Introduction to accelerators

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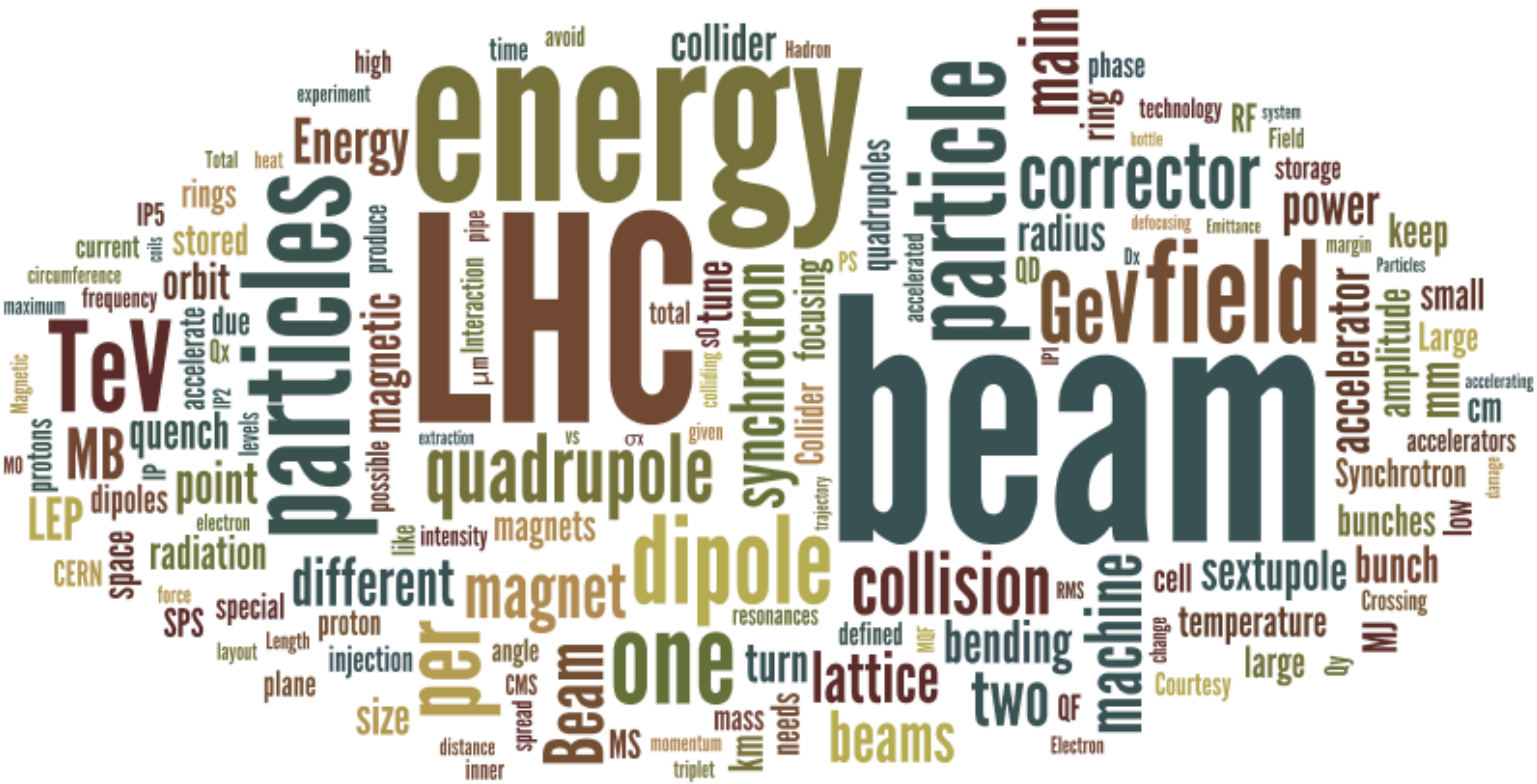
The agenda...


energy
LHC
beam
particle
particles
corrector
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GeV
TeV
quadrupole
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collision
one
magnet
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synchrotron
per
Beam
main
Energy
collider
different
machine
two
turn
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accelerator
magnetic
quench
point
radiation
orbit
MB
LEP
radius
keep
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technology
phase
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avoid
high
experiment
Hadron
RF
system
Field
bottle
Total
heat
rings
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current
IP5
coils
circumference
frequency
maximum
accelerate
due
Qx
IP2
levels
IP
protons
MO
Magnetic
dipoles
electron
CERN
space
force
SPS
special
layout
Length
proton
injection
plane
angle
CMS
size
spread
distance
inner
MS
momentum
triplet
mass
km
needs
resonances
defined
MQF
quadrupoles
accelerated
focusing
PS
QD
tune
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s0
colliding
Collider
trajectory
given
extraction
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Interaction
pipe
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possible
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IP1
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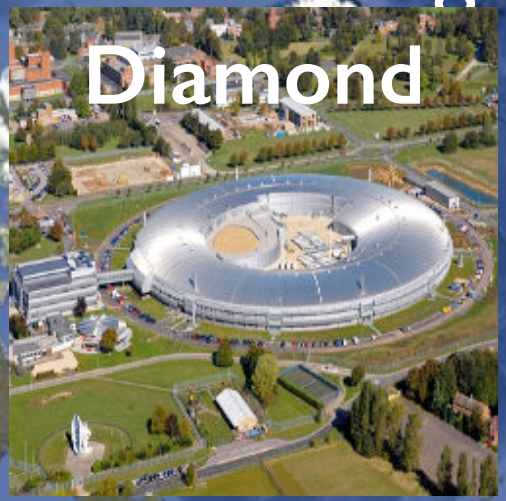
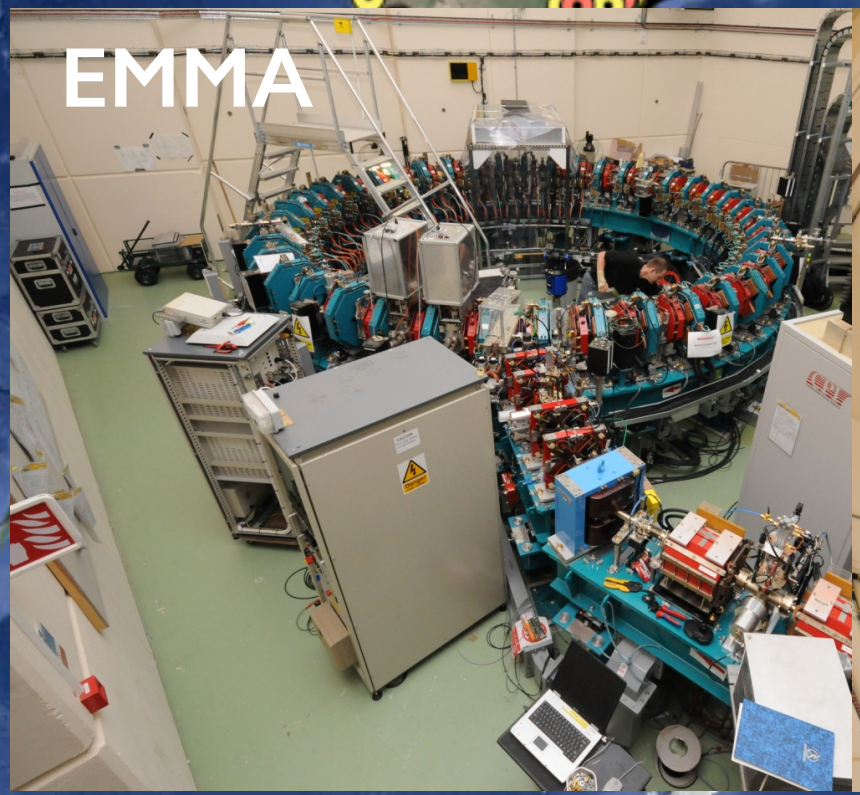
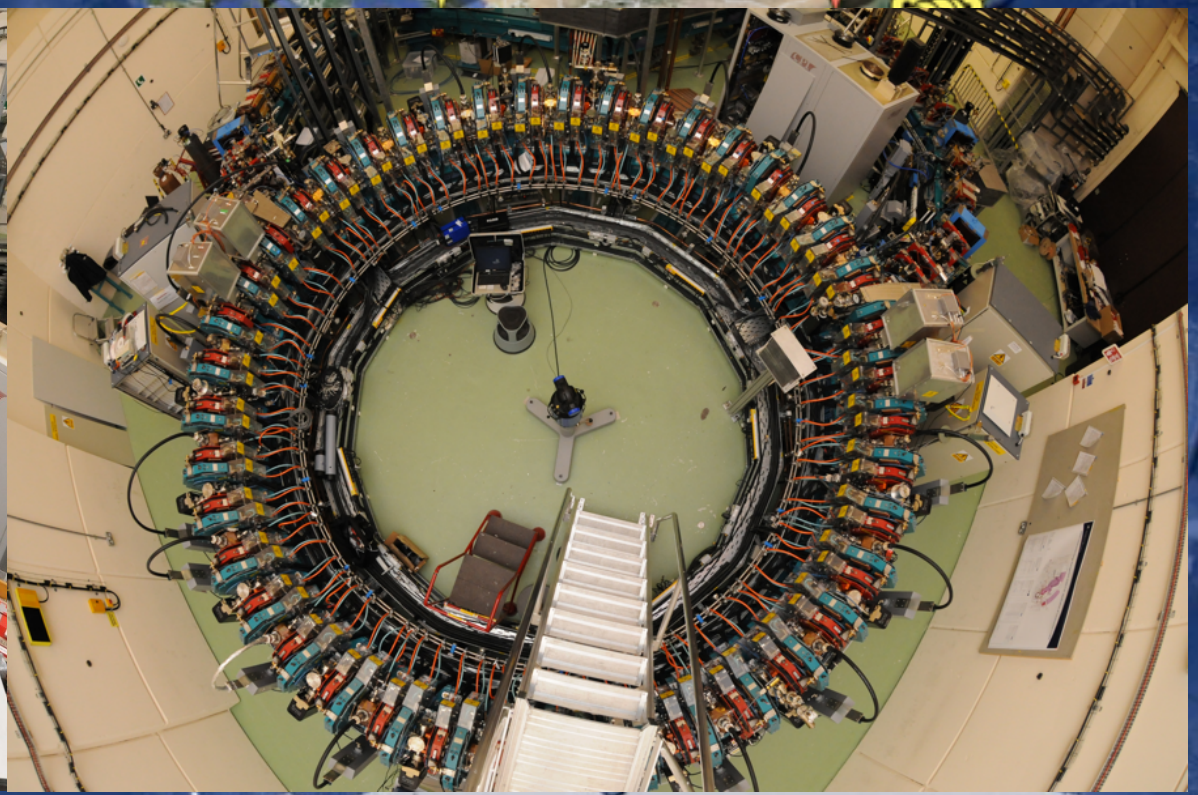
Emittance
margin
Dx
Particles
amplitude
mm
Large
accelerating
cm
accelerators
Synchrotron
damage
low
bunches
bunch
Crossing
MJ
Qy
cell
RMS
temperature
large
change
Courtesy
QF
Electron

A Google view of high energy accelerators







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بيروت
Zahle
زحلة
Baalbek
بعلبك
Yabrud
يبرود
Beit Al Dine
بيت الدين
Ad Dumayr
الضمير
Damascus
دمشق
Rachaiya
راشيا
Sidon District
صيدا
Al-Qisa
قيسا
Sour
صور
Nabatieh
النبطية
Jdaydet Artooz
جديدة عرطوز
Qana
قانا
Nahariya
Safed
Nawa
نوى
Izraa
ازرع
Acre
Karmiel
Haifa
Kiryat Ata
Tiberias
As Suwayda
السويداء
Nesher
Nazareth
Daraa
درعا
Zihron Ya'akov
Afula
Irbid
اربد
Umm al-Fahm
Hadera
Jenin
Al Hosn
الحصن
Al Mafraq
المفرق
Netanya
Jarash
جرش
Tel Aviv-Yafo
Amman
عمان
Or Yehuda
Al-Bireh
Rishon Le Tsiyon
Jerusalem
Madaba
Ashkelon
Beit Shemesh
Al Jiza
الجيزا
Gaza
Kiryat Gat
Yata
Suwaqa Al Gharbiya
سواقة الغربية
Rahat
Khan Yunis
Dahriya
Be'er Sheva
Arad
Arish
Rafa
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Terms of Use

PRESS RELEASE

3 September 2014

SESAME'S 800 MEV BOOSTER SYNCHROTRON IS NOW IN OPERATION

© 2014 SESAME: SESAME's Booster

http://home.web.cern.ch/about/updates/2015/04/sesame-passes-important-milestone-cern
http://www.sesame.org.jo/sesame/

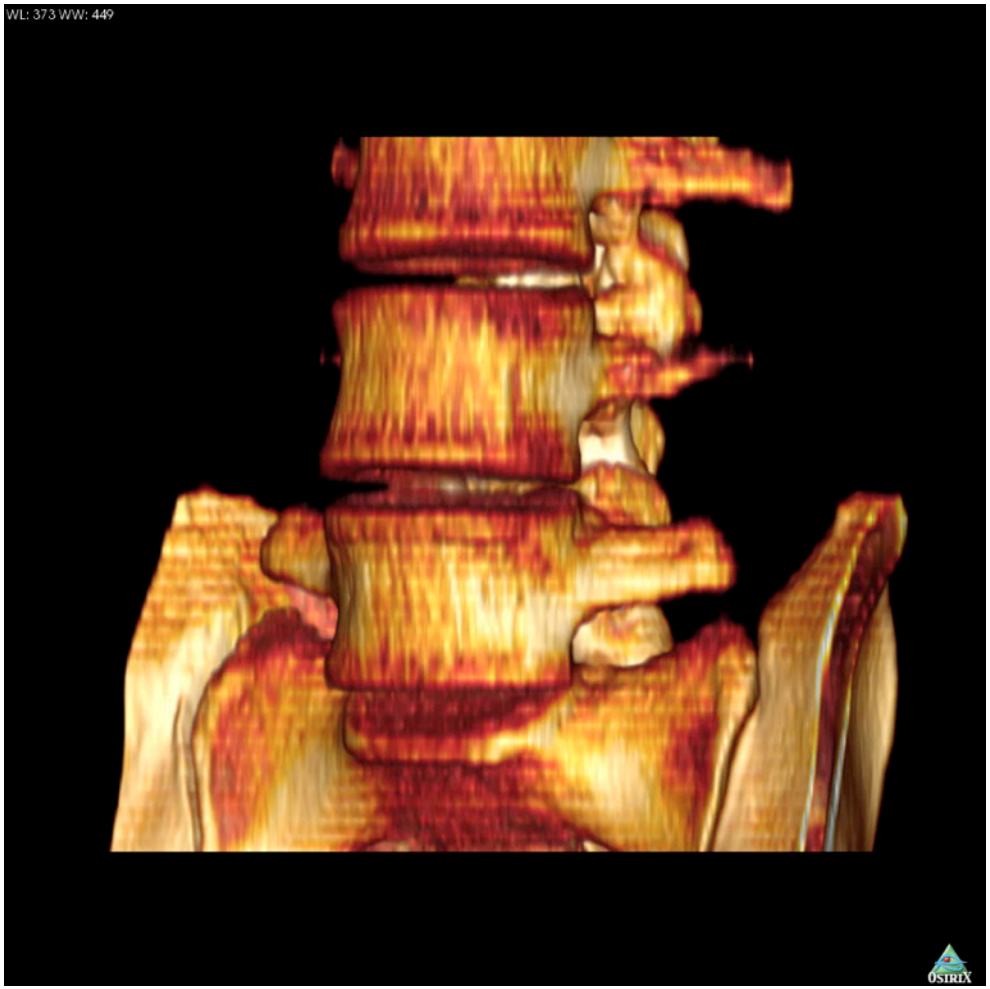
SESAME passes an important milestone at CERN

Posted by Cian O'Luanaigh on 7 Apr 2015. Last updated 7 Apr 2015, 14.58.
Voir en français

An engineer tests the installation of a vacuum chamber for SESAME, at CERN's magnet-testing facility SM18 (Image: Maximilien Brice/CERN)

The SESAME project has reached an important milestone: the first

Medical imagery



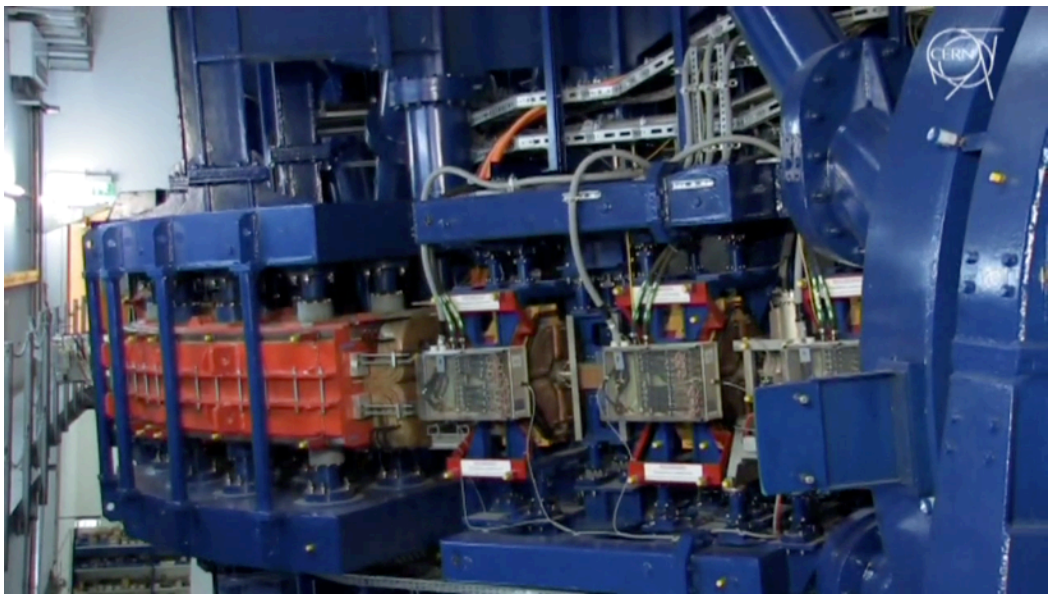
A CT (computerized tomography) scanner,
or CAT (computerized axial tomography).

x-ray machine plus detector, both rotating around the patient

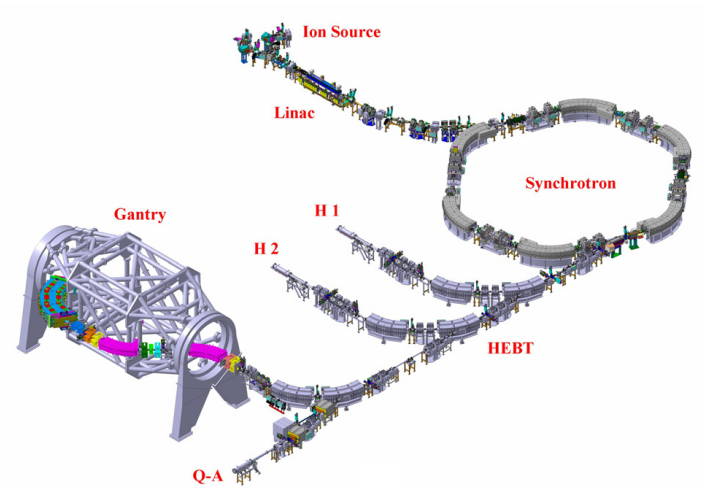
Kind of low energy particle physics fix target experiment

Image reconstruction similar to what we do for beam property diagnosis

Accelerators for cancer therapy



THE HEIDELBERG ION THERAPY (HIT)



CERN accelerator complex overview

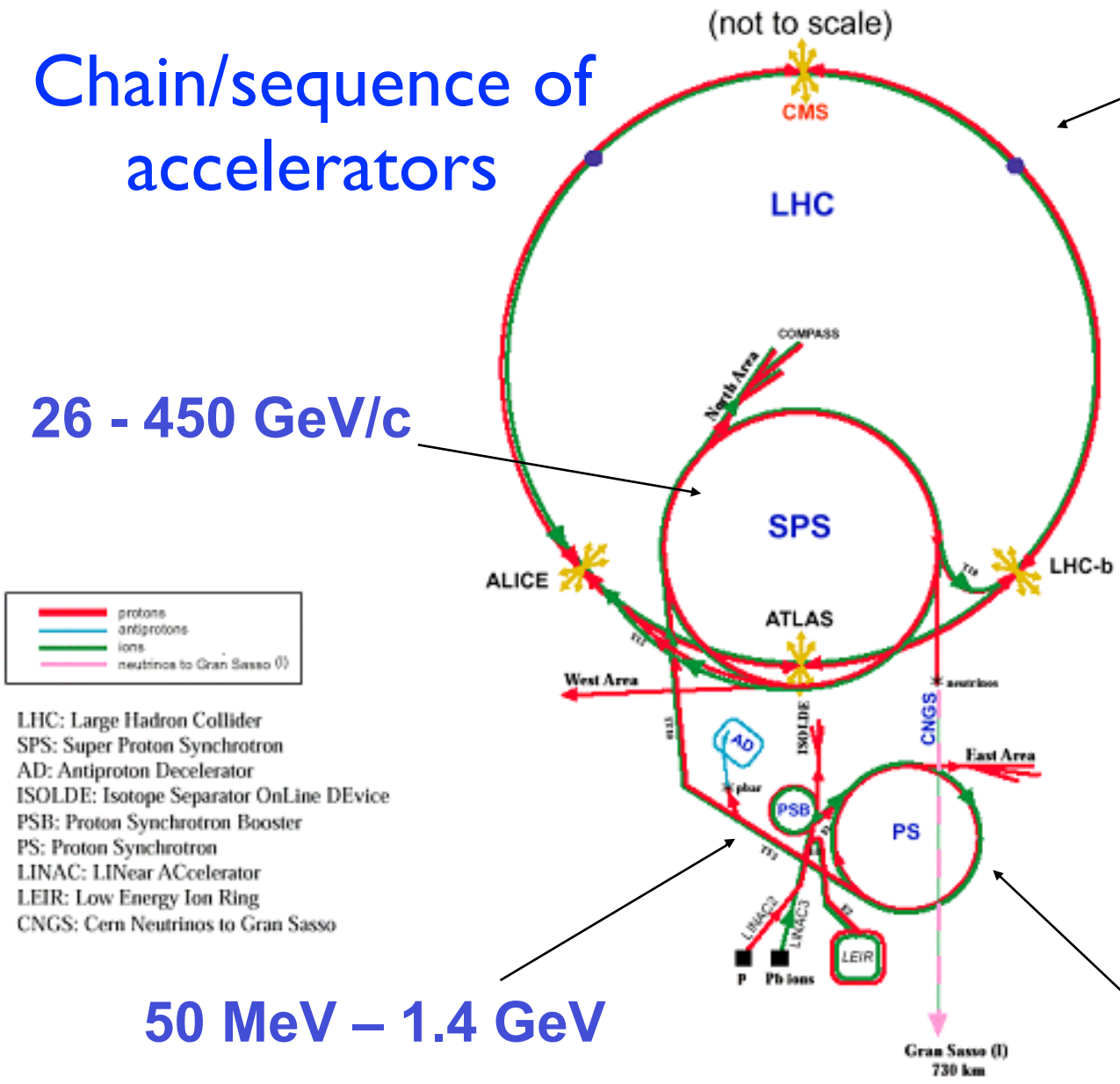
Chain/sequence of accelerators

450 GeV /c – 7 TeV /c

26 - 450 GeV/c

50 MeV – 1.4 GeV

1.4 GeV – 26 GeV/c



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

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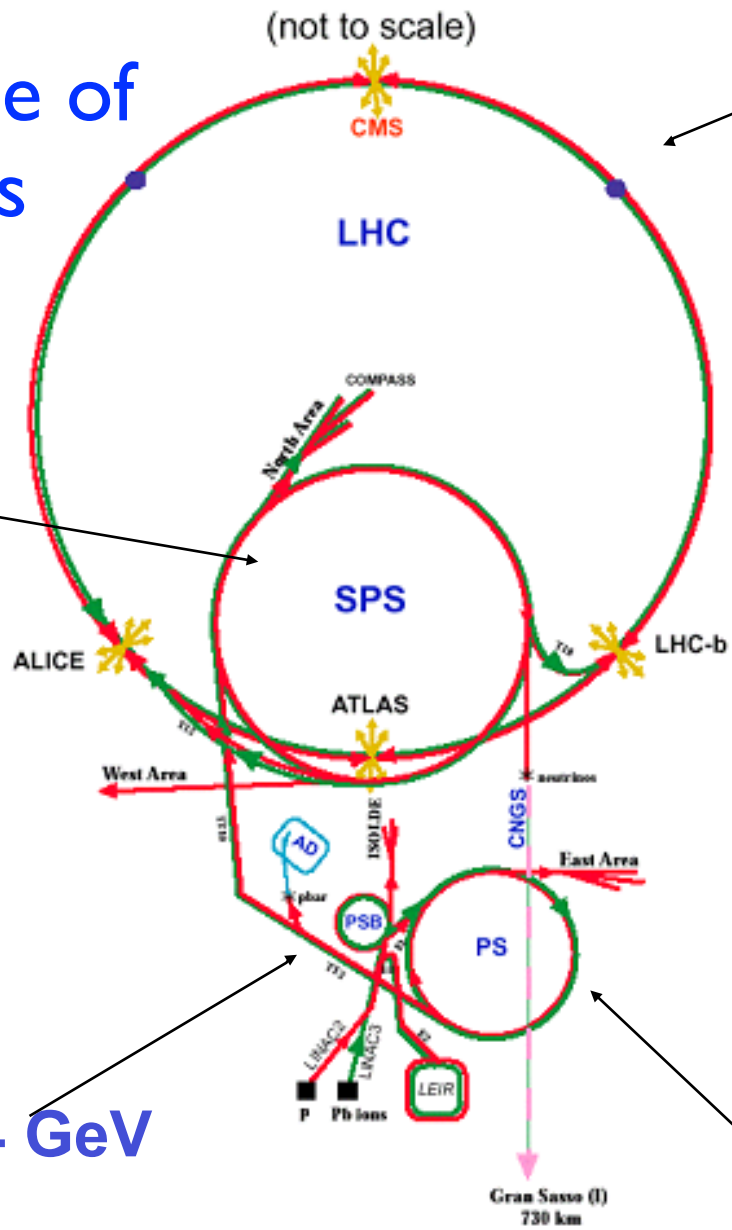

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450 GeV/c – 7 TeV/c

C ~ 27 km

26 - 450 GeV/c

C ~ 6 km

Questions:

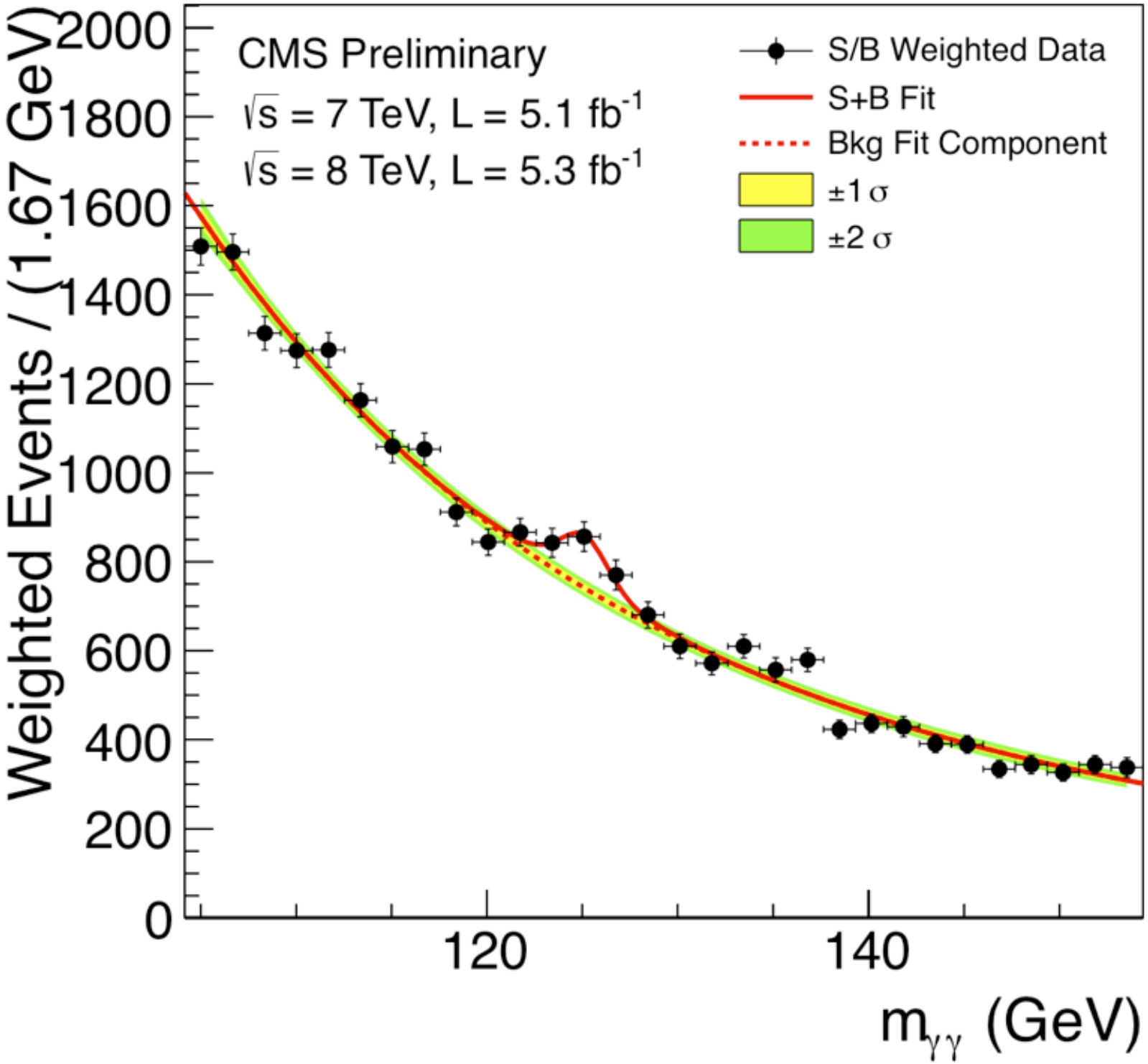
- why so many accelerators and not just the LHC?
- why rings of increasing circumference?
- why rings and linear accelerators?
- how particles go from one machine to the other?

