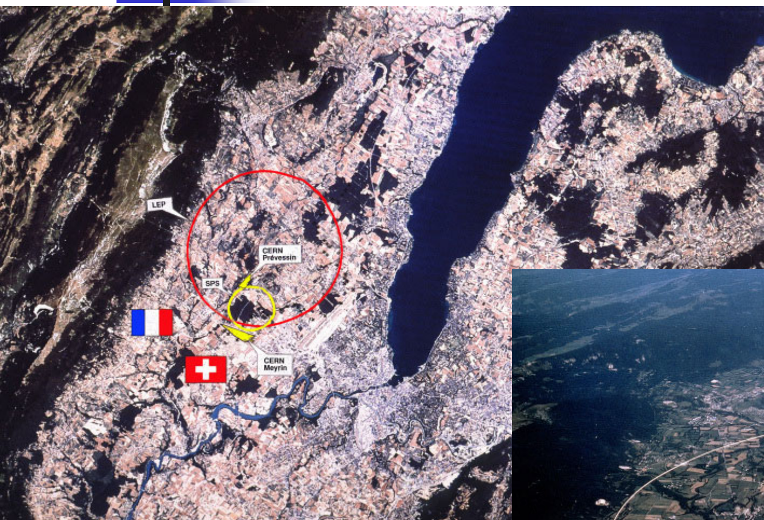
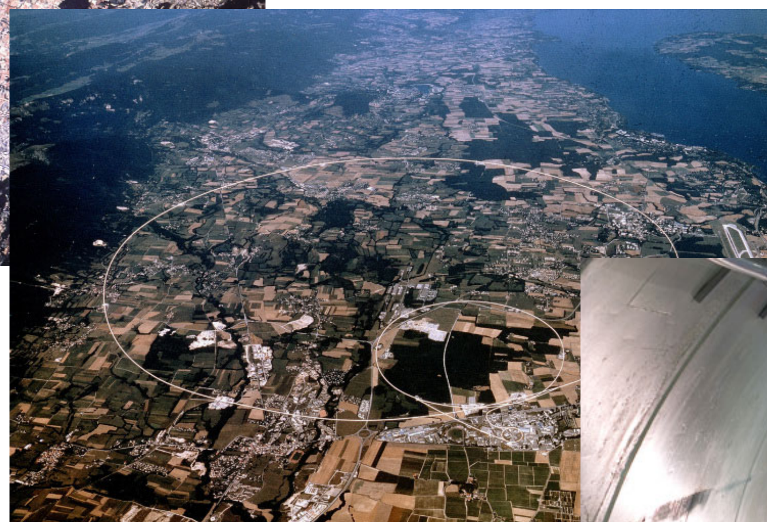
The Large Hadron Collider (LHC)



Motivations and challenges



D. Brandt, CERN

LHC: a really Large Project

•Why a circular collider ? What were the boundary conditions imposing this choice ? What has been the decision process?

• What are the real challenges ?

• Present status 2008 - 2009

• Expectations for 2009 – 2010

The energy point of view:

$$E_{cm} = mc^2$$

In order to discover/study new heavy particles, accelerators are used to provide the required center-of-mass energy E_{cm}

Basic boundary condition for the LHC:

We want to study the Higgs particle:

Energy range of interest:
a few TeV !

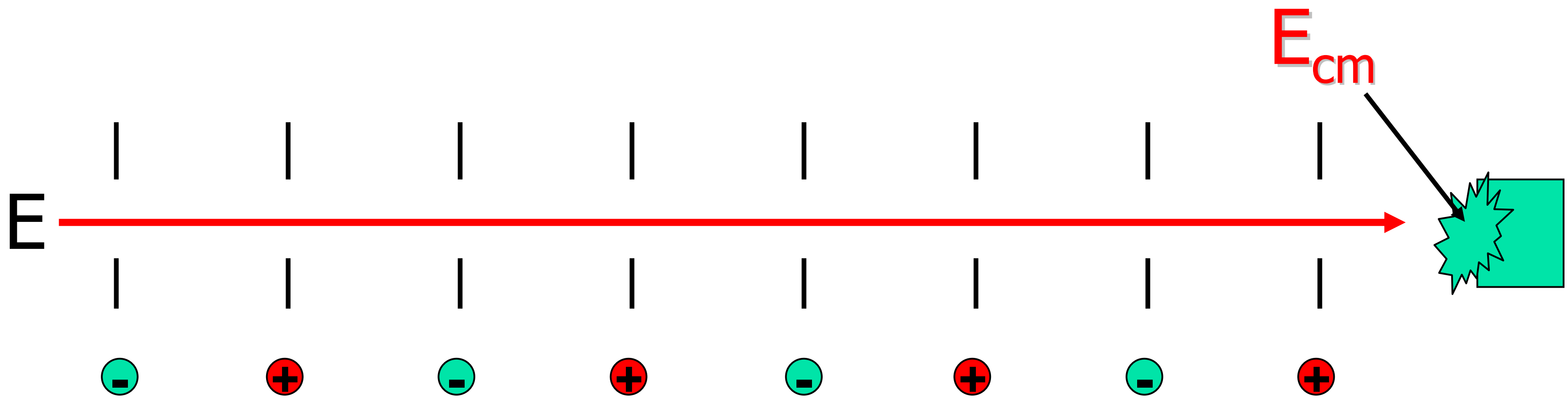
How can we do it ?

There are basically two ways to achieve this:

- Fixed target mode
- Collider mode

Fixed target mode 1

1) A linear accelerator (linac):



Single pass : high intensity possible

Fixed target mode 2

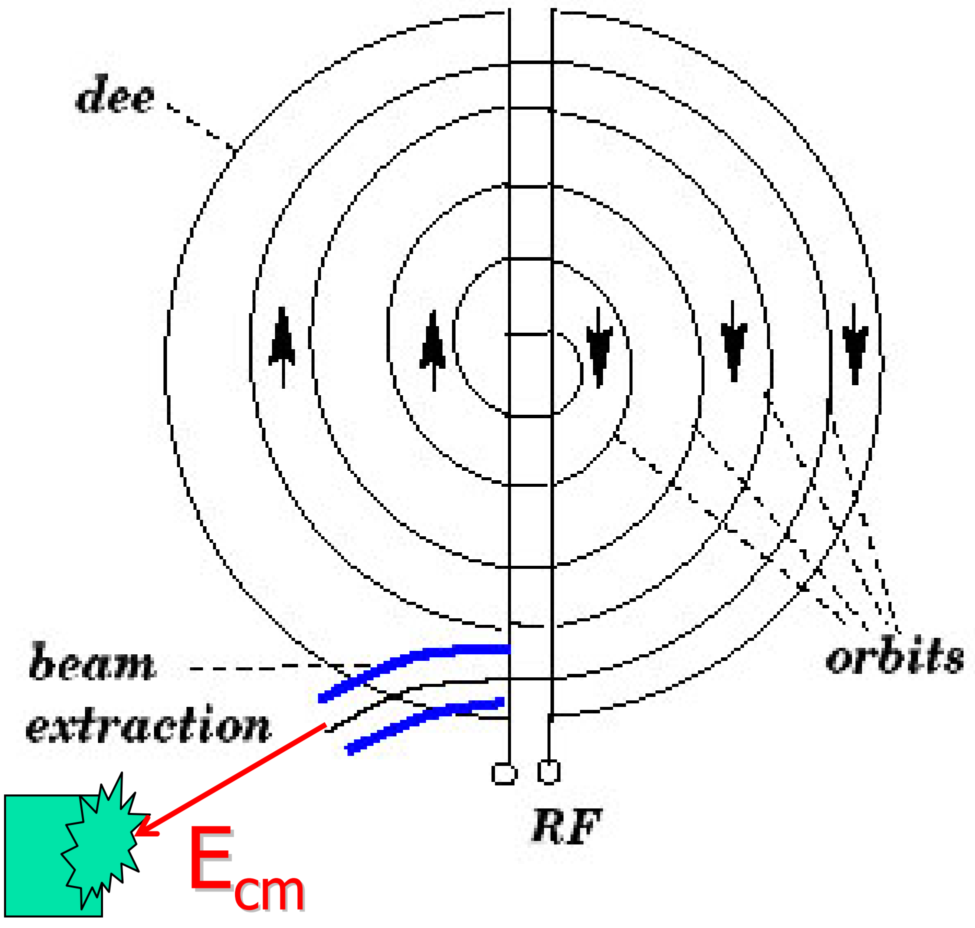
2) A Cyclotron:

huge dipole

compact design

B = constant

low energy, single pass.



Fixed target mode 3

In fixed target mode:

$$E_{c.m.} = (2m_0^2 + 2m_0E)^{1/2}$$

Problem:

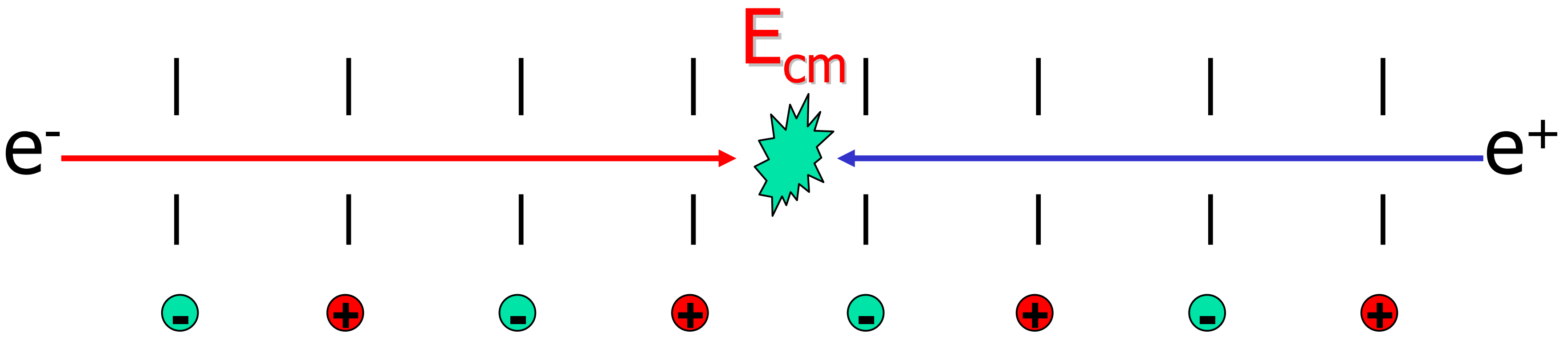
$$14\ \text{TeV} = (2m_0E)^{1/2}$$

E is not reasonable, fixed target mode not possible !

➔ We need to find a different solution !

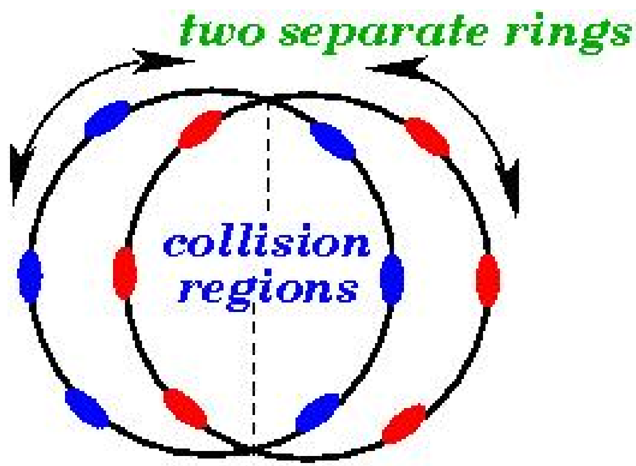
Collider mode 1 (linear):

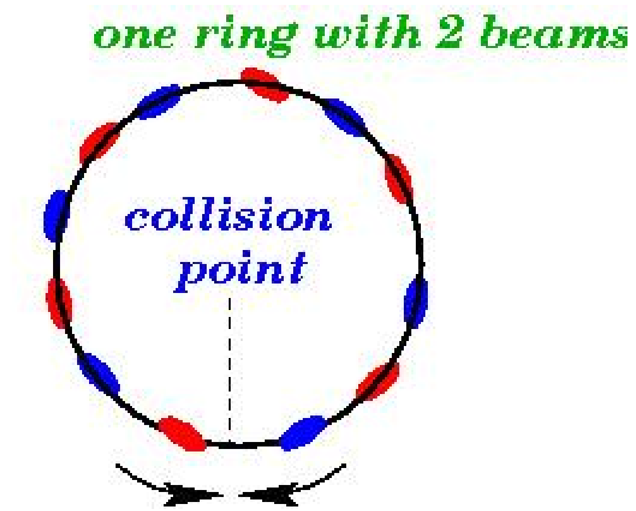
A Linear collider



High energy ➔ long machine ➔ space not available presently !

Collider mode 2 (circular):





- Same type of particles
- Twice the infrastructure
- 2 in 1 design possible
- Price !

- Particles – Anti-particles
- A single vacuum chamber !
- Many advantages !

Collider mode 3

In collider mode:

$E_{c.m.} = 2E$

14 TeV = 2E ➔ E = 7 TeV

For the LHC boundary conditions

➔ We need a collider and a circular one !

The particles point of view:

- Leptons or Hadrons ?
- Collide particles – anti-particles ?
- Collide same type of particles ?

Synchrotron radiation

- Charged particles bent in a magnetic field emit synchrotron radiation!

with $\gamma = E/E_0 = m/m_0$ and m_0 is the rest mass

Energy loss:

$$eU_0 = A \,.\, \gamma^4/\rho$$

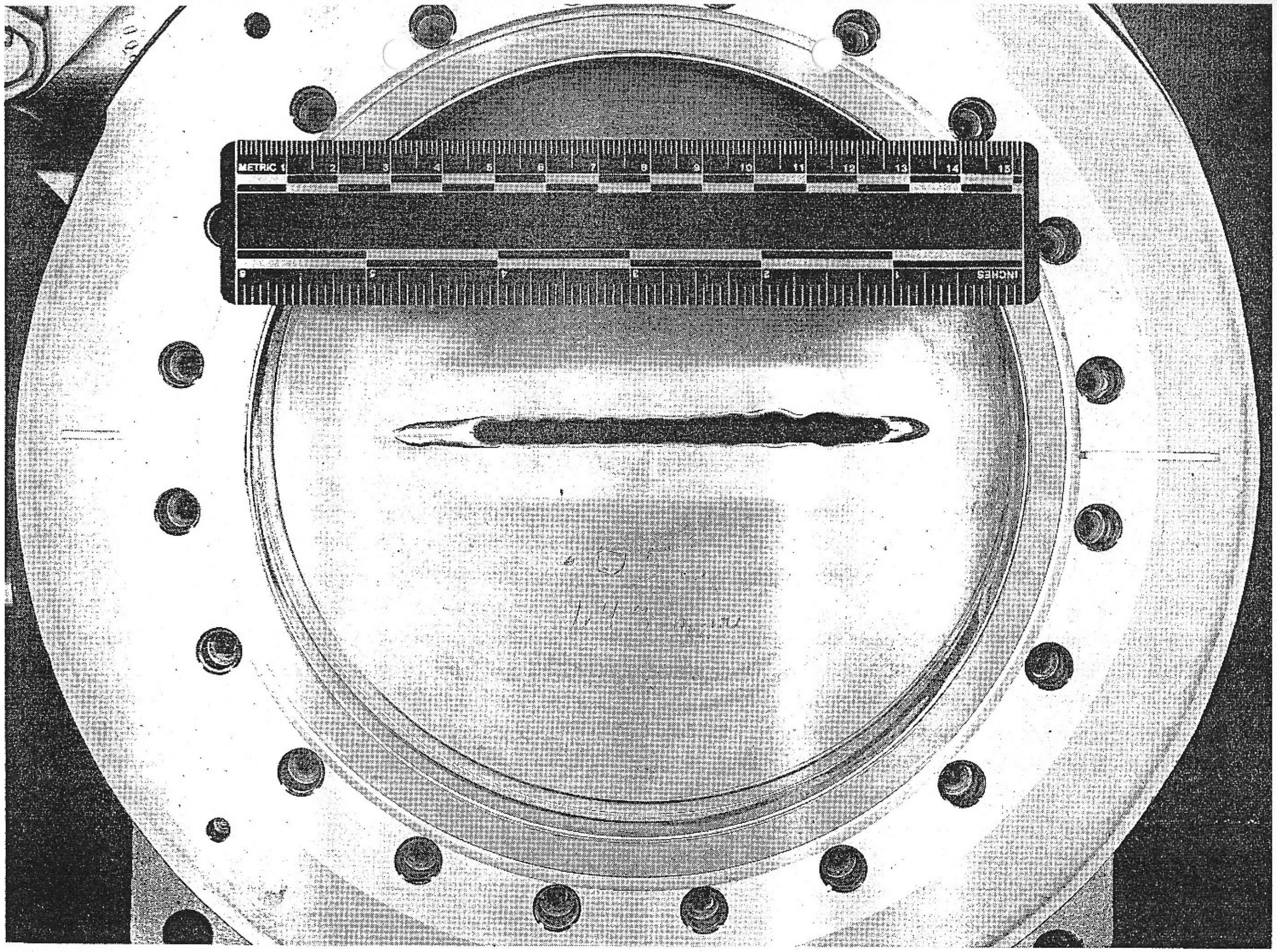
m_0 proton = 0.938 GeV/c^2

m_0 electron = 0.511 MeV/c^2

$(m_{o\text{-}p}/m_{o\text{-}e})^4 = (1836)^4 \cong 10^{13}$

Collider	B (T)	E/beam (GeV)	γ	eU_0 (GeV)
LEP ($e^+ e^-$)	0.12	100	196000	2.92
LHC (p-p)	8.3	7000	7500	0.00001

The power is all too real !



ig. 12. Damaged X-ray ring front end gate valve. The power incident on the valve was approximately 1 kW for a duration estimated to 2–10 min and drilled a hole through the valve plate.

L. Rivkin

CAS-Trieste2005

What type of particles ?

- We cannot consider leptons for the LHC. LEP is likely to have been the last circular accelerator with leptons for HEP !

- We therefore have to move to collisions with hadrons !

- What about protons – anti-protons collisions ?

- $p^+ - p^-$ collisions would be the highly preferred solution, since only one vacuum chamber required (much easier and much cheaper) !

The Performance point of view:

The Luminosity

$$dN/dt = L \times \sigma$$

$[1/s] = [1/(cm^2.s)] \times [cm^2]$

$$L = N_1.N_2.f.k/(4.\pi.\sigma_x.\sigma_y)$$

with:

$N_{1,2}$ = Number of particles per bunch ($1.15\ 10^{11}$)

f = revolution frequency (11.245 kHz)

k = number of bunches (2808)

$\sigma_{x,y}$ = horizontal and vertical beam size (17 μm)

$\sigma = < 10^{-39}$ cm^2

$L = 10^{34}$ $1/(cm^2.s)$

Optimal performance:

- Highest possible bunch intensity (N^2)
- Number of bunches
- Minimise beam size

The availability of anti-protons is such, that the performance would be smaller by at least 3 orders of magnitude ➔ implies to move to p–p collisions!

