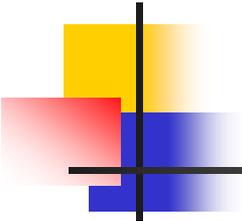


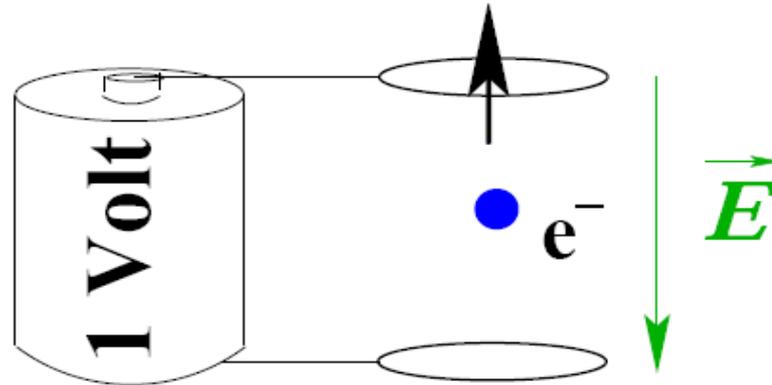
The LHC: Physics without mathematics !

D. Brandt, CERN



Some generalities ...

Units: the electronvolt (eV)



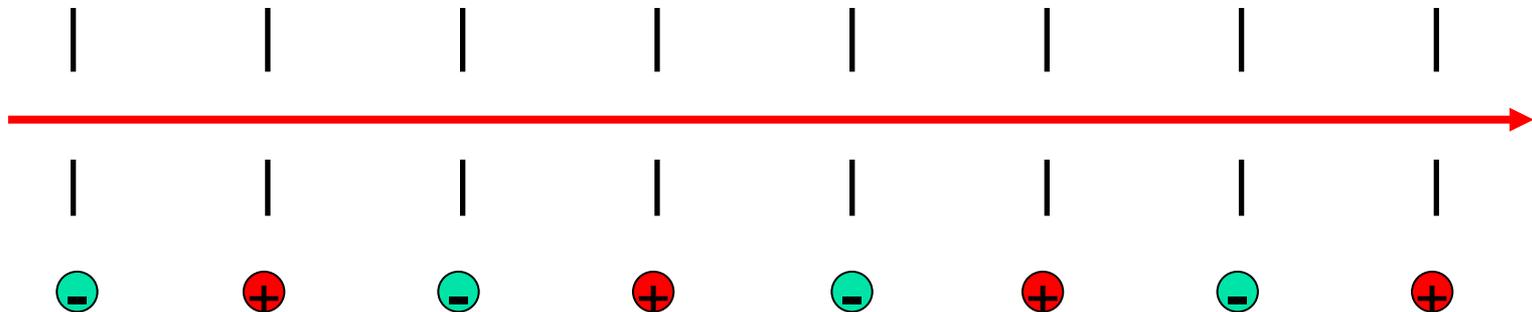
The **electronvolt (eV)** is the energy gained by an electron travelling, in vacuum, between two points with a voltage difference of 1 Volt. **$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ Joule}$**

We also frequently use the electronvolt to express masses from $E=mc^2$: **$1 \text{ eV}/c^2 = 1.783 \cdot 10^{-36} \text{ kg}$**

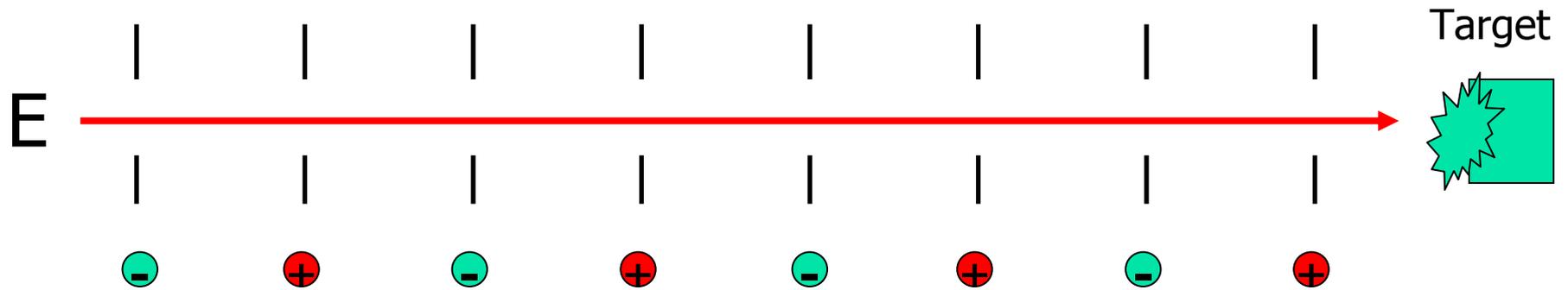
What is a Particle Accelerator?

➤ a machine to accelerate some particles ! **How is it done ?**

➤ Many different possibilities, but rather easy from the general principle:



Ideal linear machines (linacs)

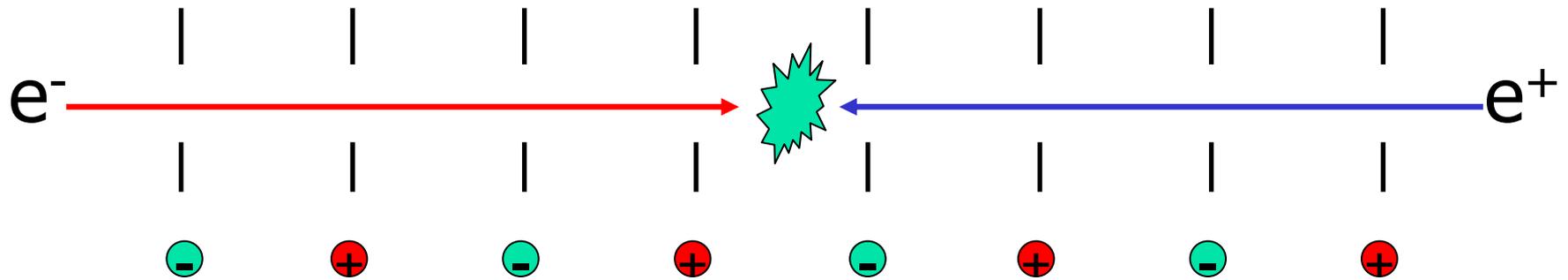


Available Energy : $E_{c.m.} = m \cdot (2+2\gamma)^{1/2} = (2m \cdot (m+E))^{1/2}$
with $\gamma = E/E_0$

Advantages: Single pass
High intensity

Drawbacks: Single pass
Available Energy

Improved solution for $E_{c.m.}$



Available Energy : $E_{c.m.} = 2m\gamma = 2E$

with $\gamma = E/E_0$

Advantages: High intensity

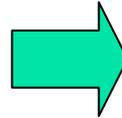
Drawbacks: Single pass

Space required

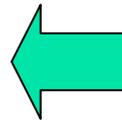
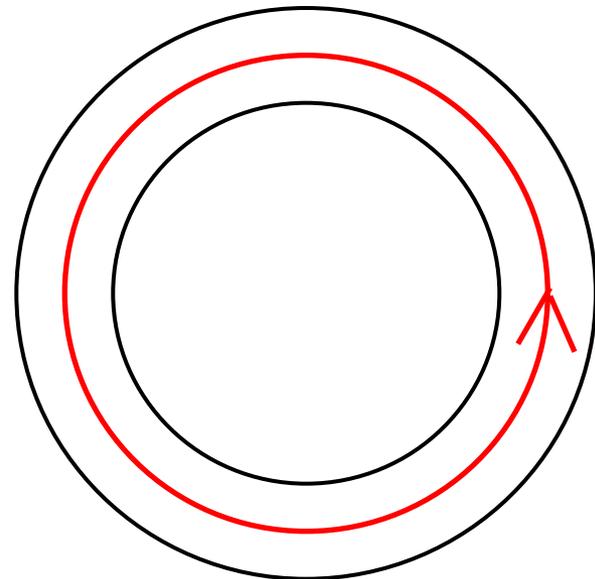
Keep particles: circular machines

Basic idea is to keep the particles in the machine for many turns.