50 MeV – 1.4 GeV

C ~ 157 m

1.4 GeV – 26 GeV/c

C ~ 630 m


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)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
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

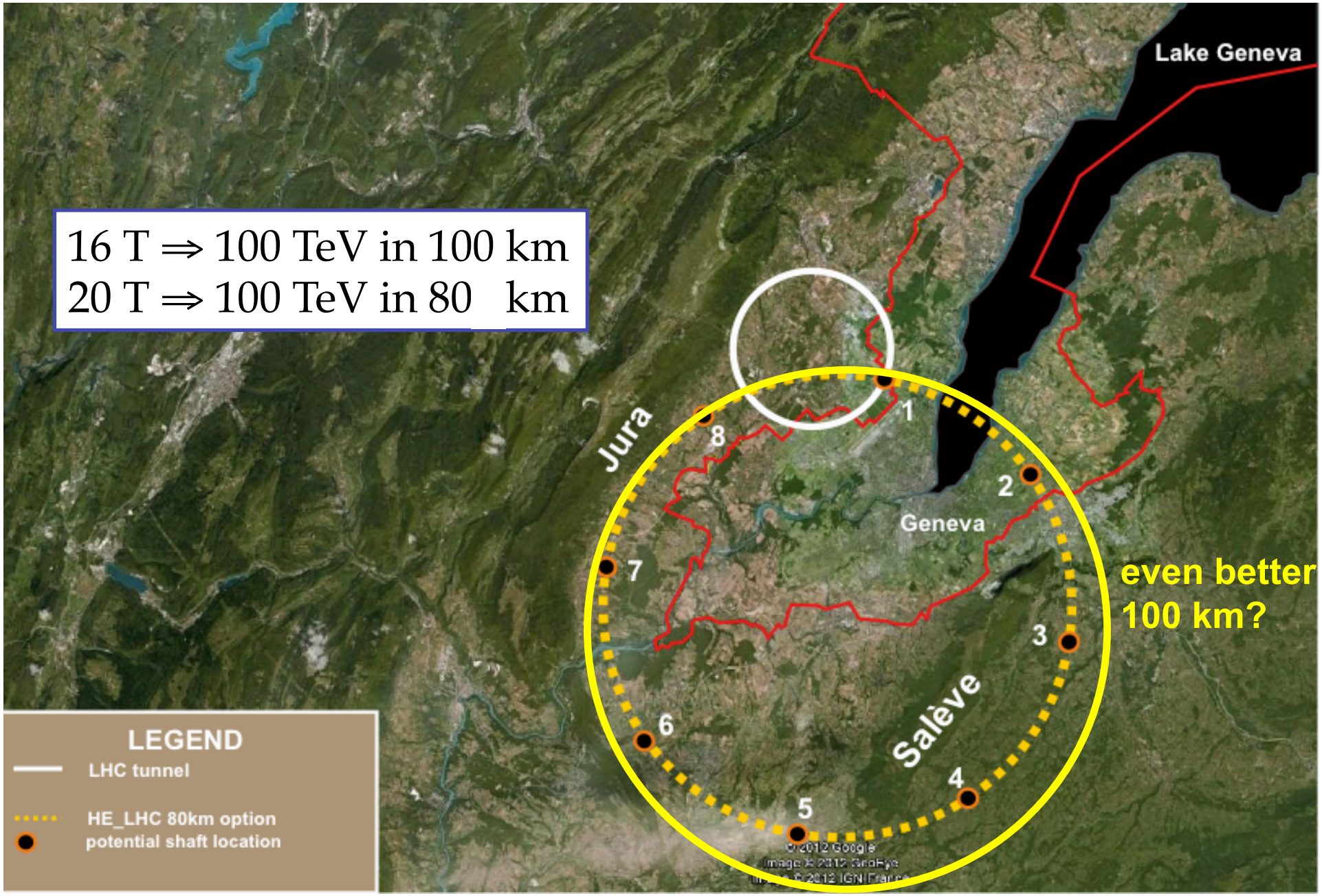
Press Release PR/56
12 February, 1960

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

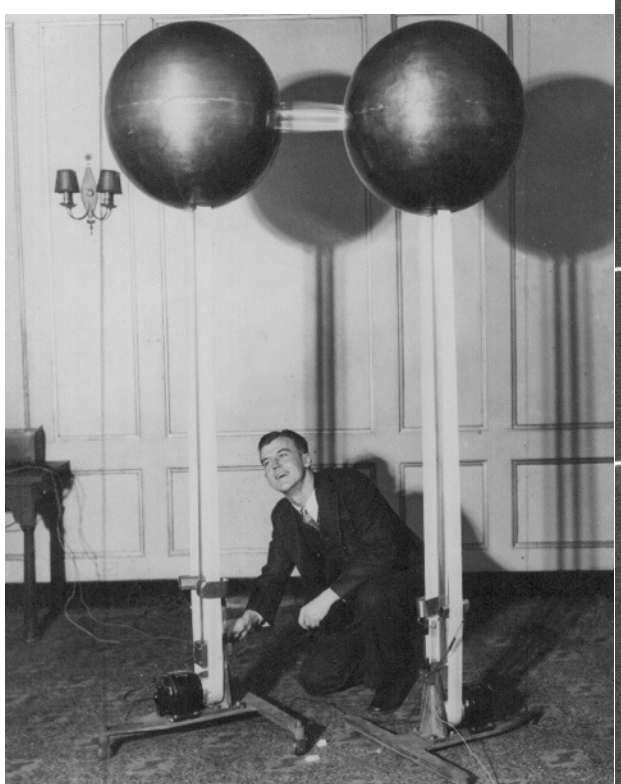
Obviously one has to find a smarter way to accelerate particles to high energies instead of piling up cellular phone batteries ....

Van De Graaf electrostatic generator (1928)

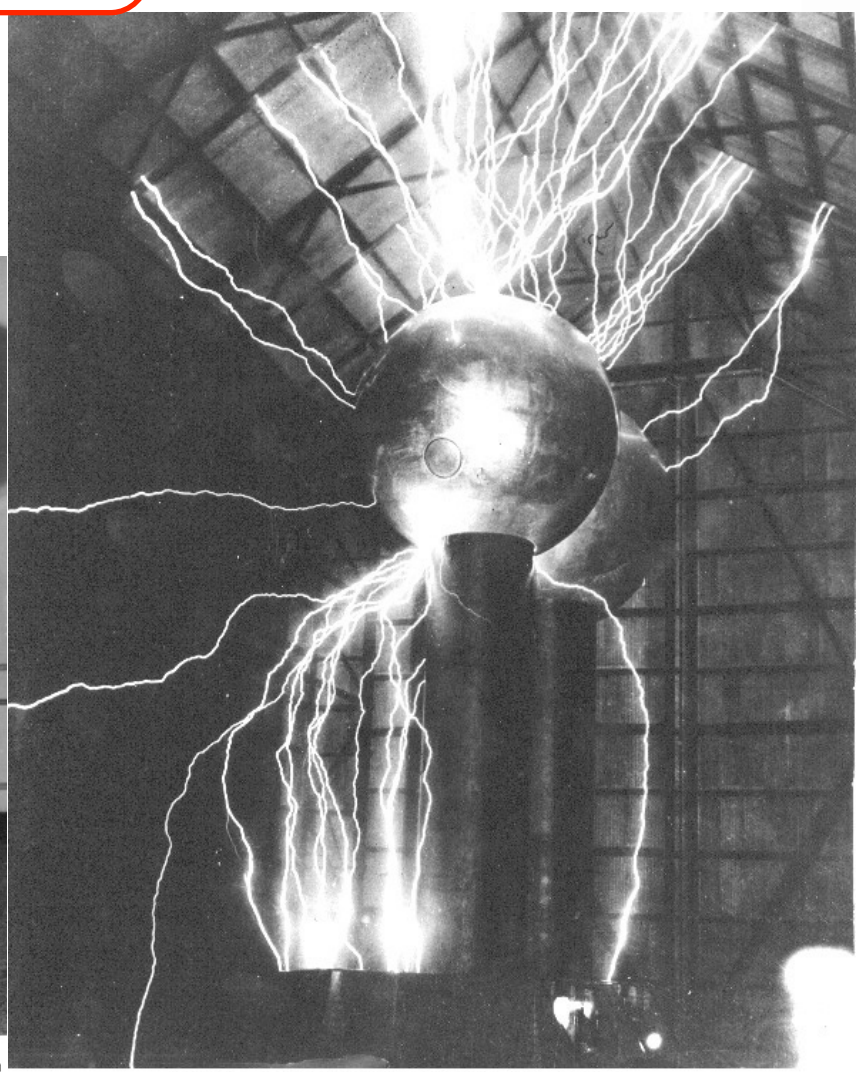
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: 10 MV

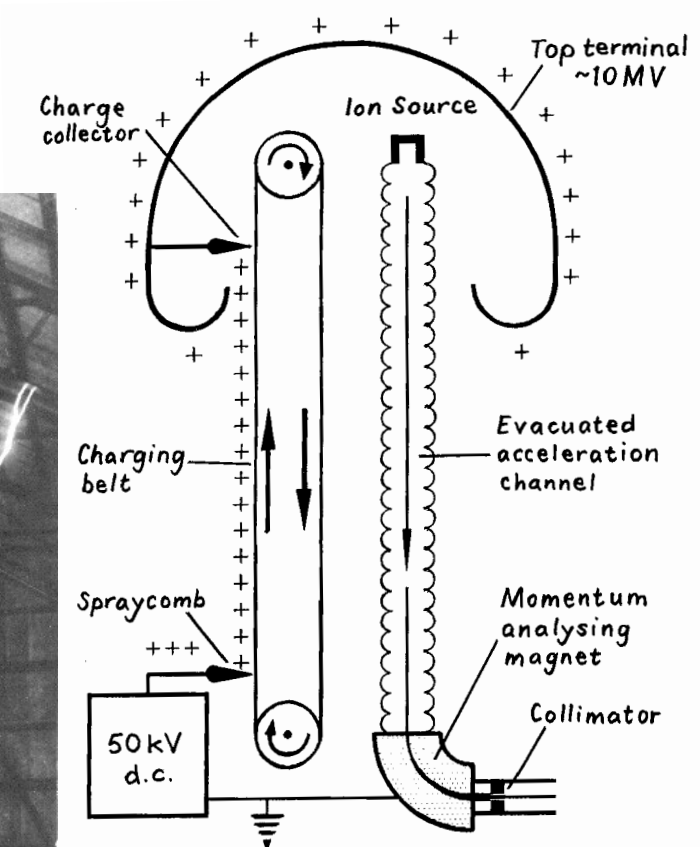
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



R. J. VAN DE GRAAFF WITH FIRST GENERATOR

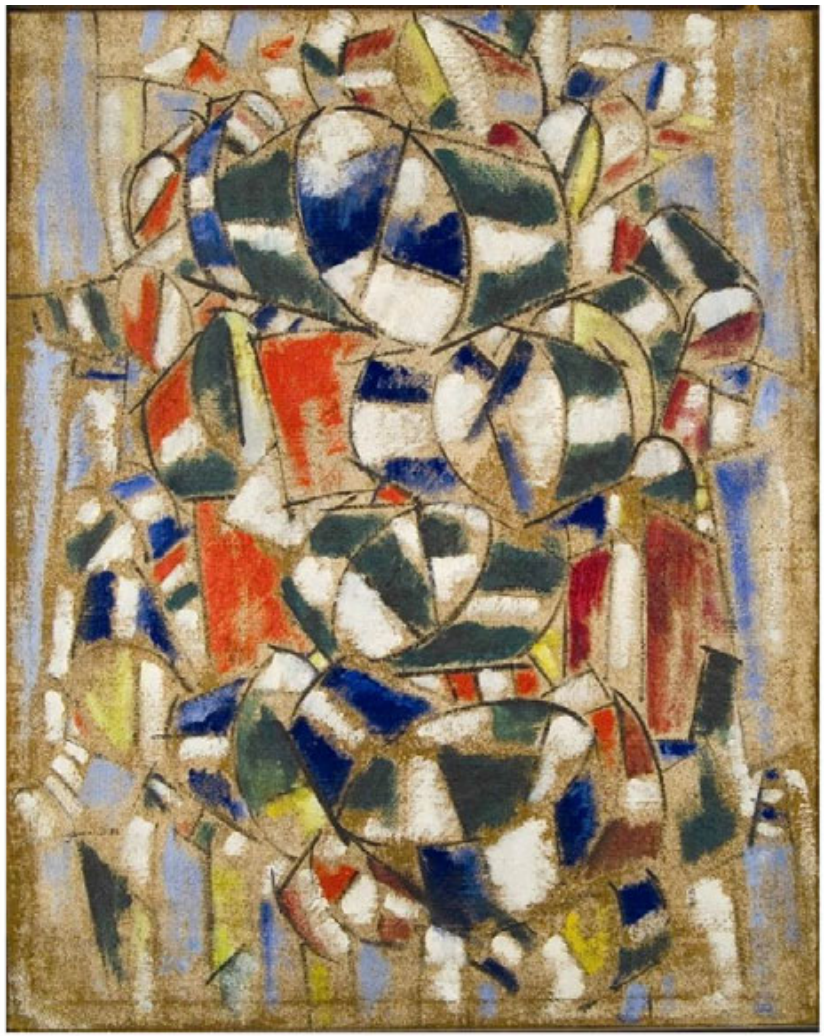


AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)



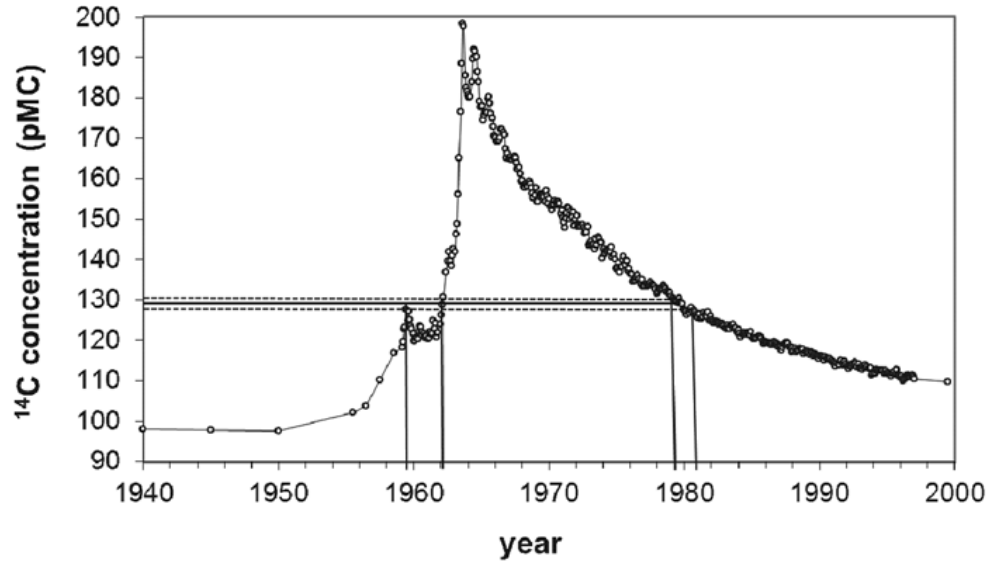
Discovering forgeries of modern art by the 14C Bomb Peak

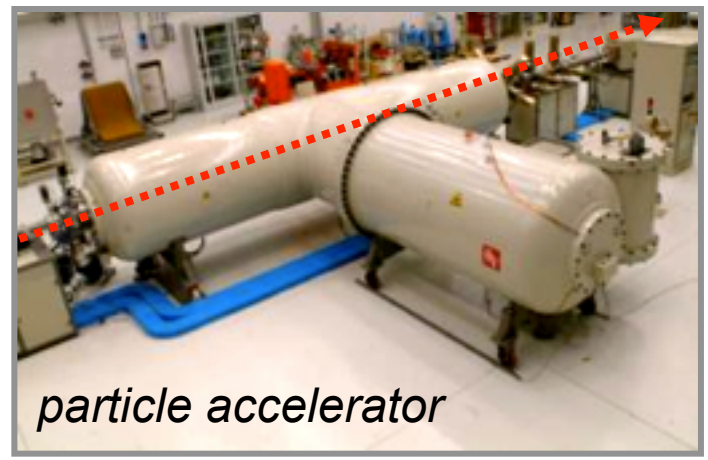
Eur. Phys. J. Plus (2014) **129**: 6
DOI 10.1140/epjp/i2014-14006-6



Contraste de formes, Fernard Leger (?)
Peggy Guggenheim Collection, Venice.

Accelerator Mass Spectrometry (AMS)
to measure rare isotopes abundance with
3MV Tandetron accelerator of INFN-LABEC in
Florence.





... by the way, one can also date French wine with isotopes

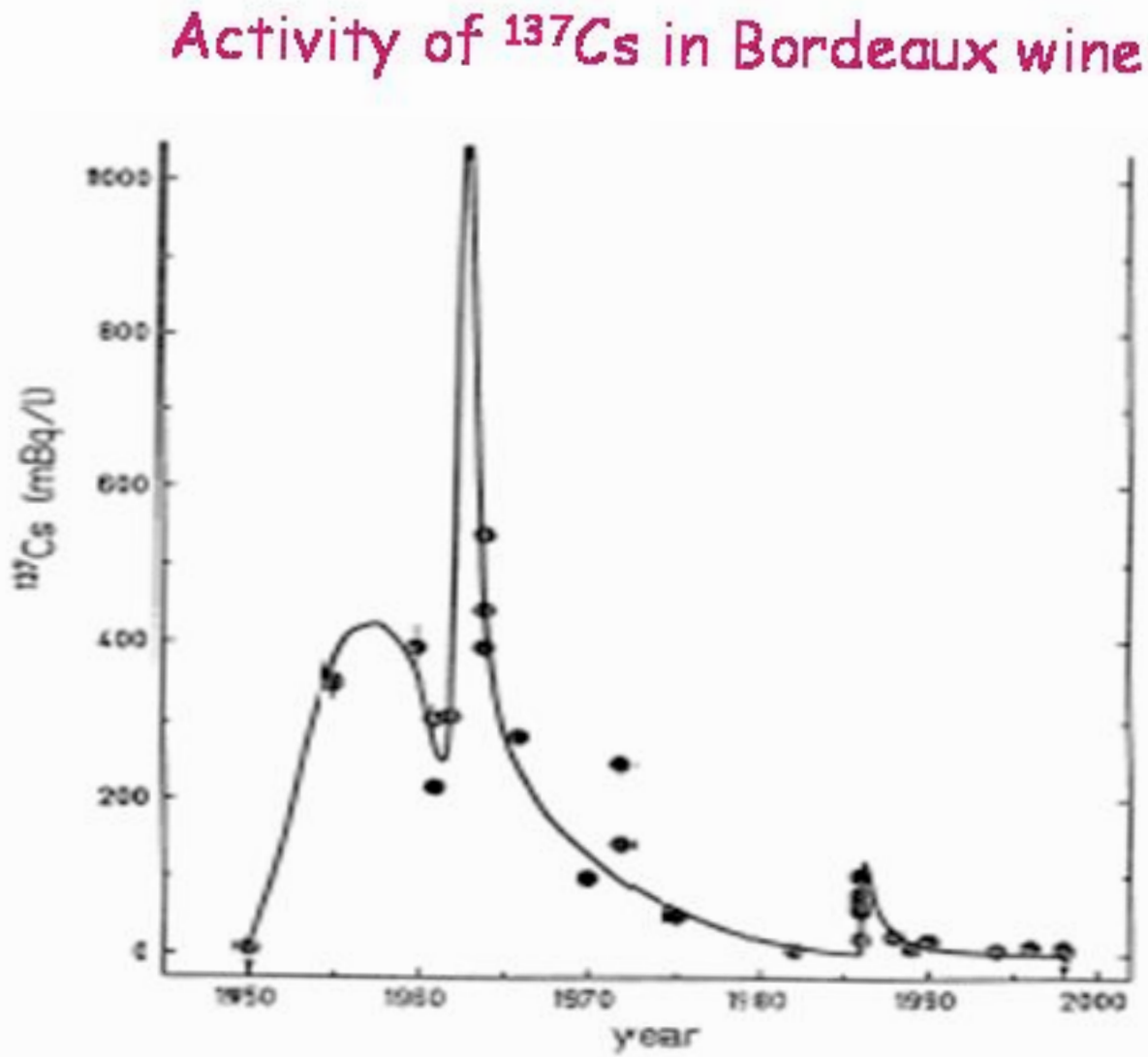
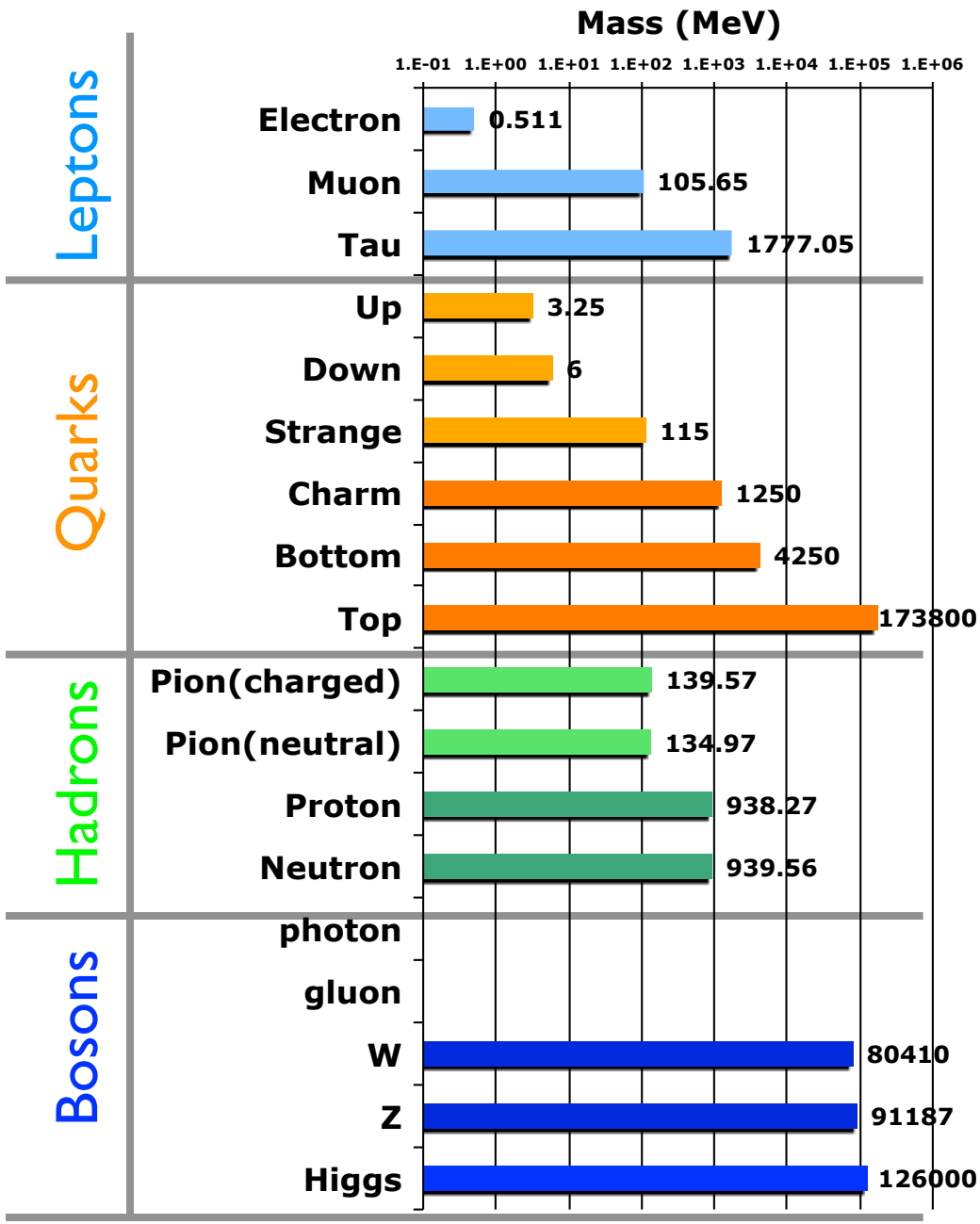
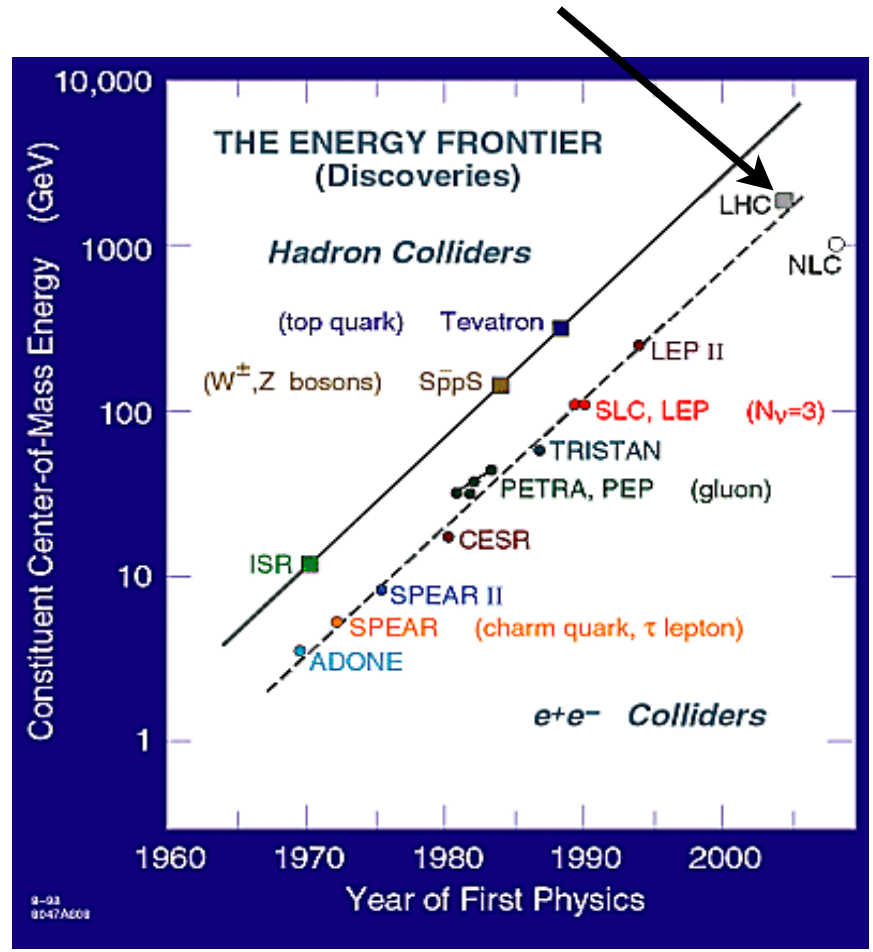


Figure 1. *Cesium activity in the Bordeaux wine as a function of the millésime.*

History/Energy line vs discovery



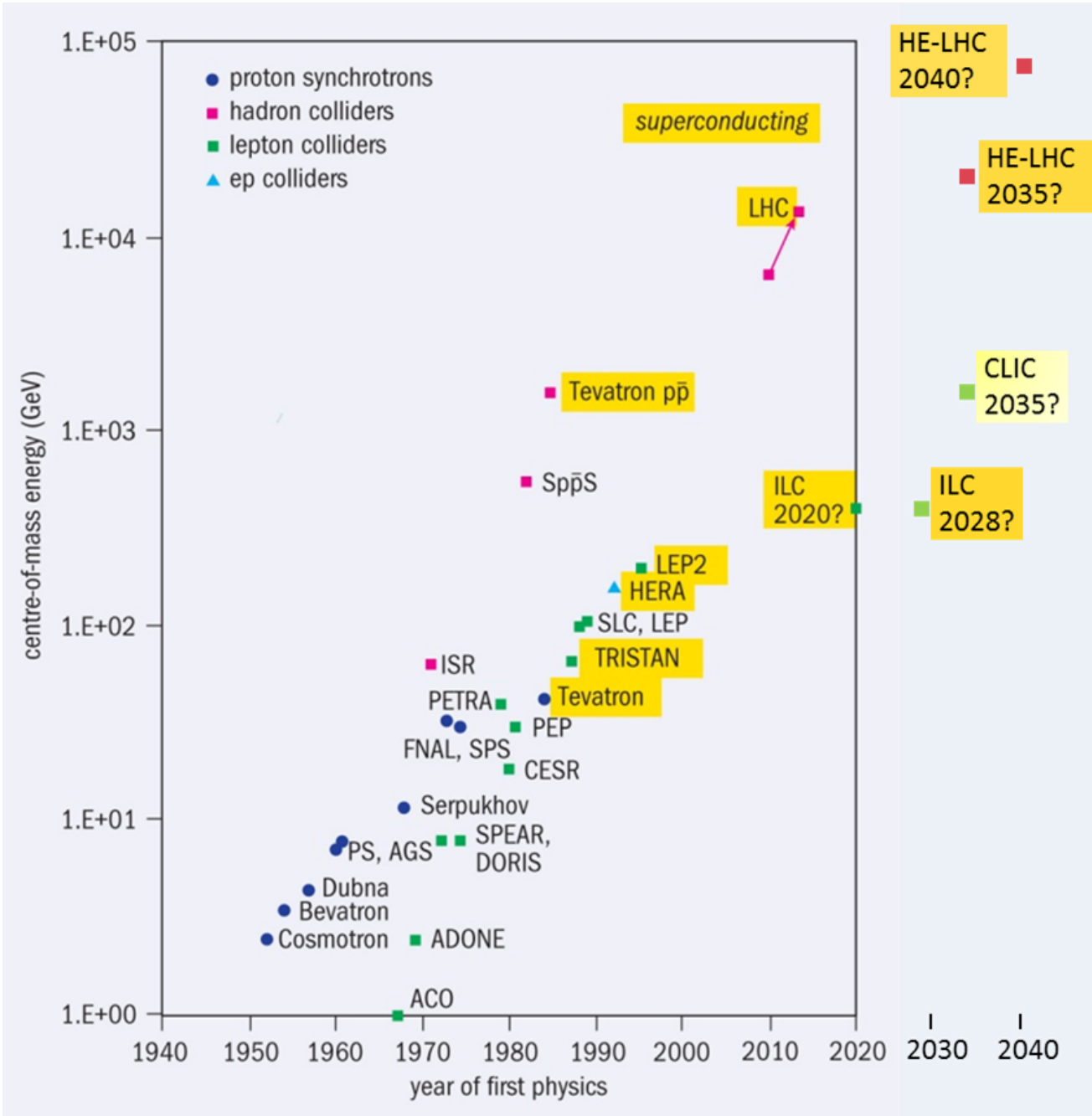
Higgs and super-symmetry ?
Or something else maybe



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-$\overline{p}$ as Tevratron, p-p as LHC)

What's the future ?