The only solution for the LHC is therefore:

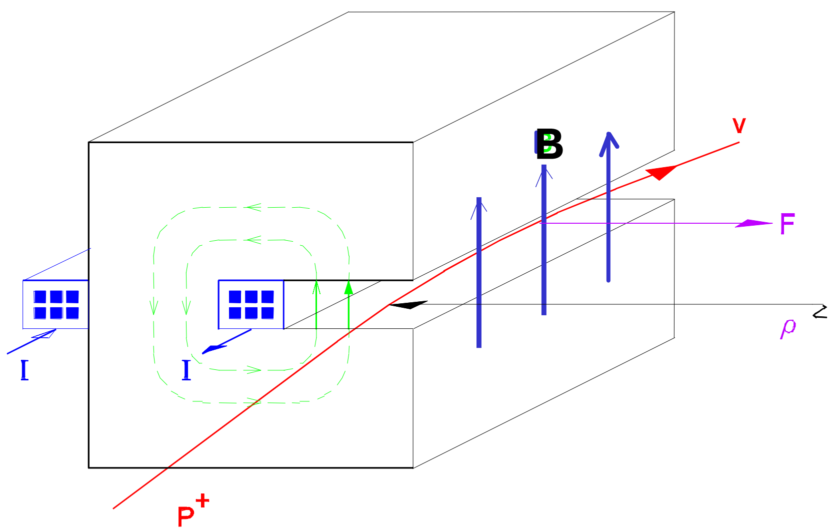
- A circular collider (synchrotron)
- With p-p collisions !

What is a Synchrotron ?

• It is a circular machine where the trajectories of the particles remain on the same radius during storage and/or acceleration:

➔ the trajectories of the particles have to be bent by means of dipole magnets !

Circular machines: Dipoles



Classical mechanics:

Equilibrium between two forces

Lorentz force	Centrifugal force
$F = e.(\underline{v} \times \underline{B})$	$F = mv^2/\rho$

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

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

Magnetic rigidity:

$$B\rho = mv/e = p/e$$

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

First fundamental challenge:

This very basic relation is of fundamental importance, because:

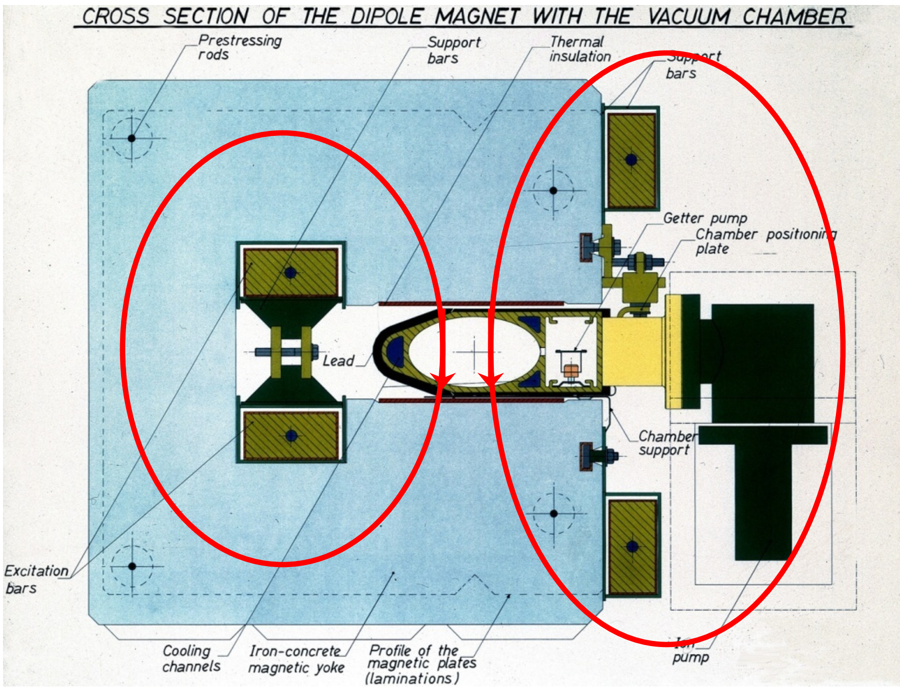
1)It shows that there is a unique relation between the momentum p and the magnetic field B.

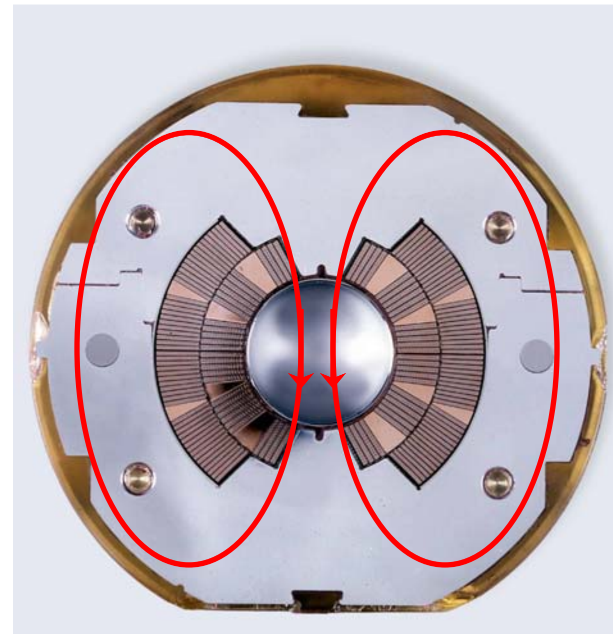
2)Once the momentum and the tunnel dimensions (ρ) are given ➔ the magnetic field B is defined !

E=7 Tev, ρ=3100 m ➔ B = 8.3 T !

➔ We need SC magnets !

Dipole Technology

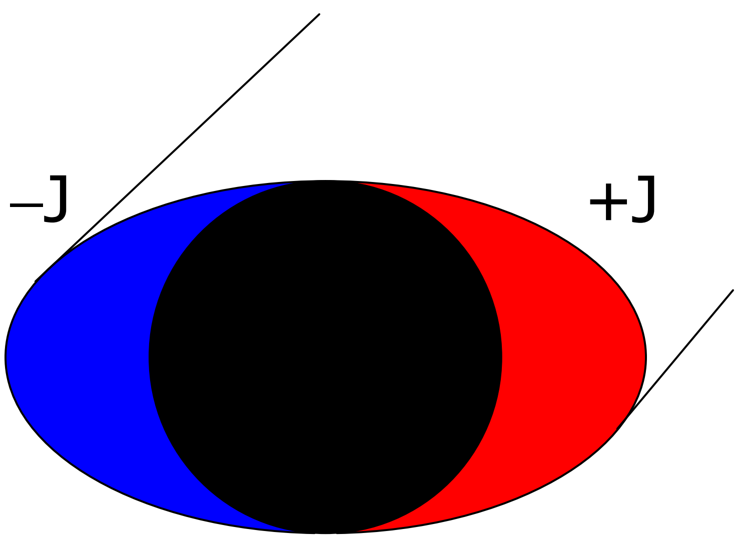




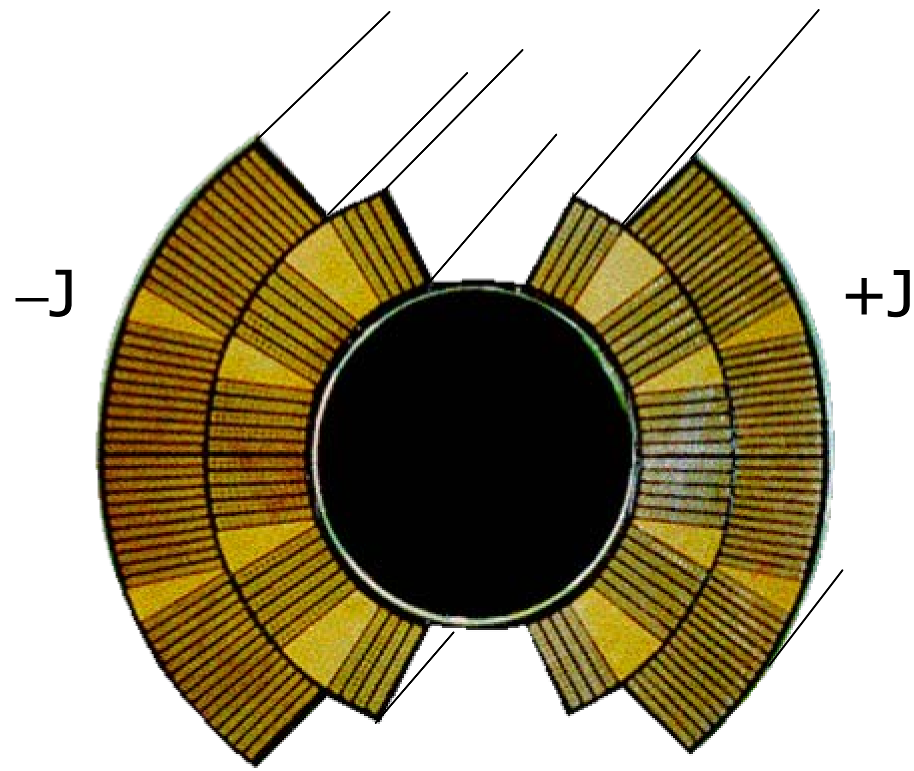
LEP: Iron yoke

LHC: SC coils

SC dipole magnet coil

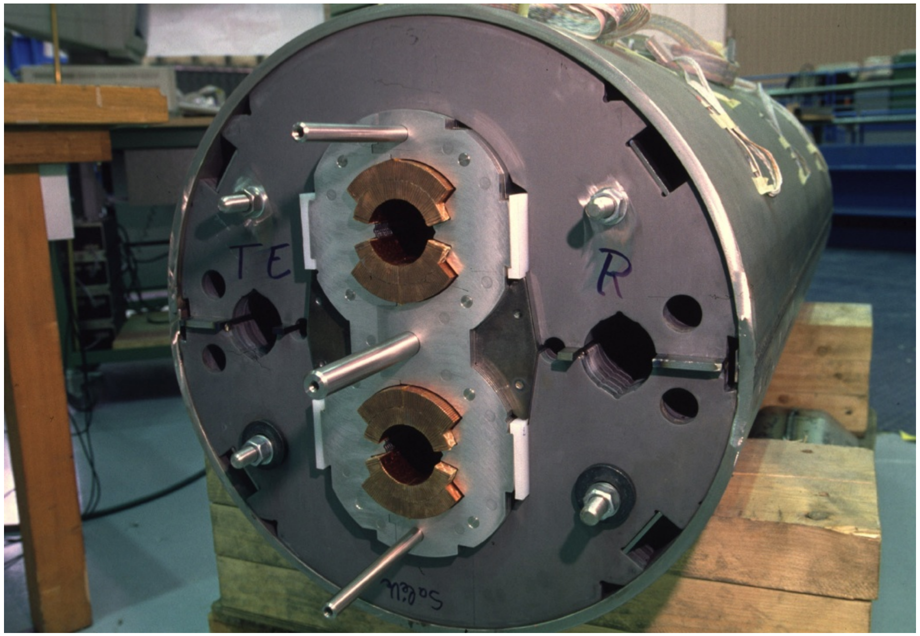


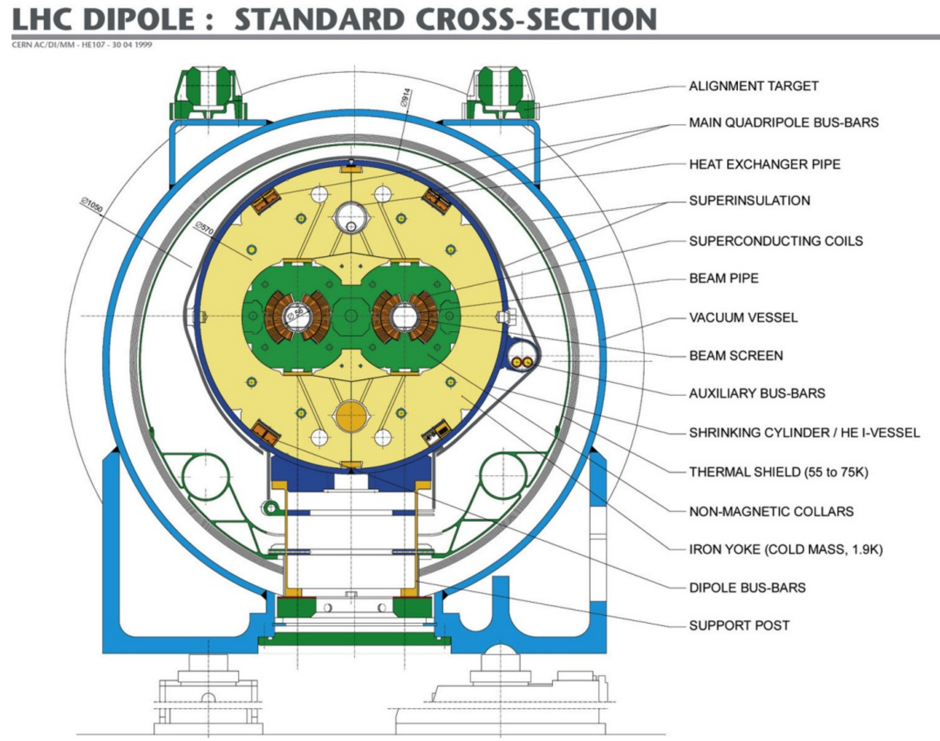
Ideal current distribution that generates a perfect dipole



Practical approximation of the ideal distribution using Rutherford cables

2-in-1 LHC Dipole

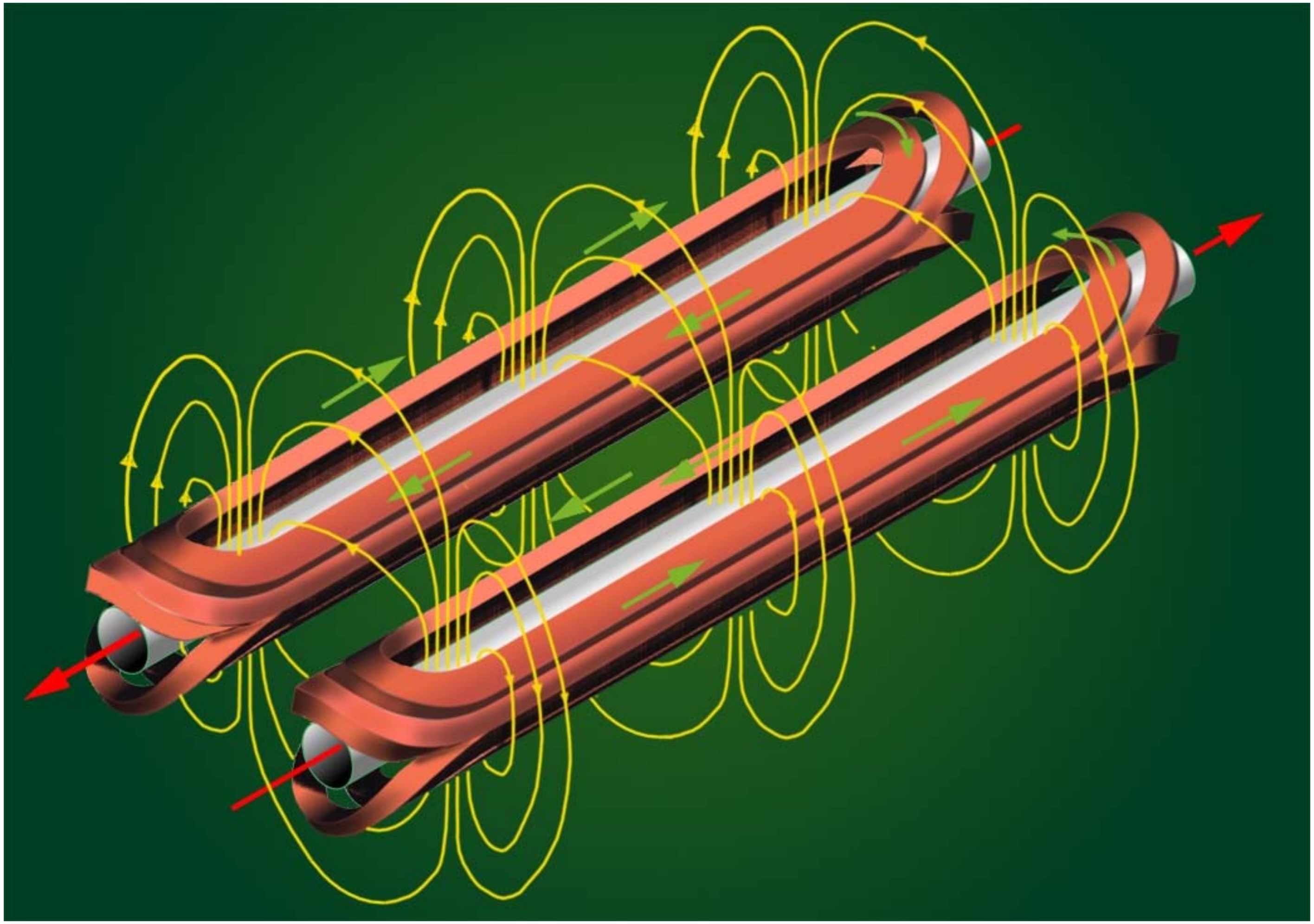




2-in-1 concept – 15 m long – 30 tons – very tight tolerances !

Dipoles are curved (2 cm sagitta) – mech. tol. at the µm level !

2-in-1 LHC Dipoles:



Ideal circular machine:

- Neglecting radiation losses in the dipoles
- Neglecting gravitation

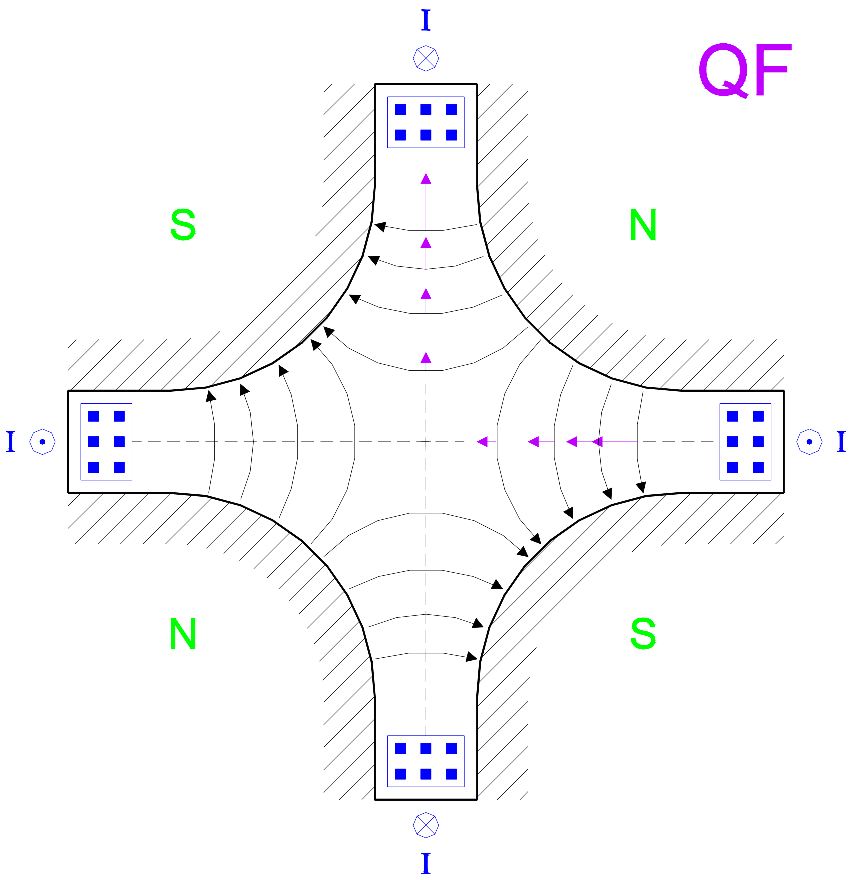
ideal particle would happily circulate on axis in the machine for ever!

