Introduction to CERN/accelerators

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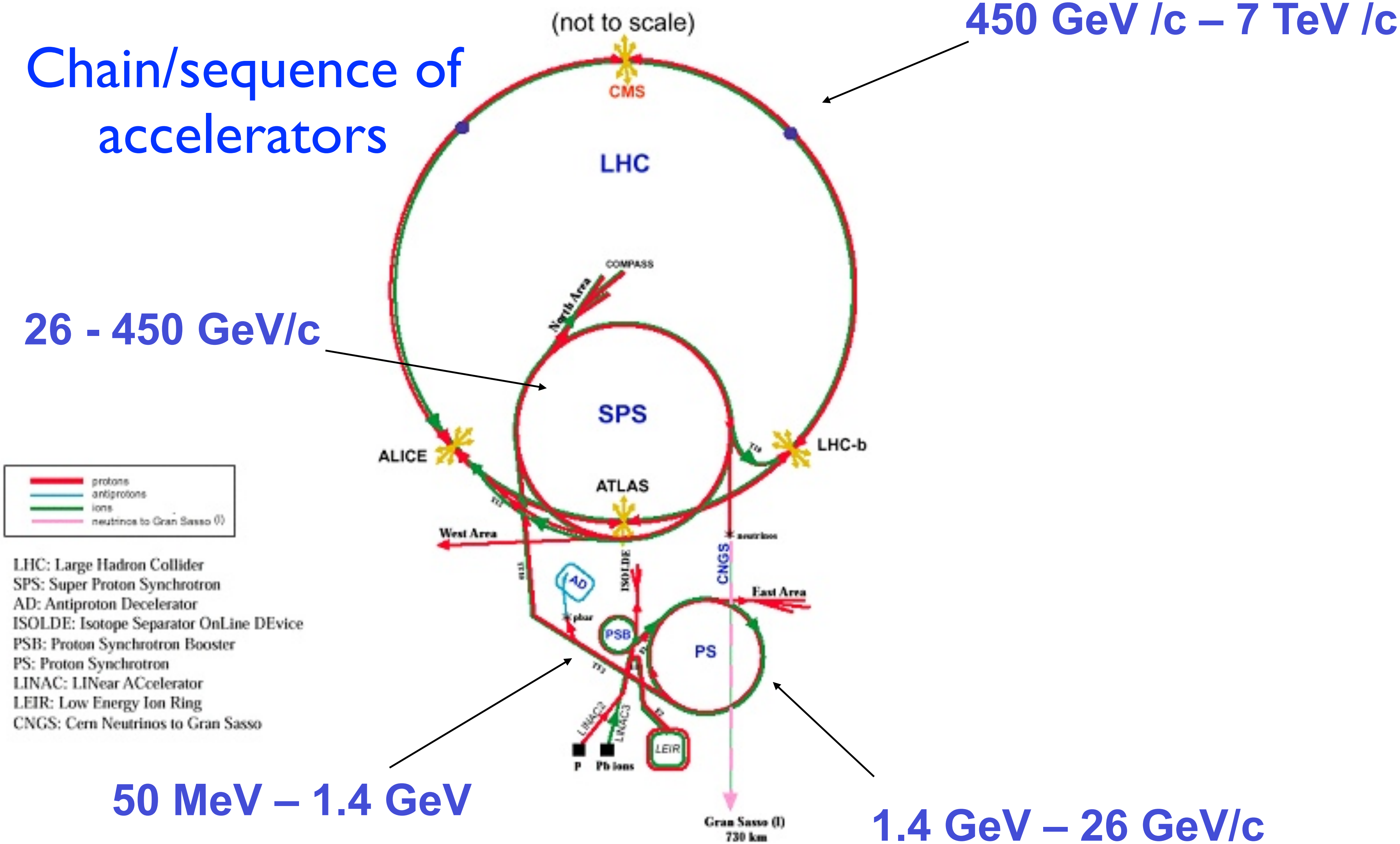
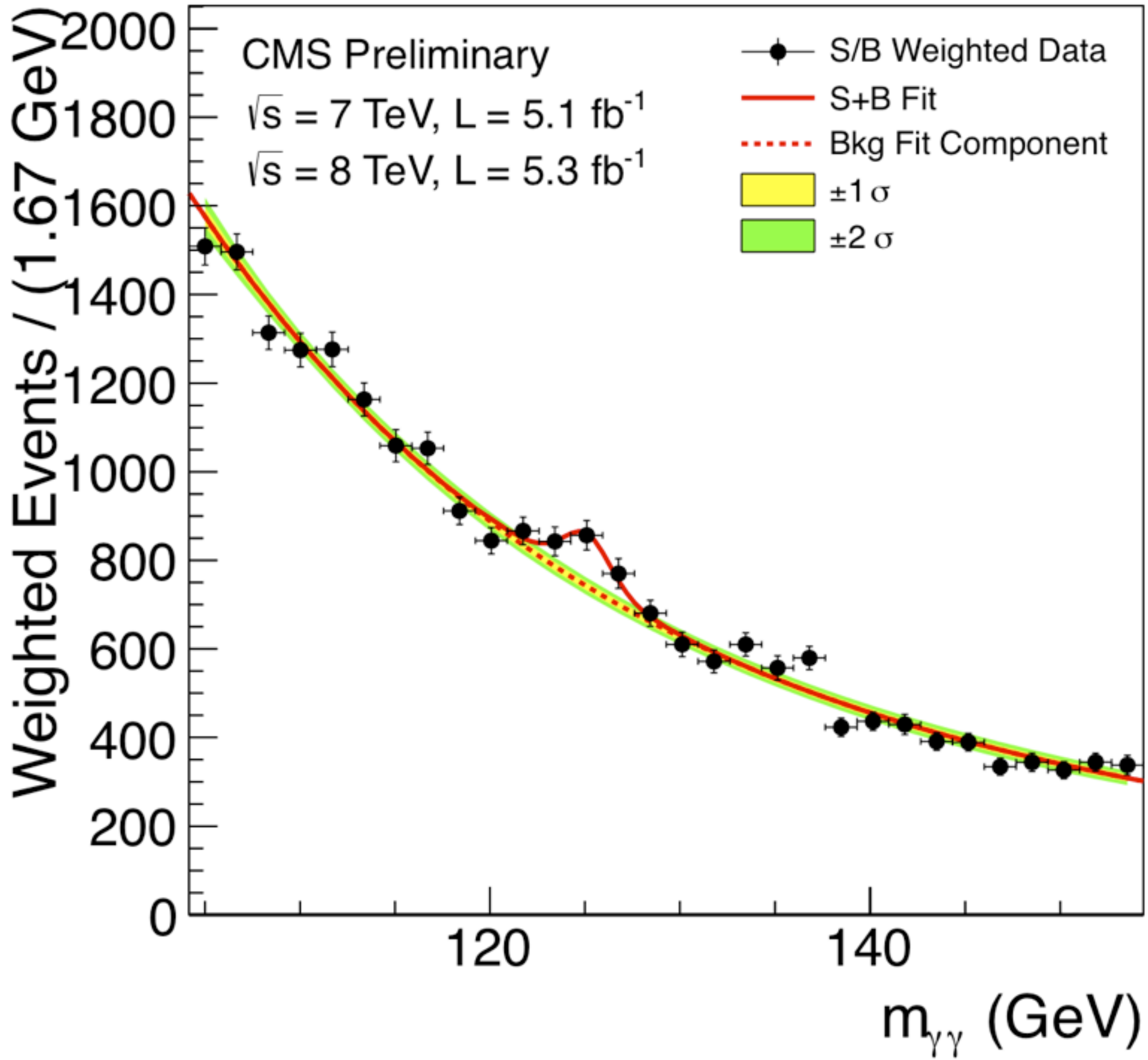
A Google view of high energy accelerators

https://maps.google.com/maps/ms?ie=UTF8&hl=en&t=h&msa=0&msid=100574363331995850370.000495f3c601139ebb21e&ll=31.052934,0&spn=163.748232,181.054688&z=2

CERN accelerator complex overview

Chain/sequence of accelerators





CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
120
140
mγγ (GeV)

SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

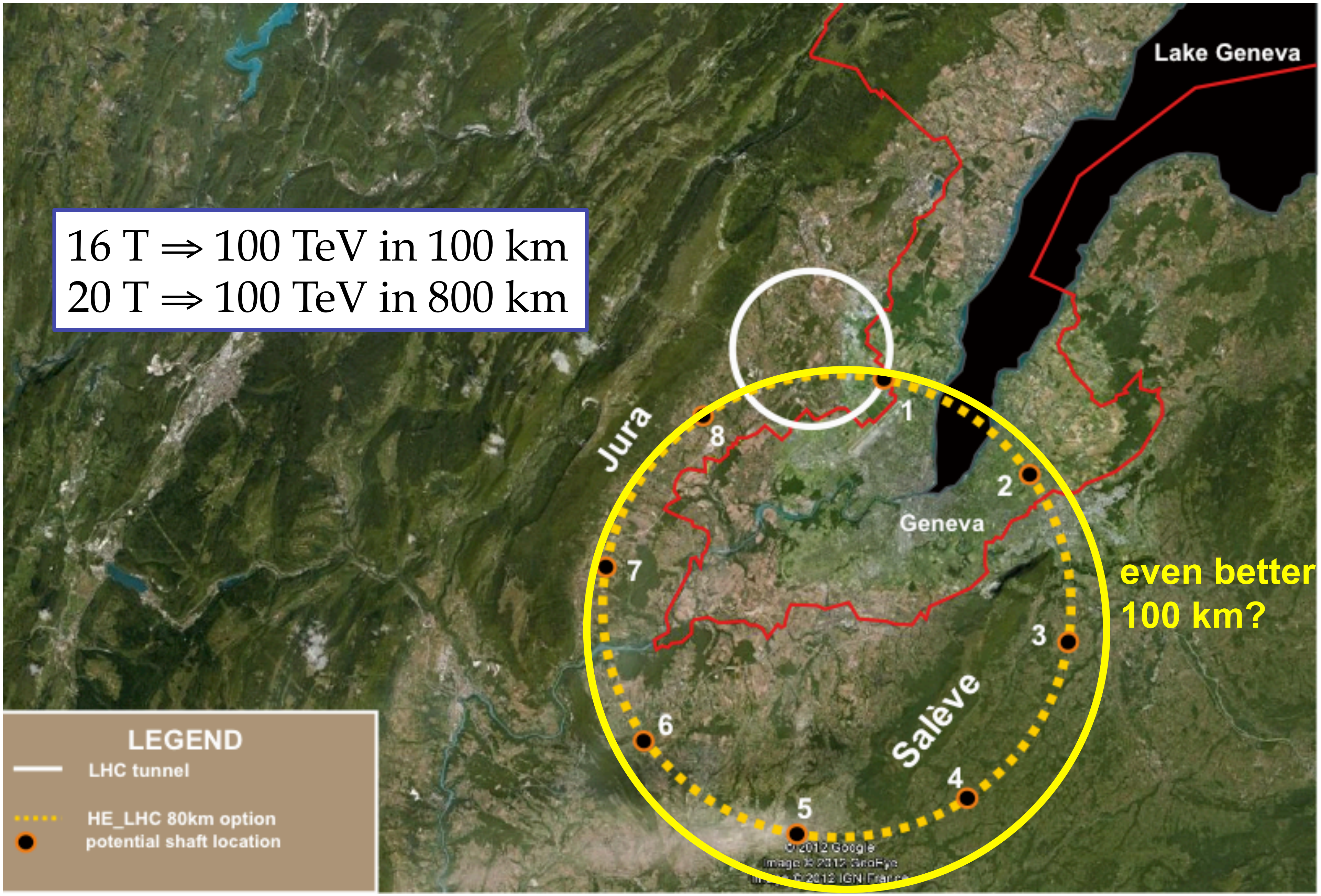
Press Release PR/56
12 February, 1960

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.

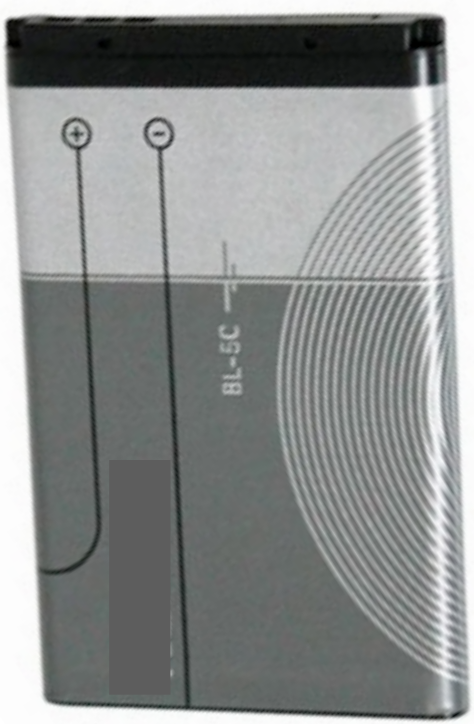
Small detail... Bohr was not completely right, the "new" elementary particles are not elementary but mesons, namely formed by quarks

What's the future ?



Interlude: a brief recall of energy scales

- WARNING: for purists or non-experts: Energy, Masses and Momentum have different units, which turn to be the same since c (speed of light) is considered equal to one.
    - Energy[GeV], Momentum [GeV/c], Masses [GeV/c^2]
      (Remember golden rule, $E=mc^2$ has to be true also for units...)
- Just an as a rule of thumb: **0.511 MeV/c^2** (electron mass) corresponds to about **9.109 10^{-31} kg**



An Example about energy scales: my cellular phone battery.

Voltage: 3.7 V
Height: 4.5 cm
proton mass ~ 1 GeV
To accelerate an electron to an energy equivalent to a proton mass:

1 GeV/3.7 eV = 270 270 270 batteries
270 270 270 batteries * 0.045 m ~ 12 000 000 m

12 000 000 m ~ THE EARTH DIAMETER

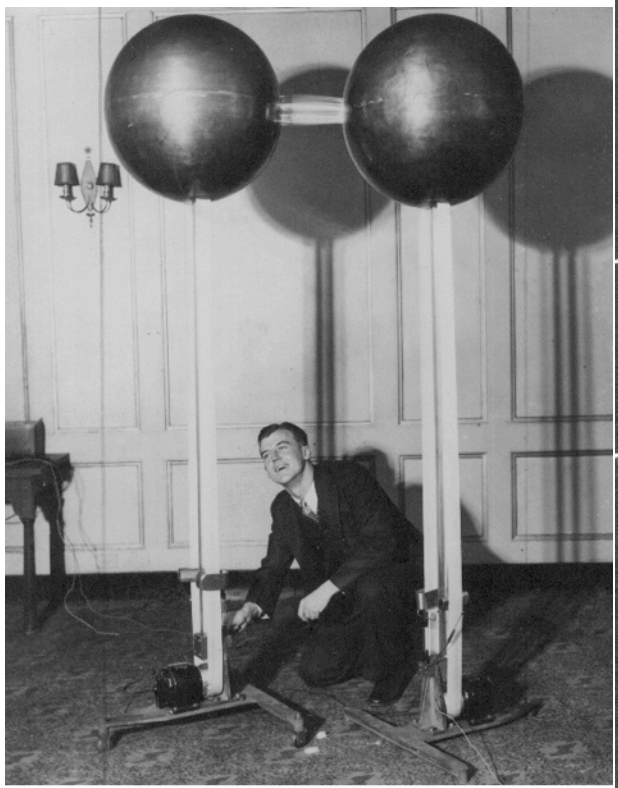
Obviously one has to find a smarter way to accelerate particles to high energies instead of piling up cellular phone batteries ....

Van De Graaf electrostatic generator (1928)

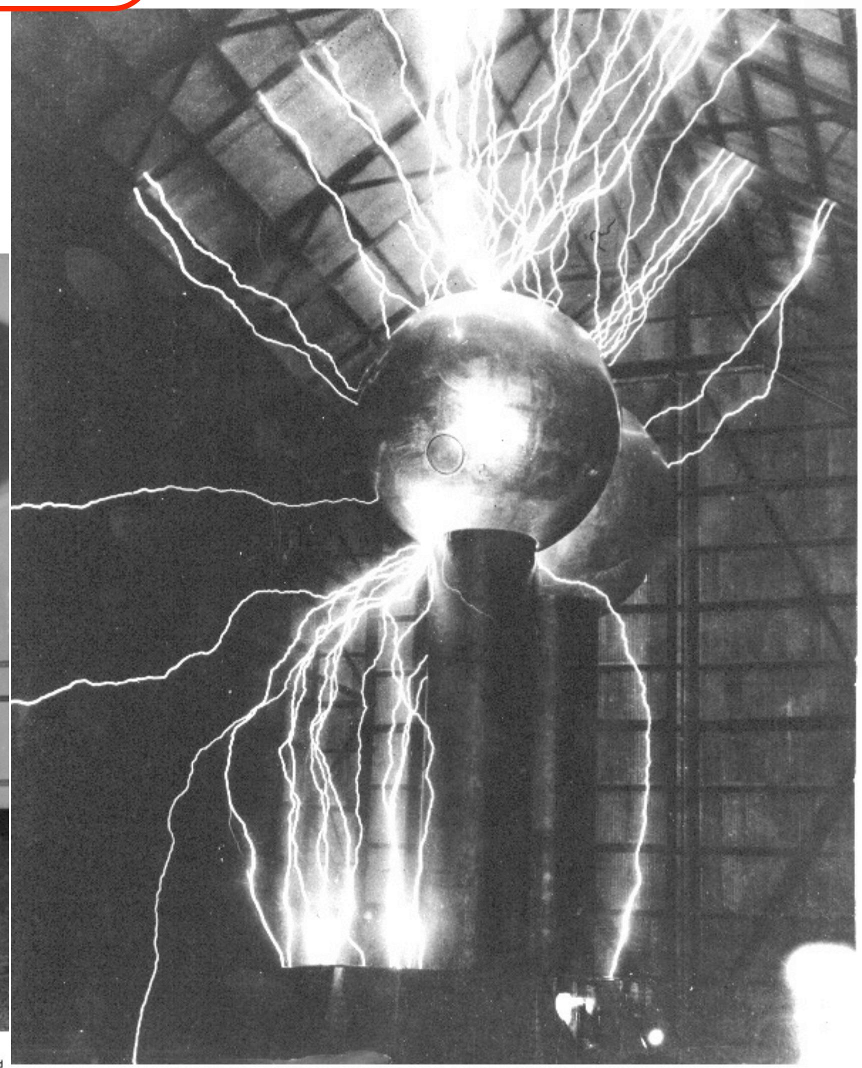
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: 10 MV

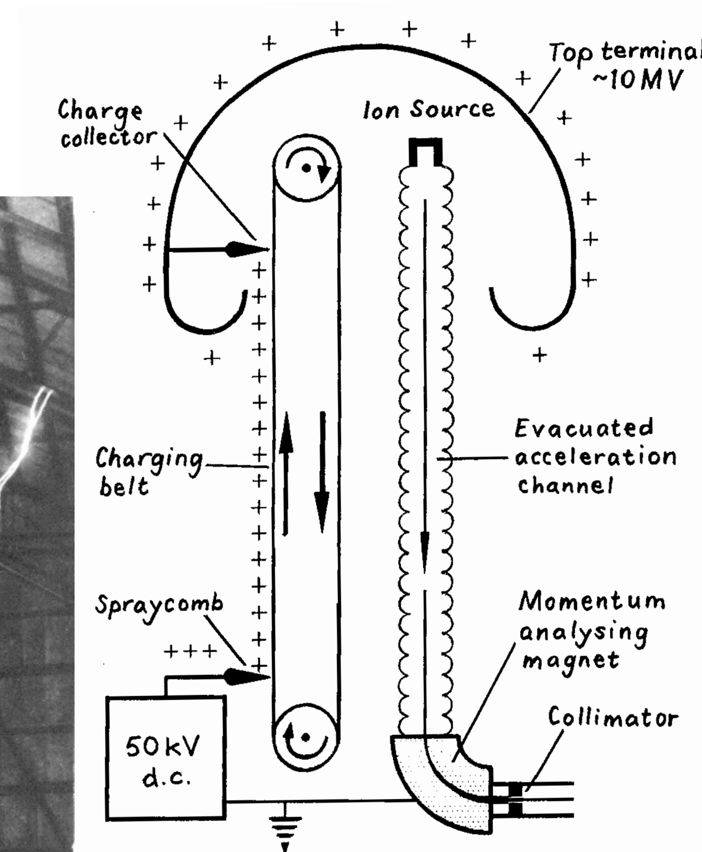
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



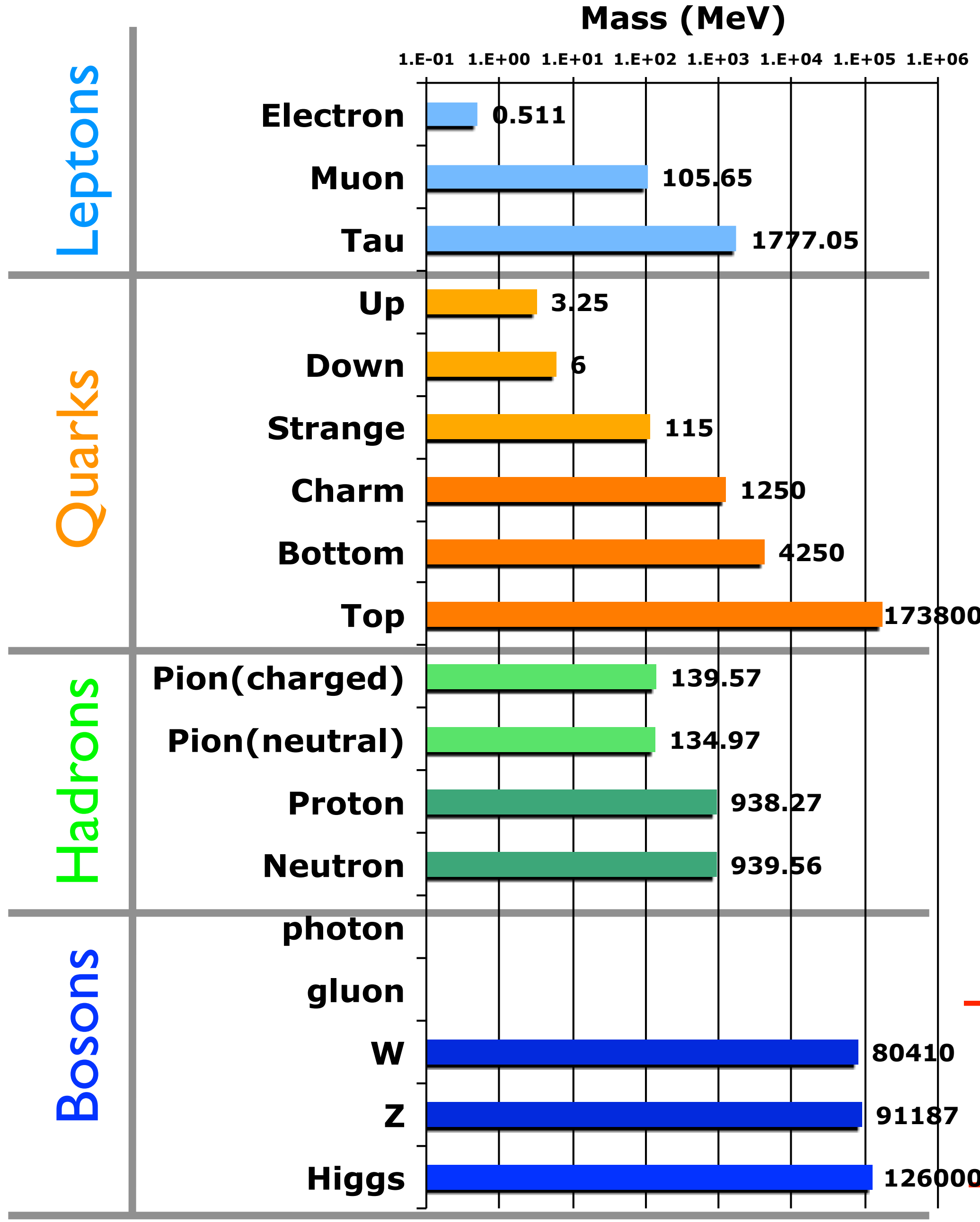
R. J. VAN DE GRAAFF WITH FIRST GENERATOR



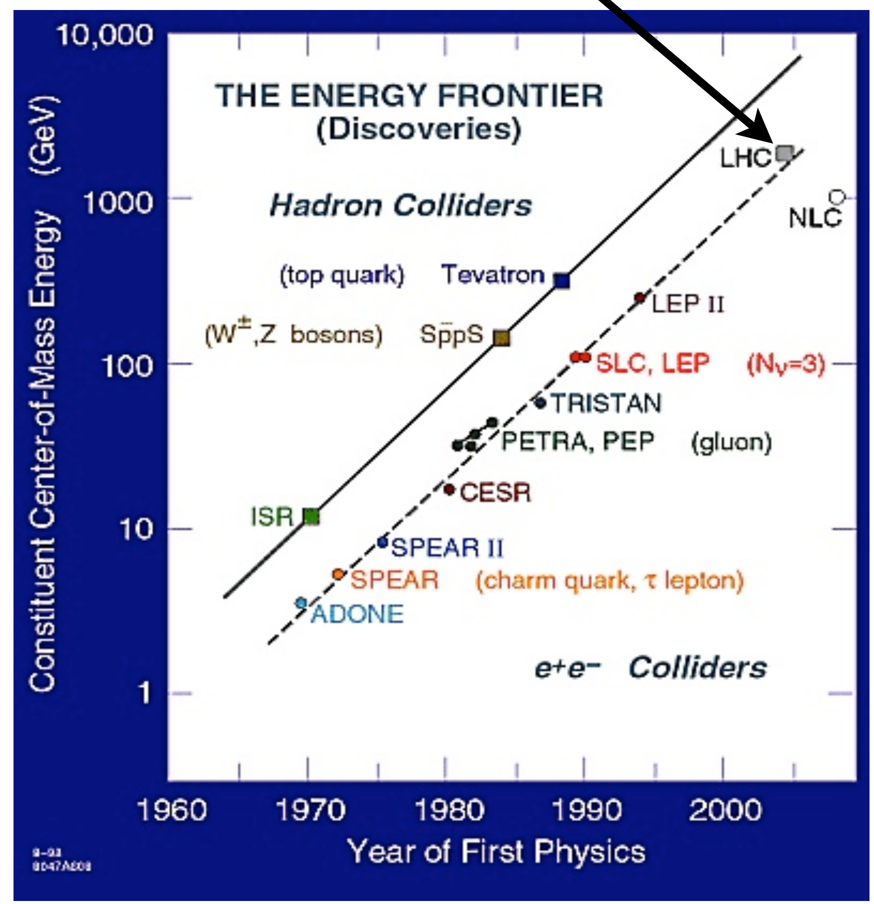
AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)



History/Energy line vs discovery



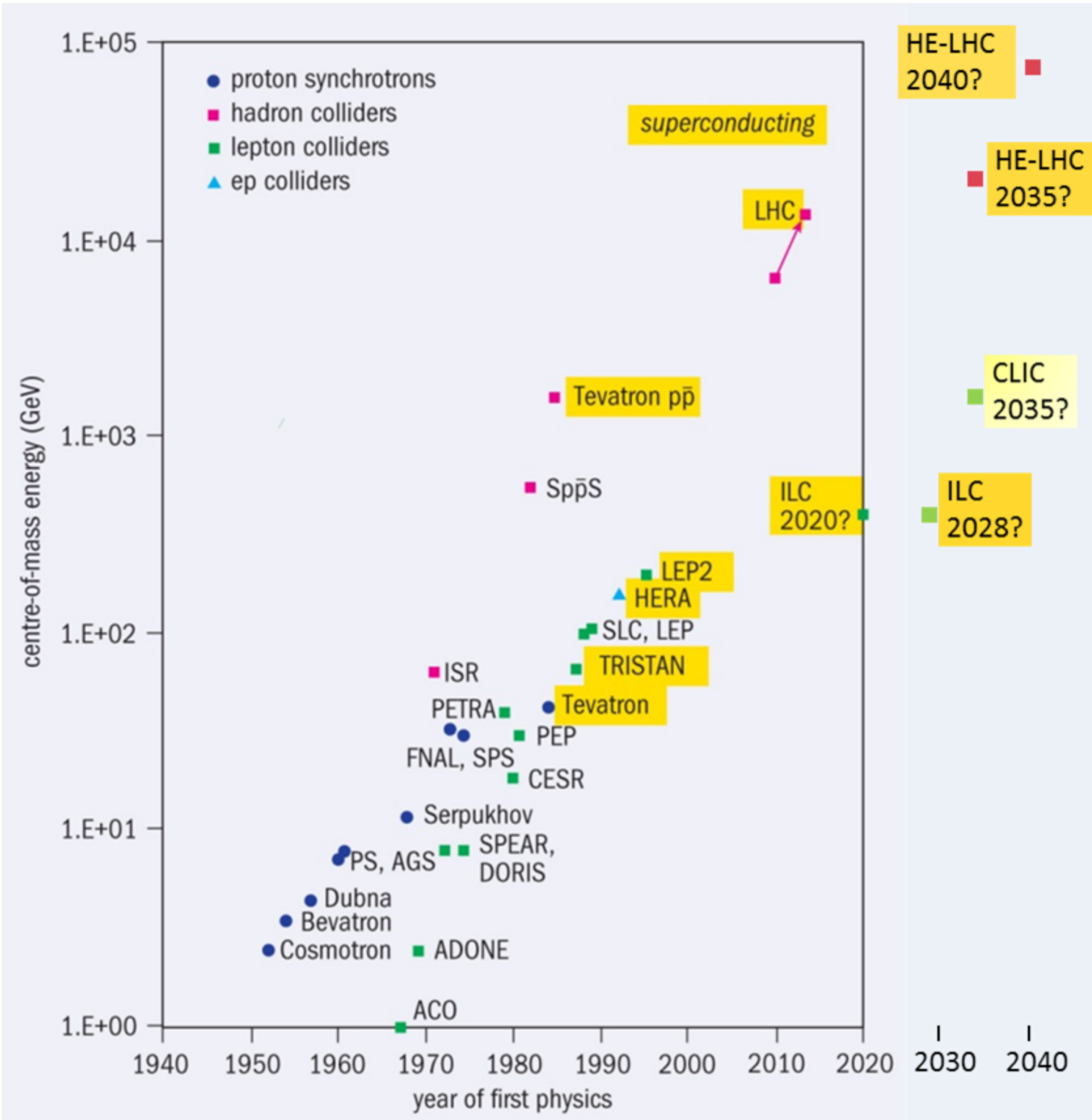
Higgs and super-symmetry ?
Or something else maybe



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

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either p-$\bar{p}$ as Tevratron, p-p as LHC)

What's the future ?



Building Blocks of an accelerator

1) A particle source

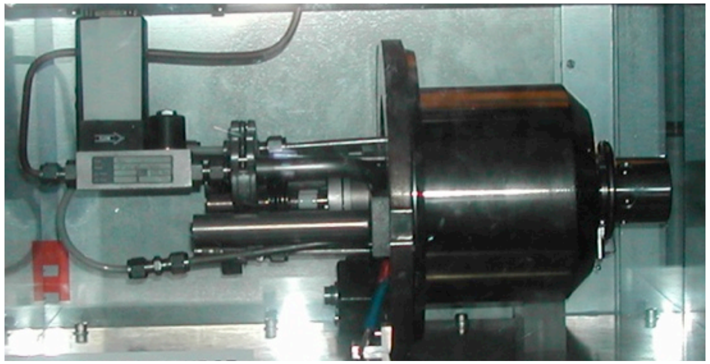
2) An accelerating system

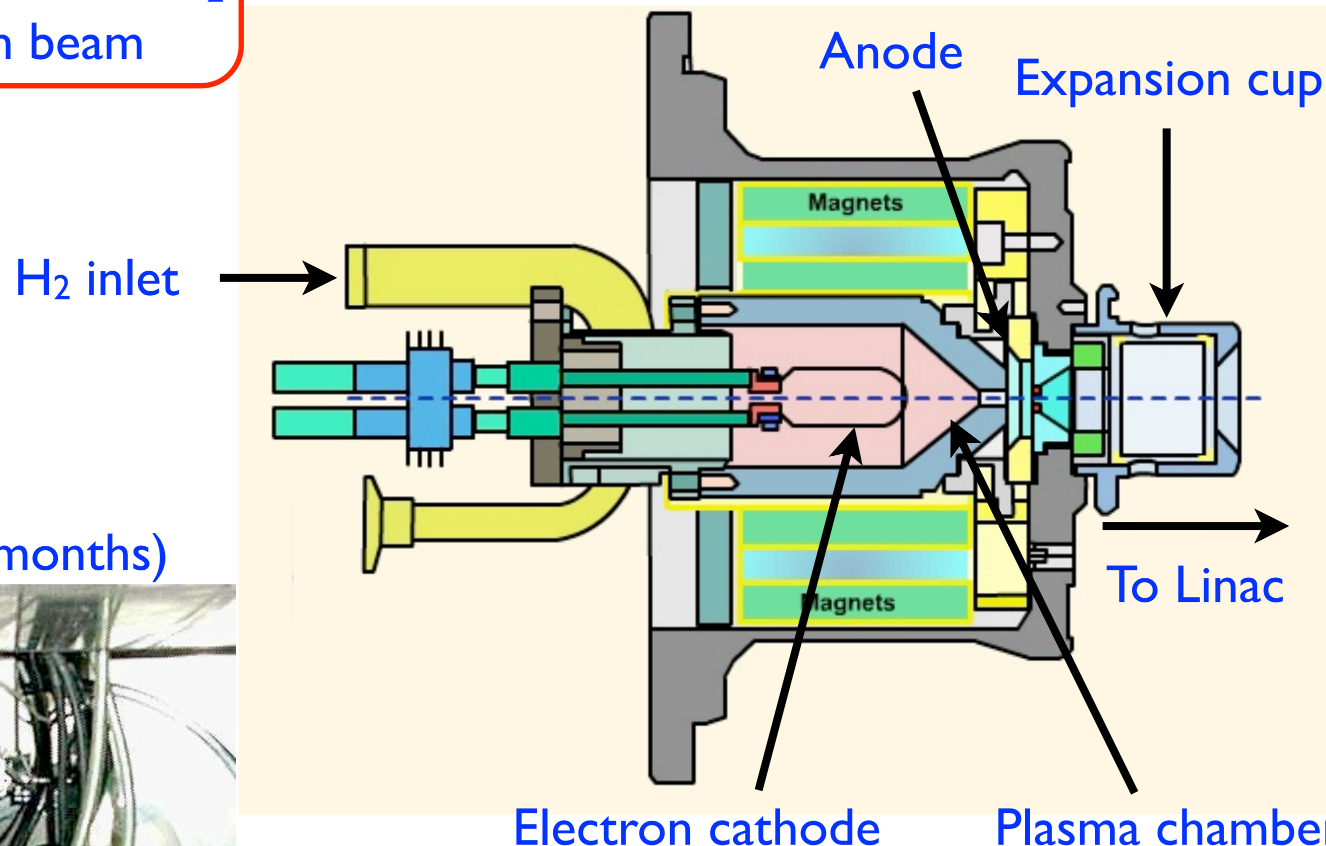
3) A series of guiding and storage devices

Everything under vacuum

How to get protons: duoplasmatron source

Protons are produced by the ionization of H_2 plasma enhanced by an electron beam





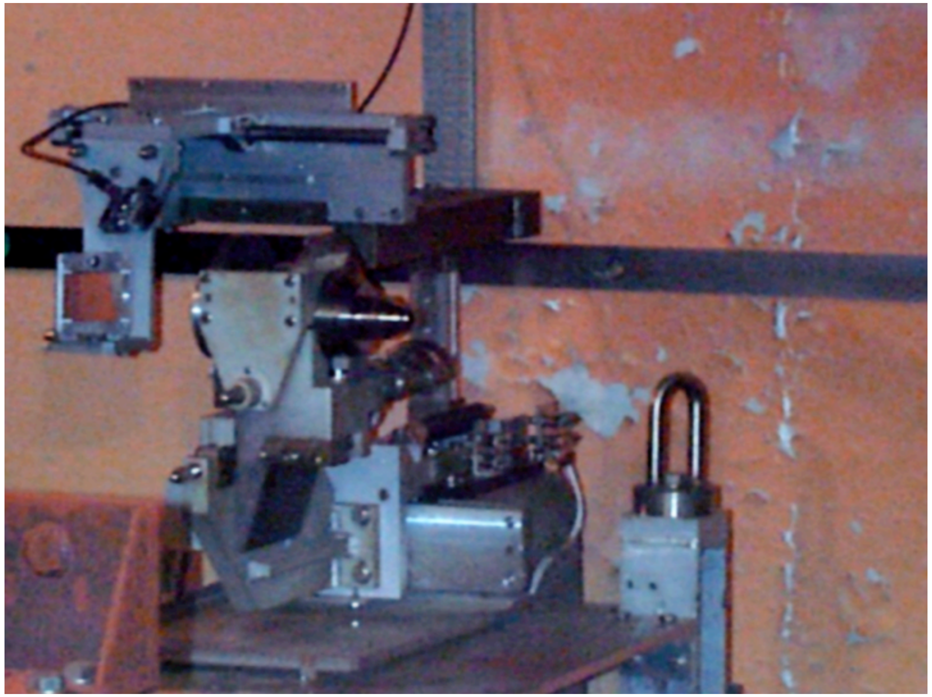
Hydrogen supply (one lasts for 6 months)

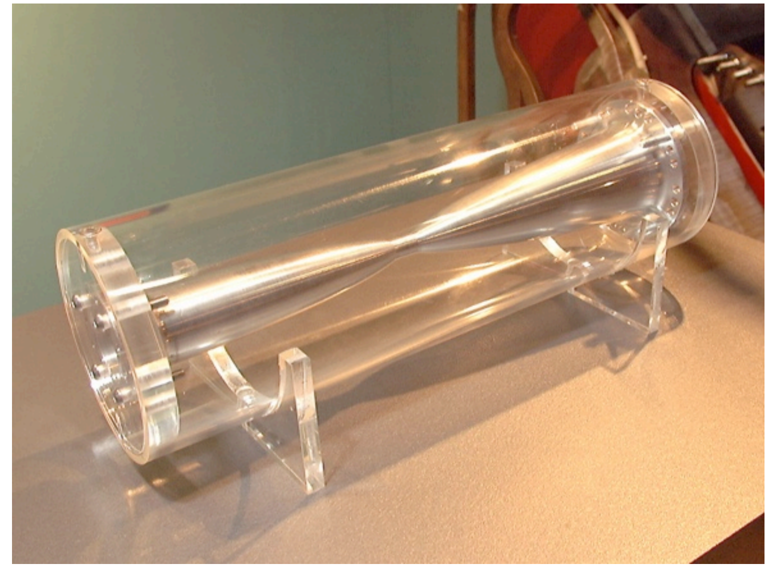
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, $v \approx 4000$ km/s

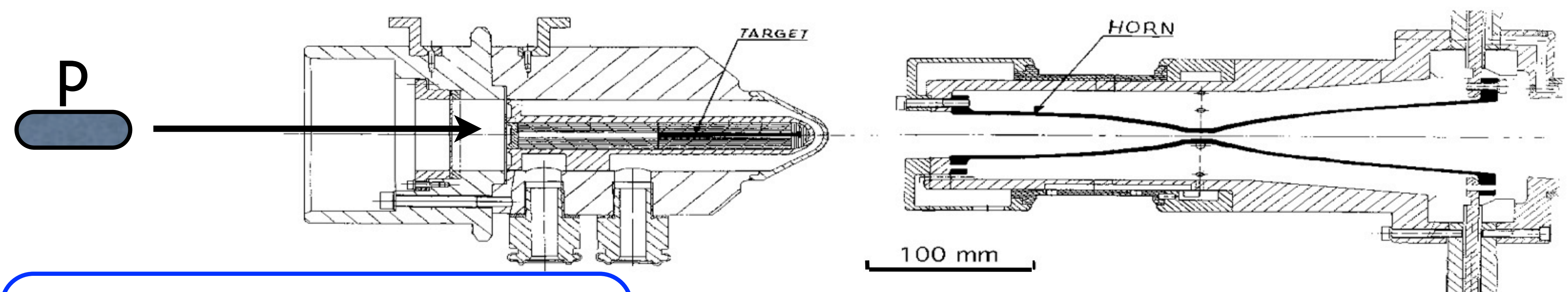
The SPACE SHUTTLE goes only up to 8 km/s

Cern Control Center: first LHC day

How to get antiprotons





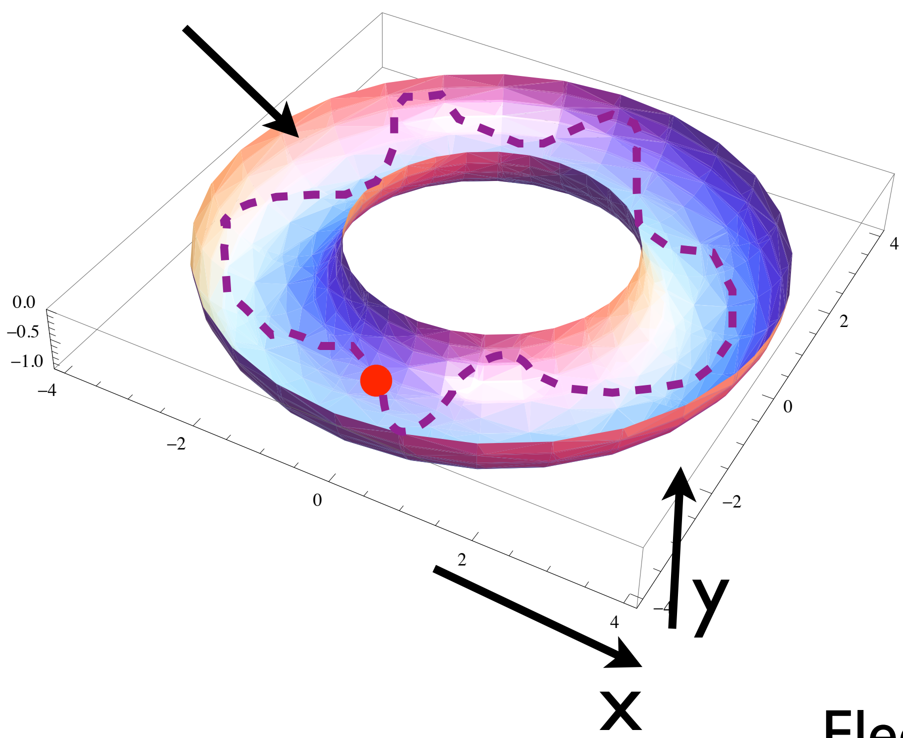


Starting from high energy p and with a very low efficiency

$$p + p \rightarrow p + p + p + \bar{p}$$

10^{13} p to have about 10^{7} antiprotons

How an accelerator works ?



Goal: *keep enough* ***CHARGED*** *particles confined in a well defined volume to accelerate them for a sufficiently long time* ***(ms - hours)***

How ? Lorentz Force!

$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

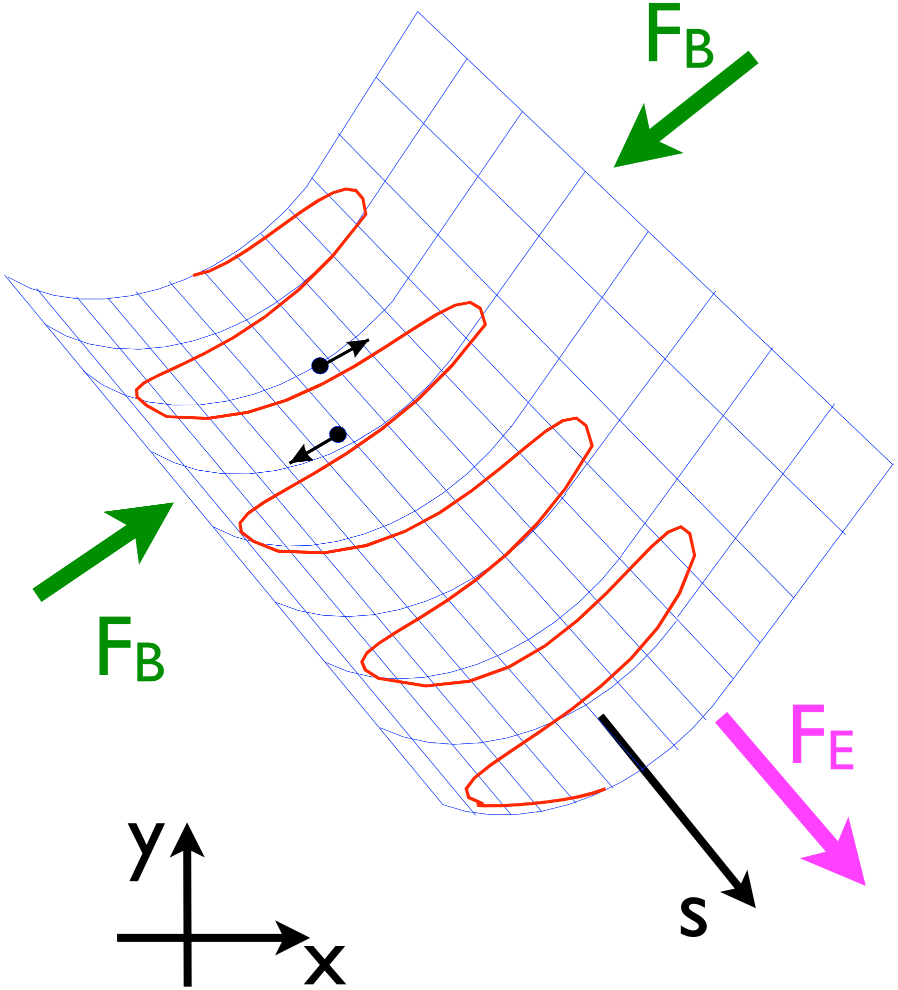
An ***accelerator*** *is formed by a sequence (called* ***lattice****) of:*

a) Magnets → Magnetic Field

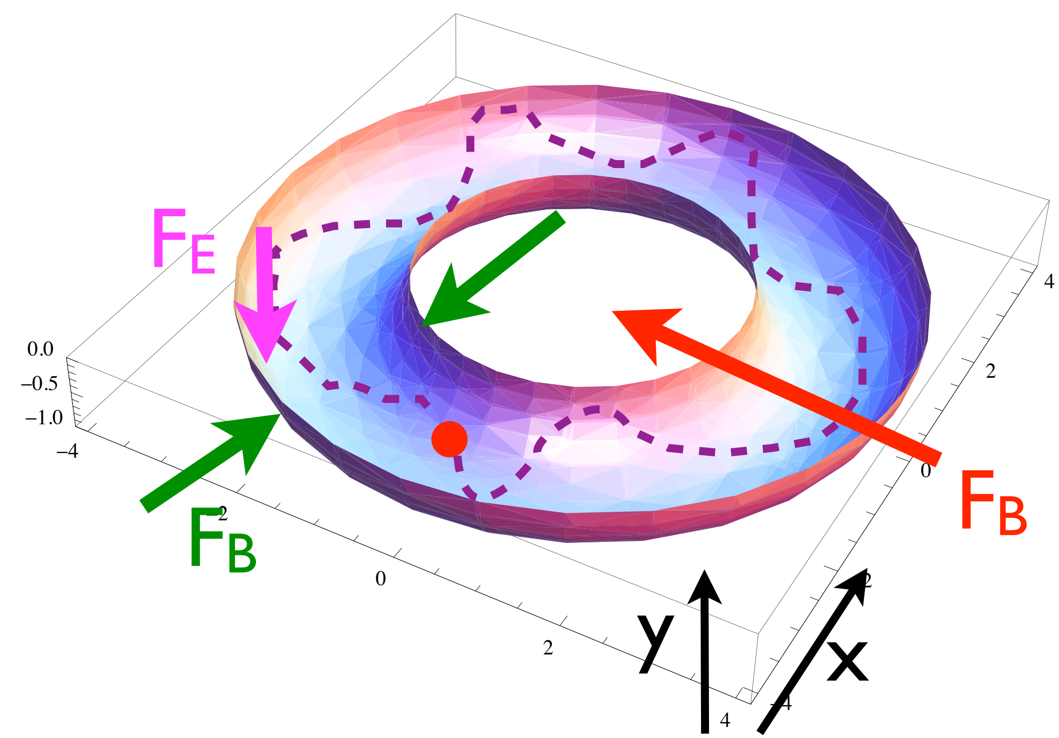
b) Accelerating Cavity → Electric Field

$$\overline{F(t)} = \underbrace{q\left(\overline{E(t)}\right.}_{F_E} + \underbrace{\overline{v(t)} \otimes \overline{B(t)}}_{F_B}\left.\right)$$

Linear Accelerator



Circular Accelerator



Cyclotron

Particle source located in a vertical B field near the center of the ring

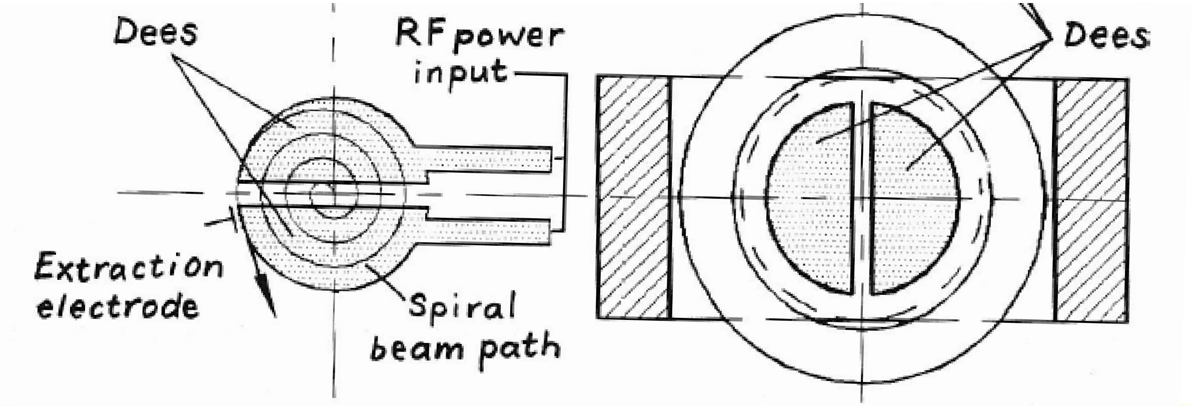
Electrical (E) RF field generated between two gaps with a fixed frequency

