The LHC:
the Large Hadron Collider

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Outline

- Why the LHC ?
- CERN and the accelerator complex
- How LHC works: a synchrotron collider
- Luminosity
- Superconductivity and accelerators
- LHC optics
- How to protect the LHC
- Hints for the future

The idea is that the lectures:

a) should not be a monologue, stop me and ask if you don't get the point
b) should show why things are like this, how they work, how they look like

SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

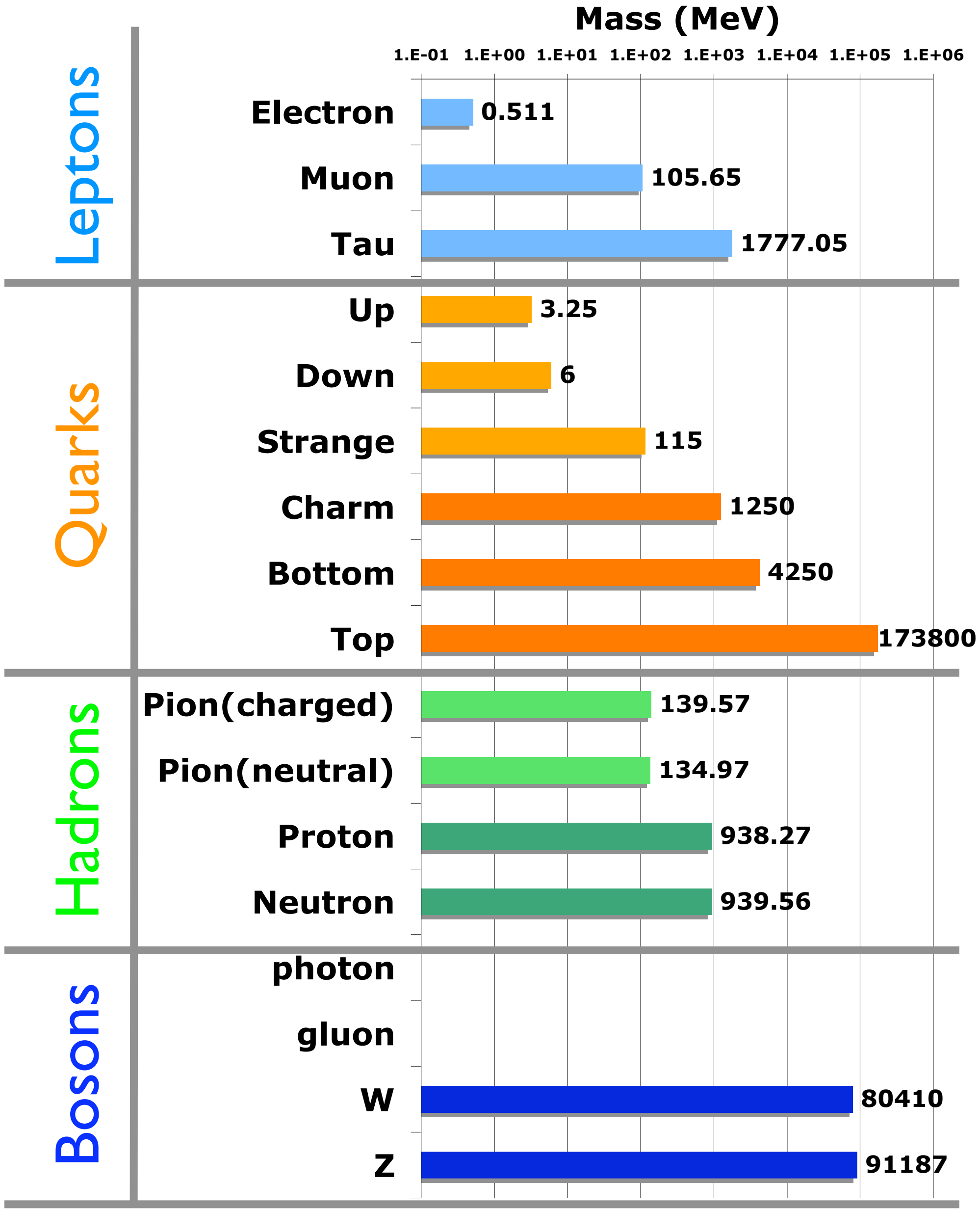
Press Release PR/56
12 February, 1960

It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays from distant stars, so the very character of the laws governing the properties of the many new elementary particles which have been discovered in recent years, and especially their transmutations in violent collisions, can only be studied by using atomic particles accelerated to immense energies. Actually we are here confronted with most challenging problems at the border of physical knowledge, the exploration of which promises to give us a deeper understanding of the laws responsible for the very existence and stability of matter.

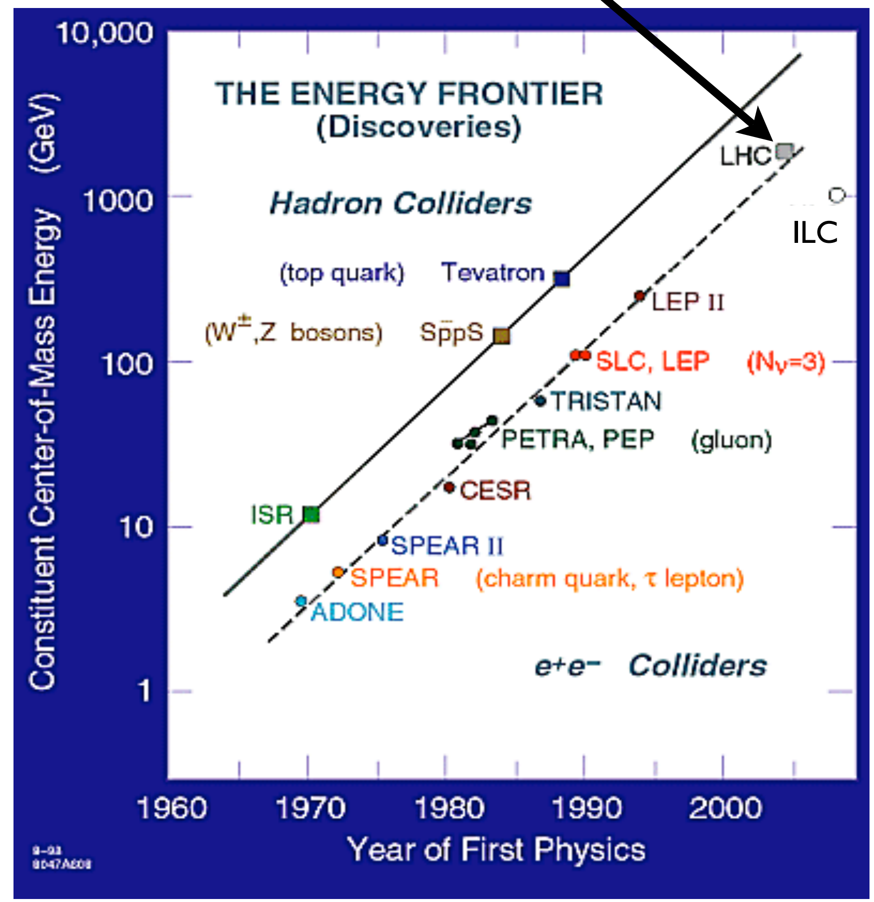
All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws. This also true for the LHC

Small detail... Bohr was not completely right, the “new” elementary particles are not elementary but mesons, namely formed by quarks

History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe



Obs: you can notice different particle species used in the different colliders

electron-positrons and hadron colliders (either p-p as Tevatron, p-p as LHC)

Constant increase in energy to discover heavier and heavier particles or rare processes.

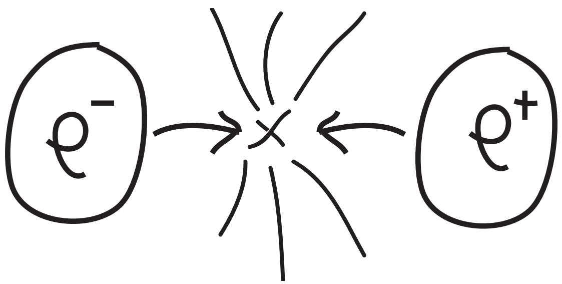
Energy is not a free parameter for colliders: *it is given by the physics one wants to do*

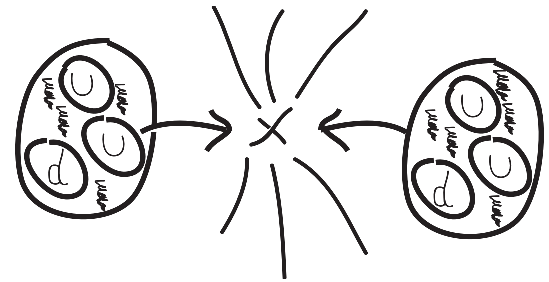
Obviously, the higher the better ... but then, why the ILC has less energy than the LHC ? (see next)

The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons





The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Ecoll (about 1 TeV LHC) < 2 Eb (14 TeV)

<u>Pros:</u> the energy can be precisely tuned to scan for example, a mass region.

Precision measurement (LEP)

<u>Pros:</u> with a single energy possible to scan different processes at different energies.

Discovery machine (LHC)

<u>Cons:</u> above a certain energy is no more possible to use electrons because of too high <u>synchrotron radiation</u>

<u>Cons:</u> the energy available for the collision is lower than the accelerator energy

What is the LHC ?

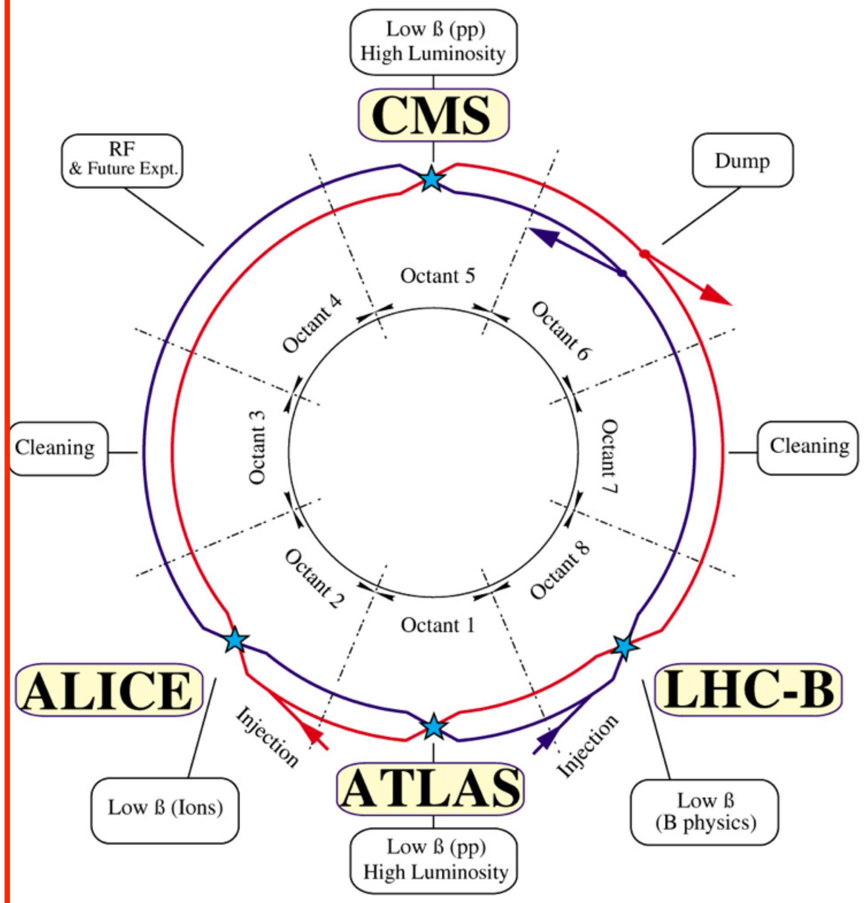
LHC: Large Hadron Collider

LHC is a ***collider*** and ***synchrotron storage ring:***
ILC is a collider but is not a synchrotron storage ring

Large: high energy needs large bending radius *due to the maximum magnetic field existing technology can produce*
26.7 km circumference

Hadrons: p p collision $\Rightarrow$
synchrotron radiation and discovery machine.

Collider: particles are stored in two separated rings which are synchrotrons, and accelerated from injection energy (450 GeV) to 7 TeV.
At 7 TeV the two beams are forced to cross in collision points to interact.
The beams are stored at 7 TeV for few 10 h to produced collisions. When the intensity is too low, the two rings are emptied and the process of injecting, accelerating, storing and colliding is restarted, until one finds the higgs or supersymmetry... then one needs a bottle of Champaign and a nobel price ...



Where is the LHC ?

Intersection point	Tunnel		LEP 200	LHC
	Depth (m)	Slope (%)		
I (Meyrin)	82.0	1.23	Injection in arcs	ATLAS
II (St Genis)	45.3	1.38	L3 and RF	ALICE and Injection
III (Crozet)	97.5	0.72		Cleaning
IV (Echenevex)	137.6	0.36	ALEPH and RF	RF
V (Cessy)	86.6	1.23		CMS
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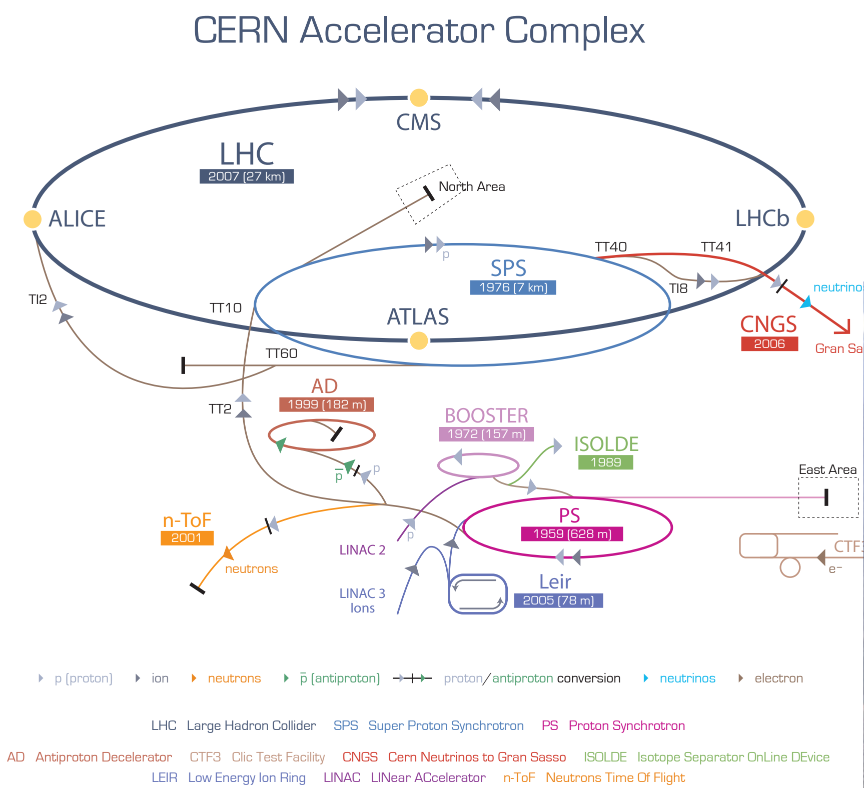
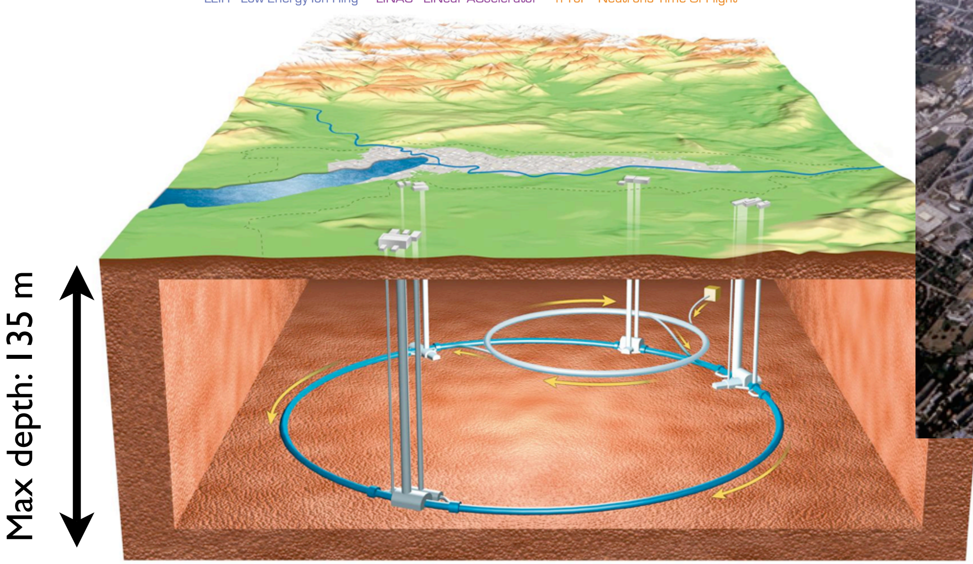




London tube: 24 m depth

Synchrotron (1952, 3 GeV, BNL)

New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the RF cavity, used to accelerate the particles has also to change.

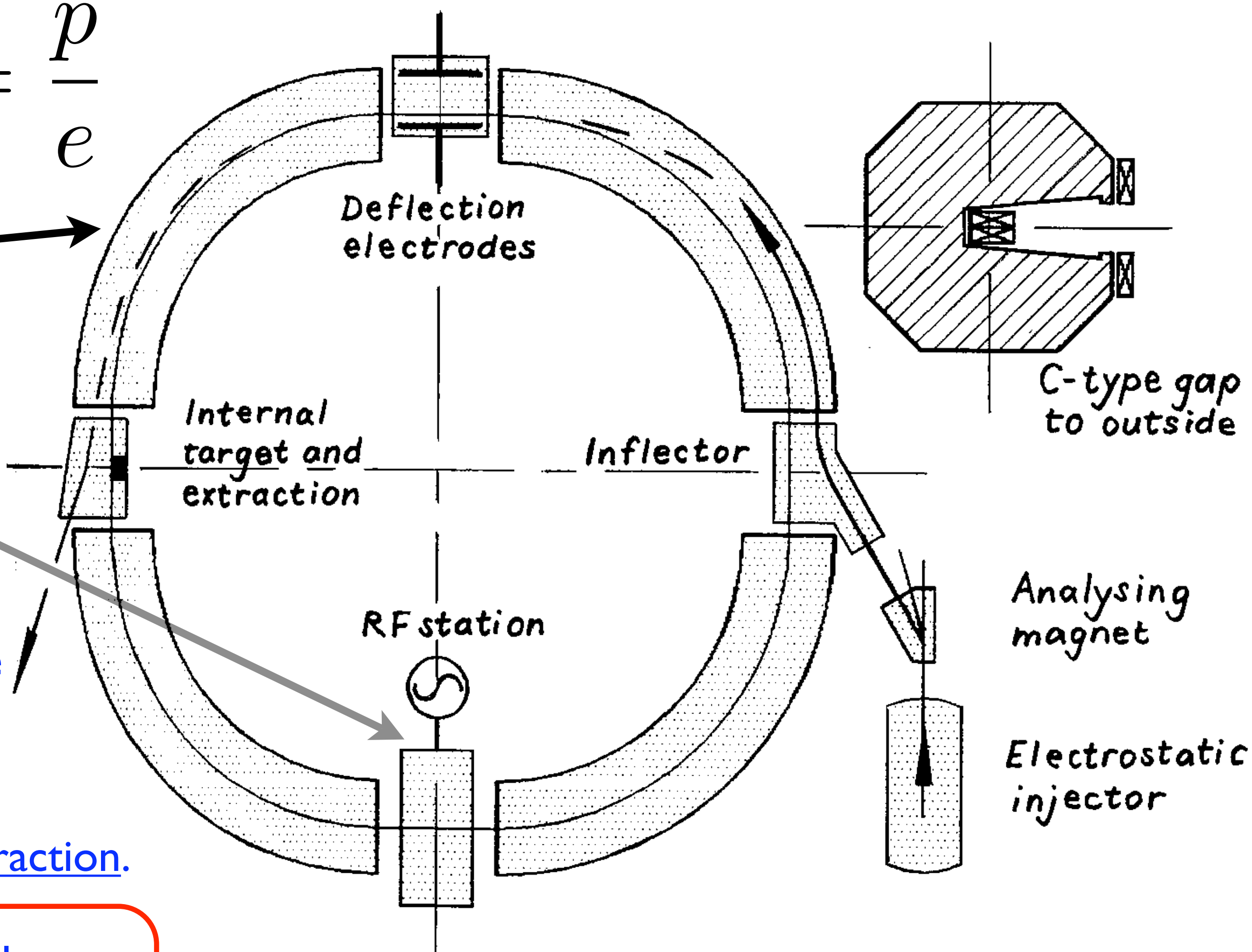
Particle rigidity: $B\rho = \frac{p}{e}$

B = B(t) magnetic field from the bending magnets

p = p(t) particle momentum varies by the RF cavity

e electric charge

ρ constant radius of curvature



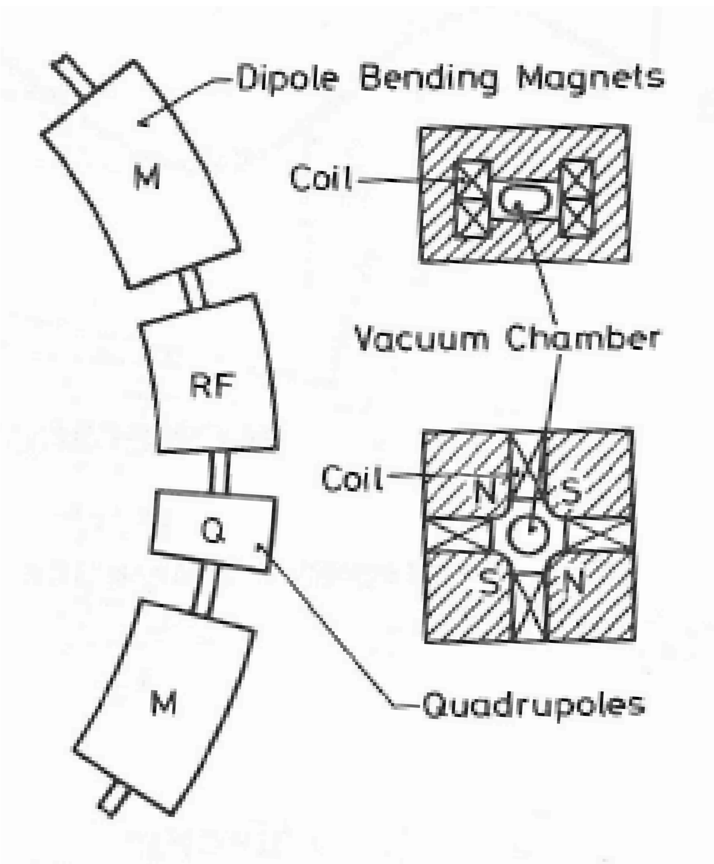
Magnetic elements for injection and extraction.

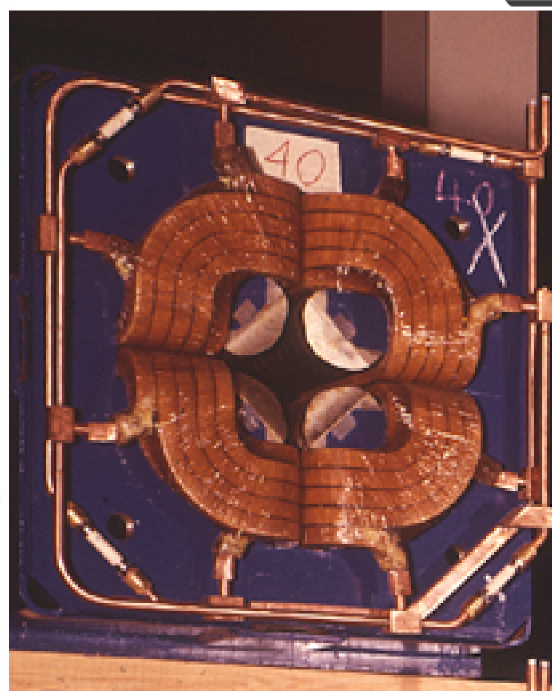
Bending strength limited by used technology to max ~ 1 T for room temperature conductors

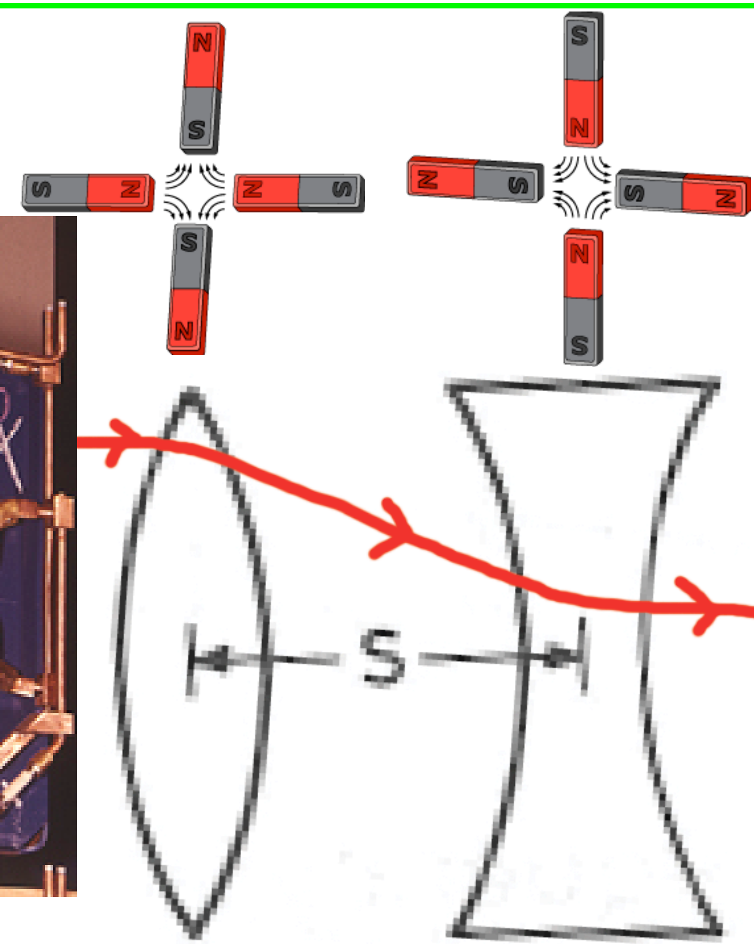
Weak focusing machine: no quadrupoles yet
Strong focusing machine, using quadrupoles, were proposed in 1952

Synchrotrons: strong focusing machine

Dipoles are interleaved with quadrupoles to focus the beam. Quadrupoles act on charged particles as lens for light. By alternating focusing and defocusing lens (Alternating Grandient quadrupoles) the beam dimension is kept small (even few mum^2).





