## Basic CAS @ online,

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Introduction
Imperfection - sources
Orbit perturbations
Optics perturbations
Linear imperfections and geology
Summary

## Accelerator lattice cell

- An accelerator is typically build using a number of basic 'cells'.
- The cell layouts of accelerators come in many 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.



## 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.

Lorentz force:

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

orthogonal to the speed and magnetic field directions


Horizontal deflection

$90^{\circ}$ rotation


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 centre - provides focussing of the beam.
- Similar to an optical lens, but a quadrupole is focussing in one plane, defocussing in the other plane.



## Skew quadrupole magnet

- A quadrupole rotated by 45 ('skew quadrupole') produces a force (deflection) in $x$ that depends on $y$ and vice-versa: such a magnet couples horizontal and vertical plane.

skew quadrupole

$$
F_{x}=-k x \underset{\substack{\text { No mixing of } \\ \text { planes }}}{ }
$$




$$
\begin{array}{ll}
\begin{array}{l}
\text { Full mixing } \\
\text { of planes }
\end{array} & F_{x}=k y \\
& F_{y}=-k x
\end{array}
$$

N-pole magnets

- The concept of normal / skew quadrupole can be applied to any 2N-pole magnet.
- Normal variant - generally referred to as $B_{N}$,
- Skew variant - generally referred to as $\mathrm{A}_{\mathrm{N}}$, rotated by $180^{\circ} / 2 \mathrm{~N}$ wrt $B_{N}$.
- Examples:

Dipole $\mathbf{N}=1$
Sextupole N=3
$\longrightarrow \mid$


## Recap on beam optics

- Quantities related to a beam optics in a circular accelerator will be needed for the lecture:
- The betatron function ( $\beta$ ) that defines the beam envelope,
- Beam size / envelope is proportional to $\sqrt{ } \beta$
- The betatron phase advance ( $\mu$ ) 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.

- This periodic oscillation is called the betatron oscillation.


## Recap on beam optics for pedestrians

- The number of oscillation periods over one machine turn is called the machine tune (Q) or betatron tune.
- In this example $Q$ is around $2.75-2$ periods and $3 / 4$ of a period.

- With coordinate change (from longitudinal position in meters to betatron phase advance in degrees) this 'rocky' oscillation is transformed into a sinusoidal oscillation.
- Convenient and simple way to analyse the beam motion.



## Introduction

## Imperfection - sources

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## Imperfections

- The first step in the design phase of an accelerations consists in building an "ideal" accelerator where all magnets have nominal fields and are perfectly aligned along the design trajectory.
a But quite rapidly the designer must confront the real world, and tolerances on errors (= imperfections) must be defined to provide specifications for component design, manufacturing and alignment.
- What is the precision on field quality?
- What is the precision and stability of the power converter that feeds current into a magnet?
- What is the tolerance on the component alignment?
- ...
- This lecture will discuss the impact of the simplest form of imperfections, the linear imperfections.


## 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 magnets.
- Imperfections (= errors) in the real accelerator optics can be introduced by uncertainties or errors on:
- Beam momentum, magnetic field model and power converter regulation.
Magnet
strength

| (angle, focal |
| :---: |
| length...) |


| Magnetic field |
| :---: |
| or gradient |
| momentum |

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 a linear collider like CLIC!
- At the CERN hadron machines we aim for accuracies of around 0.1-0.3 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 !

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## Imperfection - undesired deflection

- Linear imperfections are the simplest form of machine errors involving dipole and quadrupole fields - let us start with dipole fields.
- 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 into a machine, or when a beam is launched into a linac.
- 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.
- What causes an unintended deflection to 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.



## Coupling

- A small rotation (misalignment) of a quadrupole leads to coupling between horizontal and vertical plane which is generally not desired.
- The rotated quadrupole can be represented as a perfectly aligned quadrupole plus a small skew quadrupole.
tilted quadrupole

ideal quadrupole

skew quadrupole



## 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 integer resonance that occurs when $\mathrm{Q}=\mathrm{n} \in \mathrm{N}$


## Effect of a deflection

Particle direction


Turn no 1

Turn no 2

## Turn no 3

Turn no 4

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



Turn no 1


Turn no 2


Turn no 3

- Also a reasonable working point for Q!

Turn no 4

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

$Q=n+0.1$

$Q=n+0.2$

- The particles oscillate around a stable mean value $(Q \neq n)$ !
- The amplitude diverges as we approach $\mathrm{Q}=\mathrm{n} \rightarrow$ integer resonance
- 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.
$\square$ The general expression of the closed orbit $x(s)$ in the presence of a deflection $\theta$ is:



## 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 $(\rightarrow$ ) can be used to localize the deflection (if it is not known) $\rightarrow$ can be used for orbit correction.



## A deflection at the LHC

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


Where is the location of the deflection?

## A deflection at the LHC

- To make our life easier we divide the position by $\sqrt{ } \beta(s)$ and replace the BPM index by its phase $\mu(\mathrm{s})$.