We need something to keep the particles together in the transverse planes !

Unfortunately: real life is different!

Gravitation: Δy = 20 mm in 64 msec!	
Alignment of the machine	Limited physical aperture
Ground motion	Field imperfections
Error in magnet strength (power supplies and calibration)	
Energy or position error at injection	

Focusing with quadrupoles



$F_x = -g.x$

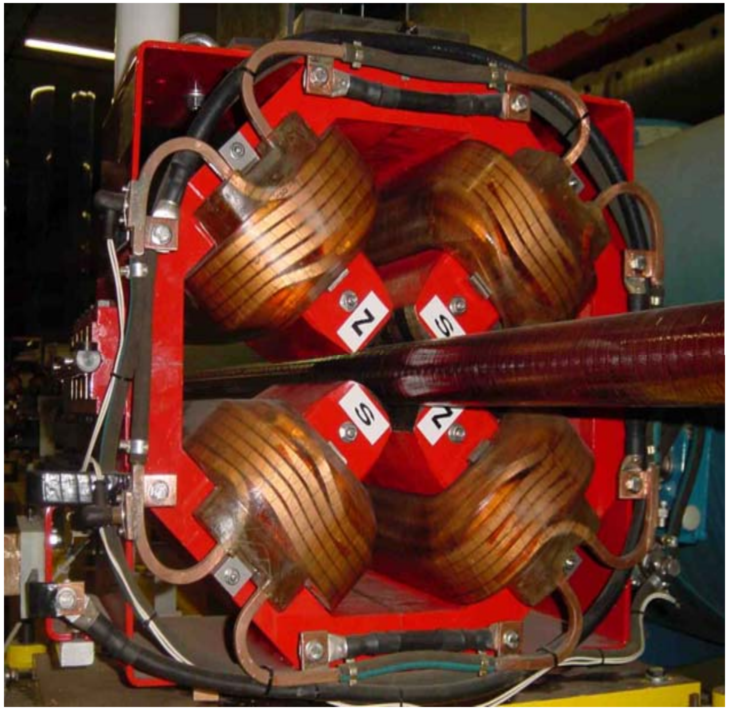
$F_y = g.y$

Force increases linearly with displacement.

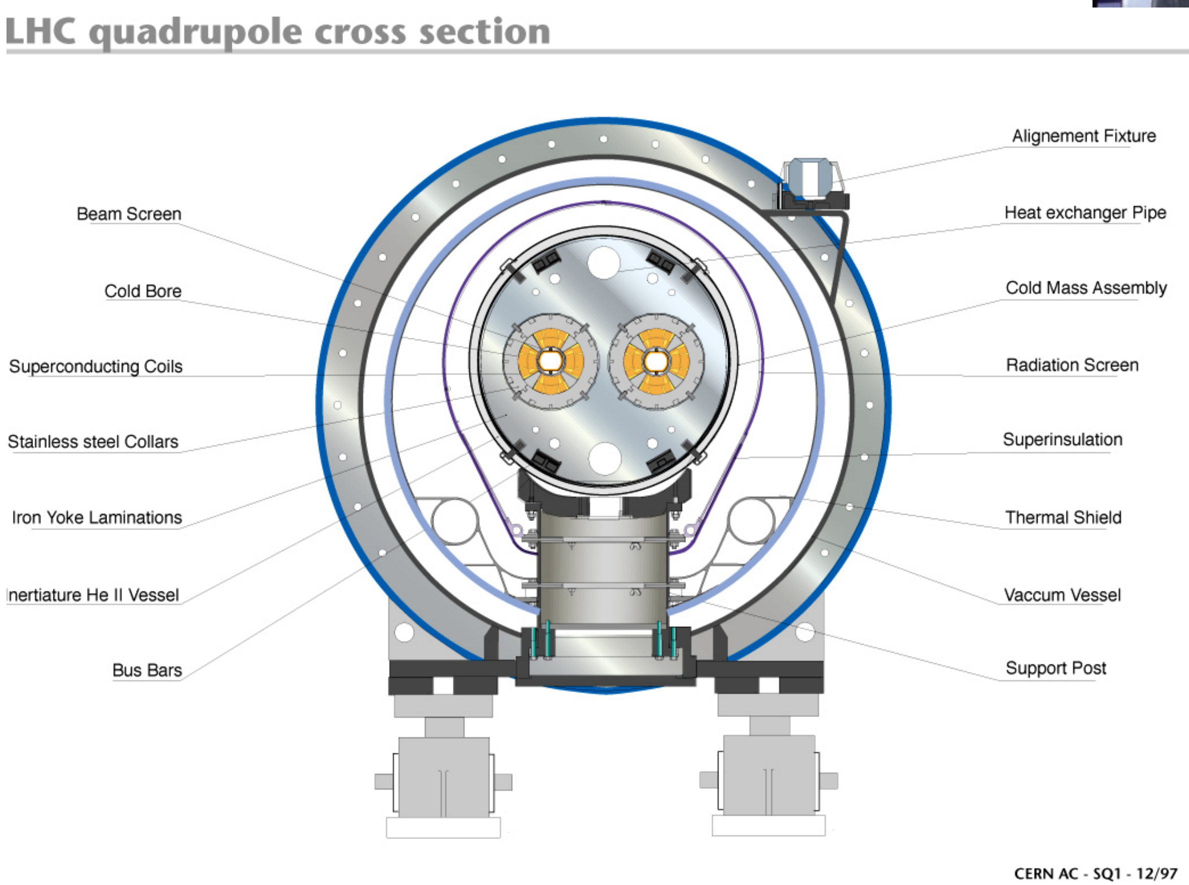
Unfortunately, effect is opposite in the two planes (H and V).

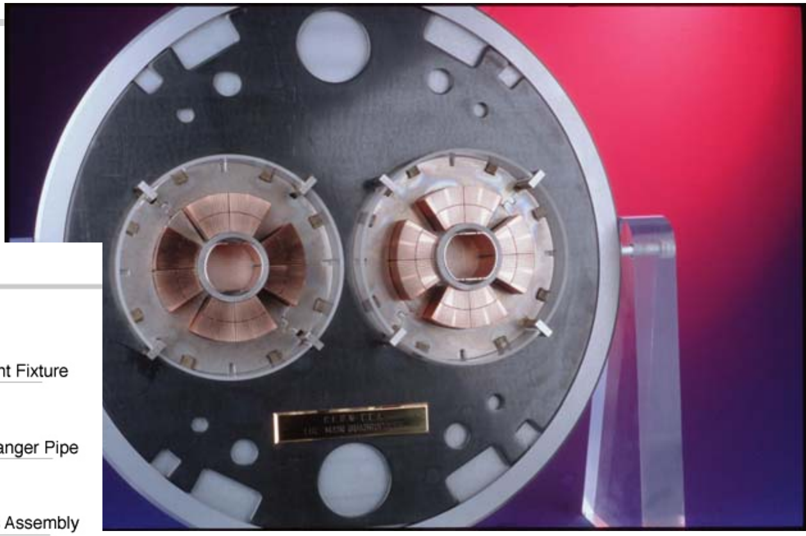
Remember: this quadrupole is focusing in the horizontal plane but defocusing in the vertical plane!

Quadrupoles:



LHC SC quadrupole





2 coils-systems in a single cryostat

Focusing properties …

A quadrupole provides the required effect in one plane…

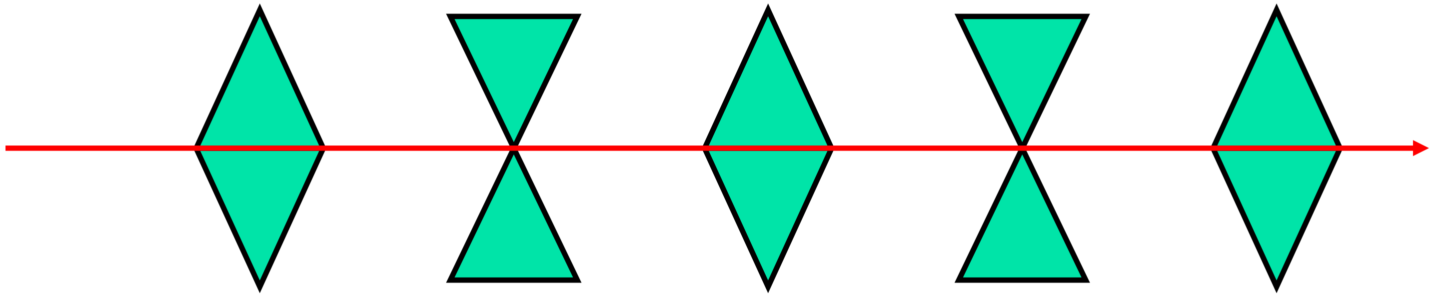
but the opposite effect in the other plane!

Is it really interesting ?

Alternating gradient focusing

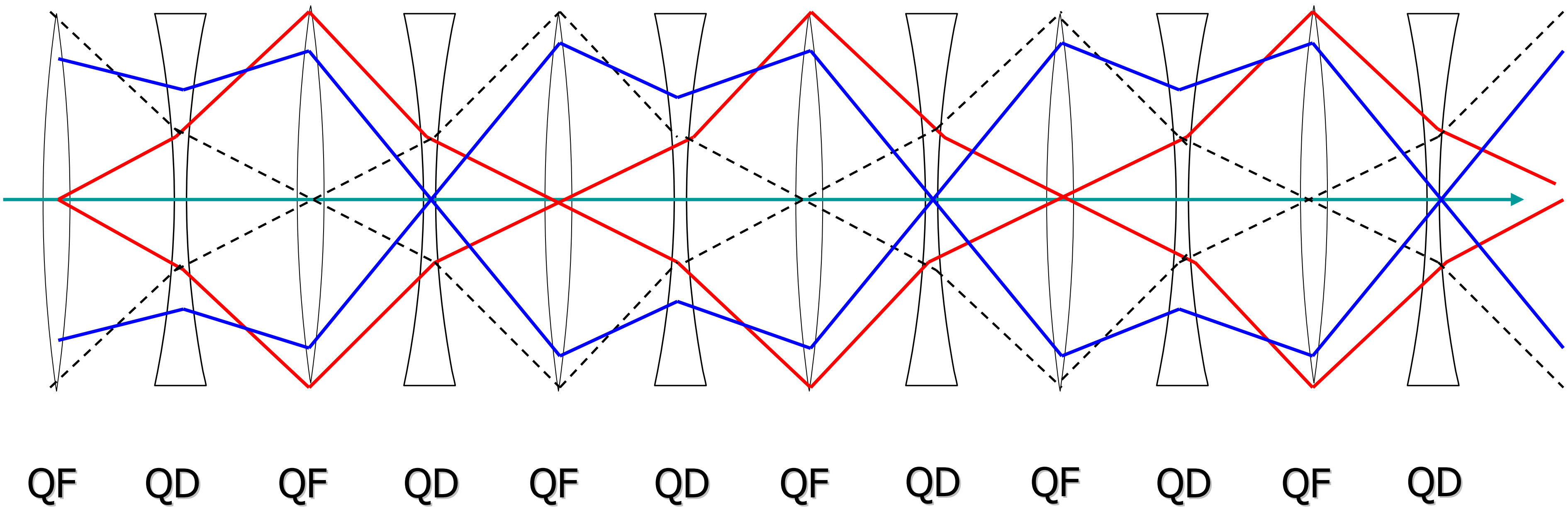
Basic idea (1950):

Alternate QF and QD



valid for one plane only (H or V) !

Alternating gradient focusing



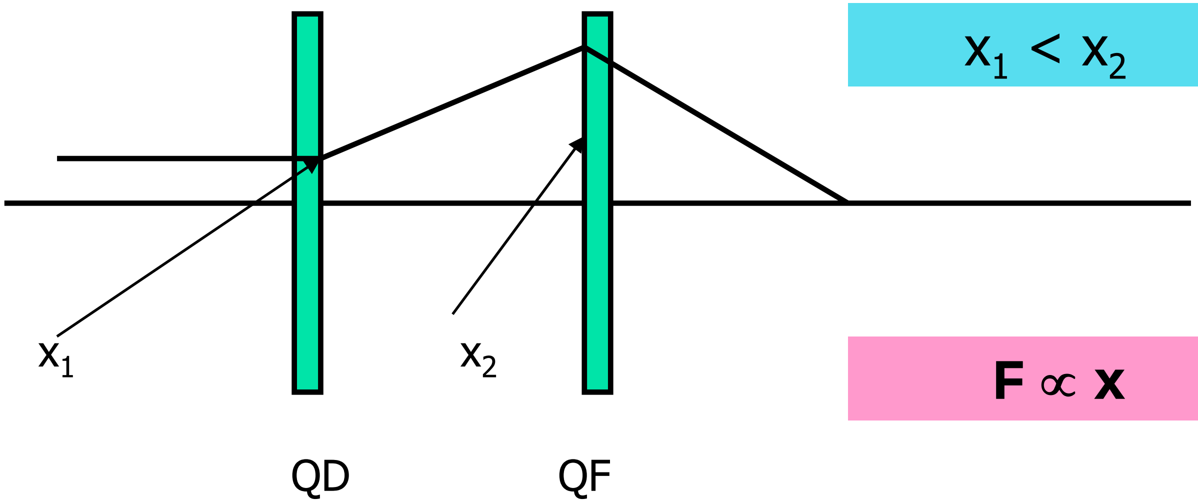
Alternating gradient focusing:

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:

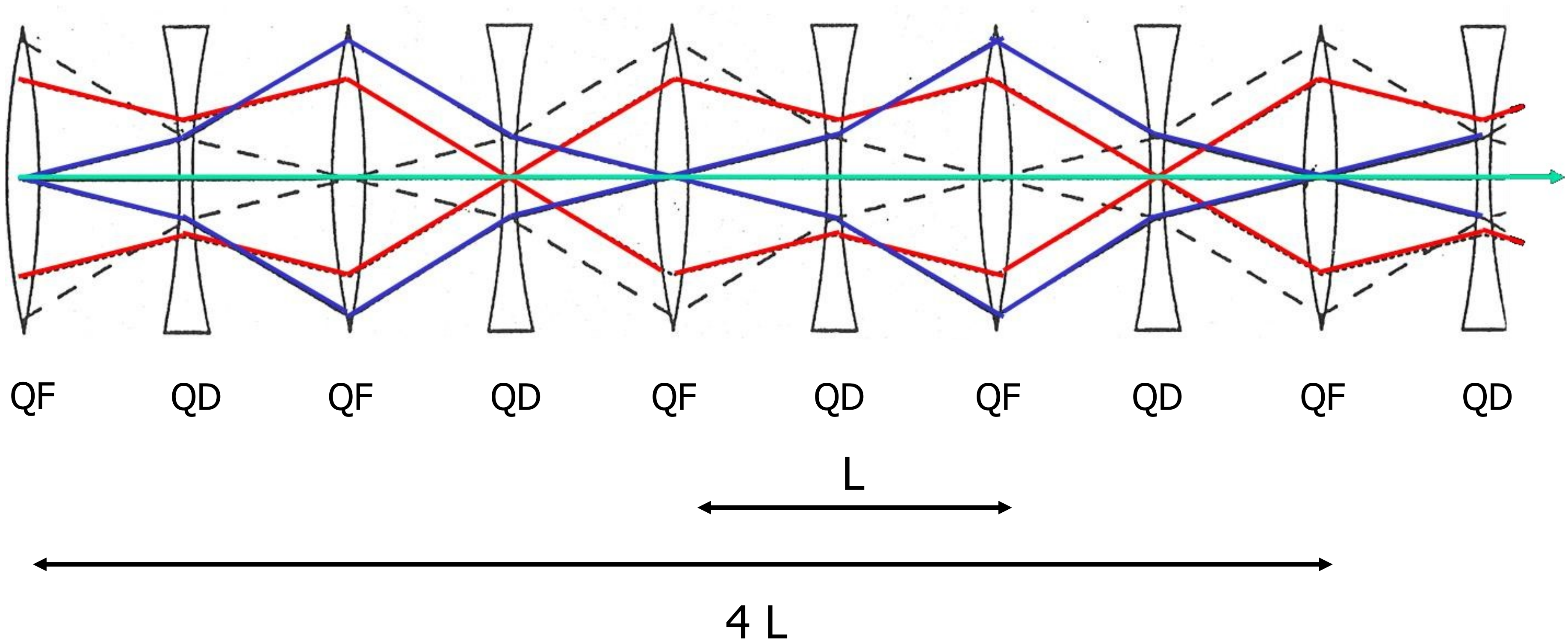


$x_1 < x_2$

$\mathbf{F} \propto \mathbf{x}$

Rigorous treatment rather straightforward !

