Experimental techniques in high-energy nuclear and particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

LECTURE 3.

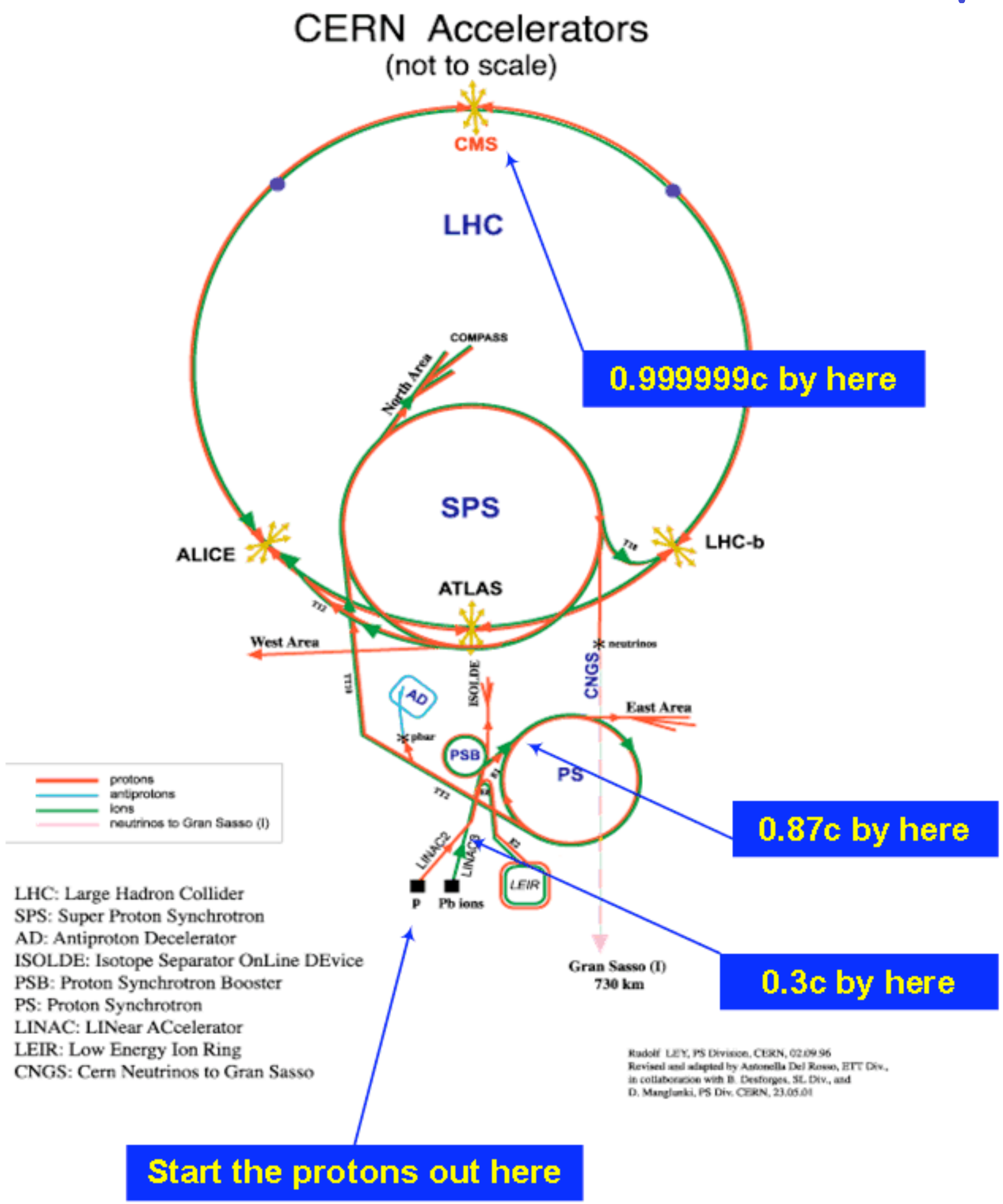
Accelerators - 2

Prof. Rino Castaldi

INFN-Pisa

rino.castaldi@pi.infn.it

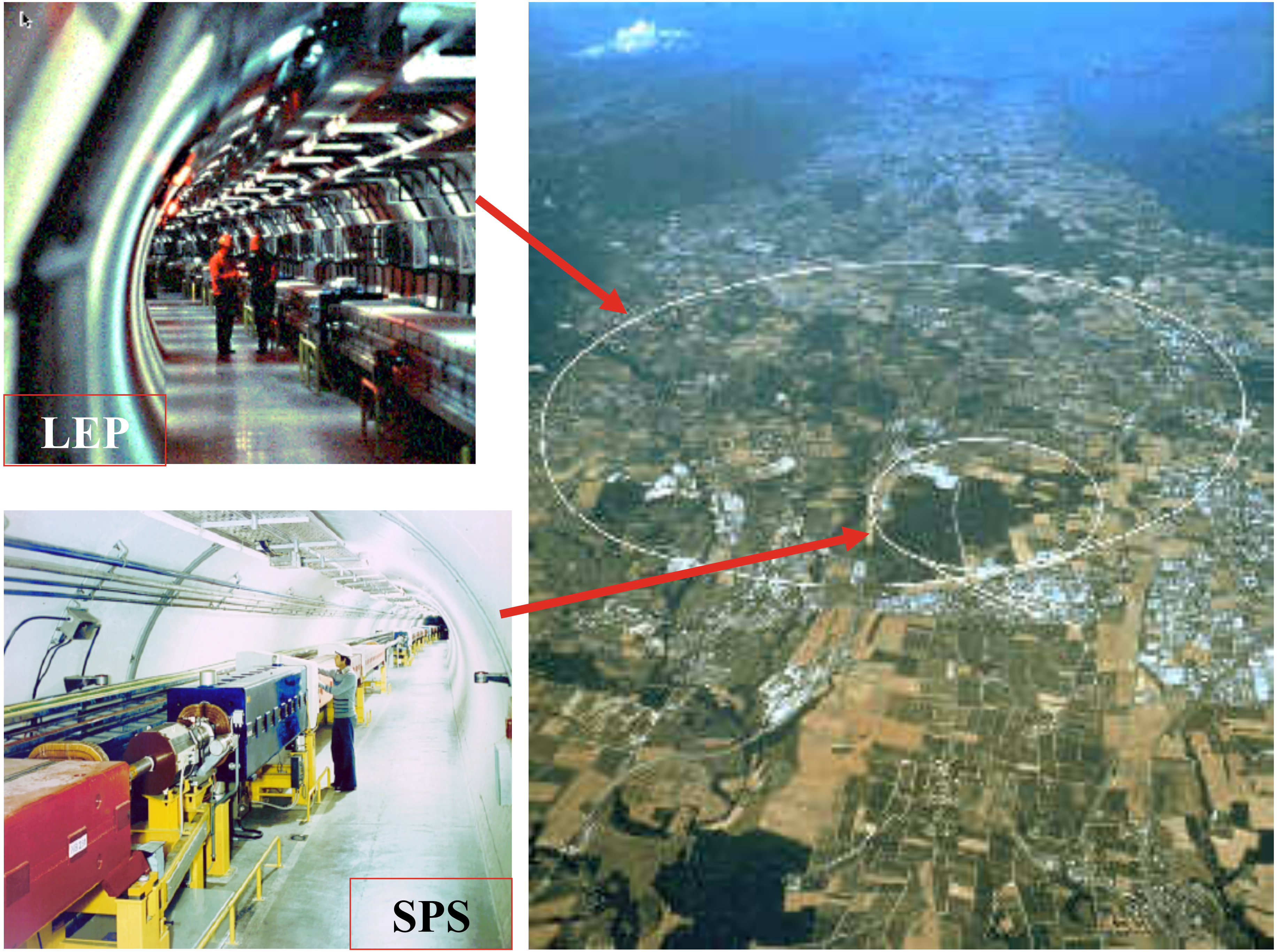
Accelerators and LHC experiments at CERN



- The energies in the CERN accelerators range **from 100 keV to** soon **7 TeV** **(now at 3.5 TeV)**.
- To do this the beam energy is increased in a staged way using **5 different accelerators**.

Energies:

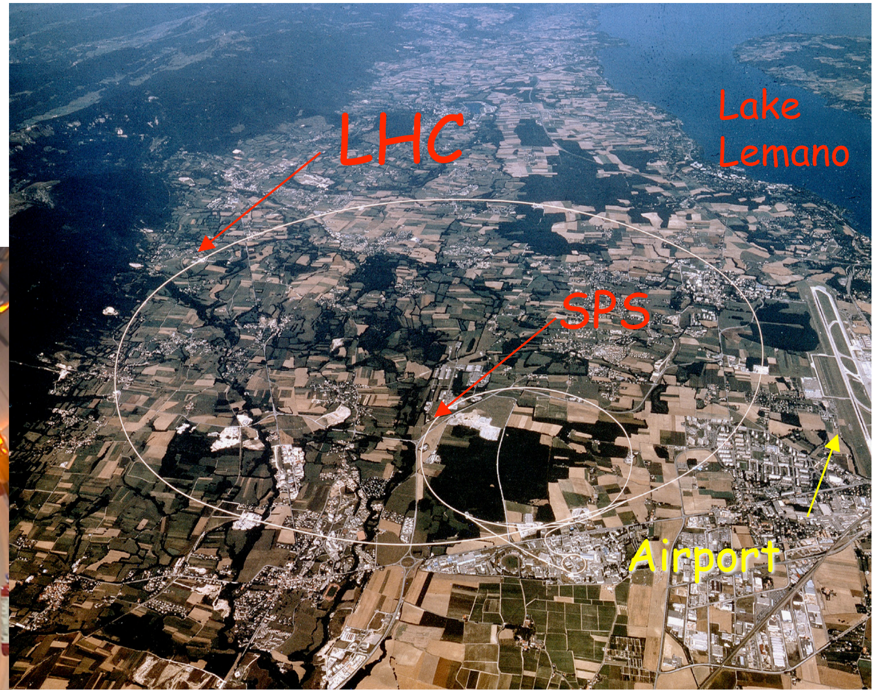
Linac	50 MeV
PSB	1.4 GeV
PS	28 GeV
SPS	450 GeV
LHC	7 TeV (now 3.5TeV)

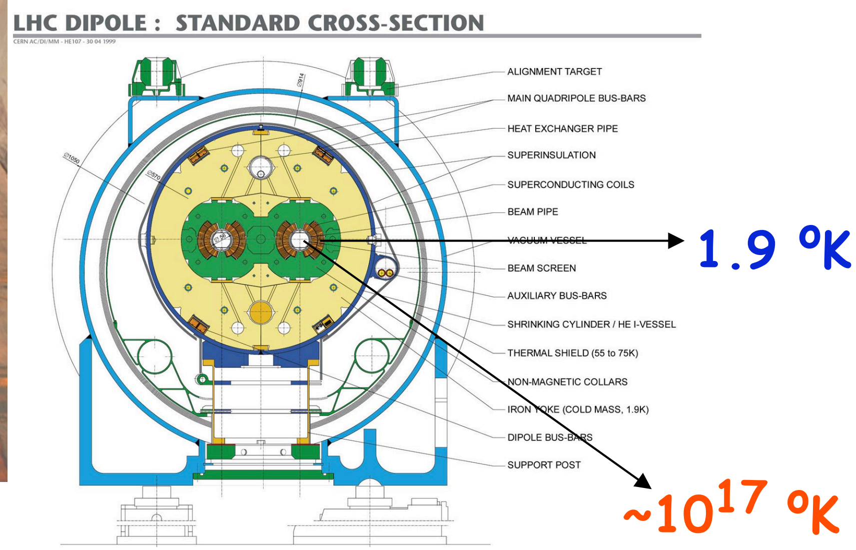

LEP
SPS

The CERN Large Hadron Collider

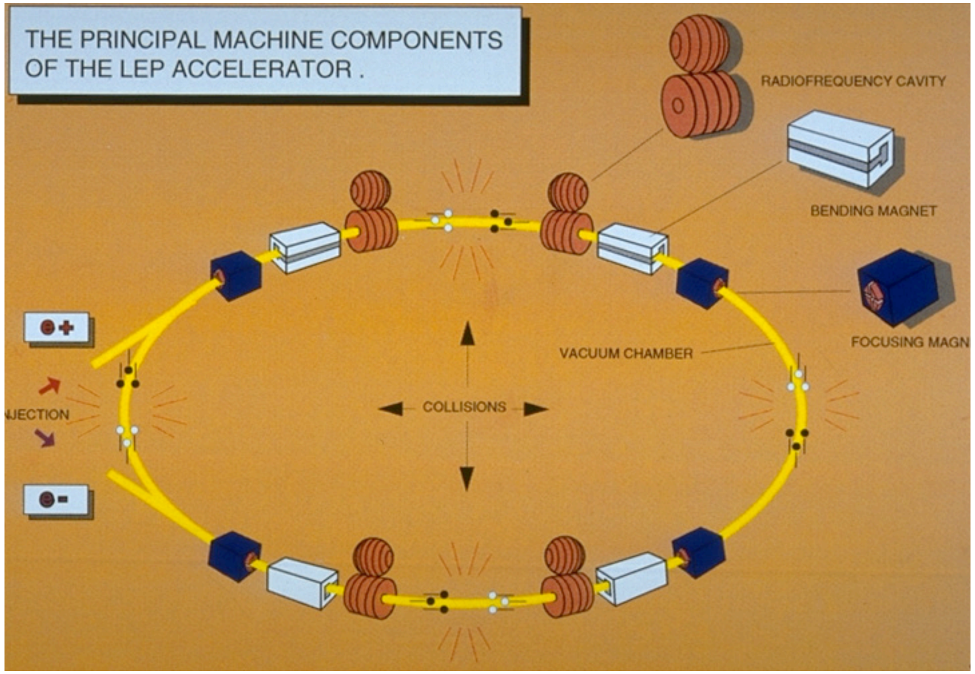
first collisions in Autumn 2009

9300 Superconductor magnets
1232 Dipoles (15m,1.9°K) 8.4Tesla 11700 A
448 Main Quads, 6618 Correctors.
Circonference 26.7 km





Basic concepts



Charged particles are accelerated, guided and confined by **electromagnetic fields**.

- Bending: Dipole magnets
- Focusing: Quadrupole magnets
- Acceleration: RF cavities

In synchrotrons, they are ramped together synchronously to match beam energy.

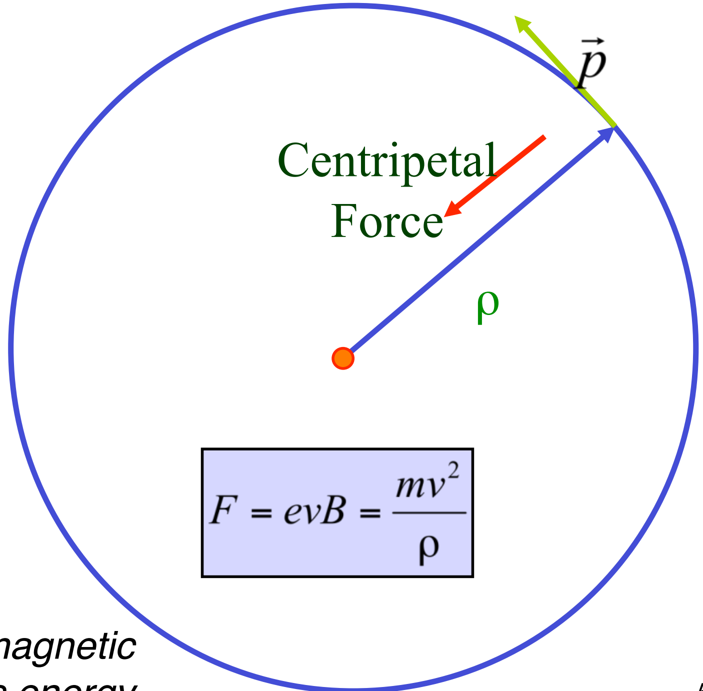
- Chromatic aberration: Sextupole magnets

Lorentz force $\vec{F} = e(\vec{v} \times \vec{B} + \vec{E})$

Magnetic rigidity $B\rho = \frac{mv}{e} = \frac{p}{e}$

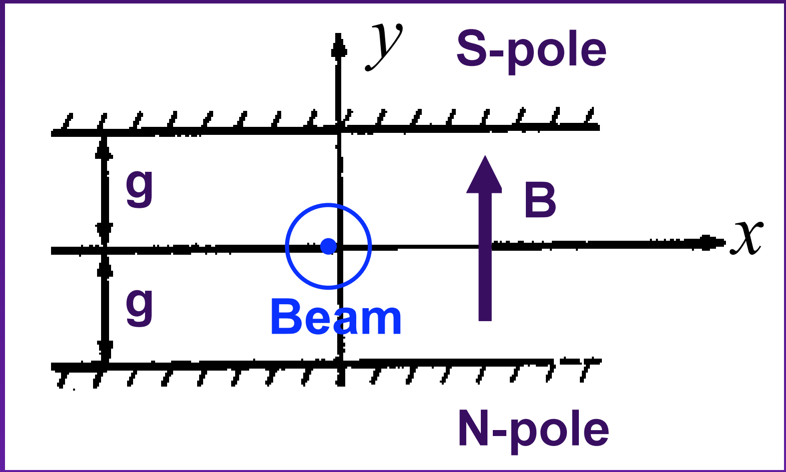
LHC: ρ = 2.8 km given by LEP tunnel!

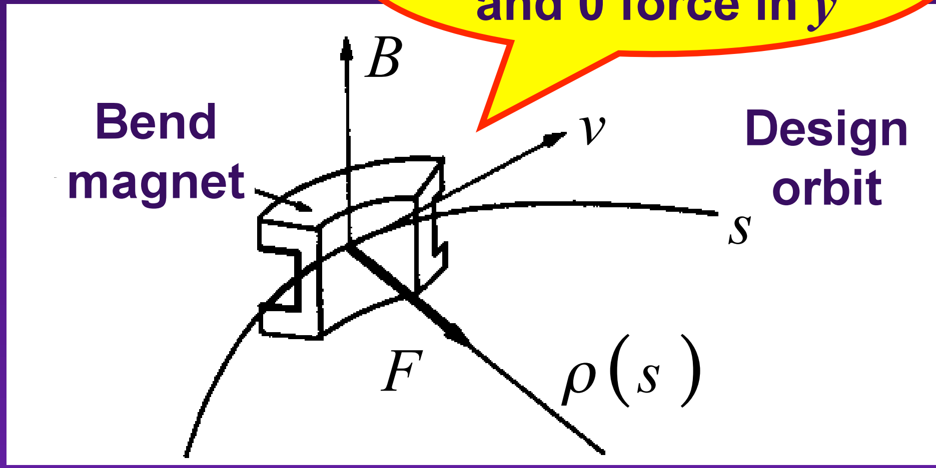
Fixes the relation between magnetic field and particle's energy



DIPOLE = Bending magnet

Constant force in x and 0 force in y





⇒ A particle, with a constant energy, describes a circle in equilibrium between the centripetal magnetic force and the centrifugal force

- BEAM RIGIDITY

$$B\,\rho\,[\mathrm{T\,m}] = 3.3356\; p_0\,[\mathrm{GeV/c}]$$

Magnetic field

Curvature radius of the dipoles

Beam momentum

TRANSVERSE BEAM DYNAMICS

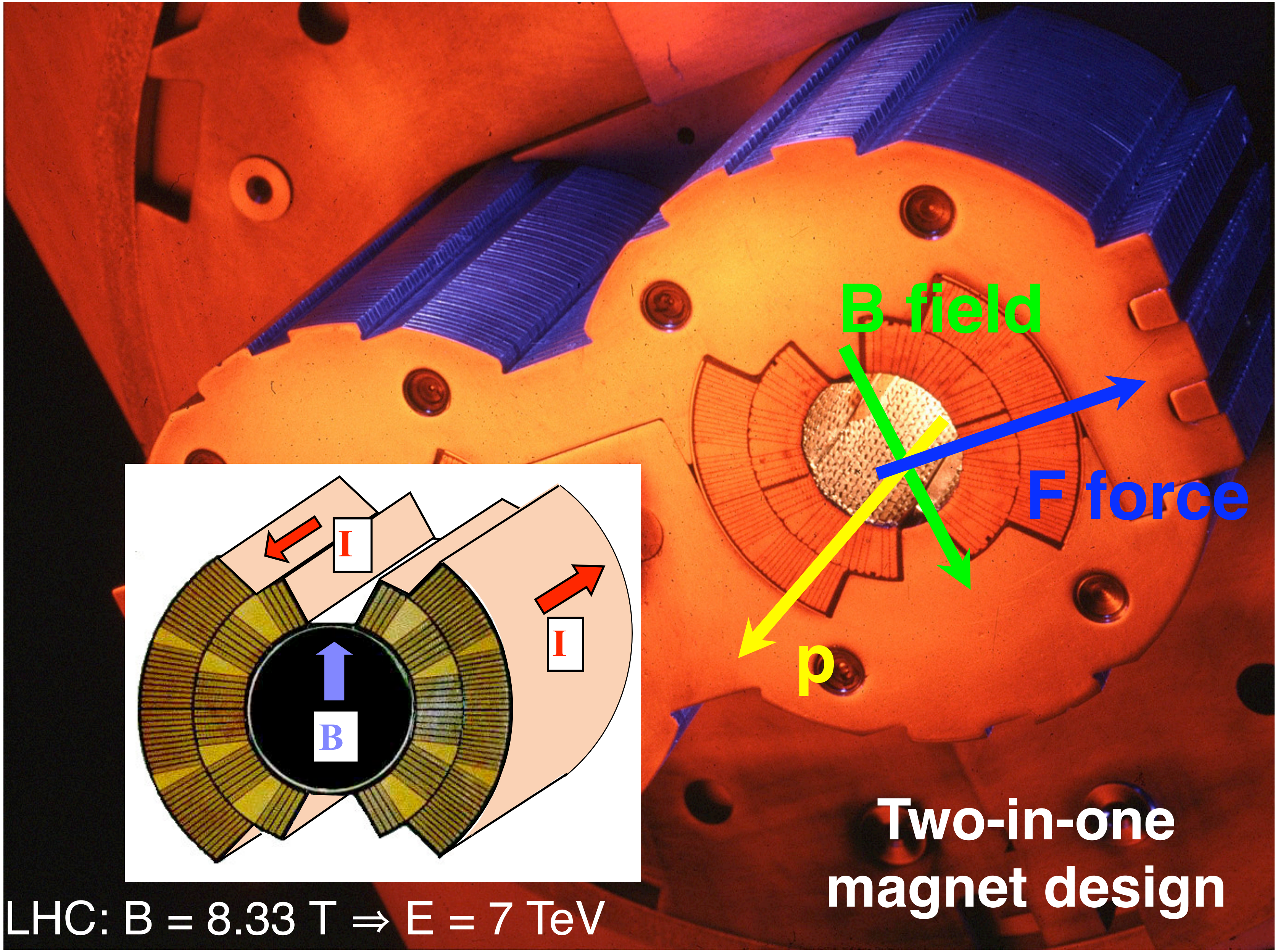
- LEP vs LHC magnets (in same tunnel) ⇒ A change in technology

	LEP	LHC
ρ [m]	3096.175	2803.95
p_0 [GeV/c]	104	7000
B [T]	0.11	8.33

Room-temperature coils

Superconducting coils

Bending



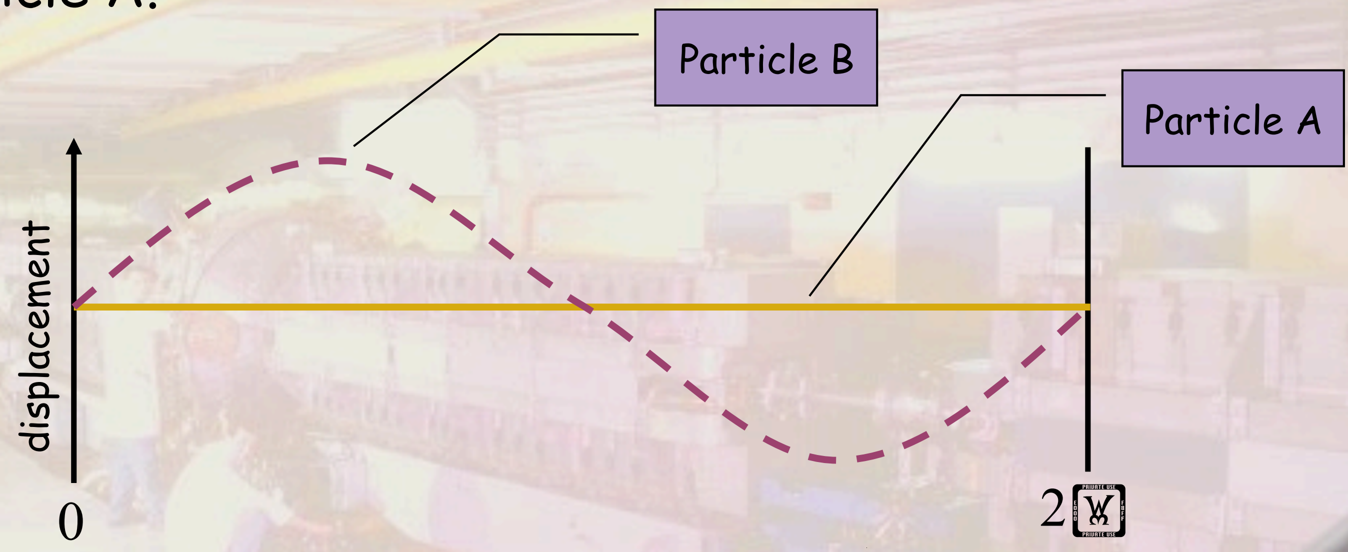
Two particles in a dipole field

- What happens with two particles that travel in a dipole field with different initial angles, but with equal initial position and equal momentum ?

- Assume that Bρ is the same for both particles.
- Lets unfold these circles……

The 2 trajectories unfolded

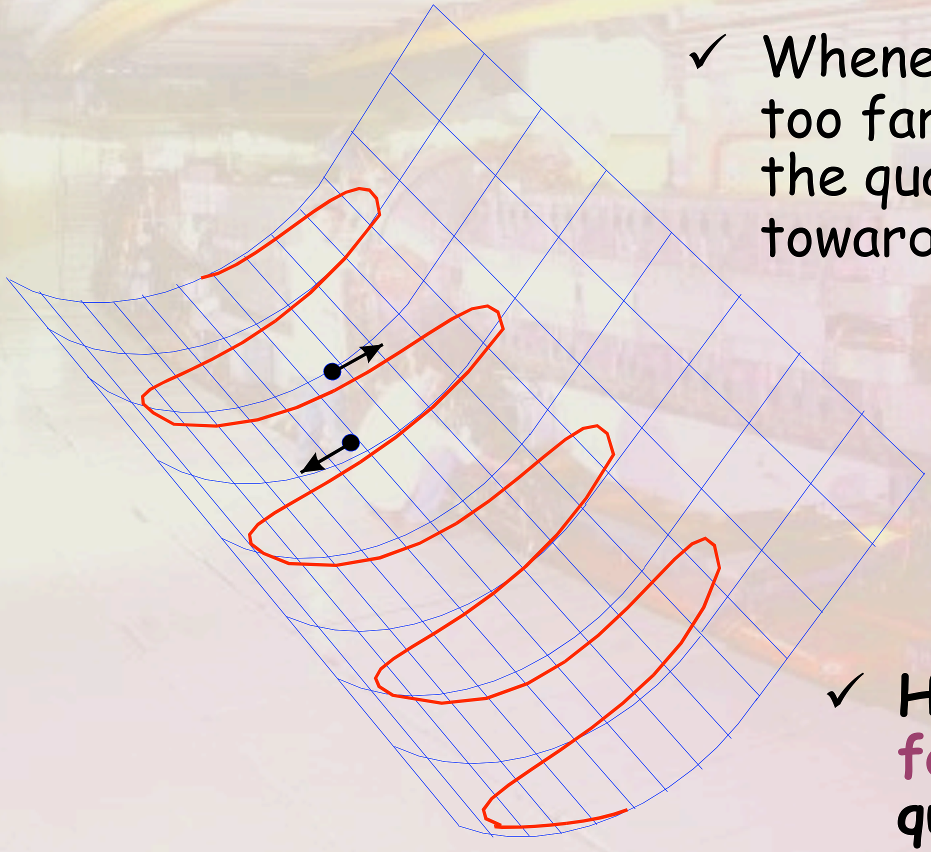
- ✓ The horizontal displacement of particle B with respect to particle A.



- ✓ Particle B oscillates around particle A.
- ✓ This type of oscillation forms the basis of all transverse motion in an accelerator.
- ✓ It is called **'Betatron Oscillation'**

The mechanical equivalent

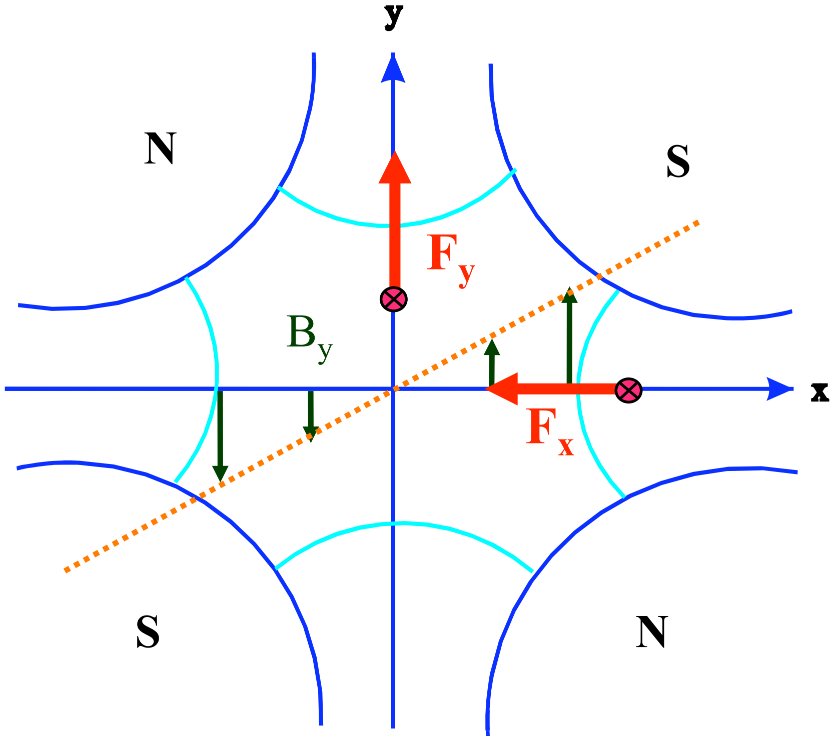
- ✓ The gutter below illustrates how the particles in our accelerator behave due to the quadrupolar fields.

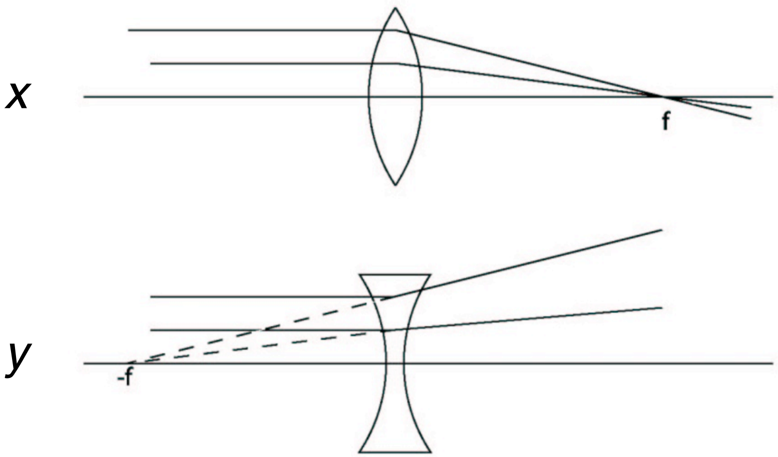


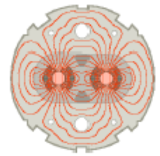
- ✓ Whenever a particle beam diverges too far away from the central orbit the quadrupoles focus them back towards the central orbit.

