The Large Hadron Collider (LHC) of CERN

Lectures of the physics doctoral school of Grenoble

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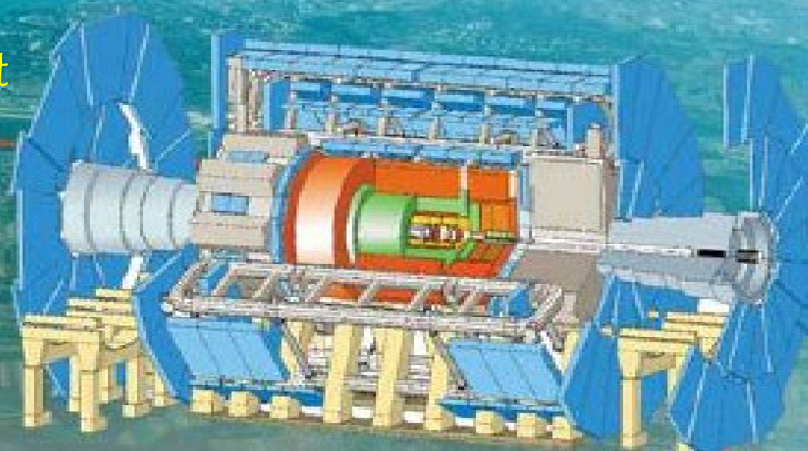


Brief history of the LHC program

-1977 : CERN DG John Adams mentions LHC as a possible continuation of LEP at CERN
-December 1983 : first working groups on the interest to build a hadron collider in the LEP tunnel organized by Carlo Rubbia
-March 1984 : first general LHC workshop organized by CERN & ECFA in Lausanne
-1985 : working group lead by Carlo Rubbia
-1987 : second general LHC workshop organized by CERN & ECFA in La Thuile
-1989 : third CERN & ECFA general LHC workshop in Barcelona : mark the formation of proto-collaborations of experimentalists
-October 1990 : fourth ECFA general LHC workshop in Aachen
-1990 : Nomination of Detector R&D Committee (DRDC) at CERN
-March 1992 : call for Expression of Interests followed by official presentation of proto-collaborations in Evian. Three Letter of Intend are sent to CERN : L3P, CMS & ATLAS
-1992 : Nomination of the LHC Committee (LHCC)
-1993 : LHCC approves ATLAS & CMS and rejects L3P
-16 December 1994 : official approval of the LHC construction at 14 TeV in two phases : 9 TeV for 2004 and 14 TeV for 2008
-20 December 1997 : final decision to build LHC in one phase at 14 TeV for 2005
-1997 : approval of ALICE
-1998 : approval of LHCb

construction phase ...

-2008 : LHC starts ...

