Linear Imperfections

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Introduction

Imperfection - sources

Orbit perturbations

Optics perturbations

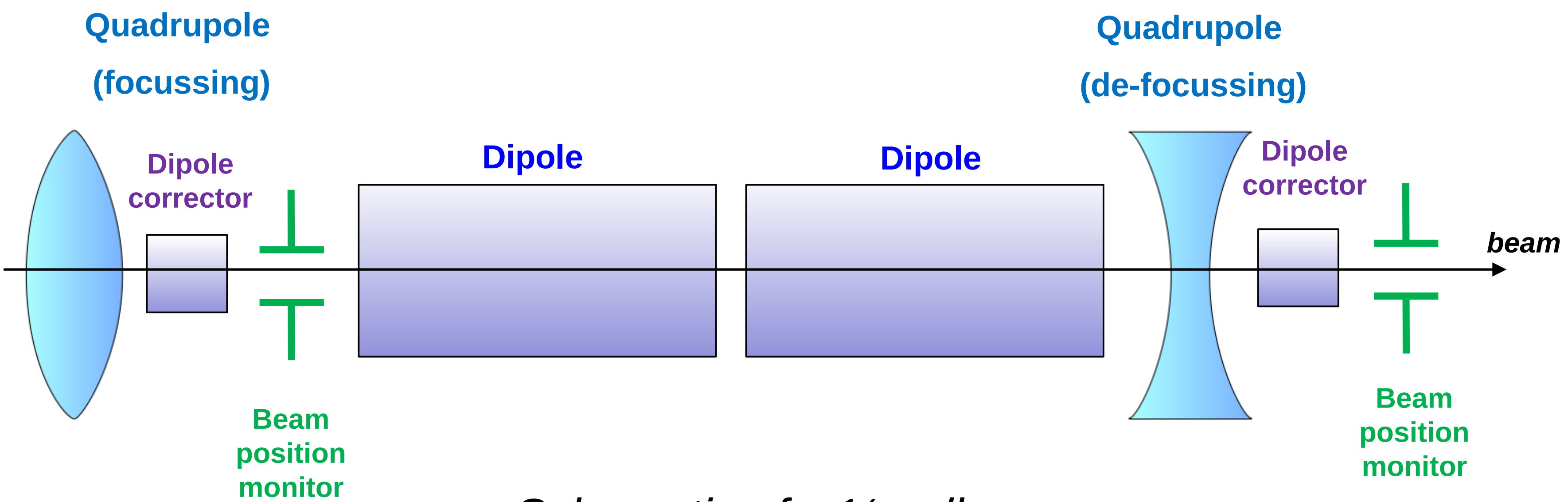
Coupling between planes

Linear imperfections and geology

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

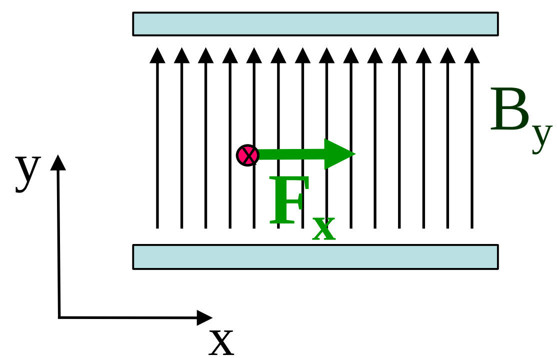
- The dipole has two magnetic poles and generates a **homogeneous field** providing a constant force on all beam particles – used to **deflect** the beam.
  - A dipole corrector is just a small version of such a magnet, dedicated to steer the beam as we will see later.

Lorentz force:

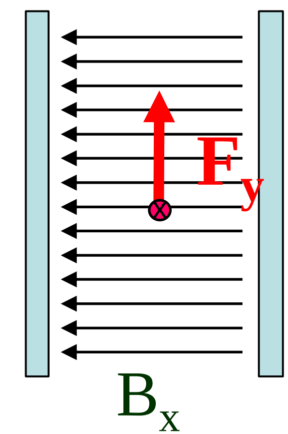
$$F = q\vec{v}\times\vec{B}$$

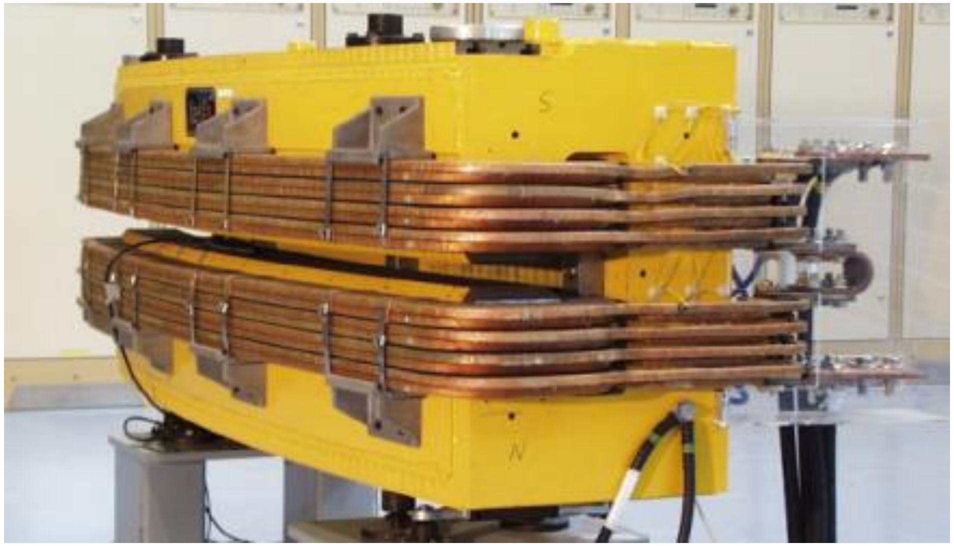
orthogonal to the speed and magnetic field directions

Horizontal deflection



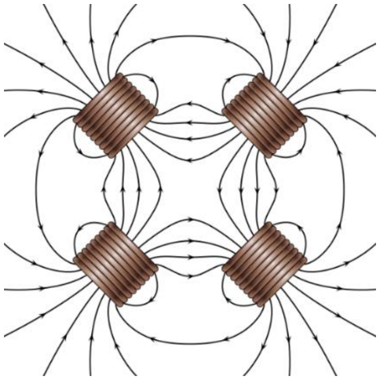
Vertical deflection

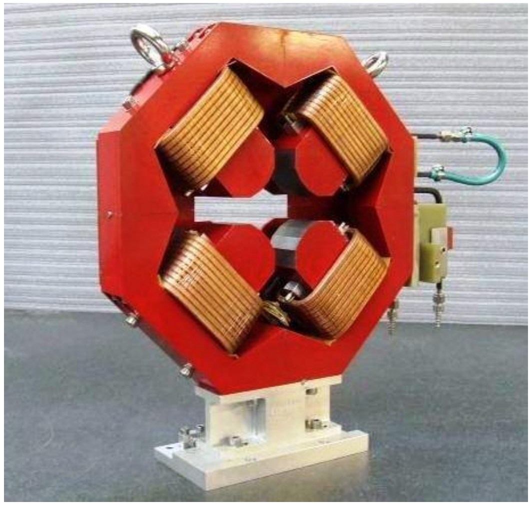


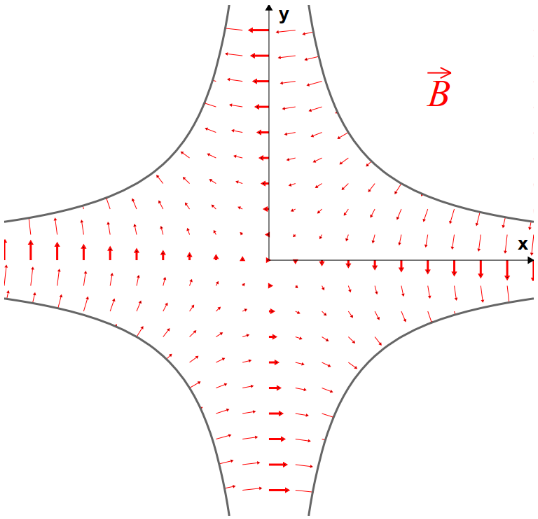


Quadrupole magnet

- 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.

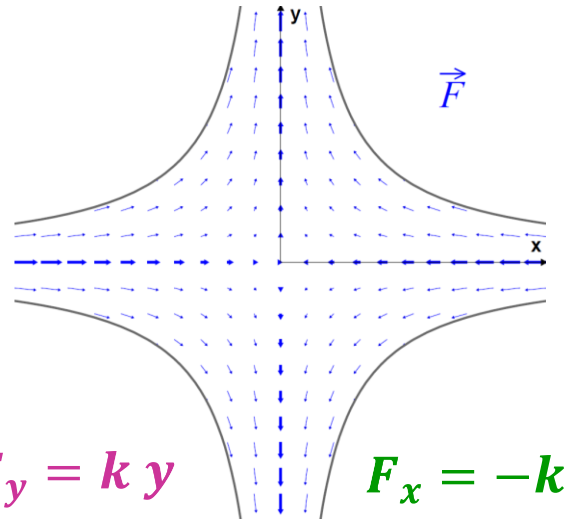






$F_y = k\,y$

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

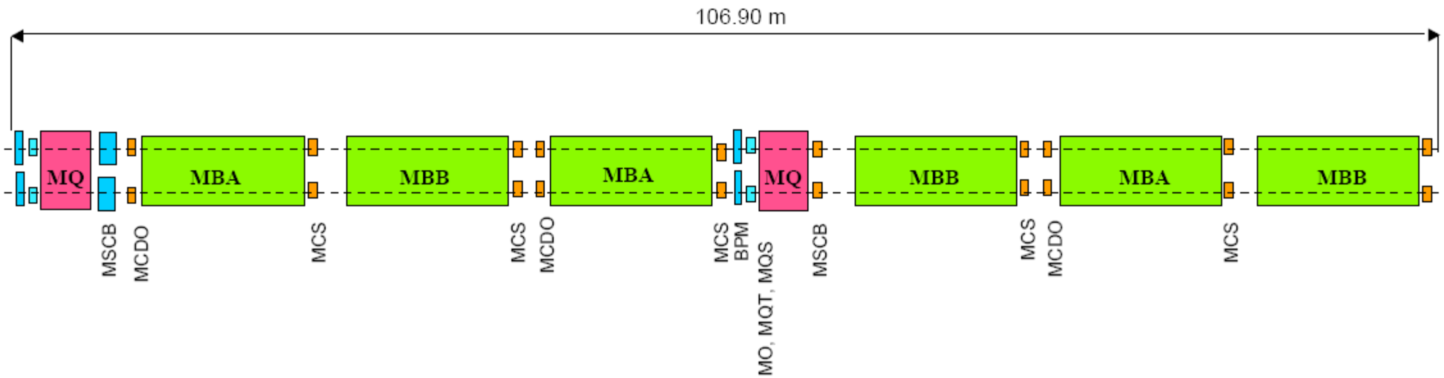


$F_x = -k\,x$

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

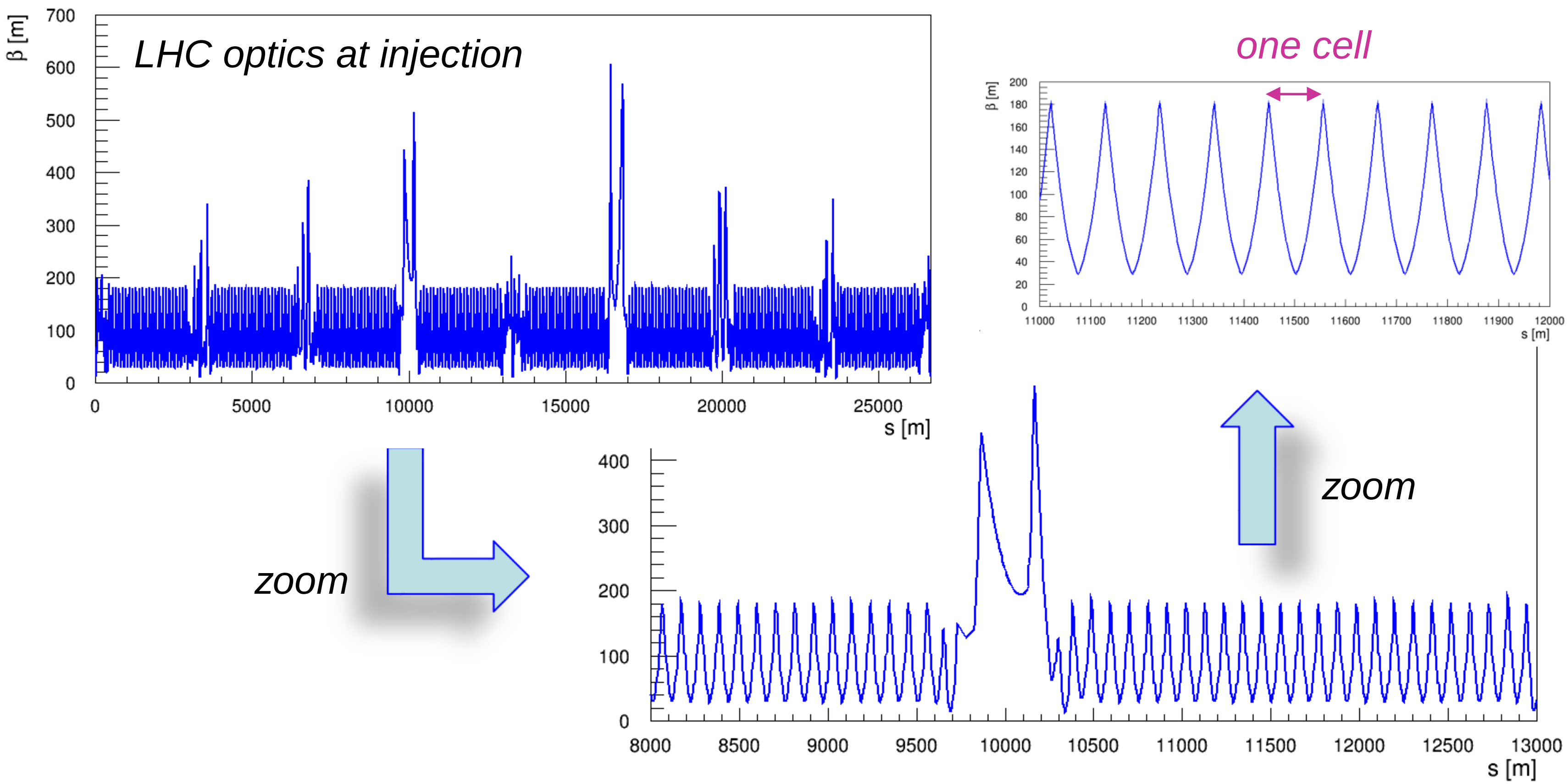
A realistic lattice - LHC

- 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.