Building Blocks of an accelerator

1) A particle source

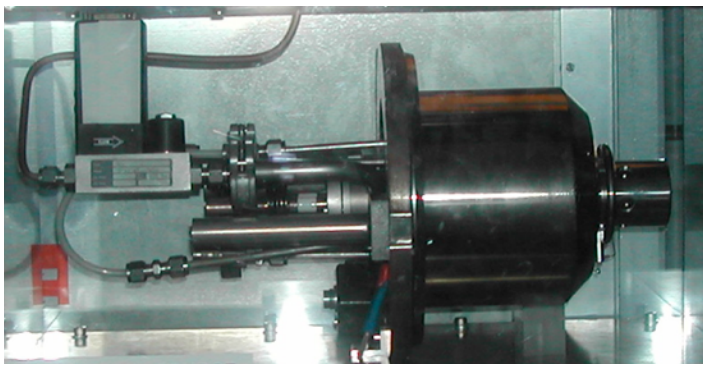
2) An accelerating system

3) A series of guiding and storage devices

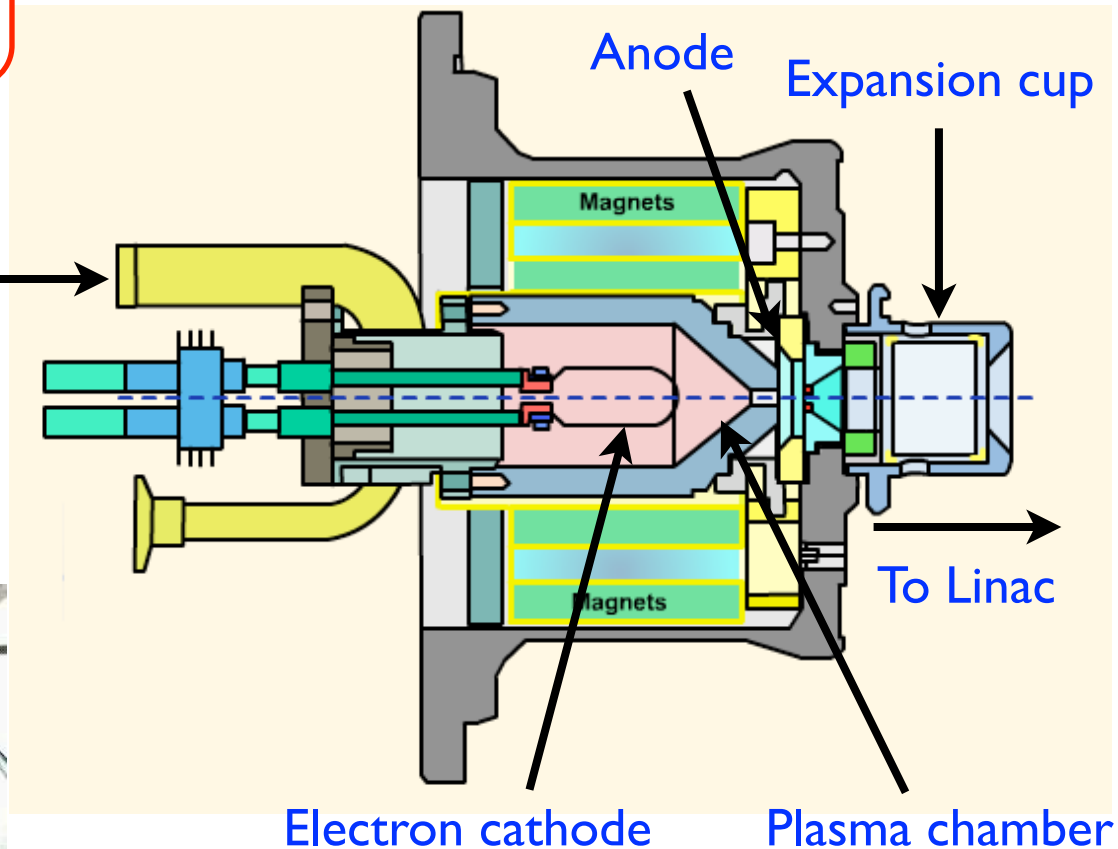
Everything under vacuum

How to get protons: duoplasmatron source

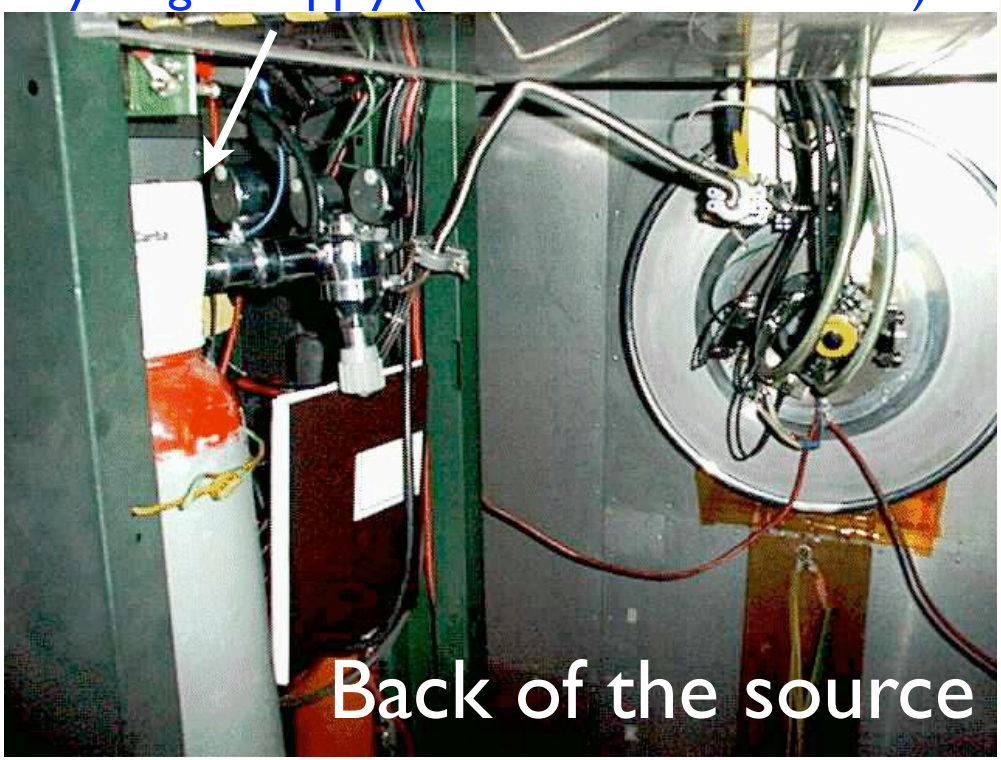
Protons are produced by the ionization of H_2 plasma enhanced by an electron beam



H_2 inlet



Hydrogen supply (one lasts for 6 months)

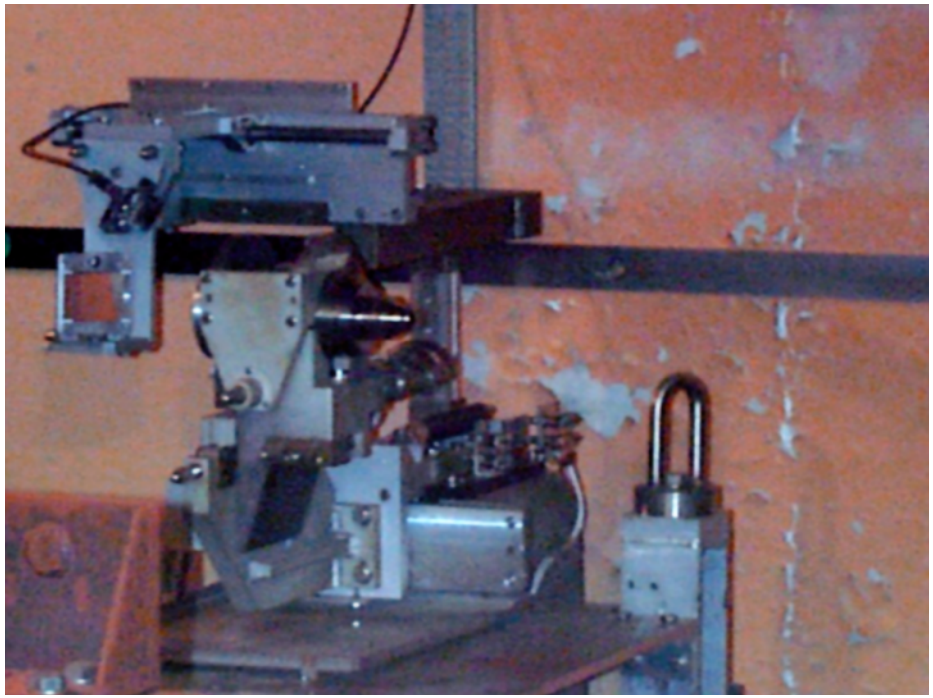


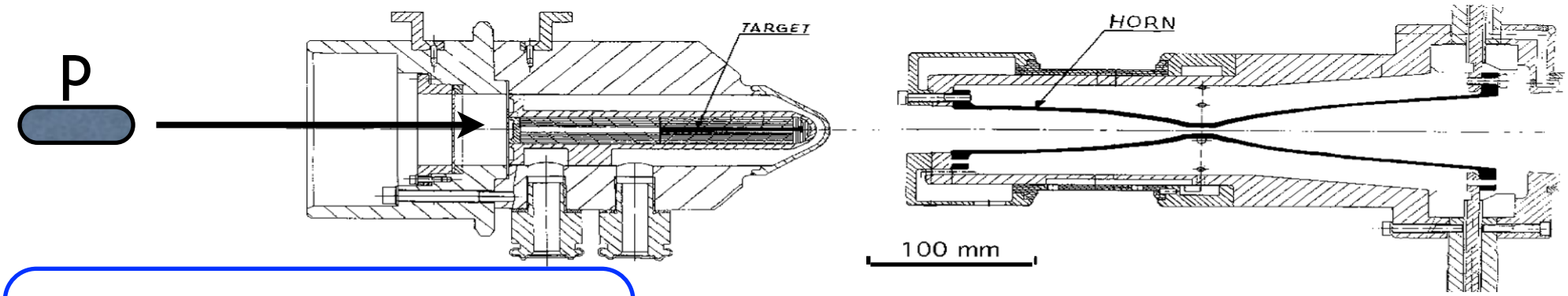
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, v ≈4000 km/s

The SPACE SHUTTLE goes only up to 8 km/s

Cern Control Center: first LHC day

How to get antiprotons





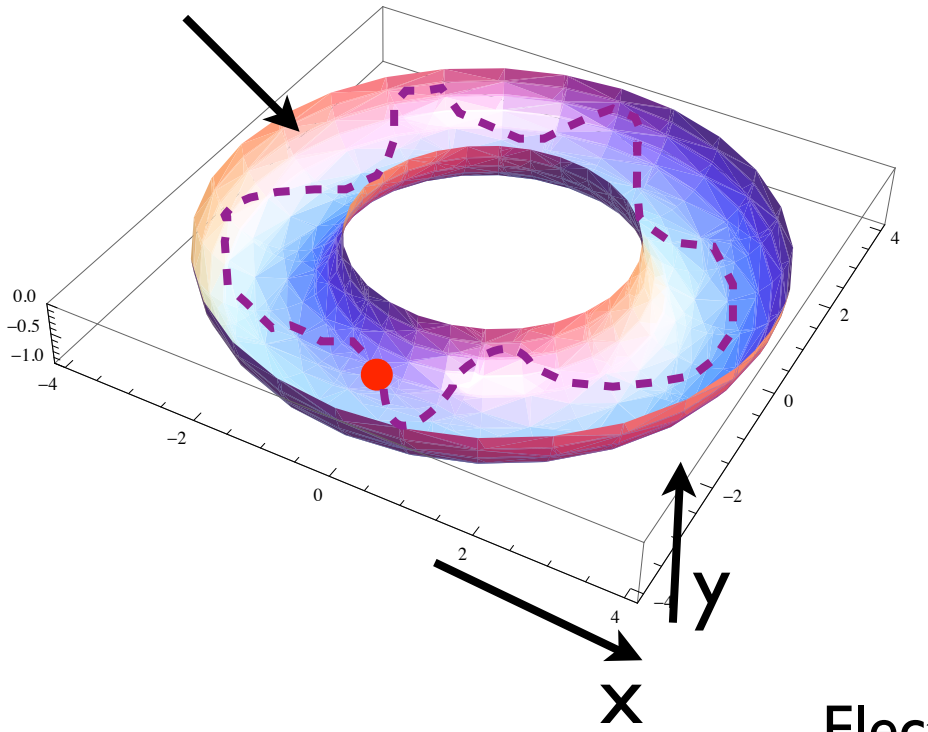
Starting from high energy p and with a very low efficiency

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

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

How an accelerator works ?

Accelerator



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:*

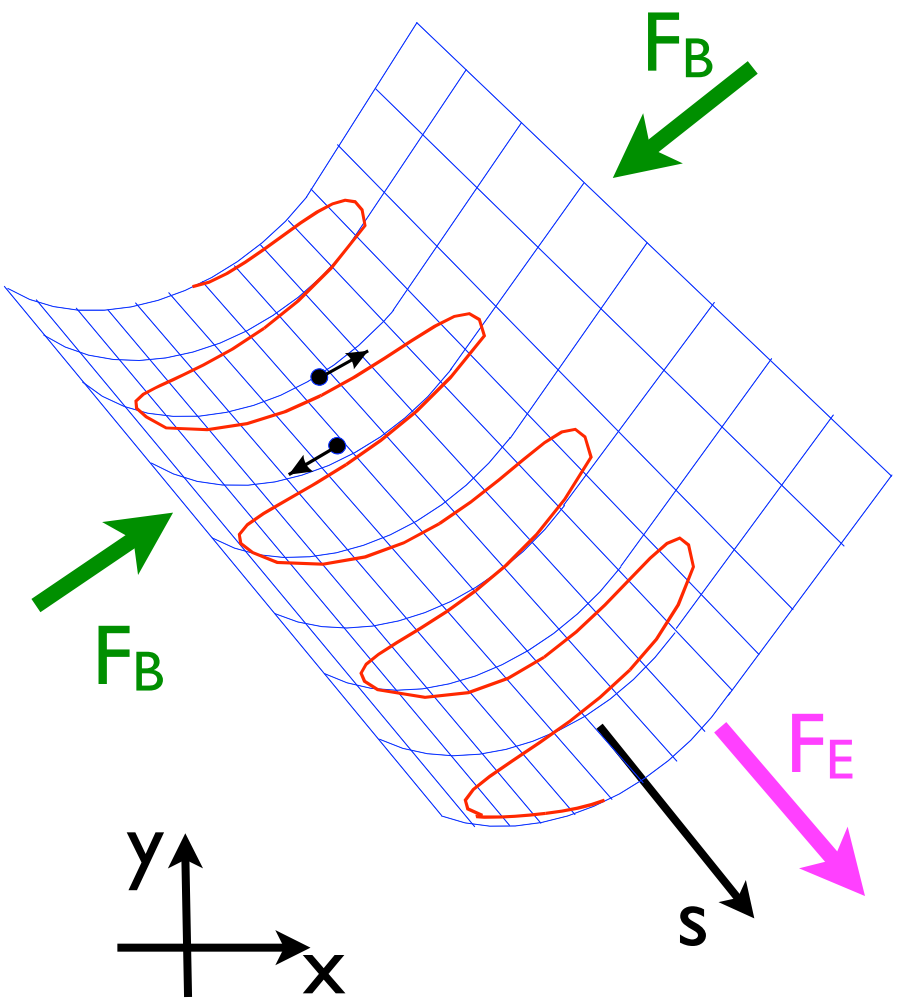
a) Magnets → Magnetic Field

b) Accelerating Cavity → Electric Field

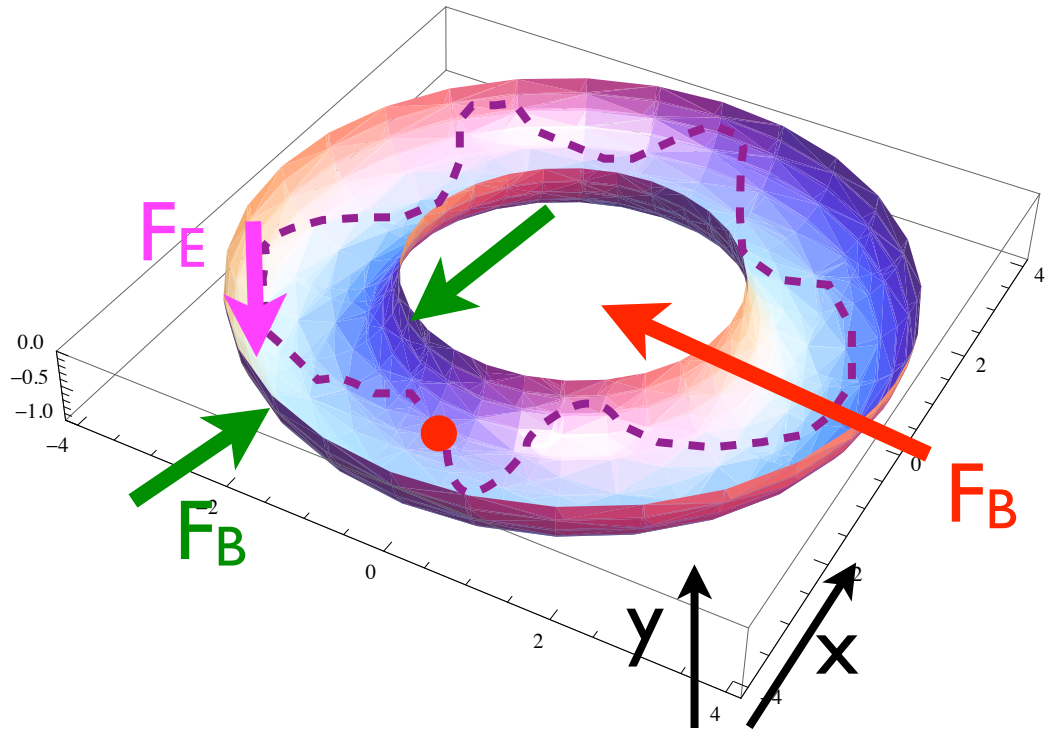
$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

F_E F_B

Linear Accelerator



Circular Accelerator



Cyclotron

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

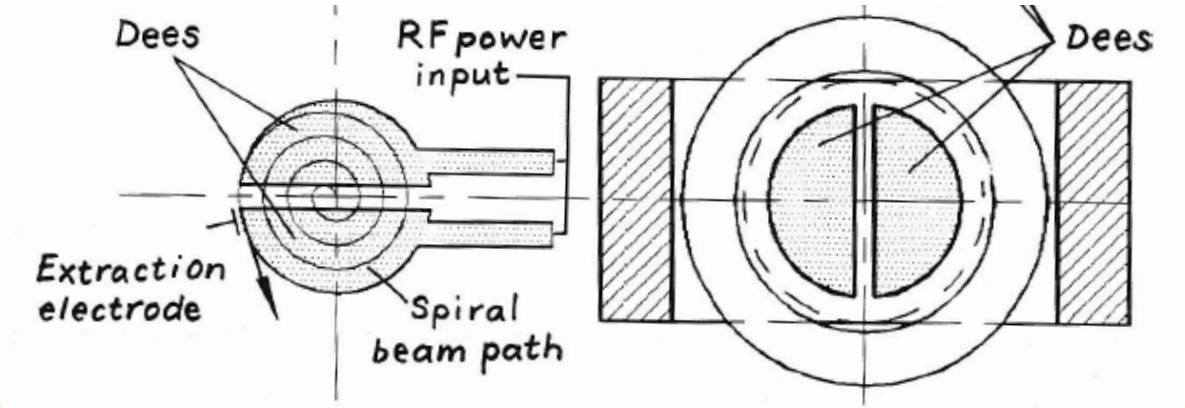
Electrical (E) RF field generated between two gaps with a fixed frequency

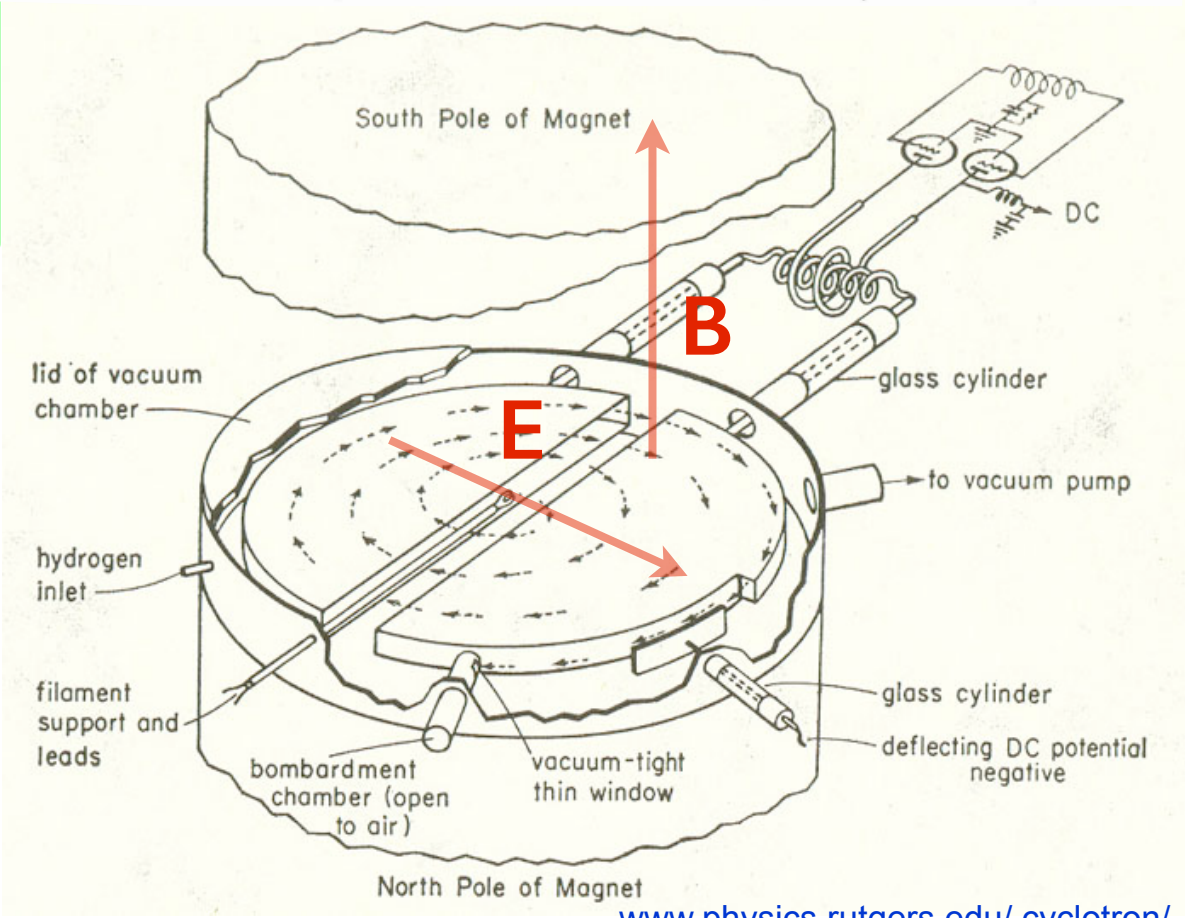
Particles spiral while accelerated by E field every time they go through the gap

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

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

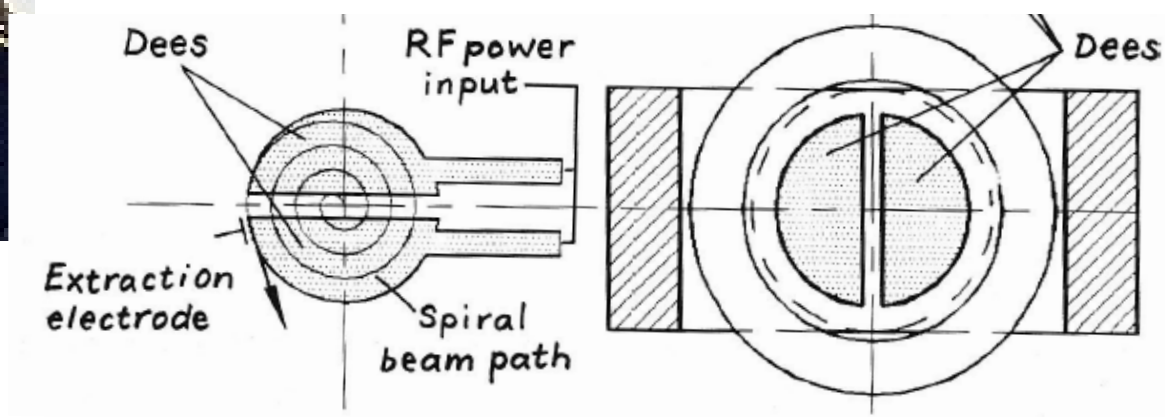




www.physics.rutgers.edu/ cyclotron/

Invented by Lawrence, got the Noble prize in 1939

The first cyclotron and the Berkeley one



Synchrotron (1952, 3 GeV, BNL)

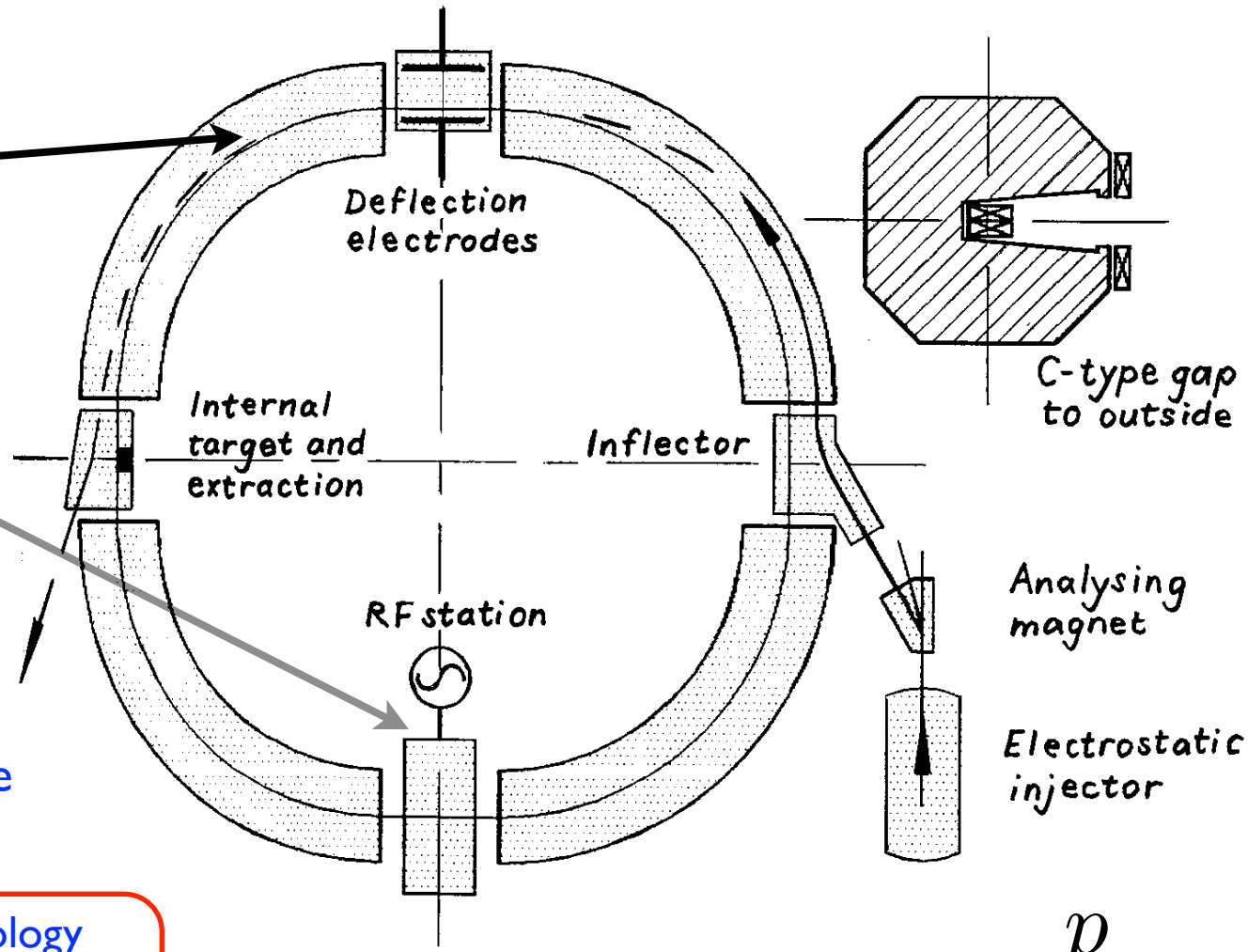
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

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

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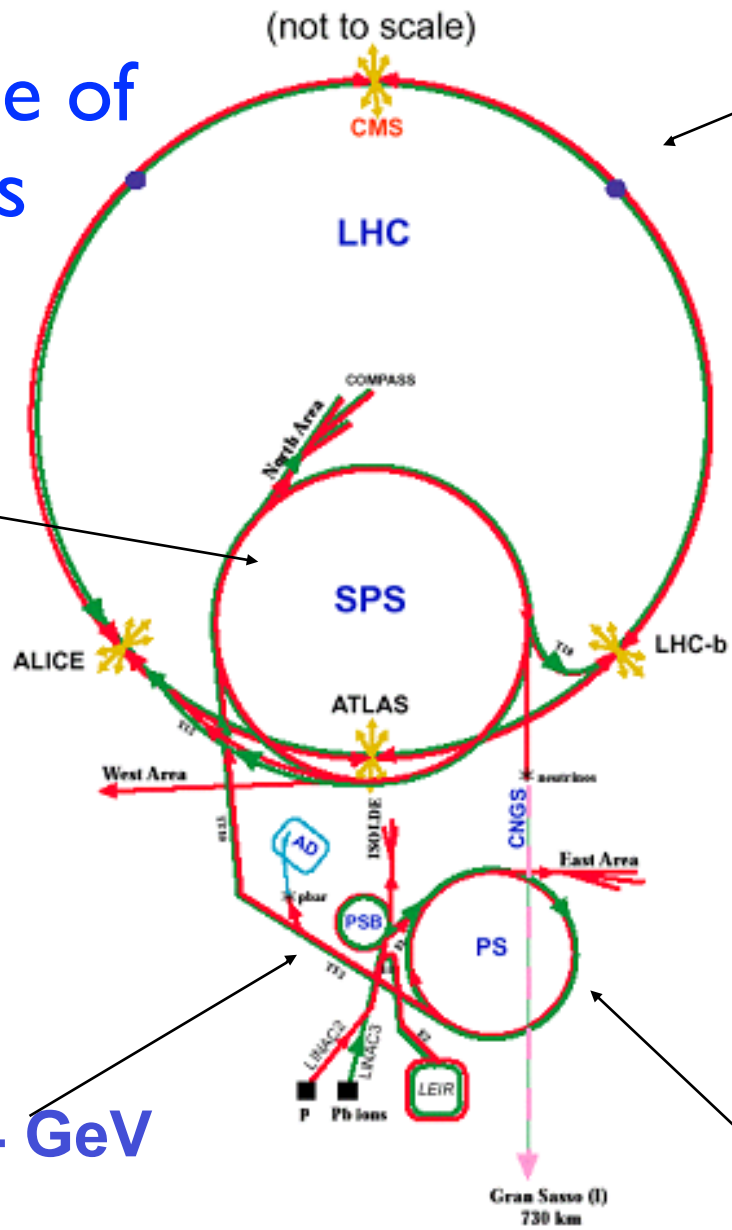

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- why rings and linear accelerators?
- how particles go from one machine to the other?