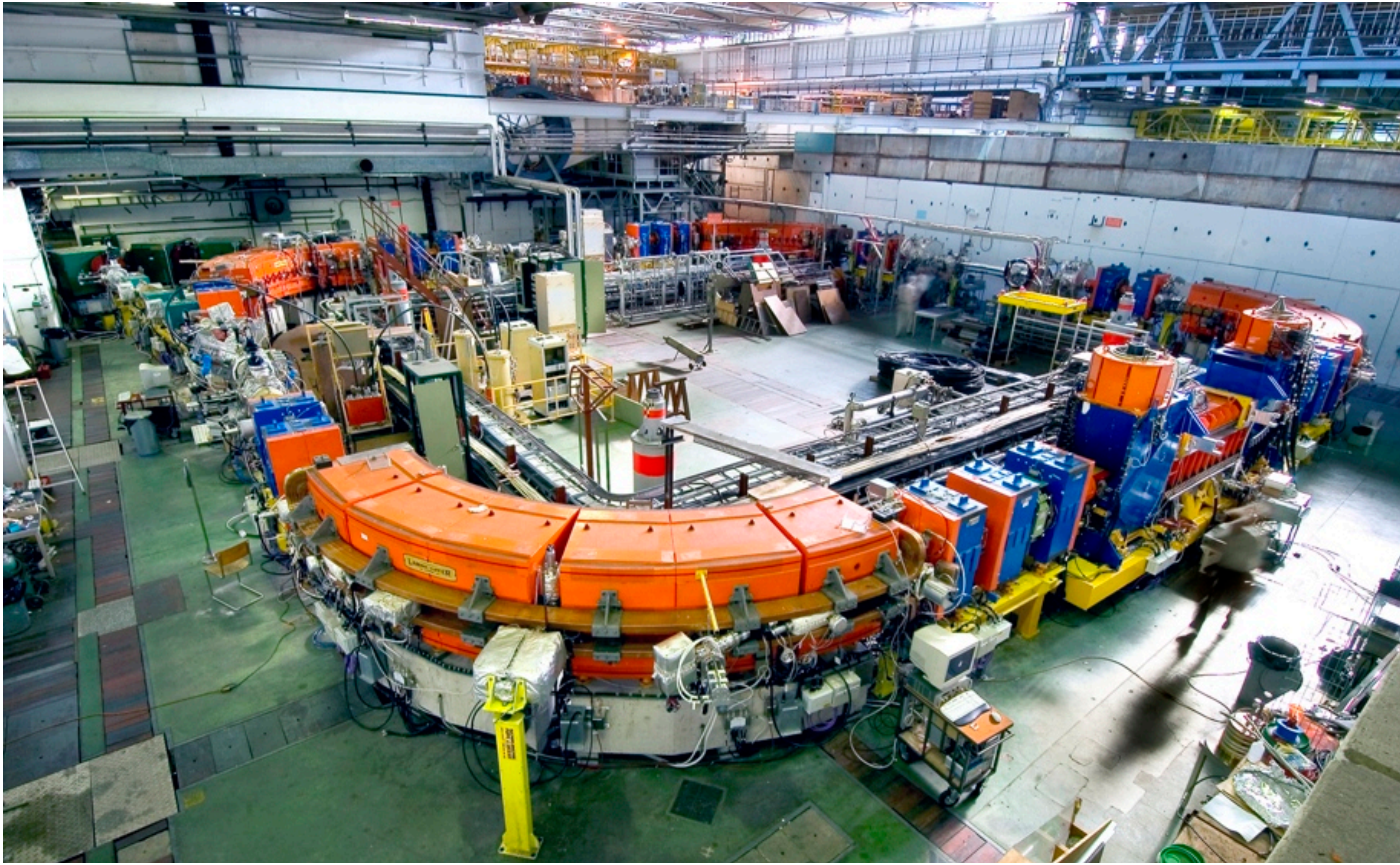


Typical lattice is FODO

focusing drift defocusing

Modern particles accelerators for high energy up to LHC energy (7 TeV) work in this way.

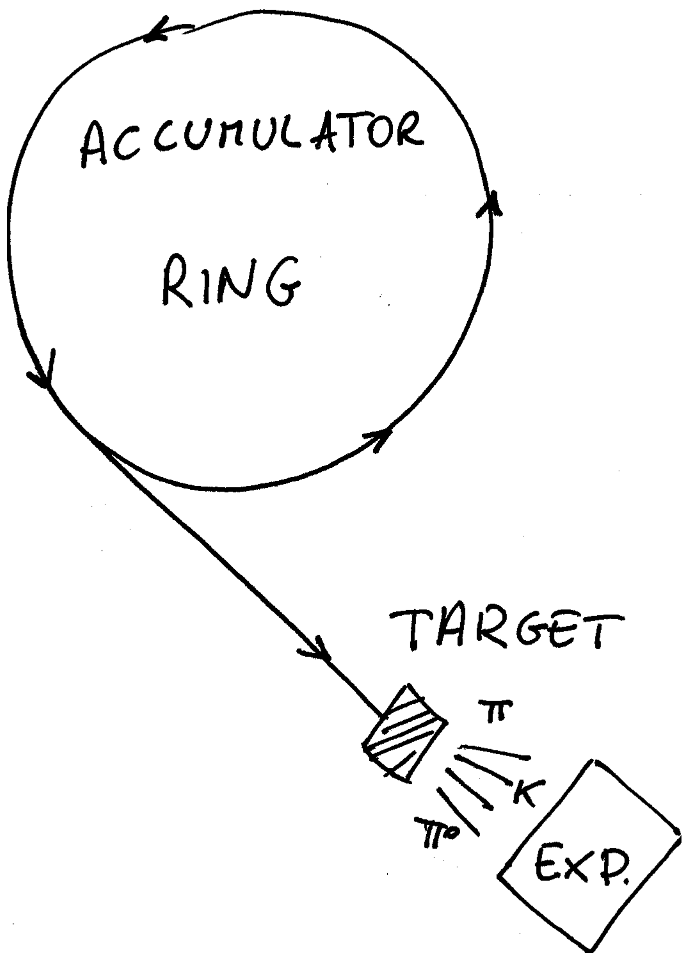
A synchrotron in a view: LEIR (Low Energy Ion Ring)



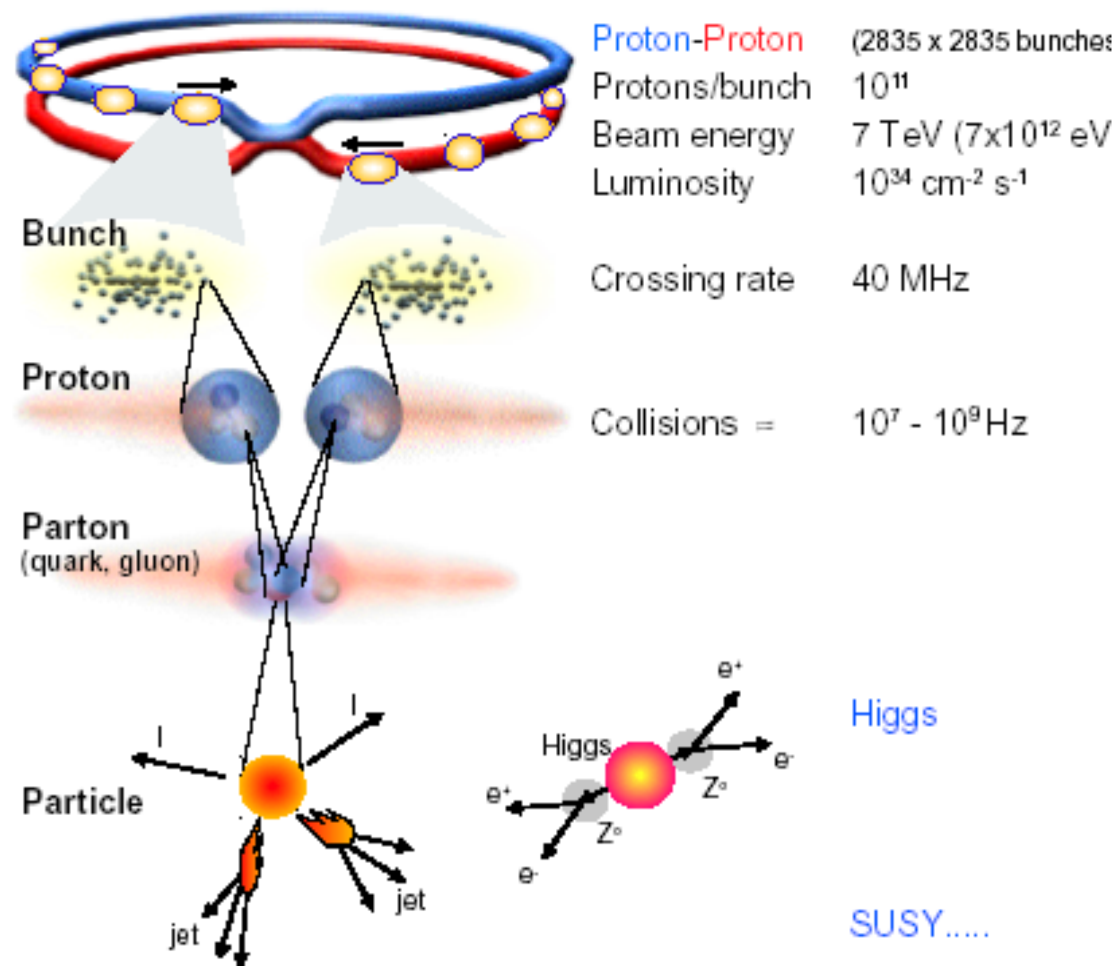
but this is for 4.2 MeV/nucl Pb ions... let climb the energy scale

Different approaches: fixed target vs collider

Fixed target



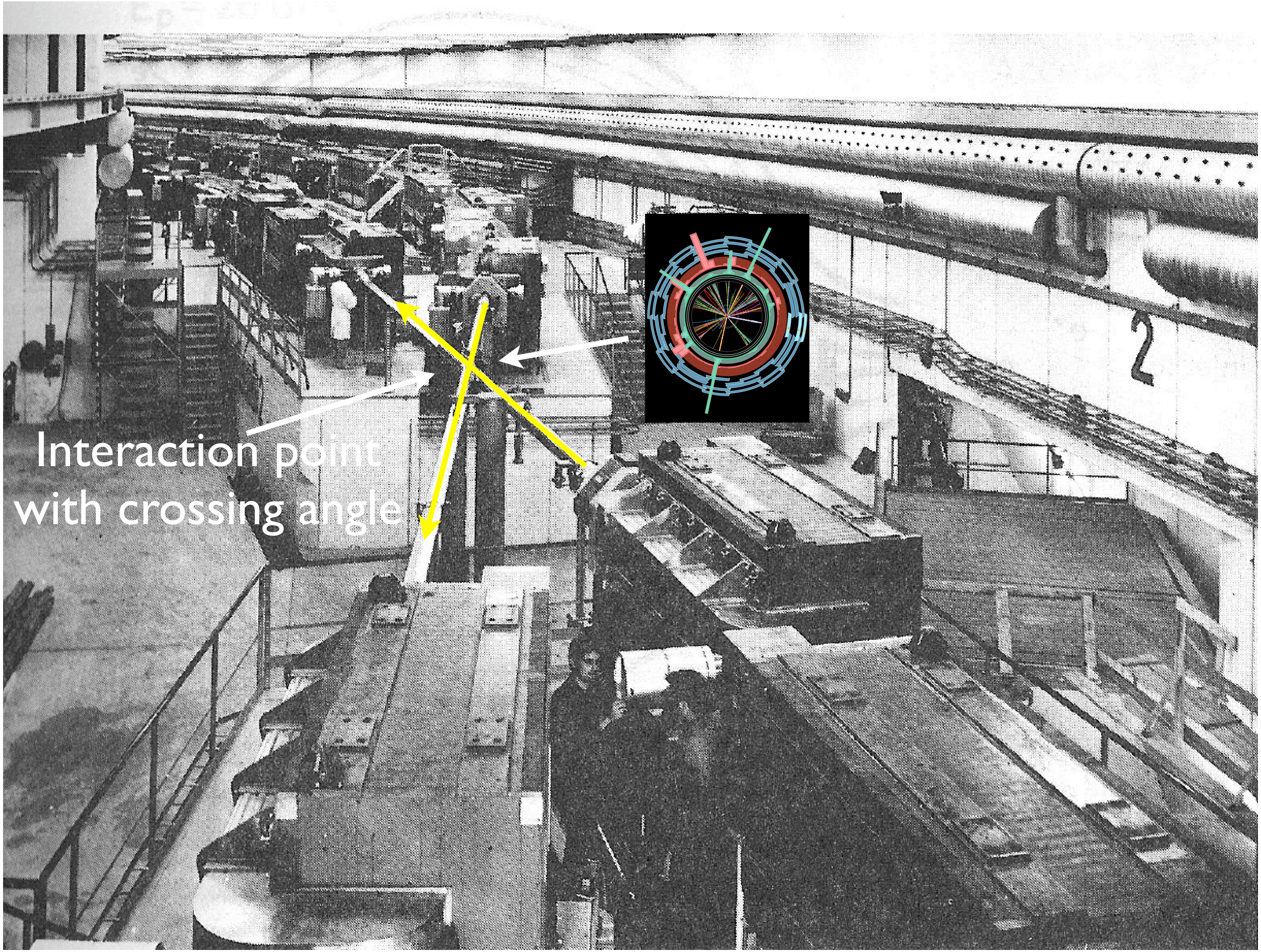
Storage ring/collider



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

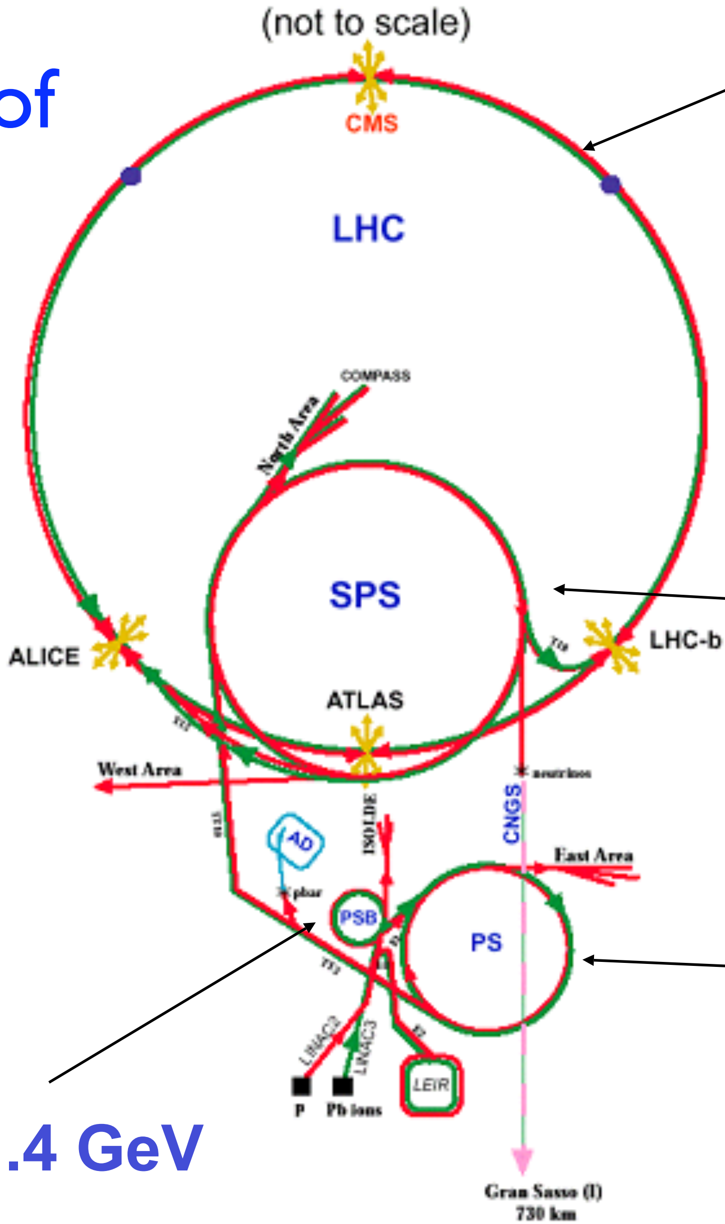
This usually is defined as $\sqrt{s}$

ISR, the first proton-proton collider



CERN accelerator complex overview

Chain/sequence of accelerators



450 GeV /c – 7 TeV /c

26 - 450 GeV/c

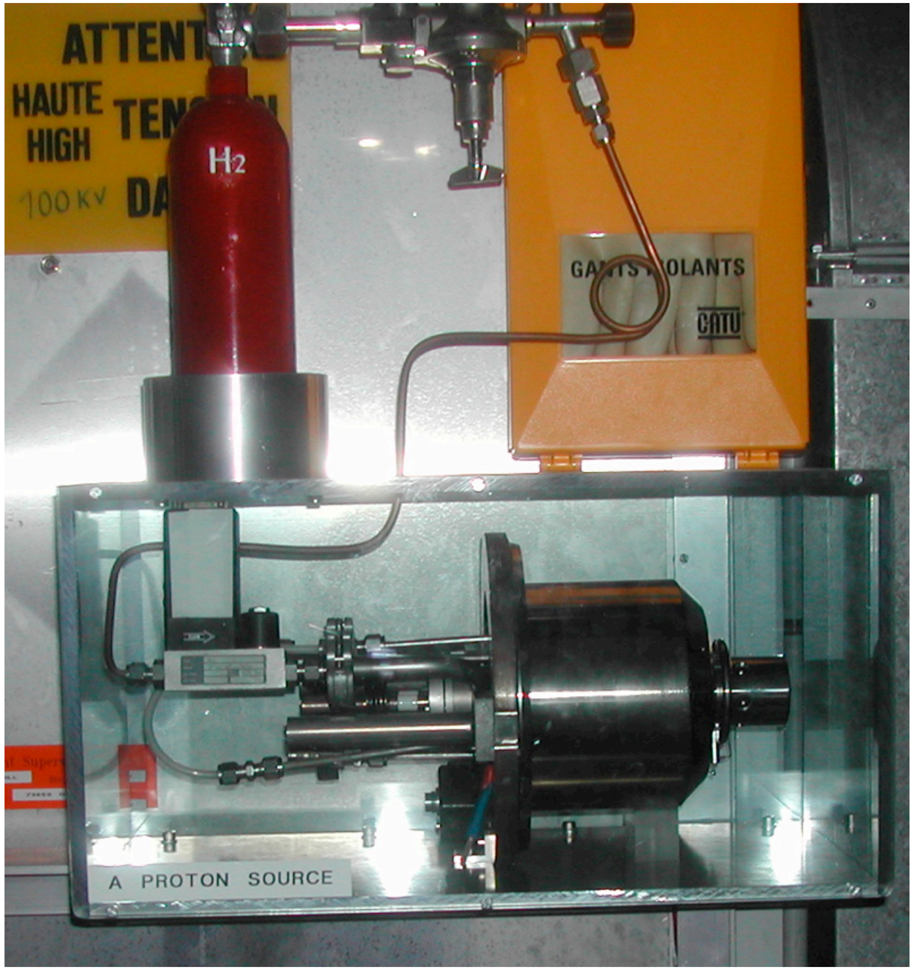
1.4 GeV – 26 GeV/c

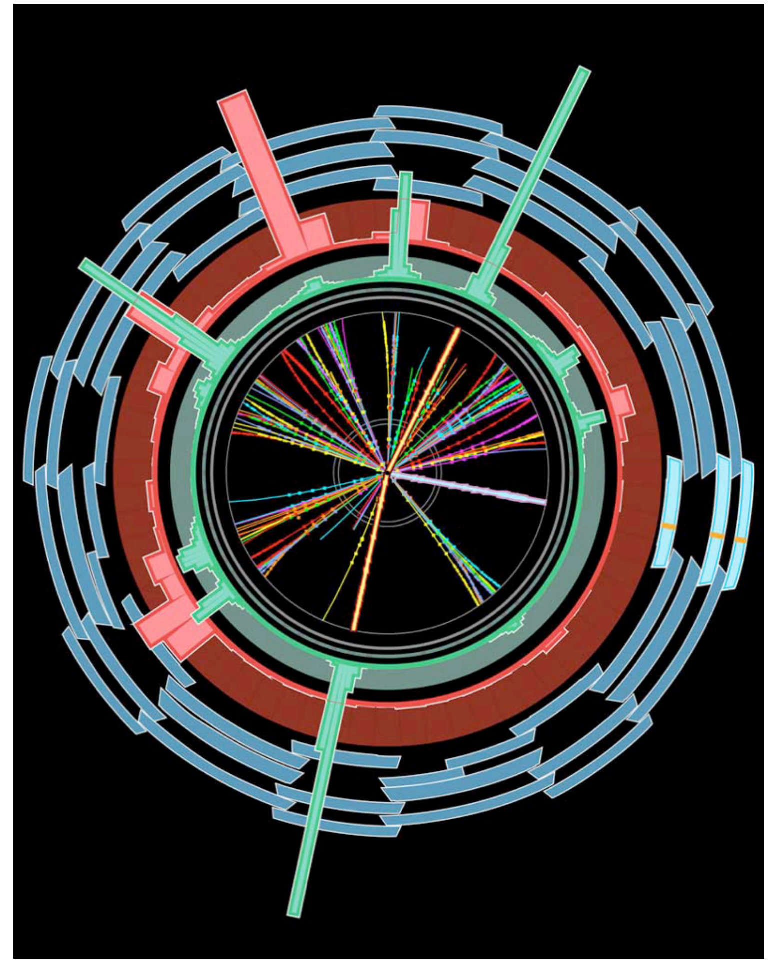
50 MeV – 1.4 GeV

- protons
- antiprotons
- ions
- neutrinos to Gran Sasso (I)

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Basically the injector chains brings you ...





from nearly a bottle of hydrogen

to a little bit before this

Where is the LHC ?

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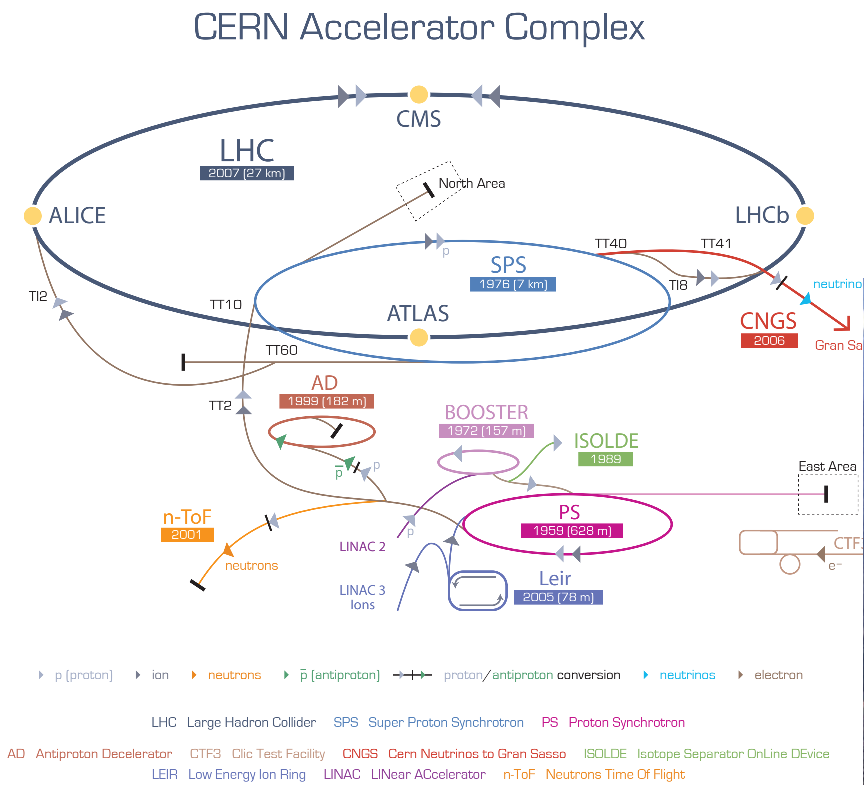
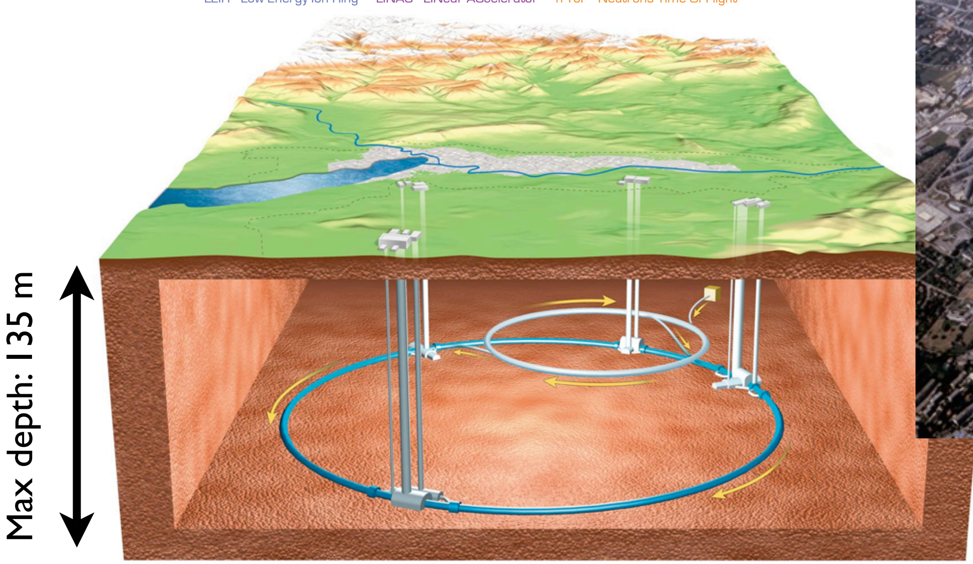
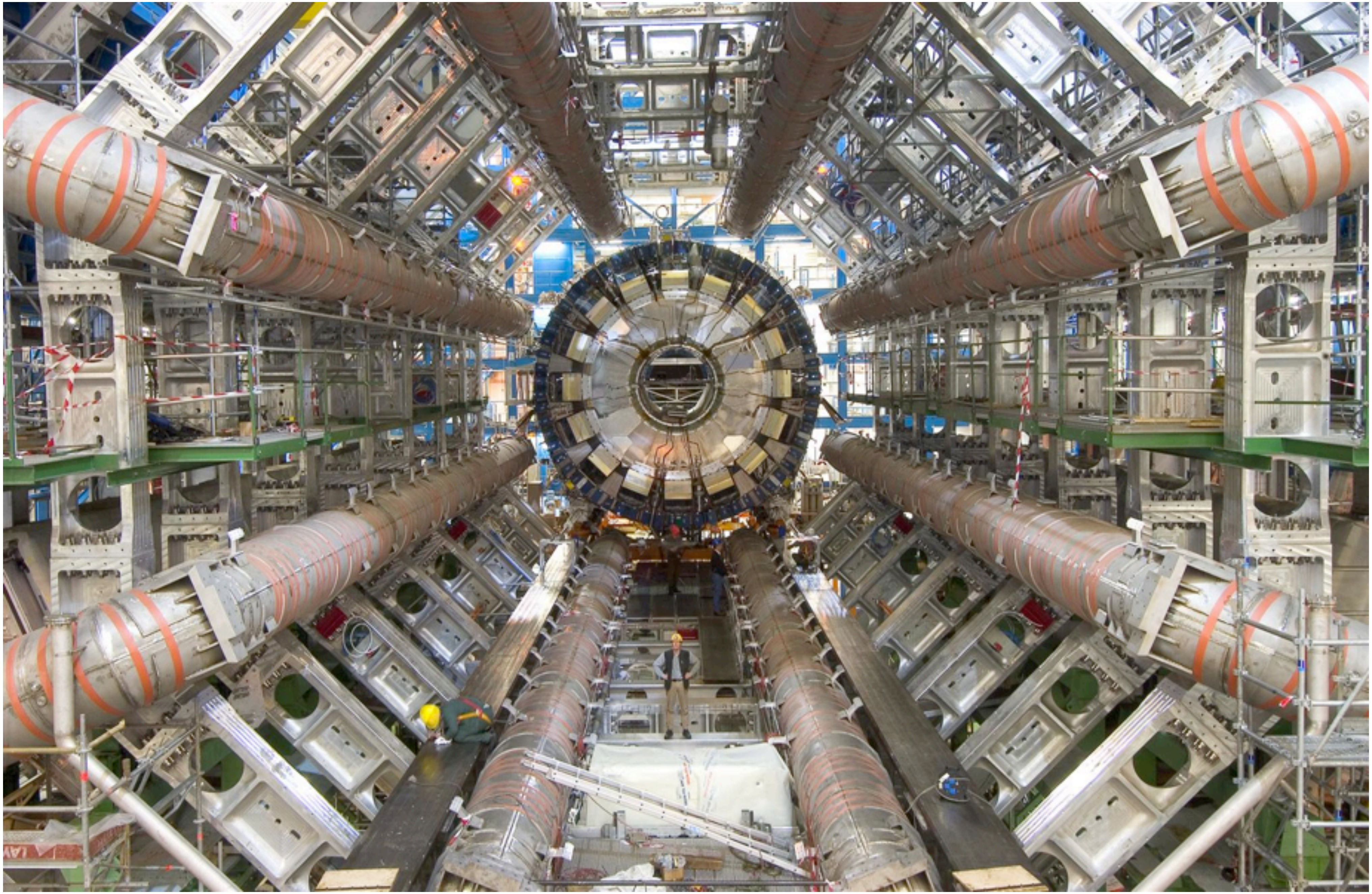