- ✓ **How can we represent the focusing gradient of a quadrupole in this mechanical equivalent ?**

Focusing



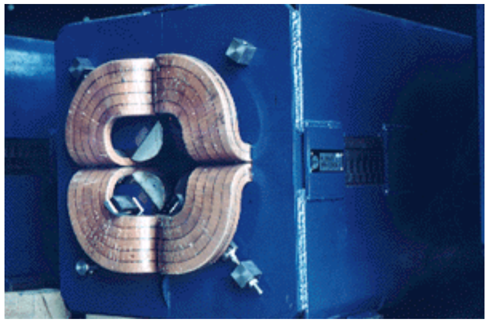




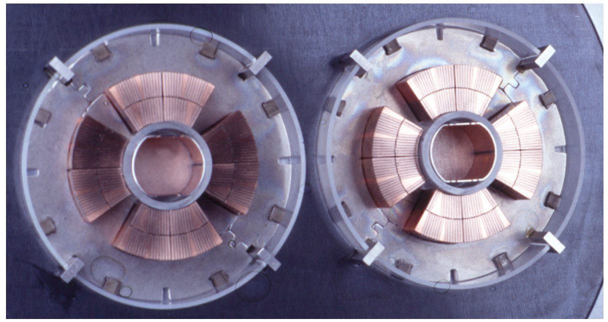
- ✓ A **Quadrupole** has **4 poles**, 2 north and 2 south
- ✓ They are **symmetrically arranged** around the centre of the magnet
- ✓ There is no **magnetic field** along the central axis.

$B_y \propto x$ $B_x \propto y$

Quadrupole (LEP)



Quadrupoles (LHC)

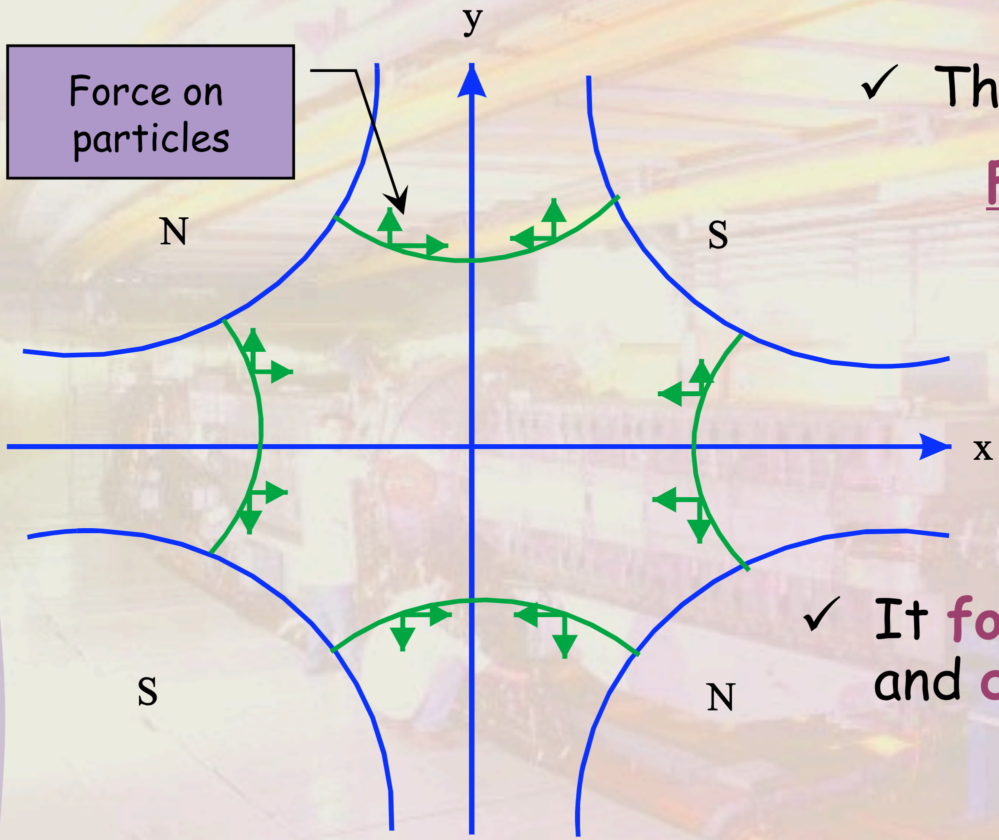


Transverse focusing is achieved with **quadrupole magnets**, which act on the beam like an optical lens.

Linear increase of the magnetic field along the axes (no effect on particles on axis).

Focusing in one plane, **de-focusing** in the other!

Types of quadrupoles



✓ This is a:

<u>Focusing Quadrupole (QF)</u>

✓ It **focuses** the beam **horizontally** and **defocuses** the beam **vertically**.

✓ **Rotating** this magnet by **90°** will give a:

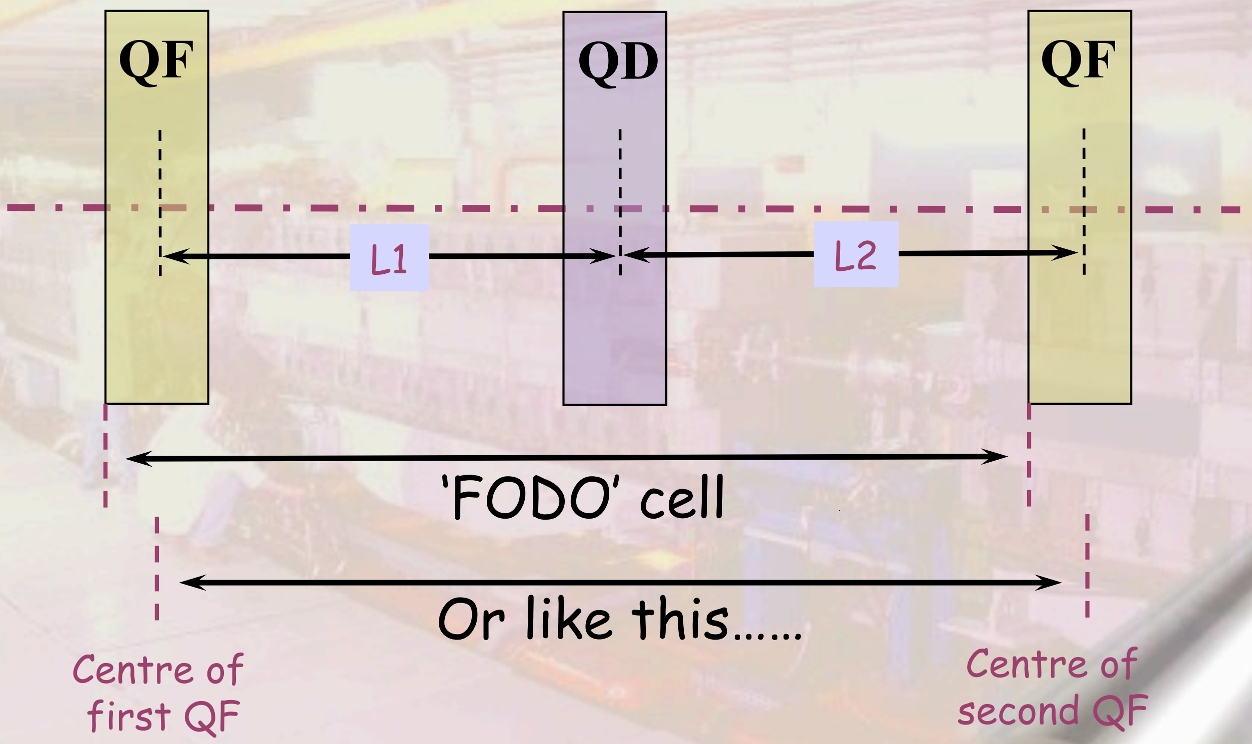
<u>**Defocusing Quadrupole (QD)**</u>

Focusing and Stable motion

- Using a combination of focusing (QF) and defocusing (QD) quadrupoles solves our problem of 'unstable' vertical motion.
- It will keep the beams focused in **both planes** when the position in the accelerator, type and strength of the quadrupoles are well chosen.
- By now our accelerator is composed of:
  - **Dipoles**, constrain the beam to some closed path (orbit).
  - **Focusing and Defocusing Quadrupoles**, provide horizontal and vertical focusing in order to constrain the beam in transverse directions.
- A combination of focusing and defocusing sections that is very often used is the so called: **FODO lattice**.
- This is a configuration of magnets where focusing and defocusing magnets alternate and are separated by non-focusing drift spaces.

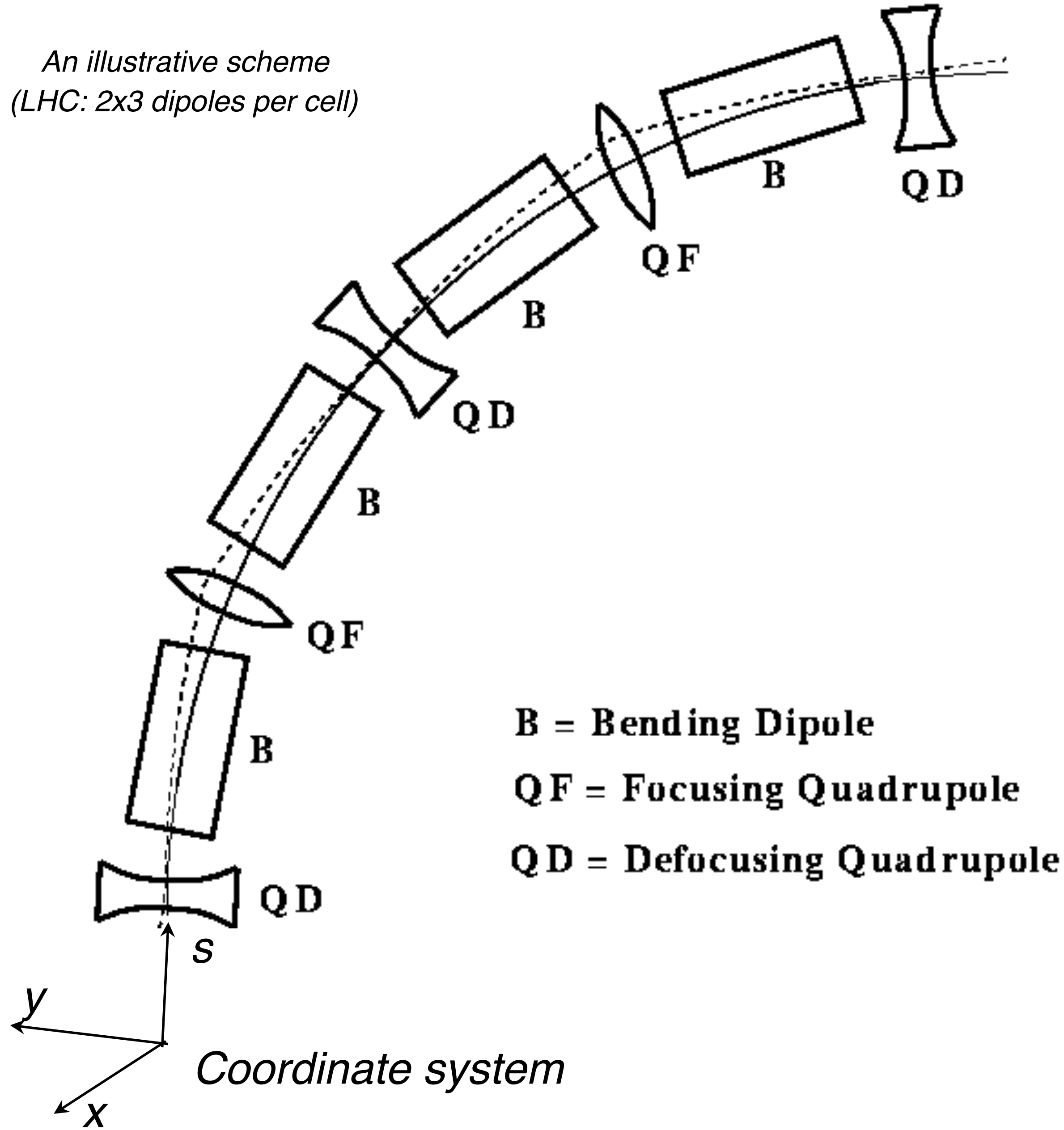
FODO cell

- ✓ The 'FODO' cell is defined as follows:



Alternating gradient lattice

An illustrative scheme
(LHC: 2x3 dipoles per cell)



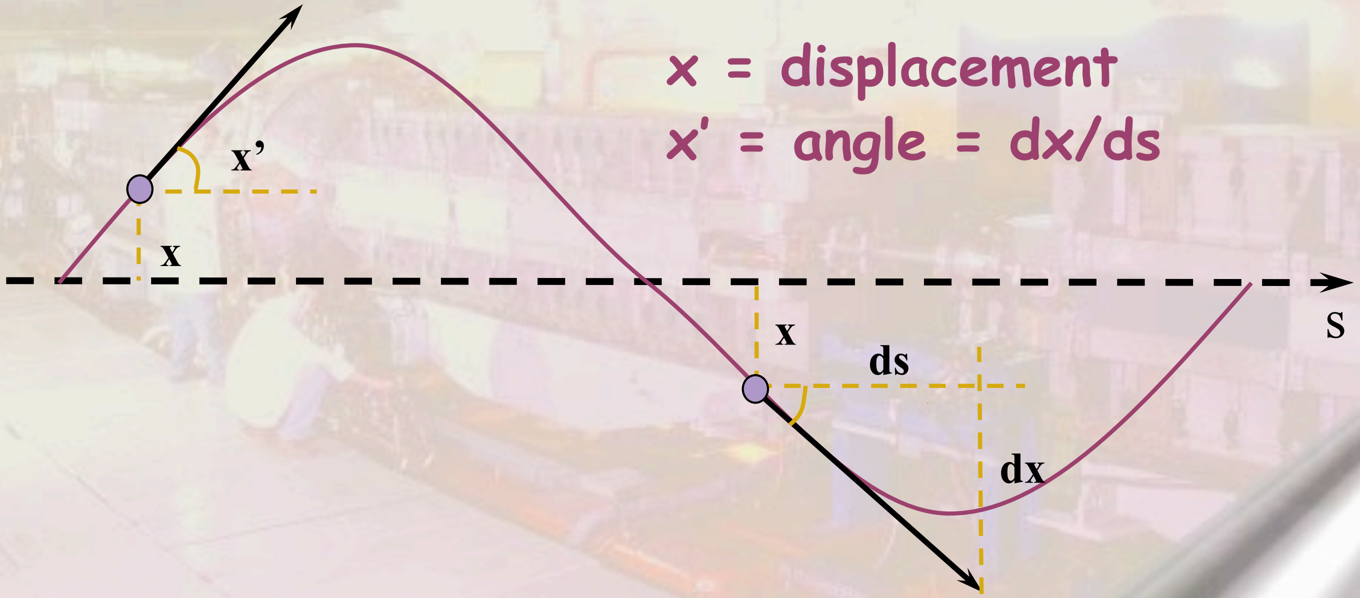
One can find an arrangement of quadrupole magnets that provides net focusing in both planes ("strong focusing").

Dipole magnets keep the particles on the circular orbit.

Quadrupole magnets focus alternatively in both planes.

The particle characterized

- ✓ A particle during its transverse motion in our accelerator is characterized by:
  - ✓ Position or displacement from the central orbit.
  - ✓ Angle with respect to the central orbit.

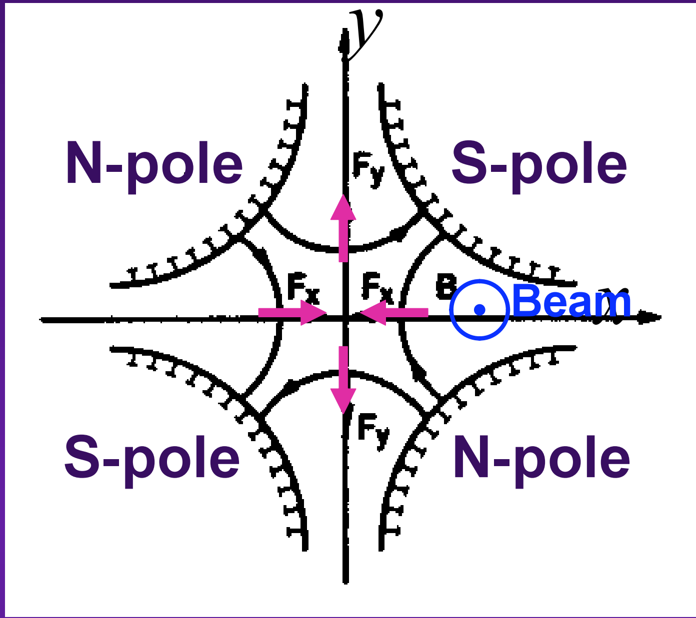


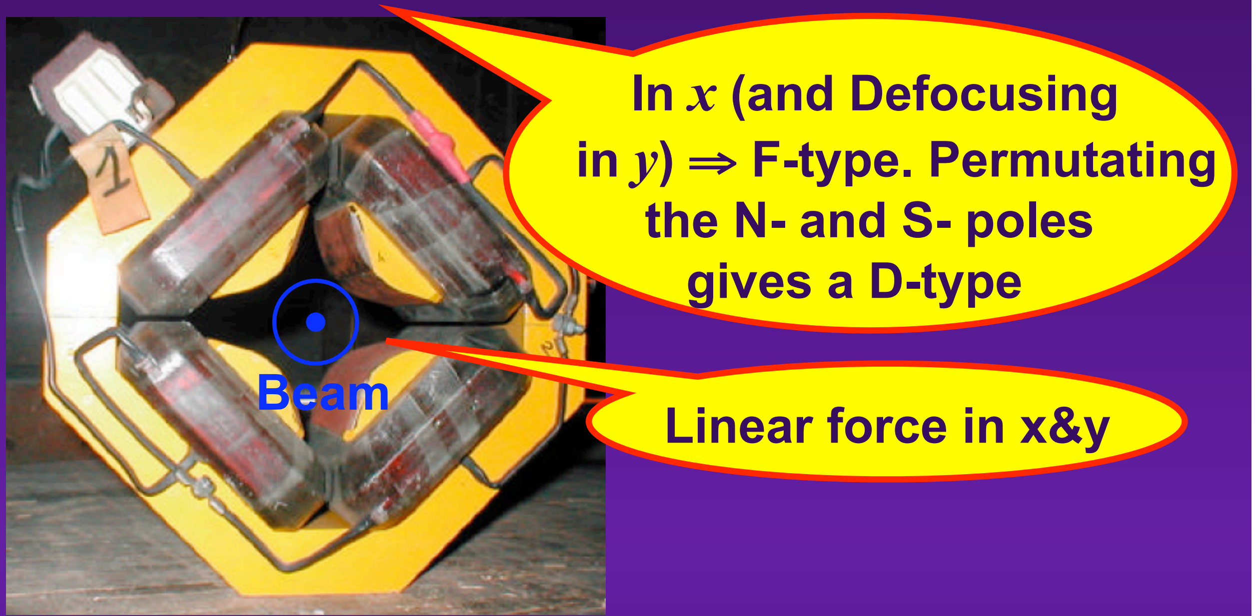
x = displacement

x' = angle = dx/ds

- ✓ This is a motion with a constant restoring force, like in the first lecture on differential equations, with the pendulum

QUADRUPOLE = Focusing magnet





$$\Rightarrow \quad x''(s) + K\,x(s) = 0$$: **Equation of a harmonic oscillator**

- **From this equation, one can already anticipate the elliptical shape of the particle trajectory in the phase space (x, x') by integration**

$$x'^2(s) + K\,x^2(s) = \text{Constant}$$

Hill's equation (2)

- ✓ In a real accelerator **K varies strongly with 's'**.
- ✓ Therefore we need to solve Hill's equation for K varying as a function of 's'

$$\frac{d^2x}{ds^2} + K(s)x = 0$$

- ✓ Remember what we concluded on the mechanical equivalent concerning the shape of the gutter……
  - ✓ The **phase advance** and the **amplitude modulation** of the oscillation are determined by the shape of the gutter.
  - ✓ The overall **oscillation amplitude** will depend on the **initial conditions**, I.e. how the motion of the ball started.

Solution of Hill's equation (1)

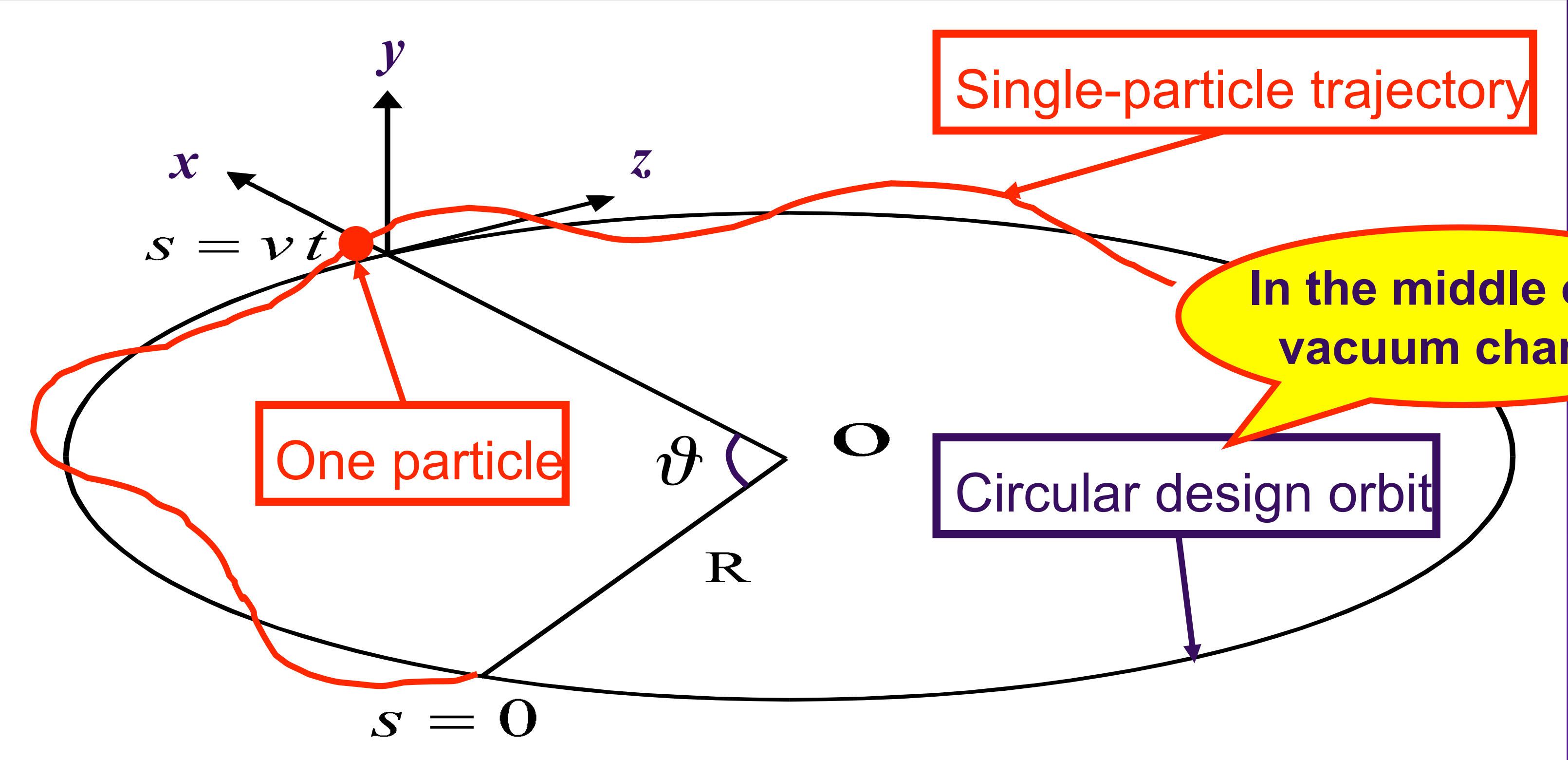
$$\frac{d^2x}{ds^2} + K(s)x = 0$$

- This is a 2nd order differential equation.
- In order to solve it lets try to guess a solution:

$$x = \sqrt{\varepsilon.\beta(s)}\cos\left(\phi(s) + \phi_0\right)$$

- ε and ϕ_0 are constants, which depend on the <u>**initial conditions**</u>.
- $\beta(s)$ = the <u>**amplitude modulation**</u> due to the changing focusing strength.
- $\phi(s)$ = the <u>**phase advance**</u>, which also depends on focusing strength.

TRANSVERSE BEAM DYNAMICS



$$\frac{d^2x}{ds^2} + K(s)x = 0$$

$$x = \sqrt{\varepsilon.\beta(s)}\cos(\phi(s) + \phi_0)$$

- ✓ $\beta(s)$ = the amplitude modulation due to the changing focusing strength.
- ✓ $\phi(s)$ = the phase advance, which also depends on focusing strength.
- ✓ ε and ϕ_0 are constants, which depend on the initial conditions.

Hill's equation

- ✓ The **betatron oscillations** exist in both horizontal and vertical planes.
- ✓ The number of betatron oscillations per turn is called the **betatron tune** and is defined as **Qx** and **Qy**.
- ✓ Hill's equation describes this motion mathematically

$$\frac{d^2x}{ds^2} + K(s)x = 0$$

- ✓ If the restoring force, K is constant in 's' then this is just a **Simple Harmonic Motion**.

Matrix Formalism

- ✓ Lets represent the particles transverse position and angle by a column matrix.

$$\begin{pmatrix} x \\ x' \end{pmatrix}$$

- ✓ As the particle moves around the machine the values for x and x' will vary under influence of the dipoles, quadrupoles and drift spaces.
- ✓ These modifications due to the different types of magnets can be expressed by a **Transport Matrix M**
- ✓ If we know x_1 and x_1' at some point s_1 then we can calculate its position and angle after the next magnet at position S_2 using:

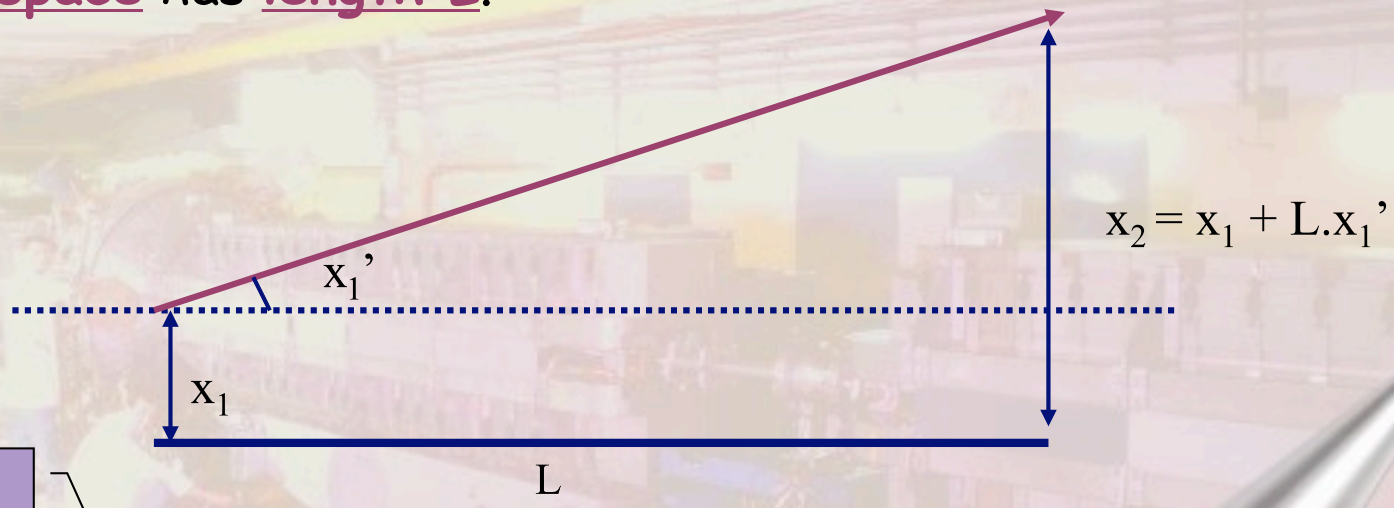
$$\begin{pmatrix} x(s_2) \\ x(s_2)' \end{pmatrix} = M \begin{pmatrix} x(s_1) \\ x(s_1)' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x(s_1) \\ x(s_1)' \end{pmatrix}$$

How to apply the formalism

- ✓ If we want to know how a particle behaves in our machine as it moves around using the matrix formalism, we need to:
  - ✓ Split our machine into separate element as dipoles, focusing and defocusing quadrupoles, and drift spaces.
  - ✓ Find the matrices for all of these components
  - ✓ Multiply them all together
  - ✓ Calculate what happens to an individual particle as it makes one or more turns around the machine

Matrix for a drift space

- ✓ A drift space contains no magnetic field.
- ✓ A drift space has length L.

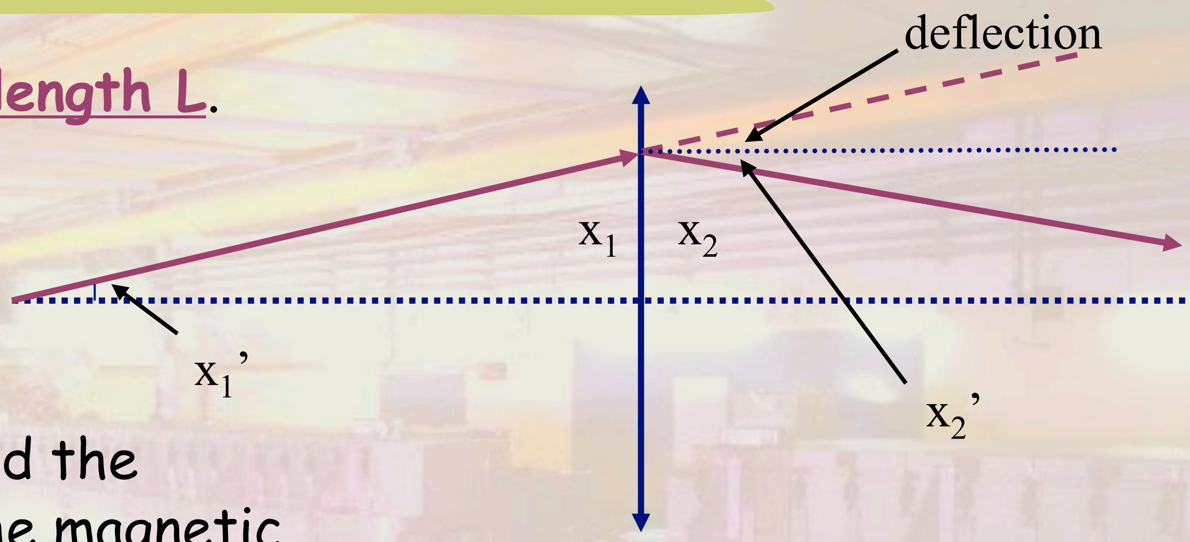


x_1' small

$$\left.\begin{aligned} x_2 &= x_1 + L x_1' \\ x_2' &= 0 + x_1' \end{aligned}\right\} \longrightarrow \begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

Matrix for a quadrupole

- ✓ A quadrupole of length L.



Remember $B_y \propto x$ and the deflection due to the magnetic field is: $\frac{LB_y}{(B\rho)} = -\frac{LK}{(B\rho)} \cdot x$

Provided L is small

$$x_2 = x_1 + 0$$
$$x_2' = -\frac{LK}{(B\rho)} x_1 + x_1'$$

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{LK}{(B\rho)} & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

Matrix for a quadrupole (2)

- We found :

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{LK}{(B\rho)} & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

- Define the focal length of the quadrupole as f= $\frac{(B\rho)}{KL}$

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

How now further ?

- ✓ For our purpose we will treat dipoles as simple drift spaces as they bend all the particles by the same amount.
- ✓ We have Transport Matrices corresponding to drift spaces and quadrupoles.
- ✓ These matrices describe the real discrete focusing of our quadrupoles.
- ✓ Now we must combine these matrices with our solution to Hill's equation, since they describe the same motion……

A quick recap…….