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



Can you localize the deflection?

## A more realistic case at LHC

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


How do we proceed to correct?

## Orbit correction

- Nowadays there are two main approaches for orbit correction:
- Matrix inversion algorithms relying on the knowledge the response $\mathbf{R ( s )}$.
- $R(s)$ is measured or calculated.
- Popular algorithms: MICADO and SVD (Singular Value Decomposition), both come with many variants.
- Machine learning with a neural network that is trained to find a solution.
- The training may be based on data or on a model, or on continuous reward-like training.
- Inversion algorithms have the advantage of higher intrinsic flexibility (correction quality and flexibility, noise reduction,...), they can be reused at different machines without need for tuning - they are 'universal'.
- Machine learning based technique are adapted to situation where the models are difficult to establish, change over time, for example in low energy machines and some linacs. A model trained on a certain machine cannot be reused elsewhere.


## Example of model inversion

- Preparation: a model of the machine has to be obtained, i.e. for each orbit corrector the expected orbit response $\mathrm{R}(\mathrm{s})$ has to be measured or computed.



## Example of model inversion - MICADO

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

- MICADO 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.


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 $\rightarrow$ 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.

- 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 more clearly when the longitudinal coordinate is again replaced by the betatron phase advance.
- The result is very similar to the case of the closed orbit kick, the error reveals itself by a kink !
- Watching closely one can observe that there are two oscillation periods per $2 \pi(360 \mathrm{deg})$ phase. The betabeating frequency is twice the frequency of the orbit !



## LHC optics correction

- Correction strategies for optics / beta-beating rely on similar principles than for orbit correction.
- Inversion algorithms - it is possible to iteratively use the similar algorithms than for orbit correction, although good optics corrections require a larger variety of analysis/fitting tools.
- Machine learning.
- Example for optics correction: at top energy of 6.5 TeV, the LHC optics errors cam be as large as 100\% before correction.
- Can be corrected to a few \% residual error with modern correction algorithms if there are enough quadrupoles that can be individual powered.

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## Linear imperfections, geology and celestial bodies

## Earth tides

## Tide bulge of a celestial body of mass $M$ at a

 distance $d$$$
\Delta R \sim \frac{M}{2 d^{3}}\left(3 \cos ^{2} \theta-1\right) \quad \begin{aligned}
& \theta=\text { angle(vertical, the } \\
& \text { celestial body) }
\end{aligned}
$$

induces surface deformations and affects the water levels of the oceans.
$\rightarrow$ impacts the alignment of a large 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 $\sim 10^{-8} \sim 1 \mathrm{~mm}$ - resolution ~ $\mathbf{1 0}^{-11}$

Gravitational wave detectors achieve sensitivities of $\sim 10^{-21}$ !

- 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 $\cong \mathrm{c}=$ constant, this fixes the length of the orbit.
- When the frequency is well adjusted, the length of the orbit $L$ matches the circumference $\boldsymbol{C}$.
- If for any reason $\boldsymbol{C}$ varies, the beam has to move radially if $L$ is kept constant.
- A mismatch between $\boldsymbol{C}$ 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 clearly on the LHC circumference by measuring the mean radial (=horizontal) beam position.



## Waves from earthquakes

Different types of body (Pressure, Shear) and surface waves (Raleigh, Love), multiple paths and reflections produce a complex signature of earthquakes at seismic measurement stations - also at the LHC.


## Costa Rica earthquake - 2012

$\square$ A magnitude 7.6 earthquake in Costa Rica (05/09/2012 @ 14:42:10 UTC) 'struck' the LHC in fill 3032 with 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.


## ... and there's the man-made waves

- HL-LHC has built huge underground structures in LHC points 1 and 5 .
- Civil engineering is not famous for working 'quietly' !
- Noise also means vibrations, vibrations mean moving magnets !

- In the early part of the CE work, an important volume of soil was moved around and compacted while LHC was operating.
- Ground compactors compact soil by... vibrating.
- ...and they managed to shake the beams colliding at the IP ~100 m underground.


## Mechanism:

- The vibrations with frequencies $\mathbf{\sim} \mathbf{2 0} \mathbf{~ H z}$ were transmitted through 100 m of rock to the tunnel magnets and their supports that resonate in the frequency range $8-22 \mathrm{~Hz}$.
- The resonant excitation generated ~ micrometer amplitude beam movements that were clearly visible on the CMS experiments luminosity (= rate of collisions).

- At first order magnetic field and misalignments errors of accelerator components induce:
- Errors on the beam orbit,
- Errors on the optics and the tune.
- The errors are often sufficiently large that modern machines operate poorly or not at all.
- Fortunately ever improving tools and algorithms have been developed over the past 50 years to correct such errors.
- However to minimize the imperfections from the start it is important to have:
- the best possible magnet (component) design,
- well measured magnetic fields,
- precise power converters,
- the best possible machine alignment.


## Thank you for your perfect attention!

