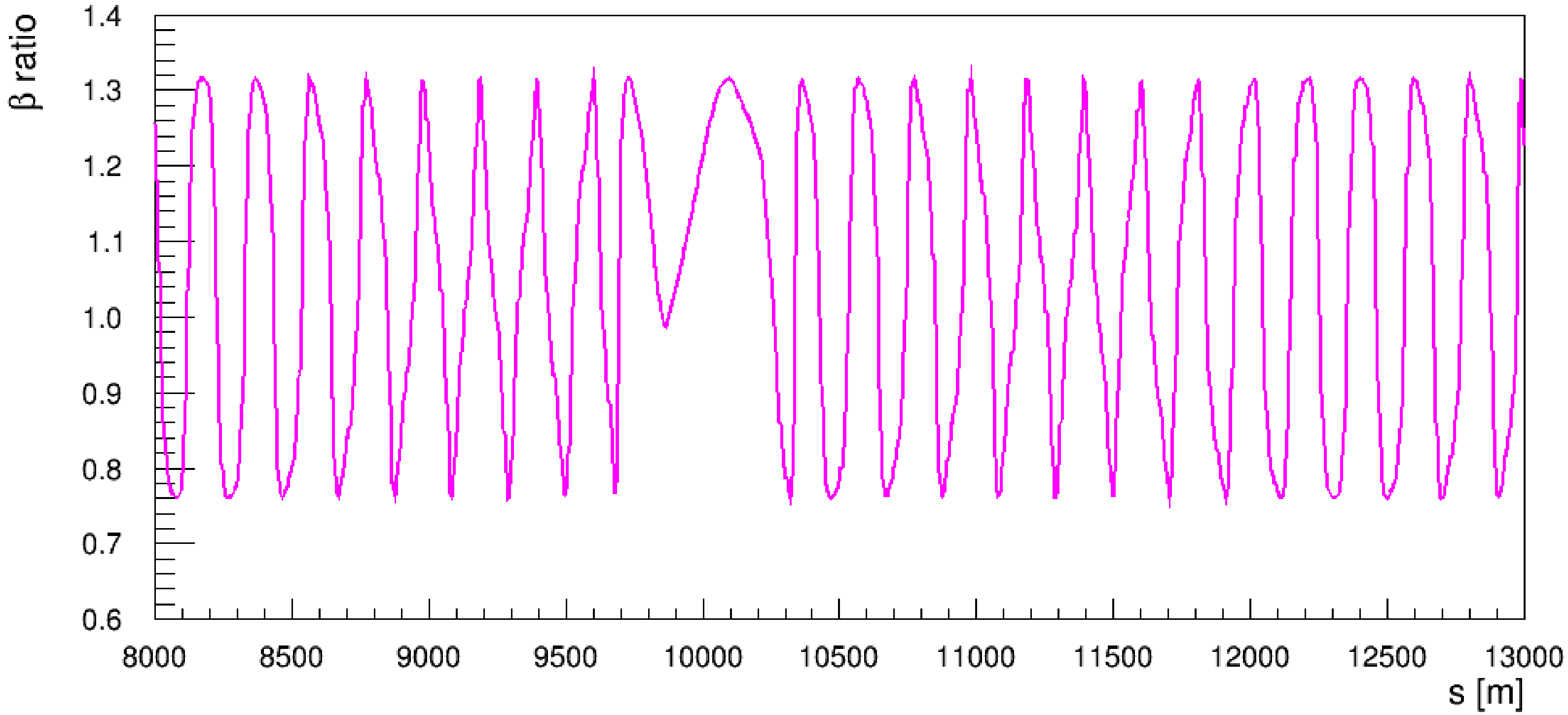
Optics perturbation

- The local beam optics perturbation… note the oscillating pattern of the error.