Move from the linear design



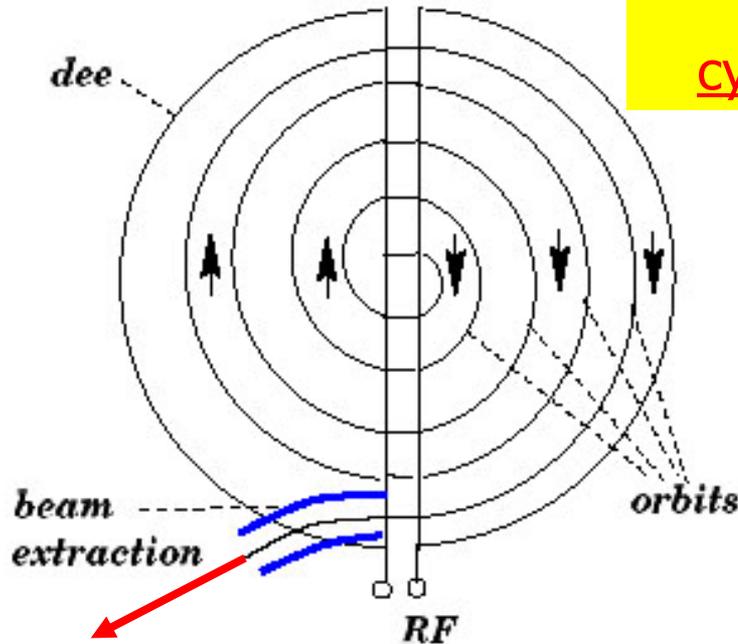
To a circular one:



➤ Need Bending

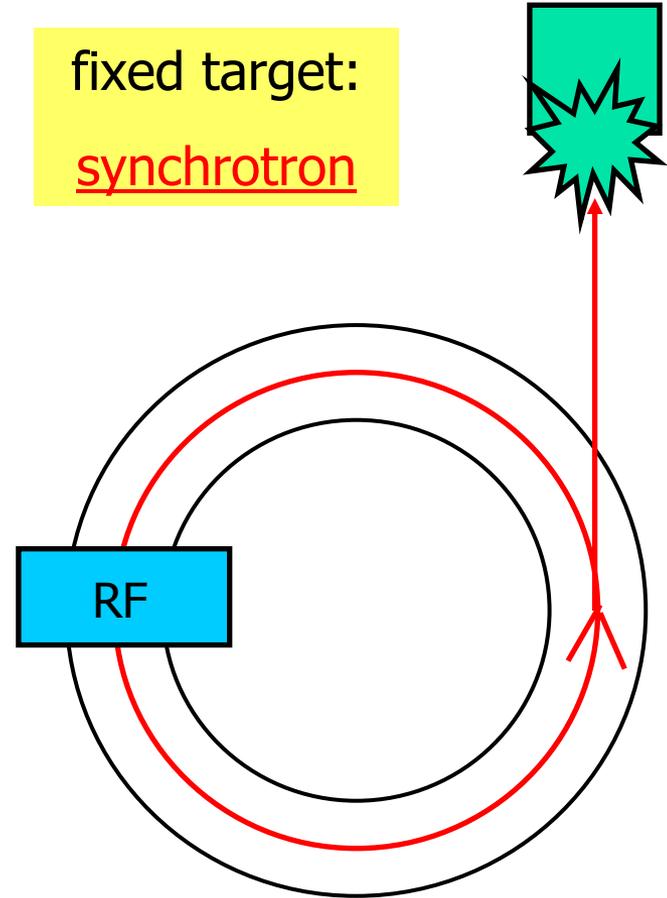
➤ Need **Dipoles!**

Circular machines ($E_{c.m.} \sim (mE)^{1/2}$)



fixed target:
cyclotron

huge dipole, compact design,
 $B = \text{constant}$
low energy, single pass.



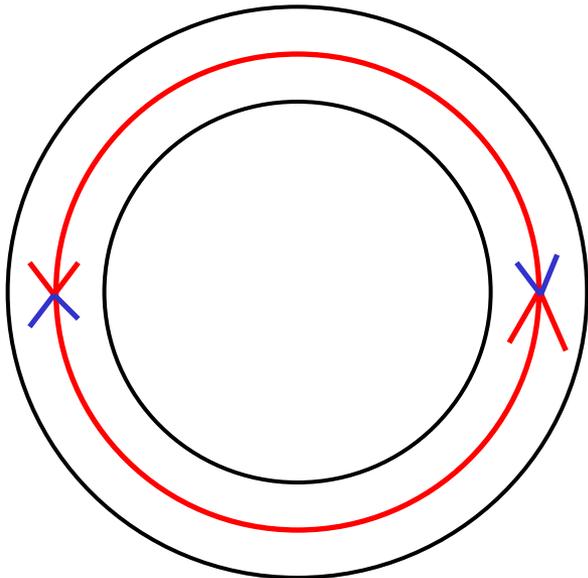
fixed target:
synchrotron

varying B , small magnets, high energy

Colliders ($E_{\text{c.m.}}=2E$)

Colliders:

electron – positron
proton - antiproton

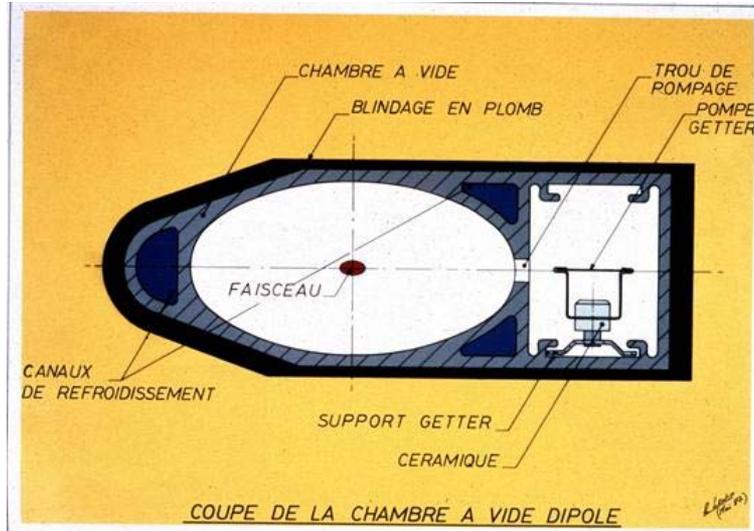


Colliders with the same type of particles (e.g. p-p) require two separate chambers. The beam are brought into a common chamber around the interaction regions

Ex: LHC

8 possible interaction regions
4 experiments collecting data

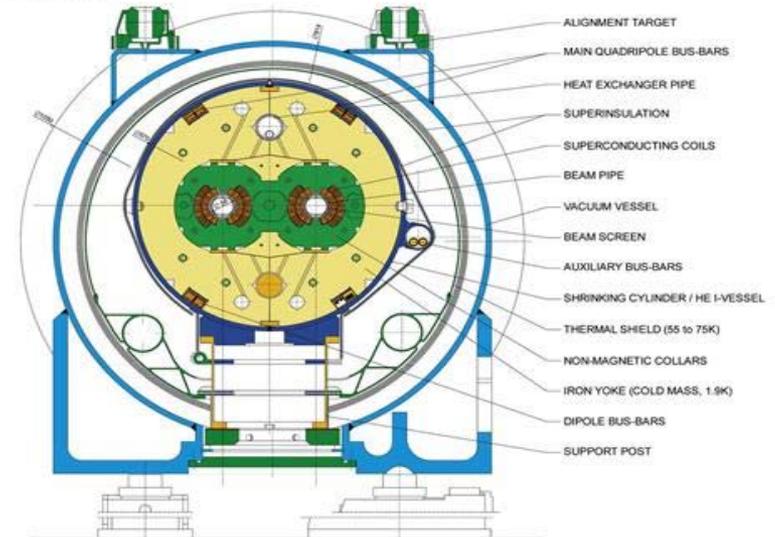
Colliders ($e^+ - e^-$) et ($p - p$)

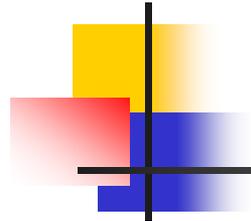


LEP

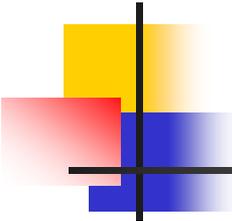
LHC

LHC DIPOLE : STANDARD CROSS-SECTION





Transverse Dynamics



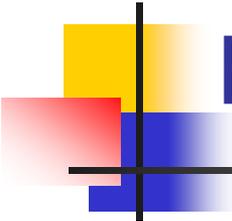
Beam Dynamics (1)

In order to describe the motion of the particles, each particle is characterised by:

- Its azimuthal position along the machine: s
- Its momentum: p
- Its horizontal position: x
- Its horizontal slope: x'
- Its vertical position: y
- Its vertical slope: y'

i.e. a sixth dimensional phase space

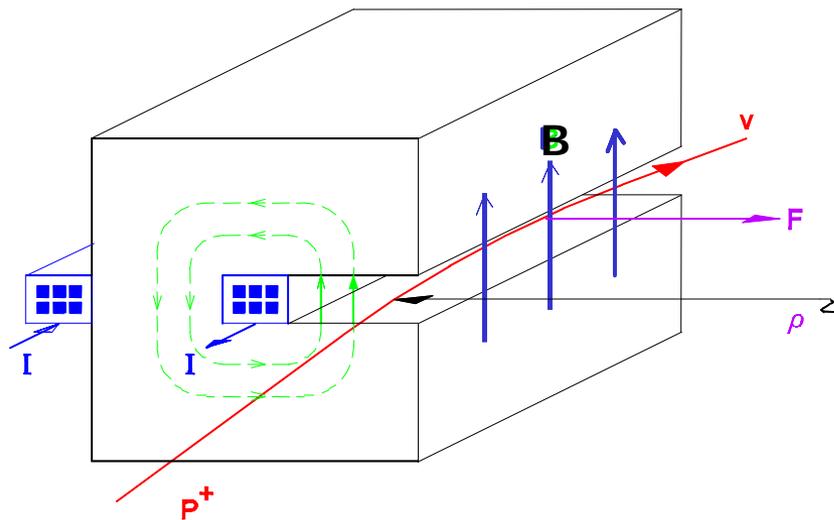
(s, p, x, x', y, y')



Beam Dynamics (2)

- In an accelerator designed to operate at the energy E_{nom} , all particles having $(s, E_{nom}, 0, 0, 0, 0)$ will happily fly through the center of the vacuum chamber without any problem. These are “ideal particles”.
- The difficulties start when:
 - one introduces **dipole magnets**
 - the energy $E \neq E_{nom}$ or $(p-p_{nom}/p_{nom}) = \Delta p/p_{nom} \neq 0$
 - either of $x, x', y, y' \neq 0$

Circular machines: Dipoles



$$p = m_0 \cdot c \cdot (\beta\gamma)$$



Magnetic rigidity:
 $B\rho = mv/e = p/e$

Classical mechanics:

Equilibrium between two forces

Lorentz force

Centrifugal force

$$F = e \cdot (\underline{v} \times \underline{B})$$

$$F = mv^2/\rho$$

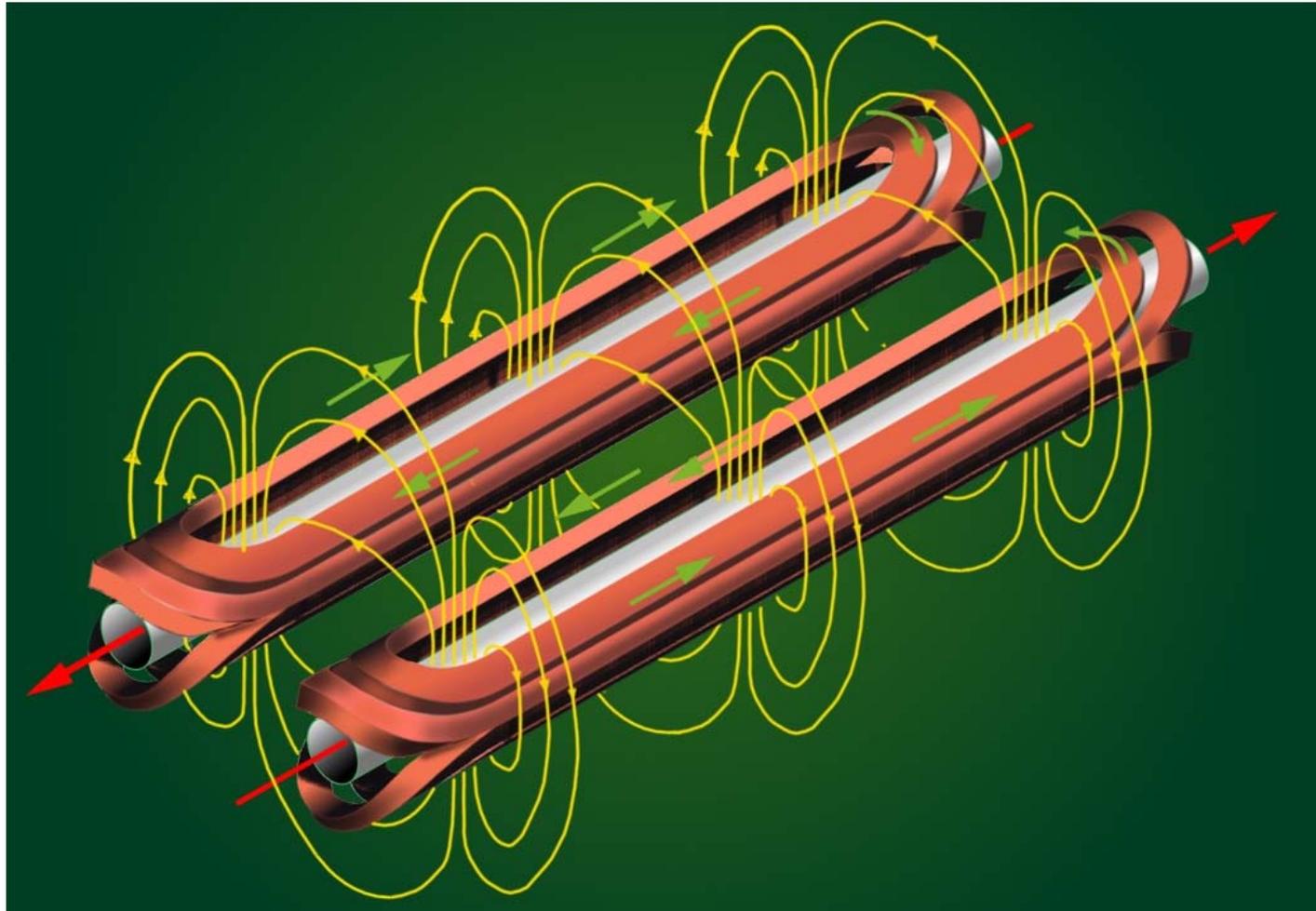
$$evB = mv^2/\rho$$

Relation also holds for relativistic case provided the classical momentum mv is replaced by the relativistic momentum p

Dipoles (1):



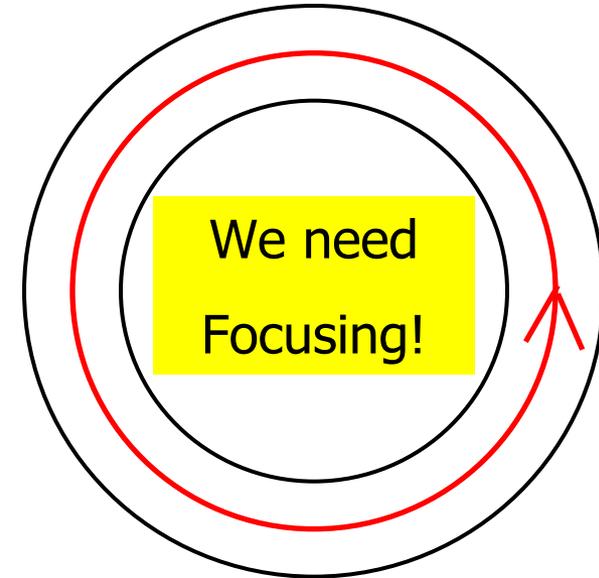
Dipoles (2):



Ideal circular machine:

- Neglecting radiation losses in the dipoles
- Neglecting gravitation

ideal particle would happily circulate on axis in the machine for ever!



Unfortunately: real life is different!

Gravitation: $\Delta y = 20$ mm in 64 msec!

