The LHC Accelerator Complex

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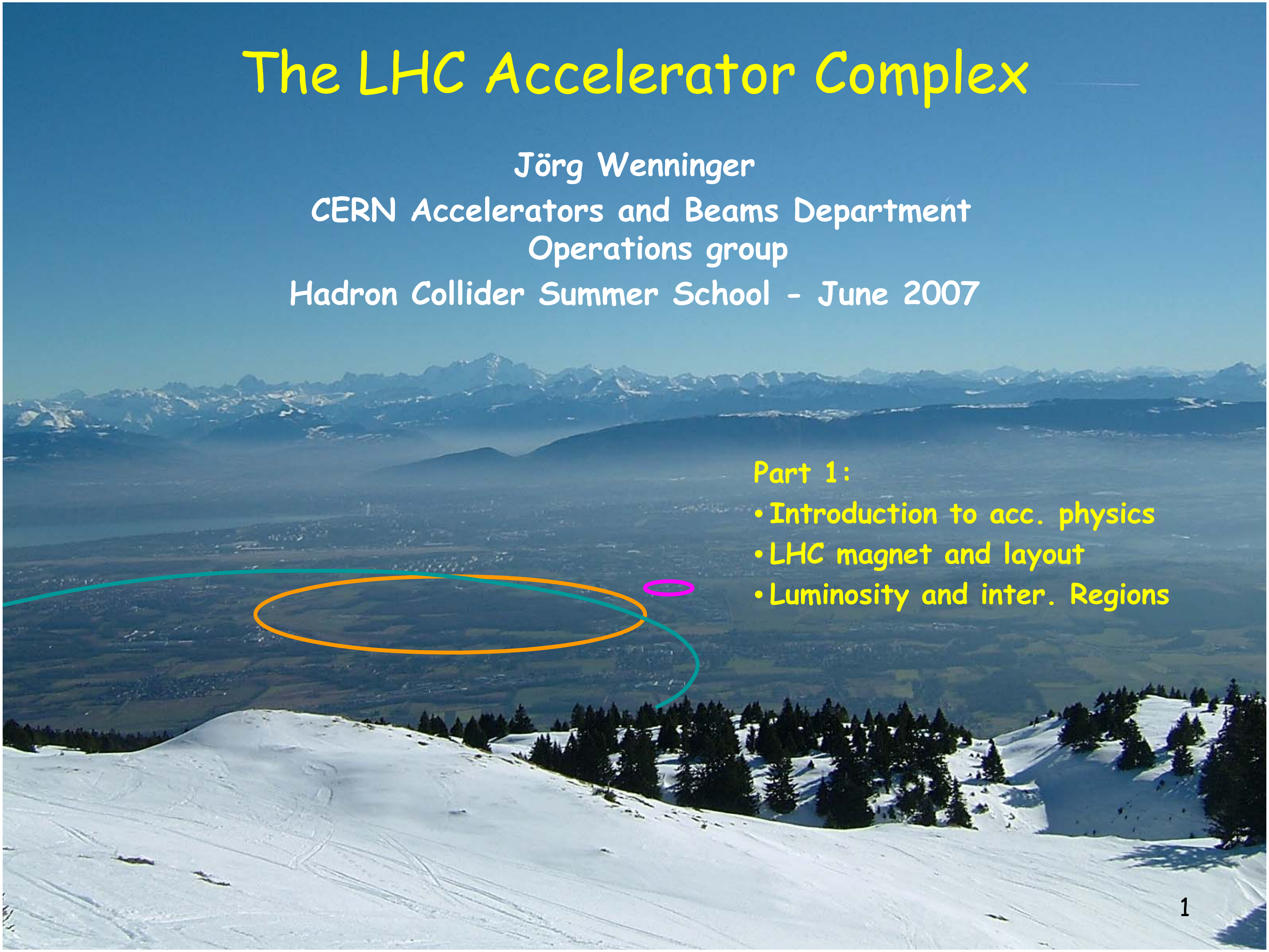


Part 1:
- **Introduction to acc. physics**
- **LHC magnet and layout**
- **Luminosity and inter. Regions**

Outline

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

Part 1

- LHC injector chain
- Machine protection
- Collimation
- 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 boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

1996 : LEP operation > 80 GeV (W boson -factory)

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of the LHC installation

2005 : Start of LHC hardware commissioning

2008 : Expected LHC commissioning with beam

7 years of construction to replace :

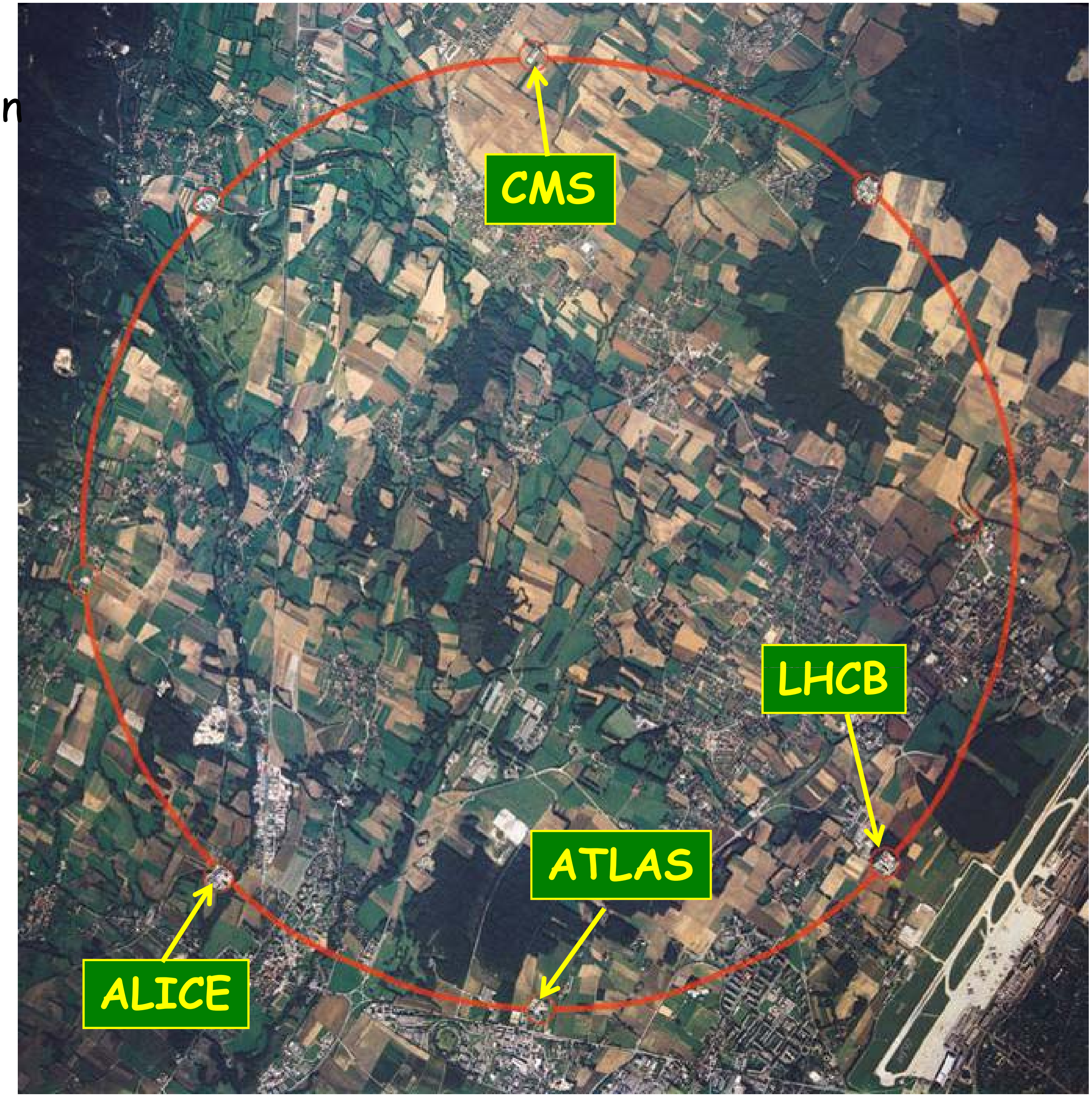
LEP: 1989-2000

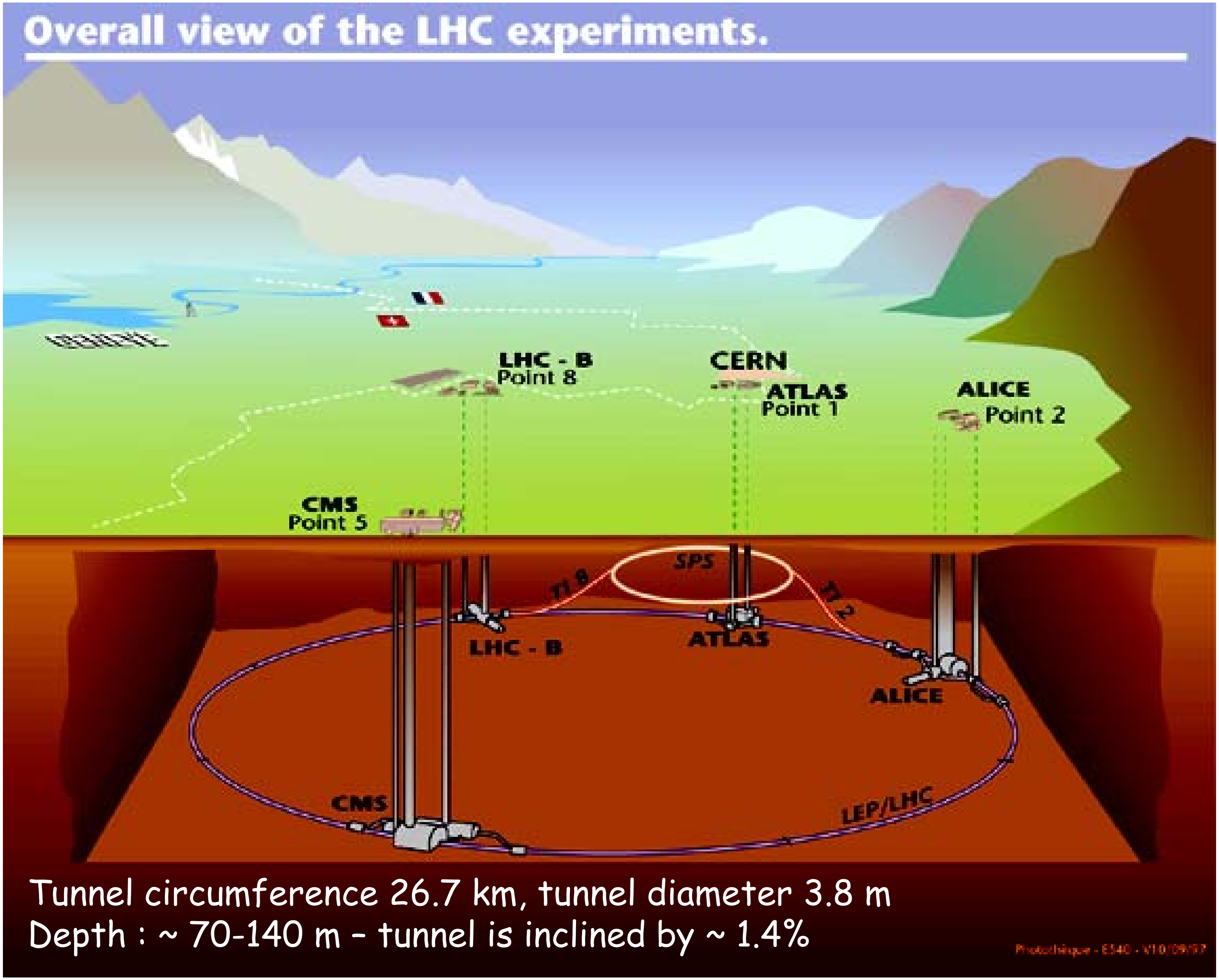
- e+e- collider
- 4 experiments
- max. energy 104 GeV
- circumference 26.7 km

in the same tunnel by

LHC : 2008-2020+

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





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	$p\bar{p}$	2×10^{32} cm^{-2} s^{-1}
SppbarS	$p\bar{p}$	6×10^{30} cm^{-2} s^{-1}

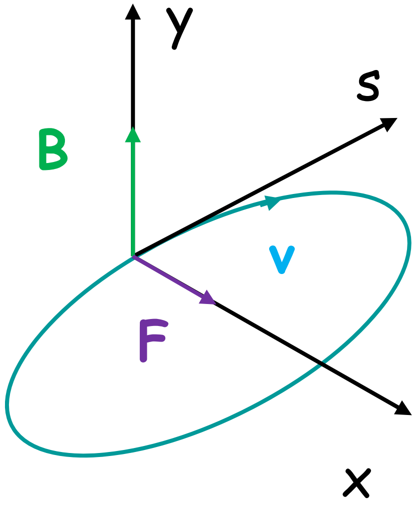
A factor 100 in luminosity

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, mim. at the collision points.

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

High beam "brillance" N/ε

(particles per phase space volume)

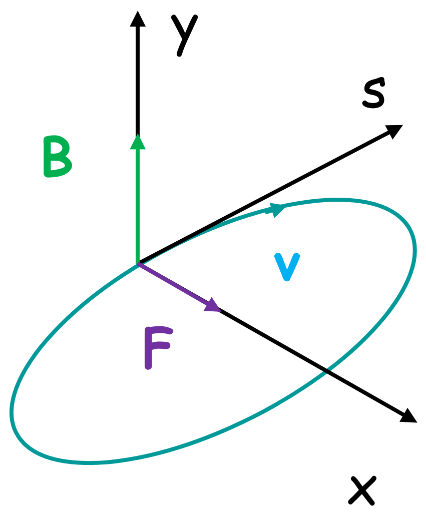
→ Injector chain performance !