- ✓ We solved Hill's equation, which led us to the definition of transverse emittance and allowed us to describe particle motion in phase space in terms of β, α etc…
- ✓ We constructed the Transport Matrices corresponding to drift spaces and quadrupoles.
- ✓ **Now we must combine these matrices with the solution of Hill's equation to evaluate β, α etc**

Matrices & Hill's equation

- ✓ We can multiply the matrices of our drift spaces and quadrupoles together to form a transport matrix that describes a larger section of our accelerator.
- ✓ These matrices will move our particle from one point $(x(s_1),x'(s_1))$ on our phase space plot to another $(x(s_2),x'(s_2))$, as shown in the matrix equation below.

$$\begin{pmatrix} x(s_2) \\ x'(s_2) \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \begin{pmatrix} x(s_1) \\ x'(s_1) \end{pmatrix}$$

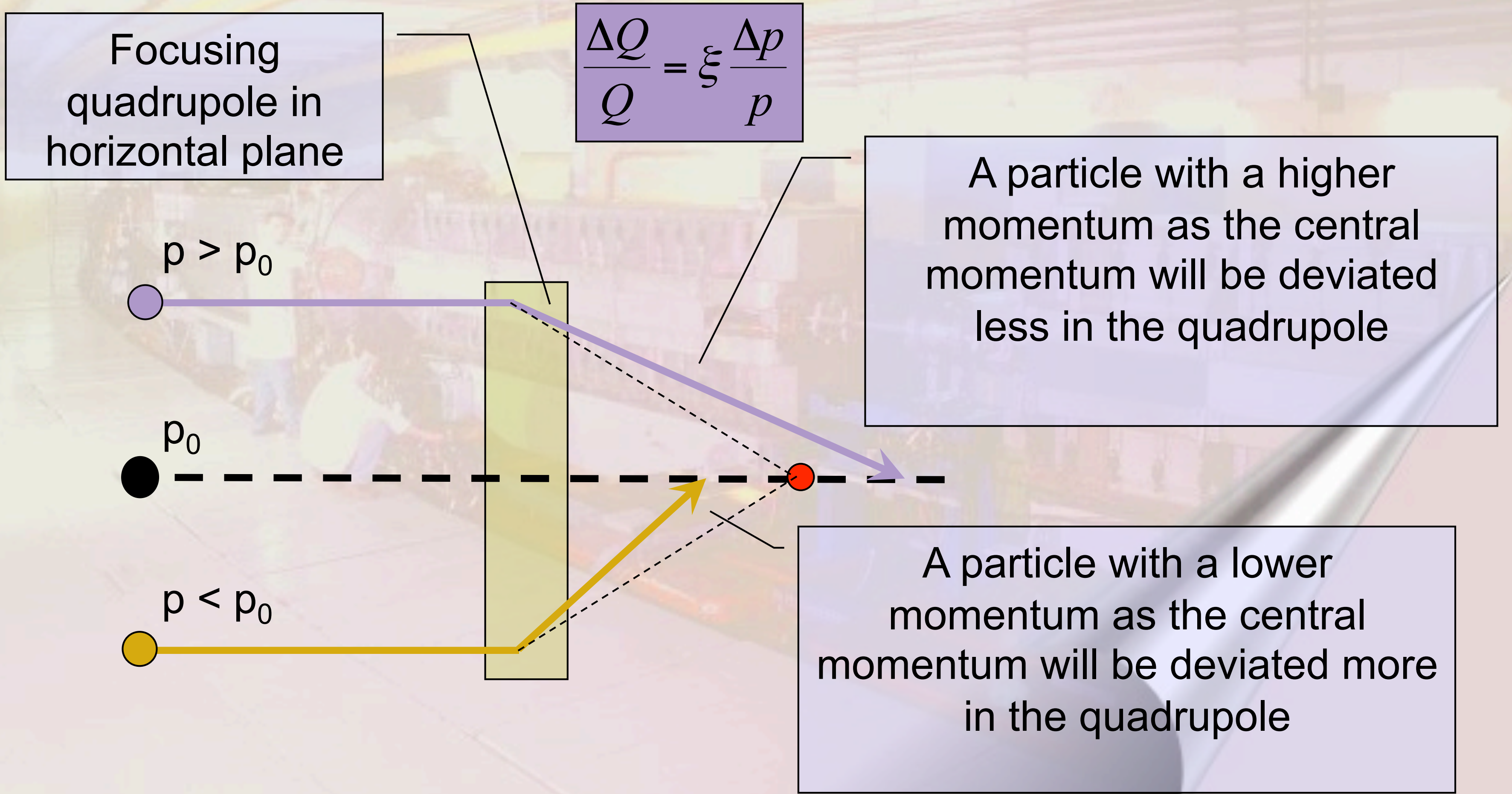
- ✓ The elements of this matrix are fixed by the elements through which the particles pass from point s_1 to point s_2.
- ✓ However, we can also express (x,x') as solutions of Hill's equation.

$$x = \sqrt{\varepsilon.\beta}\cos\phi$$ and $$x' = -\alpha\sqrt{\varepsilon/\beta}\cos\phi - \sqrt{\varepsilon/\beta}\sin\phi$$

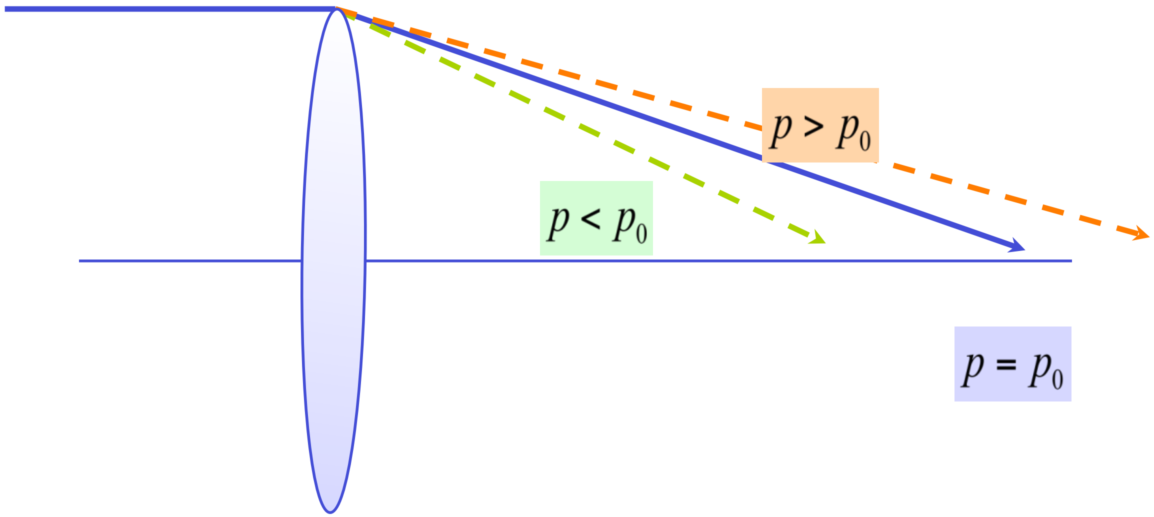
Chromaticity

✓ The chromaticity relates the tune spread of the transverse motion with the momentum spread in the beam.

$$\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p}$$



Chromaticity



$$Q' = \frac{\Delta Q}{\Delta p / p}$$

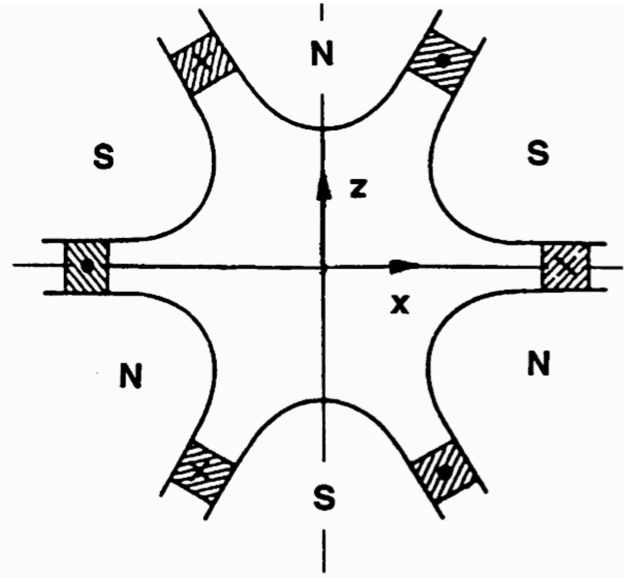
Particles with different energies have different betatron tunes.

Bad for the beam:
- Adds a tune spread
- Instabilities ("head-tail")

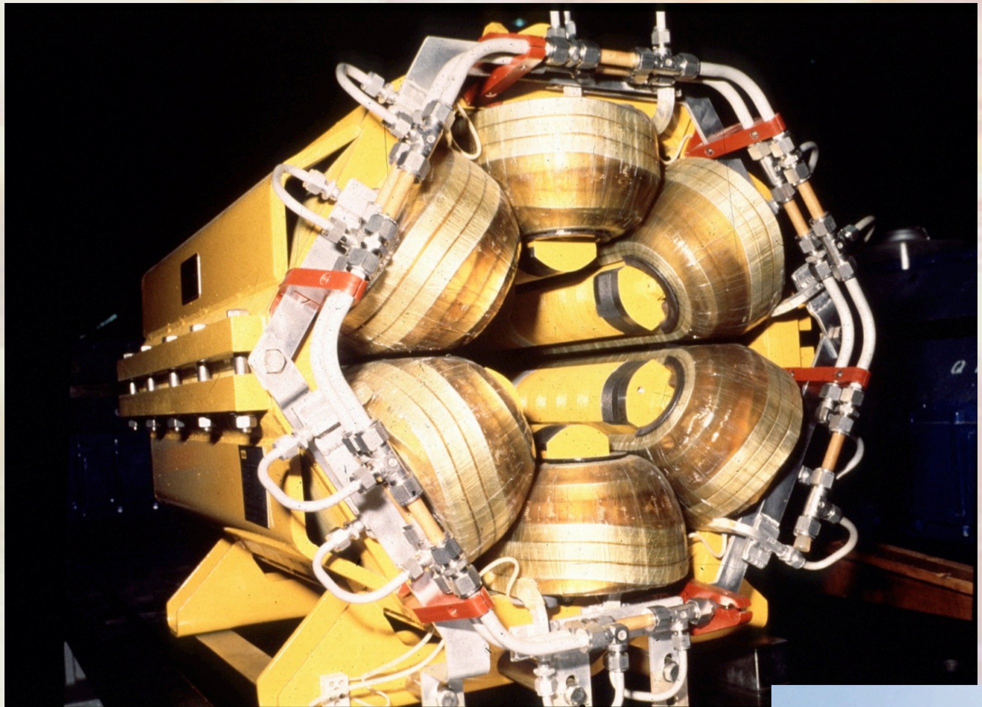
Focusing error from momentum errors ~ ***-K Δp/p***

Chromaticity corrections is done with **sextupole magnets**. The field changes as x^2.

LHC:
2 sextupole families per plane per beam for chromaticity correction.

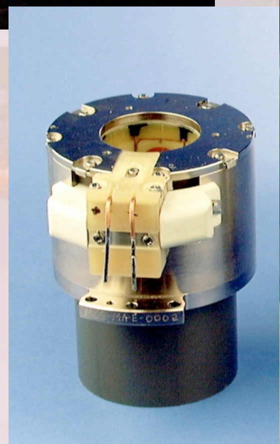


Sextupole Magnets

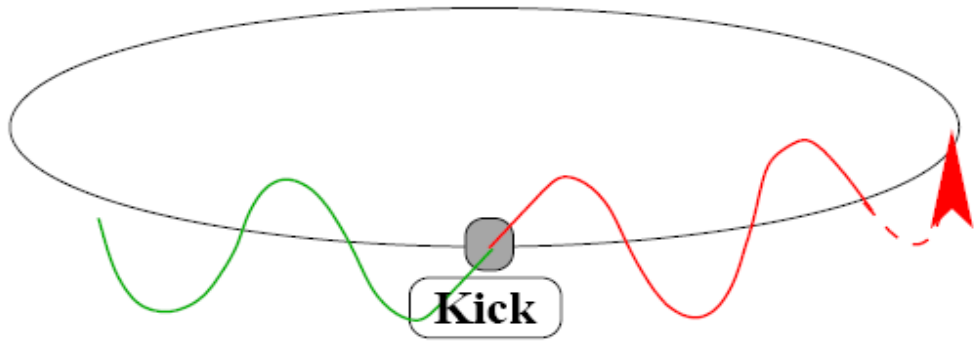


- ✓ Conventional Sextupole from LEP, but looks similar for other 'warm' machines.
- ✓ ~ 1 meter long and a few hundreds of kg.

- ✓ Correction Sextupole of the LHC
- ✓ 11cm, 10 kg, 500A at 2K for a field of 1630 T/m^2



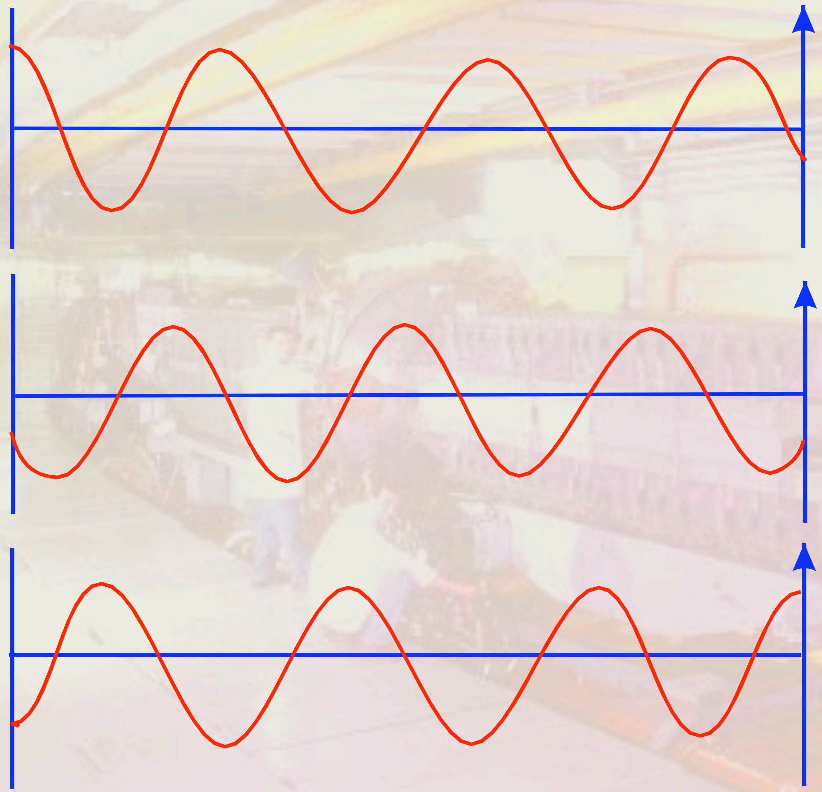
Machine imperfections



The Q-value gives the number of oscillations the particles make in one turn. If this value in an integer, the beam "sees" the same magnet-error over and over again and we may have a resonance phenomenon.(Resonance) Therefore the Q-value is not an integer.

The magnets have to be good enough so that resonance phenomena do not occur.

Q = 3.333 in more detail

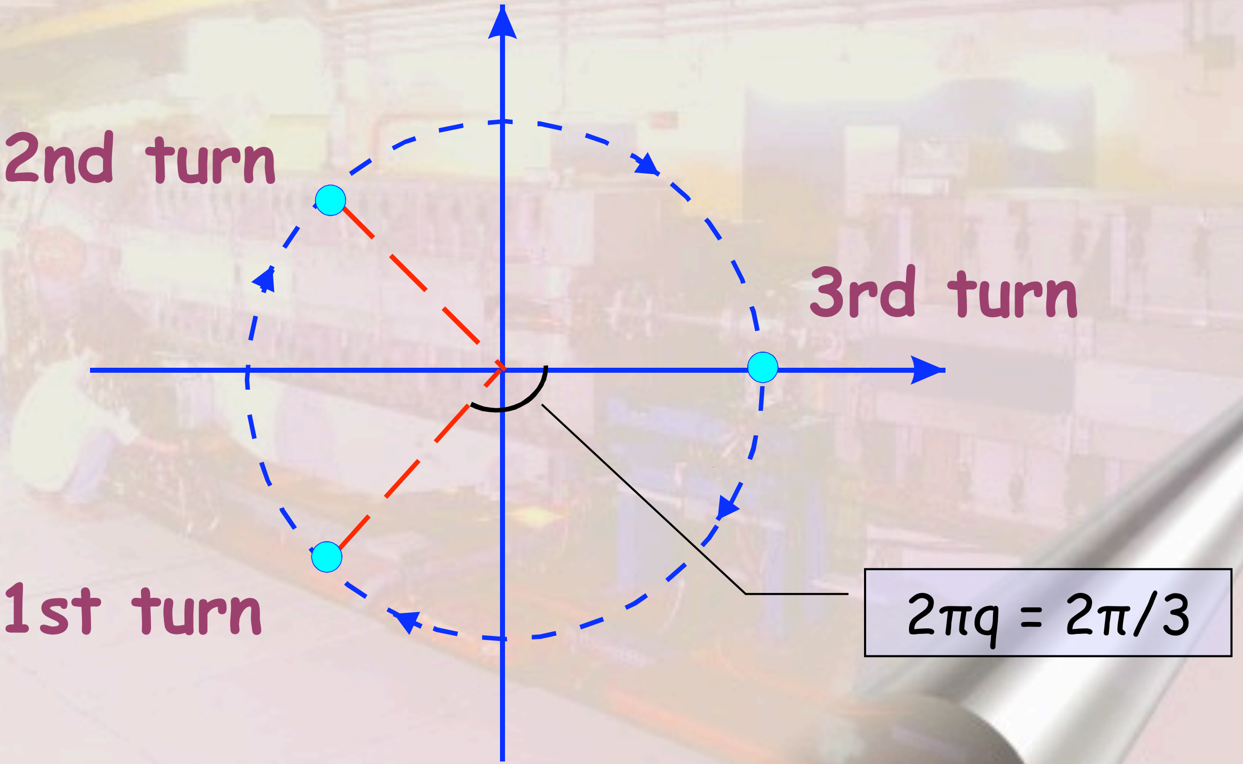


Third order resonant betatron oscillation

3Q = 10, Q = 3.333, q = 0.333

Q = 3.333 in Phase Space

- ✓ Third order resonance on a normalised phase space plot



Machine Imperfections

- ✓ There are many things in our machine, which will excite resonances:
  - ✓ The magnets themselves
  - ✓ Unwanted higher order field components in our magnets
  - ✓ Tilted magnets
  - ✓ Experimental solenoids (LHC experiments)

- ✓ The trick is to reduce and compensate these effects as much as possible and then find some point in the tune diagram where the beam is stable.

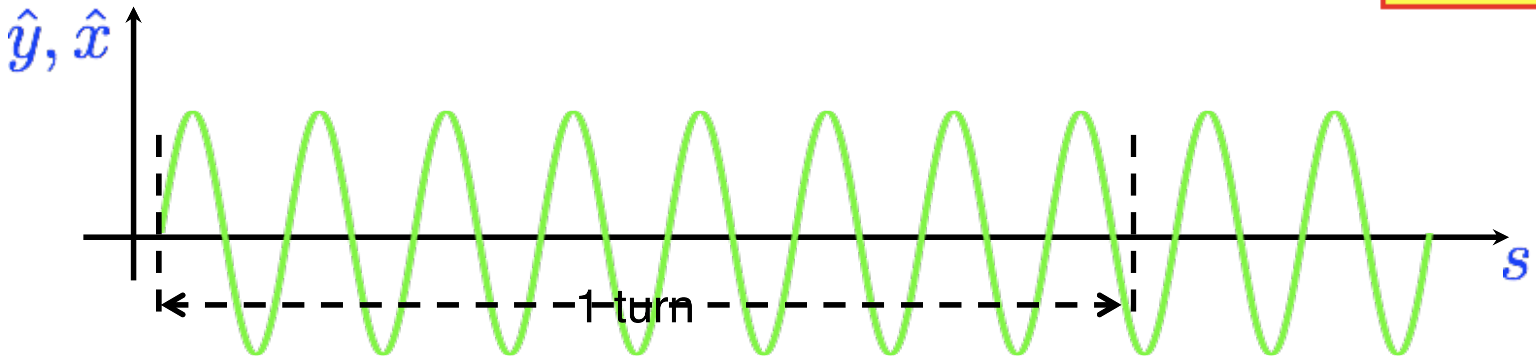
Betatron tune

Betatron phase advance over 1 turn:

$$\mu = \oint \frac{ds}{\beta(s)}$$

Betatron tune:

$$Q \equiv \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$$

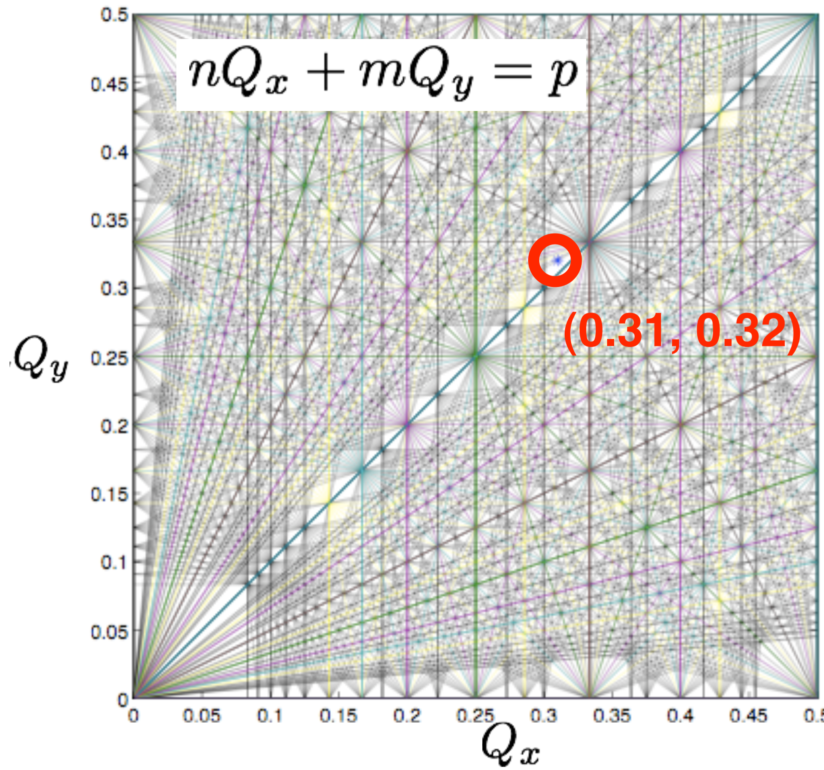


The tune is the **number of betatron oscillations per turn**.

We *normally* only care about the **fractional part** of the tune! 64.31 is 0.31!

The operating tune values (**working point**) must be chosen to avoid resonance.

The tune values must be controlled to within better than 10^{-3}, during all machine phases (ramp, squeeze, ...)



Acceleration Concepts

- Lorentz Force:

$$\frac{dp}{dt} = q \cdot \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

→ energy gain only due to electric fields!

- Scalar and Vector Potential:

$$\vec{E} = -grad\phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t}$$

- Electrostatic acceleration → $A = 0$
- Acceleration with time varying fields → $\phi = 0$

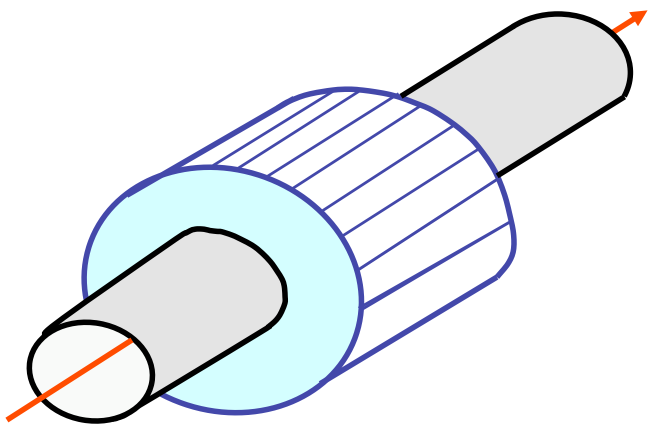
Acceleration

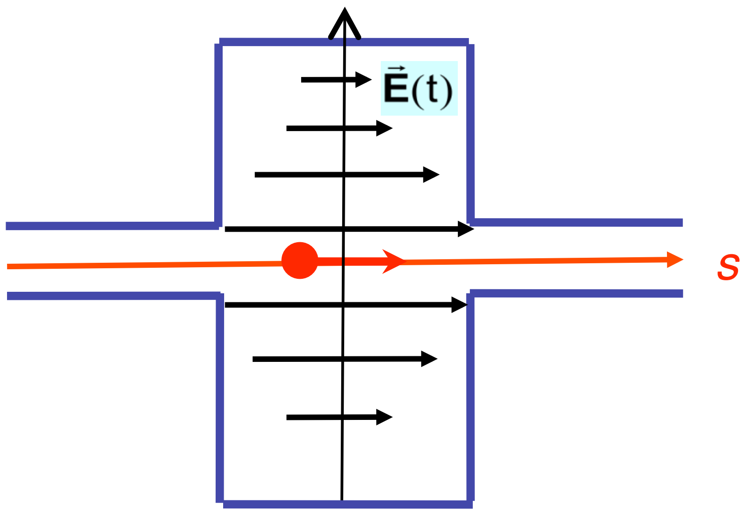
Acceleration is performed with electric fields fed into **Radio-Frequency (RF) cavities**.
RF cavities are basically resonators tuned to a selected frequency.

In circular accelerators, the acceleration is done with small steps at each turn.

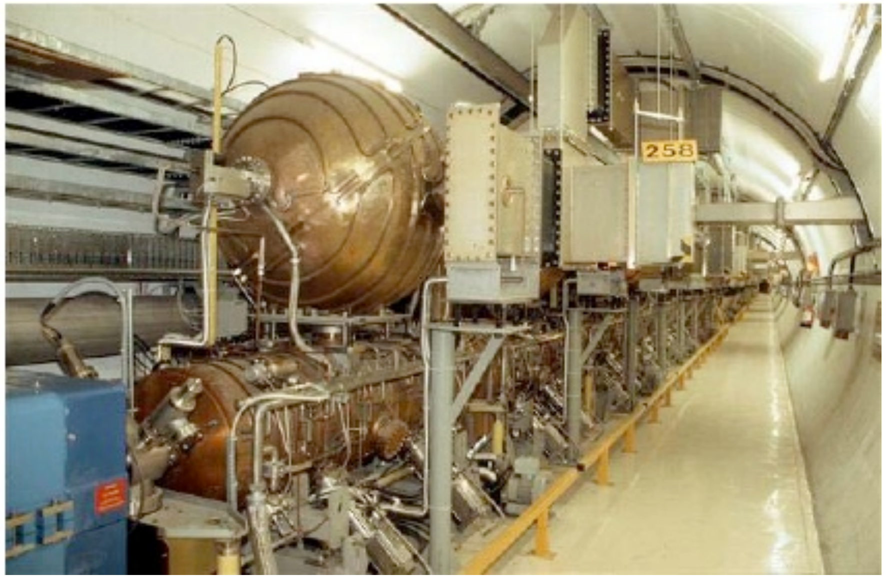
LHC: 8 RF cavities per beam (400 MHz), located in point 4

At the LHC, the acceleration from **450 GeV** to **7 TeV** lasts ~ 20 minutes (nominal!), with an average energy gain of ~ 0.5 MeV on each turn.
[Today, we ramp at a factor 4 less energy gain per turn than nominal!]

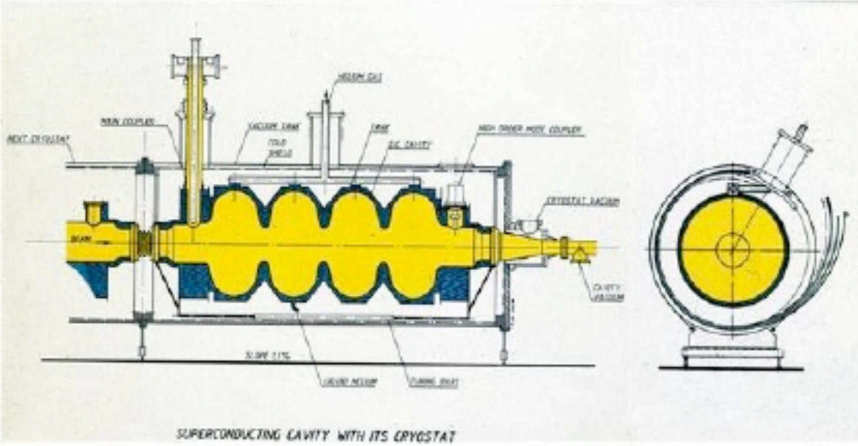




RF Cavities



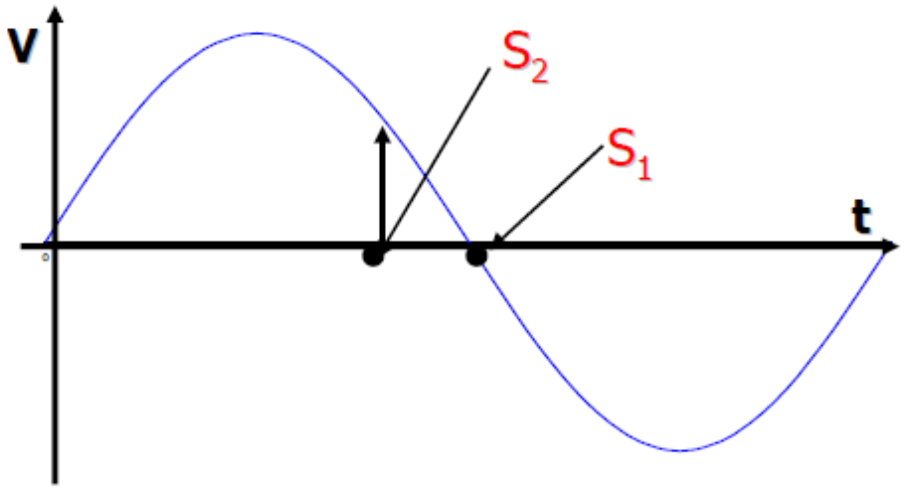
LEP cavities



LHC Superconductive cavities

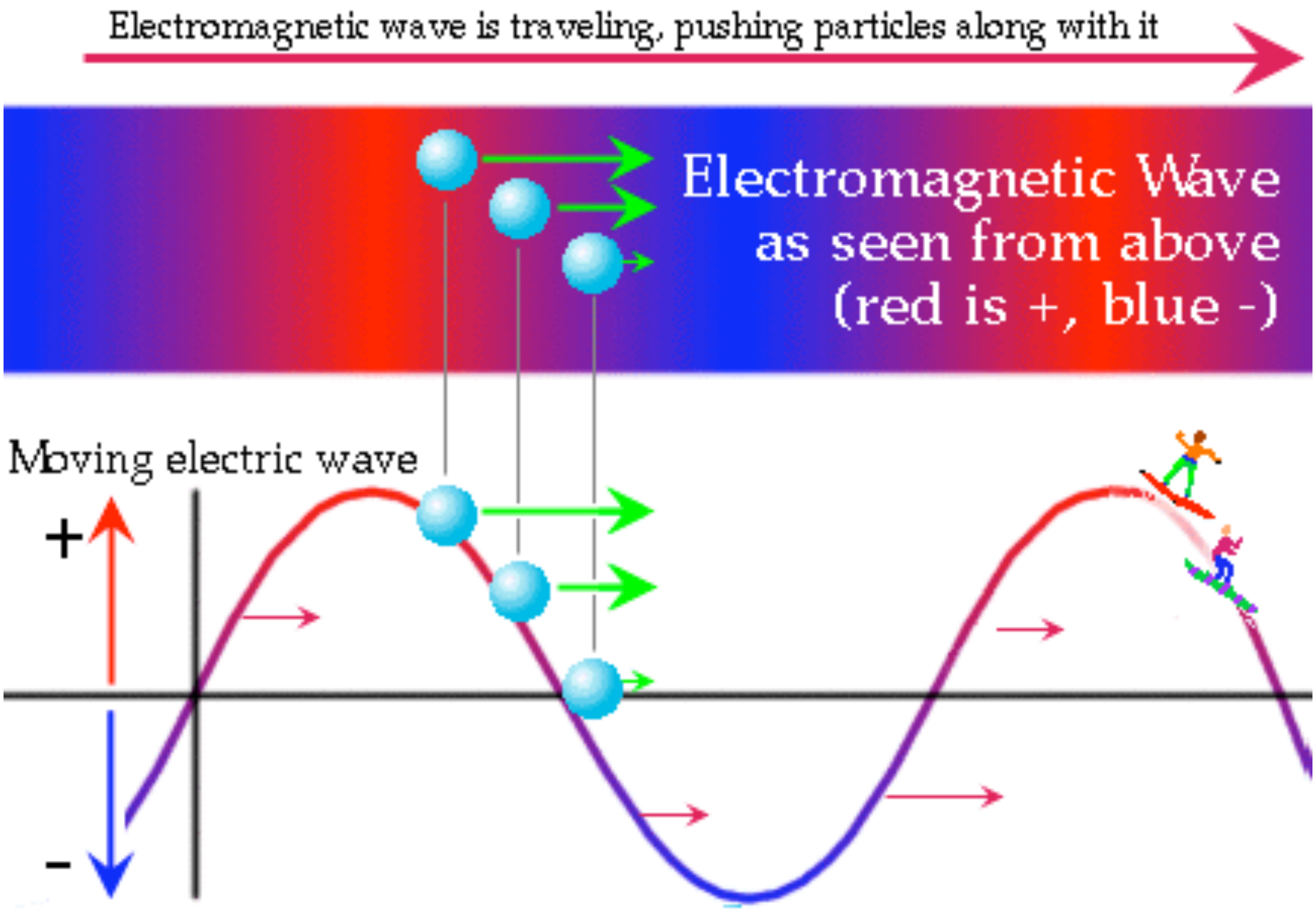
Acceleration or compensation

- We have to provide energy to the particles either to accelerate them or to compensate for the losses accumulated during one turn.
- This energy is not provided by electrostatic plates, but by RF cavities.
- The ideal particle has to arrive at the cavity exactly at the same moment turn after turn (synchroneous particle).