Alignment of the machine

Limited physical aperture

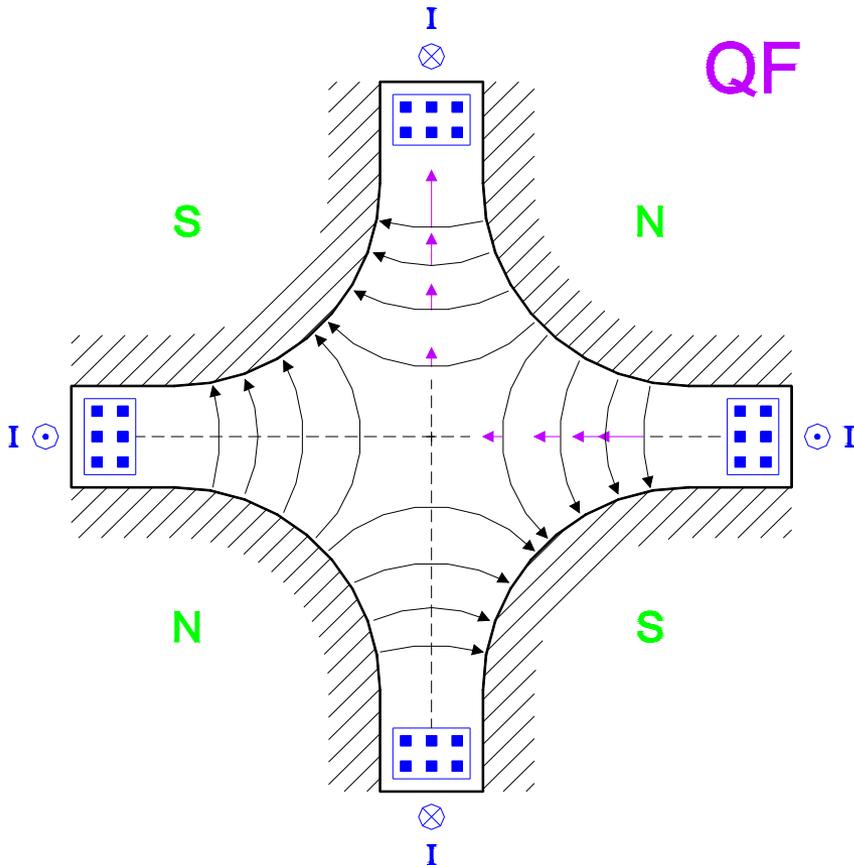
Ground motion

Field imperfections

Energy error of particles **and/or** $(x, x')_{inj} \neq (x, x')_{nominal}$

Error in magnet strength (power supplies and calibration)

Focusing with quadrupoles



$$F_x = -g \cdot x$$

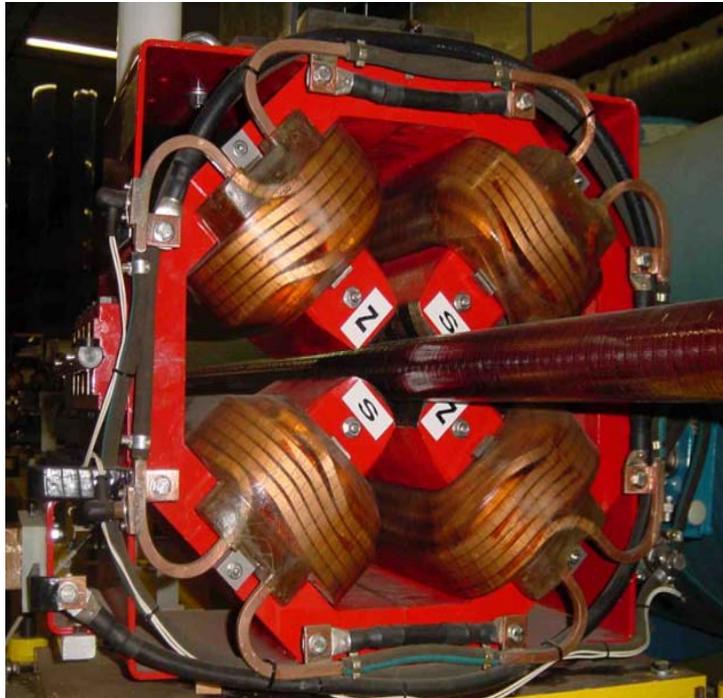
$$F_y = g \cdot y$$

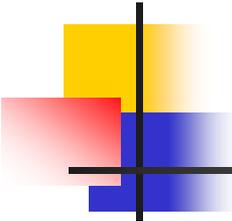
Force increases **linearly** with displacement.

Unfortunately, effect is **opposite** in the two planes (H and V).

Remember: **this** quadrupole is **focusing** in the **horizontal** plane but **defocusing** in the **vertical** plane!

Quadrupoles:





Focusing properties ...

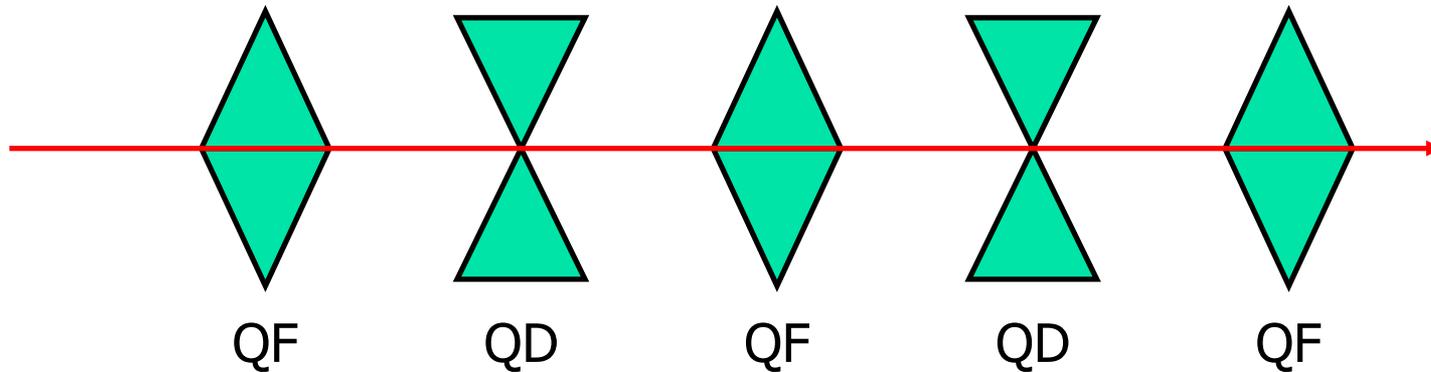
A quadrupole provides the required effect in one plane...

but the opposite effect in the other plane!

Is it really interesting ?

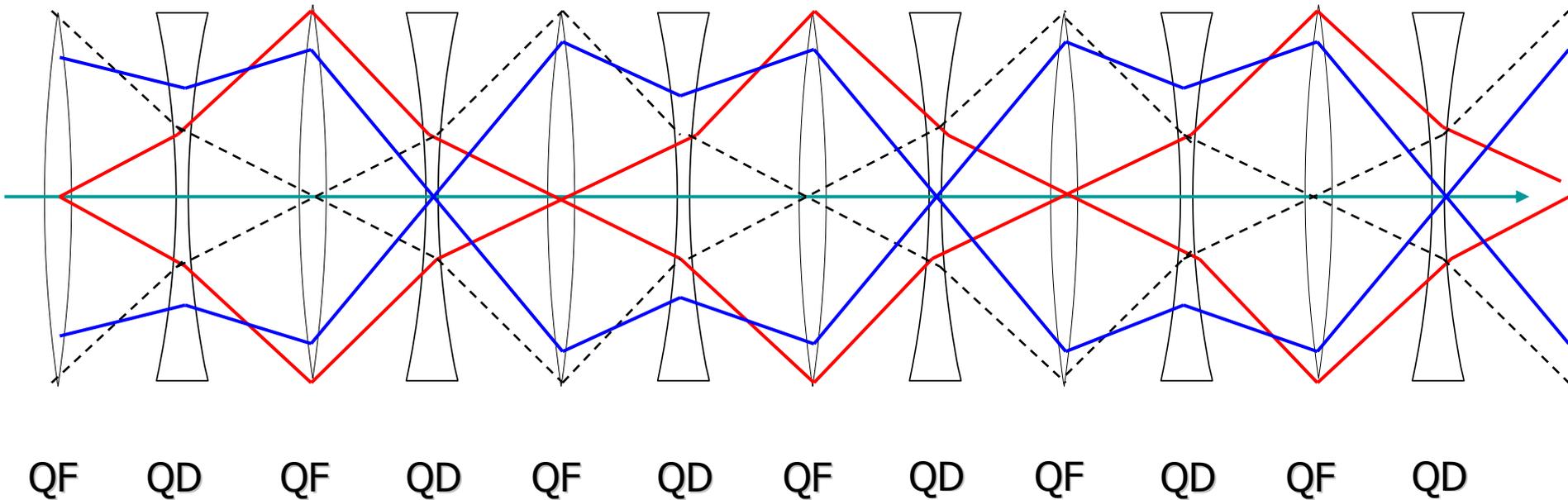
Alternating gradient focusing

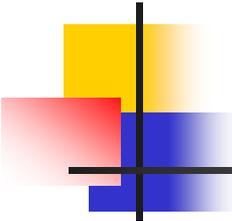
Basic new idea:
Alternate QF and QD



valid for one plane only (H or V) !