LHC : pp 2 x 7 TeV collider

LHC : 7 TeV
27 km
synchrotron
2008

SPS : 450 GeV
7 km
synchrotron
1976

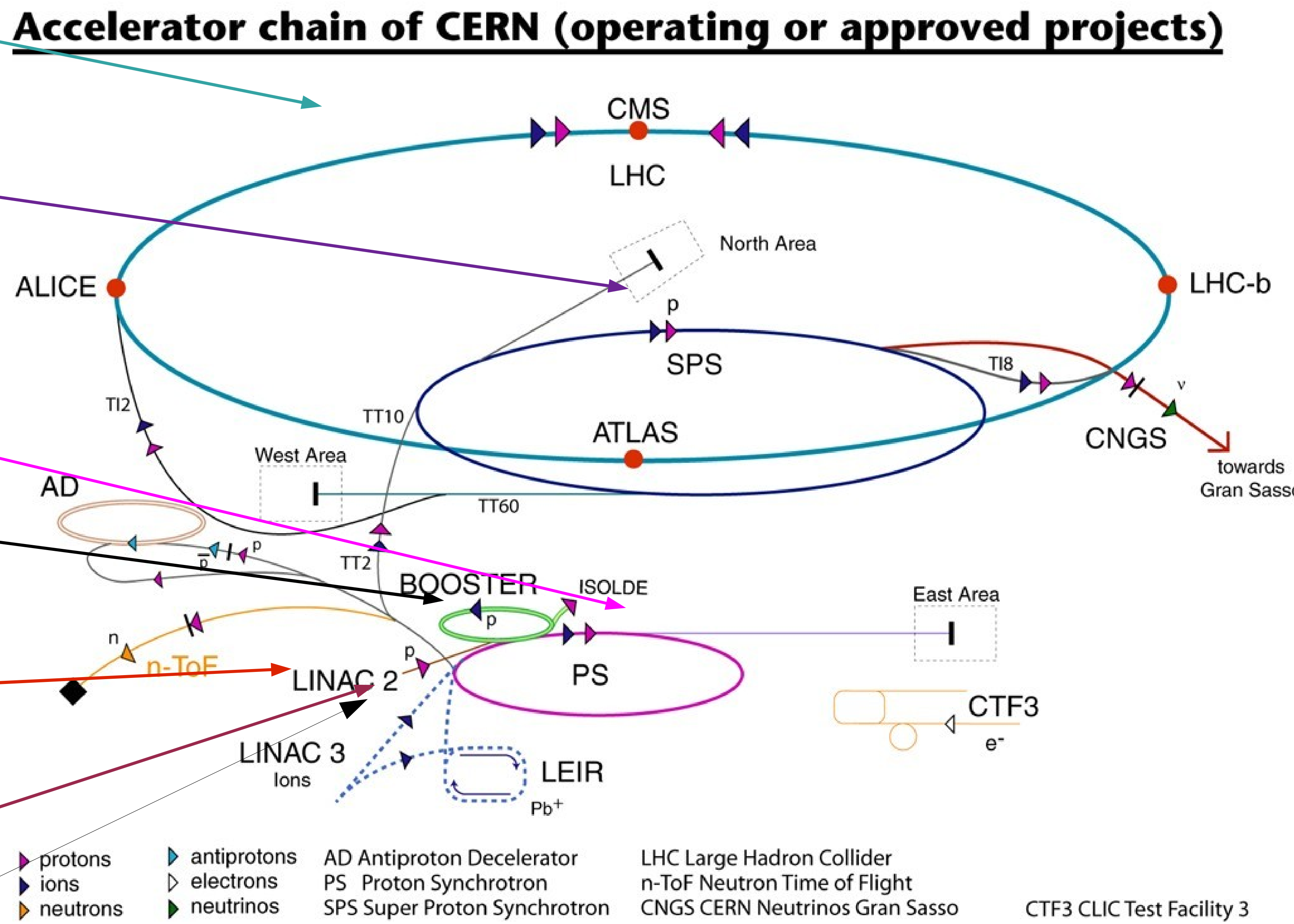
PS : 24 GeV
628 m
synchrotron
1959

BOOSTER : 1.4 GeV
157 m
synchrotron
1972

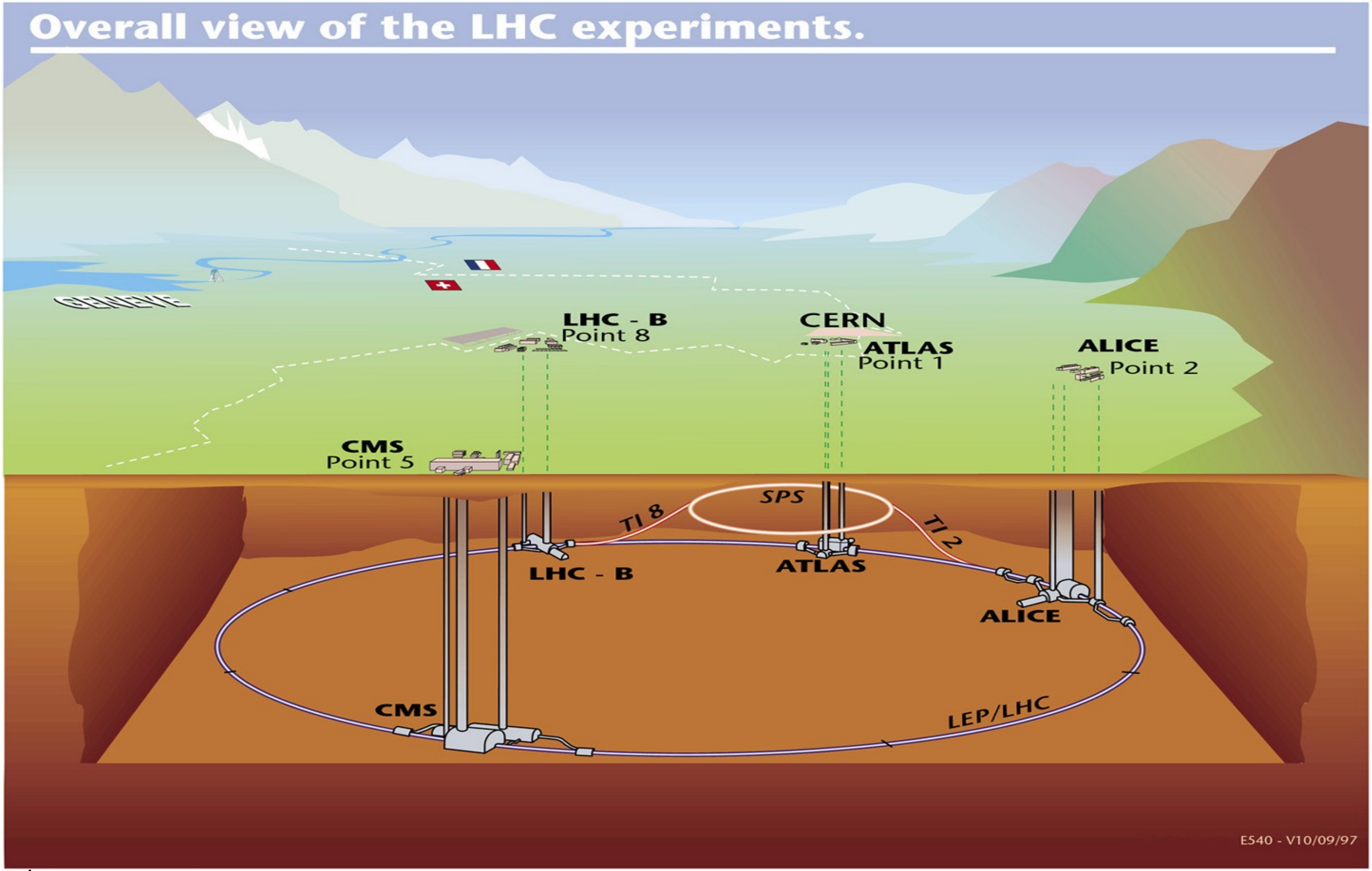
LINAC2 : 50 MeV
Alvarez Linac
1978

RFQ : 750 KeV

duoplasmatron
proton source
92 KV



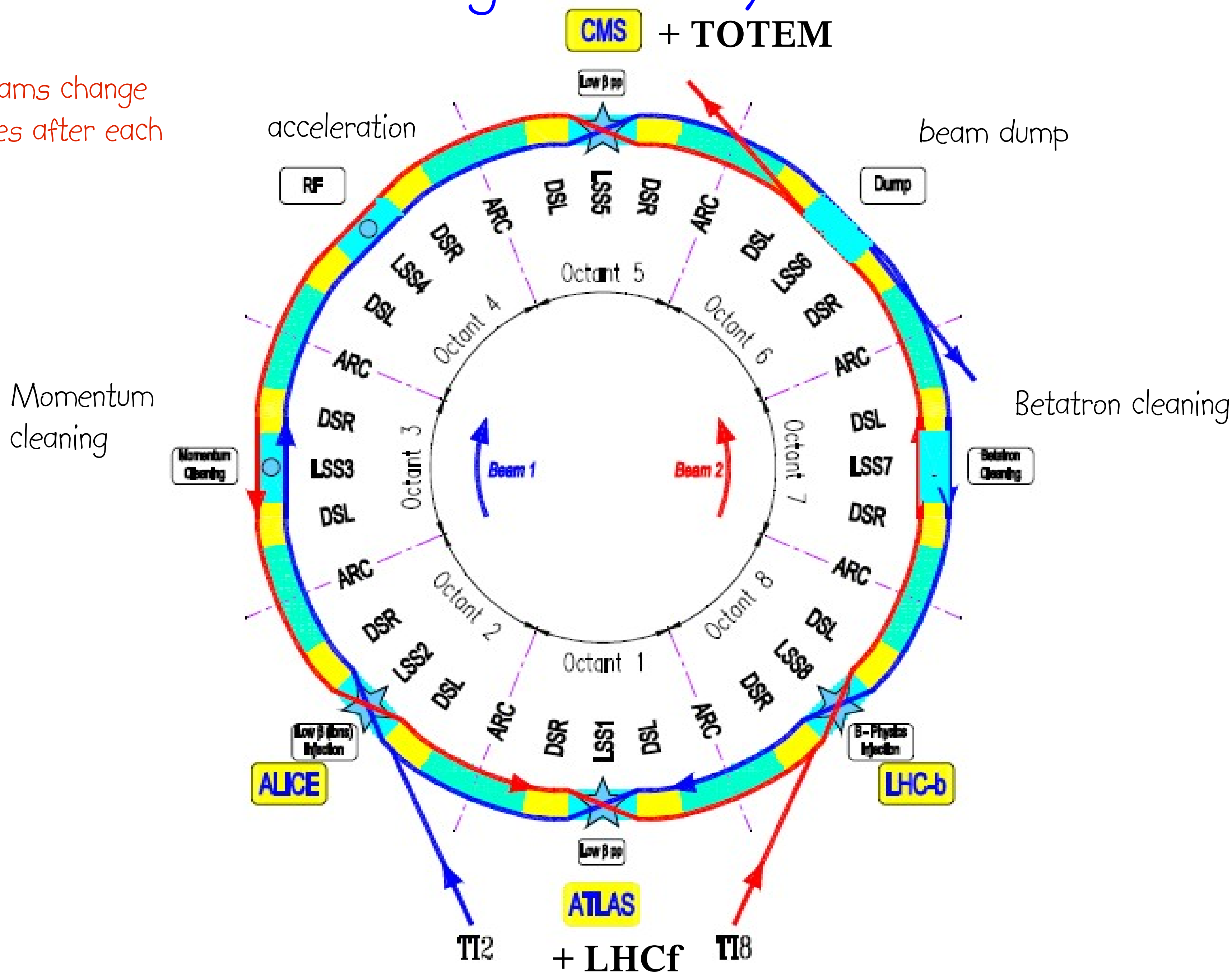
General underground view of experiments



Plus 3 smaller experiments : -TOTEM integrated into CMS
-LHCf located at +/- 140 m from ATLAS
-MeODAL located next to LHCb

LHC general layout

proton beams change
beam pipes after each
crossing !



Basic principles of charged particle acceleration

Lorentz force induced by electric and magnetic fields on a charge q :

$$\vec{F} = q\,\vec{E} + q\,\vec{V}\times\vec{B}$$

acceleration force
energy gain
and possible direction change

deflection force : direction change
and focusing
But no energy gain

Kinetic energy theorem :

$$\Delta E_{kin} = \int \vec{F}\cdot d\,\vec{s} = q\int \vec{E}\cdot d\,\vec{s} + q\int (\vec{V}\times\vec{B})\vec{V}\,dt = q\int \vec{E}\cdot d\,\vec{s} = \Delta E_{tot}$$

$$=0$$

avec : $E_{tot} = E_{kin} + m$

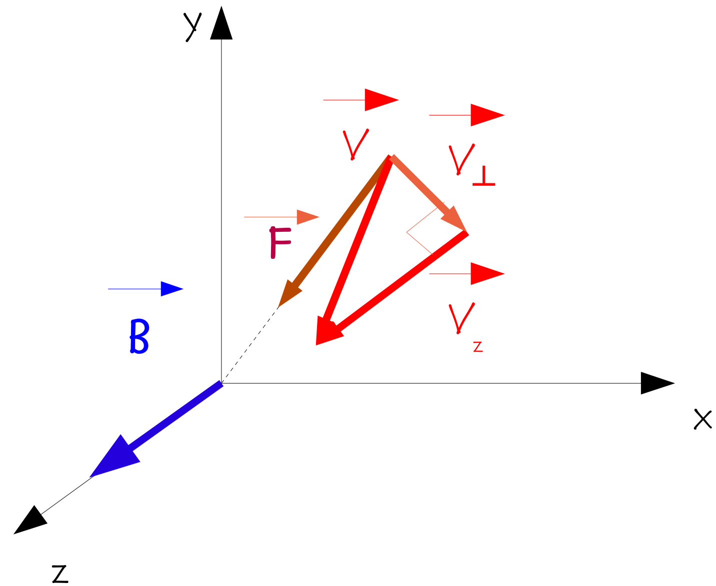
Motion of a charged particle in a uniform magnetic field

$$q = Z e$$

$$q V_{\perp} B = \gamma m \frac{V_{\perp}^2}{r}$$

$$q B = \gamma m \frac{V_{\perp}}{r}$$

$$p_{\perp} = q B r$$



$$p_{\perp}(\mathrm{GeV}) = 0.3\ z\ B(\mathrm{T})\ r(\mathrm{m})$$

r orbit radius.

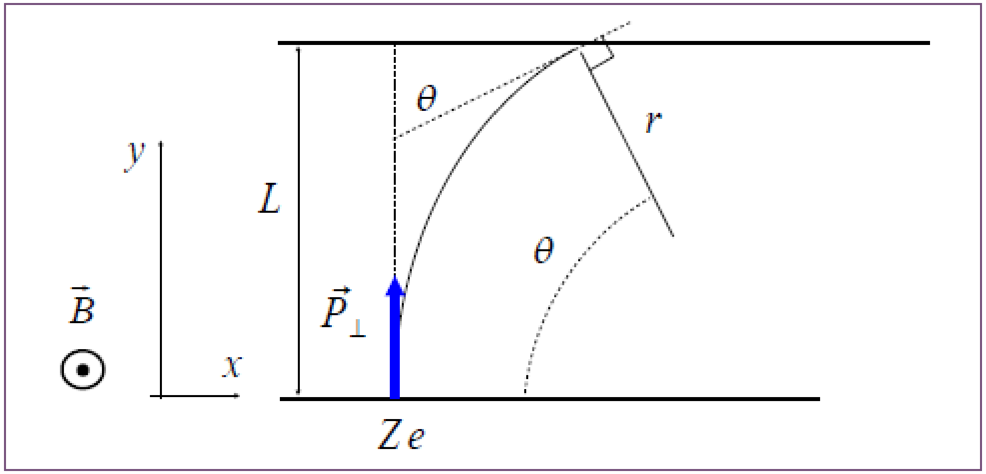
The 3D trajectory is a helix of pitch p^h given by :

$$p_z(\mathrm{GeV}) = \frac{0.3}{2\pi}\ z\ B(\mathrm{T})\ p^h(\mathrm{m})$$

Magnetic rigidity :

$$B(\mathrm{T})\ \rho(\mathrm{m}) = 3.33\ p_{\perp}(\mathrm{GeV})/z$$

Magnetic deviation angle



$$\sin\theta = \frac{L}{r} = 0.3\ z\ \frac{B(\mathrm{T})\ L(\mathrm{m})}{P_{\perp}(\mathrm{GeV})}$$

LHC main dipole magnets :

Knowing that LHC is a polygonal machine made of 1232 sides, the deviation angle per dipole is : $\theta = \frac{2\pi}{1232}$ which leads to : B L = 119 T m

The LHC main dipoles are superconducting magnets made of Nb-Ti .
They are cooled to 1.9 K using superfluid liquid helium.

