The LHC Machine

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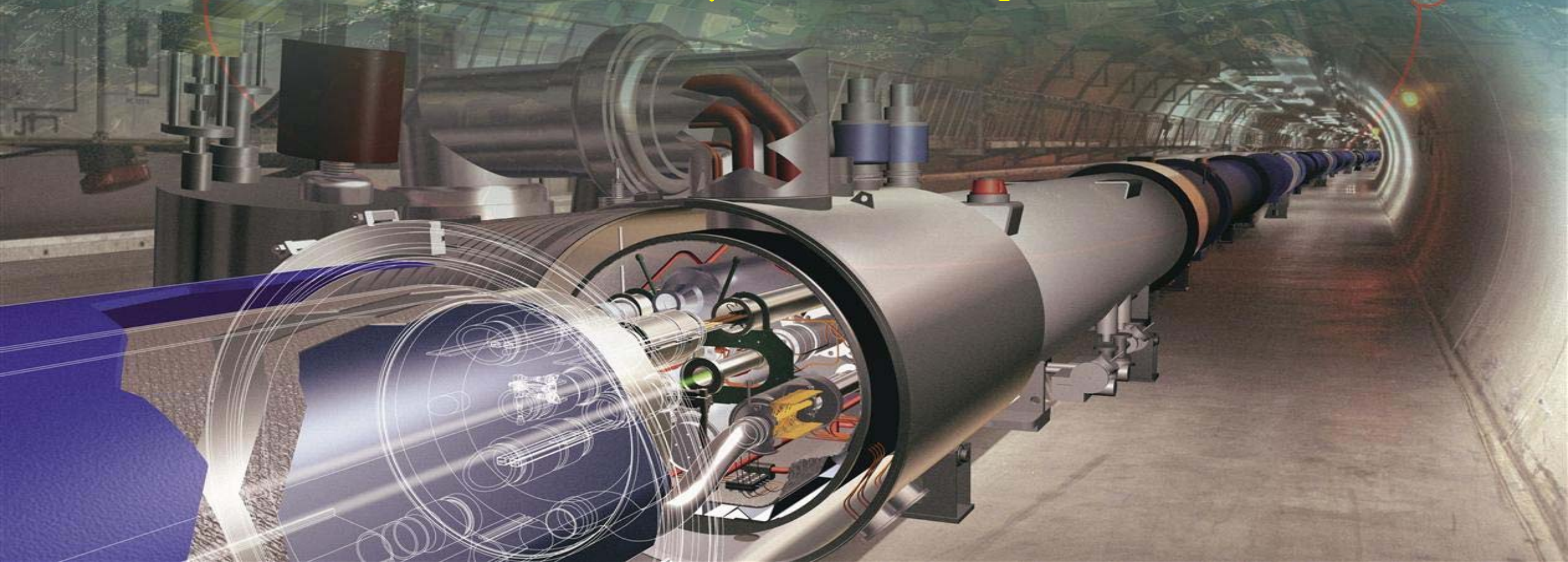
Hadron Collider Summer School - June 2009

Part 1:

- Introduction to acc. physics
- LHC magnet and layout
- Luminosity and inter. Regions



Outline

- The LHC challenges
- Introduction to magnets and particle focusing
- LHC magnets and arc layout
- LHC luminosity and interaction regions

$\}$ Part 1

- Machine protection
- Incident 19th Sept. 2008
- LHC commissioning and operation

$\}$ Part 2

LHC History

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider (SppbarS)

1989 : Start of LEP operation (Z/W boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of LHC installation

2005 : Start of LHC hardware commissioning

2008 : Start of (short) beam commissioning

Powering incident on 19th Sept.

2009 : Repair, re-commissioning and beam commissioning

7 years of construction to replace :

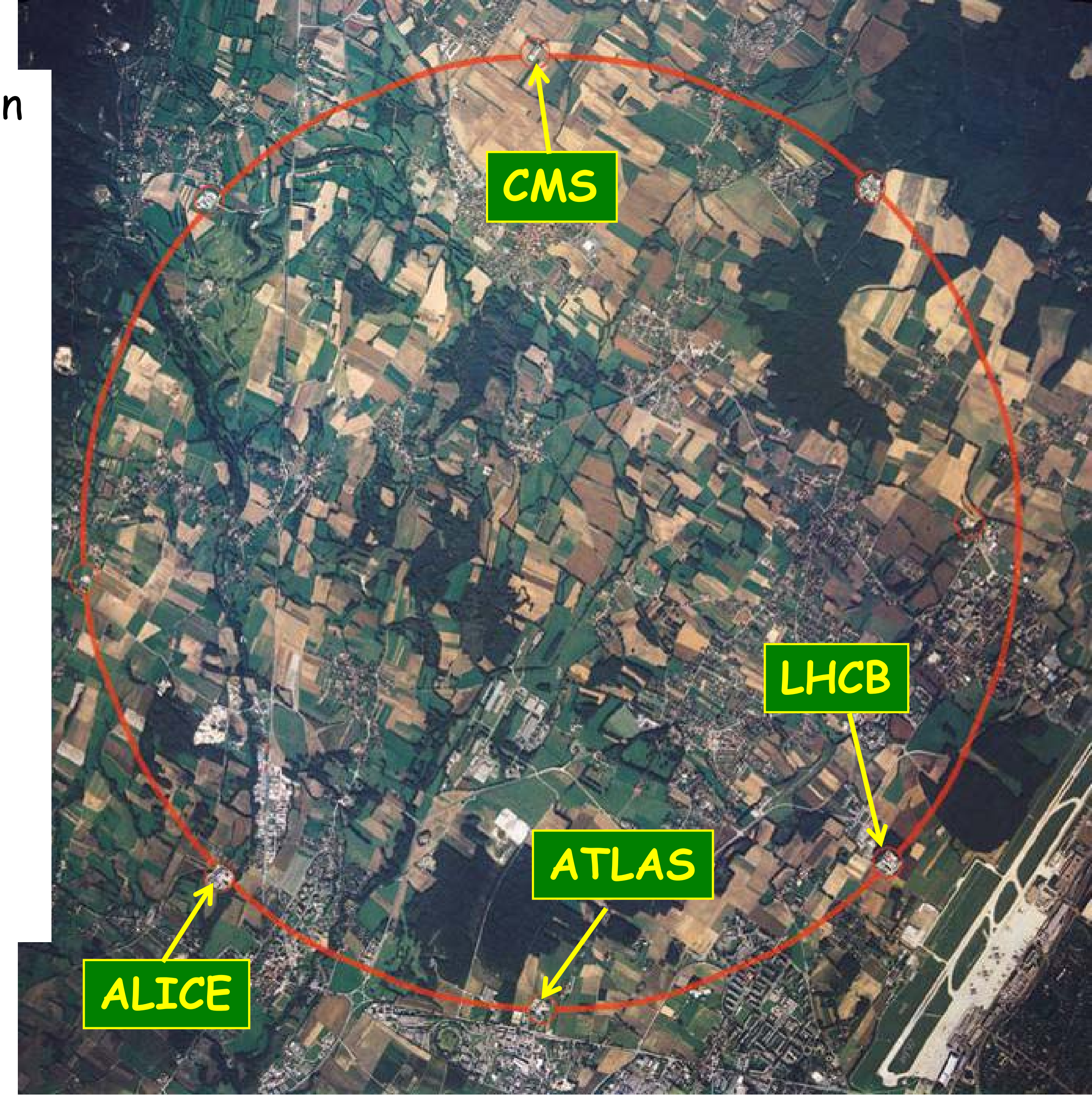
LEP: 1989-2000

- e+e- collider
- 4 experiments
- max. energy 104 GeV
- circumference 26.7 km

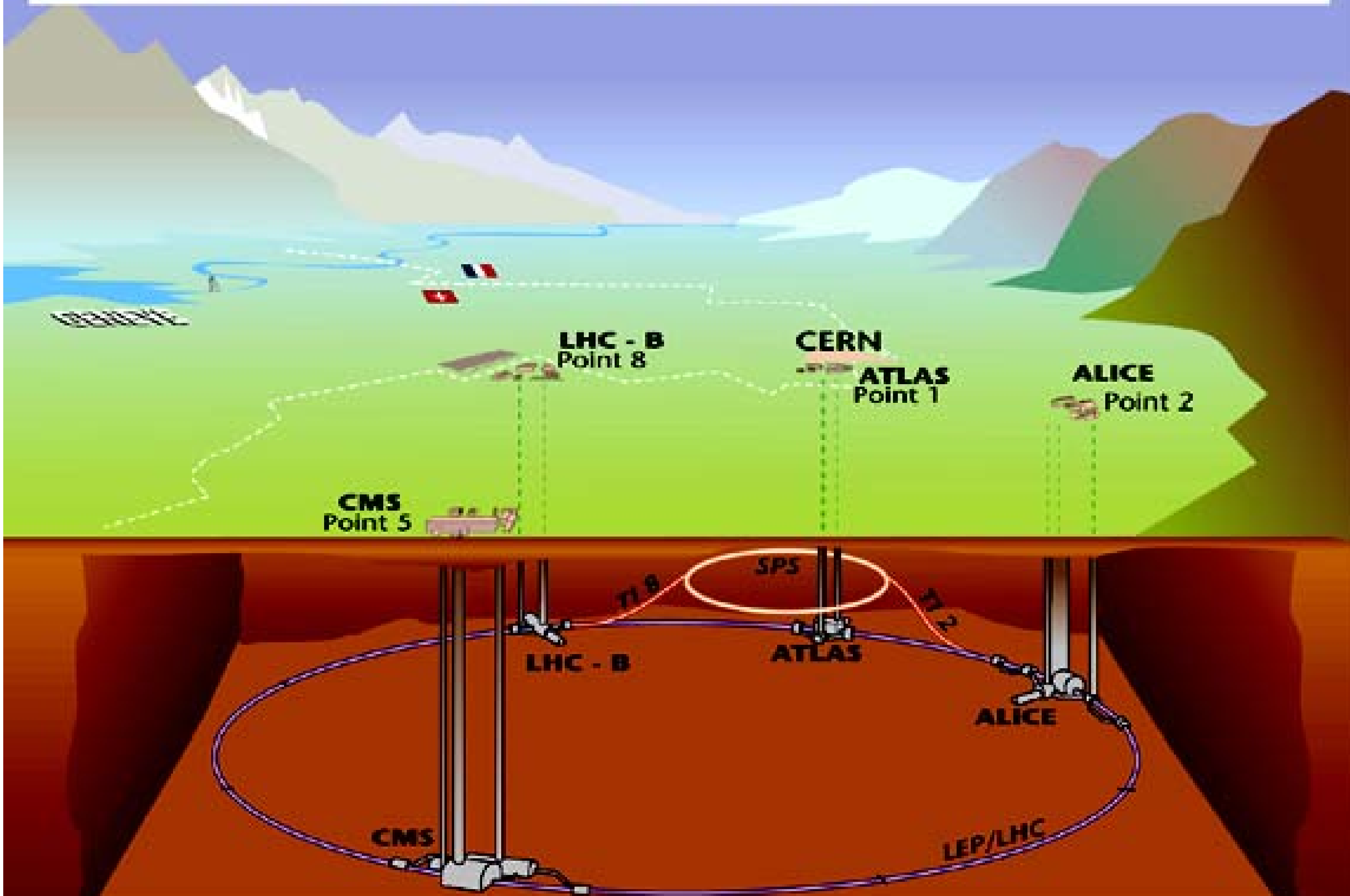
in the same tunnel by

LHC : 2008-2020+

- proton-proton & ion-ion collider in the LEP tunnel
- 4+ experiments
- energy 7 TeV



Overall view of the LHC experiments.



Tunnel circumference 26.7 km, tunnel diameter 3.8 m
Depth : ~ 70-140 m – tunnel is inclined by ~ 1.4%

LHC – yet another collider?

The LHC surpasses existing accelerators/colliders in 2 aspects :

- The energy of the beam of 7 TeV that is achieved within the size constraints of the existing 26.7 km LEP tunnel.

LHC dipole field	8.3 T
HERA/Tevatron	~ 4 T

A factor 2 in field

A factor 4 in size

- The luminosity of the collider that will reach unprecedented values for a hadron machine:

LHC	pp	~ 10^{34} cm^{-2} s^{-1}
Tevatron	$p\bar{p}$	3×10^{32} cm^{-2} s^{-1}
SppbarS	$p\bar{p}$	6×10^{30} cm^{-2} s^{-1}

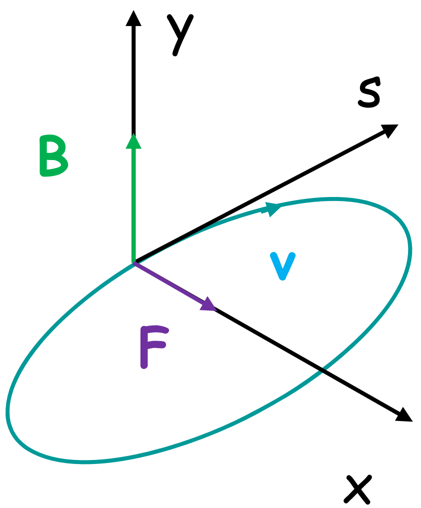
A factor 30 in luminosity

The combination of very high field magnets and very high beam intensities required to reach the luminosity targets makes operation of the LHC a great challenge !

Field challenges

The force on a charged particle is given by the Lorentz force which is proportional to the charge, and to the vector product of velocity and magnetic field:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$



To reach a momentum of 7 TeV/c given the LHC (LEP) bending radius of 2805 m:

- Bending field B = 8.33 Tesla
- Superconducting magnets

$$B = \frac{p}{e_0 \cdot R}$$

To collide two counter-rotating proton beams, the beams must be in separate vaccum chambers (in the bending sections) with opposite B field direction.

→ There are actually <u>**2**</u> LHCs and the magnets have a 2-magnets-in-one design!

Luminosity challenges

The event rate N for a physics process with cross-section σ is proprotional to the collider Luminosity L:

$$N = L\sigma$$

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

k = *number of bunches* = *2808*
N = *no. protons per bunch* = *1.15×10*^{11}
f = *revolution frequency* = *11.25 kHz*
σ^*_x, σ^*_y = *beam sizes at collision point (hor./vert.)* = *16 μm*

To maximize L:

- Many bunches (k)
- Many protons per bunch (N)
- A small beam size $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$

β^* : characterizes the beam envelope (optics), varies along the ring, min. at the collision points.

ε : is the phase space volume occupied by the beam (constant along the ring).

Optics property

Beam property

High beam "brillance" N/ε

(particles per phase space volume)

→ Injector chain performance !