The concept of the « FODO cell »

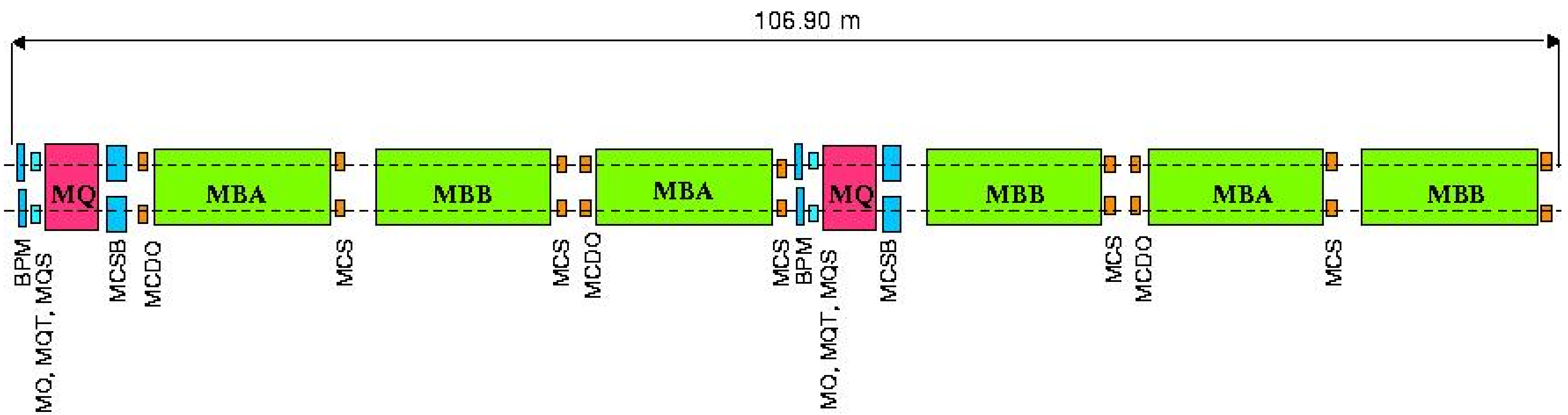


In this case: one complete oscillation in 4 cells

Number of oscillations per cell can be changed by varying the strength of the quadrupoles

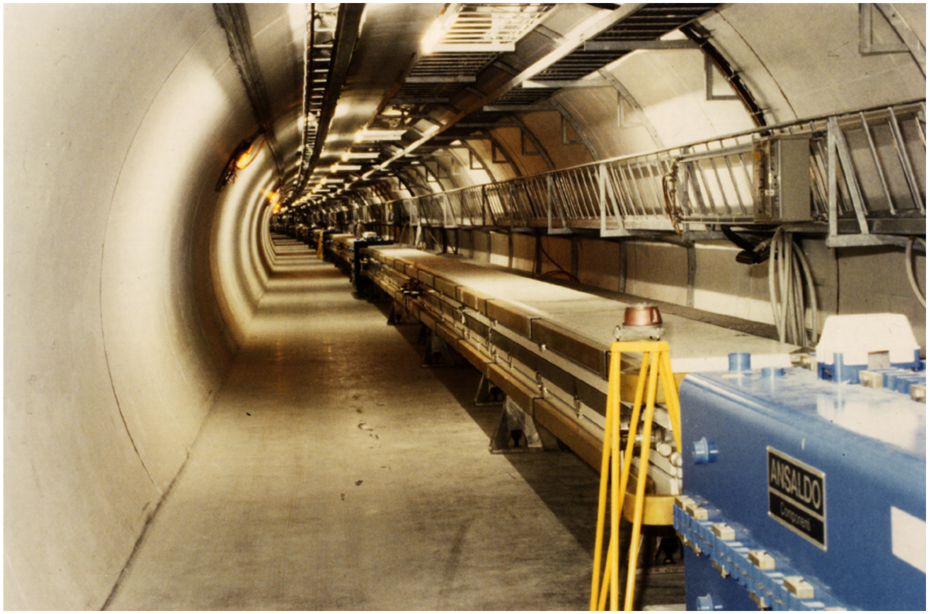
The LHC synchrotron:

The synchrotron is nothing but a periodic repetition of "cells".
This periodic repetition is called the "arc" of the machine:



For the LHC, this basic cell has a length of about 106 m !

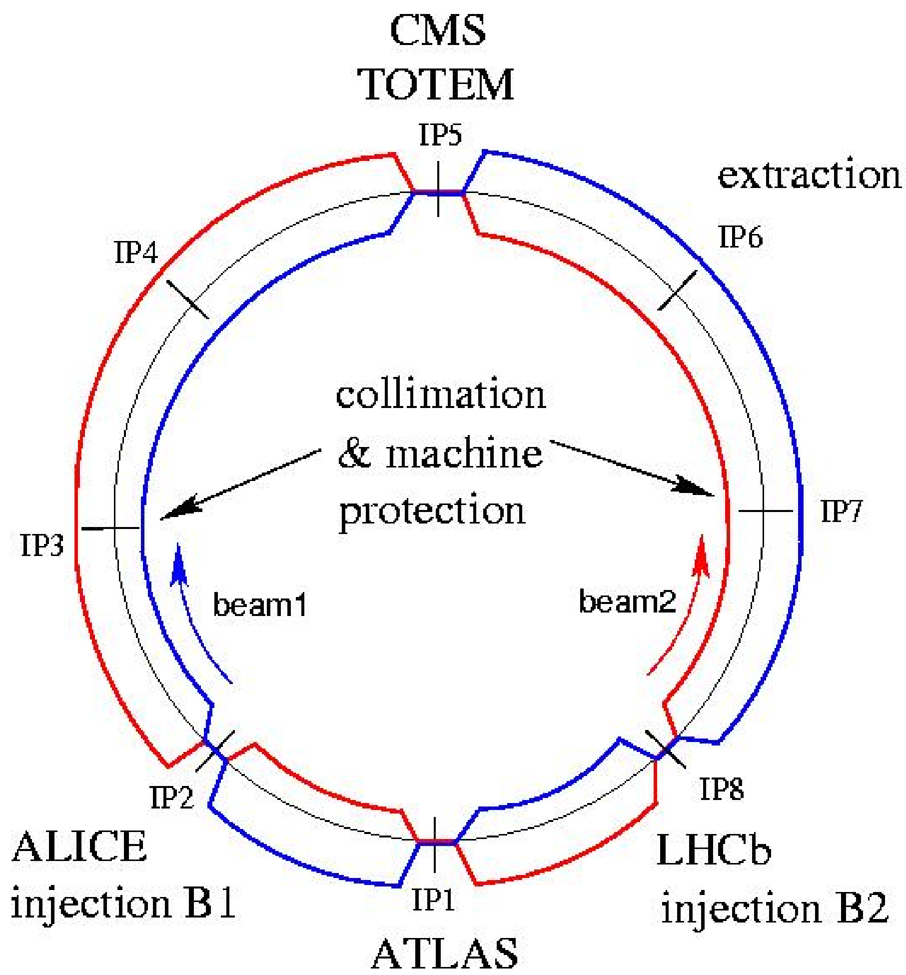
Regular periodic lattice: The Arc



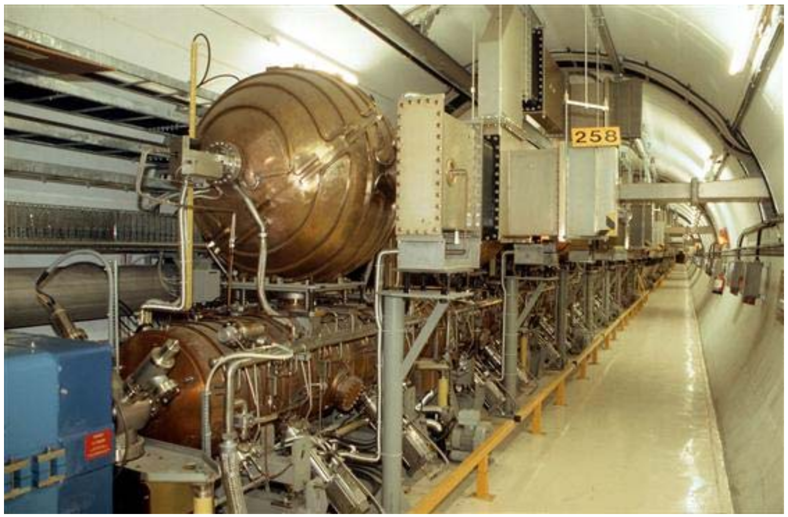
LEP

LHC

All we need for the real LHC !

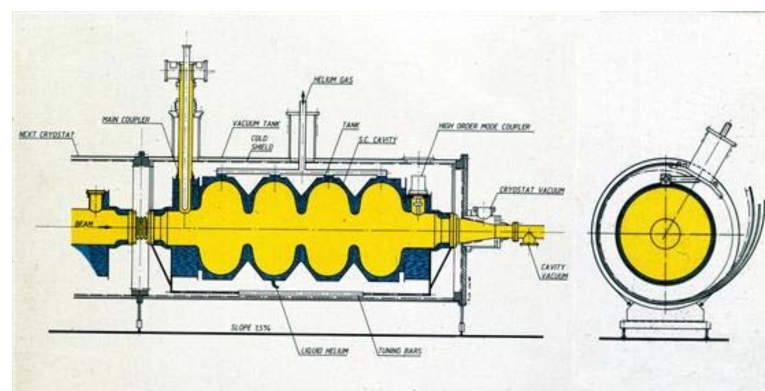


RF cavities: Accelerator !



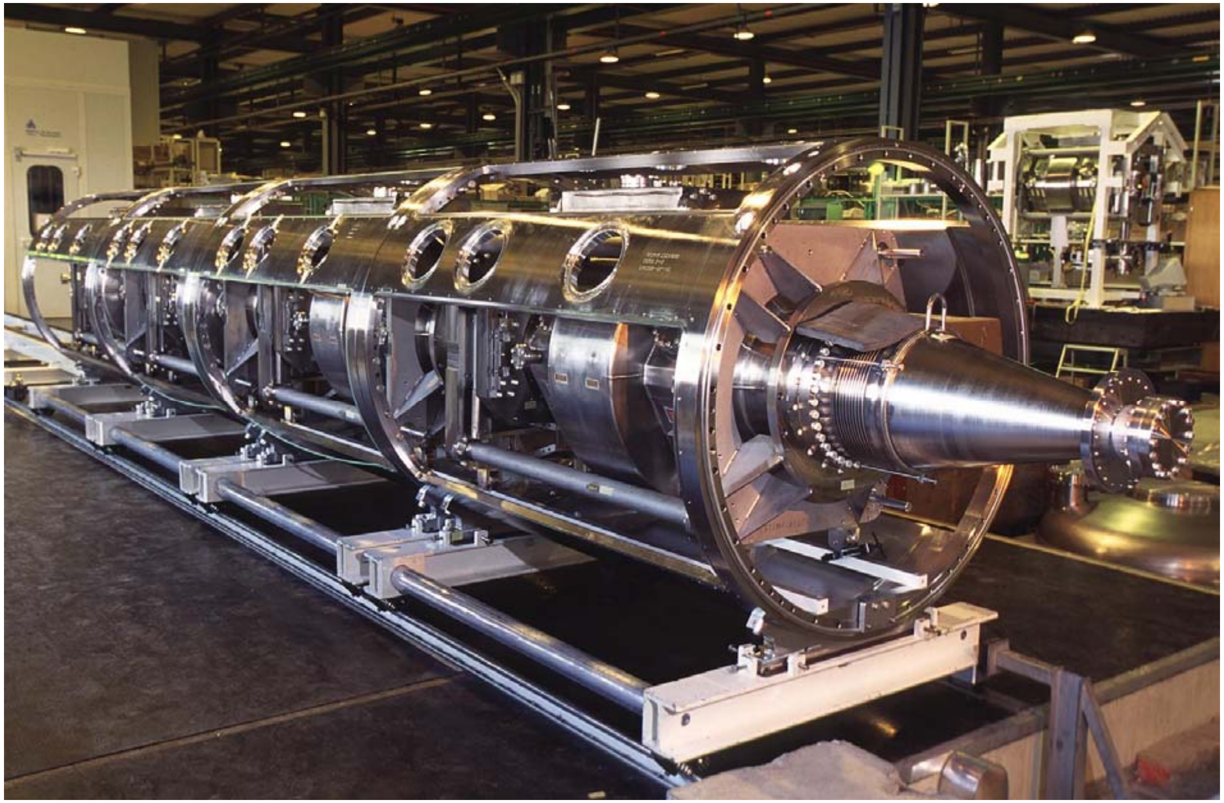
LEP "NC"

LHC "SC"



The RF System

The beams also need to be accelerated. This is achieved by means of SC RF cavities.



SC cavities 400 MHz

4 cavities/module

2 modules/beam

16 MV (5.5 MV/m)

RF: Reminder!

The RF requirement for the LHC is probably the only aspect not representing a big challenge:

Reminder:

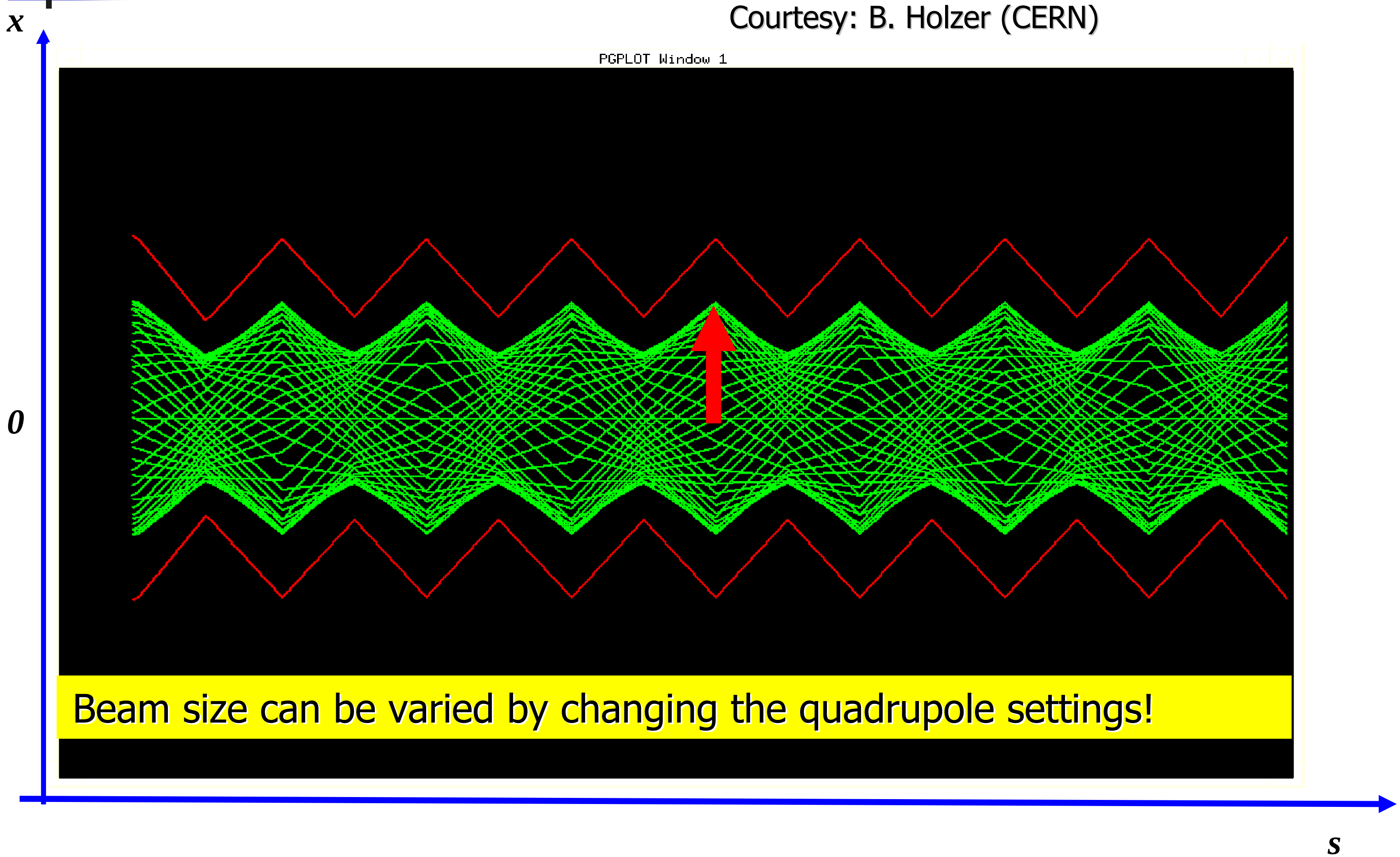
LEP: 100 GeV - RF = 3 GeV

LHC: 7 TeV - RF = 16 MV

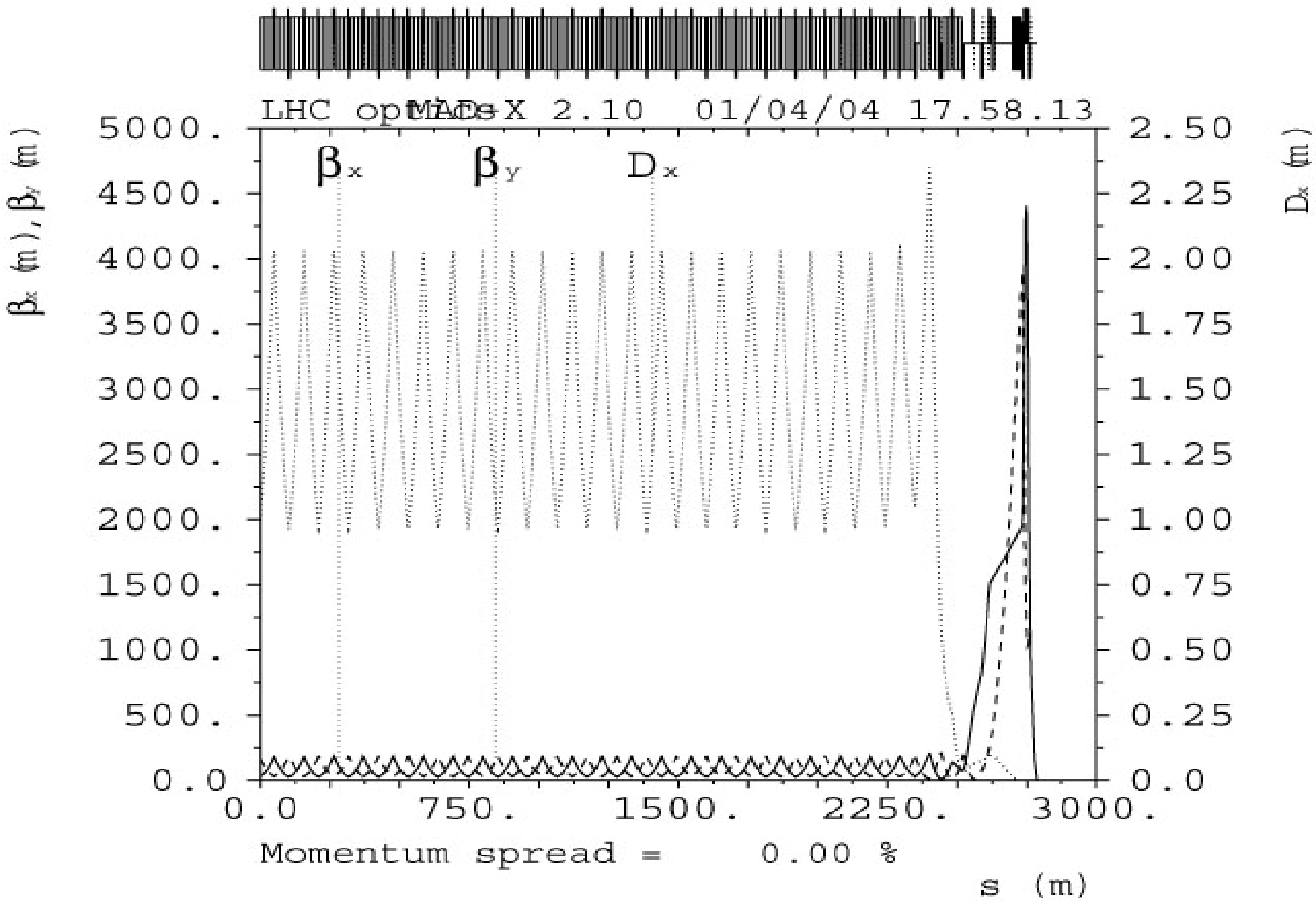
A few more details…

The beam size $\sigma = (\beta\varepsilon)^{1/2}$

Courtesy: B. Holzer (CERN)

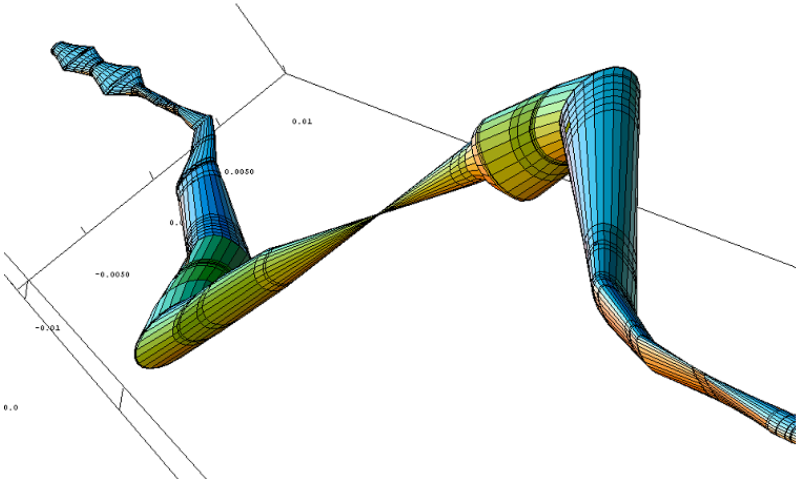


β function in the LHC:



Collisions

In order to maximise the luminosity, we aim at the smallest possible beam size at the crossing point (σ = 17 μm). Even with 10^{11} p/bunch, we have only about 20 collisions per crossing.