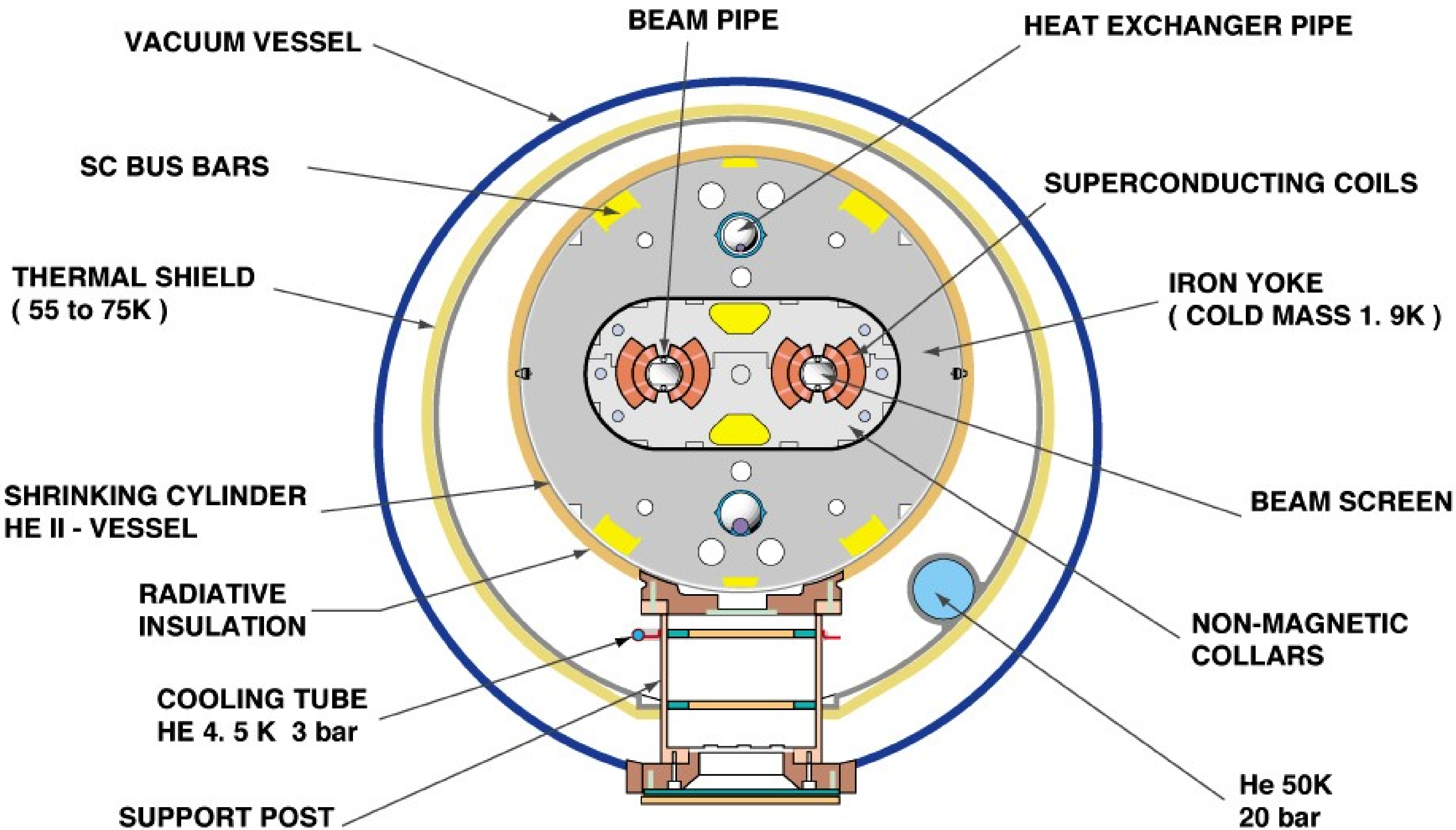
If L = 14.3 m then B = 8.33 T

The total machine circonference is 26659 m with 66% covered by main dipole magnets.

Each main dipole is curved by 9.1 mm over 14.3 m to compensate the beam sagitta.

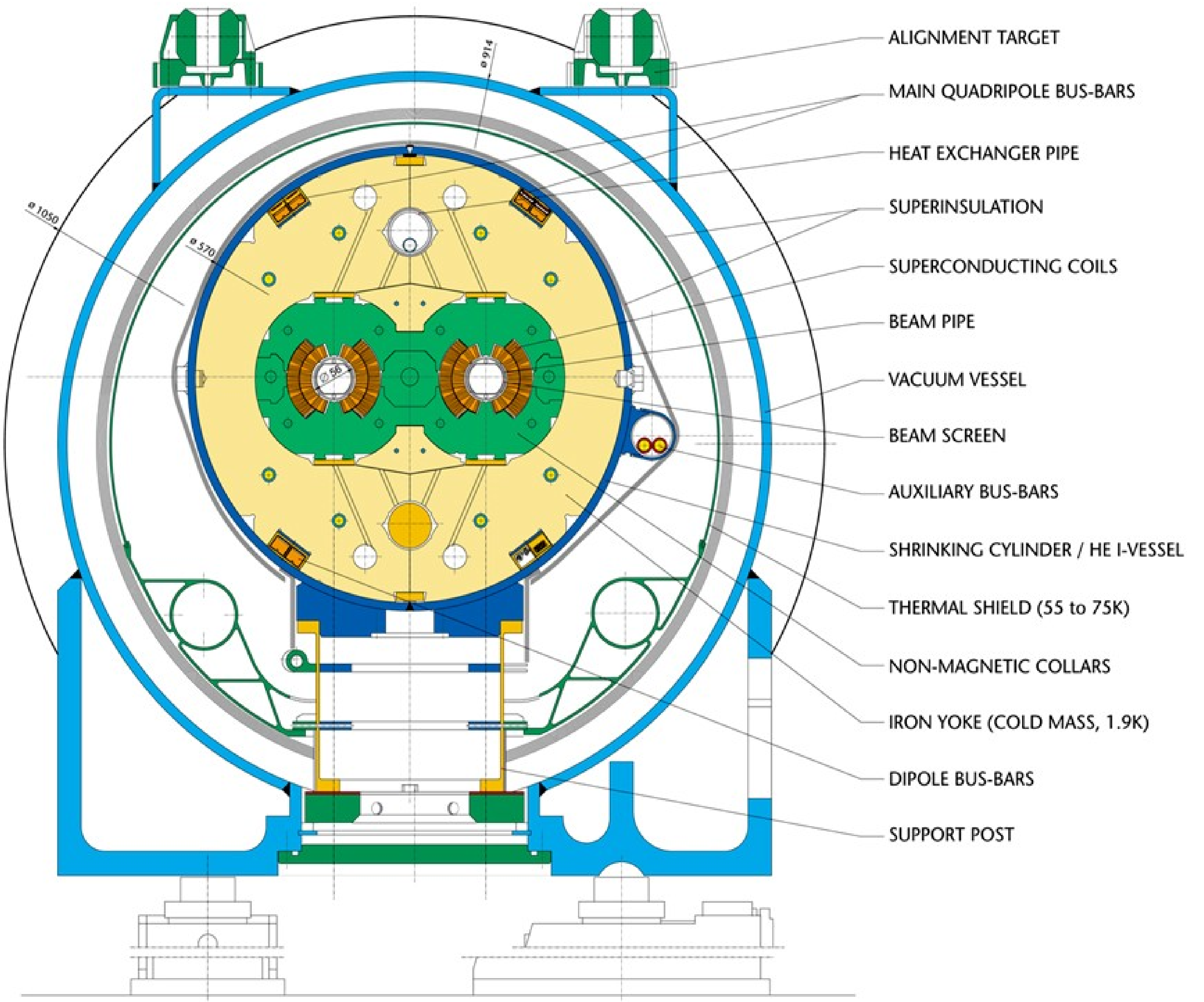
exo : show that the beam sagitta f is : $f = r\cdot(1-\cos\theta/2) \simeq \frac{r\cdot\theta^2}{8}$