Small envelope

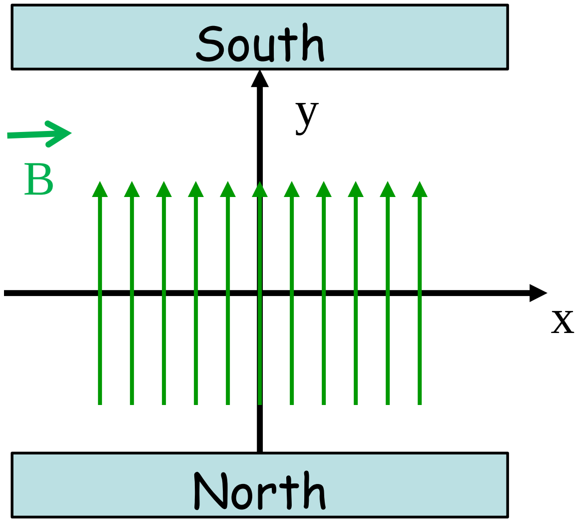
→ Strong focusing !

Introduction to Accelerator Physics

Dipole fields



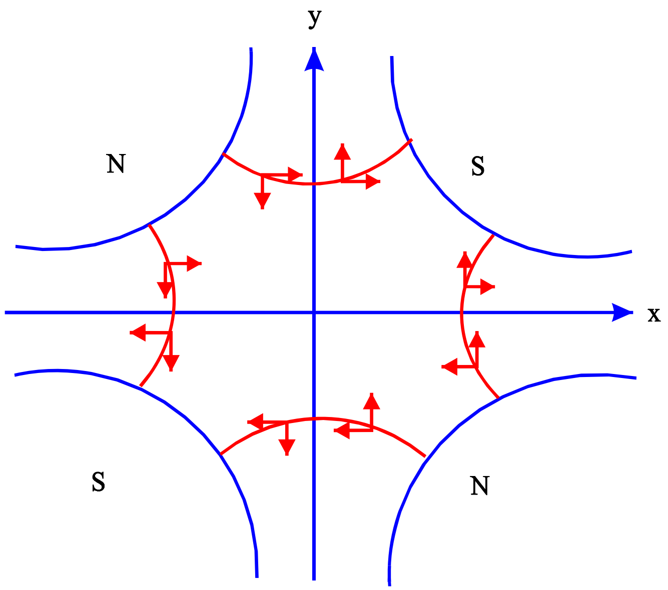
- ❑ Dipole magnets are the simplest accelerator magnets and have ‘just’ 2 poles.
- ❑ Their field is constant across the magnet.
- ❑ They are used to bend the beam and define the reference path.
- ❑ The dipoles define the beam MOMENTUM !

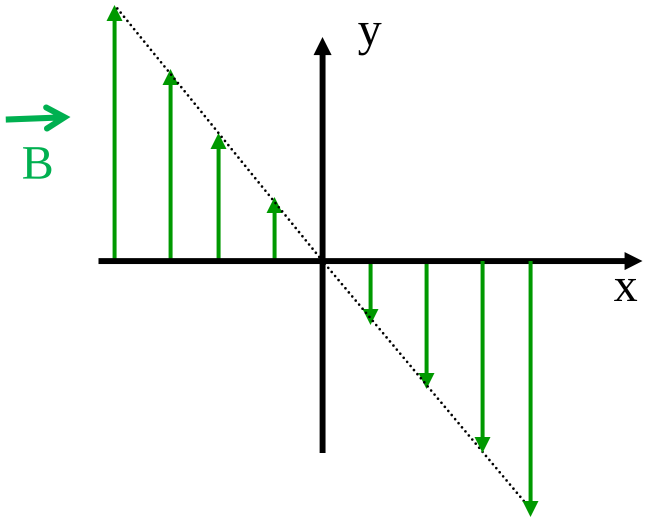


$$B = \frac{p}{e_0 \cdot R}$$

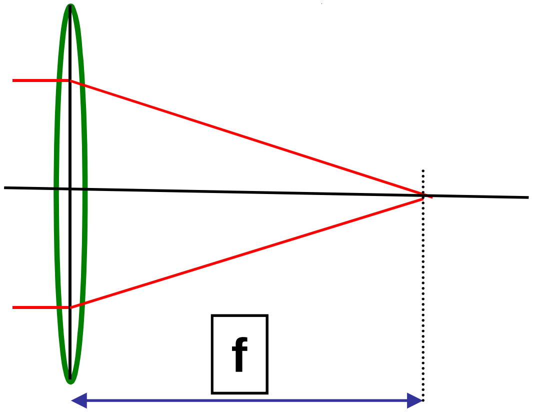
Quadrupolar field - focusing

- 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.





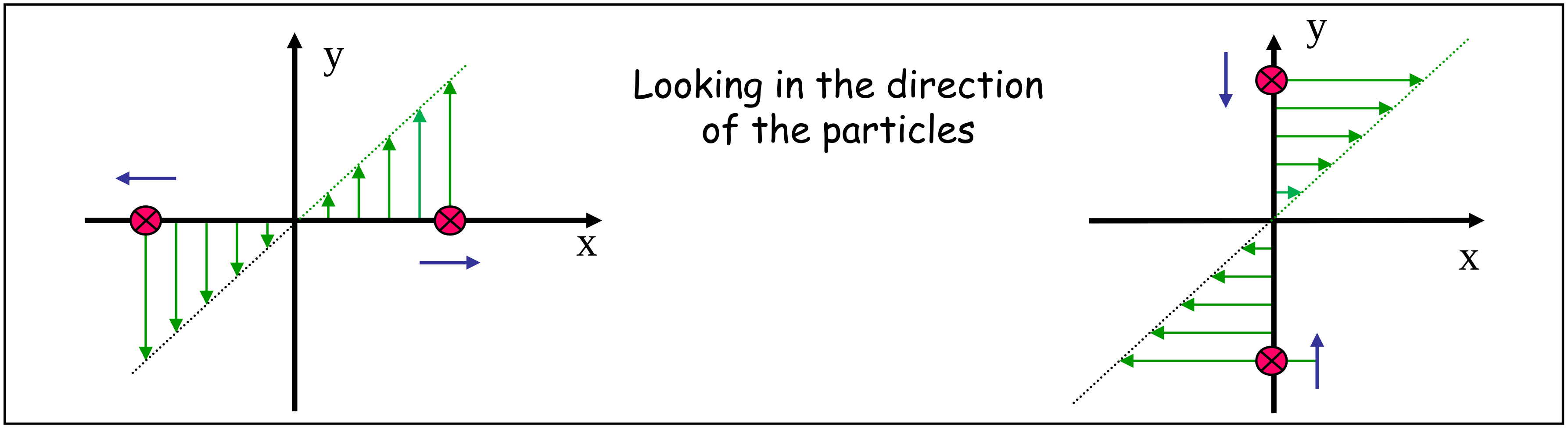
- In a given plane, the quadrupole has the same properties like a classical optical lens.



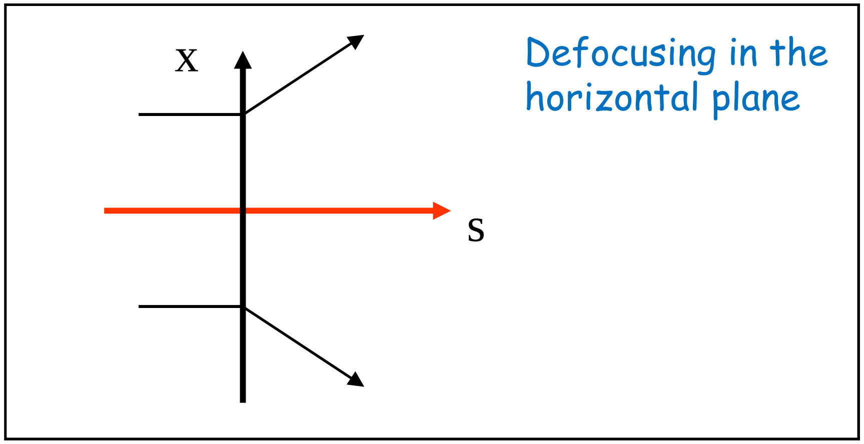
Focusing

But a quadrupole differs from an optical lens :

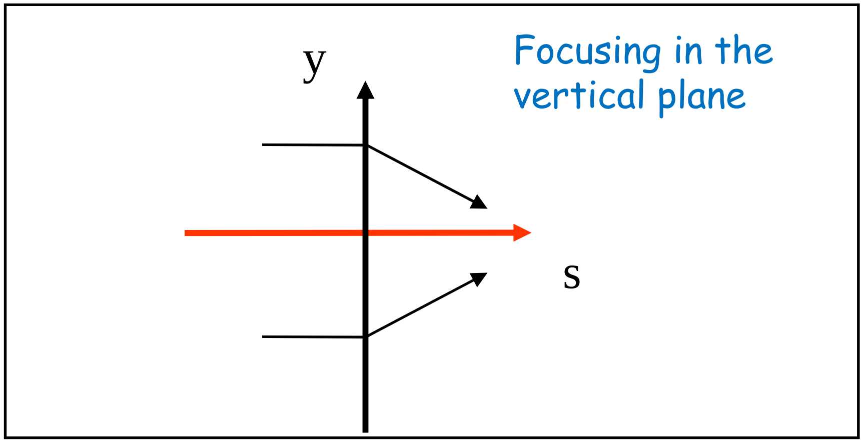
It is focusing in one plane, defocusing in the other !!!