Most protons miss each other and carry on around the ring time after time.

This is why the beams can be kept circulating for hours.

The tunes of the machine:

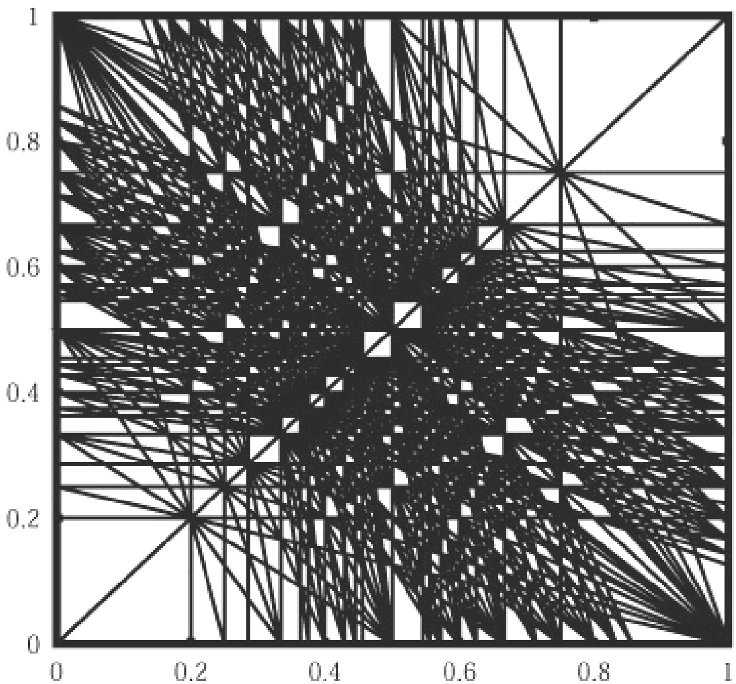
With the quadrupoles, the particles perform oscillations (betatron oscillations) around the ideal particles. The number of oscillations per turn (has to be a non-integer) in each plane is called the tune of the machine (Q_x and Q_y).

It just happens that the precise values of the tunes and, as important, the spread of these tunes within the beam is of fundamental importance for the stability of the beam.

For the LHC in physics, the spread of the tune within the beam has to remain < 0.015.

This is a real challenge for the operation of the machine !

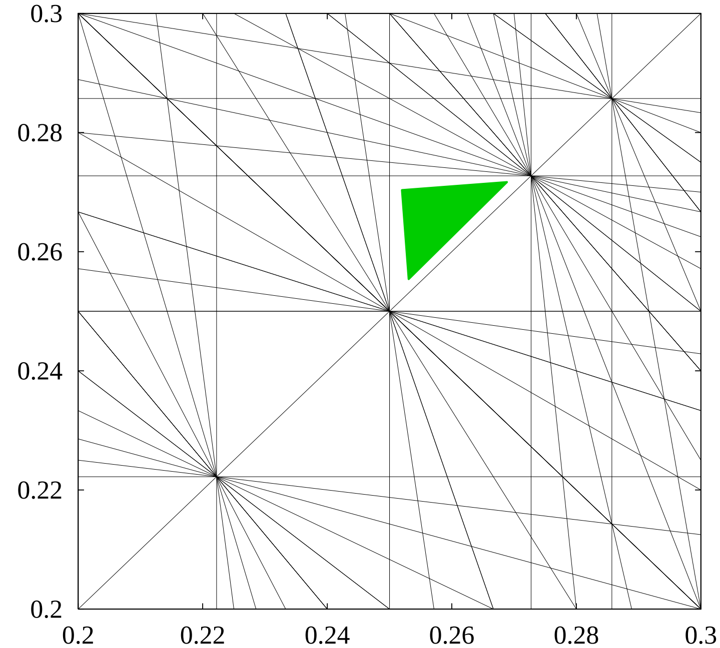
Tune diagram for protons



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

ΔQ < 0.015

LHC



Do we really have everything ...?

Well, still an important item missing…

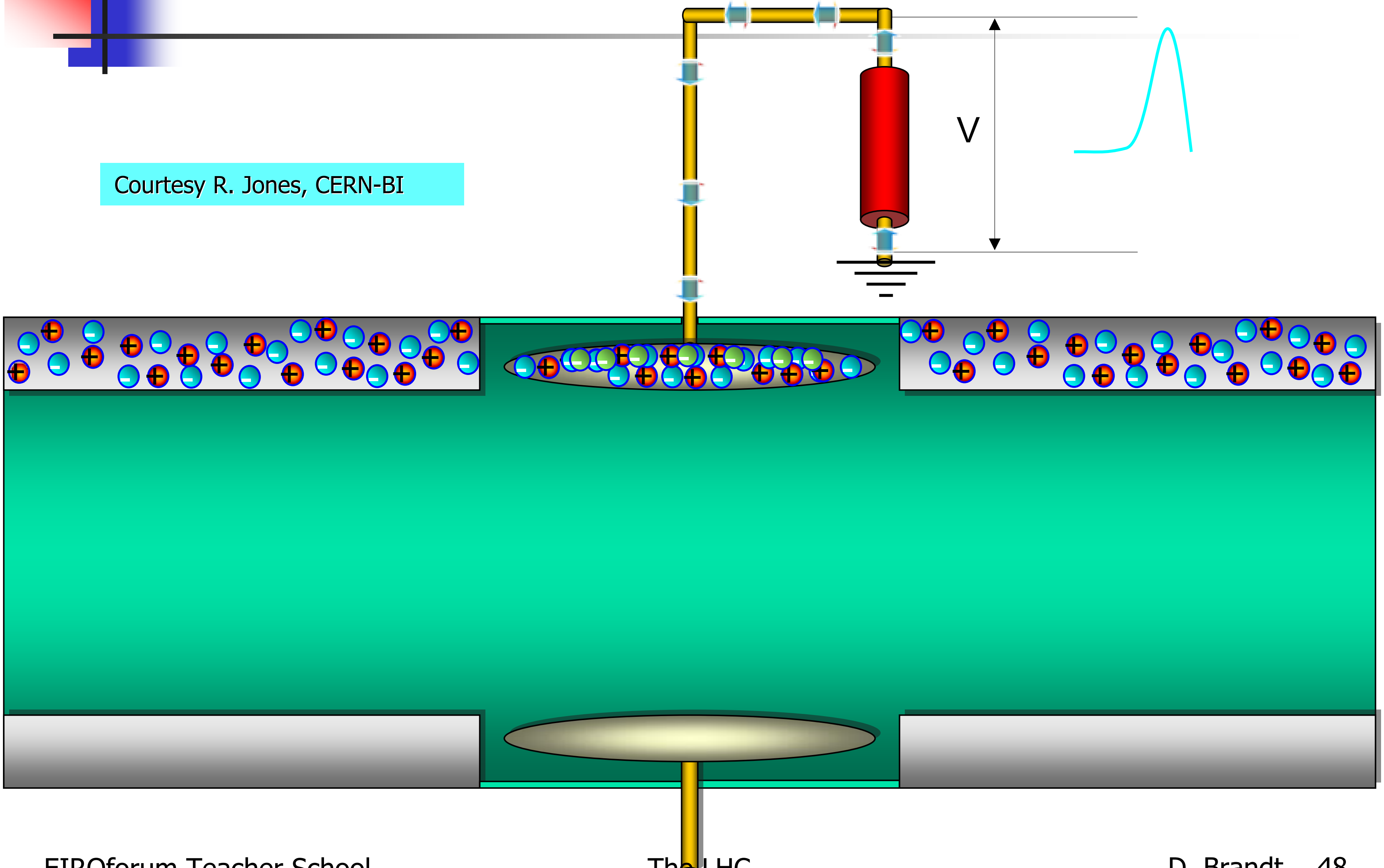
As a matter of fact, we have all the main components of the machine, but, so far, we cannot see the beam, i.e we are blind!

We therefore need to have some “eyes” to observe the beams….

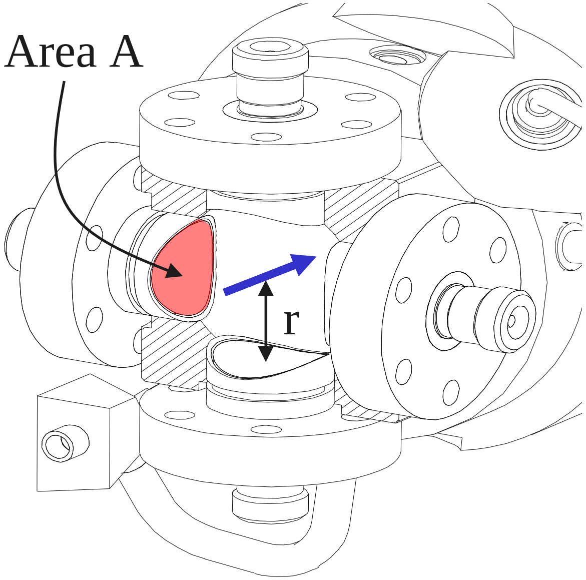
Although there are many different instruments to achieve this task, we shall restrict ourselves to mention the most common one, the button-type monitor…

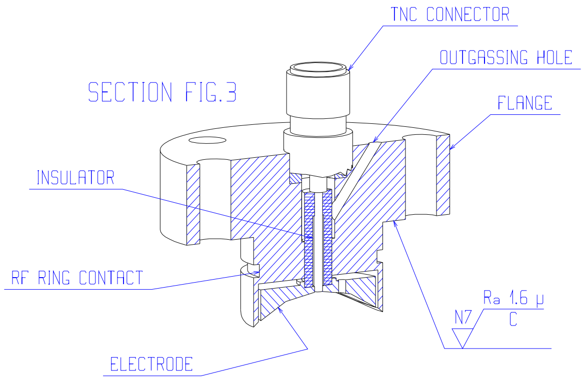
Electrostatic Monitor – The Principle

Courtesy R. Jones, CERN-BI



Electrostatic Pick-up – Button





Orbit Correction (Detail)

A very brief, non-exhaustive, review of some of the main challenges to be faced by the operation of the LHC

The LHC challenges

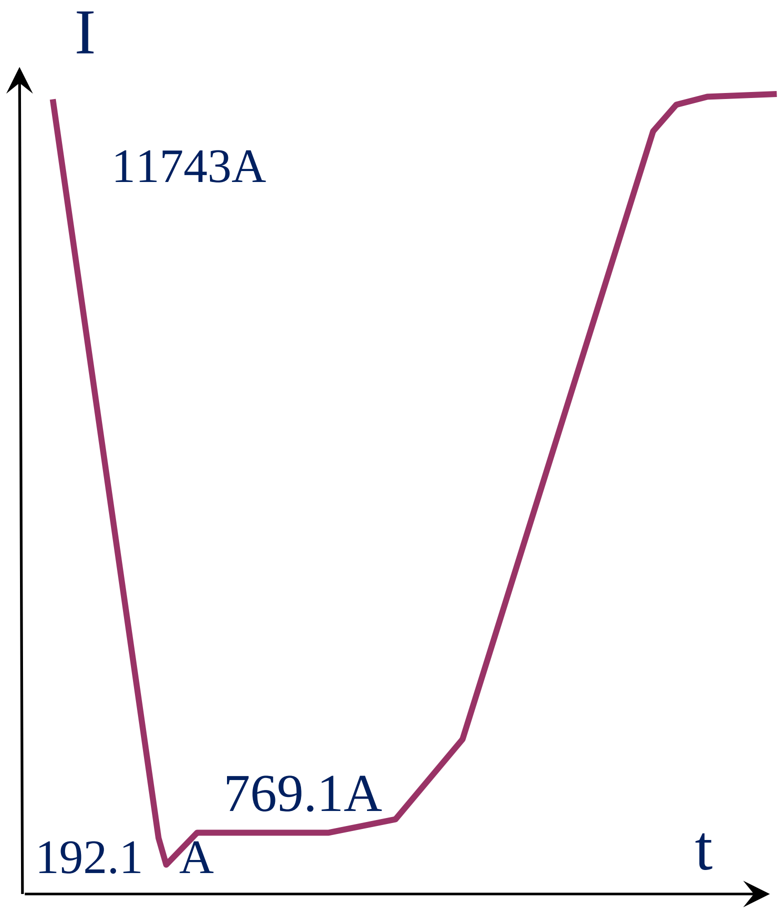
The energy of the machine:

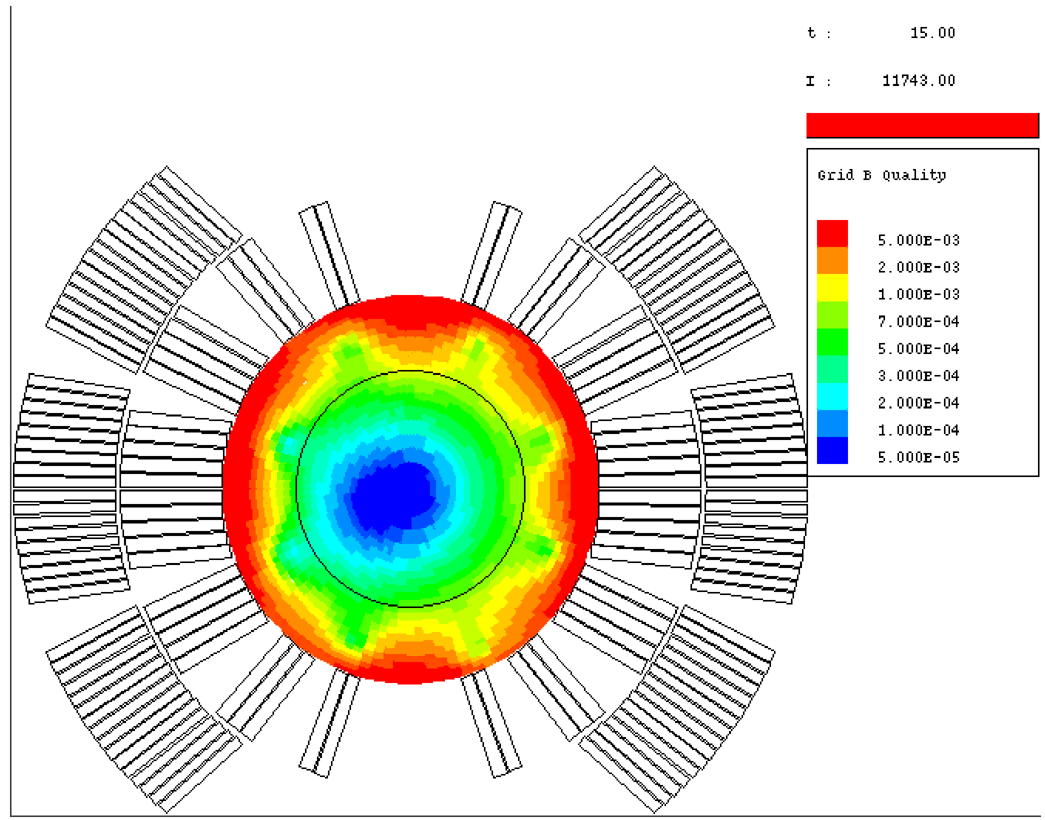
To have E_{cm} > 1 TeV when colliding protons, one needs to have a beam energy of about 5 TeV ➔ E_{beam} (LHC) = 7 Tev

The Performance:

To have a reasonable event rate, one needs a very high performance (luminosity) ➔ more than 2800 bunches per beam with 1.15 10^{11} p/bunch ! Target Luminosity: 10^{34} $cm^{-2}s^{-1}$!

Challenge: Good Field Region:





The LHC challenges

The e.m. energy stored in the magnets:

- The e.m. energy stored in the LHC magnets is about 10 GJ !
- 1 MJ is sufficient to heat and melt about 1.5 kg of Cu !
- In case of a current drop (e.g. after a magnet quench), the 10 GJ have to be quickly and safely evacuated into dedicated loads.
- The quench protection system (QPS) has therefore to fulfill incredibly high constraints.

Energy stored in the beam:

The energy of a 200 m long train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

- Energy stored in the beam
  - 1 MJ can heat and melt 1.5 kg of copper.
  - 1 MJ = energy stored in 0.25 kg of TNT.

Still a few numbers:

- Nominal beam intensity: I = 0.5 A ➔ $3\ 10^{14}$ p/beam
- Quench level: $N_{loss} < 7\ 10^{8}$ /m ➔ $2\ 10^{-6}\ N_{beam}$!
- Other SC machines: $N_{loss} / N_{beam} \sim 0.2 - 0.3$!