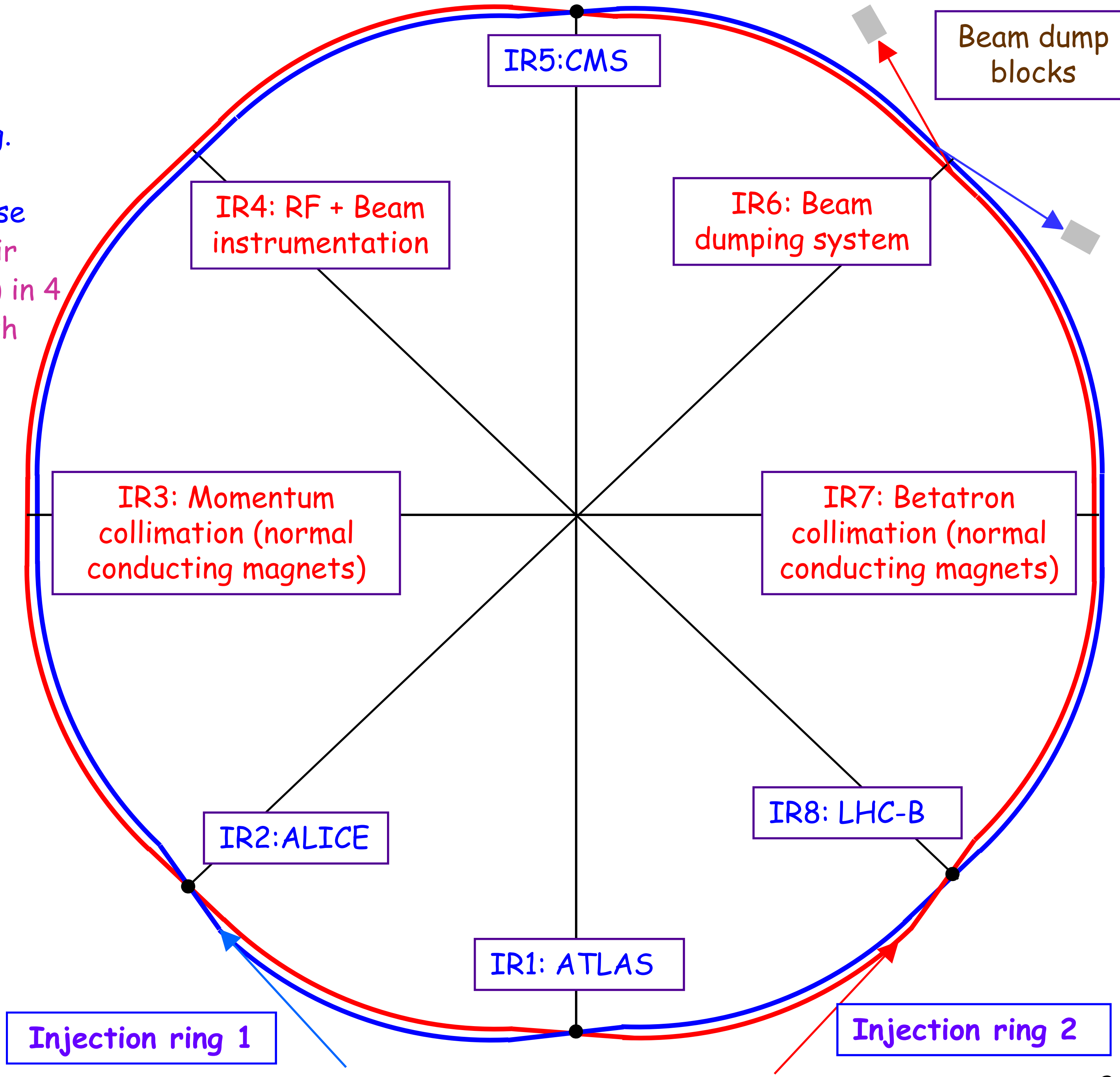
Small envelope

→ Strong focusing !

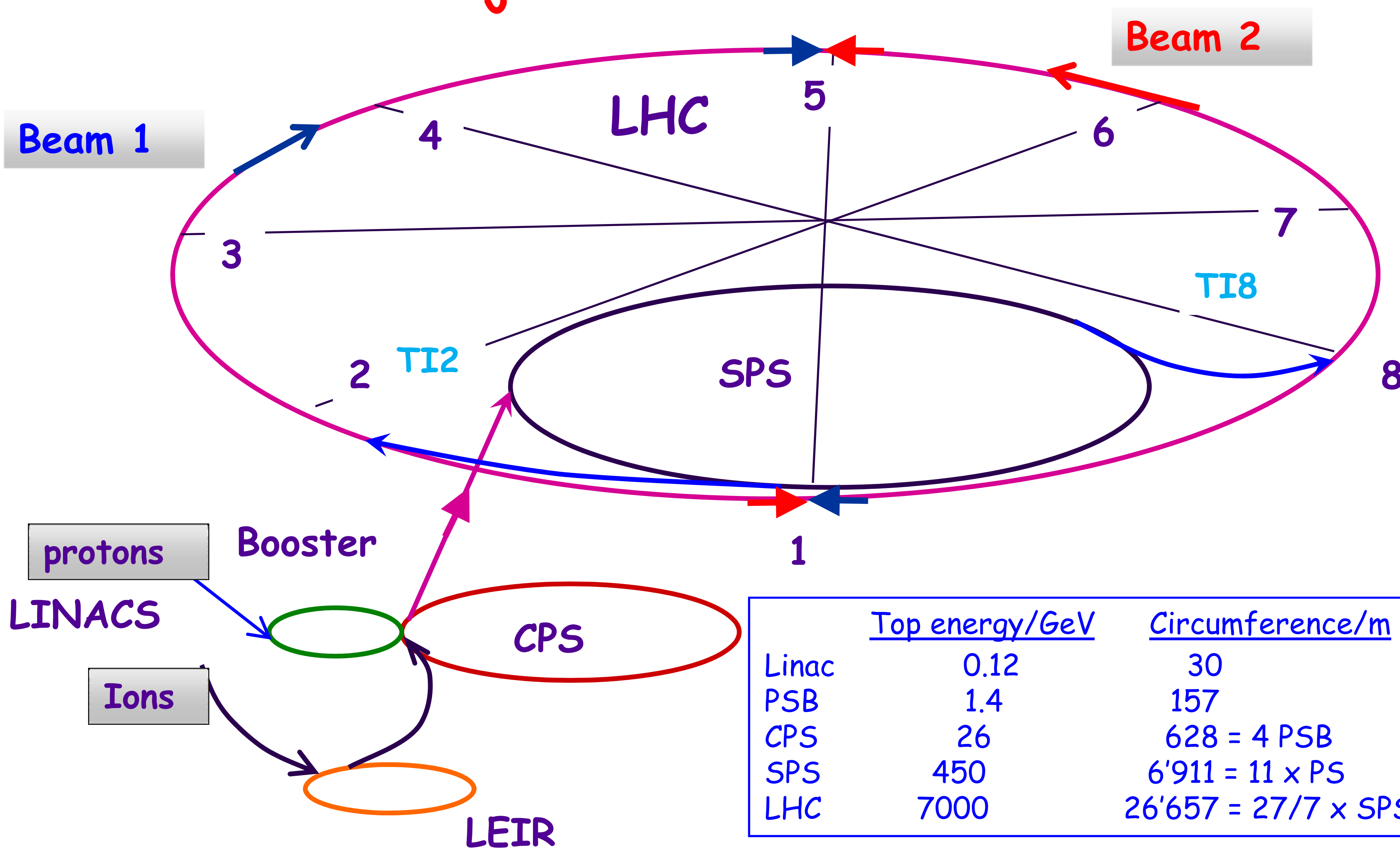
LHC Layout

- 8 arcs.
- 8 long straight sections (insertions), ~ 700 m long.
- beam 1 : clockwise
- beam 2 : counter-clockwise
- The beams exchange their positions (inside/outside) in 4 points to ensure that both rings have the same circumference !

The main dipole magnets define the geometry of the circle !



LHC and its injectors



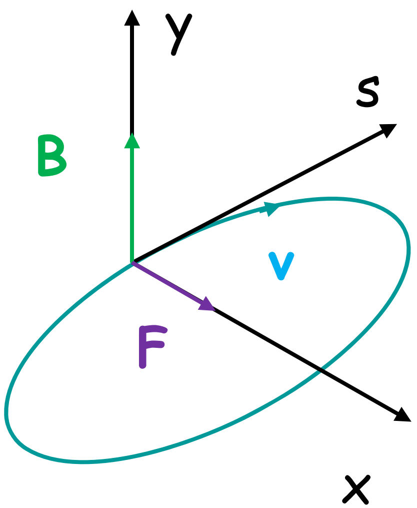
	Top energy/GeV	Circumference/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

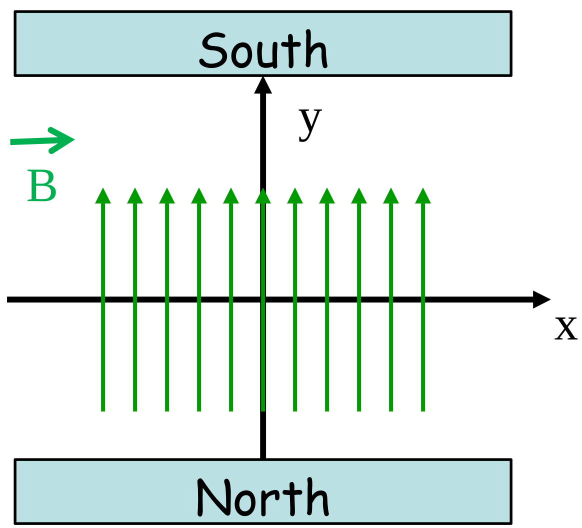
The energy gain/machine of 10 to 20
is typical for the useful range of magnets !!!

Basics of Accelerator Physics

Dipole fields

- Dipole magnets are the simplest accelerator magnets and have 'just' 2 poles.
- Their field is constant across the magnet.
- They are used to bend the beam and define the reference path.
- The dipoles define the beam MOMENTUM !

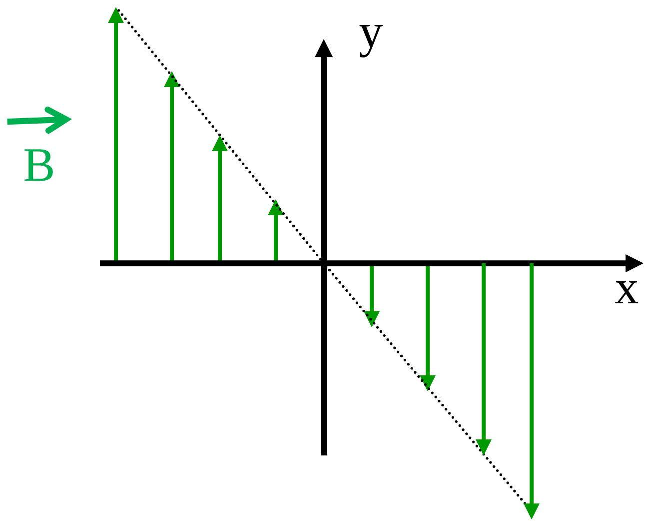


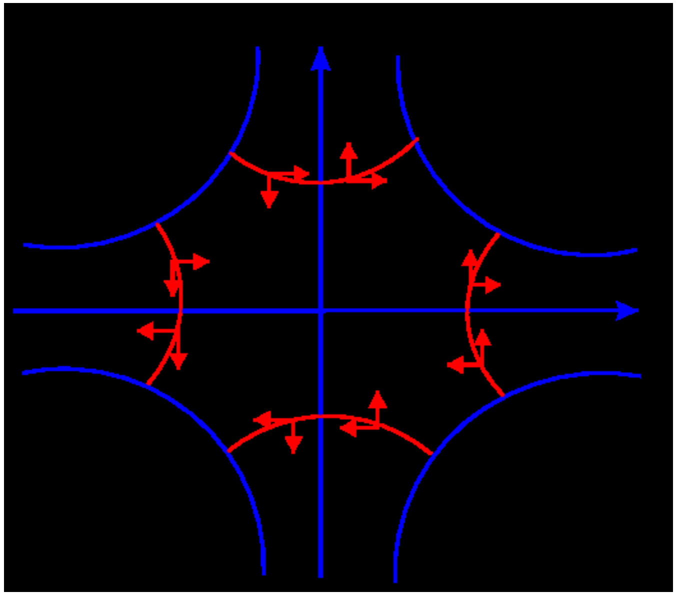


$$B = \frac{p}{e_0 \cdot R}$$

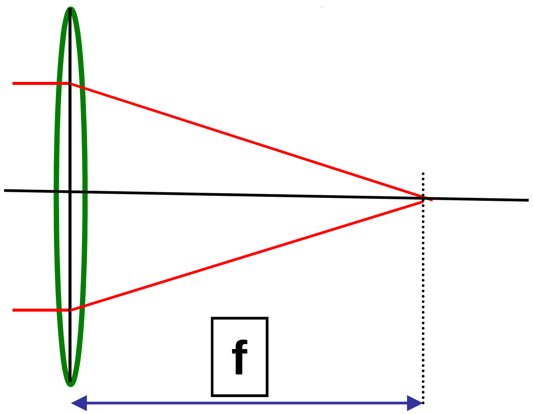
Quadrupolar field - focusing

- A quadrupole magnet has 4 poles, 2 north and 2 south.
- The poles are arranged symmetrically around the axis of the magnet.
- There is no magnetic field along the central axis.
- The field increases linearly with distance to the axis.





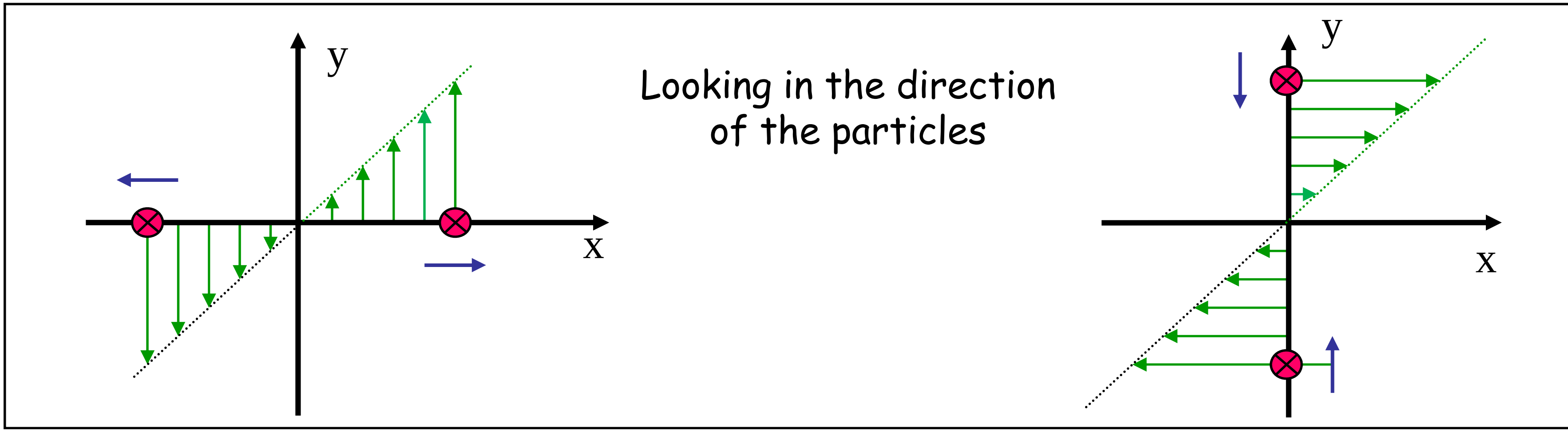
- In a given plane, the quadrupole has the same properties like a classical optical lens.