Looking in the direction of the particles

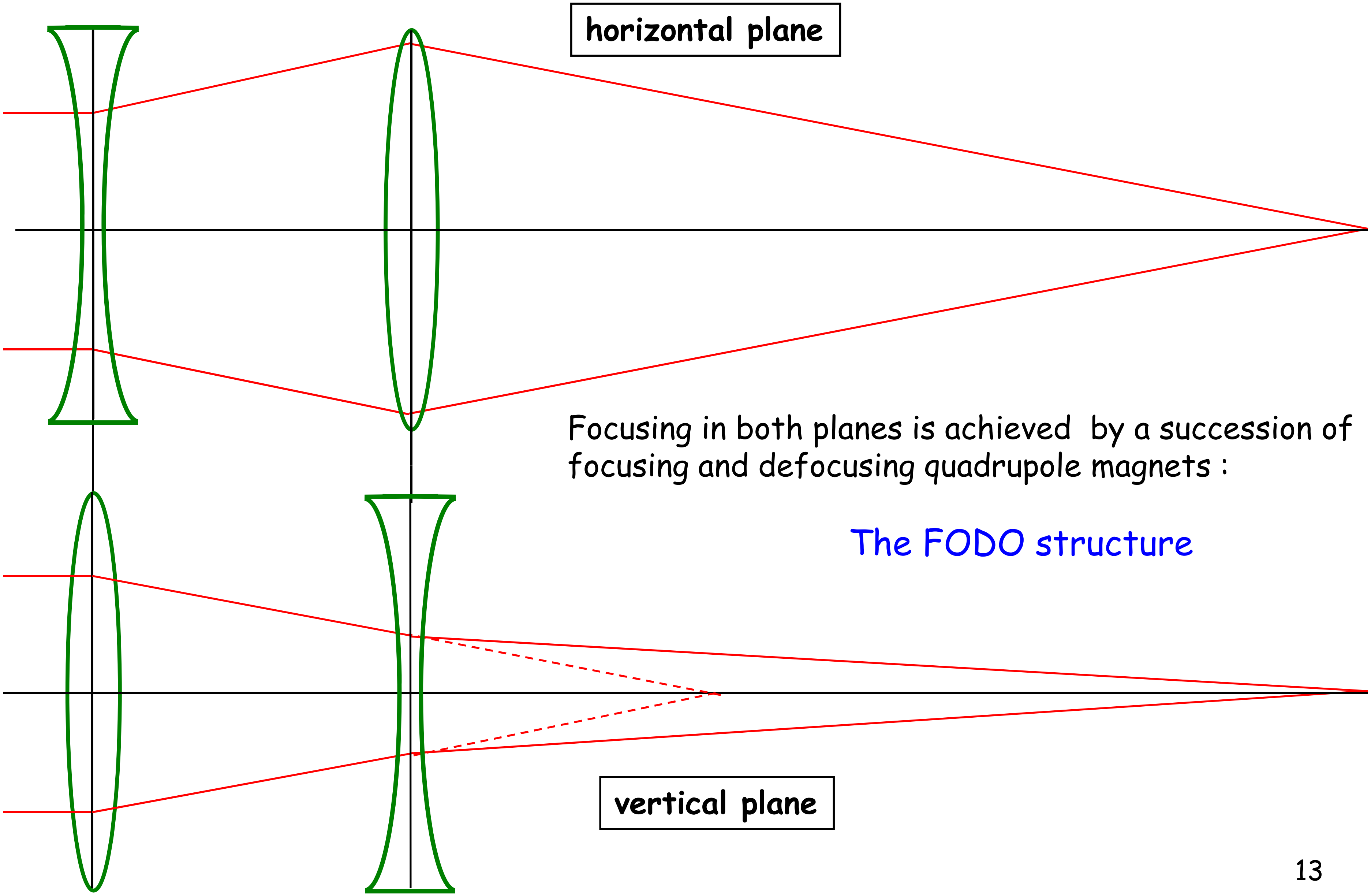


Defocusing in the horizontal plane



Focusing in the vertical plane

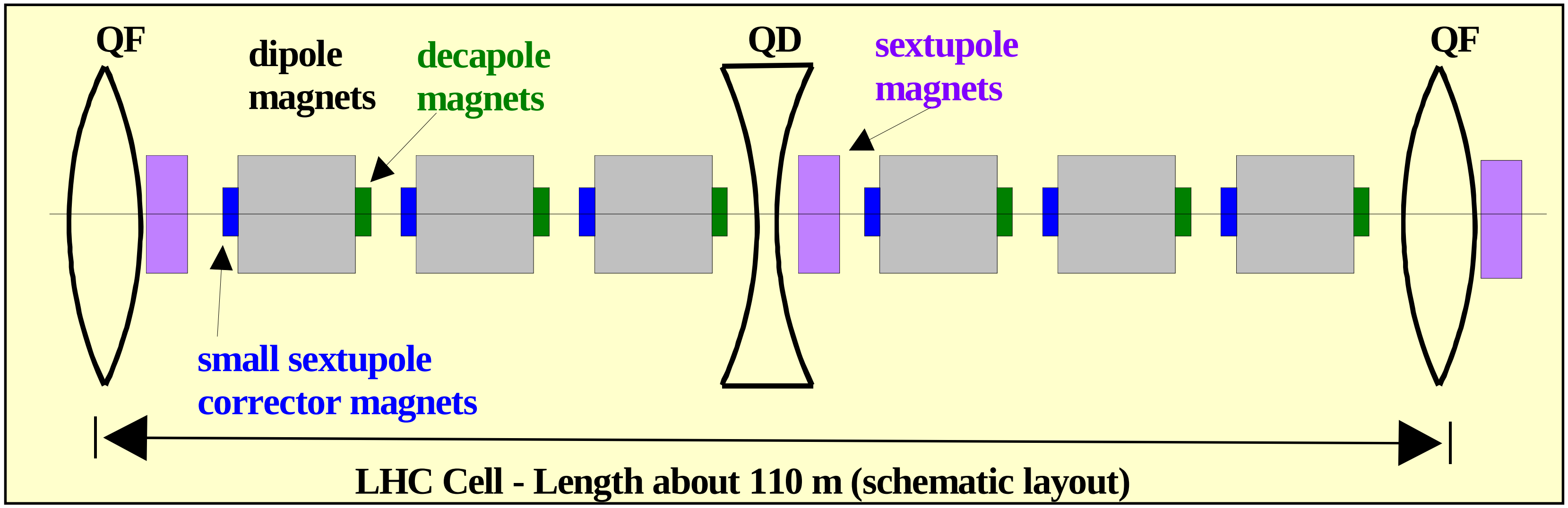
Accelerator lattice



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

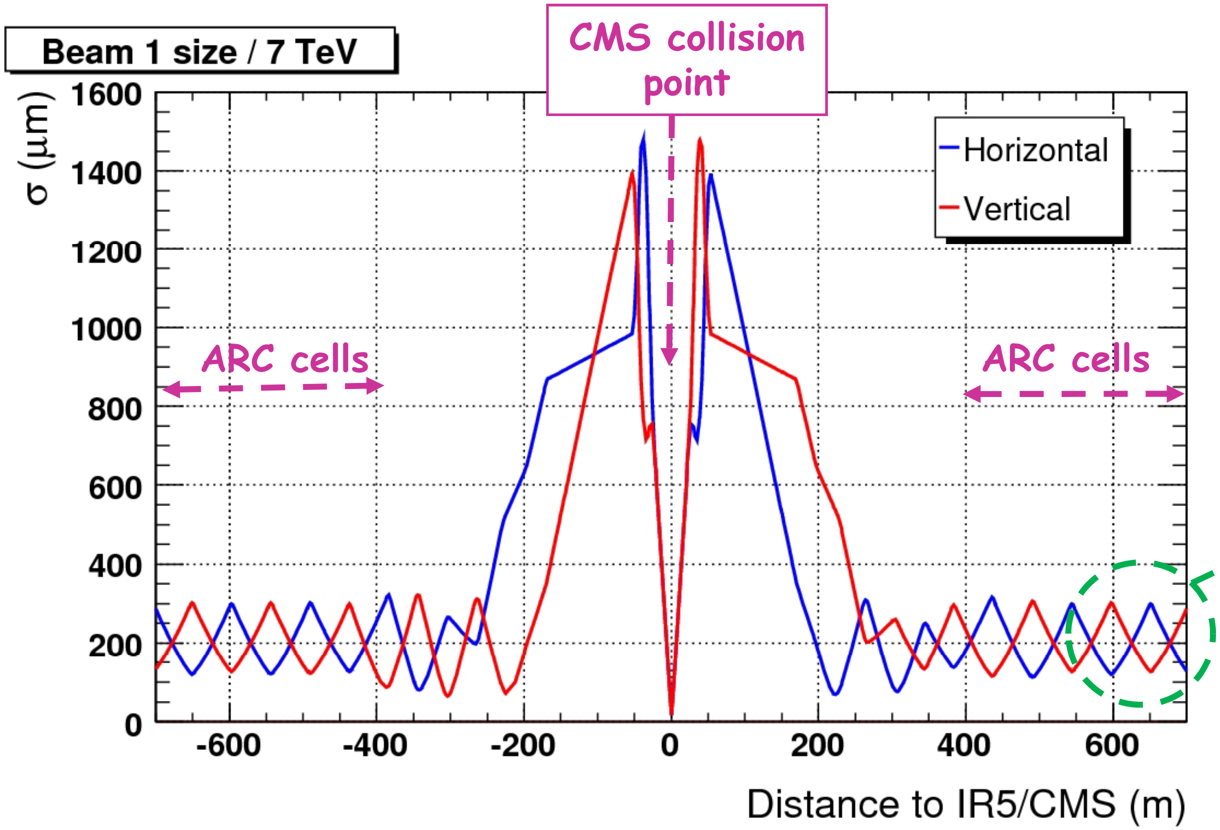
The FODO structure

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 !

Beam envelope



CMS collision point

ARC cells

ARC cells

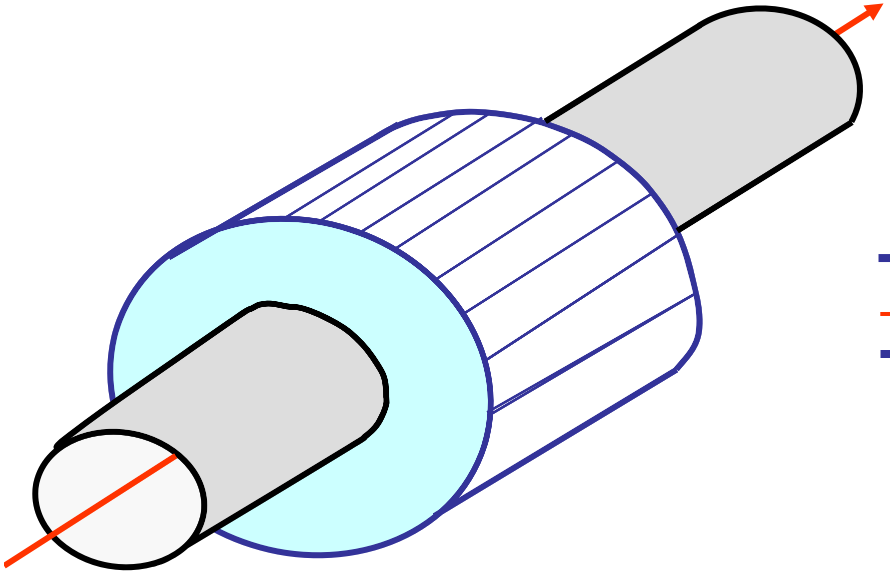
Fits through the hole of a needle!

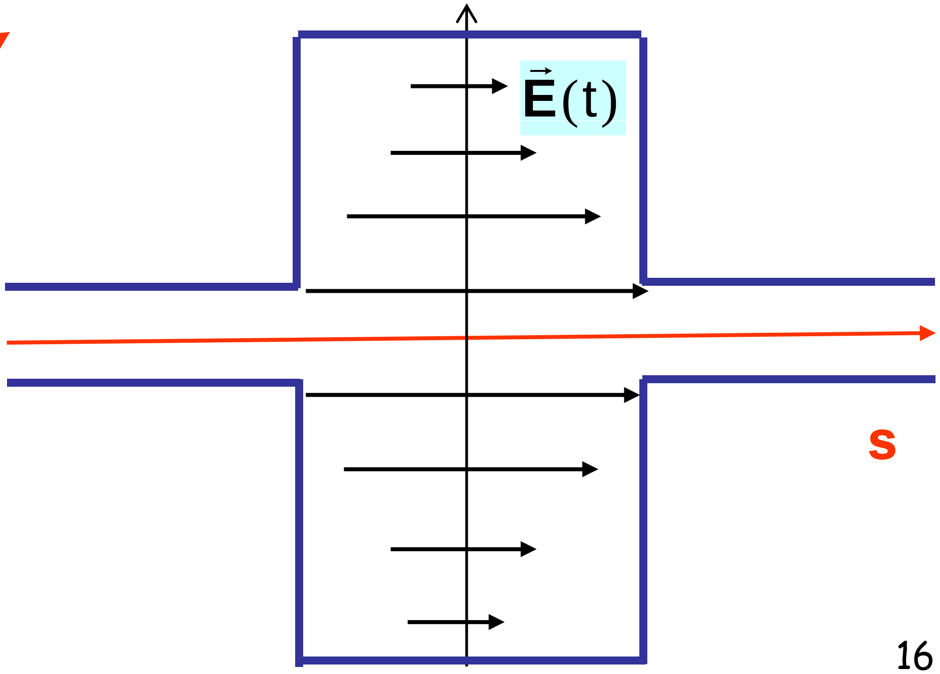
- ❑ The envelope of the size beam is given by the so-called <u>'β'-function</u> (⇔ optics):
  - In the arcs the optics follows a regular pattern.
  - In the long straight sections, the optics is matched to the 'telescope' that provides very strong focusing at the collision point.
- ❑ Collision point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





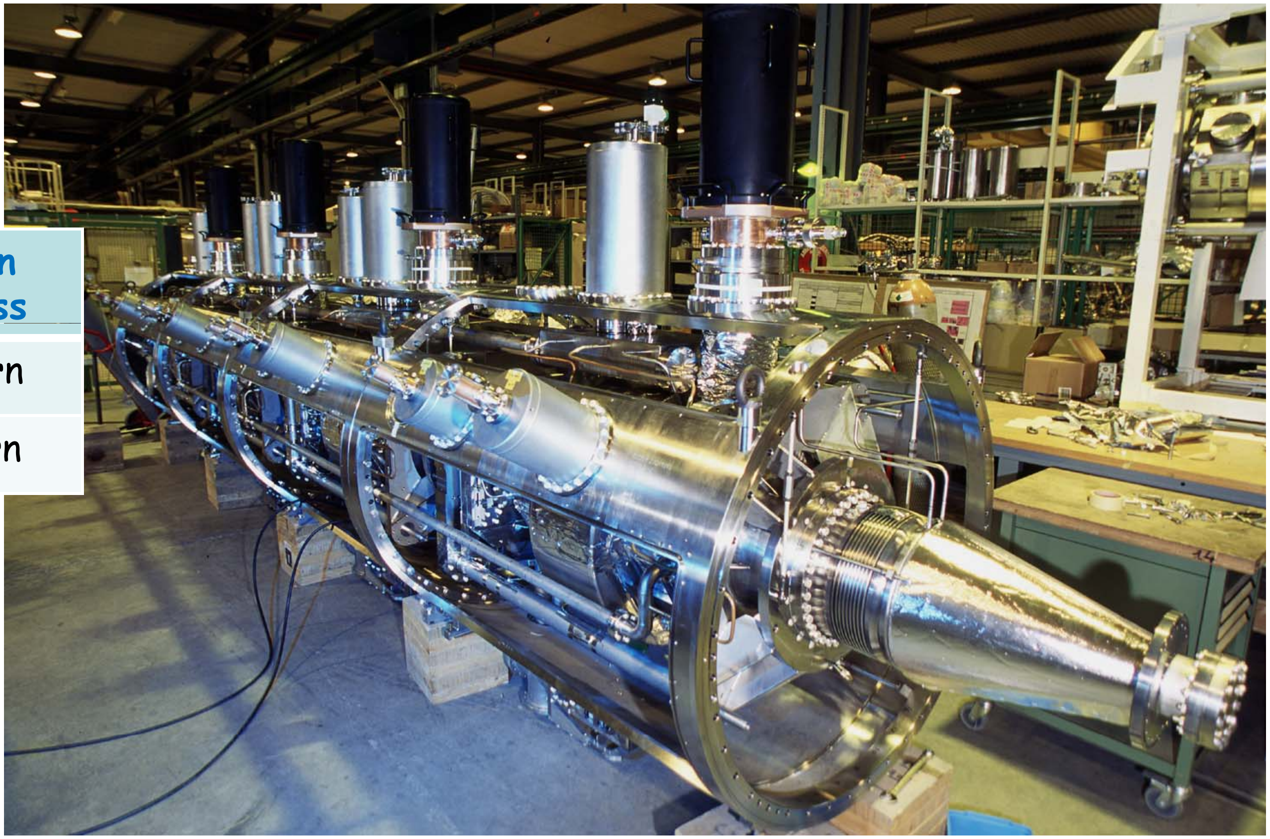
LHC RF system

- ☐ 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 !