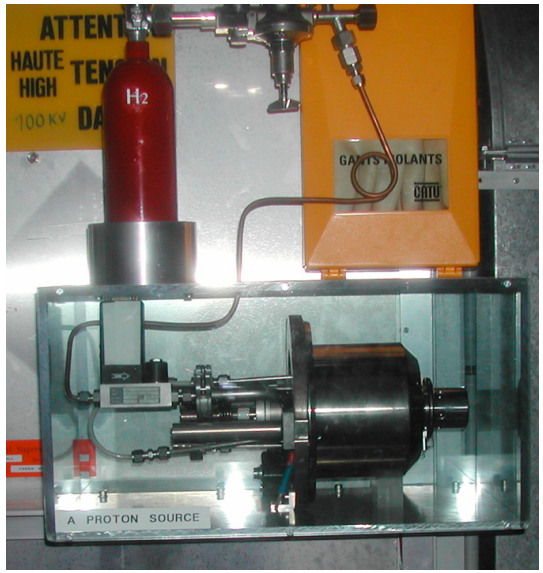
50 MeV – 1.4 GeV

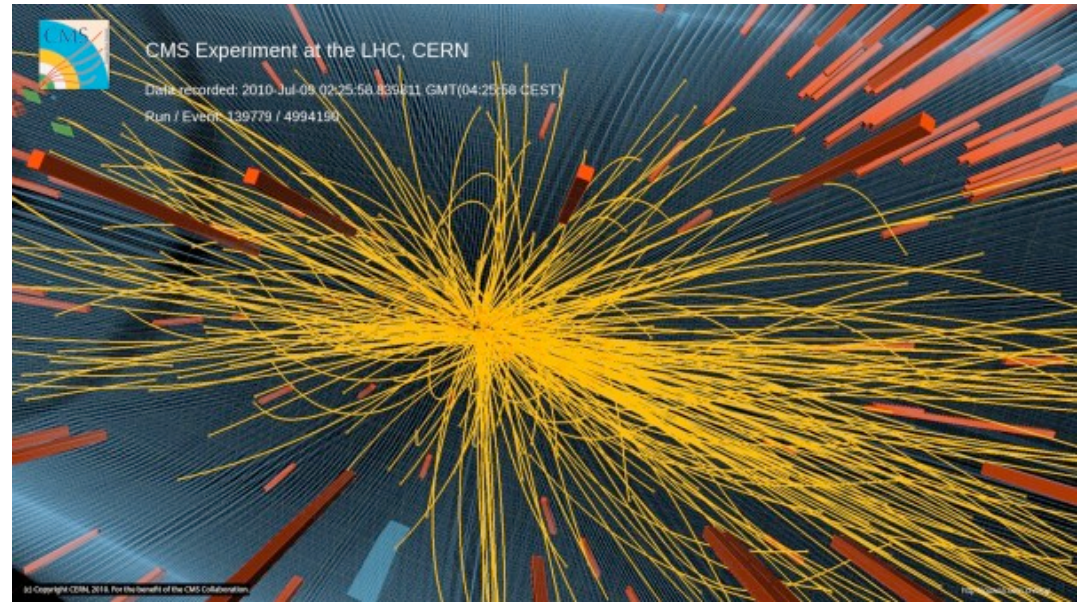
C ~ 157 m

1.4 GeV – 26 GeV/c

C ~ 630 m

Basically accelerators brings you ...





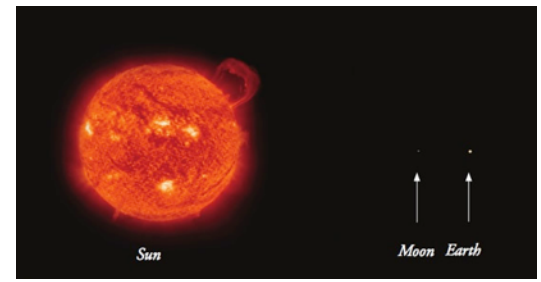
from nearly a bottle of hydrogen

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)

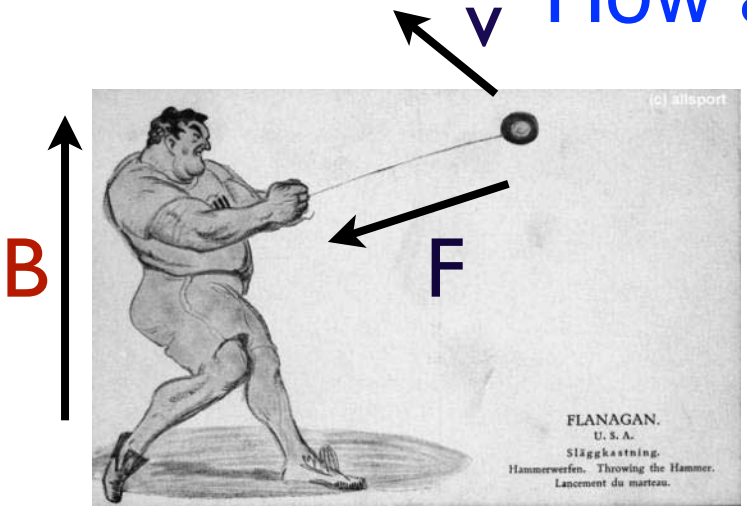
In the Linac 2, basically nothing.
In the **PSB**, a bit less than than 1.2 s.
In the **PS**, a bit less than 3.6 s
In the **SPS**, a bit less than 16.8 s
In the **LHC**, minimum 30 minutes

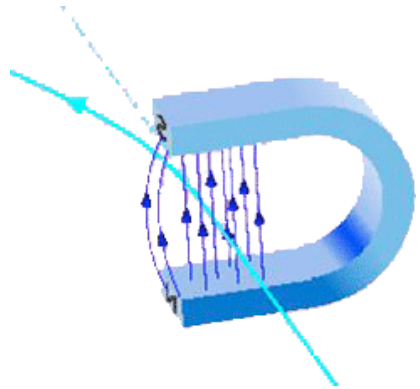
1 821.6 s → 546 480 000 km

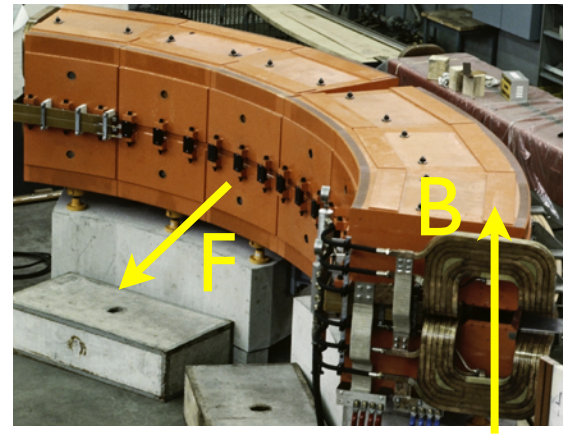


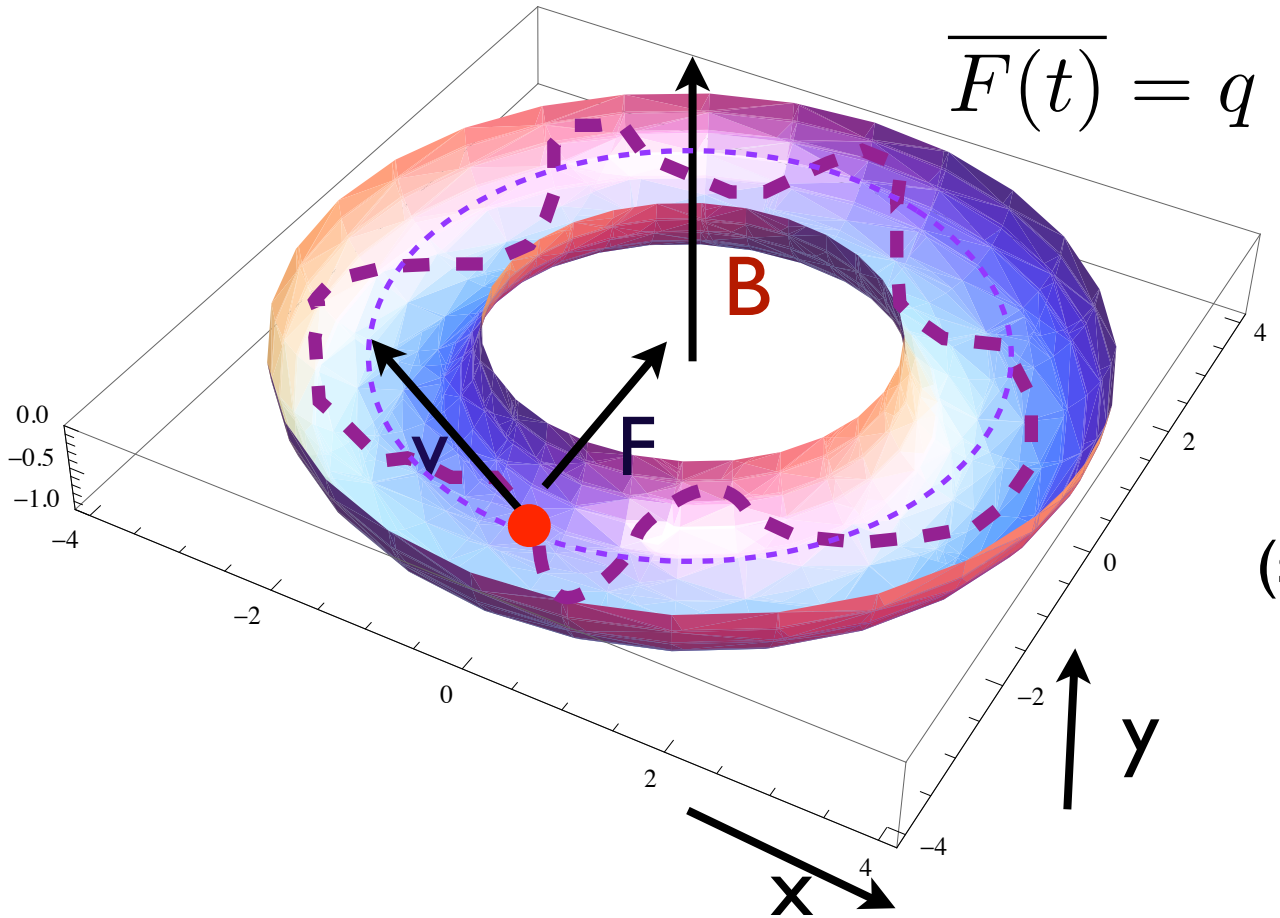
about 3.7 time the distance Sun-Earth

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

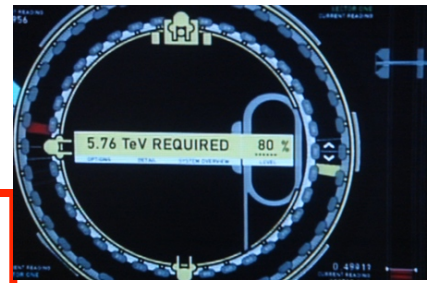
INTERLUDE: THE TERMINATOR-3 ACCELERATOR

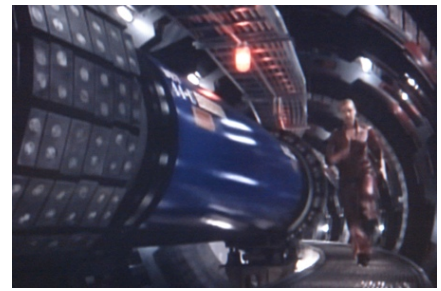
We apply some concepts to the accelerator shown in Terminator-3 [Columbia Pictures, 2003]

- Estimation of the magnetic field

No way!

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





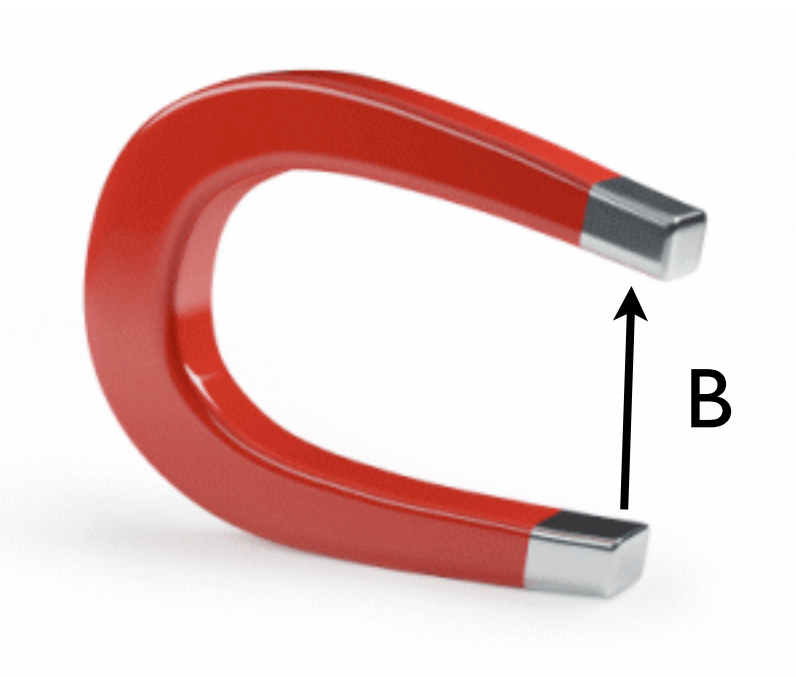
Energy of the machine (left) and size of the accelerator (right)

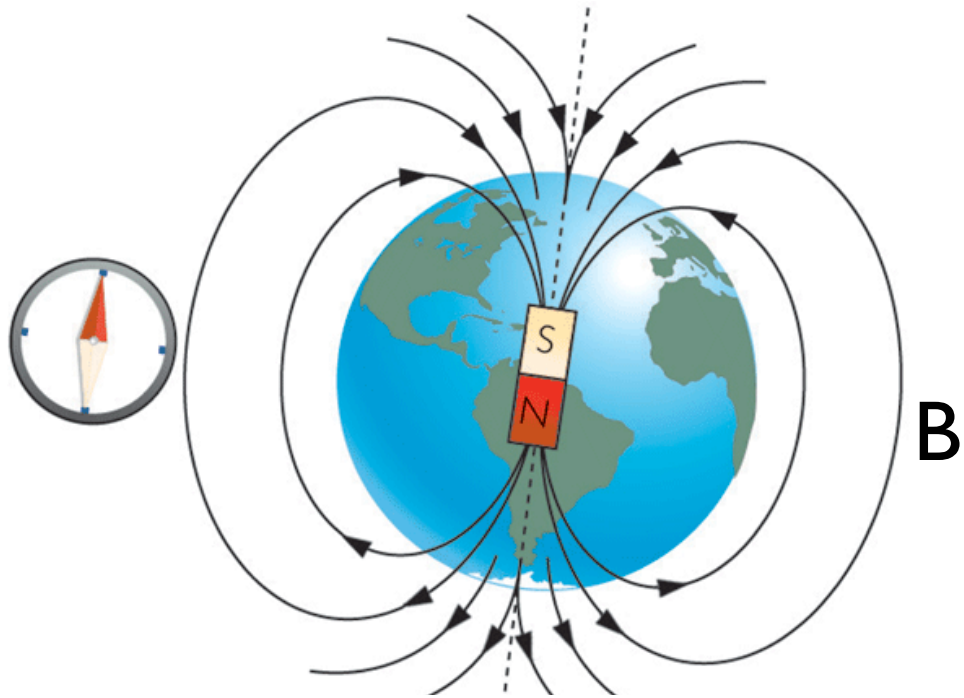
- Why the magnet is not shielded with iron ?
  - Assuming a bore of 25 mm radius, inner field of 700 T, iron saturation at 2 T, one needs 700*25/2=9000 mm=9 m of iron … no space in their tunnel !
  - In the LHC, one has a bore of 28 mm radius, inner field of 8 T, one needs 8*25/2=100 mm of iron
- Is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

A magnet whose fringe field is not shielded

From E. Todesco CERN Summer student lecture

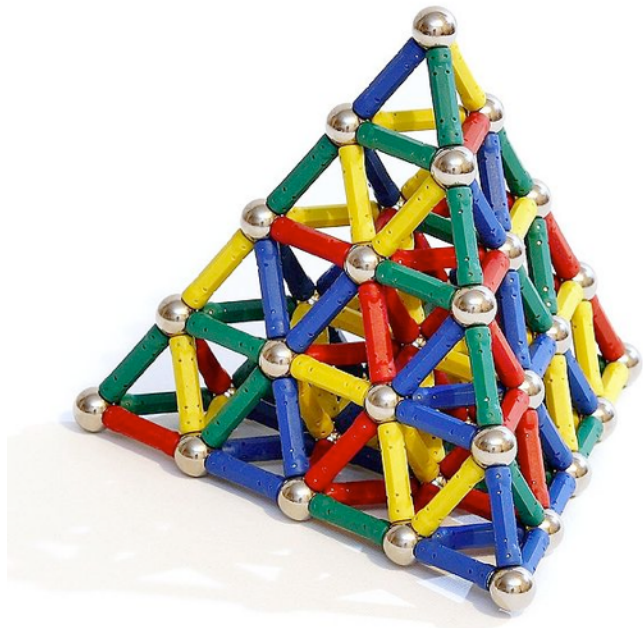
Two dipoles and magnets you should know very well



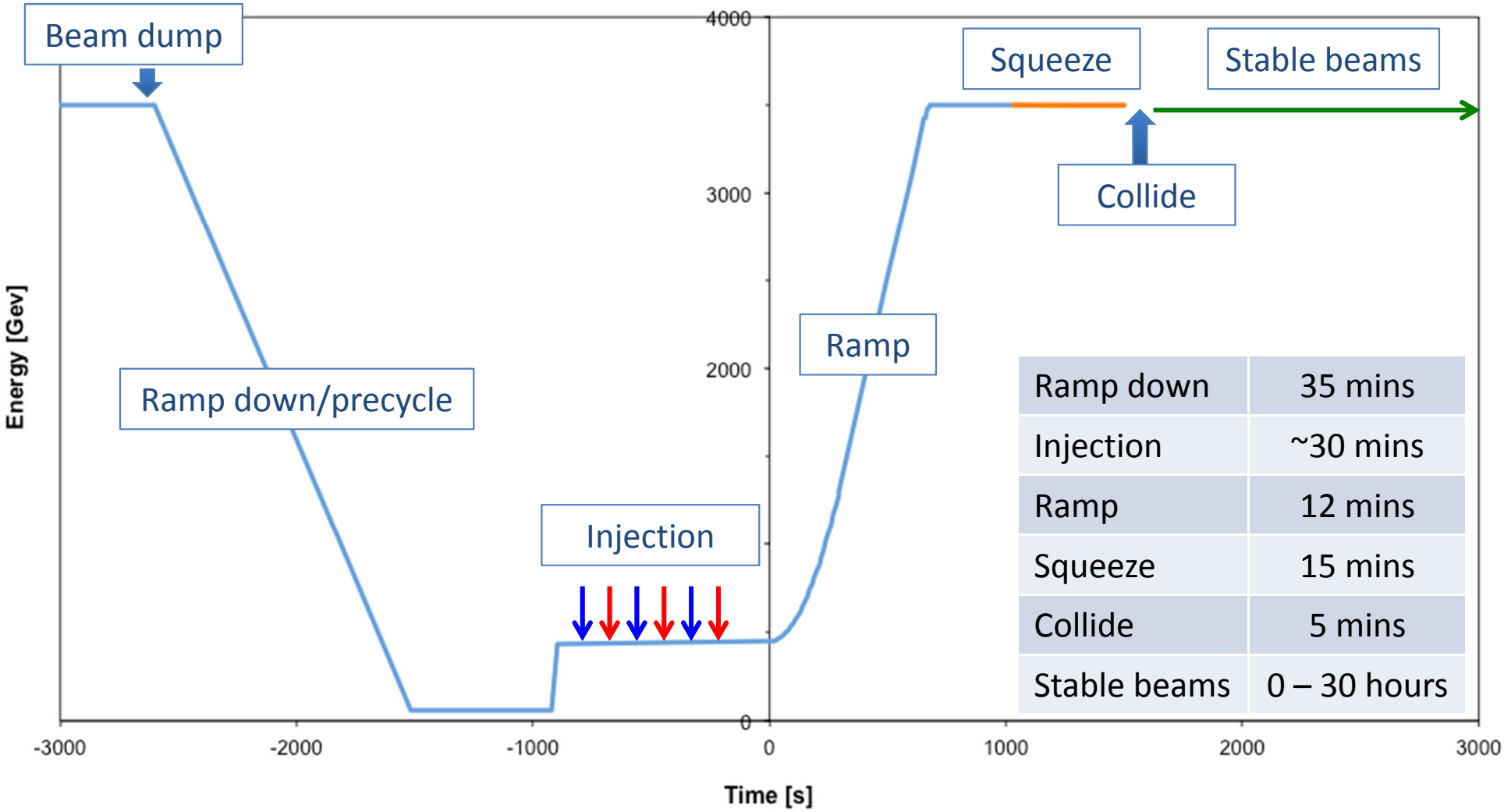


Earth Magnetic Field : ~ 0.6 Gauss

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

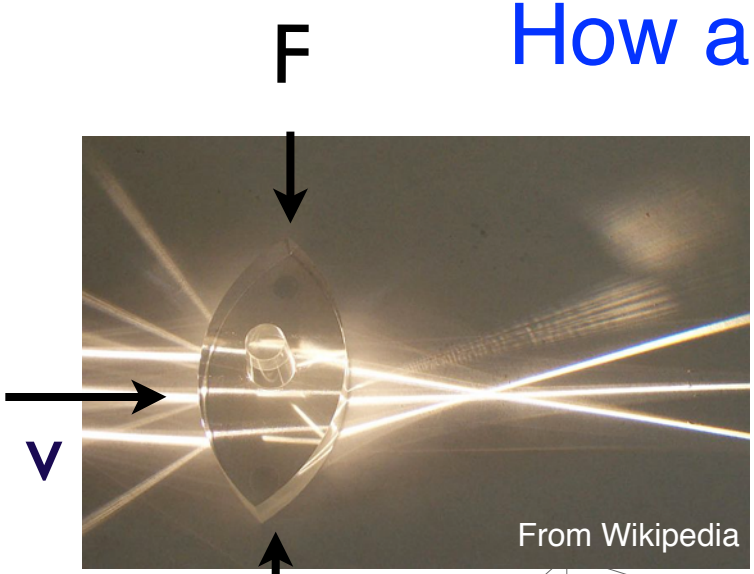


Typical LHC Operational cycle



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

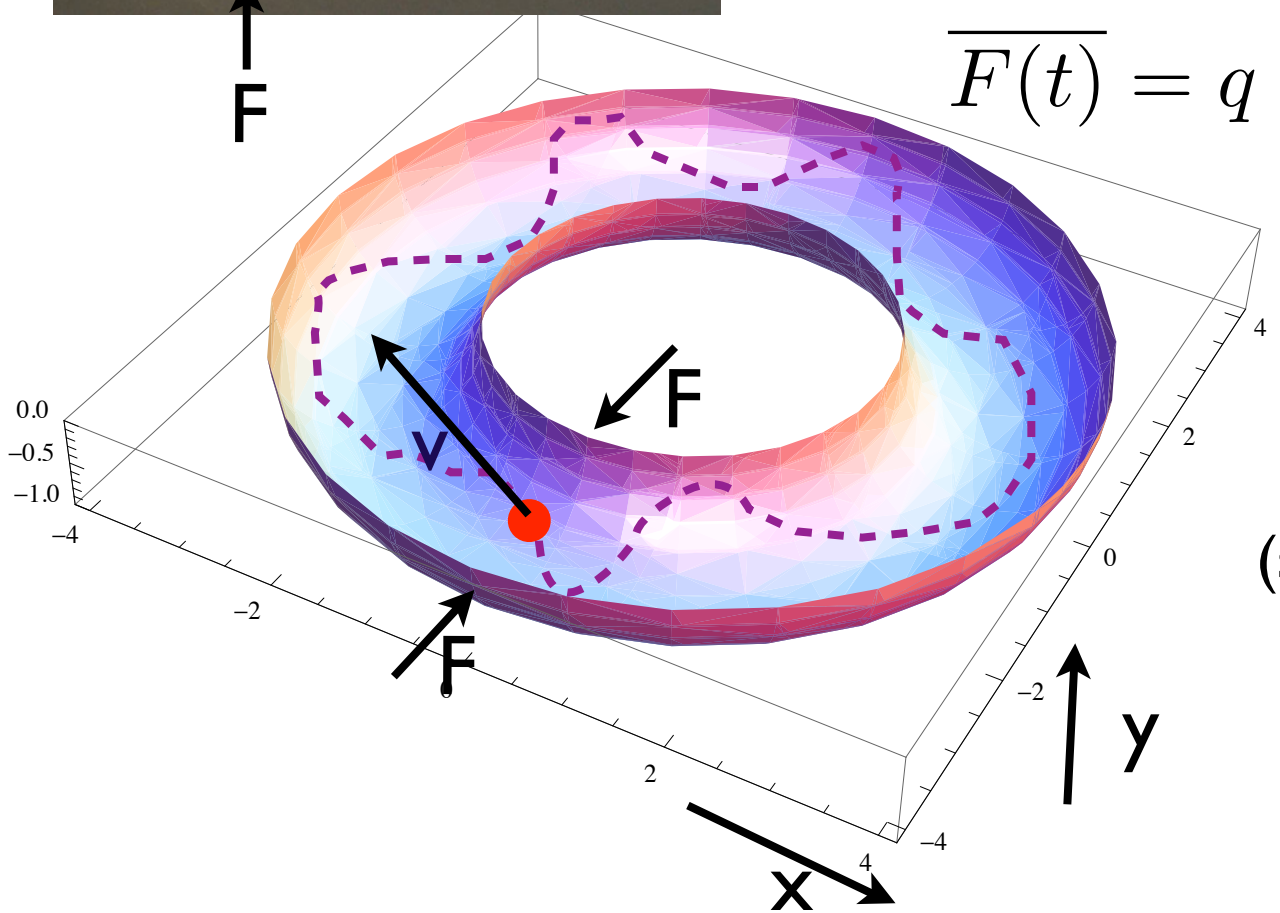
How an accelerator works ?