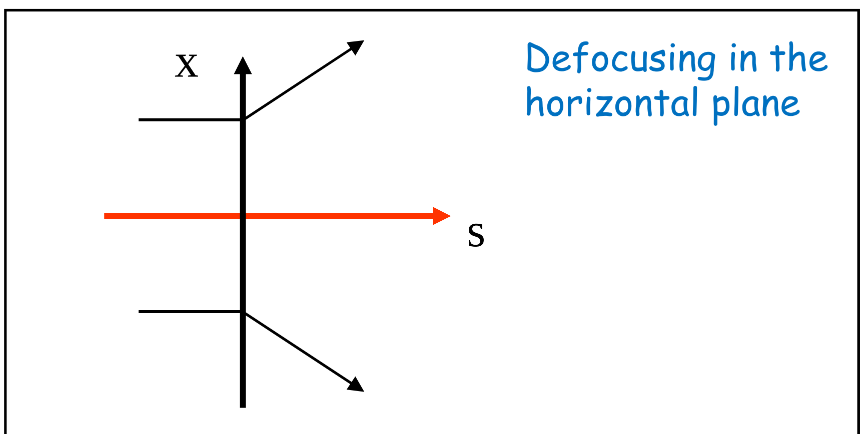


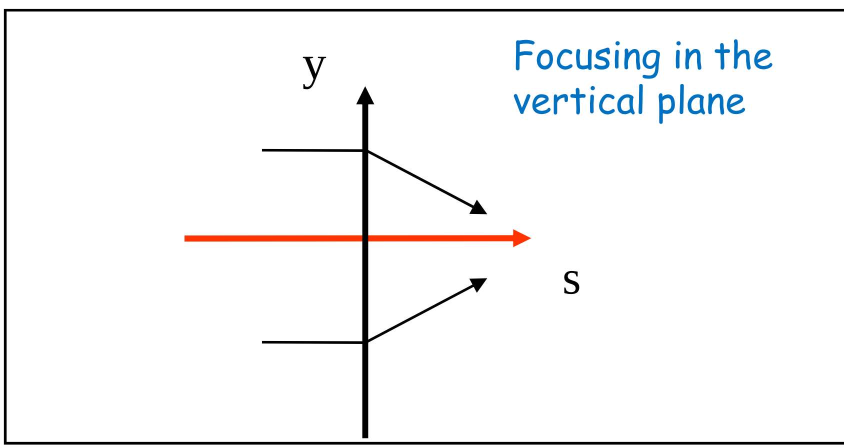
Focusing

But a quadrupole differs from an optical lens :

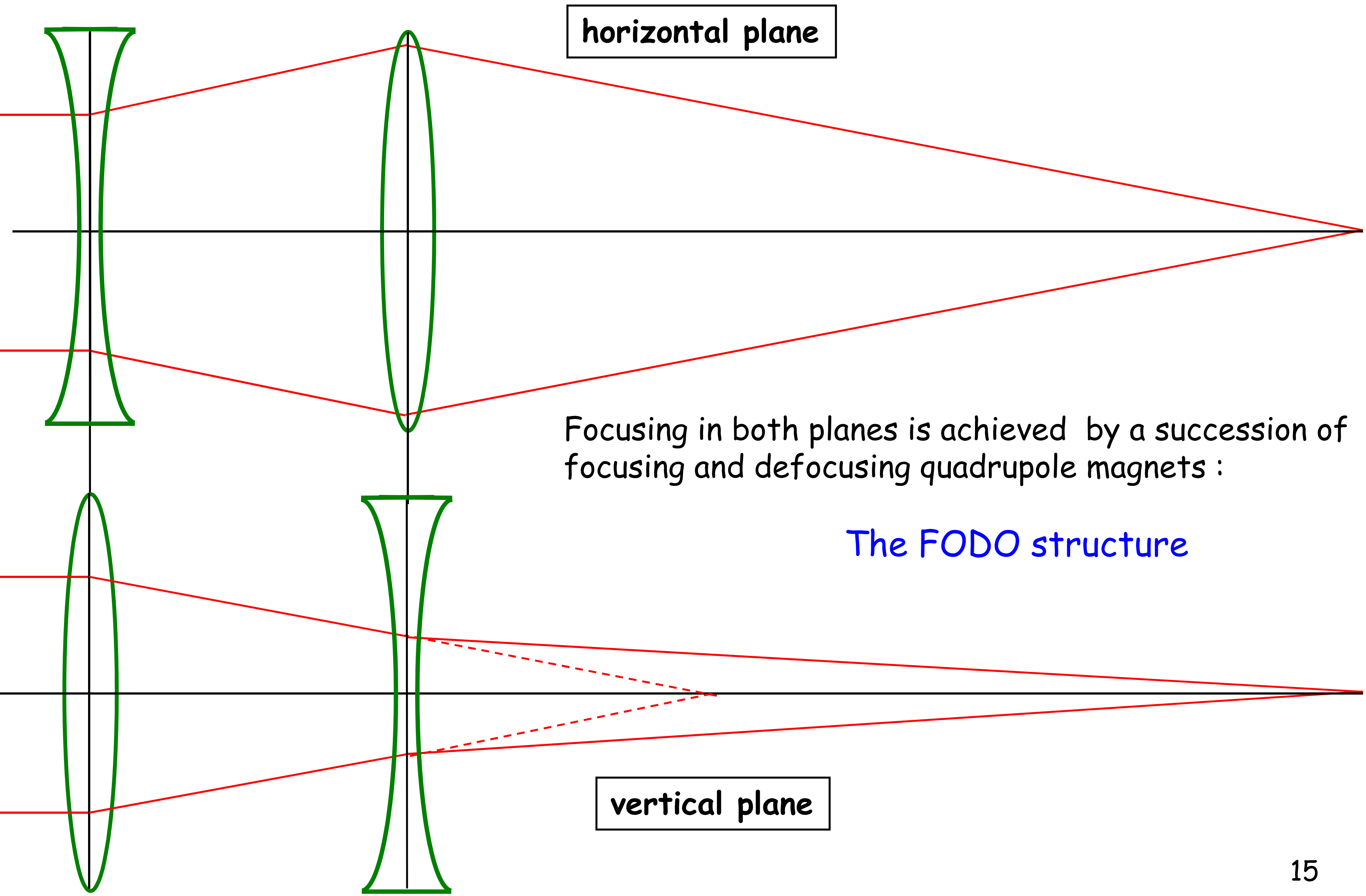
It is focusing in one plane, defocusing in the other !!!







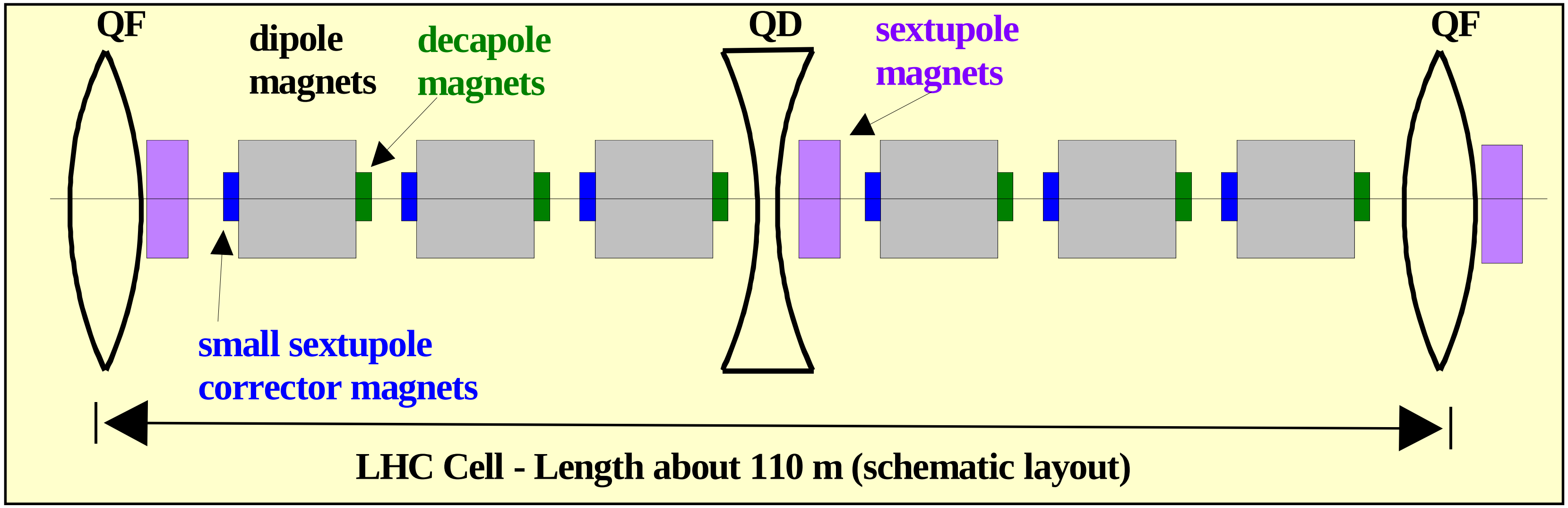
Accelerator lattice



Focusing in both planes is achieved by a succession of focusing and defocusing quadrupole magnets :

The FODO structure

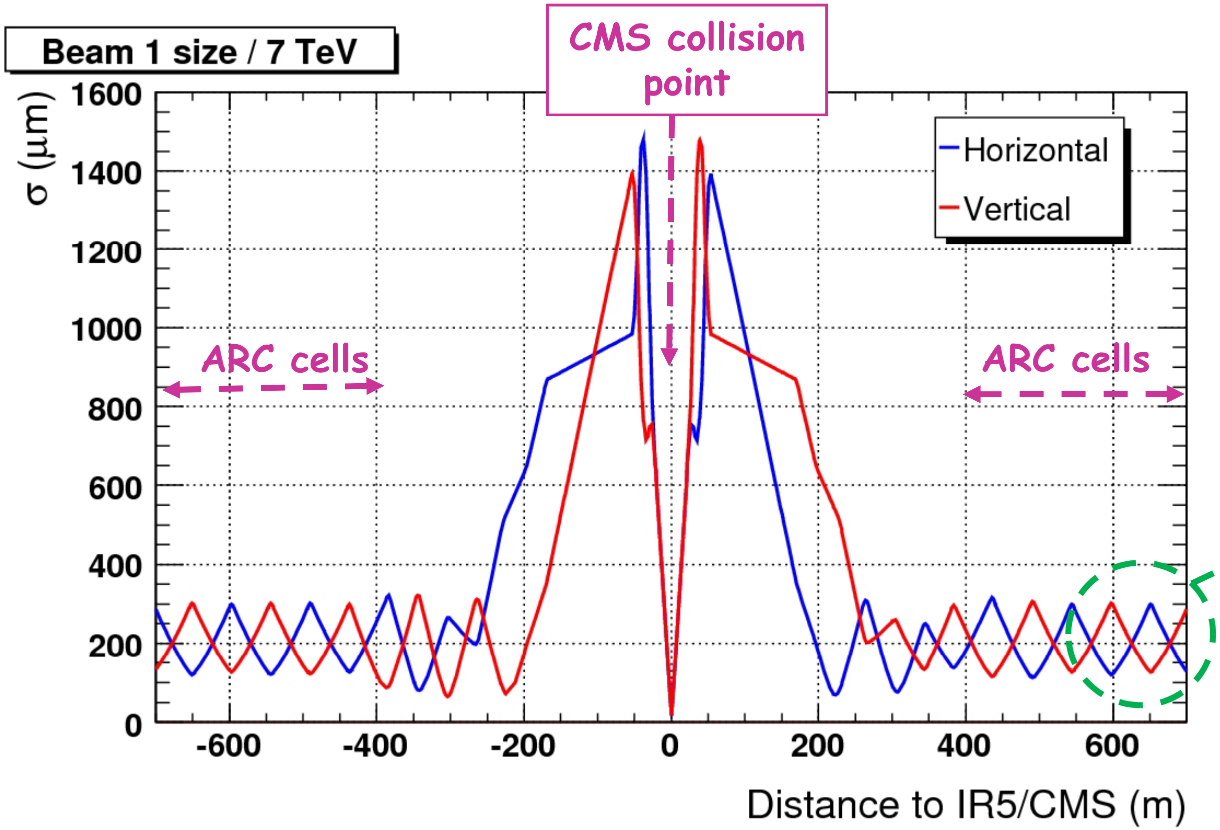
LHC arc lattice



- Dipole- und Quadrupol magnets
  - Provide a stable trajectory for particles with nominal momentum.
- Sextupole magnets
  - Correct the trajectories for off momentum particles (‚chromatic' errors).
- Multipole-corrector magnets
  - Sextupole - and decapole corrector magnets at end of dipoles
  - Used to compensate field imperfections if the dipole magnets. To stabilize trajectories for particles at larger amplitudes – beam lifetime !

One rarely talks about the multipole magnets, but they are also essential for the good machine performance !

Beam envelope

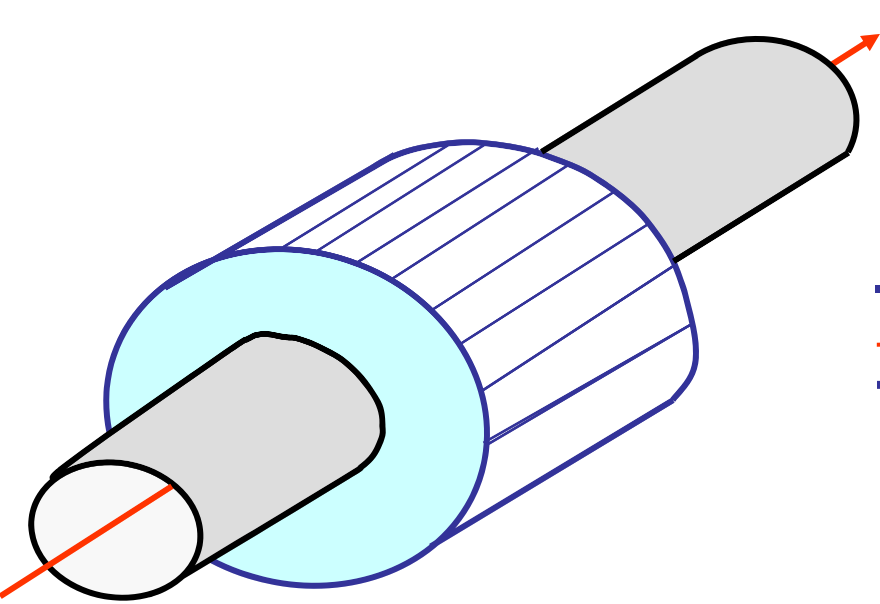


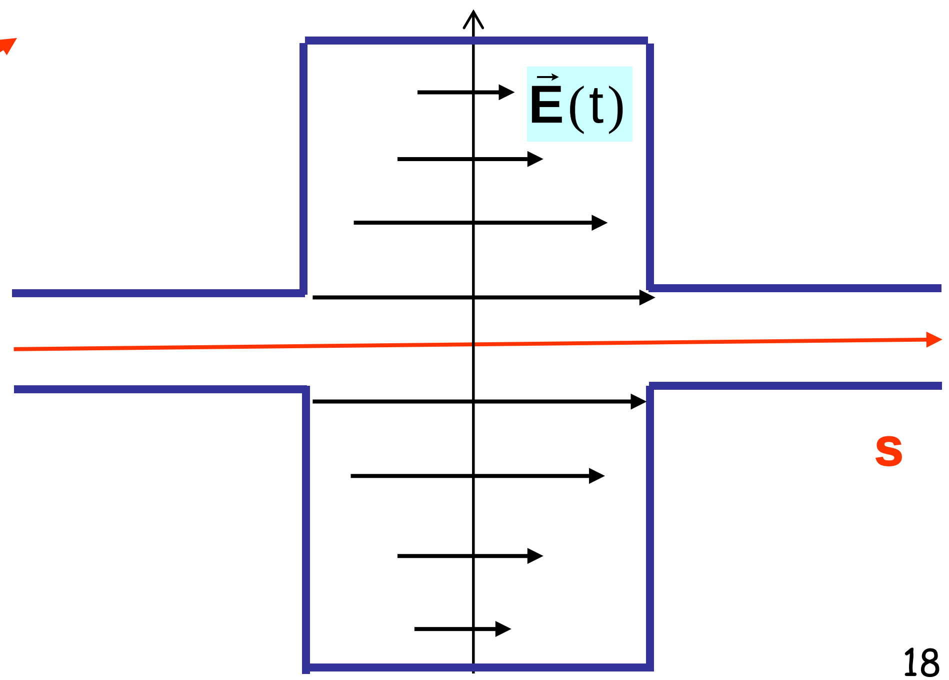
- ❑ The envelope of the size beam is given by the so-called <u>'β'-function</u> (⇔ optics):
  - In the arcs the optics follows a regular pattern.
  - In the long straight sections, the optics is matched to the 'telescope' that provides very strong focusing at the collision point.
- ❑ Collision point size (rms, defined by 'β*'):

CMS & ATLAS : 16 μm   LHCb : 22 – 160 μm   ALICE : 16 μm (ions) / >160 μm (p)

Acceleration

- Acceleration is performed using electric fields that are fed into Radio-Frequency (RF) cavities. RF cavities are basically resonators tuned to a selected frequency.
- To accelerate a proton to 7 TeV, a potential of 7 TV must be provided to the beam:
  - In circular accelerators the acceleration is done in small steps, turn after turn.
  - At the LHC the acceleration from 450 GeV to 7 TeV lasts ~ 20 minutes, with an average energy gain of ~ 0.5 MeV on each turn.