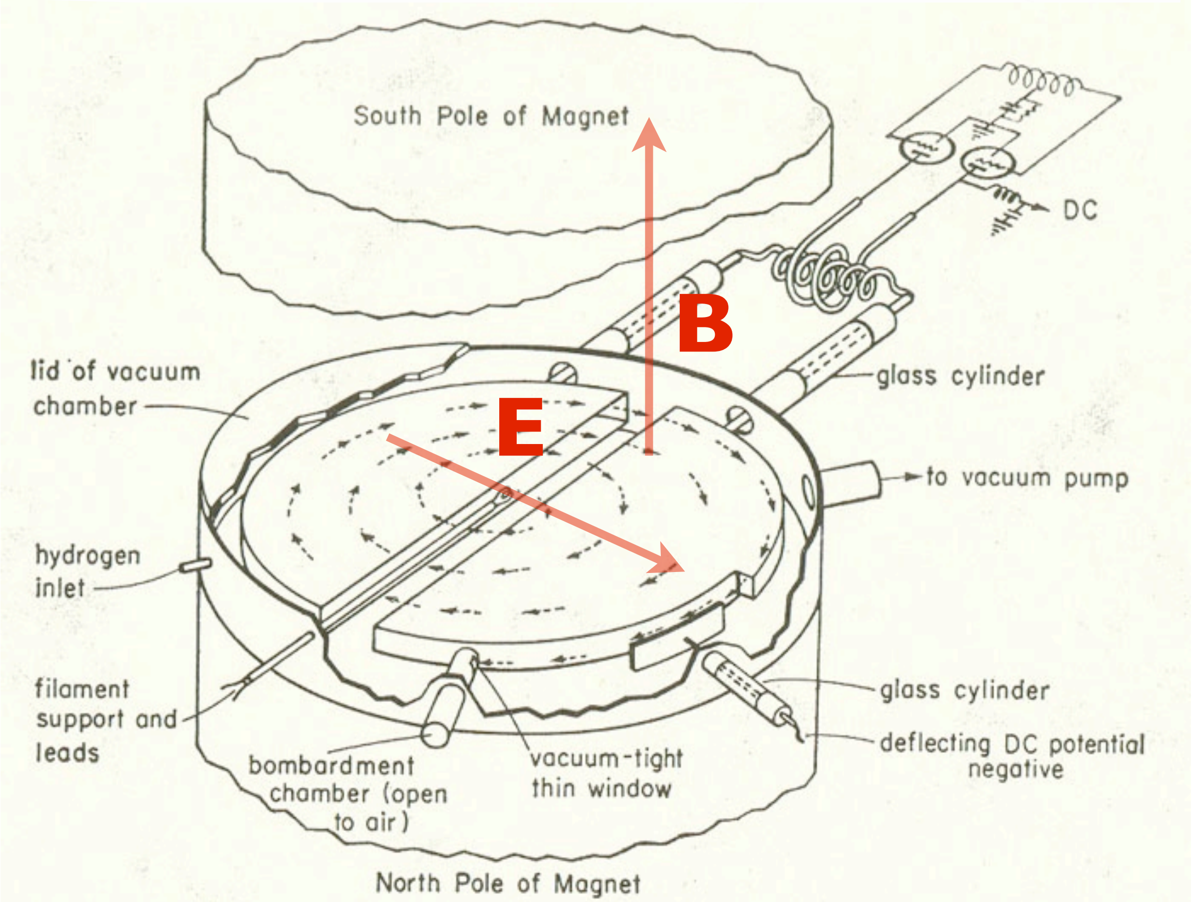
Particles spiral while accelerated by E field every time they go through the gap

$$Ep = \frac{1}{2}\frac{e^2}{m_0}B^2R^2_{max}$$

Max energy for protons: 20 MeV

Main limitations:
1) not working for relativistic particles, either high energy or electrons
2) B field at large radius not vertical

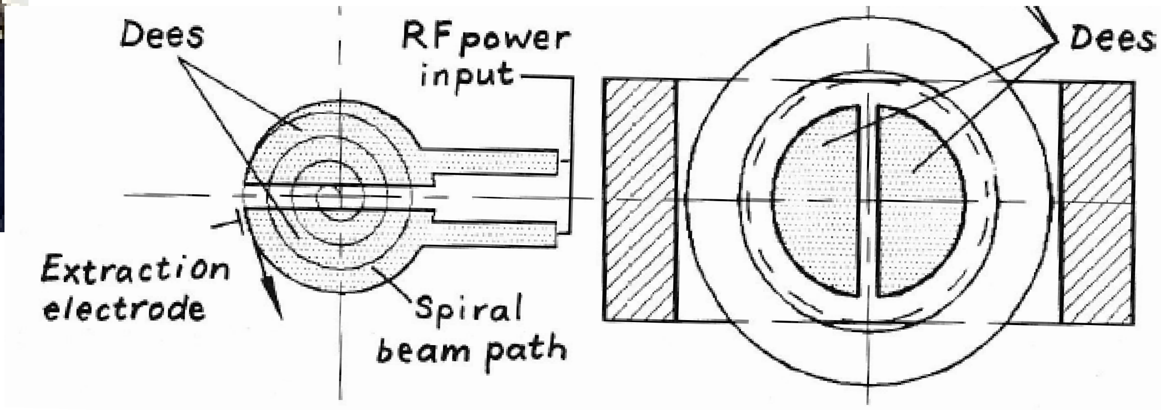




www.physics.rutgers.edu/ cyclotron/

Invented by Lawrence, got the Noble prize in 1939

The first cyclotron and the Berkeley one



Synchrotron (1952, 3 GeV, BNL)

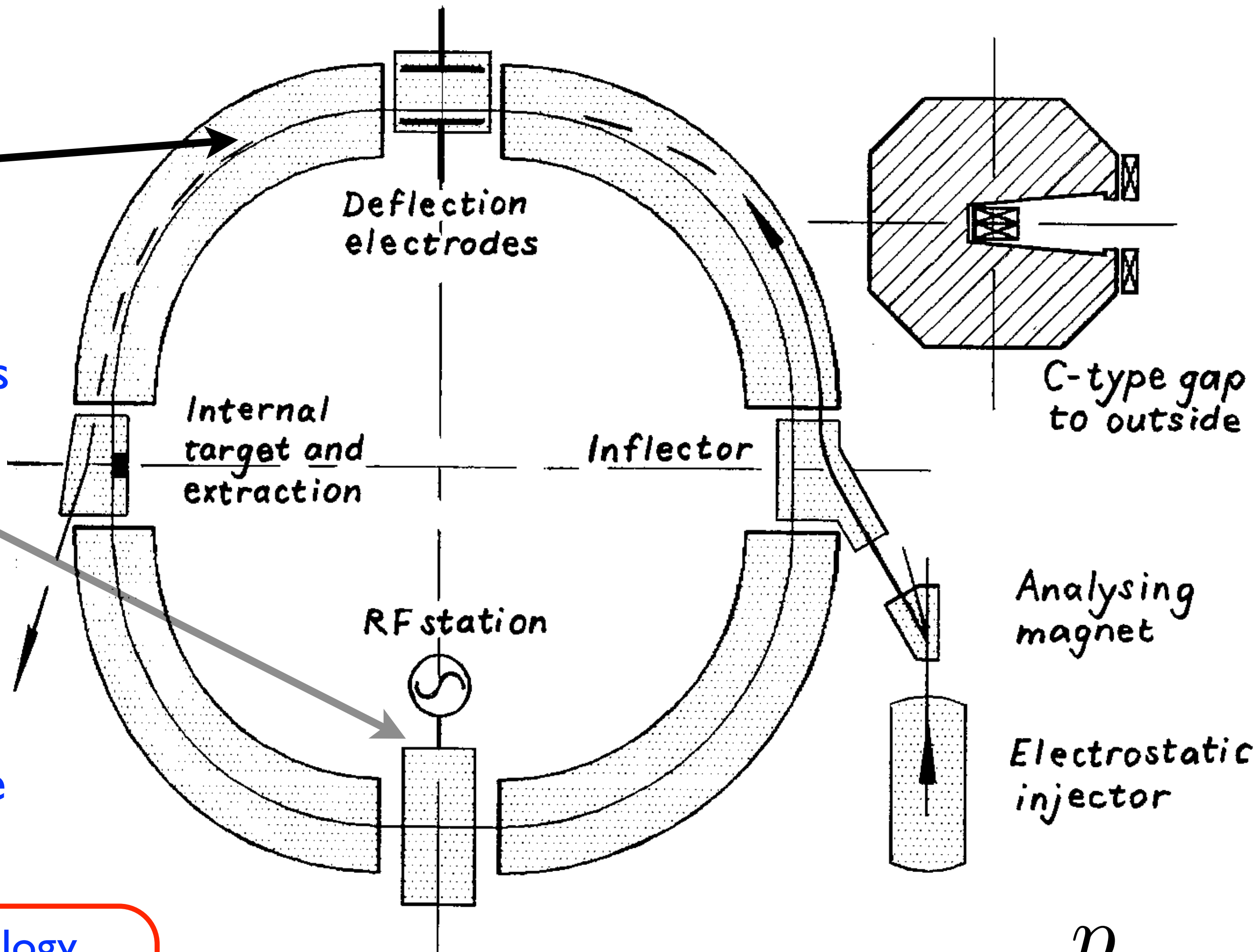
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

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

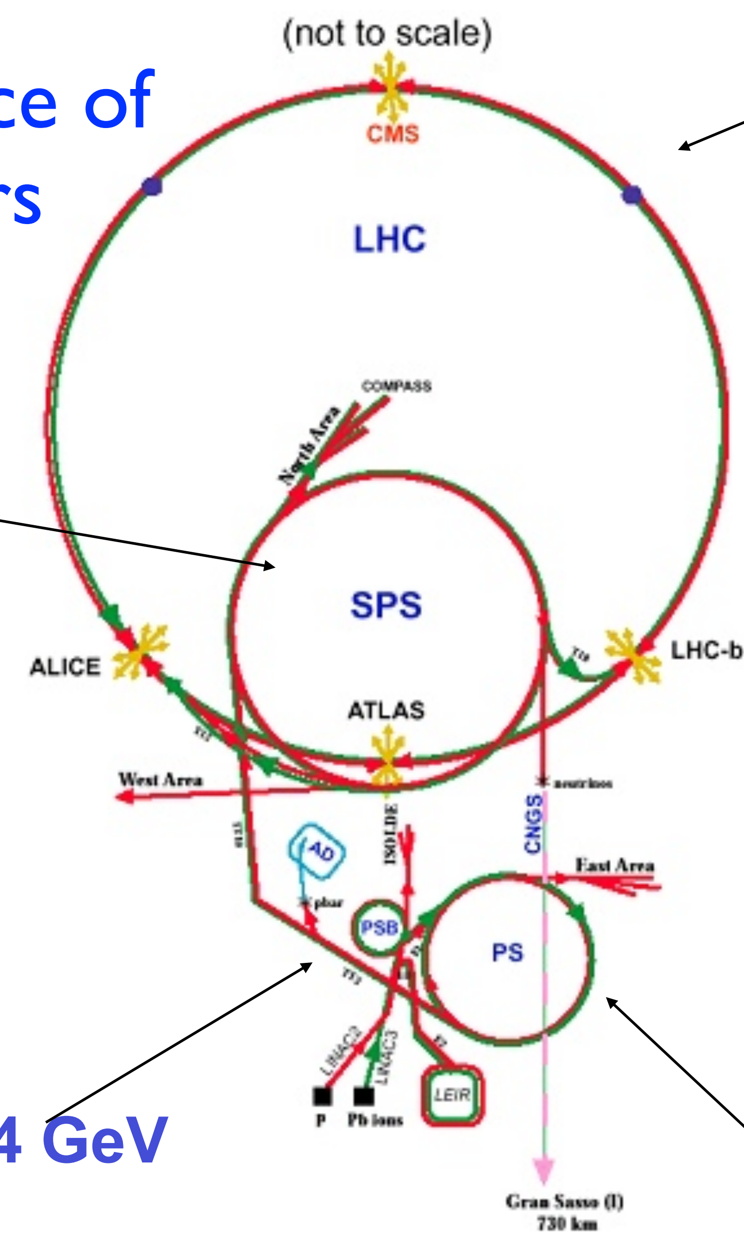


Bending strength limited by used technology to max ~ 1 T for room temperature conductors

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

CERN accelerator complex overview

Chain/sequence of accelerators



450 GeV/c – 7 TeV/c

C ~ 27 km

26 - 450 GeV/c

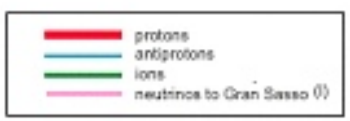
C ~ 6 km

1.4 GeV – 26 GeV/c

C ~ 630 m

50 MeV – 1.4 GeV

C ~ 157 m

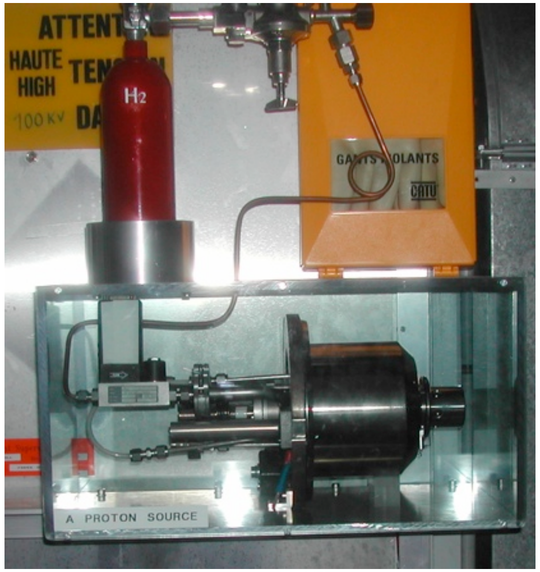


LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

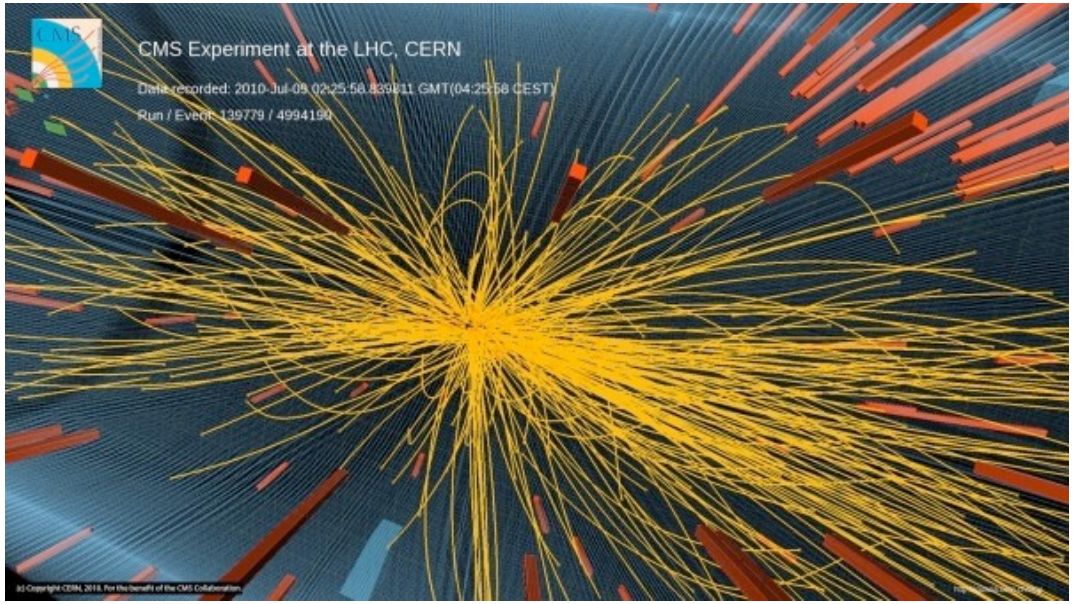
Questions:

- why so many accelerators and not just the LHC?
- why rings of increasing circumference?
- why rings and linear accelerators?
- how particles go from one machine to the other?

Basically accelerators brings you ...

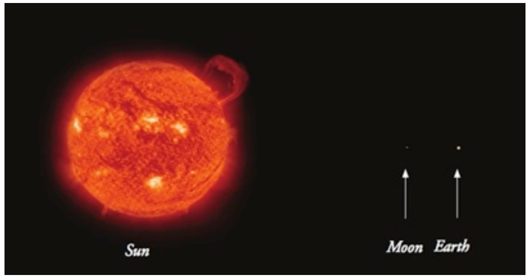


from nearly a bottle of hydrogen



to a little bit before this

How much time(distance) does it take from the source to collisions ?
(assumption, protons travels always at the speed of light)

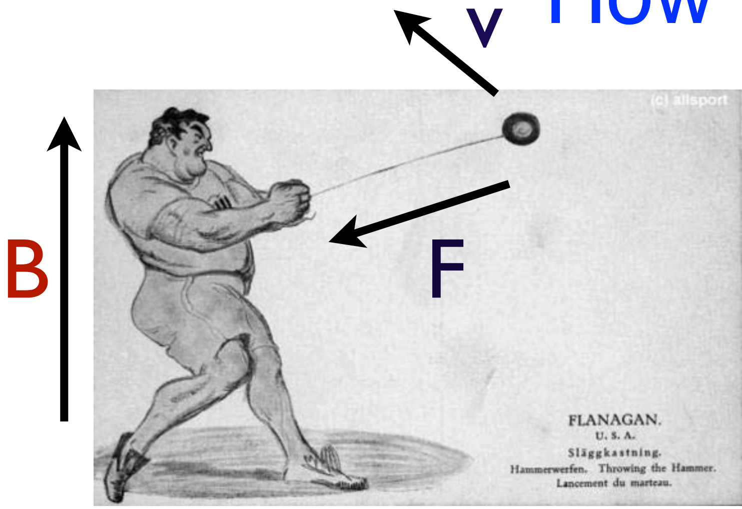


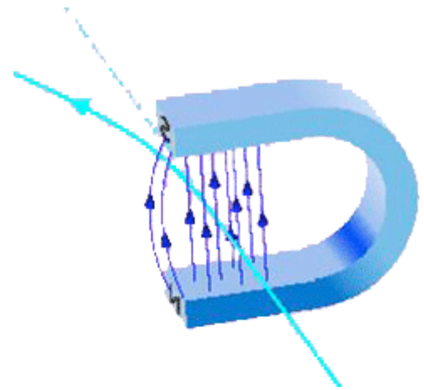
In the Linac 2, basically nothing.
In the **PSB,** a bit less than than 1.2 s.
In the **PS**, a bit less than 3.6 s
In the **SPS**, a bit less than 16.8 s
In the **LHC**, minimum 30 minutes

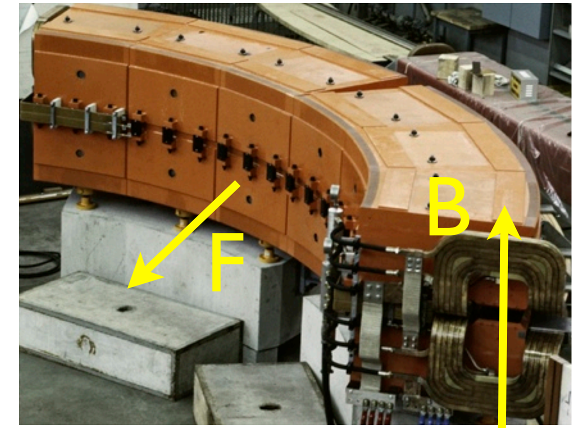
} **1 821.6 s → 546 480 000 km**

about 3.7 time the distance Sun-Earth

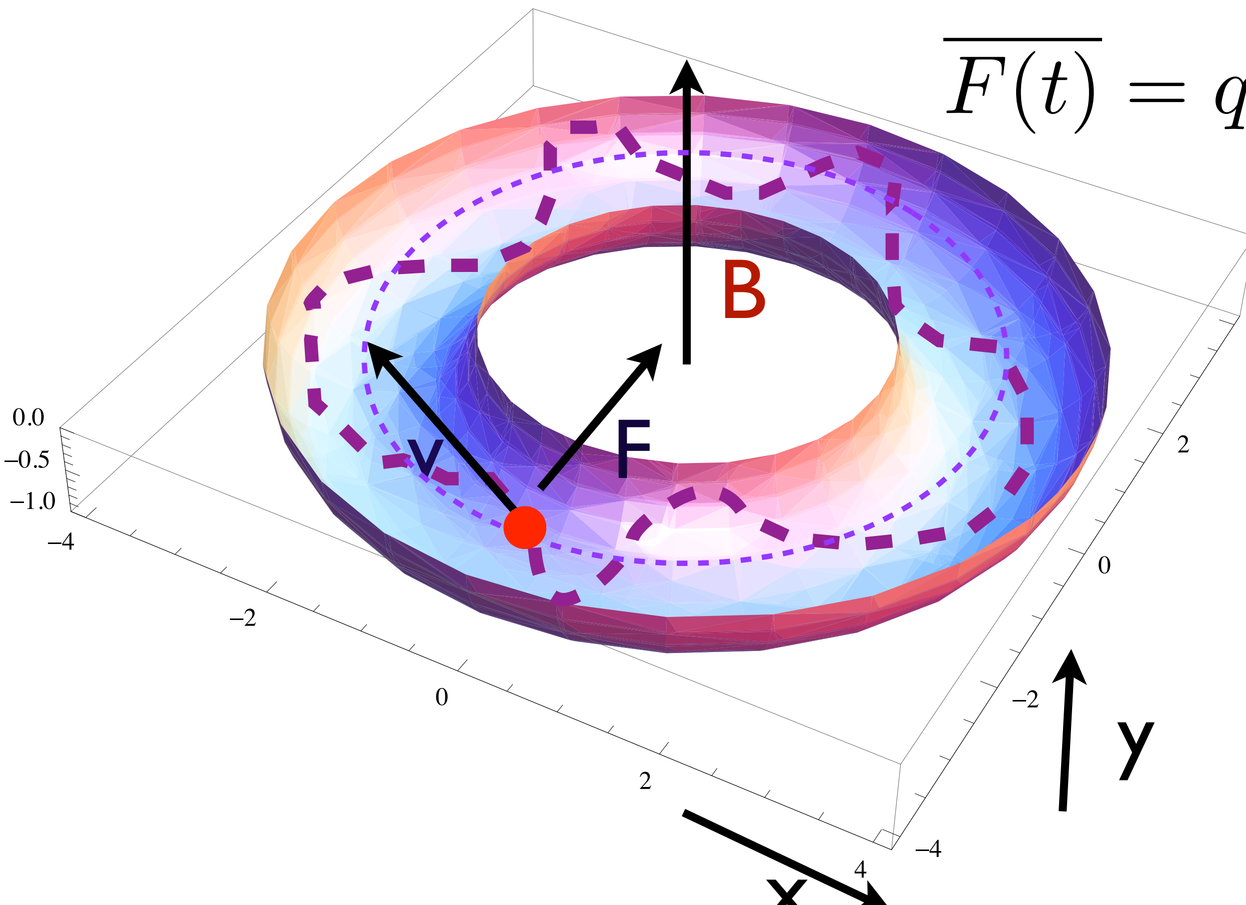
How an accelerator works ? A dipole







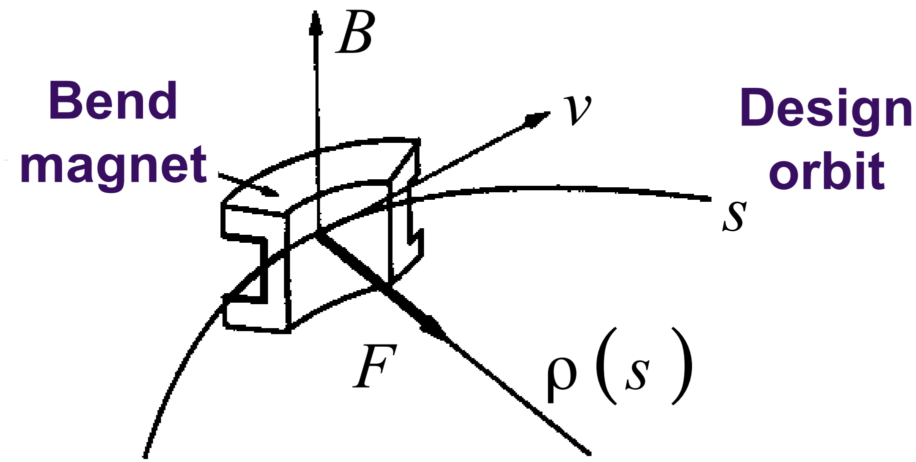
$$\overline{F(t)} = q\left(\cancel{\overline{E(t)}} + \overline{v(t)} \otimes \overline{B(t)}\right)$$



Particles of
different energy
(speed) behave differently

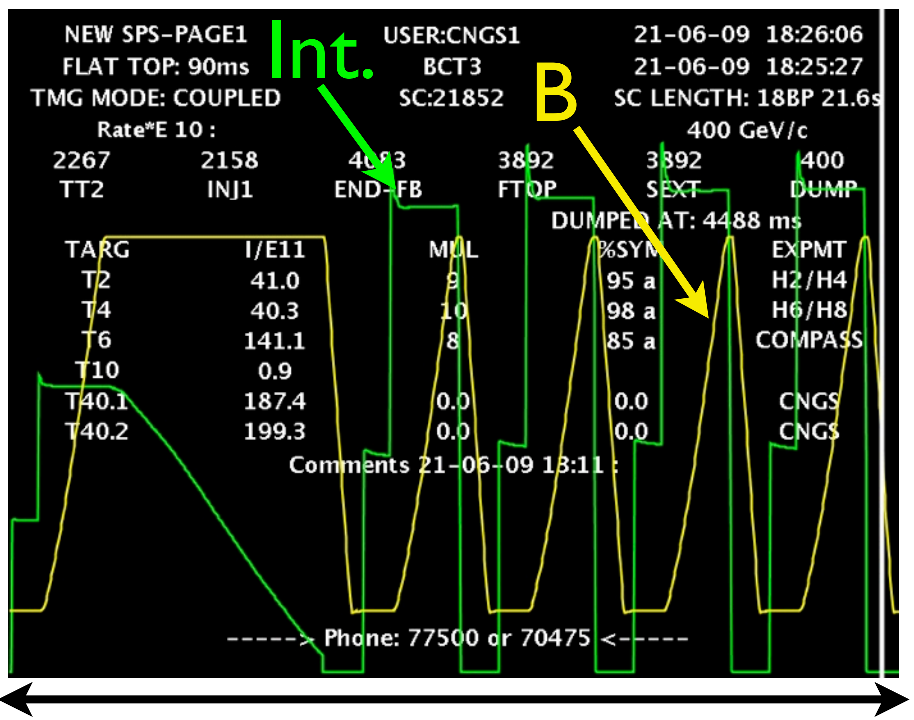
Magnetic field confines
particles
on a given trajectory

Dipoles



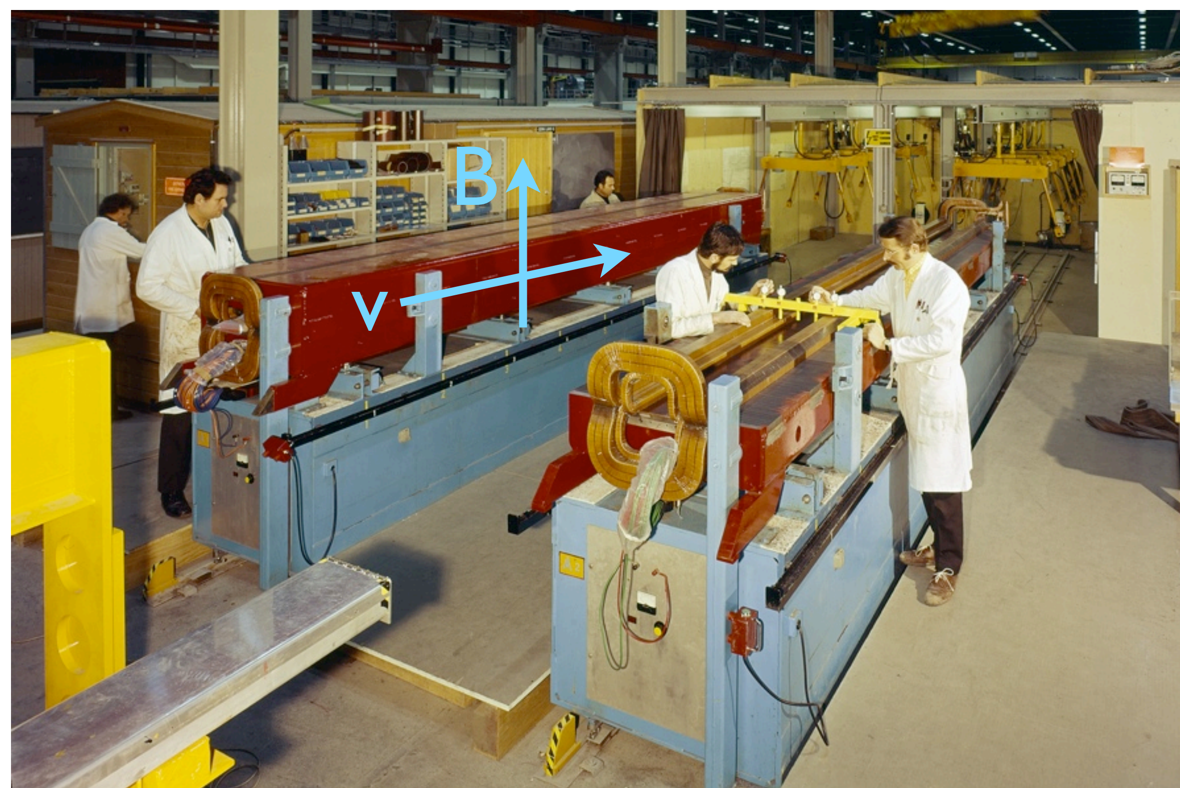
Force given by the vertical magnetic field compensates the centrifugal force to keep the particles on the central trajectory, i.e. in the center of the beam pipe.

A fast dipole, able to deflect the beam in few μs is called **kicker**. A kicker is used to extract the beam from the machine.

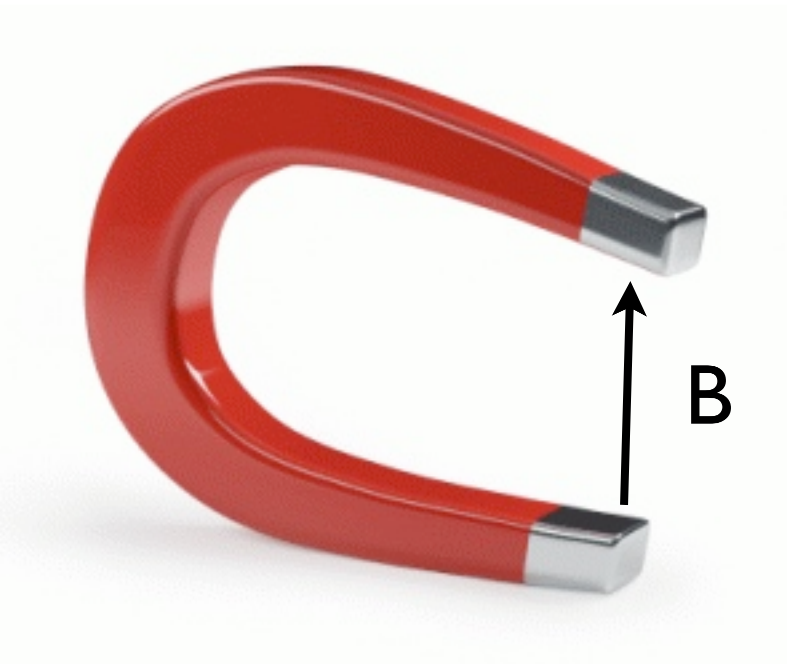


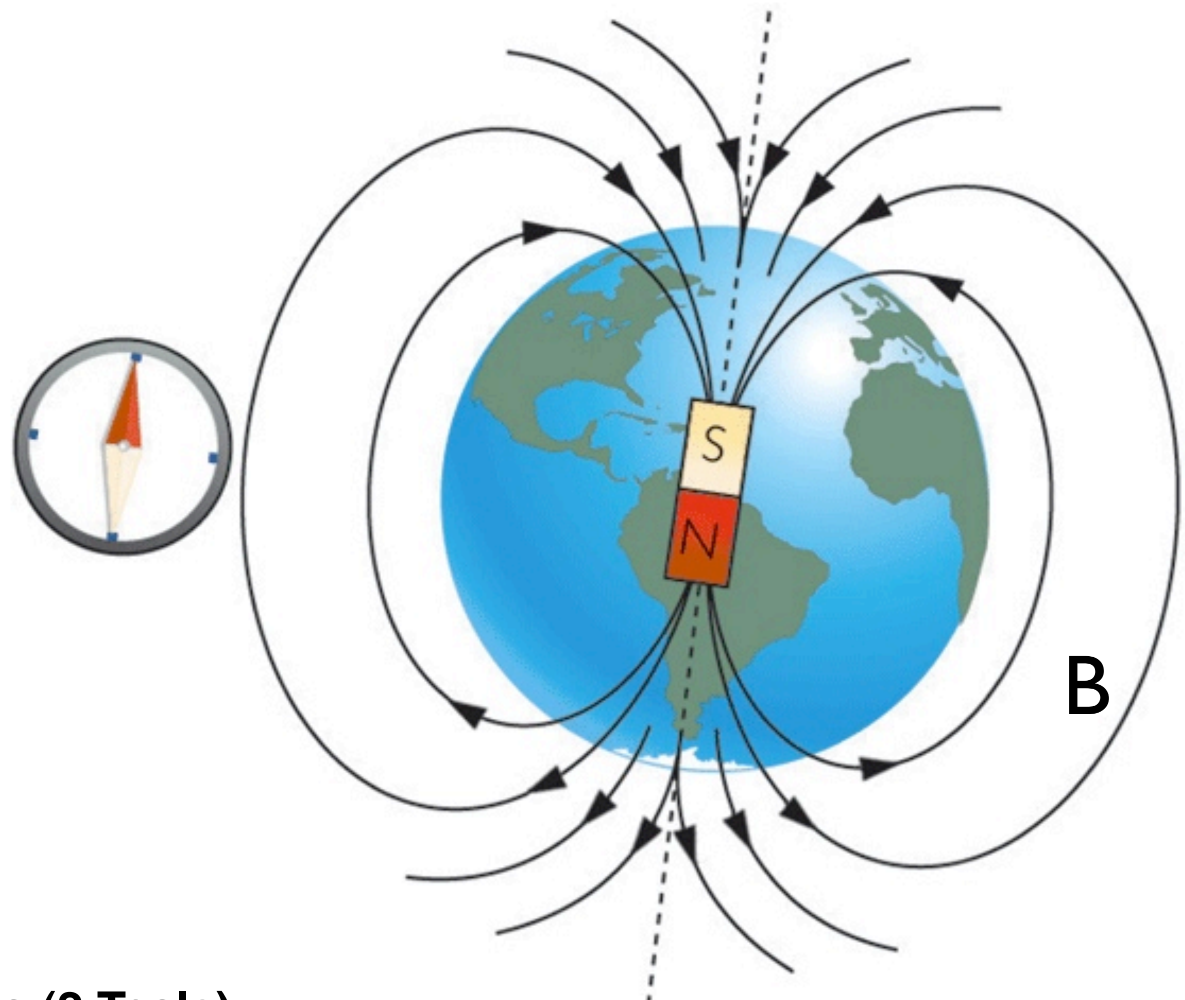
time (s) [21.6 s]

CERN-SPS dipoles, in total about 500



Two dipoles you should know we well

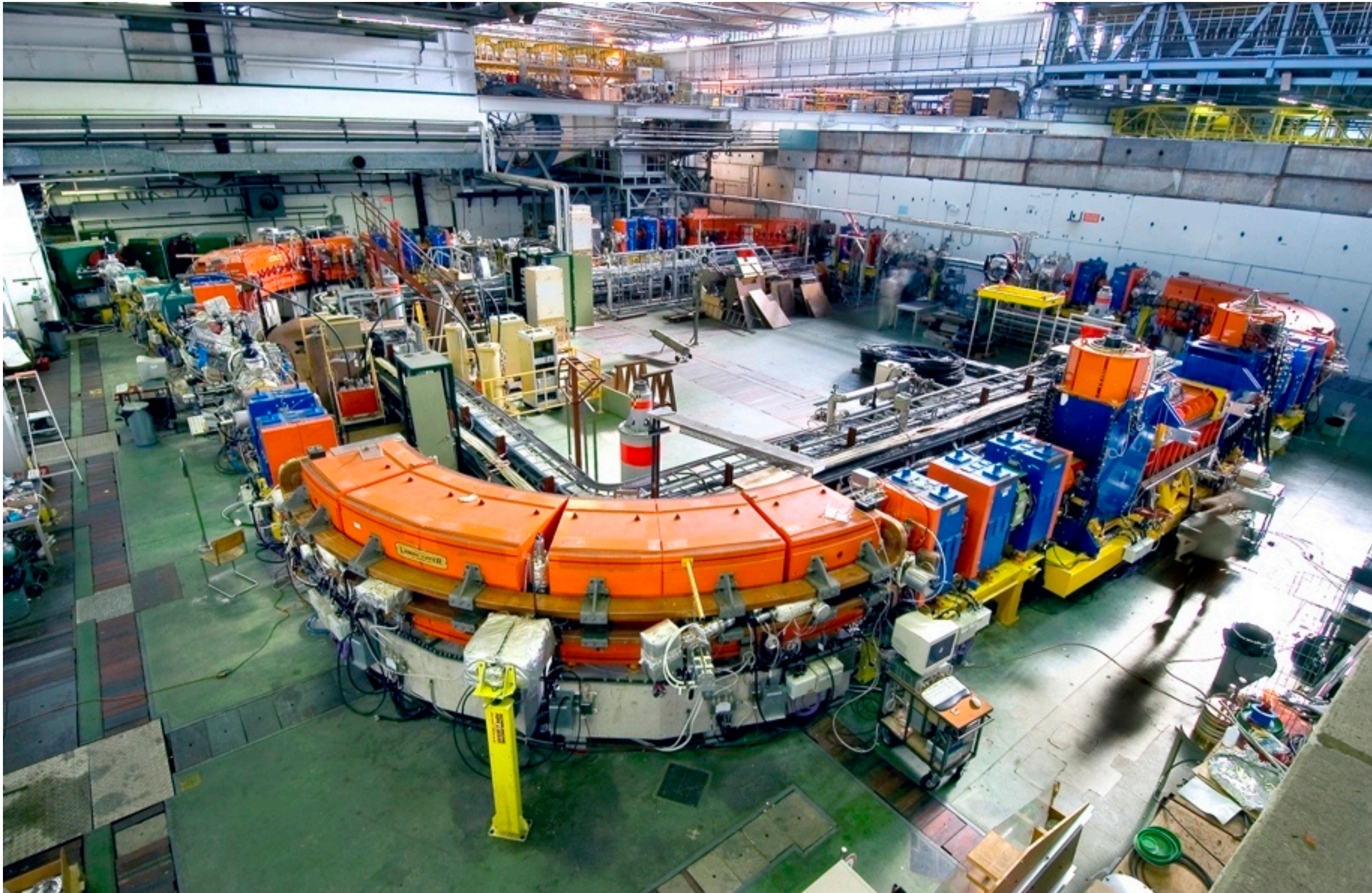




Earth Magnetic Field : ~ 0.6 Gauss

Typical SPS dipole field: ~ 20000 Gauss (2 Tesla)

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



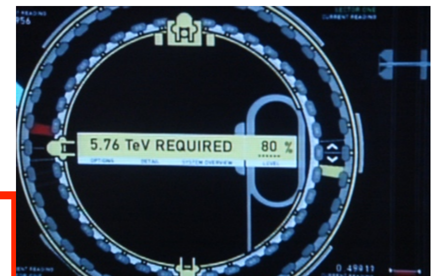
INTERLUDE:
THE TERMINATOR-3 ACCELERATOR

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

- Estimation of the magnetic field

No way!

  - Energy = 5760 GeV
  - Radius ~30 m
  - Field = 5760/0.3/30 ~ 700 T (a lot !)



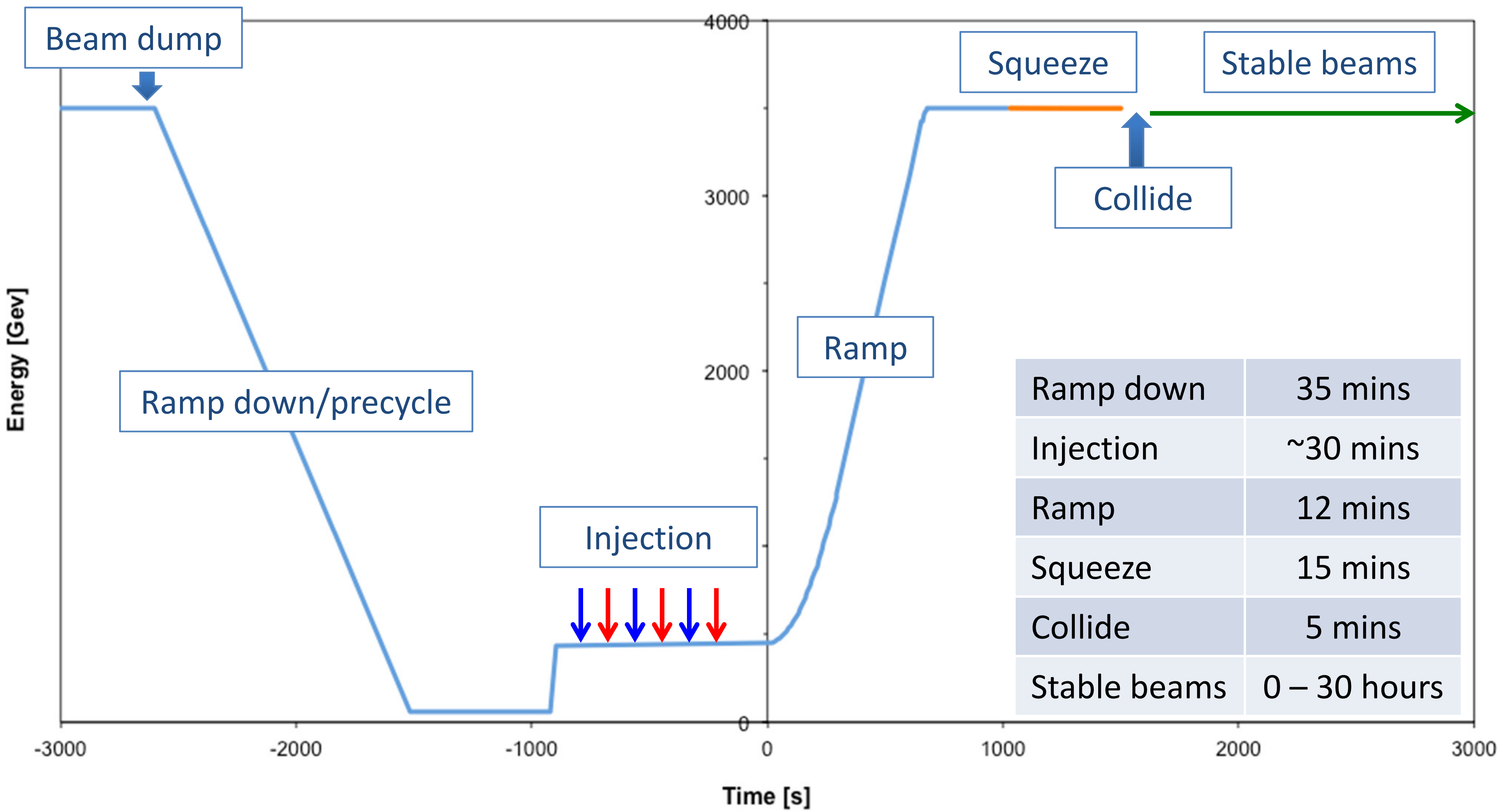
Energy of the machine (left) and size of the accelerator (right)

- 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

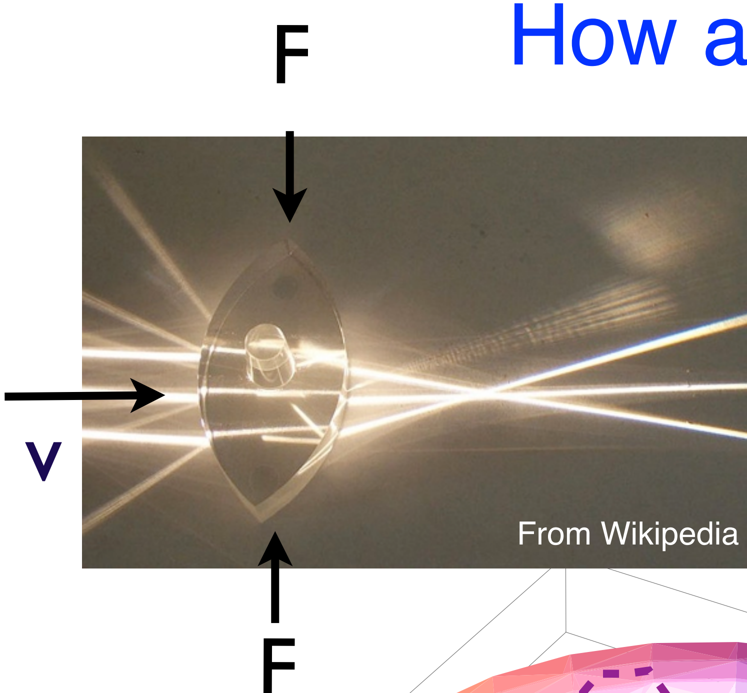
From E. Todesco CERN Summer student lecture

Typical LHC Operational cycle



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

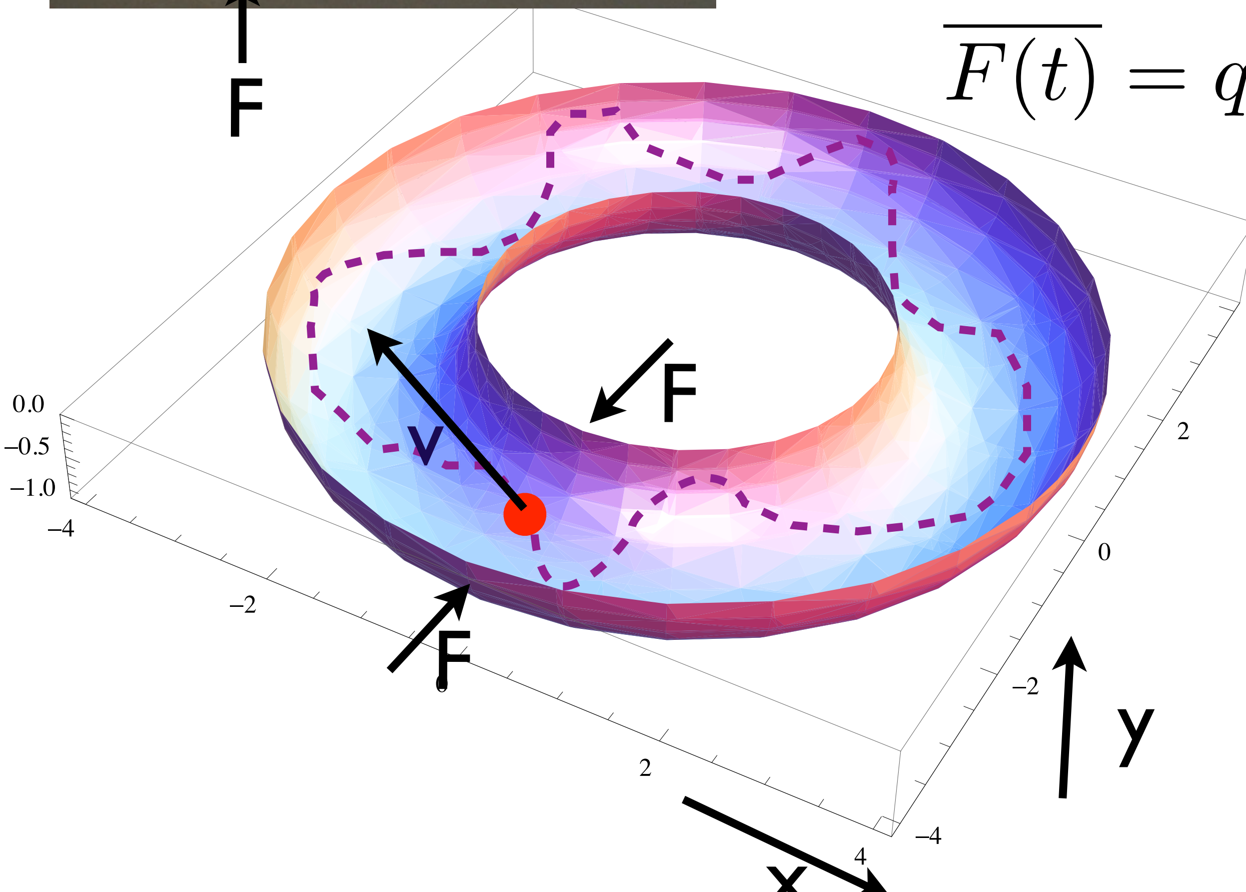
How an accelerator works ?