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

How ? Lorentz Force!

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



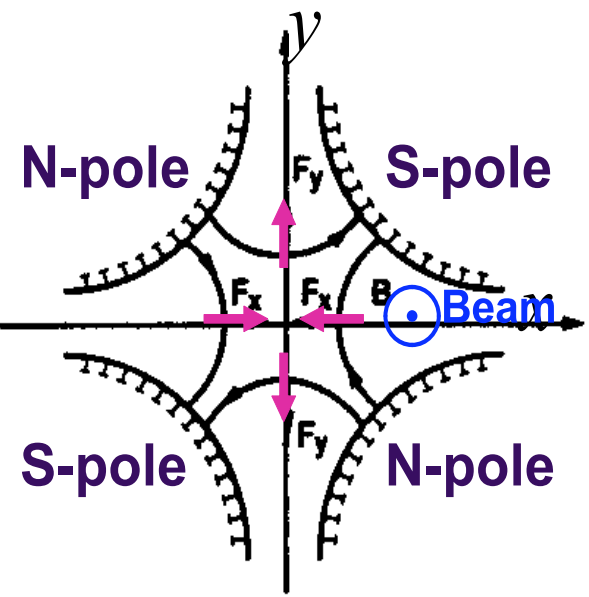
Particles of
different energy
(speed) behave differently

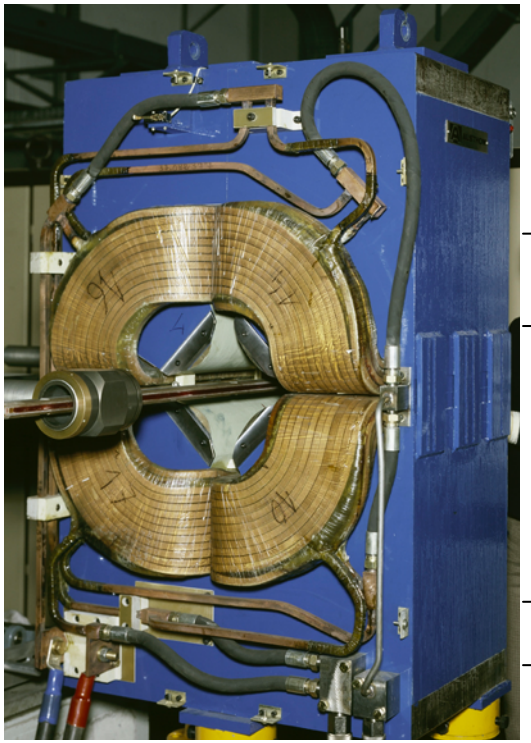
Magnetic field confines
particles
on a given trajectory

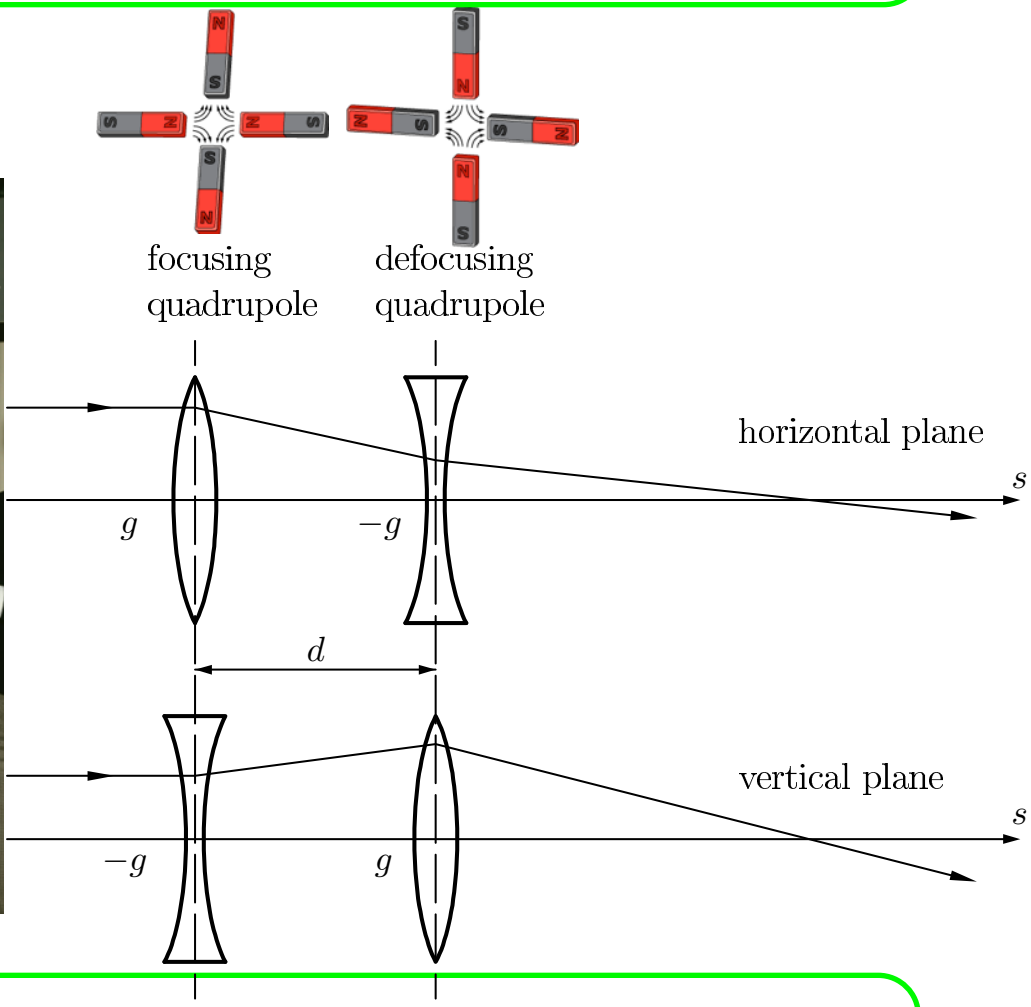
Synchrotrons: strong focusing machine

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



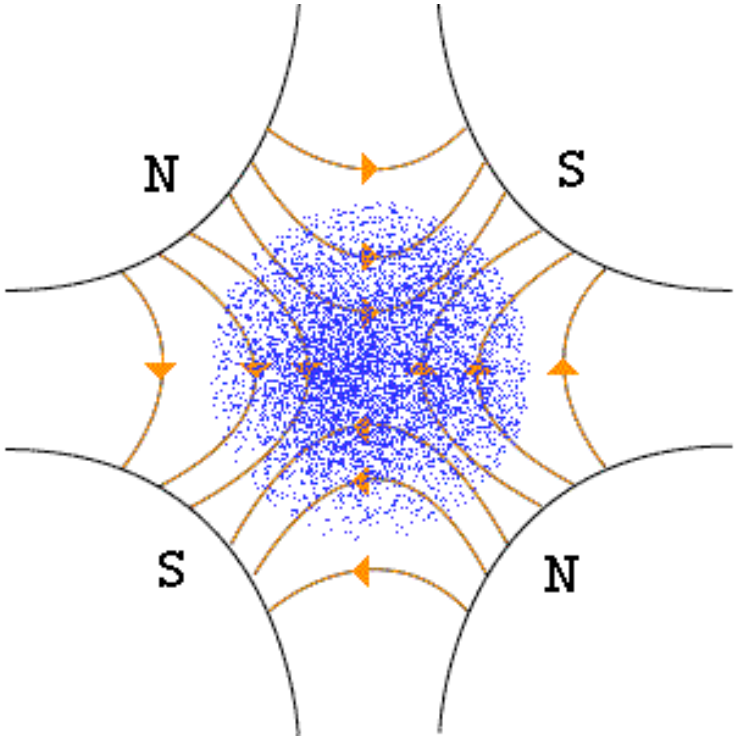




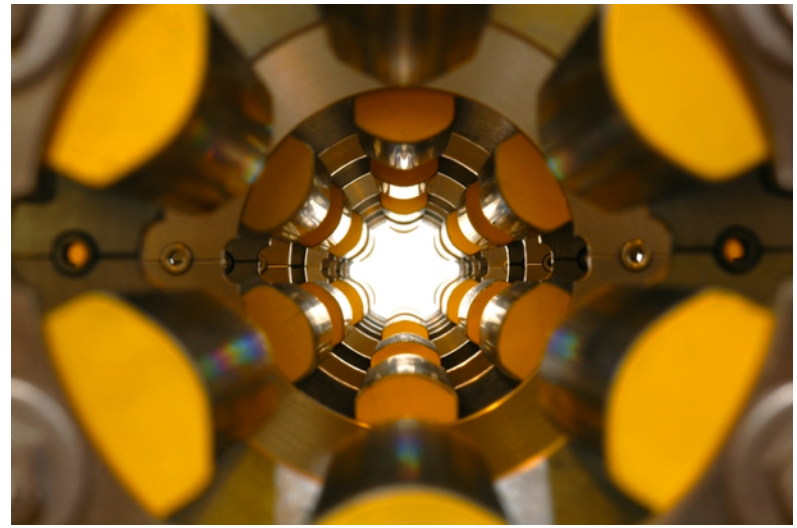
B field is focusing in one plane but defocusing in the other.

Typical lattice is FODO, focusing-drift-defocusing

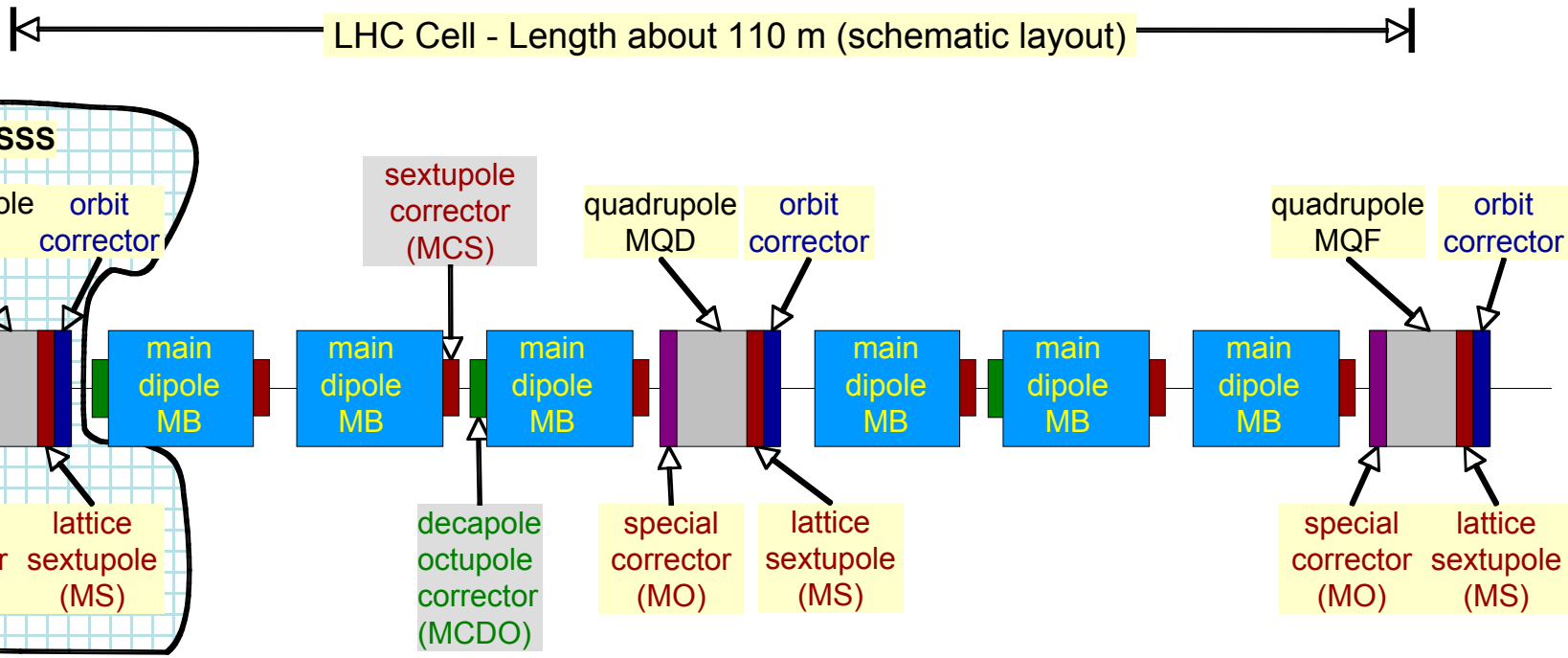
Example of FODO lattice



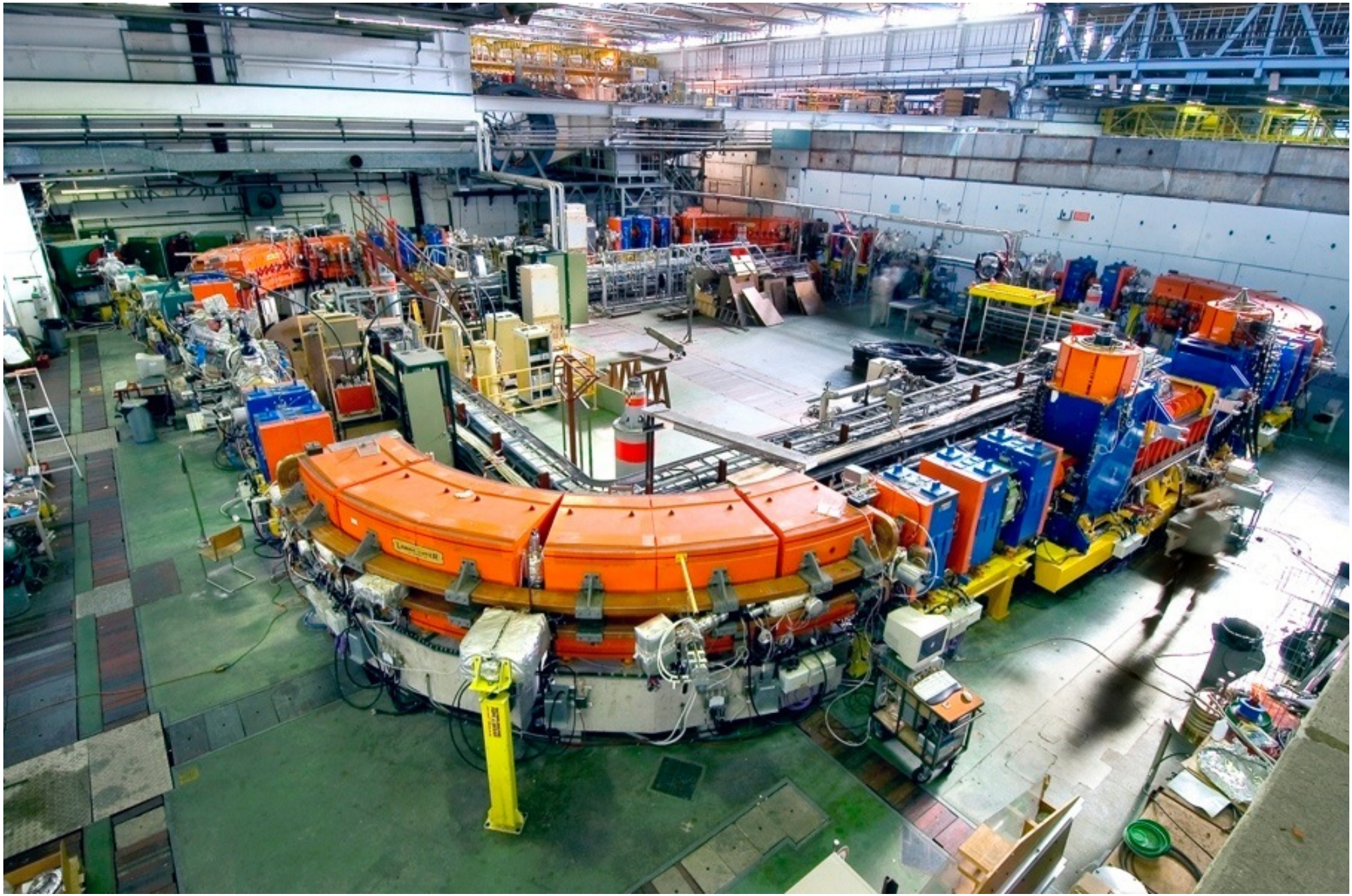
The beam point of view - Those are sextupoles - Six poles



Diamond light source - UK

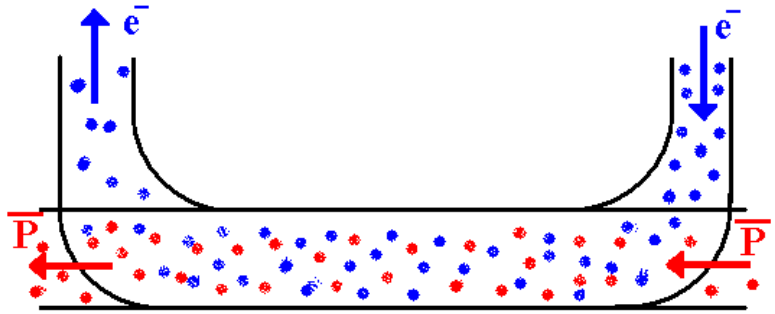


A synchrotron in a view: LEIR (Low Energy Ion Ring)



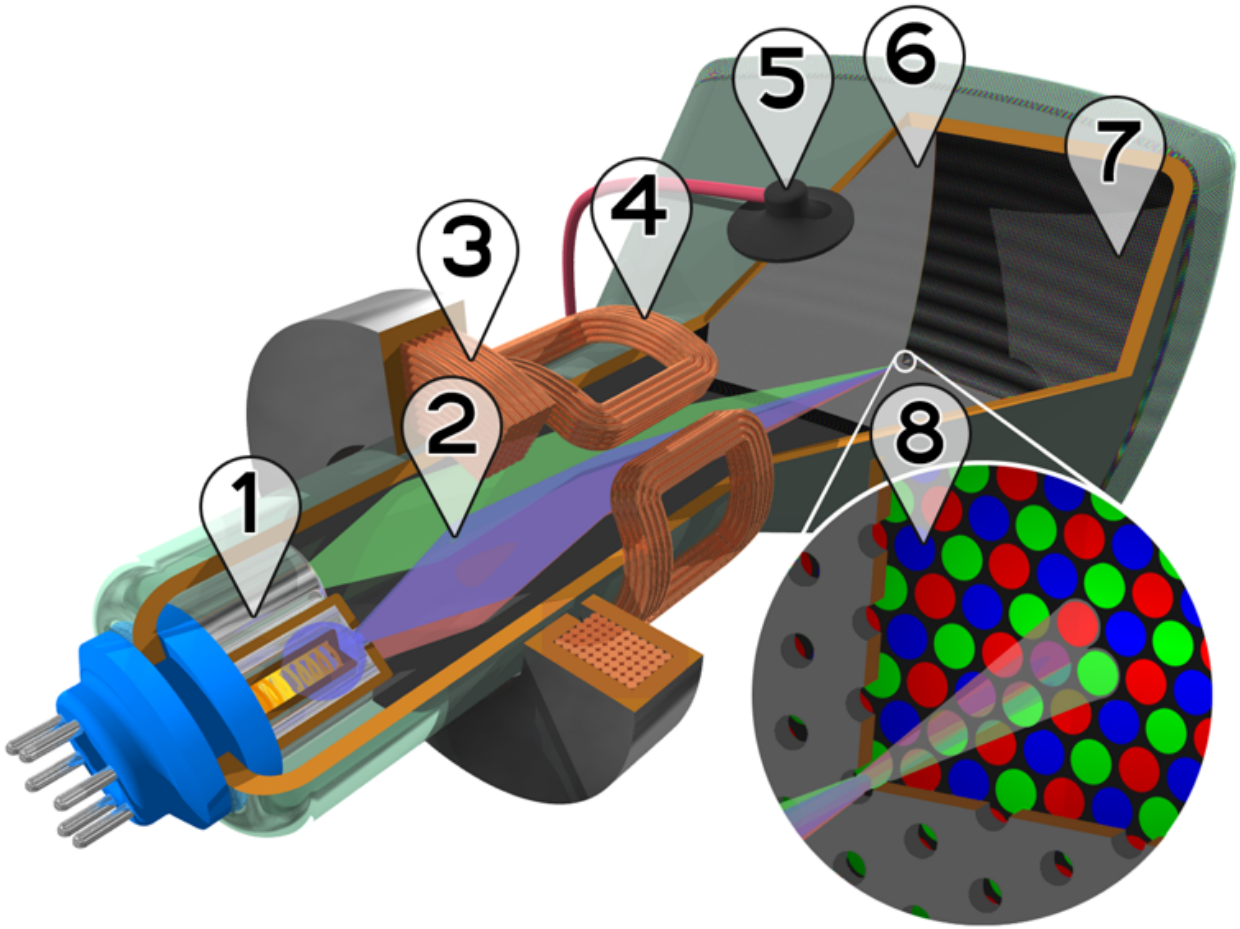
Electron cooling

“Cold electron beam”



“Hot ion beam”

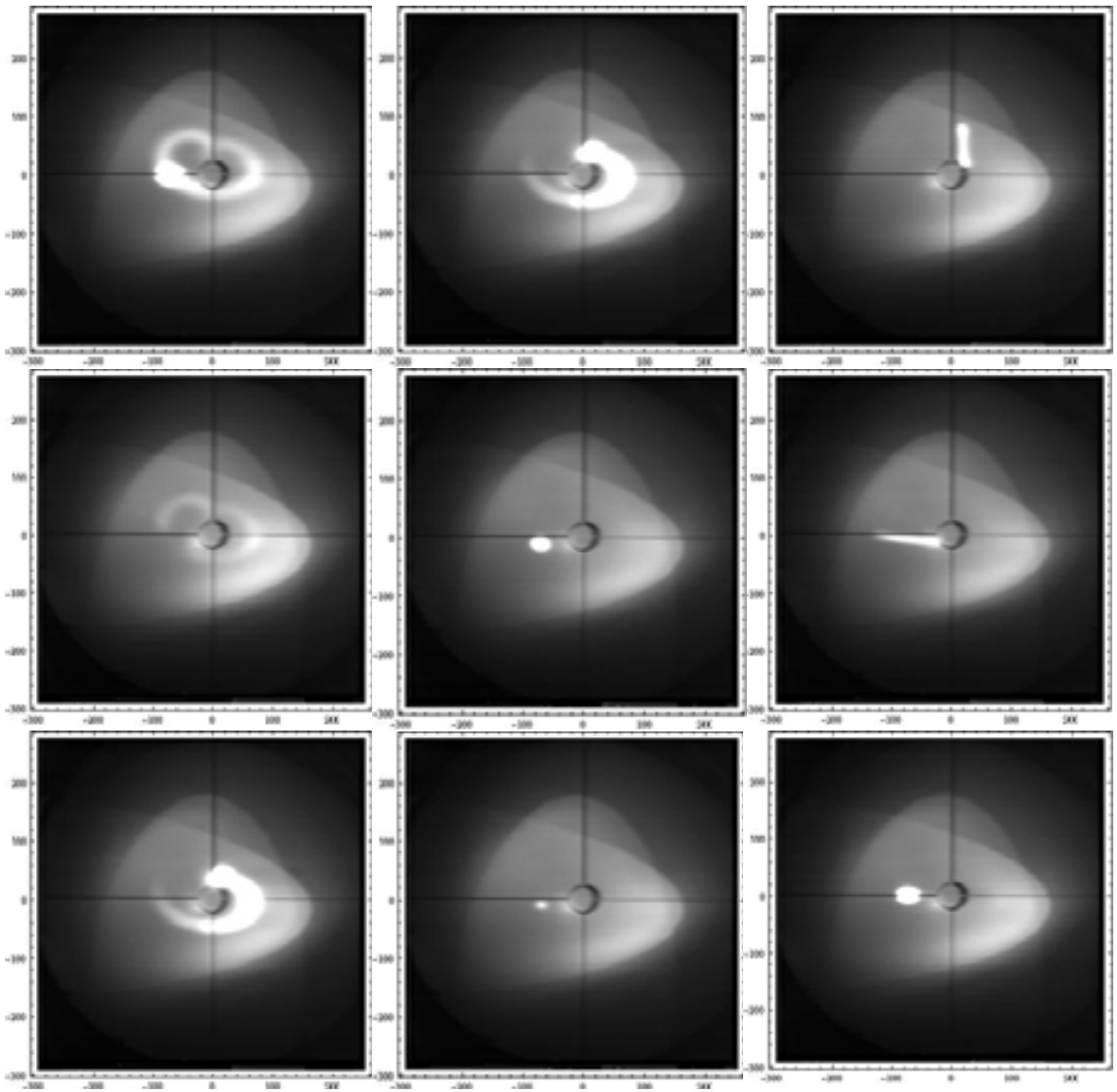
Summary: an accelerator that you know very well

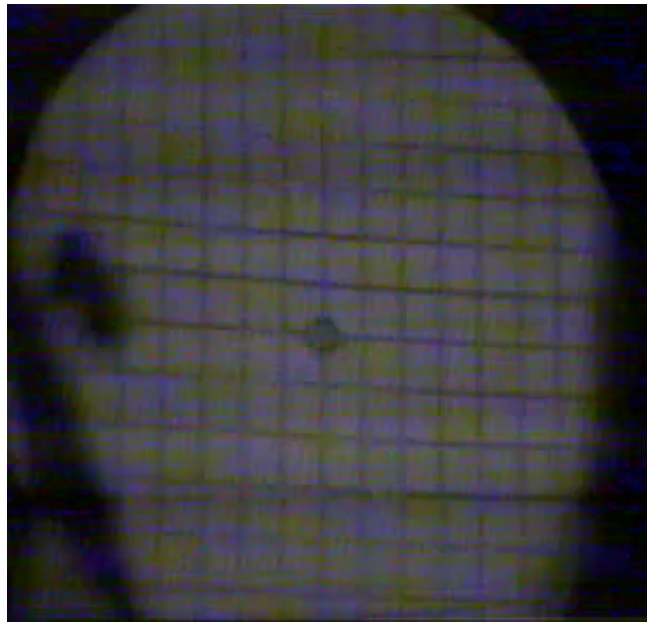


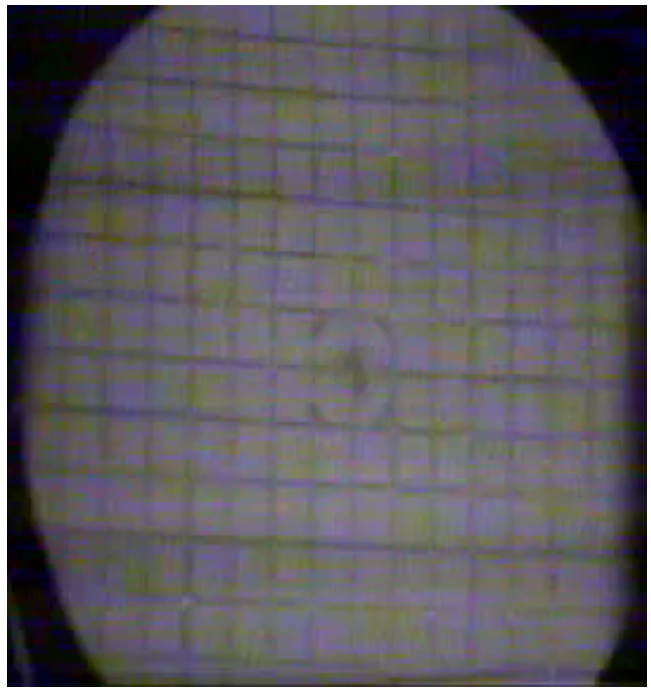
From Wikipedia

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

Real beam images



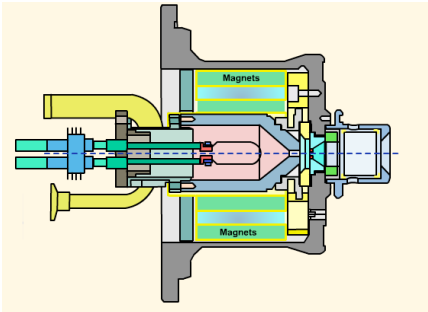




Courtesy of B. Goddard

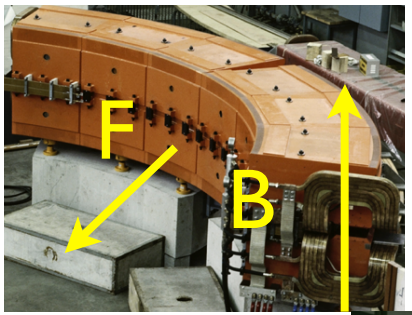
Summary: Building Blocks of an accelerator

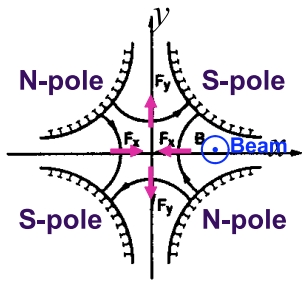
1) A particle source

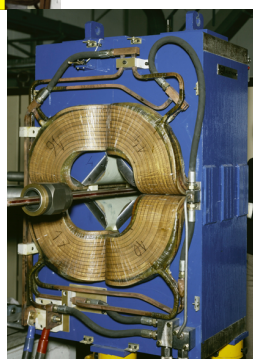


2) An accelerating system

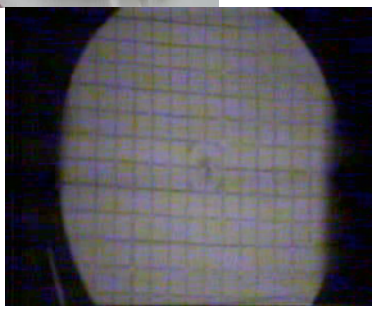
3) A series of guiding and focusing devices







Everything under vacuum



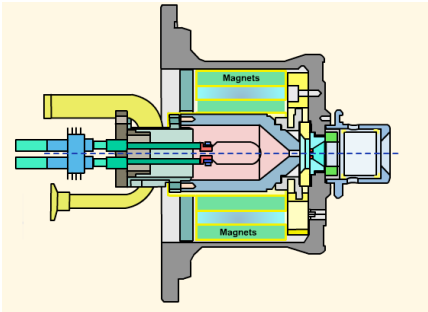
Apples vs Antiapples: protons vs antiprotons

Do protons fall in an accelerator?