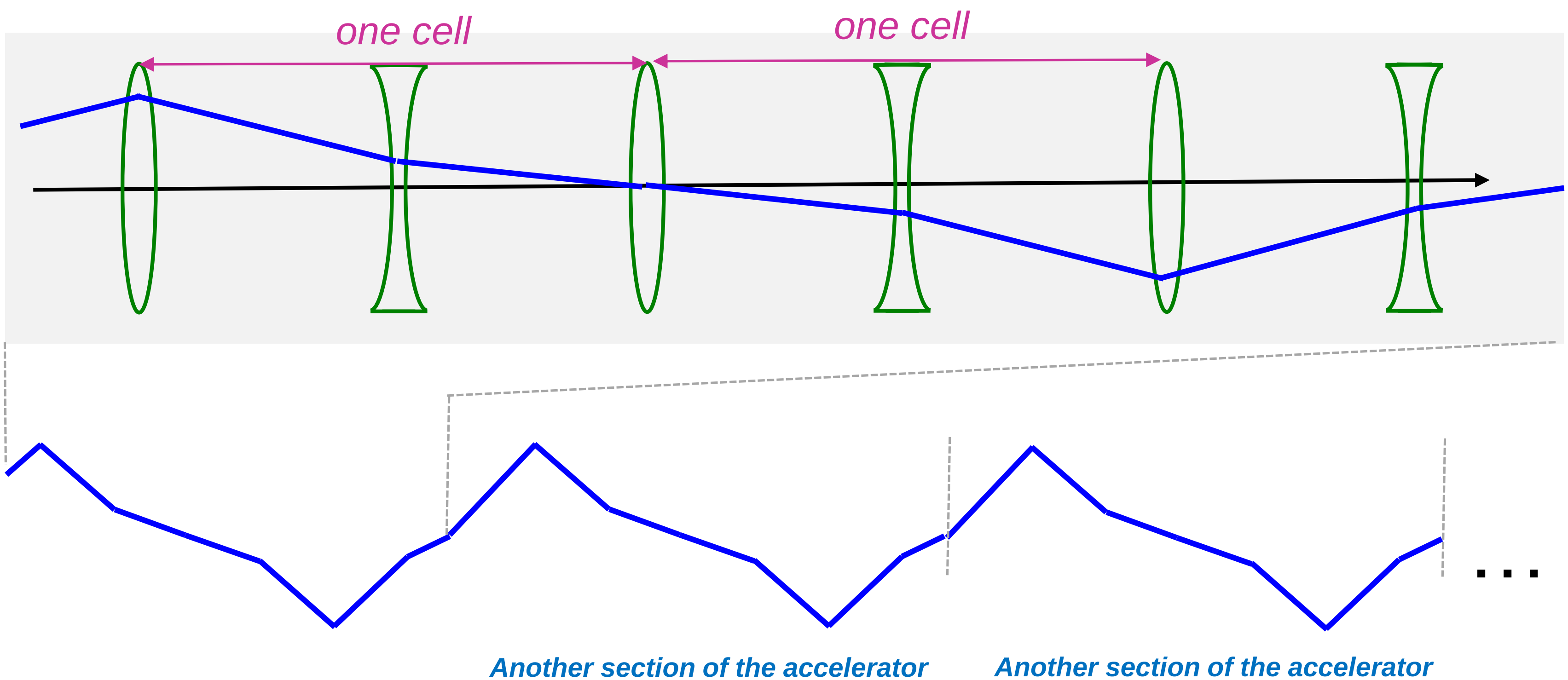
- **MB: main dipole**
- **MQ: main quadrupole**
- MQT: trim quadrupole
- MQS: skew trim quadrupole
- MO: lattice octupole (Landau damping)
- **MSCB:** sextupole + **orbit corrector dipole**
- MCS: Spool piece sextupole
- MCDO: Spool piece 8 / 10 pole
- **BPM: Beam position monitor**

- 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 √β**
  - The **betatron phase advance** (**μ**) that defines the phase of an oscillation.



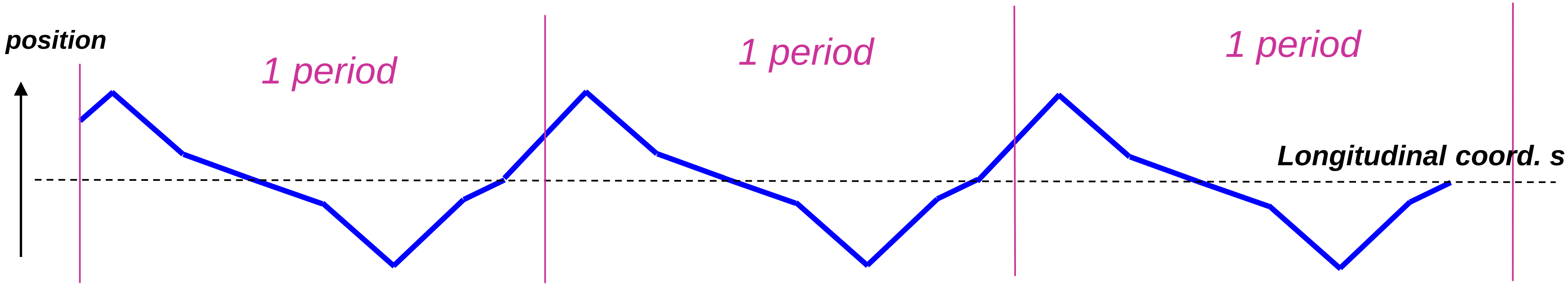
Recap on beam optics

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

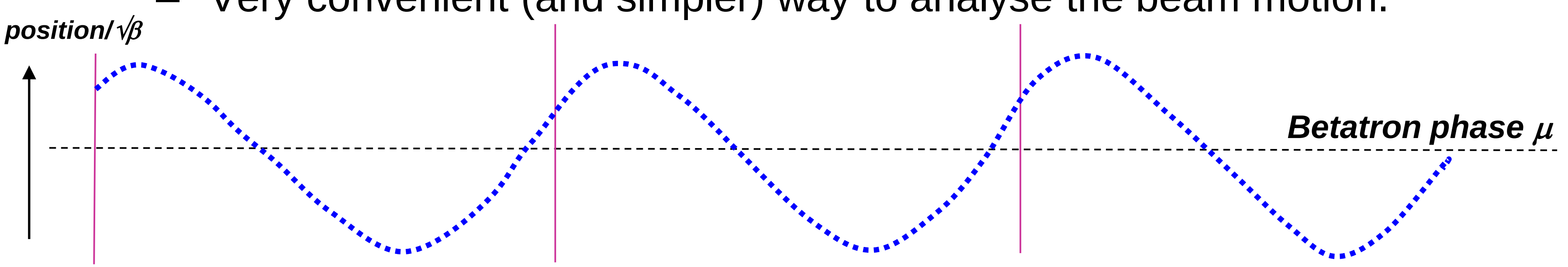


- Does this not look a bit like a periodic oscillation? This is called a betatron oscillation.

- 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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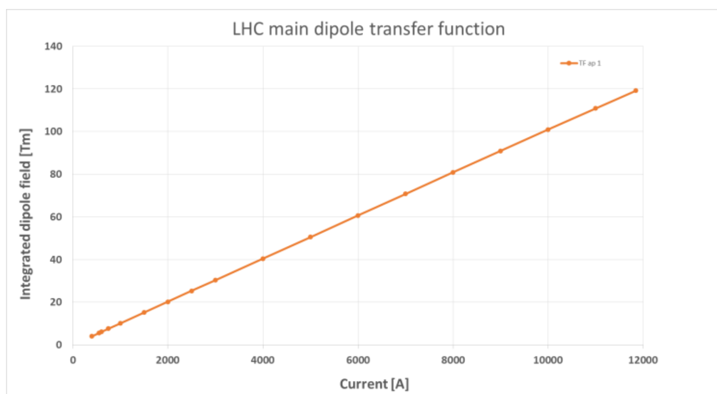
From model to reality - fields

- 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.
- **<u>Imperfections</u>** (= errors) in the real accelerator optics can be introduced by **uncertainties** or **errors** on:
  - Beam momentum, magnet calibrations and power converter regulation.

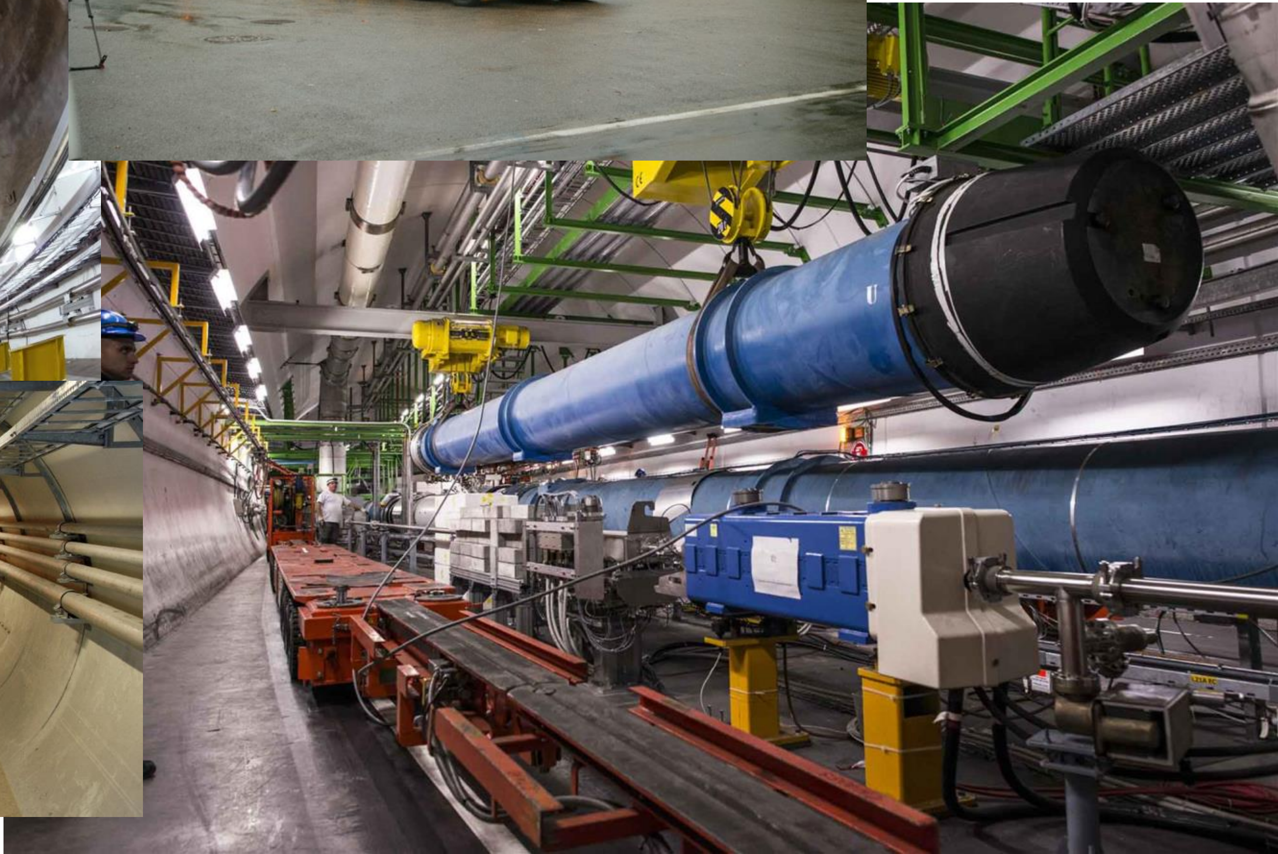
Magnet strength → **Magnetic field (gradient)** → **Requested current** → **Actual magnet current**

Beam momentum | **Magnet calibration curve (transfer function)** | **Power converter**