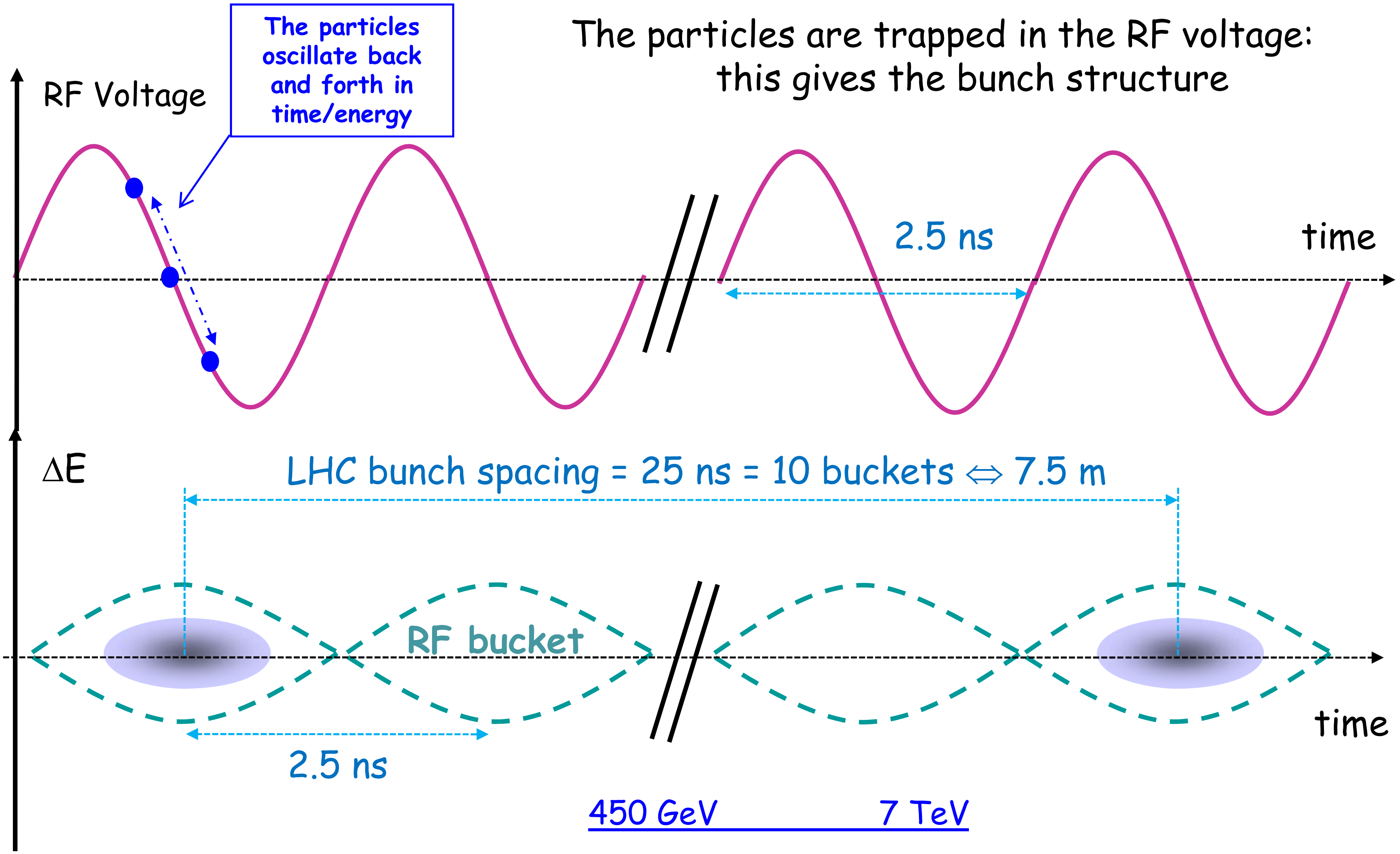
	Synchrotron radiation loss
LHC @ 7 TeV	6.7 keV /turn
LEP @ 104 GeV	~3 GeV /turn

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

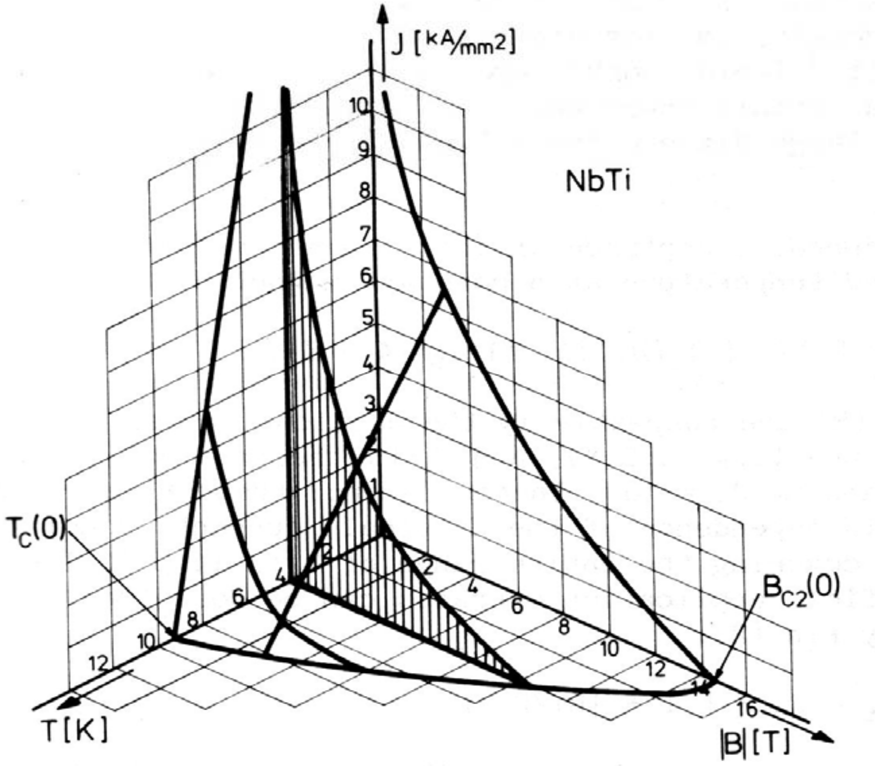


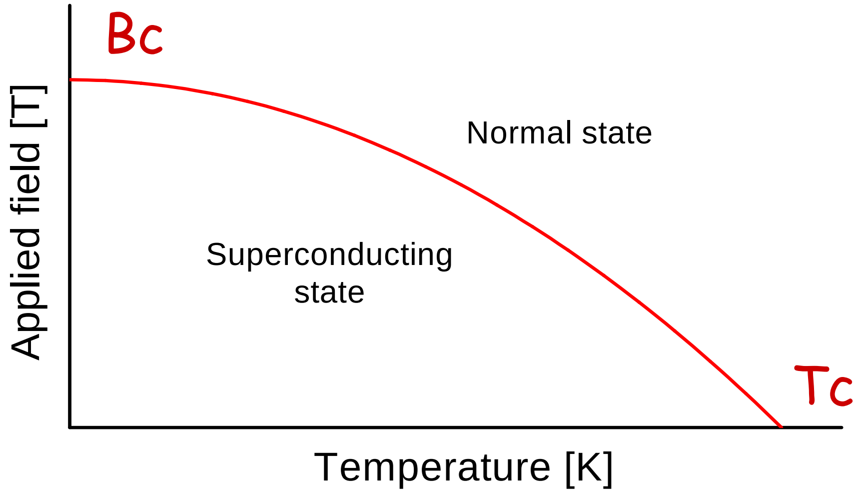
	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

Magnets & Machine Layout

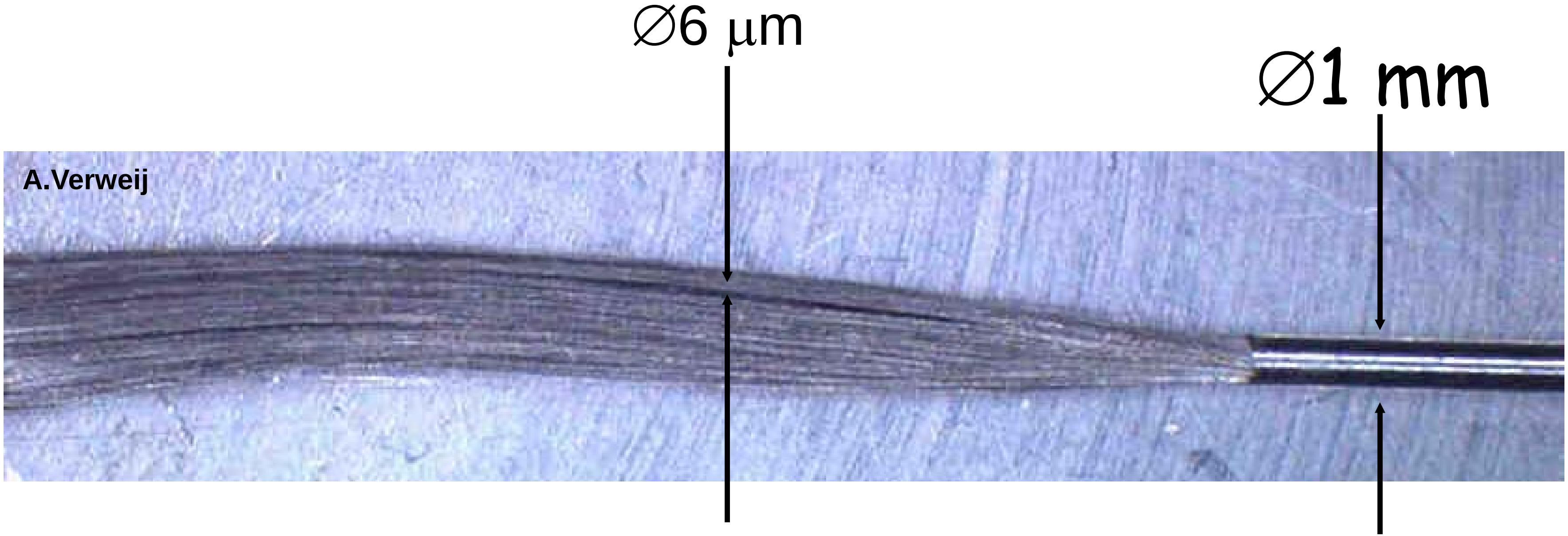
Superconductivity

- 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 !



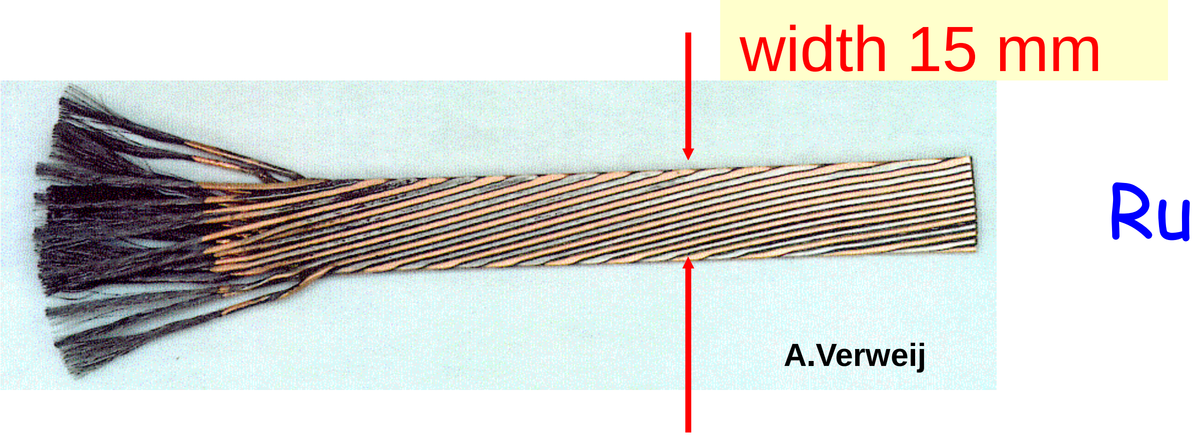


The superconducting cable



A.Verweij

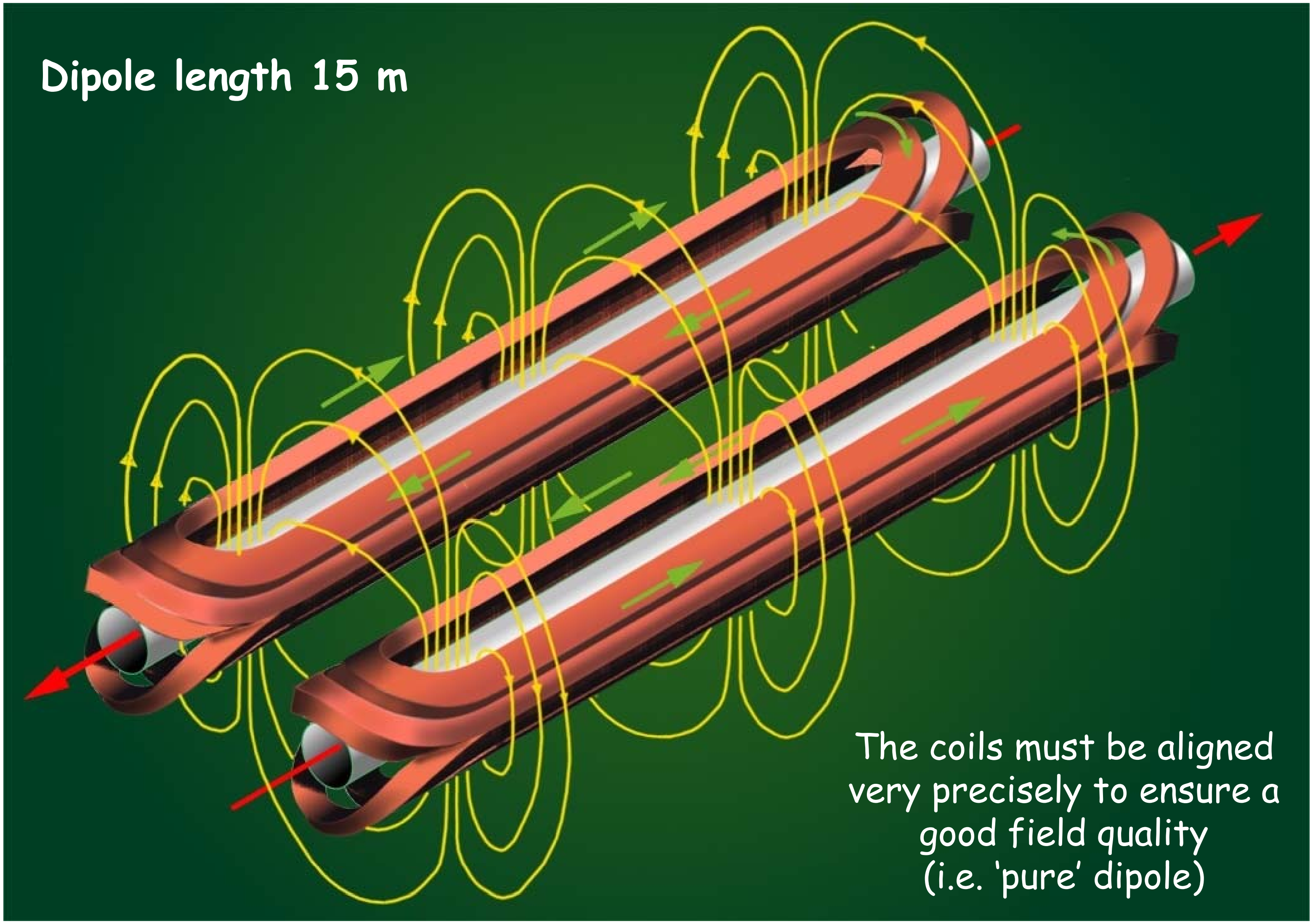
Typical value for operation at 8T and 1.9 K: 800 A