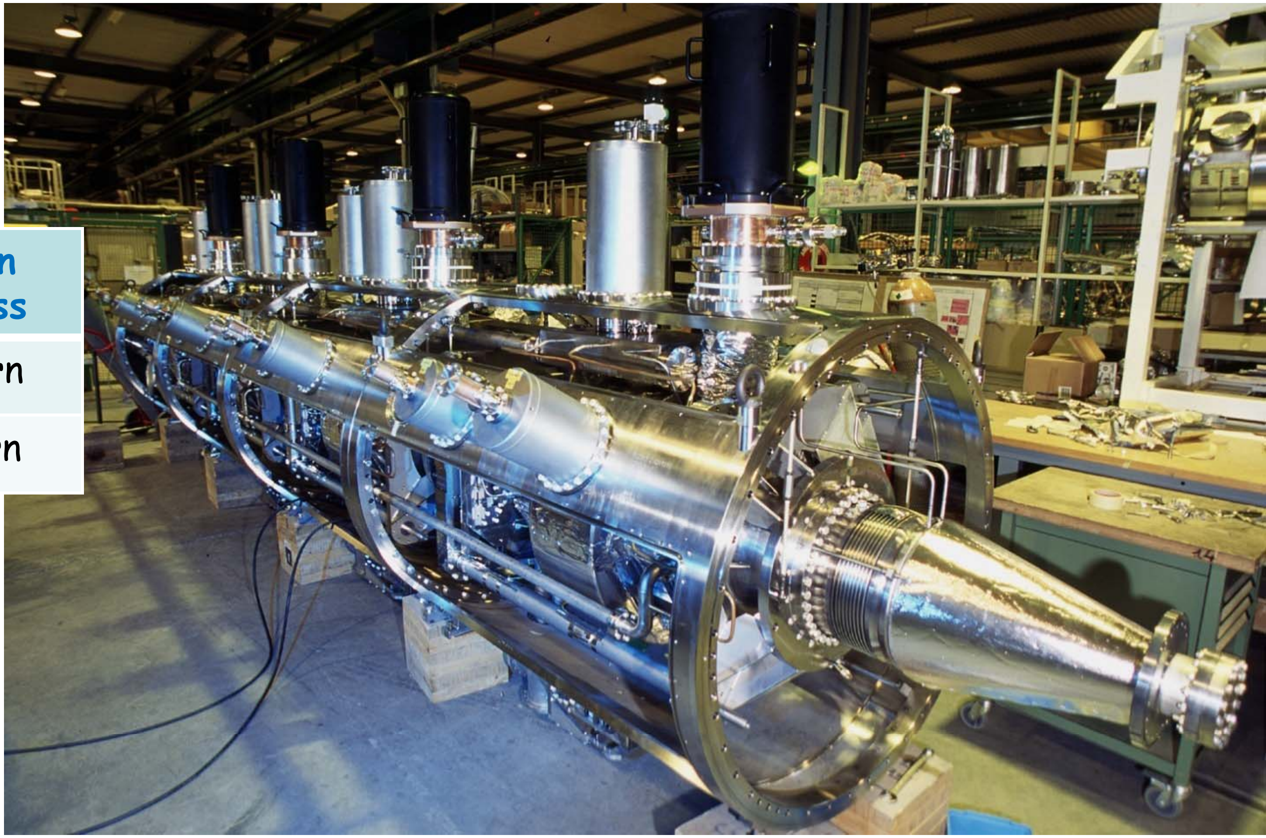
LHC RF system

- The LHC RF system operates at 400 MHz.
- It is composed of 16 superconducting cavities, 8 per beam.
- Peak accelerating voltage of 16 MV/beam.

For LEP at 104 GeV : 3600 MV/beam !

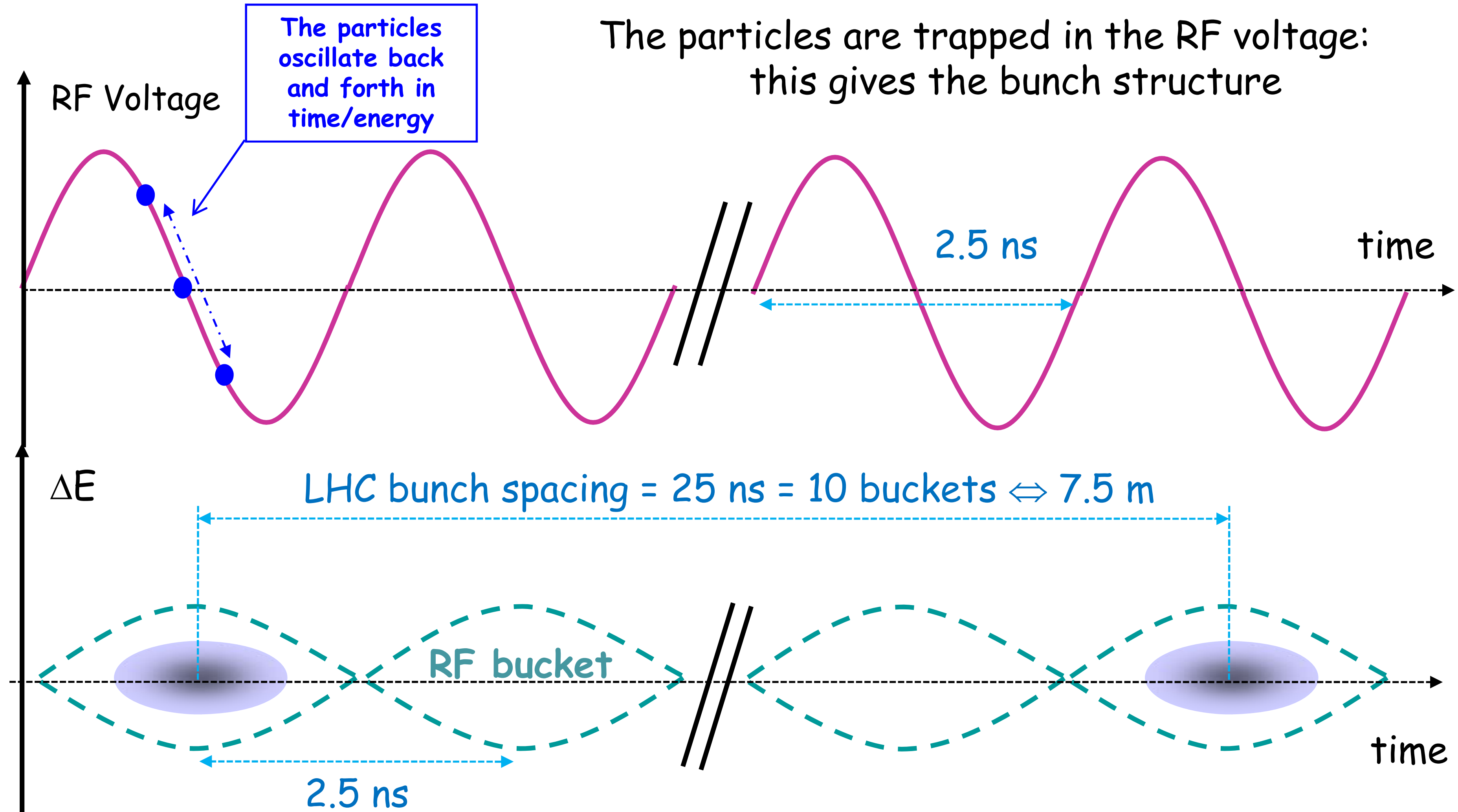
	Synchrotron radiation loss
LHC @ 7 TeV	6.7 keV /turn
LEP @ 104 GeV	~3 GeV /turn

The LHC beam radiates a sufficient amount of visible photons to be actually observable with a camera ! (total power ~ 0.2 W/m)



RF buckets and bunches

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

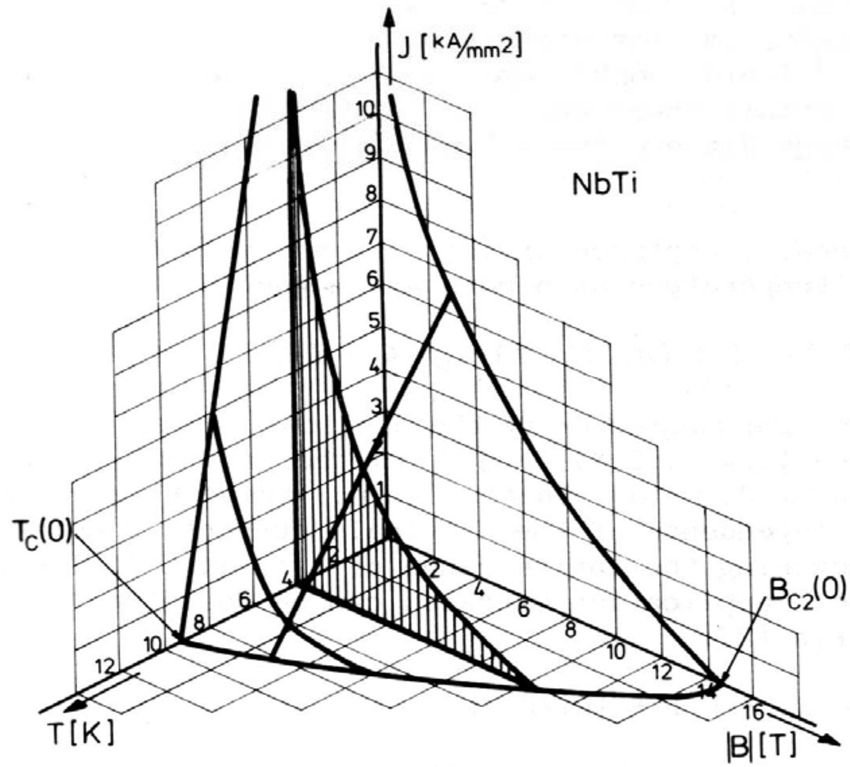


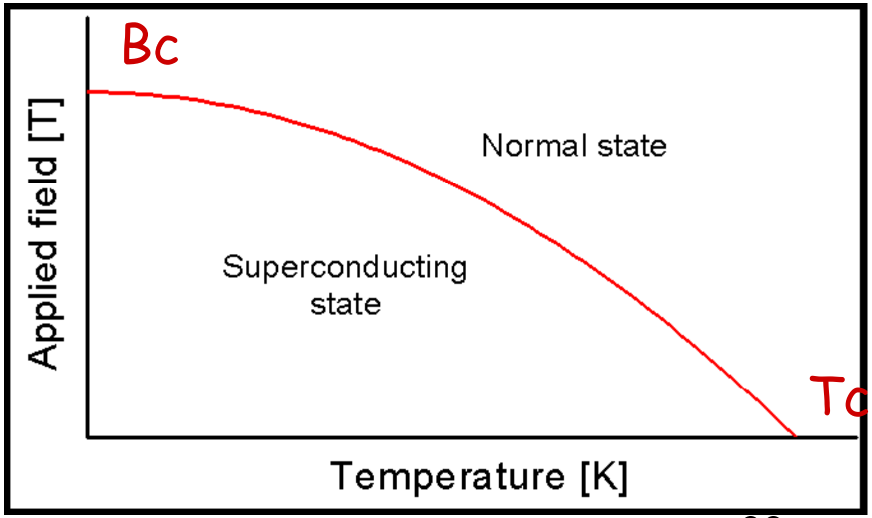
	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

Magnets & Tunnel

Superconductivity

- The very high DIPOLE field of 8.3 Tesla required to achieve 7 TeV/c can only be obtained with superconducting magnets !
- The material determines:
  - **Tc** critical temperature
  - **Bc** critical field
- The cable production determines:
  - **Jc** critical current density
- Lower temperature ⇒ increased current density ⇒ higher fields.
- Typical for NbTi @ 4.2 K
  - 2000 A/mm2 @ 6T
- To reach 8-10 T, the temperature must be lowered to 1.9 K – superfluid Helium !