Example of the LHC main dipole calibration curve

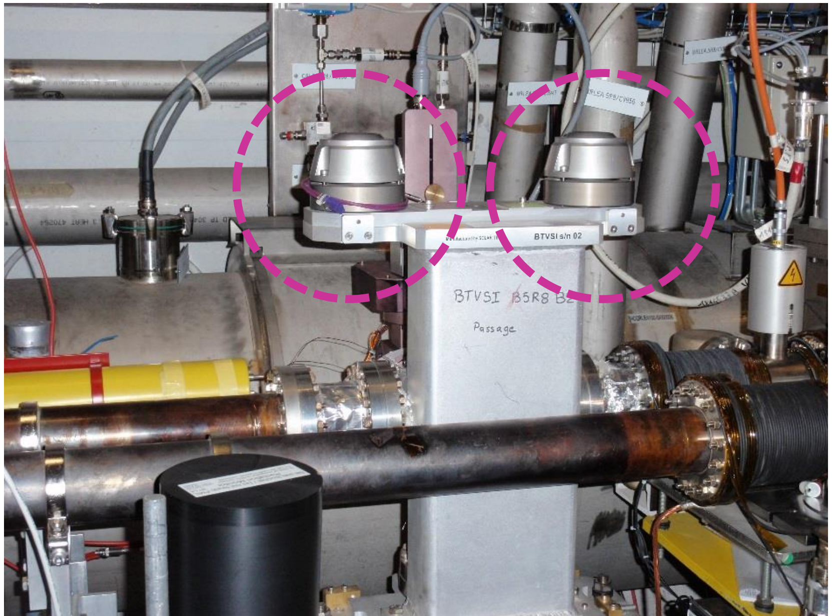


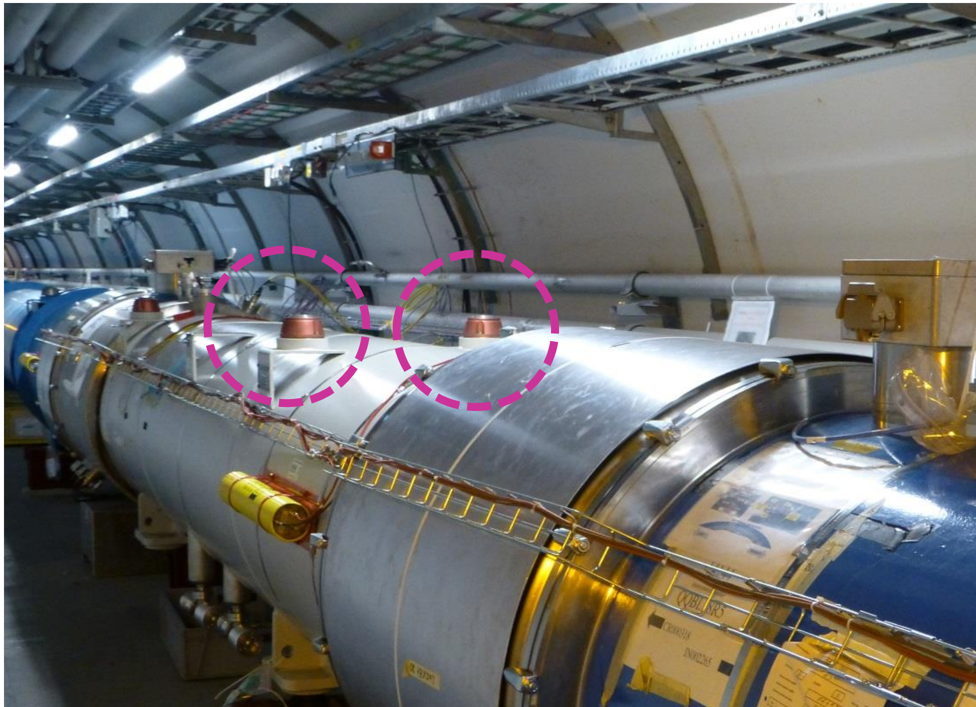
From the lab to the tunnel



From model to reality - alignment

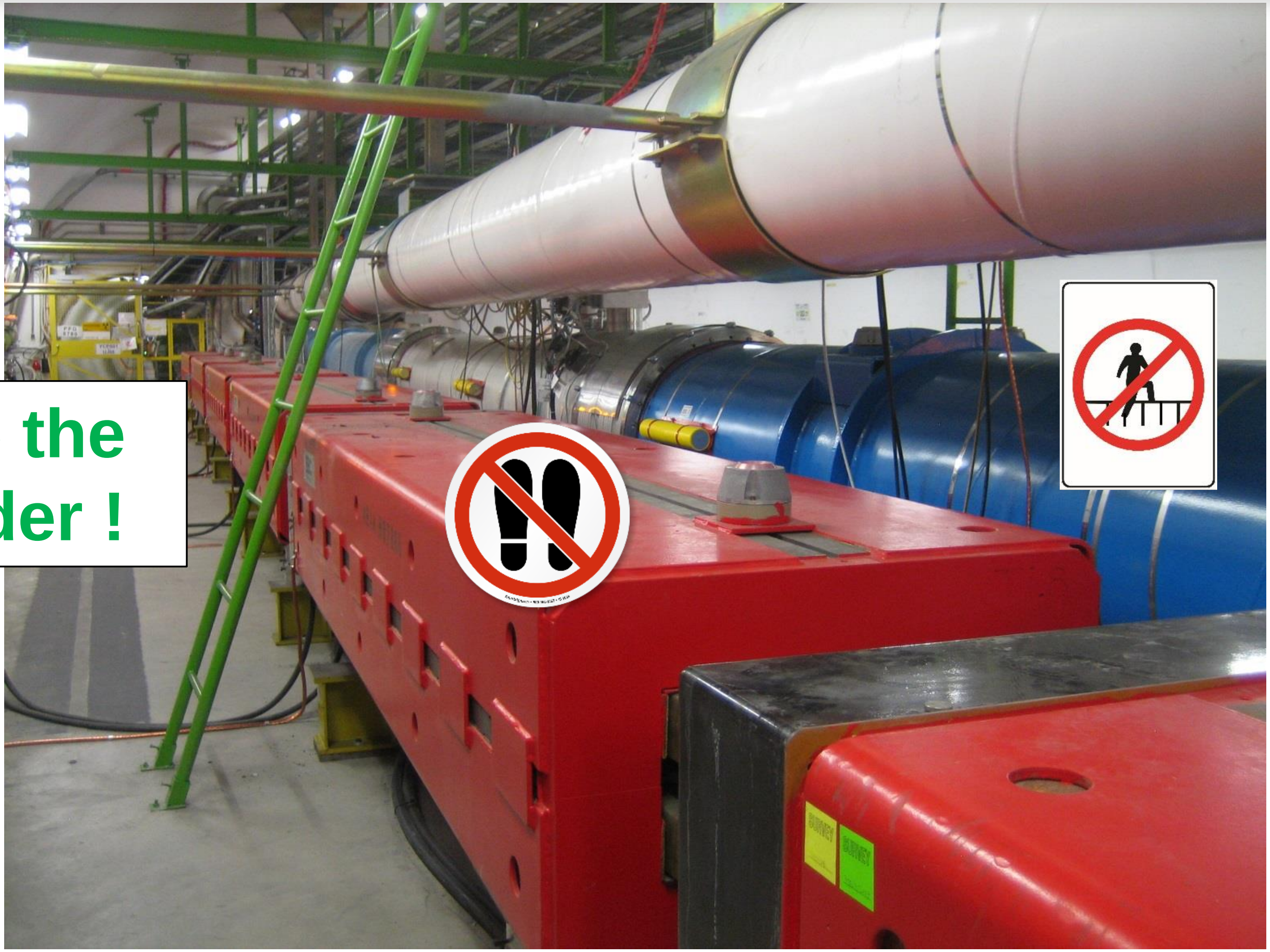
- To ensure that the accelerator elements are in the correct position the alignment must be precise – to the level of micrometres for CLIC !
  - At the CERN hadron machines we aim for accuracies of around **0.1 mm**.
- The alignment process implies:
  - Precise measurements of the magnetic axis in the 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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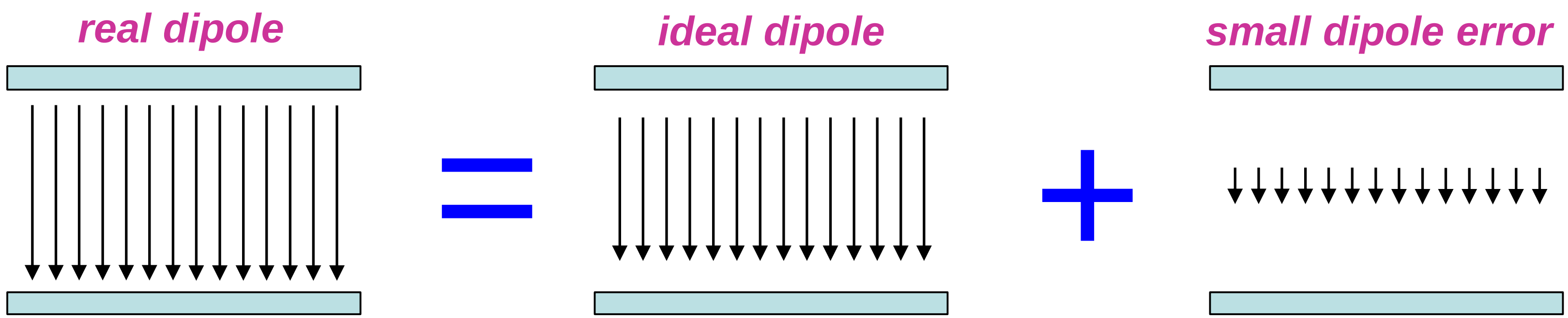
Imperfection – undesired deflection

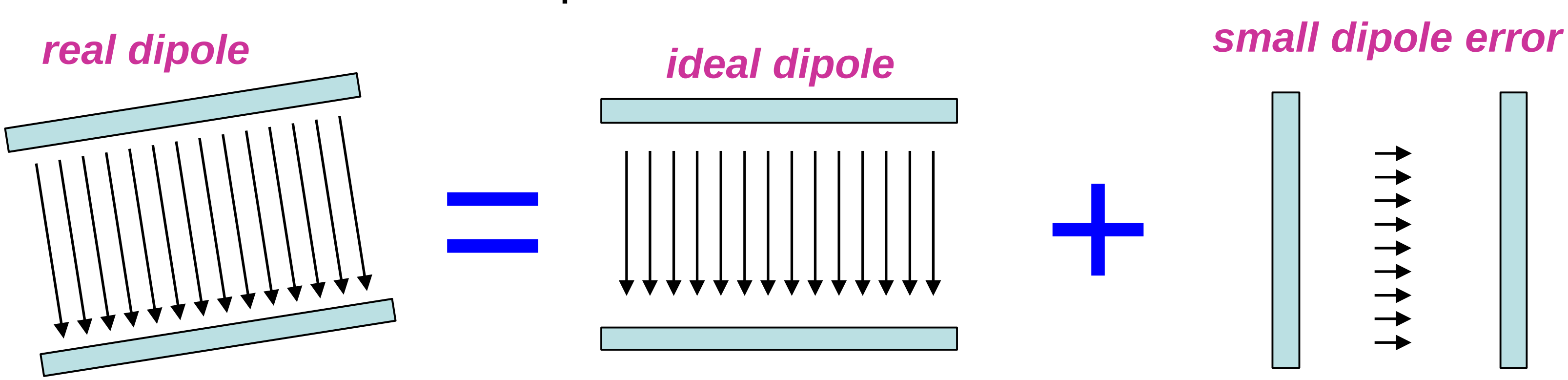
- The presence of an **unintended deflection** along the path of the beam is a first category of imperfections.
- This case is also in general the first one that is encountered when beam is first injected…
- The **dipole orbit corrector** is added to the cell to **compensate** the effect of **unintended 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.



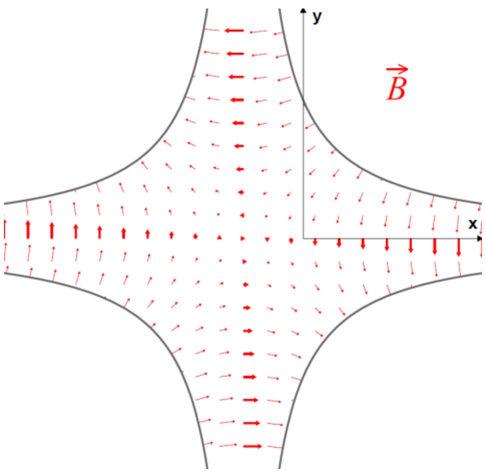
- A small rotation (misalignment) of a dipole magnet has the same effect, but in the other plane.



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.

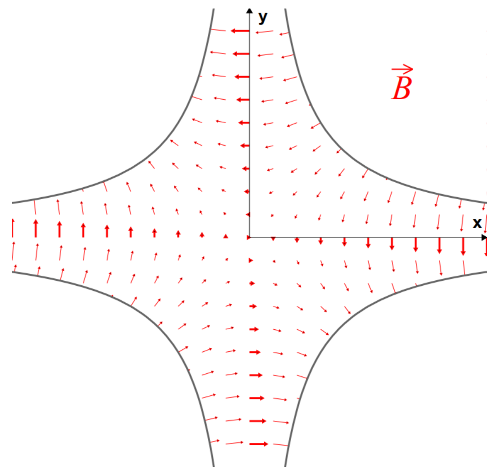
real quadrupole



Non-zero magnetic field on the beam axis !