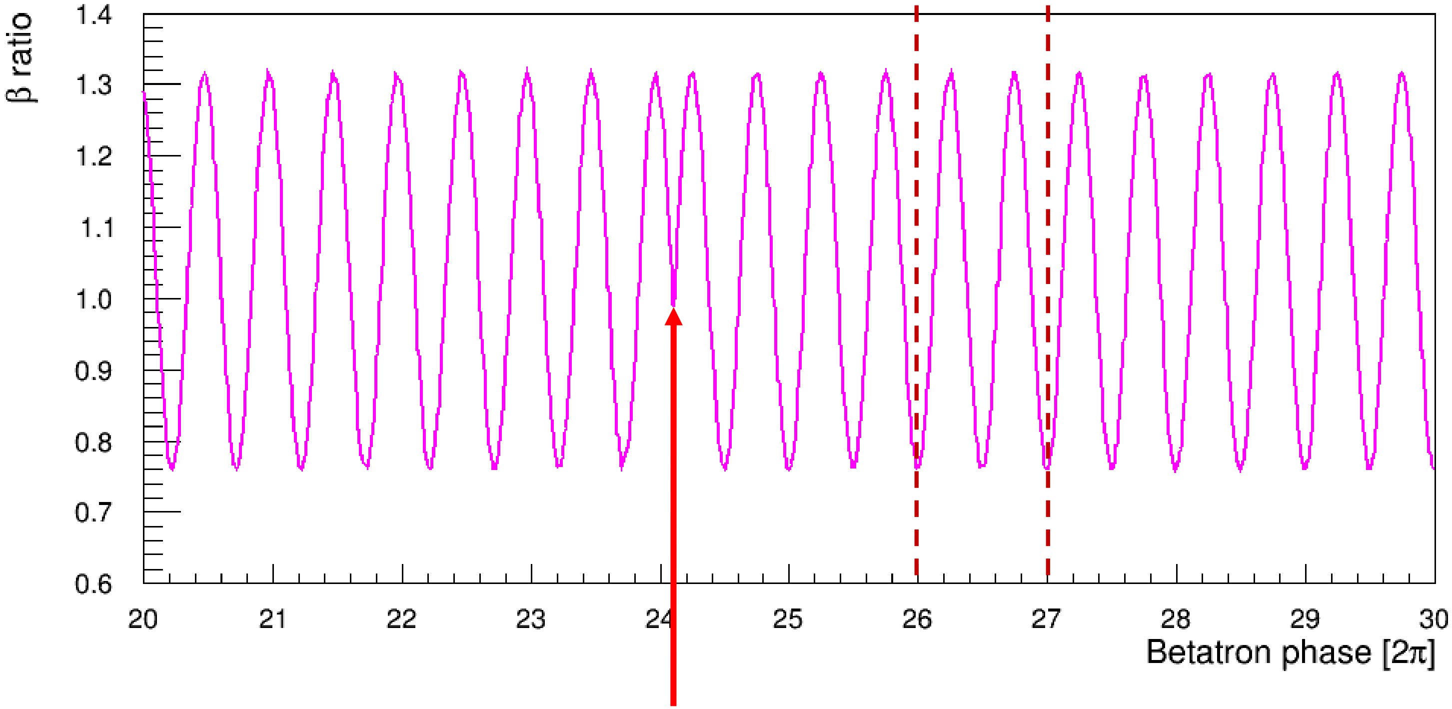
Optics perturbation

- The error is easier to analyse and diagnose if one considers the ratio of the betatron function perturbed/nominal.
- The ratio reveals an oscillating pattern called the **betatron function beating** (‘beta-beating’). The amplitude of the perturbation is the same all over the ring !



Optics perturbation

- ❑ The beta-beating pattern comes out even more clearly if we replace the longitudinal coordinate with the betatron phase advance.
- ❑ The result is very similar to the case of the closed orbit kick, the error reveals itself by a kink !
  - – If you watch closely you will observe that there are **two oscillation periods per 2π (360 deg) phase**. The beta-beating frequency is **twice** the frequency of the orbit !