Goal: keep enough particles confined in ***a well defined volume*** *to accelerate them.*

How ? Lorentz Force!

$$\overline{F(t)} = q\left(\cancel{\overline{E(t)}} + \overline{v(t)} \otimes \overline{B(t)}\right)$$



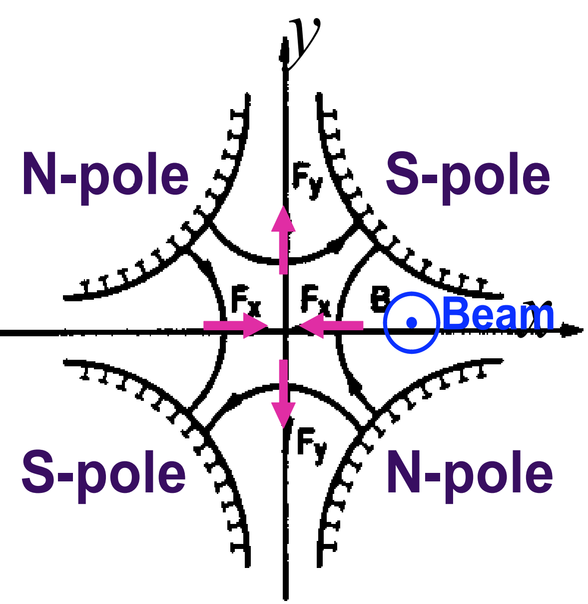
Particles of different energy (speed) behave differently

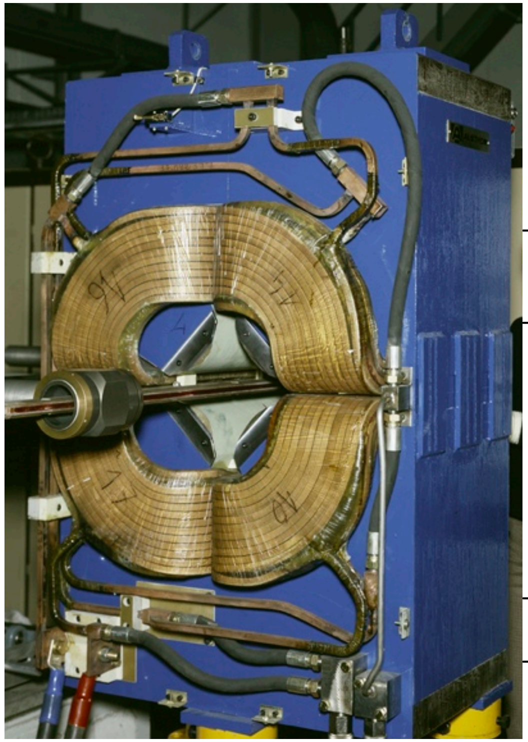
Magnetic field confines particles on a given trajectory

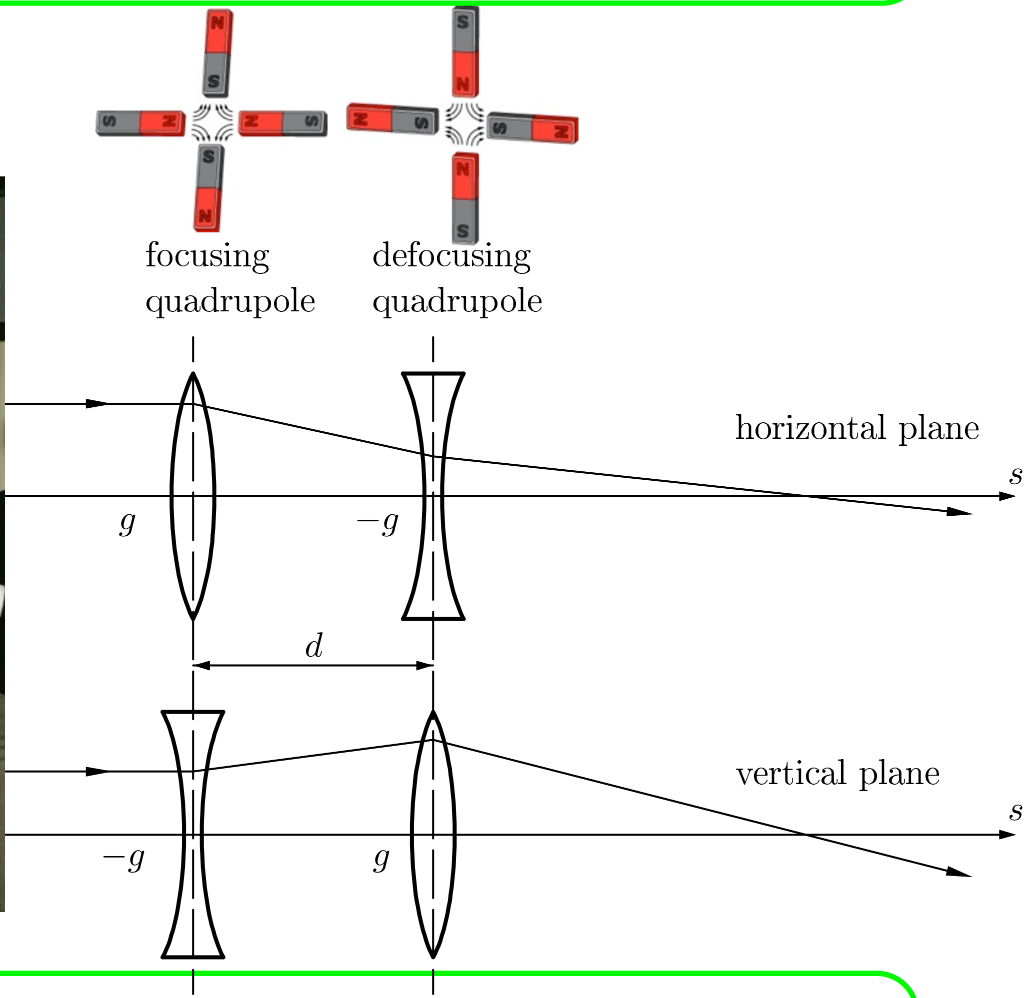
Synchrotrons: strong focusing machine

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).

QUADRUPOLE



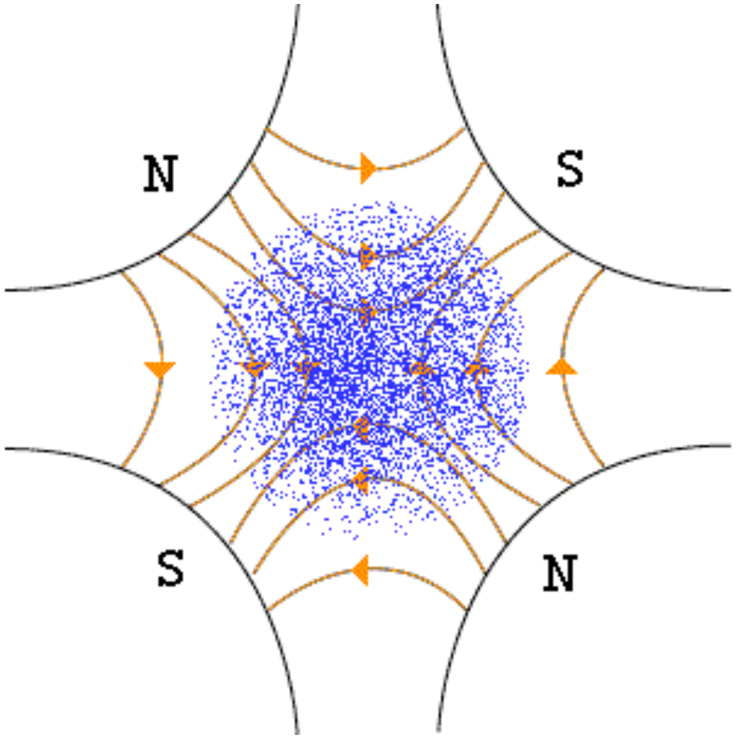




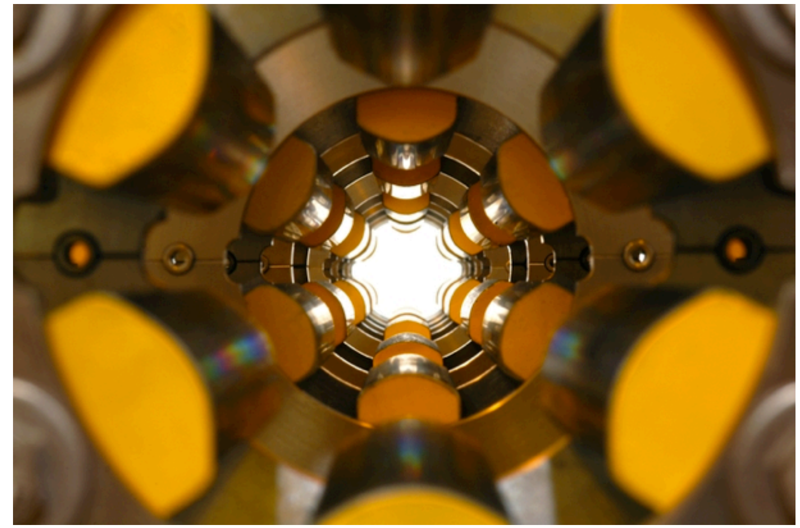
B field is focusing in one plane but defocusing in the other.

Typical lattice is FODO, focusing-drift-defocusing

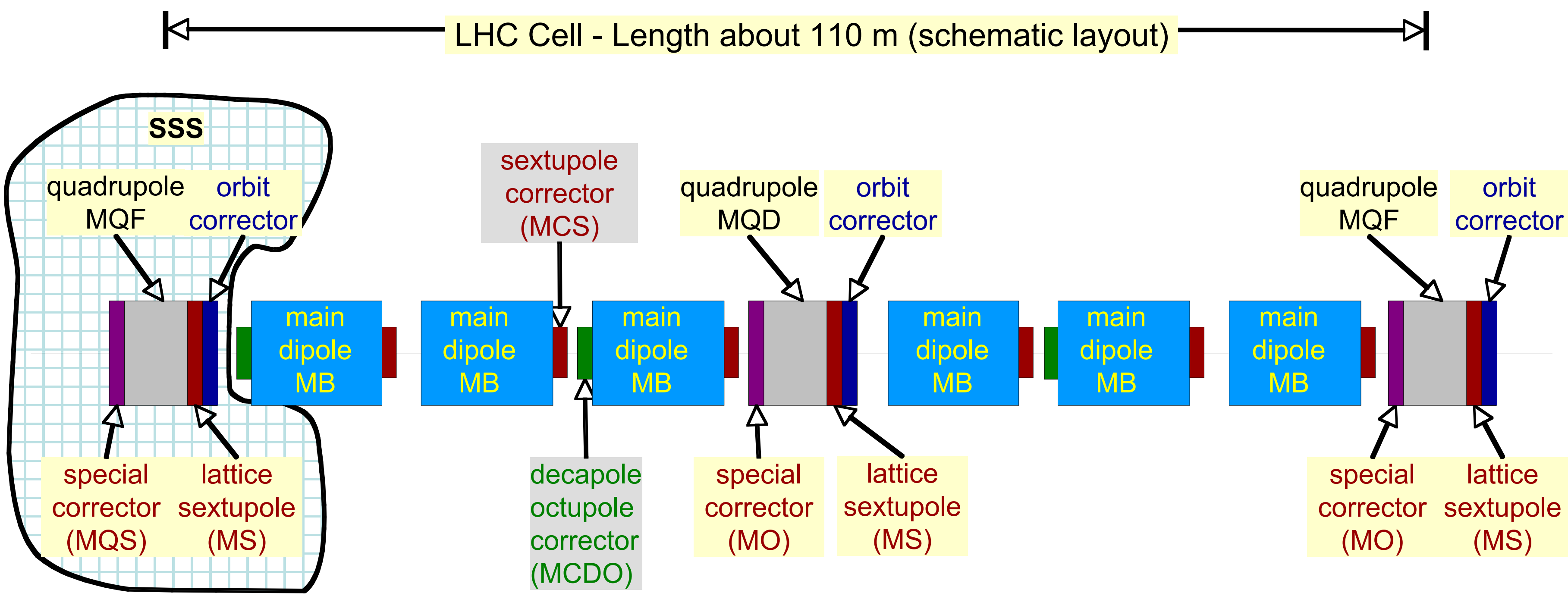
Example of FODO lattice



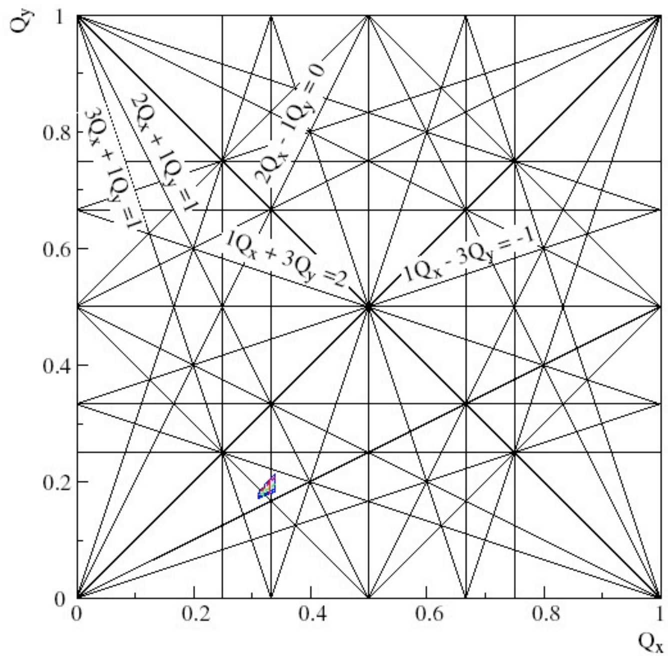
The beam point of view - Those are sextupoles - Six poles

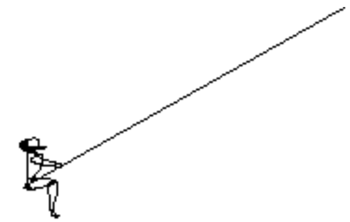


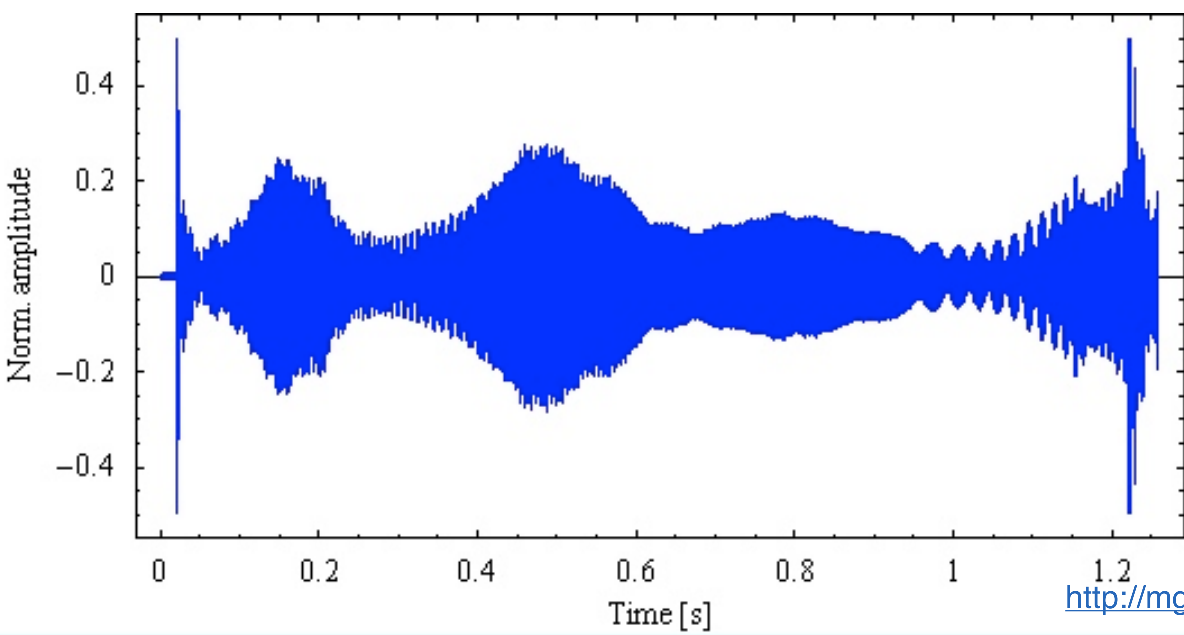
Diamond light source - UK

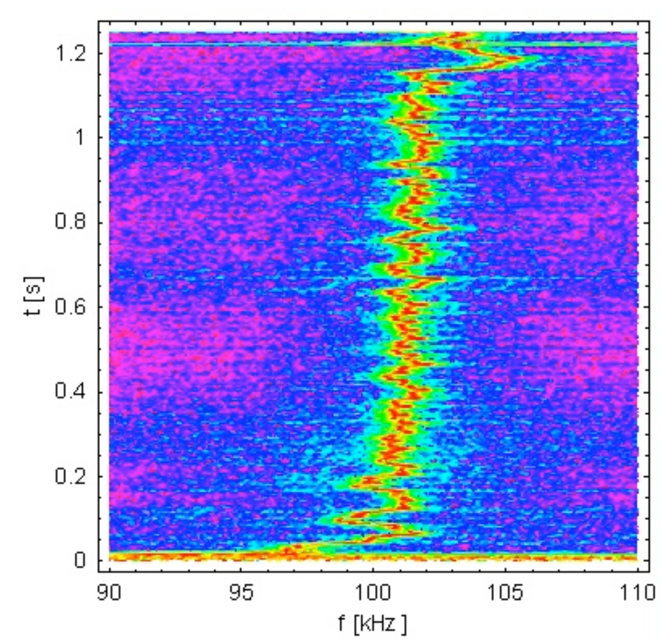


Tune: number of betatron oscillation in the transverse plane



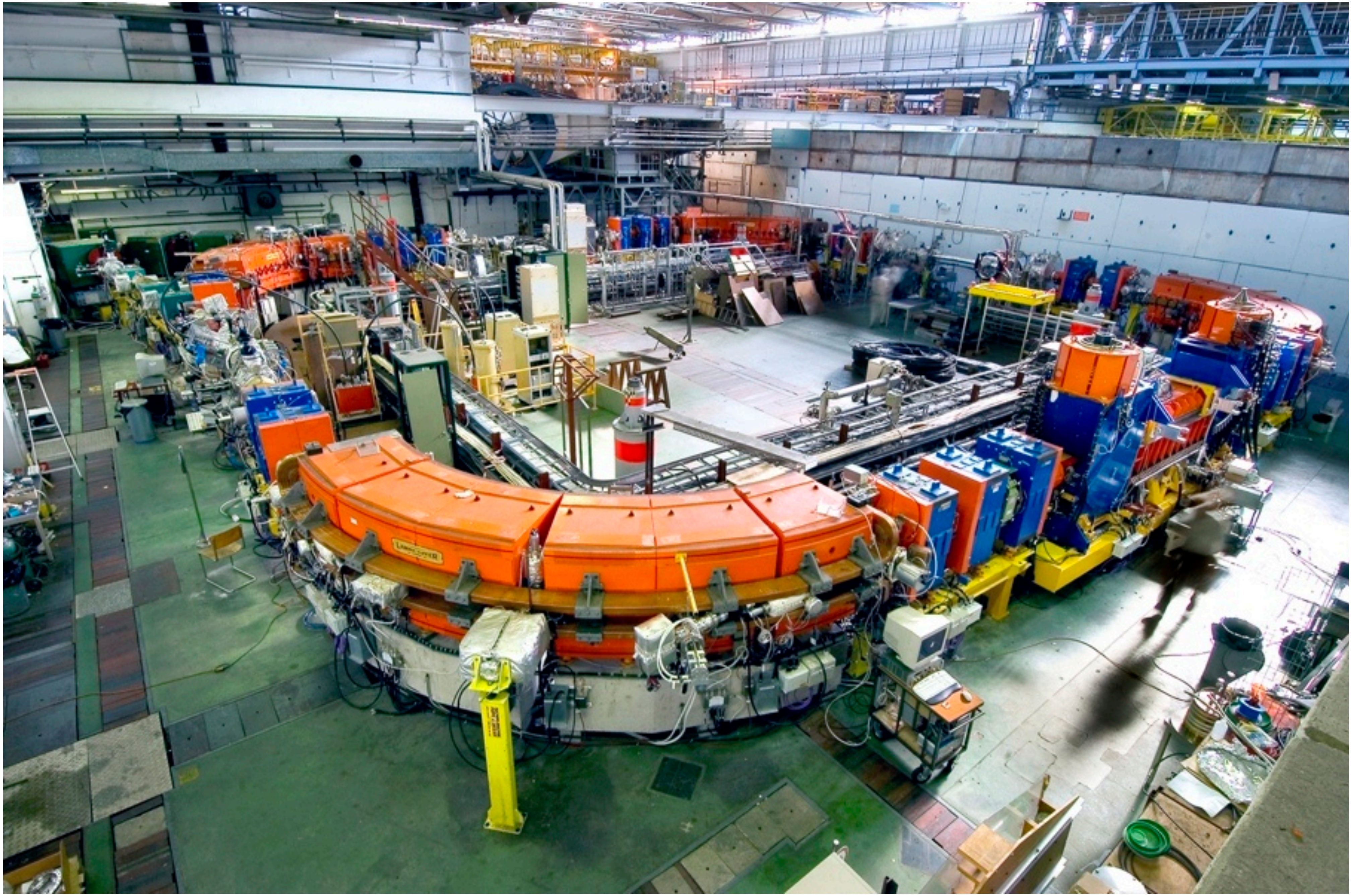




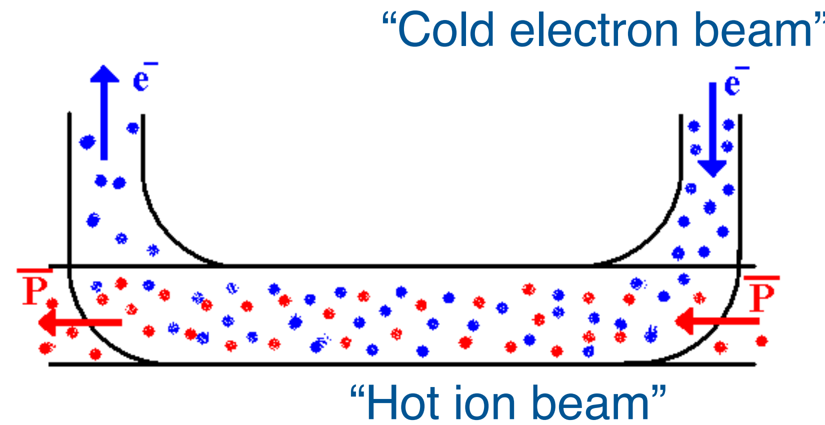


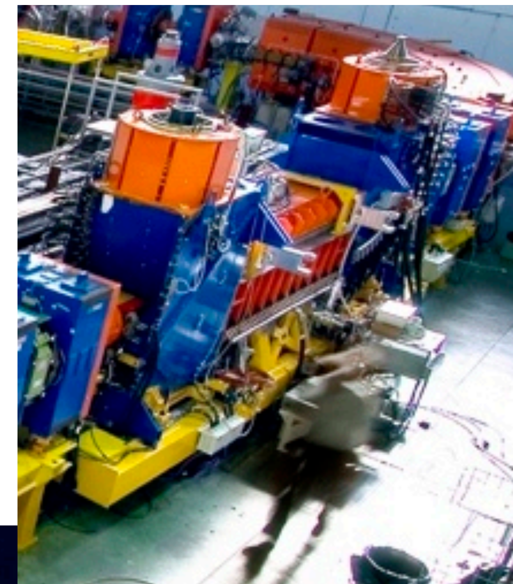
http://mgasior.web.cern.ch/mgasior/pro/3D-BBQ/ps.html

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

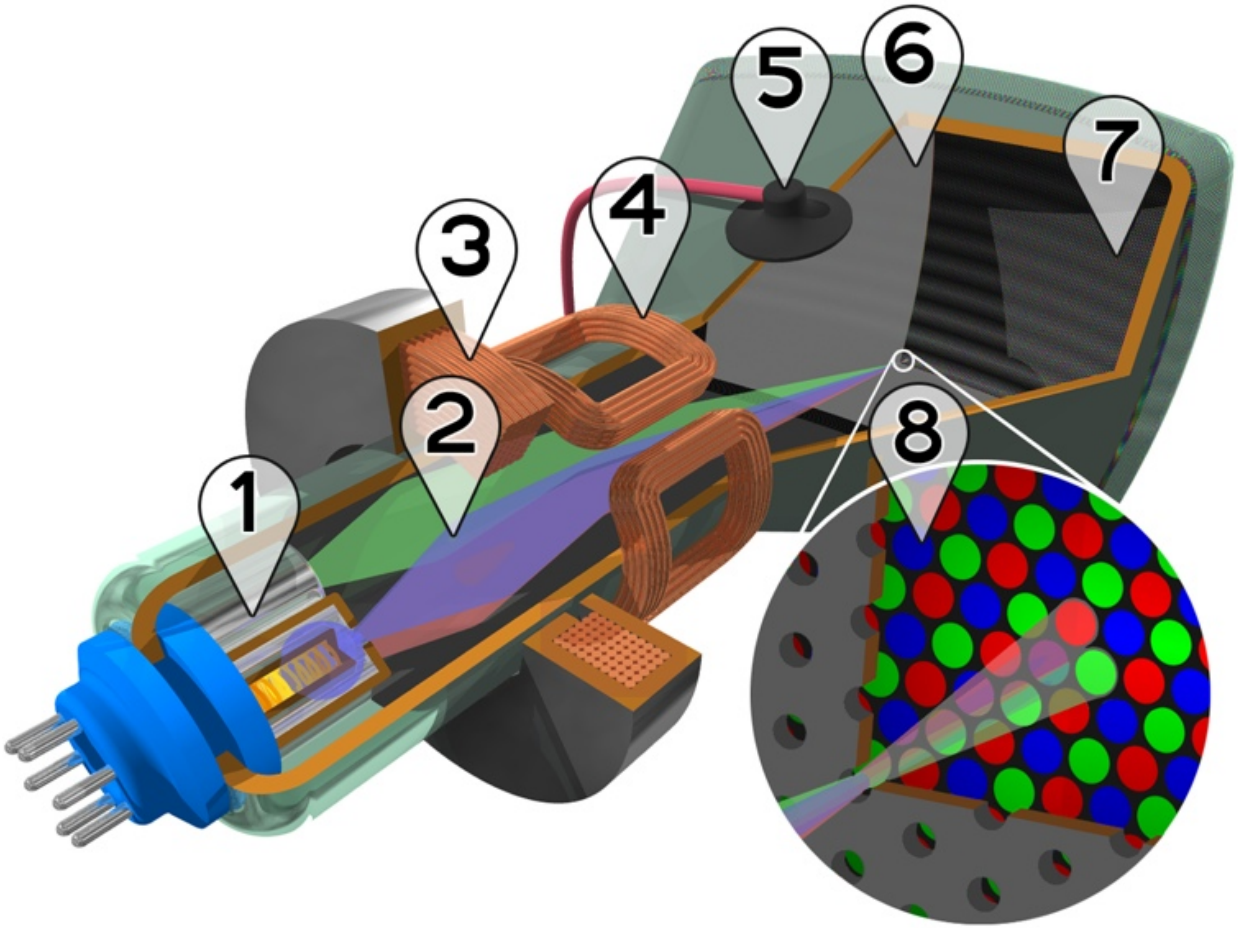


Electron cooling





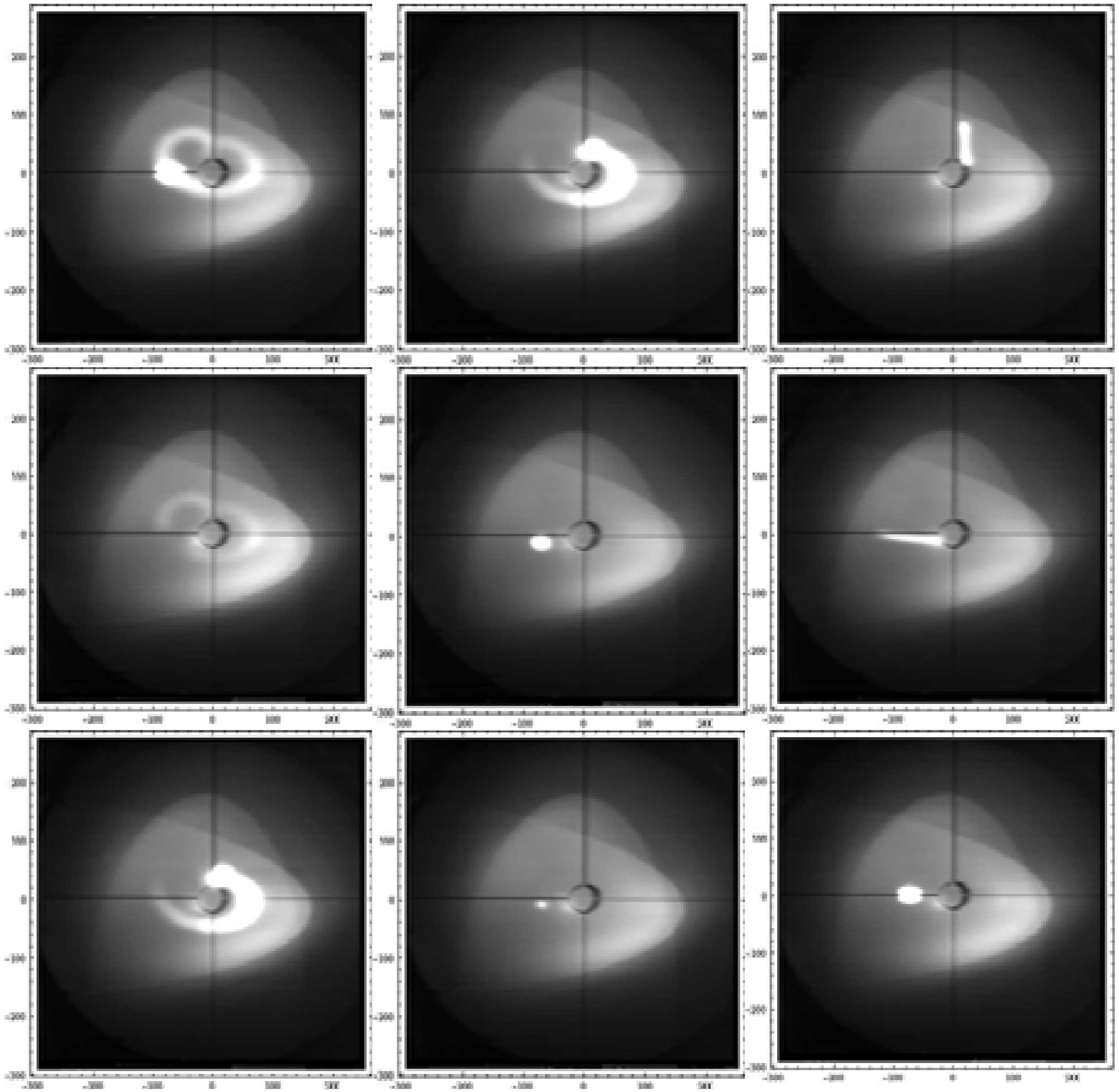
Summary: an accelerator that you know very well

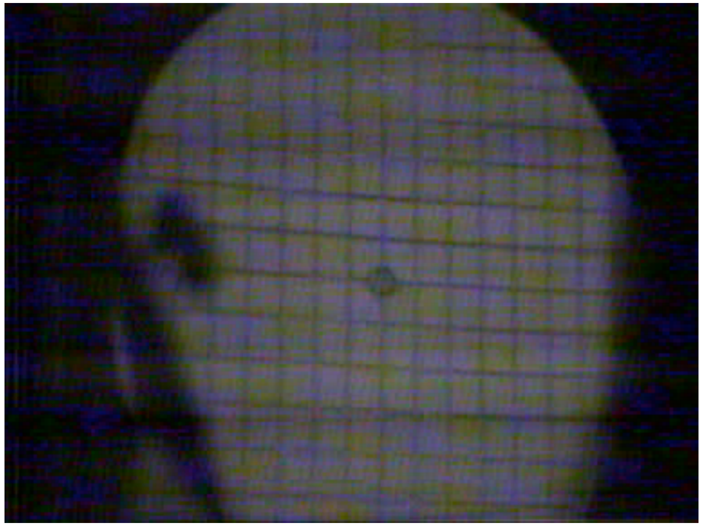


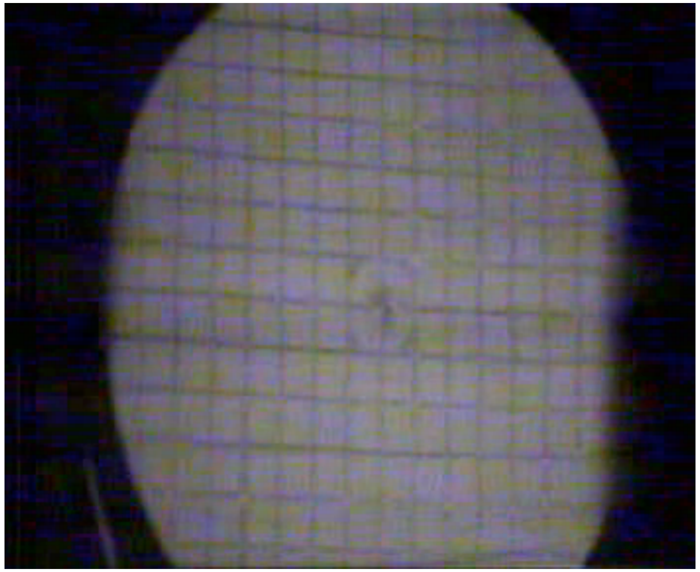
1. **Three Electron guns** (for red, green, and blue phosphor dots)
2. **Electron beams**
3. **Focusing coils**
4. **Deflection coils**
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen

From Wikipedia

Real beam images



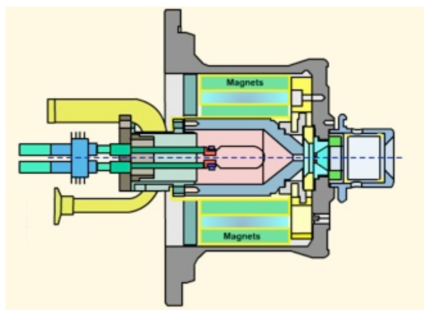




Courtesy of B. Goddard

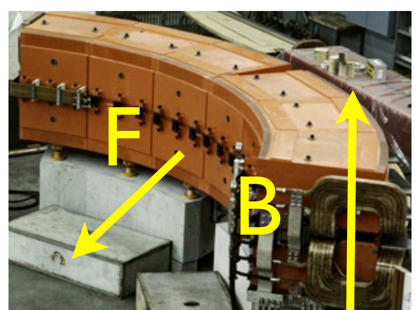
Summary: Building Blocks of an accelerator

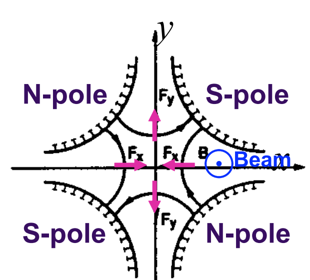
1) A particle source

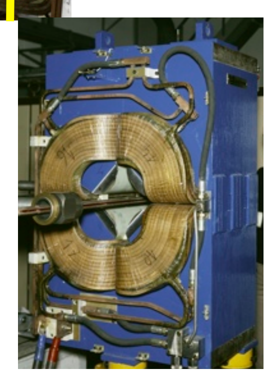


2) An accelerating system

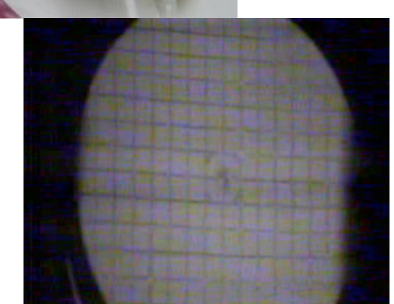
3) A series of guiding and focusing devices







Everything under vacuum



Apples vs Antiapples: protons vs antiprotons

Do protons fall in an accelerator?

And what about antiprotons?

Summary: Building Blocks of an accelerator

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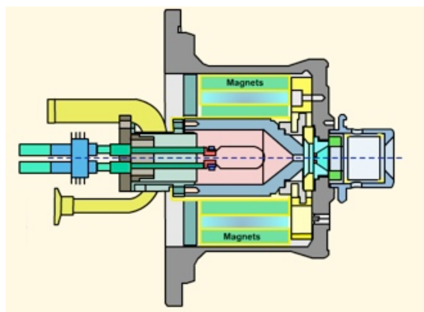

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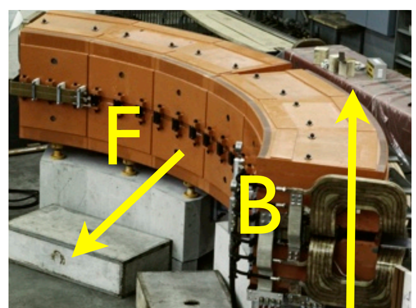

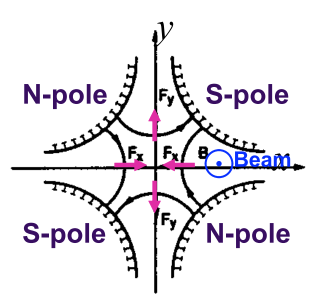

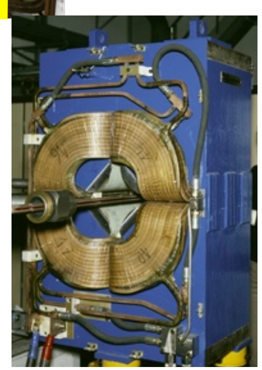

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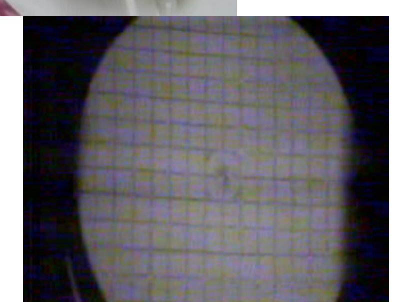
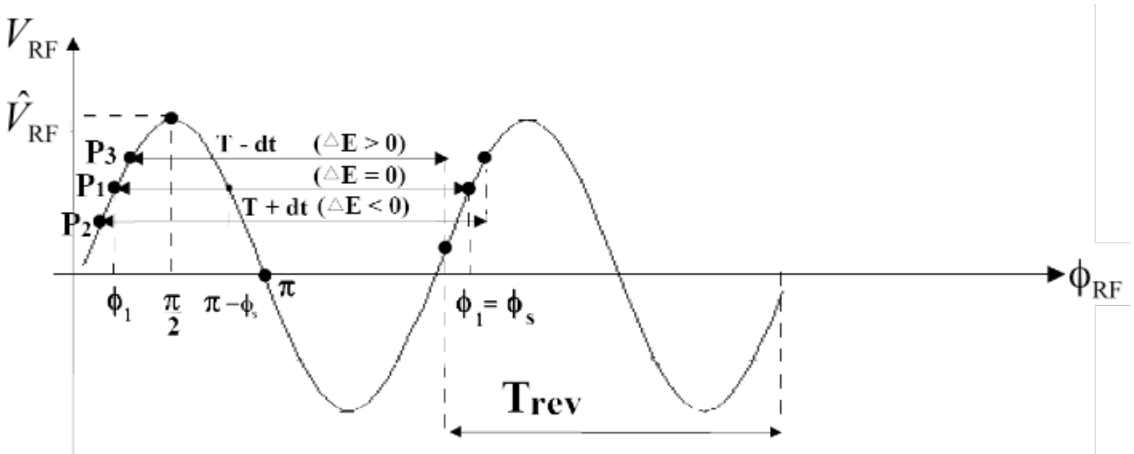
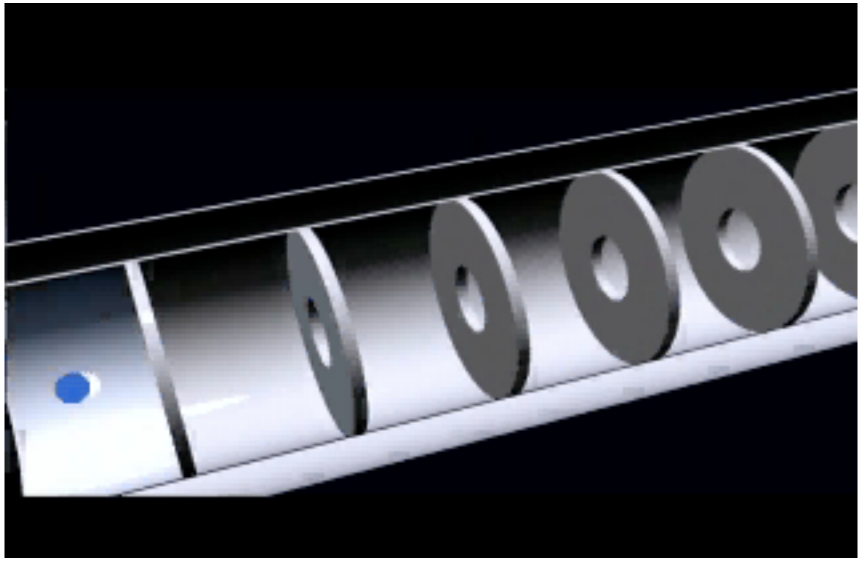


Acceleration

- Particles are accelerated by an **RF (radio frequency) electric field which is confined in cavities.**
- **The electric field varies in time as a sinus wave in such a way, that at each revolution, the particle comes back at the RF to see the acceleration.**

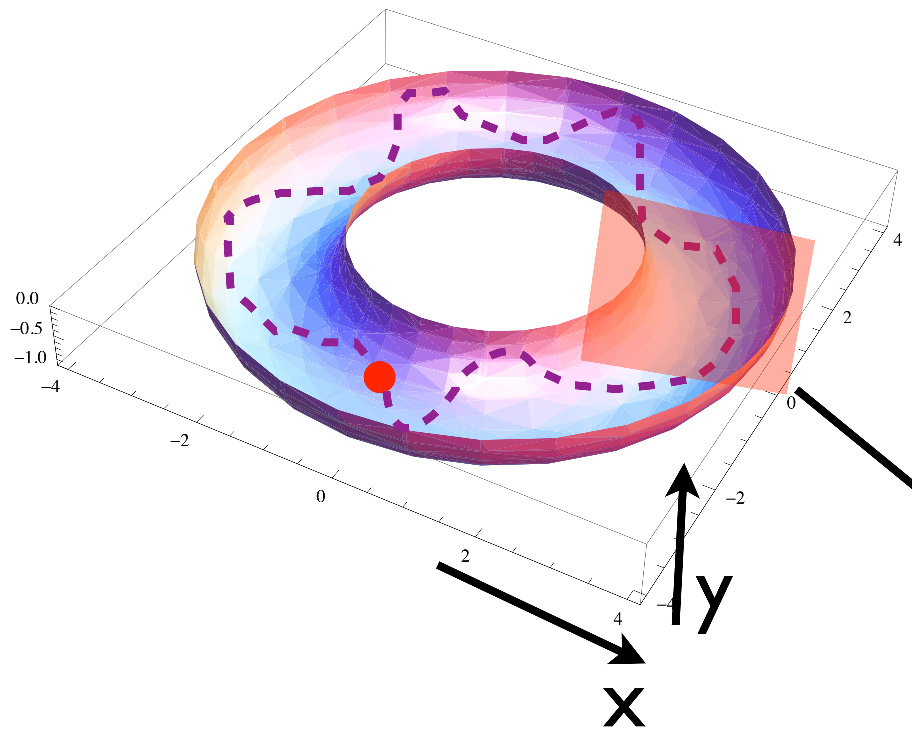
$$\Rightarrow \Delta E_1 = e\,\hat{V}_{RF}\,\sin\phi_1$$

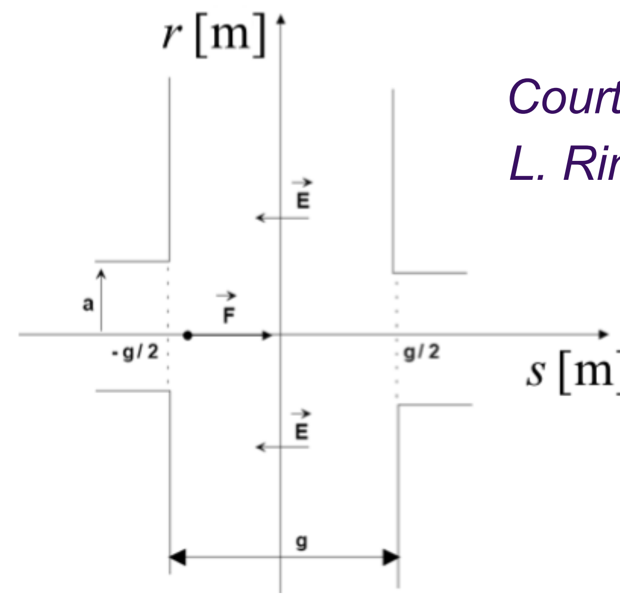




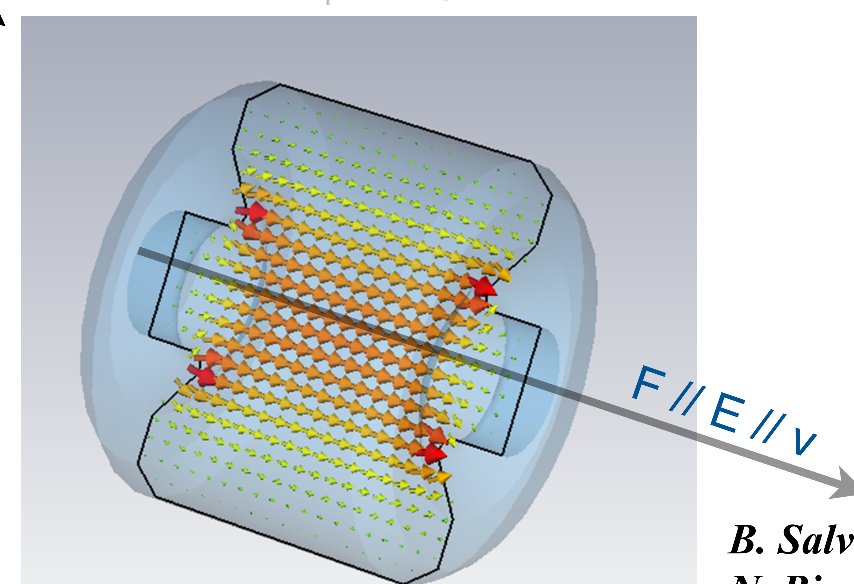
Acceleration I

Acceleration again with Lorentz force: $$\overline{F(t)} = q\left(\overline{E(t)} + \cancel{\overline{v(t)} \otimes \overline{B(t)}}\right)$$





Courtesy L. Rinolfi



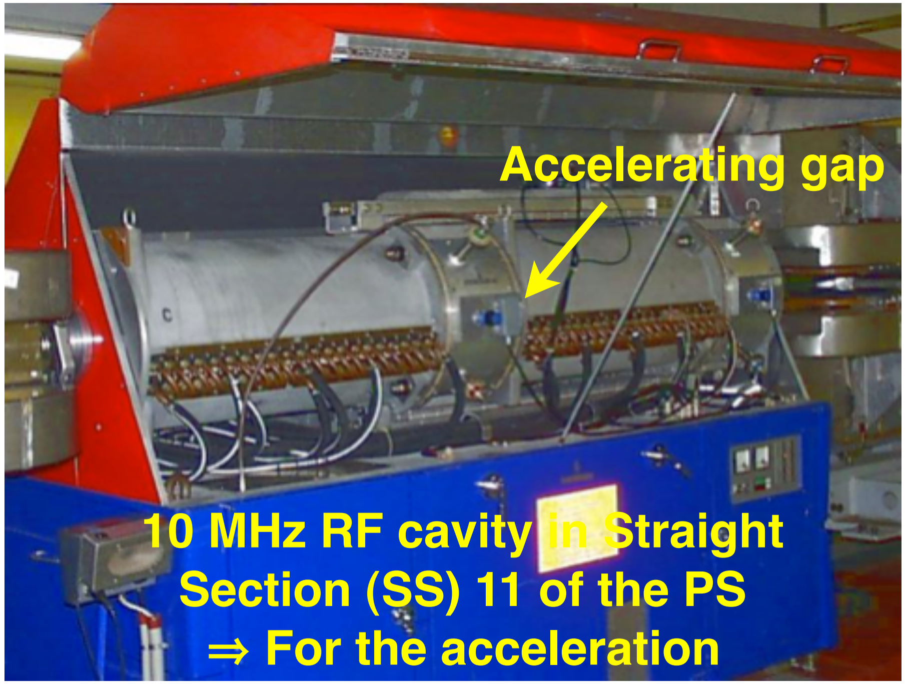
B. Salvant N. Biancacci

In a well defined part of the accelerator, **a RF (radio frequency) cavity generates an electric field parallel to the velocity of a zero divergence particle**. The cavity itself acts as a resonator.

Obs: The magnetic field associated to the RF wave is negligible (for us).

Example of RF cavities in the PS

The dimension of the cavity changes with the RF wave length



World Radio Switzerland: 88.4 MHz

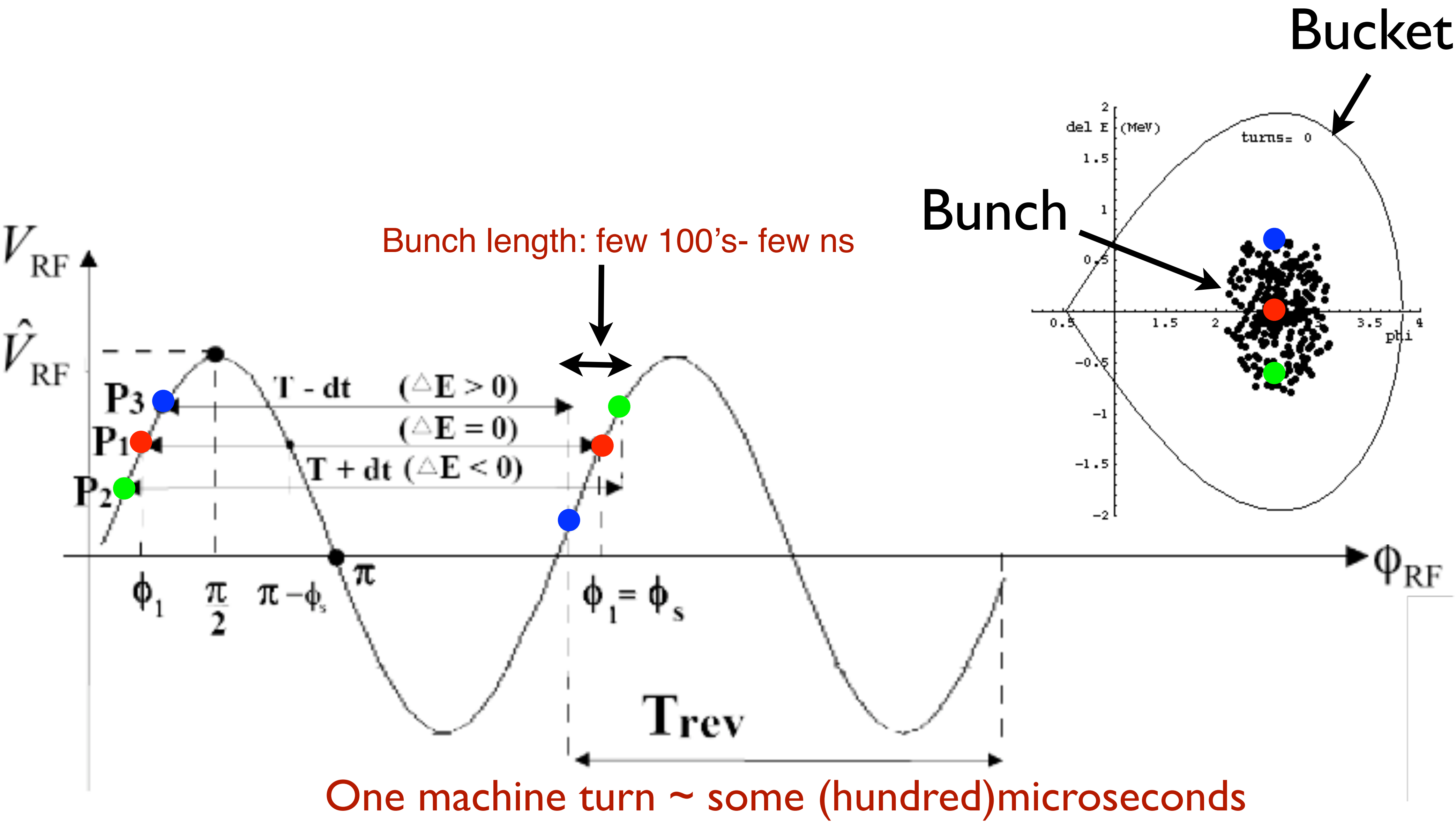
Some french radios (around Paris)

Fréquence	Radio
87,8 MHz	France inter
88,2 MHz	Générations
88,4 MHz	Marmite FM
88,4 MHz	Yvelines radio
88,6 MHz	Radio soleil
89,0 MHz	Radio France internationale
89,4 MHz	Radio libertaire
89,9 MHz	TSF Jazz
90,4 MHz	Nostalgie
90,9 MHz	Chante France
91,3 MHz	Chérie FM
91,7 MHz	France musique
92,1 MHz	Le Mouv'
92,4 MHz	France culture
92,5 MHz	Evasion FM

100,7 MHz	Fréquence protestante
100,7 MHz	Radio Notre Dame
101,1 MHz	Radio classique
101,5 MHz	Radio Nova
101,9 MHz	Fun radio
102,3 MHz	Ouï FM
102,7 MHz	MFM Radio
103,1 MHz	RMC
103,5 MHz	Virgin radio
103,9 MHz	RFM
104,3 MHz	RTL
104,7 MHz	Europe 1

Longitudinal focusing, a pendulum ...