Equilibrium:

$$f_{RF} = h \, . \, f_{rev}$$



Electromagnetic wave is traveling, pushing particles along with it
Electromagnetic Wave
as seen from above
(red is +, blue -)
Moving electric wave
+
-

- **TRANSITION ENERGY: The increase of energy has 2 contradictory effects**

  - **An increase of the particle's velocity**
  - **An increase of the length of the particle's trajectory**

According to the variations of these 2 parameters, the revolution frequency evolves differently

  - **Below transition energy: The velocity increases faster than the length ⇒ The revolution frequency increases**
  - **Above transition energy: It is the opposite case ⇒ The revolution frequency decreases**
  - **At transition energy: The variation of the velocity is compensated by the variation of the trajectory ⇒ A variation of energy does not modify the frequency**

Transition

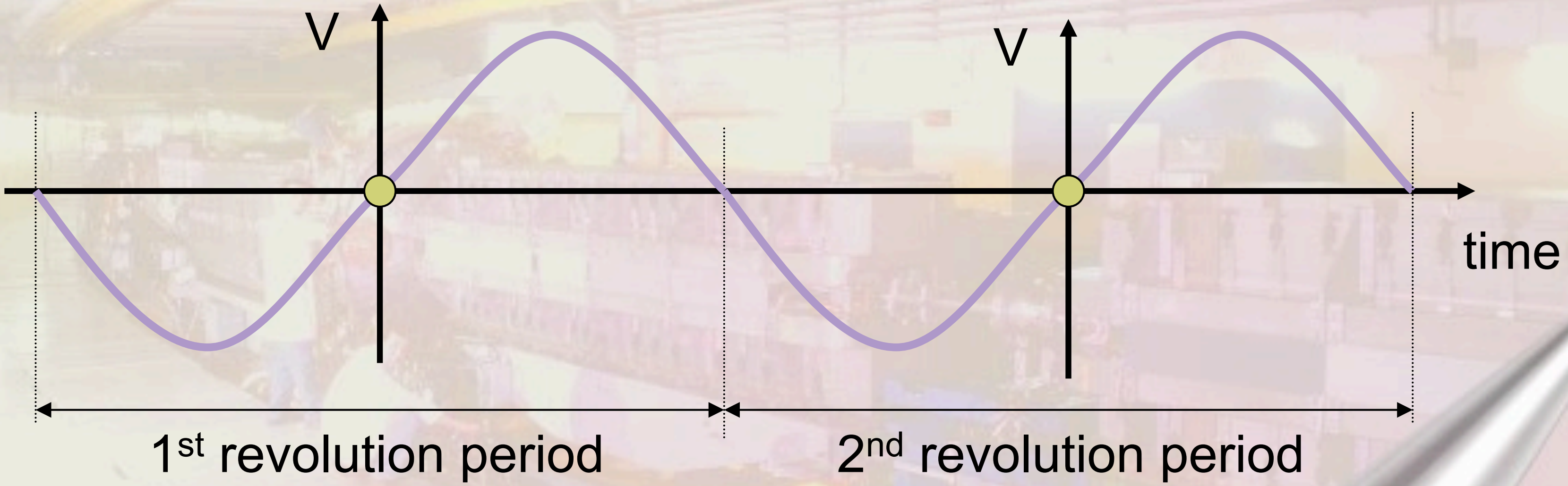
- **Lets look at the behaviour of a particle in a constant magnetic field.**
- <u>Low momentum</u> $(\beta << 1, \gamma \Rightarrow 1)$ ⟶
- The revolution frequency increases as momentum increases
- <u>High momentum</u> $(\beta \approx 1, \gamma >> 1)$ ⟶
- The revolution frequency decreases as momentum increases
- For one particular momentum or energy we have:

$$\frac{1}{\gamma^2} = \alpha_p$$

- This particular energy is called the <u>Transition energy</u>

A Single particle in a longitudinal electric field (below transition)

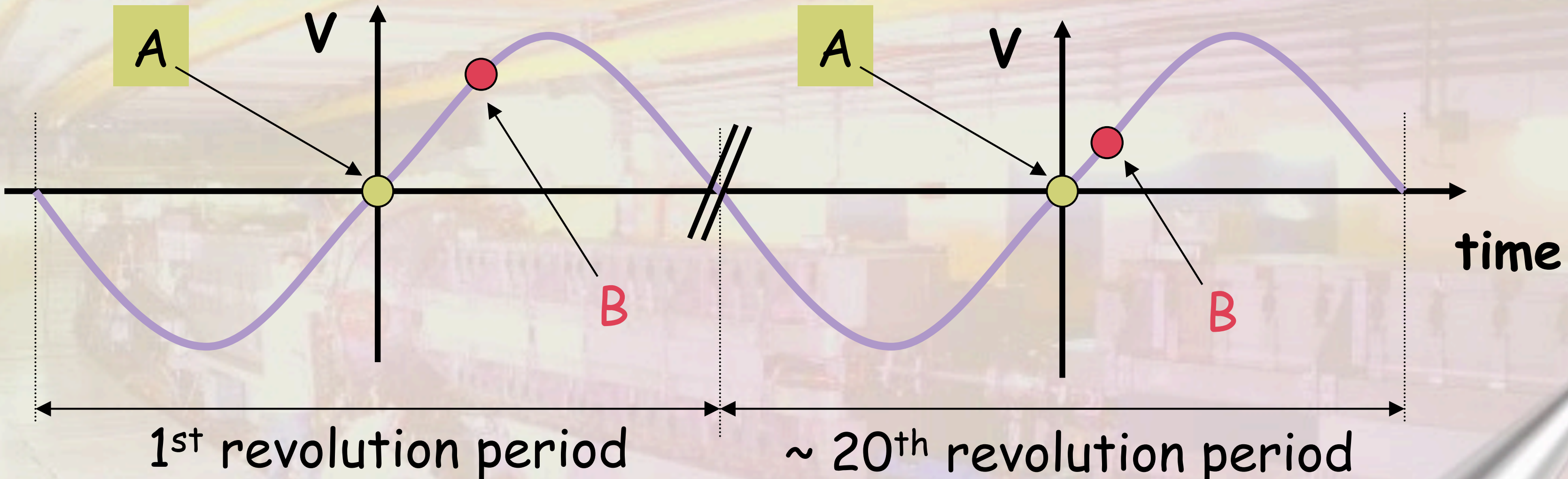
- Lets see what a low energy particle does with this oscillating voltage in the cavity.



- Set the oscillation frequency so that the period is exactly equal to one revolution period of the particle.

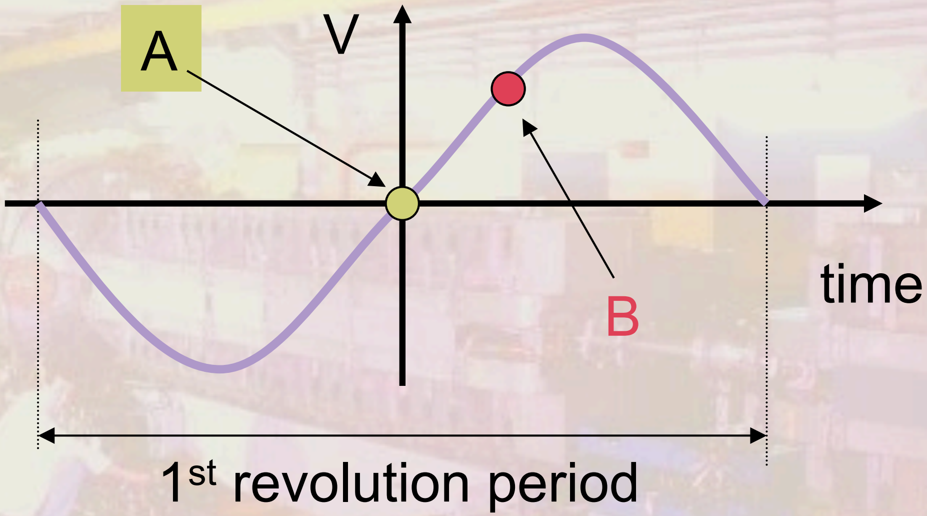
Add a second particle to the first one

- Lets see what a second low energy particle, which arrives later in the cavity, does with respect to our first particle.

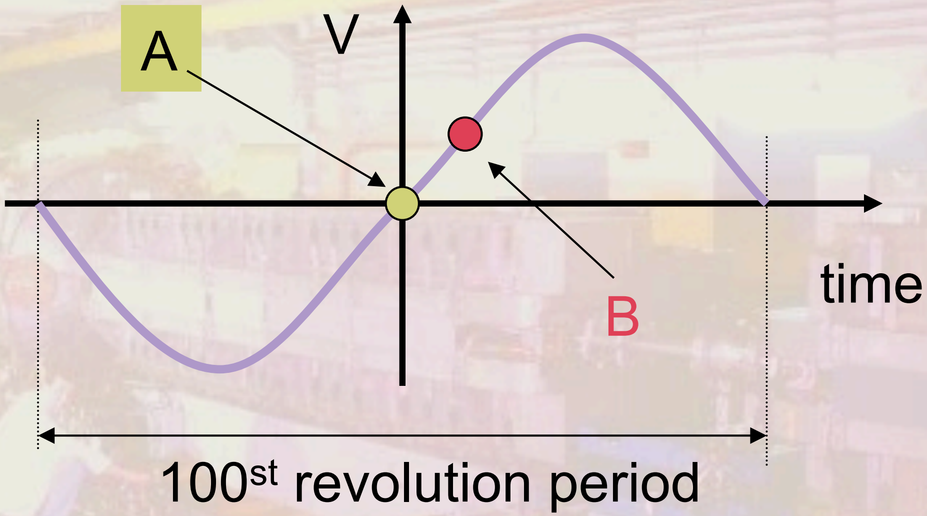


- B arrives late in the cavity w.r.t. A
- B sees a higher voltage than A and will therefore be accelerated
- After many turns B approaches A
- B is still late in the cavity w.r.t. A
- B still sees a higher voltage and is still being accelerated

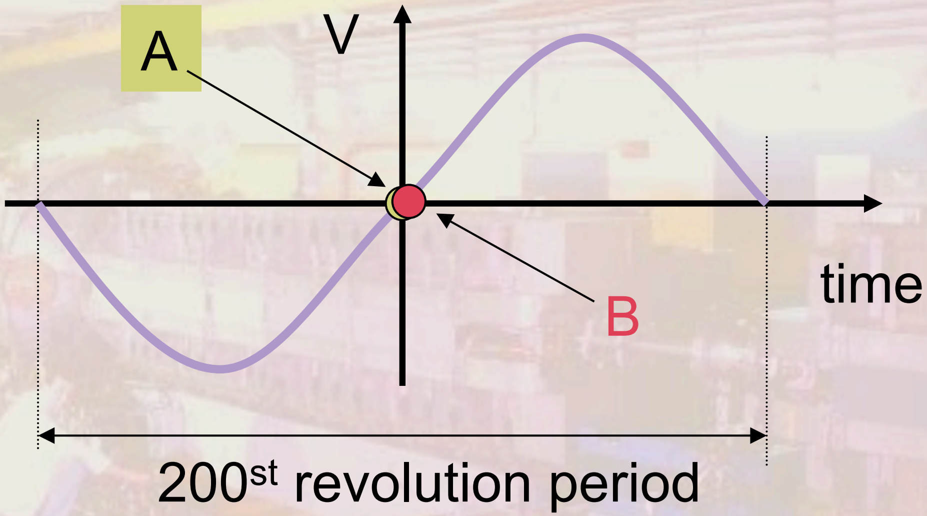
Lets see what happens after many turns



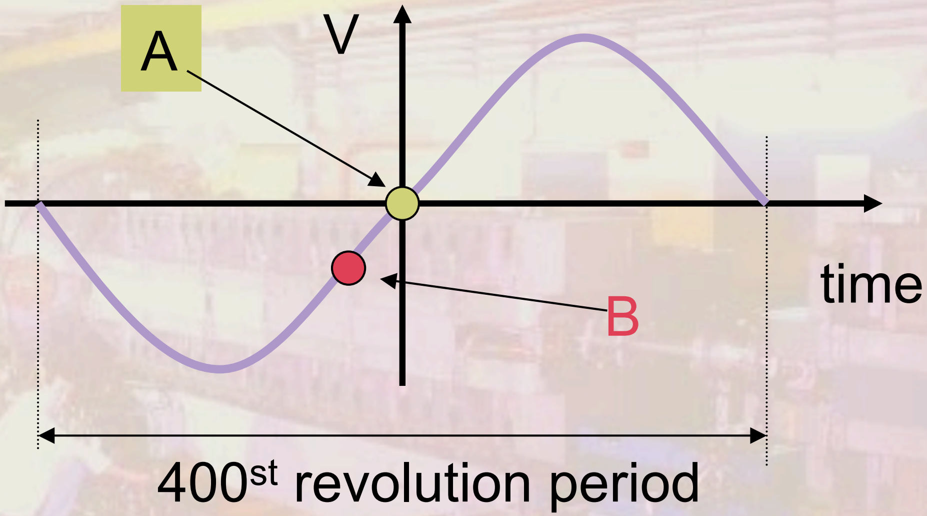
Lets see what happens after many turns



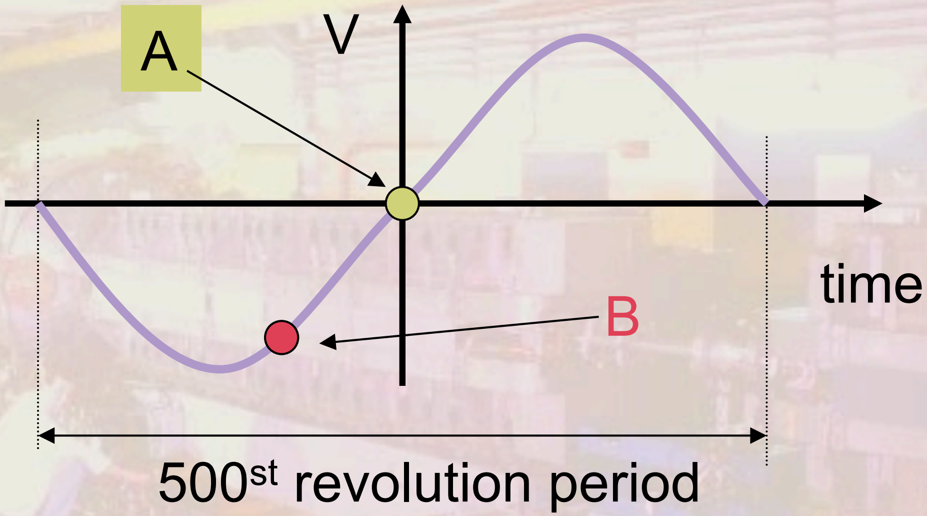
Lets see what happens after many turns



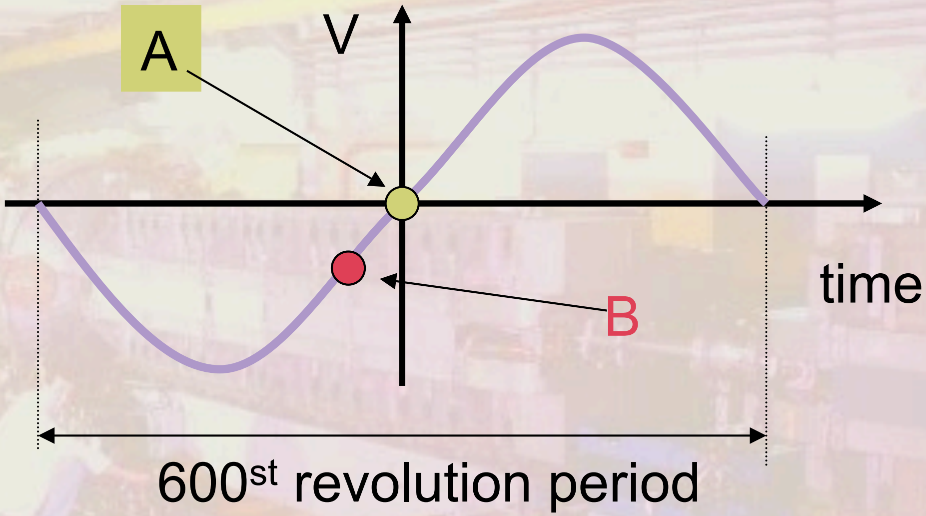
Lets see what happens after many turns



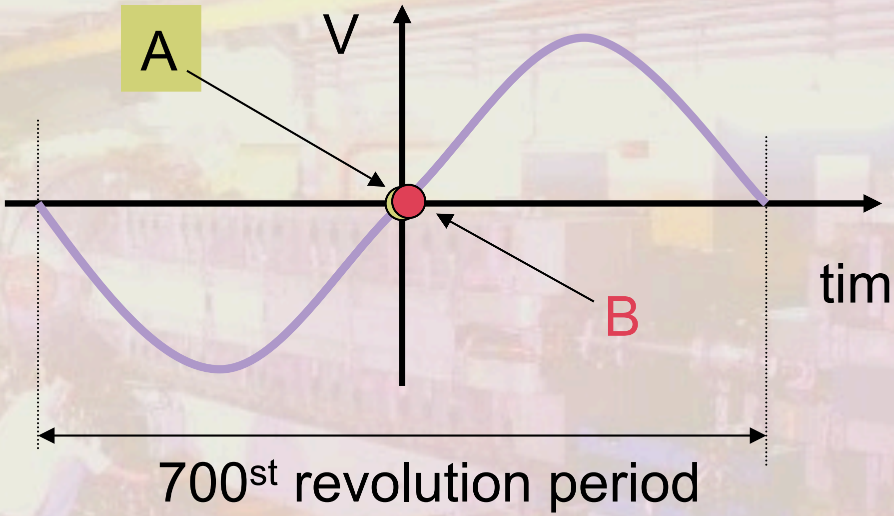
Lets see what happens after many turns



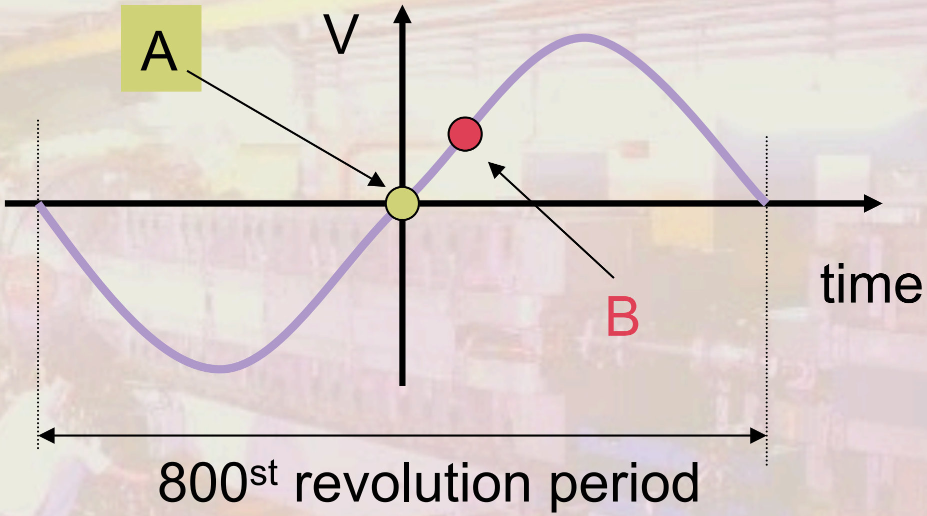
Lets see what happens after many turns



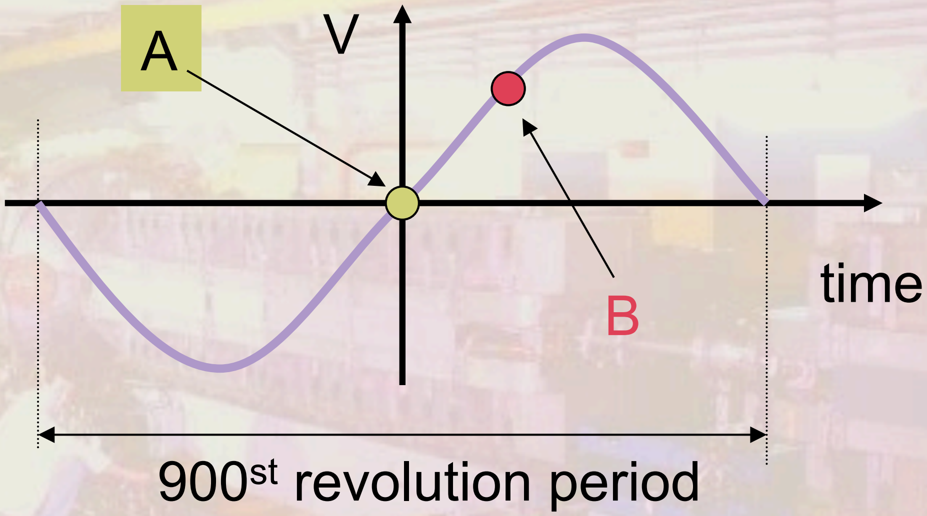
Lets see what happens after many turns



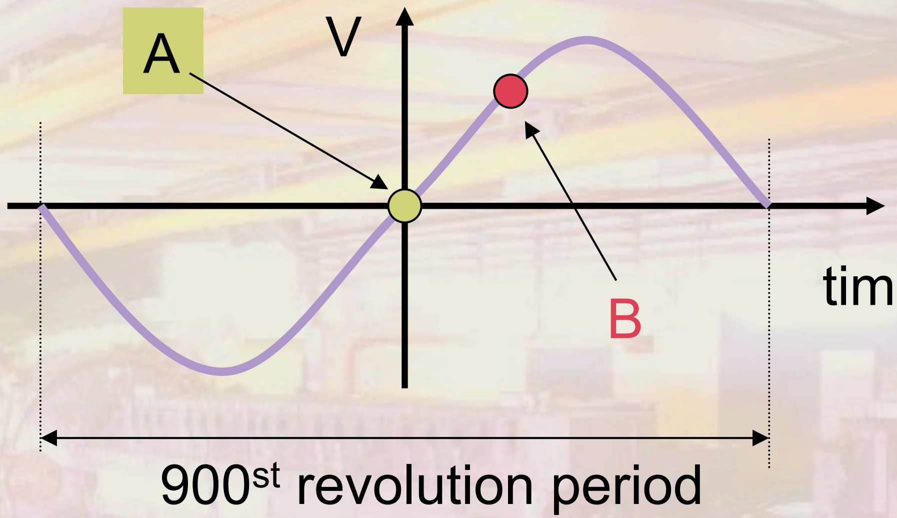
Lets see what happens after many turns



Lets see what happens after many turns



Synchrotron Oscillations



- Particle B has made 1 full oscillation around particle A.
- The amplitude depends on the initial phase.

Exactly like the pendulum

- We call this oscillation:

Synchrotron Oscillation

What happens beyond transition ?

- Until now we have seen how things look like below transition

Higher energy ⇨ faster orbit ⇨ higher F_{rev} ⇨ next time particle will be earlier.

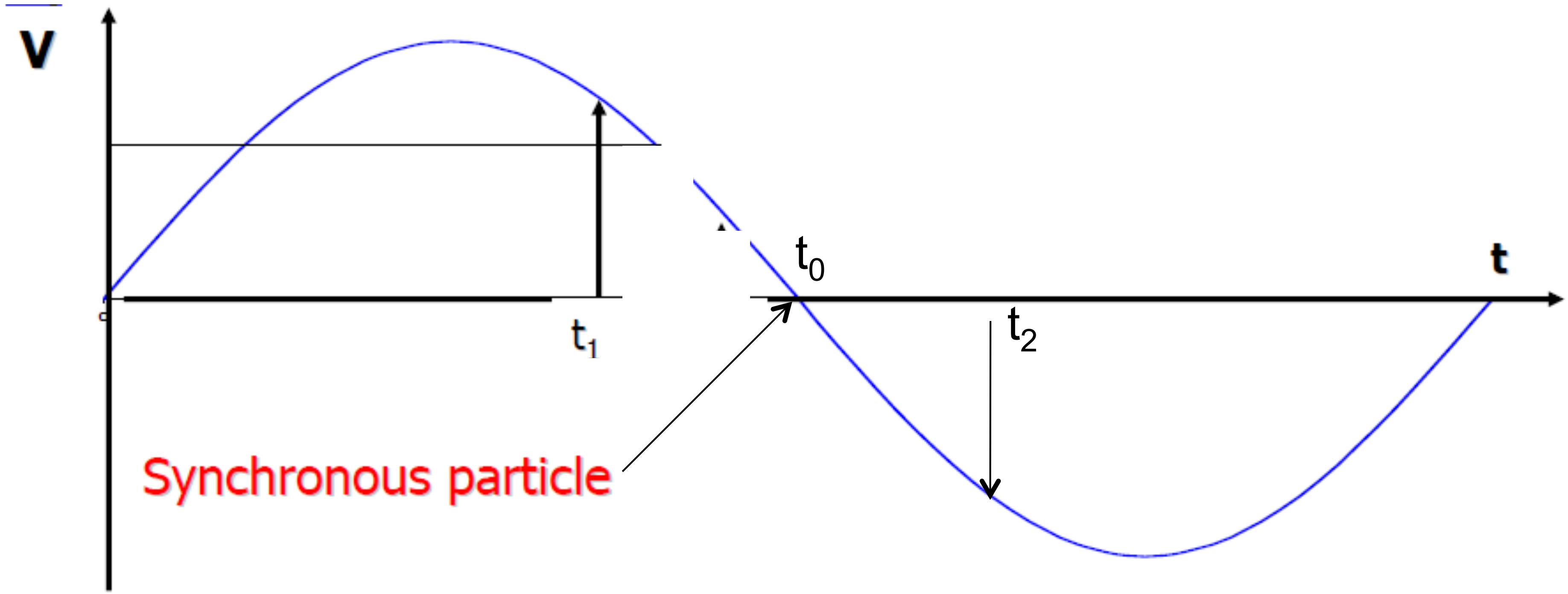
Lower energy ⇨ slower orbit ⇨ lower F_{rev} ⇨ next time particle will be later.

- What will happen above transition ?

Higher energy ⇨ longer orbit ⇨ lower F_{rev} ⇨ next time particle will be later.

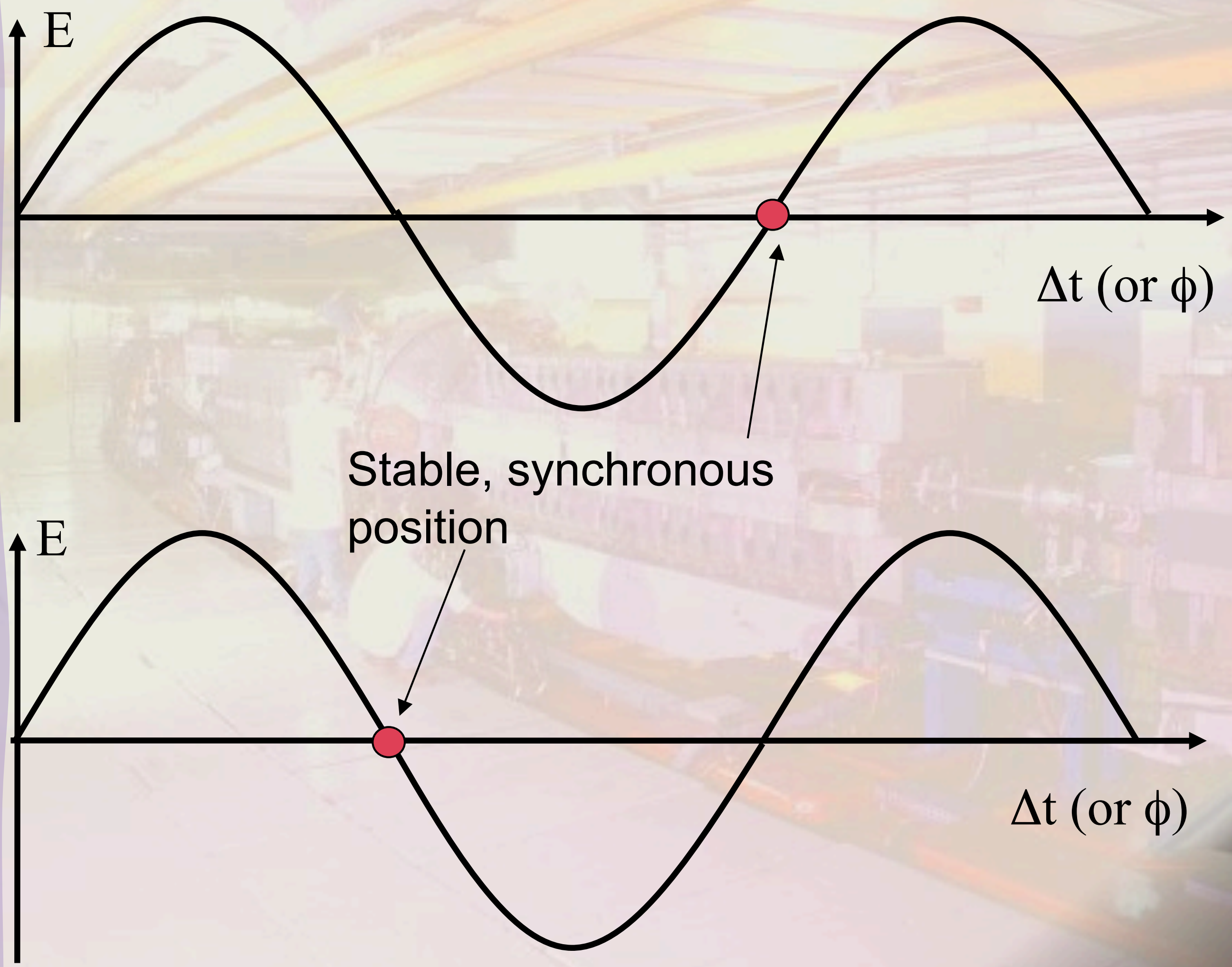
Lower energy ⇨ shorter orbit ⇨ higher F_{rev} ⇨ next time particle will be earlier.