- In case of a problem requiring warming up:
  - ➔ 3 weeks to get to 300 K
  - ➔ time for repair work
  - ➔ 6 weeks to get back to 2 K

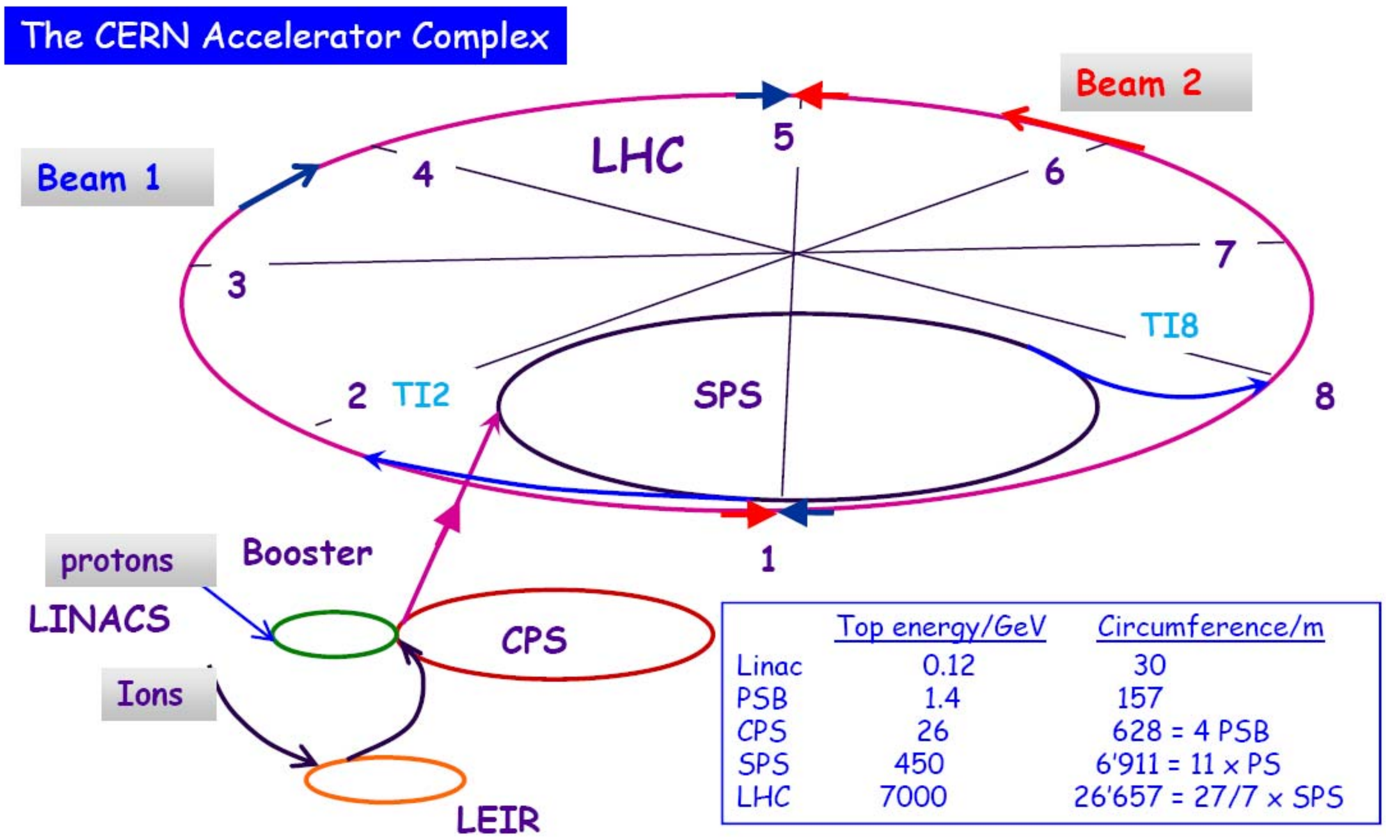
Conclusion:

The Machine Protection System is certainly the biggest challenge of the LHC Project, it has to:

• Make sure that for any unforeseen failure (beam dynamics or equipment), the beams will be extracted towards the dumps and nowhere else. Similarly, the e.m. energy stored in the magnets should be safely evacuated to the loads.

• For any possible event leading to a particle loss, the system must guarantee that the lost particles will be stopped by the collimation system (almost an infinity of possible scenarios).

Illustration: The injection

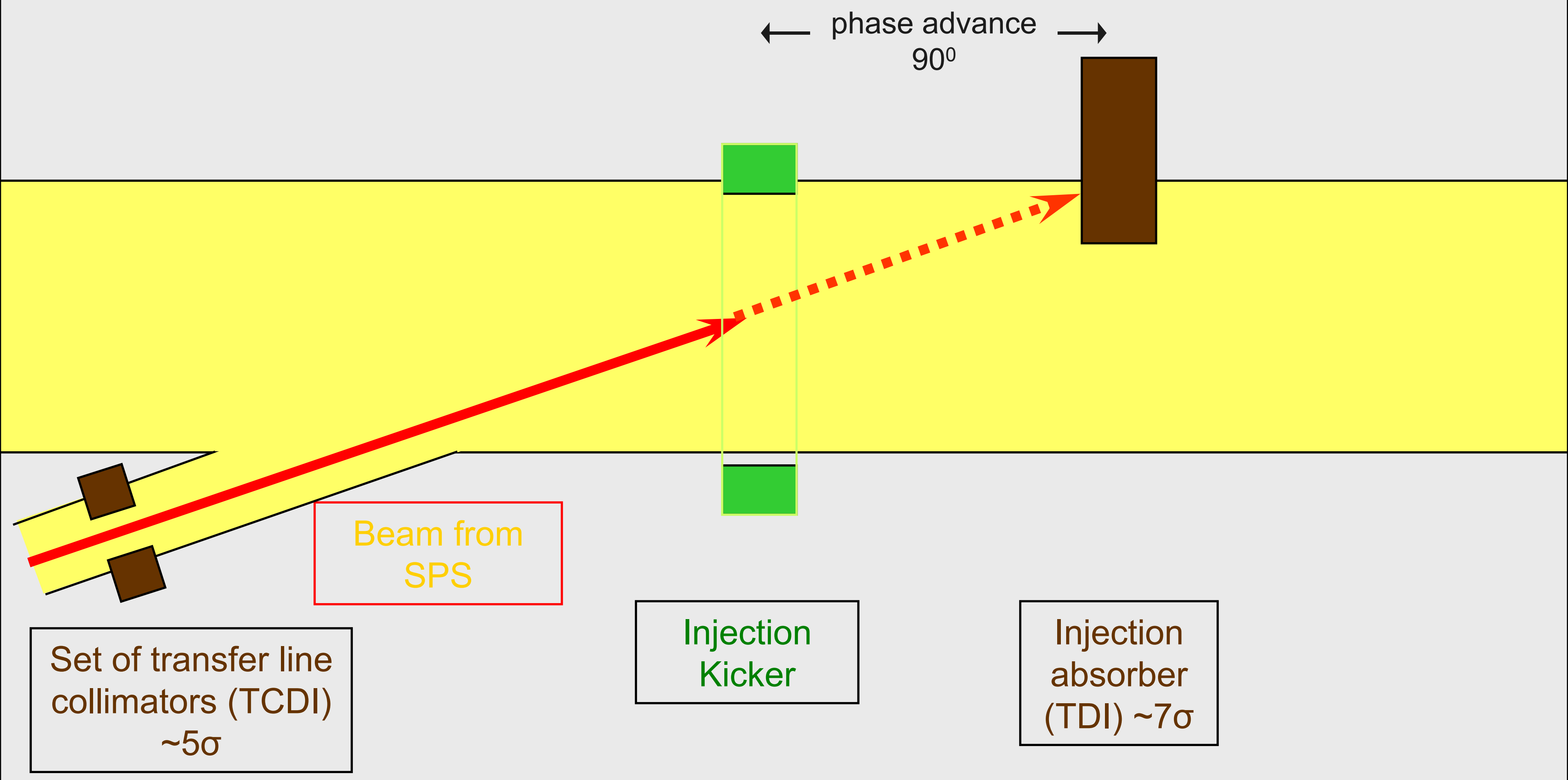


	Top energy/GeV	Circumference/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

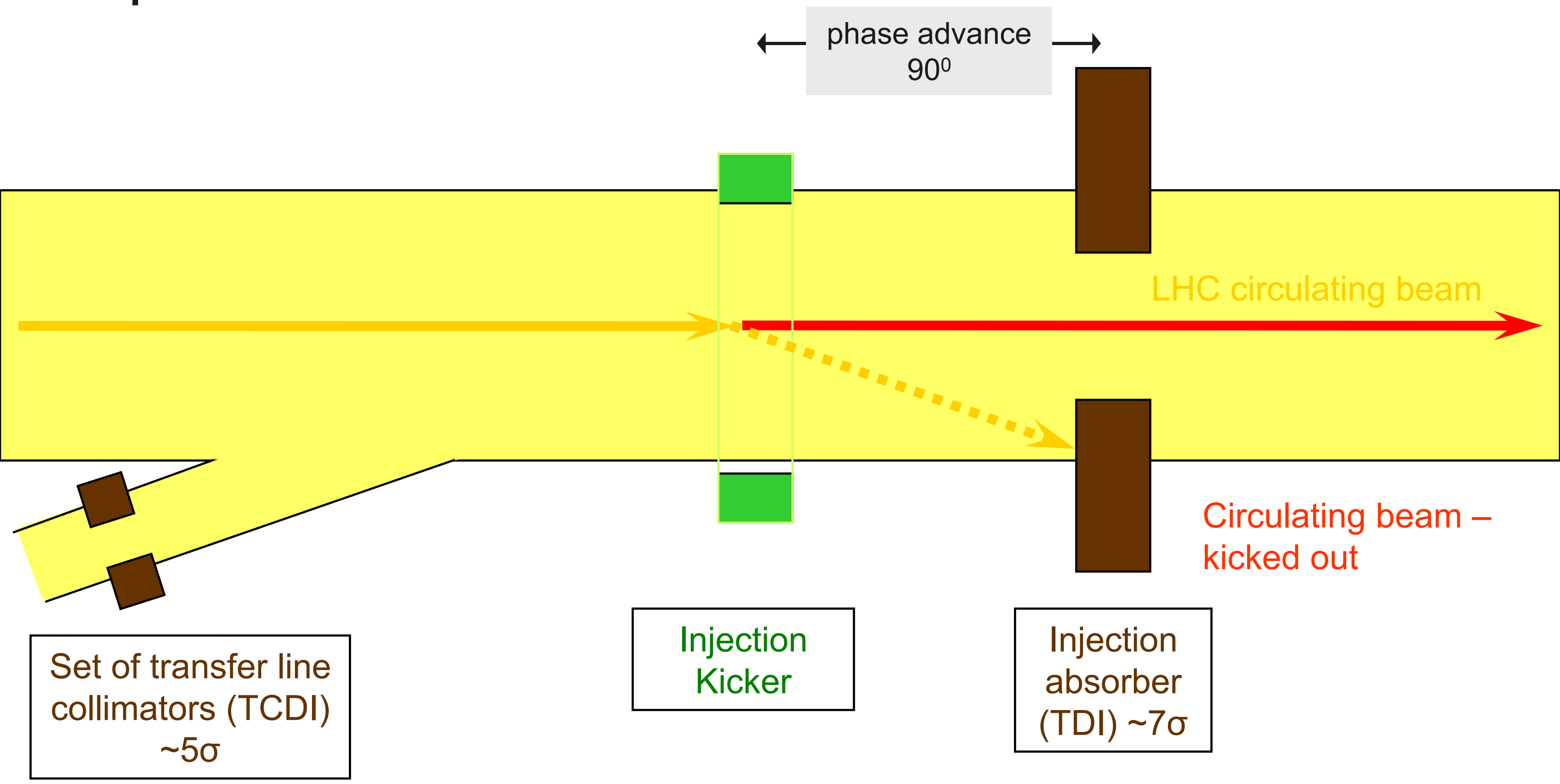
Note the energy gain/machine of 10 to 20 - and not more !
The gain is typical for the useful range of magnets !!!

48

Protection at injection



Protection at injection



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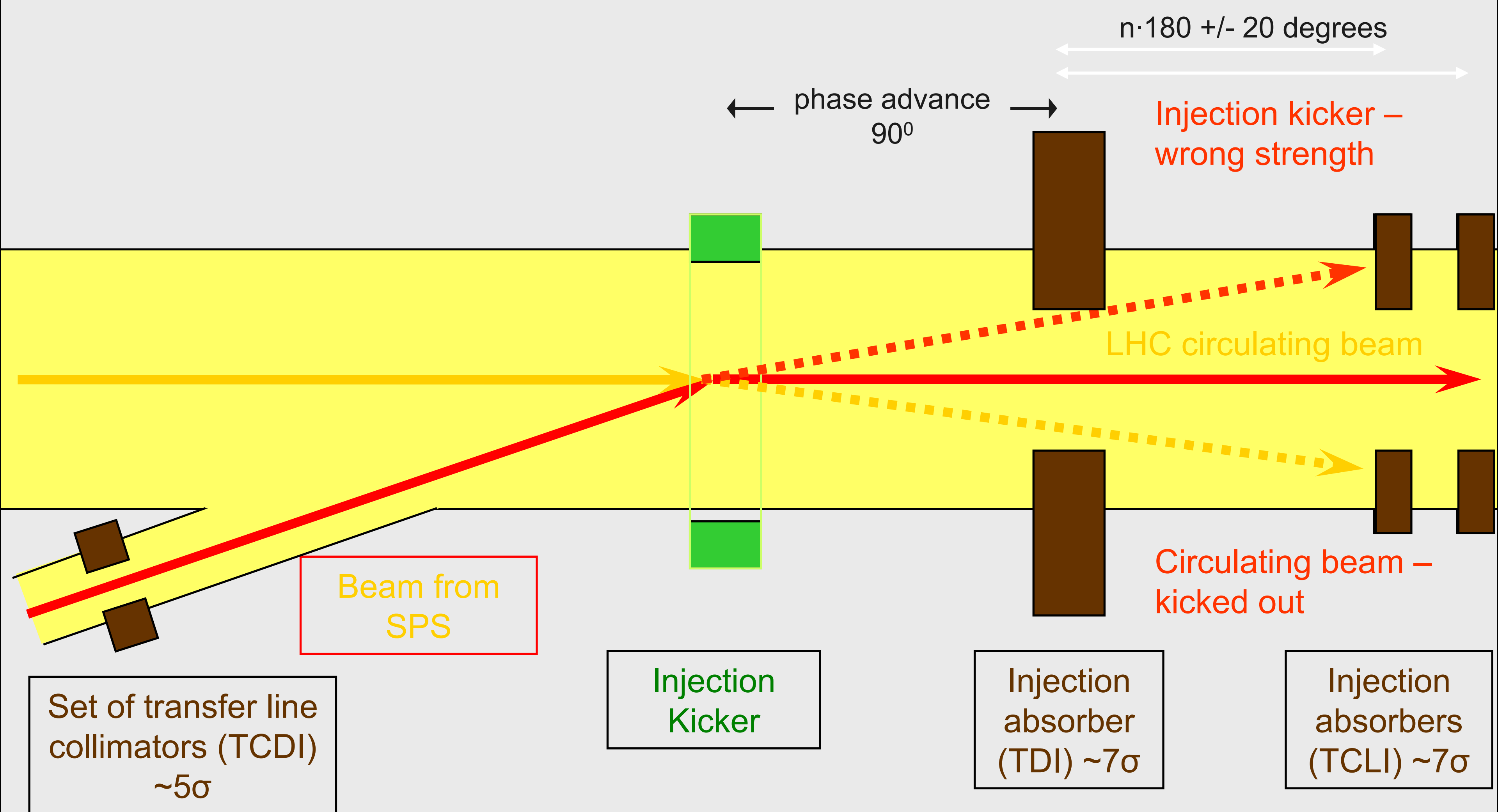
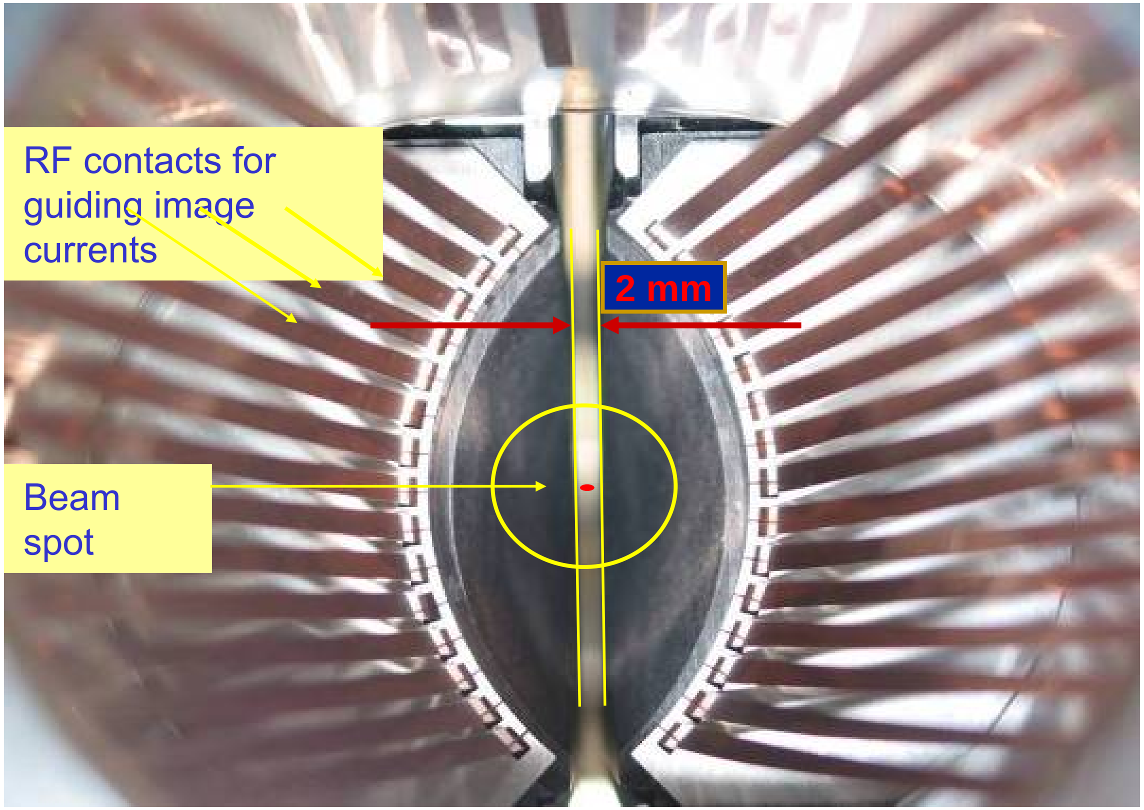