CROSS SECTION OF LHC DIPOLE

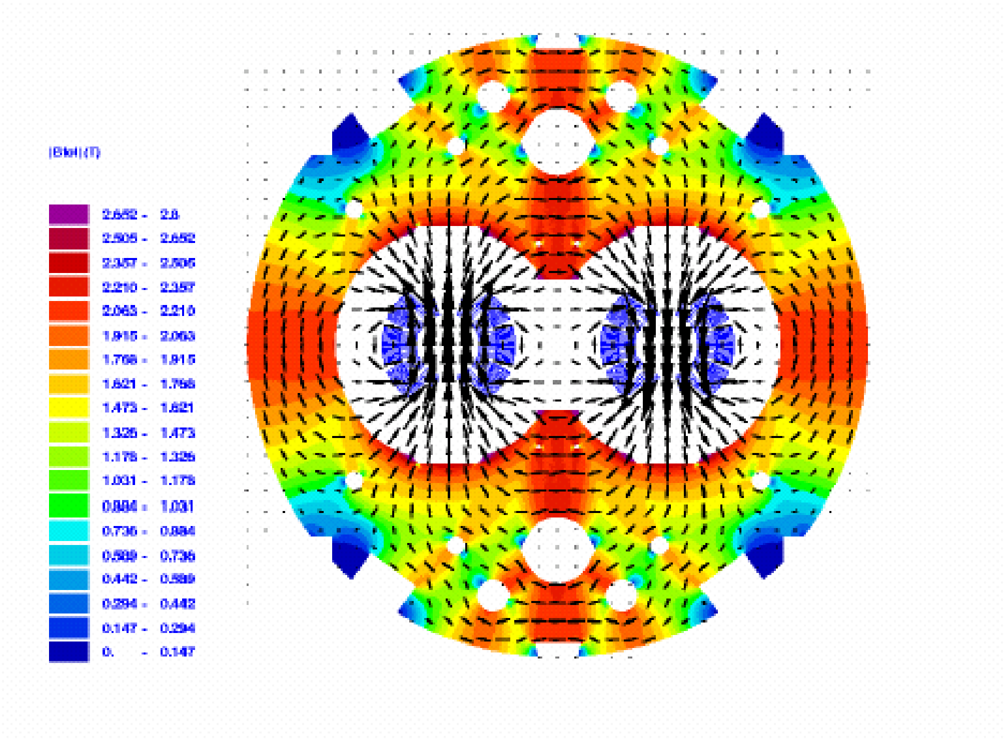


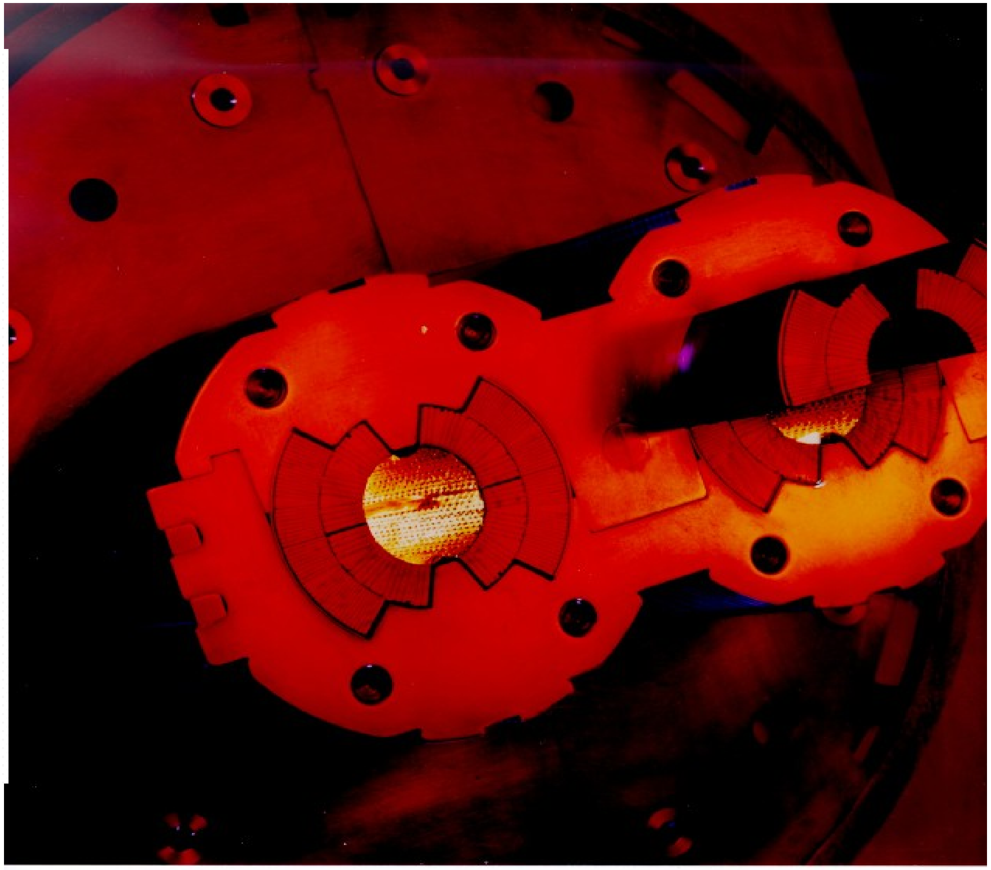
CERN AC _HE107A_ V02/02/98

LHC DIPOLE : STANDARD CROSS-SECTION



CERN AC/DI/MM - HE107 - 30 04 1999

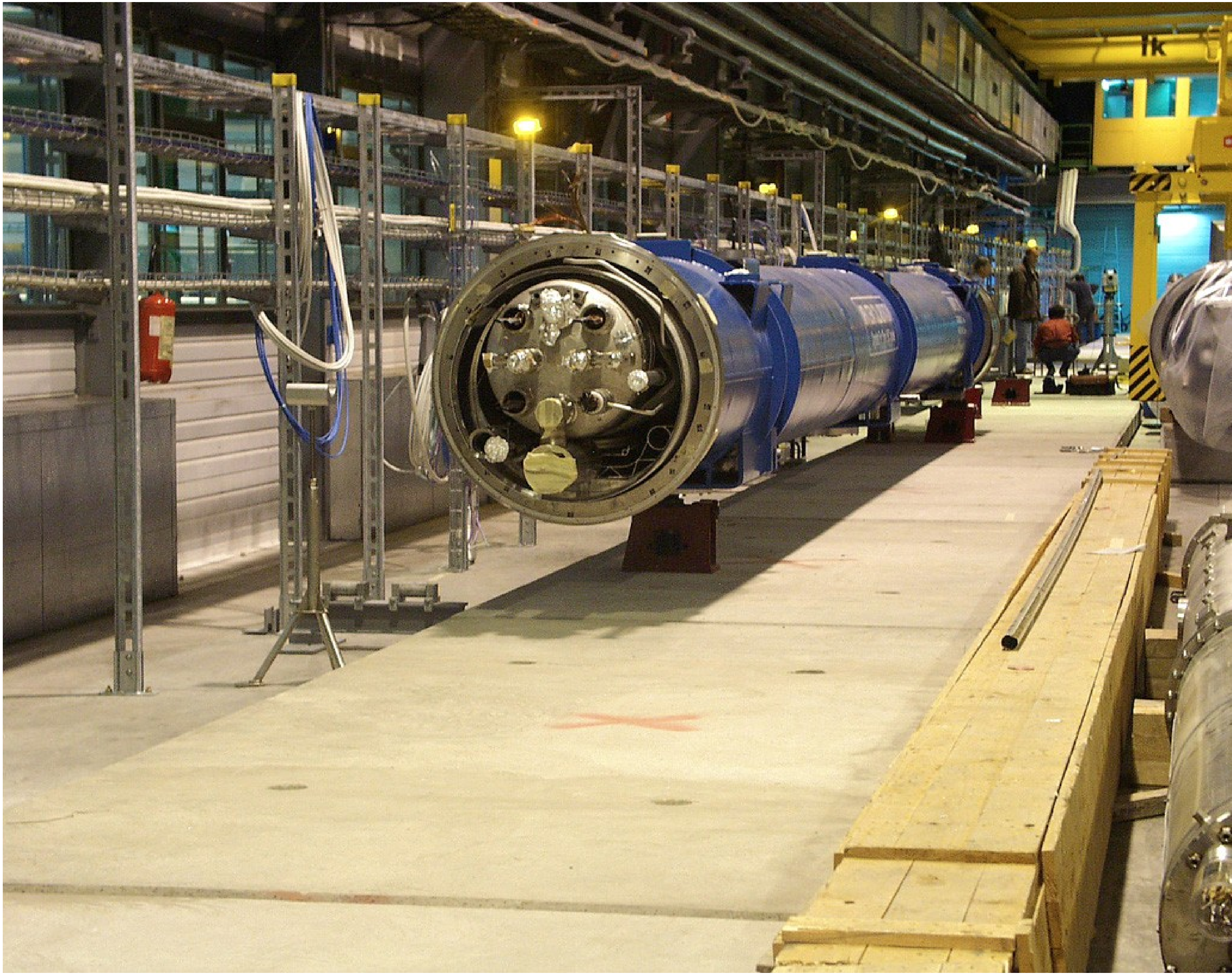


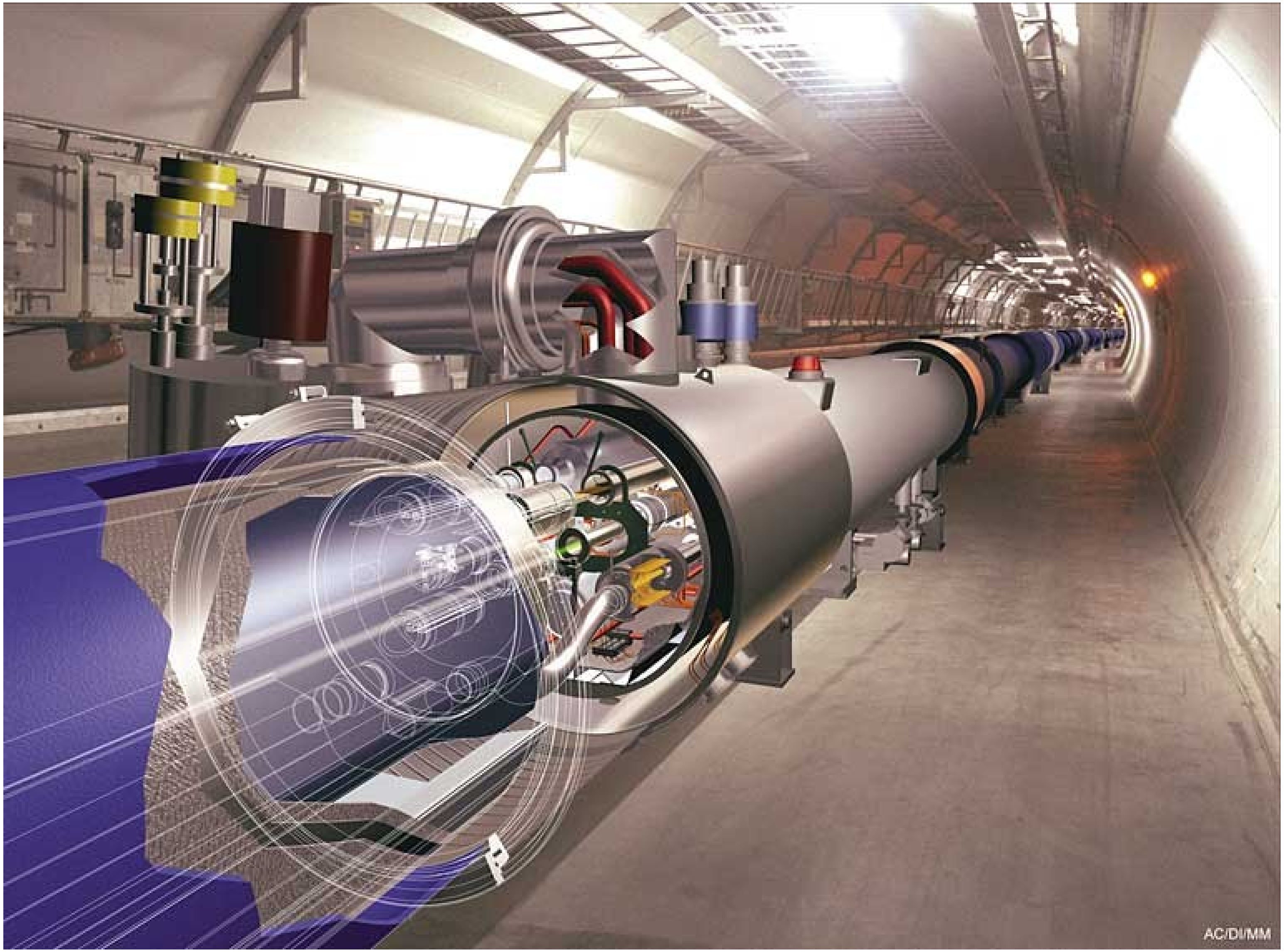


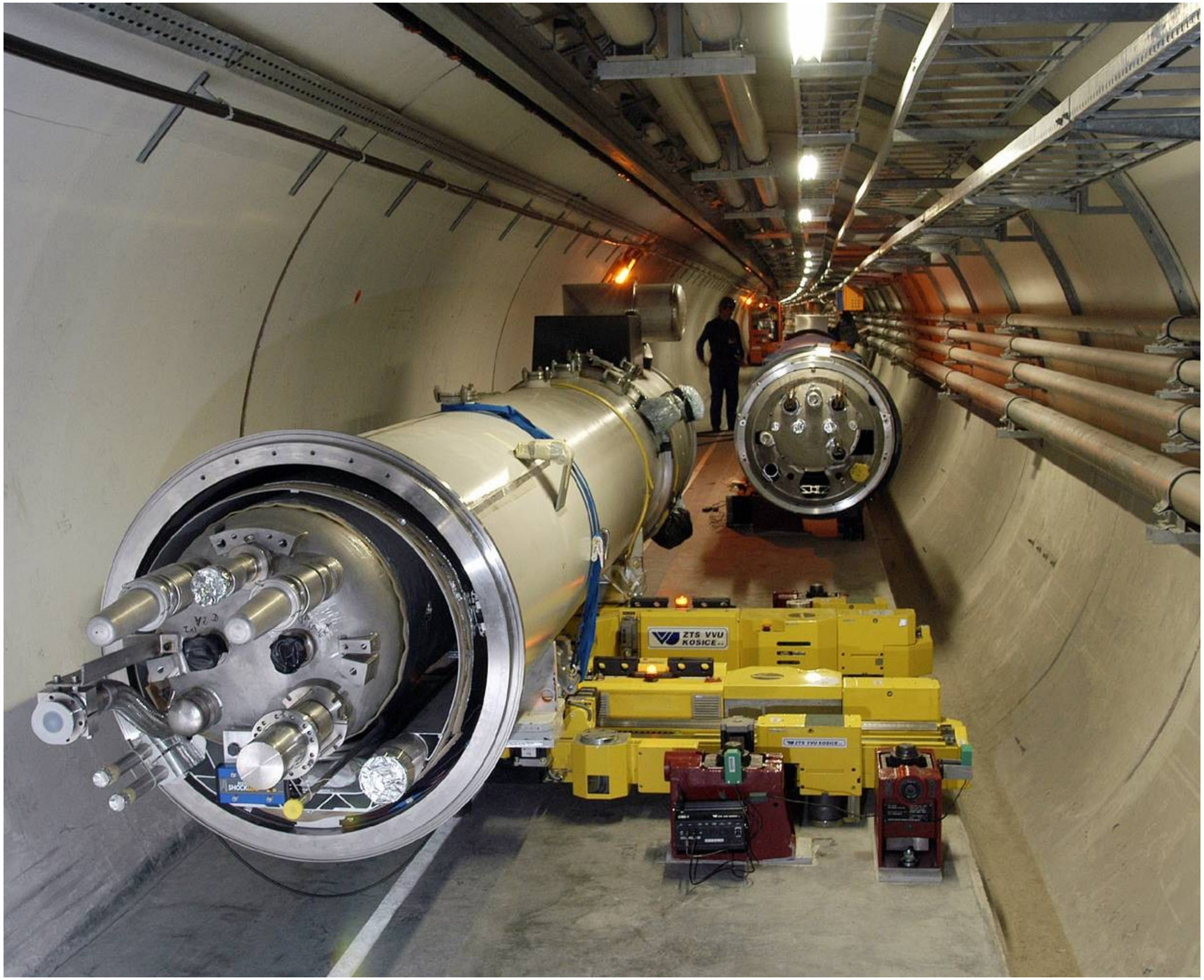
field reproducibility ~ 10^{-3}

Field homogeneity ~ 10^{-4}

Winding precision < 50 μm

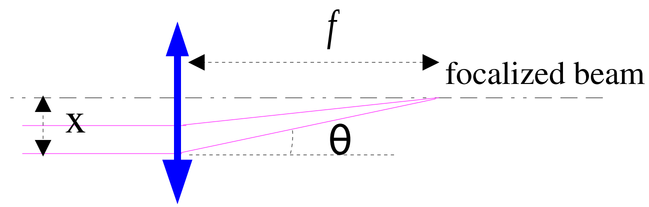



AC/DI/MM

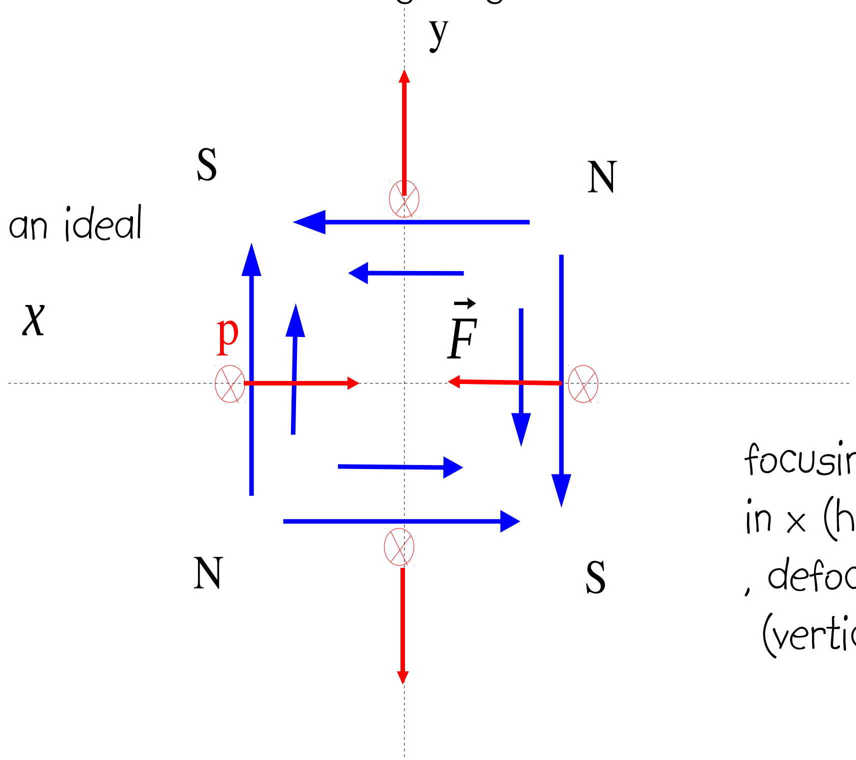

ZTS VVU
KOSICE

Beam focusing

Beam steering is not sufficient, beam focusing is also needed.



A thin quadrupole of length l is a focusing or defocusing magnetic lens.



focusing in x (horizontal), defocusing in z (vertical)

The x (y) magnetic field component induced by an ideal quadrupole linearly grows as a function of the y (x) distance to its axis :

$$B_y = \frac{\partial B_y}{\partial x} x \,,\, B_x = \frac{\partial B_x}{\partial y} y$$

with :