=

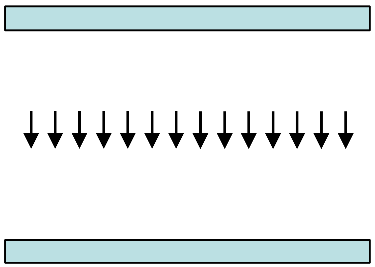
ideal quadrupole



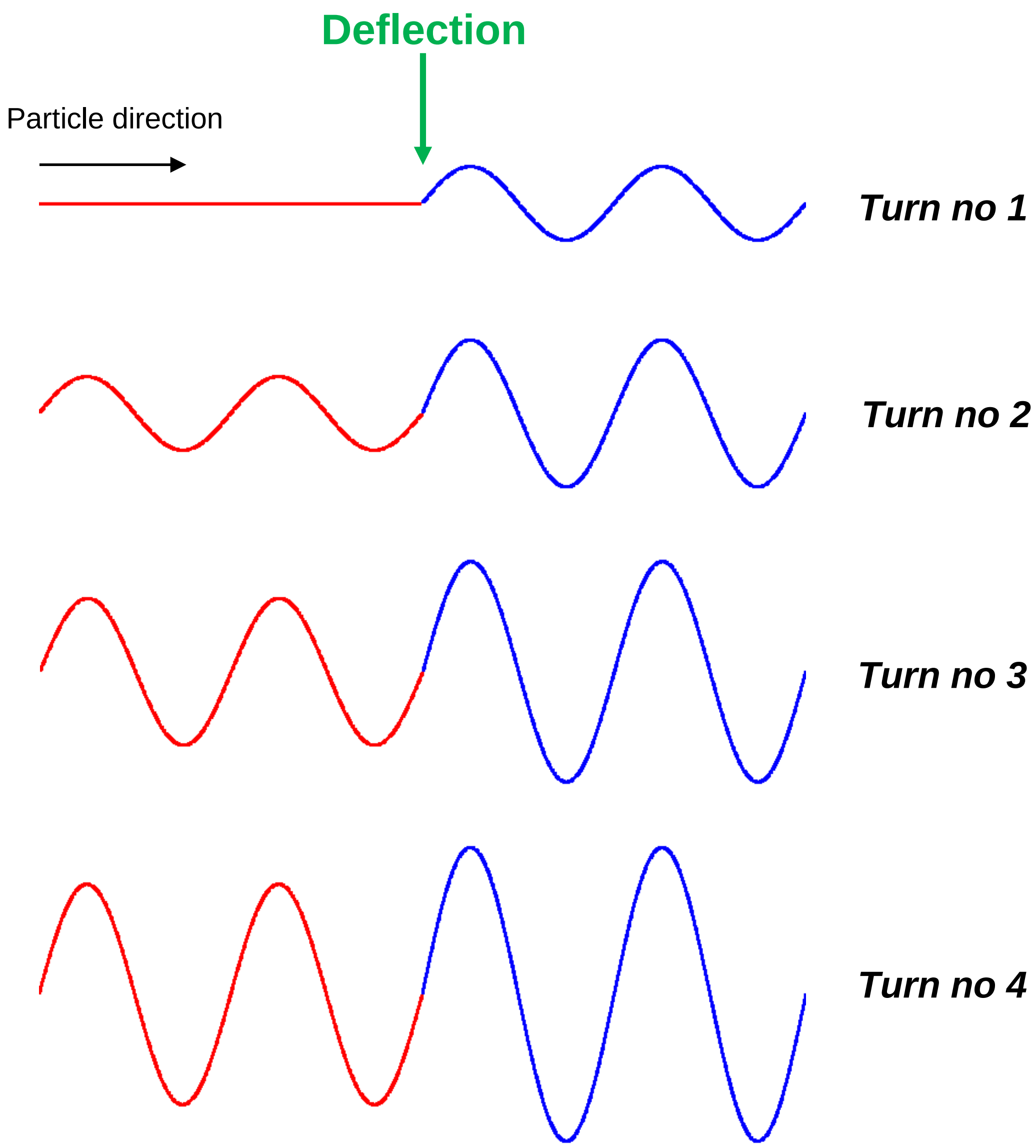
No magnetic field on the beam axis

+

small dipole error

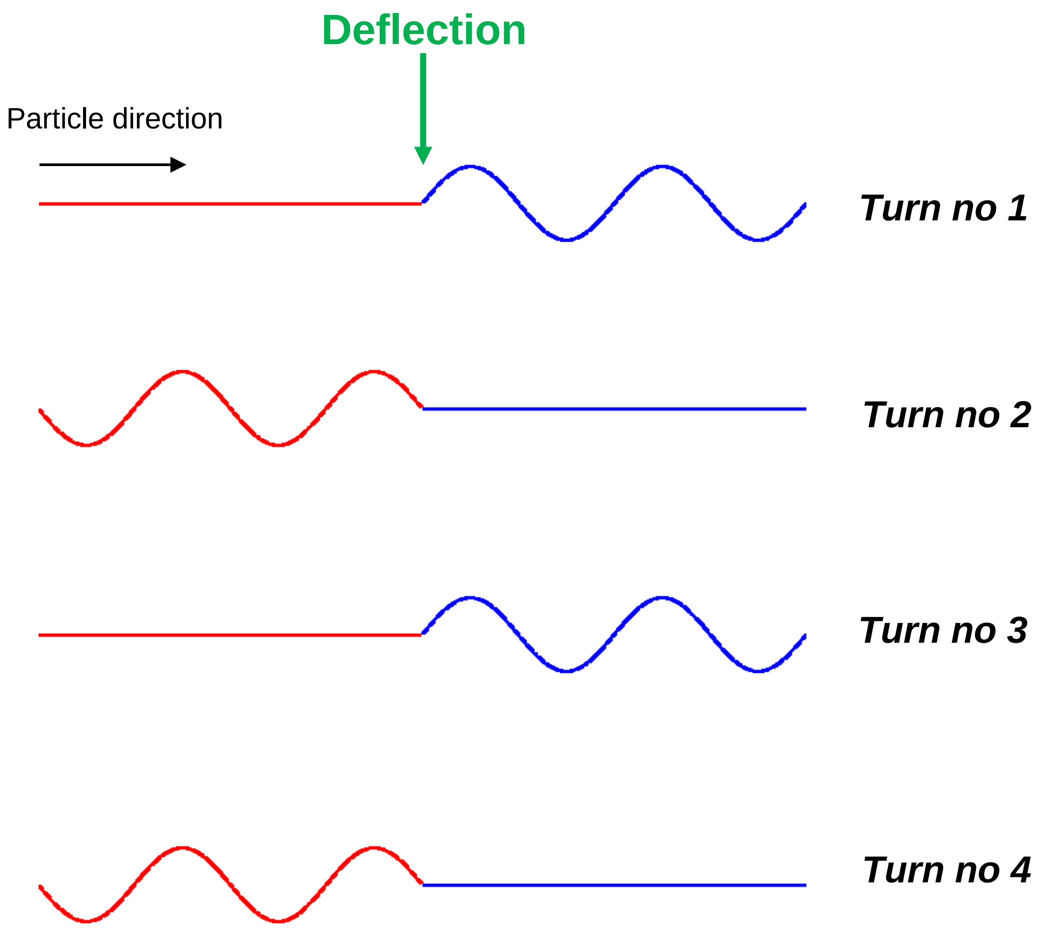


Effect of a deflection

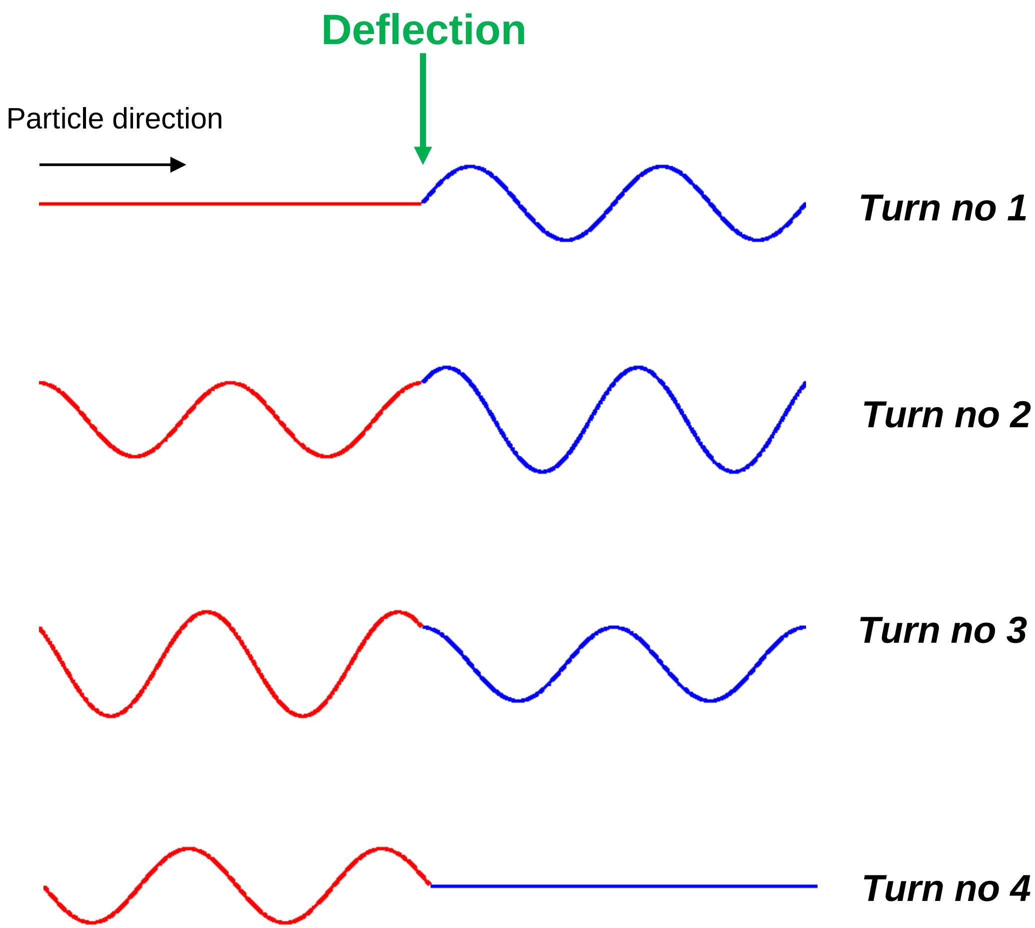


- We set the machine tune to an integer value:
  - $Q = n \in N$
- When the tune is an integer number, **the deflections add up on every turn** !
  - The amplitudes diverge, the particles do not stay within the accelerator vacuum chamber.
- We just encountered our first **resonance** – the <u>integer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

Effect of a deflection



- We set the machine tune to a half integer value:
  - $Q = n+0.5, n \in N$
- 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!

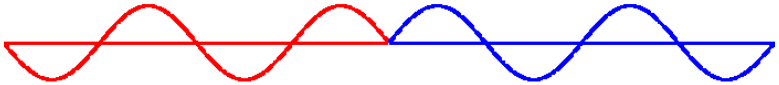


- We set the machine tune to a quarter integer value:
  - $Q = n+0.25$, $n \in N$
- For quarter tune values, **the deflections compensate every four turns** !
  - The amplitudes are stable.
- Also a reasonable working point for Q!

Many turns reveal something

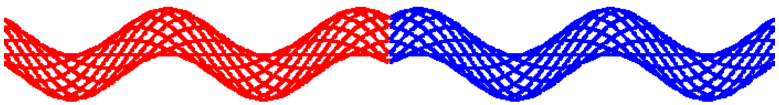
- Let's plot the 50 first turns on top of each other and change Q.
  - All plots are on the same scale

Q = n + 0.5

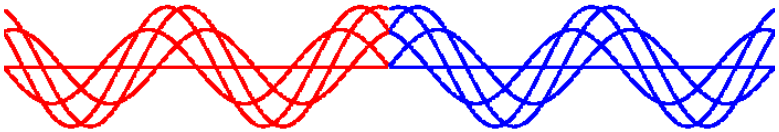


Q = n + 0.4

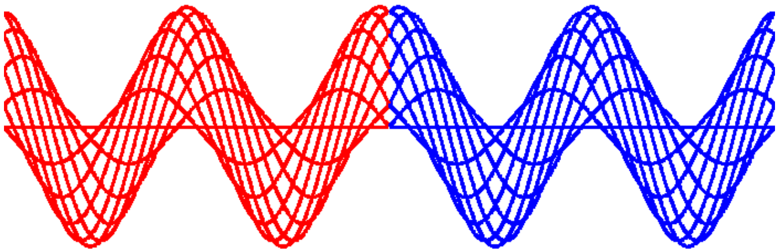
Q = n + 0.3



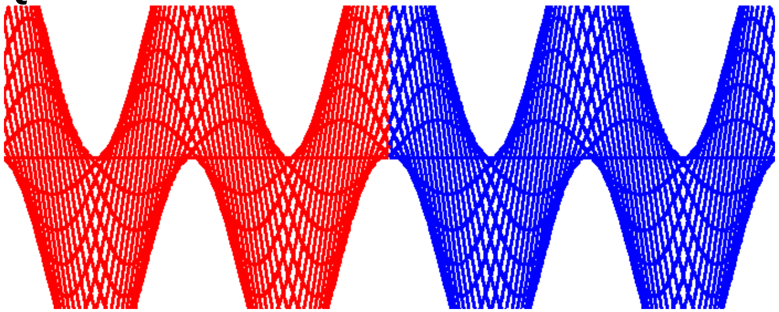
Q = n + 0.2



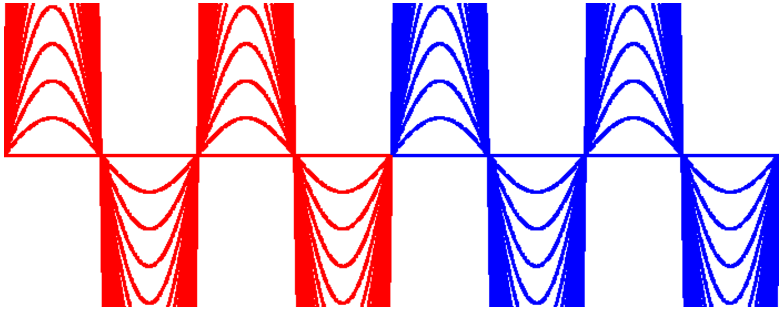
Q = n + 0.1



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

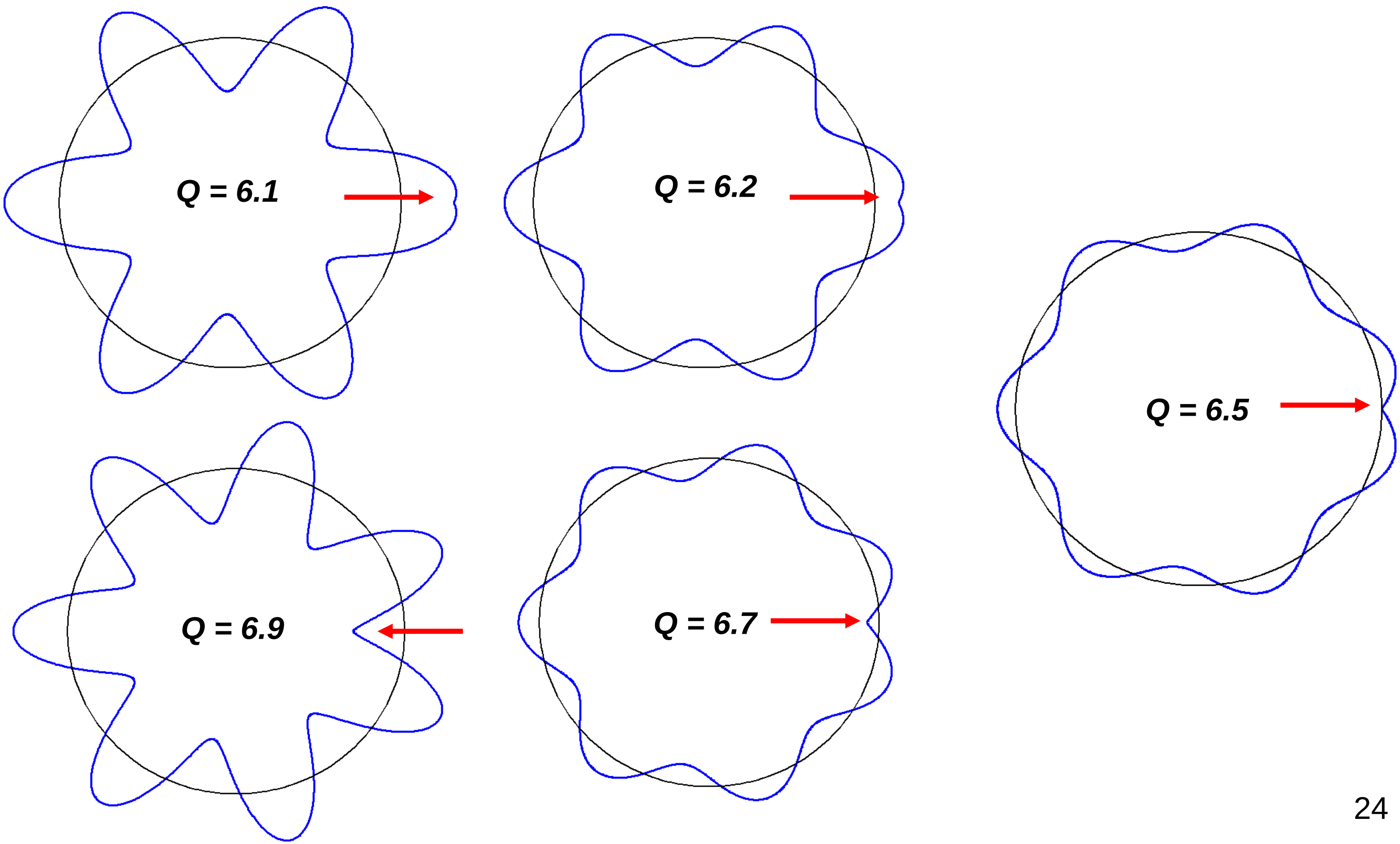
kink at the location of the deflection

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

divergence for Q = n

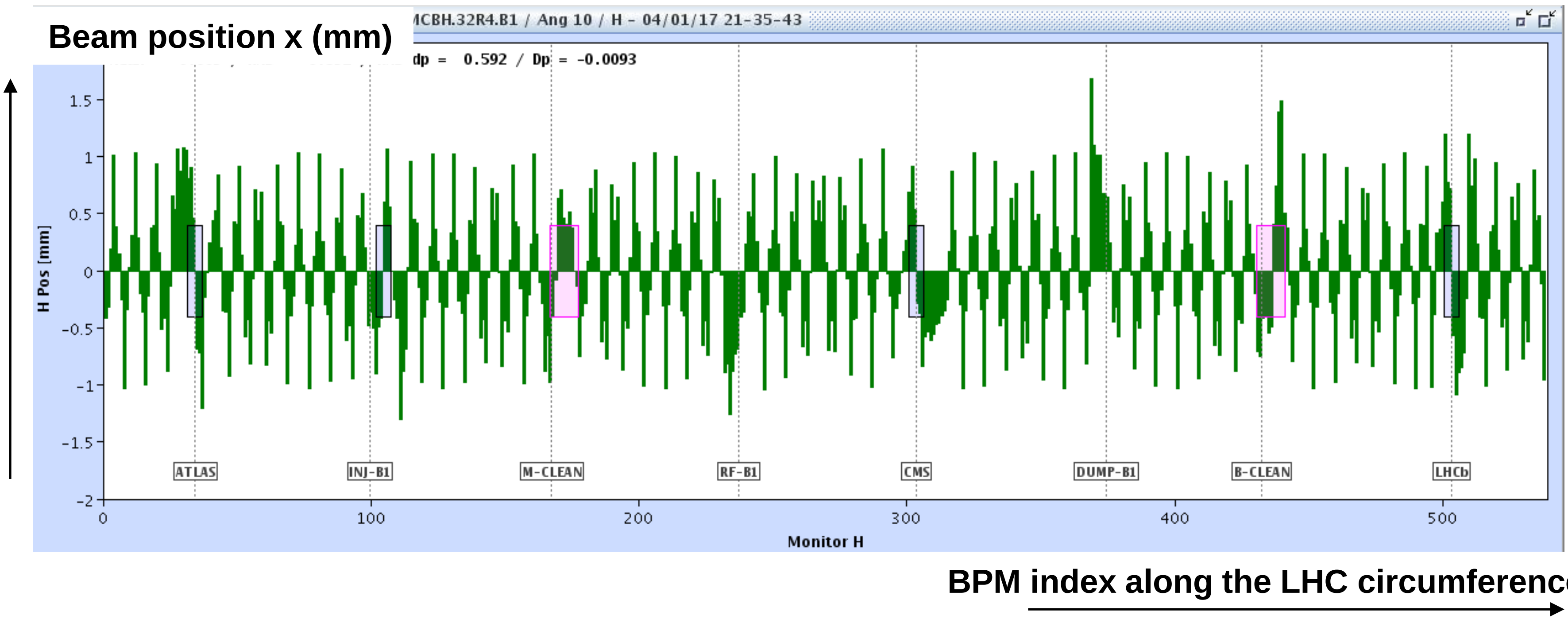
Closed orbit example

- 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.