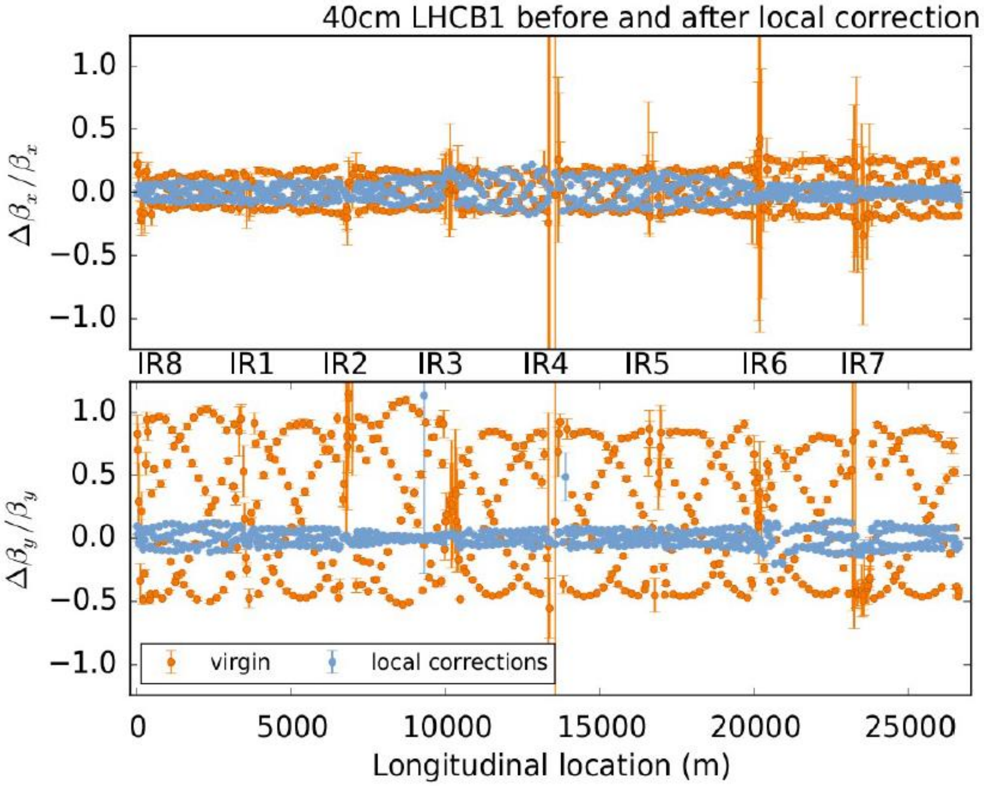


Correction

- How can one correct such beta-beating?
- The correction strategy with MICADO can be applied !
  - You can build the response of any gradient change on the optics (β).
  - You can use MICADO to look for the best possible solution.
  - The correcting elements are the quadrupole themselves (adjust their current).
- For optics corrections more sophisticated and powerful algorithm provide however better correction strategies.

LHC optics correction

- In collision at top energy of 6.5 TeV, the optics is wrong by 100% before correction.
  - Can be corrected to a few % residual error with modern correction algorithms.



Introduction

Imperfection - sources

Orbit perturbations

Optics perturbations

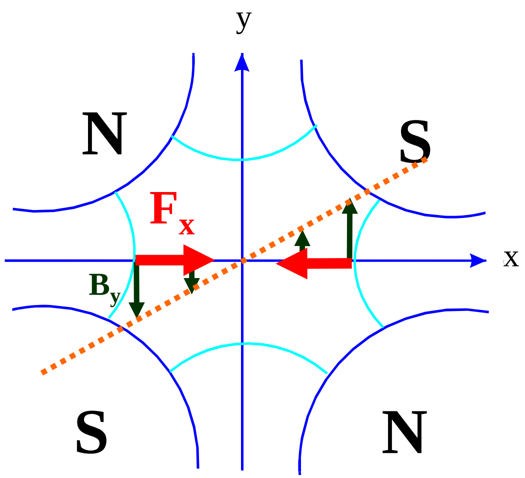
Coupling between planes

Summary

Tilted quadrupole

- If a quadrupole is rotated by 45º (‘skew quadrupole’) one obtains an element where the force (deflection) in x depends on y and vice-versa: the horizontal and vertical planes are **coupled**.