Off momentum particles
(above transition)



On momentum particle arrives at t_0 ➔ $V = V_0$ ➔ o.k.
$\Delta p/p > 0$ have a longer path ➔ arrive late, e.g. t_2 ➔ $V_2 < V_0$
$\Delta p/p < 0$ have a shorter path ➔ arrive early, e.g. t_1 ➔ $V_1 > V_0$

Before and After Transition



Before transition

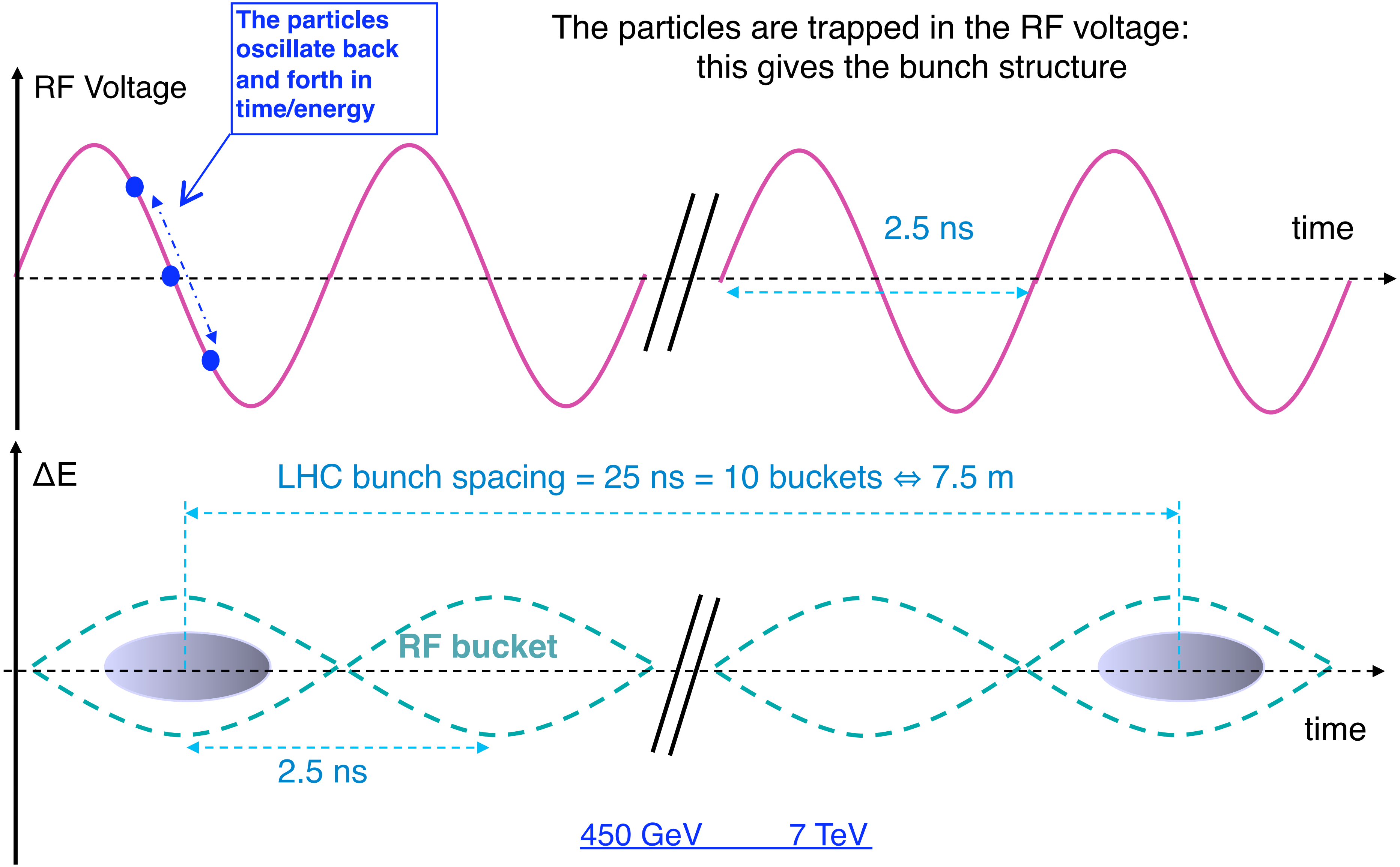
After transition

What are the implication for the RF ?

- For particles below transition we worked on the rising edge of the sine wave.
- For Particles above transition we will work on the falling edge of the sine wave.

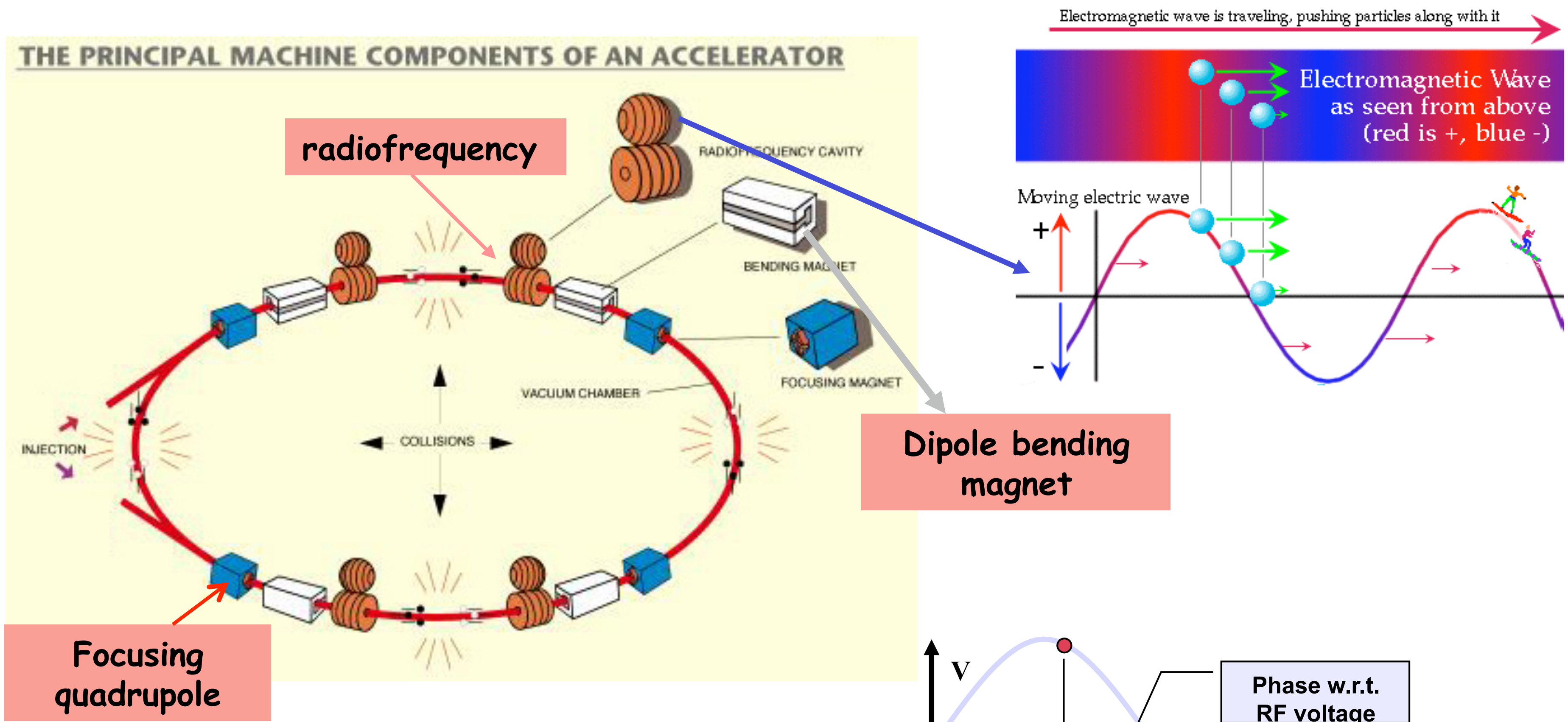
Buckets and bunches

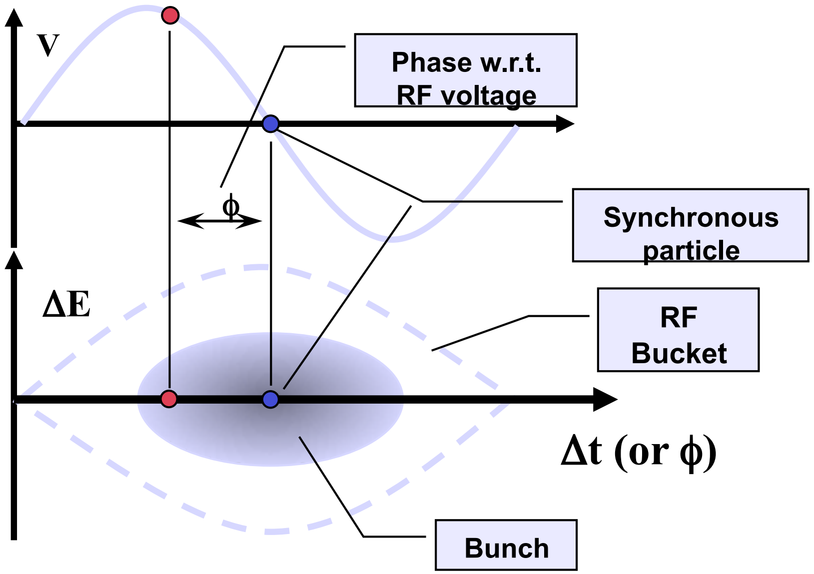
The particles are trapped in the RF voltage:
this gives the bunch structure



	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

Sincrotron acceleration





To accelerate the particles in stable orbits, the magnetic field has to increase and the frequency has to be adjusted to keep the particles on the reference trajectory.

Examples

- **CERN**

PS, SPS, SPPbarS, LEP, LHC

- **FERMILAB**

TEVATRON

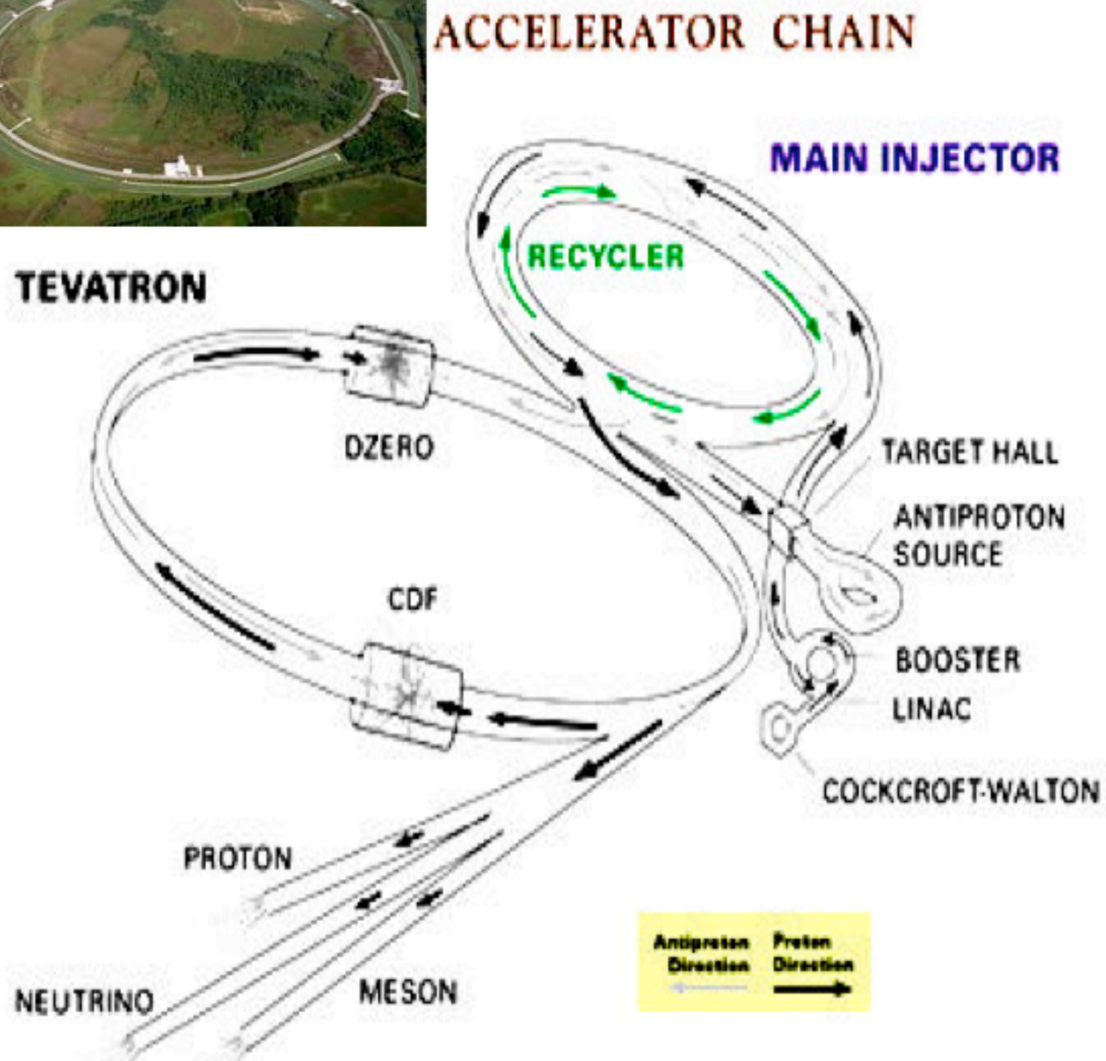
- **DESY**

HERA

- **SLAC**

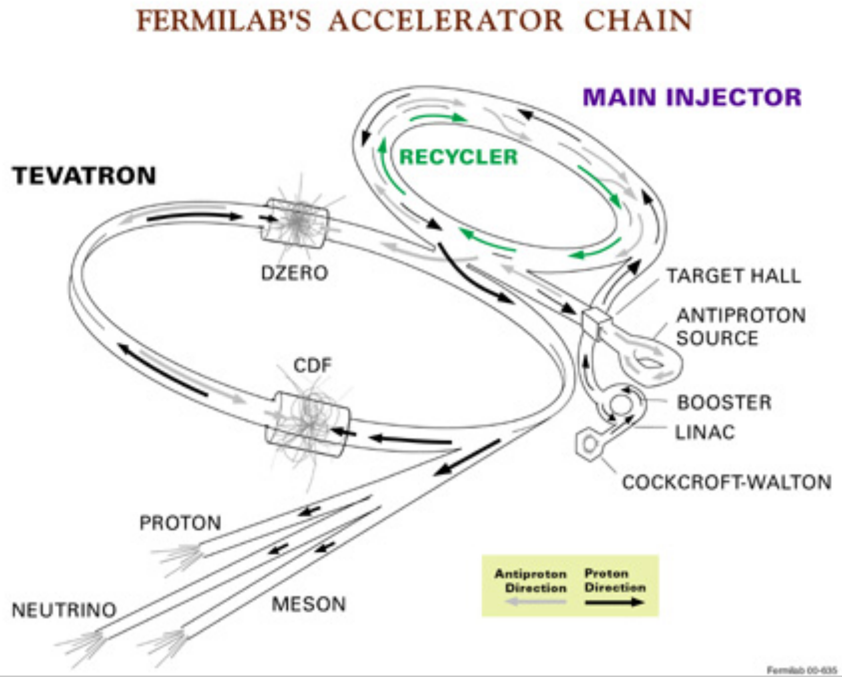
SLC, PEP II

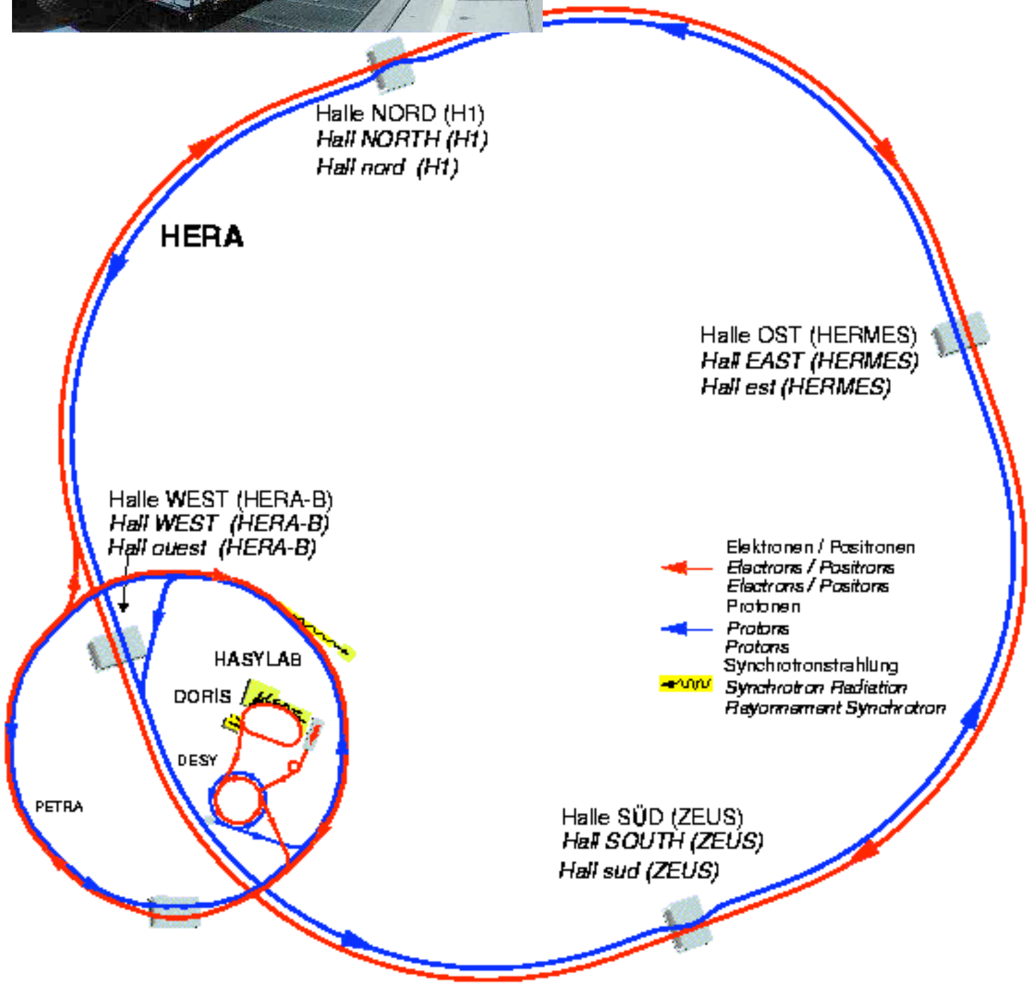
Tevatron



- Operation
  1985 - now,
  FERMILAB, Chicago
- Circumference
  4 miles
- Particles
  protons - antiprotons
- Beam energy
  0.9 TeV → 1 TeV
- Luminosity
  10^{30} - 10^{32} cm^{-2} sec^{-1}
- L_{int}
  Run Ia+Ib : 110 pb^{-1}
- Experiments
  CDF, DØ
- Characteristics:
  - 'dirty' environment (see LHC later)
  - high interaction rate

Fermilab from the air

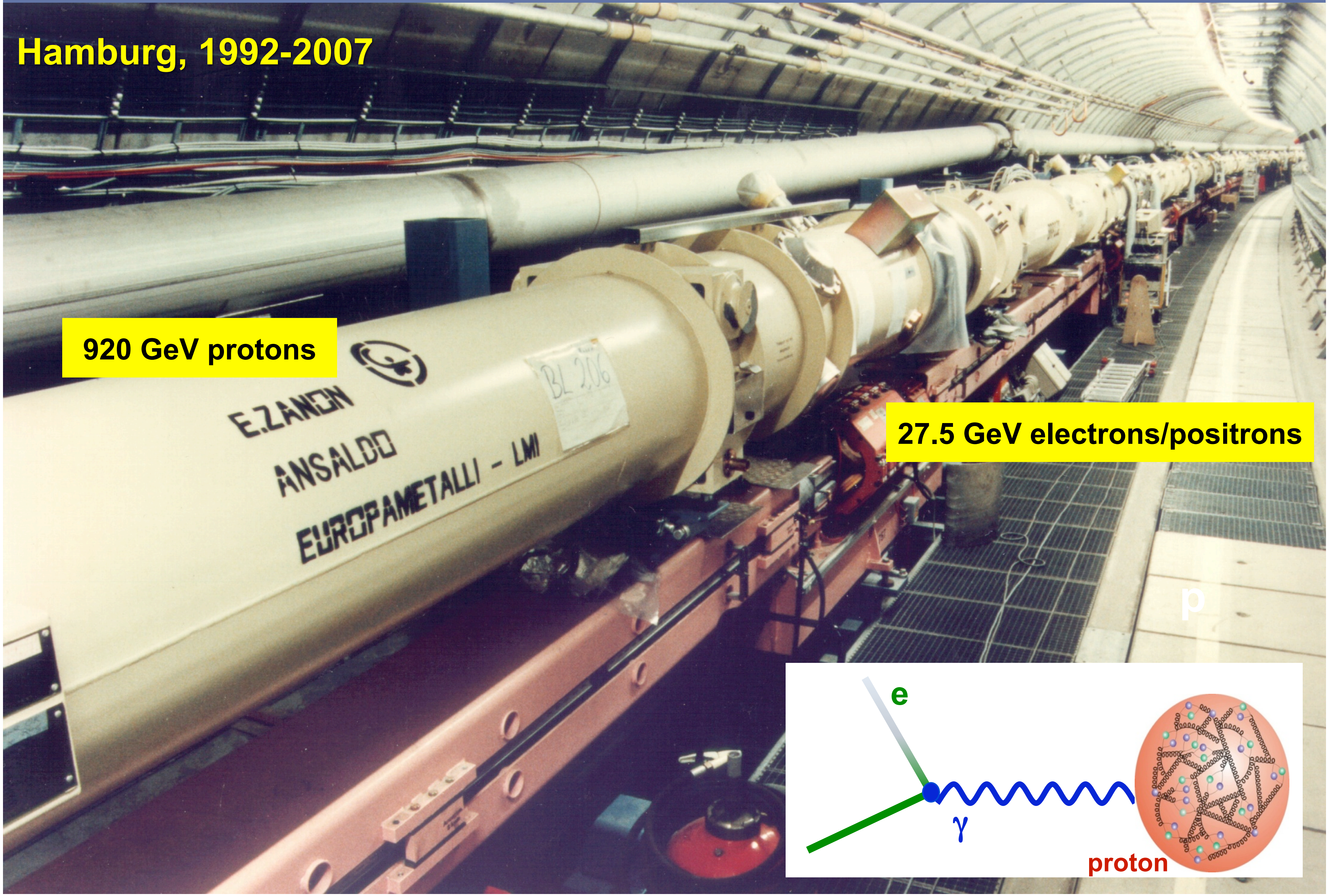


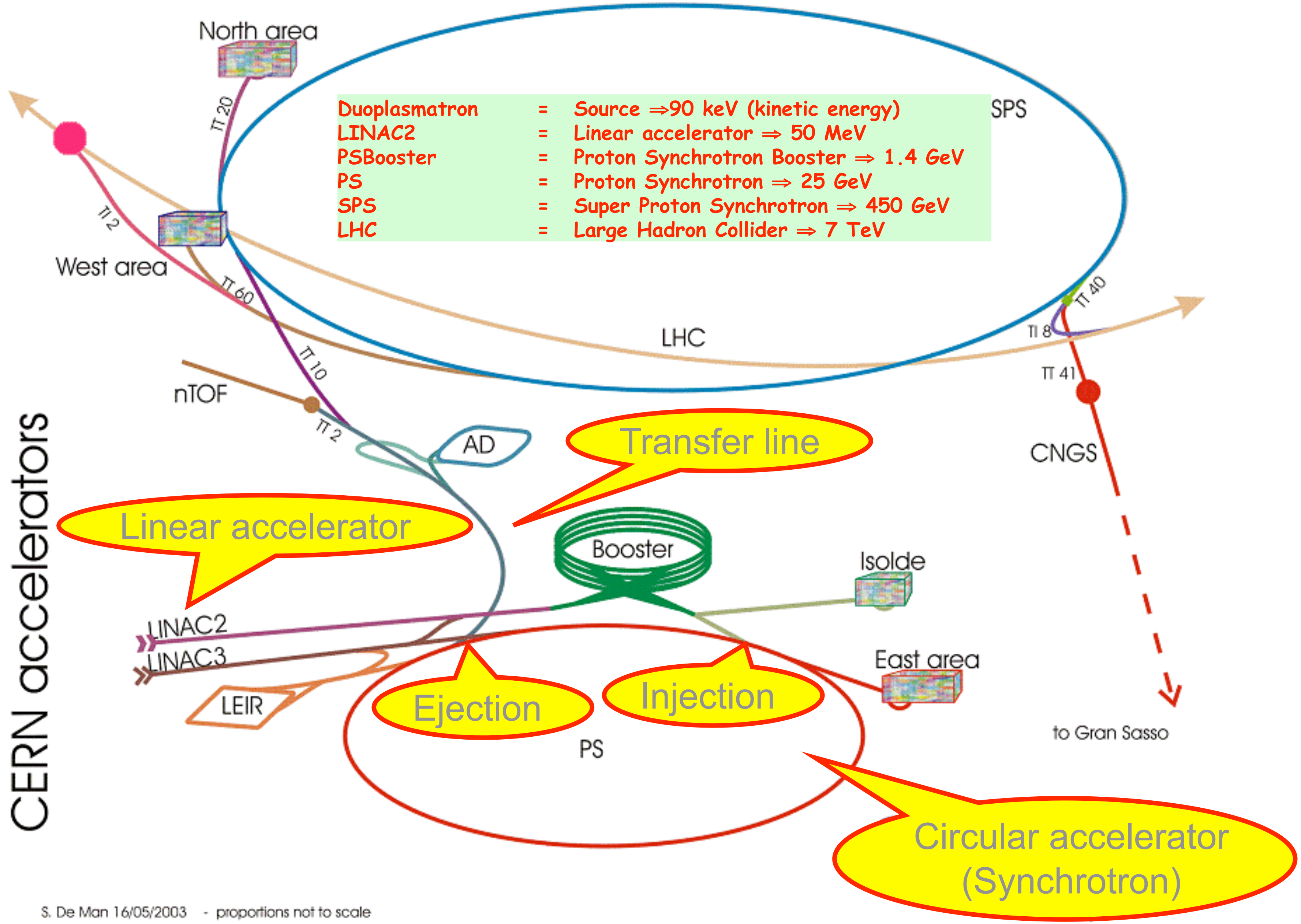


HERA

- **Operation**
  1992 - now,
  DESY, Hamburg
- **Circumference**
  6.3 km
- **Particles**
  electrons (or positrons) - protons
- **Beam energy**
  e = 28 GeV , protons = 820 GeV
- **Luminosity**
  about 2×10^{31} cm^{-2} sec^{-1}
- L_{int}
  up to now : about 180 pb^{-1}
- **Experiments**
  H1, ZEUS, HERA-b, HERMES
- **Characteristics:**
  - only lepton-hadron collider
  - superconducting magnets for proton ring

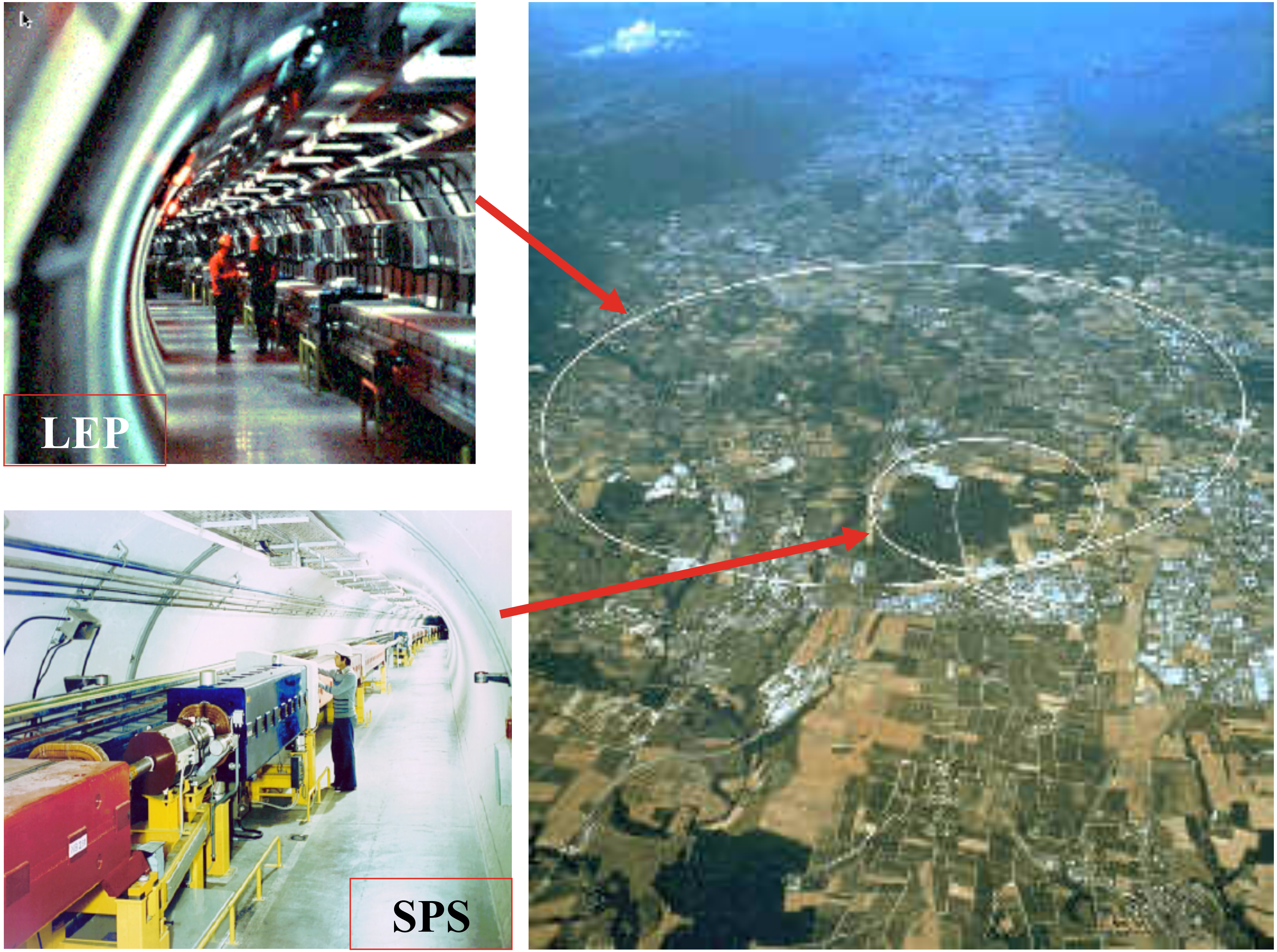
HERA - Electron Proton Collider (6.3 km)