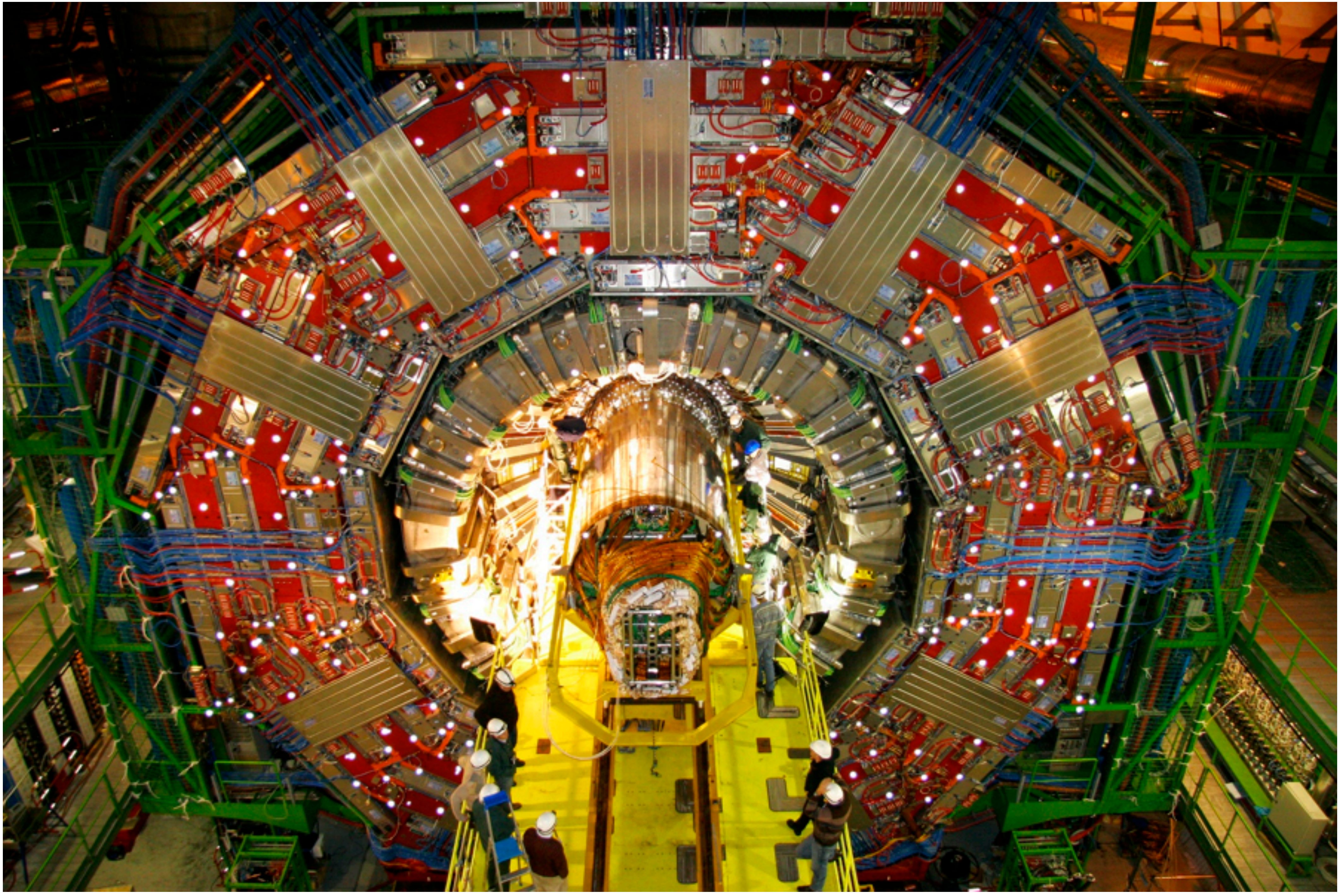


London tube: 24 m depth

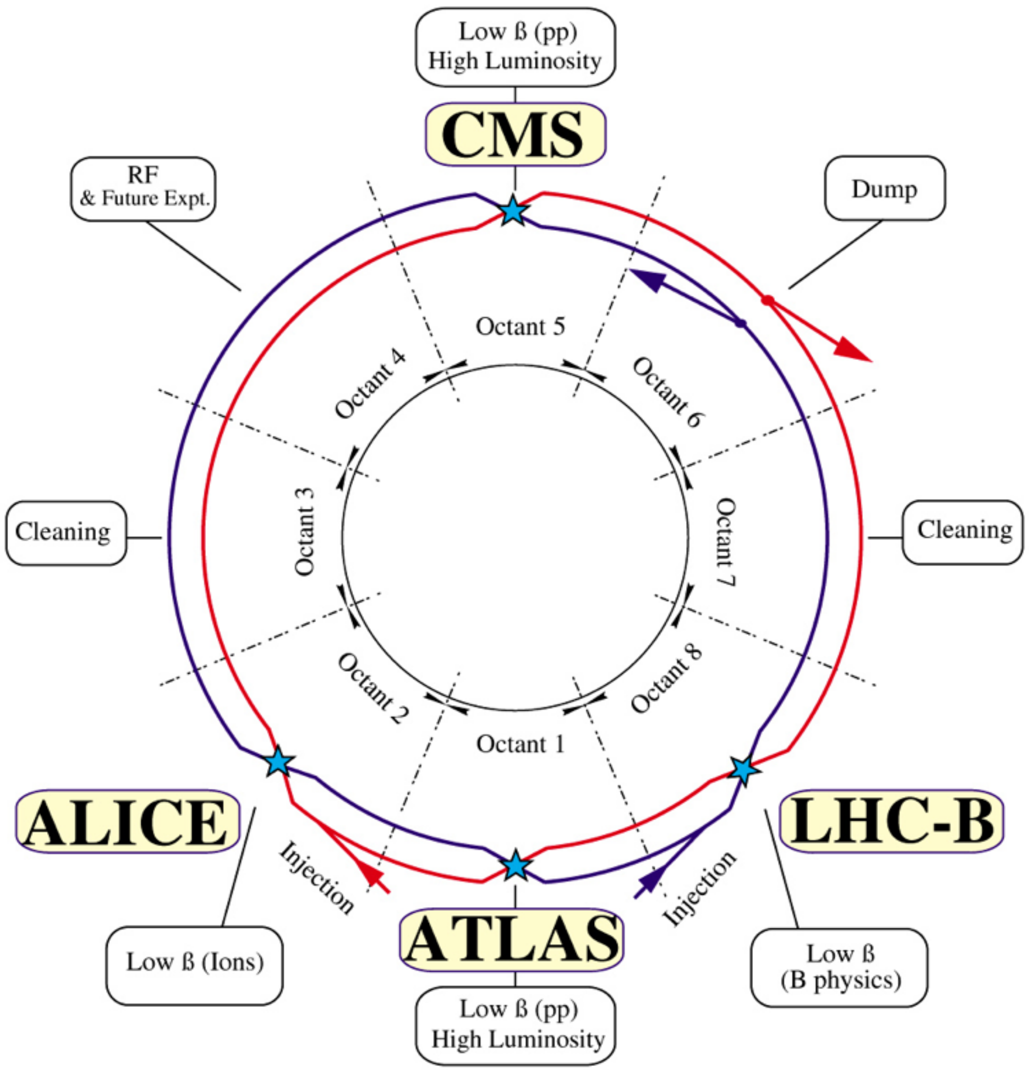
ATLAS



CMS



LHC layout and few parameters



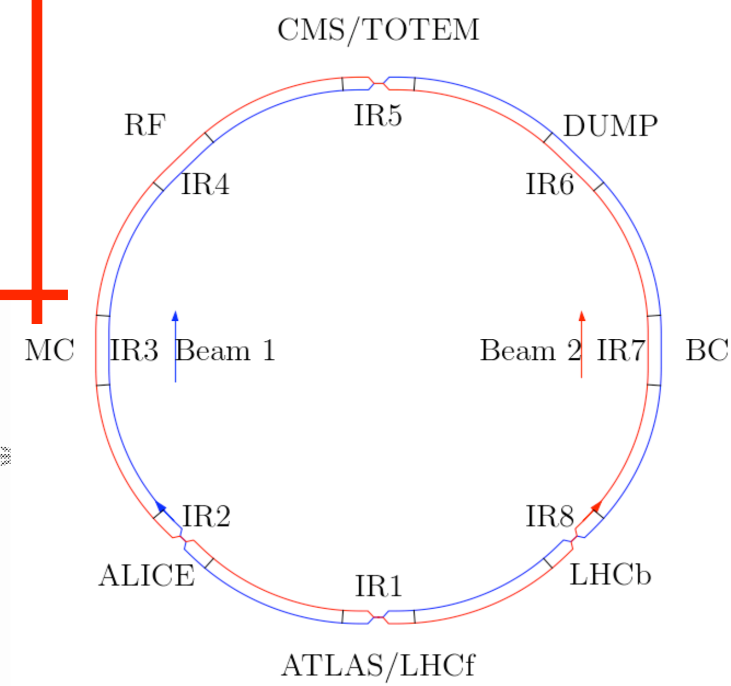
Particle type	protons (heavy ions, Pb82+)
Energy	450 GeV (injection) 7 TeV (collision energy) 2,75 TeV/u (ions collision)
Circumference	26658 m
Revolution frequency	11,245 kHz
Number of rings	1 (two-in-one magnet design)
Number of accelerators	2 (2 independent RF system)
Interaction Points (IP) or Collision Points or Low beta insertions	4 (ATLAS, CMS, ALICE, LHCb)
Cleaning insertions or collimation insertions	2
Beam dump extractions	2
RF insertion	1

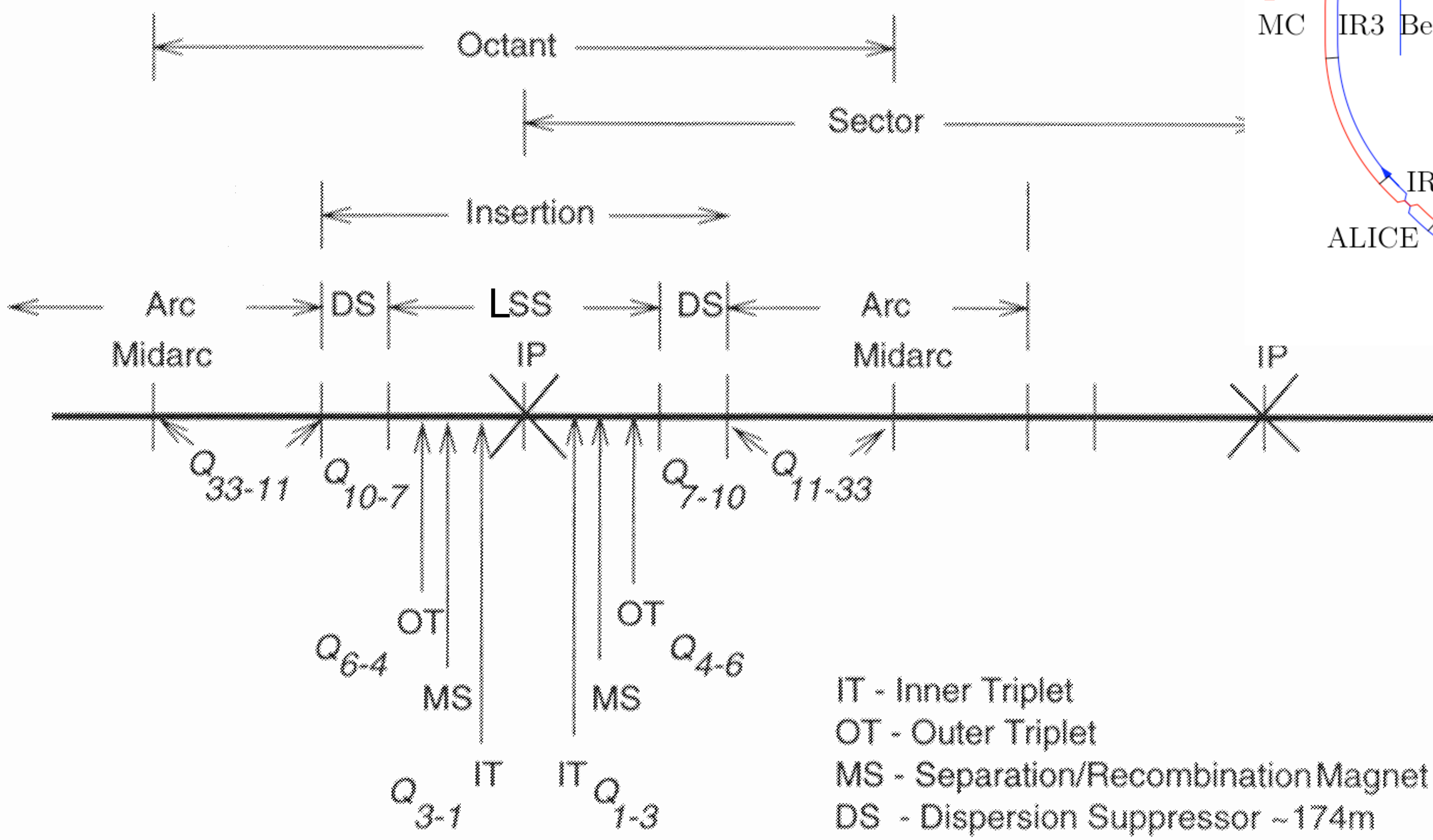
LHC cost ~1,899.64 MEUR, without the tunnel... ONE F1 season costs about 1,500 MEUR

The LHC-lattice terminology

Reference Frame for the lectures:

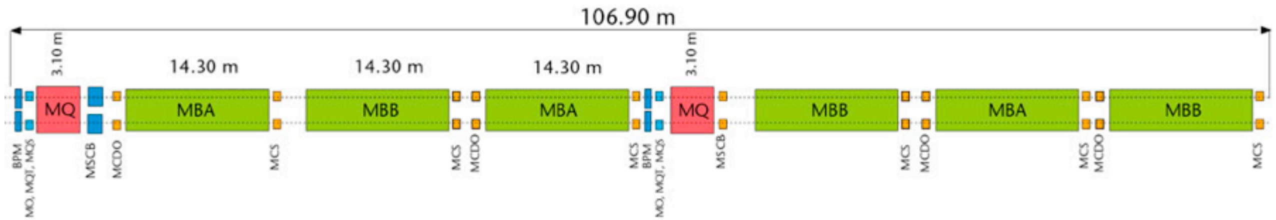
- x is the horizontal coordinate, positive means outside the ring
- y is the vertical coordinate, positive means up
- z is the direction of the particles,
  - positive clockwise for beam 1
  - positive anticlockwise for beam 2





IT - Inner Triplet
OT - Outer Triplet
MS - Separation/Recombination Magnet
DS - Dispersion Suppressor ~174m
LSS - Straight Section ~528m (Long straight section)
Arc ~ 2460m

Basics components of the LHC



Regular 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

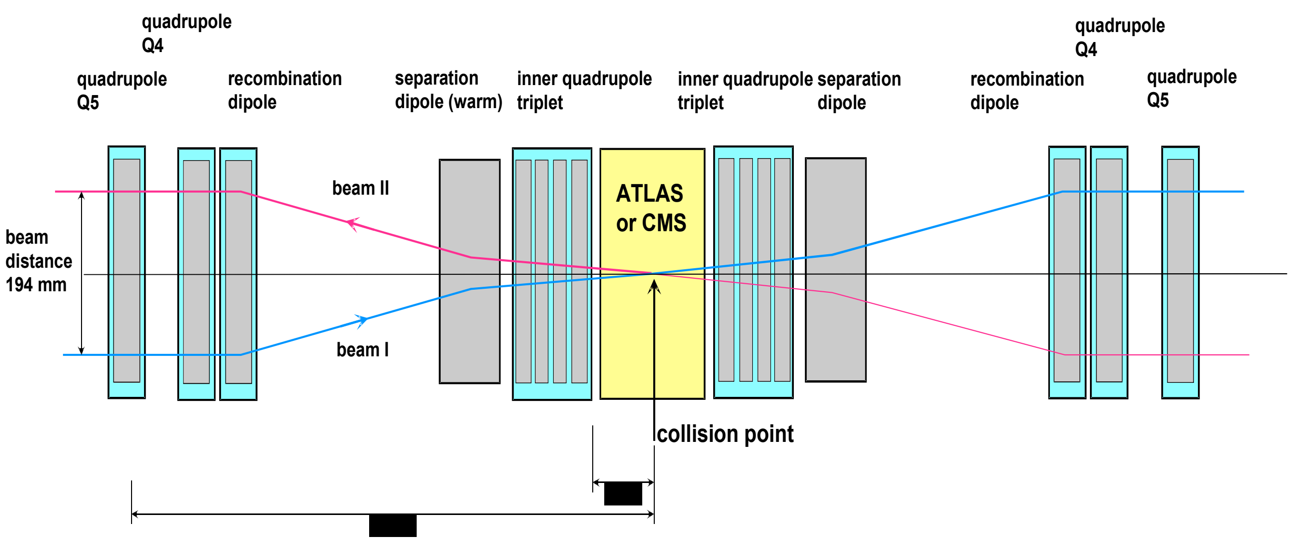
HF226 - v10/99

Synchrotron:

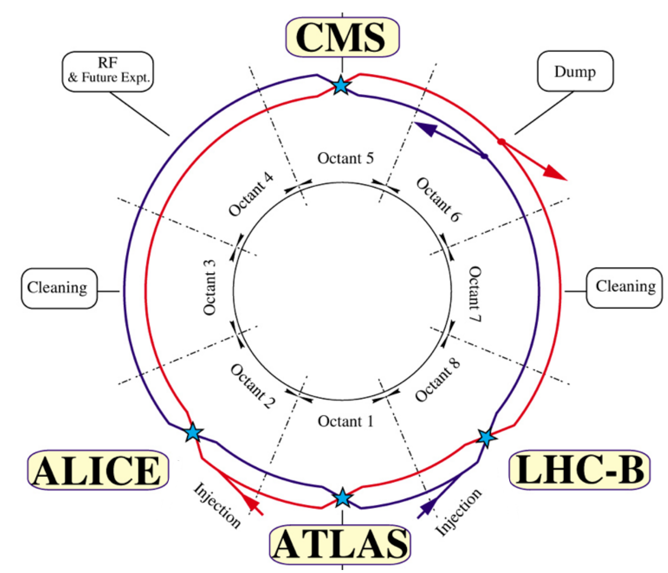
a) dipoles to bend particles with increasing field vs time i.e. vs energy

b) quadrupoles to focus the beam and keep it in the aperture. FODO

c) interaction point with final focusing to collide the two beams

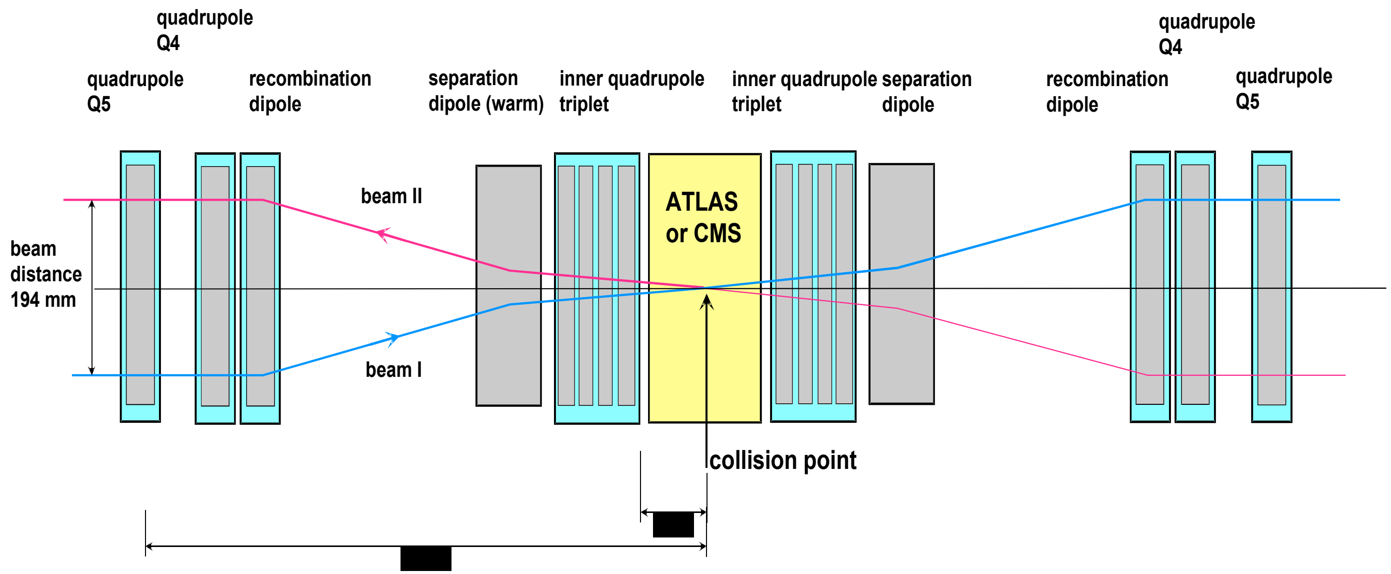


Example for an LHC insertion with ATLAS or CMS



Interaction points

Let start with collisions



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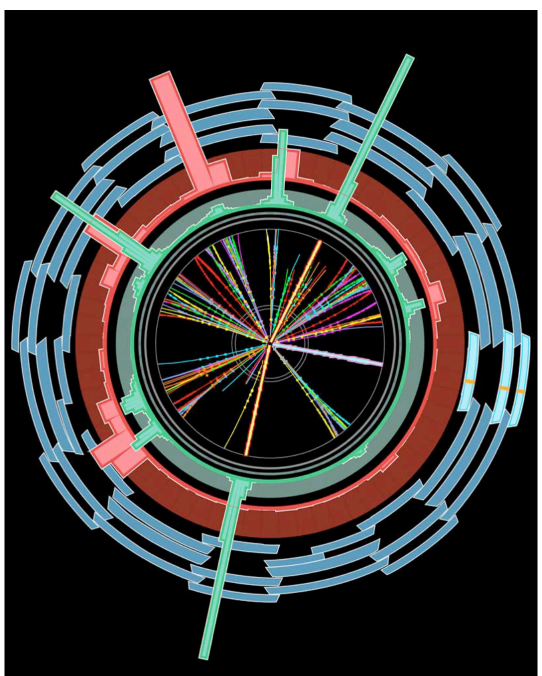
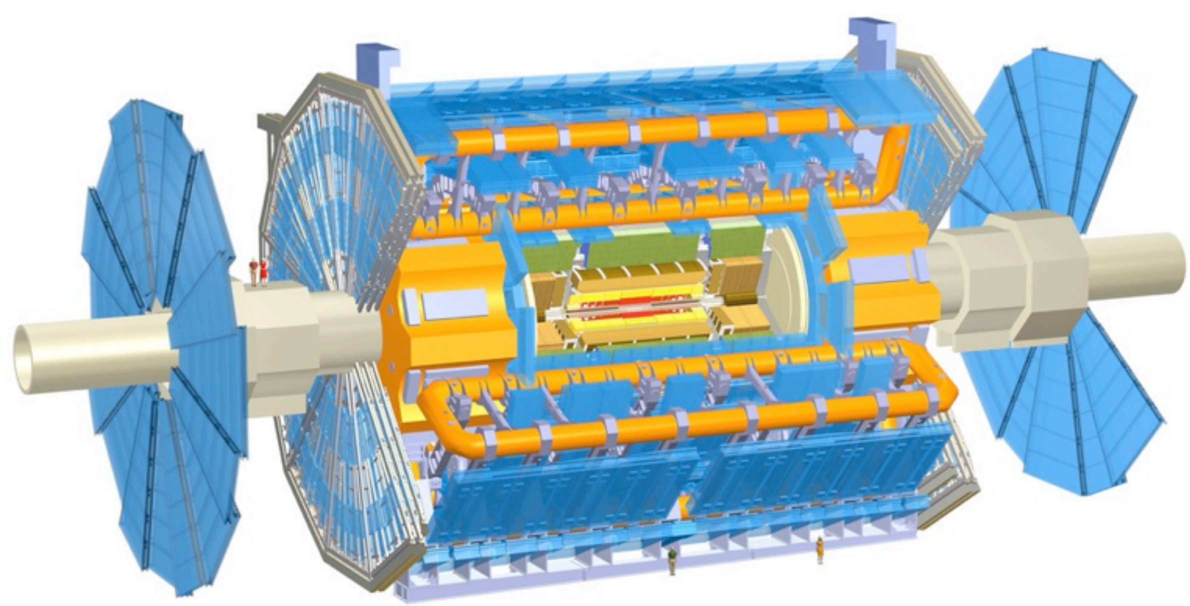
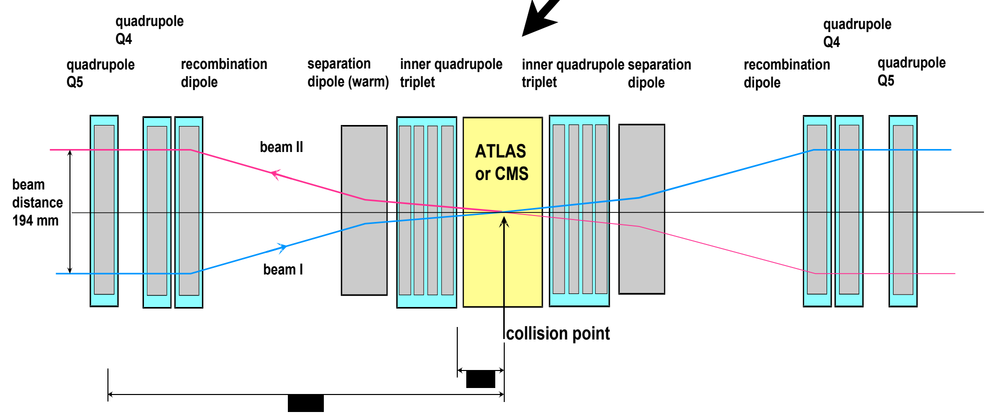