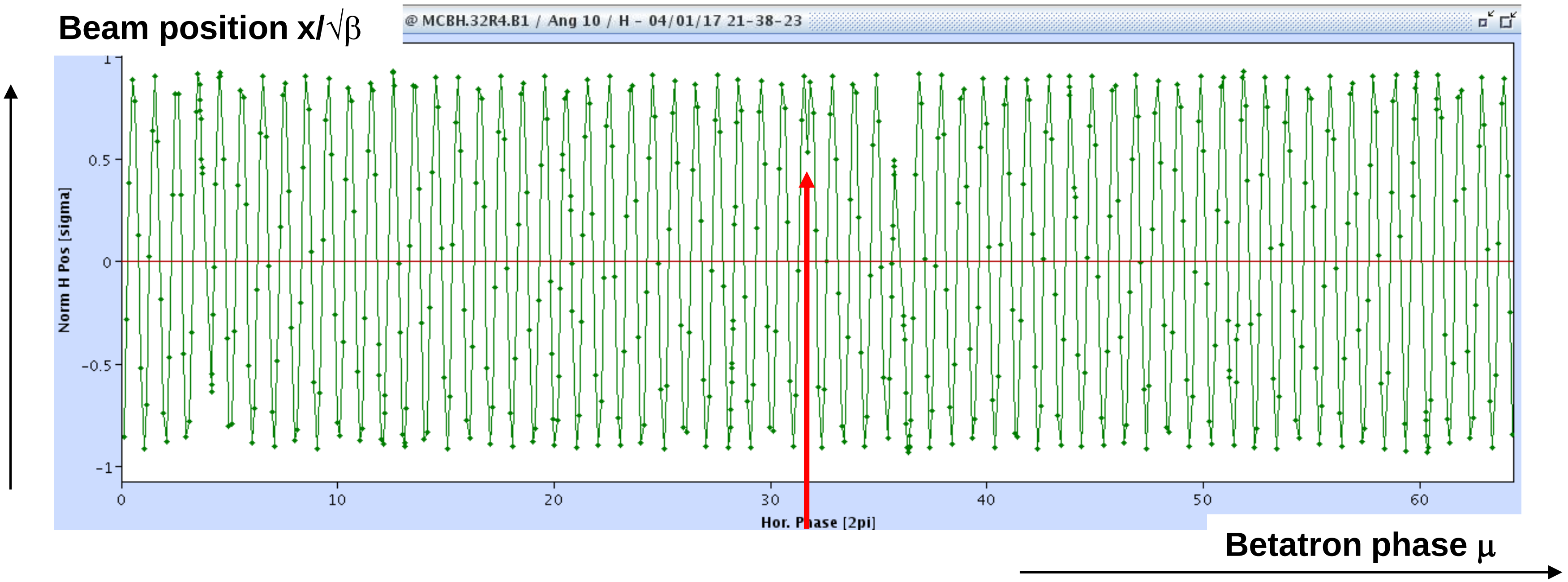
BPM index along the LHC circumference

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).

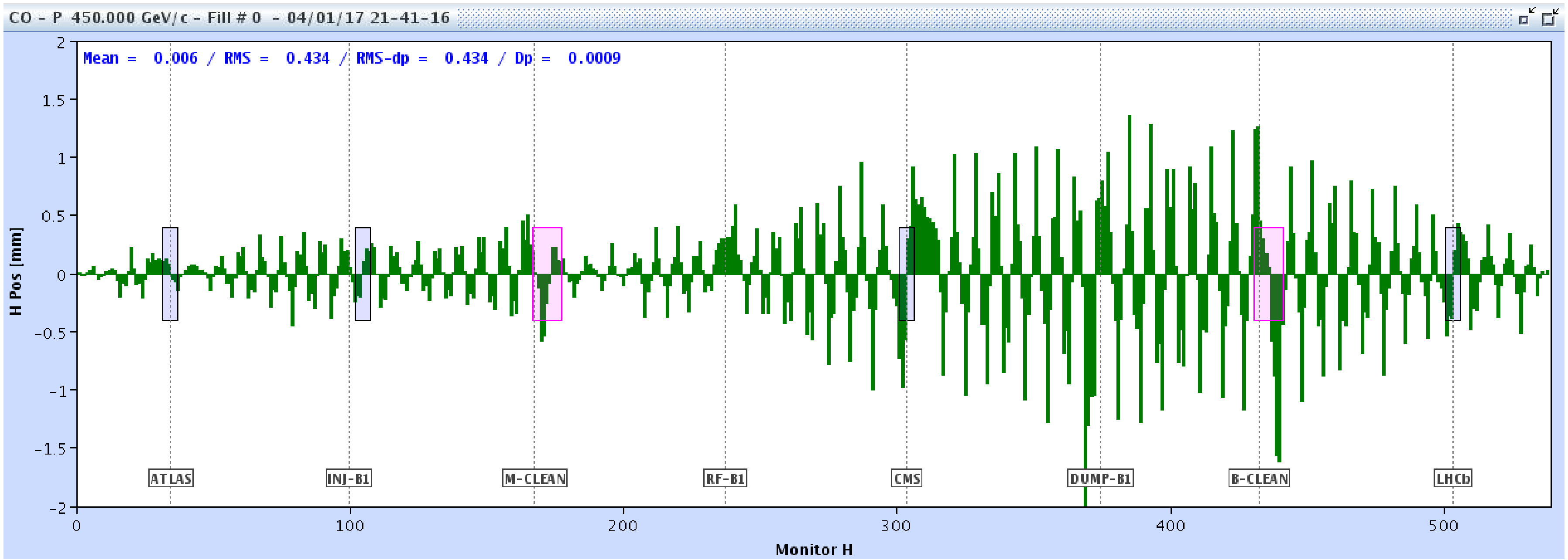
$$\frac{x(s)}{\sqrt{\beta(s)}} = \frac{\sqrt{\beta_\theta}\cos(|\mu(s)-\mu_\theta| - \pi Q)}{2\sin(\pi Q)}\theta \propto \cos(|\mu(s)-\mu_\theta| - \pi Q)$$



Can you localize the deflection now?