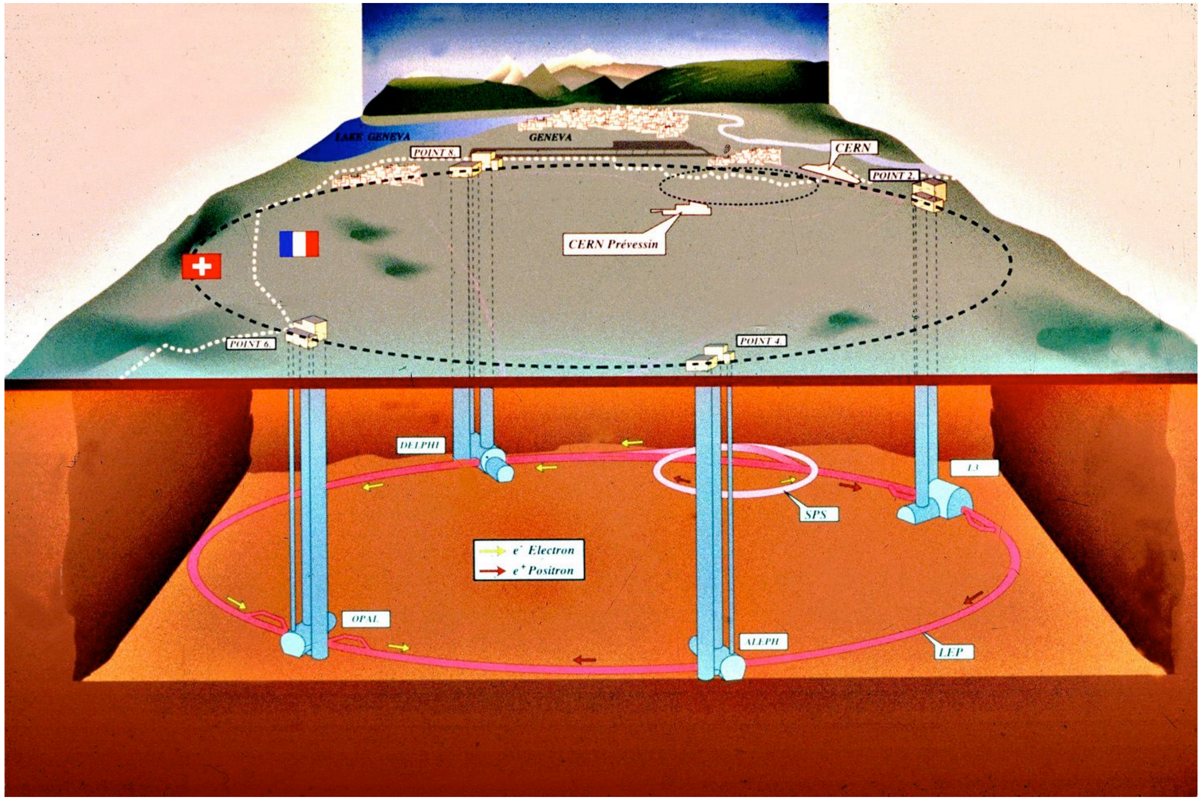


LHC beam in the injector chain

ISR
Interaction point
with crossing angle

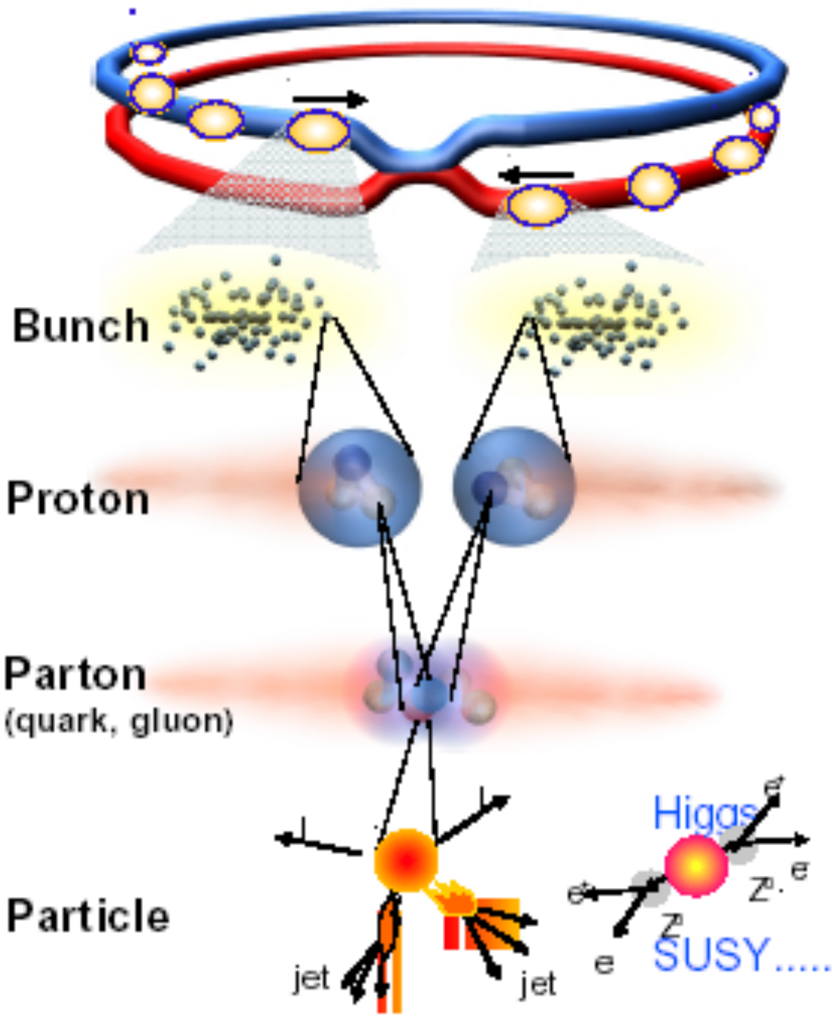

LEP
SPS

LEP



- Operation
  1989 - 2000, CERN, Geneva
- Circumference
  27 km
- Particles
  electrons - positrons
- Beam energy
  45 GeV → 104.5 GeV
- Luminosity
  10^{31} - 10^{32} cm^{-2} sec^{-1}
- L_{int}
  $\approx$1000 pb^{-1}
- Experiments
  ALEPH, DELPHI, L3, OPAL
- Characteristics:
  - very clean environment
  - very small backgrounds

Collisions at LHC



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} $cm^{-2}s^{-1}$

Crossing rate 40 MHz

Collisions rate ≈ 10^7 - 10^9 Hz

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

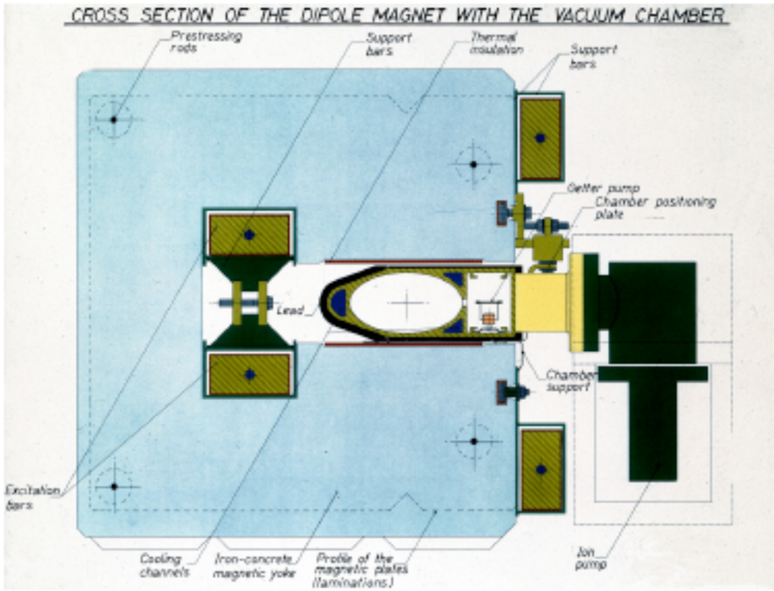
LEP vs LHC: Magnets, a change in technology

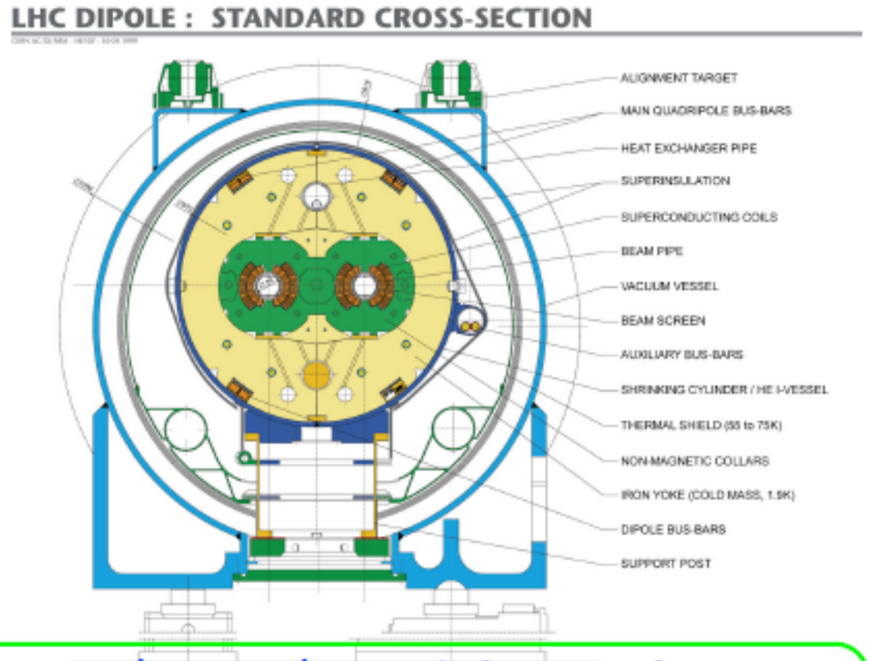
Bending Field → ***p(TeV) = 0.3 B(T) R(Km)***

(earth magnetic field is between 24,000 nT and 66,000 nT)

Tunnel R ≈ 4.3 Km LHC 7 TeV → B ≈ 8.3 T → ***Superconducting coils***

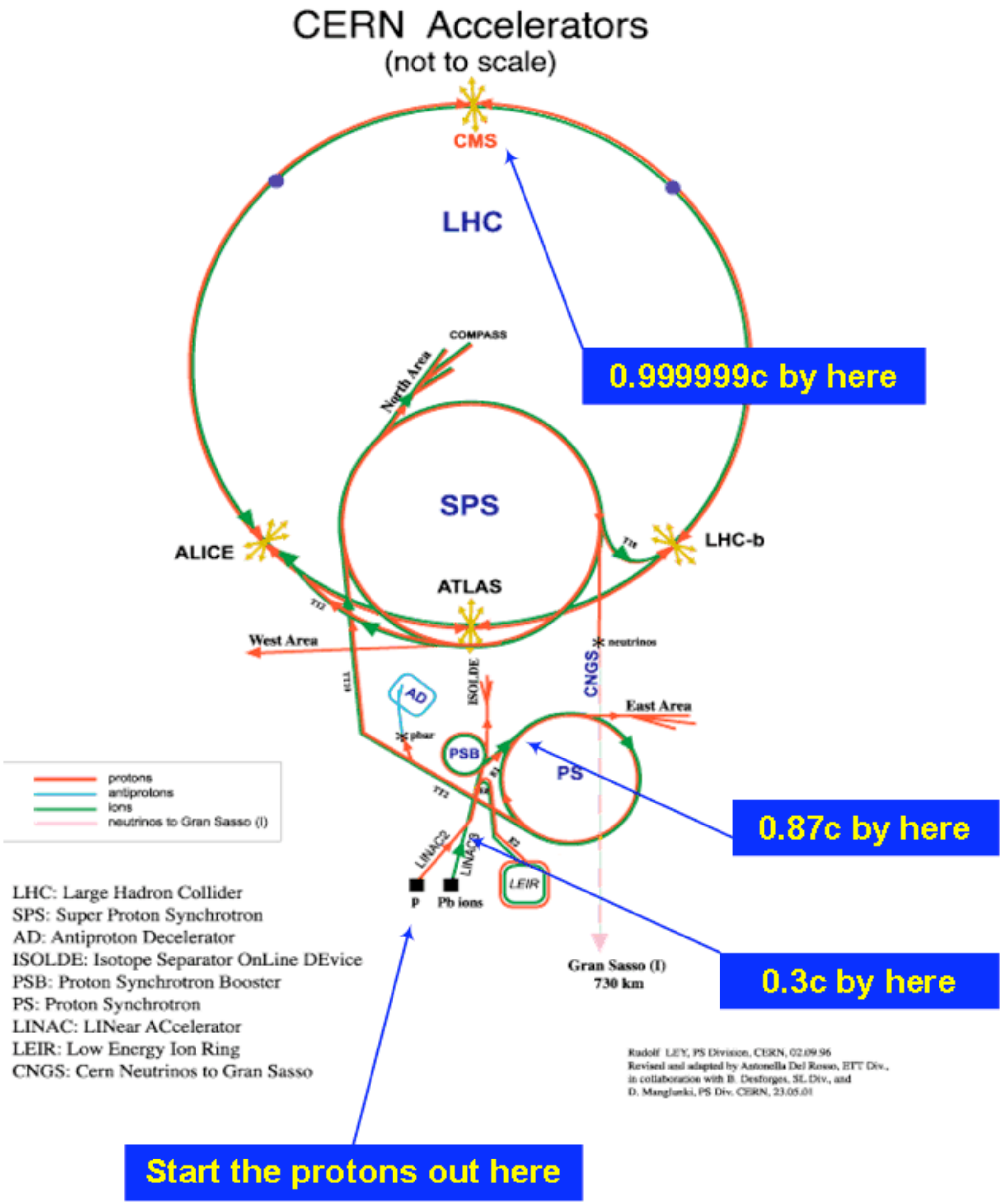
LEP 0.1 TeV → B ≈ 0.1 T → ***Room temperature coils***





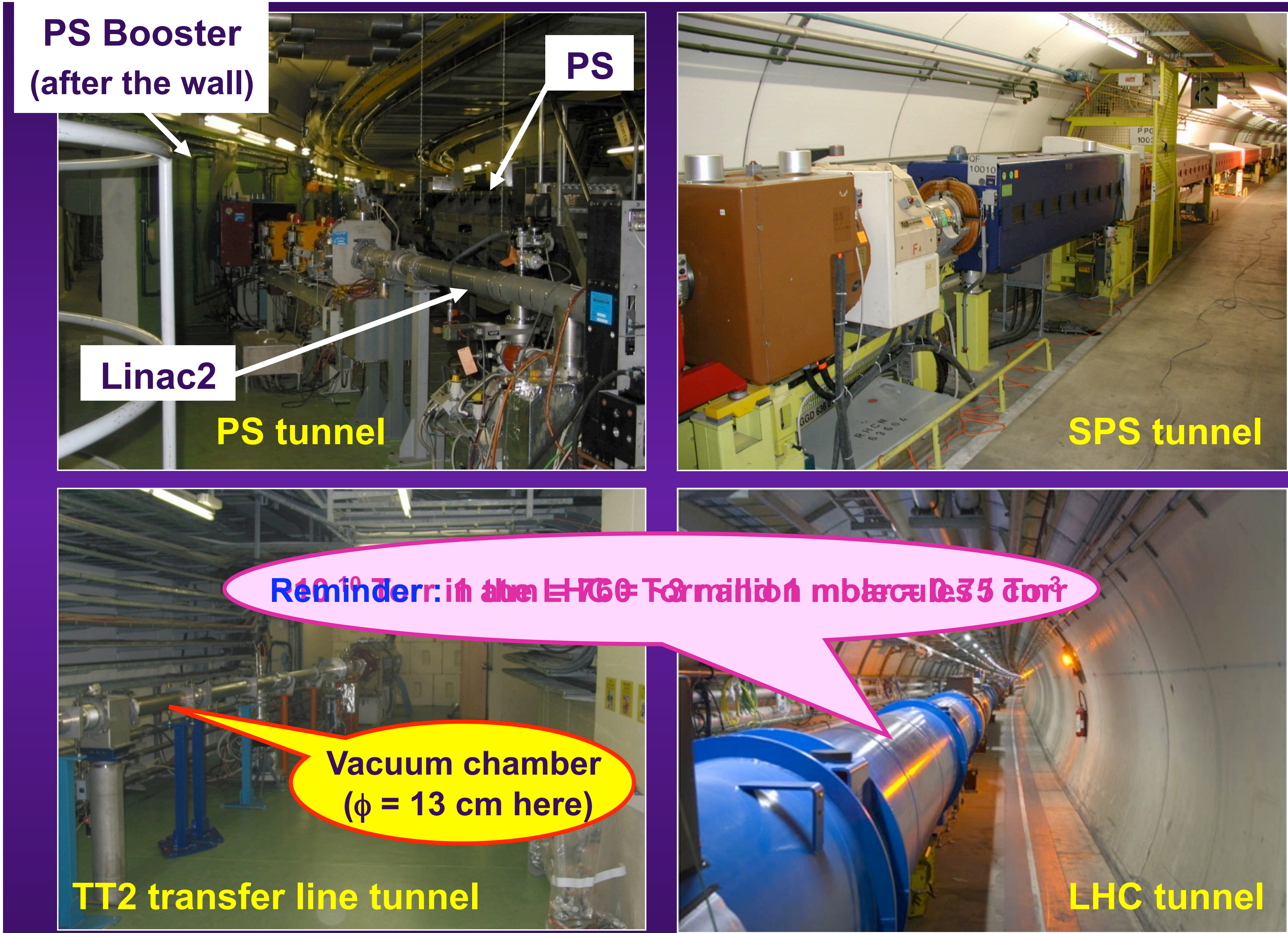
Protons can go up in energy more than electrons because they ***emit less synchrotron radiation.*** Bending (dipoles) and focusing (quadrupoles) strengths require high magnetic fields generated by superconductors

Accelerators and LHC experiments at CERN



Energies:

Linac	50 MeV
PSB	1.4 GeV
PS	28 GeV
SPS	450 GeV
LHC	7 TeV


PS Booster
(after the wall)
PS
Linac2
PS tunnel
SPS tunnel
Reminder: 1 atm = 760 Torr, 1 mbar = 0.75 Torr
10^-10 Torr: in the LHC = 3 million molecules/cm³
Vacuum chamber
(ϕ = 13 cm here)
TT2 transfer line tunnel
LHC tunnel

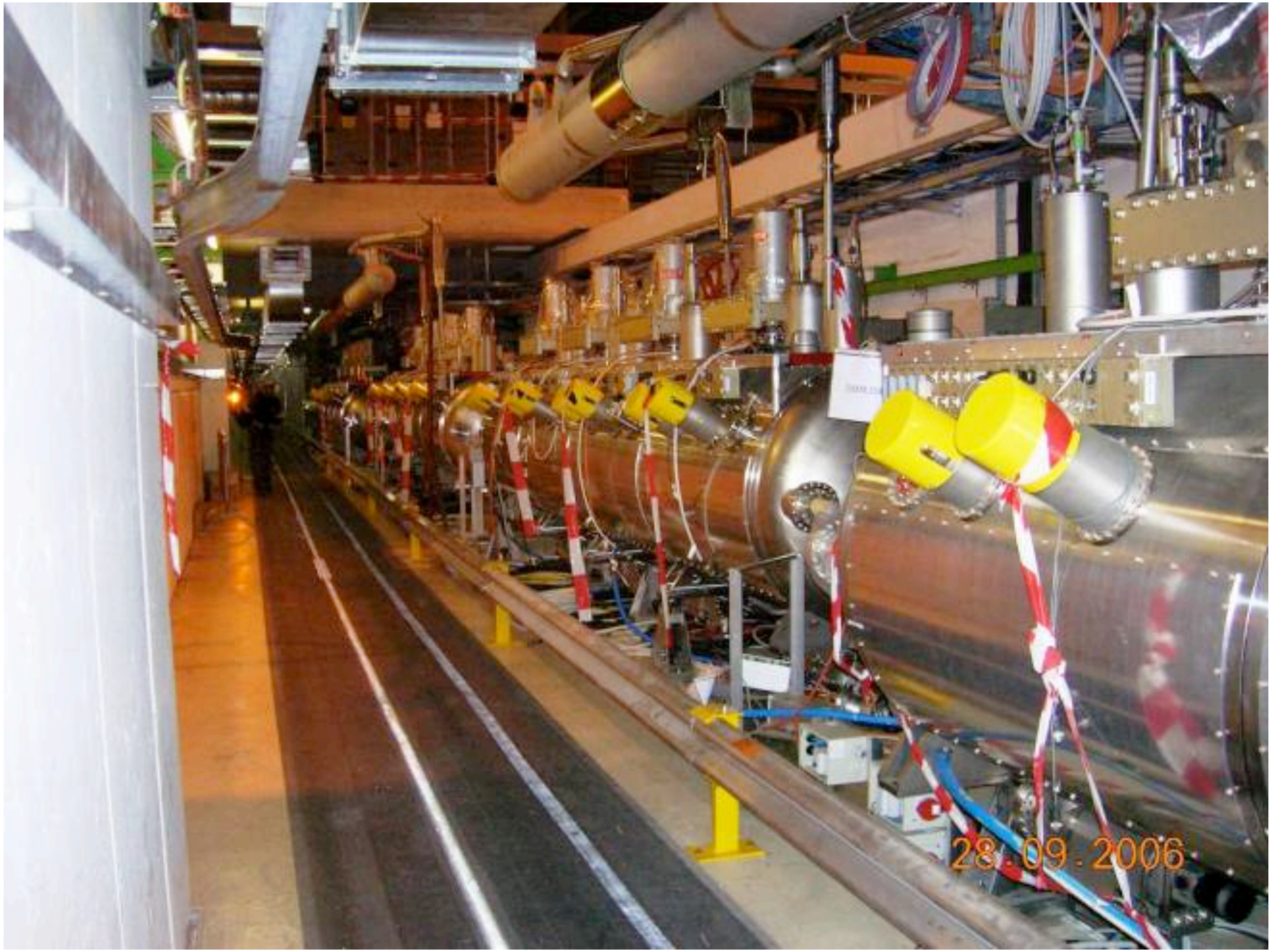
The LHC arcs

1232 main dipoles + 3700 multipole corrector magnets

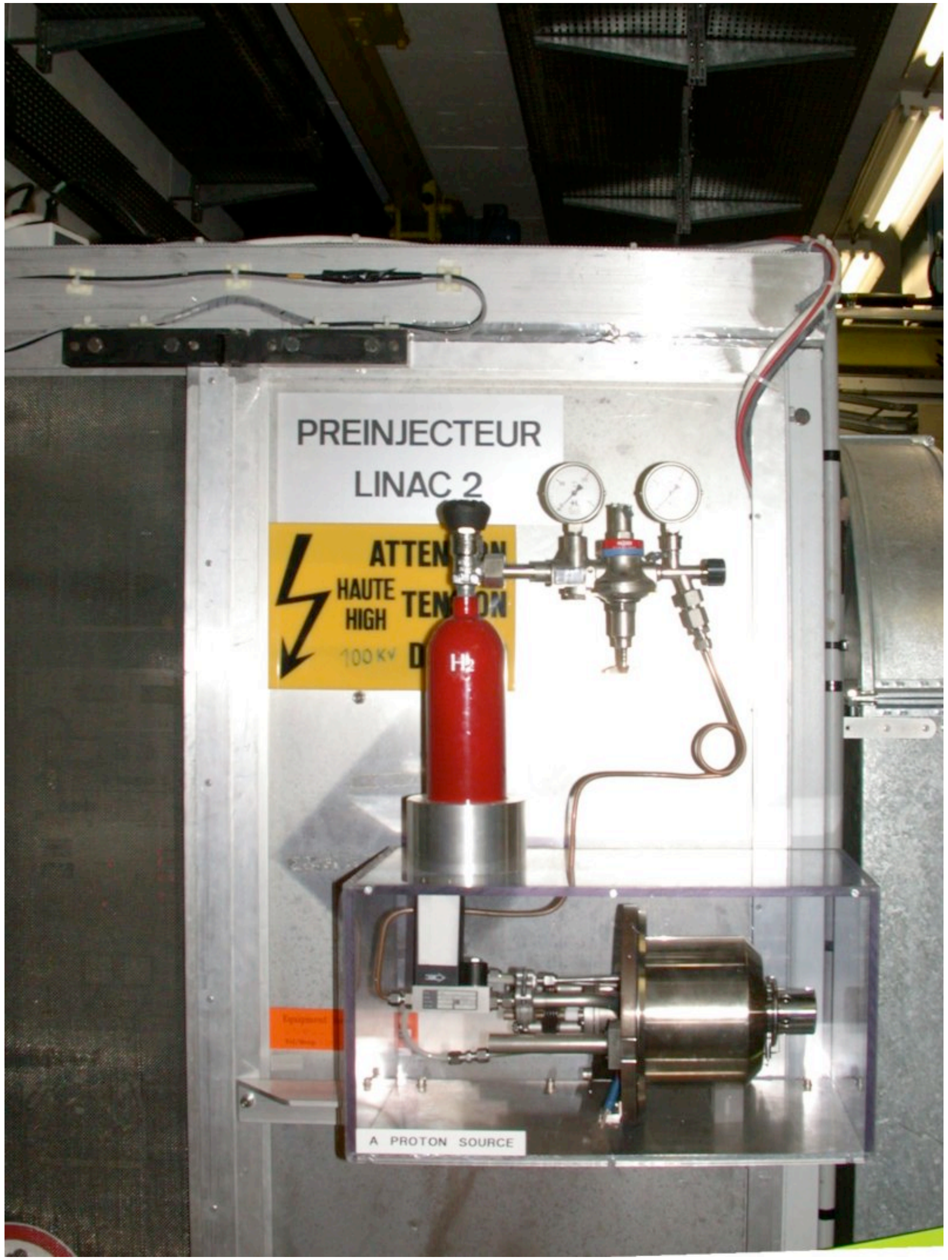
392 main quadrupoles + 2500 corrector magnets

MCS: Sextupole corrector (b3)
MCDO: Assembly of spool correctors consists of an octupole insert **MCO** (b4) and a decapole magnet **MCD** (b5)
MQT: Trim quarupole corrector
MS: arc sextupole corrector
MQS: skew quad lattice corrector
MCBH: Horizontal dipole corrector
MCBV: Vertical dipole corrector
MO: Lattice octupole

RF - tunnel view

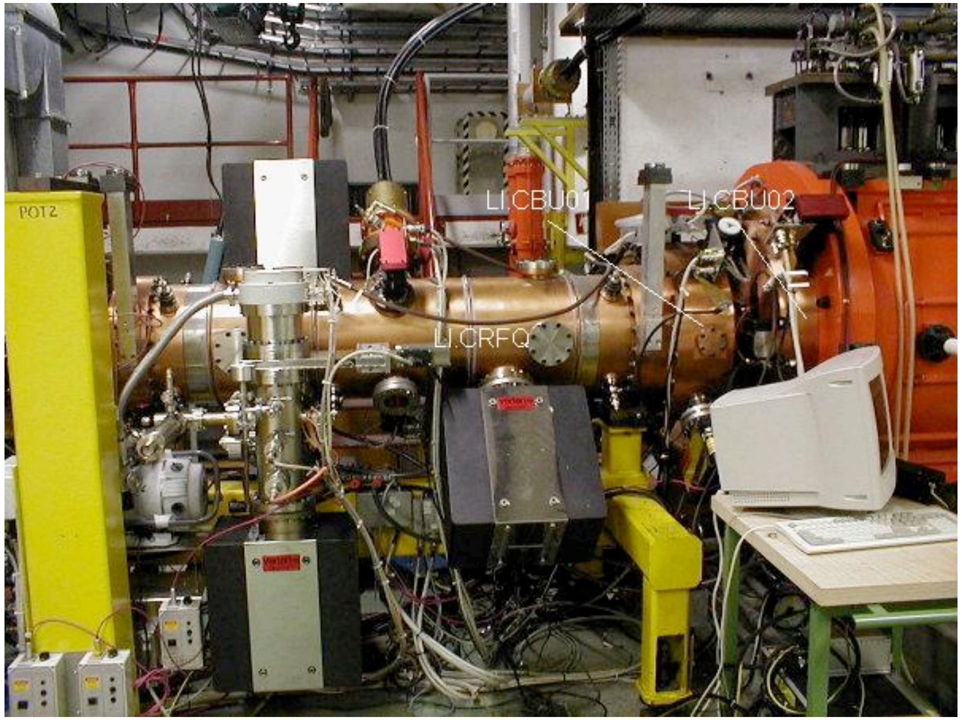


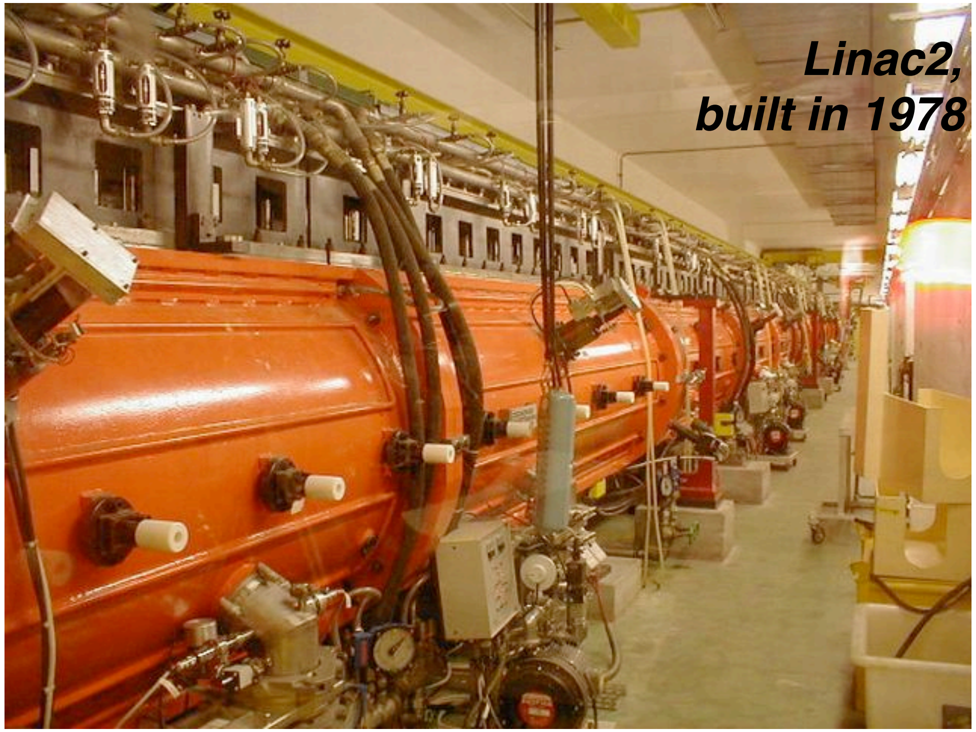
Bottle of Hydrogen, to start with!