$$\frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} = \mathrm{cte}$$

quadrupole strength k :

$$k = \frac{1}{B_y \rho} \frac{\partial By}{\partial x} \qquad [k] = \mathrm{m}^{-2}$$

Therefore : $\sin\theta \approx \tan\theta \approx \frac{x}{f} \approx \theta = \frac{l}{\rho} = \frac{l B_y}{B_y \rho} = l \frac{(\partial B_y / \partial x) x}{B_y \rho} = l k x$

Finally : $f = \frac{1}{k\, l}$

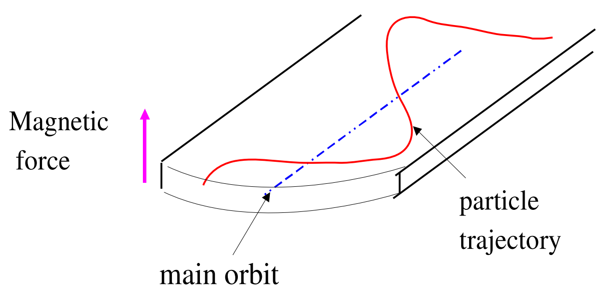
Beam focusing

Doublet (or triplet) of quadrupoles separated by a distance d : $\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$

If : $f1 = -f2 = f'$ $\qquad f = \frac{|f_1 f_2|}{d} = \frac{f'^2}{d}$

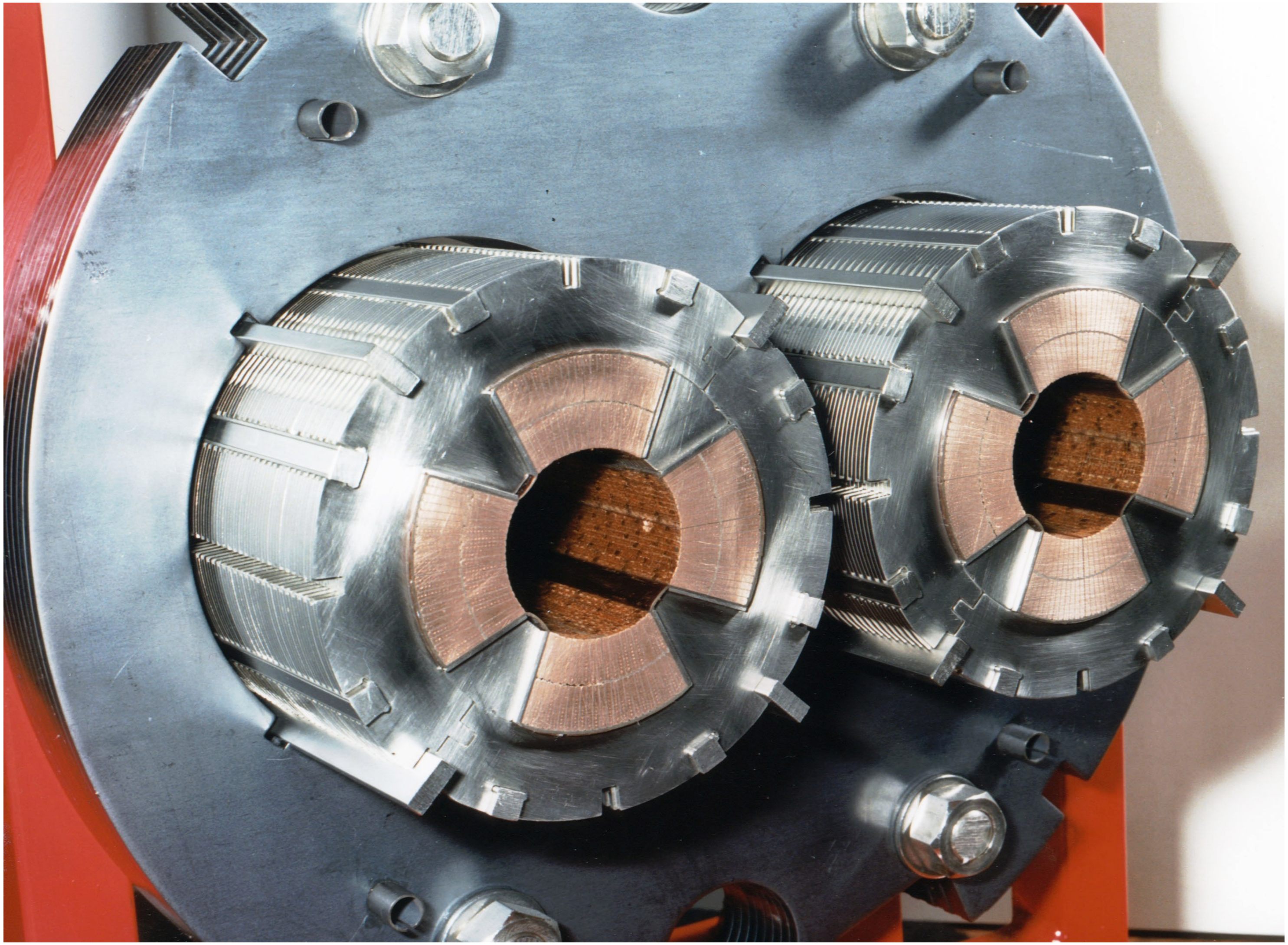
A focusing quadrupole followed by a defocusing quadrupole is equivalent to a globally focusing lens featuring the same focal distance in all directions.

By placing a succession of quadrupoles along the beam path, alternatively focusing and defocusing, the beam is guided along the synchrotron circumference.