- Particles are confined within a range in phase and energy called **BUCKET** and are grouped into **bunches by the electric field**.



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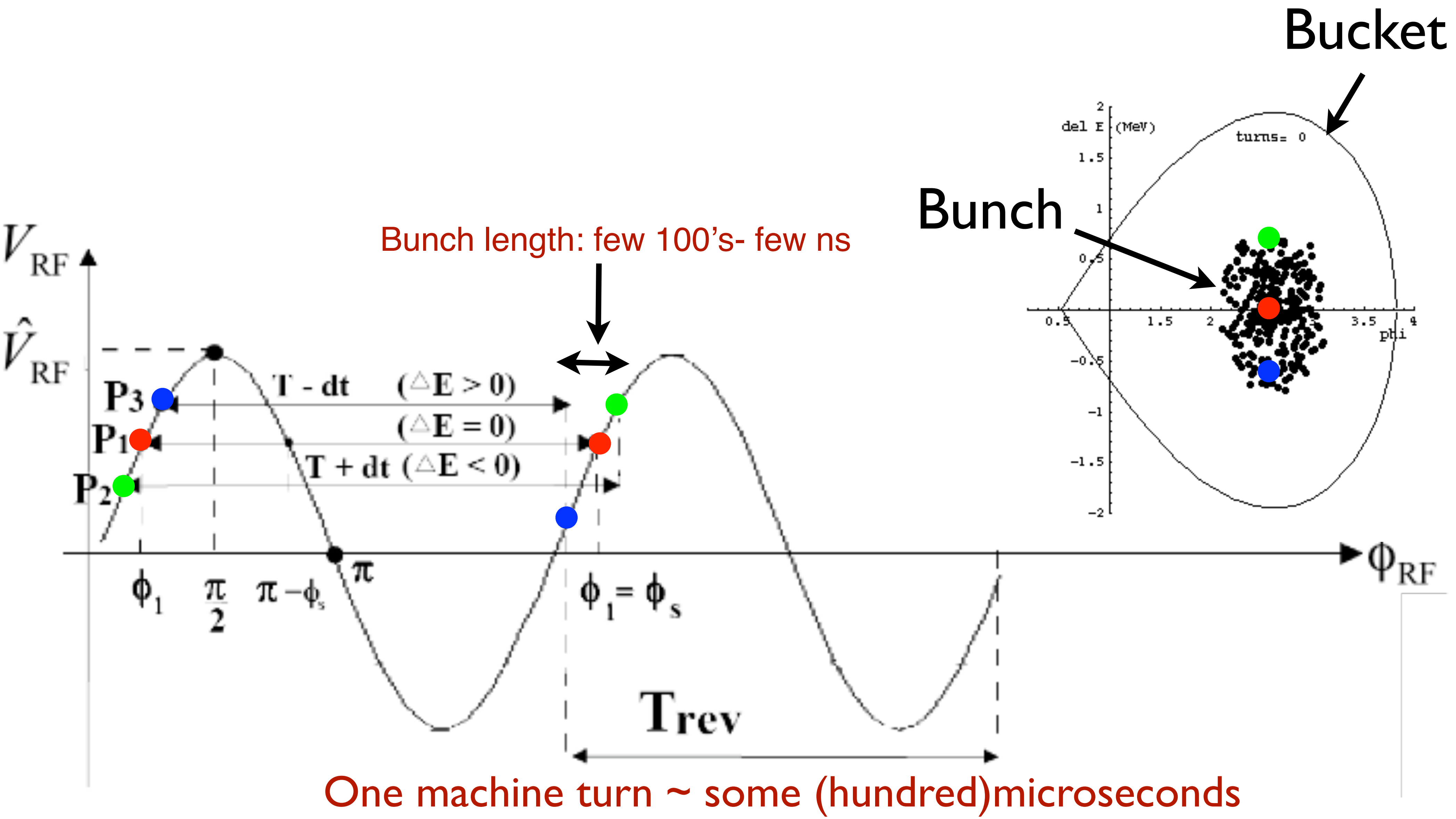
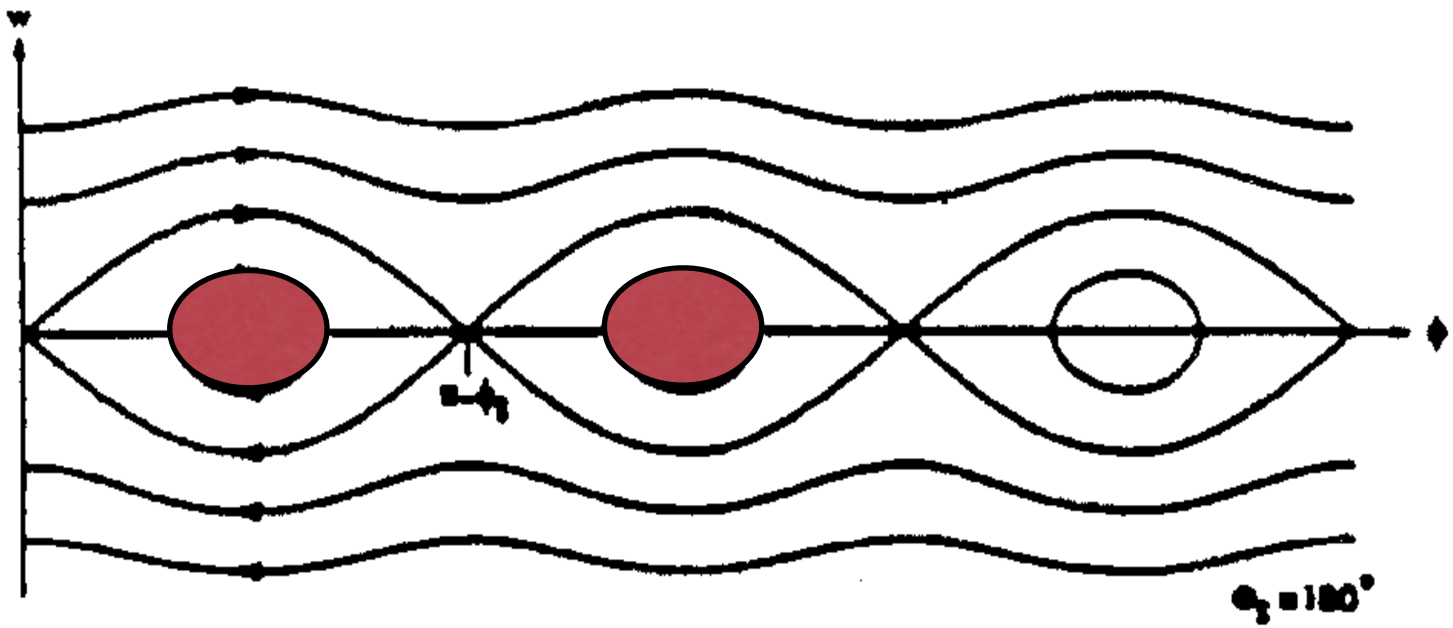


A chain of buckets



Courtesy
E. Wilson

Number of buckets:

possible positions along the machine circumference where ***there could be a bunch.***

In the example: 3 buckets and 2 bunches

[redacted]

What is the LHC ?

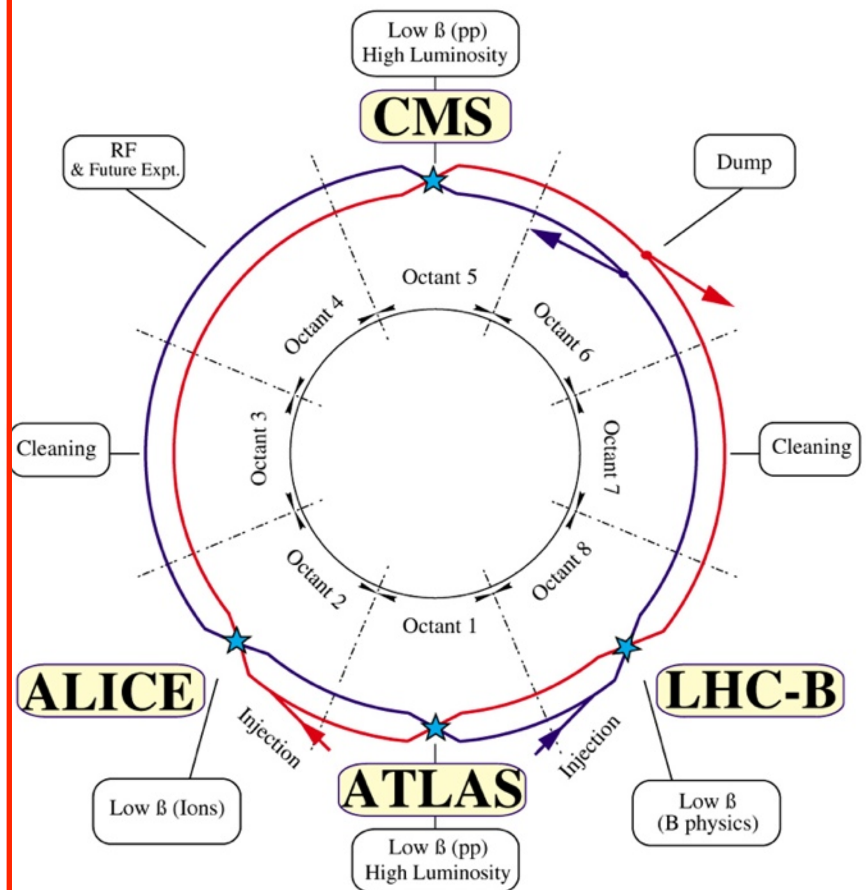
LHC: Large Hadron Collider

LHC *is a* ***collider*** *and* ***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 ⇒ a) synchrotron radiation
b) discovery machine.

Collider: particles are stored in two separated rings which are <u>synchrotrons</u>, 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 ...



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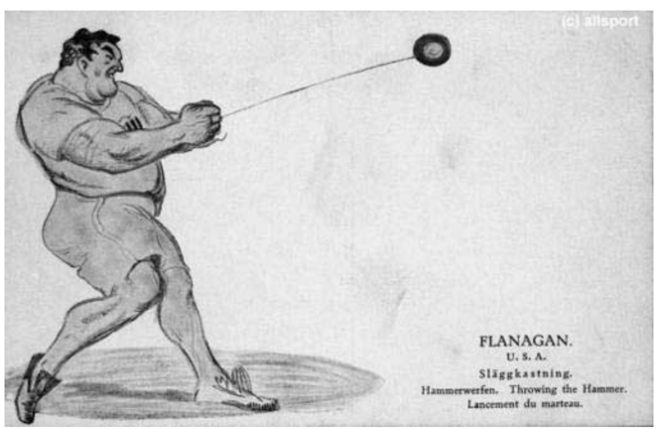
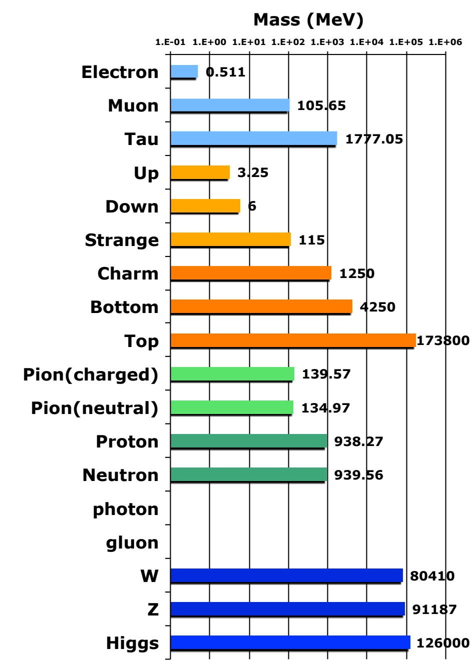
26.7 km circumference

Limited by technology



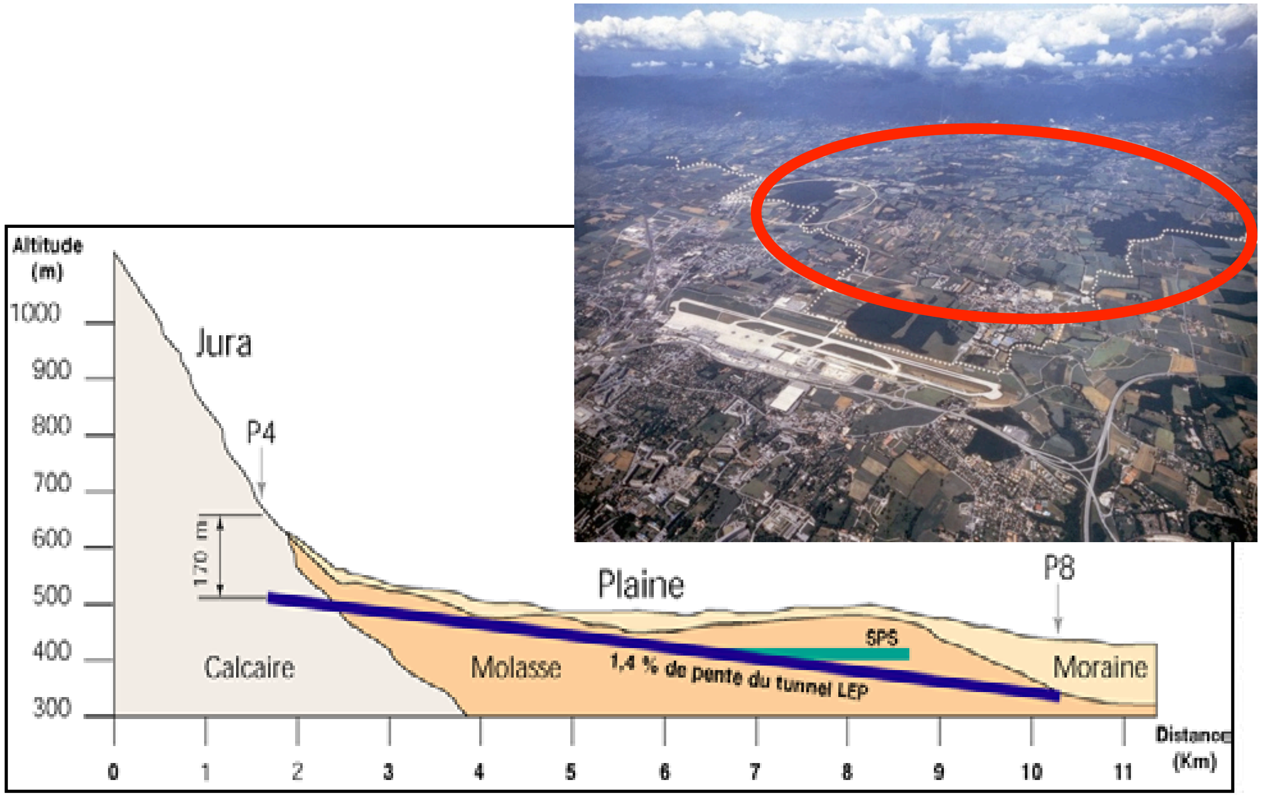
$$k = \frac{1}{\rho} = \frac{e}{p} B = \frac{e\mu_0}{p} \frac{nI}{h}$$



Radius: limited by cost,
and by the radius of the earth...

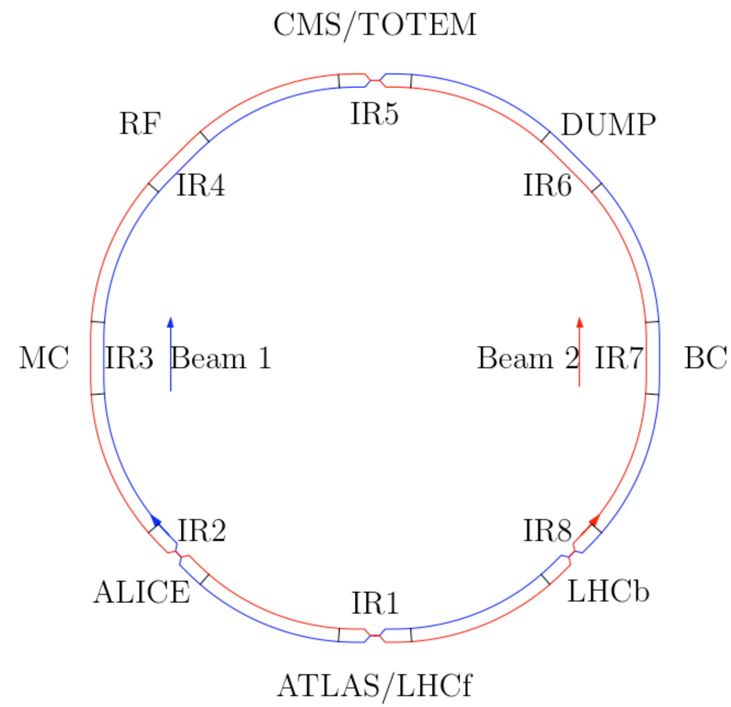
Given by the physics
This will depend on the mass of the particles we want to discover

LHC geometry: it is not flat... and it is not round



Tunnel build almost entirely on a geological layer called “Molasse”, easy to tunnel, but reach of water.

Slope is 1.4%



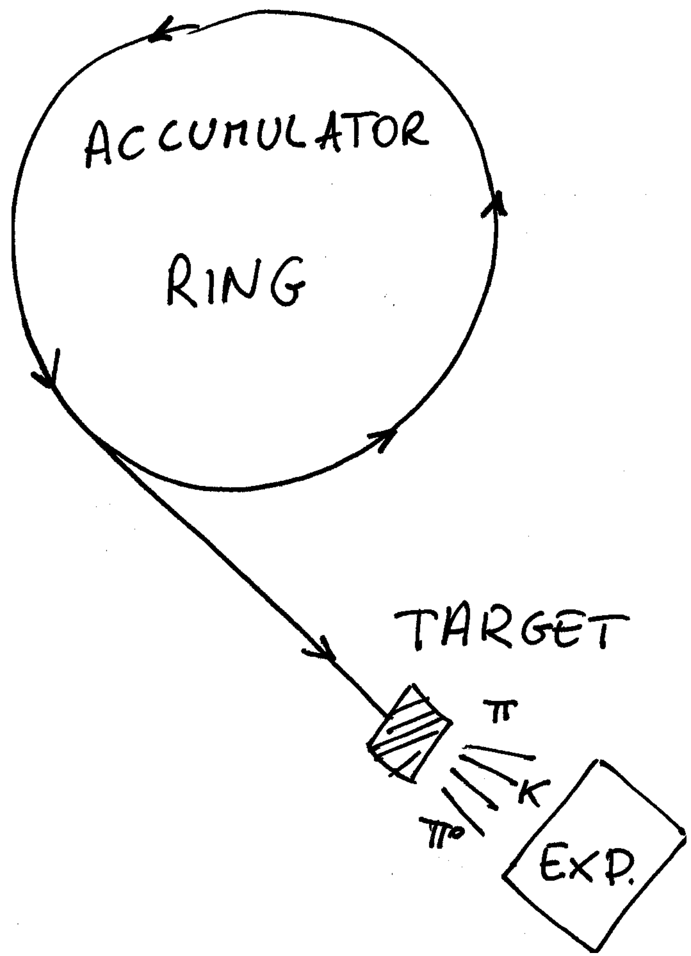
LHC: 8 independent sectors

8 straight sections

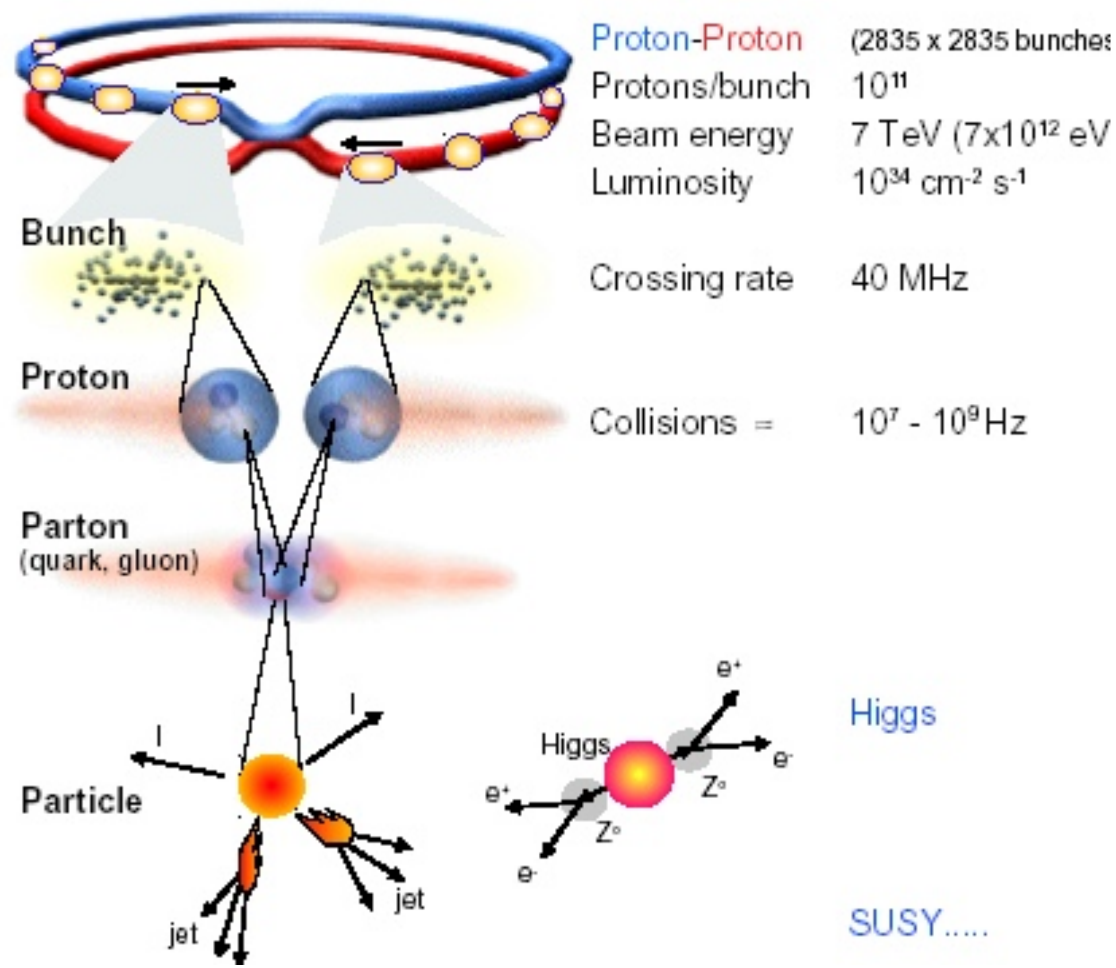
8 arcs

Different approaches: fixed target vs collider

Fixed target



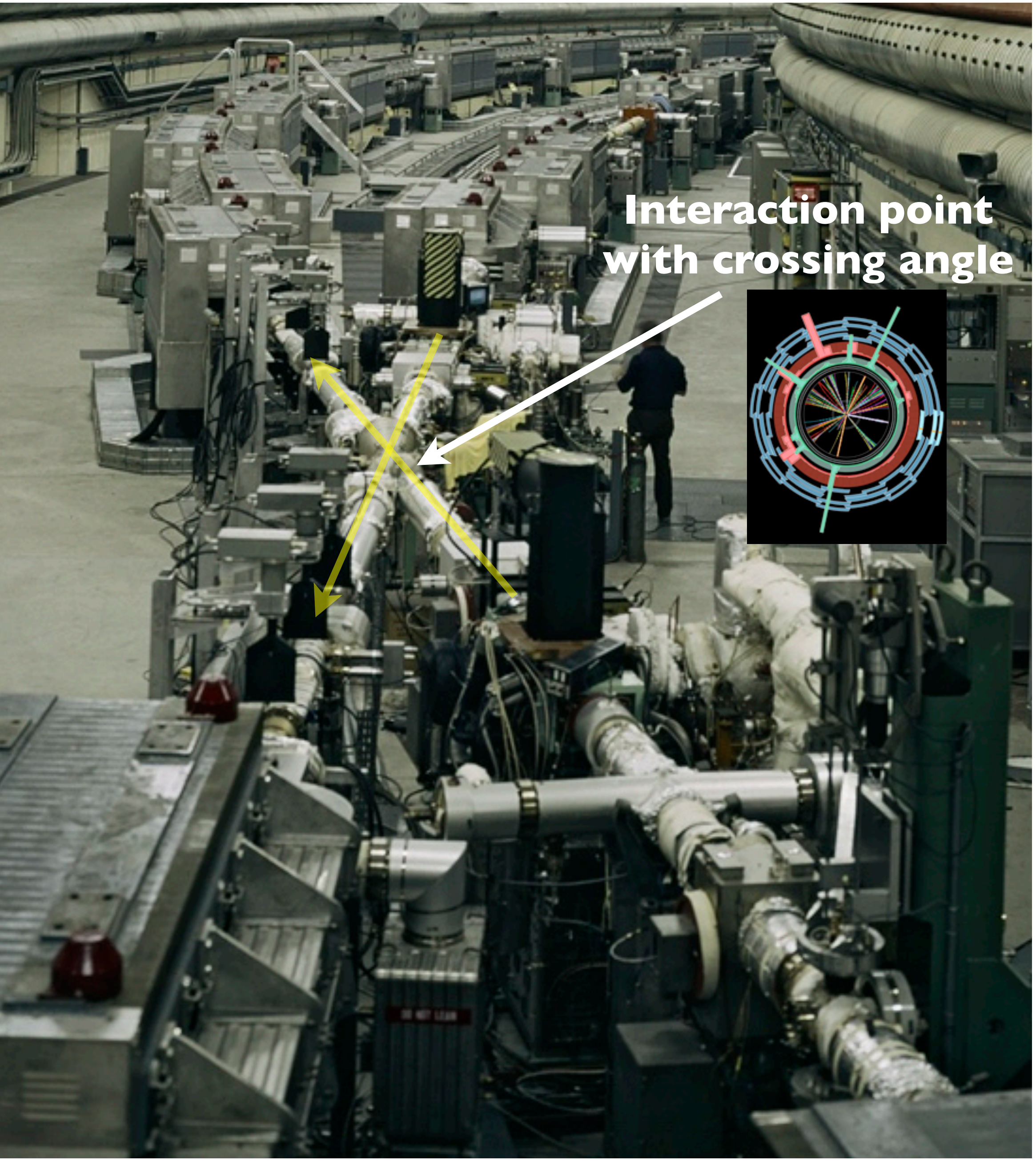
Storage ring/collider

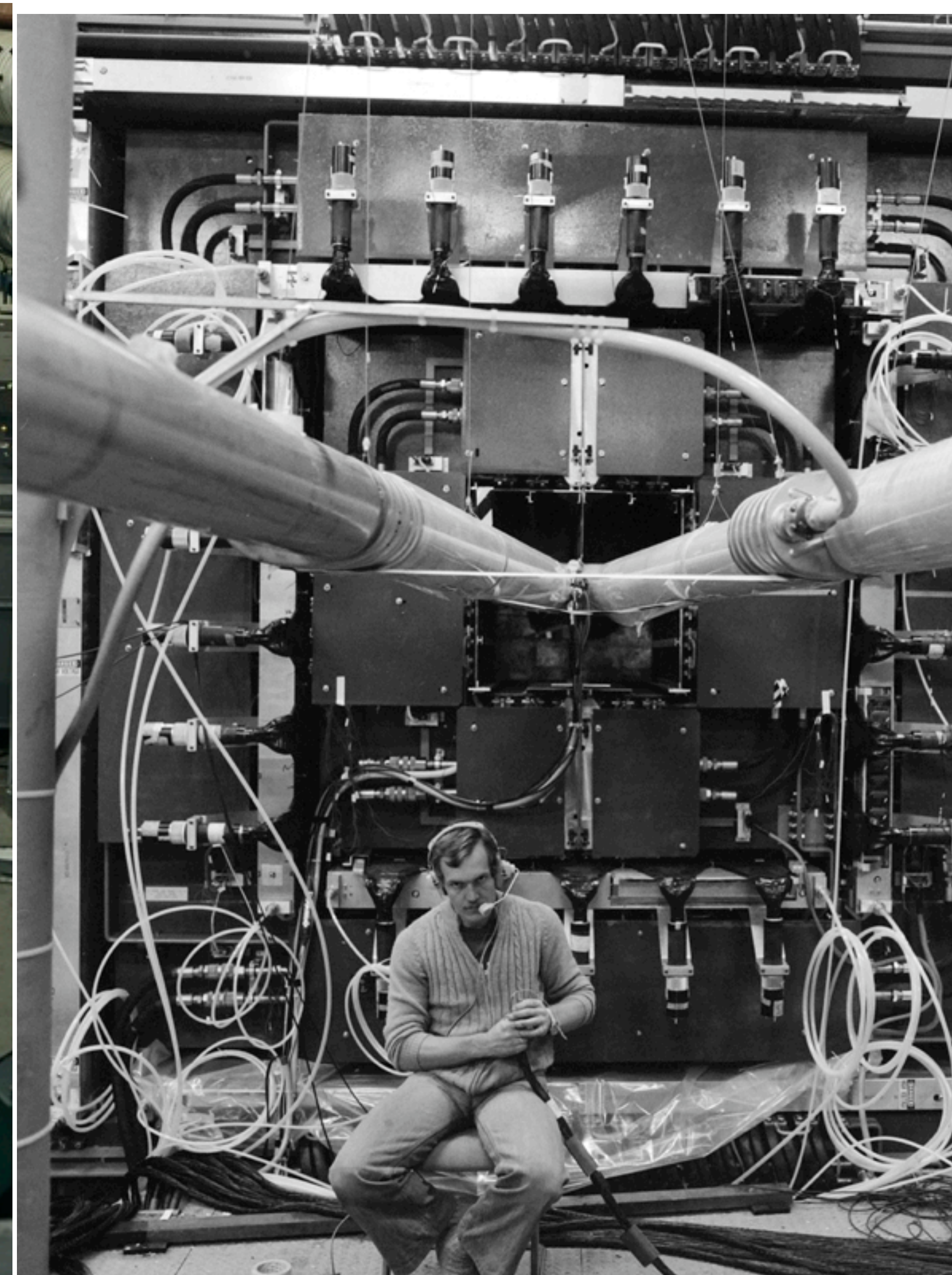


$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)}$$ << $$E_{CM} = 2\left(E_{beam} + mc^2\right)$$

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

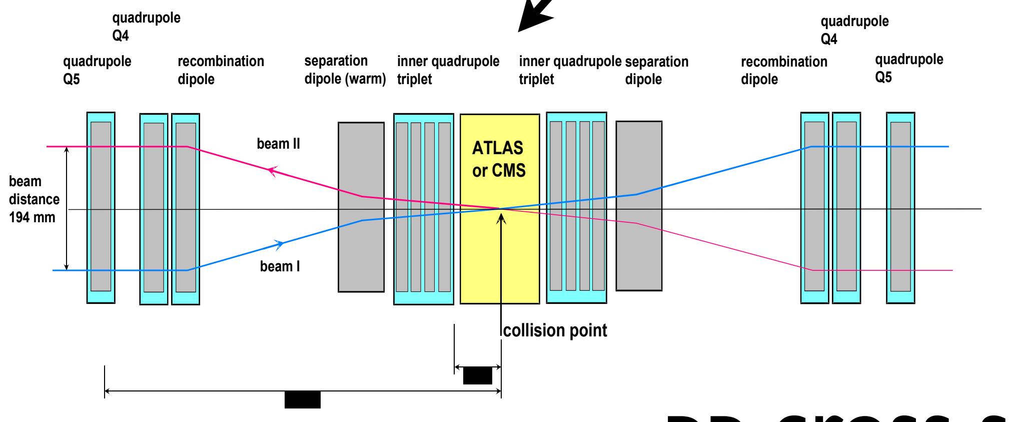
ISR: first proton-proton collider



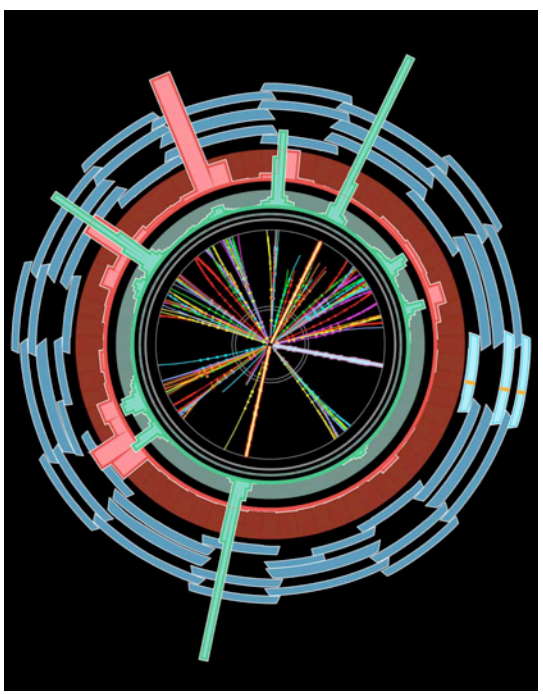


Luminosity

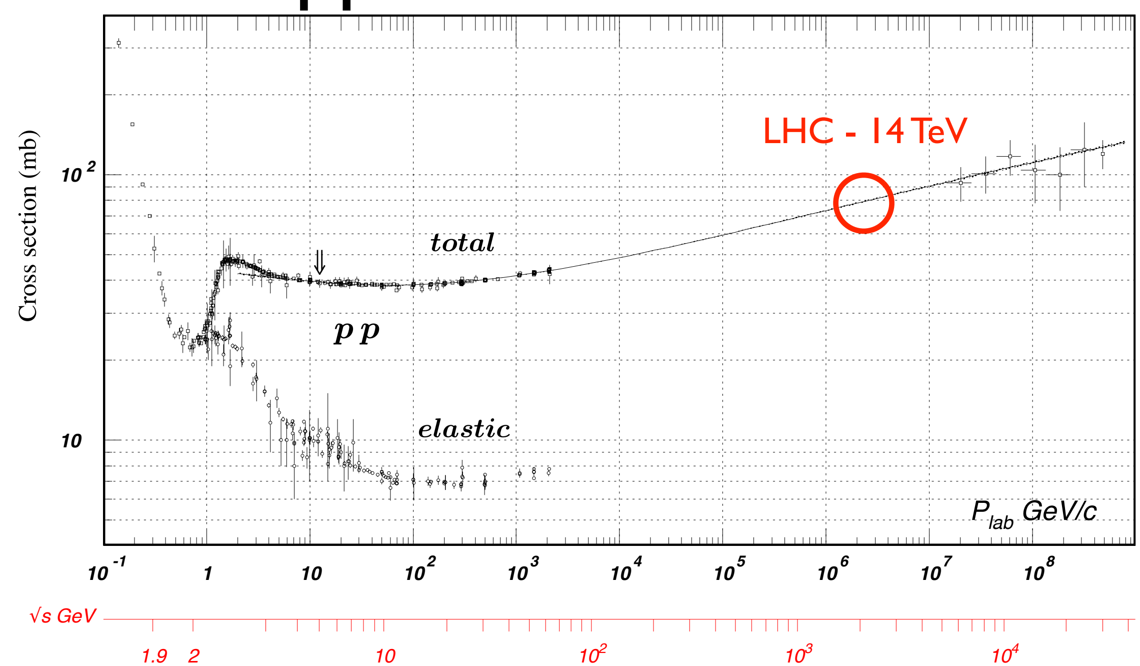
$$N_{event} = L\sigma_{event}$$



Example for an LHC insertion with ATLAS or CMS



pp cross section



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

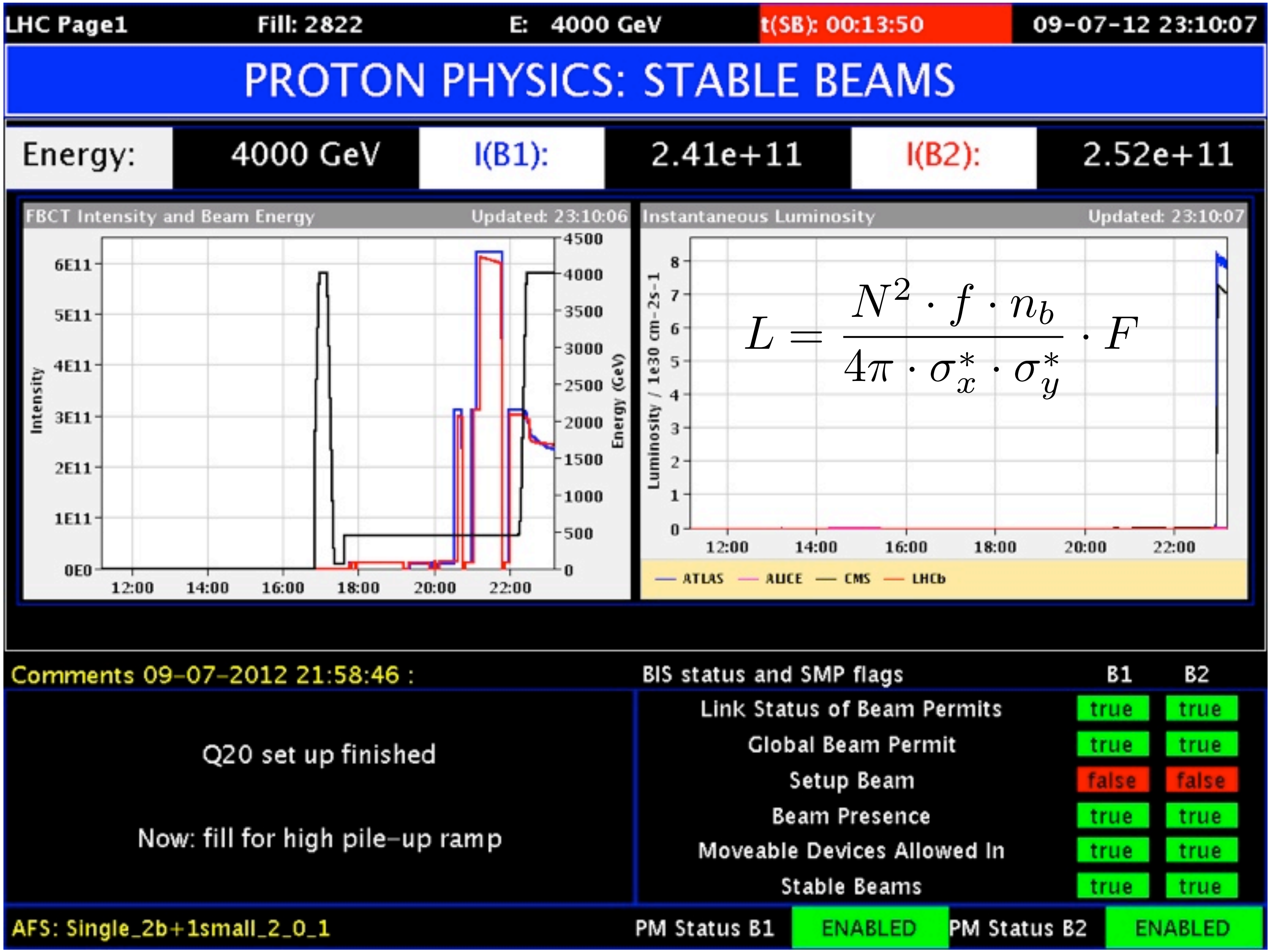
Beam dimension at the IP

$$\sigma_{x,y}^* = \sqrt{\beta_{x,y}^* \cdot \epsilon_{x,y}}$$

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

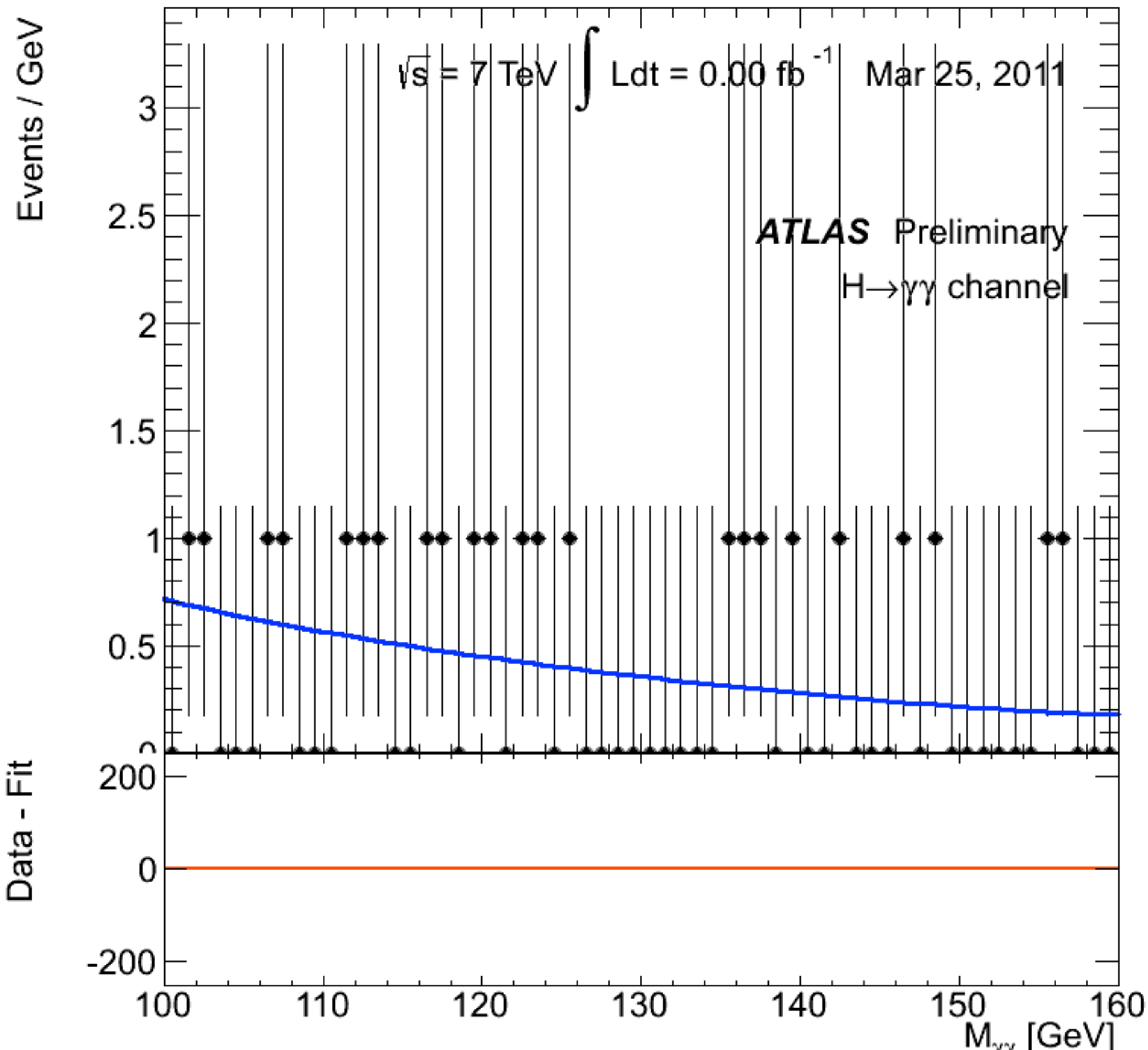
At first look, the smaller the better

LHC Operational page

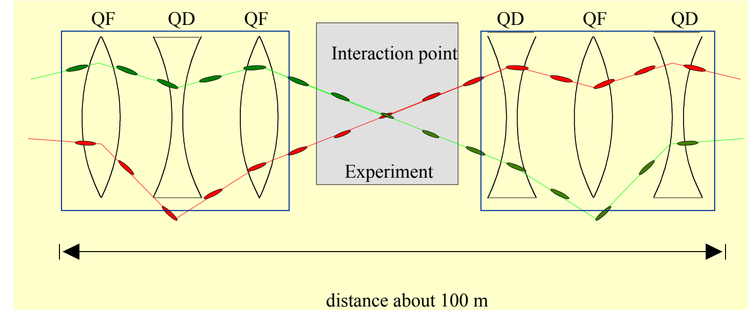


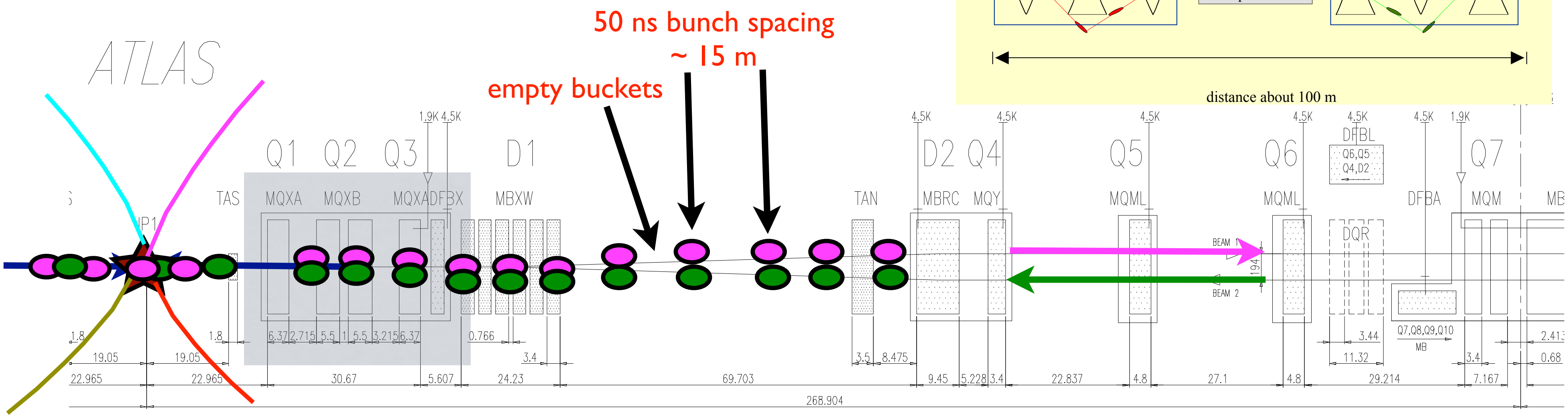
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

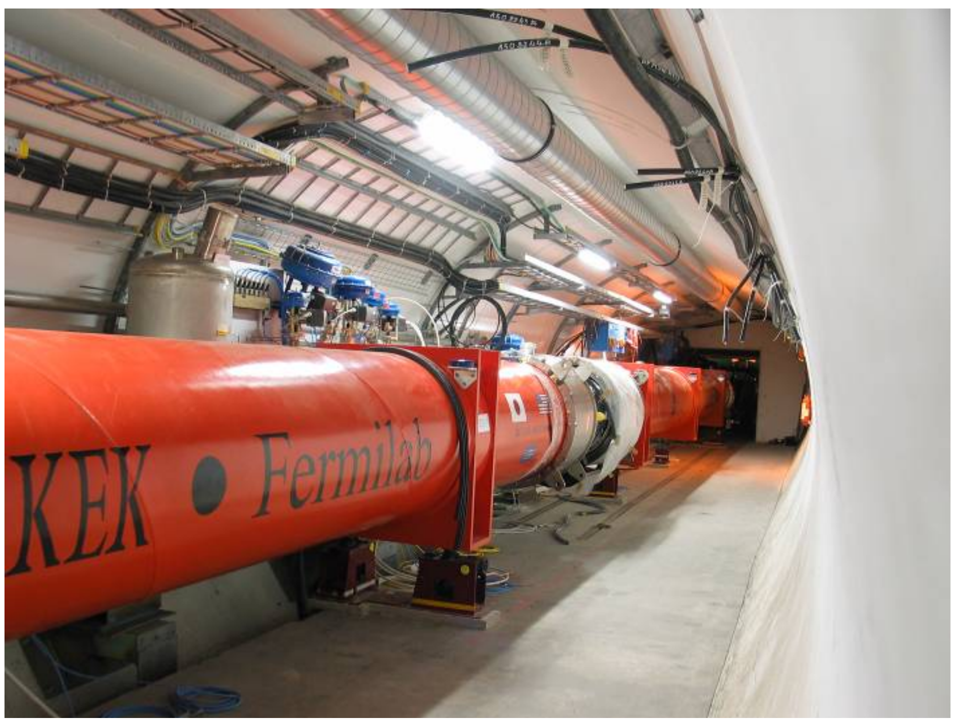
Where we are now ...