And what about antiprotons?

Summary: Building Blocks of an accelerator

1) A particle source



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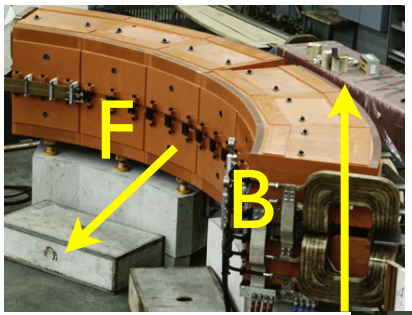
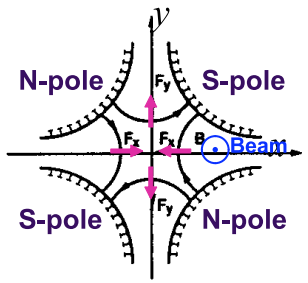
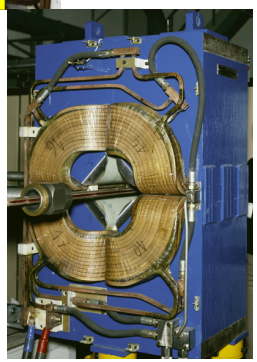
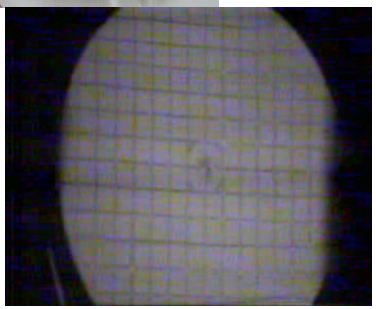






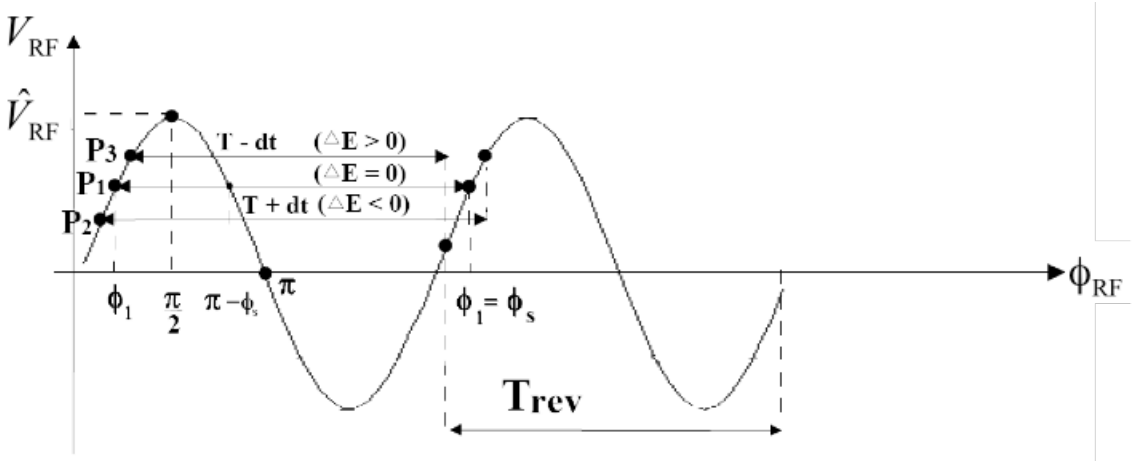
Everything under vacuum

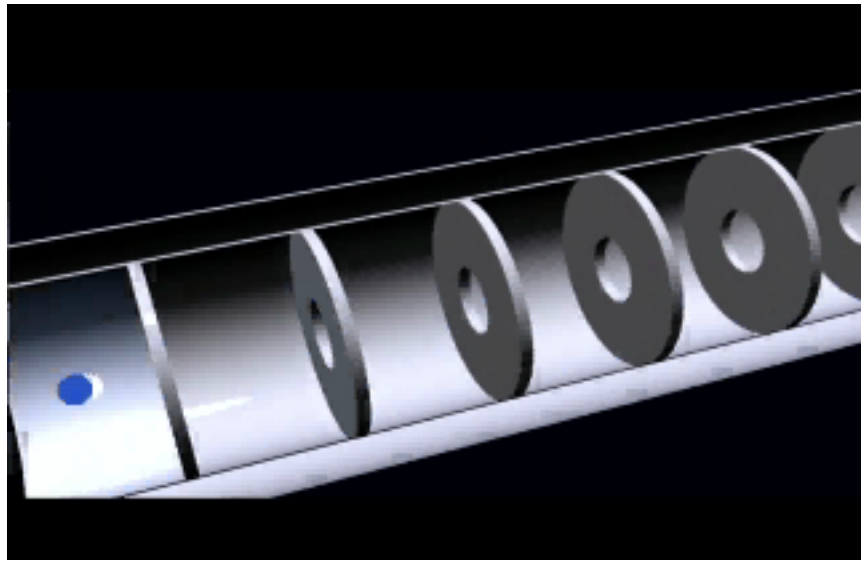


Acceleration

- 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.**

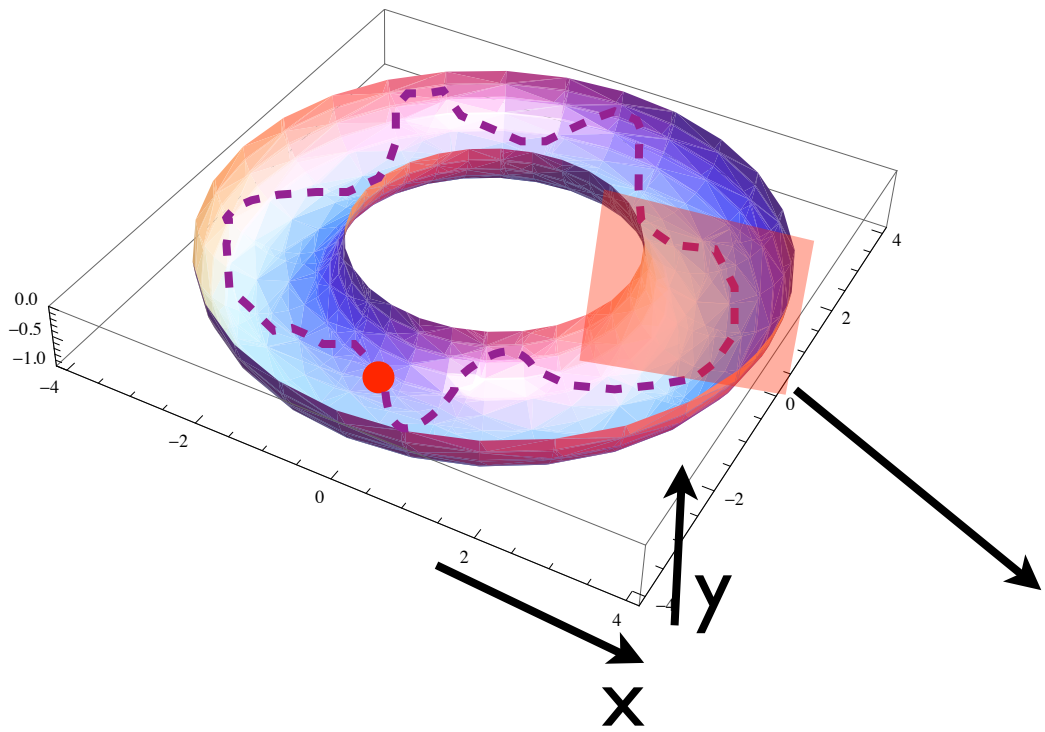
$$\Rightarrow \Delta E_1 = e\,\hat{V}_{\mathrm{RF}}\,\sin\phi_1$$

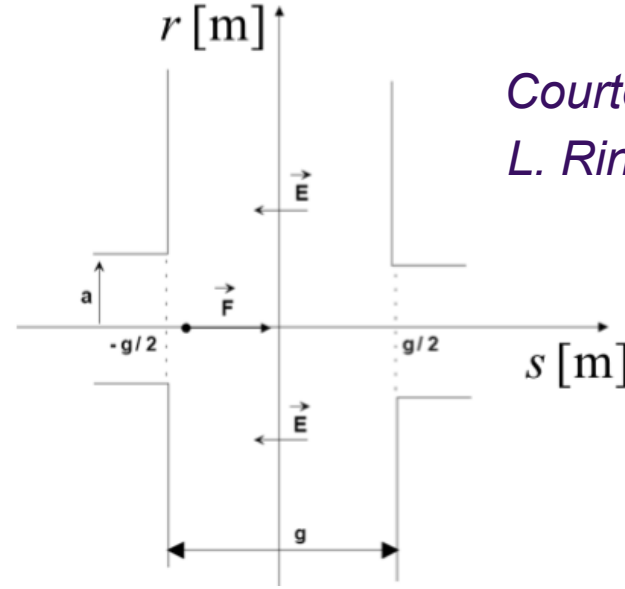




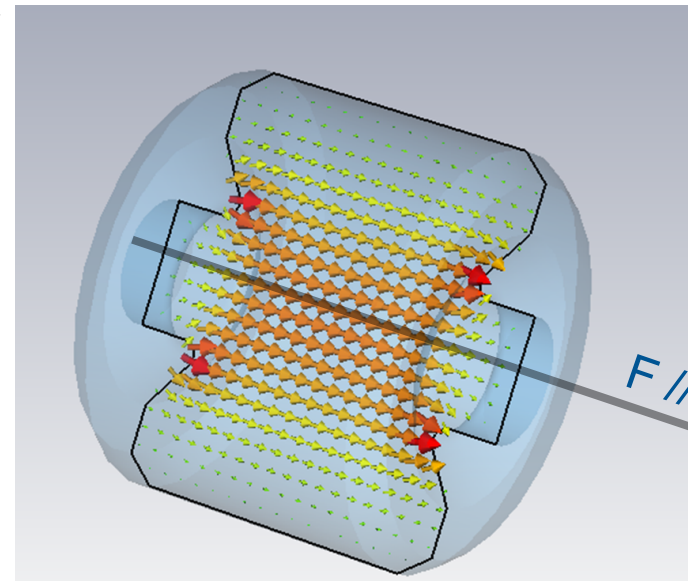
Acceleration I

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





Courtesy
L. Rinolfi



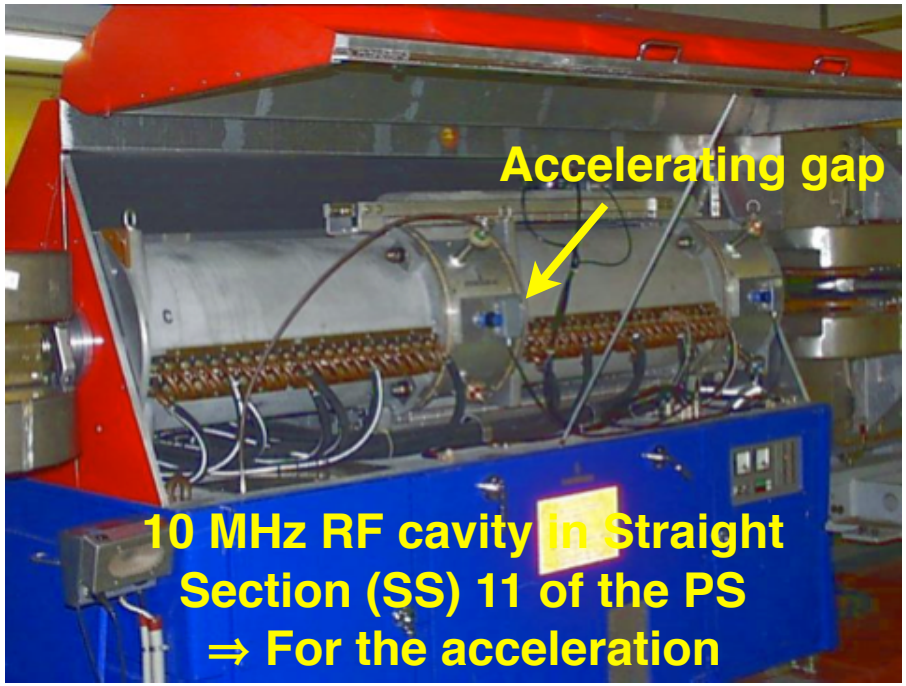
B. Salvant
N. Biancacci

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 UK radios (in MHz)

87.7: Radio North Angus (Brechin Infirmary)
87.7: Radio North Angus (Montrose Infirmary)
87.7: 87.7 Bailrigg FM
87.7: UWS Radio
87.7: Bridge fm (Ashludie Hospital)
87.7: Bridge fm (Royal Victoria Hospital)
87.7: Bridge fm (Ninewells Hospital & Carseview Centre)
87.7: Radio Branwen
87.7: Fresh FM
87.7: Radio Lonsdale
87.7: Hospital Radio Plymouth
87.7: Xpression FM (Duryard Halls and Birks Halls)
87.7: Xpression FM (Lafrowda and Exeter Halls)
87.7: Withybush FM
87.7: Storm 87.7FM
87.7: Radio Glangwili
87.8: Radio Bronglais
88.0: Real Radio (Wrexham)
88.1-90.3: BBC Radio 2
88.4: Gaydio (Manchester)
88.6: BBC Radio Sheffield (Sheffield)
88.8: BBC Radio Jersey
89.0: Manx Radio
89.1: Big City Radio
89.3: BFBS Blandford

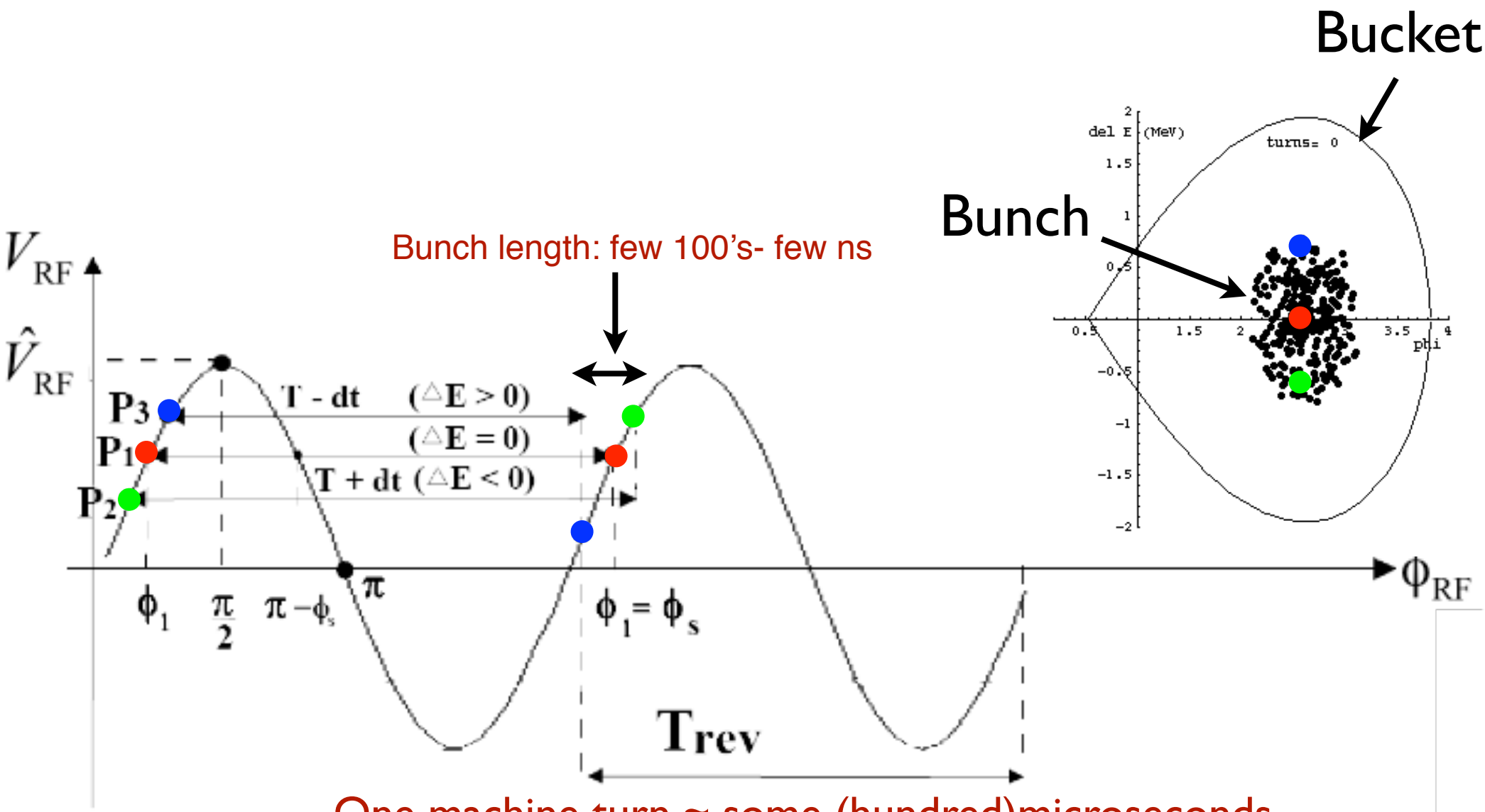
102.5: Citybeat 96.7 102.5FM (Newtownabbey, Carrickfergus, Bangor)
102.5: Clyde 1
102.5: MFR
102.5: The Pulse of West Yorkshire (Halifax & Huddersfield)
102.5: 102.5 Radio Pembrokeshire
102.5: Soundart Radio
102.5: Caithness FM
102.5: 102.5 FM Skyline
102.5: NE1fm 102.5
102.5: 102.5 The Bridge
102.5: Eava FM
102.5: BFBS Aldershot
102.6: Heart (Chelmsford)
102.6: Star Radio (Richmond)
102.6: Heart (Yeovil and Taunton)
102.6: Metro Radio (Alnwick)
102.6: NECR (Kildrummy)
102.6: Signal 1
102.6: Heart (Oxford)
102.6: Sine FM
102.7: Heart (Peterborough)
102.7: Heart (Reigate and Crawley)
102.7: BBC Radio Leeds (Keighley)
102.7: Cuillin FM

Radio Caroline: 1485/1520 kHz

from wikipedia

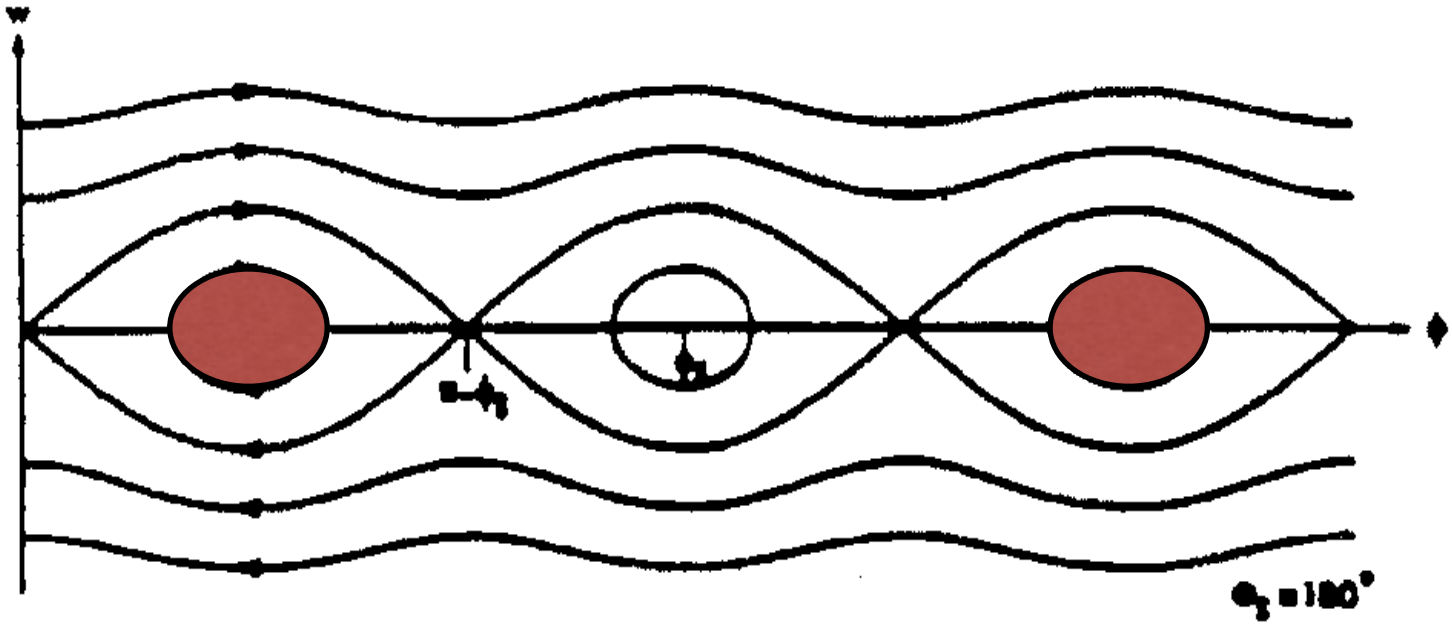
Longitudinal focusing, a pendulum …

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



One machine turn ~ some (hundred)microseconds

A chain of buckets

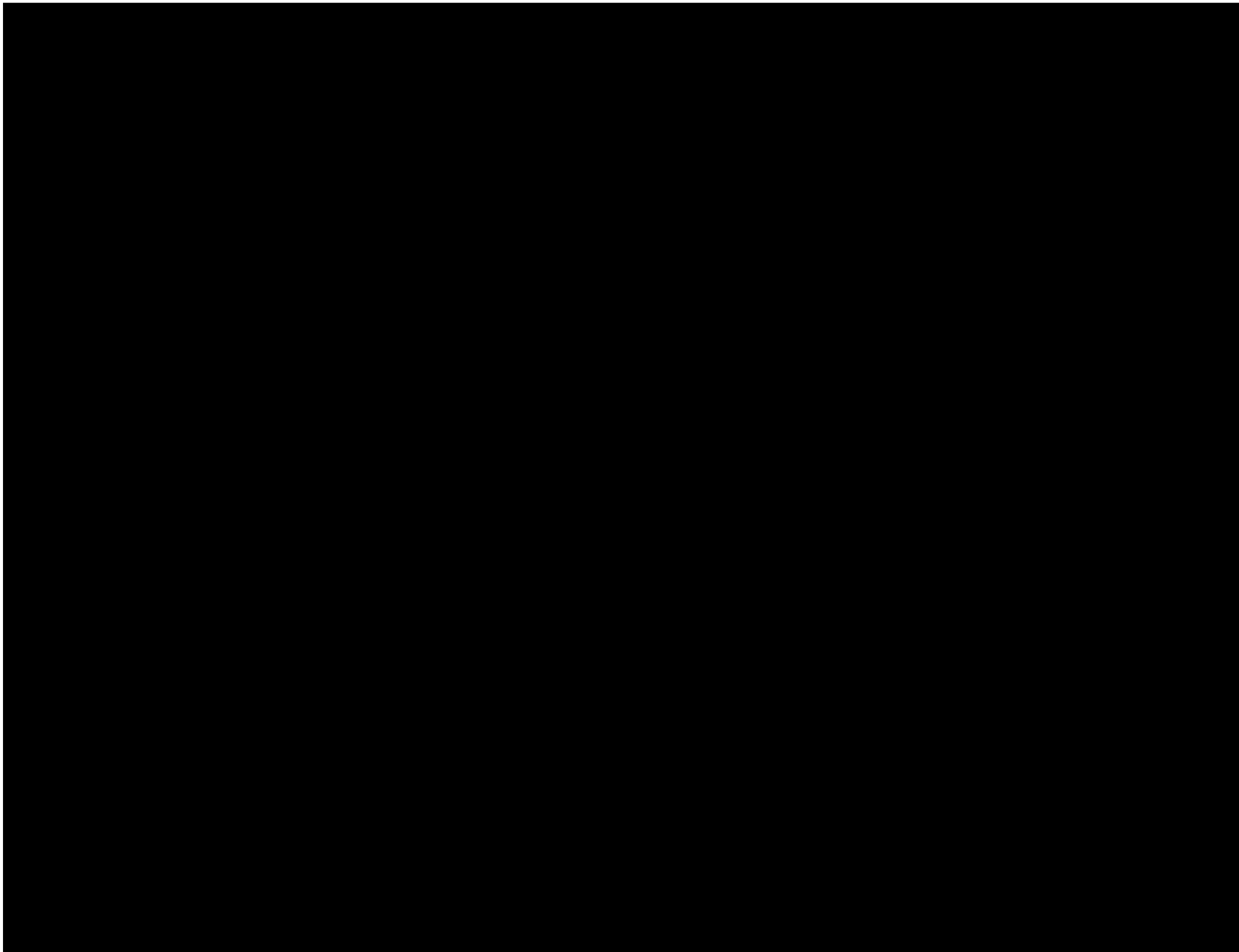


Courtesy
E. Wilson

Number of buckets:

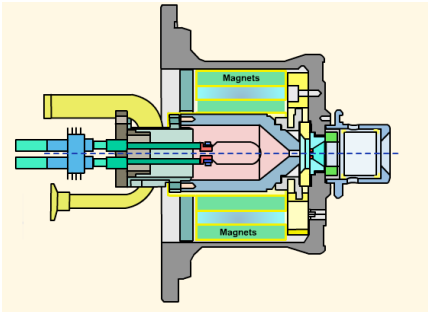
possible positions along the machine circumference where ***there could be a bunch.***

In the example: 3 buckets and 2 bunches



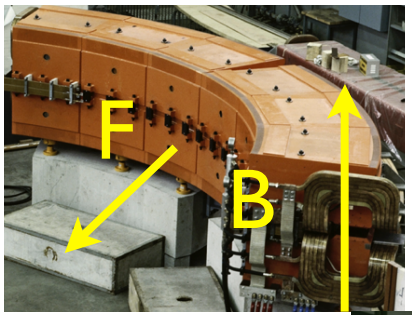
Summary: Building Blocks of an accelerator

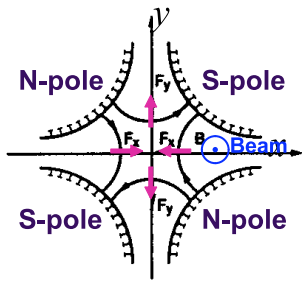
1) A particle source

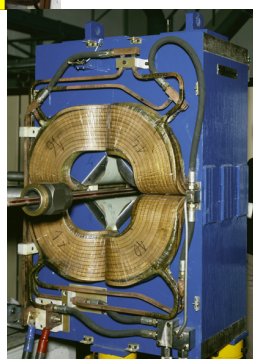


2) An accelerating system

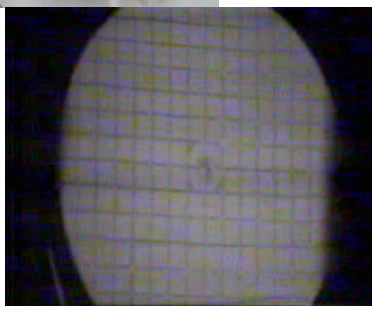
3) A series of guiding and focusing devices







Everything under vacuum



What is the LHC ?

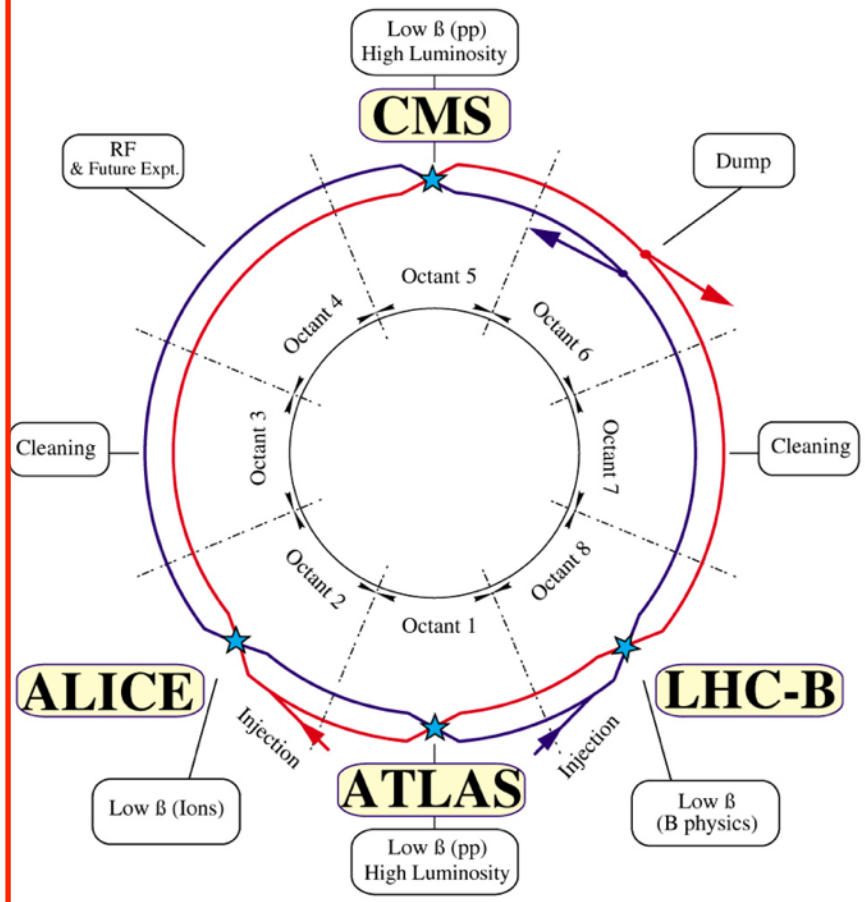
LHC: Large Hadron Collider

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***

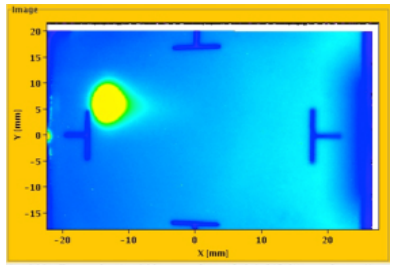
Hadrons:
p p collision ⇒ a) synchrotron radiation
b) discovery machine.