The particles possessing a small transverse momentum oscillate around the central synchrotron orbit like a ball submitted to gravity in a concave guide : this is called the betatron motion. Care should then be taken to avoid to amplify the betatron amplitude as this would lead to a beam loss : in particular the betatron wavelength should never match one of the machine characteristic dimensions.

Main LHC Quadrupoles



Field gradient = 223 T/m , magnetic length = 3.1 m

exercise : compute the strength and the focal distance of these quadrupoles

$k = 9.56\ 10^{-3}\ m^{-2}$ (at max. power)

$f = 33.7$ m (min. value)

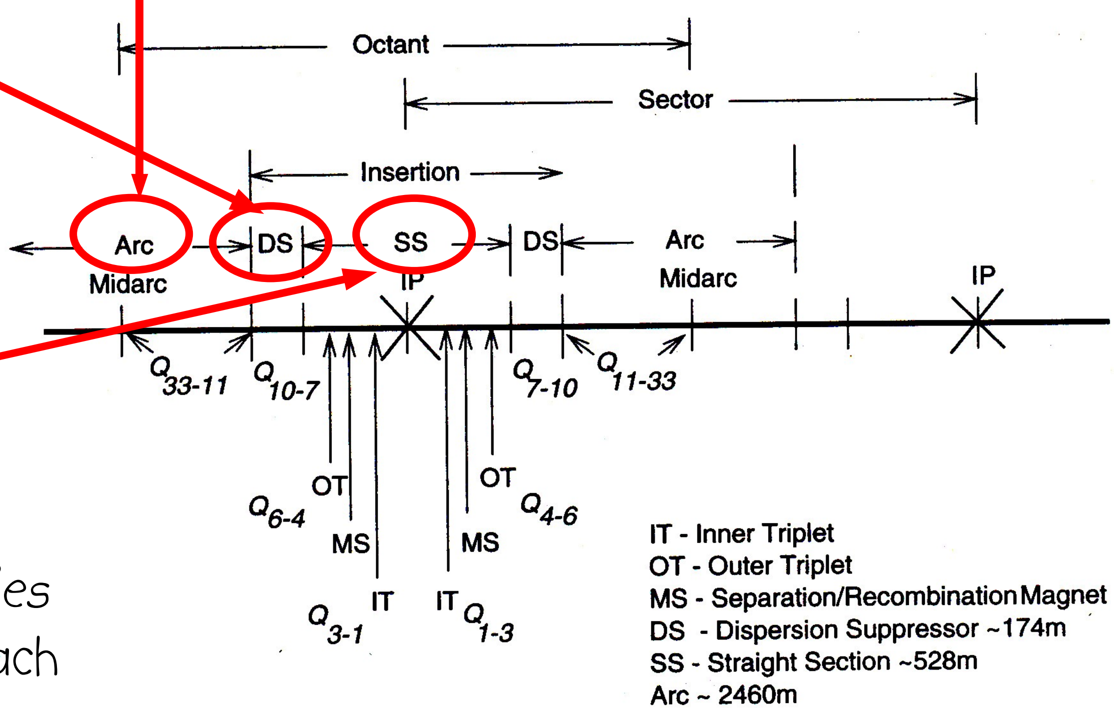
LHC machine structure

8 identical octants : 8 arcs, 8 straight sections, 16 dispersion suppressors

arc : 23 cells (FODO) of 2 quadrupoles (F et D) and 6 main bending dipoles
+ correction magnets (orbit correctors, octupoles, sextupoles, decapoles ...)

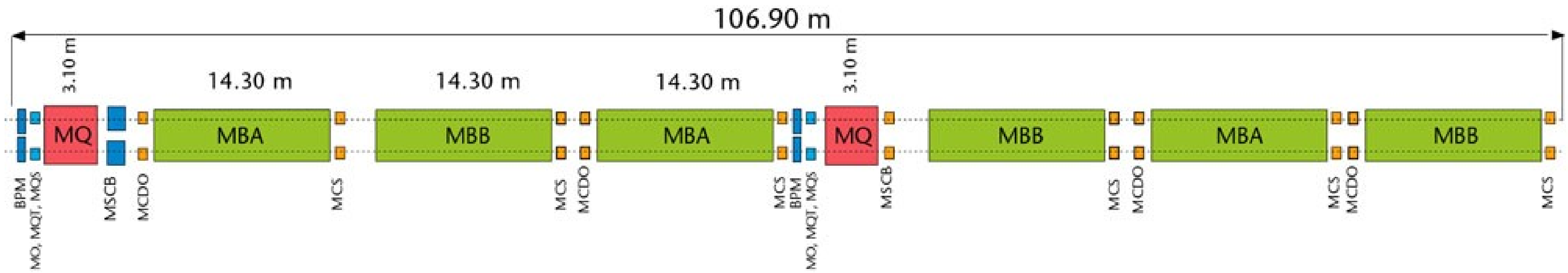
dispersion suppressor :
8 dipoles + 4 quadrupoles

straight section :
12 focusing quadrupoles (4 x 3) +
separation & recombinaison
magnets



8 superconducting acceleration cavities in one of the straight sections for each beam.

Schematic layout of one LHC cell (23 periods per arc)



- MQ: Lattice Quadrupole
- MO: Landau Octupole
- MQT: Tuning Quadrupole
- MQS: Skew Quadrupole
- MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
- BPM: Beam position monitor
- MBA: Dipole magnet Type A
- MBB: Dipole magnet Type B
- MCS: Local Sextupole corrector
- MCDO: Local combined decapole and octupole corrector

HF226 - v10/99

Luminosity

$$L_0 = \frac{f_r \, n_b \, N_1 N_2}{4\pi \, \sigma_x \sigma_y}$$

N_1 number of particles per bunch in beam 1

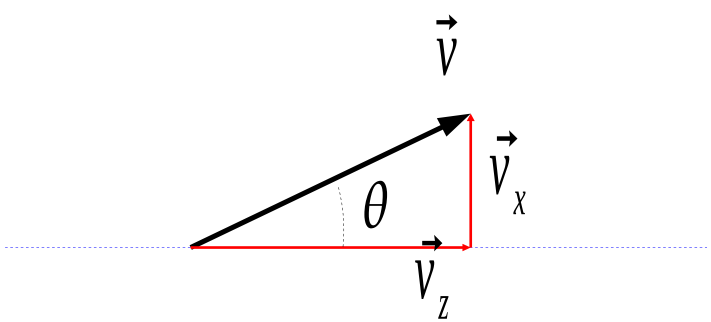
N_2 number of particles per bunch in beam 2

f_r revolution frequency

n_b number of bunches per beam

σ_x and σ_y are the standard deviations of the beam profile at the collision point.

If the beams are not strictly parallel, i.e. if there exists a transverse momentum component, then for each particle i, its divergence angle may be related to its transverse velocity through :



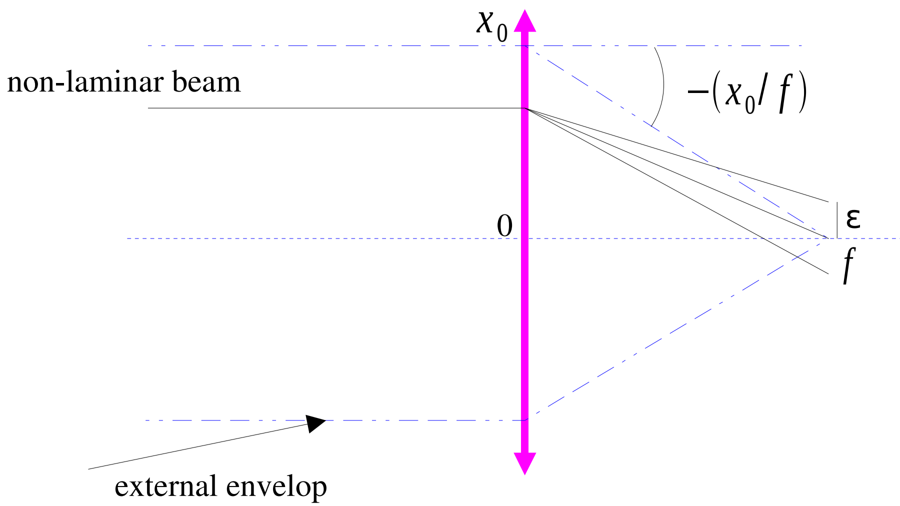
$$\sin\theta = \frac{v_x}{v_z} \simeq \theta$$

In the particle phase space : $\{x^i, v_x^i, y^i, v_y^i, z^i, v_z^i\}$

or : $\{x^i, x'^i, y^i, y'^i, s^i, \delta^i\}$

where : $x'^i = \frac{v_x^i}{v_s^i}$ $\quad y'^i = \frac{v_y^i}{v_s^i}$ $\quad \delta^i = \frac{E^i - E_0}{E_0}$ $\quad E_0 = \langle E^i \rangle$

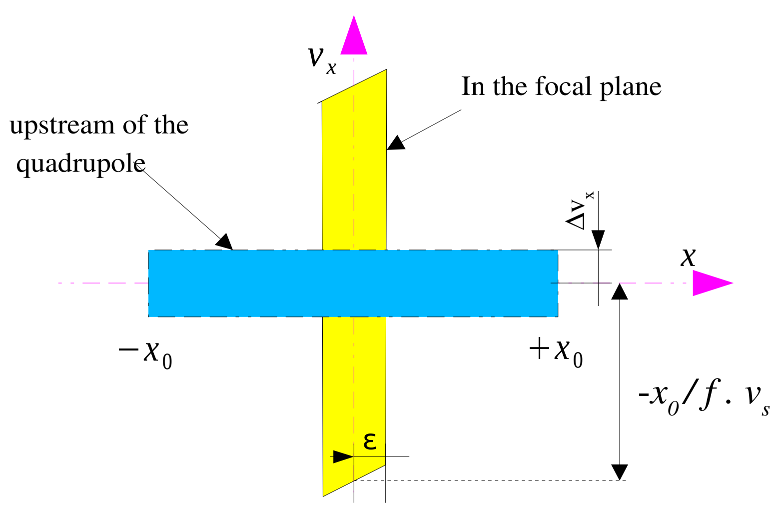
Straight section focusing



f is the quadrupole focal distance

At the focal point, the transverse speed is in between : $-(x_0/f)\cdot v_s$ and $+(x_0/f)\cdot v_s$