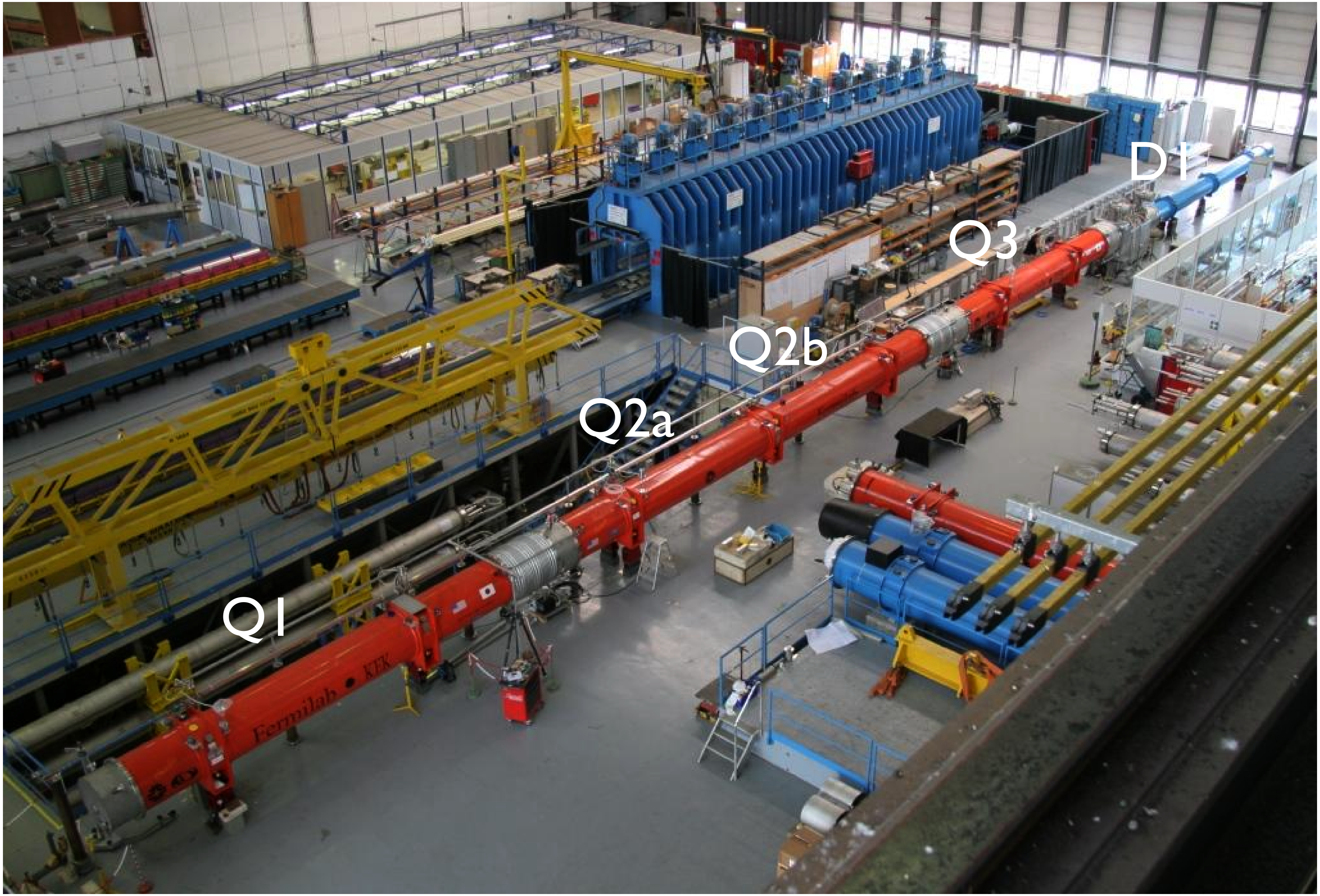
Inner triplet: final focusing
⇒ how to make the beam small at the IP



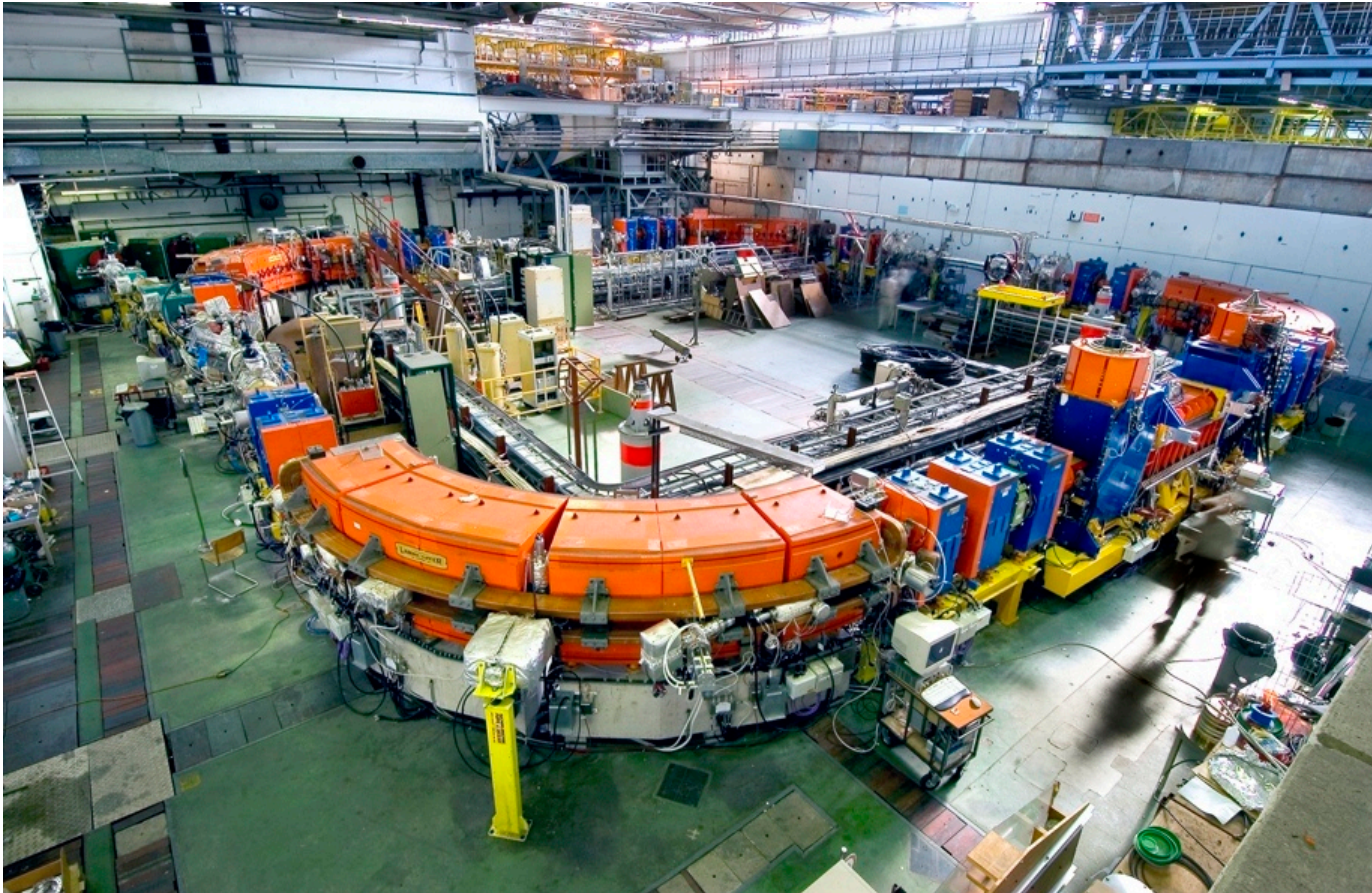




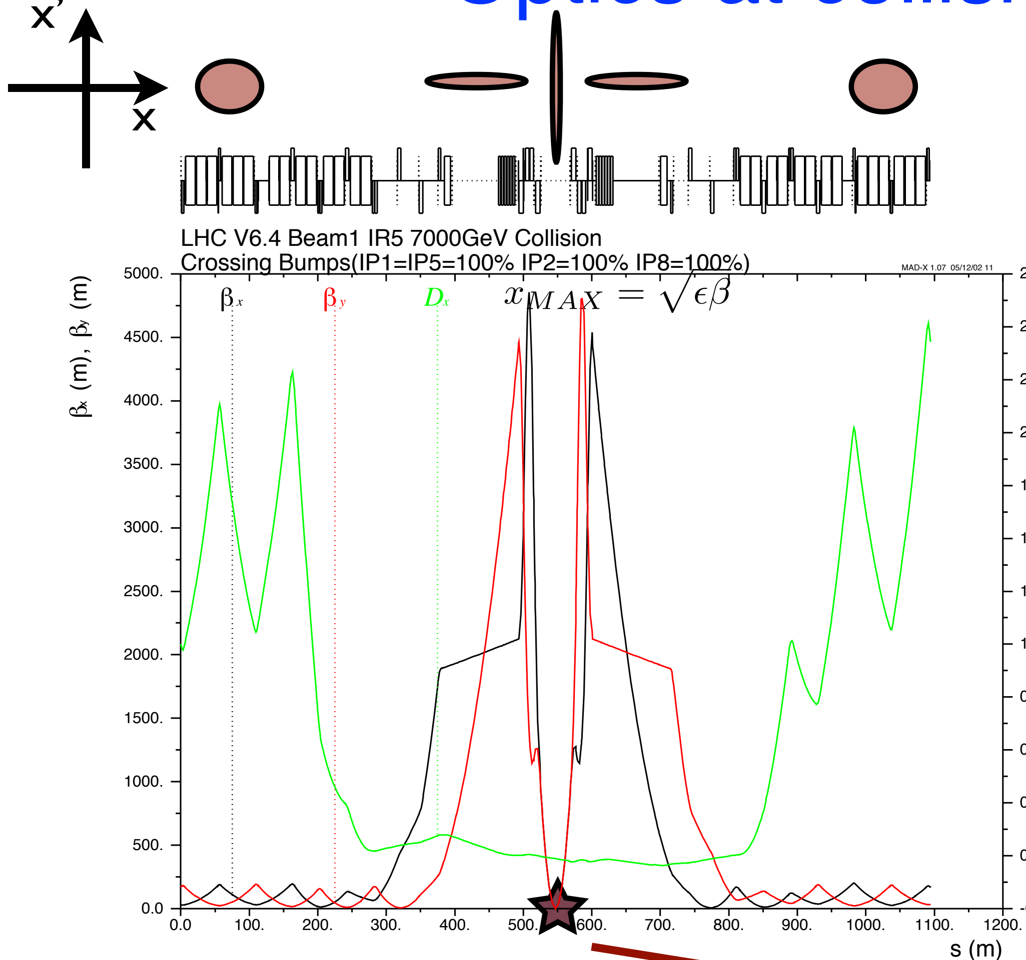
Triplets before lowering in the tunnel

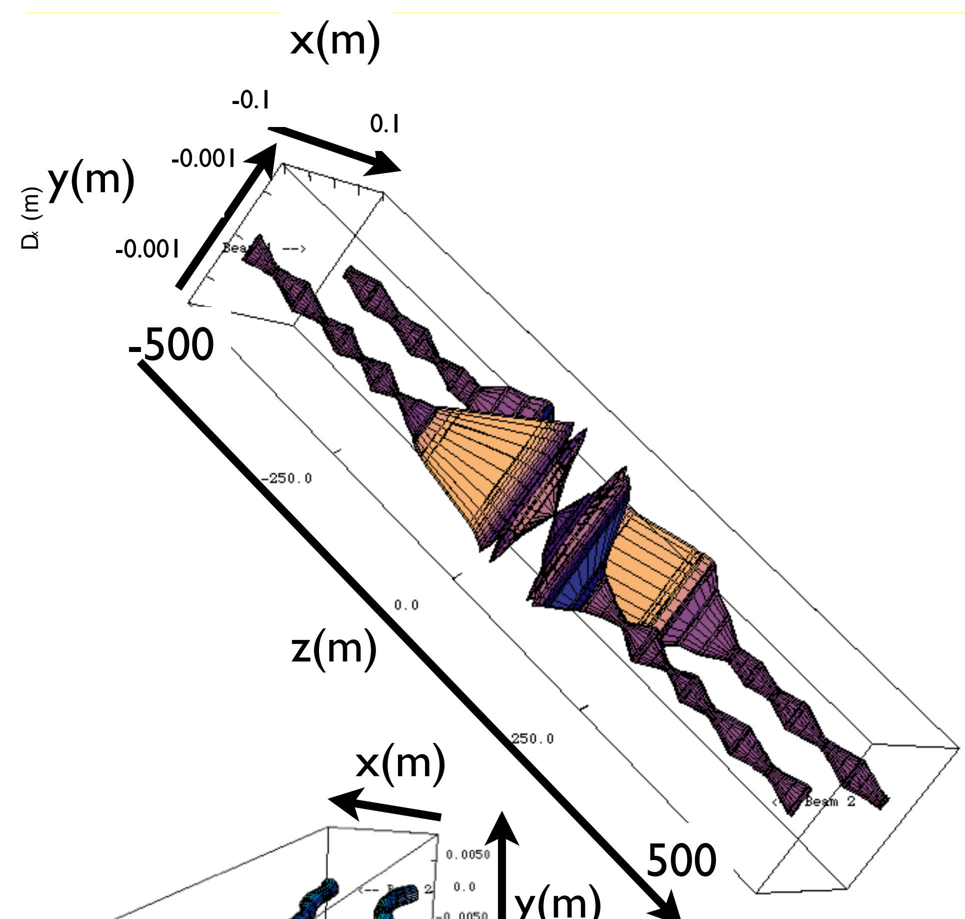


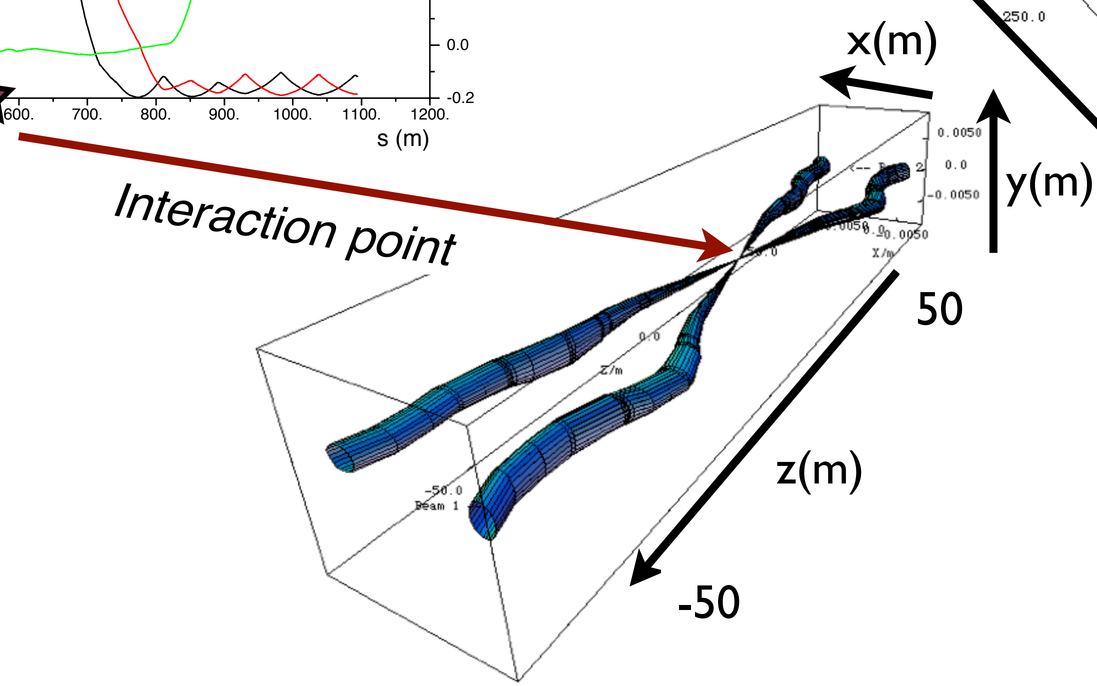
A synchrotron in a view: LEIR (Low Energy Ion Ring)



Optics at collision IP5- CMS

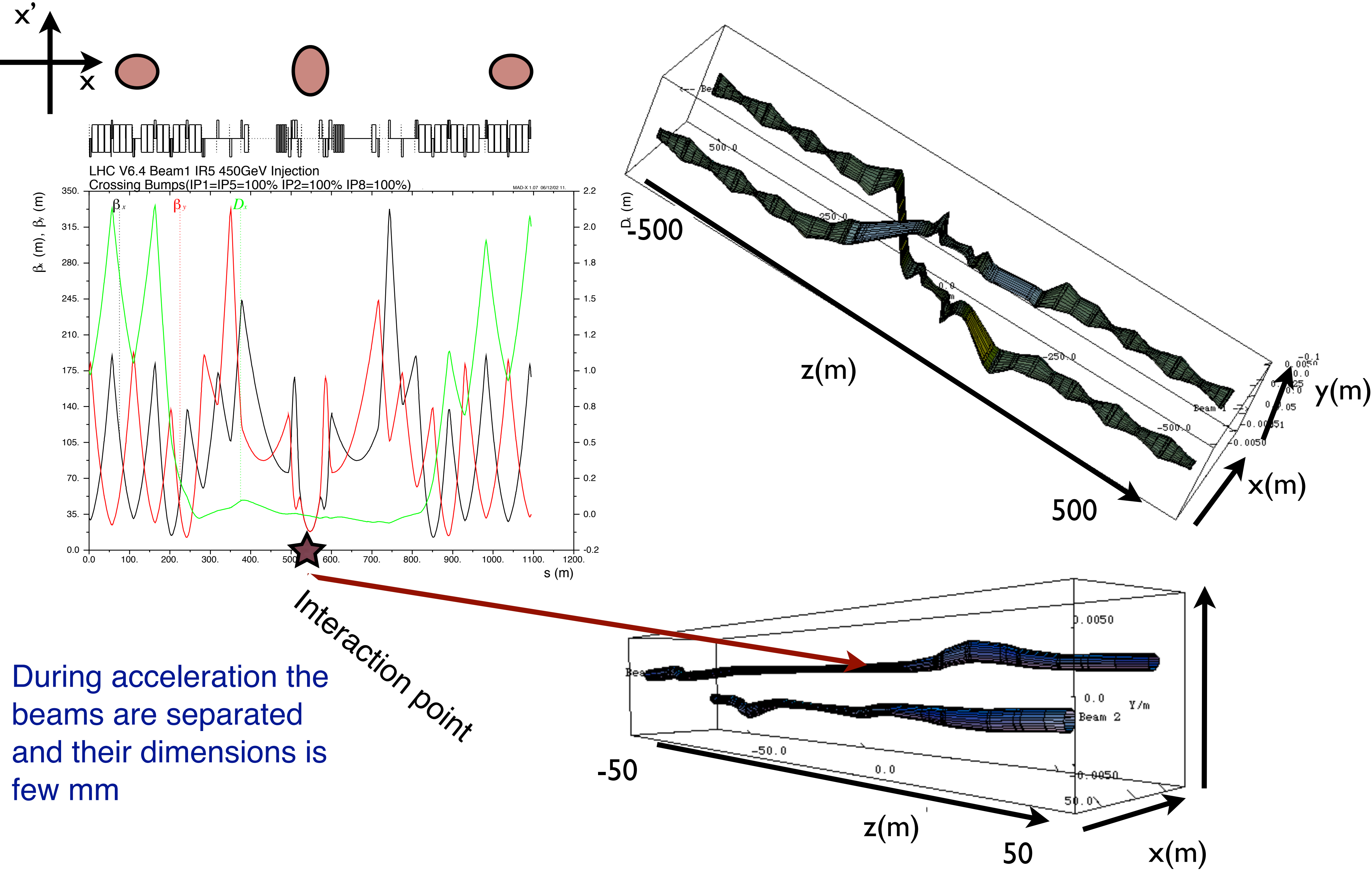






At collision the beams are "squeezed" down to few microns at the interaction point

Injection optics and during acceleration IP5- CMS



During acceleration the beams are separated and their dimensions is few mm

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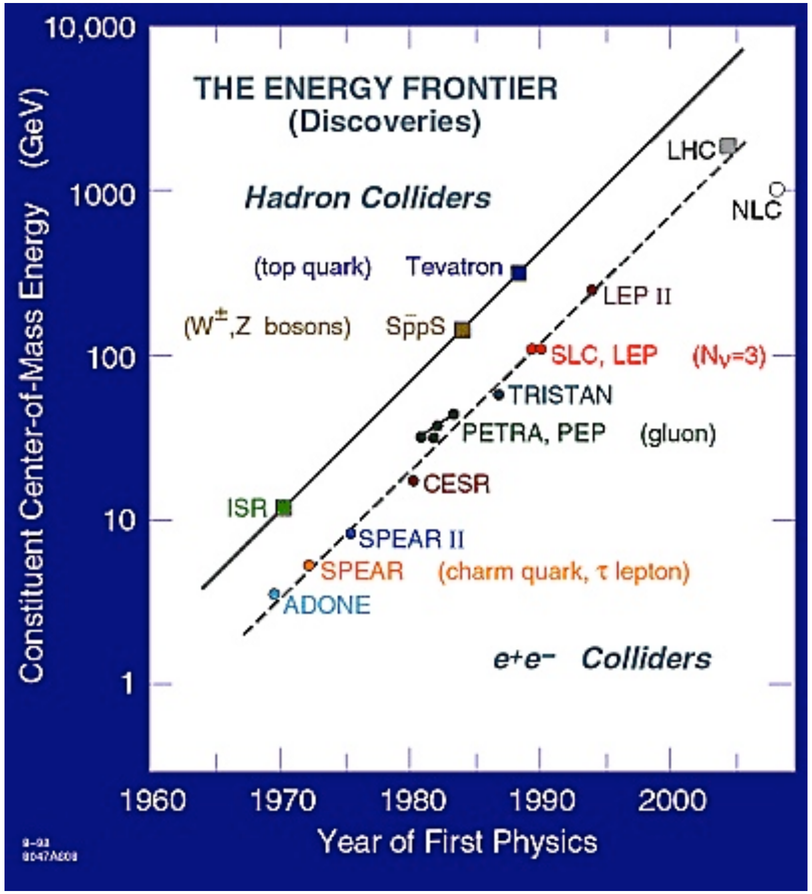
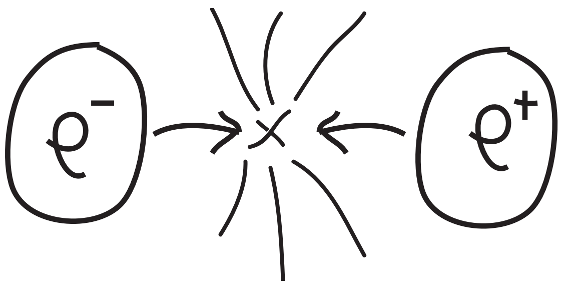


The proper particle for the proper scope

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



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

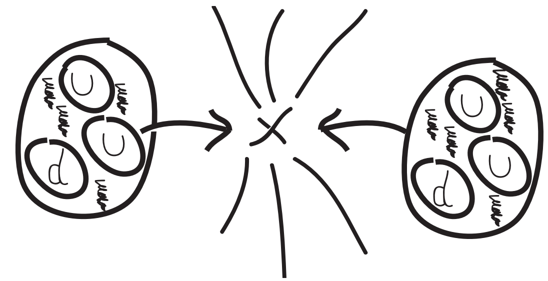
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

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

Precision measurement (LEP)

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

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



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 < 2 Eb (8 TeV)

Pros: with a single energy possible to scan different processes at different energies.

Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

Synchrotron radiation

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Power radiated per particle goes like:

$$P = \frac{2c \times E^4 \times r_0}{3\rho^2 \left(m_0 \times c^2\right)^3}$$

4th power of the energy
(2nd power)$^{-1}$ of the bending radius
(4th power)$^{-1}$ of the particle mass

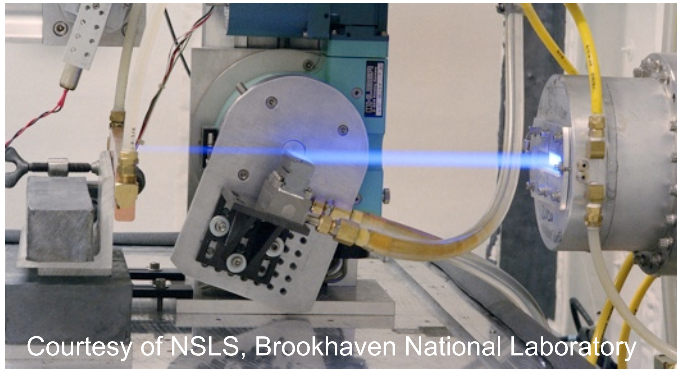
$r_0 = \frac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

ρ particle bending radius

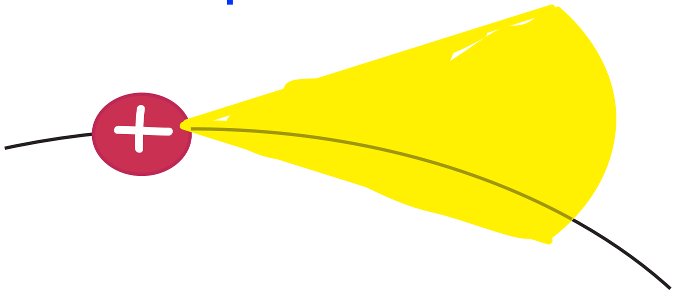
Energy lost per turn per particle due to synchrotron radiation:

e- ≈ some GeV (LEP)

p ≈ some keV (LHC)

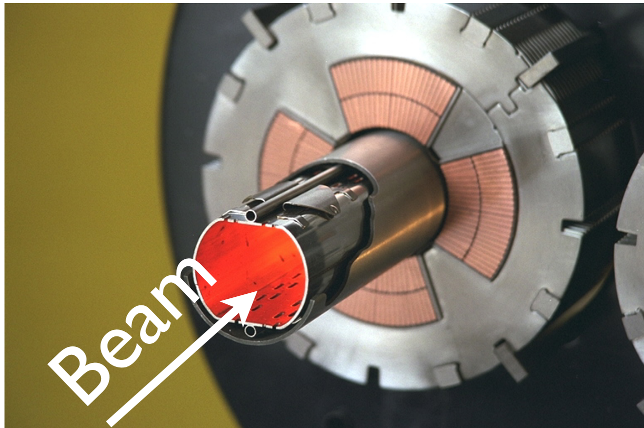

Courtesy of NSLS, Brookhaven National Laboratory

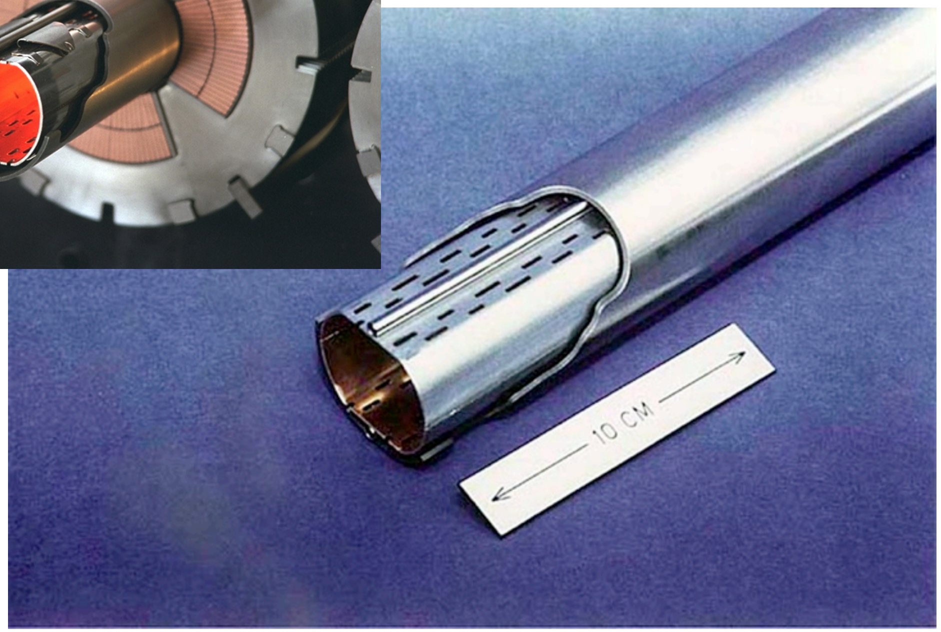
We must protect the LHC coils even if energy per turn is so low



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.

What is the LHC ?

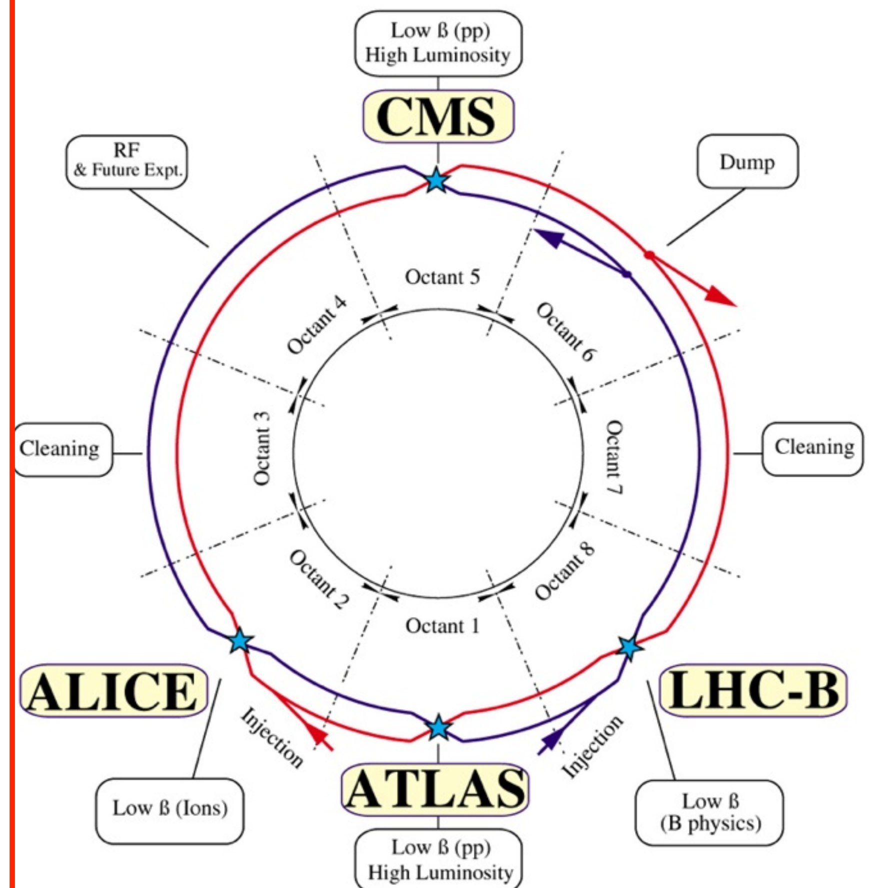
LHC: Large Hadron Collider

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

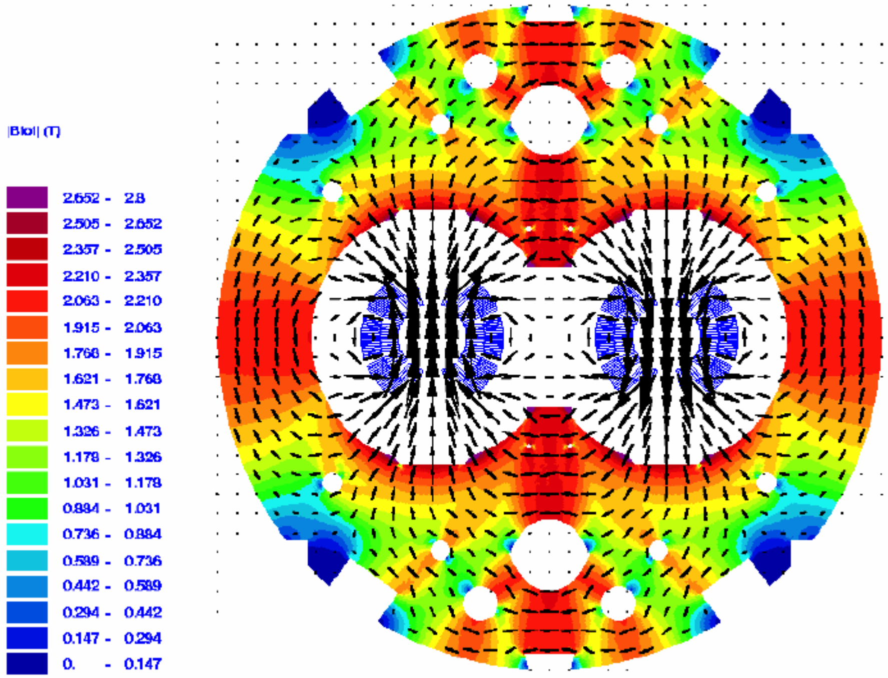
Large: high energy needs large bending radius *due to the maximum magnetic field existing technology can produce*
26.7 km circumference

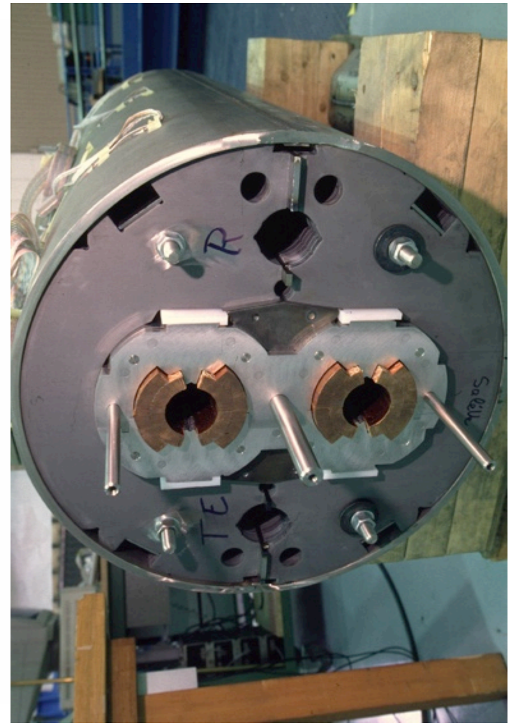
Hadrons: p p collision ⇒ synchrotron radiation and discovery machine.

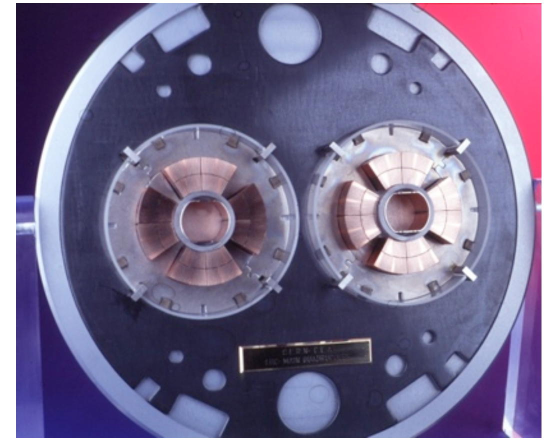
Collider: particles are stored in two separated rings which are synchrotrons, and accelerated from injection energy (450 GeV) to 7 TeV.
At 7 TeV the two beams are forced to cross in collision points to interact.
The beams are stored at 7 TeV for few 10 h to produce collisions. When the intensity is too 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 ...



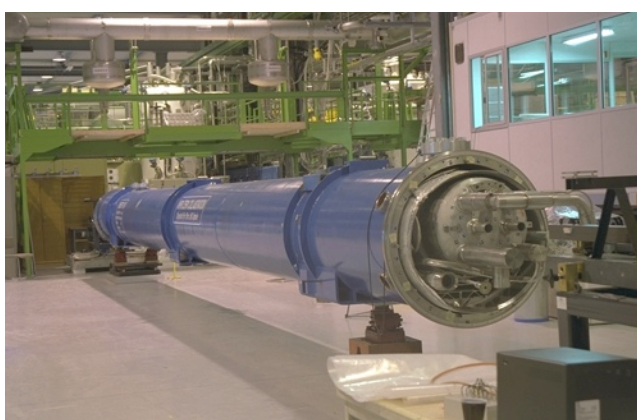
Two-in-one magnet design

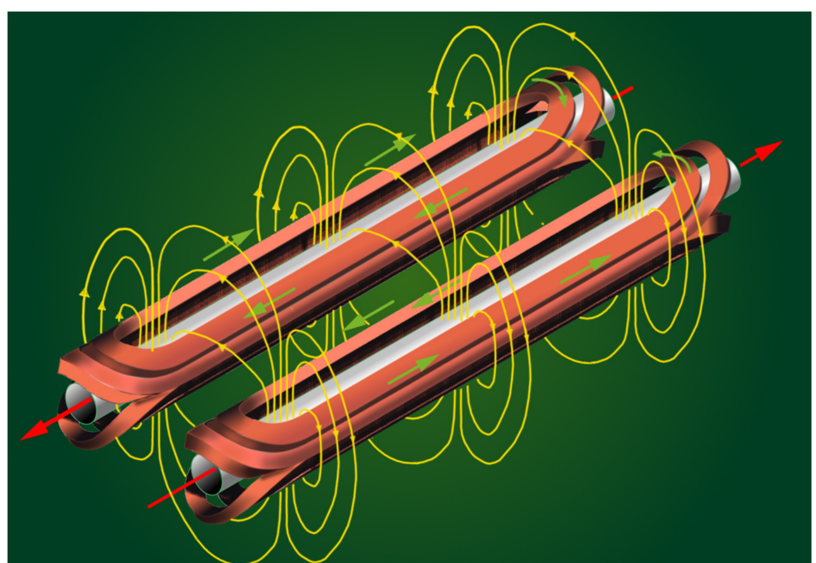




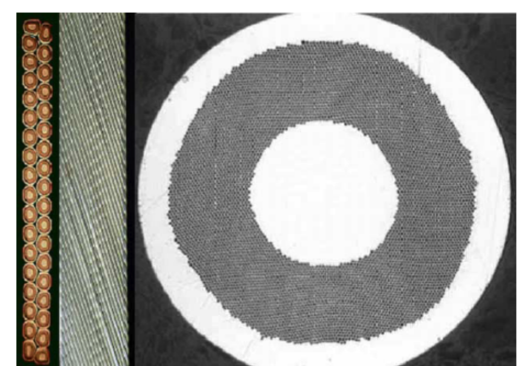


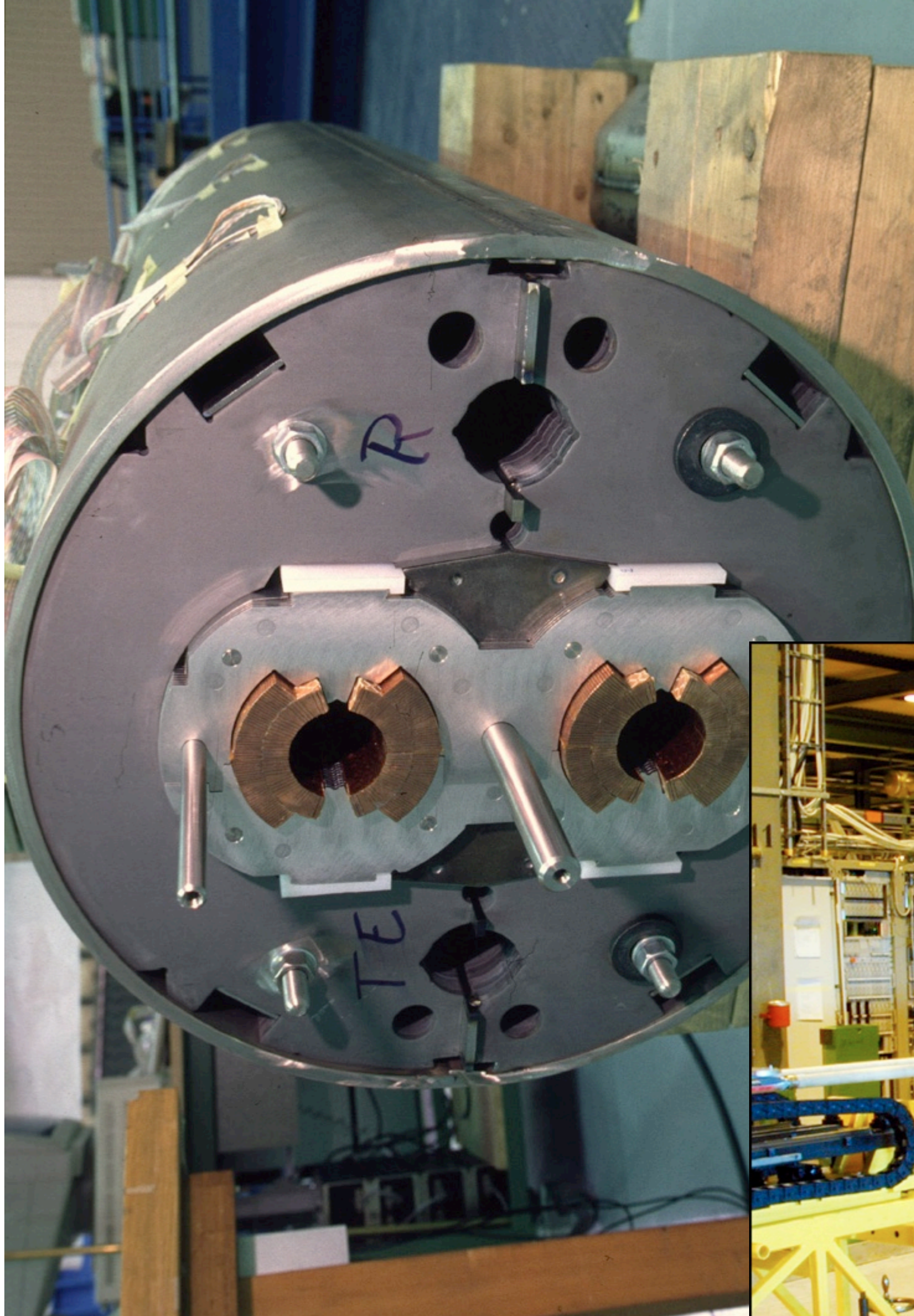
The LHC is one ring where two accelerators are coupled by the magnetic elements.





Nb -Ti superconducting cable in a Cu matrix





At 7 TeV:

I_{max} = 11850 A Field=8.33 T

Stored energy= 6.93 MJ

The energy stored in the entire LHC could lift the Eiffel tower by about 84 m

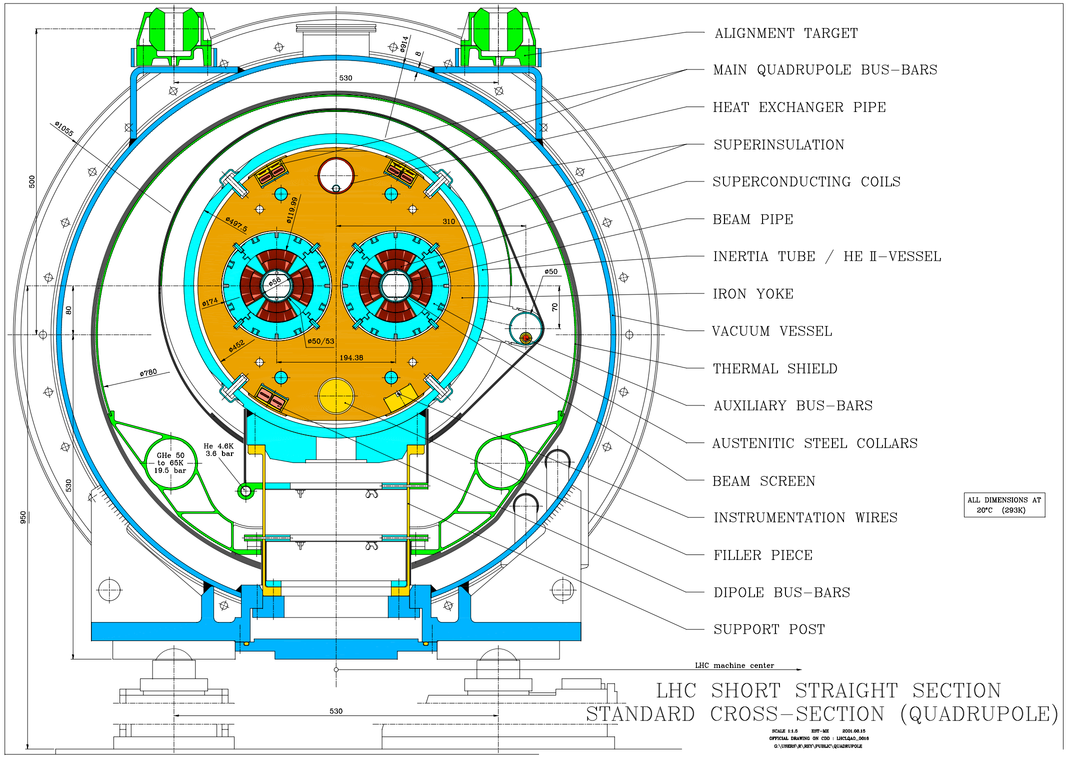
Weight = 27.5 Tons

Length =15.18 m at room temp.

Length (1.9 K)=15 m - ~10 cm

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

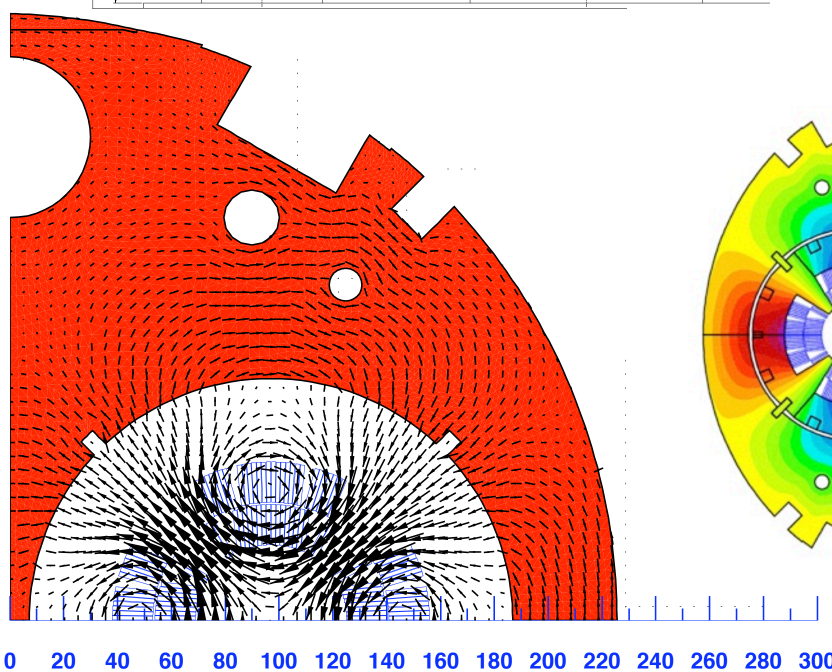
Quadrupoles are also two-in one

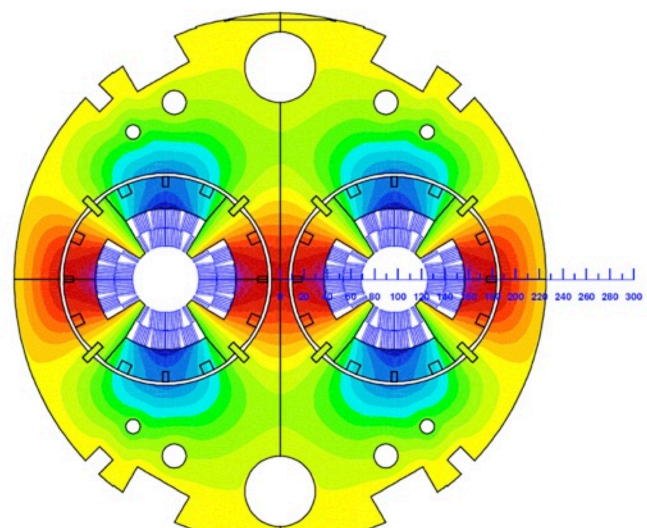


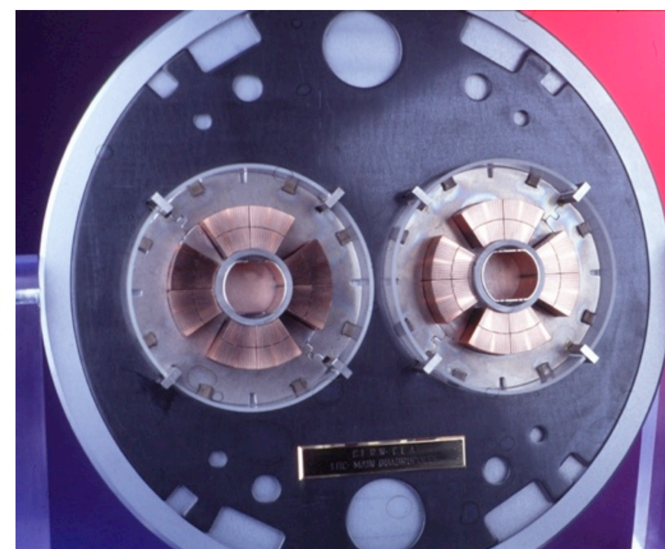
At 7 TeV:

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

Weight = 6.5 Tons
Length =3.1 m







Why do we have to protect the machine ?

Total stored beam energy at top energy (7 TeV), nominal beam, 334 MJ (or 120 kg TNT)

Nominal LHC parameters: $1.15\ 10^{11}$ protons per bunch

2808 bunches

0.5 A beam current

British aircraft carrier:

HMS Illustrious and Invincible weigh 20,000 tons all-up and fighting which is 2 x 10^7 kg.

Or the USS Harry S. Truman (Nimitz-class) - 88,000 tons.

Energy of nominal LHC beam = 334 MJ or 3.34 x 10^8 J

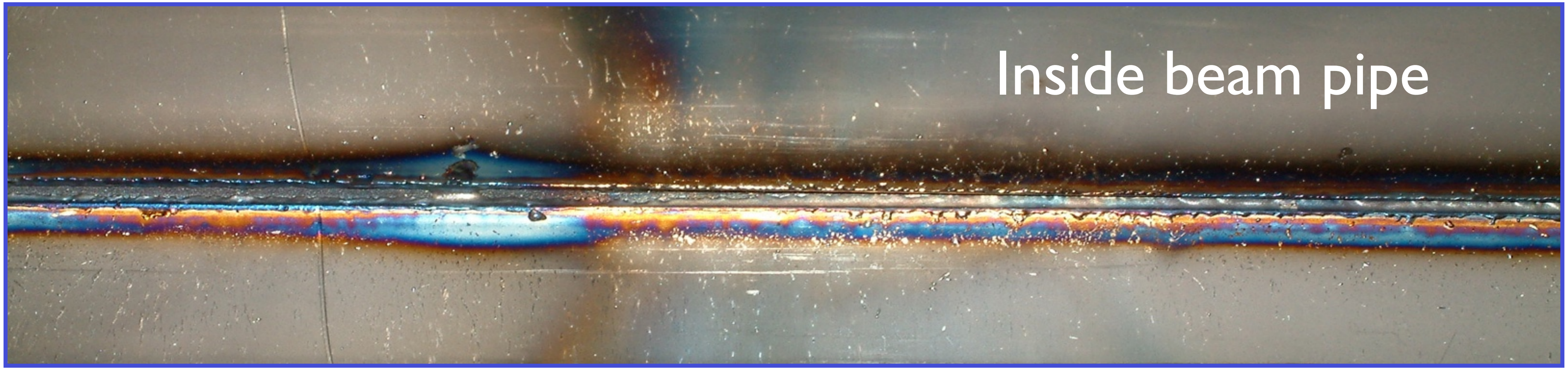
which corresponds to the aircraft carrier navigating at v=5.8 m/s or 11.2 knots (or around 5.3 knots if you're an American aircraft carrier)

So, what if something goes wrong?

What is needed to intercept particles at large transverse amplitude or with the wrong energy to avoid quenching a magnet?

Few years ago something went wrong during a test ...

LHC extraction from the SPS
450 GeV/c, 288 bunches
Transverse beam size 0.7 mm (1 σ)
1.15 x 10^{11} p+ per bunch, for total intensity of 3.3 x 10^{13} p+
Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)



B.Goddard CERN AB/BT

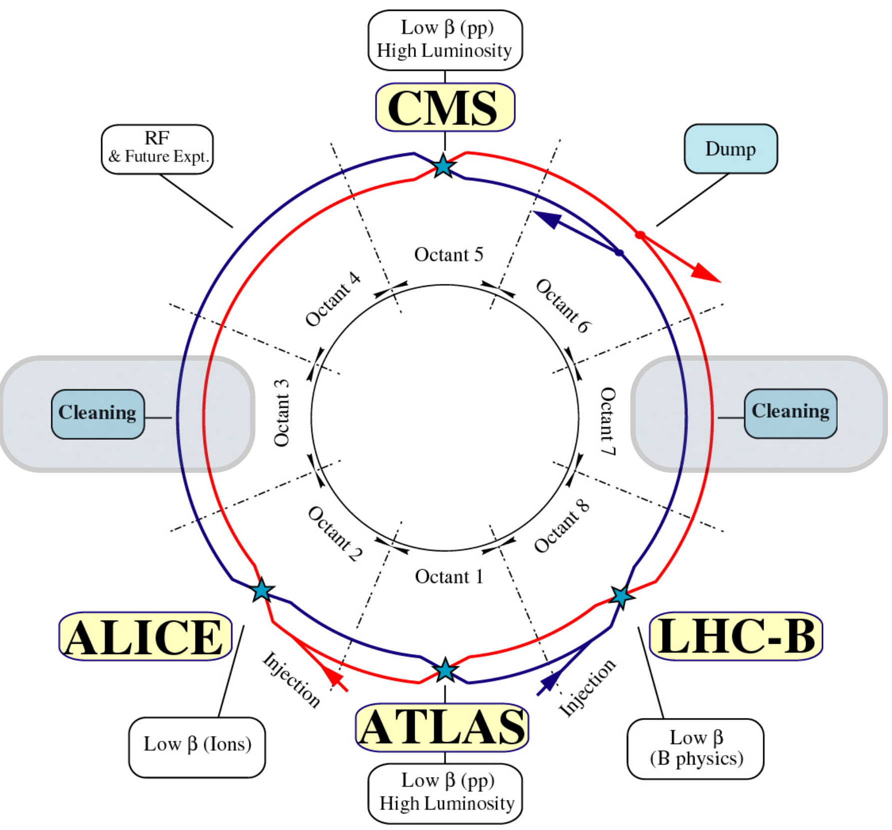
Collimation system for machine protection

Two sections in LHC dedicated to beam cleaning:

IR3 momentum cleaning → remove particles with too large dp/p
($> \pm 10^{-3}$)

IR7 betatron cleaning → remove particles at too large amplitude.