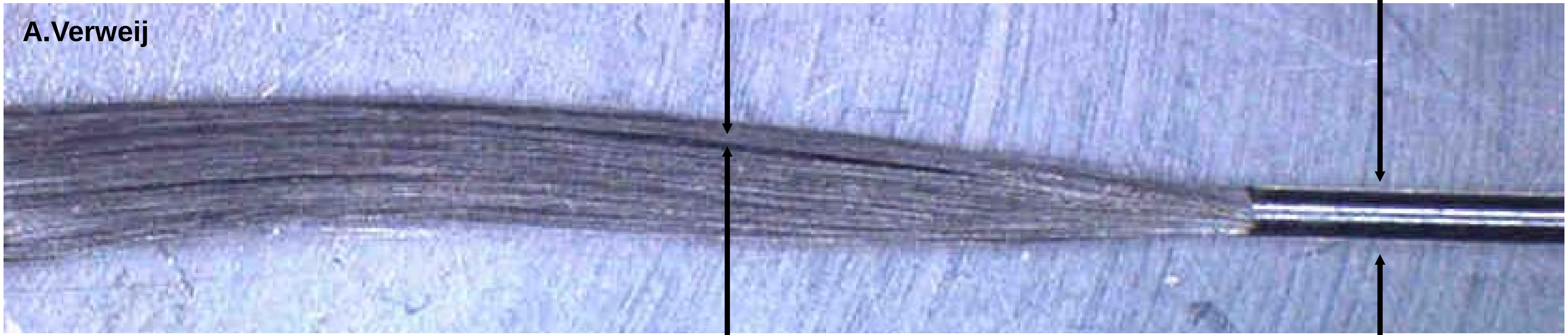




The superconducting cable

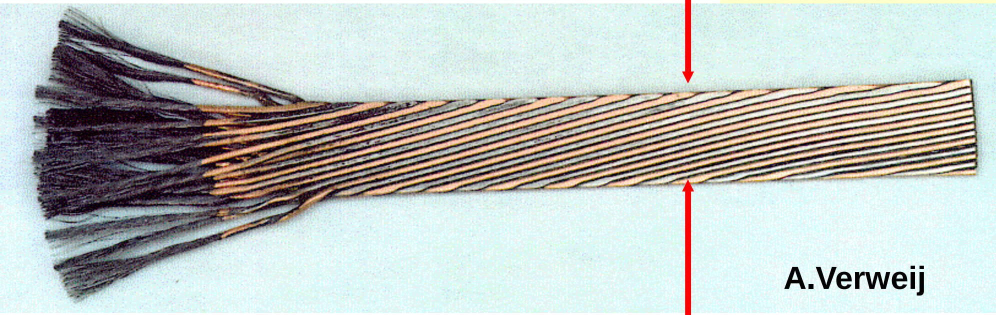
$\varnothing 6\ \mu m$

$\varnothing 1$ mm



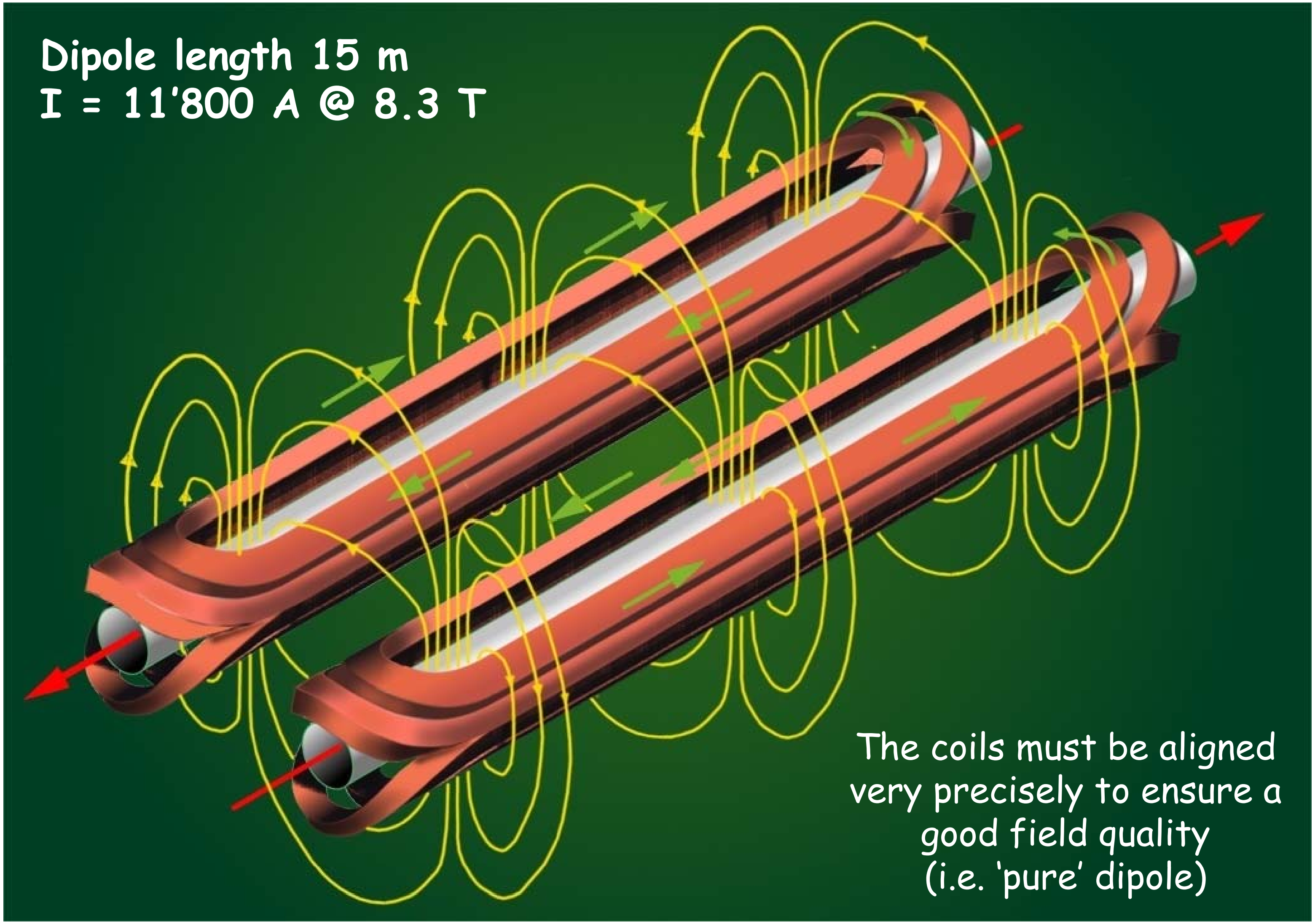
Typical value for operation at 8T and 1.9 K: 800 A

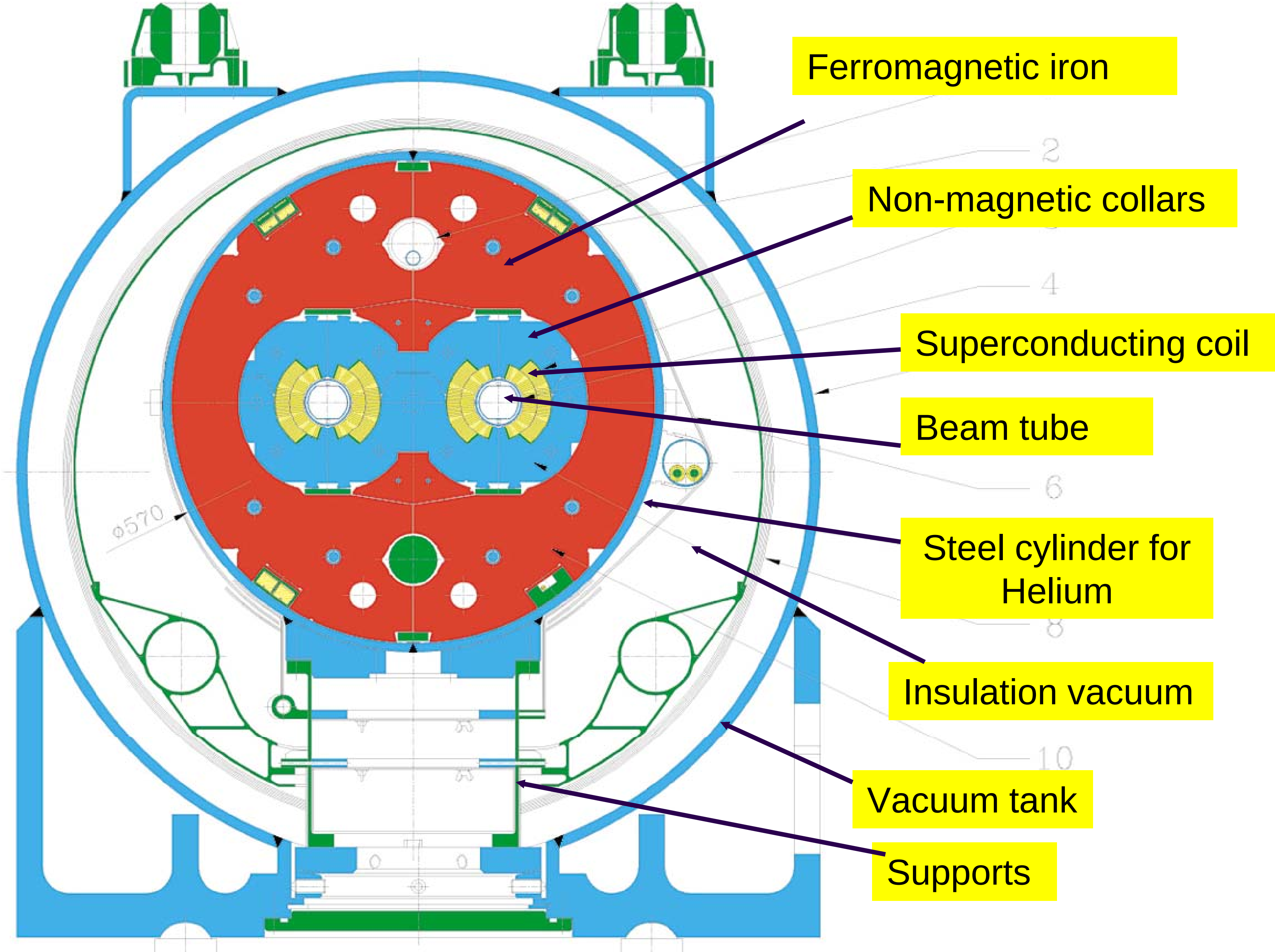
width 15 mm



Rutherford cable

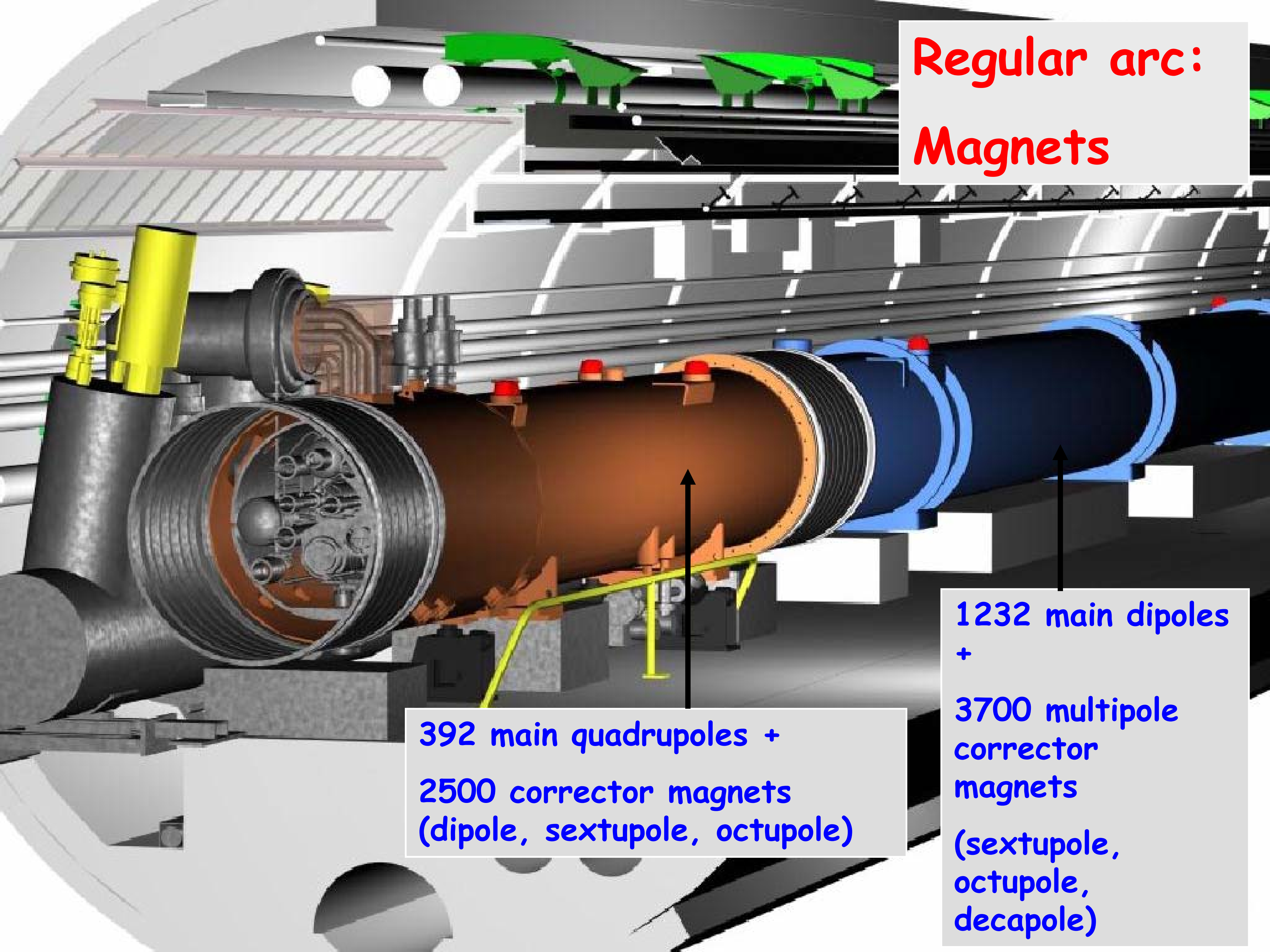
Coils for dipoles





Weight (magnet + cryostat) ~ 30 tons, Length 15 m

Regular arc: Magnets



392 main quadrupoles +

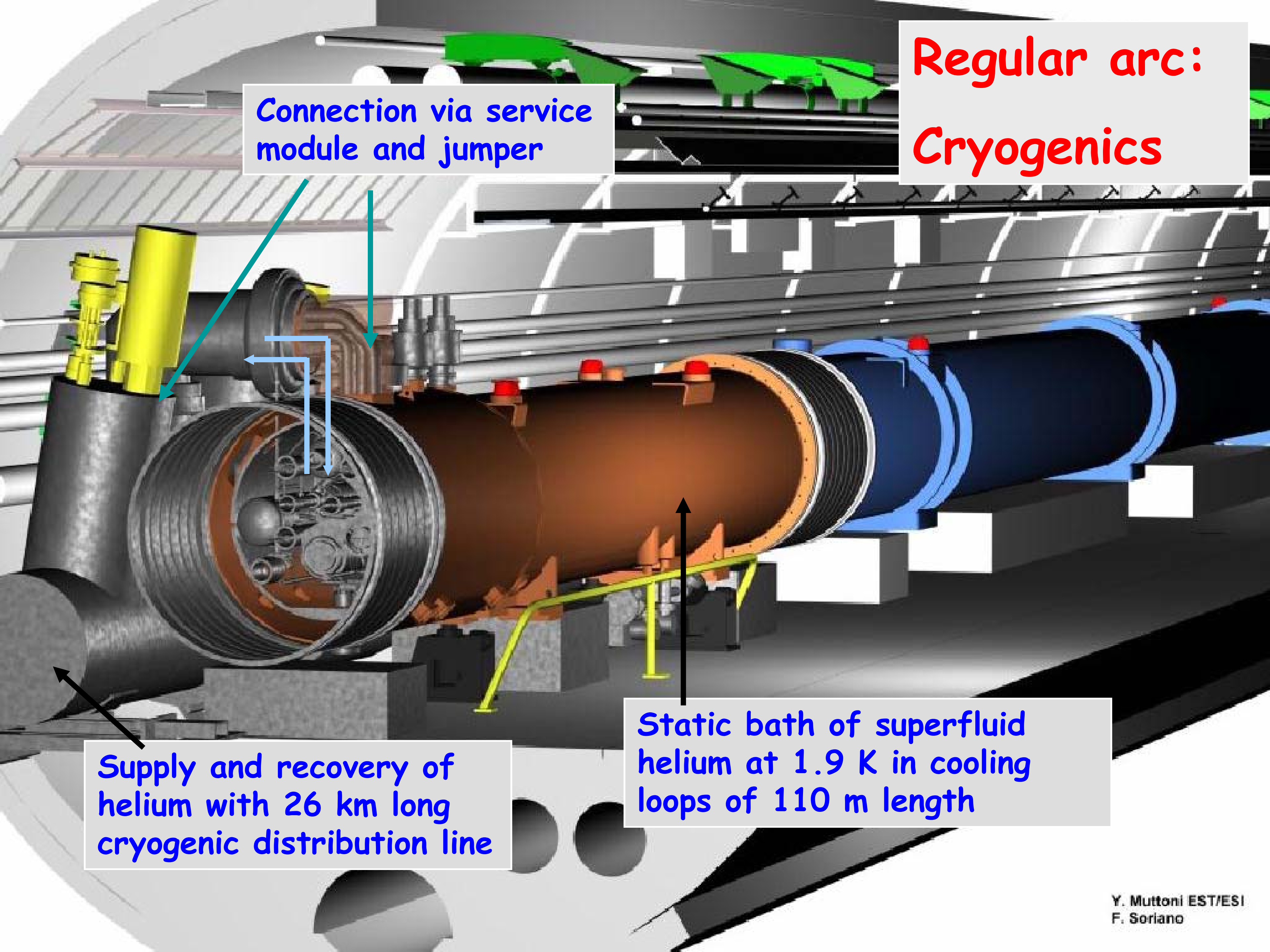
2500 corrector magnets (dipole, sextupole, octupole)