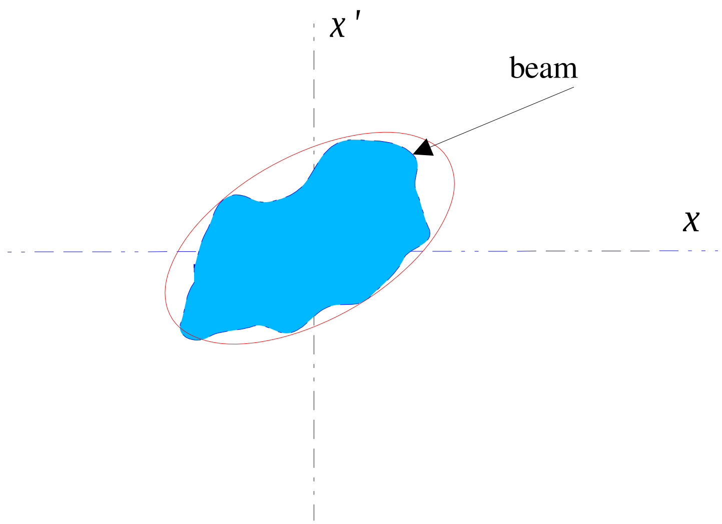
In the hypothesis of a conservative process (no inelastic internal collisions, radiation emission neglected), Liouville's theorem may be applied. It leads to the conservation of the beam phase space area.



$$A_p = A_f = 4\epsilon \frac{x_0}{f}\cdot v_s = 4\, x_0 \Delta v_x$$

soit : $$\epsilon = \frac{\Delta v_x}{v_s}\cdot f$$

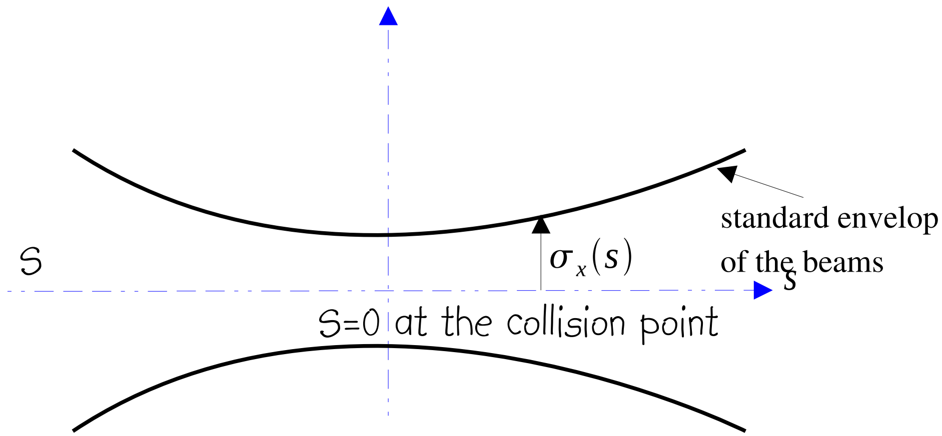
Emittance and focusing



The beam emittance is the area of ellipse encompassing the occupied beam phase space in a given direction.

$$\epsilon_x = \iint_{ellipse} dx\, dx'/\pi$$

In the case of a straight section :



$$\sigma_x(s) = \sqrt{(\beta_x^* + \frac{s^2}{\beta_x^*}) \cdot \epsilon_x}$$

where : β_x^* is the betatron function value at s=0.

Put together :

$$L_0 = \frac{f_r\, n_b\, N_1 N_2}{4\pi \sqrt{\beta_x^*\, \epsilon_x} \sqrt{\beta_y^*\, \epsilon_y}}$$

and if the beam is round :

$$L_0 = \frac{f_r\, n_b\, N_1 N_2}{4\pi\, \beta^*\, \epsilon}$$

LHC luminosity

revolution frequency : 11.25 kHz

number of bunches per beam : 2808

Each bunch may contain up to 1,15 10^{11} protons.

Normalized emittance : $\epsilon^* = \beta \gamma \epsilon = 3.75\, 10^{-6}$ m rad $\Rightarrow \epsilon = 5\, 10^{-10}$ m rad for 7 TeV protons

Betatron function value at collision point : $\beta^* = 0.55\,\mathrm{m}$

$$\sigma_x = \sigma_y = \sqrt{\epsilon \beta^*} = \sqrt{5 \cdot 10^{-10} \cdot 0.55} = 16.6\,\mu\mathrm{m}$$

The LHC beam is round in the transverse plane.

$$L_0 = \frac{3.16 \cdot 10^7}{4\pi} 1.15^2 \frac{10^{22}}{0{,}55 \cdot 5.10^{-10}} = 1.21 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Taking into account the 285 mrad crossing angle brings a reduction factor of 0,84 :

$$L_{LHC}^{max} = 1.01\, 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

LHC main features

Energy	0.45 – 7 TeV
Bending dipole field	0.535 – 8.3 T
Nominal luminosity	10^{34} cm^{-2} s^{-1}
Beam current	0.582 A
Collision period	25 ns
Number of bunches per beam	2808
Number of particles / bunch	1.15 10^{11}
Stored magnetic energy	13 GJ
Stored one beam energy	362 MJ
Revolution frequency	11.245 KHz
RF frequency	400.8 MHz
RF harmonic	35640
Energy gain per turn	485 keV
Normalized transverse emittance	3.75 µm.rad
rms bunch length	7.55 cm
Horizontal betatron number	64.32
Vertical betatron number	59.32
betatron function at crossing point	0.55 m
max. betatron function in arcs	180 m
Synchrotron frequency	61.8 – 21.4 Hz
Total synchrotron radiation power per beam	3.6 KW
Luminosity life time	14.9 h
Acceleration time	20 min

exercise : find the beam current value and the total energy stored per beam.

Do the bunches occupy all the machine circumference ?

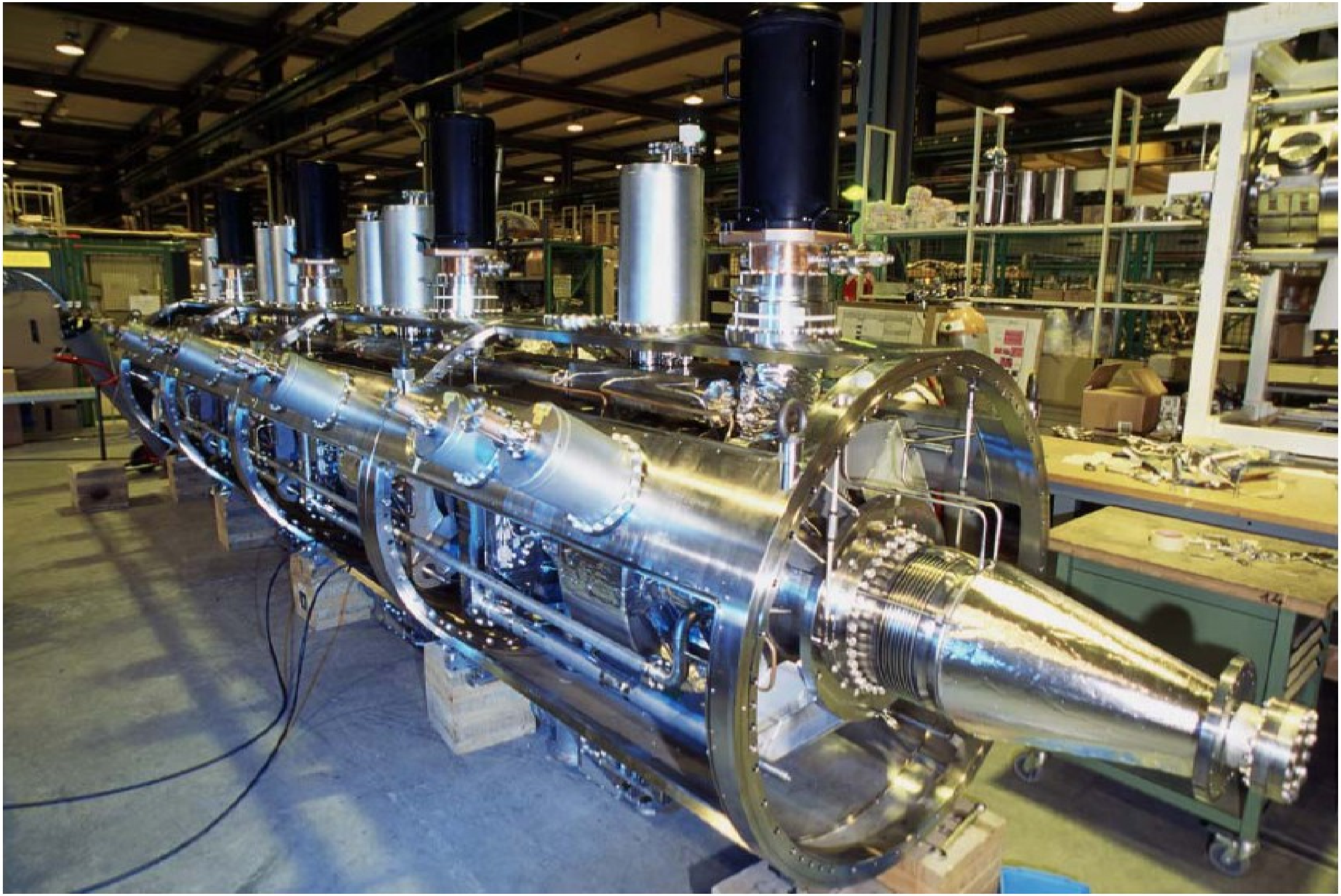
Heavy ion features (Pb – Pb)	
Total center-of-mass energy	1150 TeV
Luminosity	1 10^{27} cm^{-2} s^{-1}
Normalized transverse emittance	1,5 µm . rad
Betatron function at collision point	0,5 m
number of bunches	592

exercise : find the total center-of-mass energy in Pb-Pb collision mode .