Done by intercepting particle with 2 stage collimation



Movable collimators, they to be robust

Materials chosen:
Metals where possible
or C-C fibers

Robustness required,
listen to 10^{13} p on a
C-C Jaw

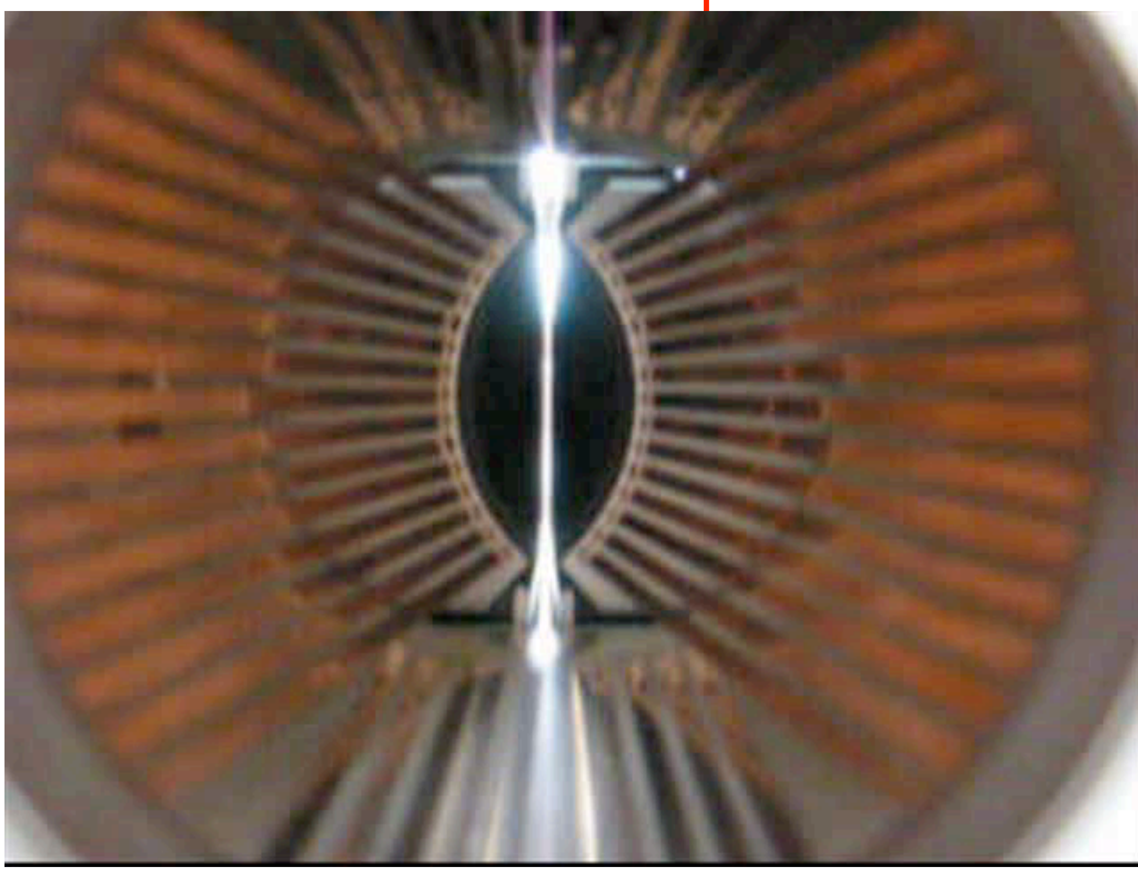
SPS experiment:

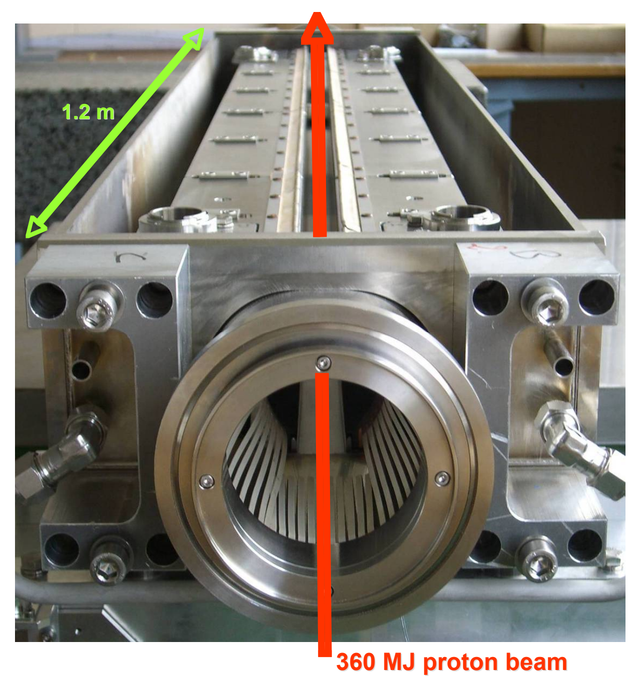
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

b) 3e13 protons , 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw ⇒ full design CASE

equivalent to about 1/2 kg of TNT

from S. Redaelli





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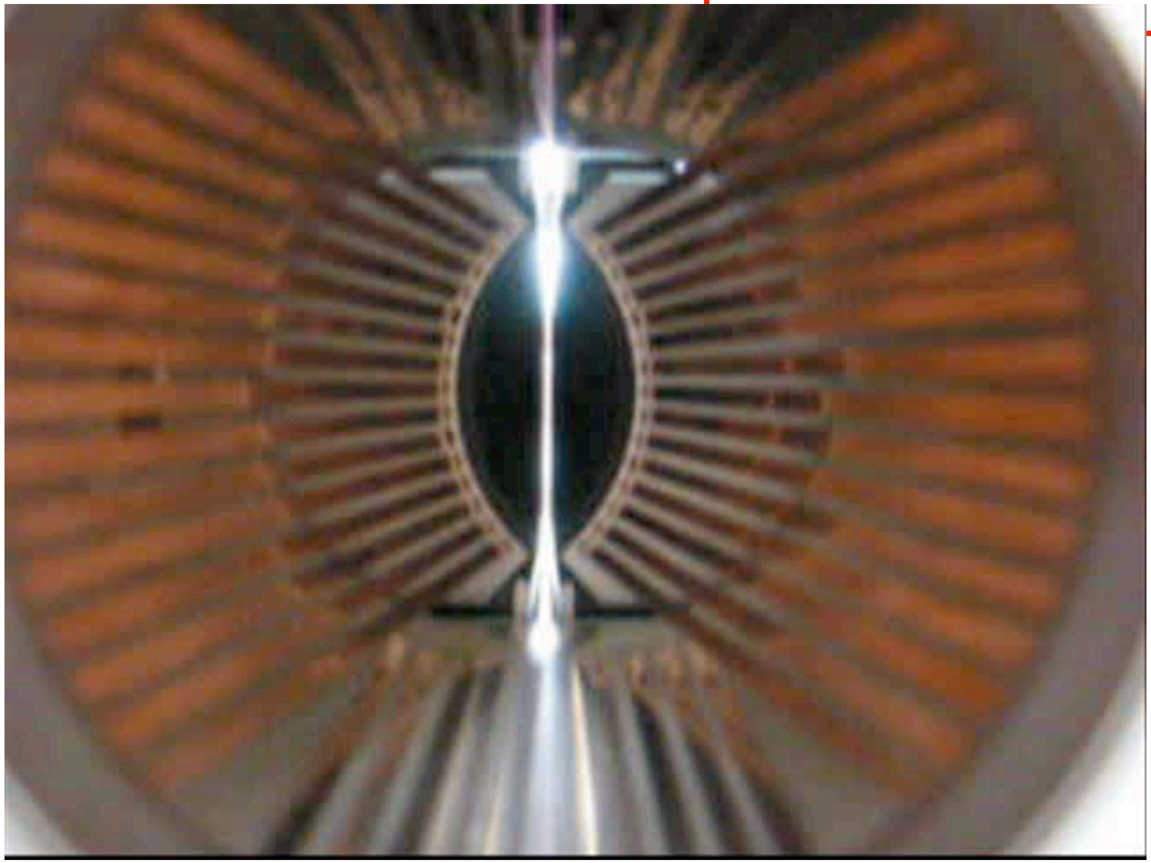

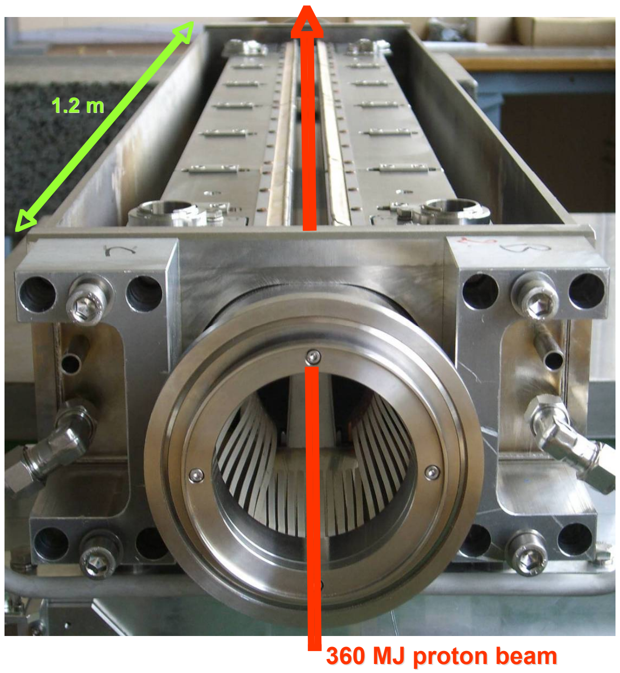

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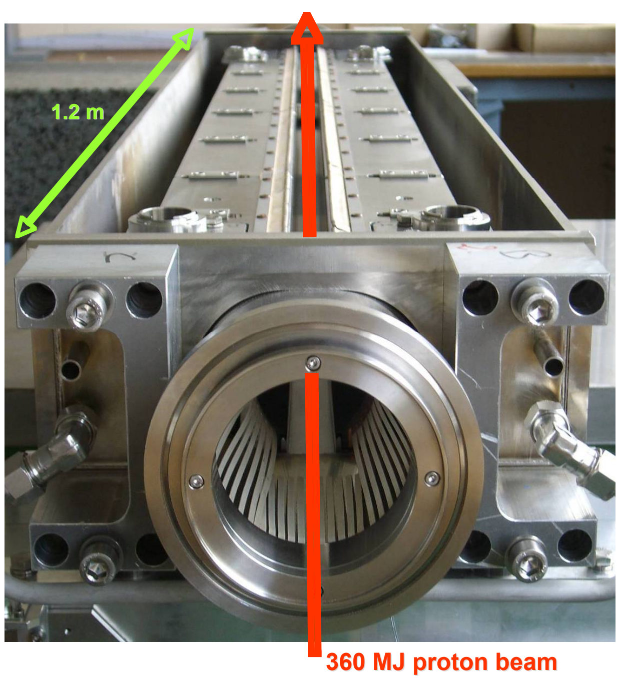
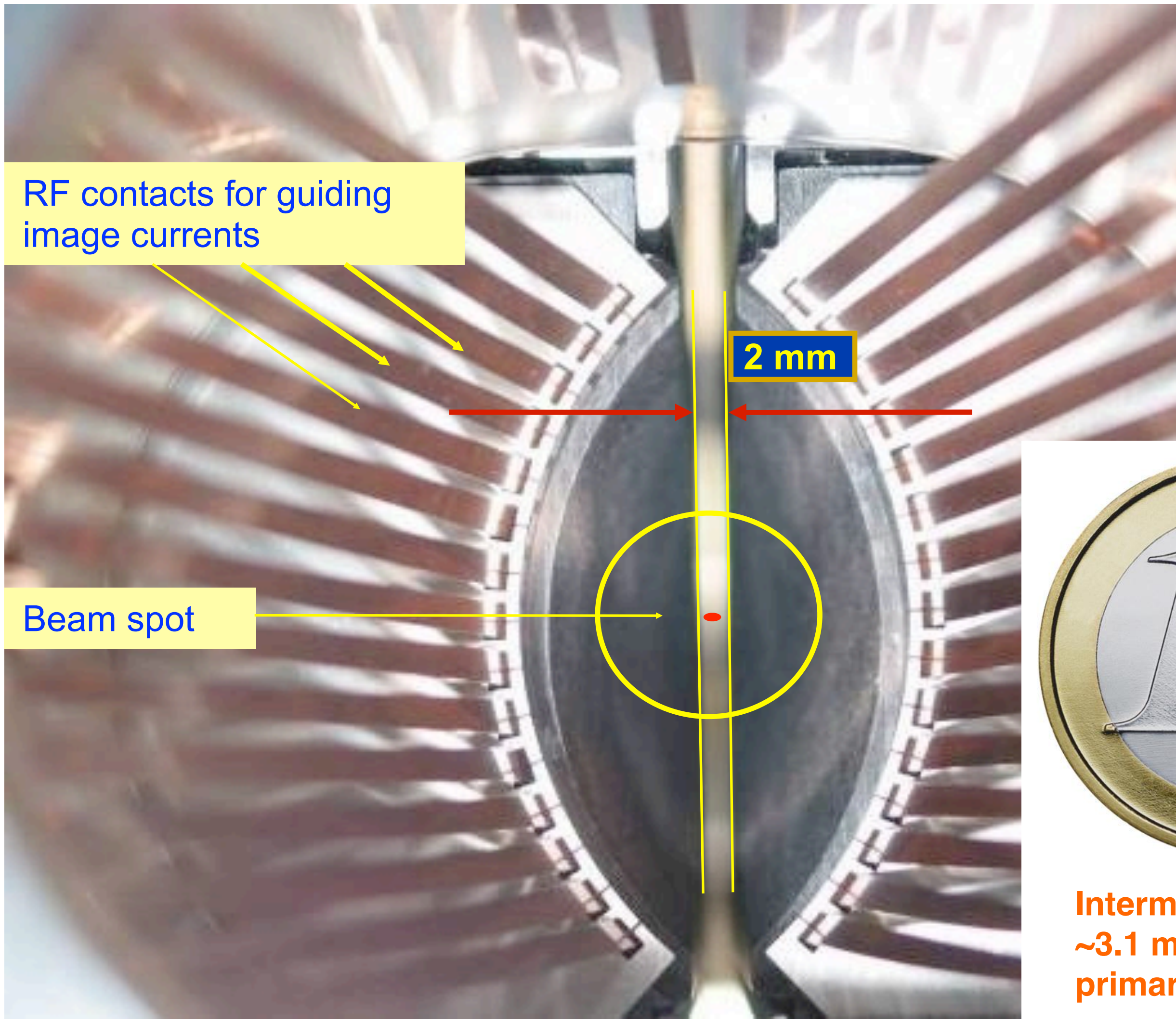
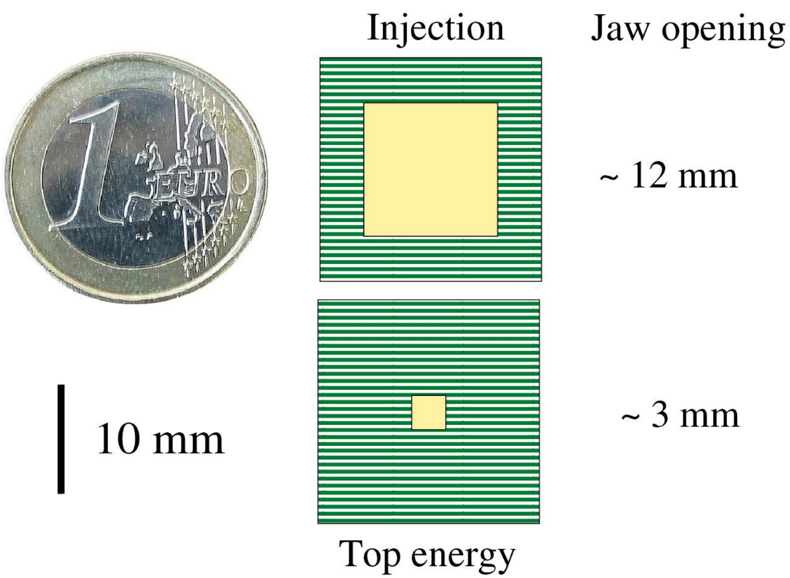
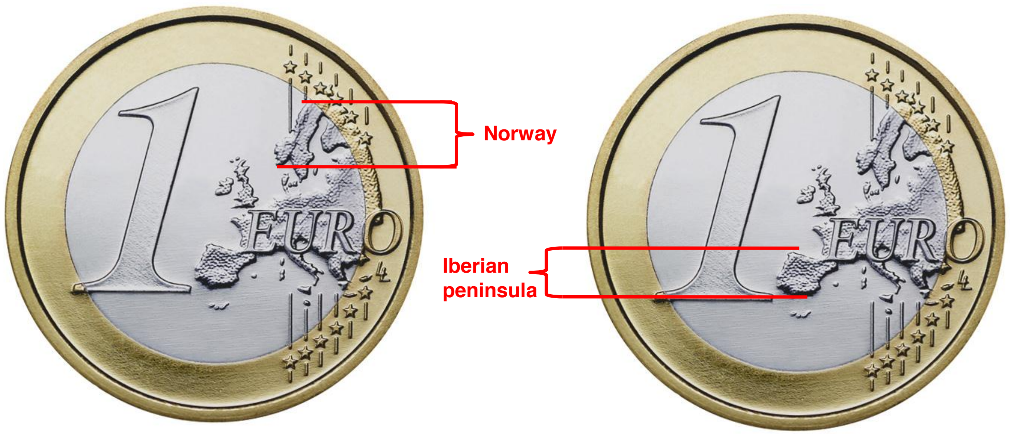


At 7 TeV, beam really small, 3σ diam. ~ 1.2 mm







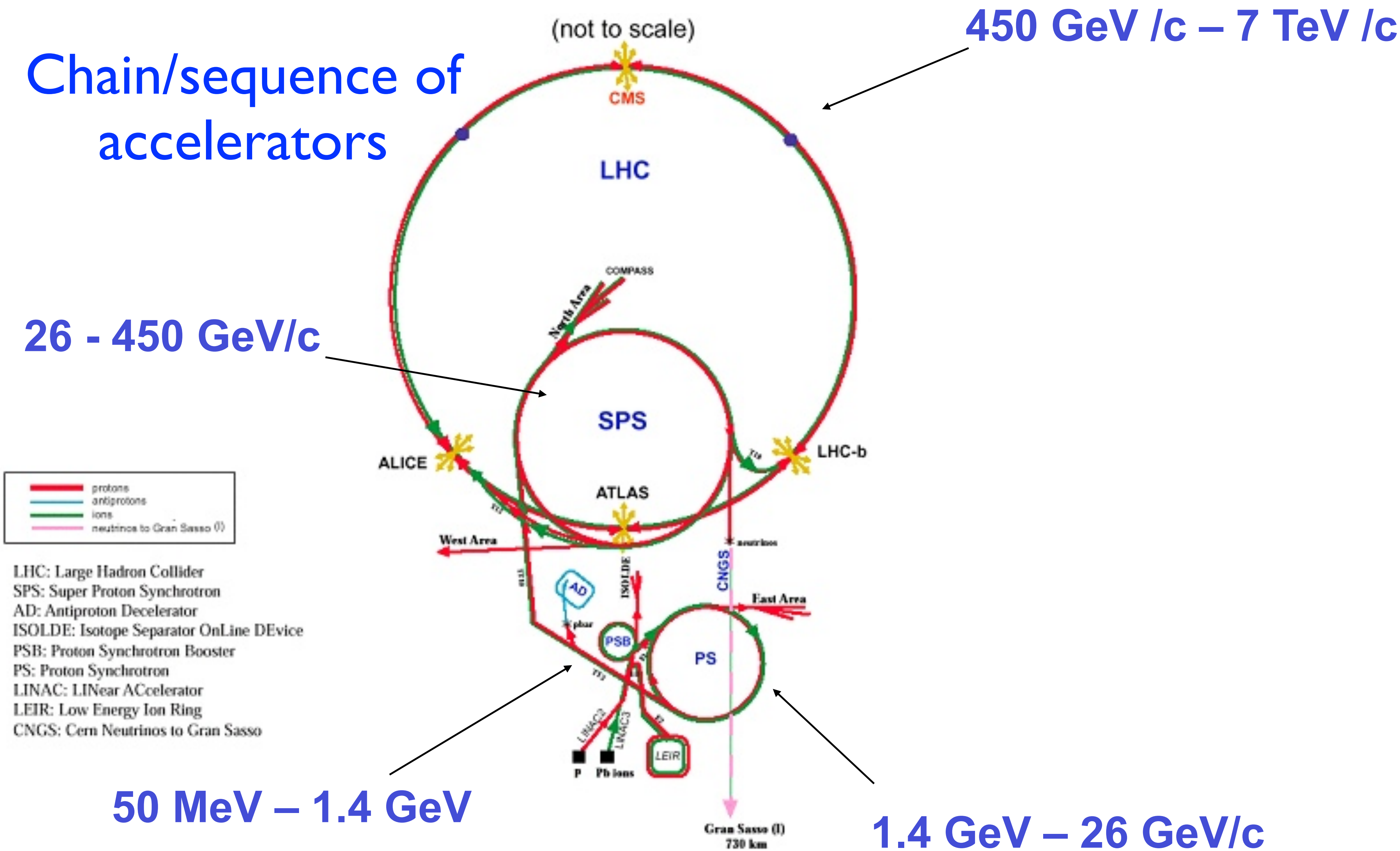
Intermediate settings (2011):
~3.1 mm gap of
primary collimator

Tight settings:
~2.2 mm gap of
primary collimator

Precision required for collimator movements about 25 μm

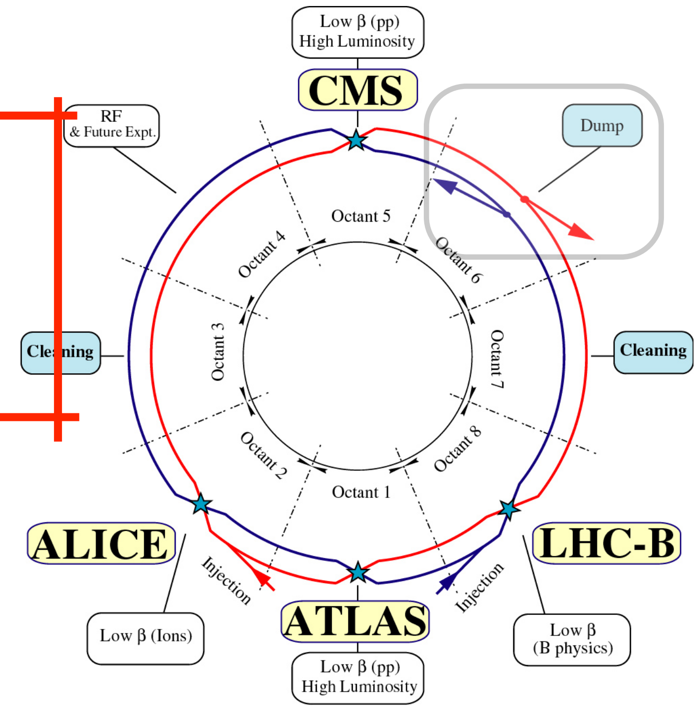
CERN accelerator complex overview

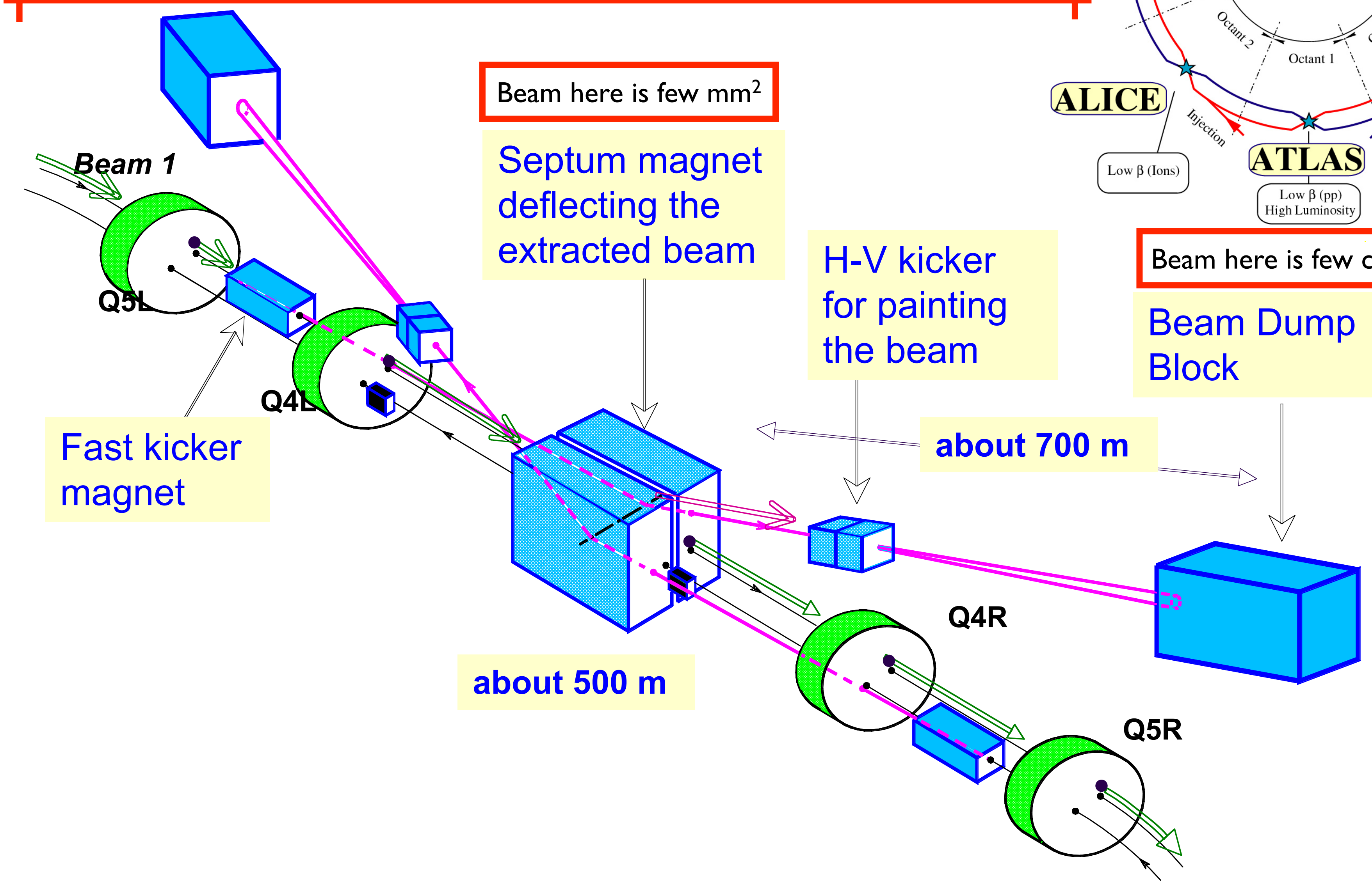
Chain/sequence of accelerators



Beam extraction, LHC as example

At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn.
Beam dump built to absorb full power at full energy.

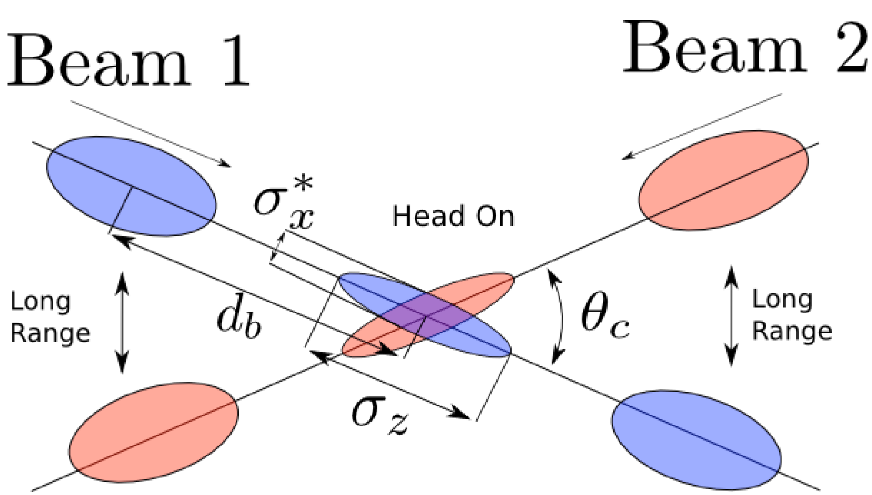




Few LHC numbers ...

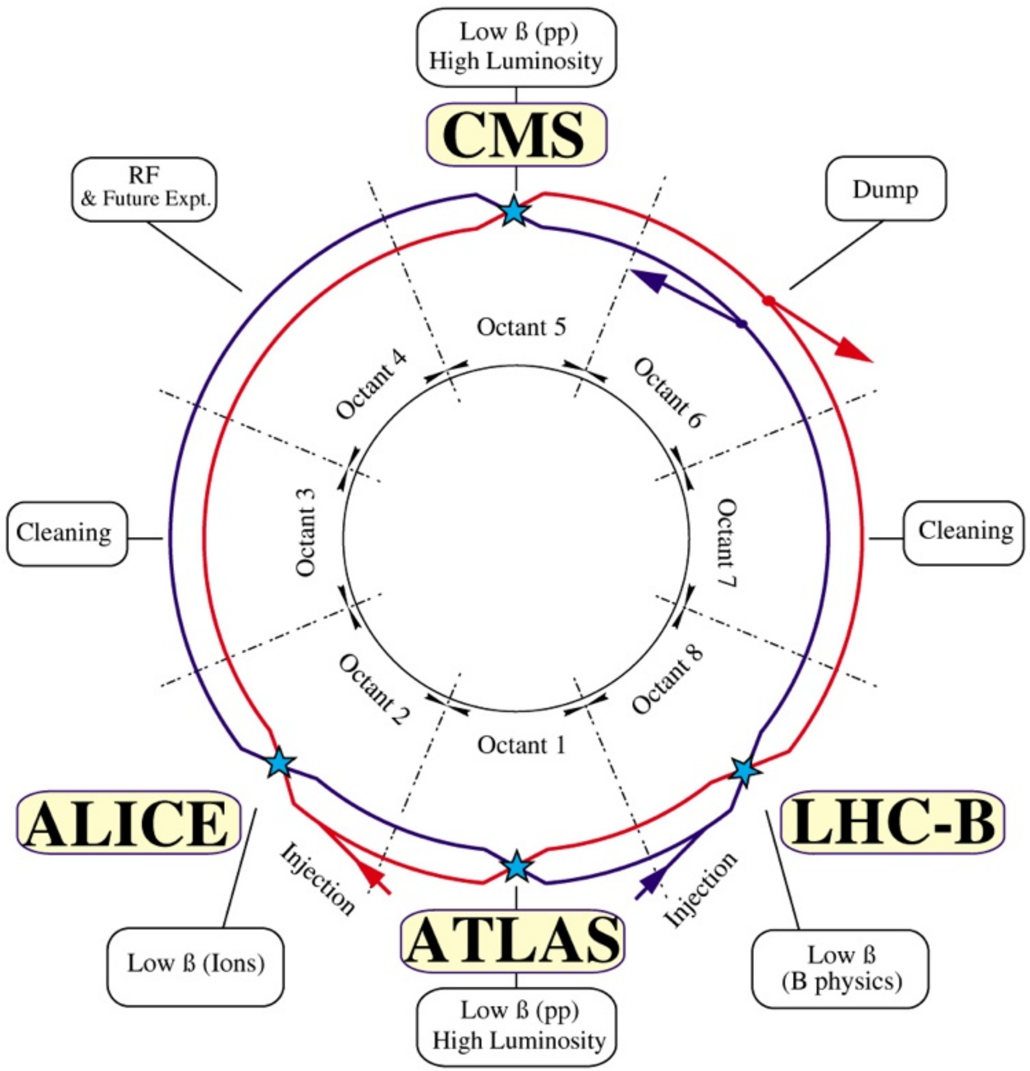
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

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



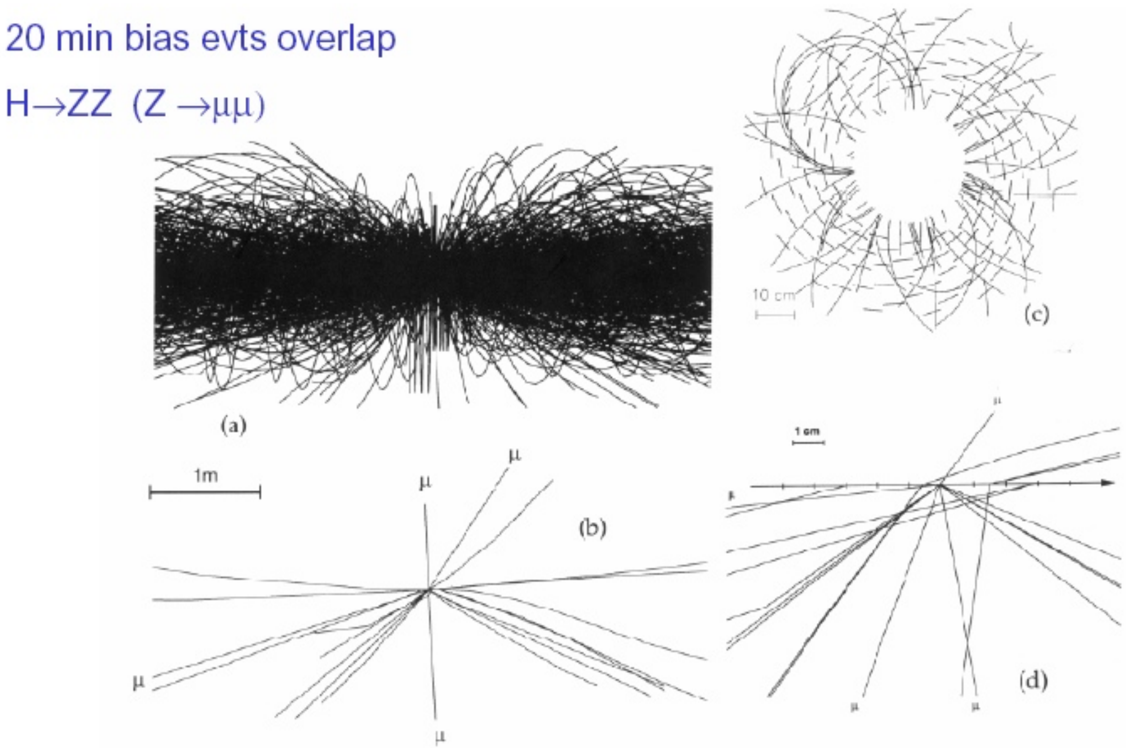
Luminosity	1 10^{34} /cm^2/s (IP1 IP5)
Particle per bunch	1,15 10^{11}
Bunches	2808
Revolution frequency	11,245 kHz
Crossing rate	40 MHz
Nomalised Emittance	3.75 µm rad
β-function at the collision point	0.55 m
RMS beam size @ 7 TeV at the IP1-5	**16.7 µm**
Circulating beam current	0.584 A
Stored energy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

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** **1 turn= 89 mus**
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

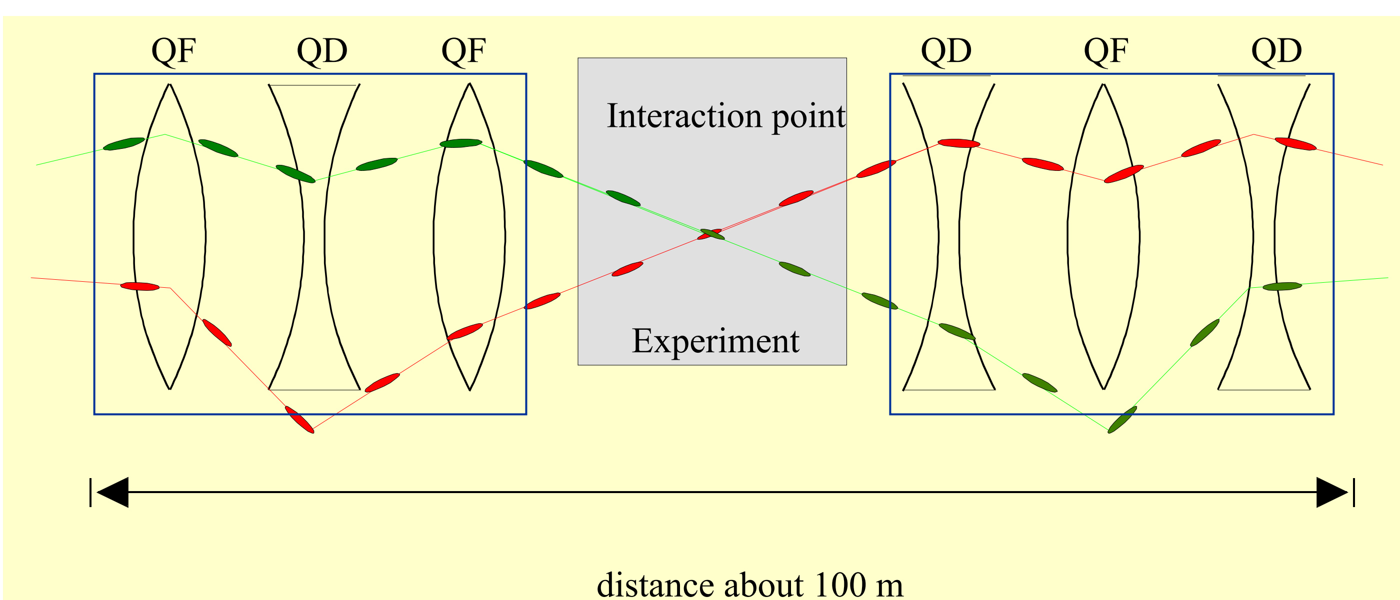
Crossing angle



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

~ 30 unwanted collision per crossing

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



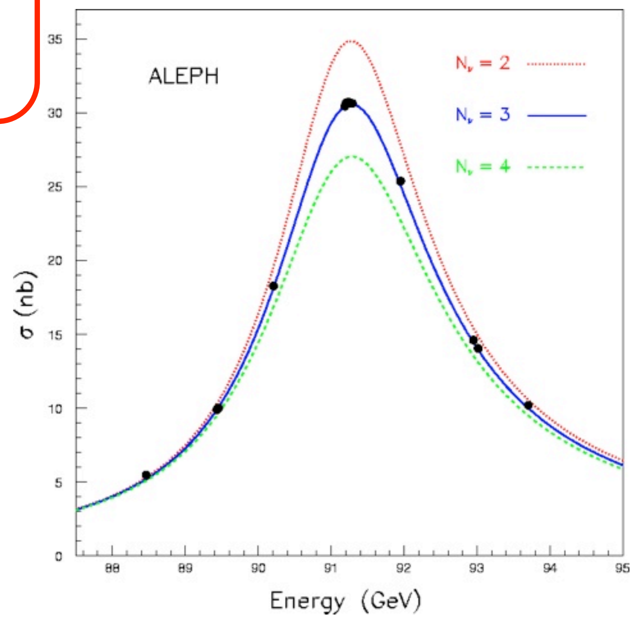
Θ_c	crossing angle	285 μrad
σ_z	RMS bunch length	7.55 cm
σ^*	RMS beam size (ATLAS-CMS)	16.7 μm
F	L reduc. Factor	0.836

What can influence an accelerator?

The physics case:
the Z mass at LEP has been measured with an error of 2 MeV.
Energy of the accelerator has to be know better than 20 ppm.

Energy measurements obtained by during last years of LEP operation

Nominal (GeV)	E_{CM} (LEP) (GeV)
181	180.826 ± 0.050
182	181.708 ± 0.050
183	182.691 ± 0.050
184	183.801 ± 0.050
Combined	182.652 ± 0.050



What can influence the energy of a collider?

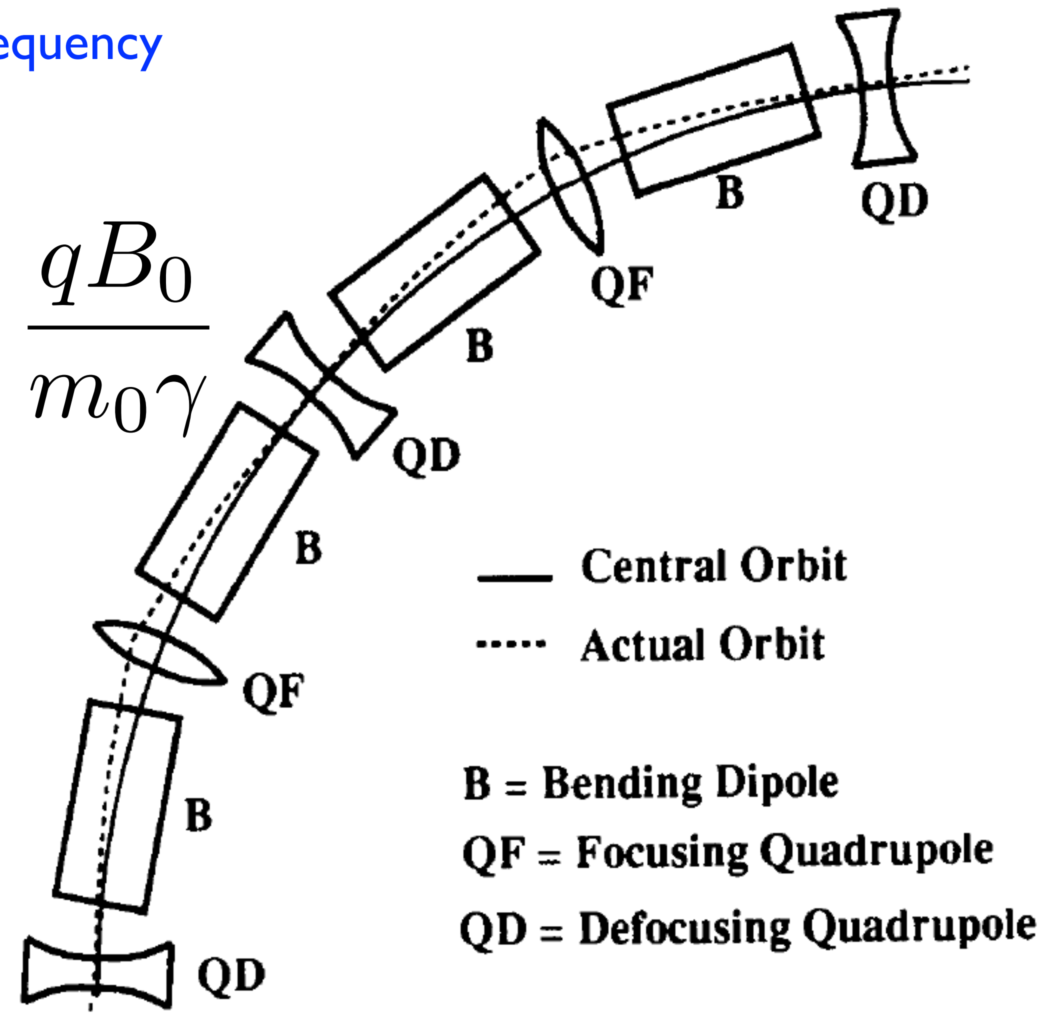
“Rappel”of strong focusing synchrotron optics

Stable orbit is bent by the main dipoles, centered in the quadrupoles, no field

Energy fixed by bending strength and cavity frequency

$$f_{RF} = h \cdot f_{rev}$$

$$f_{rev} = \frac{v}{C_c} = \frac{v}{2\pi\rho} = \frac{1}{2\pi} \cdot \frac{qB_0}{m_0\gamma}$$



A variation of the Circumference C induces changes in the energy proportional to α, the momentum compaction factor.

$$\frac{\Delta E(t)}{E_0} = -\frac{1}{\alpha} \frac{\Delta C(t)}{C_c}$$

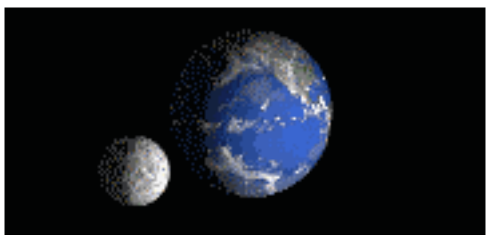
In LEP $\alpha = 1.86\ 10^{-4}$ a small variation the circumference induces a large variation in energy

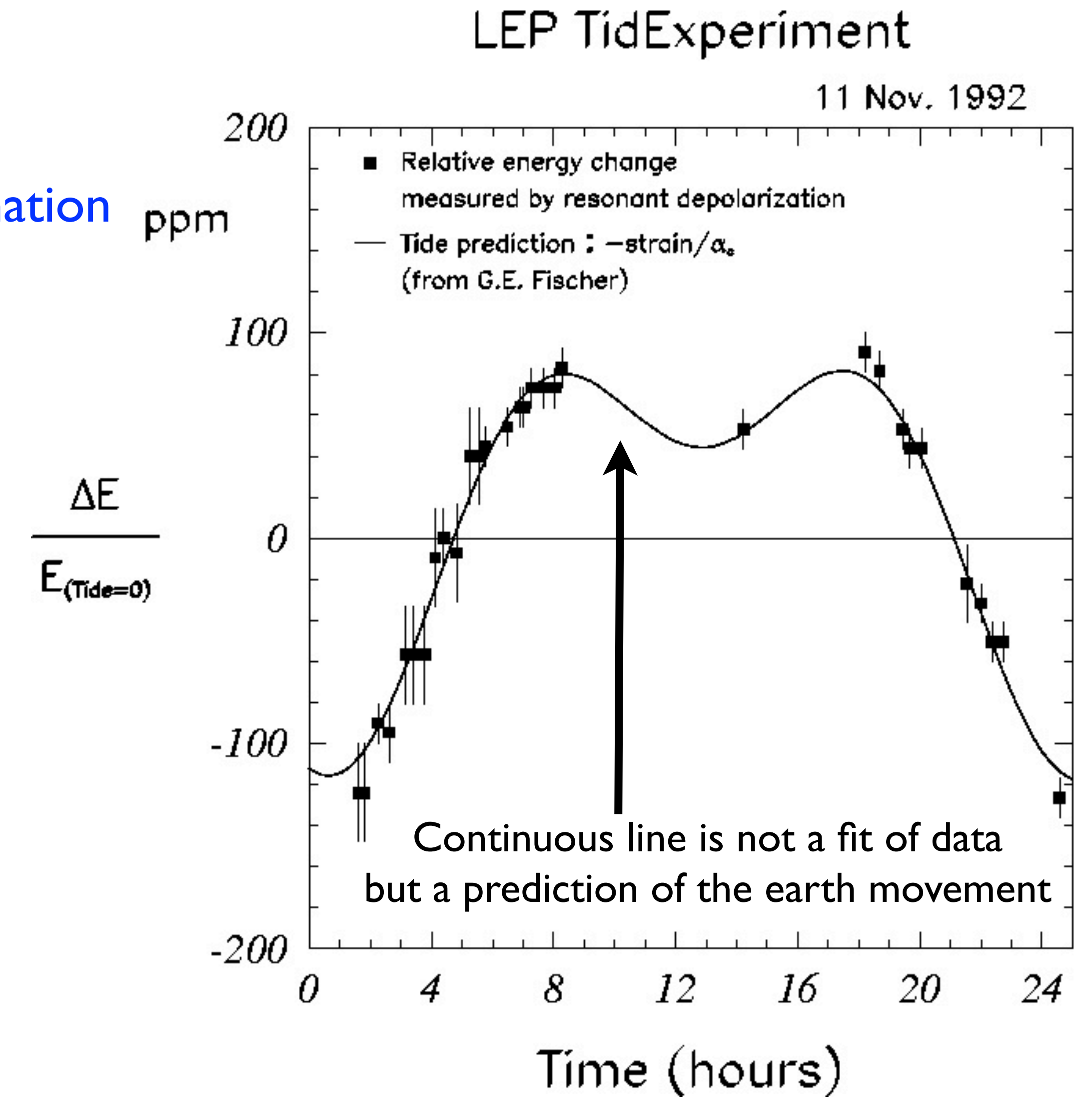
Moon tides can change earth geometry

Moon induces a earth deformation similar to water tide.