Luminosity

$$N_{event} = L\sigma_{event}$$



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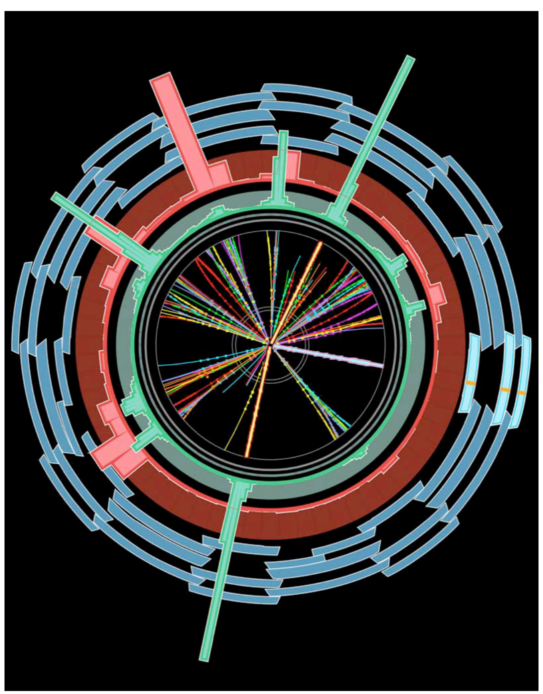
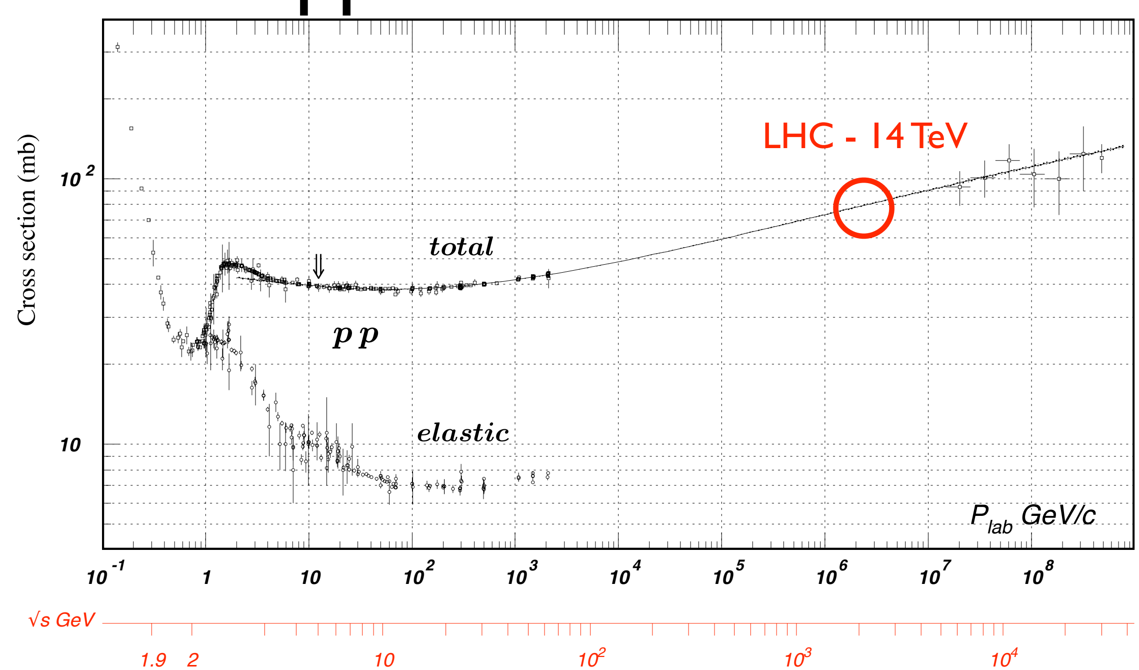
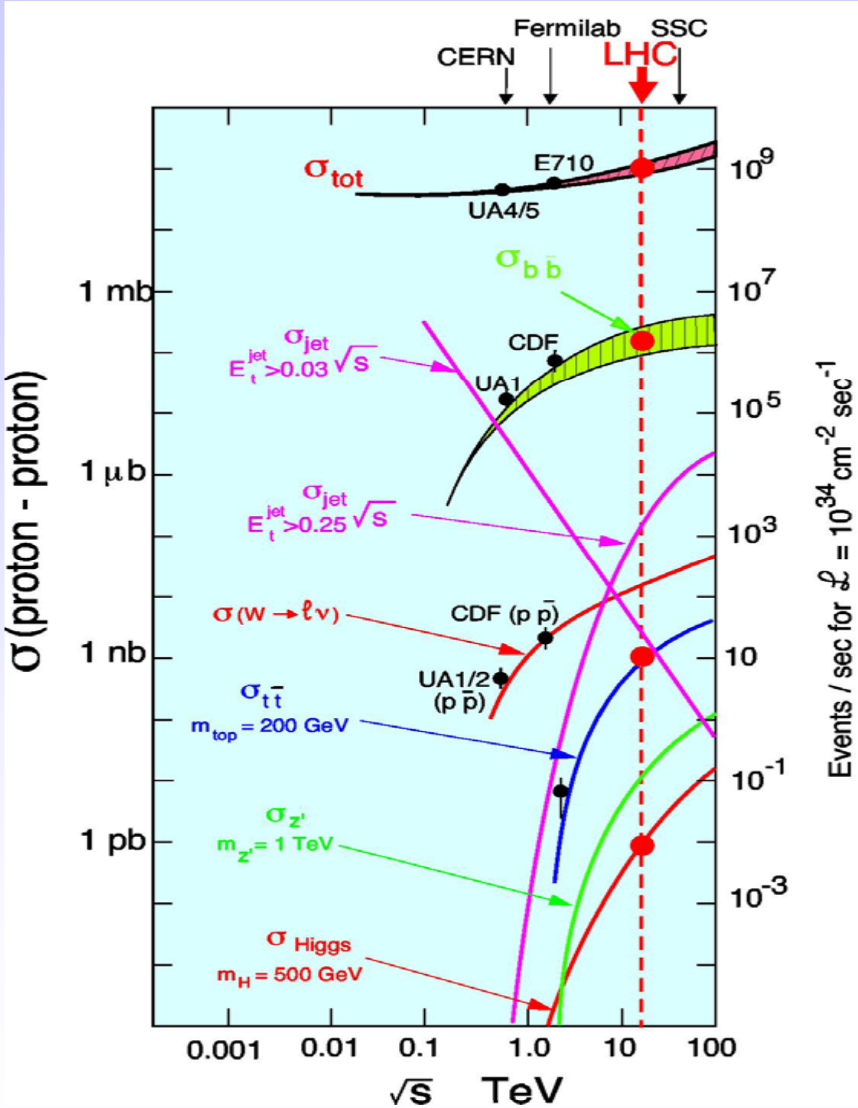


pp cross section



Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs	5 10^6 / s
• tt pairs	8 / s
• W → e ν	150 / s
• Z → e e	15 / s
• **Higgs (150 GeV)**	**0.2 / s**
• **Gluino, Squarks (1 TeV)**	**0.03 / s**

LHC is a factory for:
top-quarks, b-quarks, W, Z, ……. Higgs, ……

The only problem: you have to detect them !

Luminosity

Number of particles per bunch
$N_{beam1} * N_{beam2} = N^2$

Revolution frequency

Number of bunches

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

Geometric Reduction factor
due to crossing angle

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

Beam dimension at the IP

$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y} \cdot \epsilon_{x,y}}$$

At first look, the smaller the better

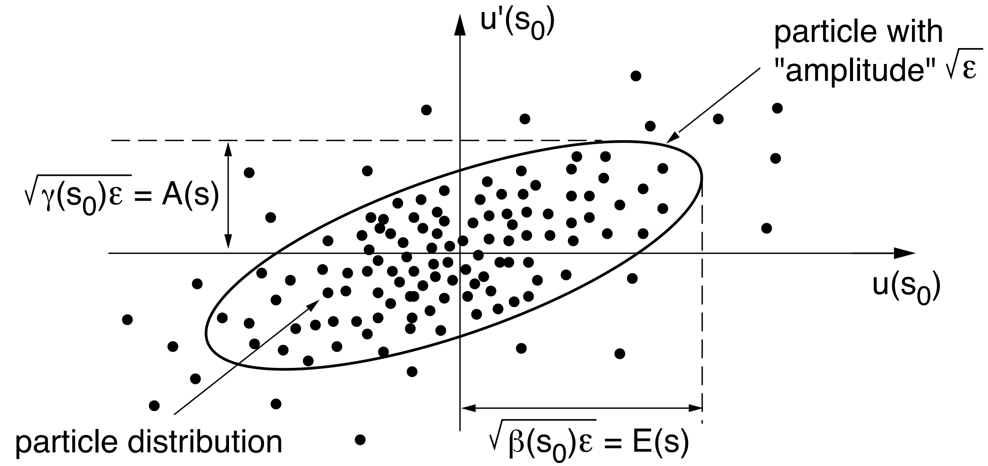
Definition of beam emittance

$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y} \cdot \epsilon_{x,y}}$$

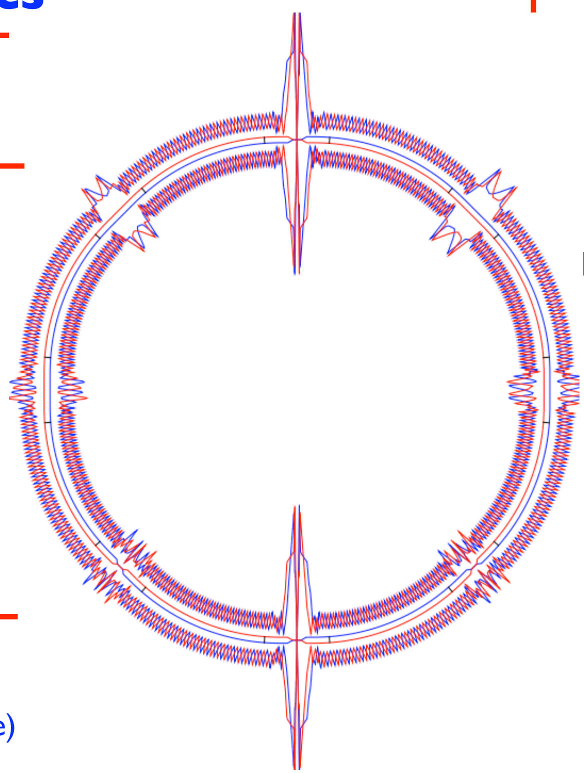
Beam physical dimension

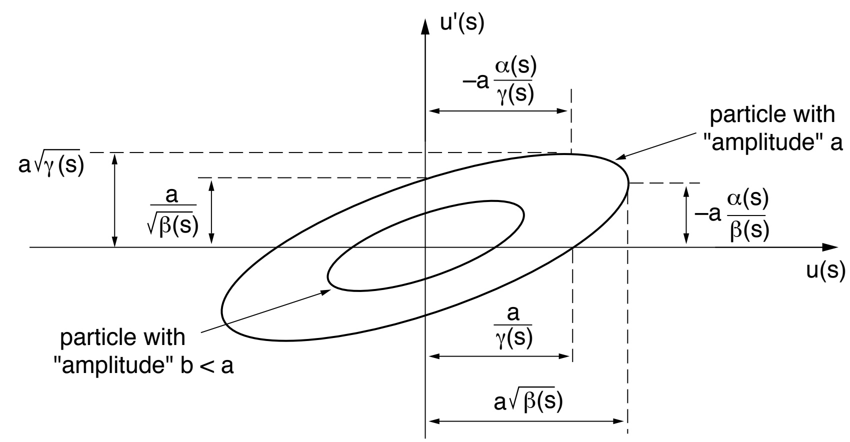
Optical machine parameter that depends on the lattice of the machine, in particular on the ***QUADRUPOLES.***
The interaction POINT is built as a FOCAL POINT for the machine optics

Emittance: *Parameter which describes the spread of the particles in the phase space (xx') or (yy').*



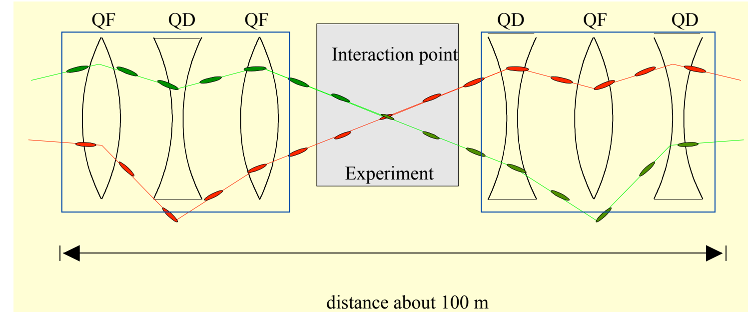
By knowing the setting of the quadrupoles and the beam emittance, one can compute the beam dimension in the entire LHC

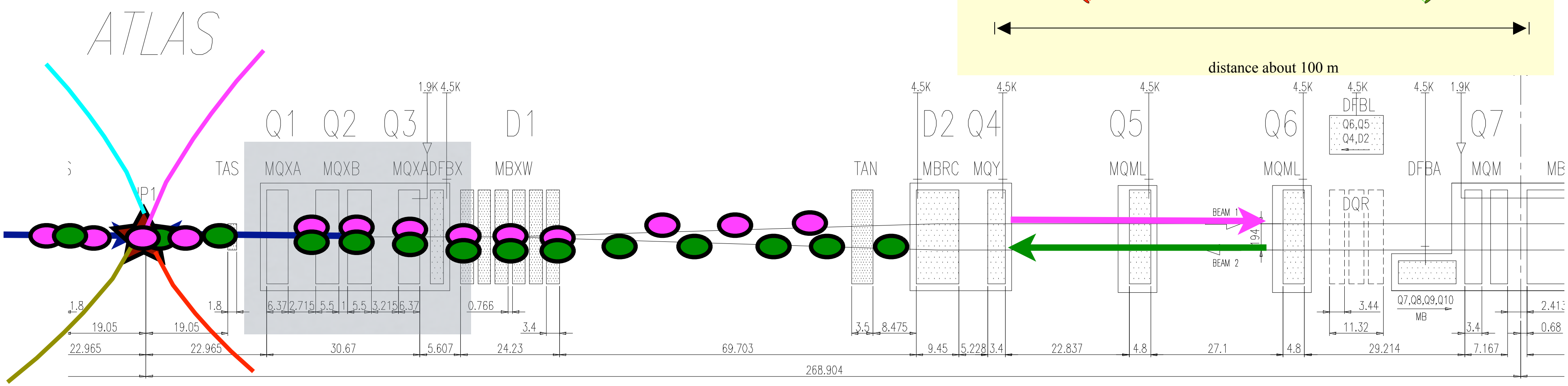


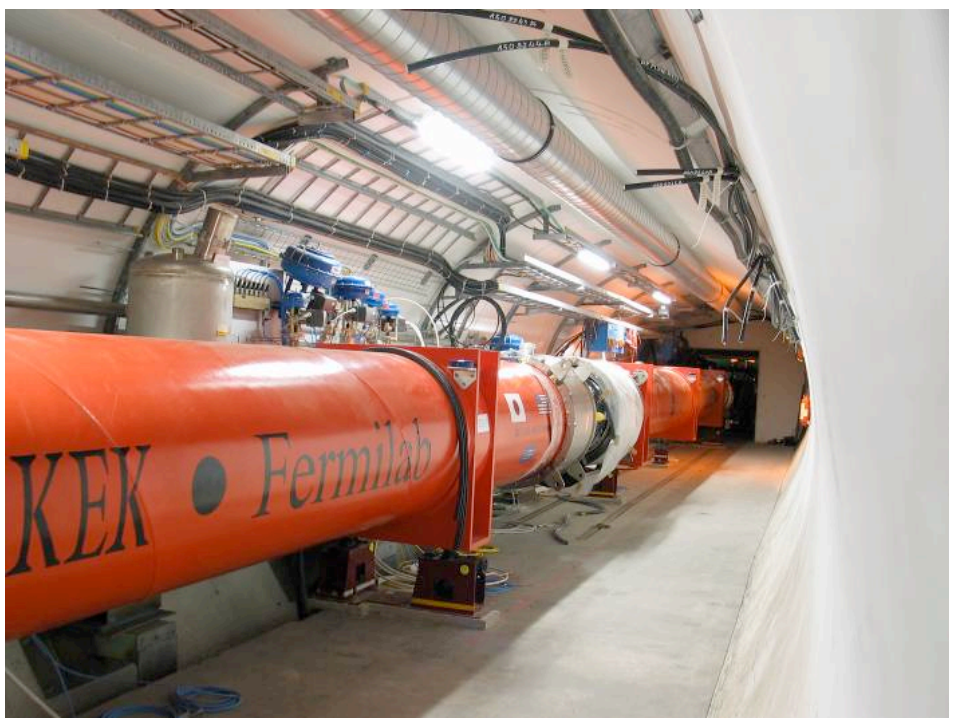


(See slide 49, 51 and 55 Hillert lecture)

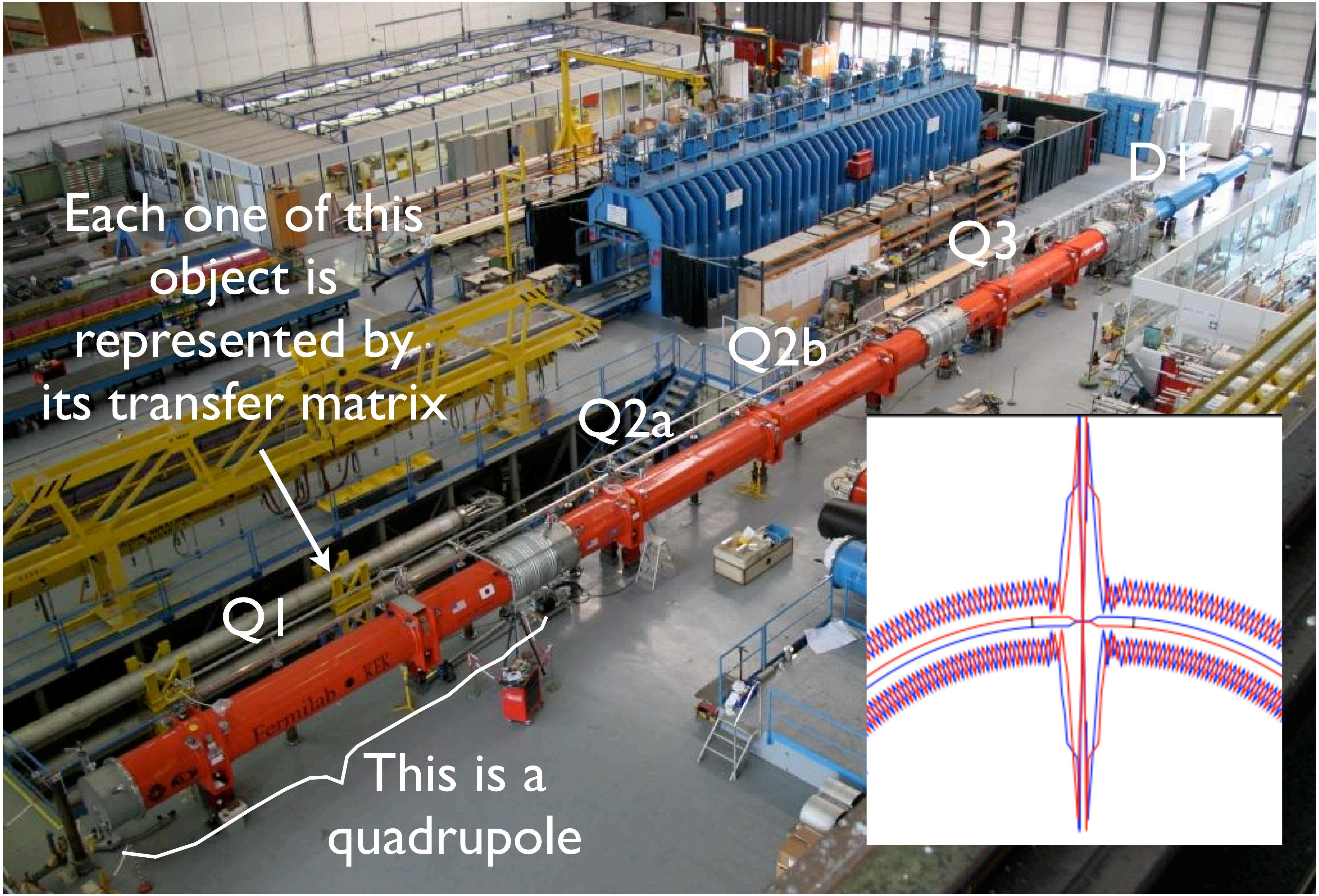
Inner triplet: final focusing
⇒ how to make the beam small at the IP







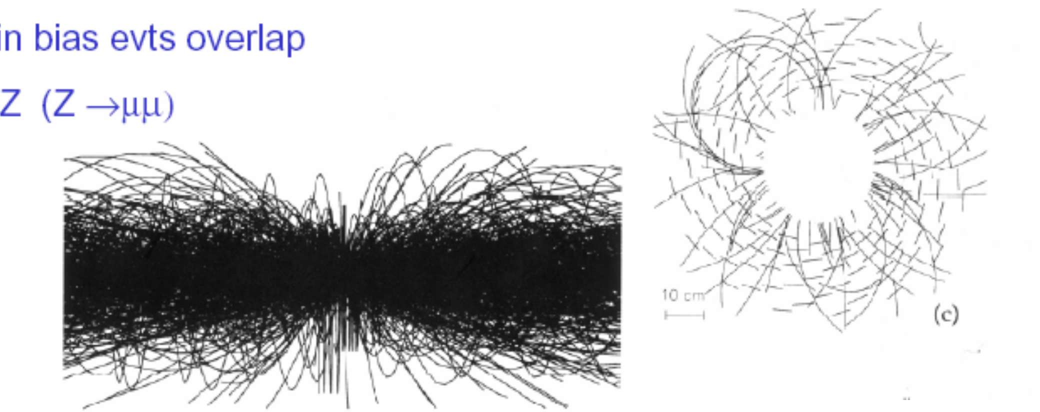
Triplets before lowering in the tunnel

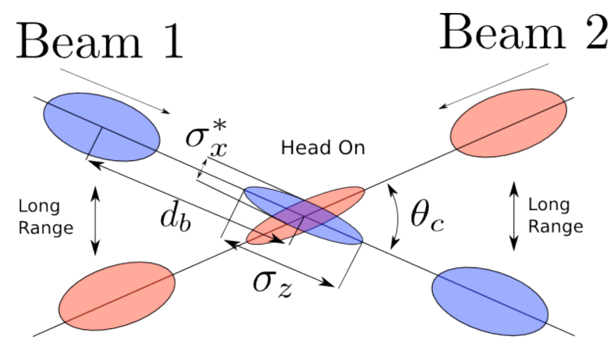


Crossing angle

20 min bias evts overlap

H→ZZ (Z →μμ)

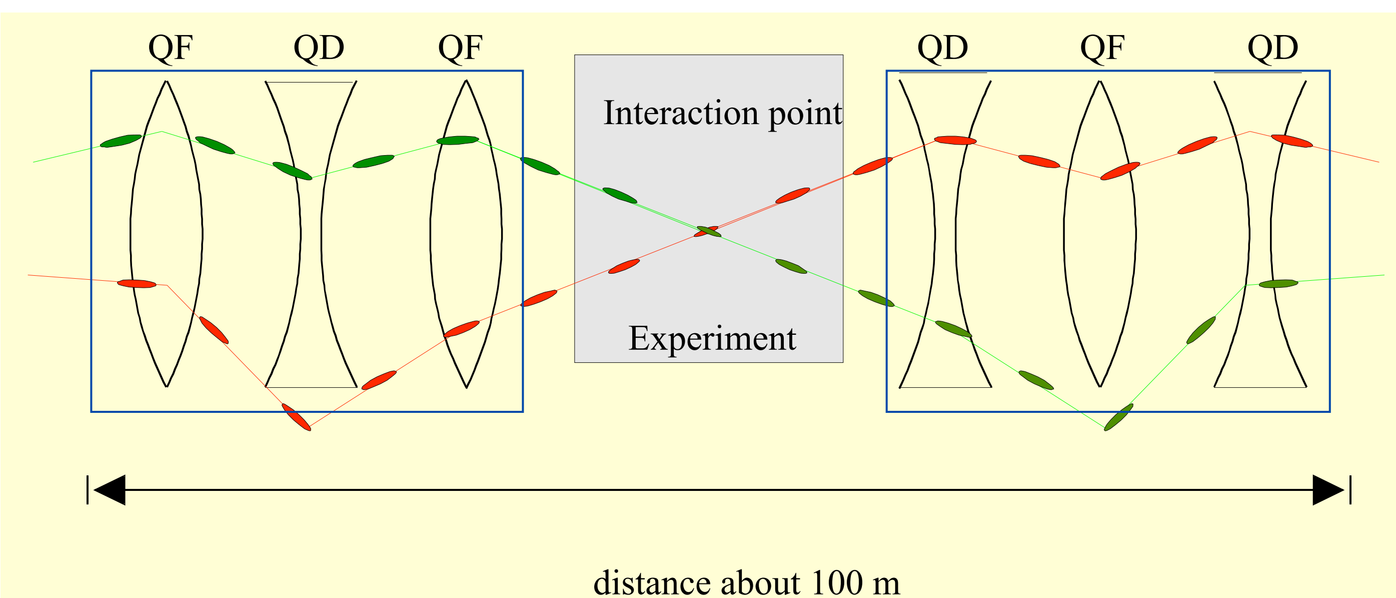




Angle @ IP to avoid that the 2808 bunches collides in other places than the IP in the LSS.