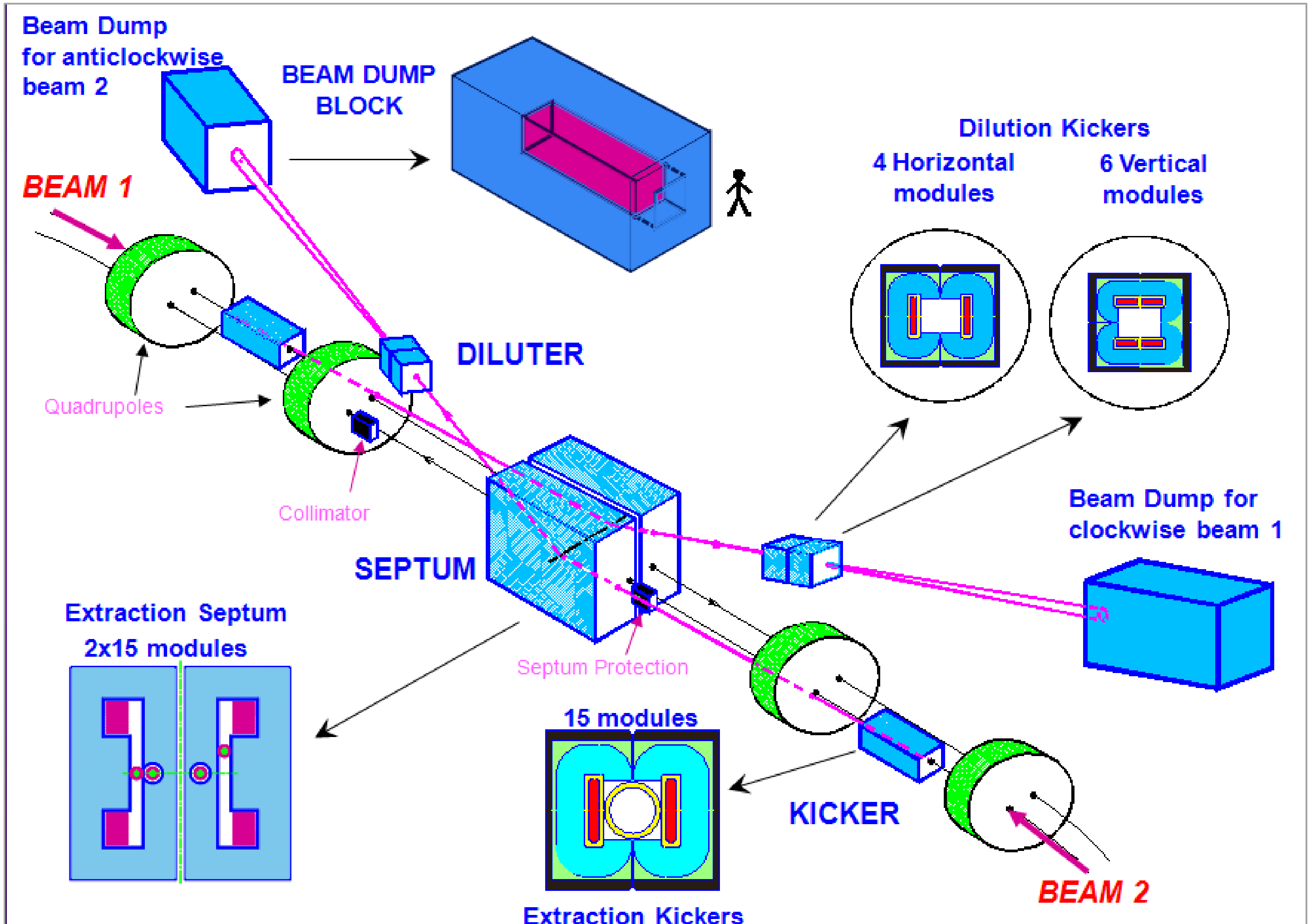
The collimators



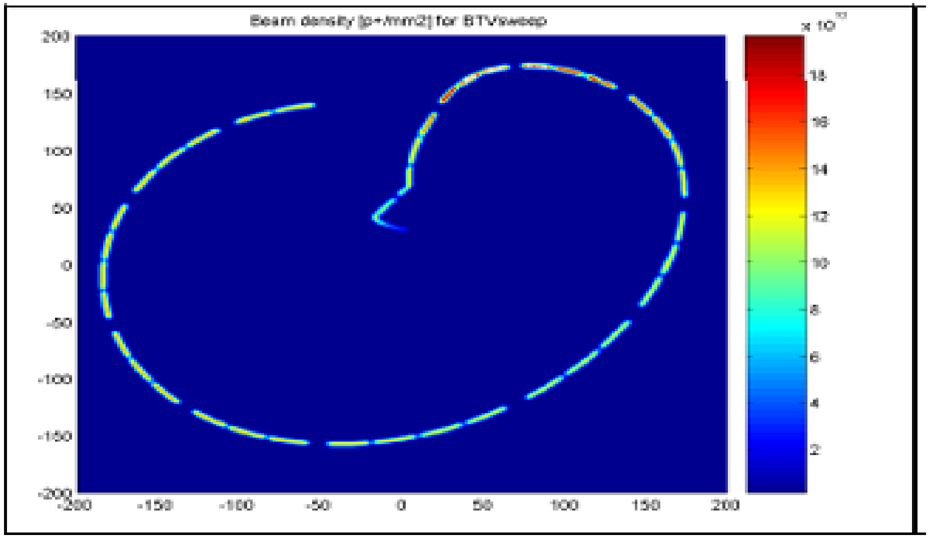
Required efficiency: robust material (Graphit) and very near to the beam

➔ not ideal for the impedance of the machine, i.e. I_{max} !

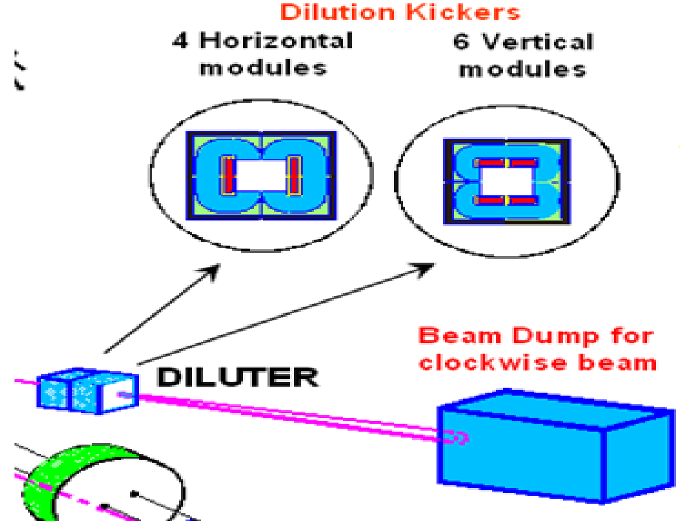
The Beam Dump



The Diluters



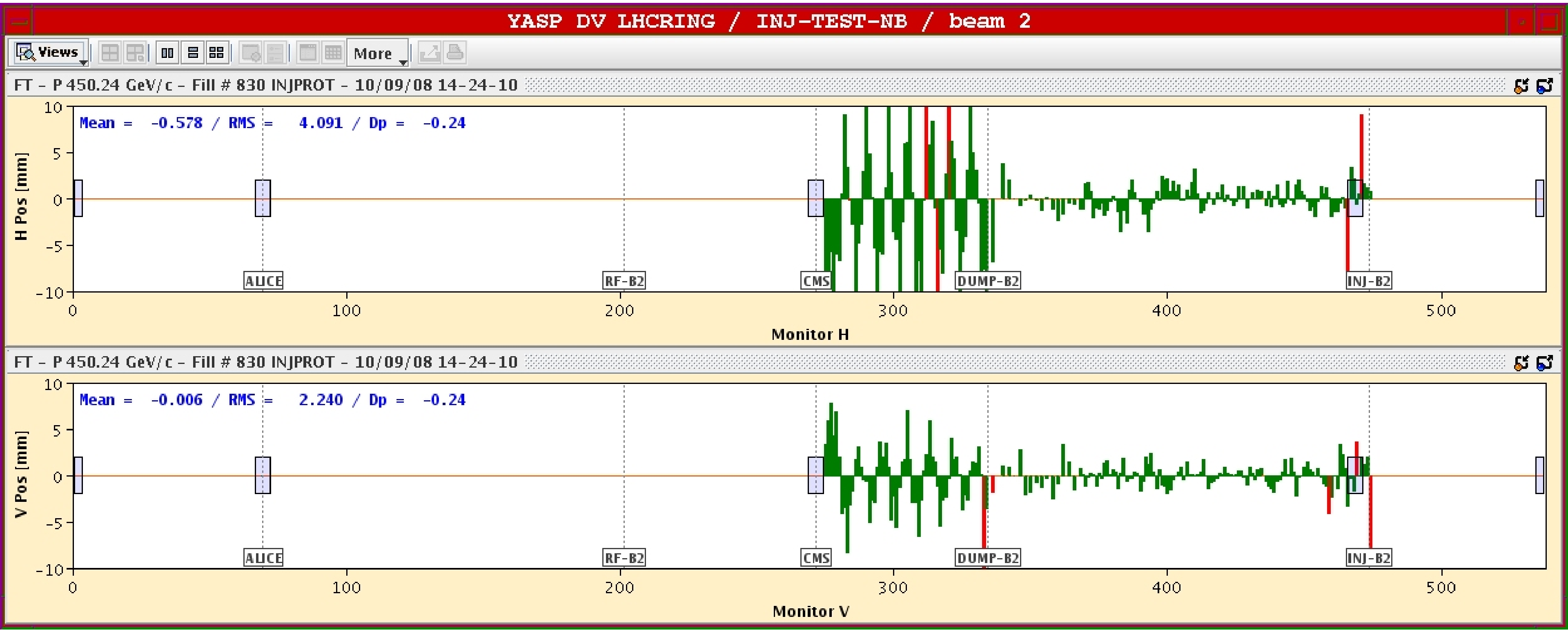
Nominal



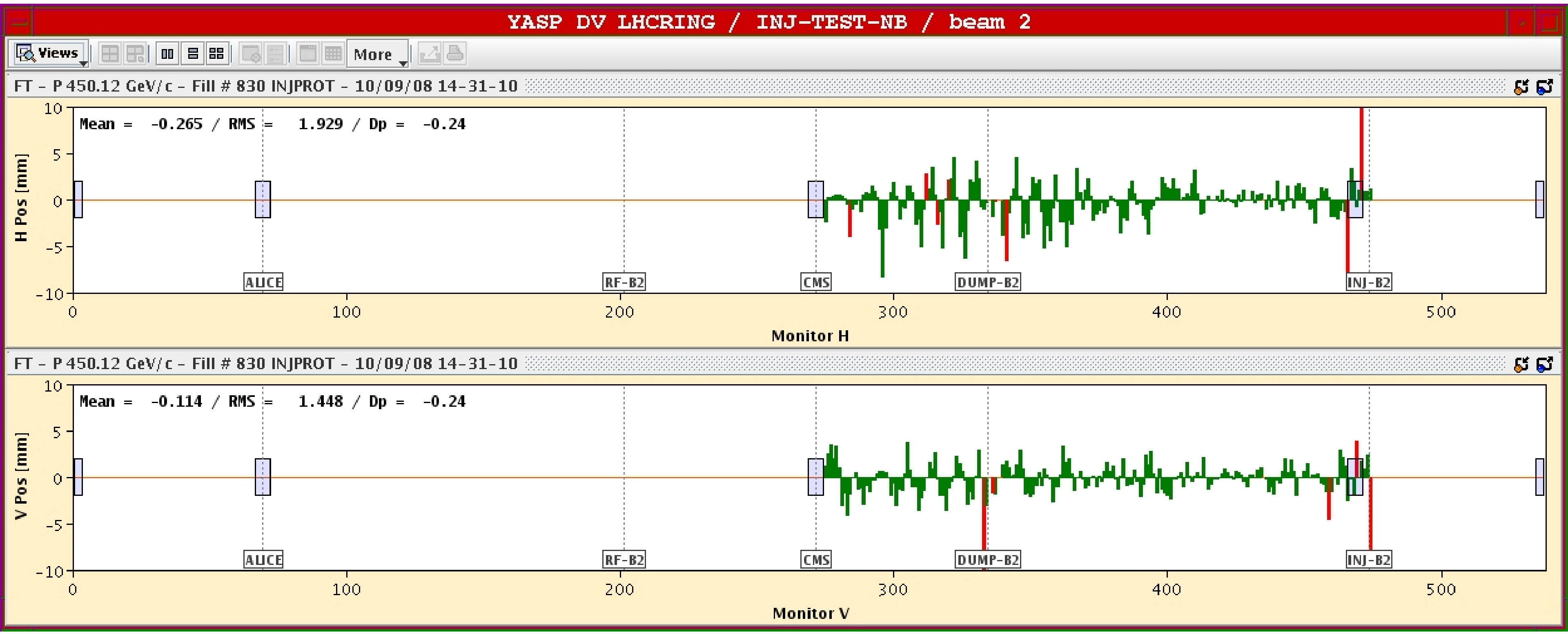
Beam pattern at beam dump absorber. The dilution kickers “paint” the beam across the dump block to reduce the incident intensity.

First experiences with beam in the LHC

September 10th 2008

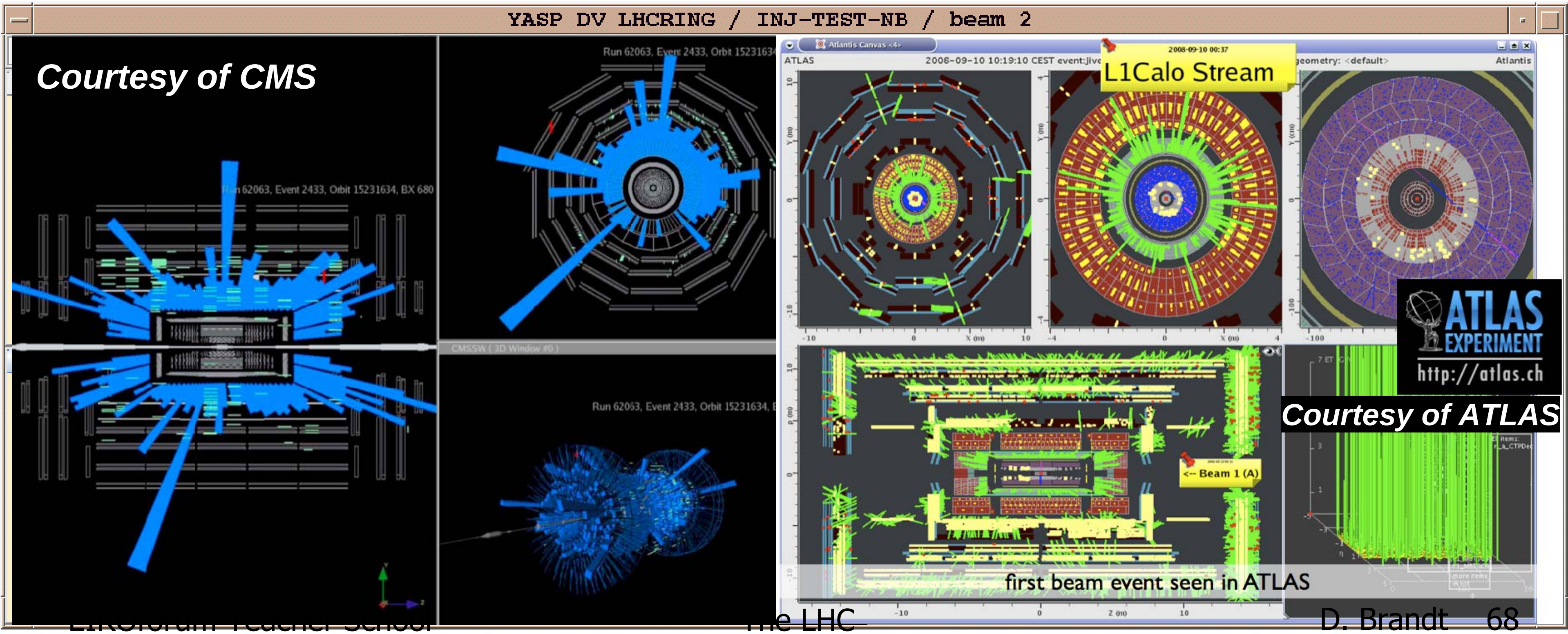


September 10th 2008

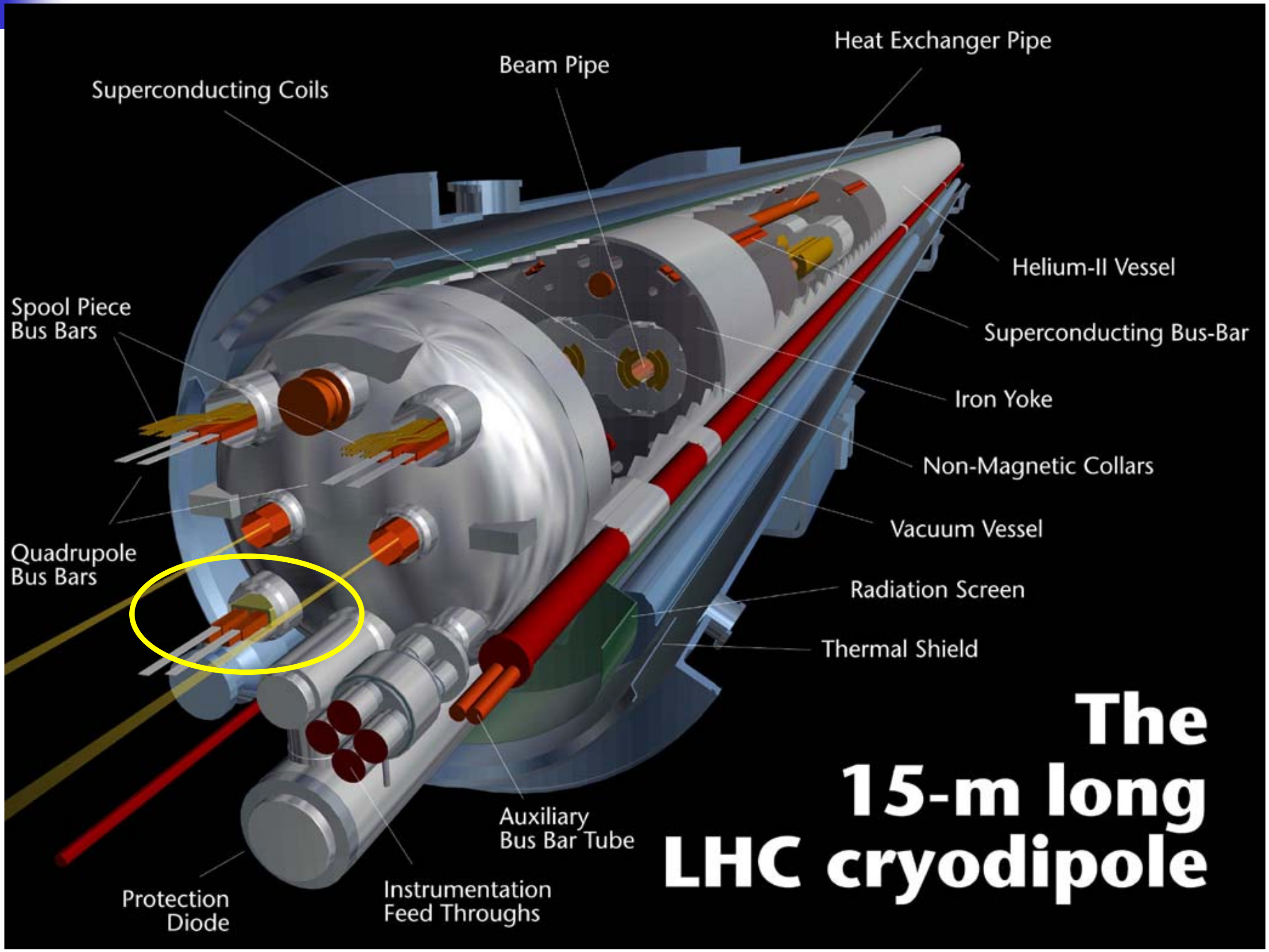


September 10th 2008: First beam

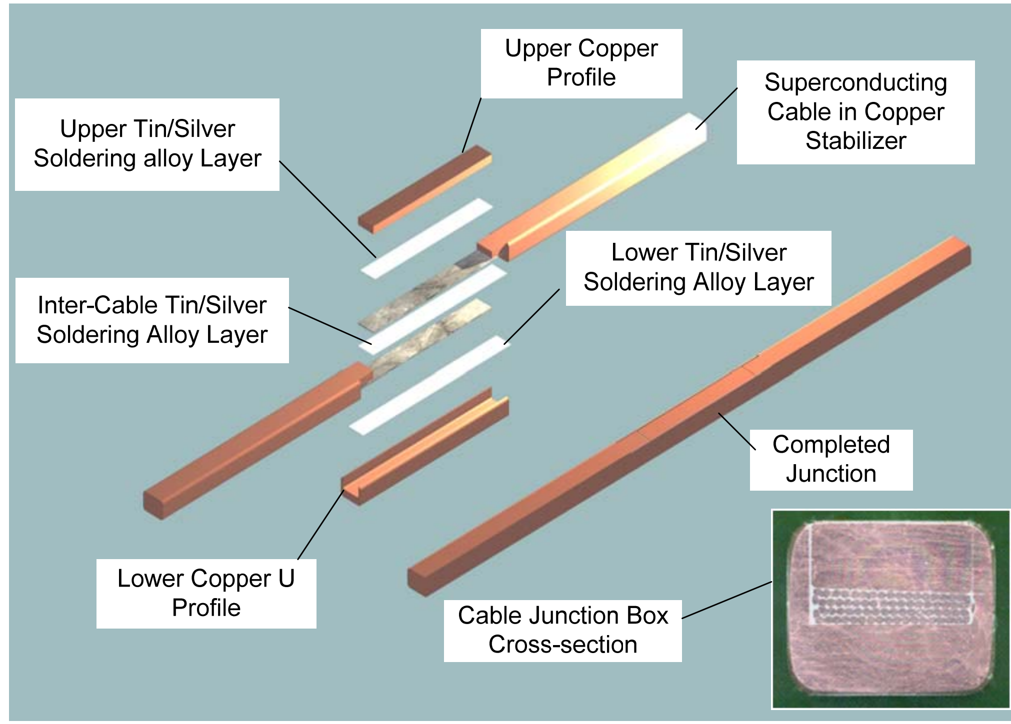
Courtesy: H. Schmickler and J. Wenninger - CERN