normal quadrupole

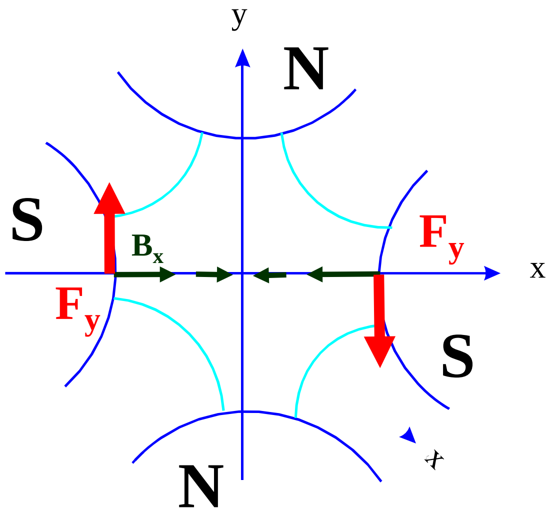


$$F_x = -k\,x$$

$$F_y = k\,y$$

No mixing of planes

skew quadrupole



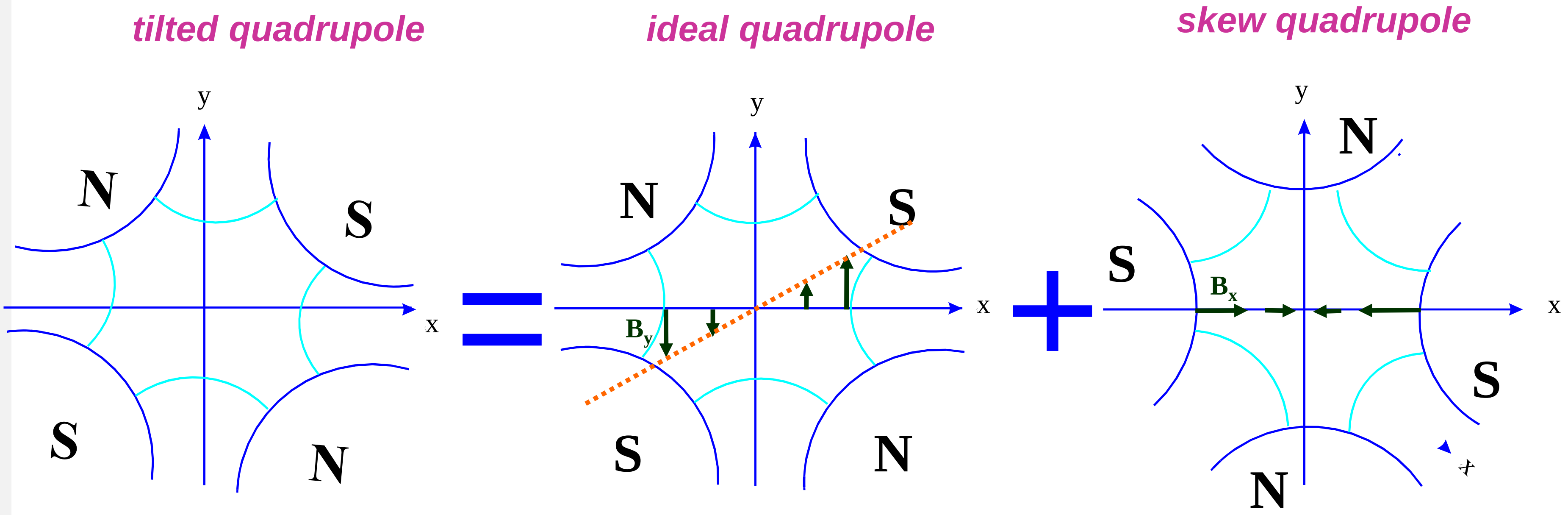
$$F_x = k\,y$$

$$F_y = -k\,x$$

Full mixing of planes

Coupling

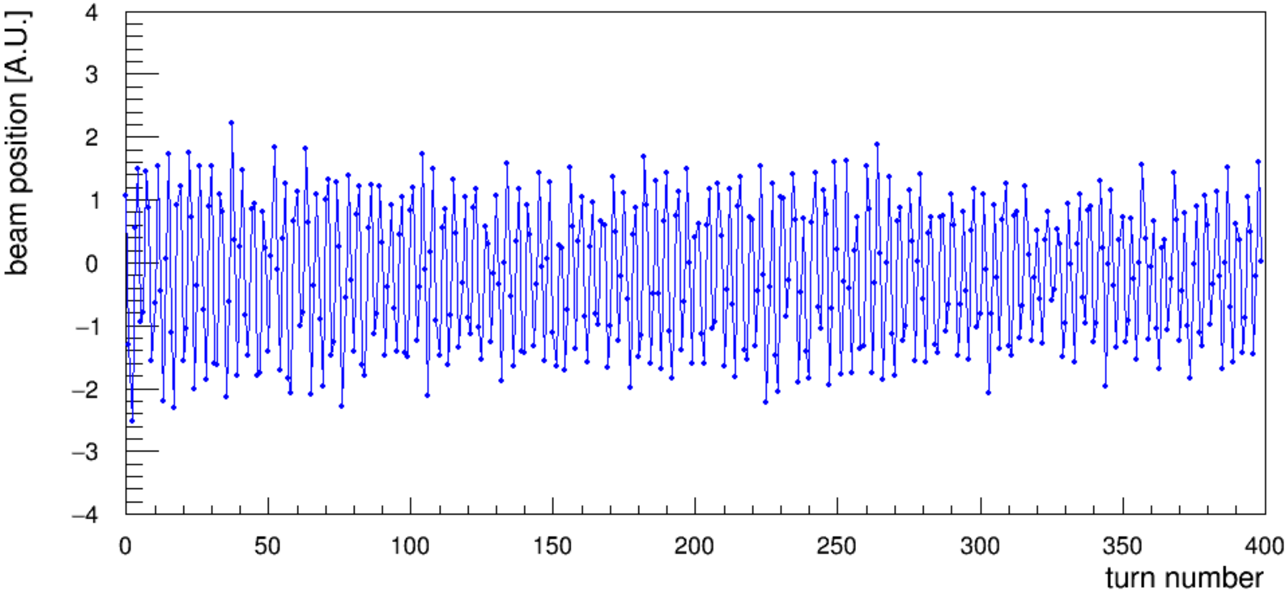
- Small quadrupole tilts lead to coupling of the x and y planes.
- The coupling can be corrected by installing dedicated skew quadrupoles to compensate for alignment errors.