~ 30 unwanted collision per crossing

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

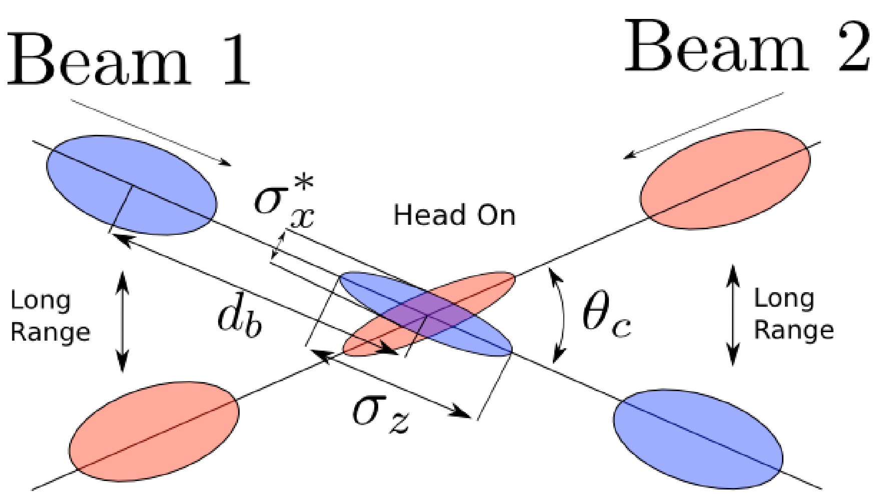


Θ_c	crossing angle	285 μm
σ_z	RMS bunch length	7.55 cm
σ^*	RMS beam size (ATLAS-CMS)	16.7 μm
F	L reduc. Factor	0.836

Few LHC numbers ...

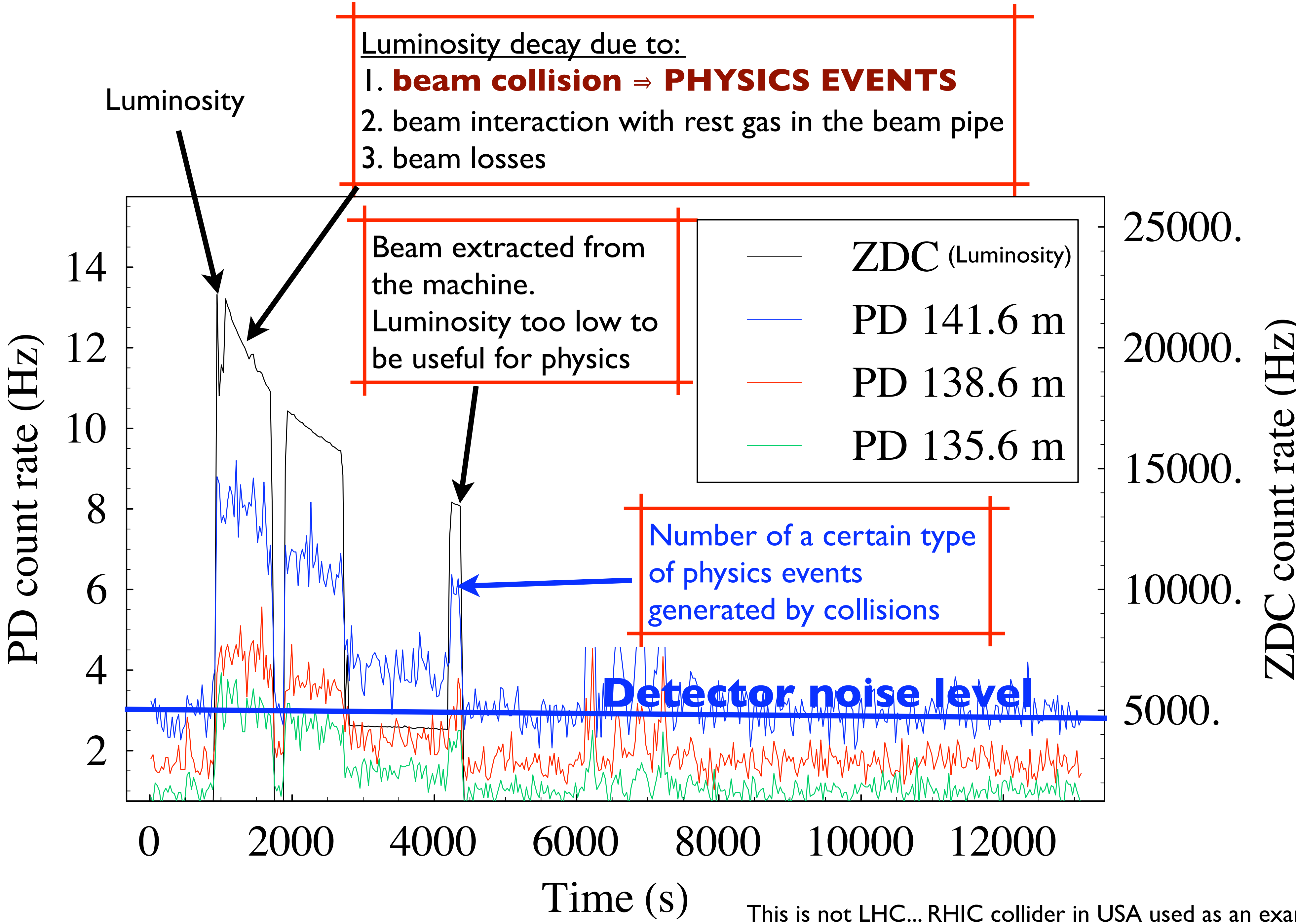
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

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

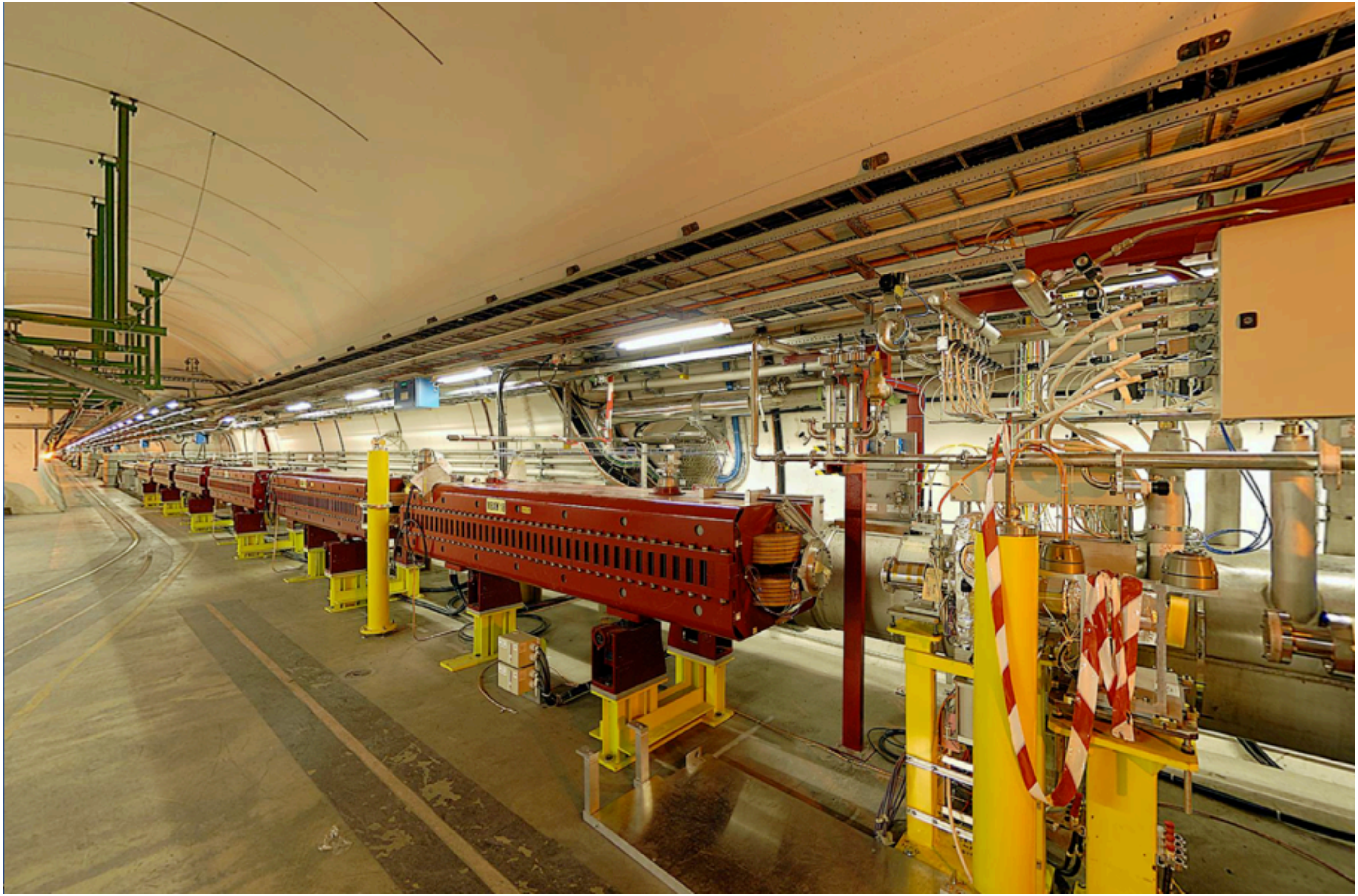


Luminosity	1*10^{34} /cm^2/s (IP1 IP5)
Particle per bunch	1,15 10^{11}
Bunches	2808
Revolution frequency	11,245 kHz
Crossing rate	40 MHz
Normalised Emittance	3.75 μm rad
β-function at the collision point	0.55 m
RMS beam size @ 7 TeV at the IP1-5	16.7 μm
Circulating beam current	0.584 A
Stored energy per beam	362 MJ

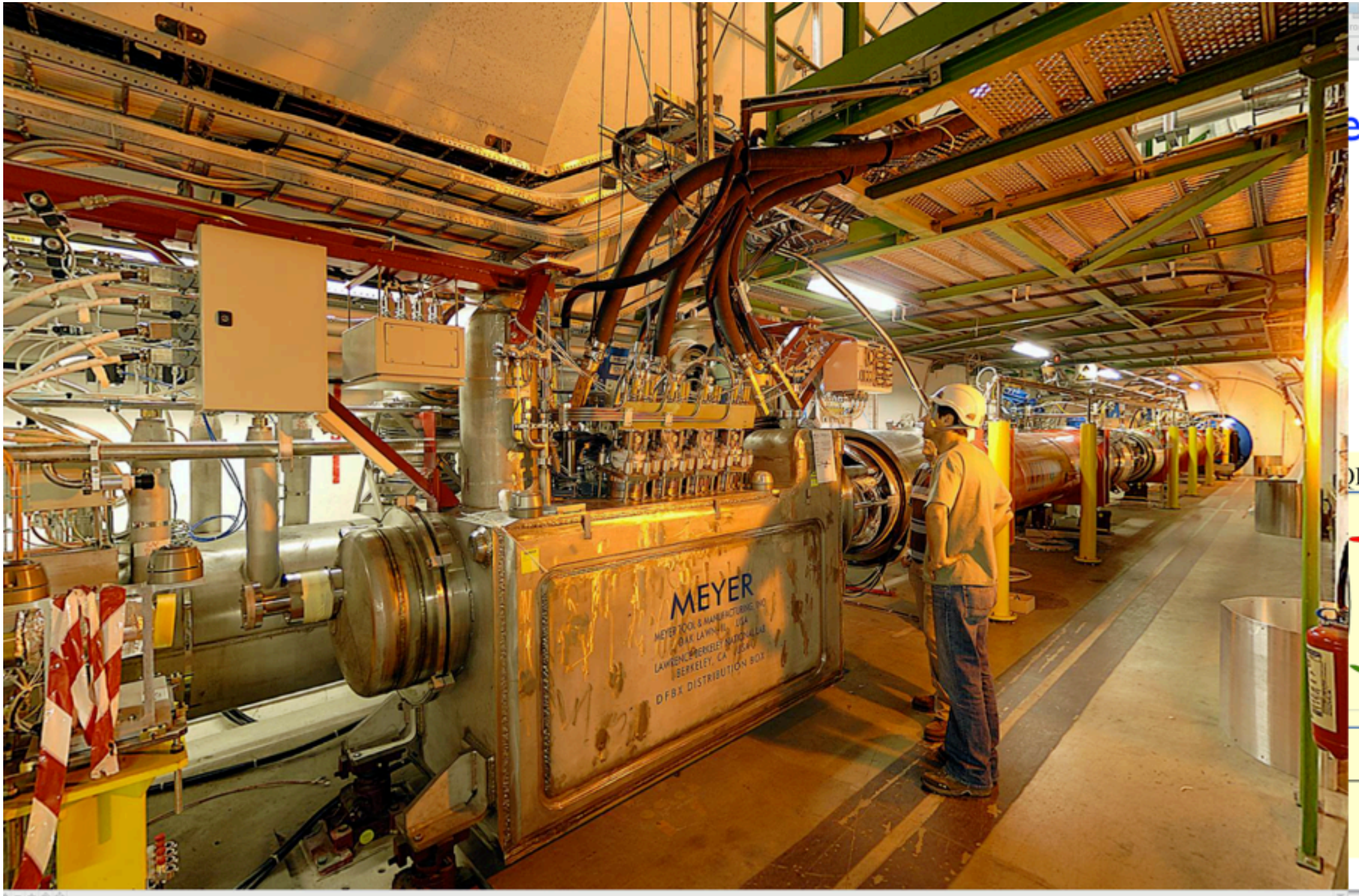
Example of Luminosity vs time in a running collider



This is not LHC... RHIC collider in USA used as an example

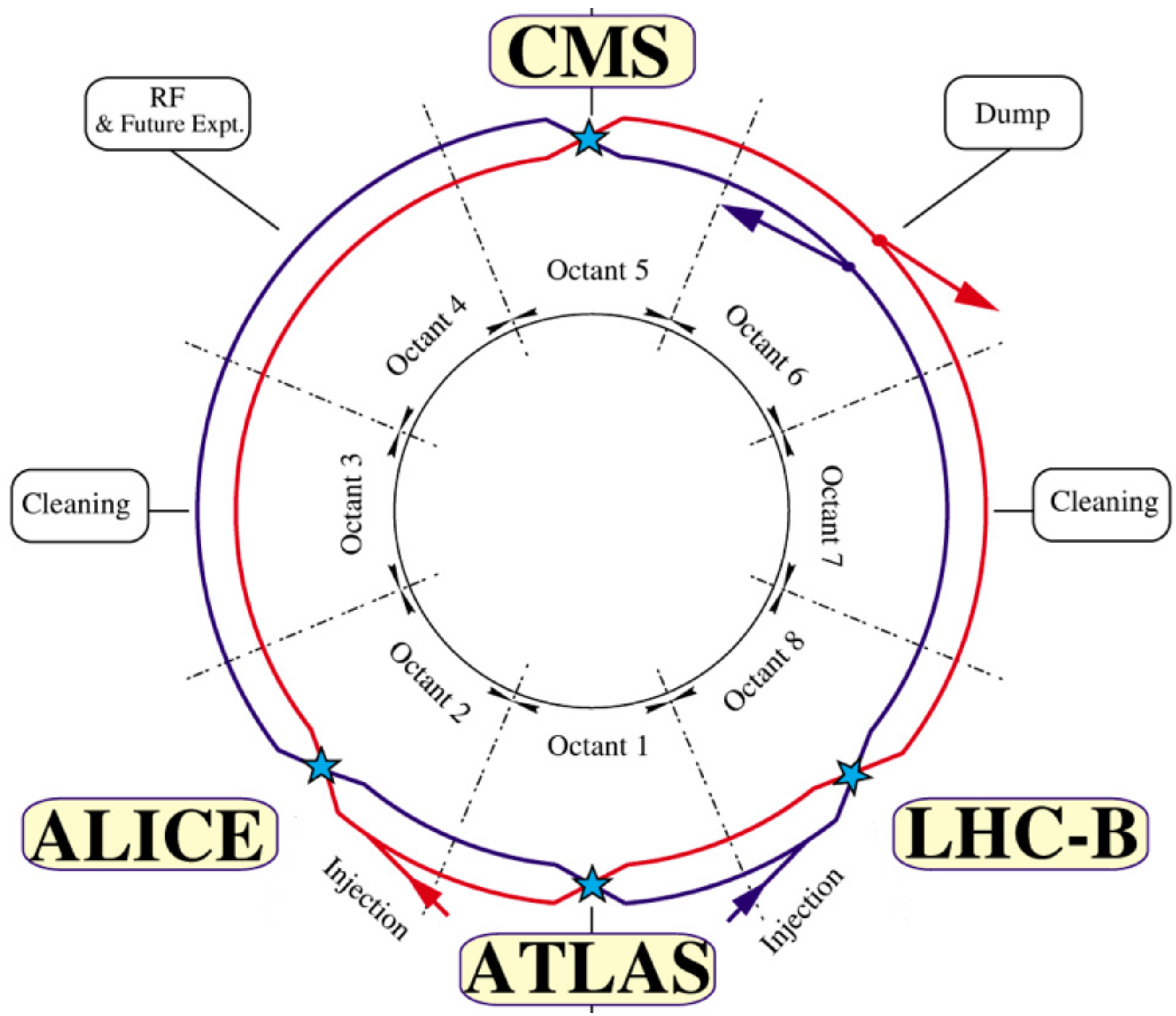


Near the IPs



http://petermccready.com/portfolio/

From collision point to the LHC ring



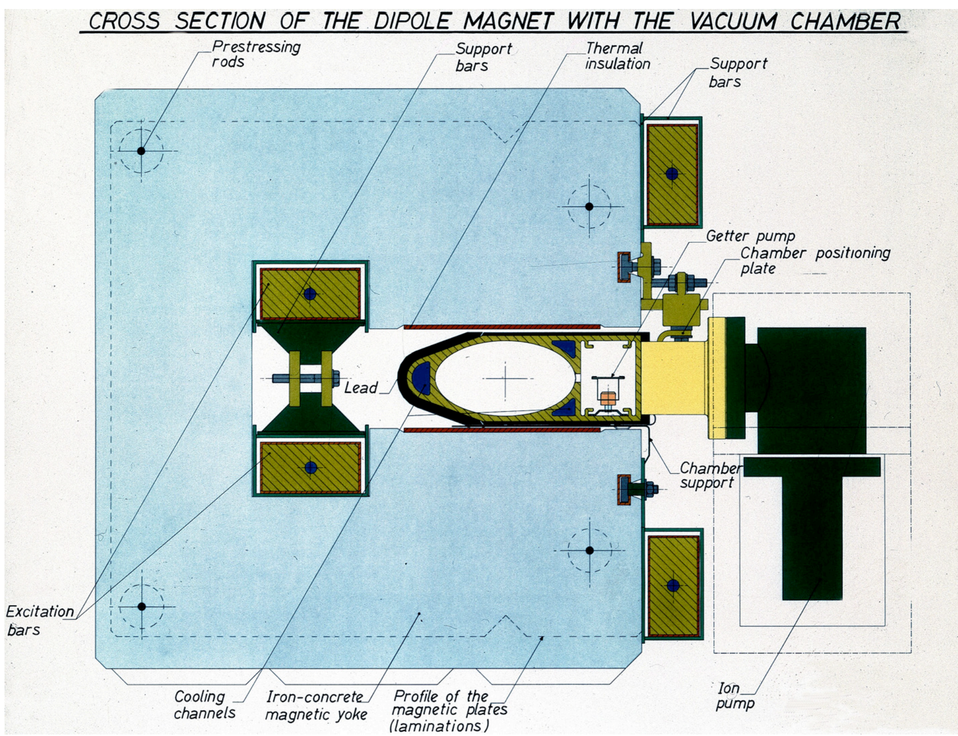
LEP vs LHC: Magnets, a change in technology

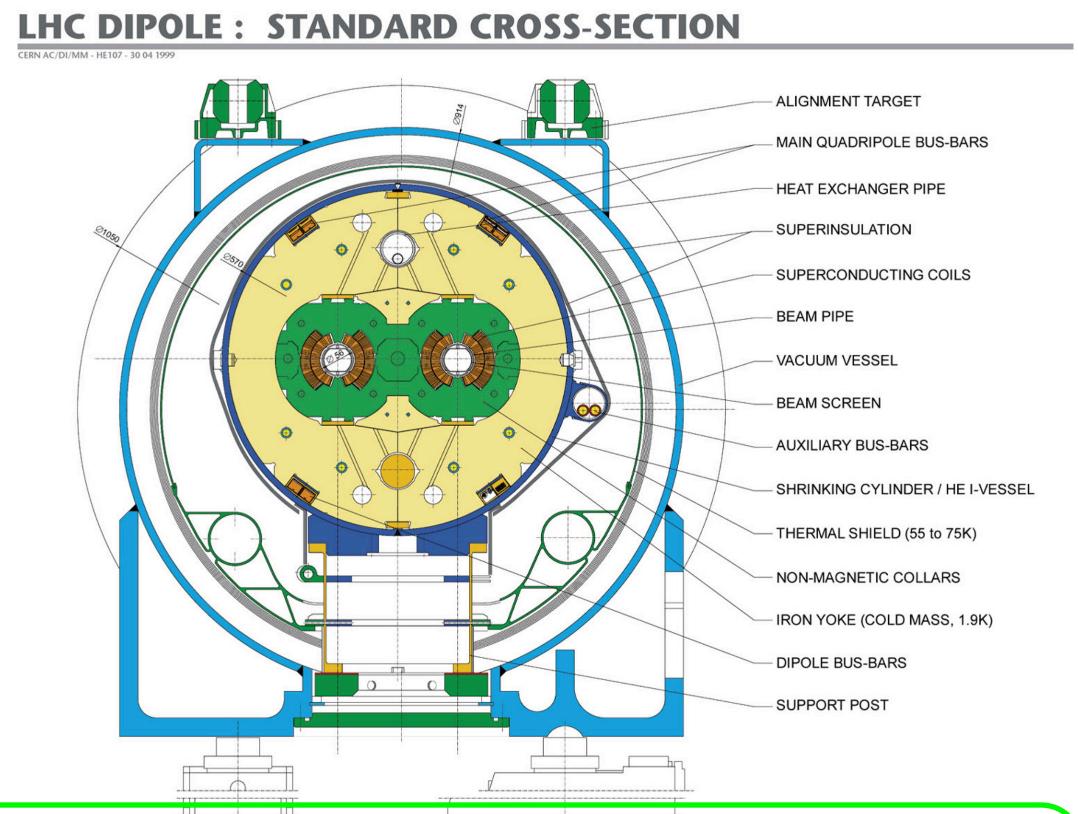
Bending Field → ***p(TeV) = 0.3 B(T) R(Km)***

(earth magnetic field is between 24000 nT and 66000 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

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

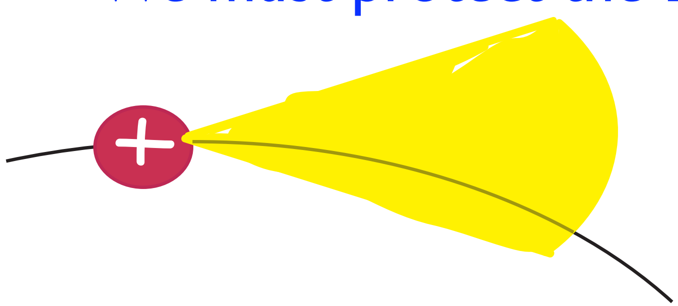
ρ particle bending radius

Energy lost per turn per particle due to synchrotron radiation:

e- some GeV (LEP)

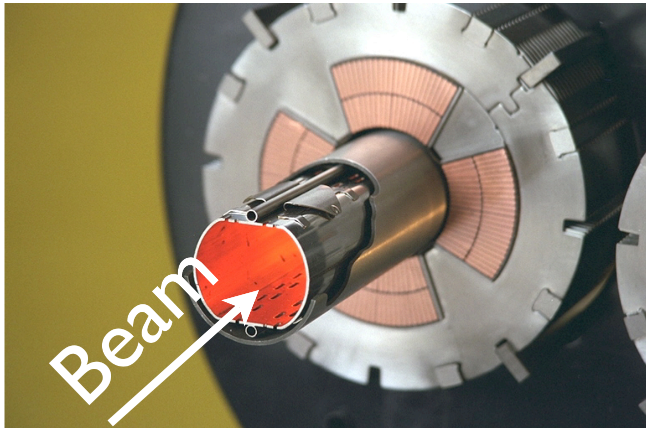
p some keV (LHC)

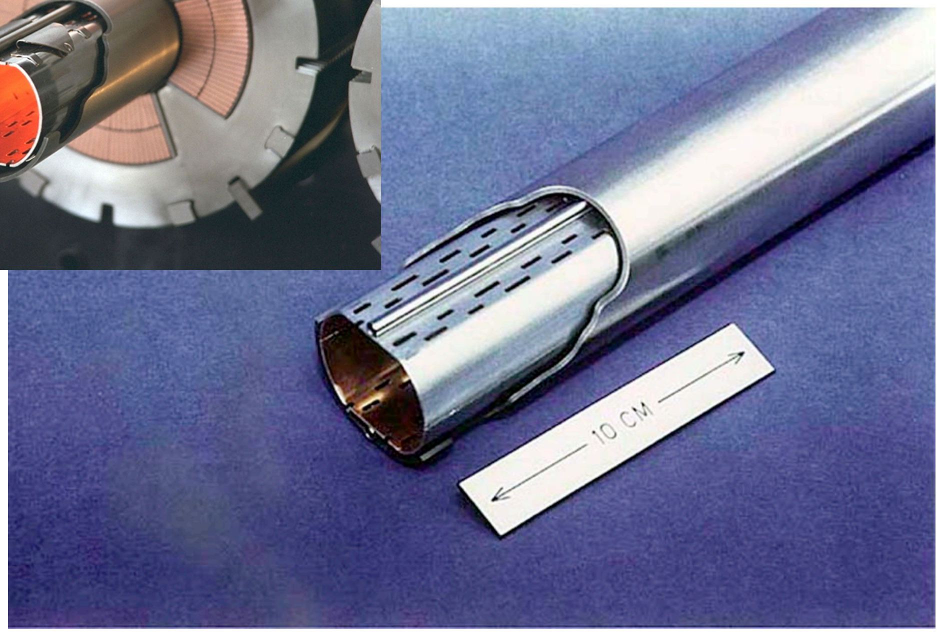
We must protect the LHC coils even if energy per turn is so low



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

LHC beam screen with cooling pipes





Beam screen to protect Superconducting magnets from Synchrotron radiation.