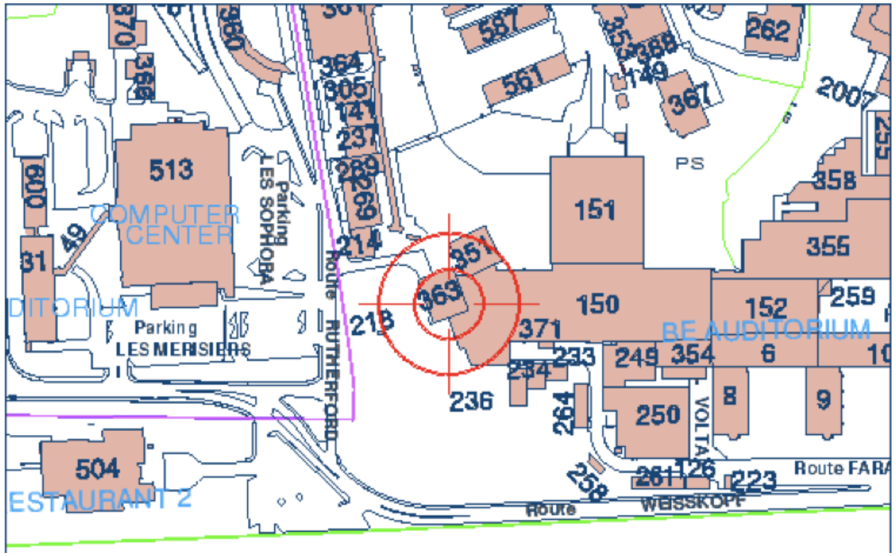
The real bottle is inside the cage

Linac2: some pictures

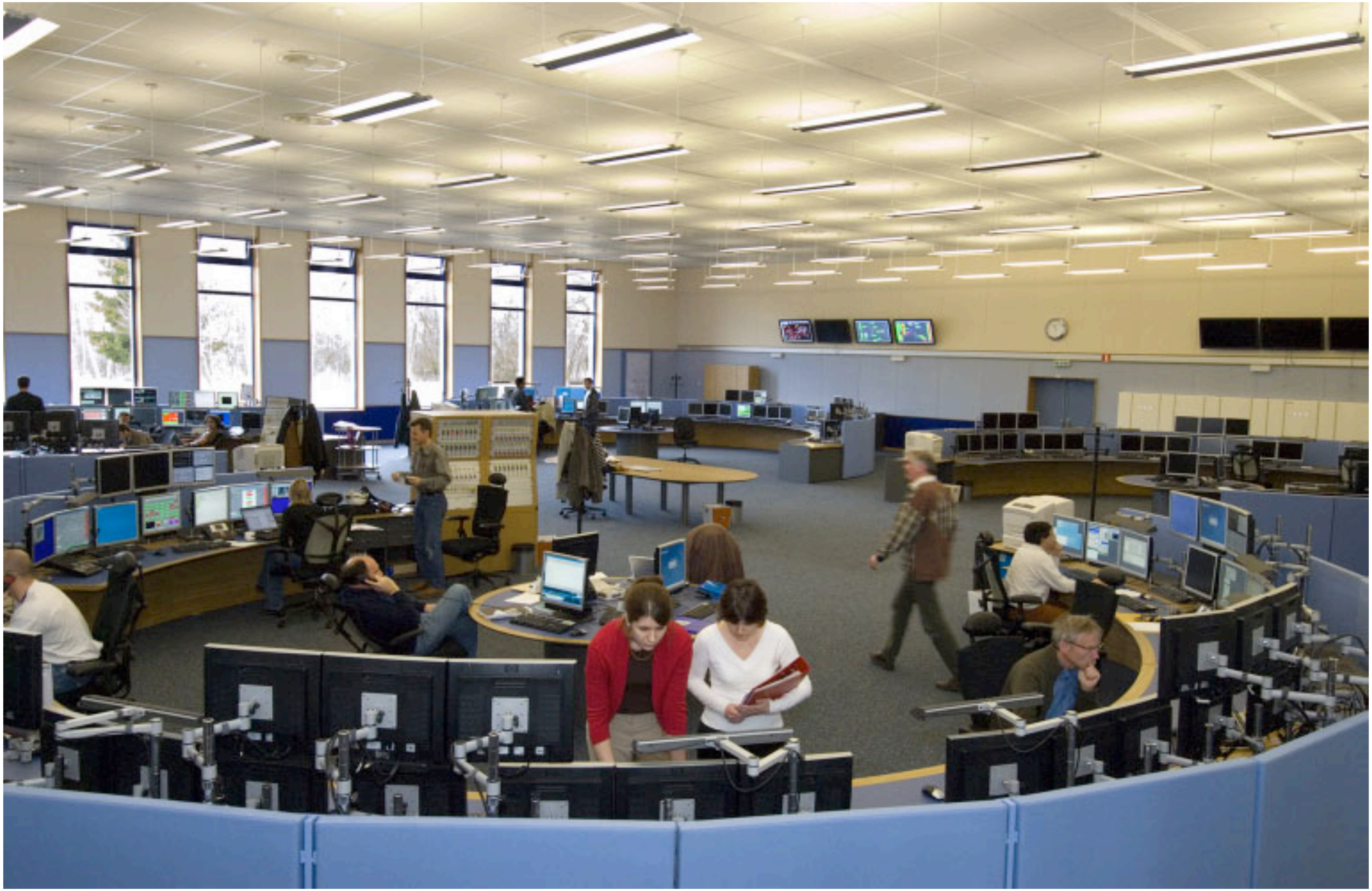




Downstream of Linac2, the proton beams will only encounter **circular accelerators** (and transfer lines)



CERN Control Centre - Layout



MORE SLIDES

Synchrotron radiation

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Power radiated per particle goes like:

4th power of the energy
(2nd power)$^{-1}$ of the bending radius
(4th power)$^{-1}$ of the particle mass

$$P = \frac{2c \times E^4 \times r_0}{3\rho^2 \left(m_0 \times c^2\right)^3}$$

$r_0 = \frac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

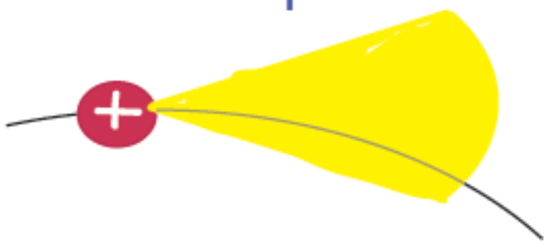
ρ particle bending radius

Energy lost per turn per particle due to synchrotron radiation:

e- $W(MeV) = 8.85 \times 10^{-5} \times E^4(GeV)/\rho^2(km)$ $\approx$ 2 GeV (LEP)

p $W(keV) = 7.8 \times 10^{-3} \times E^4(TeV)/\rho^2(km)$ $\approx$ 6 keV (LHC)

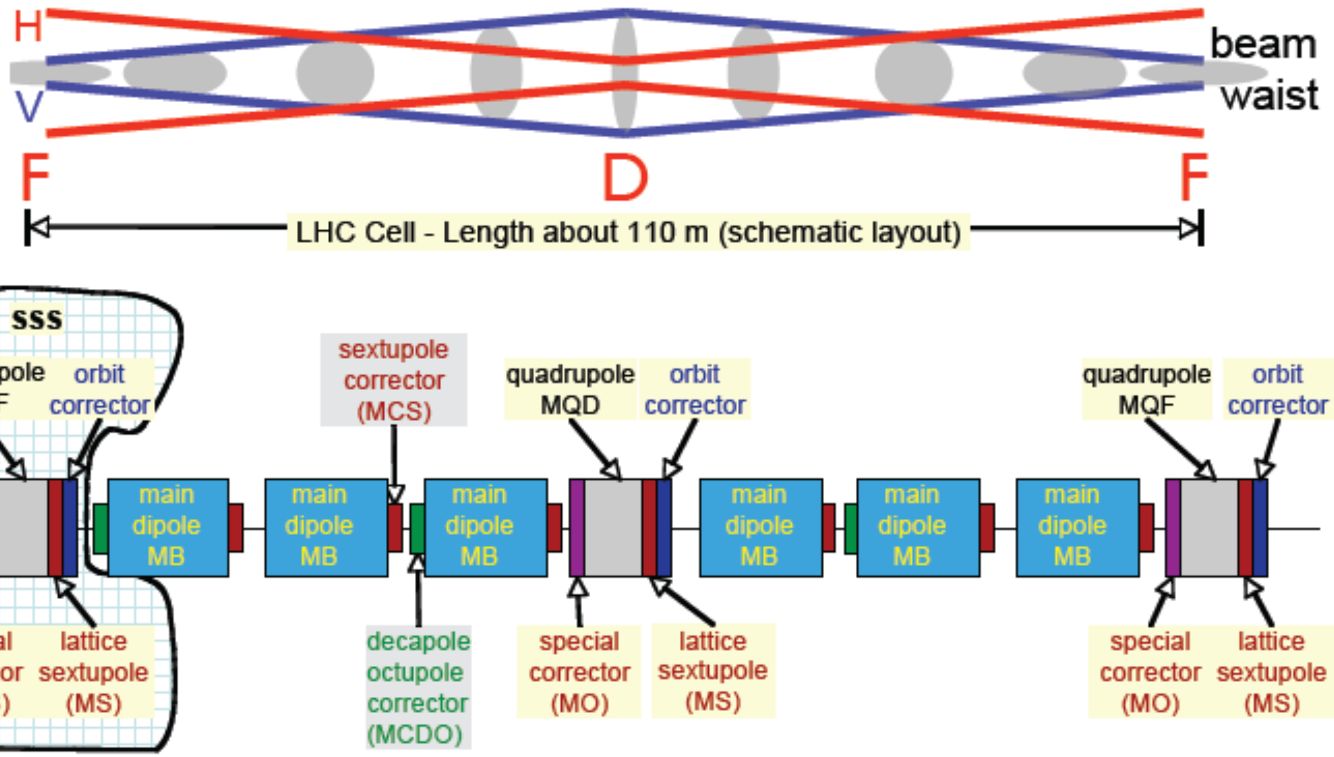
We must protect the LHC coils even if energy per turn is so low



Power lost per m in dipole: 0.206 W
Total radiated power per ring: 3.6 kW

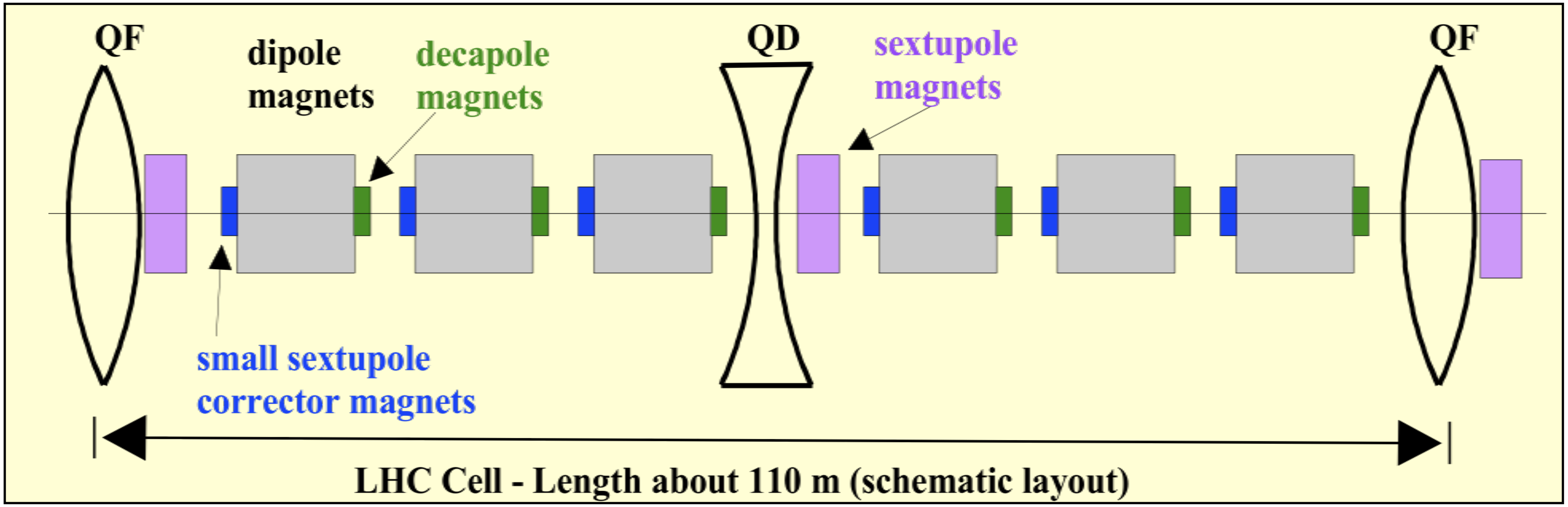
LHC optics, ARC lattice

Classical FODO cell with about 90⁰ phase advance per cell
(F=focusing, O=drift, D=defocusing)



2-in-1 design true also for the optics:
a quadrupole F for beam 1 (circulating clockwise) is D for beam 2 circulating anticlockwise

Inside one cell



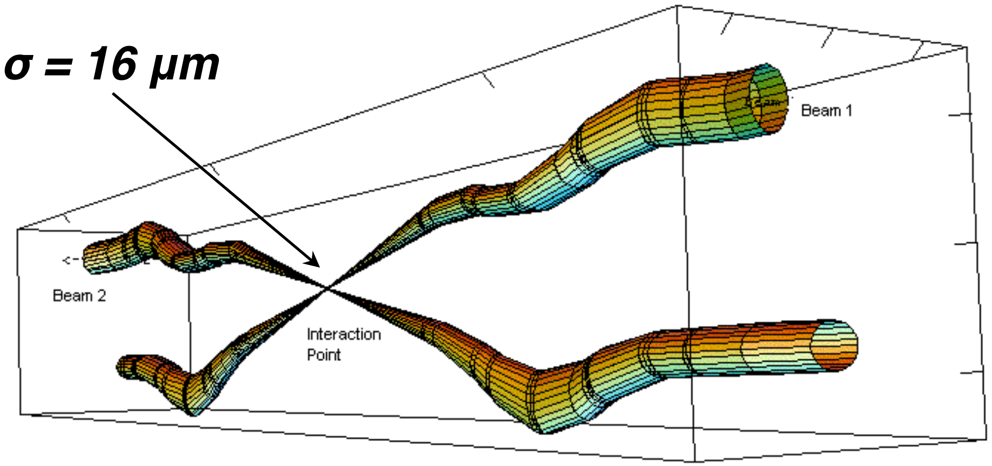
LHC design parameters

Nominal LHC parameters	
Beam injection energy (TeV)	0.45
Beam energy (TeV)	7.0
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Max stored beam energy (MJ)	362
Norm transverse emittance (μm rad)	3.75
Colliding beam size (μm)	16
Bunch length at 7 TeV (cm)	7.55

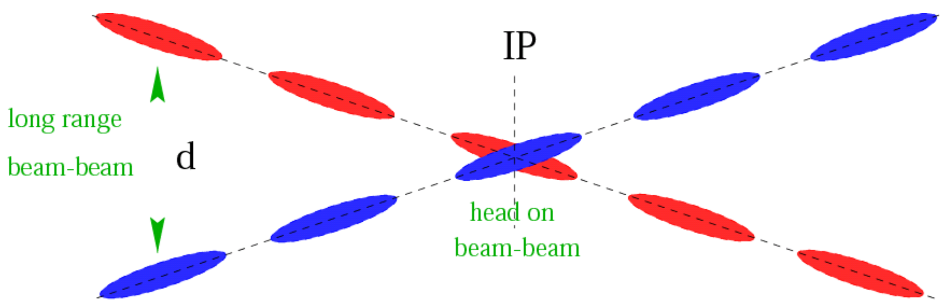
$$L = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

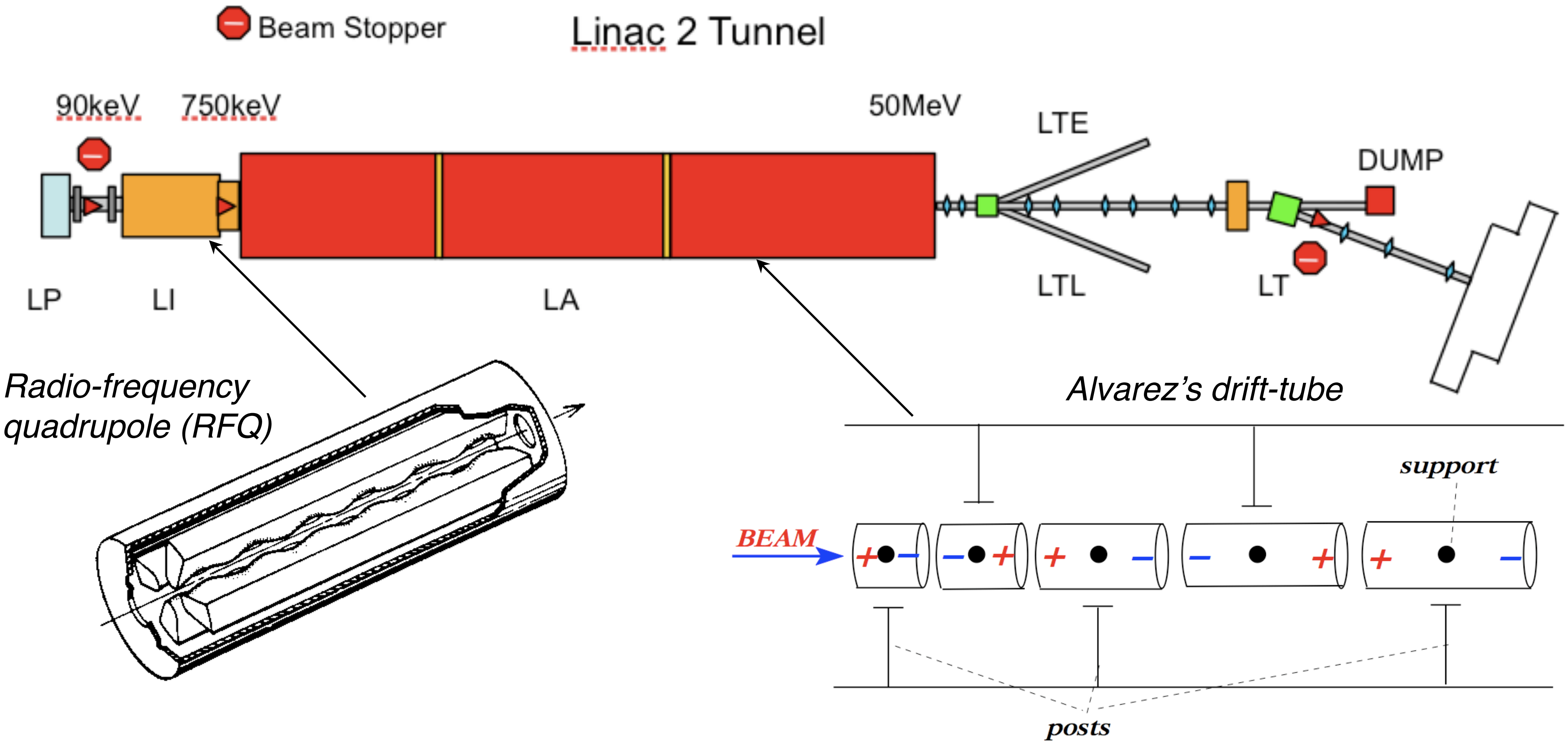
- $\beta^* = 0.55$ m
- Crossing = 285 μrad
- $L = 10^{34}$ cm^{-2} s^{-1}



Relative beam sizes around IP1 (Atlas) in collision

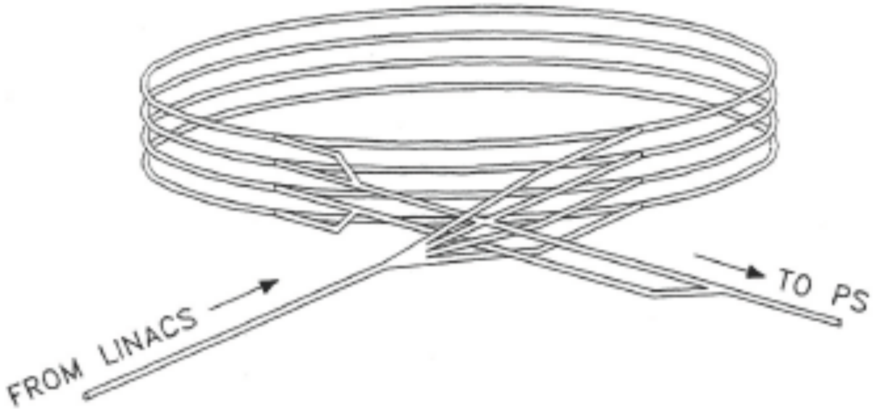


Linac2 - layout and parameters



Delivered beam current:	**~150mA**
Beam energy:	90 keV (source) → 750 keV (RFQ) → **50 MeV**
Repetition rate:	**1 Hz**
Radio-frequency system:	202 MHz

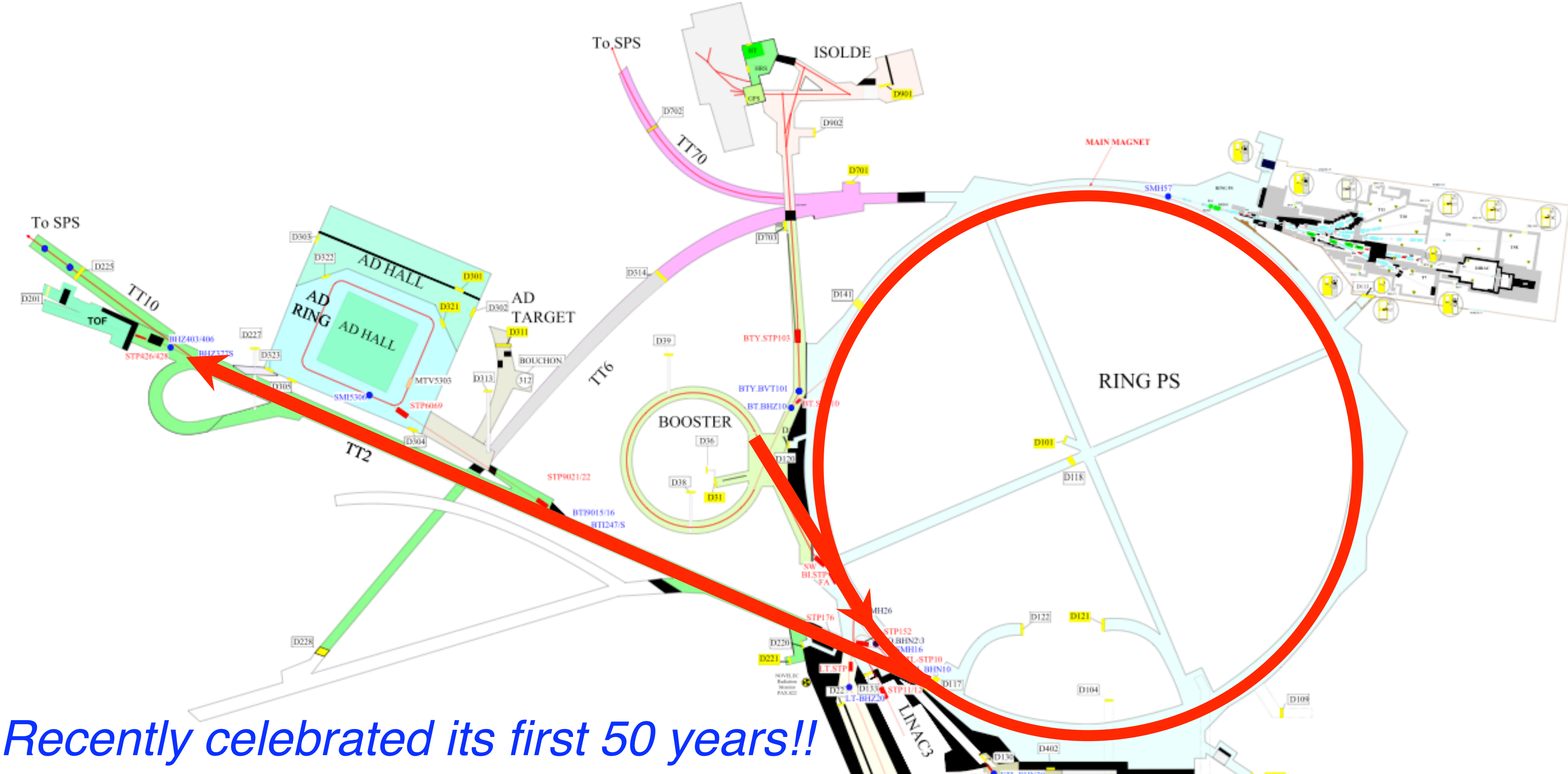
PS Booster



Sketch of the PS Booster with:
- Distribution of Linac beam into 4 rings
- Recombination prior to transfer

- Constructed in the 70ies to increase the intensity into the PS
- Made of four stacked rings
- Acceleration to $\mathbf{E_{kin}=1.4\ GeV}$
- Intensities > $\mathbf{10^{13}}$ **protons** per ring obtained (i.e., four times design!!)
- Several types of beams with different characteristics
  - → *Physics beams for ISOLDE*
  - → *Beams for AD/PS/SPS physics*
  - → *LHC beams*

Proton Synchrotron



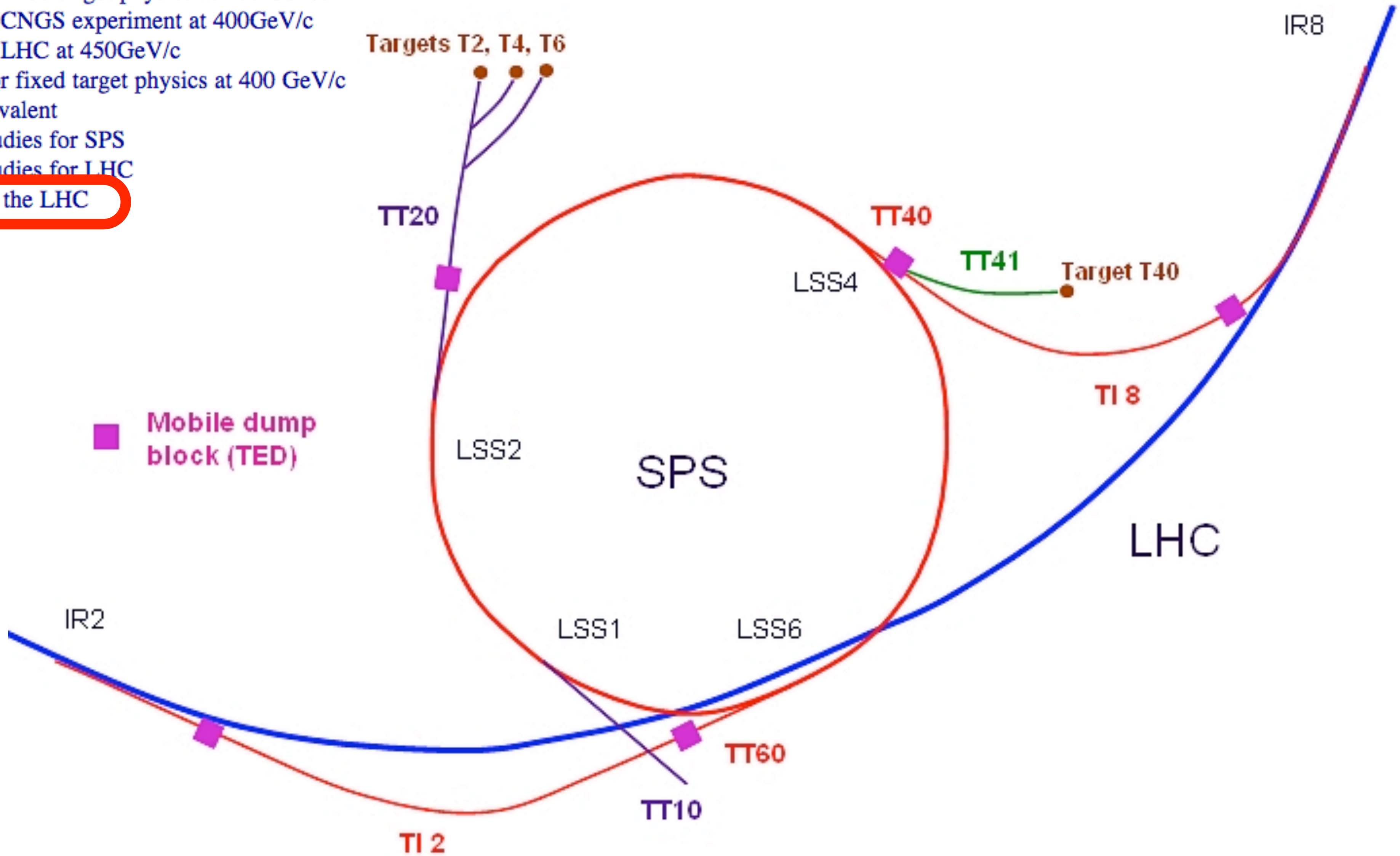
Recently celebrated its first 50 years!!