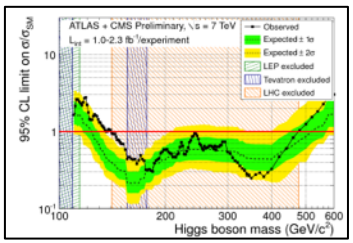
Collider: particles are stored in two separated rings which are synchrotrons, and accelerated from injection energy (450 GeV) to 7 TeV.
At 7 TeV the two beams are forced to cross in collision points to interact.
The beams are stored at 7 TeV for few 10 h to produced collisions. When the intensity is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



The LHC run1 timeline 1/2

August 2008
First Injection tests





December 2011
5.6 fb^{-1}

Energy: **4 TeV**

March 2012
4 TeV

September 10, 2008
Circulating beams

November 20, 2009
Beams back

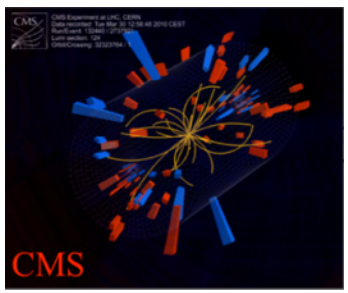
June 28, 2011
1380 bunches

1380

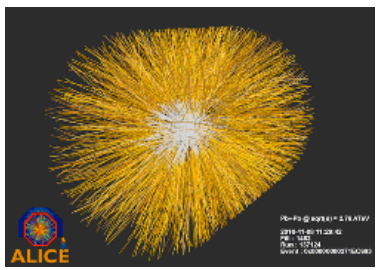
2008 2009 2010 2011 2012

September 19, 2008
Incident

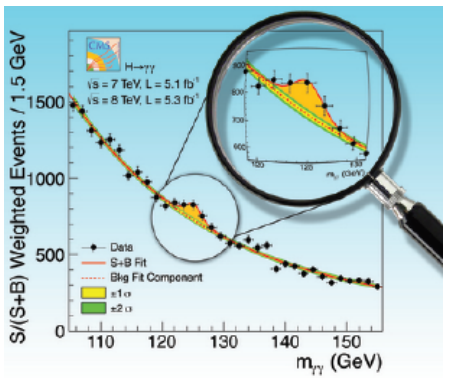
March 30, 2010
First collisions at 7 TeV CM



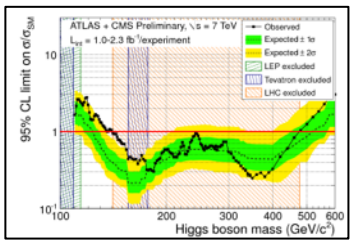
November 2010
First Lead ion run



July 4, 2012
Higgs Seminar



The LHC run1 timeline 2/2



Comments (21–Feb–2013 09:05:25)
Phone:77600

*** END OF RUN 1 ***
No beam for a while. Access required
time estimate: ~2 years

December 2011
5.6 fb^{-1}

Energy: **4 TeV**

March 2012
4 TeV

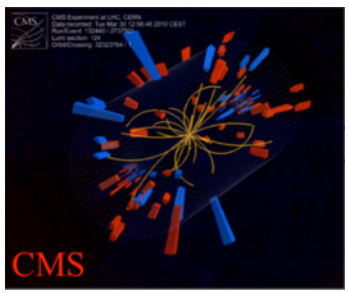
February 21, 2013
Long shutdown 1

June 28, 2011
1380 bunches

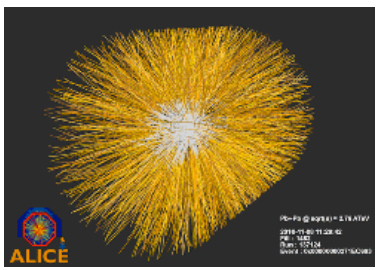
1380

2010 | 2011 | 2012 | 2013

March 30, 2010
First collisions at 7 TeV CM



November 2010
First Lead ion run



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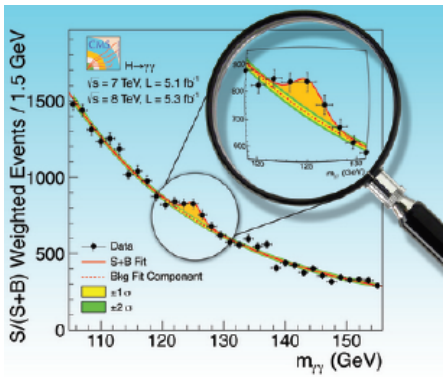
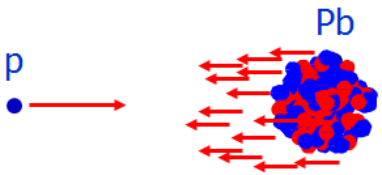


January 2013
Protons & Lead



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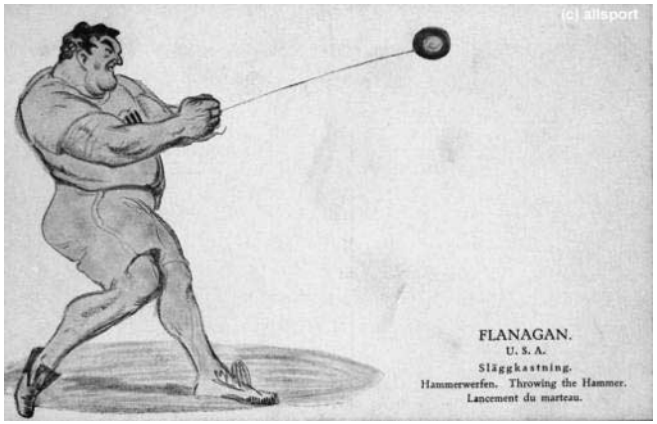
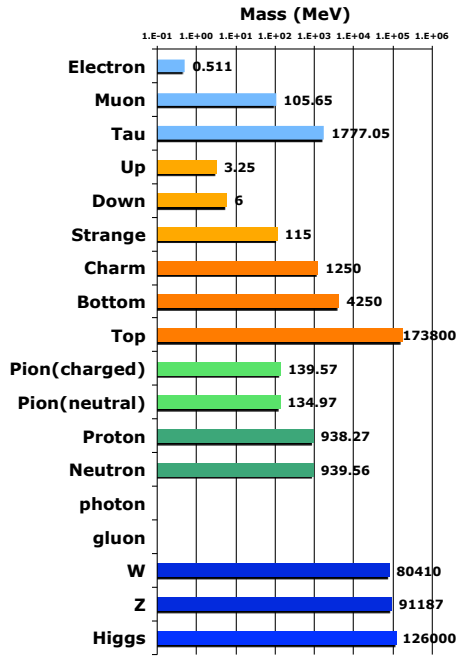
LHC is a ***collider*** and ***synchrotron storage ring:***
ILC is a collider but is not a synchrotron storage ring

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

Limited by technology



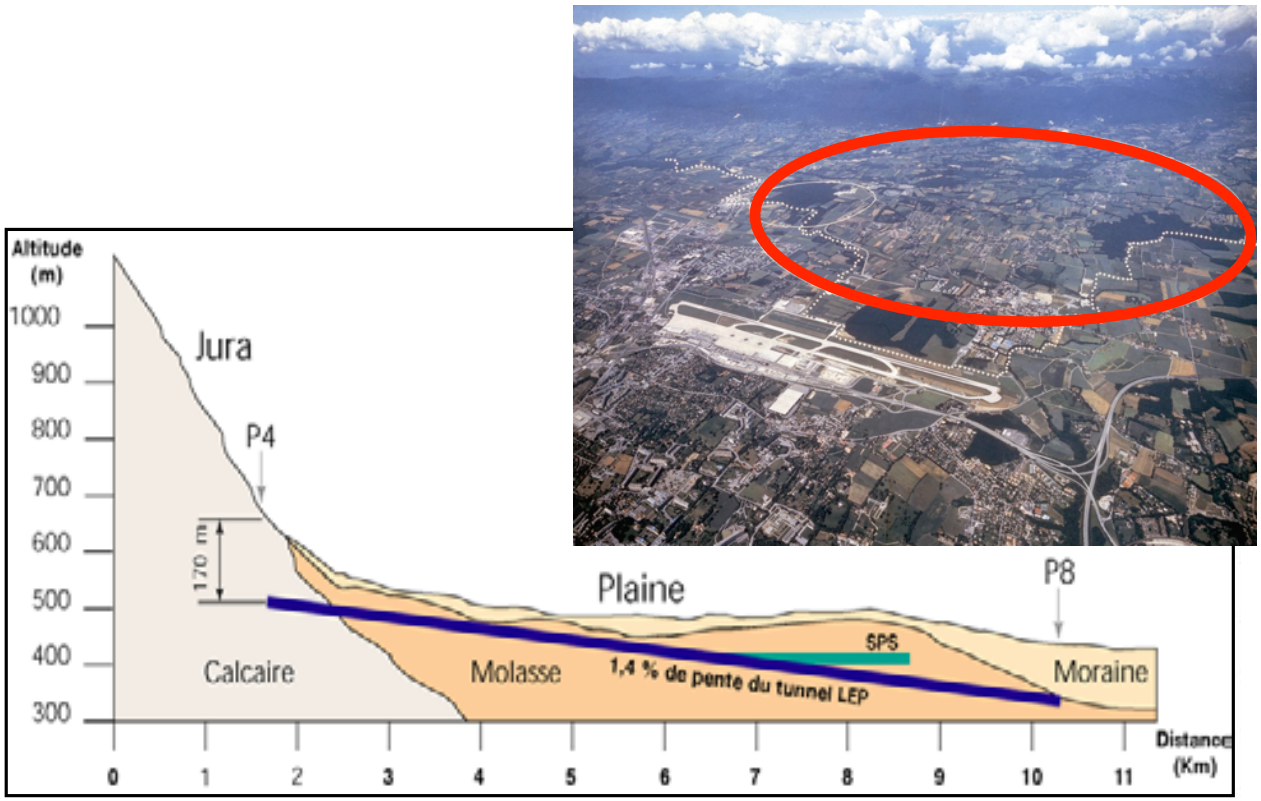
$$k = \frac{1}{\rho} = \frac{e}{p}B = \frac{e\mu_0}{p}\frac{nI}{h}$$



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

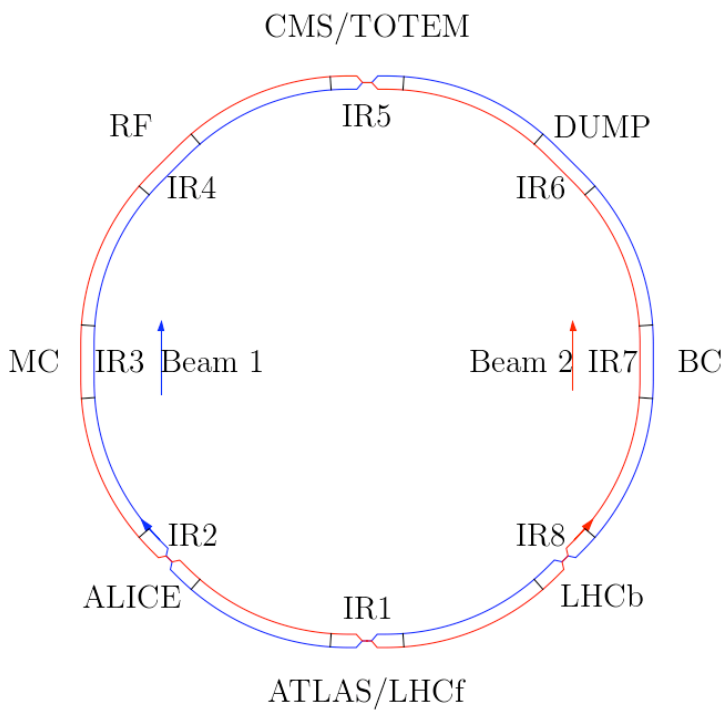
Given by the physics
This will depend on the mass of the particles we want to discover