Holes for vacuum pumping

Atmosphere pressure = 750 Torr

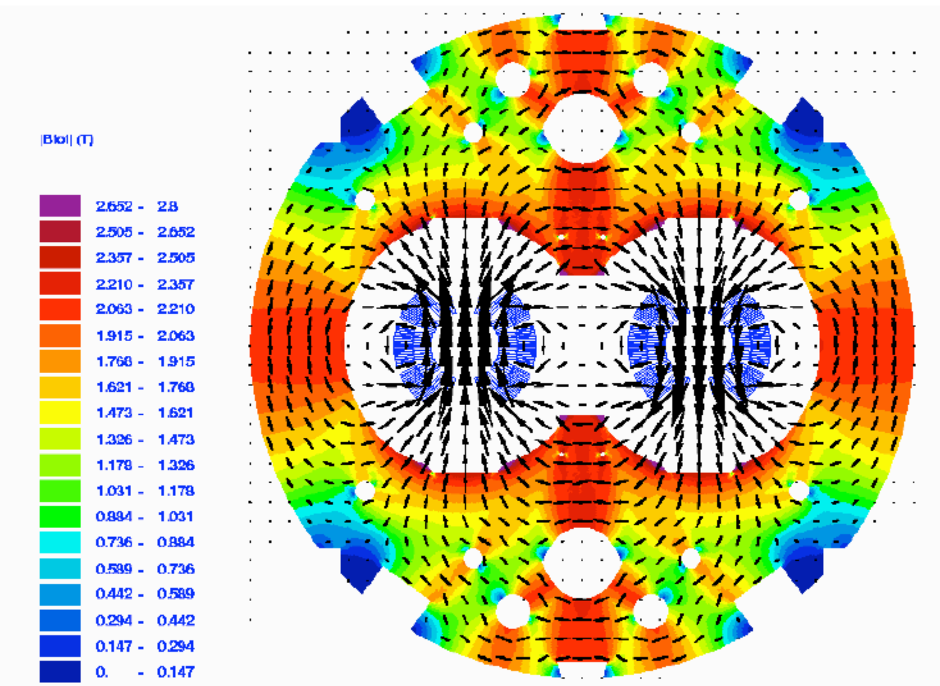
Moon atmospheric pressure = 5 10^{-13} Torr

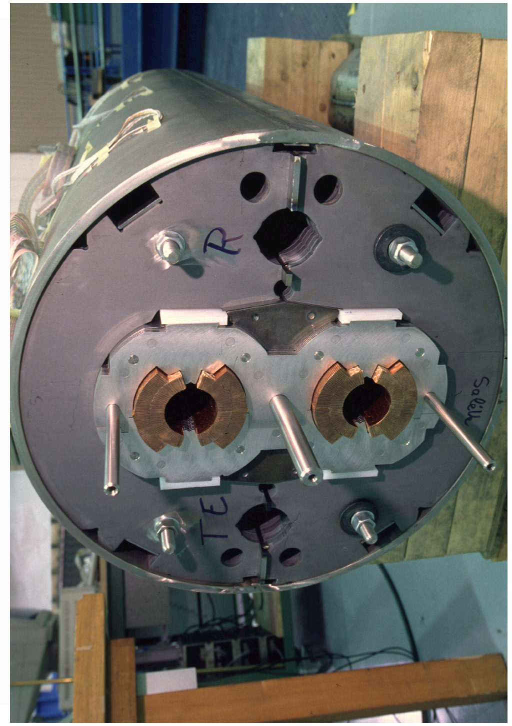
Vacuum required to avoid unwanted collision far from the IPs and decrease the Luminosity

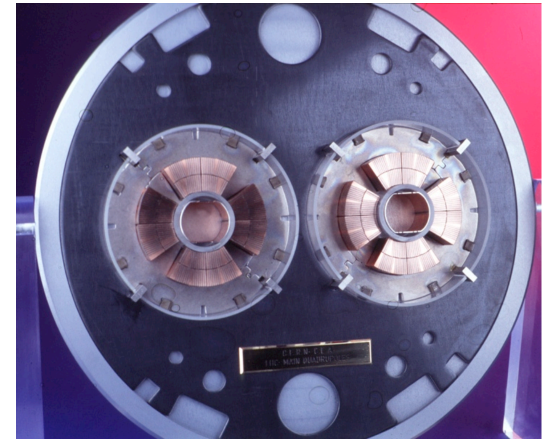
Typical vacuum: 10^{-13} Torr

There is ~6500 m^3 of total pumped volume in the LHC, like pumping down a cathedral.

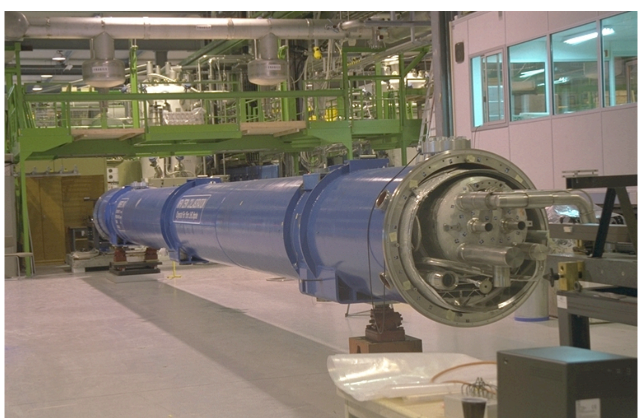
Two-in-one magnet design

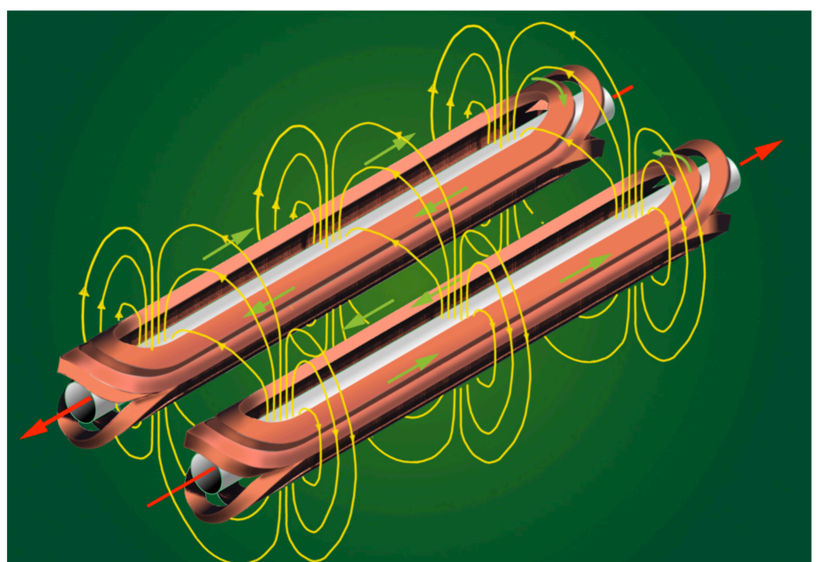




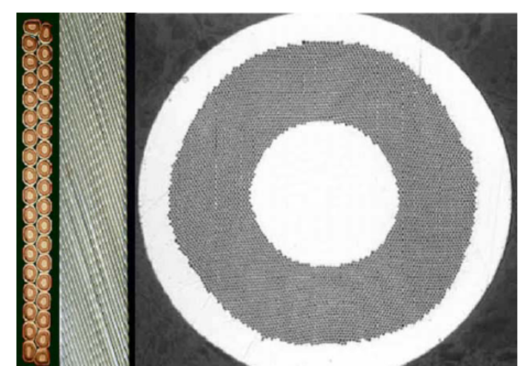


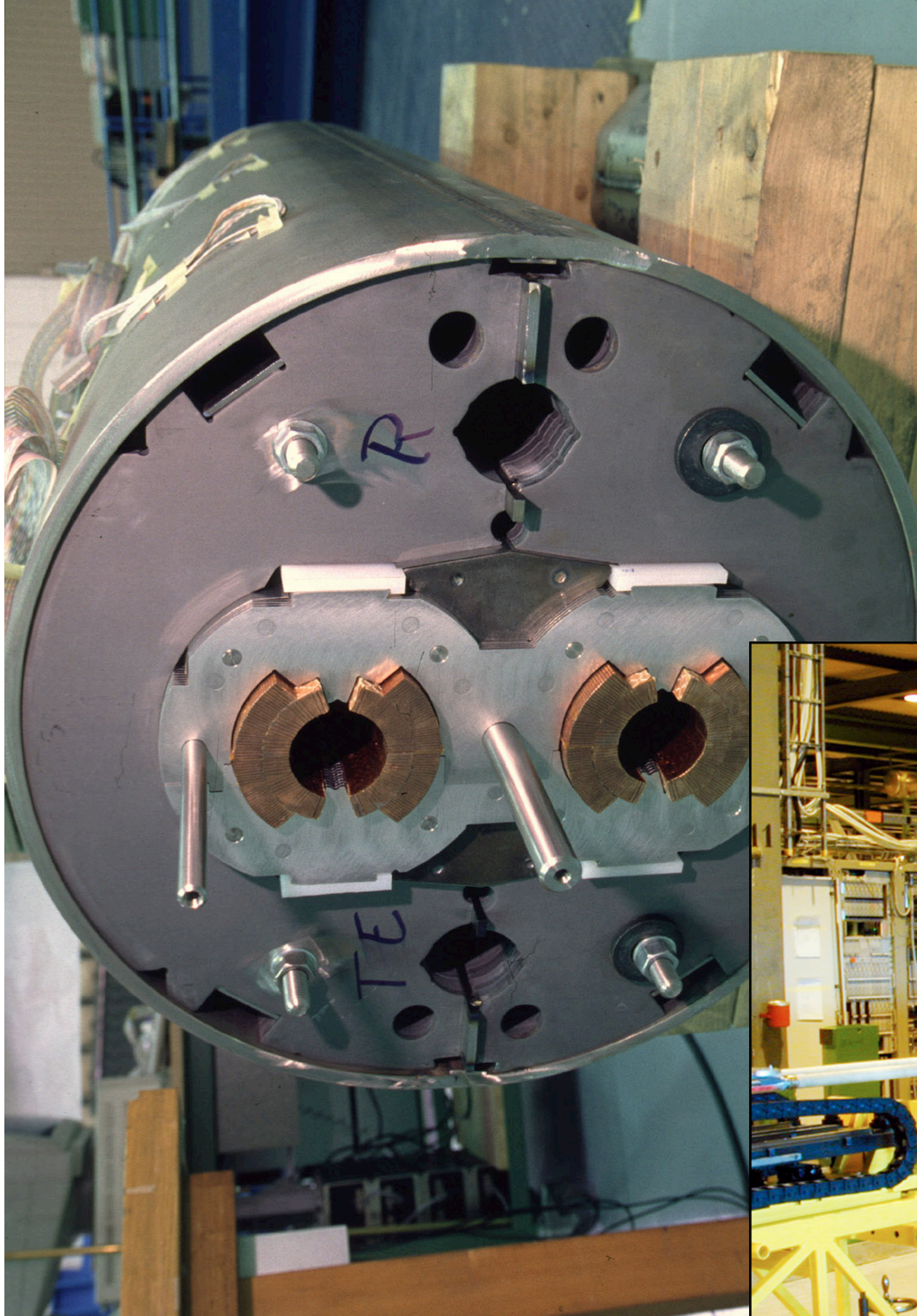
The LHC is <u>one ring</u> where <u>two accelerators</u> are coupled by the magnetic elements.





Nb -Ti superconducting cable in a Cu matrix





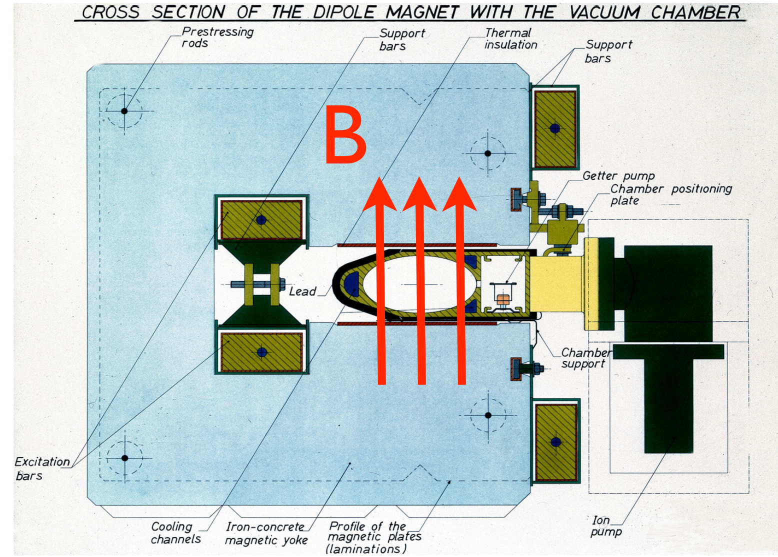
At 7 TeV:

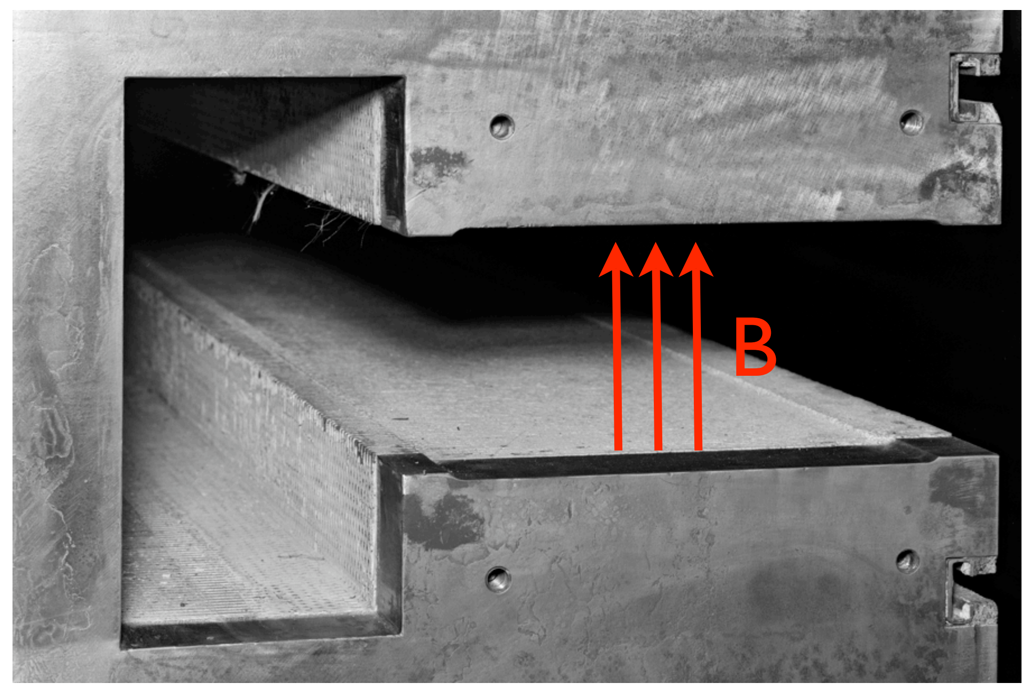
I_{max} = 11850 A Field=8.33 T
Stored energy about 7 MJ
Weight = 27.5 Tons
Length =15.18 m at room temp.
Length (1.9 K)=15 m - ~10 cm

Test bench for magnetic measurements at 1.9 K

PS: they are not straight,
small bending of 5.1 mrad

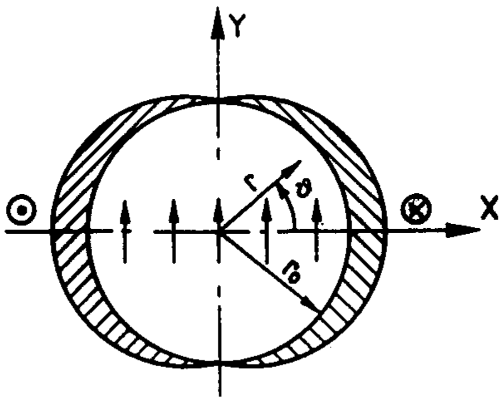
From LEP to the LHC, iron-concrete yoke ...

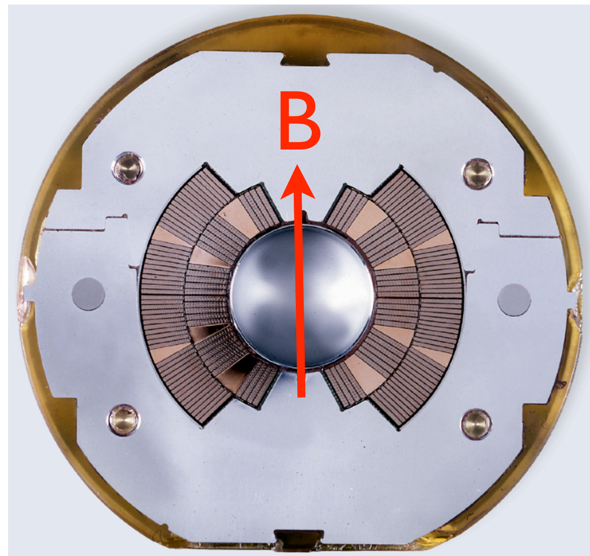




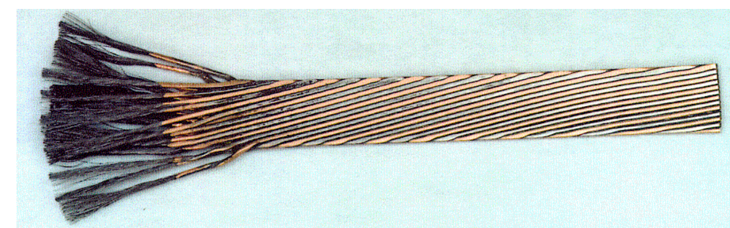
Cosθ coil of main dipoles

Cos nϑ





A 2D cosθ current distribution generates a "***quasi***-*perfect vertical field*" in the aperture between the two conductors.

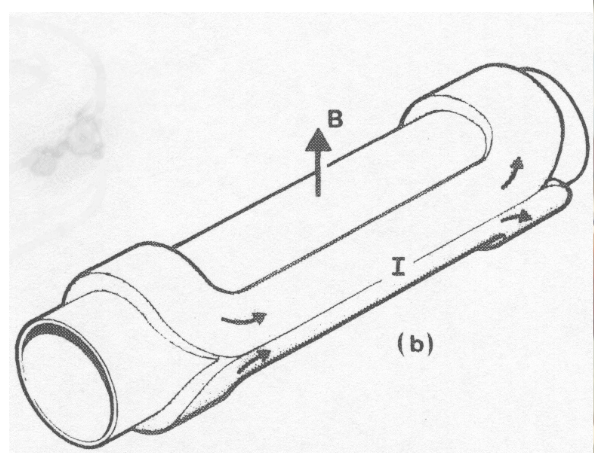


$$I = I_o \cos\vartheta$$

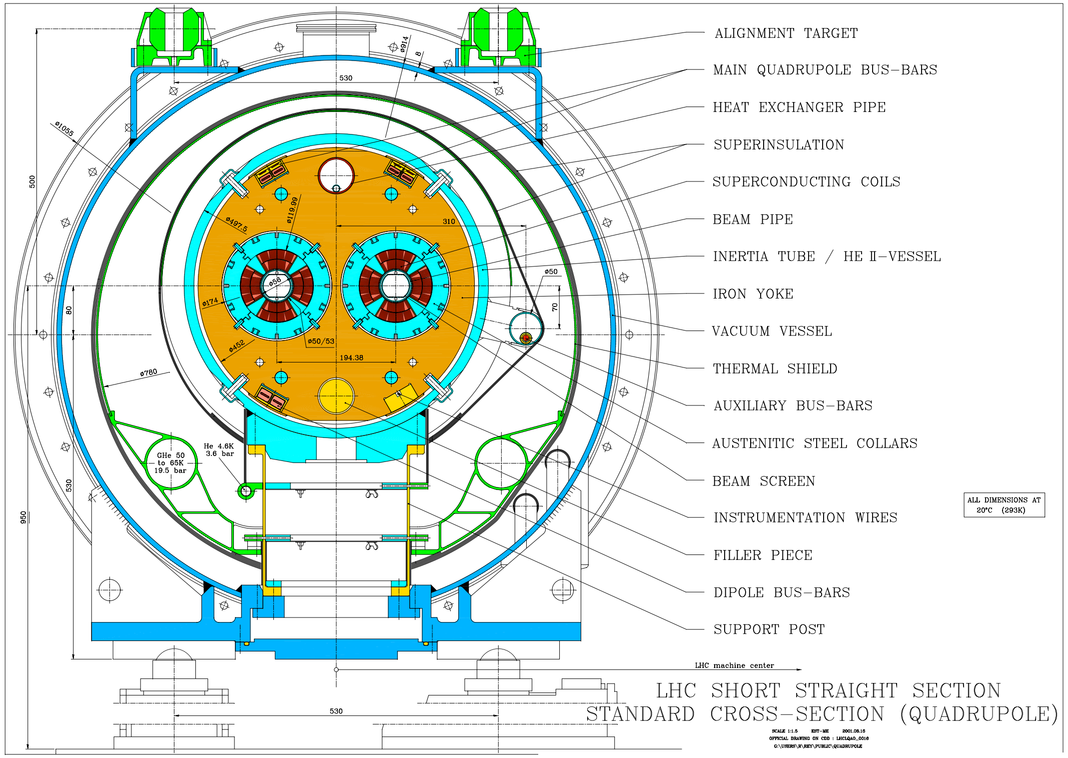
$$B_\vartheta = \frac{\mu o \ I_o}{2\ r_o} \cos\vartheta \qquad B_x = o$$

$$B_\vartheta = \frac{\mu o \ I_o}{2\ r_o} \sin\vartheta \qquad B_y = \frac{\mu o \ I_o}{2\ r_o}$$

Dipolar Vertical field



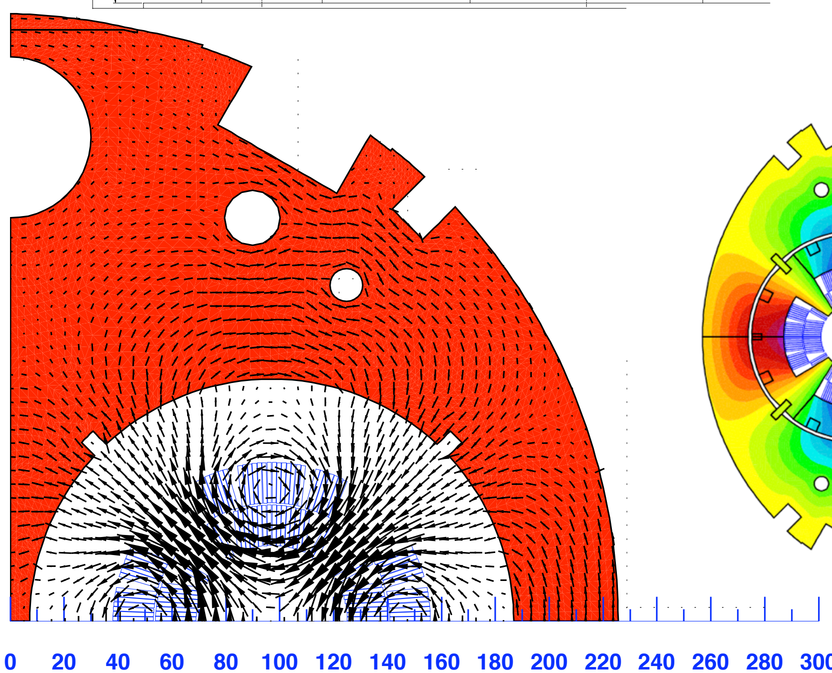
Quadrupoles are also two-in one

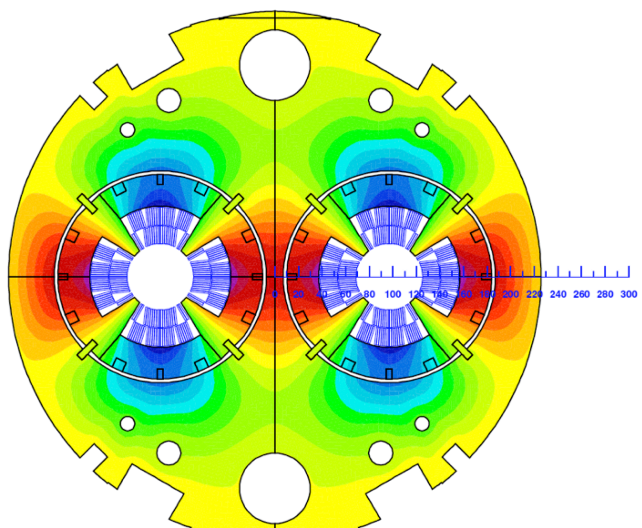


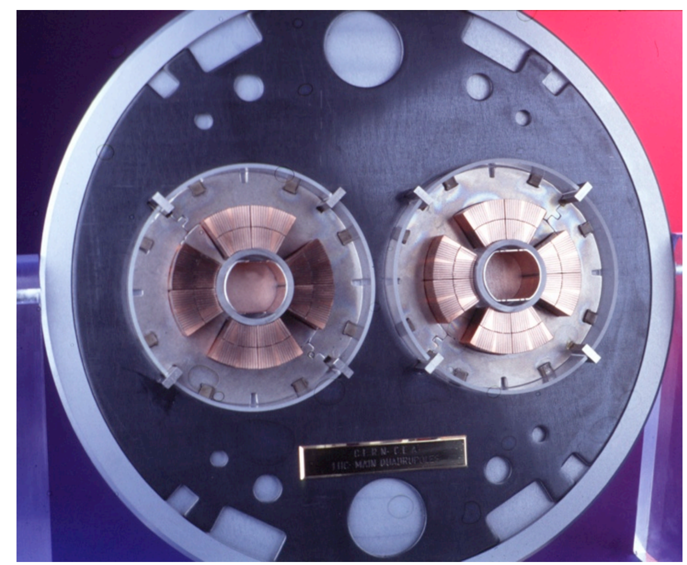
At 7 TeV:

I_{max} = 11850 A
Field=225 T/m

Weight = 6.5 Tons
Length =3.1 m





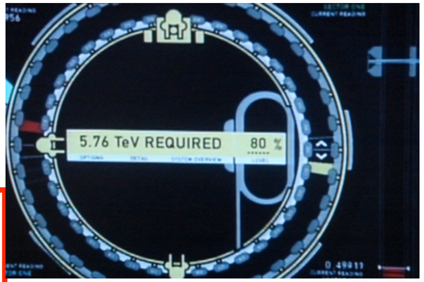


Quadrupoles being assembled before installation

INTERLUDE: THE TERMINATOR-3 ACCELERATOR

We apply some concepts to the accelerator shown in Terminator-3 [Columbia Pictures, 2003]

- Estimation of the magnetic field
  - Energy = 5760 GeV
  - Radius ~30 m
  - Field = 5760/0.3/30 ~ 700 T (a lot !)