Alternating gradient focusing





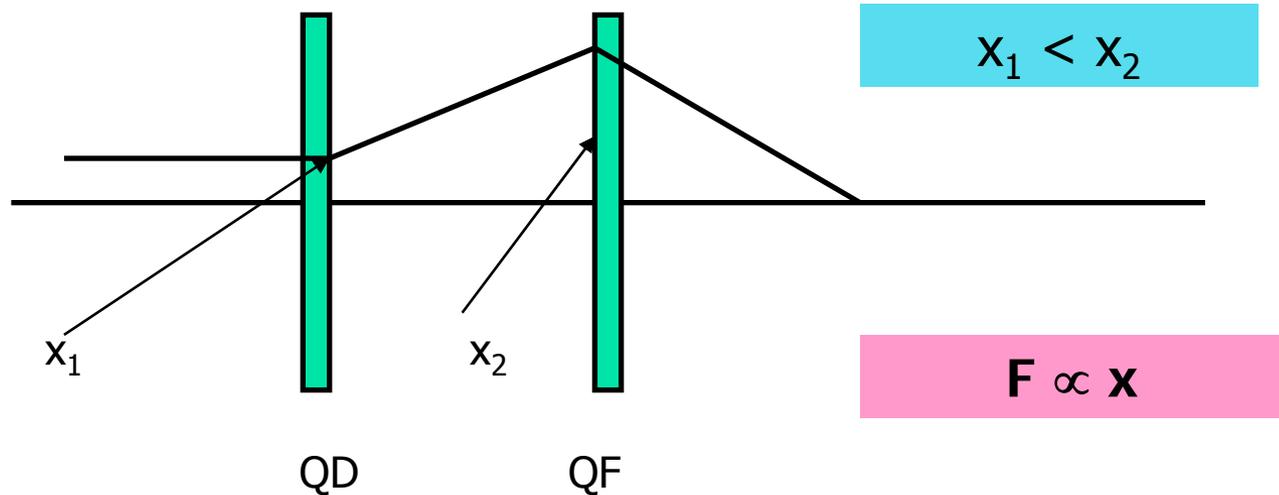
Alternating gradient focusing:

Particles for which $x, x', y, y' \neq 0$ thus oscillate around the ideal particle ...

but the trajectories remain inside the vacuum chamber !

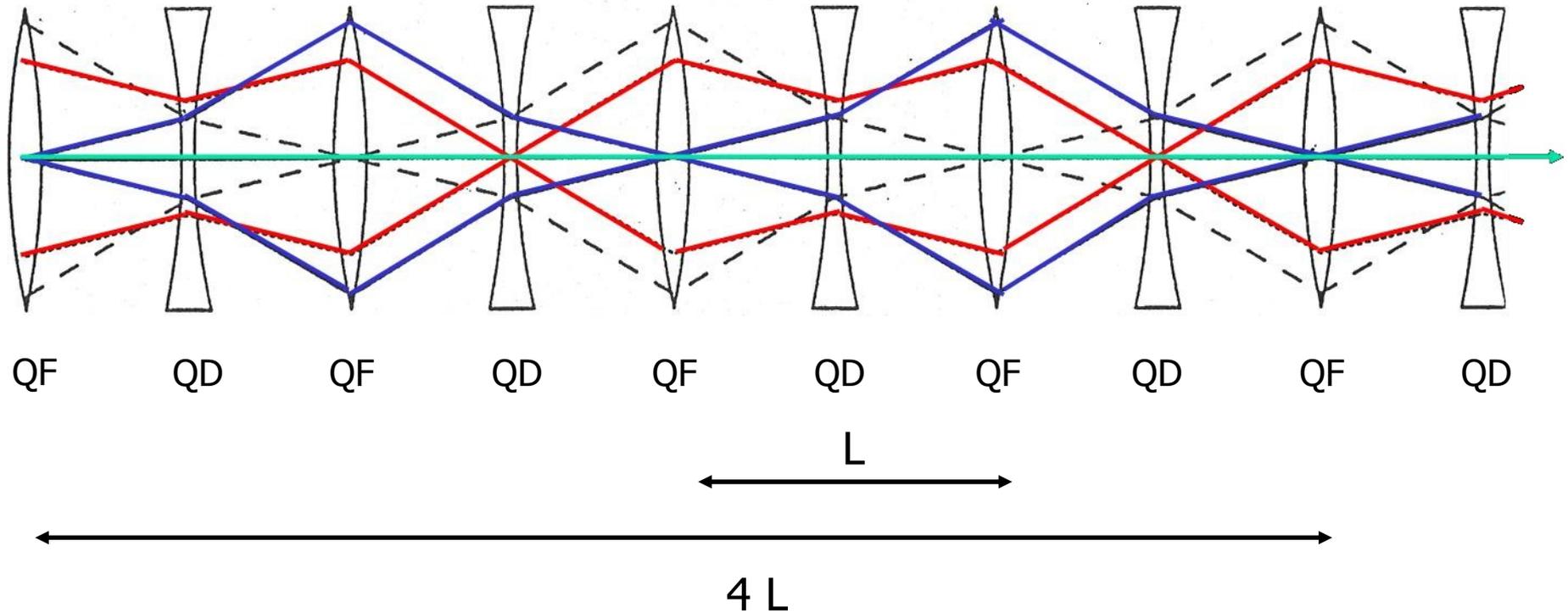
Why net focusing effect?

Purely intuitively:



Rigorous treatment rather straightforward !

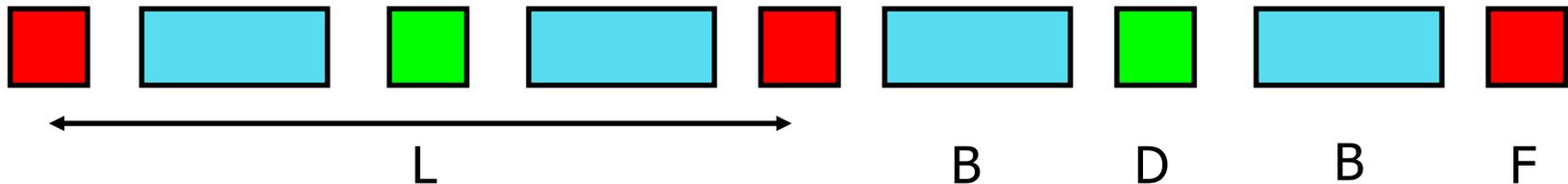
The concept of the « FODO cell »



One complete oscillation in 4 cells $\Rightarrow 90^\circ / \text{cell} \Rightarrow \mu = 90^\circ$

Circular machines (no errors!)

The accelerator is composed of a **periodic** repetition of **cells**:



➤ The phase advance per cell μ can be modified, in each plane, by varying the strength of the quadrupoles.

➤ The ideal particle will follow a **particular** trajectory, which **closes on itself** after one revolution: **the closed orbit**.

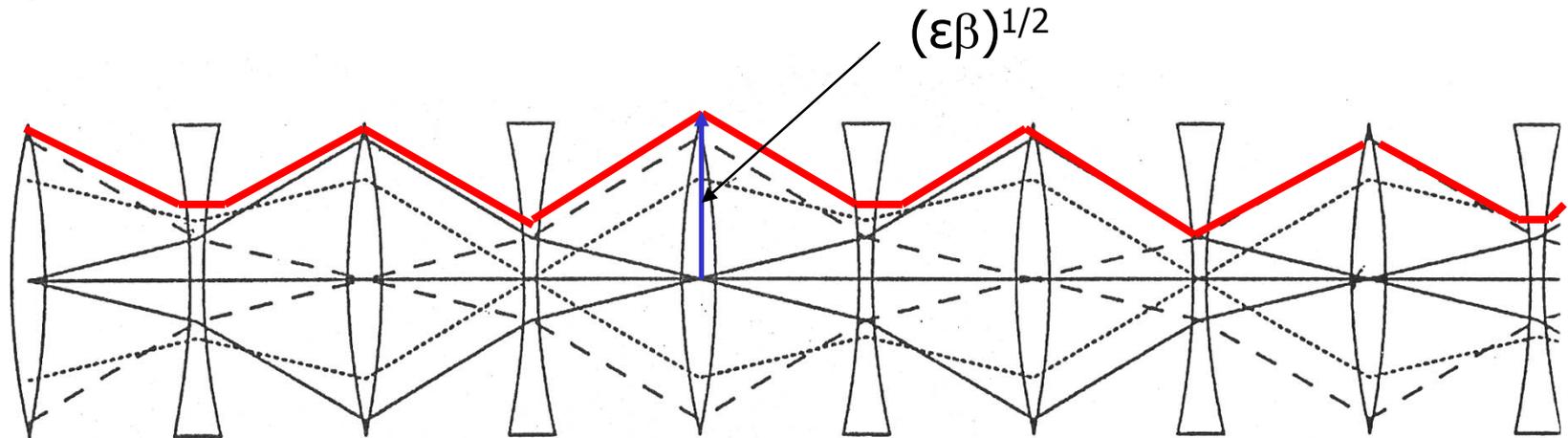
➤ The real particles will perform oscillations **around the closed orbit**.