September 19th

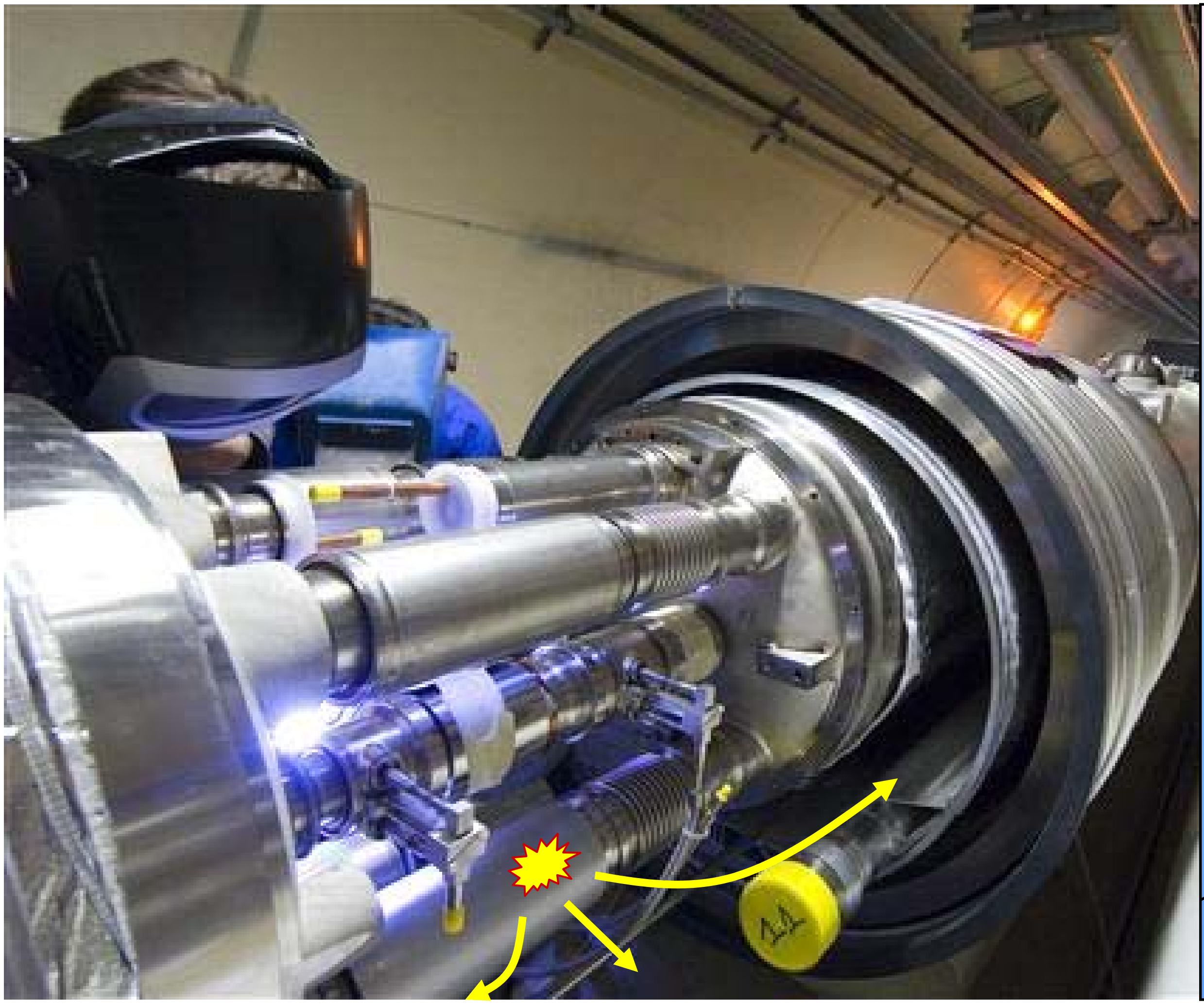


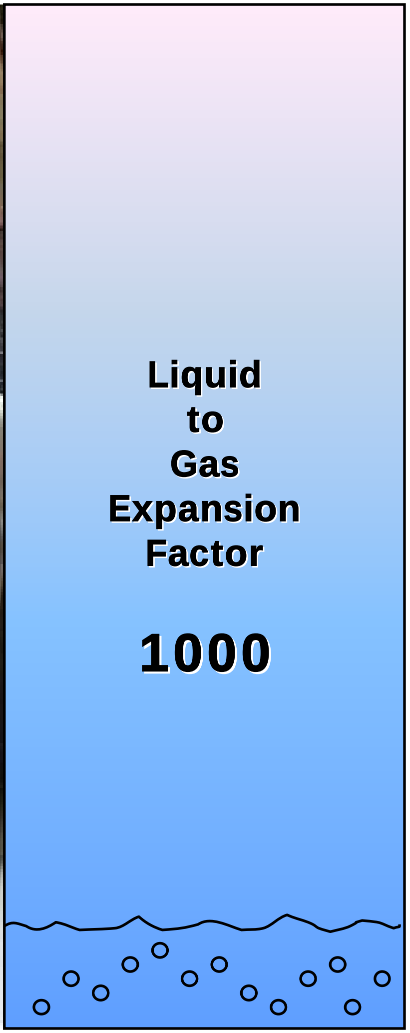
September 19th



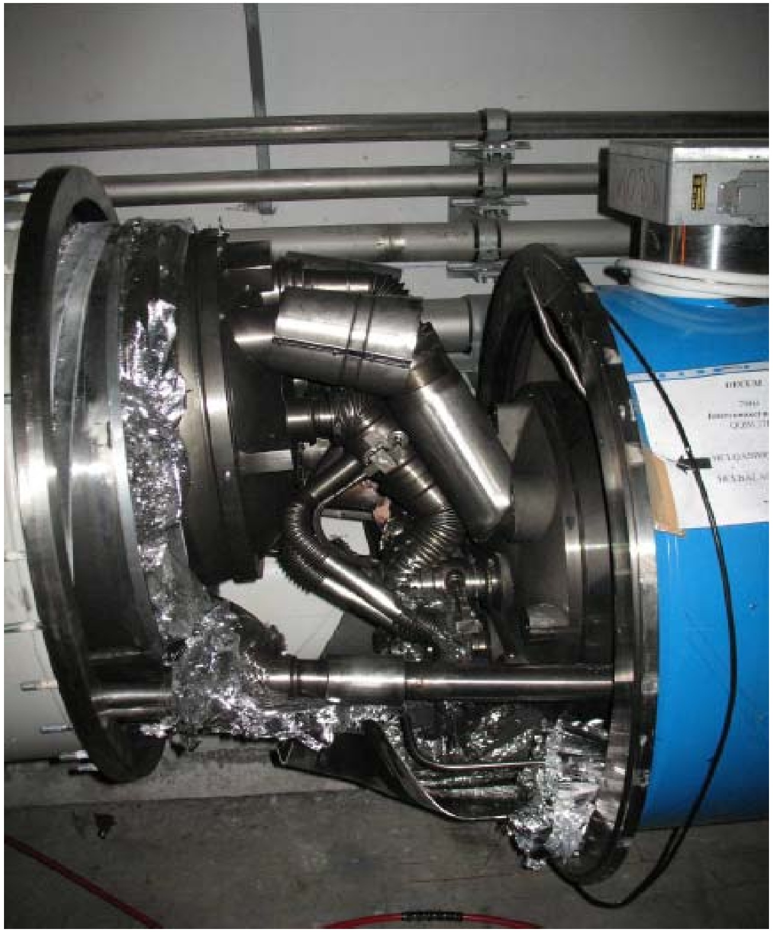
Bad electrical connection at one end of the welding

September 19th (Arc and He release)





September 19th

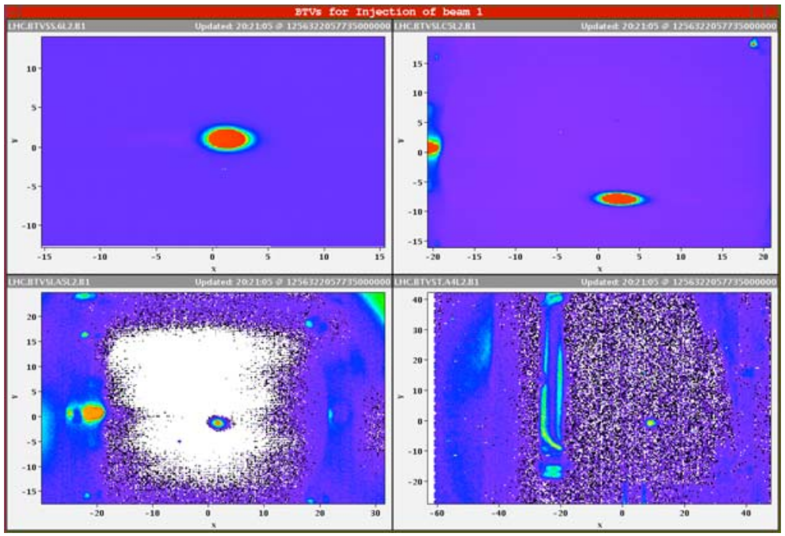


November 2009

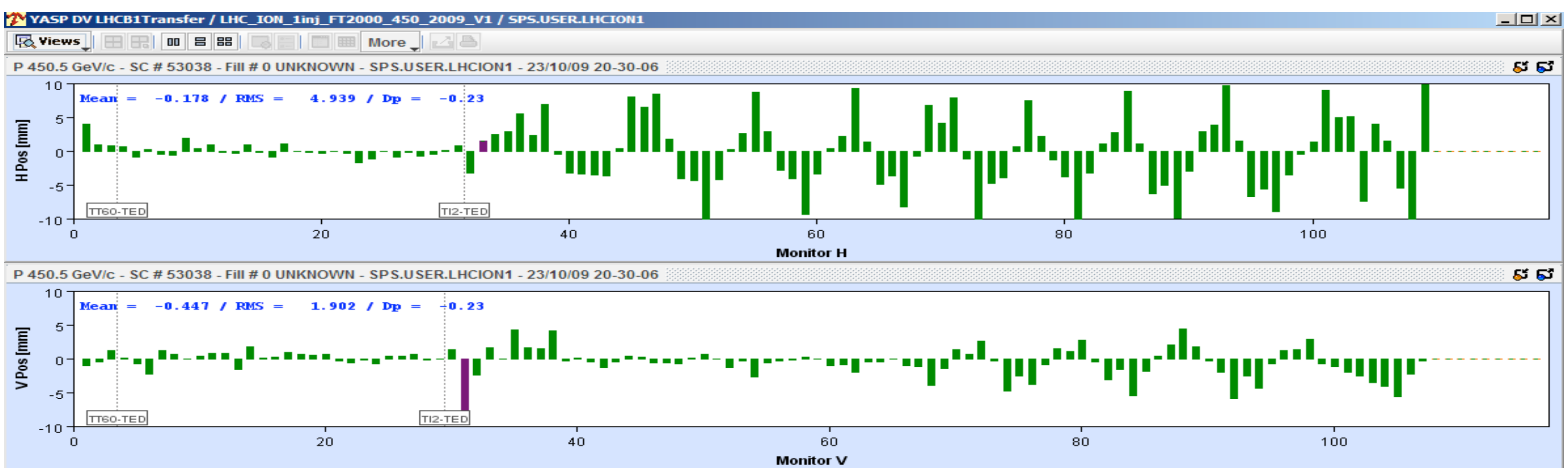
Ready to start again, but taking into account all what we learned from the 2008 incident

➔Slower and safer programme …

First beams in 2009

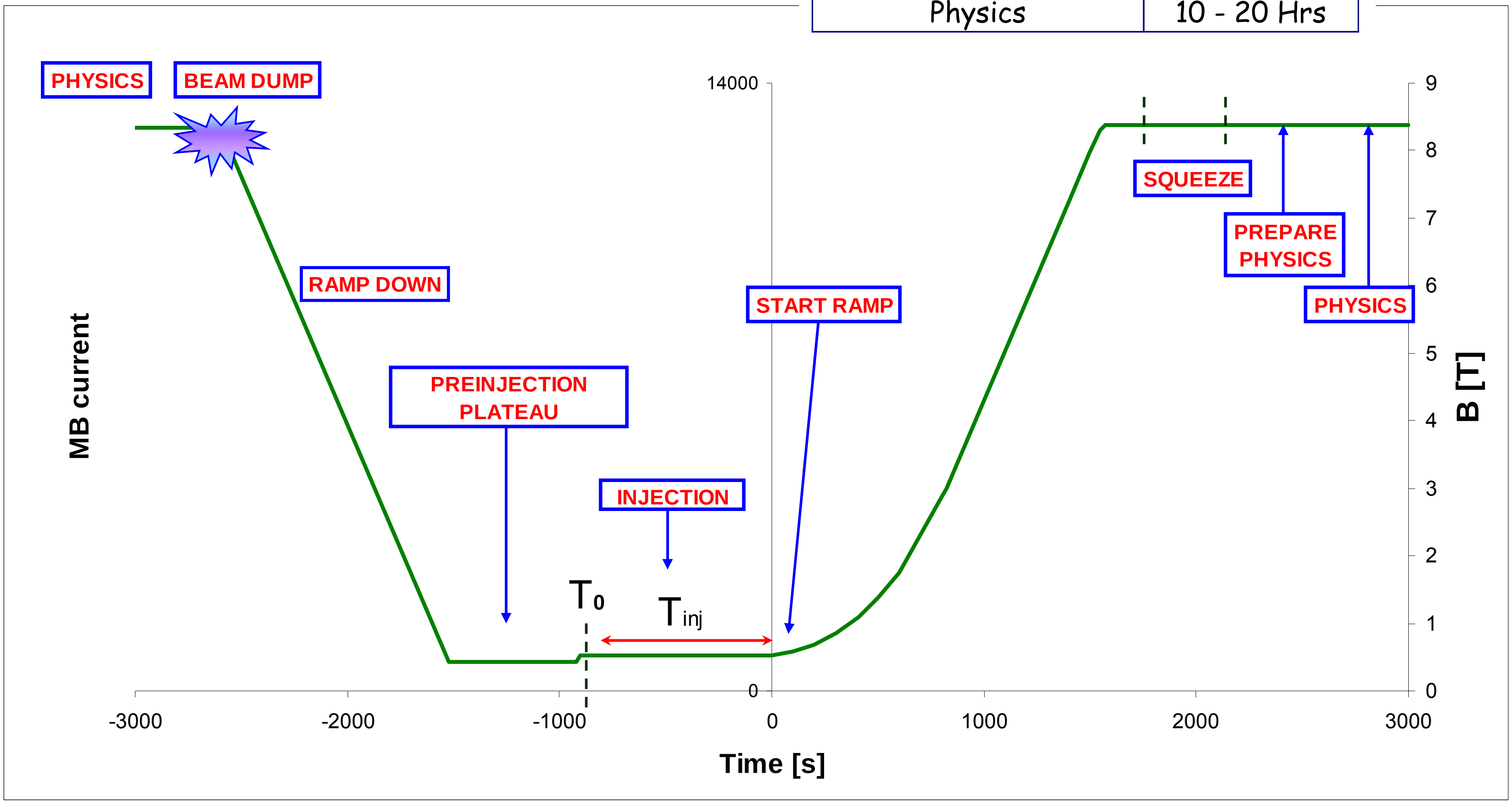


First Lead ions in the LHC



Nominal Cycle

Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs



Programme for 2009

- The Machine Protection System has to be carefully tested
  ➔ low intensities to avoid quenches.

- Experiments would like to calibrate the detectors:

  1 collision per turn
  1 bunch going through without collision

➔ We will start with 2 x 2 bunches in the machine.

- Collisions at 450 GeV

- Commission the ramp to 1.1 TeV

- Collisions at 1.1 TeV (2 x 2)

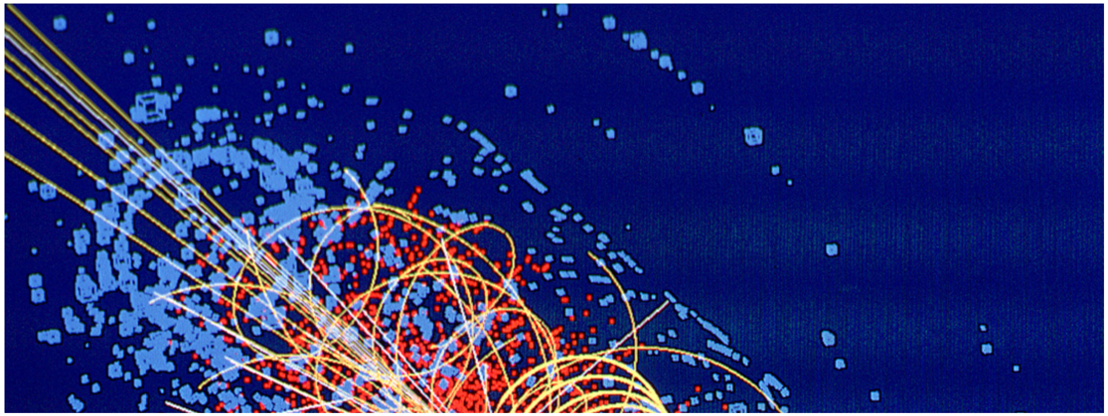
Programme for 2010

- Commission the ramp to 3.5 TeV
- Collisions at 3.5 TeV
- Increase number of bunches to 43, 156, …
- Introduce crossing angle
- Introduce beta-squeeze
- Increase intensity

In Summary:

A lot of challenging and fascinating things to do …

By the time of your next visit…



Thank you very much for your attention !