A more realistic case at LHC

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



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

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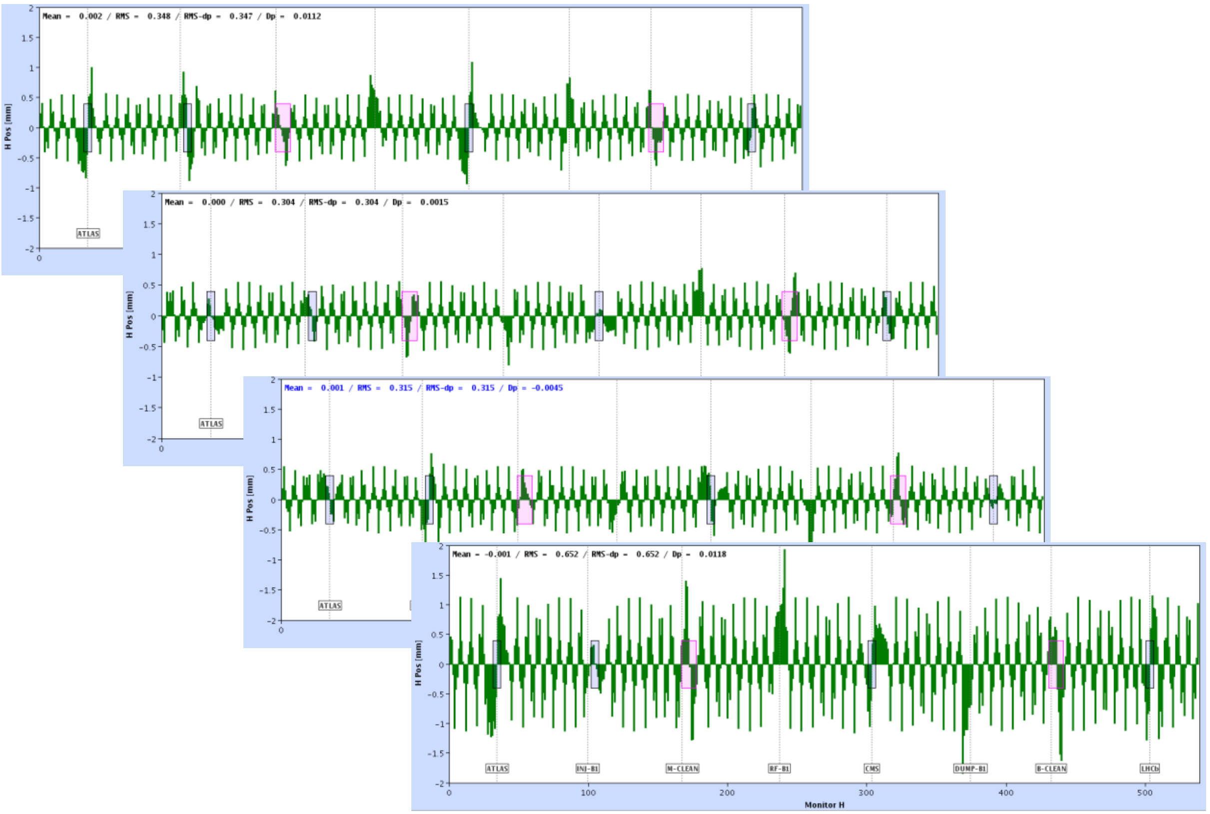
CALL MICADO (A, B, NDIM, M, N, AP, XA, NA, NB, NC, EPS, ITER, DP, X, NX, R, RHO).
```

* 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.



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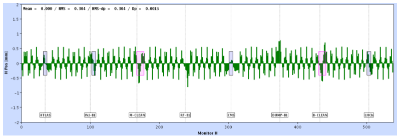
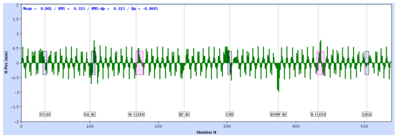
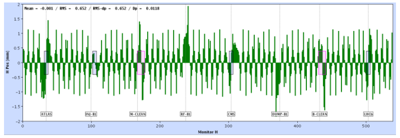
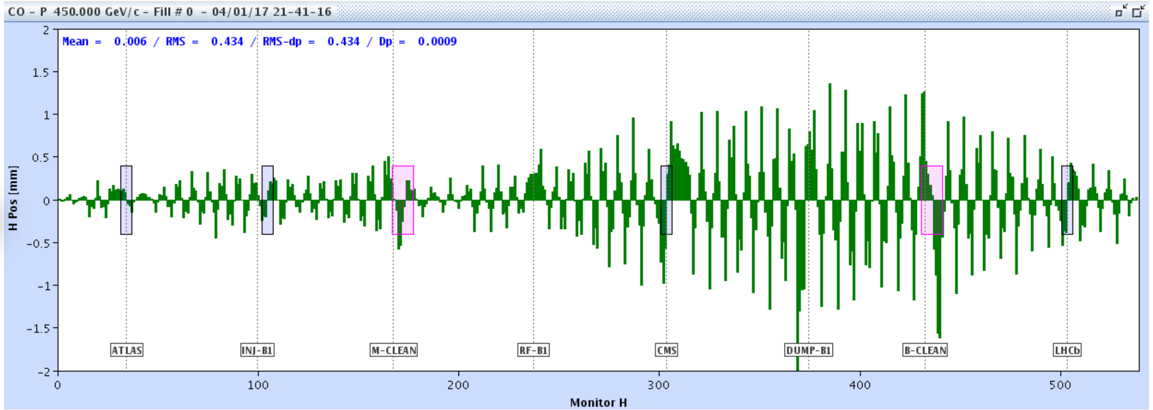
MICADO - how does it work?

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







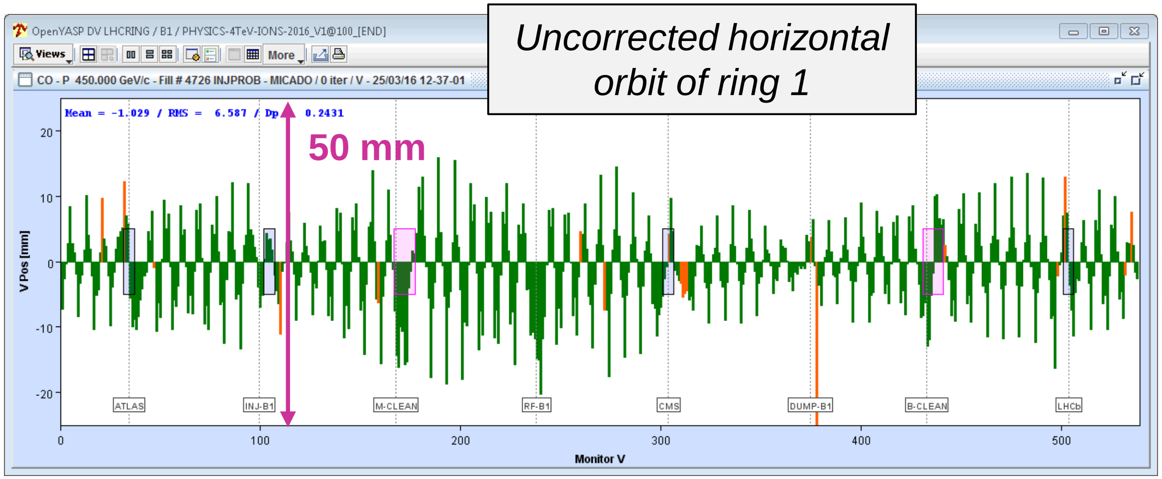


…

- 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).

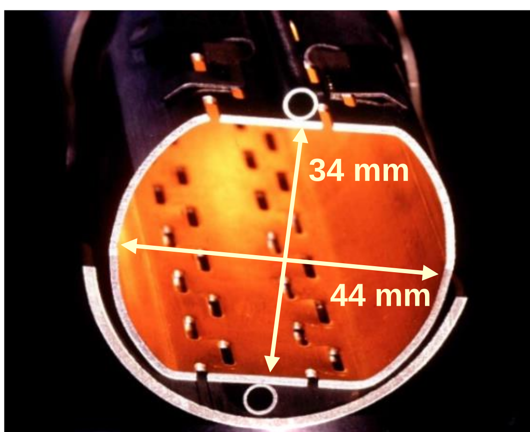
LHC orbit correction example

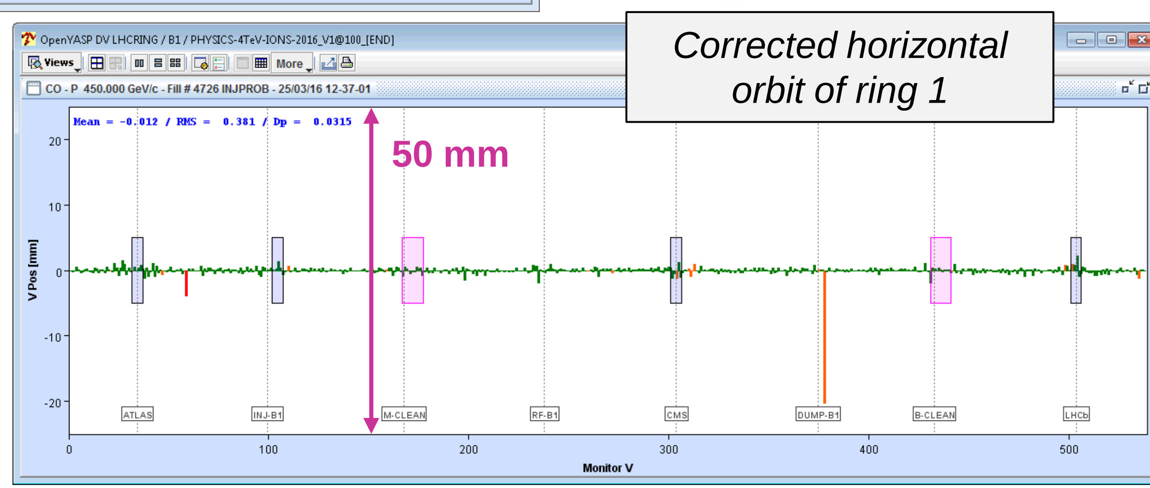
- The raw orbit at the LHC can have huge errors, but the correction (based partly on MICADO) brings the deviations down by more than a factor 20.



MICADO & Co

LHC vacuum chamber





At the LHC a good orbit correction is vital !

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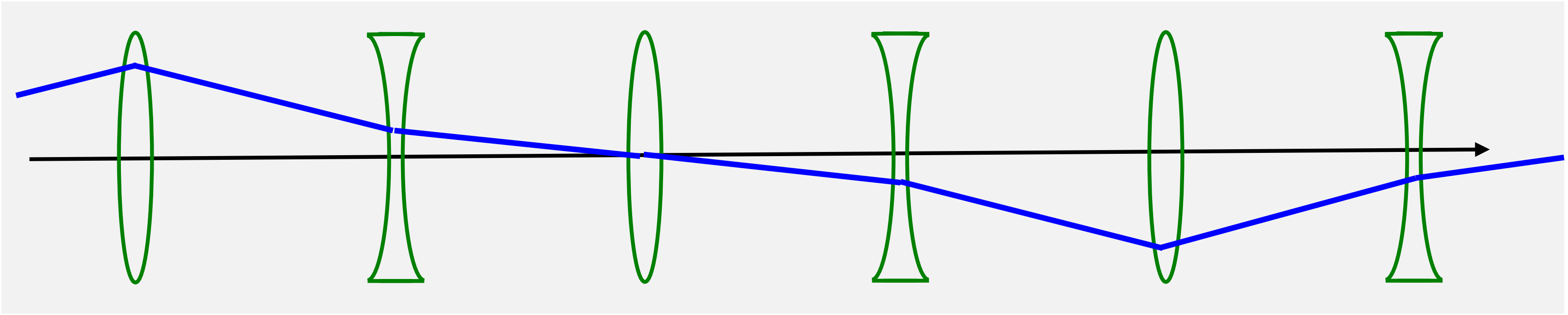
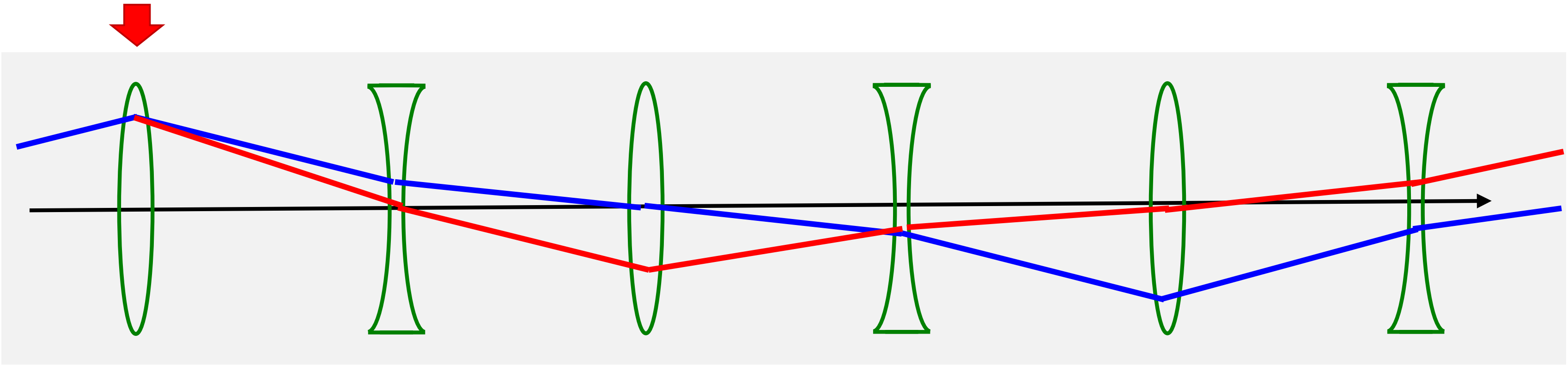
Quadrupole gradient errors

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



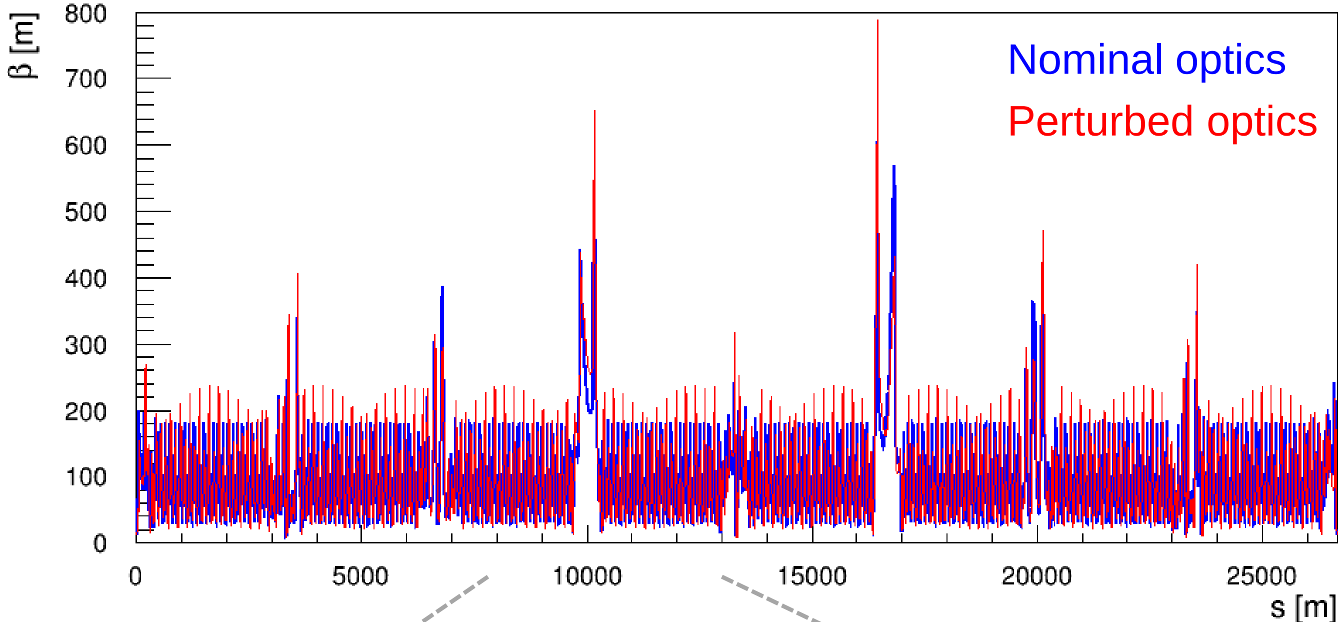
Too strong gradient / lens

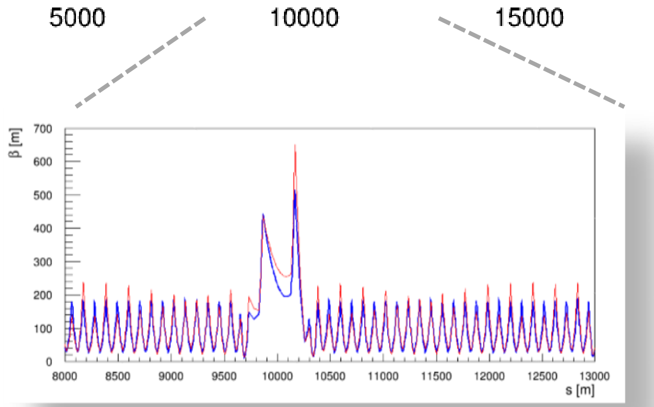


*The oscillation period is affected → **change of tune**, here Q increases !*

- 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

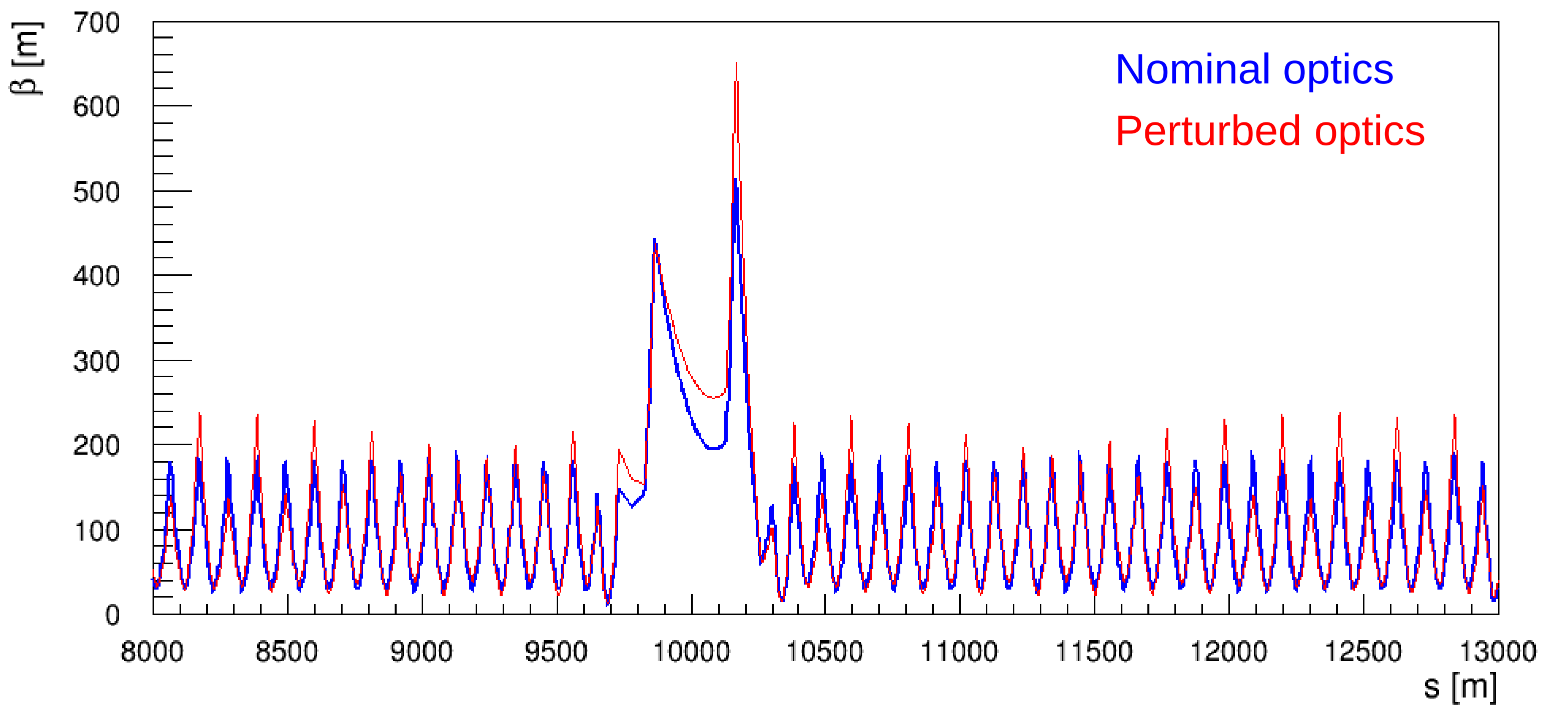




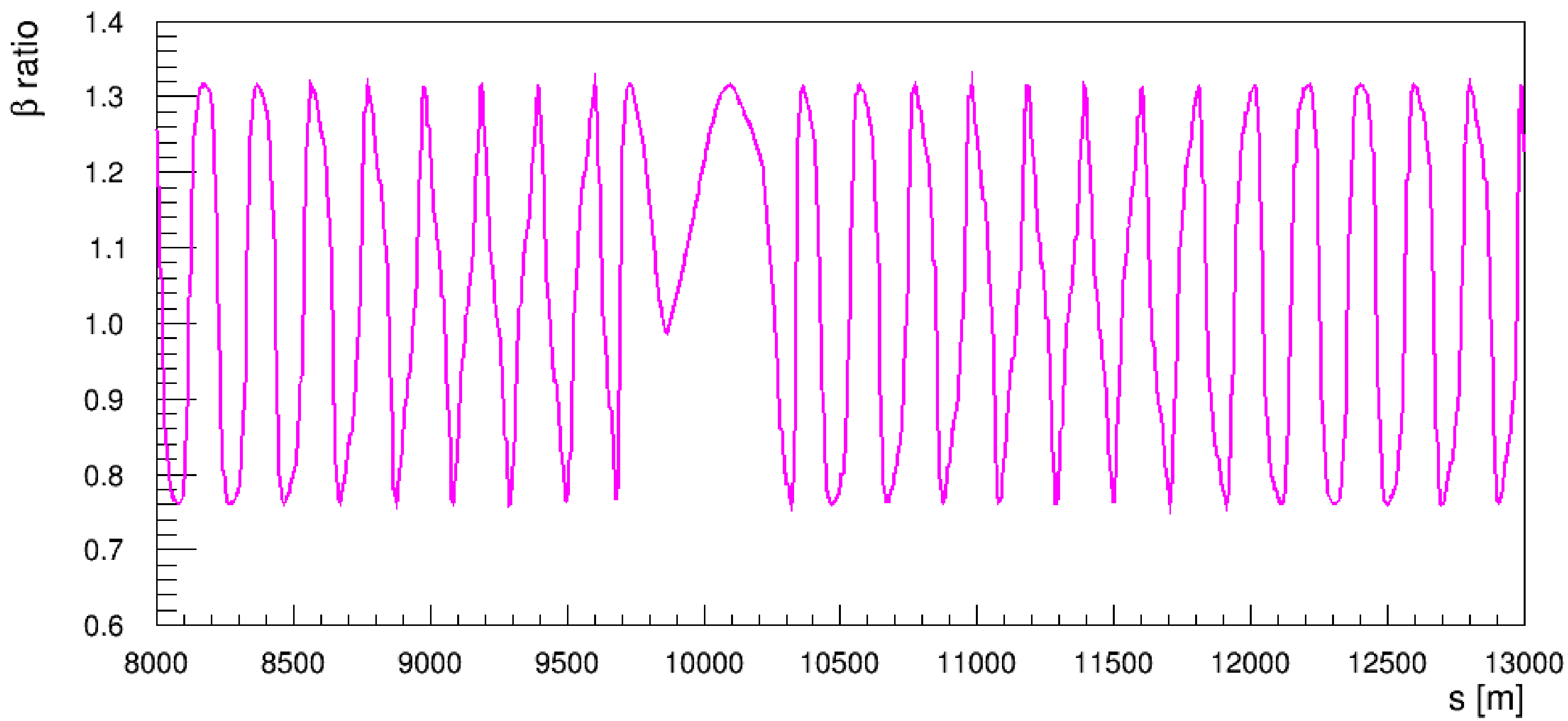
Zoom into a subsection

Optics perturbation

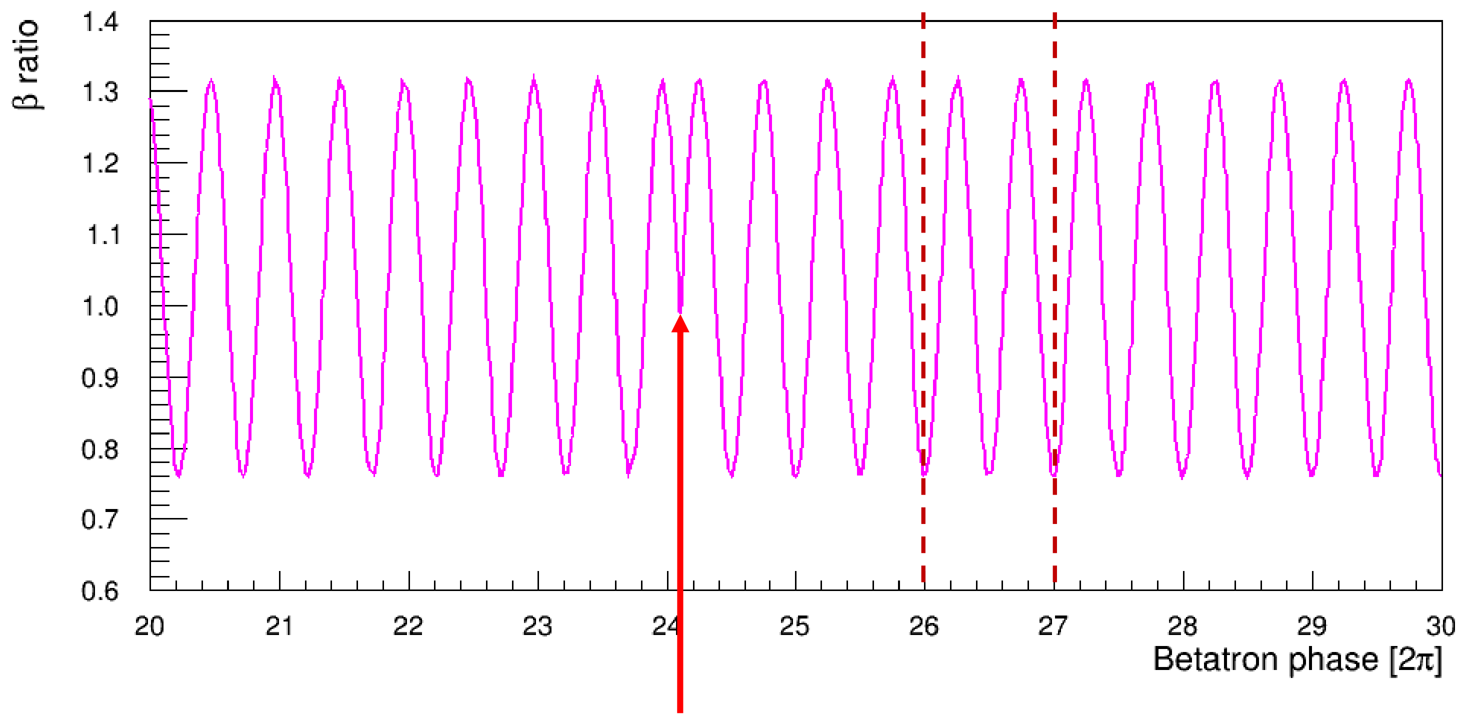
- The local beam optics perturbation… note the oscillating pattern of the error.



- 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 !



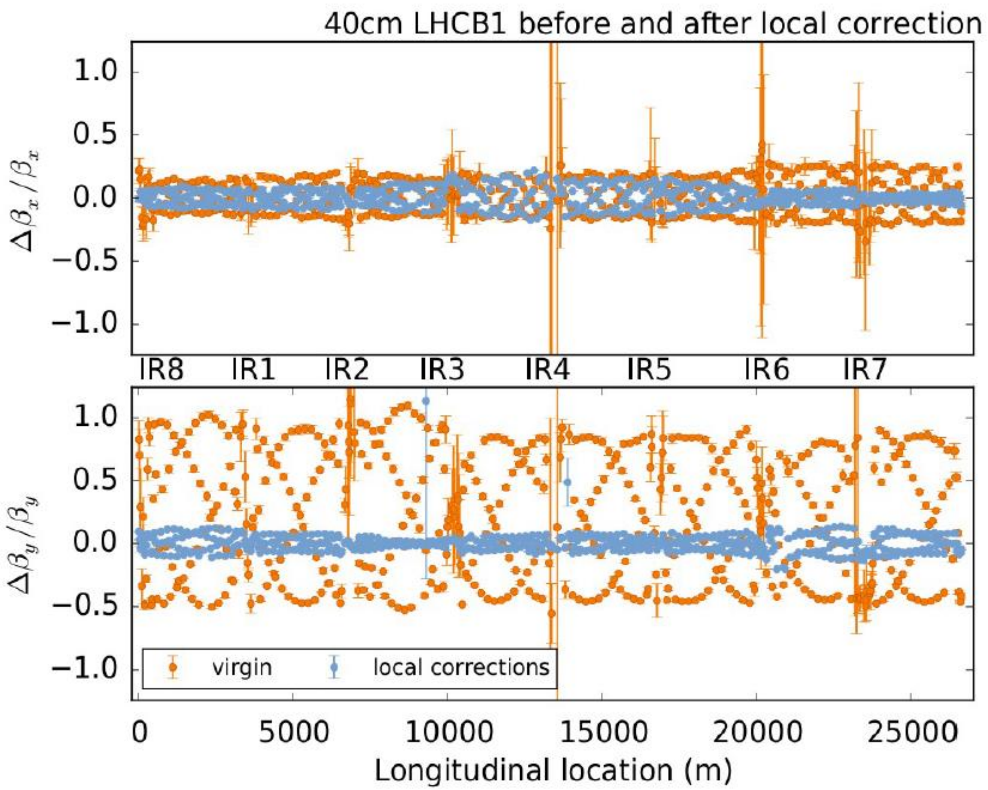
- The beta-beating pattern comes out even more clearly if we replace the longitudinal coordinate with the betatron phase advance.
- The result is very similar to the case of the closed orbit kick, the error reveals itself by a kink !