LHC operation :

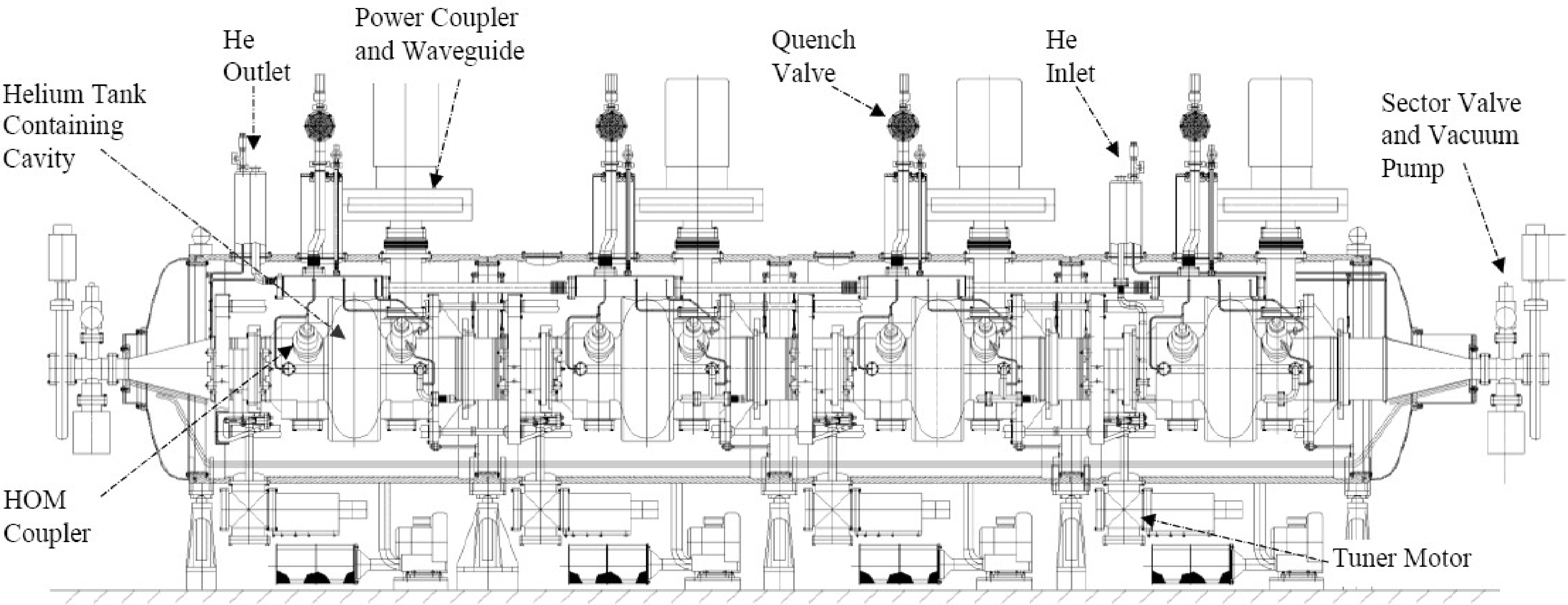
- 200 days/year
- ~12 h runs (~luminosity life time)
- 2-5 h feeling time of new beam

Acceleration Cavities



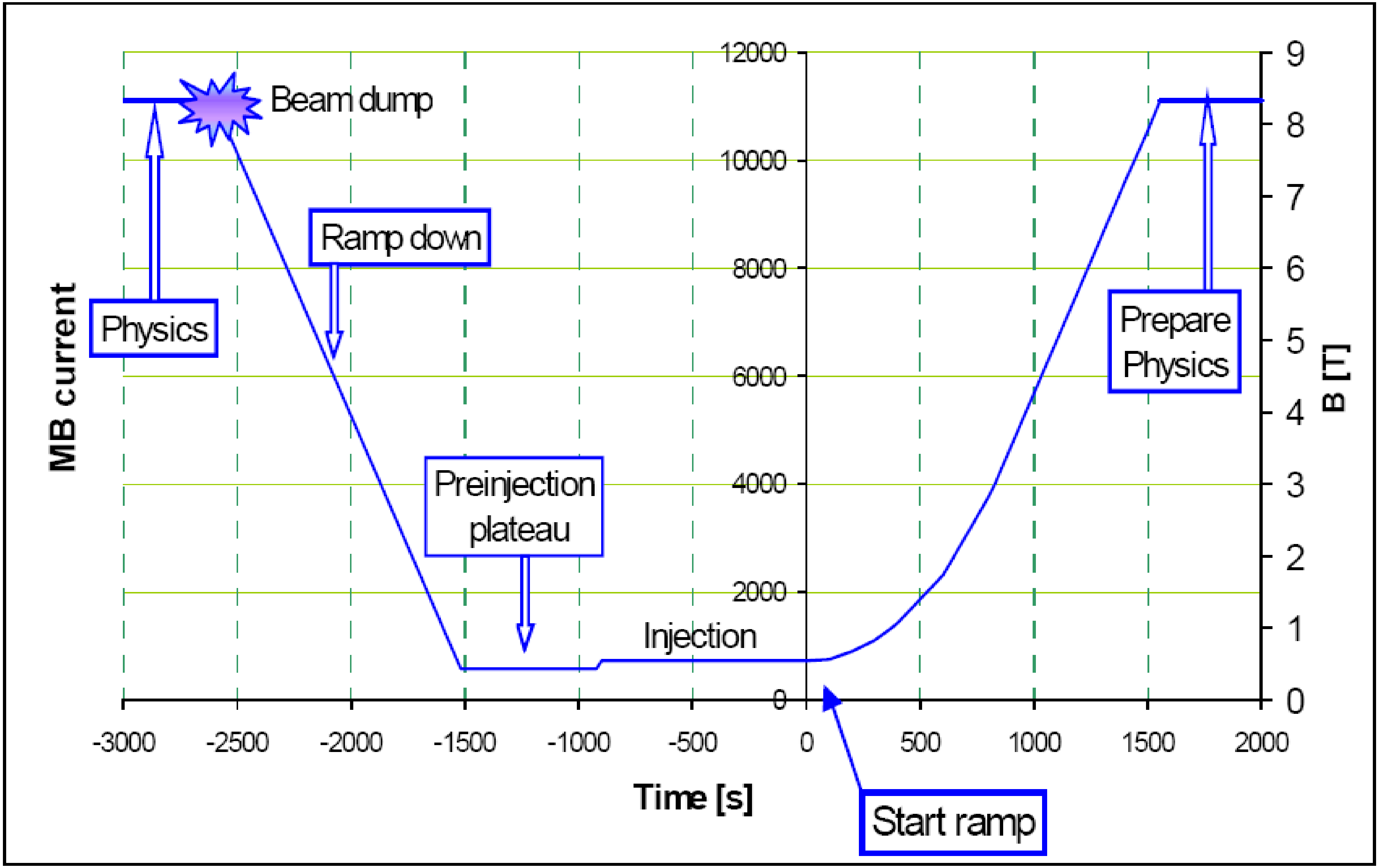
Cryomodule containing 4 acceleration cavities

Acceleration cavities



Cryomodule containing 4 acceleration cavities

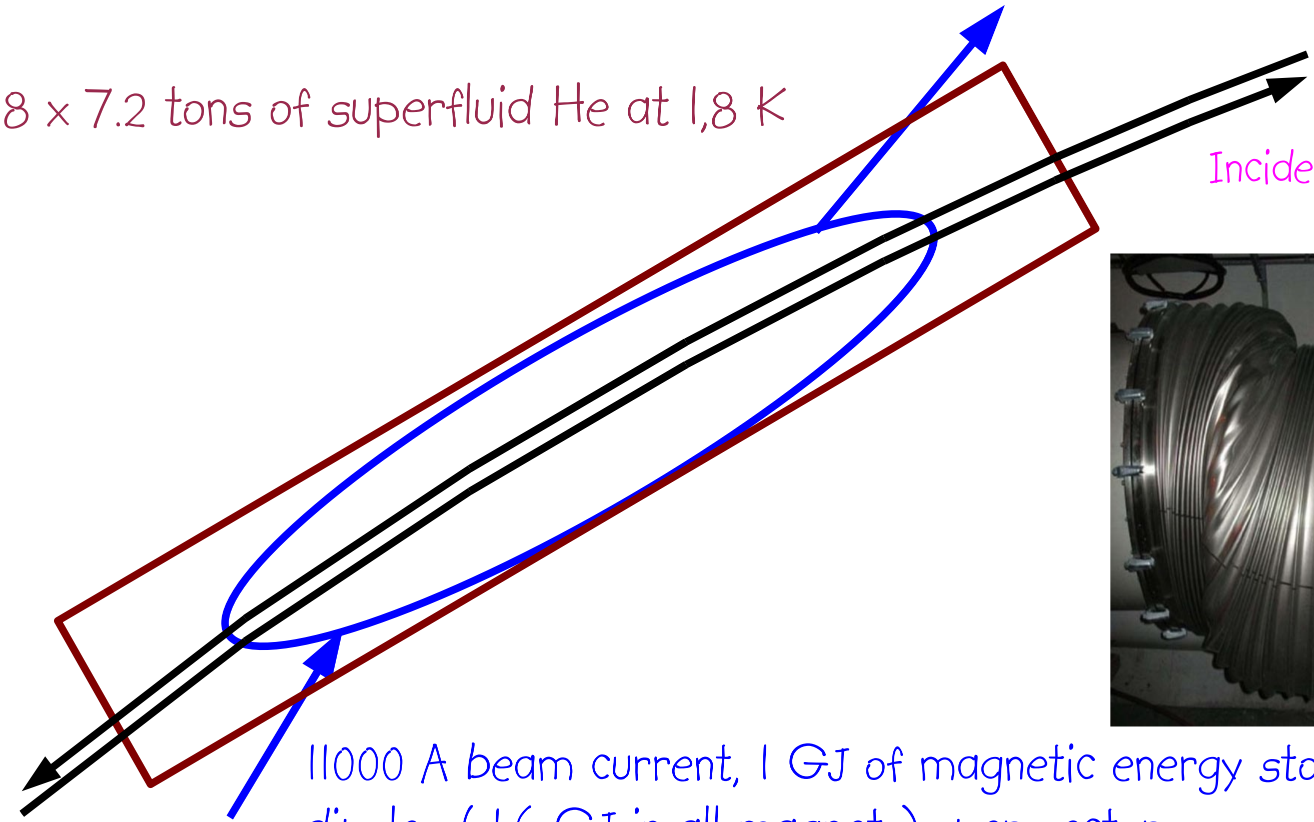
Operation cycle



LHC : Acceleration technology pushed to the frontier

720 MJ stored on both beams

8 x 7.2 tons of superfluid He at 1,8 K



Incident of 19 September 2008

11000 A beam current, 1 GJ of magnetic energy stored in main dipoles (1,6 GJ in all magnets) per sector

exercise : VLHC

The design of a 100 TeV proton-proton collider is briefly studied.
In a first approach, the same type of bending dipoles as for LHC are used with 70% of the synchrotron circumference covered by these magnets.

a) compute the deviation angle per LHC dipole.
b) determine the number of dipoles contained in arcs using a FODO cell and octant structure comparable to LHC.
c) Adding 16 dipoles for each of the 8 straight sections, determine the total number of dipoles. Deduce the deviation angle per dipole and their nominal magnetic field.
d) which is the circumference and the tunnel radius of the machine?
e) which is the sagitta per dipole ?
f) determine the product of the quadrupole field gradient and magnetic length to obtain a focal distance of 40 m. What should its length be if the field gradient is 250 T/m ? Is it realistic ? What should be done to improve on this point ?

g) Redo the design if 16 T bending dipoles are available.