A.Verweij

Rutherford cable

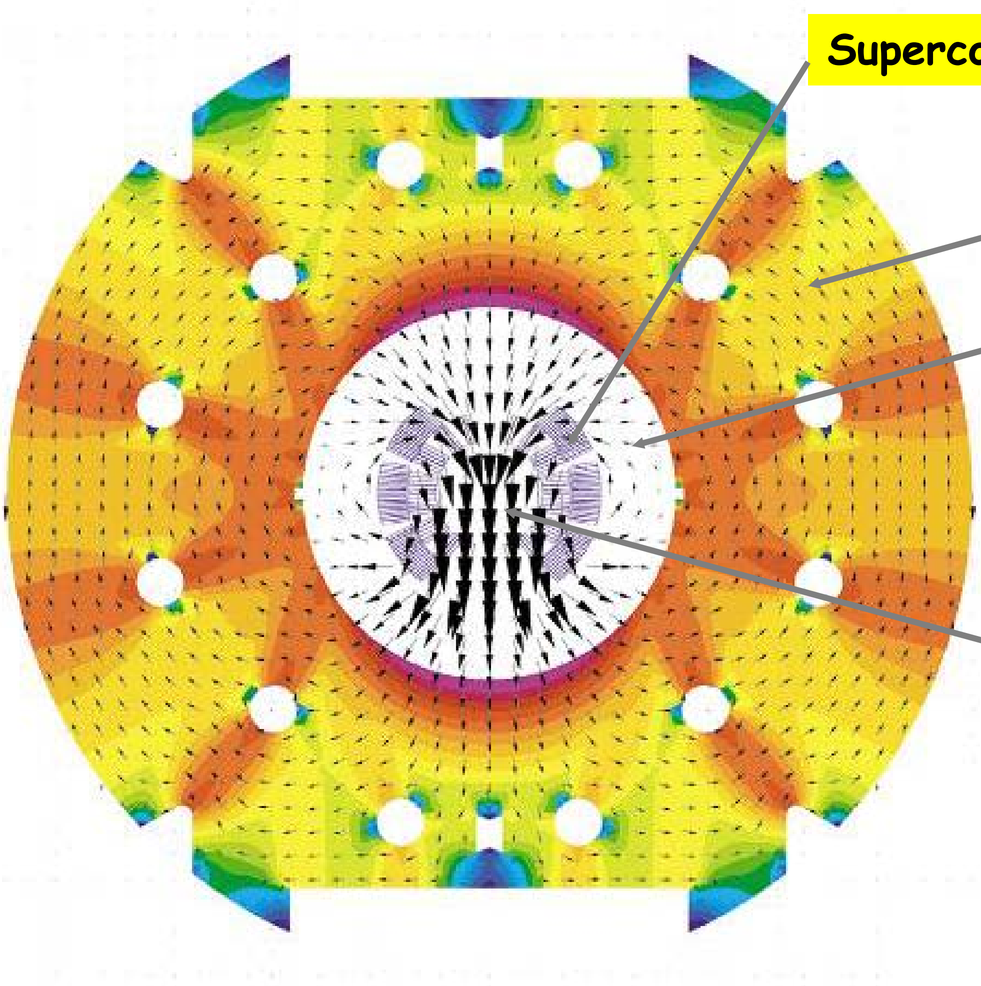
Coils for dipoles



Dipole length 15 m

The coils must be aligned very precisely to ensure a good field quality (i.e. 'pure' dipole)