  - If you watch closely you will observe that there are **two oscillation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

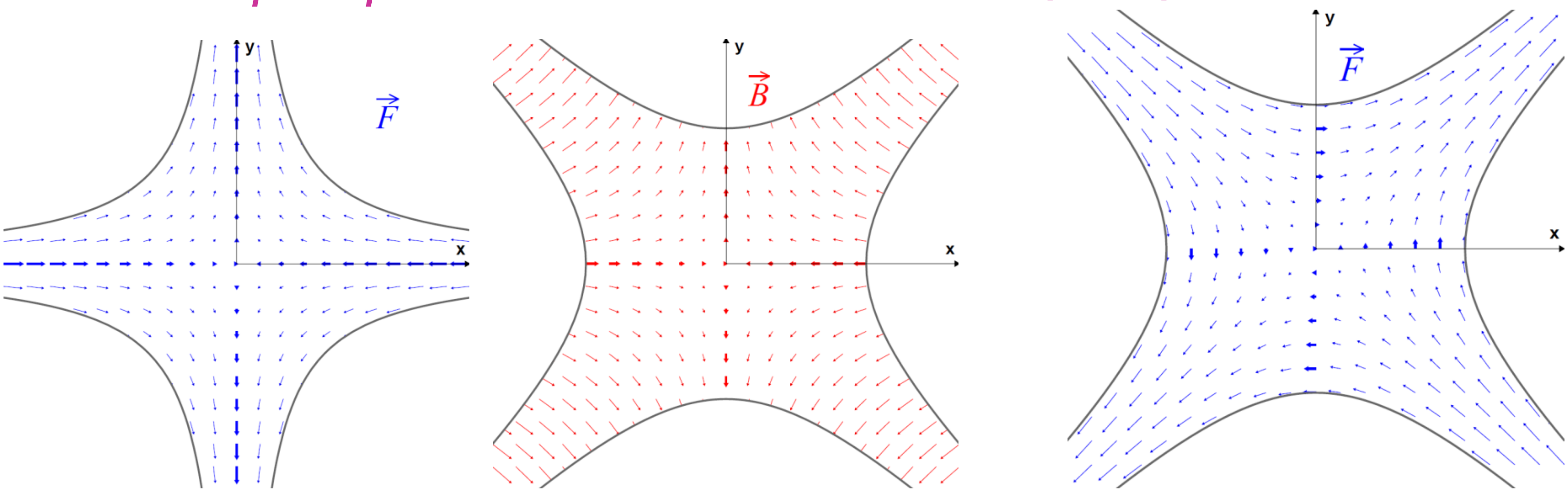
- In collision at top energy of 6.5 TeV, the optics is wrong by 100% before correction.
  - Can be corrected to a few % residual error with modern correction algorithms.



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 ***skew quadrupole***



$$F_x = -k\,x$$
$$F_y = k\,y$$

No mixing of planes

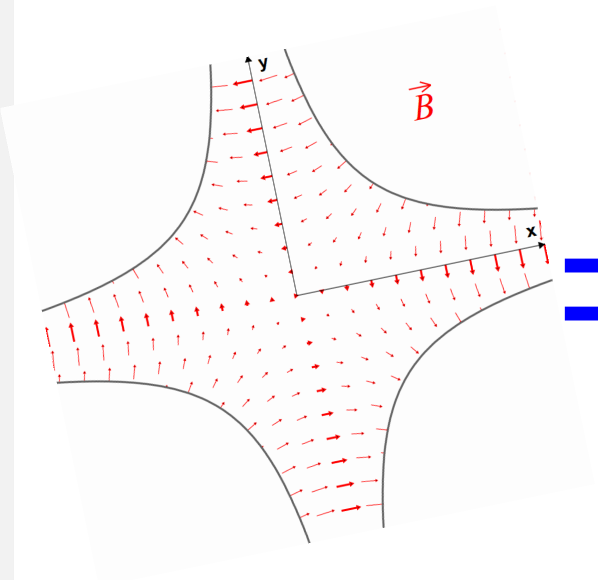
Full mixing of planes

$$F_x = k\,y$$
$$F_y = -k\,x$$

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.

tilted quadrupole ***ideal quadrupole*** ***skew quadrupole***



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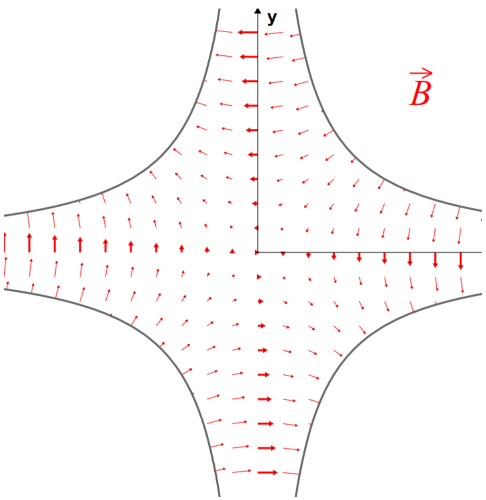

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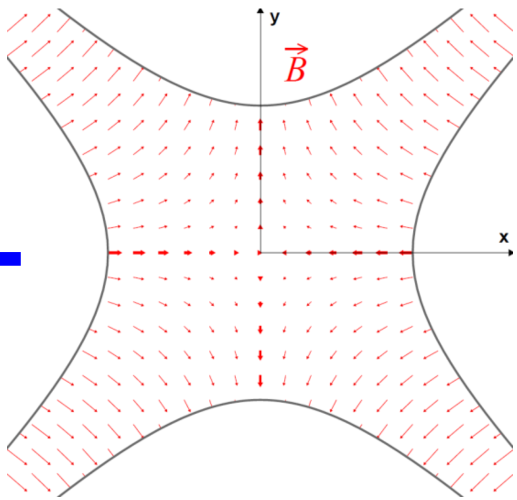
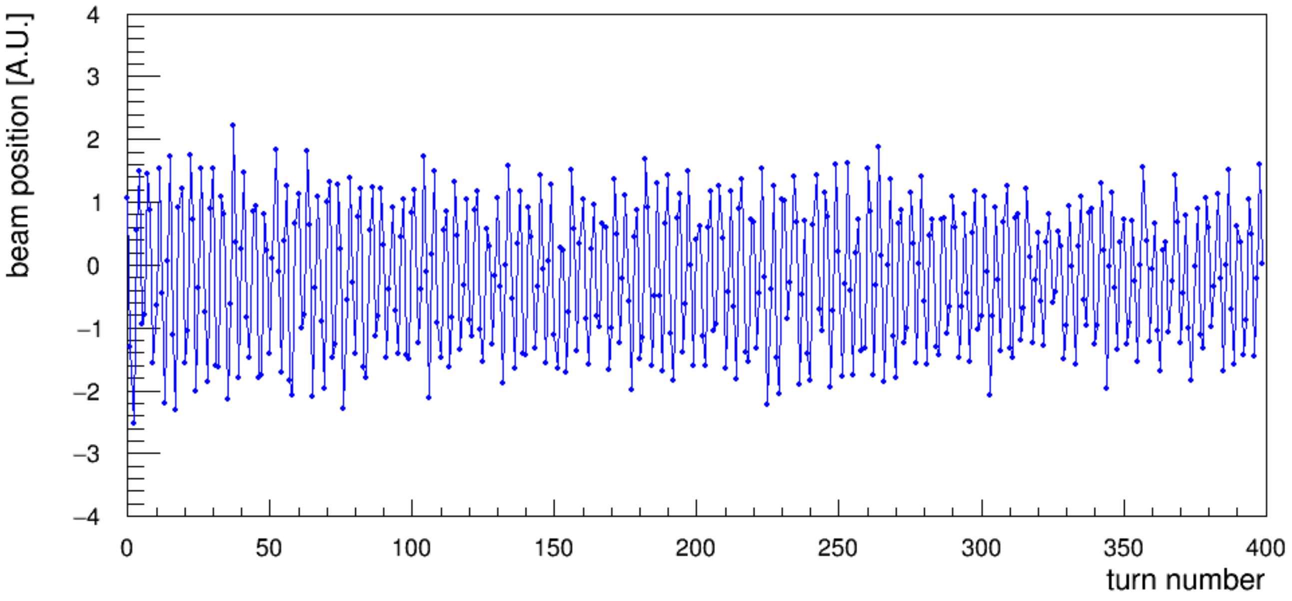


Coupling and tune observation

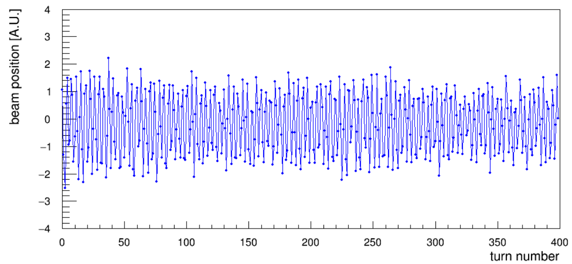
- The simplest thing to determine if there is coupling is to kick the beam in one plane to generate an oscillation, and then observe the oscillations or the frequency content.
  - Or just use the natural beam oscillations if they exist.
- If coupling is present, then for a horizontal kick there will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

Turn by turn recording of the beam position at one BPM



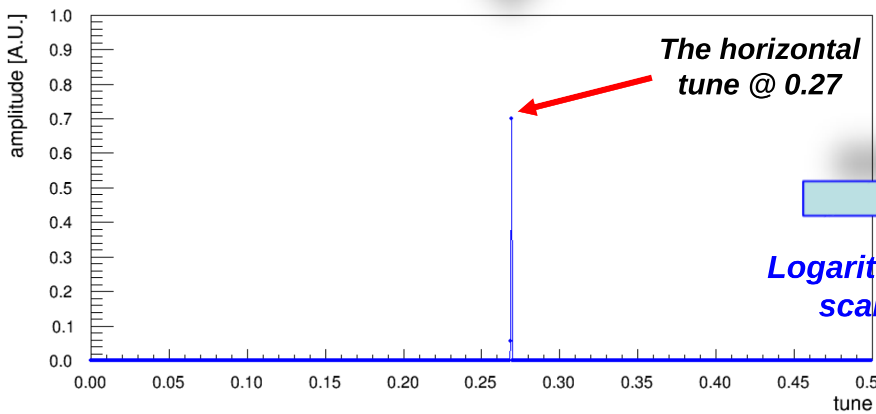
Coupling observation

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

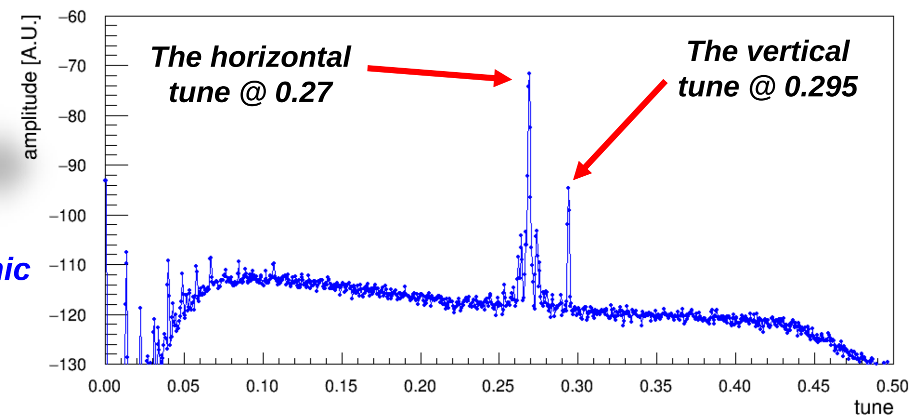


Example : horizontal beam position at a BPM observed turn by turn

Fourrier analysis



Logarithmic scale



- 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.

Linear imperfections, geology and celestial bodies

Earth tides

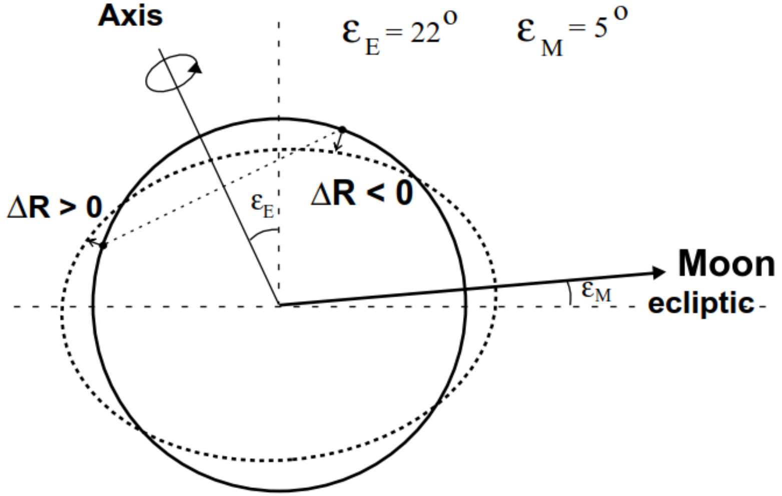
Tide bulge of a celestial body of mass M at a distance d

$$\Delta R \sim \frac{M}{2d^3}(3cos^2\theta - 1)$$

***θ* = angle(vertical, the celestial body)**

induces surface deformations and affects the water levels of the oceans.

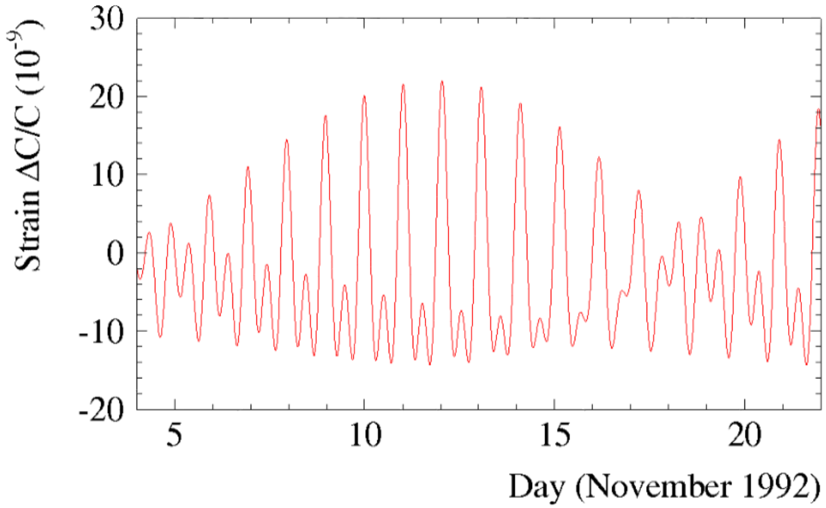
→ impacts the alignment of the entire accelerator !



Such **Earth tides** alter the accelerator circumference:

- The Moon contributes 2/3, the Sun 1/3.