From the Proton Synchroton to the Large Hadron Collider - 50 Years of Nobel Memories in High-Energy Physics

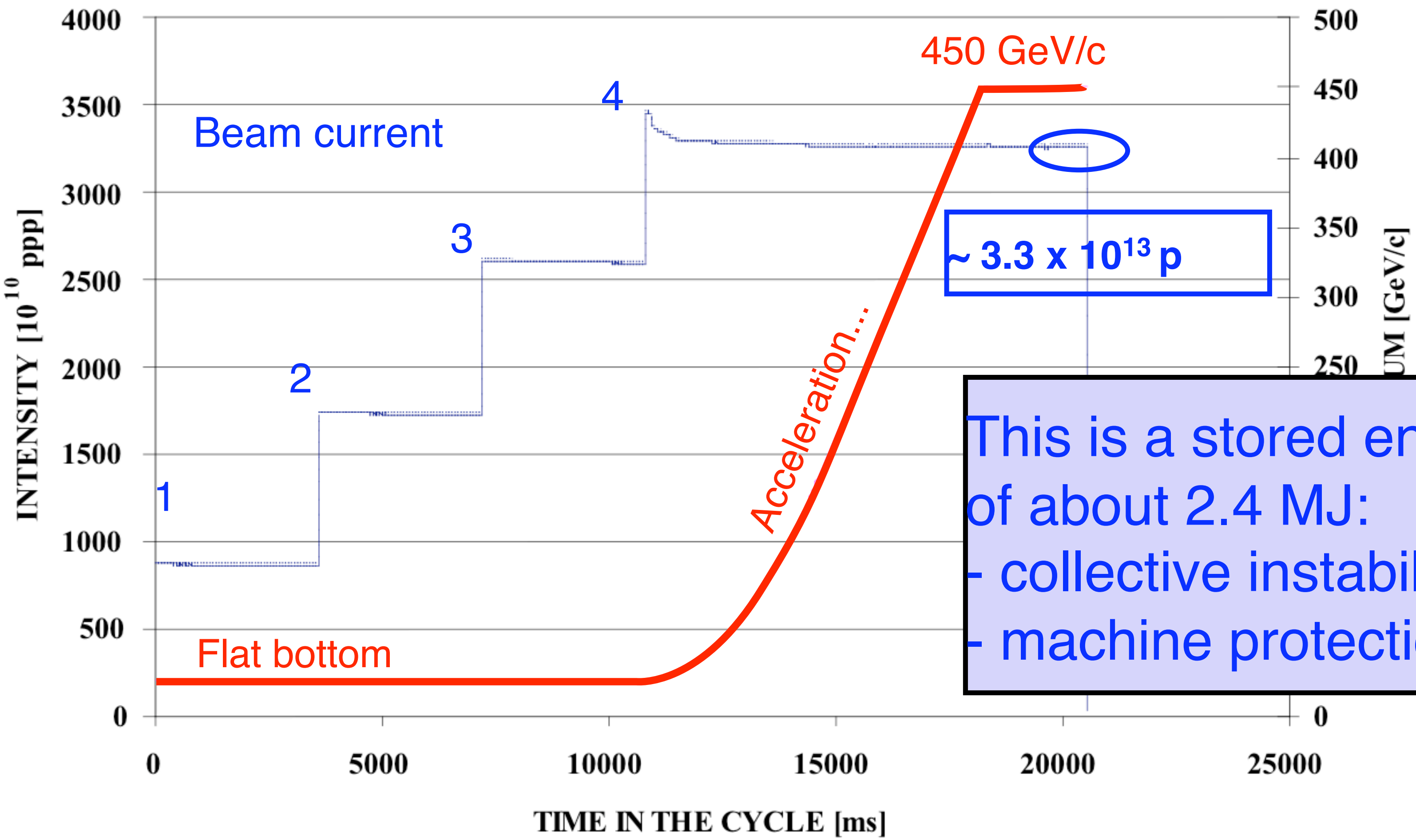
from Thursday 03 December 2009 at **14:00** to Friday 04 December 2009 at **17:00** (Europe/Zurich)
at **CERN** (**500-1-001 - Main Auditorium**)

Super-Proton Synchrotron

- Circumference : 6.9 km
- 2.5 km of secondary beam lines.
- protons for fixed target physics at 400 GeV/c
- protons for CNGS experiment at 400GeV/c
- protons for LHC at 450GeV/c
- lead ions for fixed target physics at 400 GeV/c proton equivalent
- machine studies for SPS
- machine studies for LHC
- Injector for the LHC

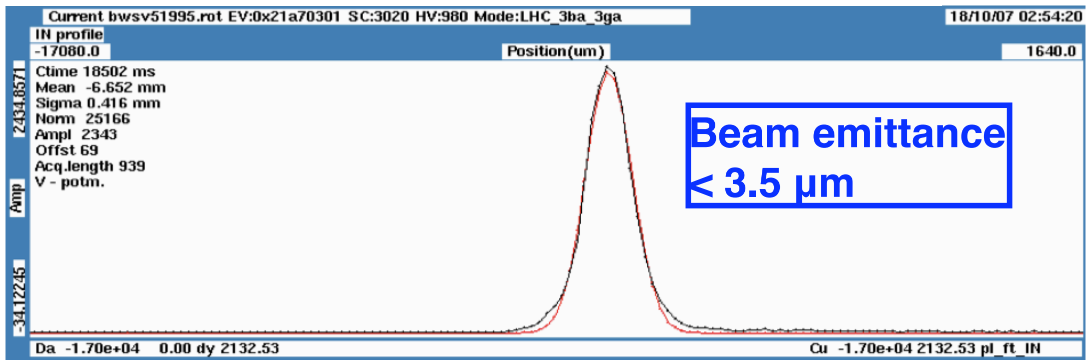


Nominal LHC beams at the SPS

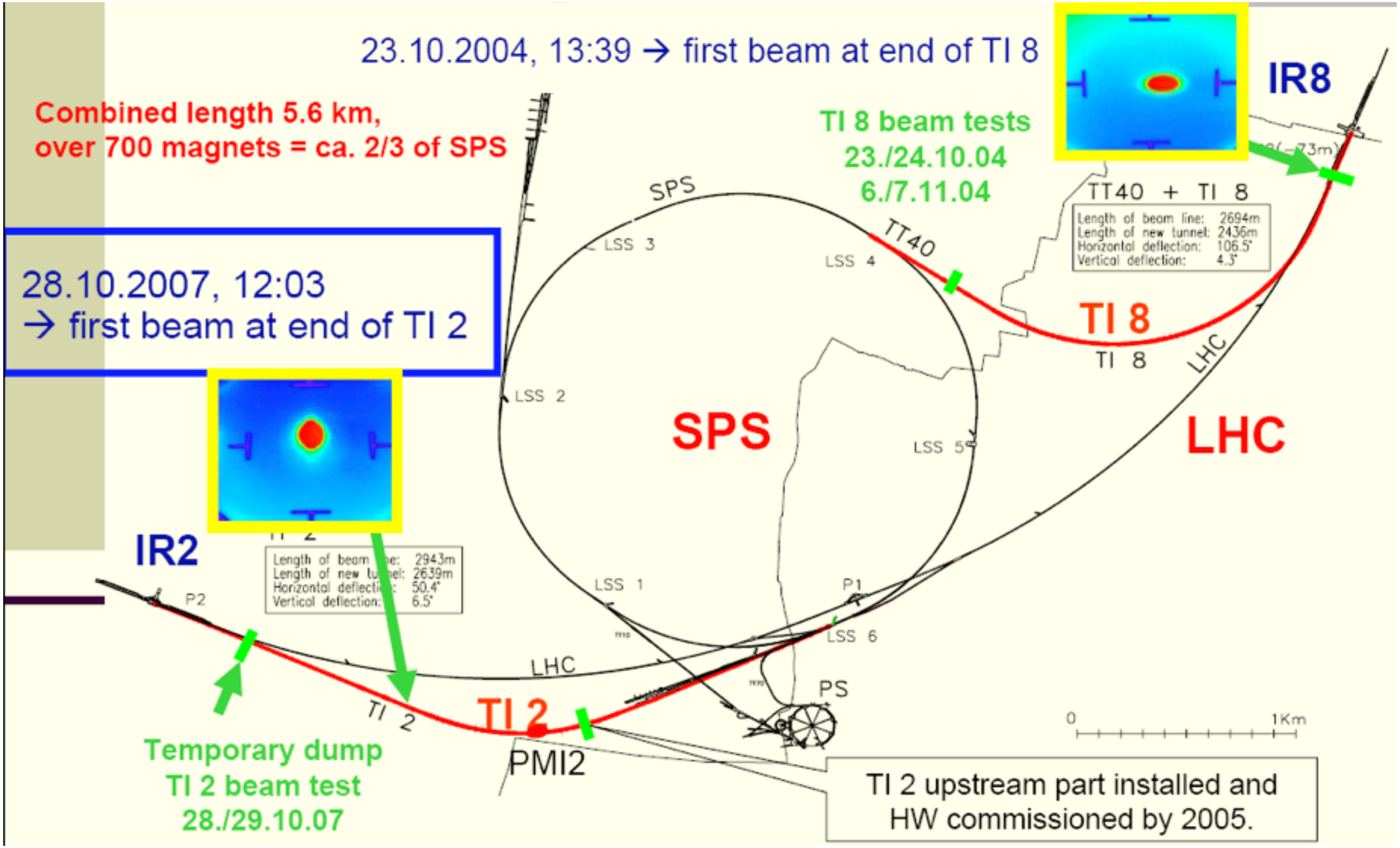


This is a stored energy of about 2.4 MJ:
- collective instabilities
- machine protection!

Nominal LHC beams basically achieved in the SPS in 2004! Injectors have been since long ready for the nominal LHC...

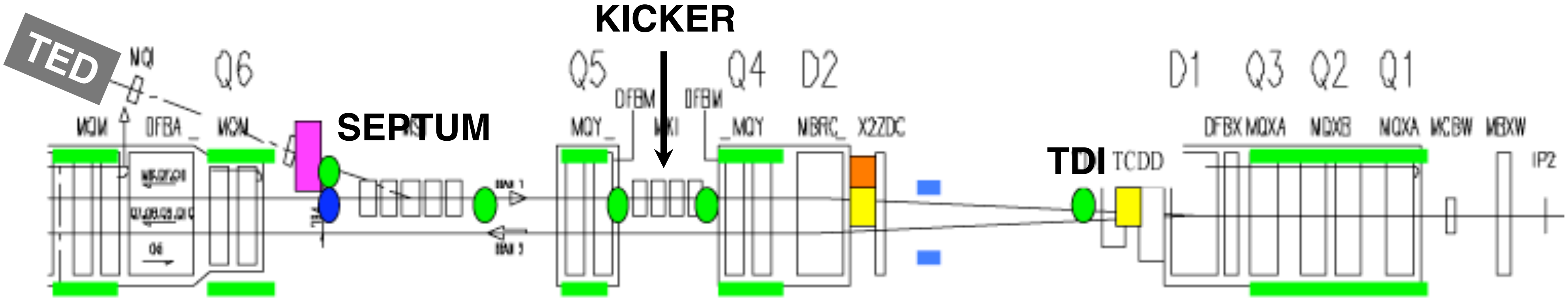


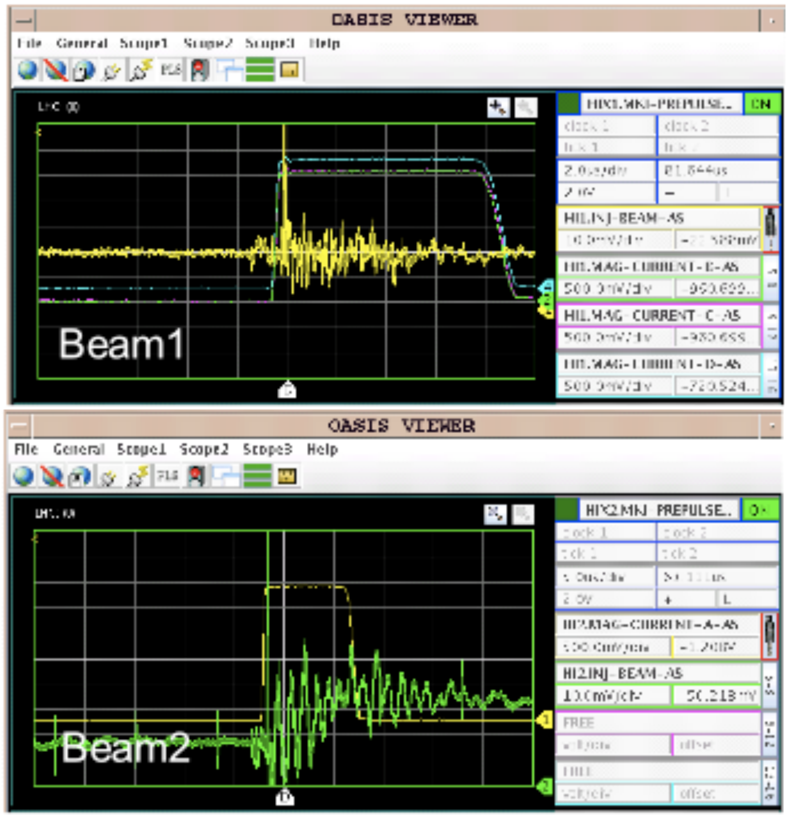
SPS-to-LHC transfer lines

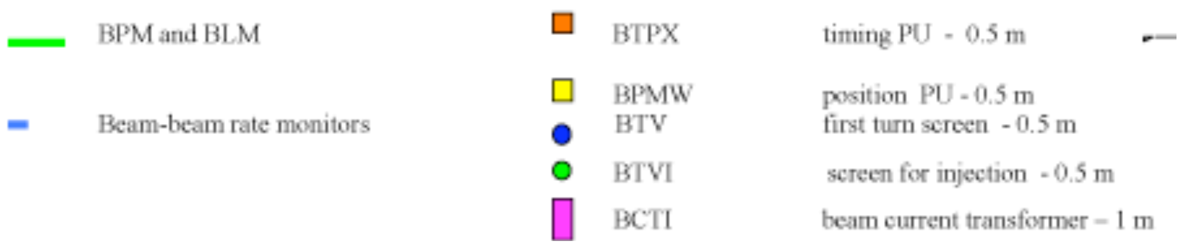


Courtesy of J. Uythoven

Injection



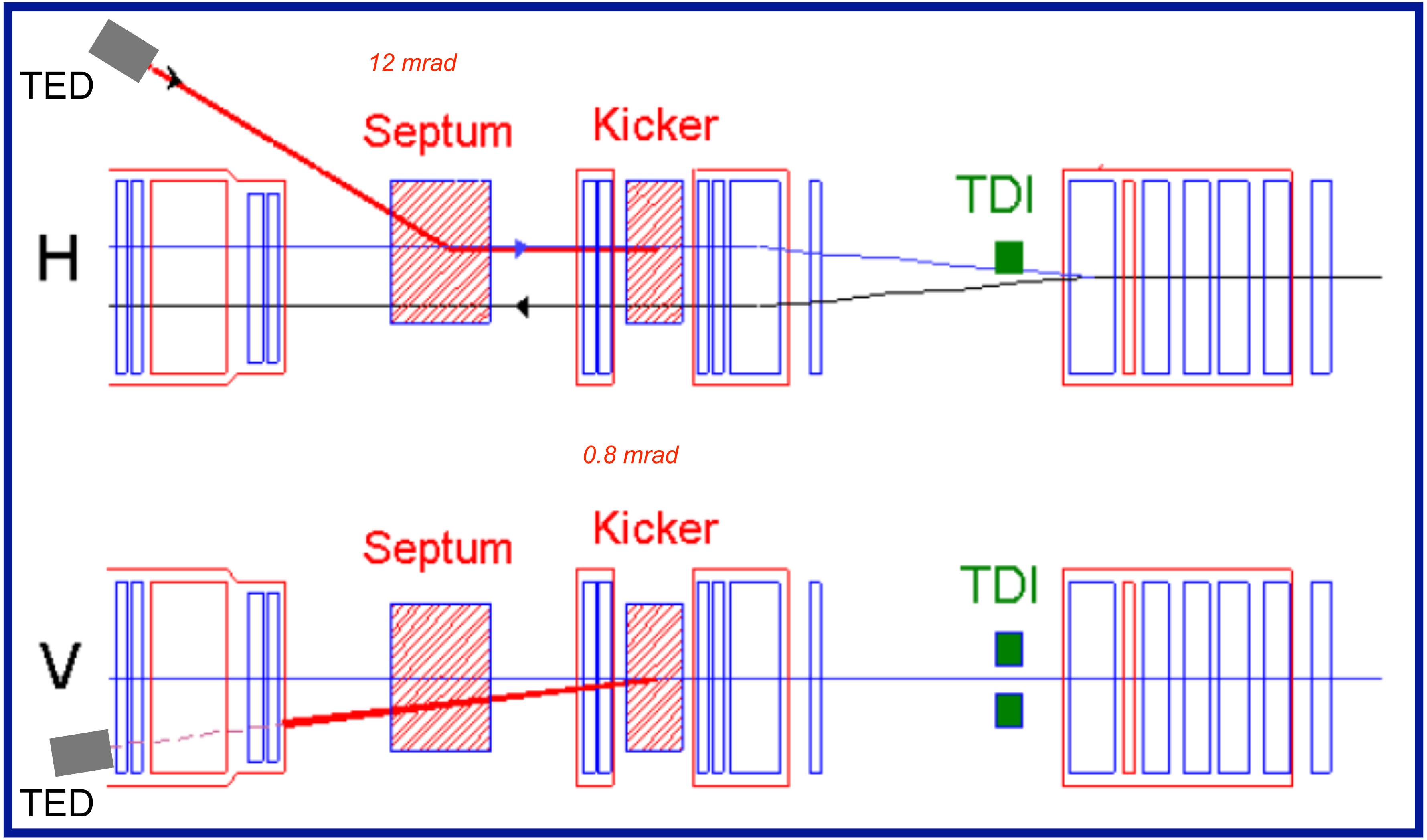




Extensively tested during TI2/8 commissioning and sector tests:

- synchronization of kickers with extracted beam
- steering of the transfer lines
- protection settings
- injection quality checks

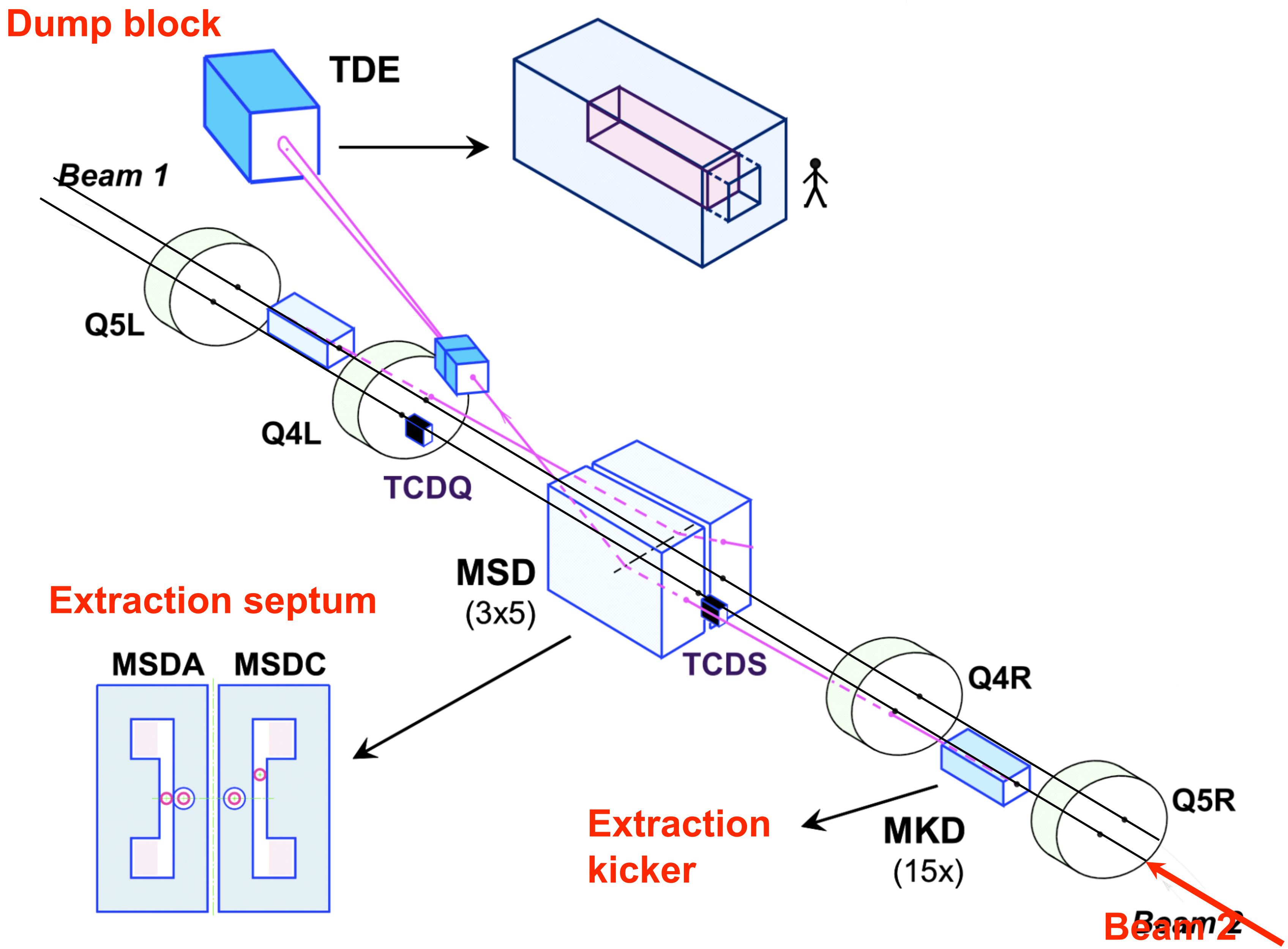
Injection elements



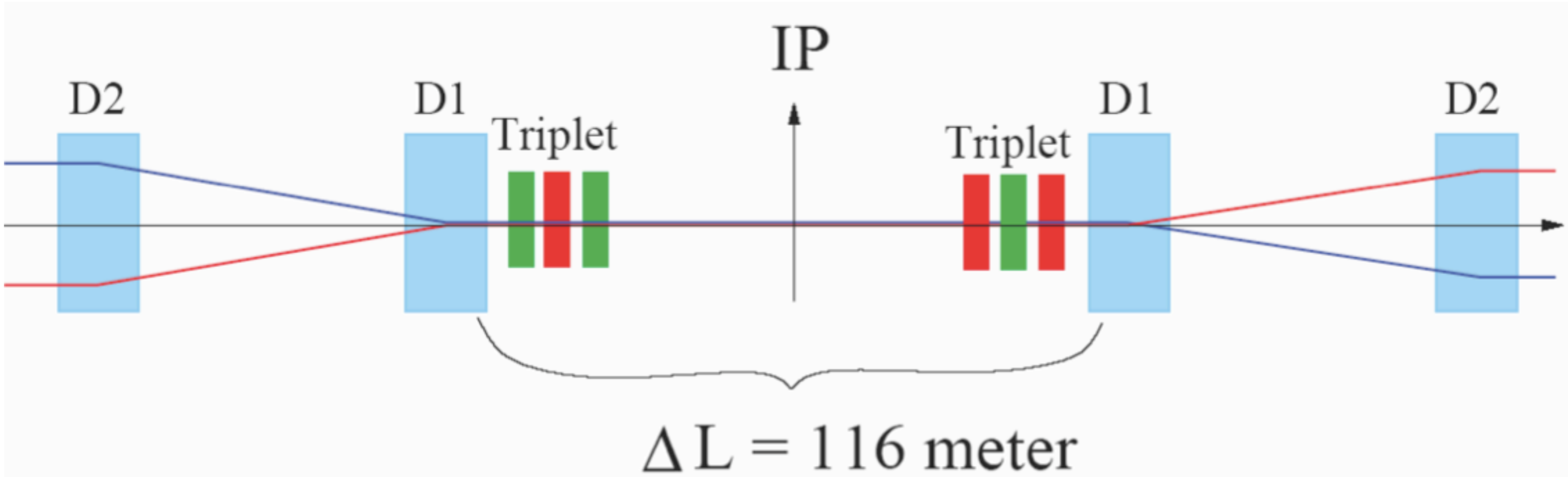
From the LHC Page1

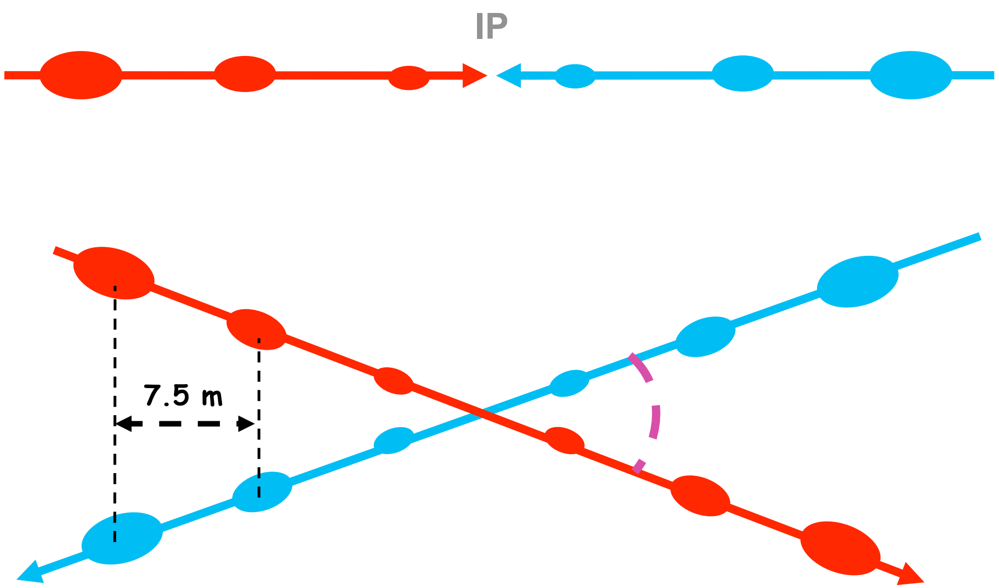
TED TI2 position:	BEAM	TDI P2 gaps/mm	up: 9.05	down: 9.04
TED TI8 position:	BEAM	TDI P8 gaps/mm	up: 8.32	down: 8.36

Beam dump (IP6)



Interaction region layout





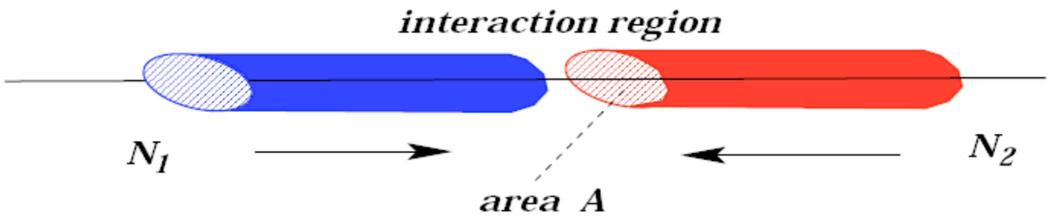
- With more than 154 bunches, we need a crossing angle to avoid parasitic collisions outside the IP.
- Beams are separated in the other plane during injection and ramp

$$\mathcal{L} = \frac{N^2 n_b f_{\rm rev}}{4\pi\sigma_x\sigma_y} F$$

$$F = 1/\sqrt{1 + \left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

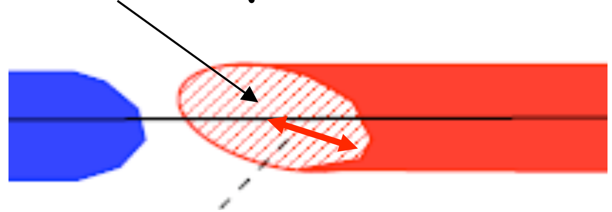
Luminosity: the beam size

We need a small beam in the collision point

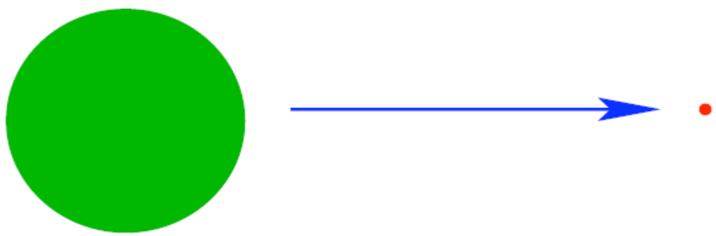


$$L = \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon\beta*} F$$

$$\sigma = \sqrt{\varepsilon\beta*}$$



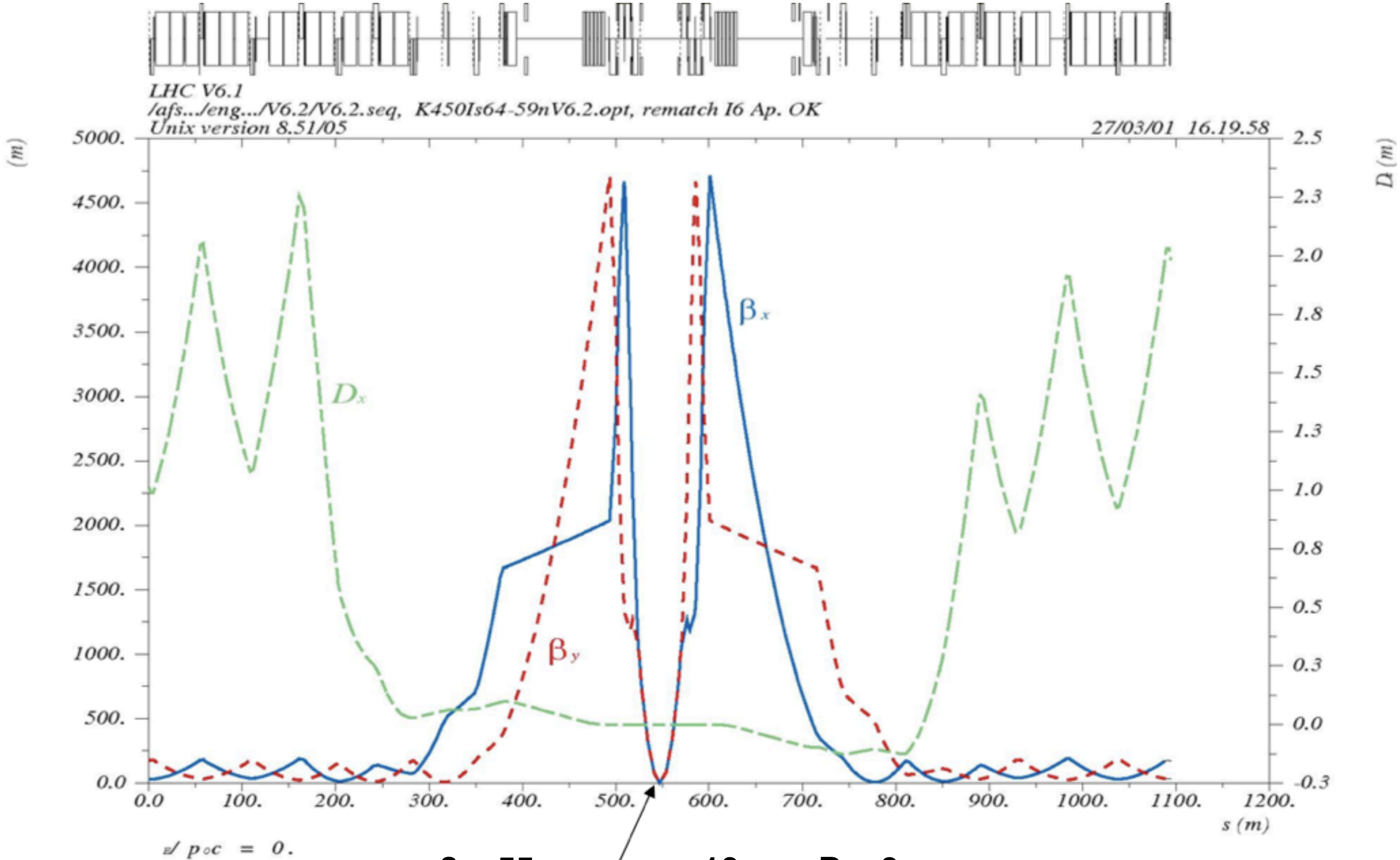
LHC:



$\langle\beta\rangle_{arc}$ = 80 meter

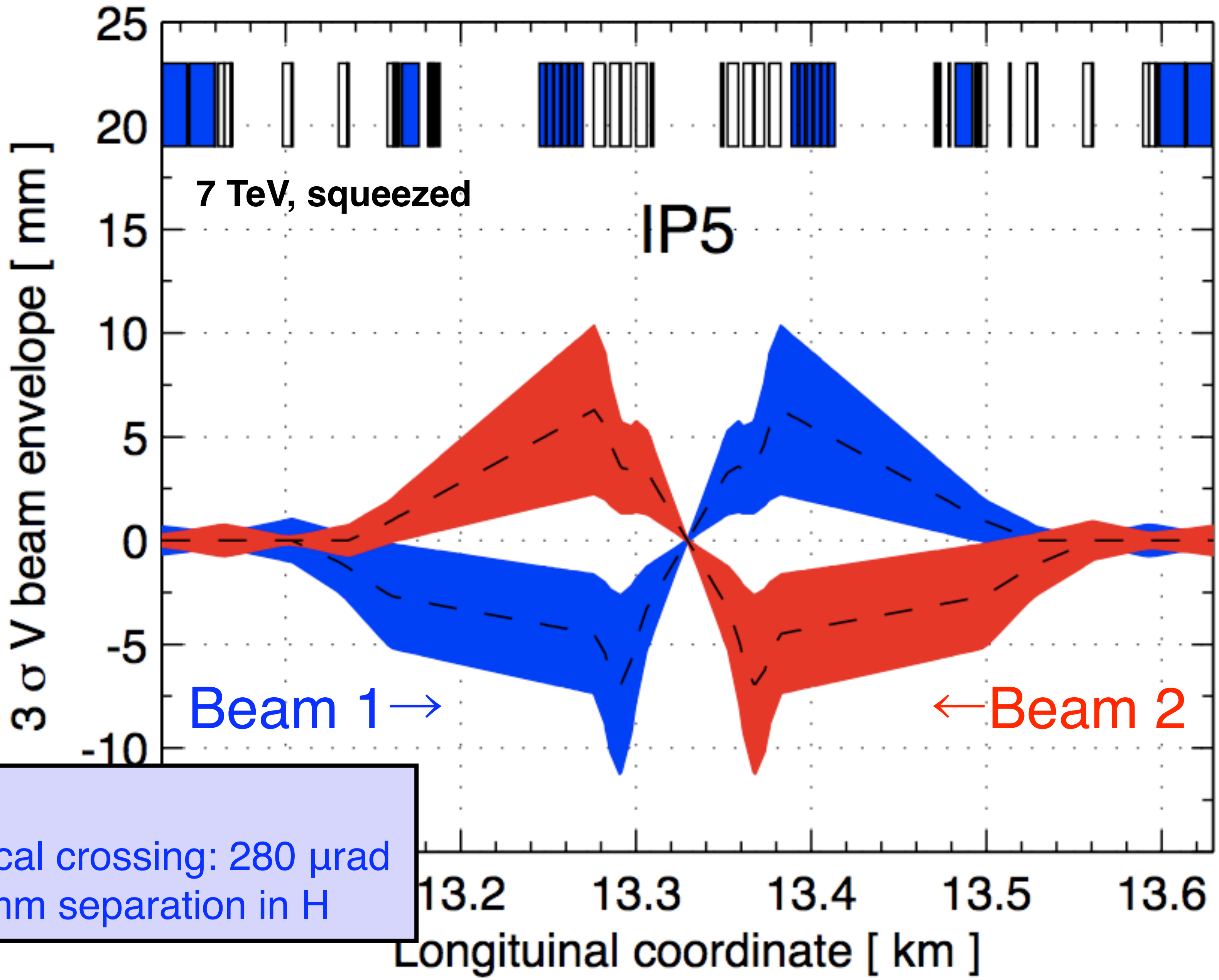
β_{IP} = 0.5 meter

Beta functions for IP1 and IP5



β = 55 cm → σ = 16 μm; D = 0m

Beam envelope



IP5:
Vertical crossing: 280 μrad
0.5 mm separation in H