Dipole field map - cross-section

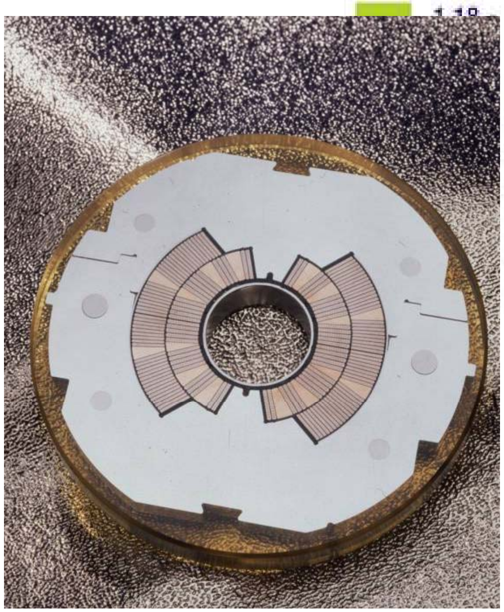


Superconducting coil

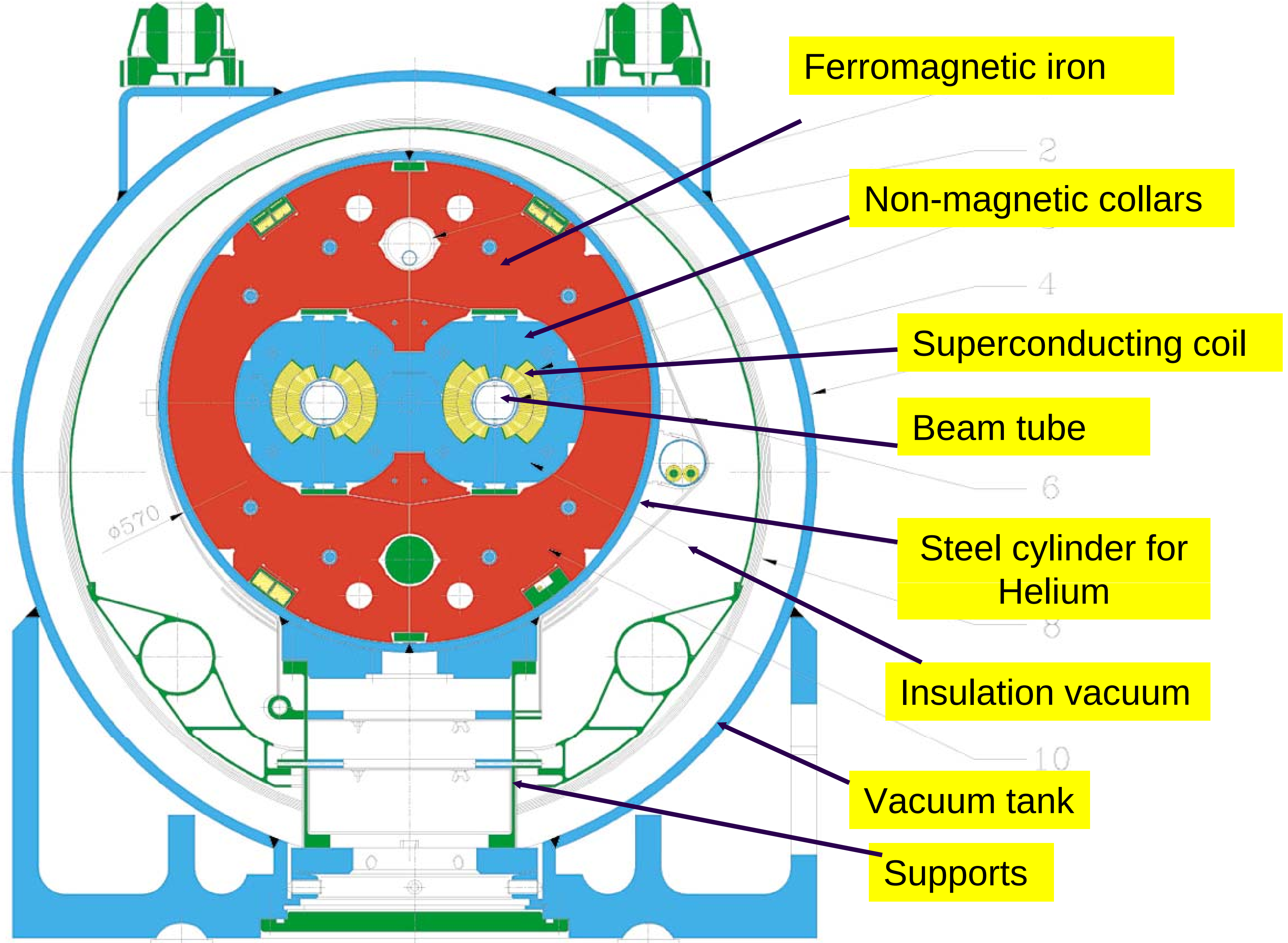
Iron

Non-magnetic collars

Beam



B = 8.33 Tesla   I = 11800 A   L = 0.1 H



Ferromagnetic iron

Non-magnetic collars

Superconducting coil

Beam tube

Steel cylinder for Helium

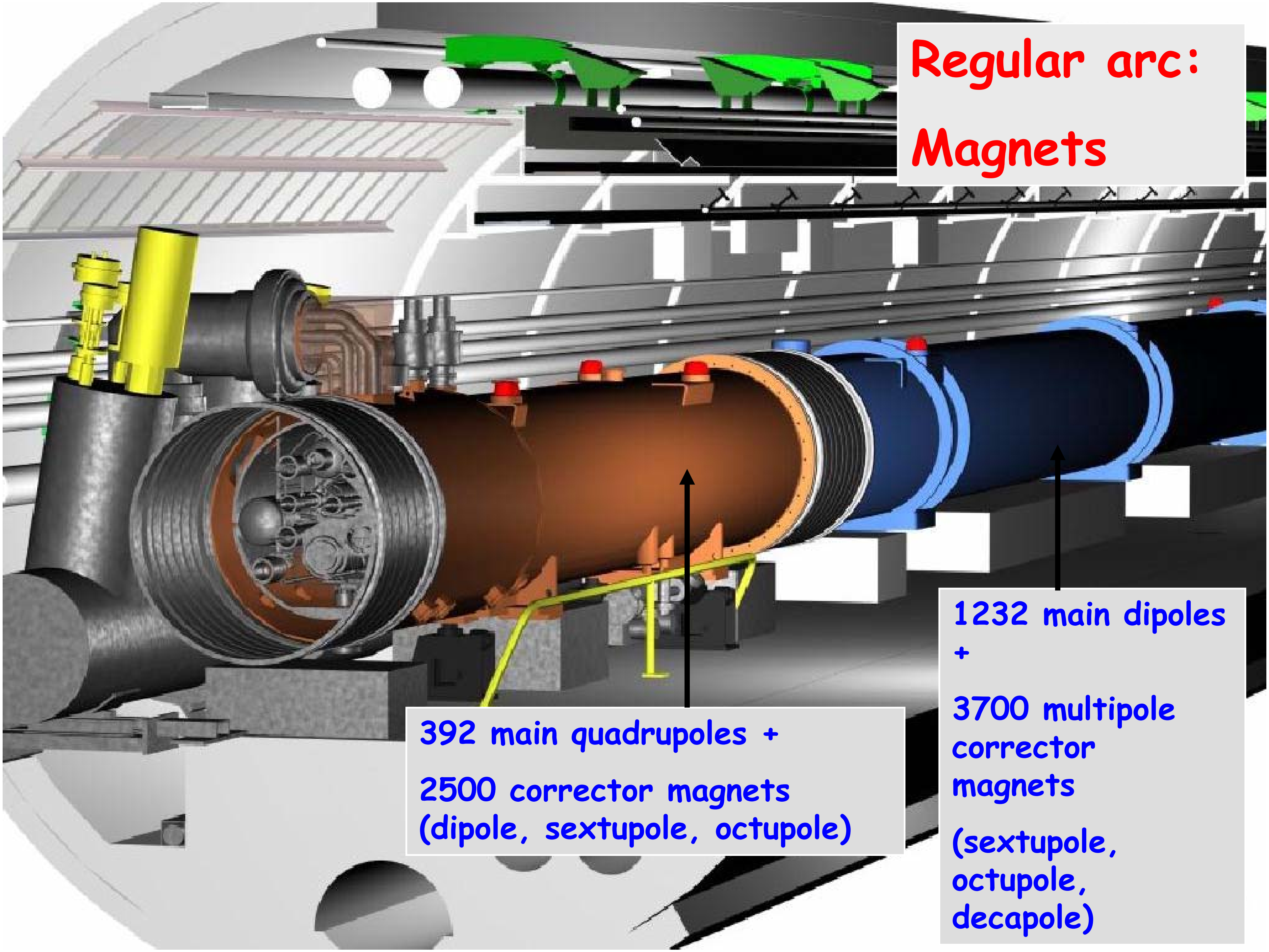
Insulation vacuum

Vacuum tank

Supports

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

Regular arc: Magnets



392 main quadrupoles +

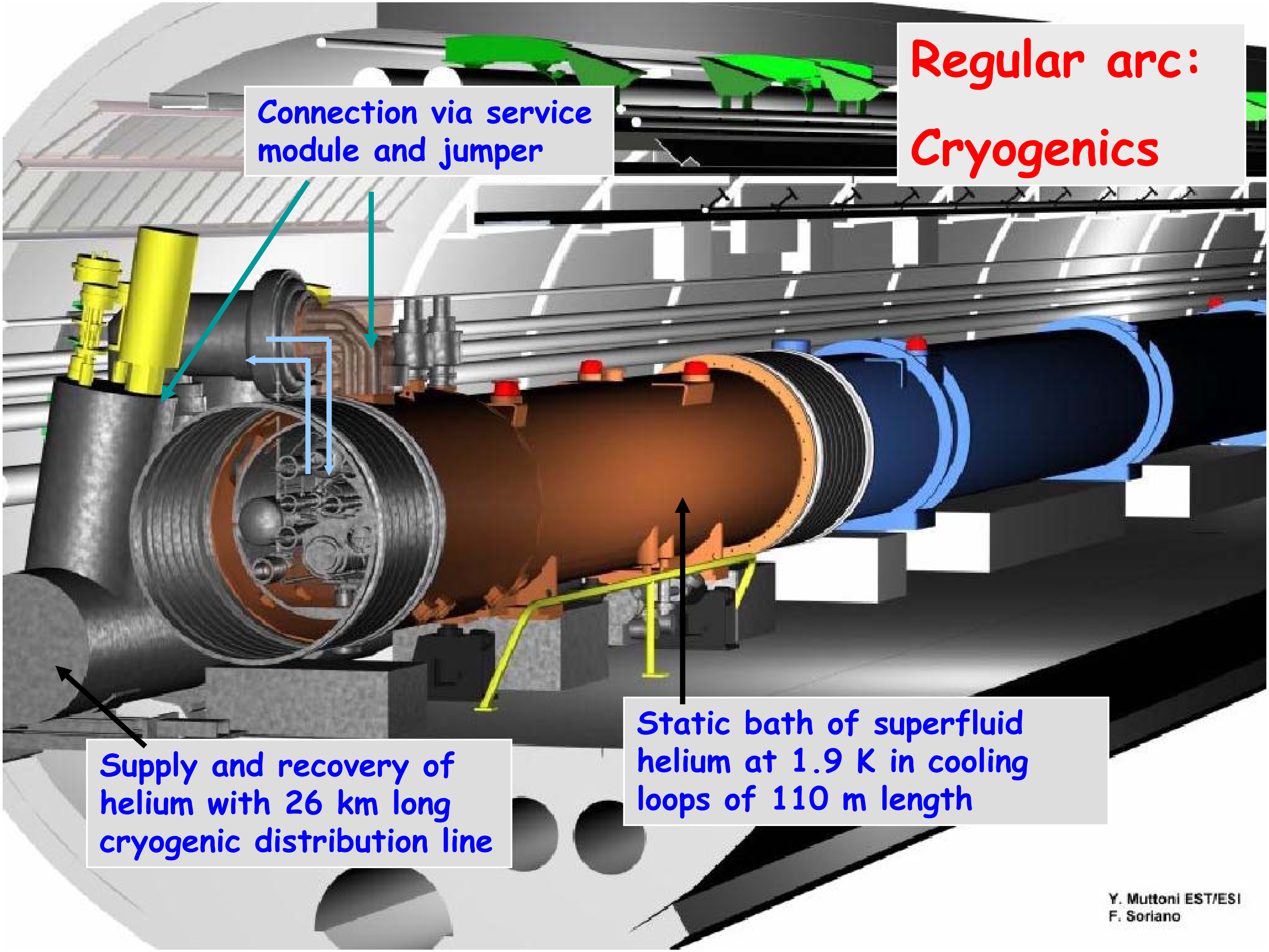
2500 corrector magnets (dipole, sextupole, octupole)

1232 main dipoles +

3700 multipole corrector magnets

(sextupole, octupole, decapole)

Regular arc: Cryogenics



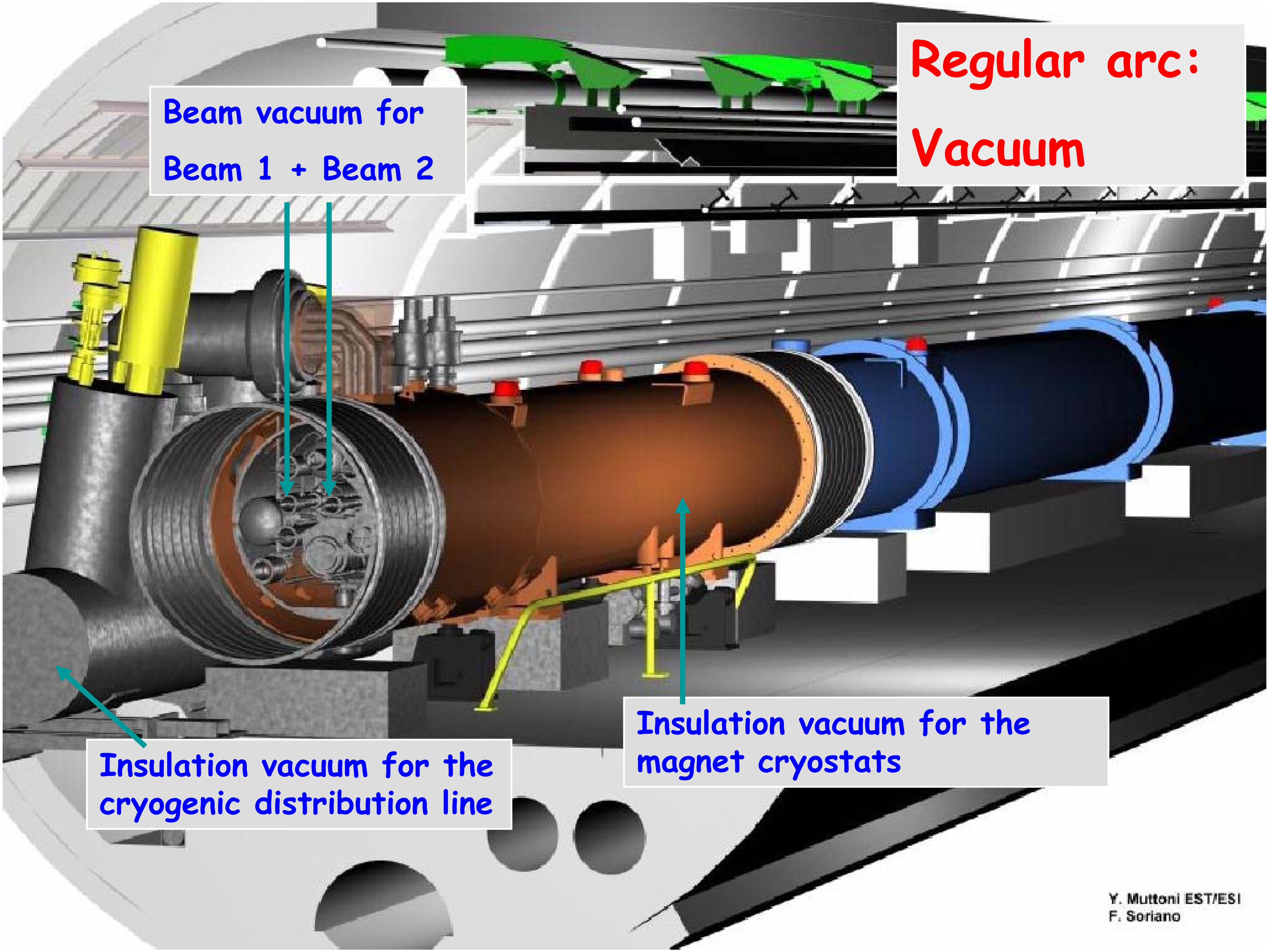
Connection via service module and jumper

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



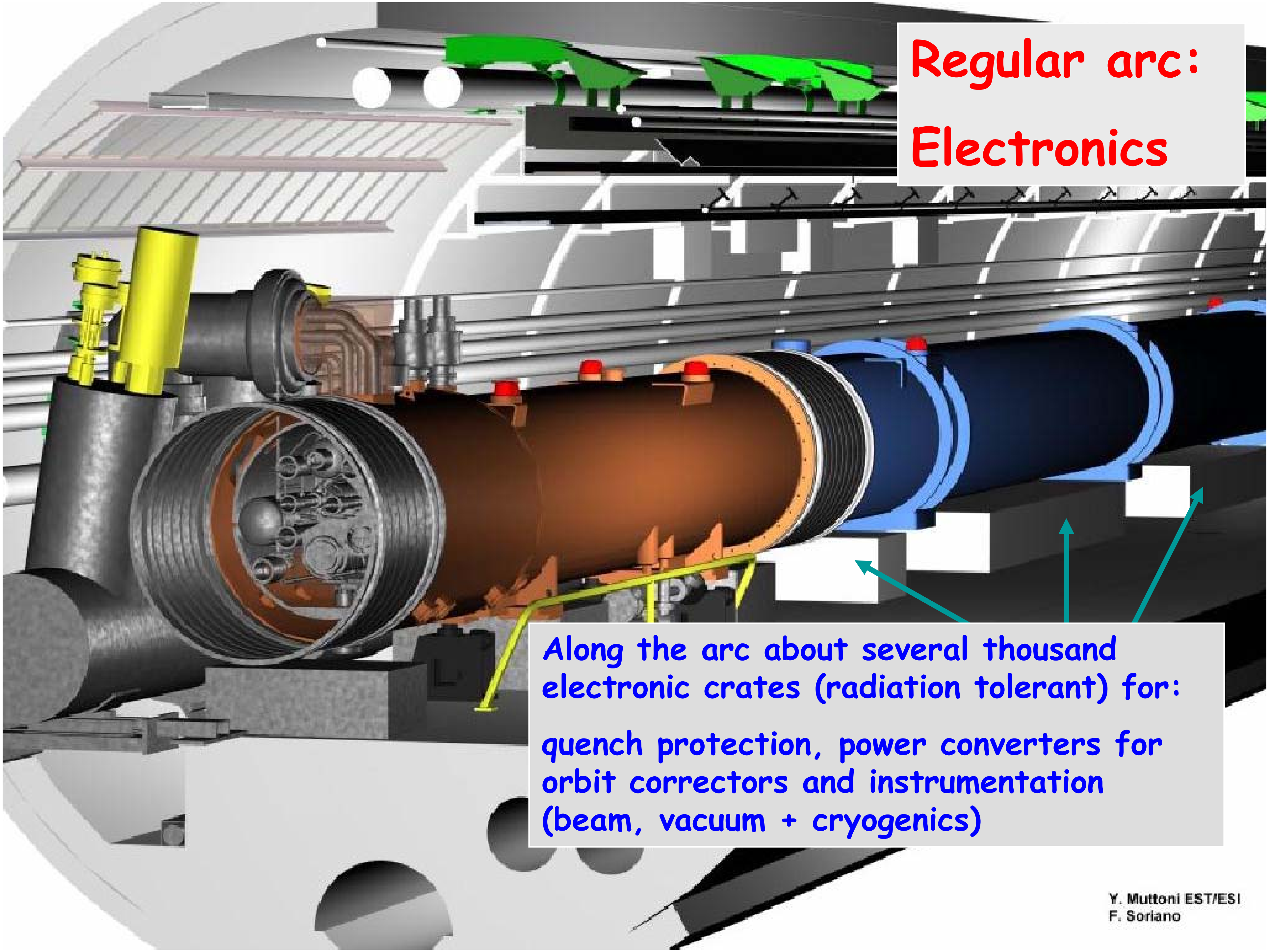
Beam vacuum for
Beam 1 + Beam 2

Insulation vacuum for the cryogenic distribution line

Insulation vacuum for the magnet cryostats

Y. Muttoni EST/ESI
F. Soriano

Regular arc: Electronics



Along the arc about several thousand electronic crates (radiation tolerant) for:

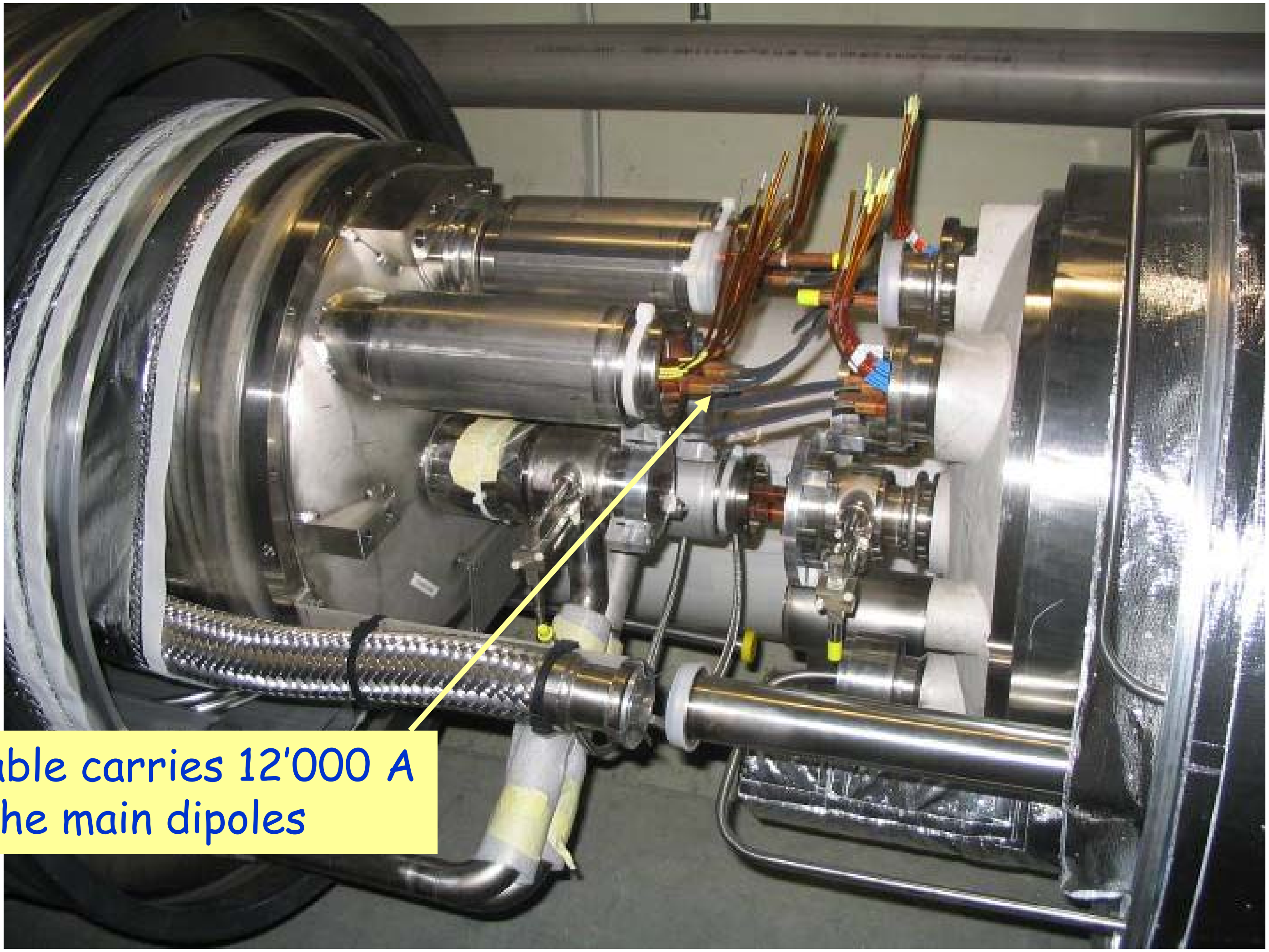
quench protection, power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)

Y. Muttoni EST/ESI
F. Soriano

Tunnel view

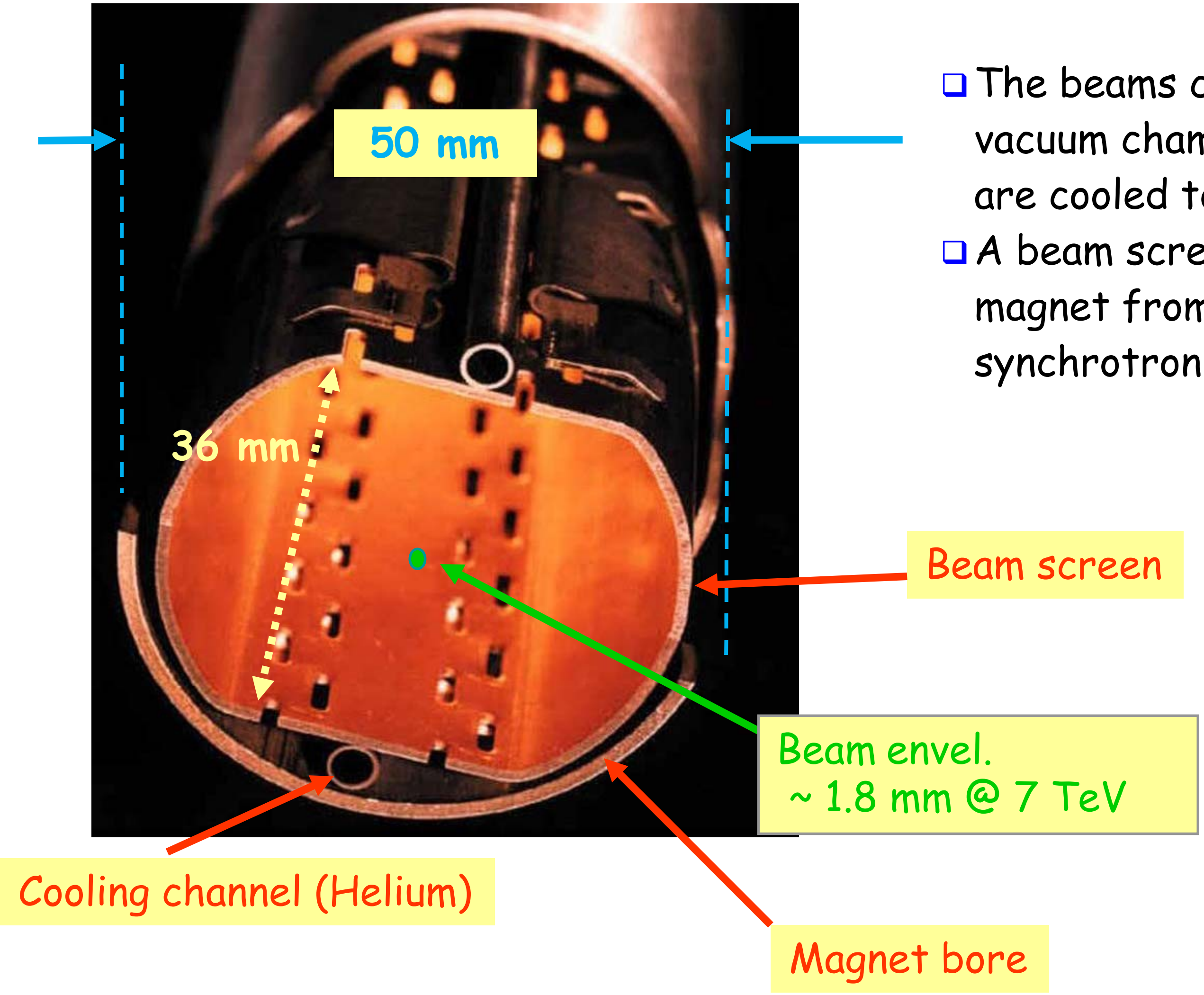
Complex interconnects

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 dipoles

Vacuum chamber

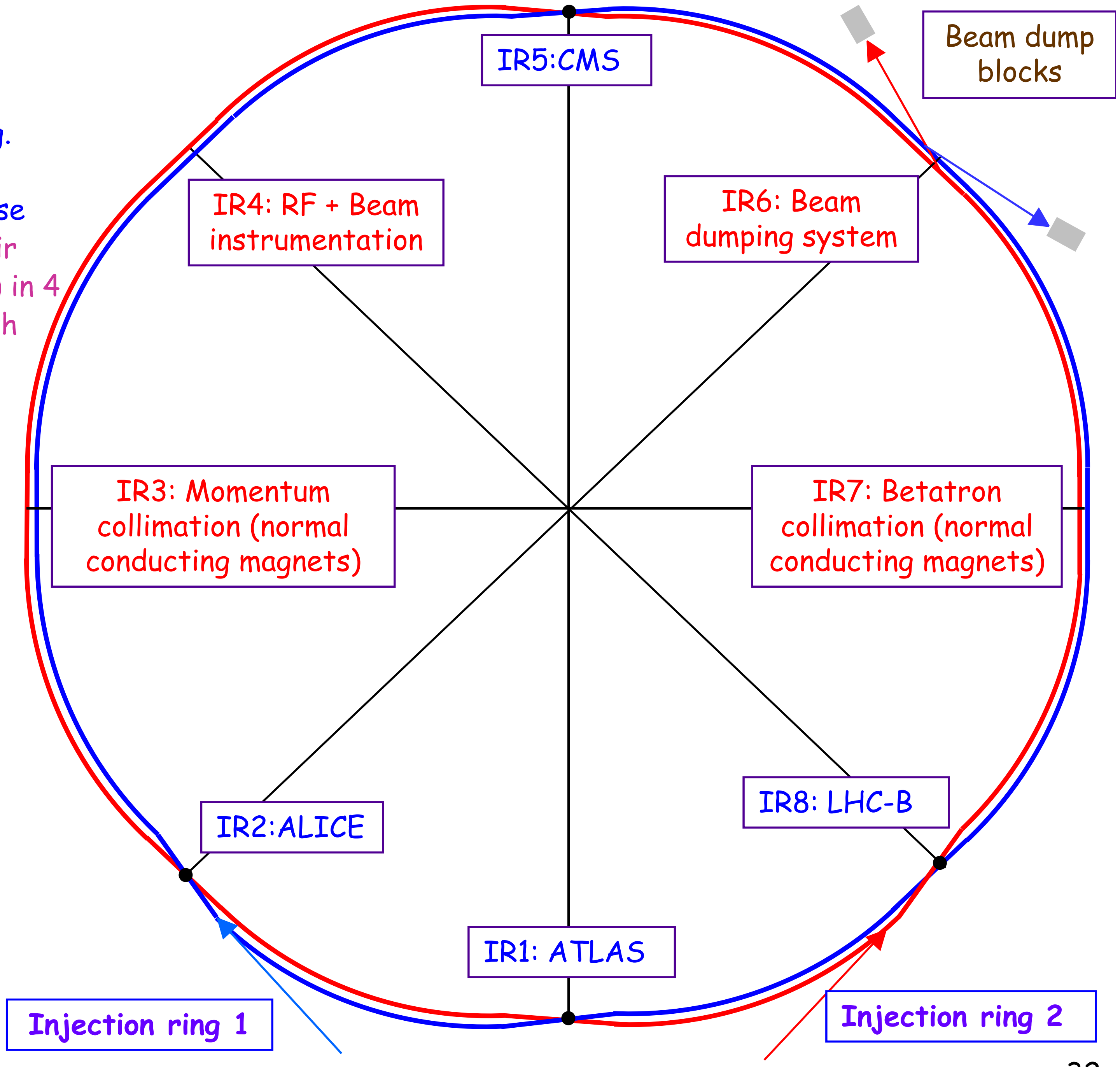


- ❑ The beams circulate in two ultra-high vacuum chambers made of Copper that are cooled to T = 4-20 K.
- ❑ A beam screen protects the bore of the magnet from image currents, synchrotron light etc from the beam.

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 !



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 !!

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

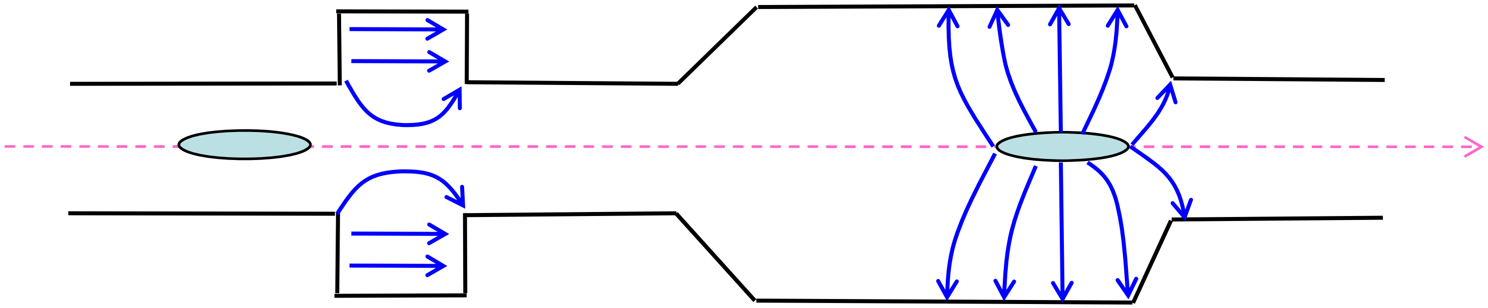
- f : the revolution frequency is given by the circumference, f=11.246 kHz.
- N : the bunch population – N=1.15x10^{11} protons
    - Injectors (brighter beams)
    - Collective interactions of the particles
    - Beam encounters
- k : the number of bunches – k=2808
    - Injectors (more beam)
    - Collective interactions of the particles
    - Interaction regions
    - Beam encounters
- $\sigma*$: 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 COLLECTIVELY unstable 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 !