➤ The number of **oscillations for a complete revolution** is called the **Tune Q** of the machine (Q_x and Q_y).

Regular periodic lattice: The Arc



The beta function $\beta(s)$



The β -function is the **envelope** around all the trajectories of the particles circulating in the machine.

The β -function has a **minimum at the QD** and a **maximum at the QF**, ensuring the net focusing effect of the lattice.

It is a **periodic function** (repetition of cells). The oscillations of the particles are called **betatron motion** or **betatron oscillations**.

Why introducing this function?

The β function is a fundamental parameter, because it is directly related to the beam size (**measurable quantity !**):

Beam size [m]

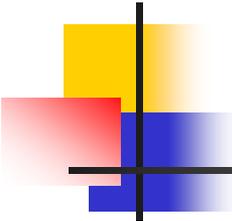
$$\sigma_{x,y}(s) = (\varepsilon \cdot \beta_{x,y}(s))^{1/2}$$

σ (IP) = 17 μm
at 7 TeV ($\beta=0.55$ m)

The emittance ε characterises the quality of the injected beam (kind of measure how the particles depart from ideal ones). It is an **invariant** at a given energy.

ε = beam property

β = machine property (quads)



Off momentum particles:

- These are “non-ideal” particles, in the sense that they do not have the right energy, i.e. all particles with $\Delta p/p \neq 0$

What happens to these particles when traversing the magnets ?

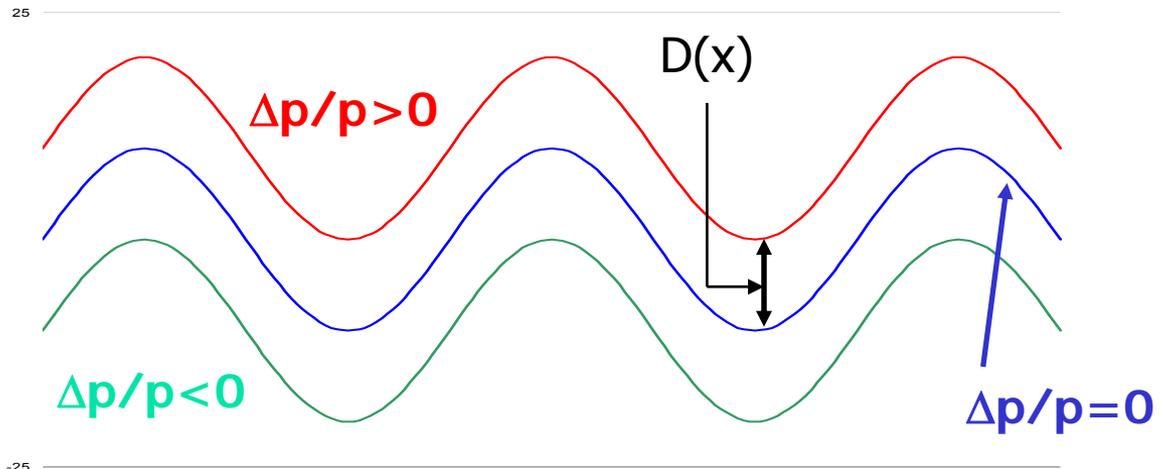
Off momentum particles ($\Delta p/p \neq 0$)

Effect from Dipoles

- If $\Delta p/p > 0$, particles are **less** bent in the dipoles → should spiral out !
- If $\Delta p/p < 0$, particles are **more** bent in the dipoles → should spiral in !

No!

There is an equilibrium with the restoring force of the quadrupoles

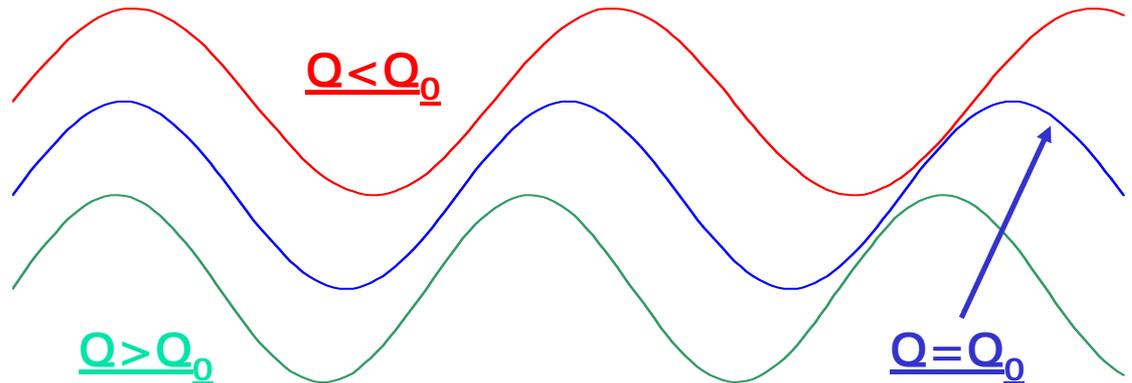


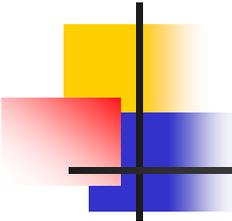
Off momentum particles ($\Delta p/p \neq 0$)

Effect from Quadrupoles

- If $\Delta p/p > 0$, particles are **less** focused in the quadrupoles → **lower Q !**
- If $\Delta p/p < 0$, particles are **more** focused in the quadrupoles → **higher Q !**

Particles with different momenta would have a different **betatron tune** $Q=f(\Delta p/p)$!





The chromaticity Q'

Particles with different momenta ($\Delta p/p$) would thus have different tunes Q .
So what ?

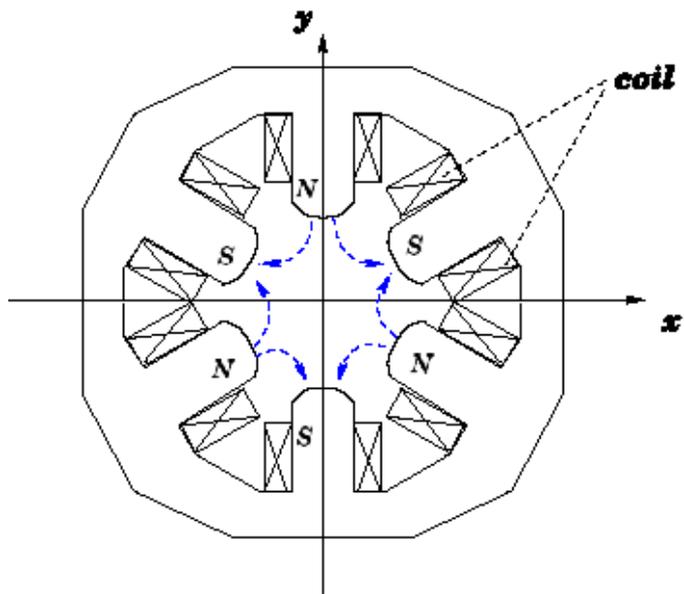
unfortunately

- The tune dependence on momentum is of **fundamental** importance for the **stability** of the machine. It is described by the **chromaticity** of the machine Q' :

$$Q' = \Delta Q / (\Delta p/p)$$

The chromaticity has to be carefully **controlled and corrected** for stability reasons.