Total deformation of the LEP about 4 mm
Energy variation of 100 ppm

The 12 h cycle is due to the earth deformation

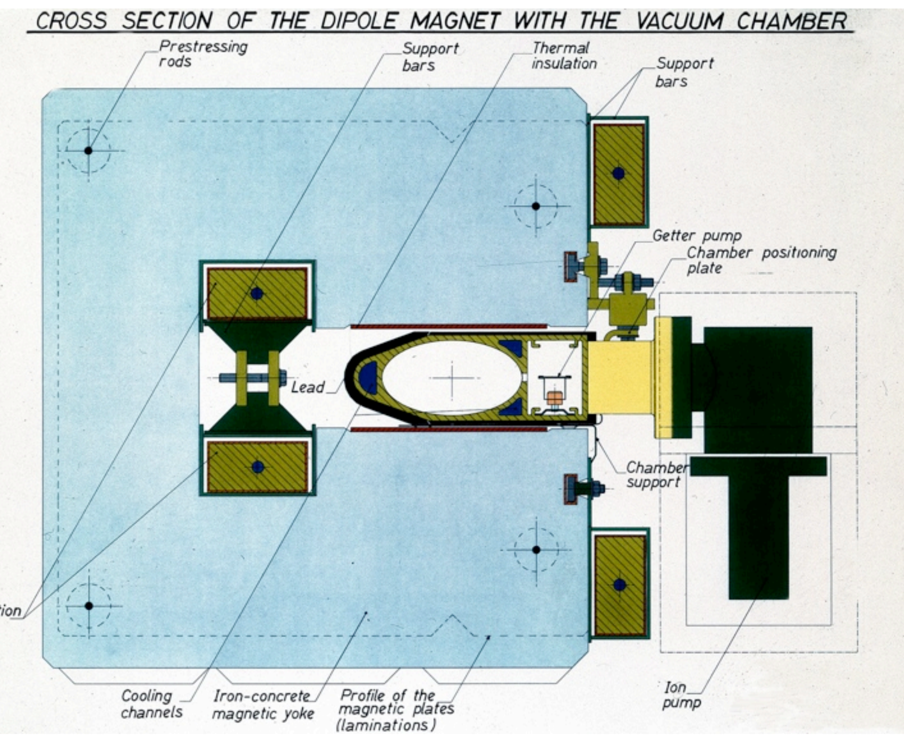


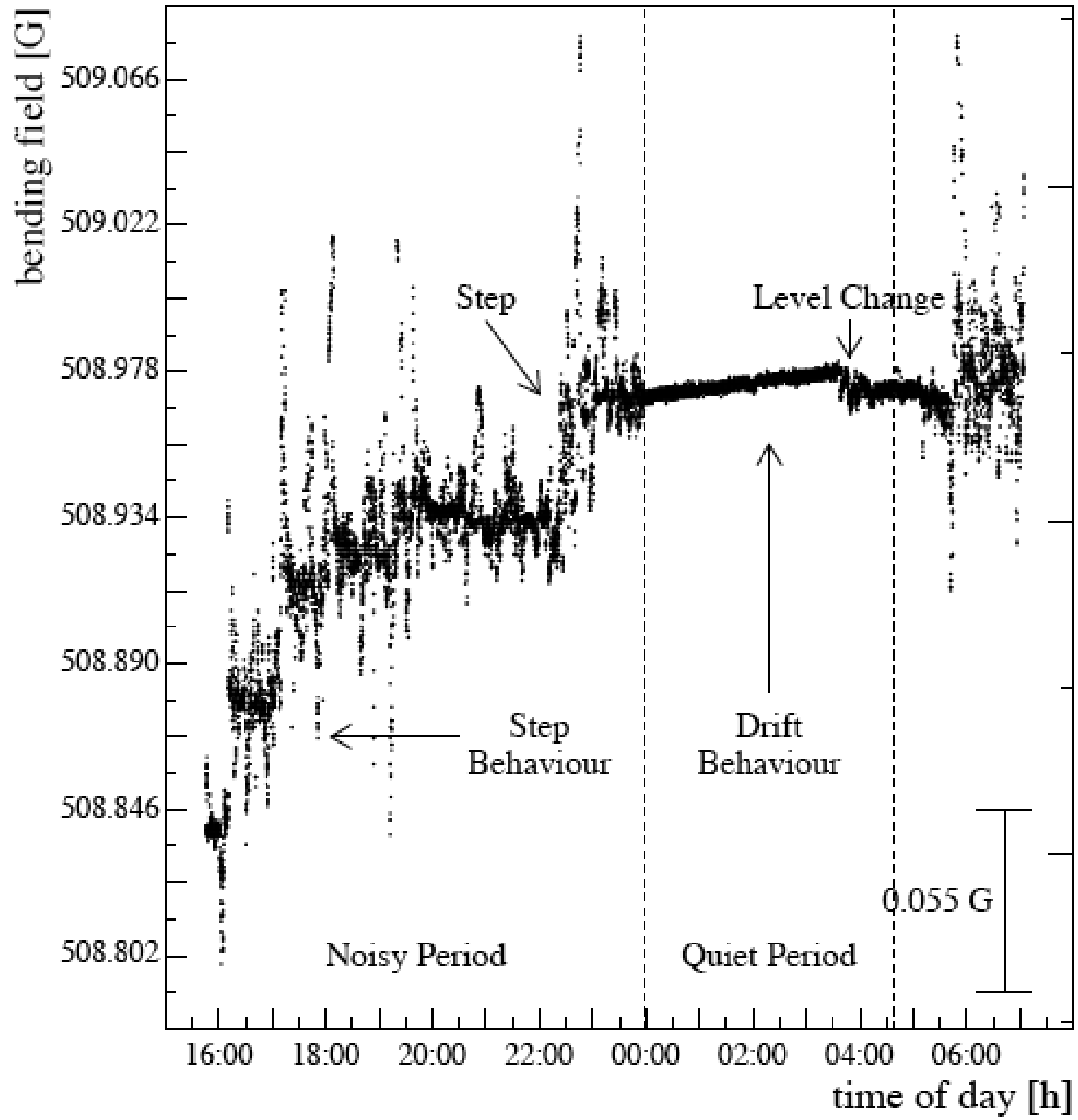


The effect is modulated by the different tide intensities and by the SUN tides

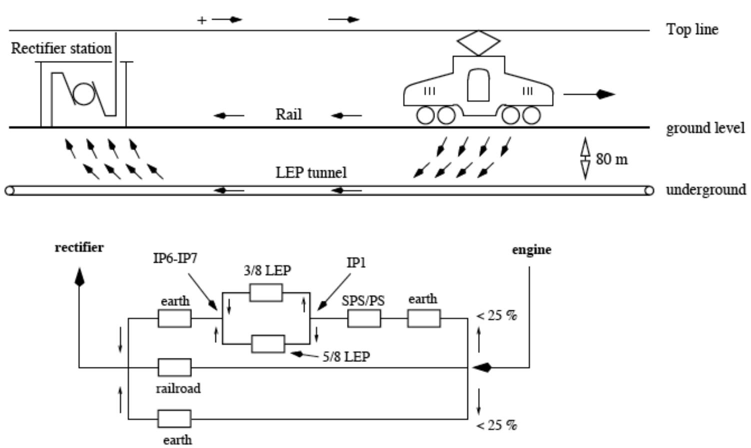
The problem: an accelerator is not in the middle of nothing

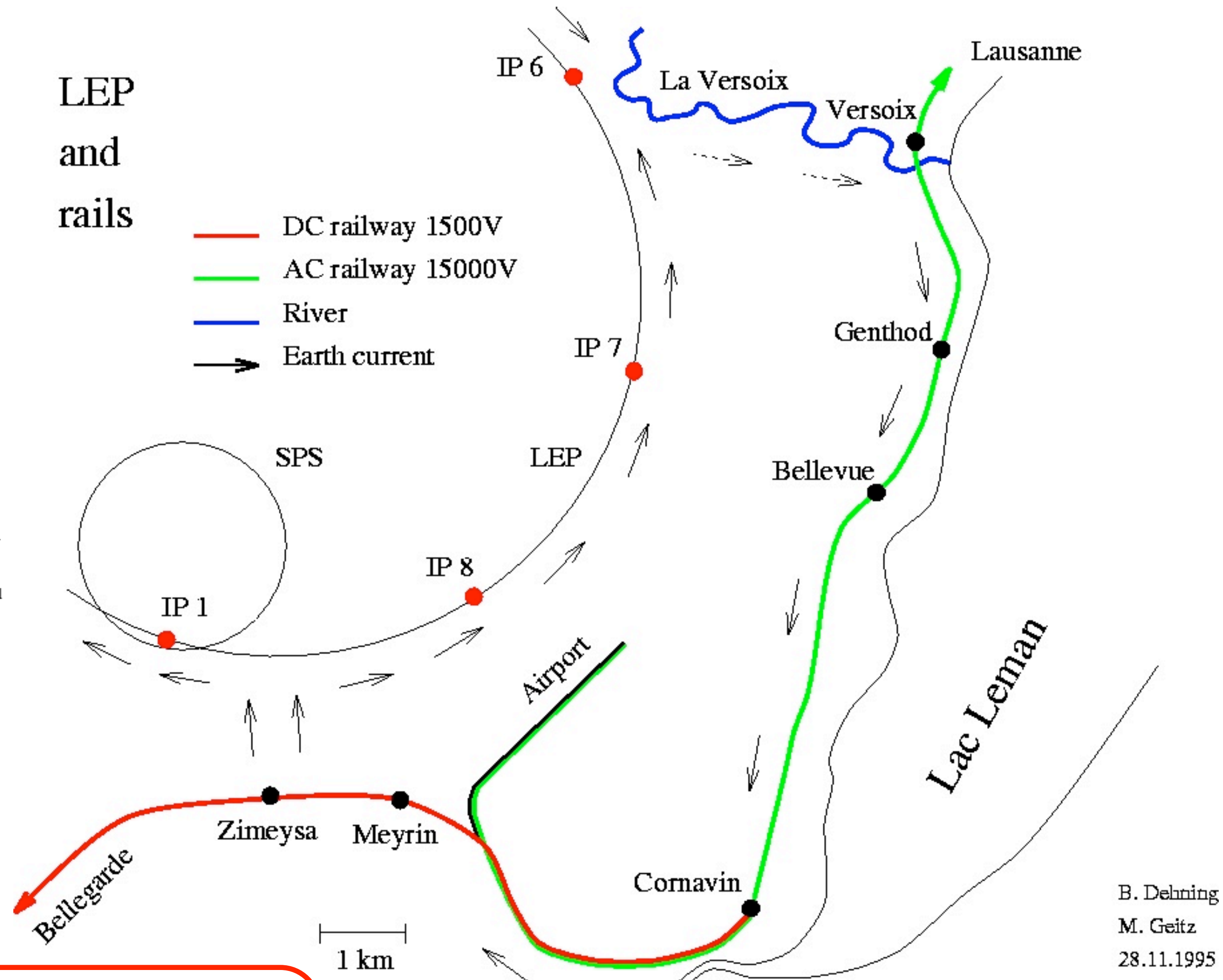
Observed variation of the bending strength of the LEP dipoles during the day





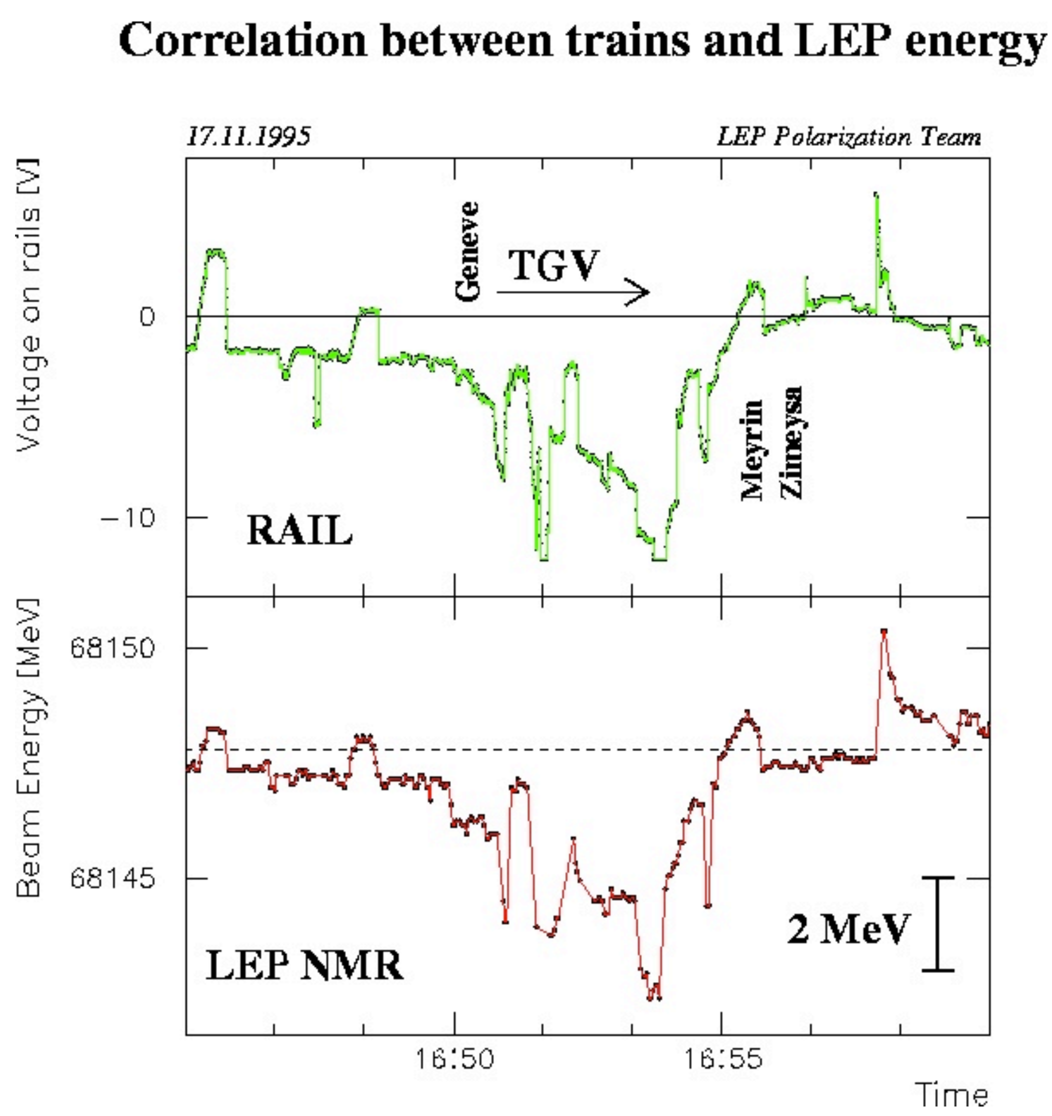
Influence of train leakage current





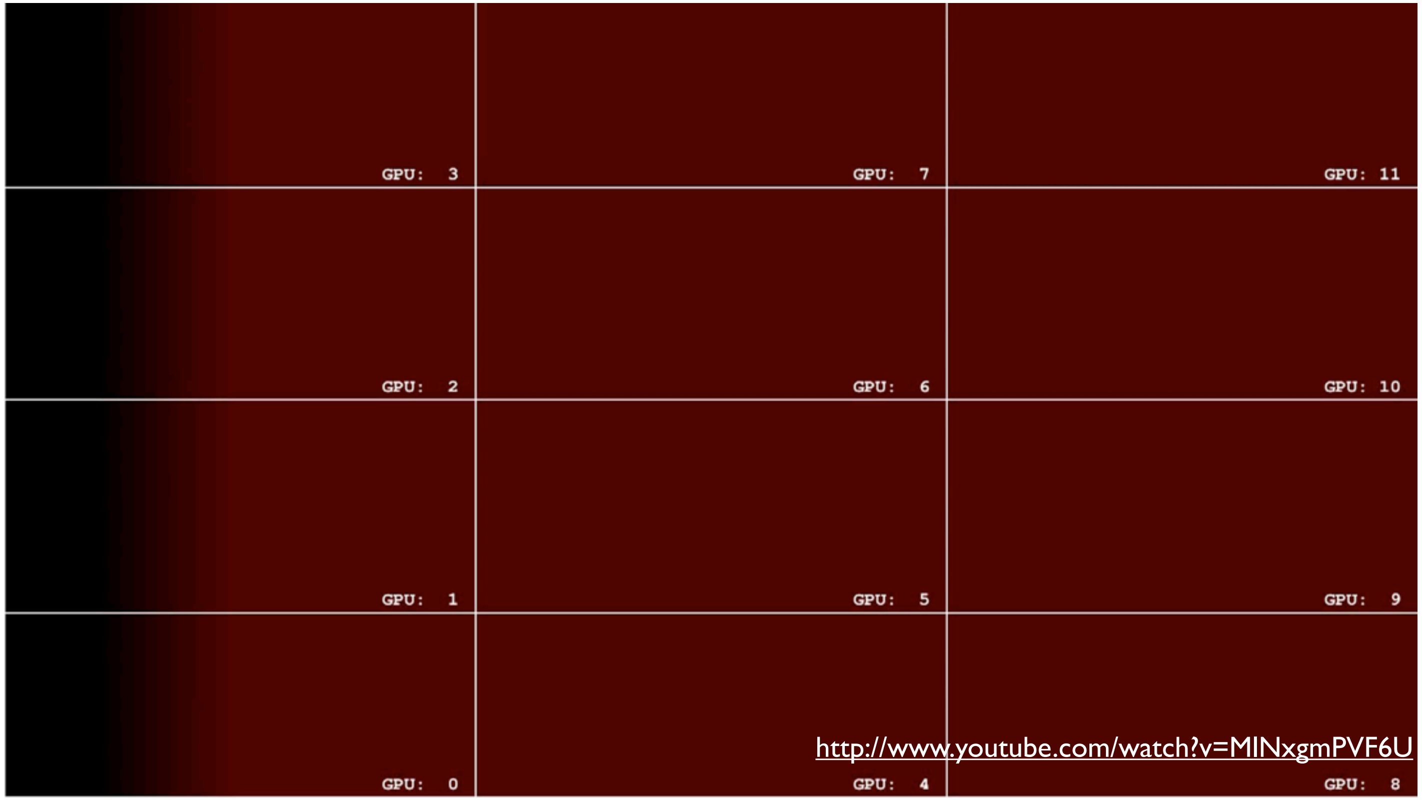
LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

The evidence, TGV to Paris at 16:50 ...



The future (personal view, pretty long term...)

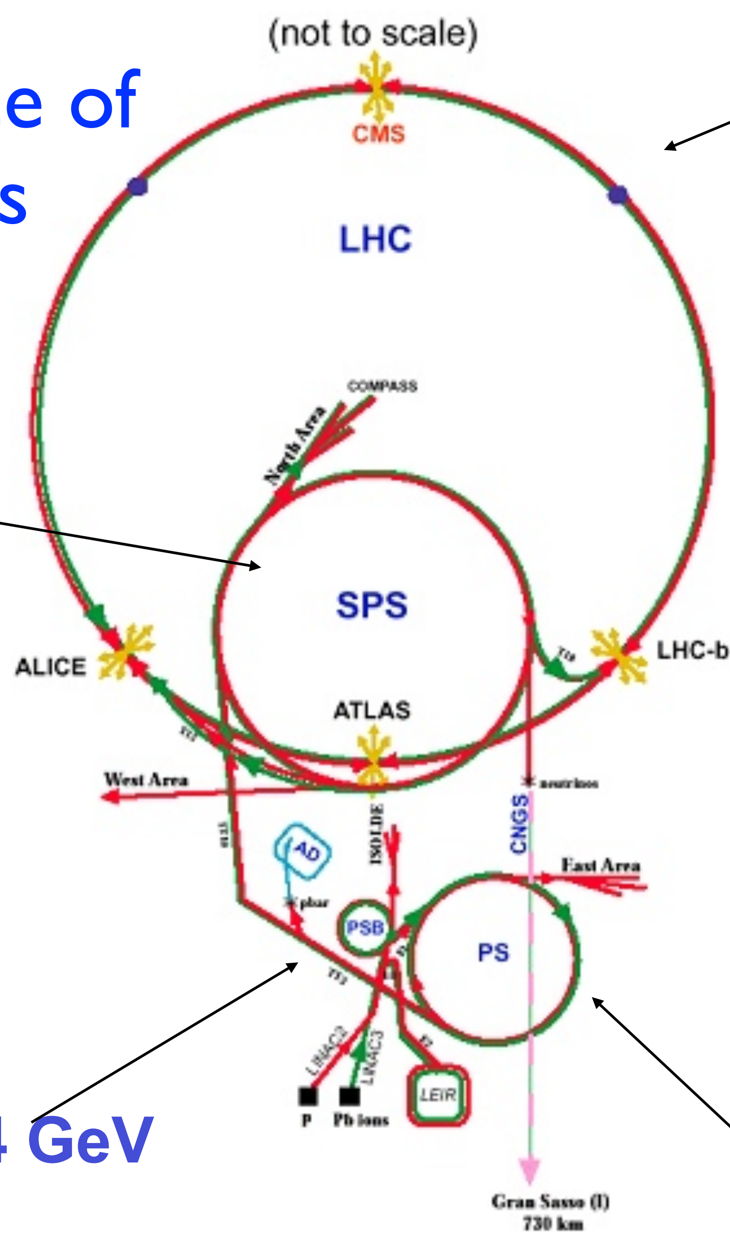
- **Laser plasma acceleration : few GeVs per meter ....**

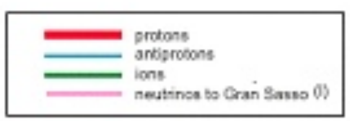


... that's not for tomorrow... yet...

CERN accelerator complex overview

Chain/sequence of accelerators





450 GeV/c – 7 TeV/c

C ~ 27 km

26 - 450 GeV/c

C ~ 6 km

1.4 GeV – 26 GeV/c

C ~ 630 m

50 MeV – 1.4 GeV

C ~ 157 m

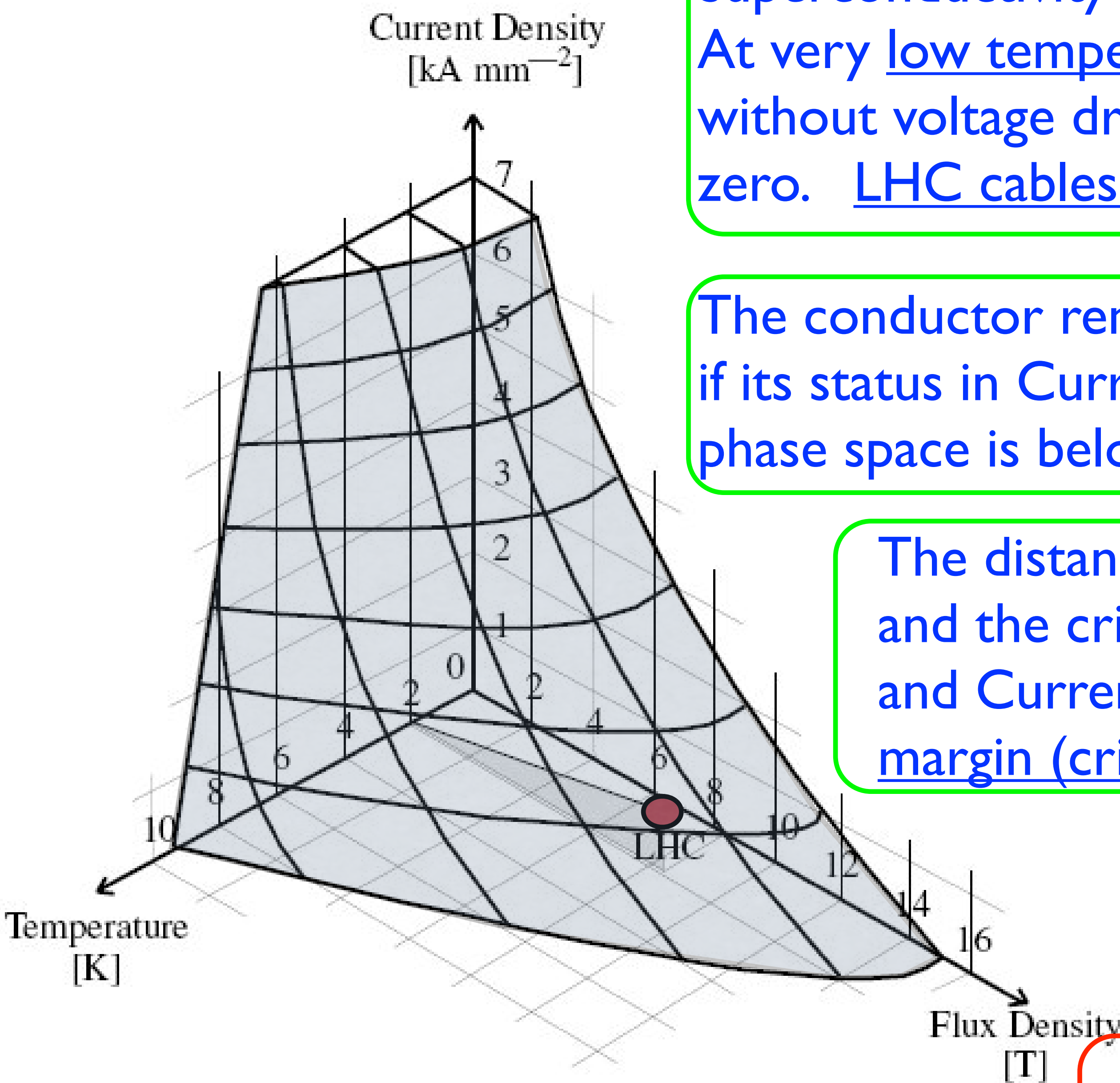
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Questions:

- why so many accelerators and not just the LHC?
- why rings of increasing circumference?
- why rings and linear accelerators?
- how particles go from one machine to the other?

Thanks for your attention!!!

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)

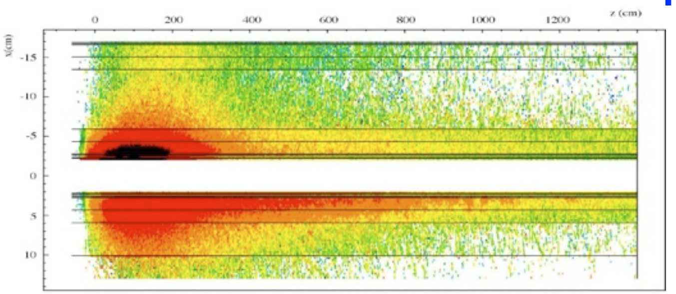
Transition to a normal conducting state is called magnet quench

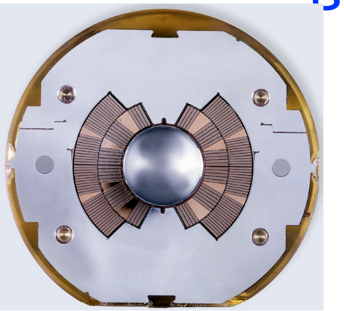
What can increase the temperature in a magnet ?

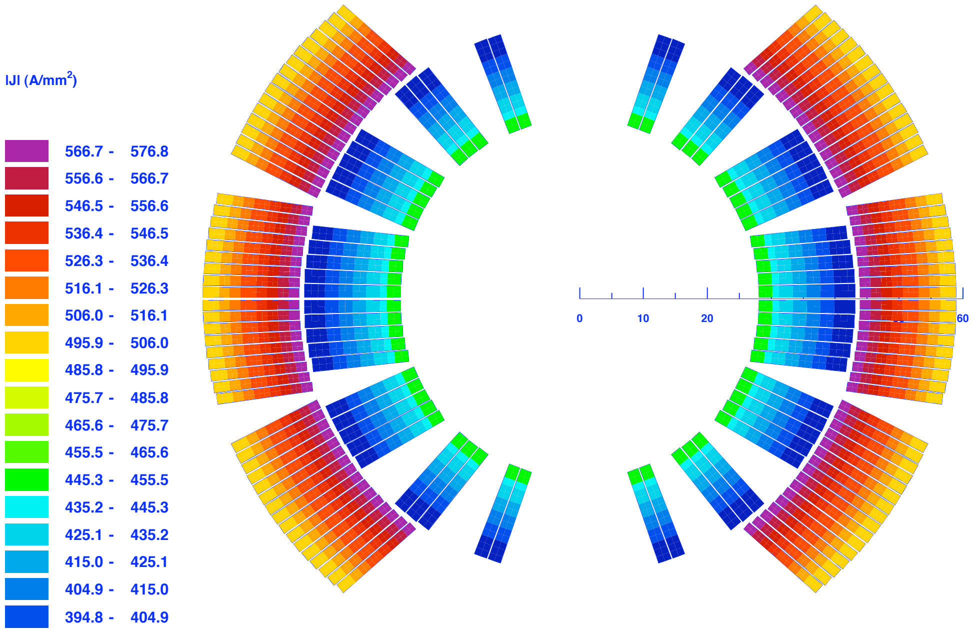
V. V. S. Introduction to Superconductivity II

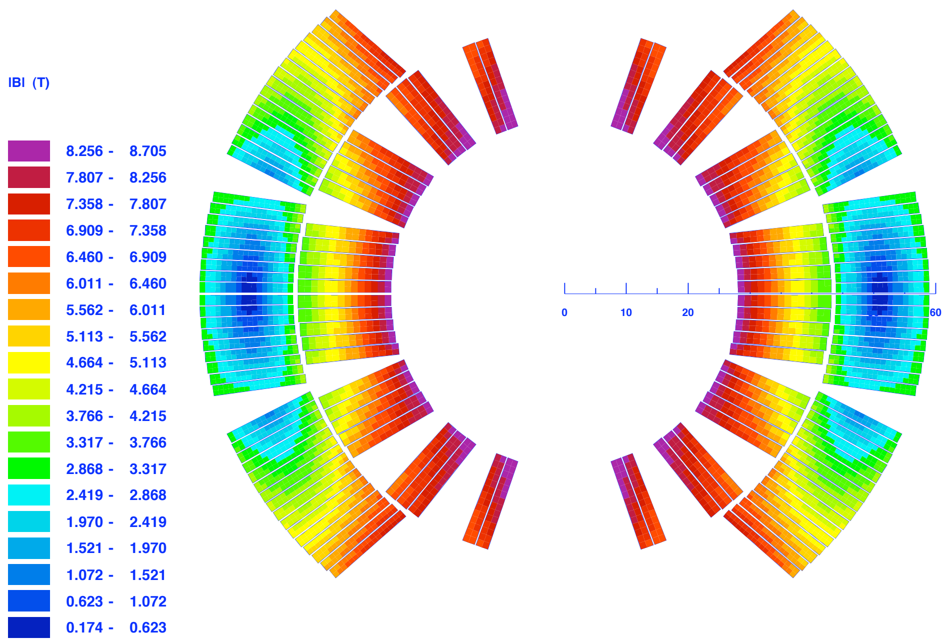
Beam losses can eat the temperature margin because of energy deposition

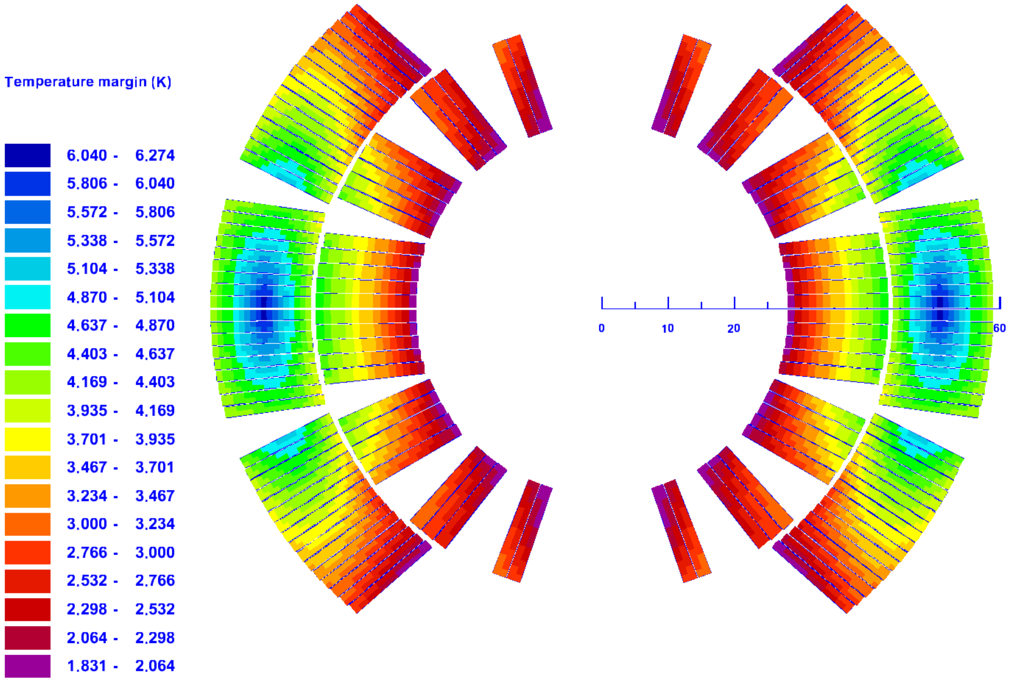
Limit of accepted losses: ~ **10 mW/cm³** to avoid ΔT> 2 K, the temperature margin











Courtesy of Stephan Russenschuck

How much is 10 mW/cm^3 ?

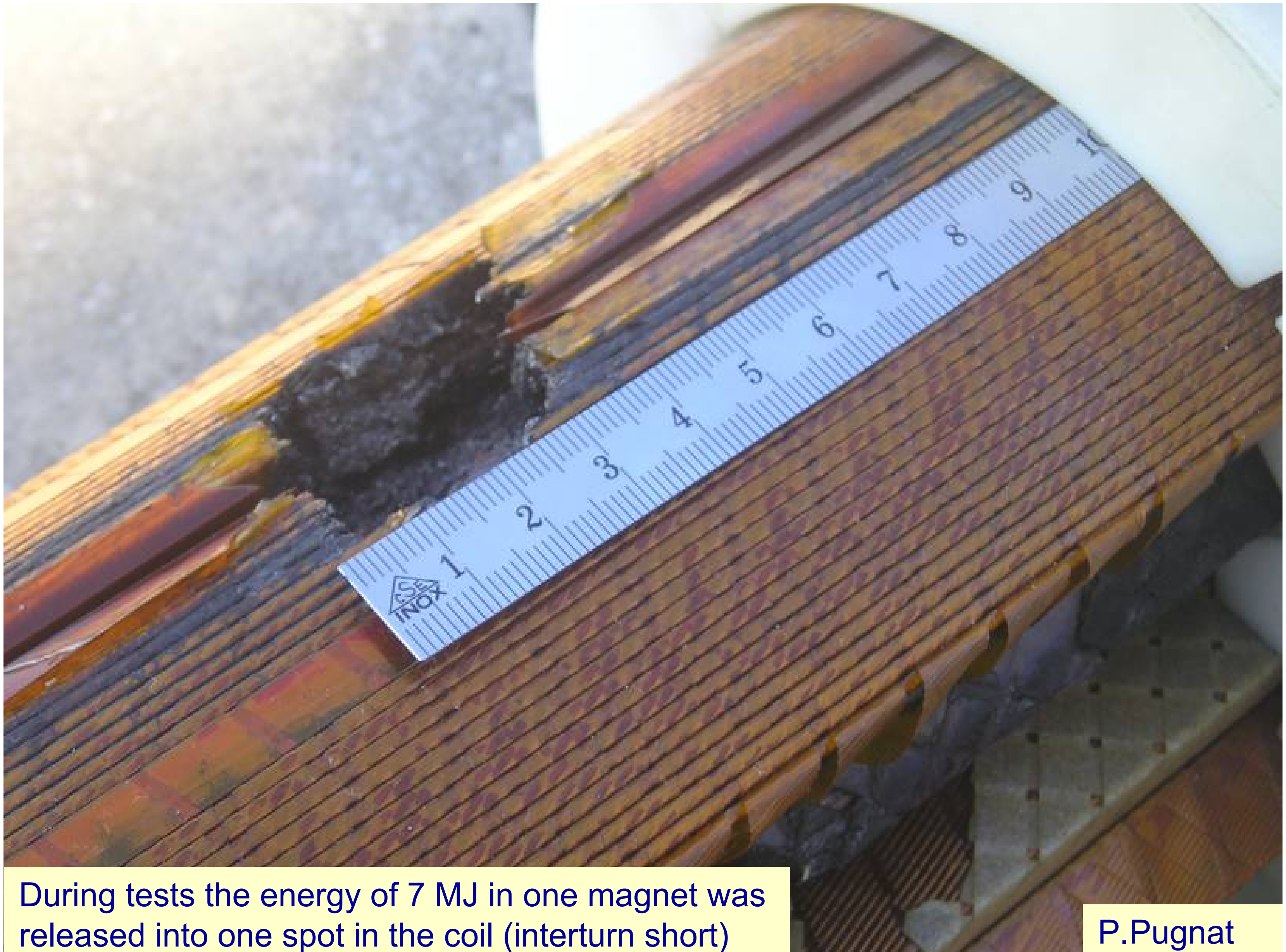
A fluorescente (known as neon) tube can be typically 1.2 m long with a diameter of 26 mm, with an input power of 36 W.

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

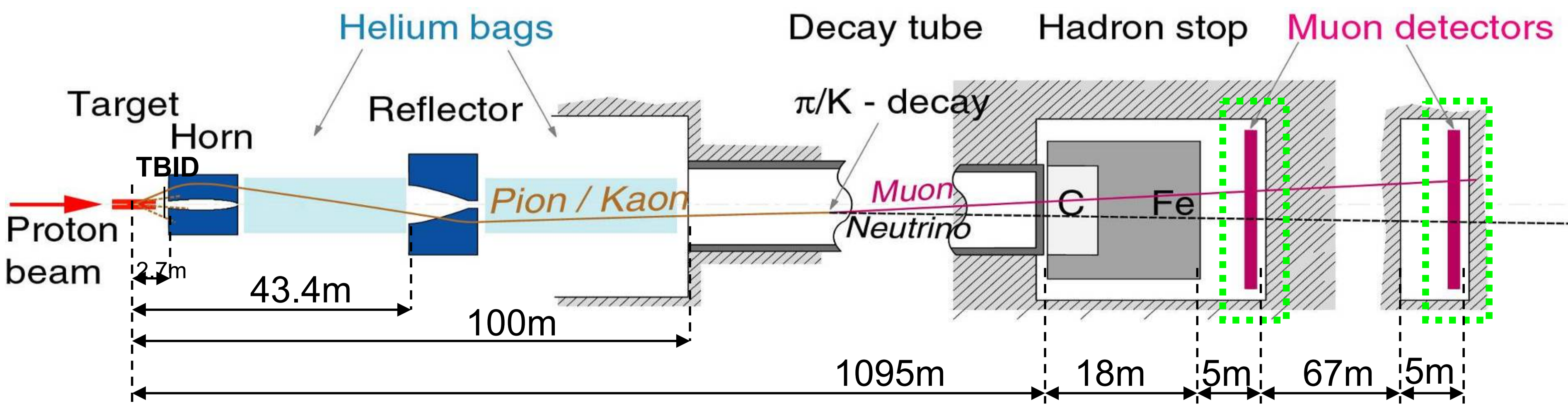
When something goes wrong.... bad quench...

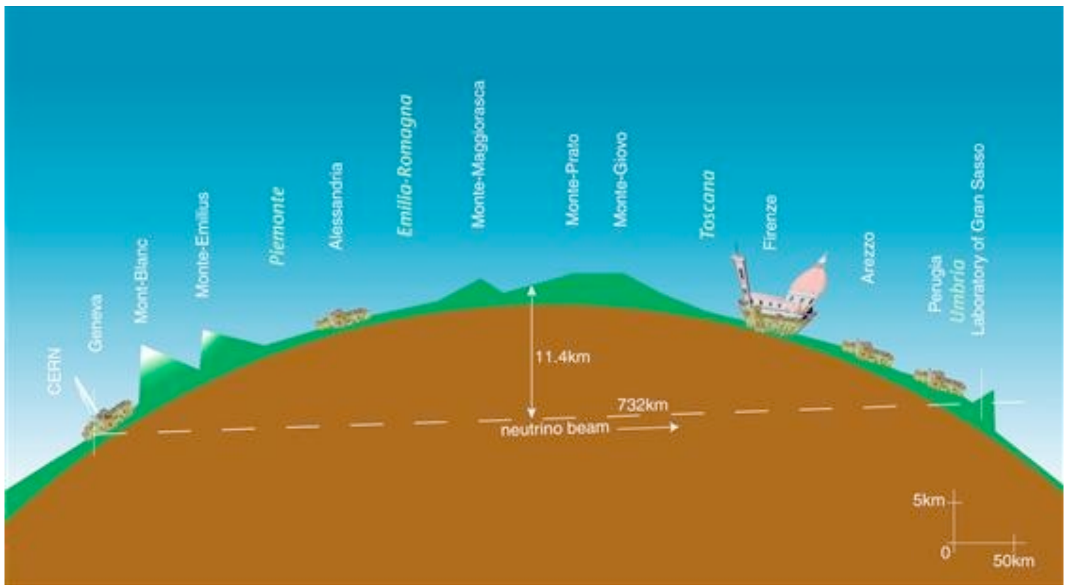


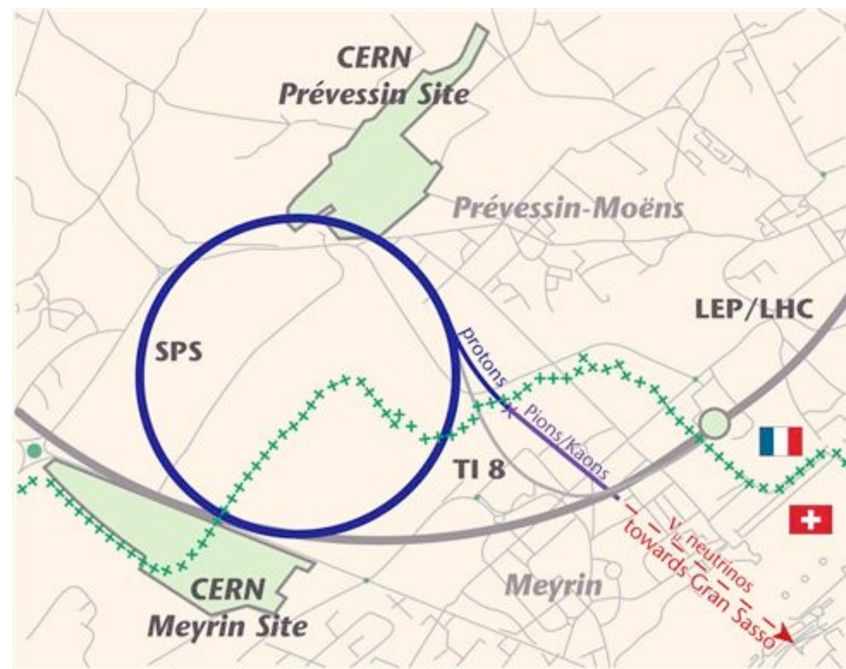
During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short)

P.Pugnat

CNGS, conventional neutrino beam



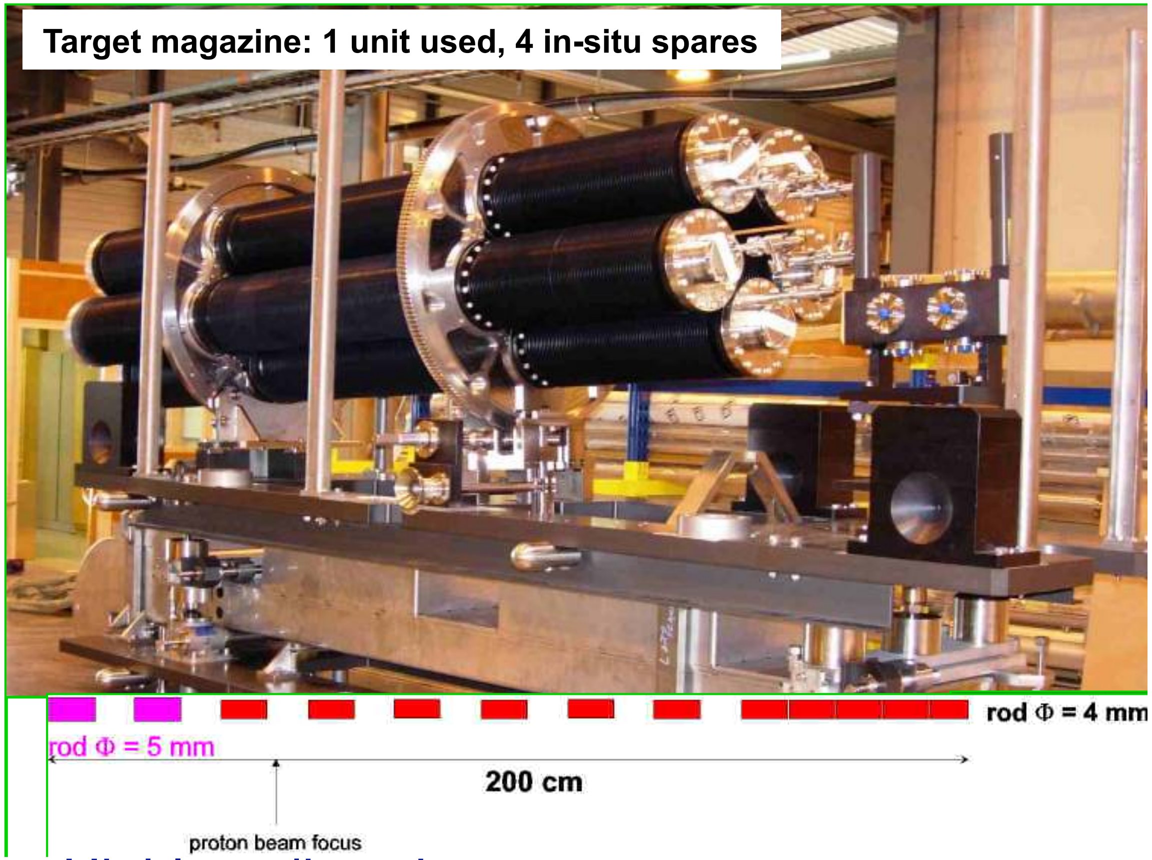


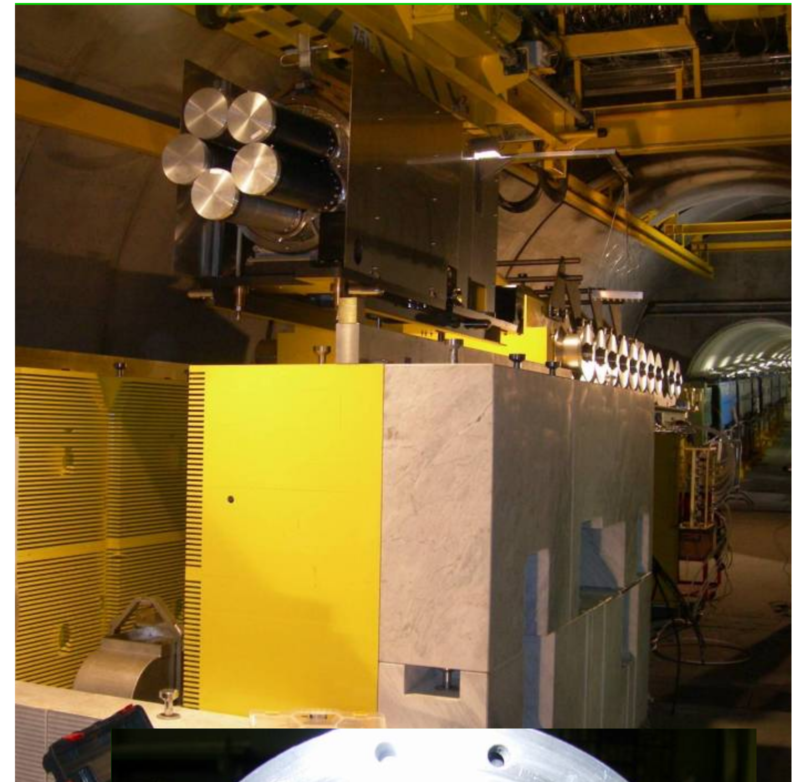


CNGS looks for ν_τ appearance in a beam of ν_μ

The beam is sent from the SPS at 400 GeV/c on the C target. **It is “only” a 450 kW beam**

CNGS target station



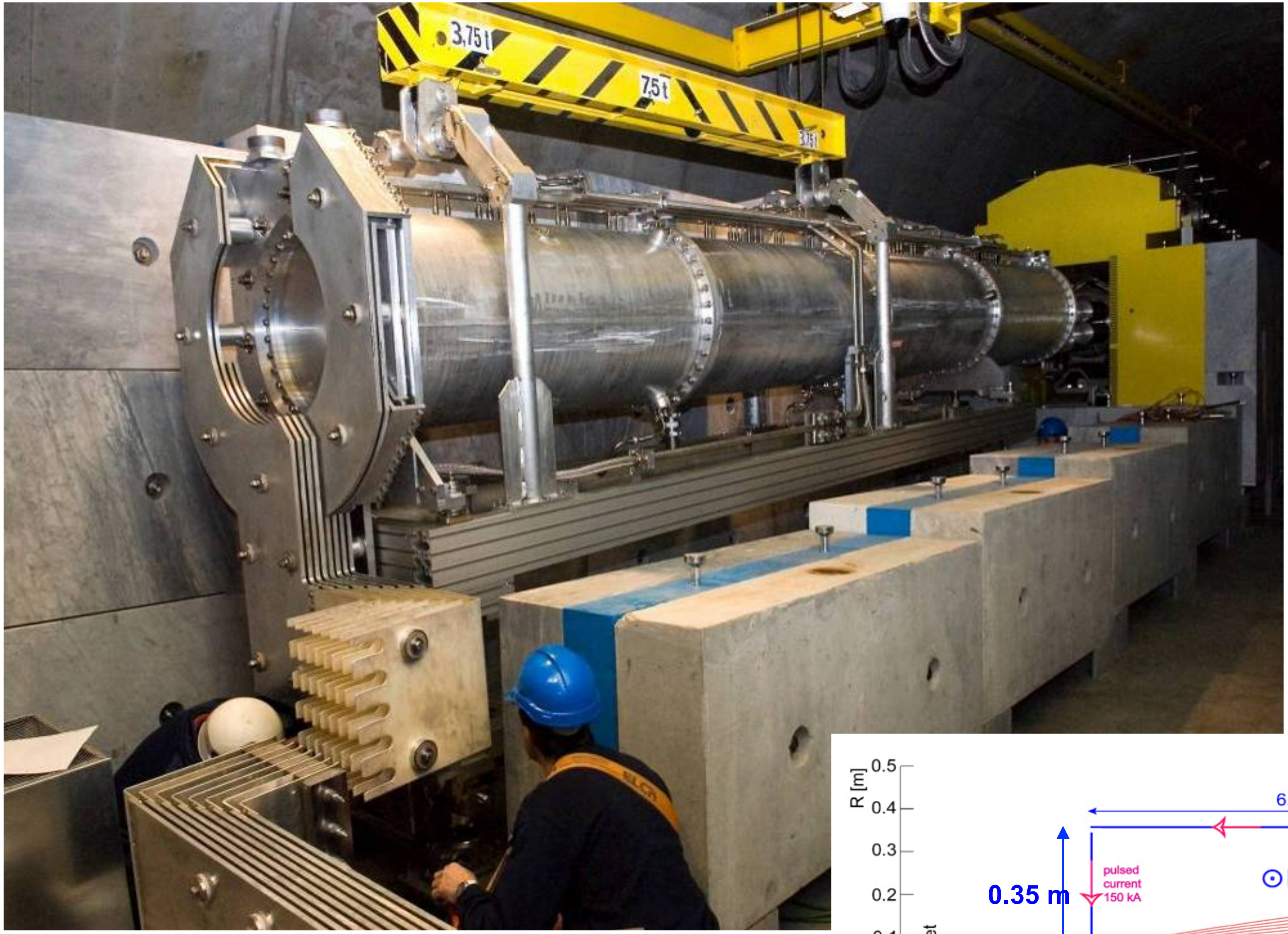


Highly radioactive area.

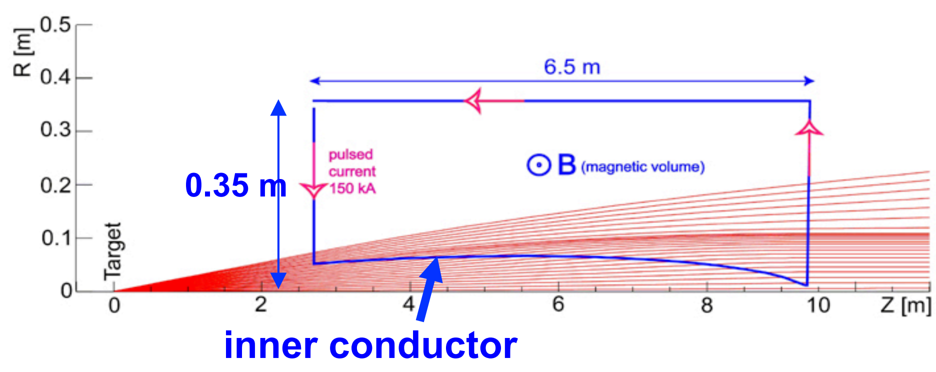
Everything has to be built to be remotely handled

For CNGS, 5 Carbon targets in situ.
One used, the other
four in case of failure (never happened).