Coupling and tune observation

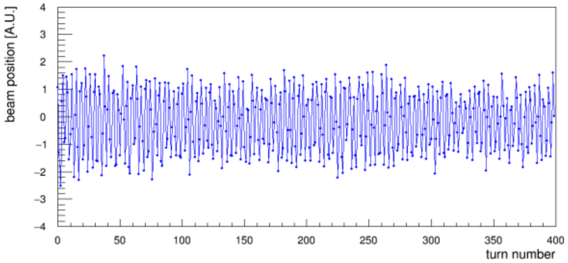
- The simplest thing to determine if there is coupling is to kick the beam in one plane to generate an oscillation, and then observe the oscillations or the frequency content.
  - Or just use the natural beam oscillations if they exist.
- If coupling is present, then for a horizontal kick there will be a small vertical oscillation (and vice-versa).

Turn by turn recording of the beam position at one BPM

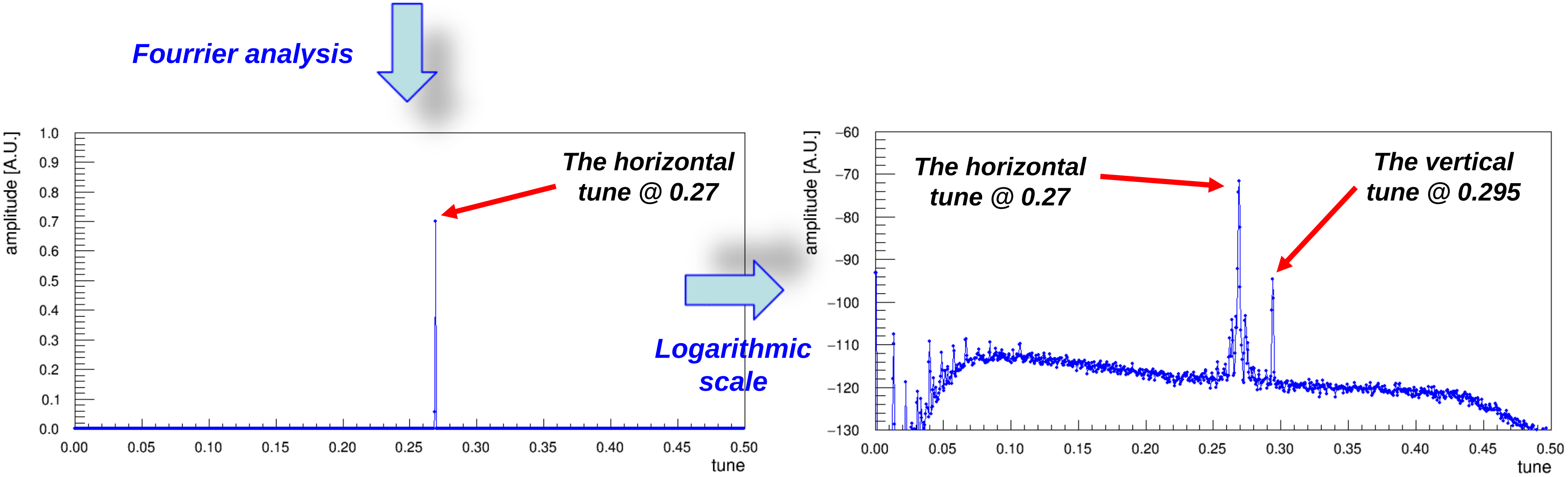


Coupling observation

- We apply a **Fourrier analysis** to the position data to extract the beam oscillation frequencies.



Example : horizontal beam position at a BPM observed turn by turn



- The **ratio of the vertical to horizontal amplitude** measures the amount of coupling → now one can tune the skew quadrupoles until the vertical tune peak disappears.

Summary

- We have seen that magnetic field errors and misalignments of accelerator components induce:
  - Errors on the beam orbit,
  - Errors on the optics and the tune,
  - Coupling between the horizontal and vertical planes.
- The errors are often sufficiently large (for sure at LHC) that the machine operates poorly or not at all.
- Since the 1970’s ever improving tools and algorithms have been developed to correct for such errors.
- However to minimize the imperfections from the start we need:
  - well measured calibration curves of magnets,
  - precise power converters,
  - the best possible machine alignment.

What value for the tunes?

- Various collider tune working points.