The sextupoles (SF and SD)

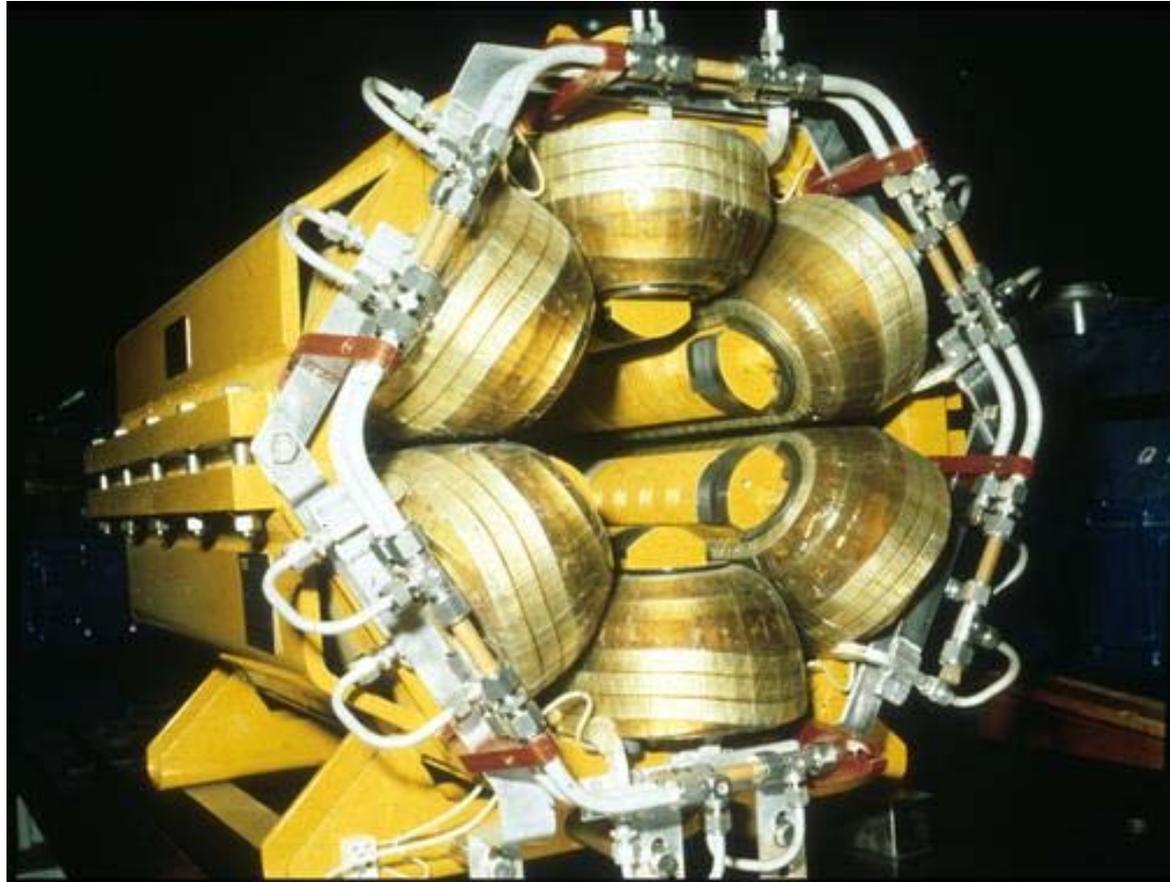


$$\triangleright \Delta X' \propto X^2$$

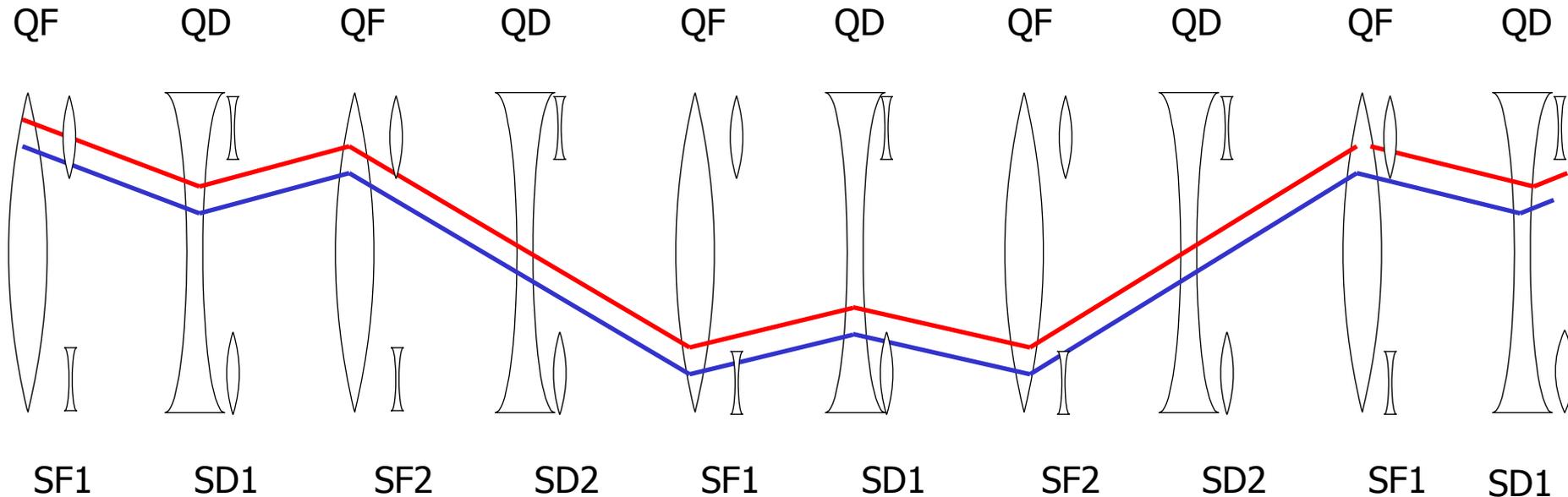
- A SF sextupole basically « adds » focusing for the particles with $\Delta p/p > 0$, and « reduces » it for $\Delta p/p < 0$.
- The chromaticity is corrected by adding a sextupole after each quadrupole of the FODO lattice.

Sextupoles:

SPS



Chromaticity correction

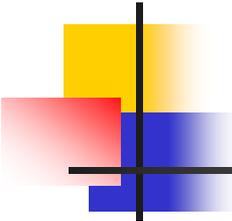


The undesired effect of sextupoles on particles with the **nominal energy** can be avoided by grouping the sextupoles into « families ».

Nr. of families:

$$N = (k * 180^\circ) / \mu = \text{Integer}$$

$$\text{e.g. } 180^\circ / 90^\circ = 2$$



Transverse stability of the beam:

So, **apparently**, the tunes Q_x and Q_y have to be **selected** and **controlled** very accurately. Why this ?

LHC in collision:

$$Q_x = 64.31$$

$$Q_y = 59.32$$

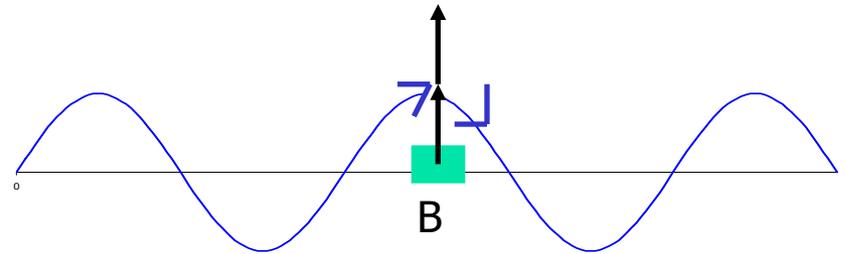
Forbidden values for Q

- An error in a **dipole** gives a kick which has always the same sign!

Integer Tune $Q = N$

Forbidden!

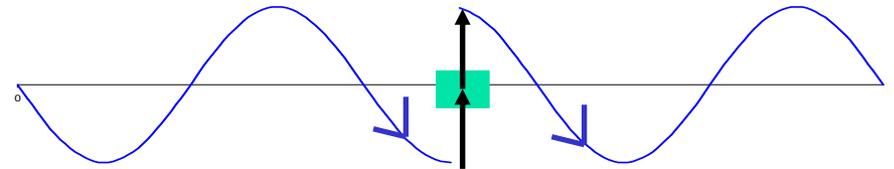
The perturbation adds up!



Half-integer Tune $Q = N + 0.5$

O.K. for an error in a dipole!

The perturbation cancels after each turn!