CNGS horn

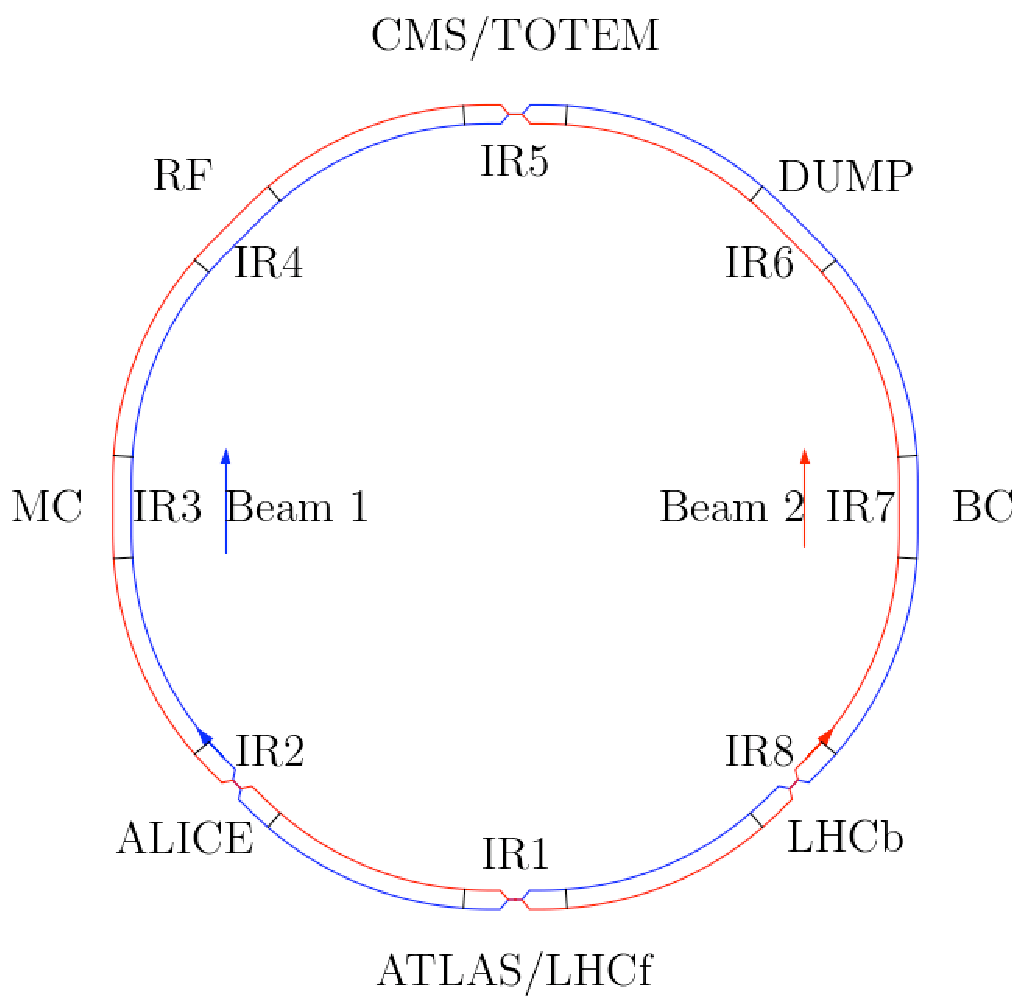


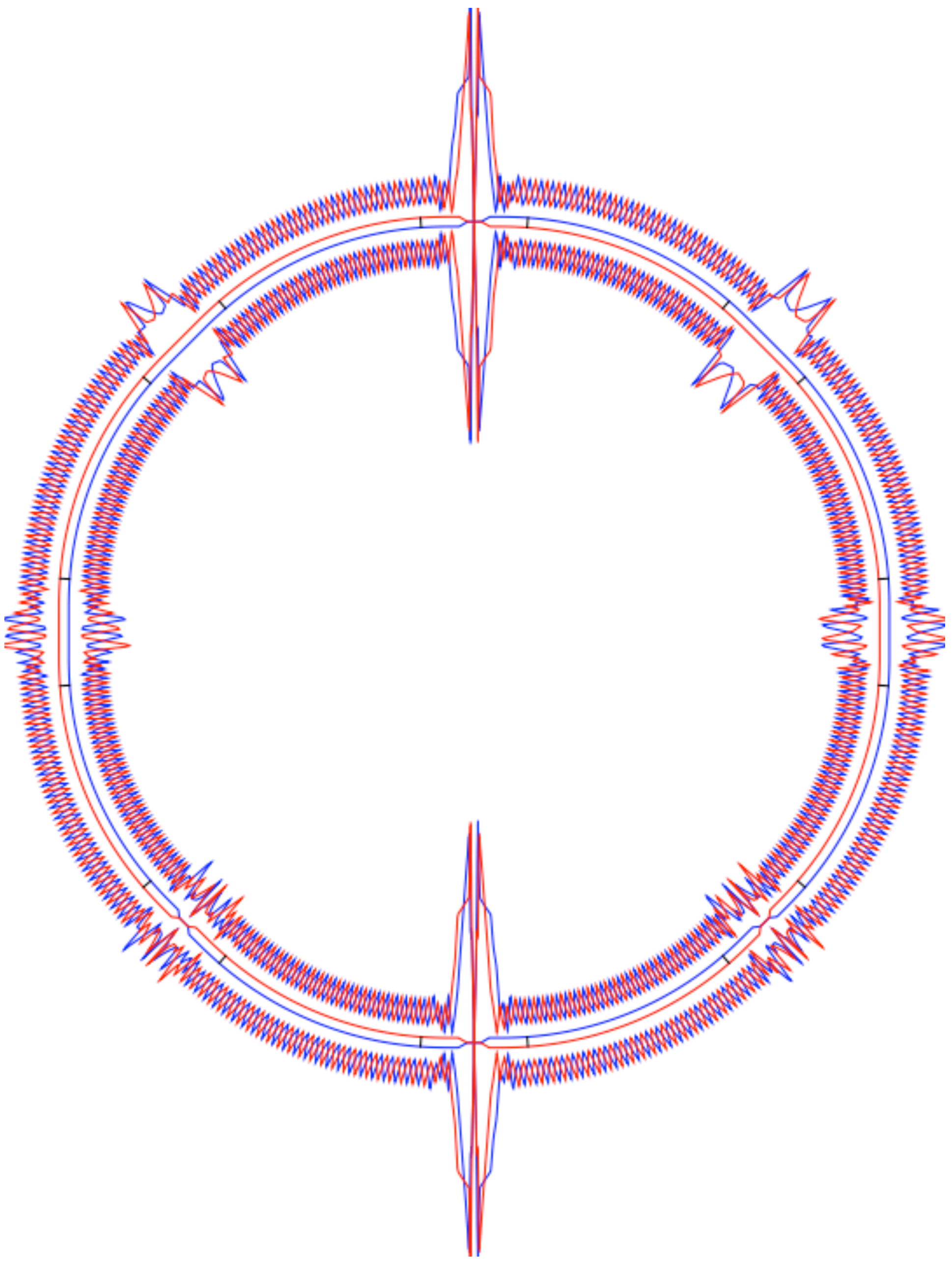
3,75 t
7,5 t
3,75 t



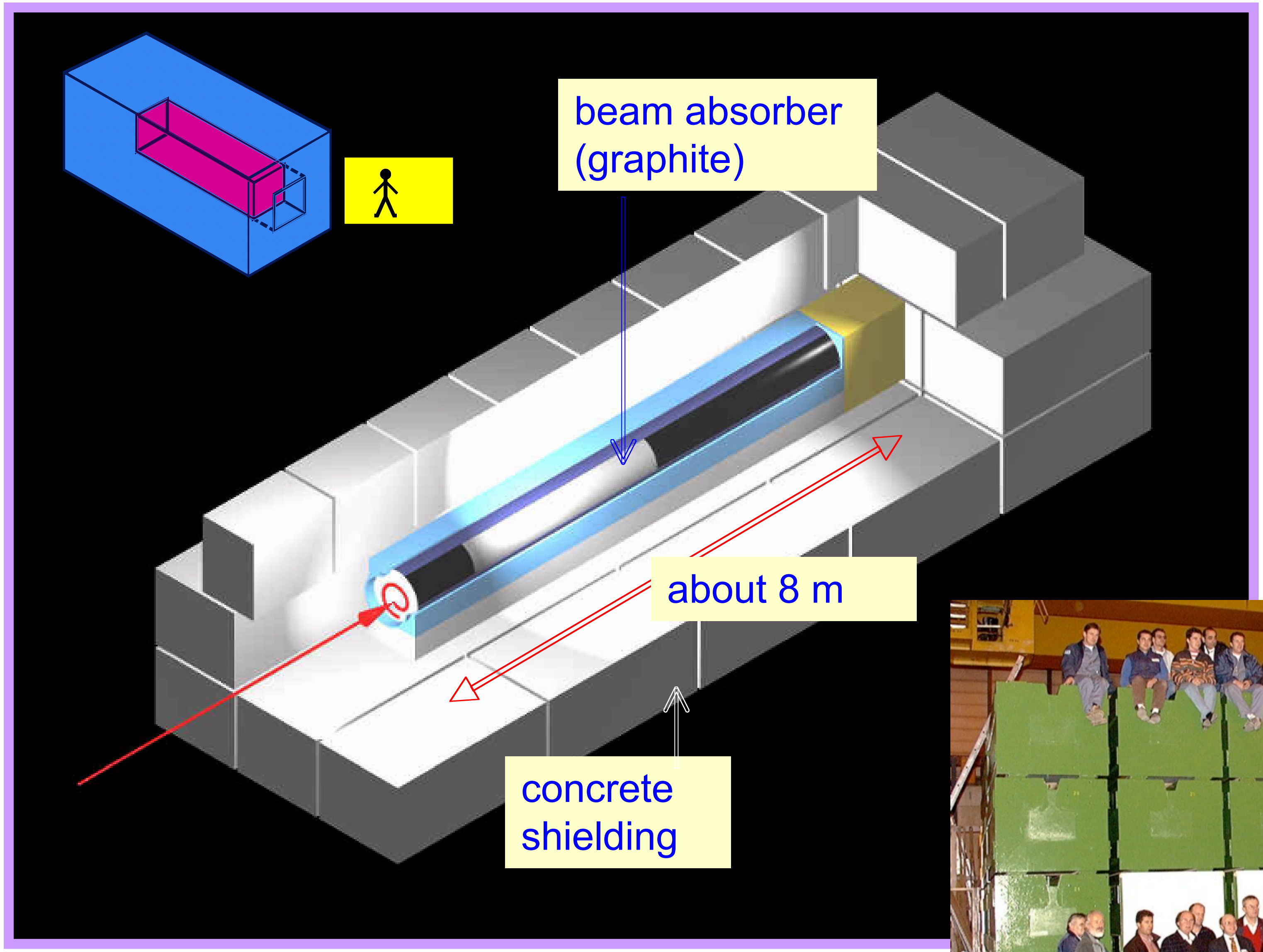
R [m]
0.5
0.4
0.3
0.2
0.1
0
6.5 m
0.35 m
pulsed current 150 kA
B (magnetic volume)
Target
0
2
4
6
8
10
Z [m]
inner conductor

The LHC collision optics in one slide





Scheme of one of the beam absorbers



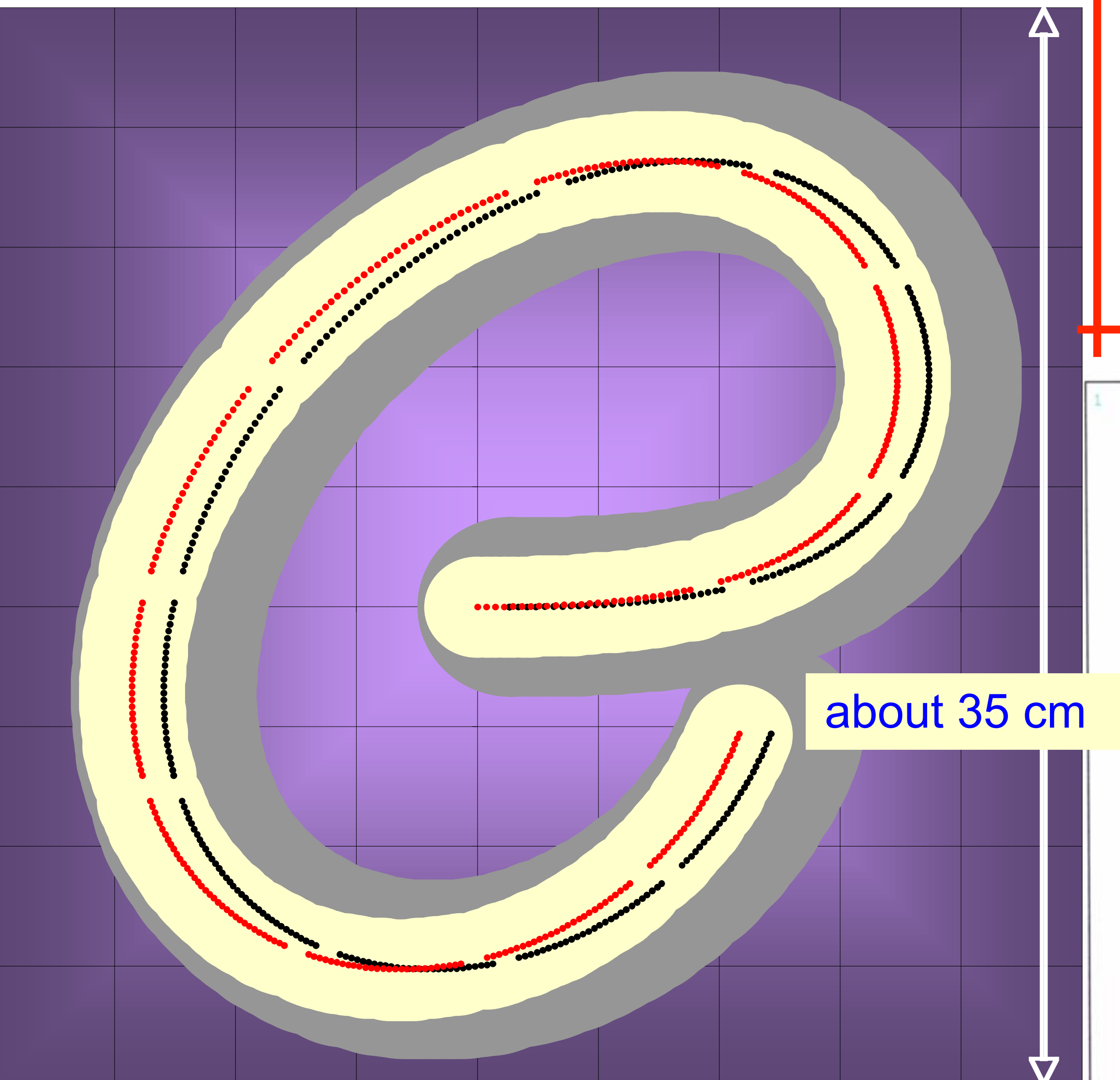
L.Bruno

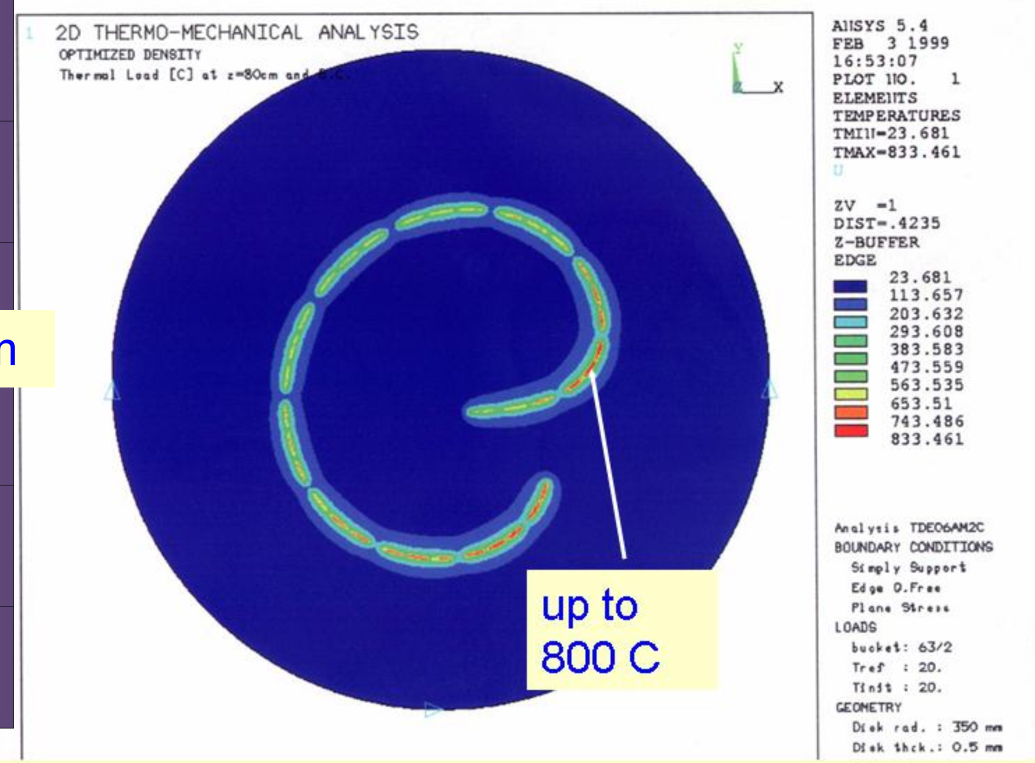
Spot size on the beam dump

To reduce energy deposition peak, proton swept by fast kickers to for a spiral on the transverse face of the dump.

Beam impact in less than 0.1 ms

Even like this, maximum temperature rise about 800 C.





L.Bruno: Thermo-Mechanical Analysis with ANSYS

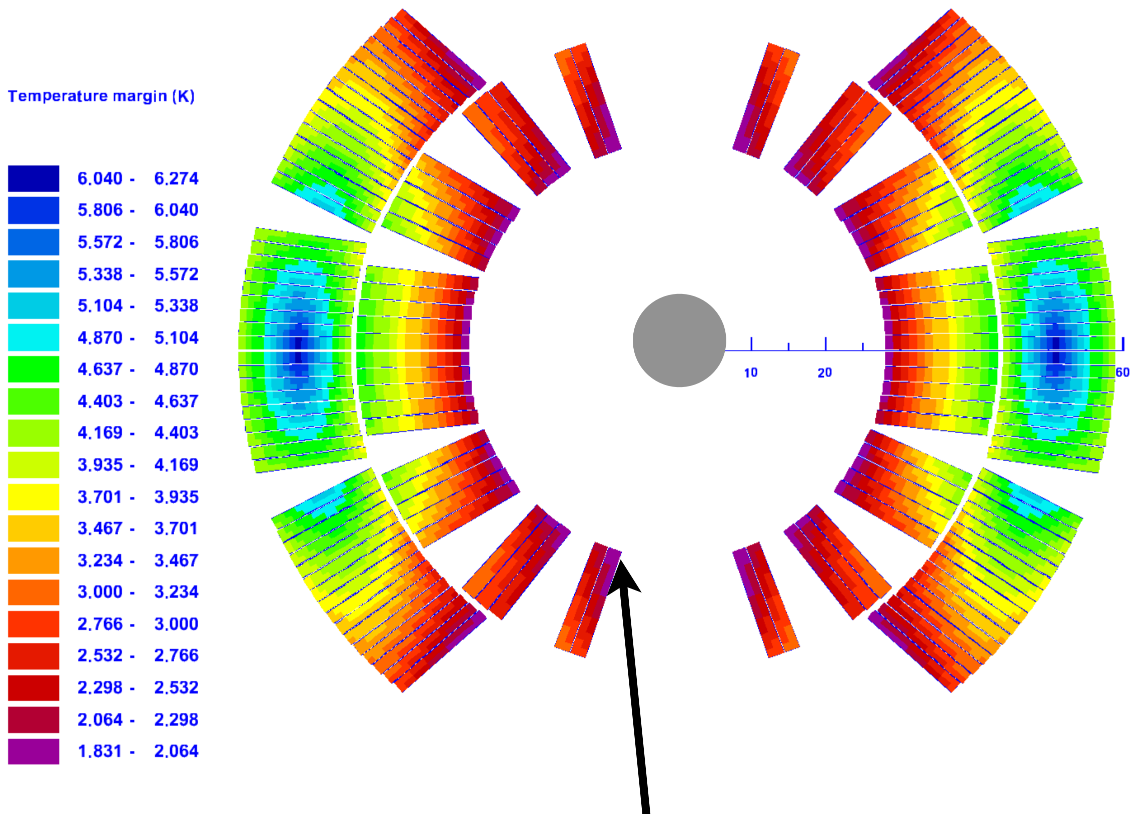
Few numbers for dipoles

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.

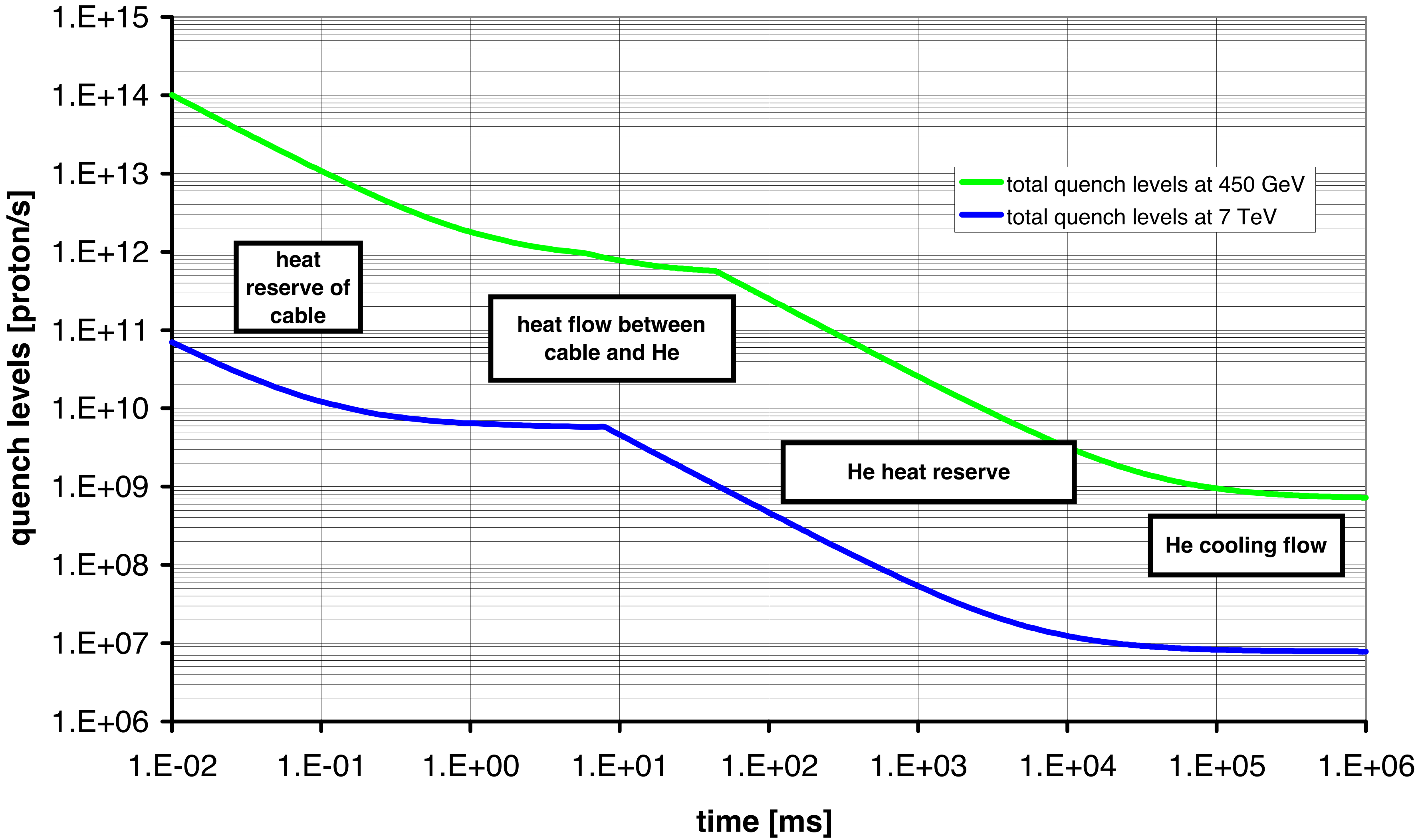
The different time scale of the two processes helps:

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.

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....

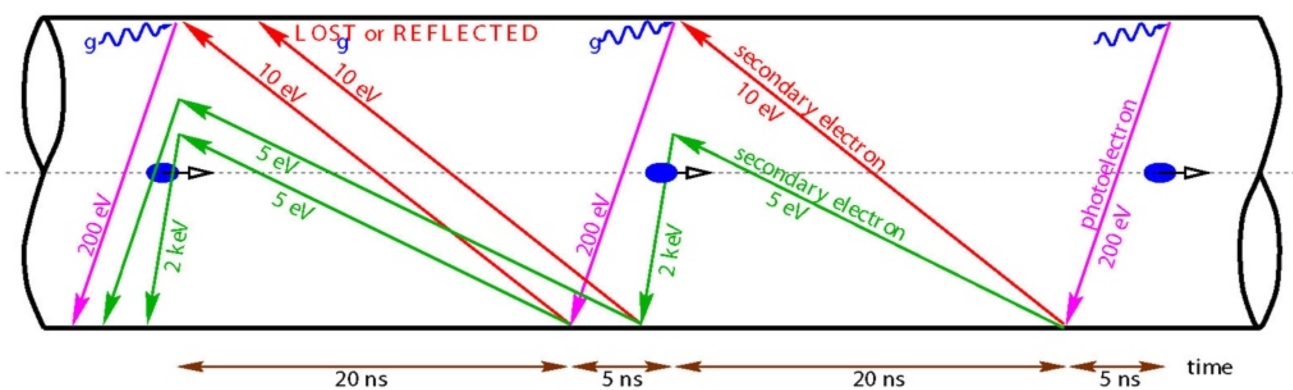


Electron clouds

Electron cloud in the vacuum beam pipe can be created by "avalanche" process :

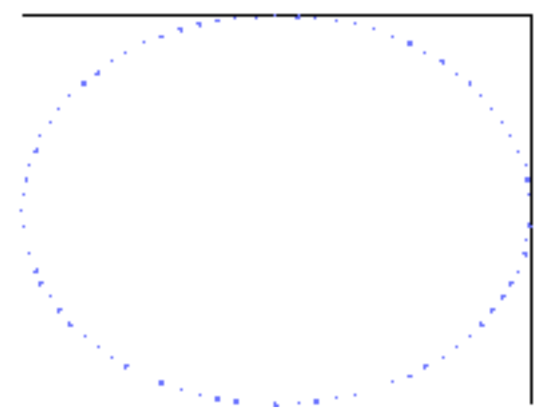
1. few primary e⁻ generated by as photoelectrons, from residual gas ionization, extract by Synchrotron radiation
2. p+ bunches accelerate e⁻ (this depends from the bunch separation, i.e. 25 nsec in the LHC)
3. e⁻ impact on the wall and extract secondary e⁻

and so on ... and the cloud can generate:
a) heating of the beam pipe ⇒ magnet heating b) beam instabilities



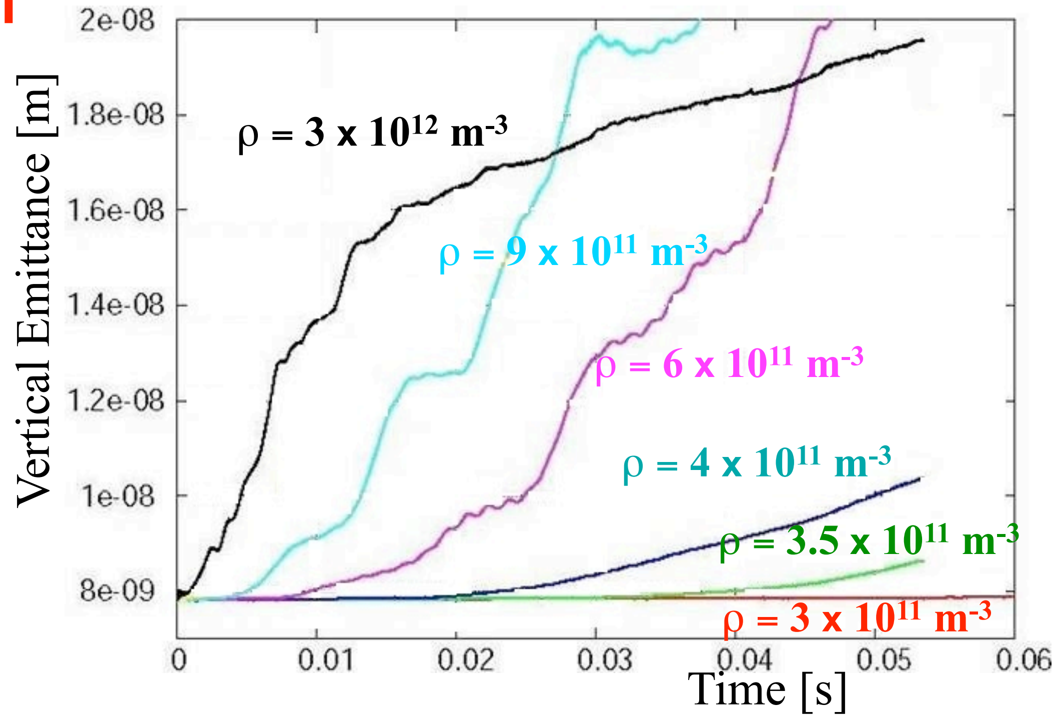
(Courtesy F.Ruggiero)

Animation from O. Brüning simulation
→ 10 subsequent bunch passages
Color describes the formation of the electron cloud

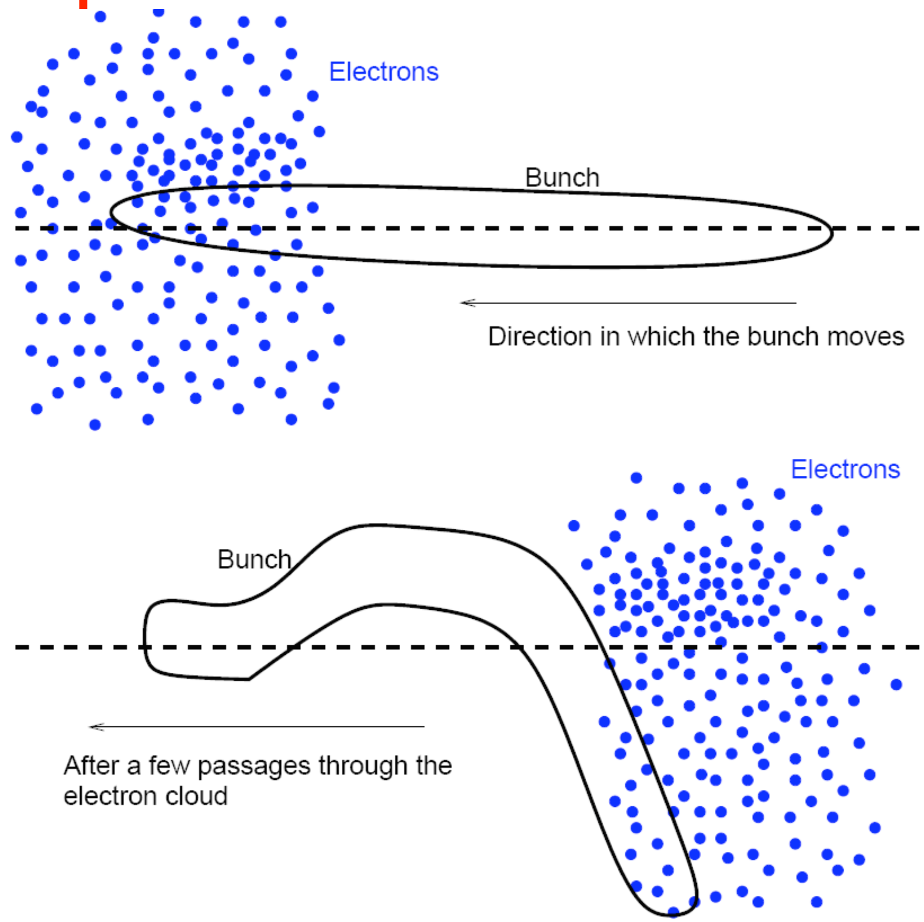


Electron clouds issues on beam

1. Bunch passage, electrons accumulated near beam centroid
2. If there is offset between head and tail:
   → tail feels transverse electric field created by head
   → tail become unstable
3. Particles mix longitudinally
   → also head can become unstable (above threshold)



Vertical emittance vs. time, for different EC densities @ LHC injection

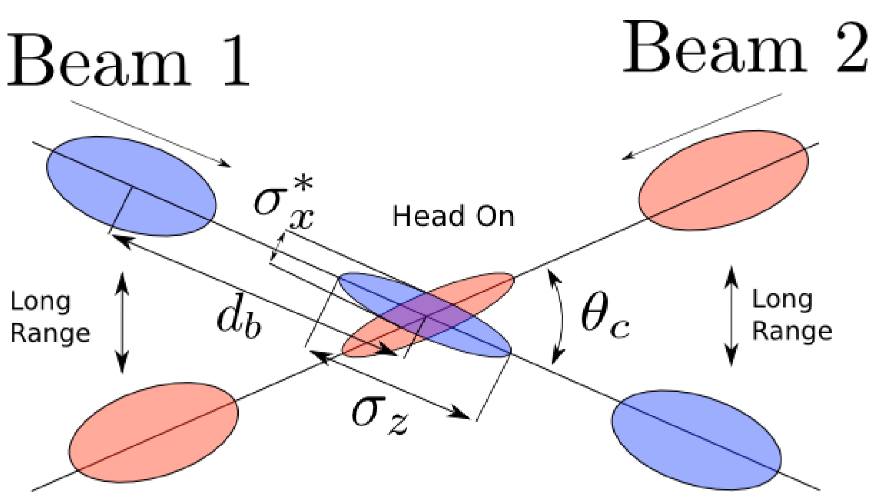


From E. Benedetto

Few LHC numbers ...

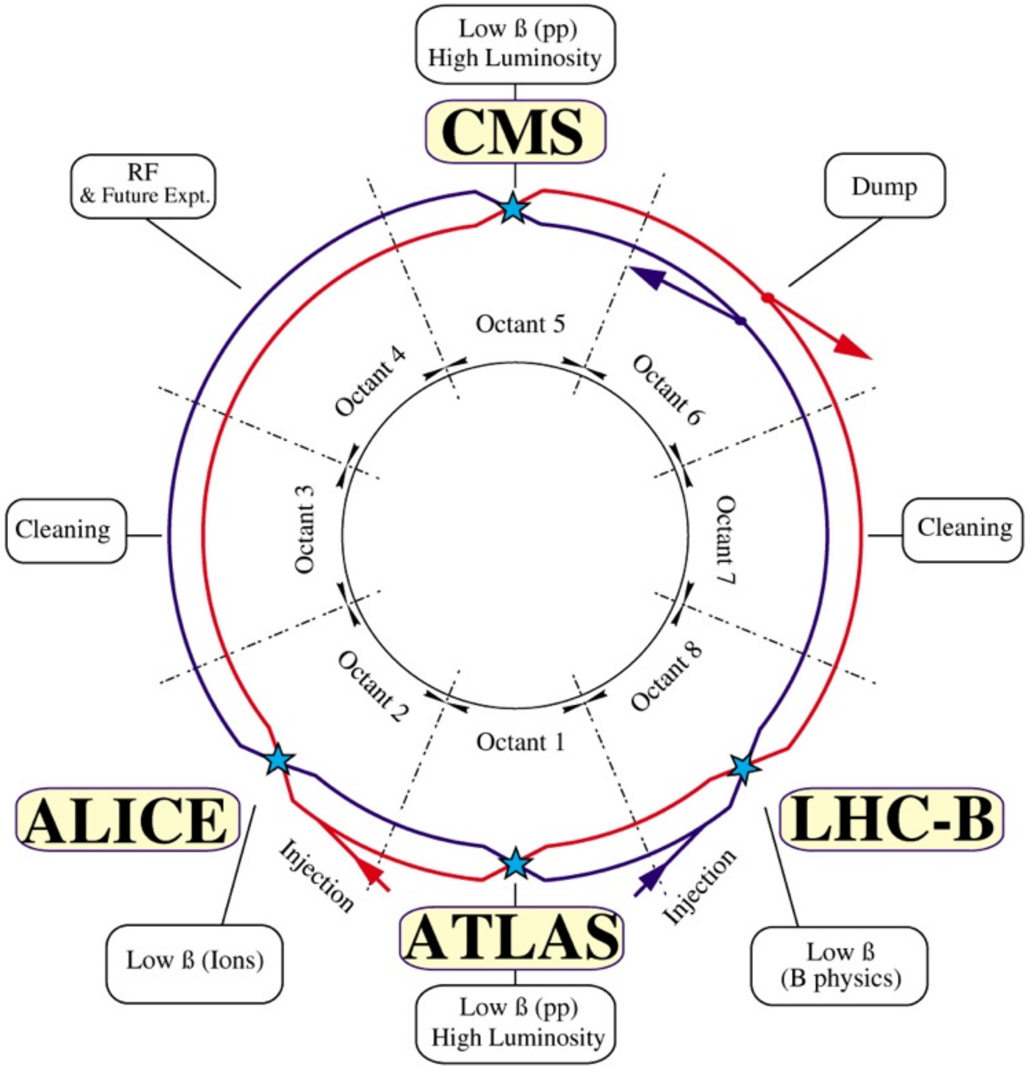
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

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



Luminosity	1 10^{34} /cm²/s (IP1 IP5)
Particle per bunch	1,15 10^{11}
Bunches	2808
Revolution frequency	11,245 kHz
Crossing rate	40 MHz
Nomalised 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

LHC layout and few parameters

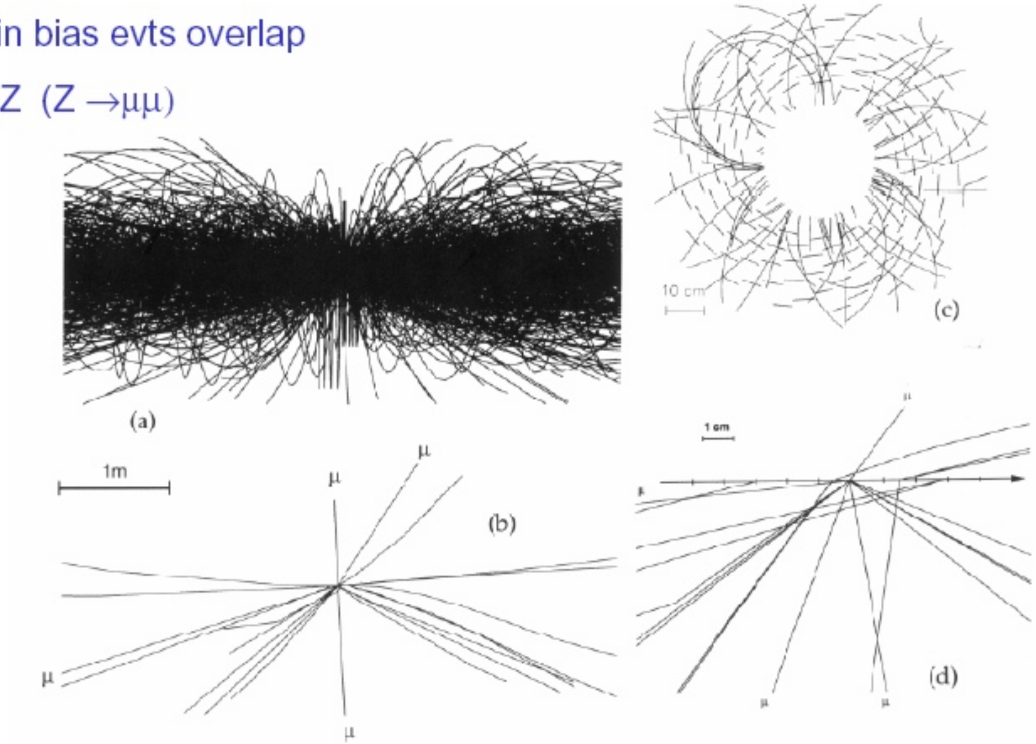


Particle type	protons (heavy ions, Pb82+)
Energy	450 GeV (injection) 7 TeV (collision energy) 2,75 TeV/u (ions collision)
Circumference	26658 m
Revolution frequency	**11,245 kHz** **1 turn= 89 mus**
Number of rings	1 (two-in-one magnet design)
Number of accelerators	2 (2 independent RF system)
Interaction 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

Crossing angle

20 min bias evts overlap

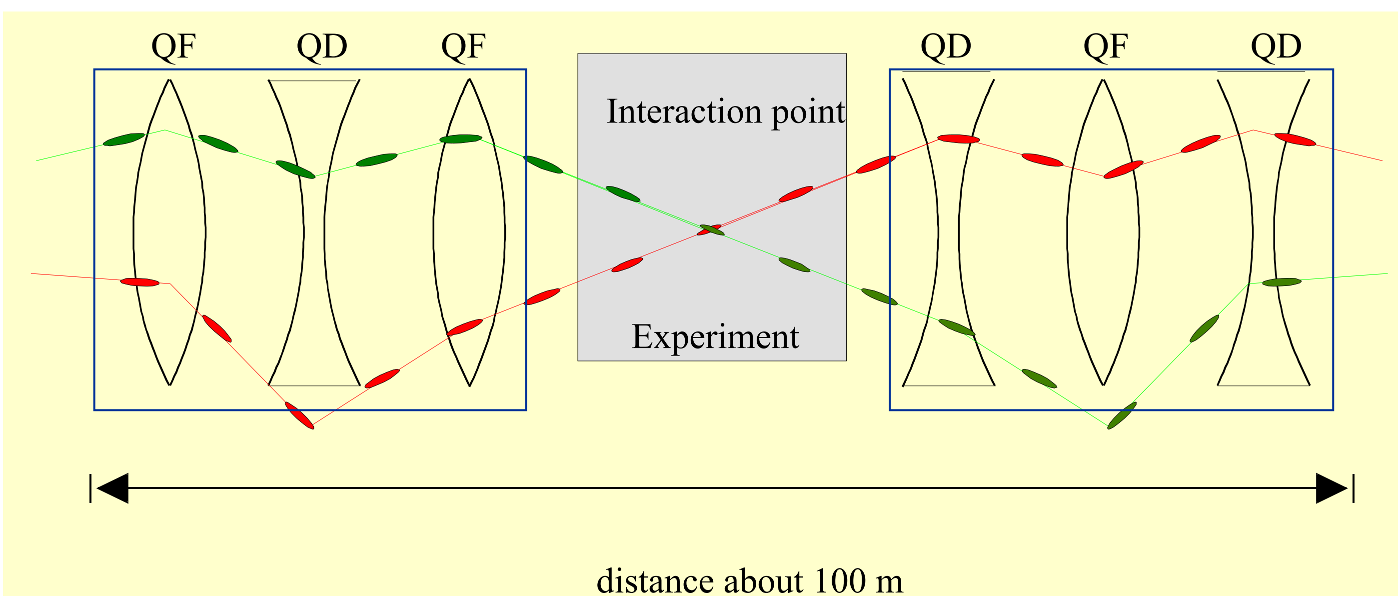
H→ZZ (Z →μμ)



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

Definition of beam emittance

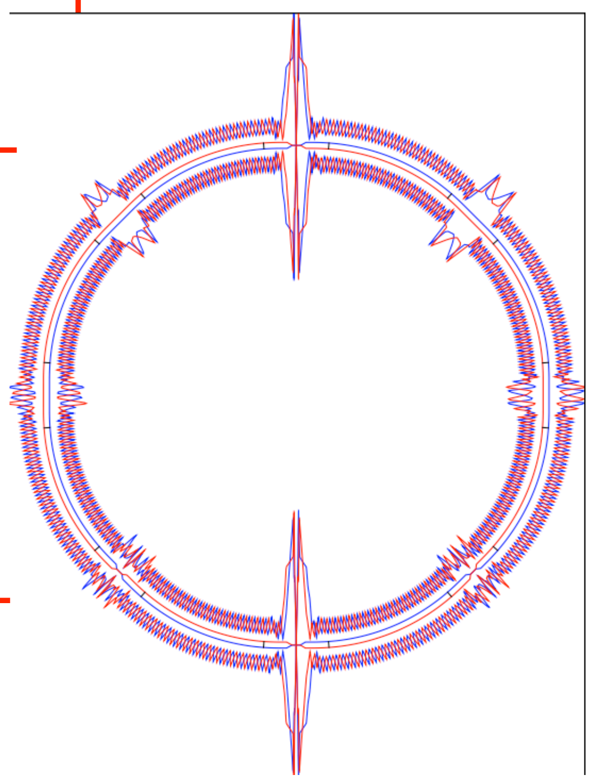
$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y} \cdot \epsilon_{x,y}}$$

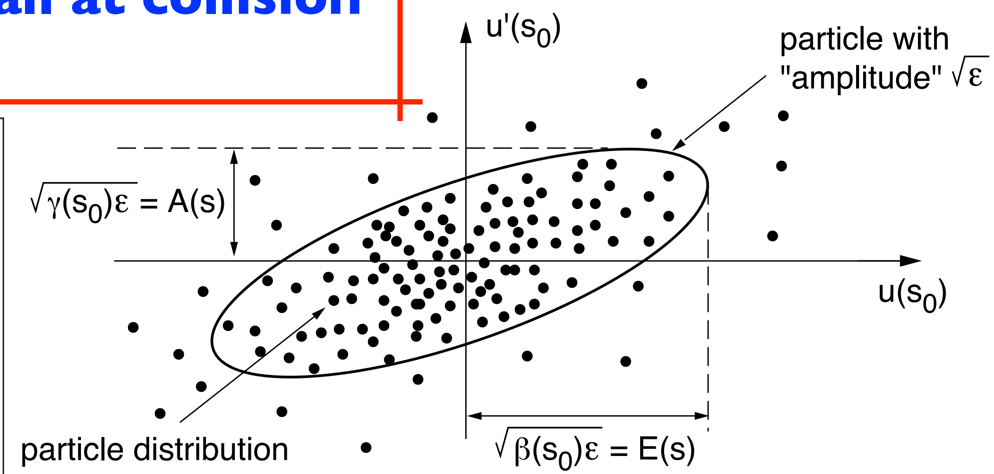
Beam physical dimension

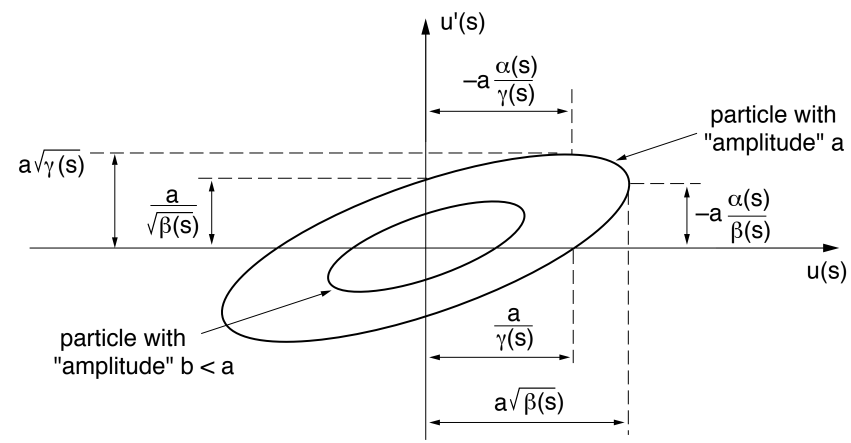
Optical machine parameter that depends on the lattice of the machine, in particular on the **QUADRUPOLES.**
Beta has to be small at collision at the IP

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, <u>one can compute the beam dimension in the entire LHC</u>

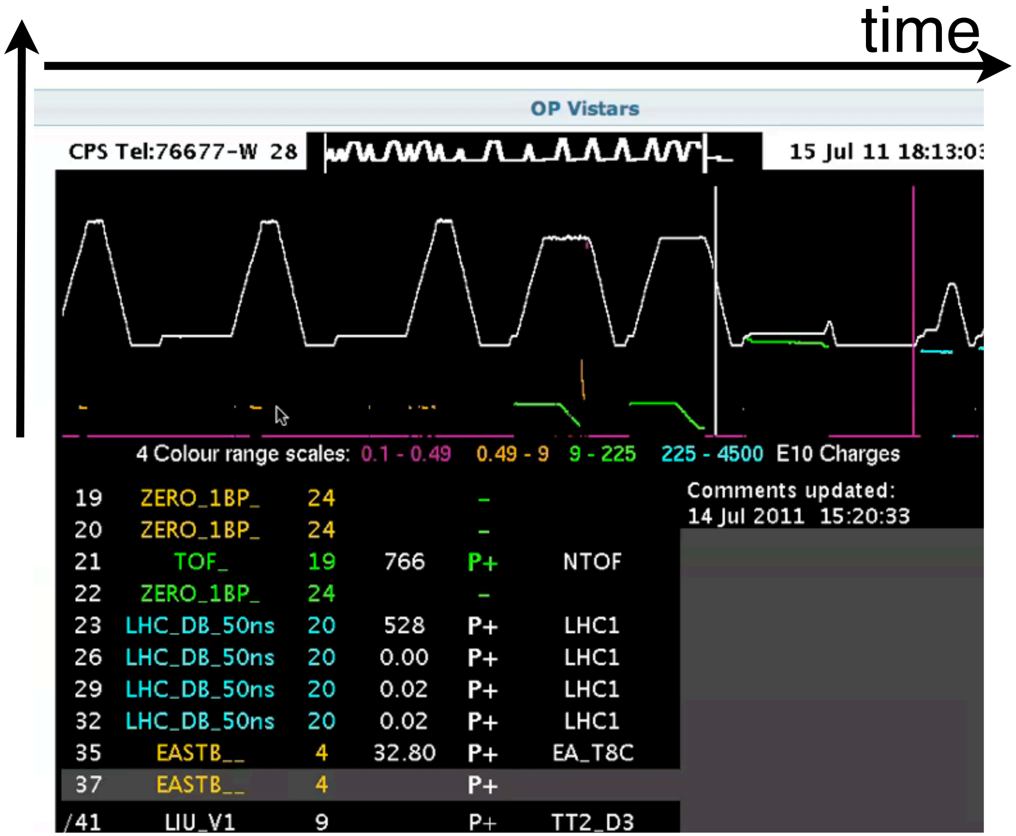






An example of cycling machine: the CERN-PS (Proton Synchrotron)

B(t) or E(t)



$$\frac{dB}{dt} = 24\, G/ms$$

PS is a slow synchrotron: pulses every 1.2 s (or multiples)

PS radius: 100 m

Injection: B = 1013 G (0.1013 T) E = 1.4 GeV

Extraction (max): 12000 G (1.2T) E ~ 26 GeV

Which coolant ? Liquid superfluid helium

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