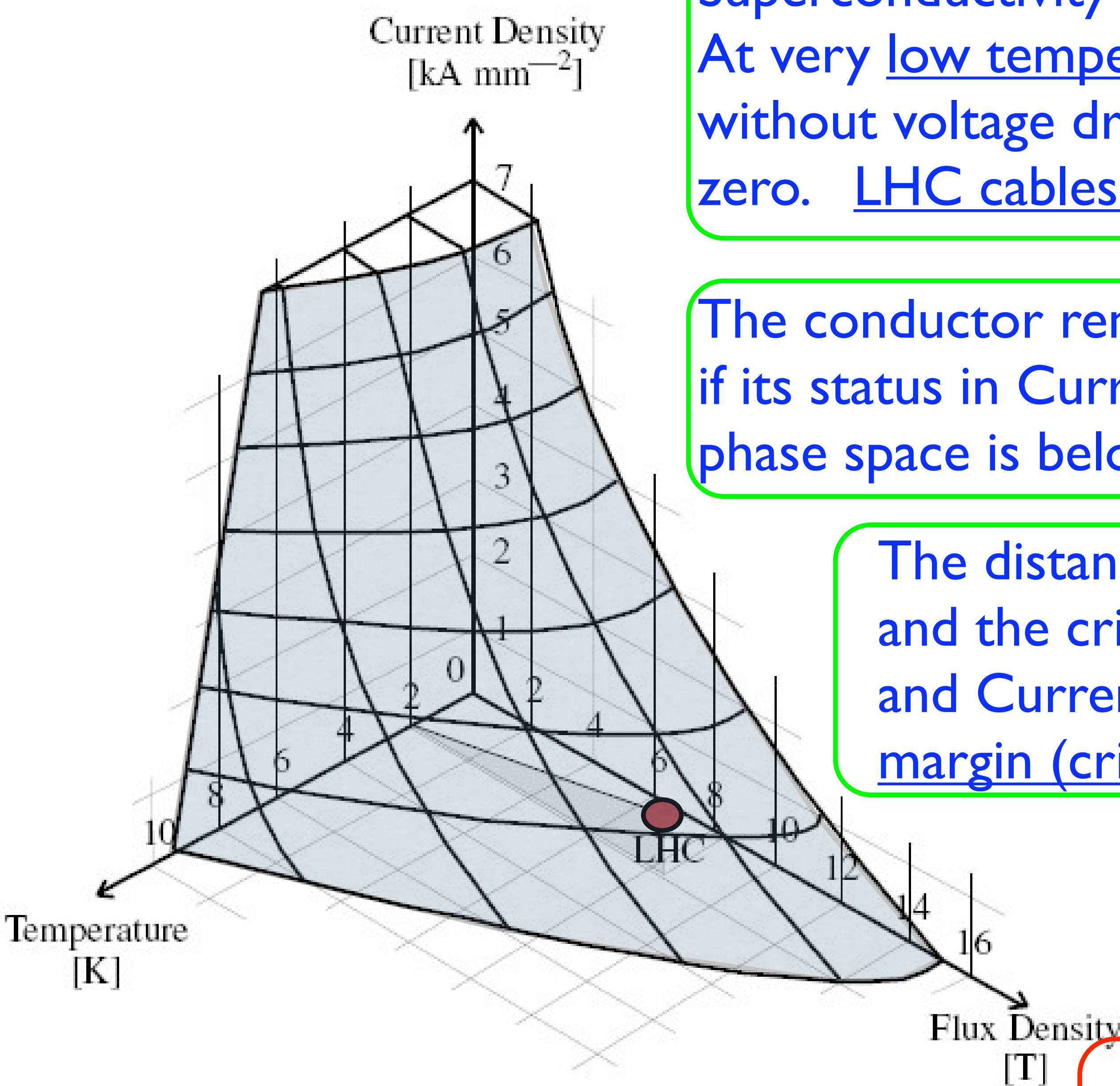


Energy of the machine (left) and size of the accelerator (right)

- Why the magnet is not shielded with iron ?
  - Assuming a bore of 25 mm radius, inner field of 700 T, iron saturation at 2 T, one needs 700*25/2=9000 mm=9 m of iron … no space in their tunnel !
  - In the LHC, one has a bore of 28 mm radius, inner field of 8 T, one needs 8*25/2=100 mm of iron
- Is it possible to have 700 T magnets ??

A magnet whose fringe field is not shielded

Very, very short introduction to Superconductivity for accelerators



Superconductivity is a property of some materials. At very low temperature they can carry currents without voltage drop, i.e. their resistivity goes to zero. LHC cables: Nb-Ti working at 1.9 K

The conductor remains Superconductor if its status in Current Density, Temperature, B field phase space is below the Critical Surface

The distance between the working point and the critical surface for a fixed B field and Current Density is the temperature margin (critical temperature)

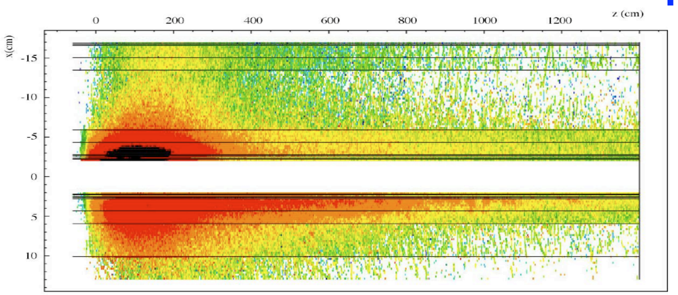
Transition to a normal conducting state is called magnet quench

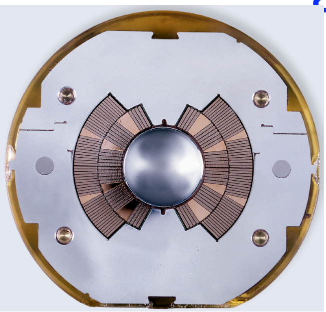
What can increase the temperature in a magnet ?

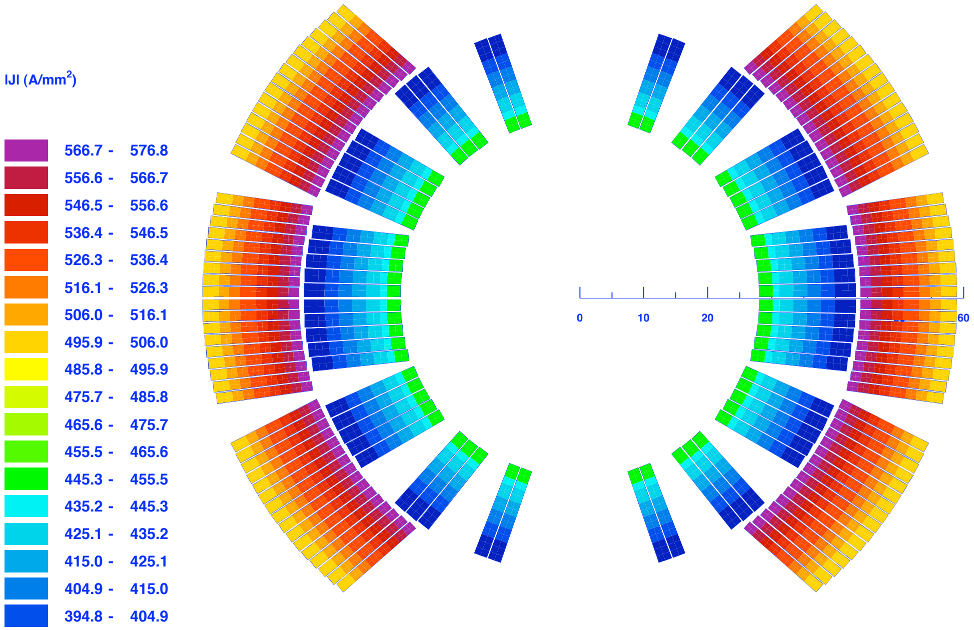
V. V. S. Introduction to Superconductivity II

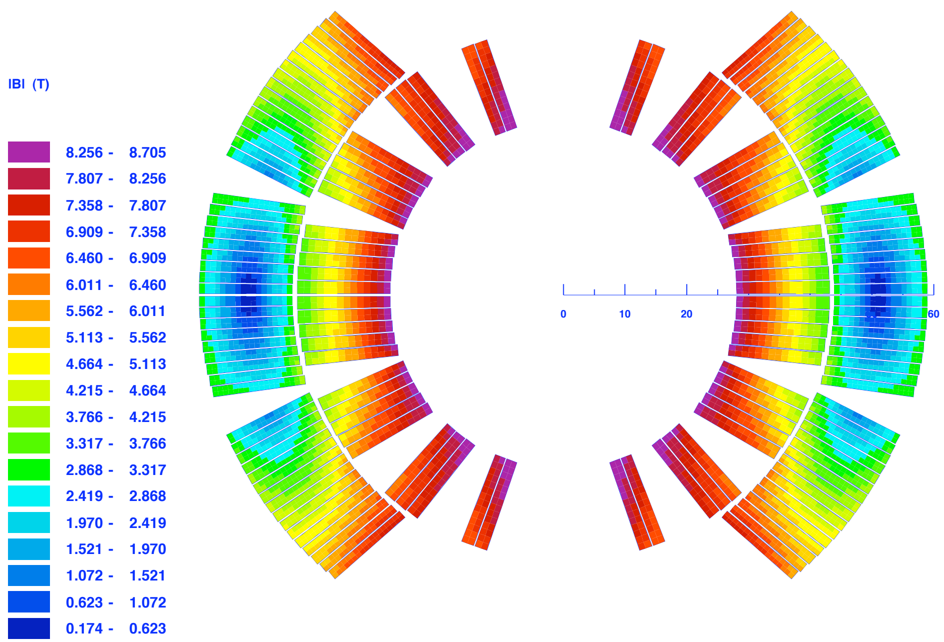
Beam losses can eat the temperature margin because of energy deposition

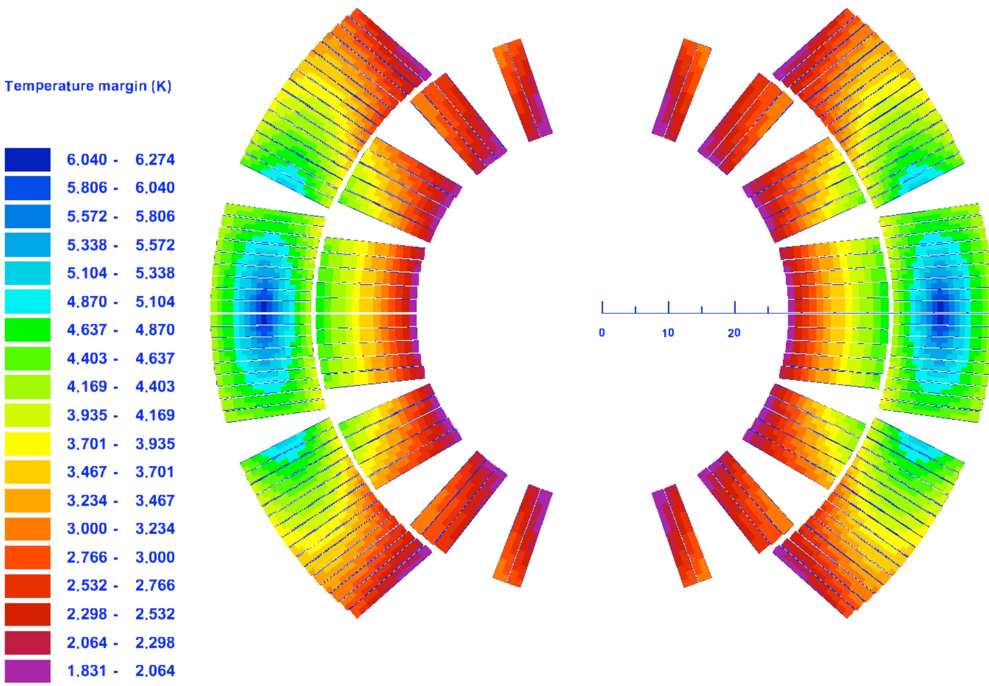
Limit of accepted losses: ~ **10 mW/cm³** to avoid ΔT> 2 K, the temperature margin











Courtesy of Stephan Russenschuck

How much is 10 mW/cm^3 ?

A fluorescente (known as neon) tube can be typically 1.2 m long with a diameter of 26 mm, with an input power of 36 W.

This makes a power density of about 56 mW/cm^3.

The power of a neon tube can quench about 5 LHC dipoles at collision energy.... because one does not need 10 mW/cm^3 for the entire volume of a magnet, but for about 1 cm^3.

If you do the same basic computation with a normal 100 W resistive bulbs is even worst

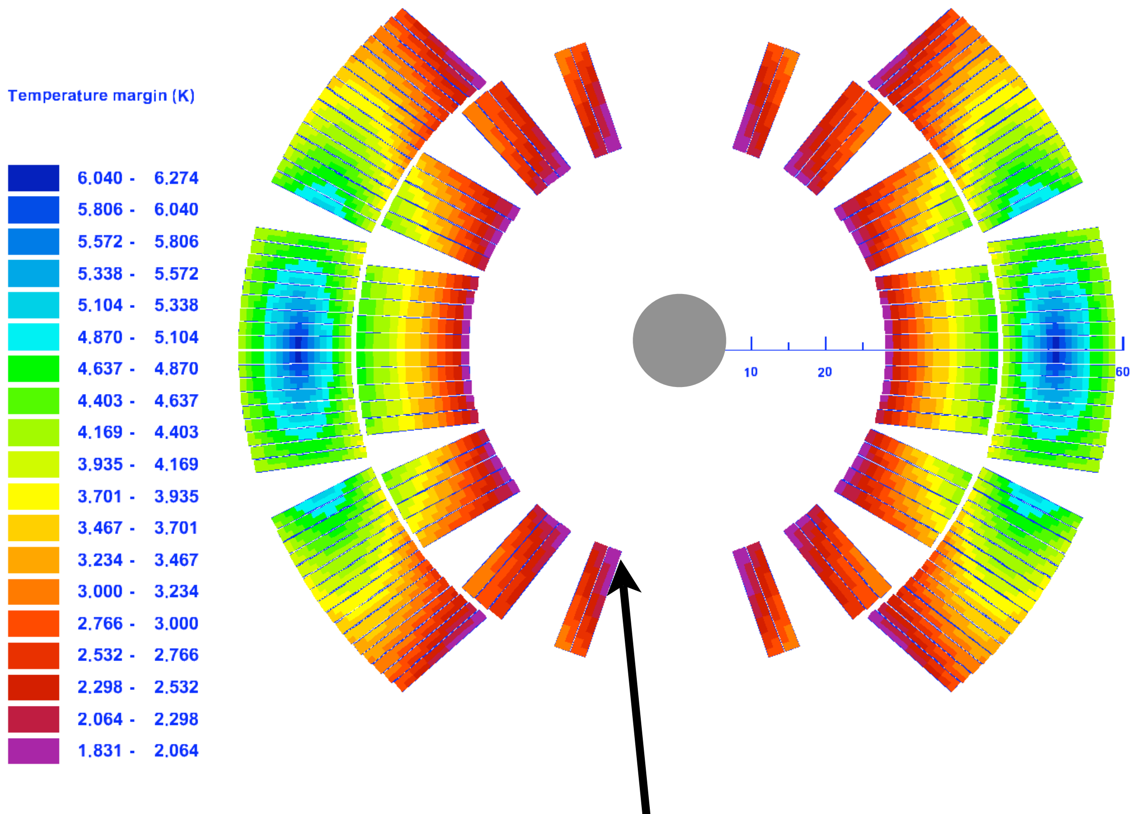
Few numbers for dipoles

Injection B (0.45 TeV energy)	Current at injection field	Nominal B (7 TeV energy)	Current at nominal field	Stored energy (2 apertures) at 8.33 T	Ultimate field	Maximum quench limit of the cold mass	Magnetic length at 1.9 K and at nominal B	Bending radius 1.9 K	Total mass
0.54 T	763 A	8.33 T	11850 A	6.93 MJ	9.00 T	9.7 T	14312 mm	2803.98 m	~ 27.5 t

		r [m]	B [T]	E [TeV]
FNAL	Tevatron	758	4.40	1.000
DESY	HERA	569	4.80	0.820
IHEP	UNK	2000	5.00	3.000
SSCL	SSC	9818	6.79	20.000
BNL	RHIC	98	3.40	0.100
CERN	LHC	2801	8.33	7.000
CERN	LEP	2801	0.12	0.100

The length of the LHC dipoles (15 m) has been determined:
by the best design for the tunnel geometry and installation and
by the maximal dimensions of (regular) trucks allowed on European roads.

Temperature margin and quenches....



Lower temperature margin near the beam !

Limiting beam losses:
10^8 p/m at small grazing angle
for a total circulating intensity of 3.3 10^{14} p

Other possible sources of quenches:

1. ***mechanical friction***, for example during current ramp, between the conductors. Few µm are enough. Magnets are "trained" before installation and they keep memory of the training at least since the next quench.

2. ***failure of the cooling system.*** Depending on the case of failure, magnets can heat up slowly or not...

but every dipole stores about 7 MJ at collision

the stored energy is about 350 MJ per beam

So, one need:

1. *to exclude the magnet from the ARC powering*, since all the magnets are IN SERIES per ARC.

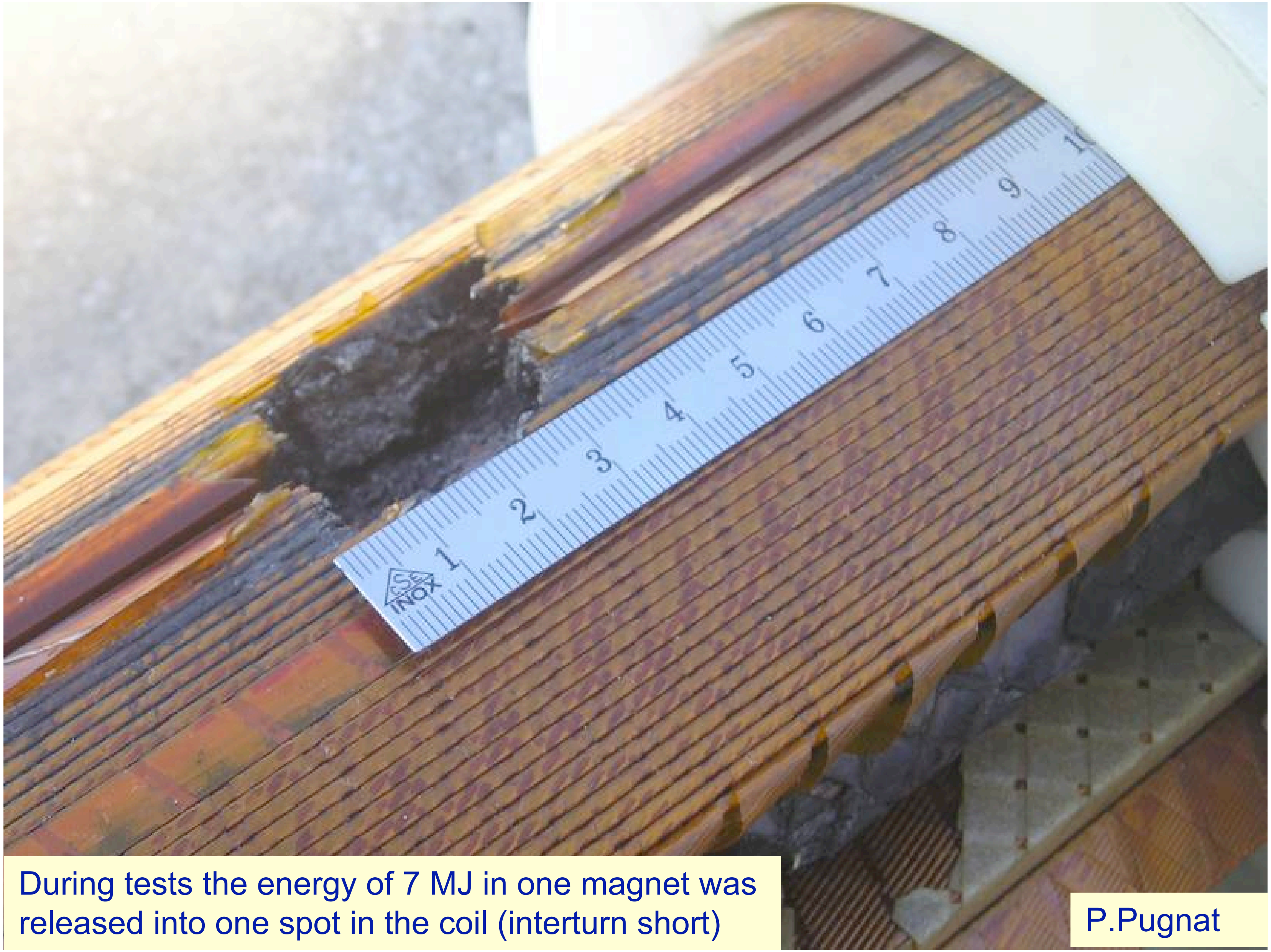
2. *to discharge fast the power of the quenching magnet octant (time constant about 100 s)*, and dispersing by heating up the magnet the power that otherwise will accumulate near the quenching zone.

3. *to extract the beam as fast as possible*, meaning within one turn from the quench detection, before risking to damage mechanically the machine with the beam.

The different time scale of the two processes helps:

1 beam turn every ~ 90 µs while a *quench develops on at least few ms*. However, quench detection, power extraction and beam extraction has to be fast and reliable.

When something goes wrong.... bad quench...