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions possible (~%).

LEP tide predictions for Nov. 1992

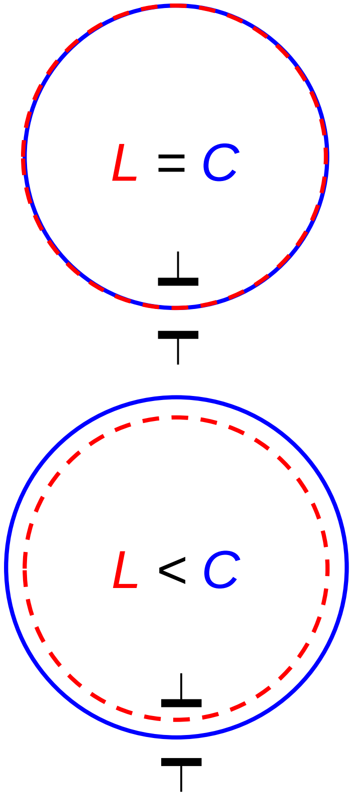


The relative circumference change amounts to ***~10^{-8} ~ 1 mm****.*

Gravitational wave detectors *achieve sensitivities of* ***~10^{-21}*** *!*

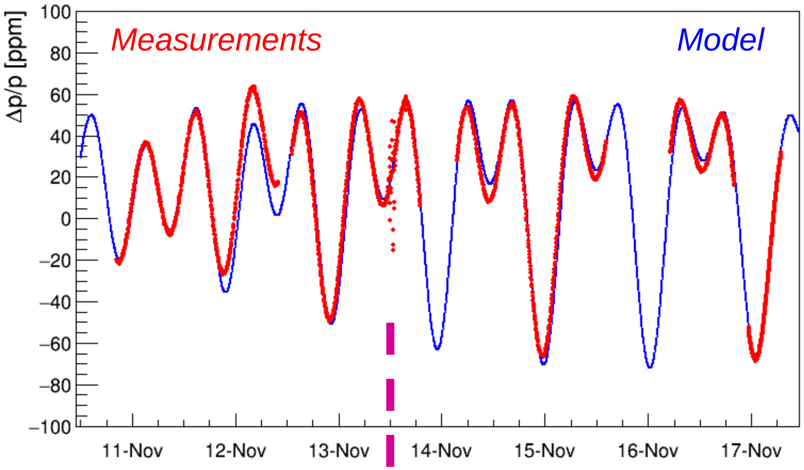
- At the LHC the beams are 'captured' by the RF system which forces the beams to remain synchronous with the RF frequency.
  - Because at LHC the speed ≅ c = constant, this fixes the length of the orbit.

- When the frequency is well adjusted, the length of the orbit ***L*** matches the circumference ***C***.
- If for any reason ***C*** varies, the beam has to move radially if ***L*** is kept constant.
- A mismatch between ***C*** and ***L*** can be observed on the mean radial orbit using the BPMs that move with the ring.
  - As a side effect it also changes very slightly the beam energy (level of 0.01%).



LHC circumference observations

- Tides are observed very clealy on the LHC circumference by measuring the mean radial (=horizontal) beam position.

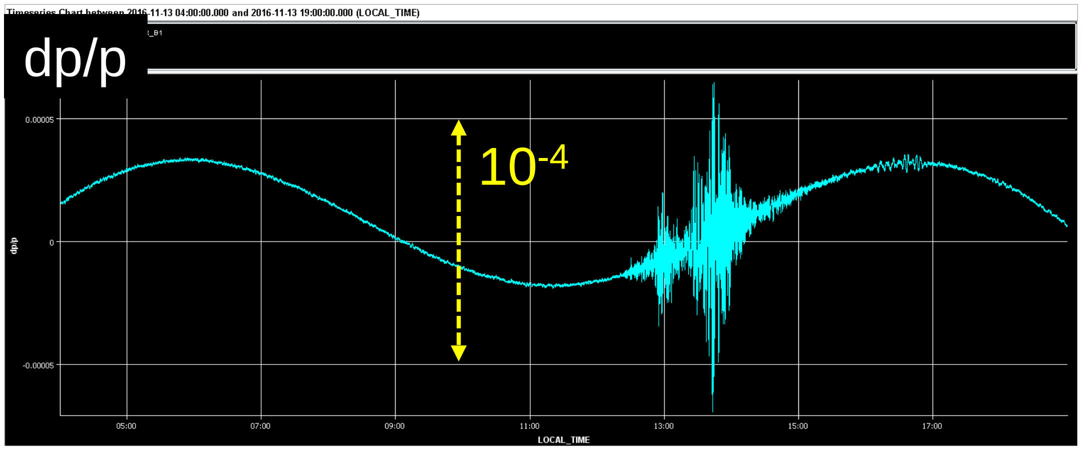


Tide observations (from orbit changes) over one week at 4 TeV in 2016

(expressed in energy change $\Delta p/p$)

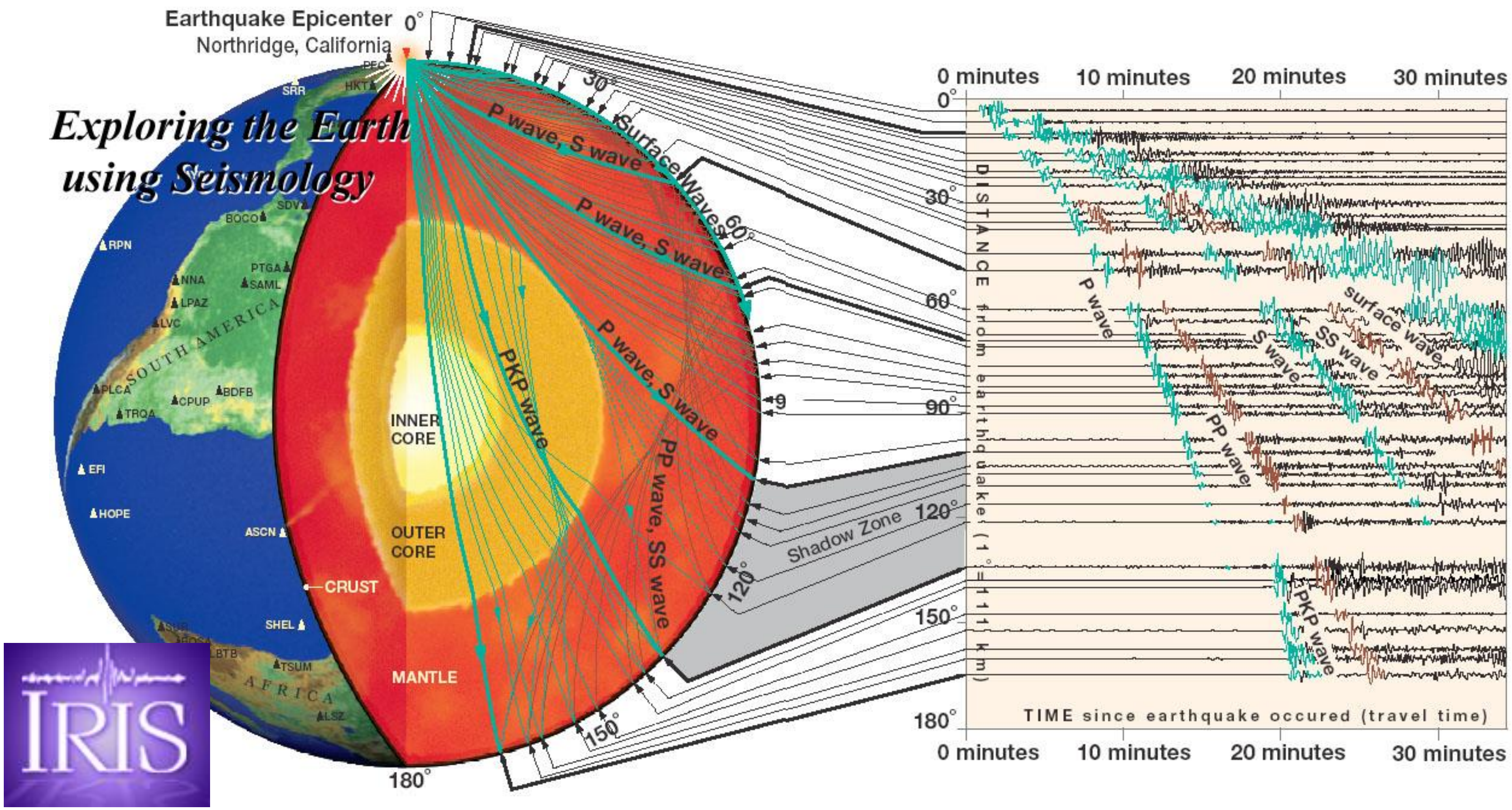
Earthquake in New Zealand

The pressure waves induce a modulation of the circumference



Waves from earthquakes

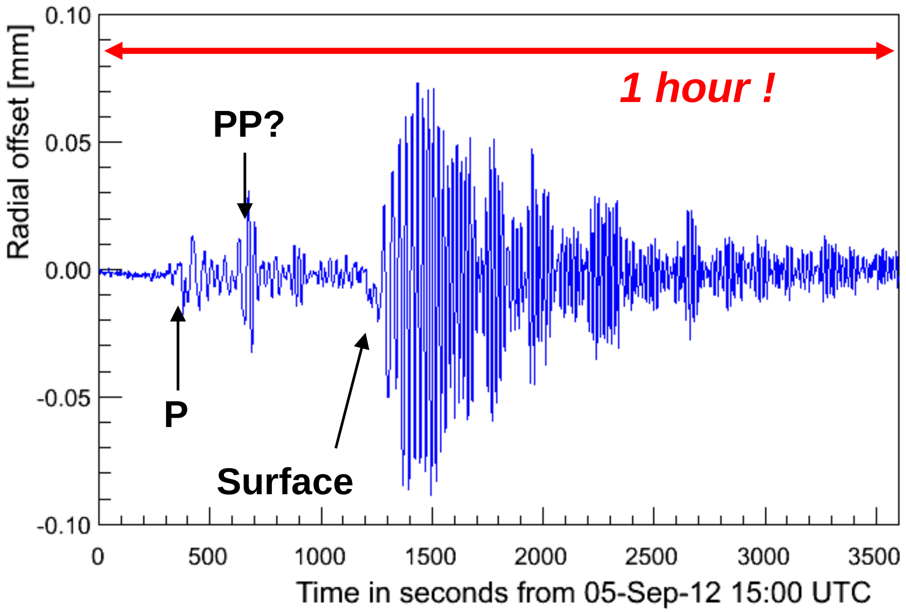
Different types of body (**P**ressure, **S**hear) and surface waves (**R**aleigh, **L**ove), multiple paths and reflections produce a complex signature of earthquakes at seismic measurement stations – also at the LHC.

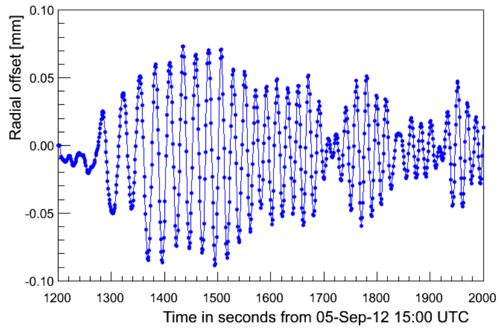


L. Braille (Purdue U.) / The IRIS (Incorporated Research Institutions for Seismology) consortium

Costa Rica earthquake - 2012

- A **magnitude 7.6** earthquake in Costa Rica (05/09/2012 @ 14:42:10 UTC) 'struck' the LHC in **fill 3032** during stable colliding beams.
  - Arrival of the first waves at CERN ~15:06 UTC.





- The arrival of the different waves can be observed on the radial beam position – equivalent to largest tides.

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.