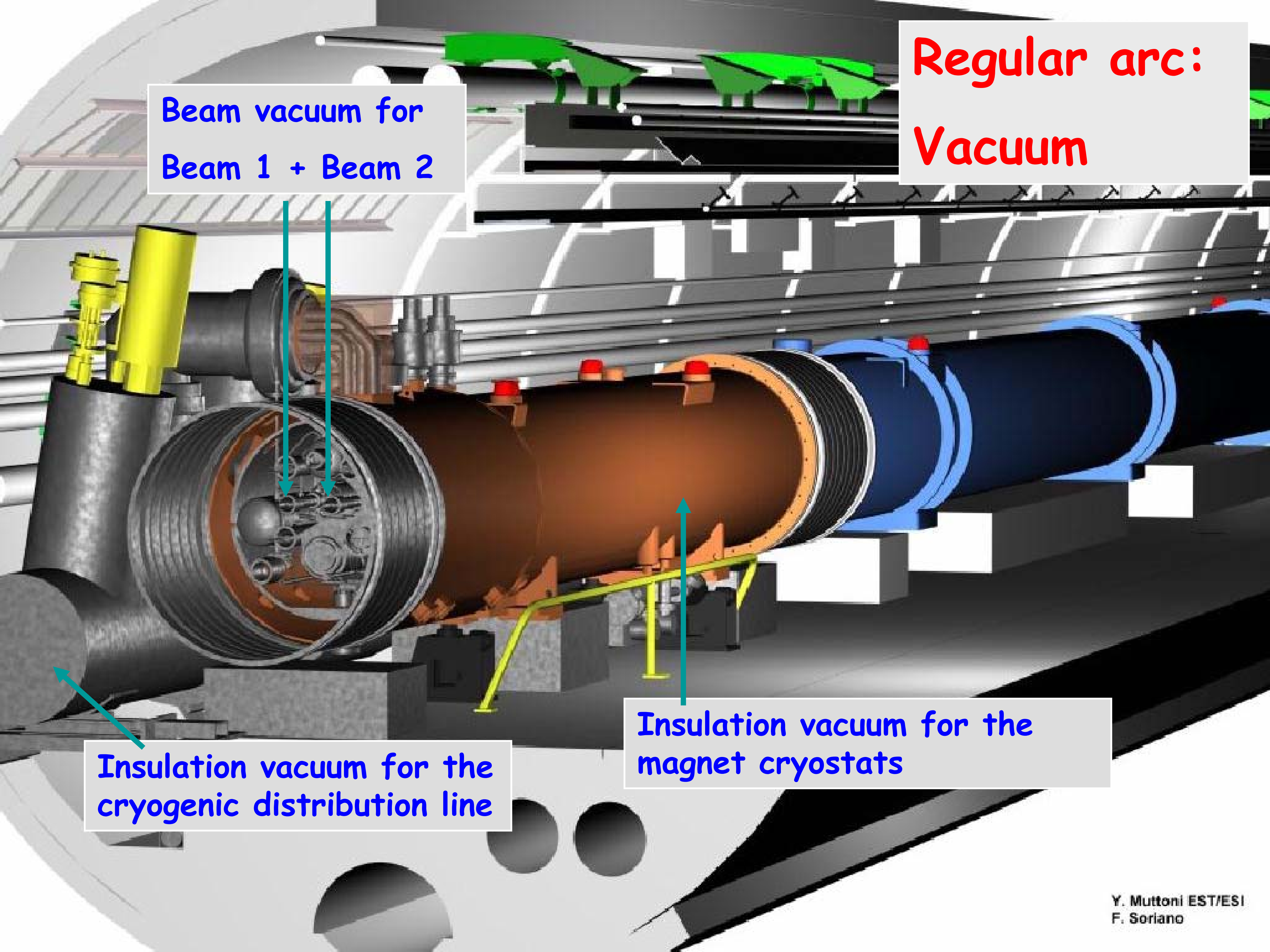
1232 main dipoles

+

3700 multipole corrector magnets

(sextupole, octupole, decapole)


Regular arc:
Cryogenics
Connection via service module and jumper
Supply and recovery of helium with 26 km long cryogenic distribution line
Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length
Y. Muttoni EST/ESI
F. Soriano

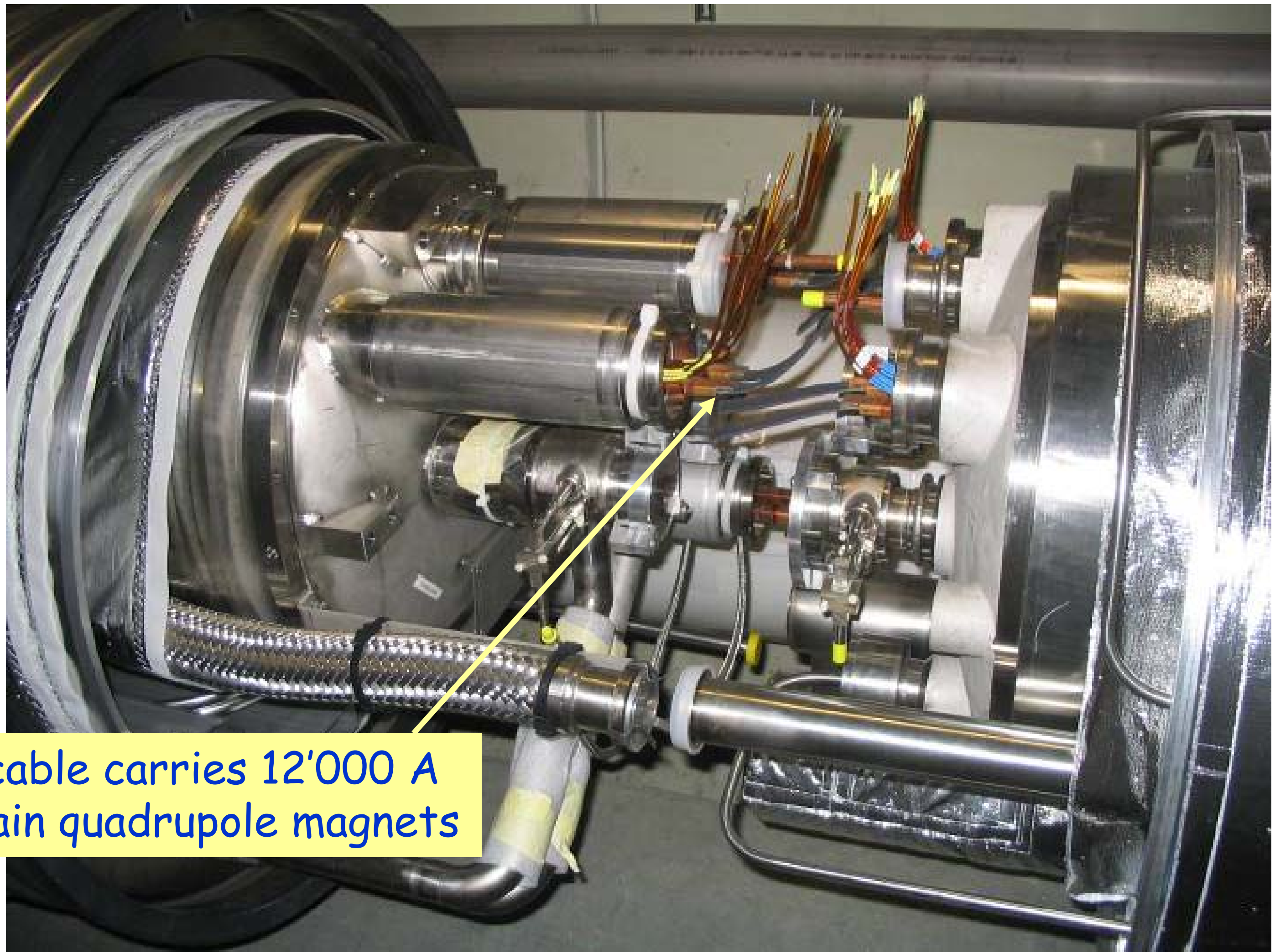

Regular arc:
Vacuum
Beam vacuum for
Beam 1 + Beam 2
Insulation vacuum for the
magnet cryostats
Insulation vacuum for the
cryogenic distribution line
Y. Muttoni EST/ESI
F. Soriano

Tunnel view (1)

Tunnel view (2)

Complex interconnects

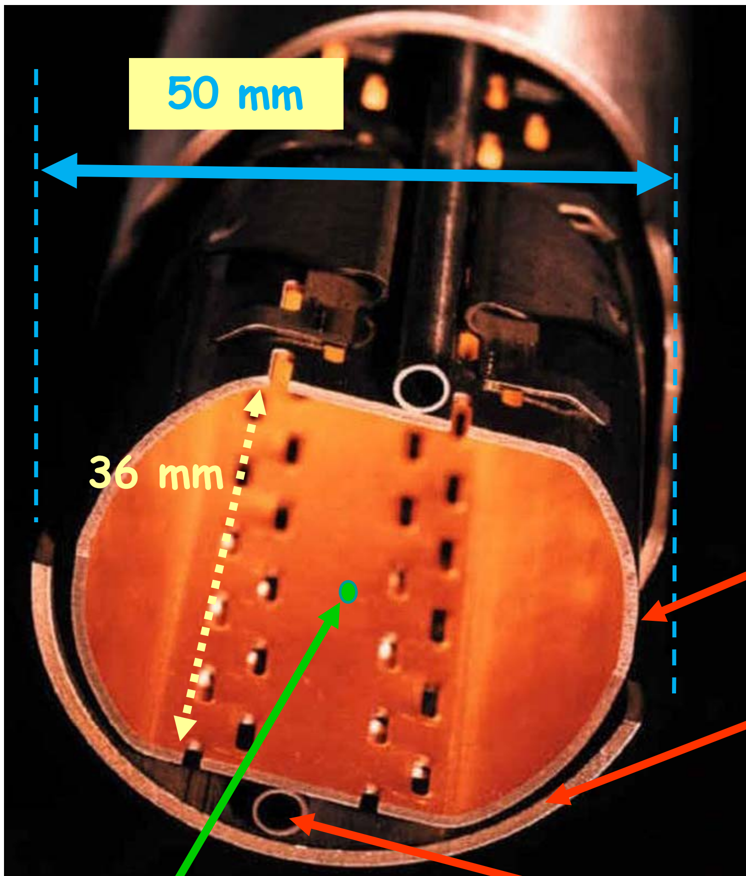
Many complex connections of super-conducting cable that will be buried in a cryostat once the work is finished.



This SC cable carries 12'000 A for the main quadrupole magnets

Vacuum chamber

- The beams circulate in two ultra-high vacuum chambers, P ~ 10^{-10} mbar.
- A Copper beam screen protects the bore of the magnet from heat deposition due to image currents, synchrotron light etc from the beam.
- The beam screen is cooled to T = 4-20 K.

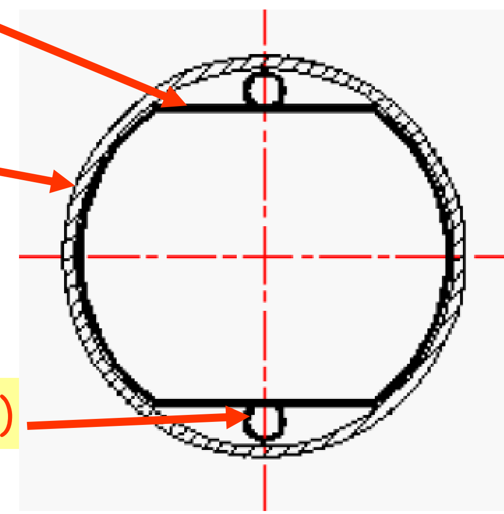


Beam screen

Magnet bore

Cooling channel (Helium)

Beam envel.
~ 1.8 mm @ 7 TeV



Luminosity and Interaction Regions

Luminosity

Let us look at the different factors in this formula, and what we can do to maximize L, and what limitations we may encounter !!

$$L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*}$$

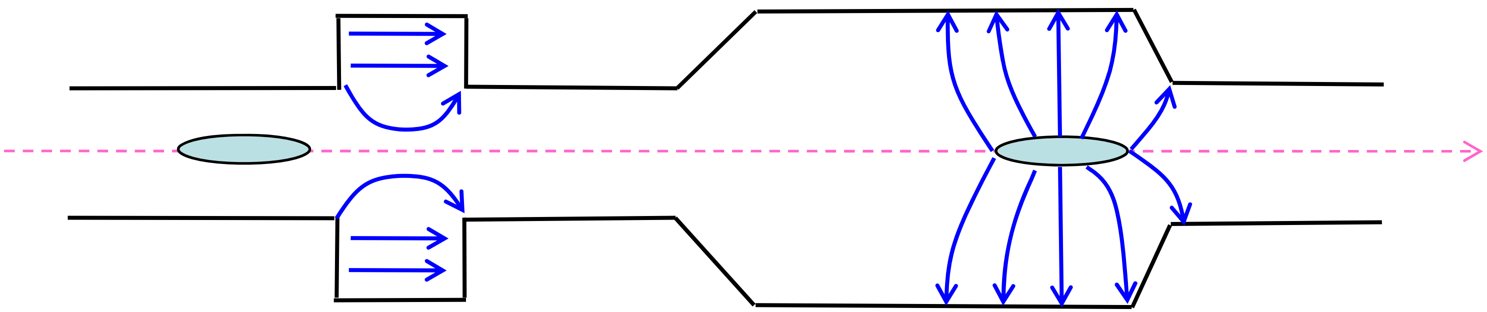
- f : the revolution frequency is given by the circumference, f=11.246 kHz.
- N : the bunch population – $N=1.15\times10^{11}$ protons
  - Injectors (brighter beams)
  - Collective interactions of the particles
  - Beam encounters
- k : the number of bunches – k=2808
  - Injectors (more beam)
  - Collective interactions of the particles
  - Interaction regions
  - Beam encounters
- σ^* : the size at the collision point – $\sigma^*_y=\sigma^*_x=16\ \mu m$
  - Injectors (brighter beams)
  - More focusing – stronger quadrupoles