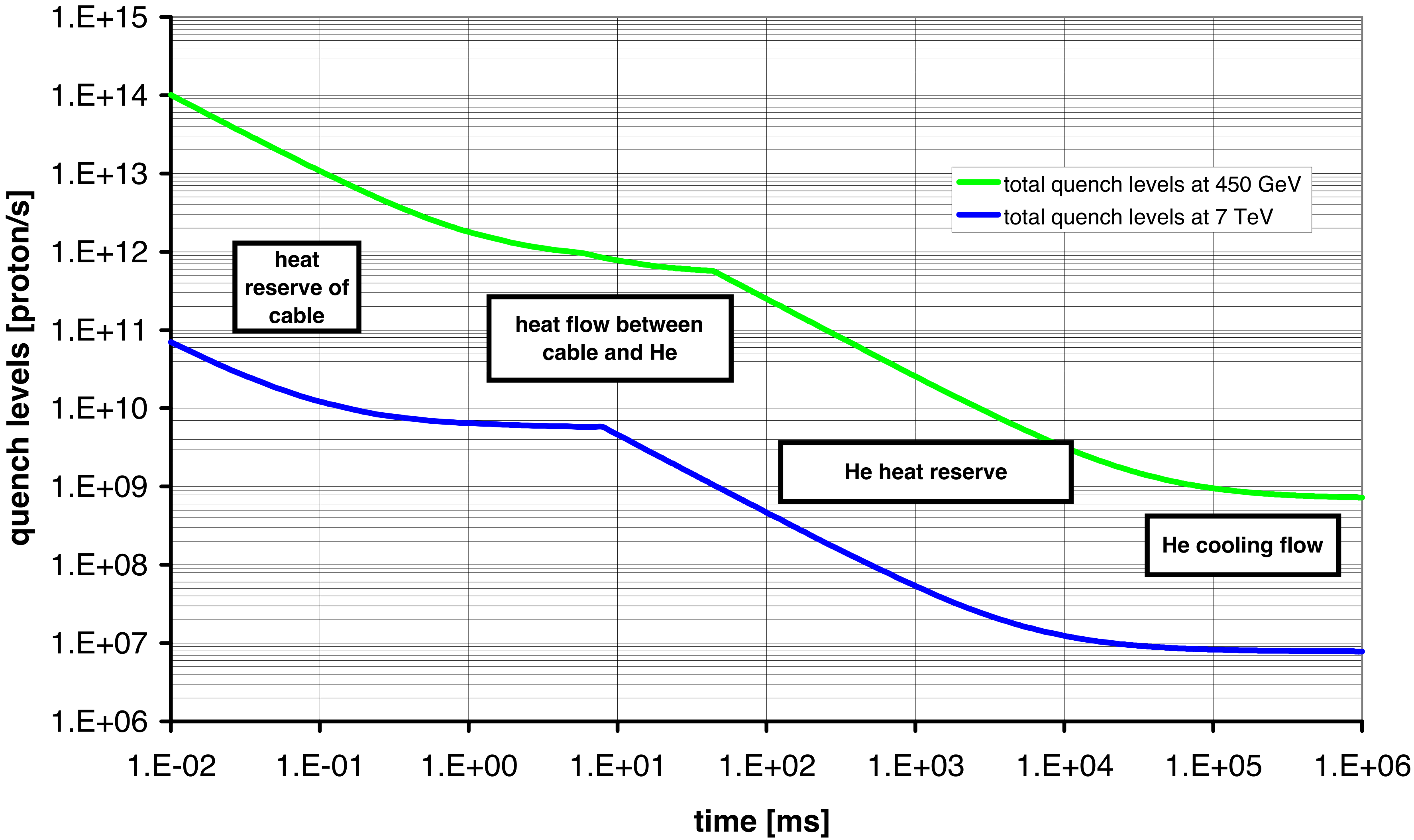
During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short)

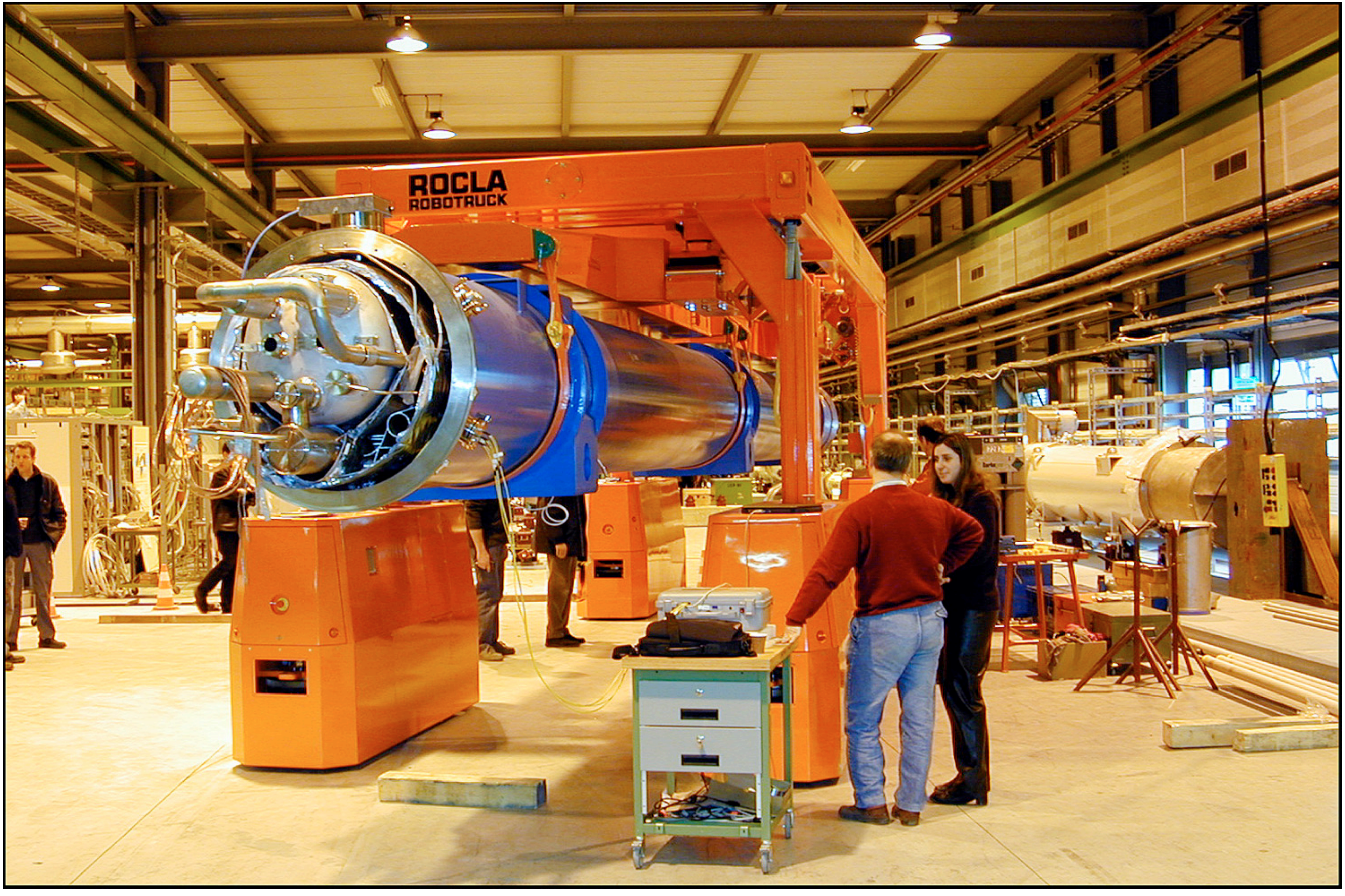
P.Pugnat

Quench levels are varying with energy ....

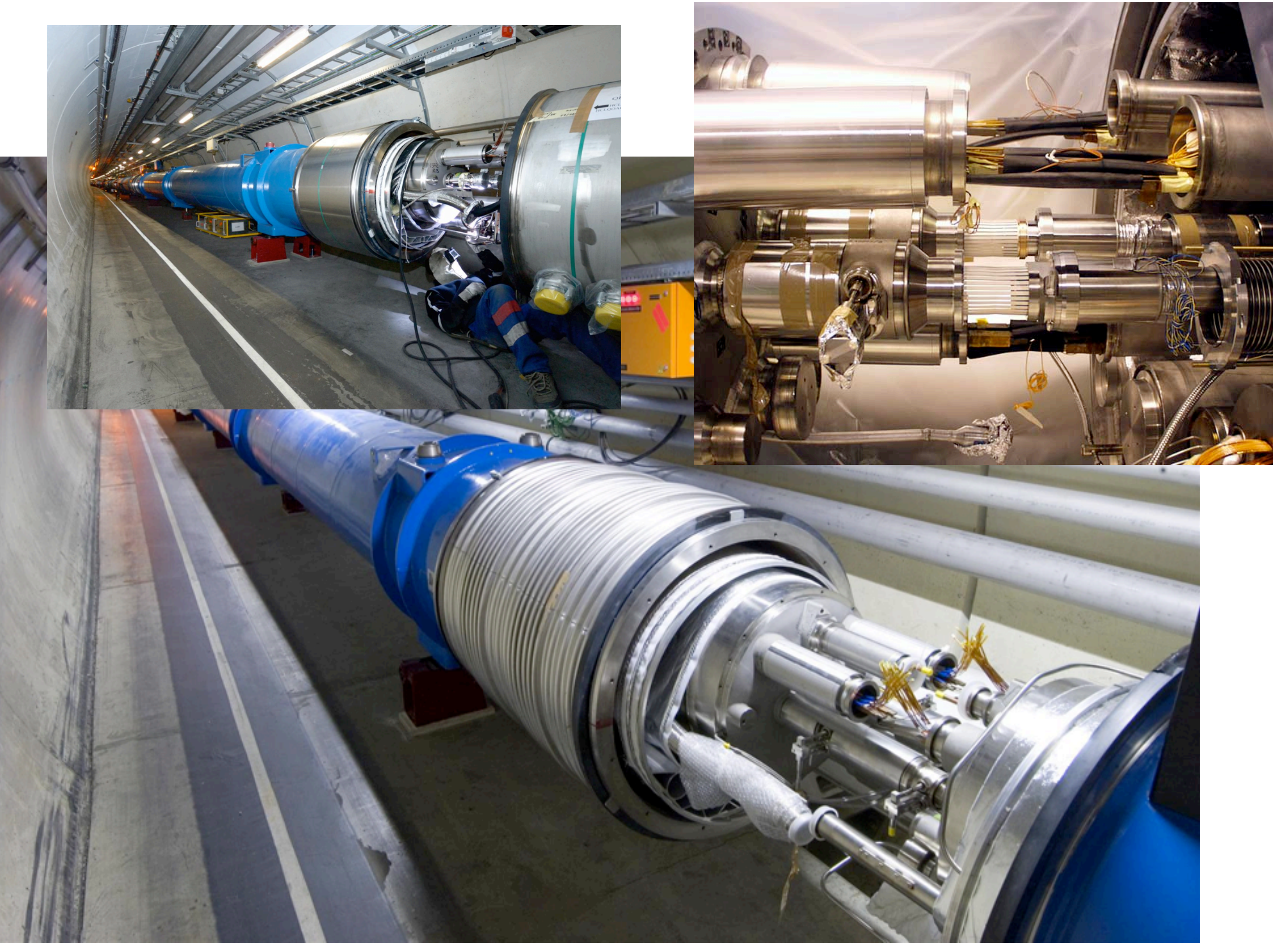
In a synchrotron, the magnetic field increases with energy to keep particles on the circular trajectory. This means that both the current as the field are larger at 7 TeV than at 450 GeV.

The Temperature margin is the reduced, one can loose less particles....



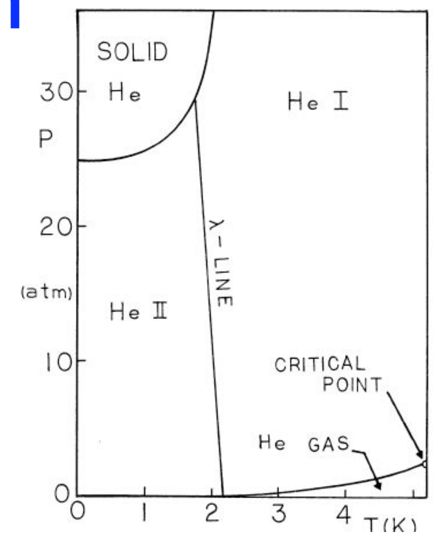

ROCLA
ROBOTRUCK

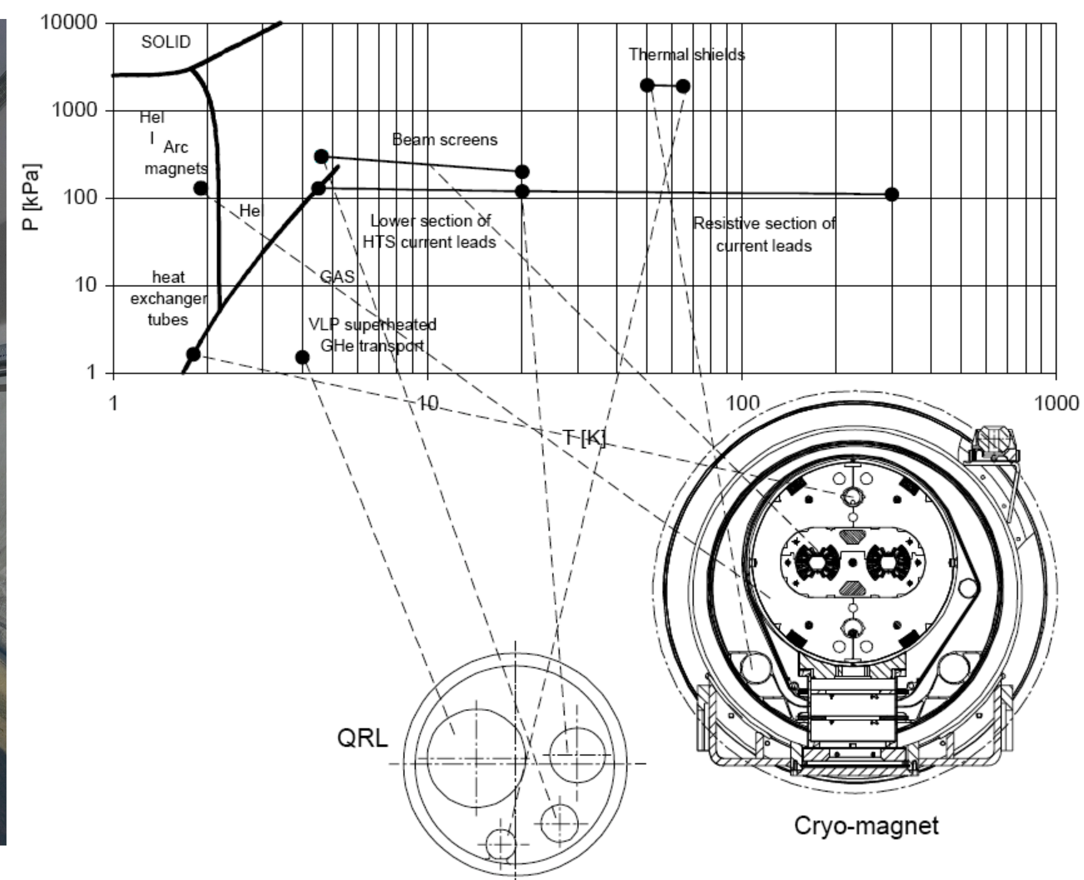
LHC during installation



Which coolant ? Liquid superfluid helium

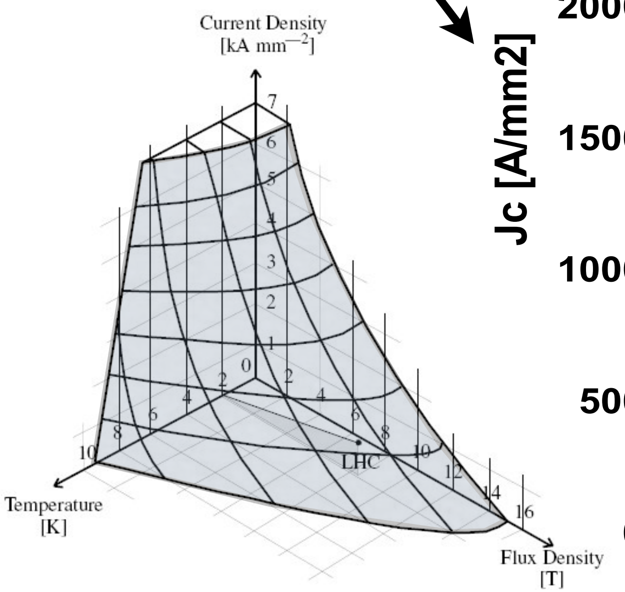
LHC cryogenics will need <u>40,000</u> leak-tight pipe junctions.
<u>12 million litres</u> of liquid nitrogen will be vaporised during the initial cooldown of <u>31,000 tons</u> of material and the total inventory of liquid helium will be <u>700,000 l (about 100 tonnes)</u>

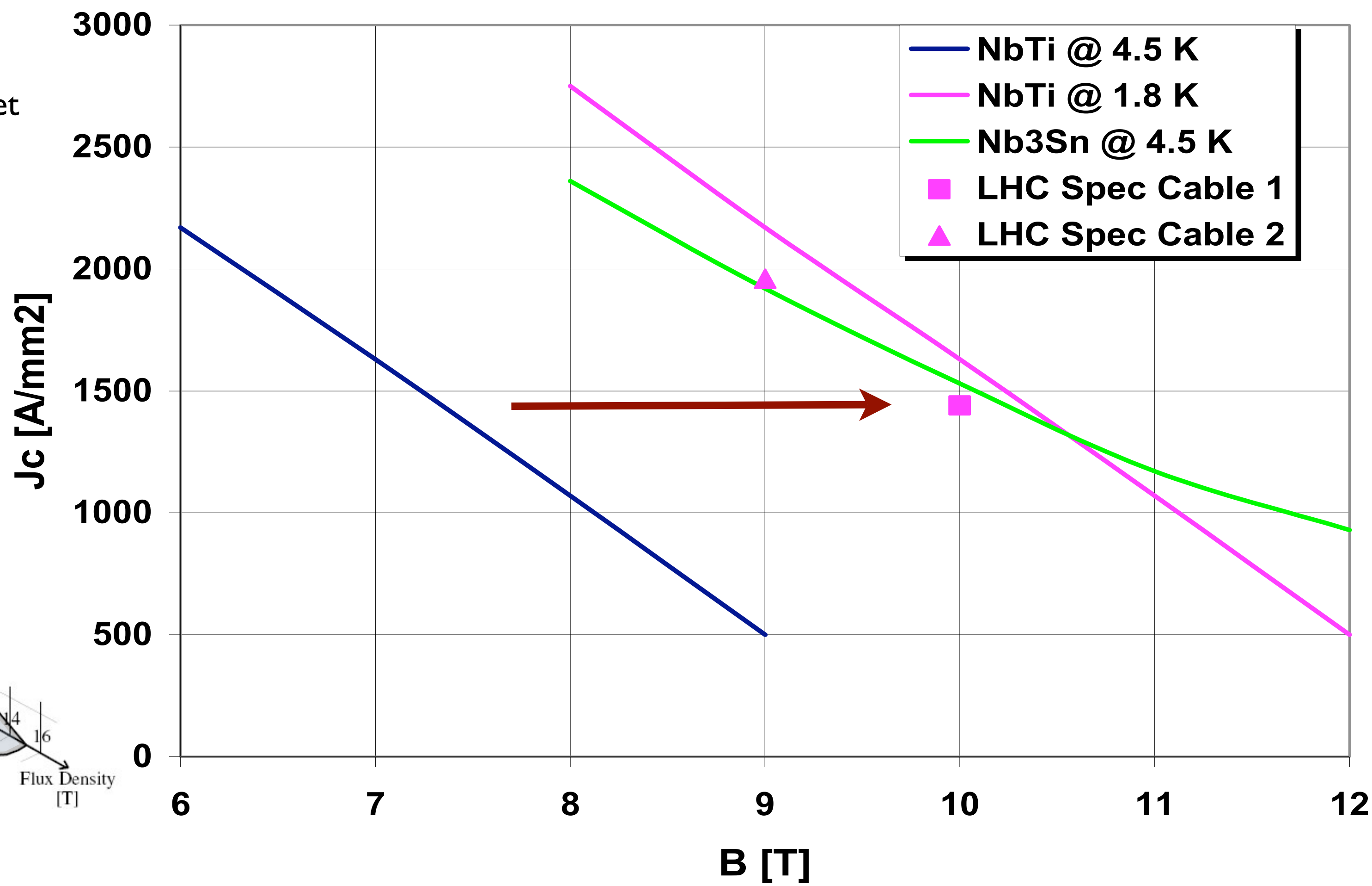




Why 1.9 K and not 4.5 K (Hera-like) ?

Current density
at which the magnet
quenches



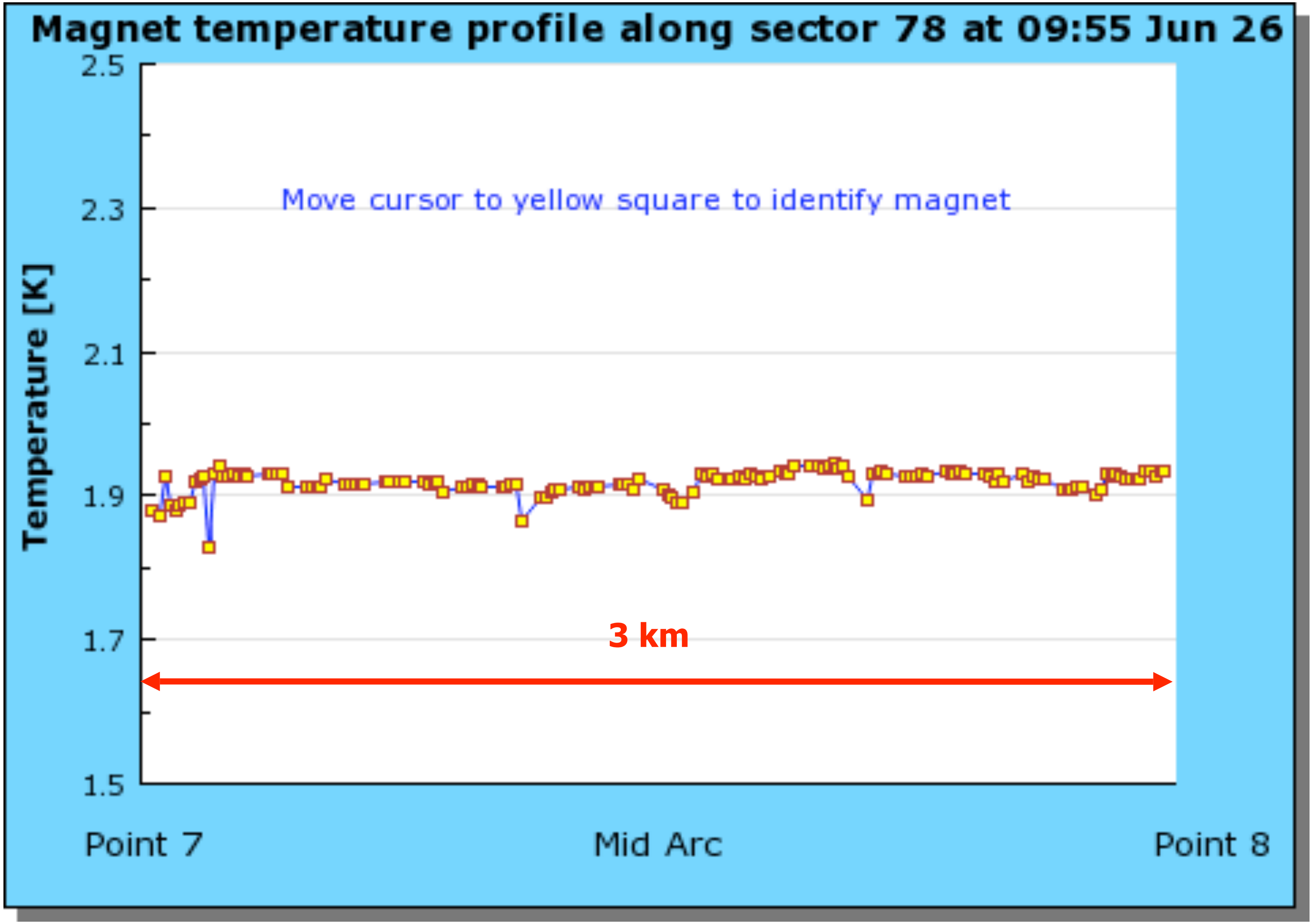


Gain of 3 T lowering the temperature for 4.5 K to 1.9 K.
Gain in dipoles bending strength and hence of MAX energy

The minimum temperature on the MOON is 126 K

From P. Lebrun

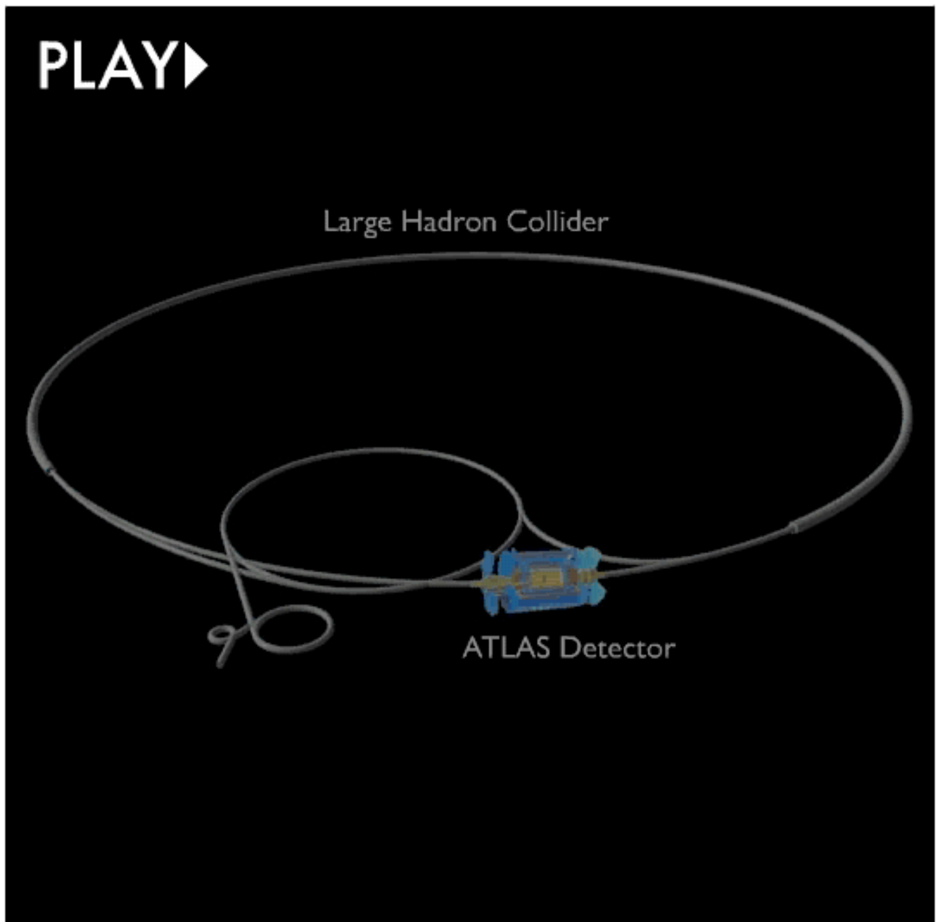
Cooling down one octant



The coldest place on earth...

Why particle accelerators ?

- *Why accelerators:* need to produce under <u>controlled conditions</u> HIGH INTENSITY, at a CHOSEN ENERGY particle beams of GIVEN PARTICLE SPECIES to do an EXPERIMENT
- An experiment consists of studying the results of colliding particles either onto a fixed target or with another particle beam.



The cosmo is already doing collisions with different mechanisms:

while I am speaking about $66\ 10^9$ particles/cm^2/s are traversing your body, with this spectrum before being filtered by the atmosphere.

The universe is able to accelerate particles up to 10^6 MeV protons