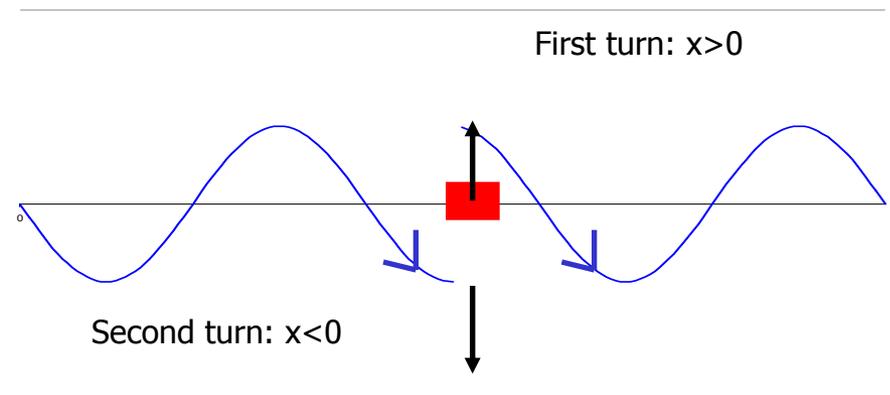
Forbidden values for Q

- An error in a **quadrupole** gives a kick whose sign depends on x ($F \propto x$)

Half-integer Tune $Q = N + 0.5$

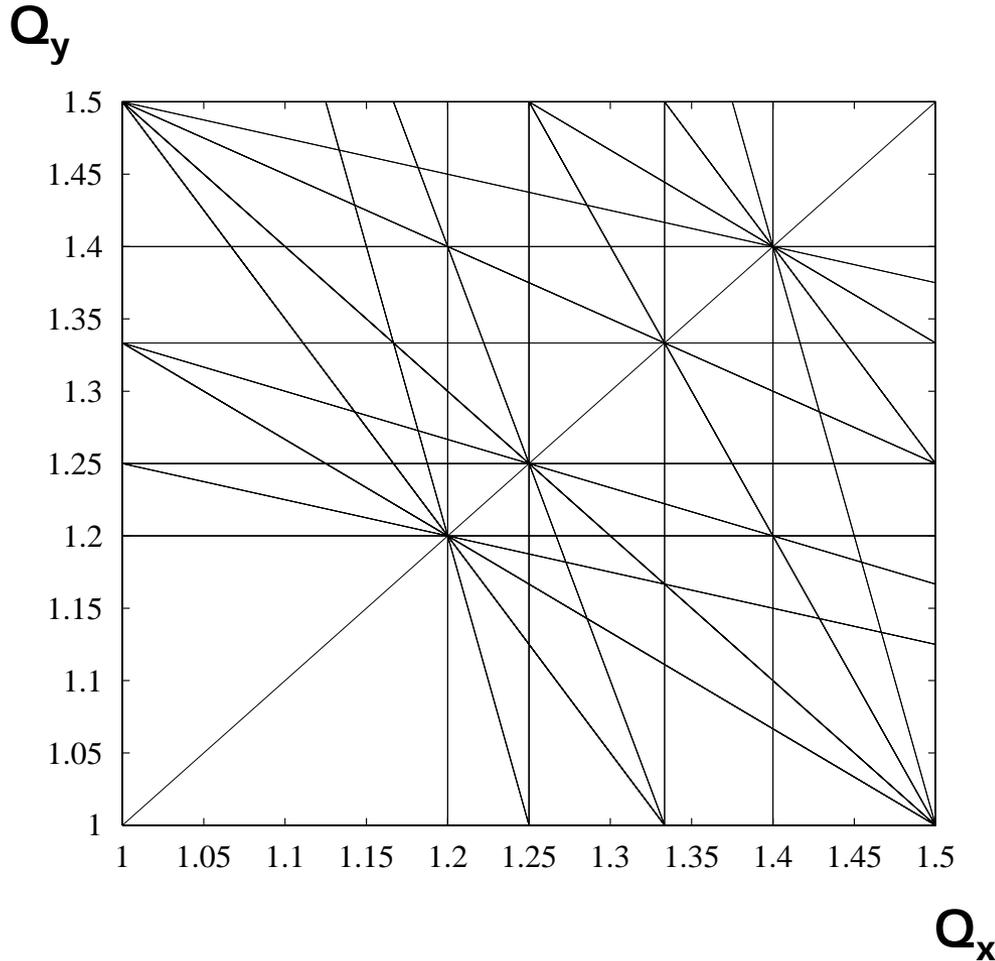
Forbidden !

The amplitude of the oscillation is steadily increasing!



1/3 integer tune would be o.k. for a quadrupole, but **NOT** for a sextupole ...

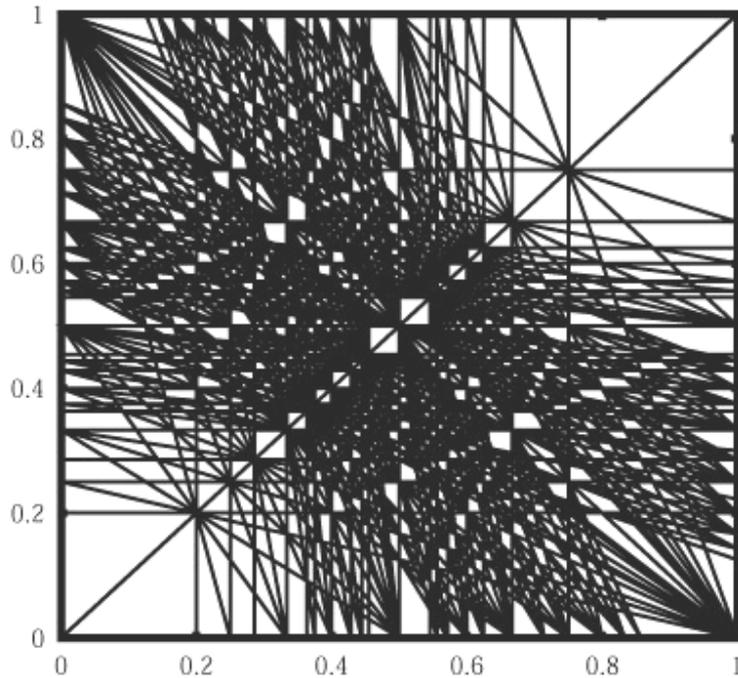
Tune diagram for leptons:



Tune values
(Q_x and/or Q_y)
which are **forbidden**
in order to avoid
resonances

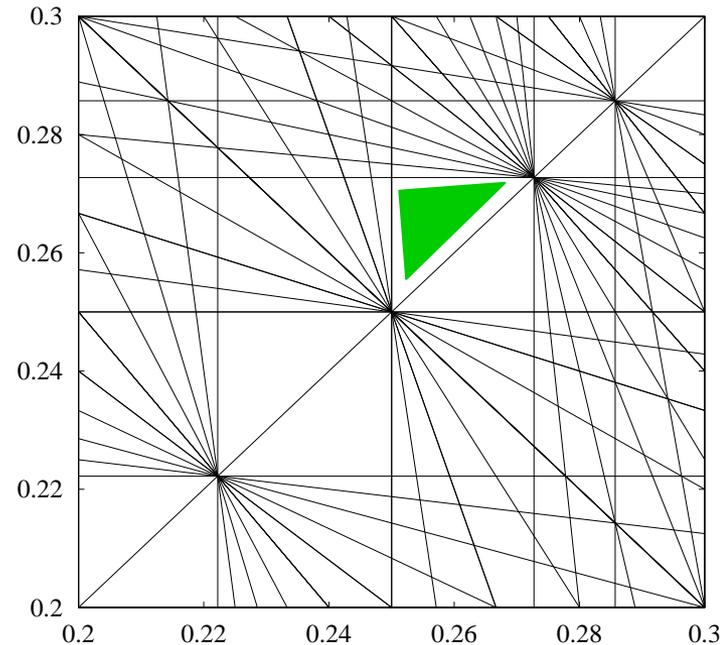
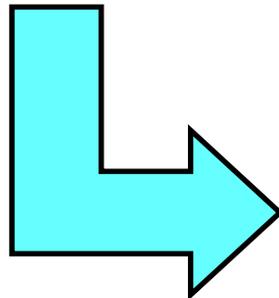
The lowest the order of
the resonance, the most
dangerous it is.

Tune diagram for protons



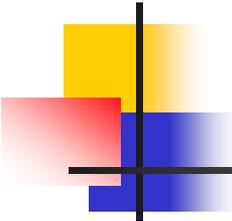
Due to the energy spread in the beam, we have to accommodate an « **area** » rather than a point!

LHC



Summary for the transverse planes:

- A particle is described by its **position** and its **slope** (x, x') and (y, y')
- The circular trajectory is achieved with **dipoles**.
- The particles are kept together in the chamber with **quadrupoles**.
- The particles perform **betatron oscillations** around the **closed orbit**.
- The number of oscillations per turn (**the tune Q**) has to be carefully selected in order to avoid **resonances**.
- The phase advance per cell (μ) can be modified with **quadrupoles**.
- The **natural chromaticity** of the machine Q' (<0) is compensated with **sextupoles**.



Where are we ?

We have covered the **transverse beam dynamics** and we have learned that, essentially, the machine is composed of a periodic repetition of dipoles, quadrupoles and sextupoles.

Is there still anything missing ?

A system to accelerate the particles

A system to get efficient collisions