For k = 1:

$$L = 3.5\times10^{30} cm^{-2} s^{-1}$$

Collective (in-)stability

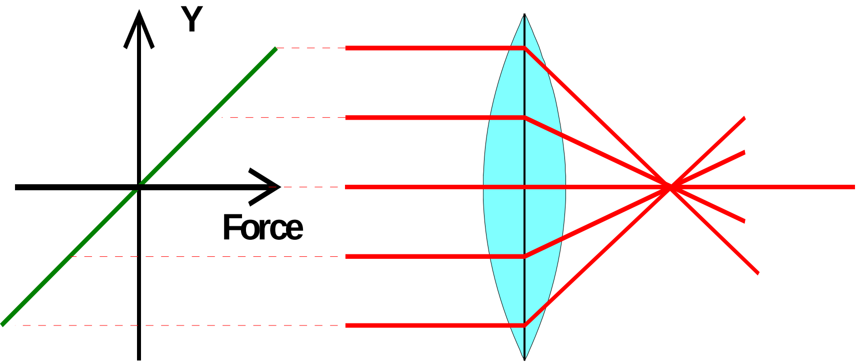
- The electromagnetic field of a bunch interacts with the chamber walls (finite resistivity !), cavities, discontinuities etc that it encounters:



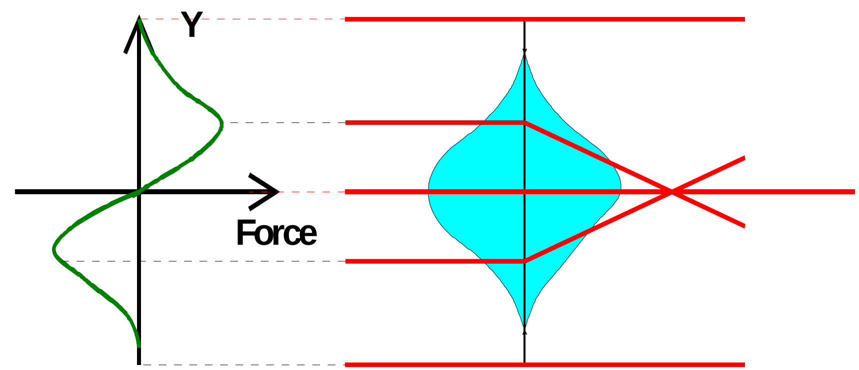
- The fields act back on the bunch itself or on following bunches.
- Since the fields induced by of a bunch increase with bunch intensity, the bunches may become <u>COLLECTIVELY unstable</u> beyond a certain intensity, leading to poor lifetime or massive looses intensity loss.
- Such effects can be very strong in the LHC injectors, and they will also affect the LHC – in particular because we have a lot of carbon collimators (see later) that have a very bad influence on beam stability !

→ limits the intensity per bunch and per beam !

'Beam-beam' interaction



Quadrupole lens



Beam(-beam) lens

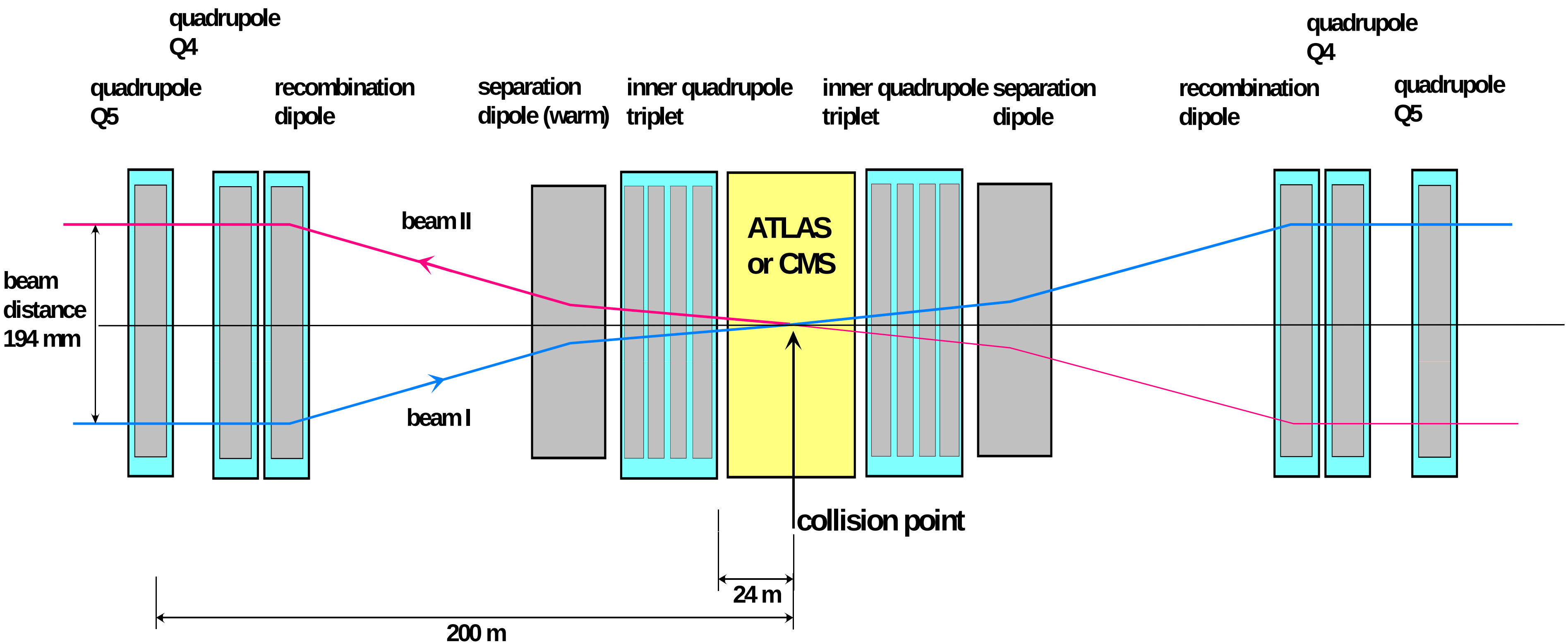
- When a particle of one beam encounters the opposing beam at the collision point, it senses the fields of the opposing beam.
- Due to the typically Gaussian shape of the beams in the transverse direction, the field (force) on this particle is non-linear, in particular at large amplitudes !
- The effect of the non-linear fields can become so strong (when the beams are intense) that large amplitude particles become unstable and are lost from the machine:

  → poor lifetime

  → background

THE INTERACTION OF THE BEAMS SETS A LIMIT ON THE BUNCH INTENSITY!

Combining the beams for collisions



Example for an LHC insertion with ATLAS or CMS

- The 2 LHC beams circulate in separate vacuum chambers in most of the ring, but they must be brought together to collide.
- Over a distance of about 260 m, the beams circulate in the same vacuum chamber and they are a total of ~ 120 long distance beam encounters in ATLAS, CMS, ALICE and LHCb.

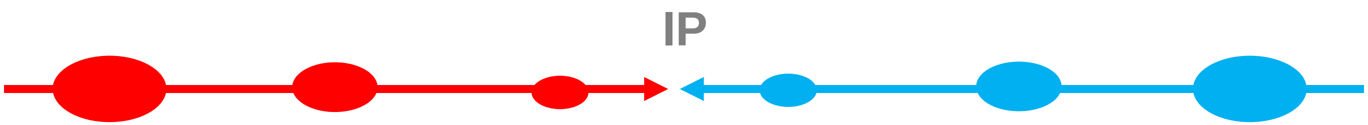
Crossing angles

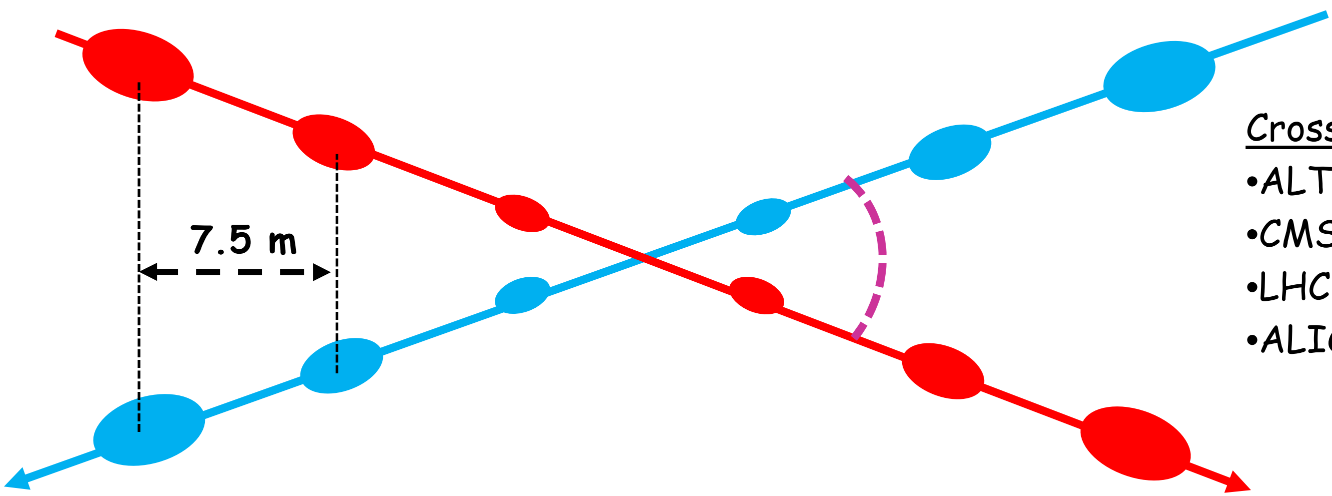
- Since every collision adds to our 'Beam-beam budget' we must avoid un-necessary direct beam encounters where the beams share a common vacuum:

COLLIDE WITH A CROSSING ANGLE IN ONE PLANE !

- There is a price to pay :

  A reduction of the luminosity due to the finite bunch length of 7.6 cm and the non-head on collisions → L reduction of ~ 17%.



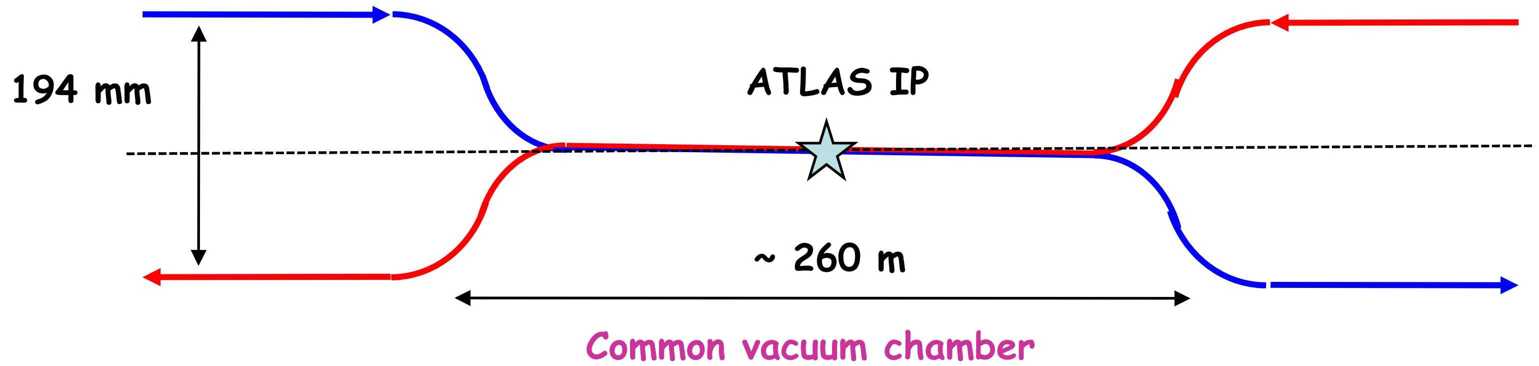


<u>Crossing planes & angles</u>

•ALTAS	Vertical	280 μrad
•CMS	Horizontal	280 μrad
•LHCb	Horizontal	300 μrad
•ALICE	Vertical	400 μrad

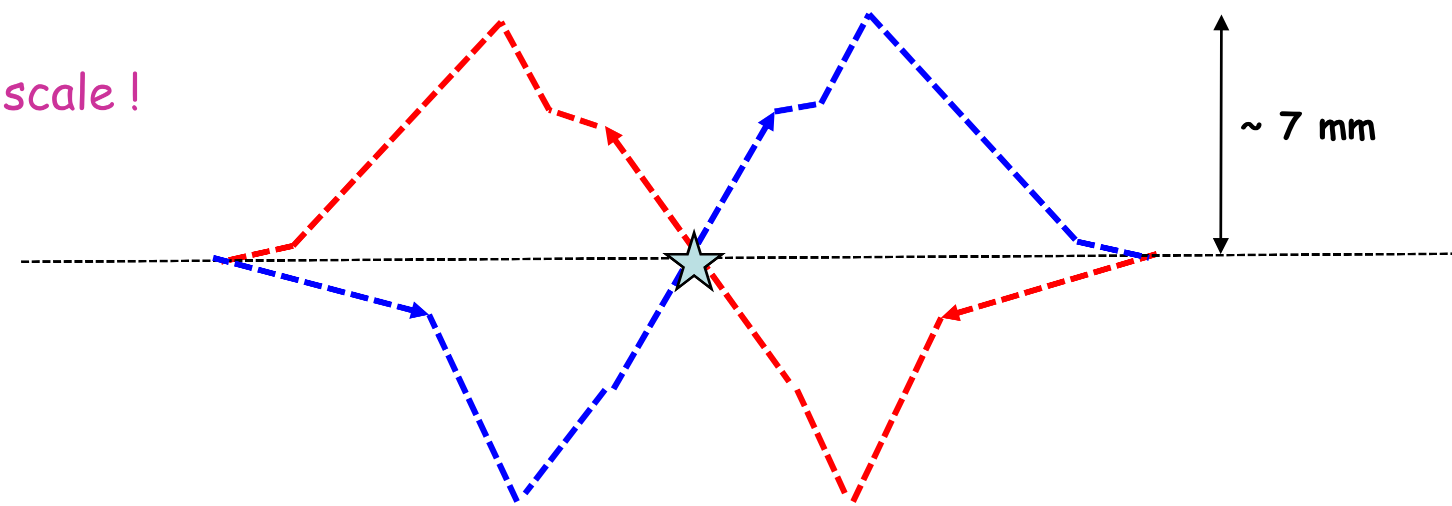
Separation and crossing : ATLAS

Horizontal plane: the beams are combined and then separated



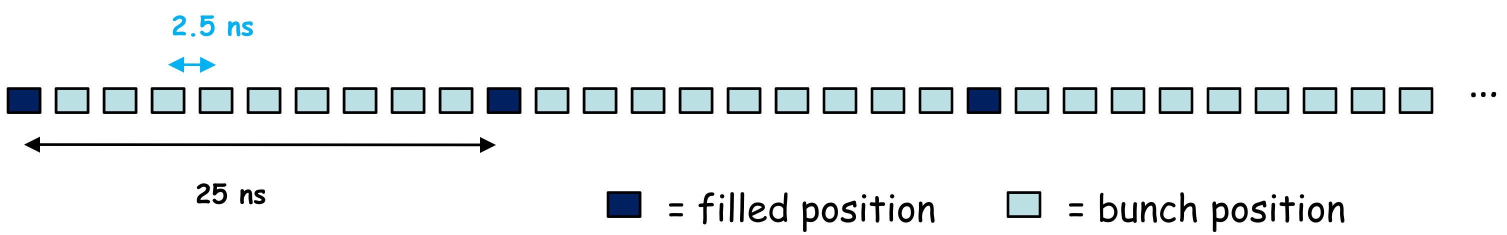
Vertical plane: the beams are deflected to produce a crossing angle at the IP

Not to scale !