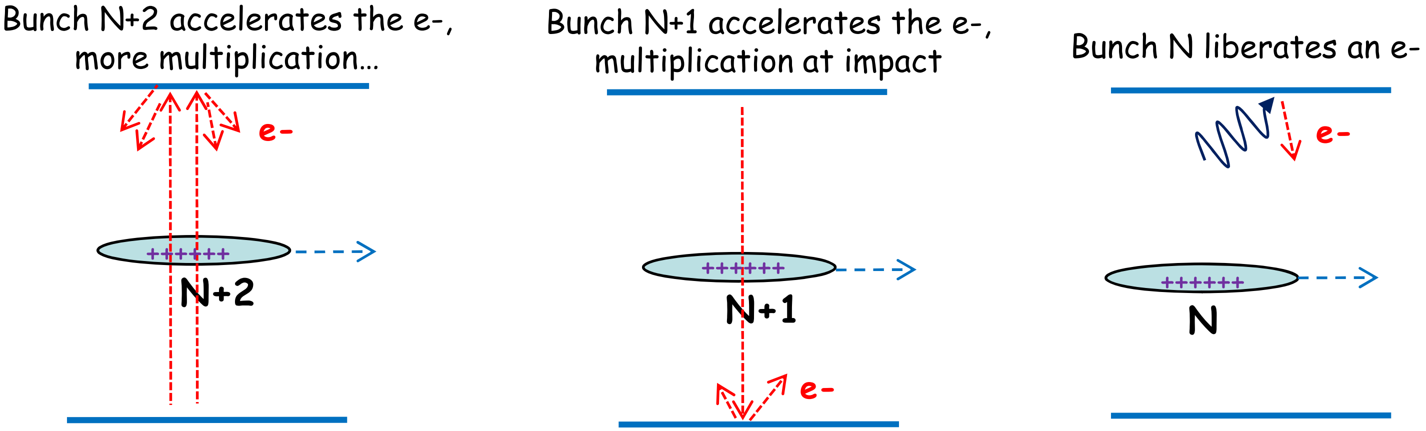
→ limits the intensity per bunch and per beam !

Electron clouds…

… affect high intensity beams with positive charge and closely spaced bunches.

- Electrons are generated at the vacuum chamber surface by beam impact, photons…
- If the probability to emit secondary e- is high (enough), more e- are produced and accelerated by the field of a following bunch(es) and multiplication start…
- The cloud of e- that may build up can drive the beam unstable, and at the LHC, overload the cryogenic system by the heat they deposit on the chamber walls !
- This effect depends strongly on surface conditions, simulations are tricky because they are very sensitive to very low energy (~ eV) electrons. The latest simulation indicate that the problem may be less severe than initially anticipated but …

→ The cloud can 'cure itself' because the impact of all those electrons cleans the surface, reduces the electron emission probability and eventually the cloud disappears !

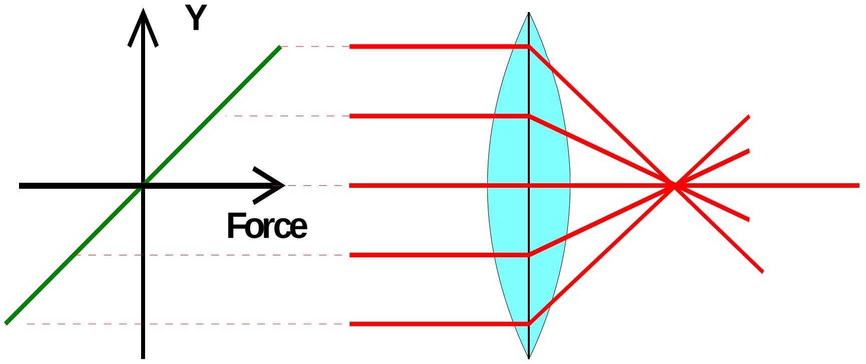


Bunch N+2 accelerates the e-, more multiplication…

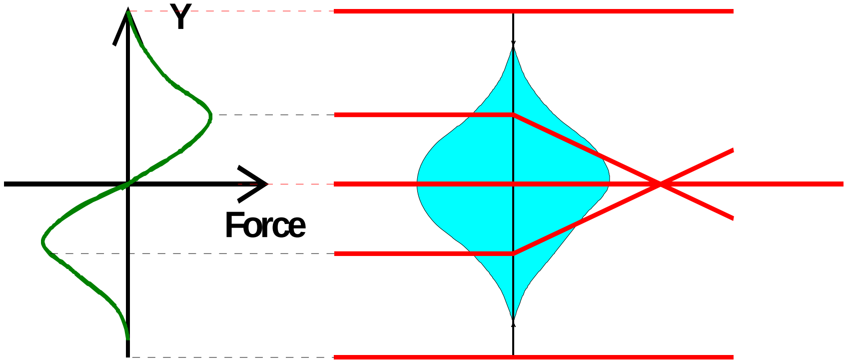
Bunch N+1 accelerates the e-, multiplication at impact

Bunch N liberates an e-

‘Beam-beam’ interaction



Quadrupole lens

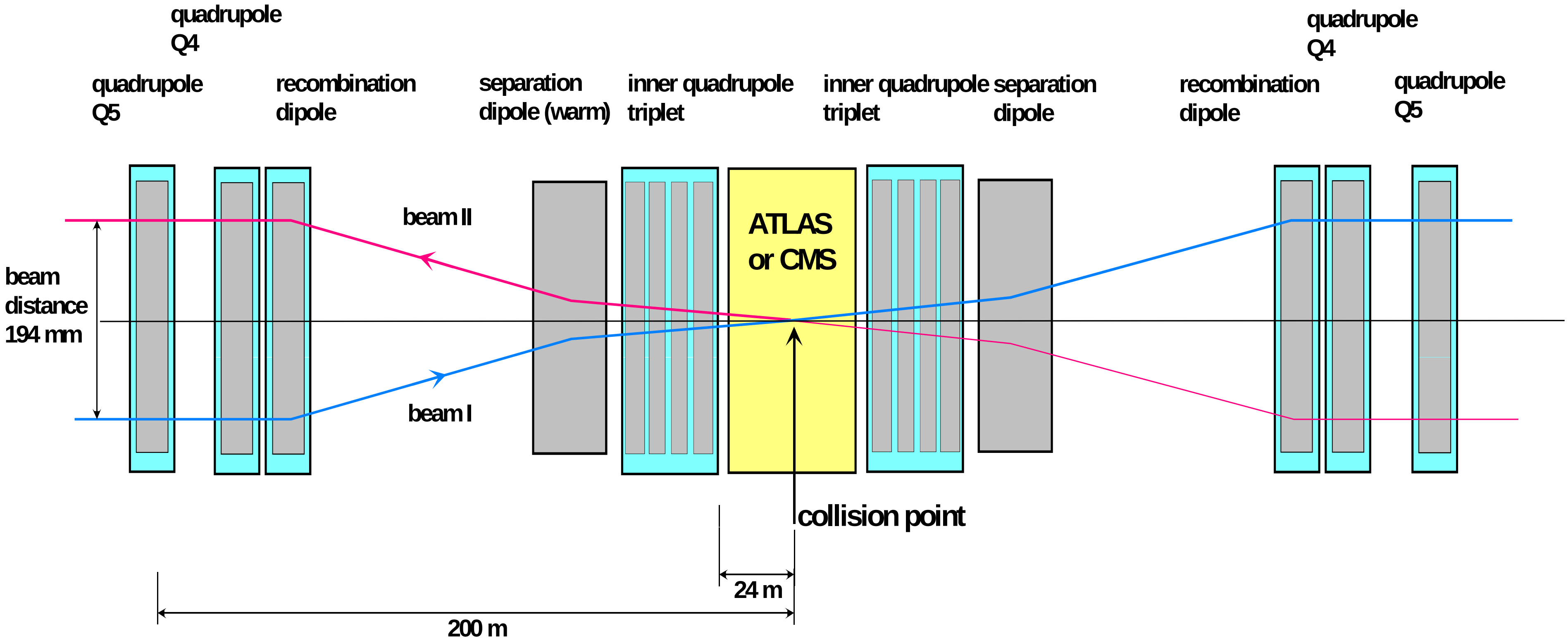


Beam(-beam) lens

- 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 encounters in ATLAS, CMS, ALICE and LHCb.

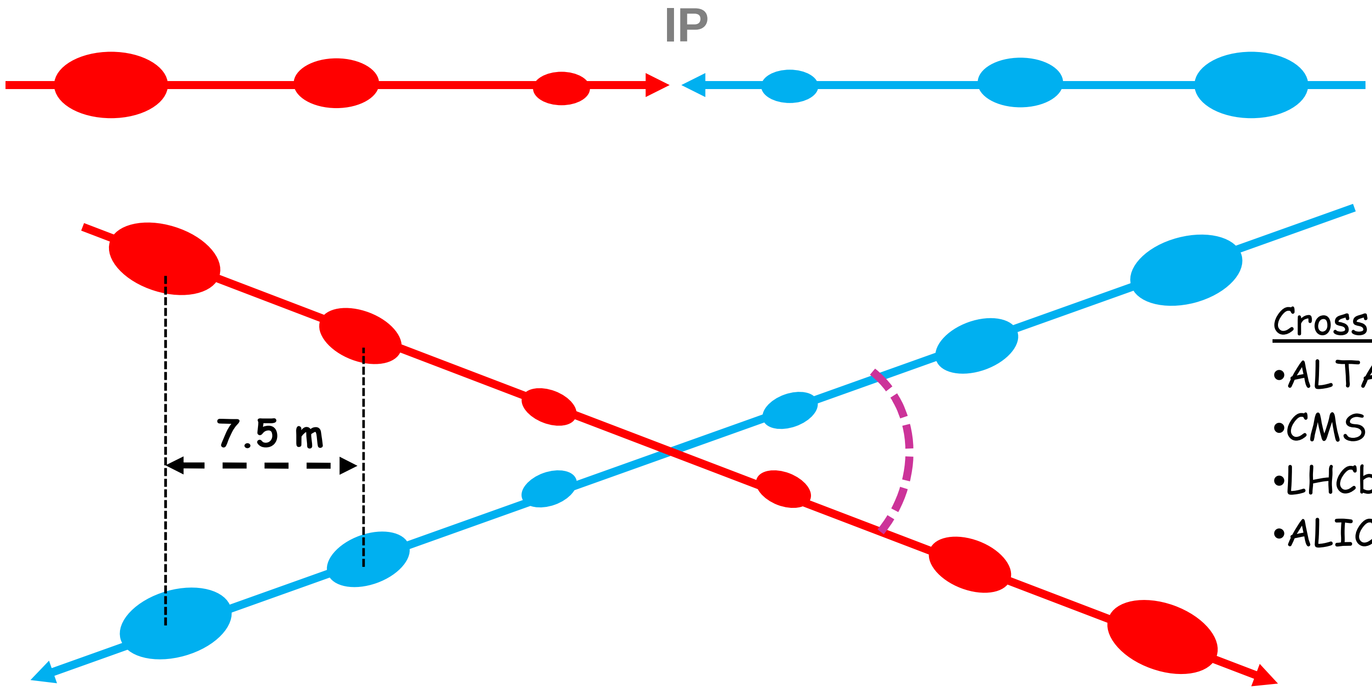
Crossing angles

- ❑ 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 :

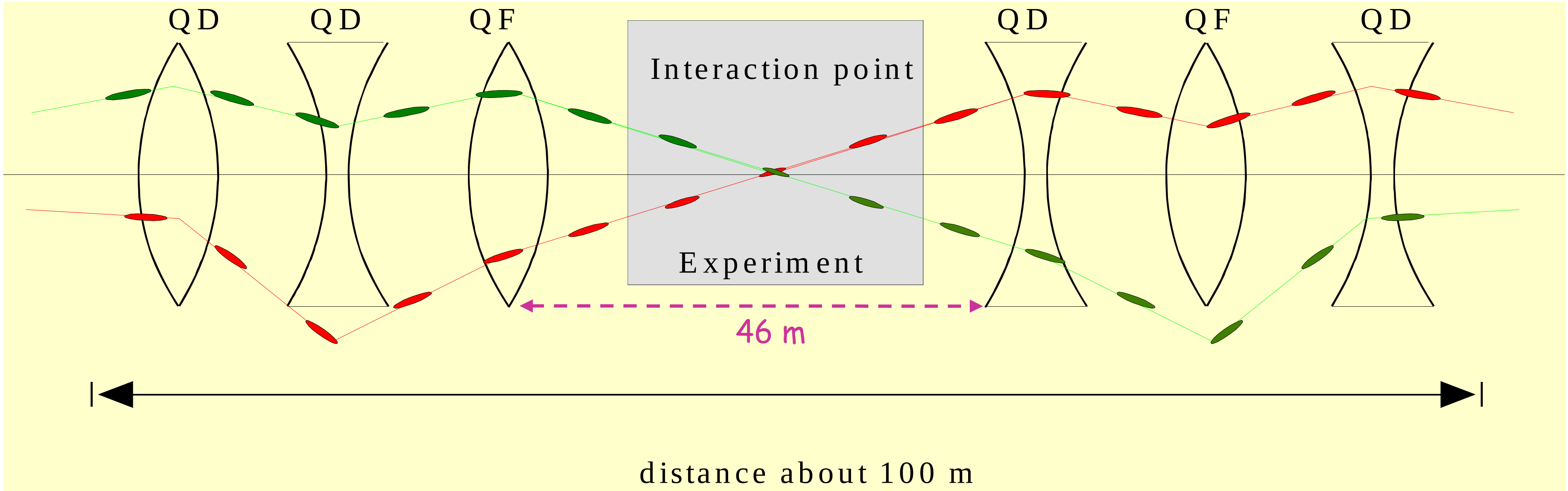
  A reduction of the luminosity due to the finite bunch length of 7.6 cm and the non-head on collisions → L reduction of ~ 17%.



<u>Crossing planes & angles</u>

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

Interaction region layout



- The quadrupoles are focusing for beam 1, defocusing for beam 2, and vice-versa !
- The final focus is made with the high gradient and large aperture 'triplet' quadrupoles (US-JAPAN) :
  - Large beam size ~ 100 x size at IP
  - Large beam separation from crossing angle ~ 12 mm
- Beam sizes :

at IP (ATLAS, CMS)	16 μm
in the triplets	~1.6 mm
in the arcs	~0.2 mm

Tevatron

- 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.
- 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 !).
- 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:

Luminosity gain of LHC comes basically from k !!

Tricky to operate !!