Collision schemes

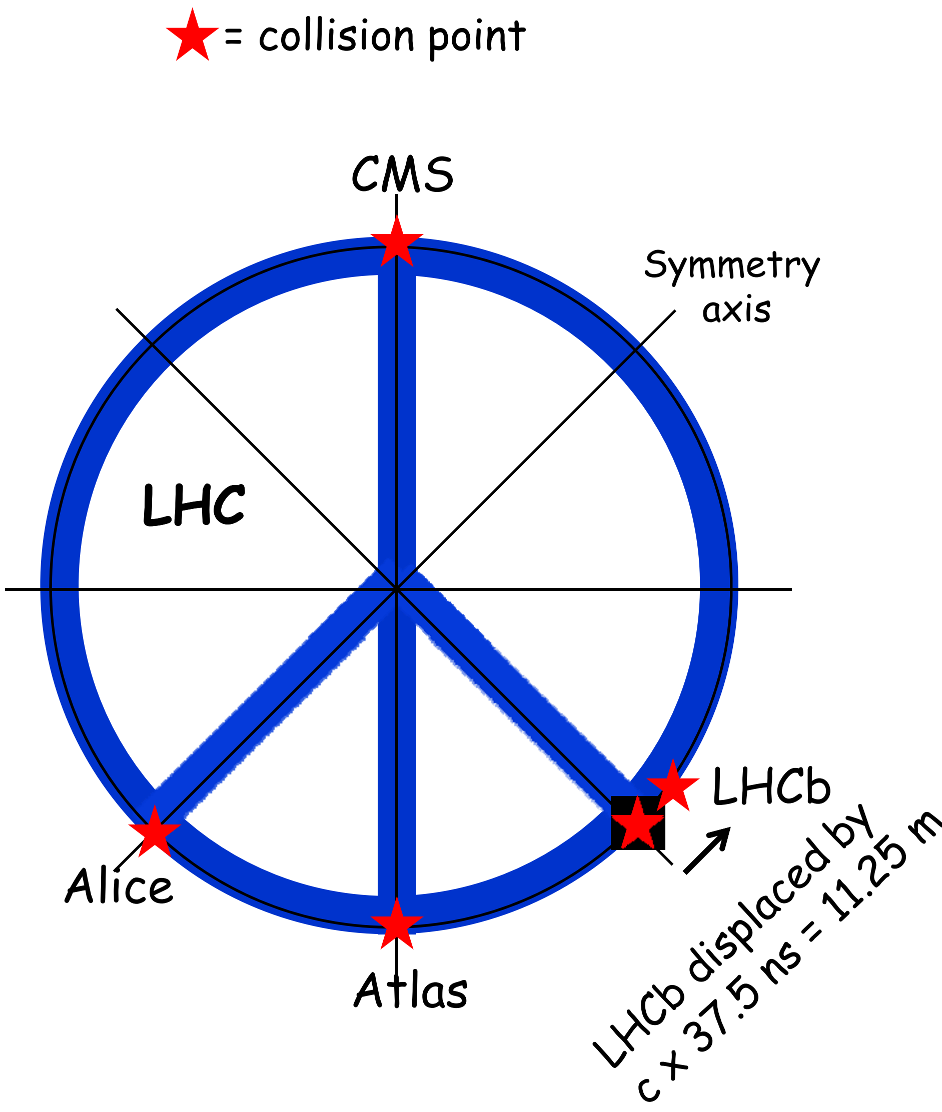
- The 400 MHz RF system provides 35'640 possible bunch positions (buckets) at a distance of 2.5 ns along the LHC circumference.
- A priori any of those positions could be filled with a bunch…
- The smallest bunch-to-bunch distance is fixed to 25 ns, which is also the nominal distance: limits the max. number of bunches to 3564.



- In practice there are fewer bunches because holes must be provided for the fast pulsed magnets (kickers) used for injection and dump.
- But the LHC is very flexible and can operate with many bunch patterns.

Collision point symmetry

- ATLAS, ALICE and CMS are positioned on the LEP symmetry axis (8 fold sym.)
- LHCb is displaced from the symmetry axis by 11.25 m <<-->> 37.5 ns.
- For filling patterns with many bunches this is not an issue, but it becomes a bit tricky with few bunches.



Filling pattern example: 1x1

- With 1 bunch per beam, there are 2 collision points at opposite sides of the ring.

- Depending on their position along the circumference, the 2 bunches can be made to collide:

  in ATLAS and CMS,

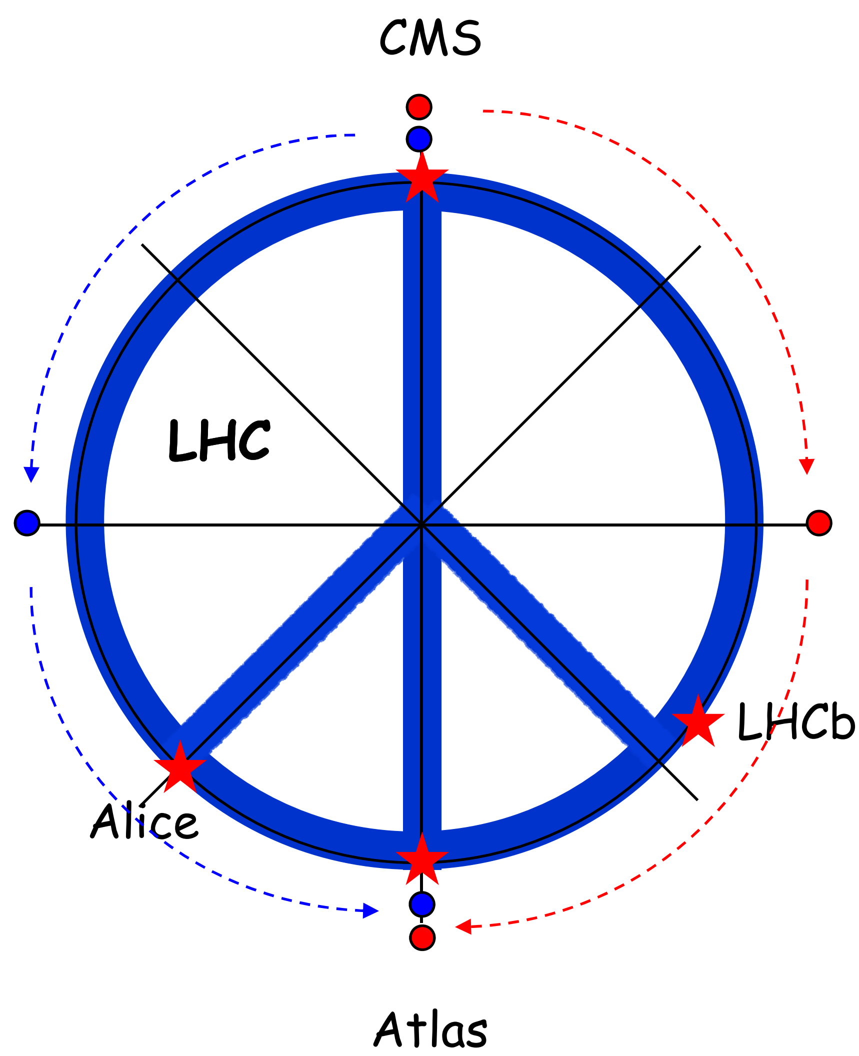
  OR

  in ALICE,

  OR

  in LHCb,

  but never in all experiments at the same time !!



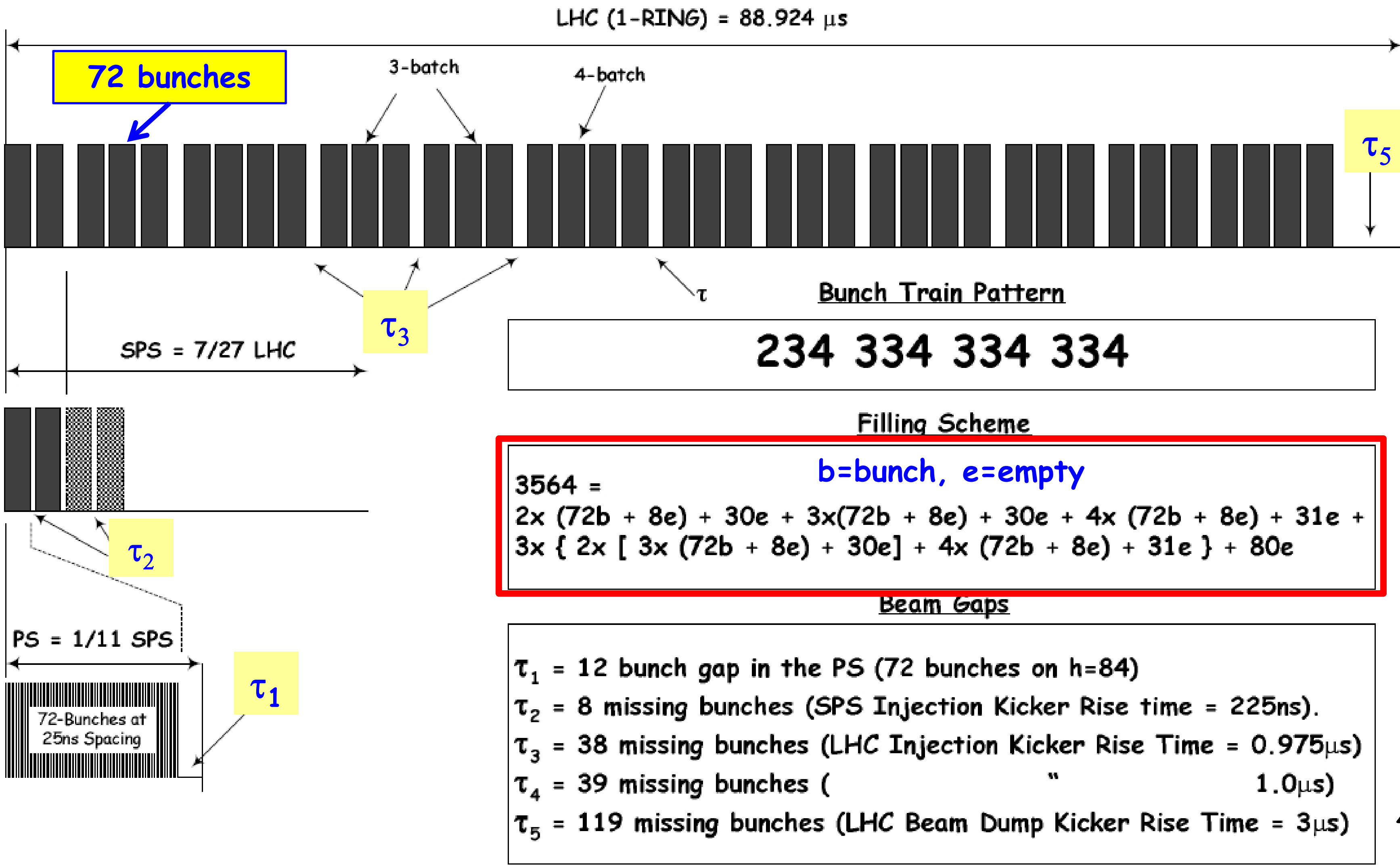
Filling patterns

Schema	Nominal bunch distance (ns)	No. bunches	Comment
43x43	2025	43	No crossing angle required
156x156	525	156	No crossing angle required
25 ns	25	2808	Nominal p filling
50 ns	50	1404	
75 ns	75	936	
Ion nominal	100	592	Nominal ion filling
Ion early	1350	62	No crossing angle required

- In the 43x43 and 156x156 schemes, some bunches are displaced (distance $\neq$ nominal) to balance the ALICE and LHCb luminosities.
- For the multi-bunch schemes (25, 50, 75, 100 ns) there are larger gaps to accommodate fast injection magnets ('kickers') risetimes.
- All schemes have a $\geq 3\ \mu s$ long particle free gap for the beam dump kicker.

Nominal filling pattern

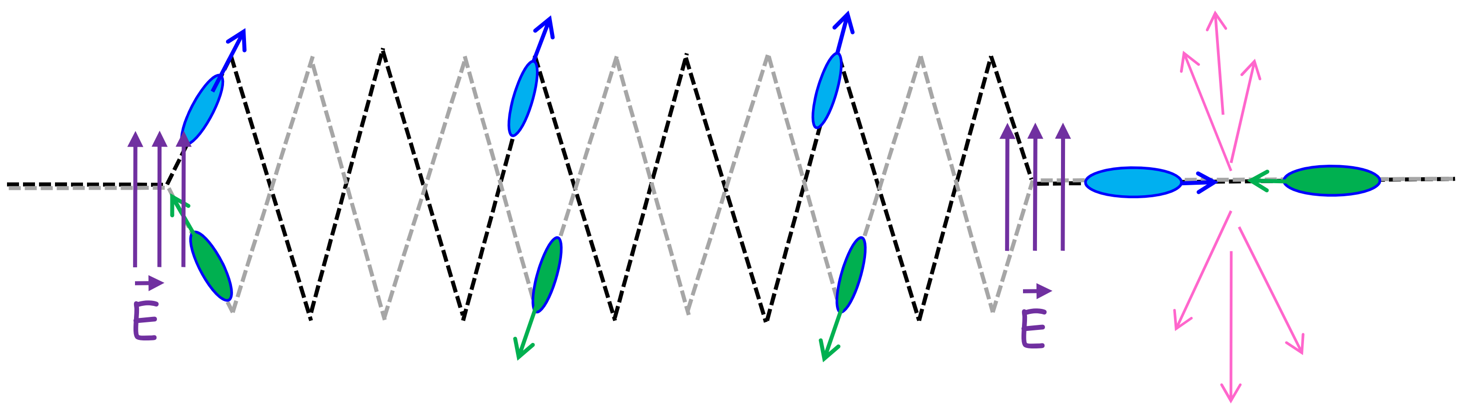
- The nominal pattern consists of 39 groups of 72 bunches (spaced by 25 ns), with variable spacing to accommodate the rise times of the injection and extraction magnets ('kickers').
- There is a long 3 μs gap (τ_5)for the LHC dump kicker (see later).



Tevatron I

- The Tevatron is presently the 'energy frontier' collider in operation at FNAL, with a beam energy of 980 GeV and a size of ~ $\frac{1}{4}$ LHC.
- It is the first super-conducting collider ever build.
- It collides proton and anti-proton bunches that circulate in opposite directions in the SAME vacuum chamber.
- One of the problems at the TEVATRON are the long-distance encounters of the bunches in the arc sections. A complicated separation scheme with electrostatic elements has to be used:

Tricky to operate !!



Tevatron II

- The Tevatron has undergone a number of remarkable upgrades and it presently collides 36 proton with 36 anti-proton bunches (k=36), with bunch populations (N) similar to the ones of the LHC (but there are always fewer anti-protons !).

- Compare LHC and Tevatron:

$$L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*}$$

$f_{Tevatron} \approx 4\ f_{LHC}$

$k_{LHC} \approx 100\ k_{Tevatron}$

$N^2/(\sigma_x\ \sigma_y) \sim \text{equal}$

Tevatron gets a factor 4 'for free' because of ring size !!

$L_{LHC} \approx 30\ L_{Tevatron}$

Luminosity gain of LHC comes basically from the number of bunches (k) !!