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%



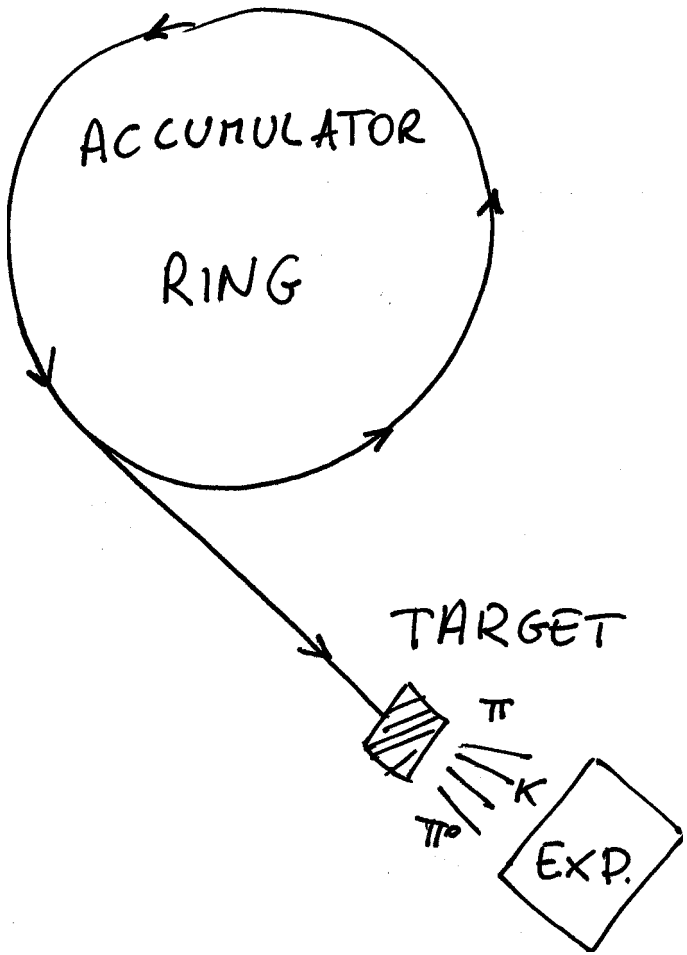
LHC: 8 independent sectors

8 straight sections

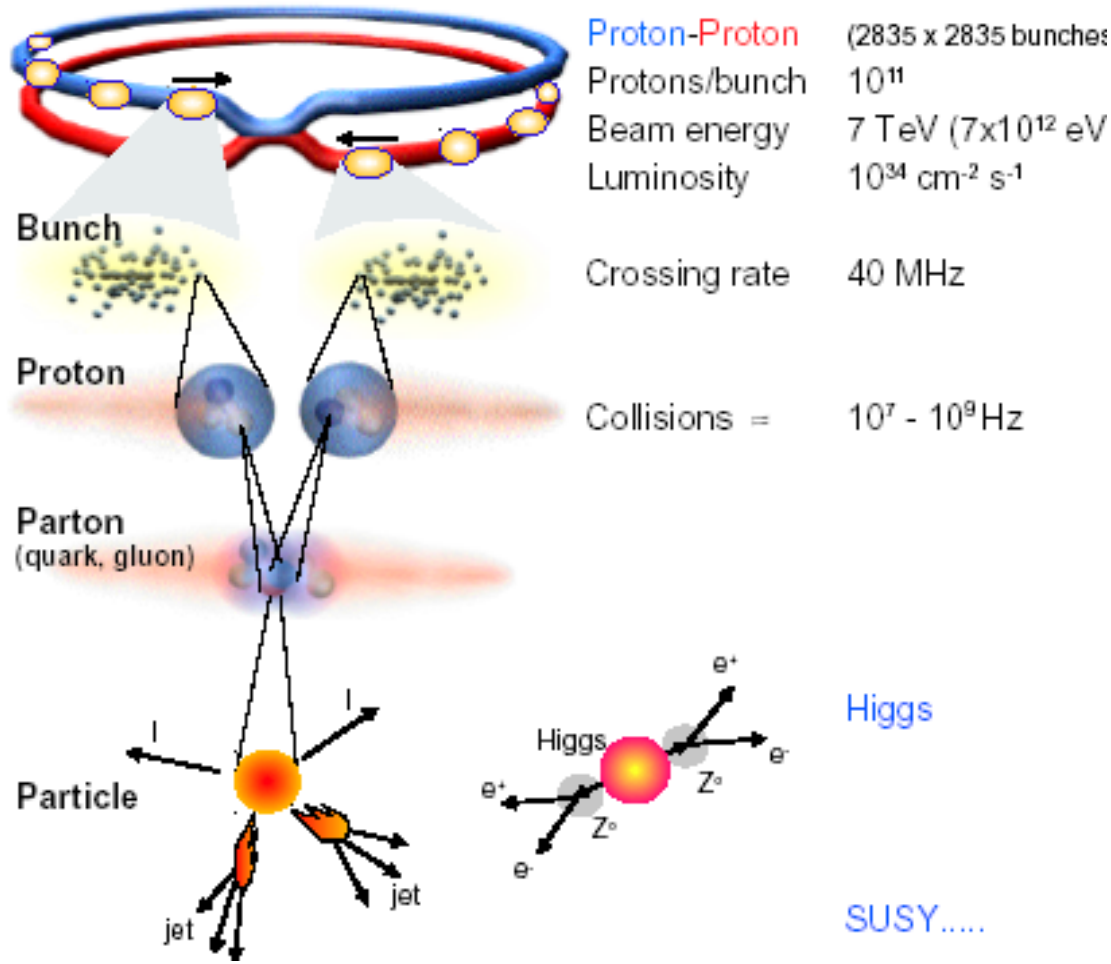
8 arcs

Different approaches: fixed target vs collider

Fixed target



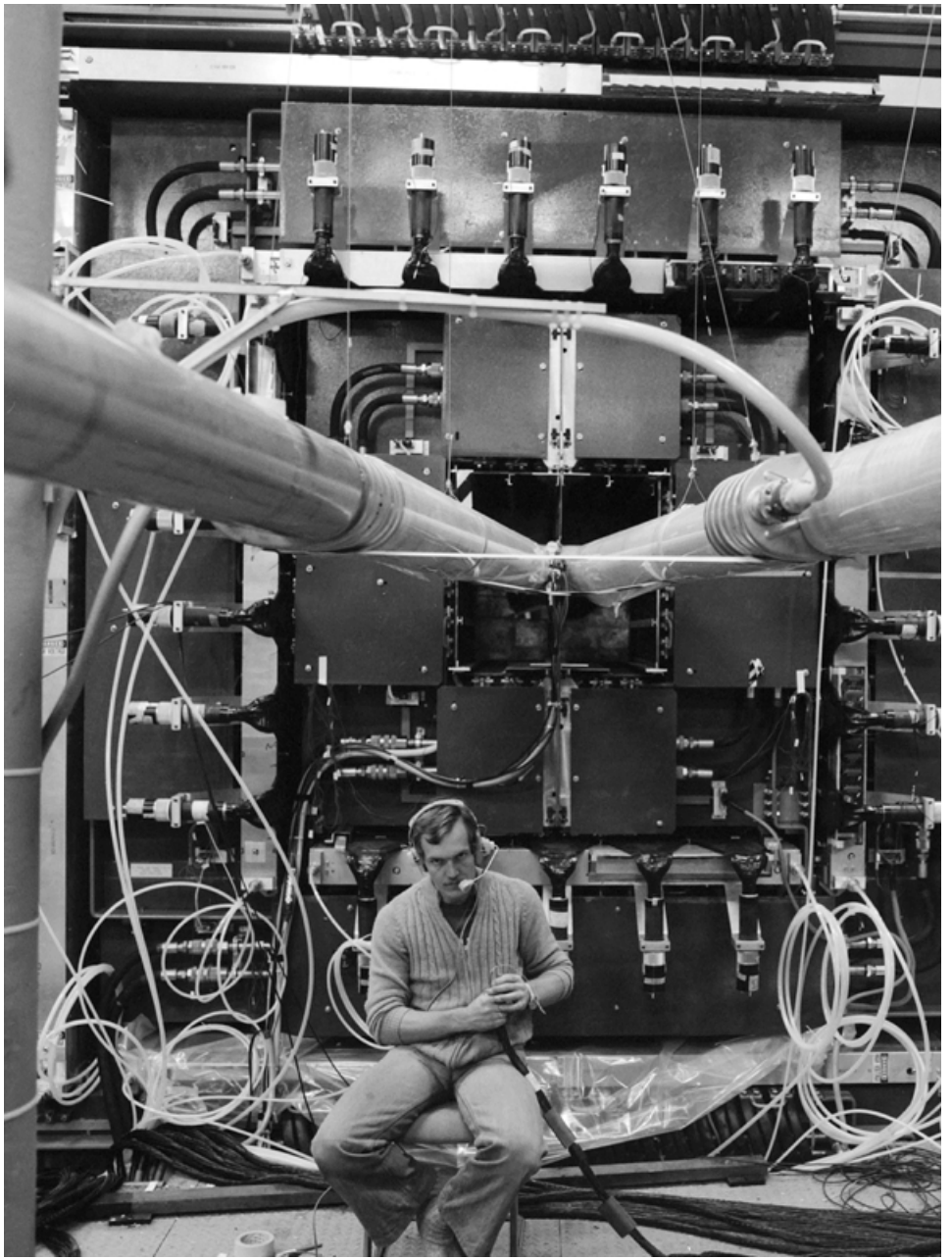
Storage ring/collider

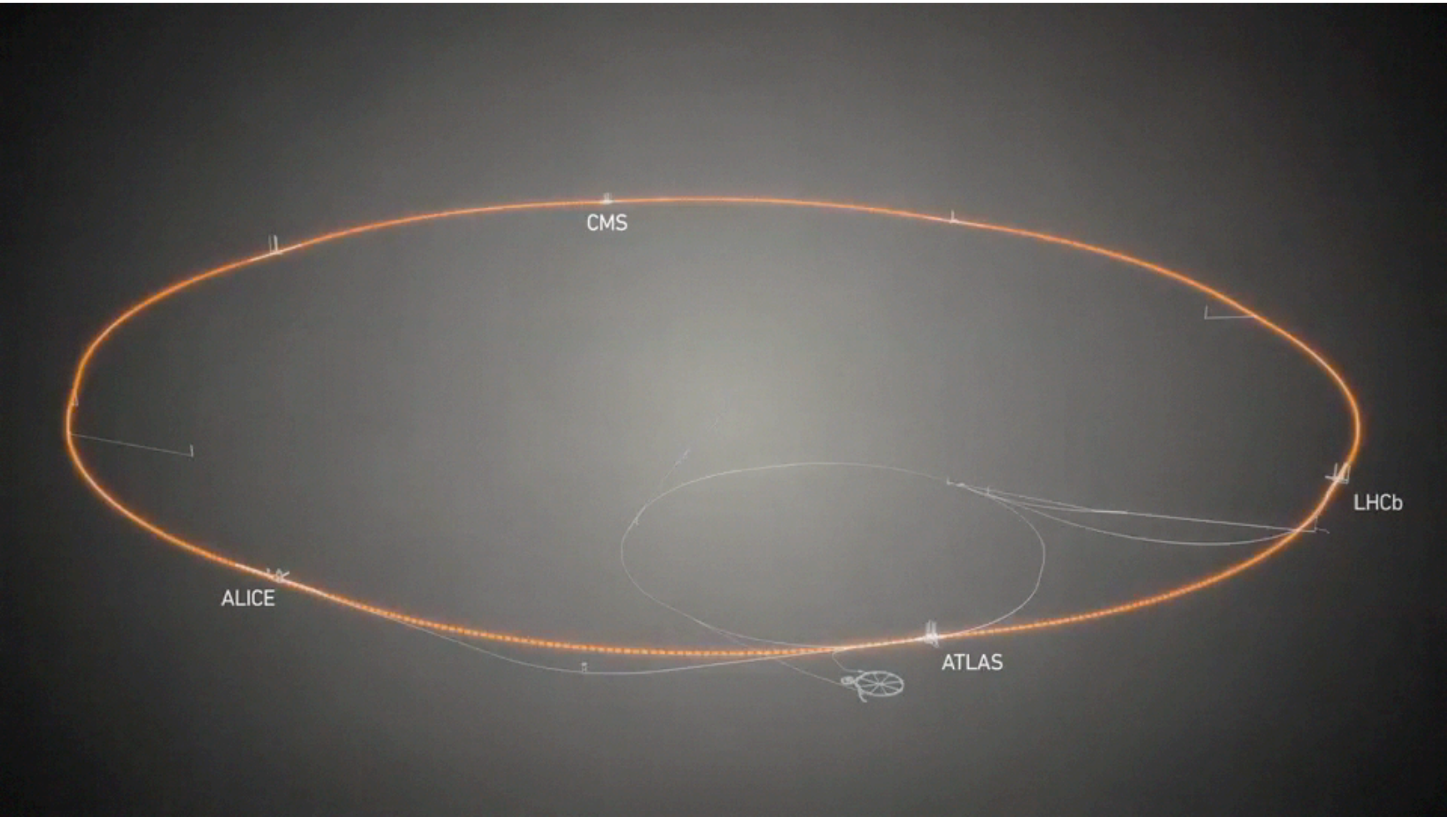


$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

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

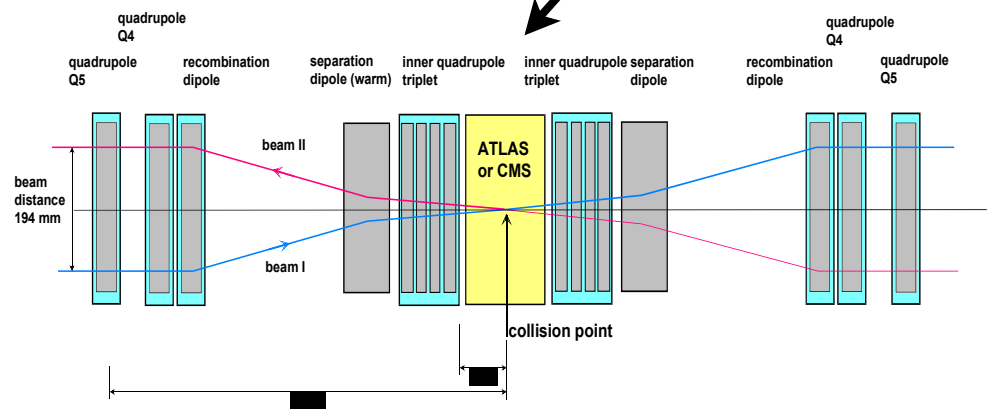
ISR: first proton-proton collider



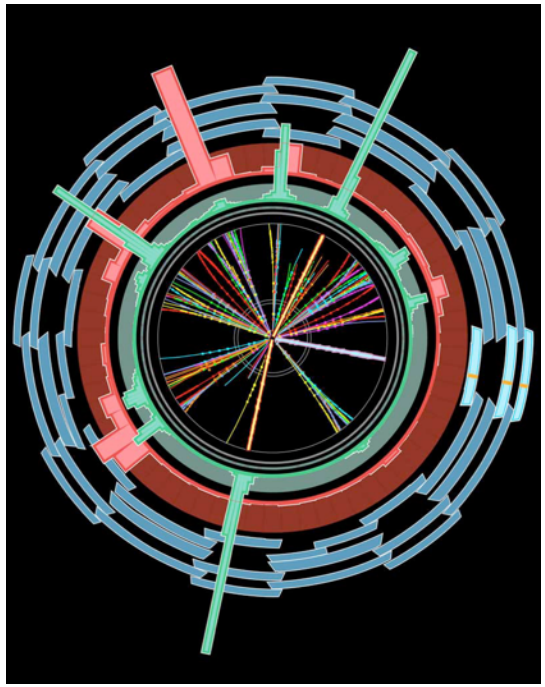

CMS
LHCb
ALICE
ATLAS

Luminosity

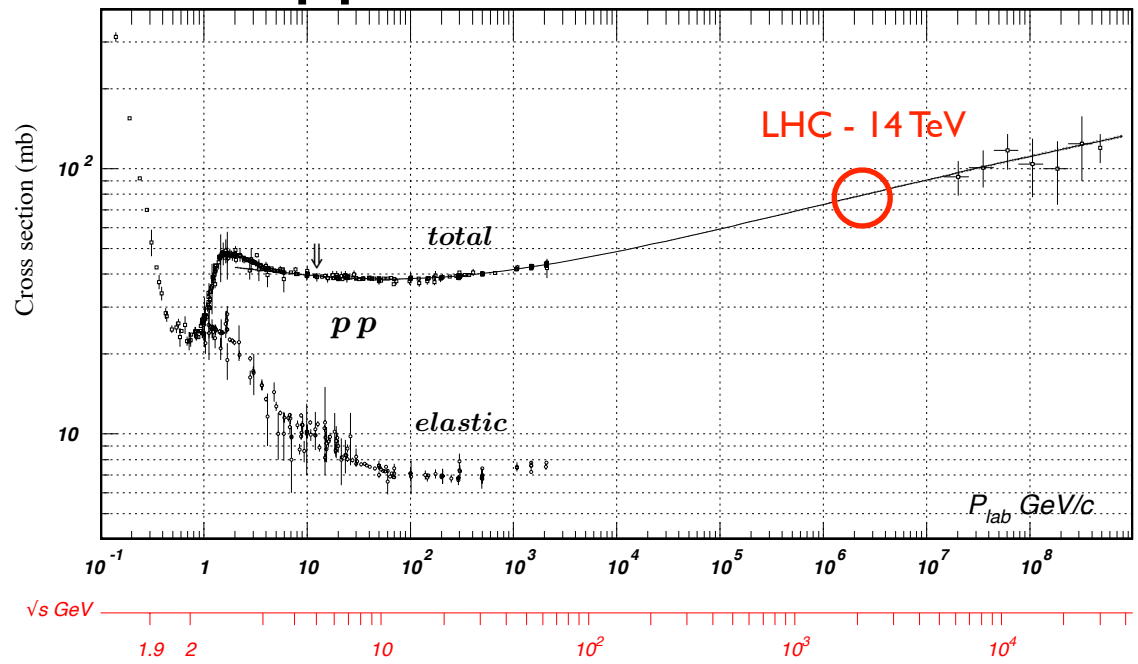
$$N_{event} = L\sigma_{event}$$



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

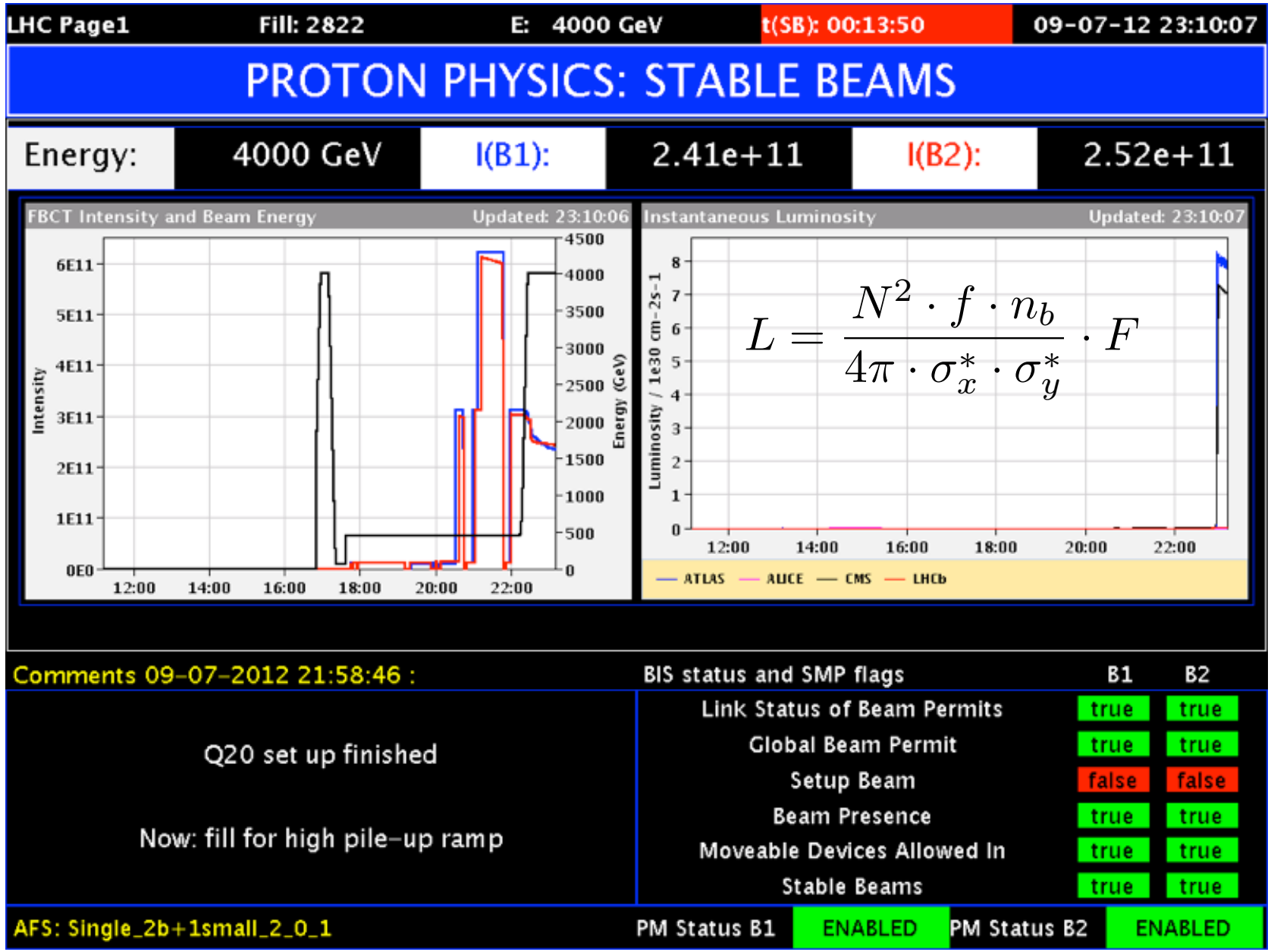
Beam dimension at the IP

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

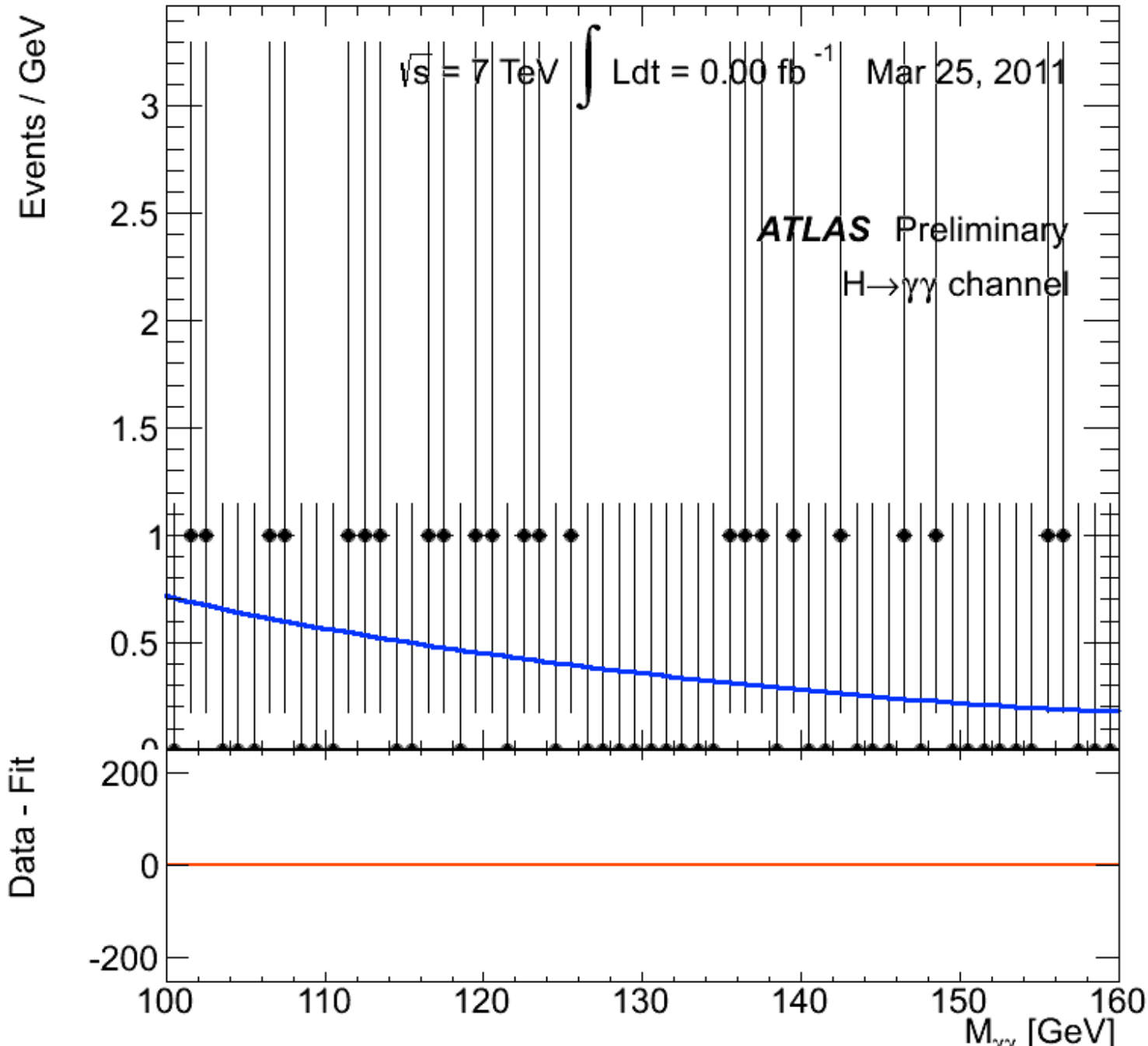
$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}$$

At first look, the smaller the better

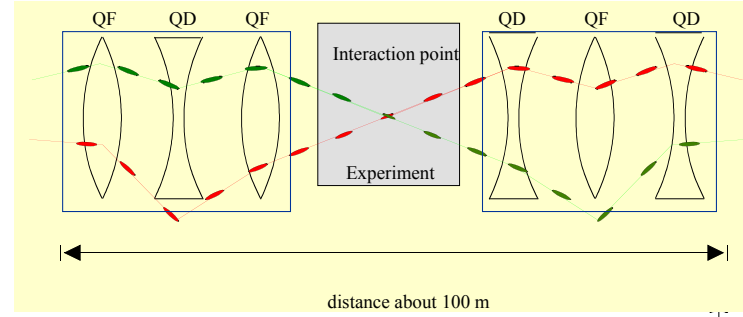
LHC Operational page

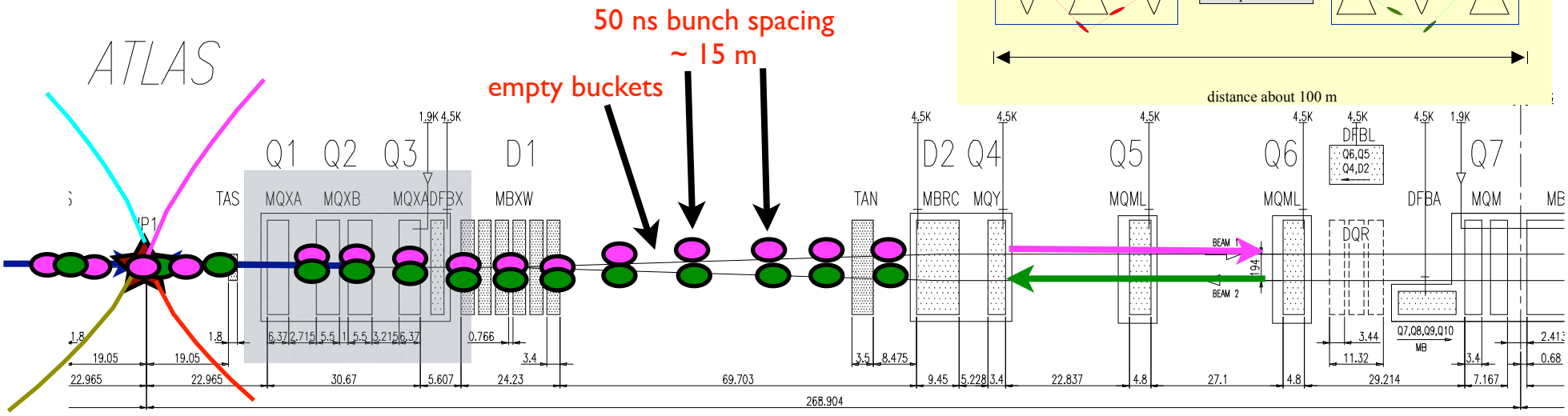


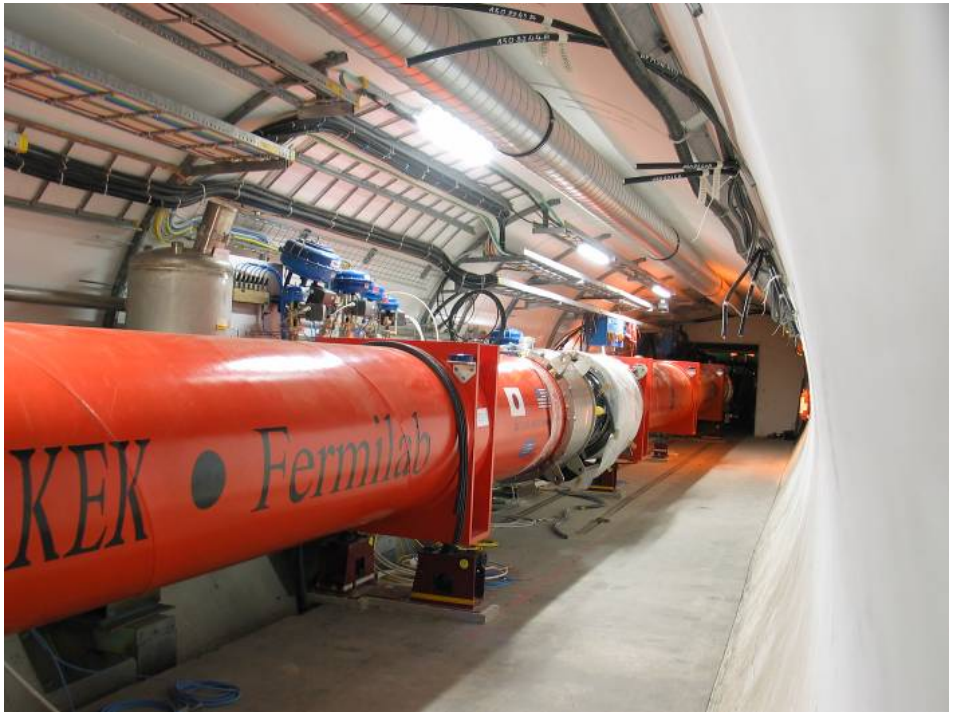
Where we are now ...



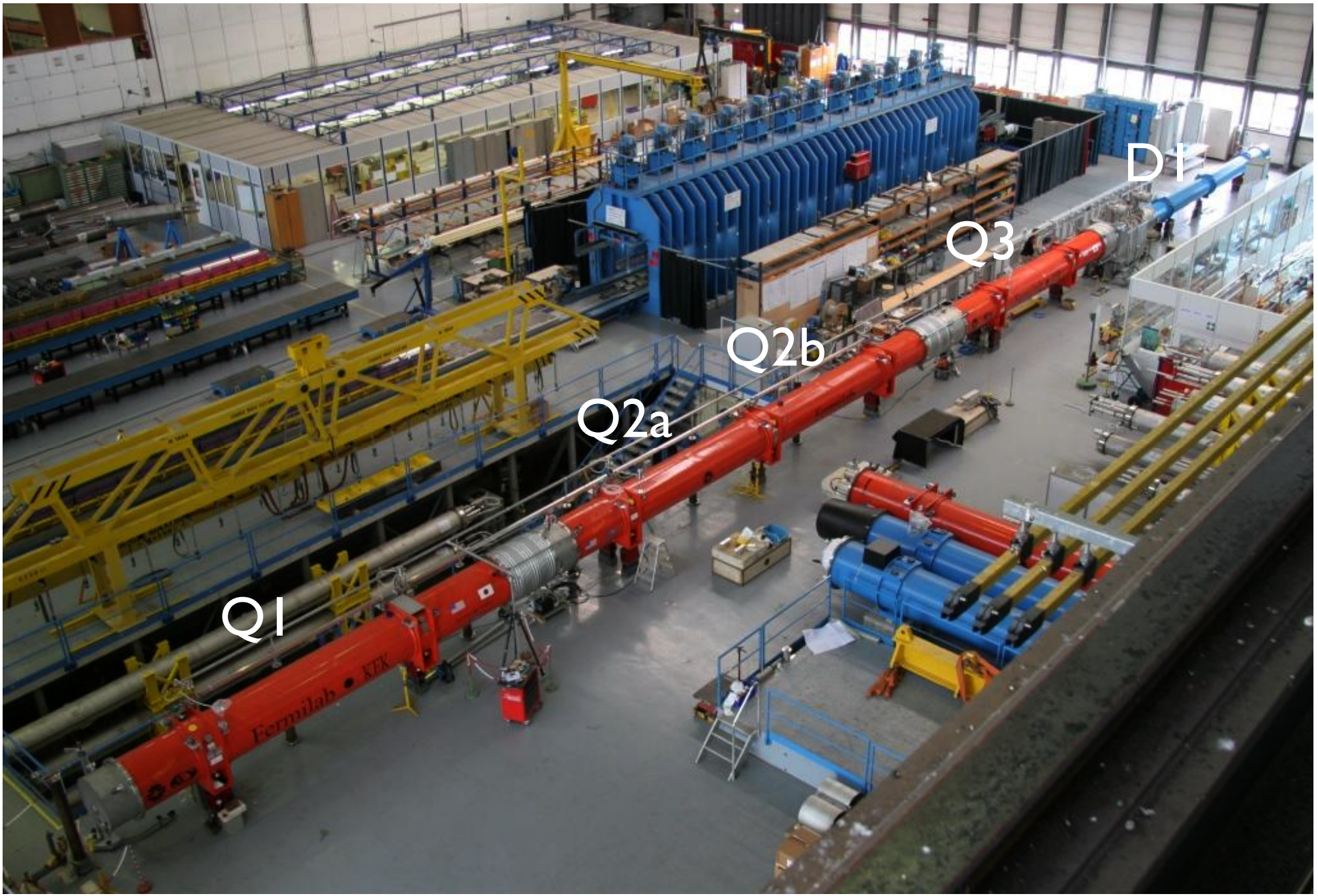
Inner triplet: final focusing
⇒ how to make the beam small at the IP



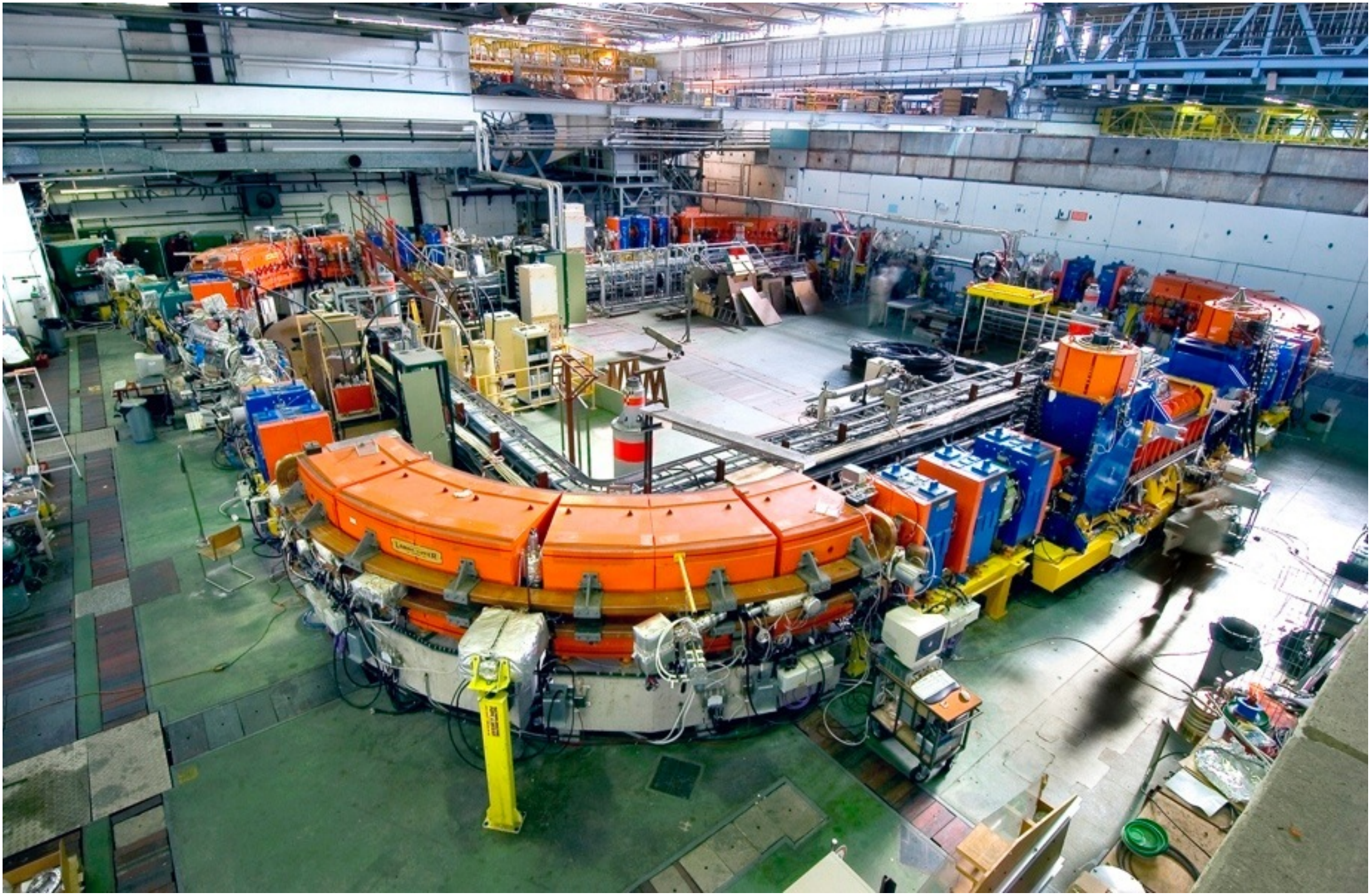




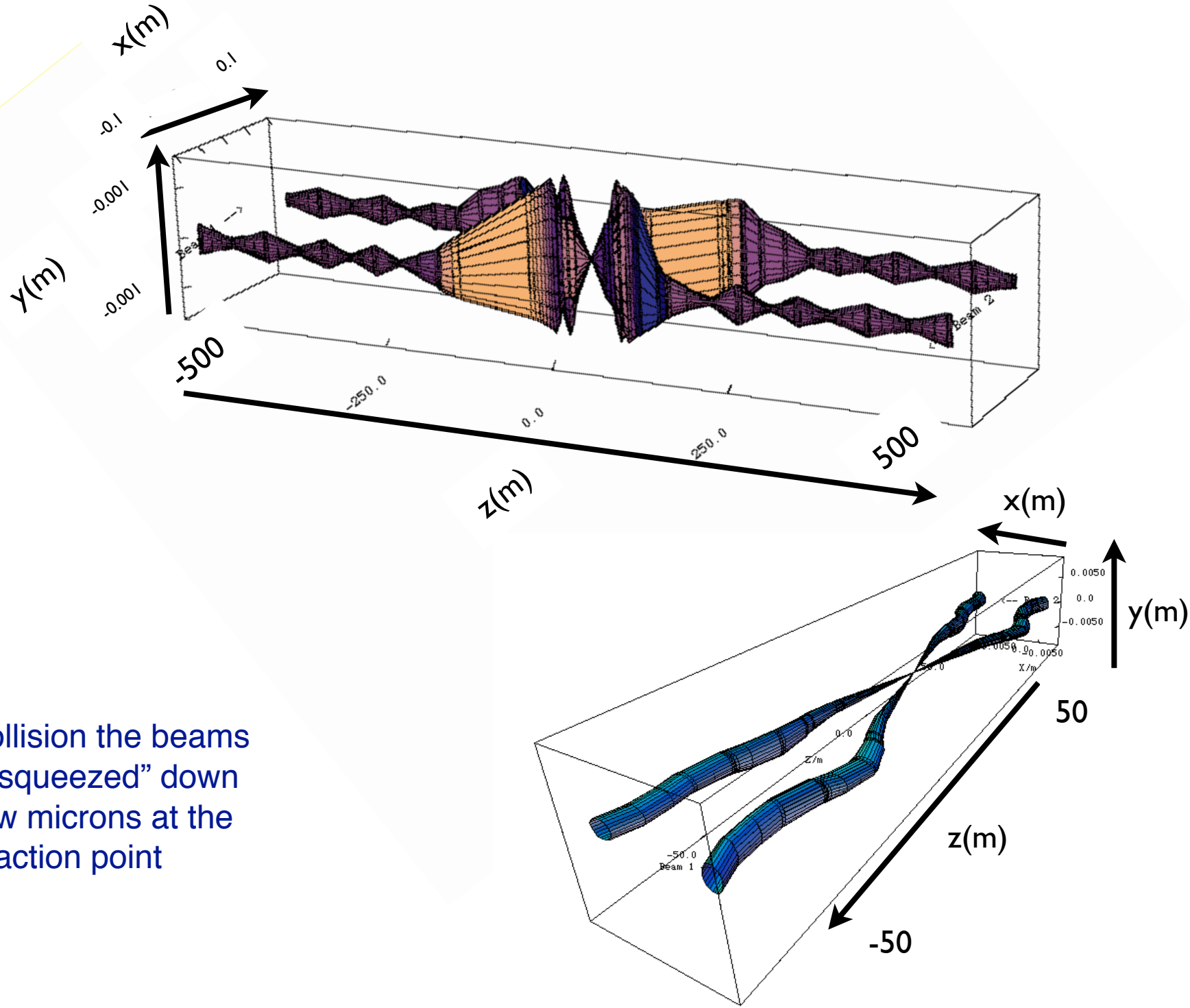
Triplets before lowering in the tunnel



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

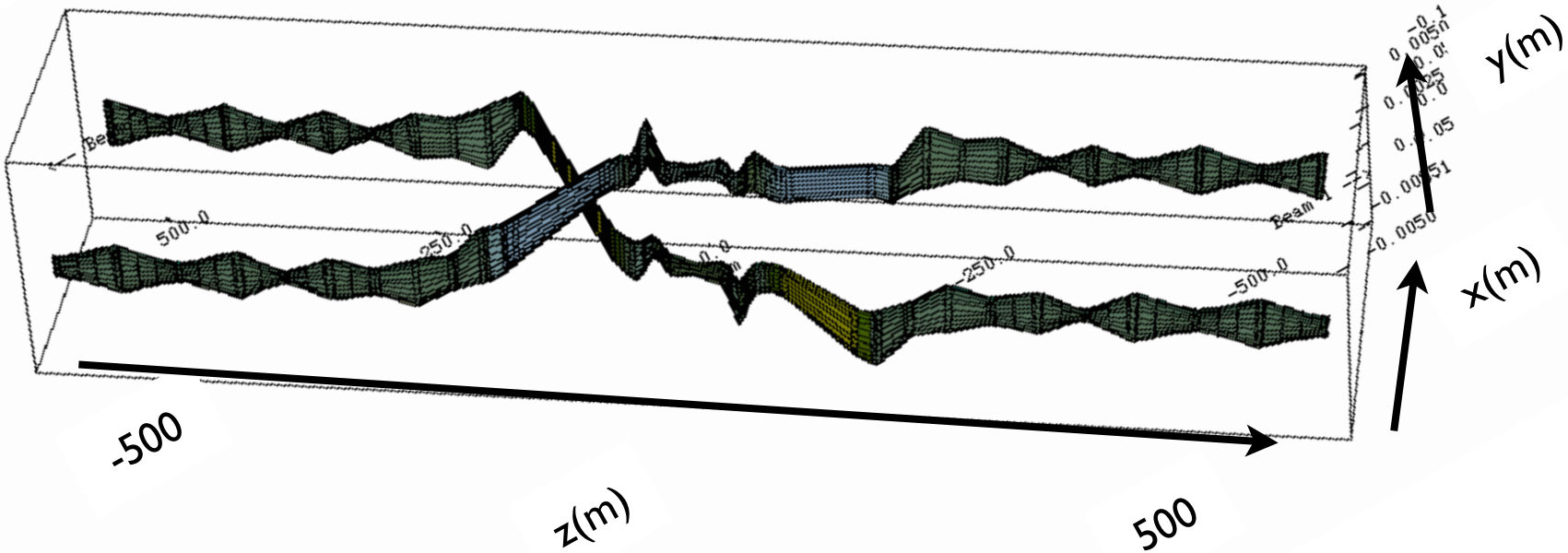


Optics at collision IP5- CMS

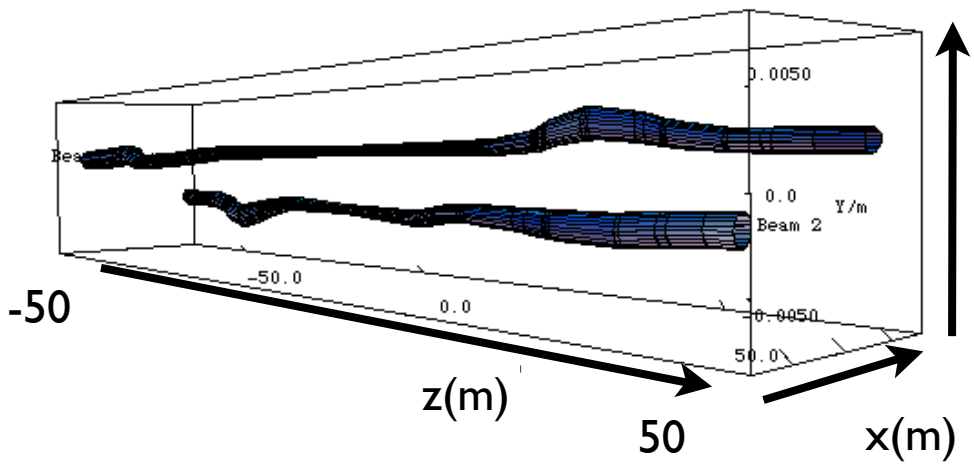


At collision the beams are “squeezed” down to few microns at the interaction point

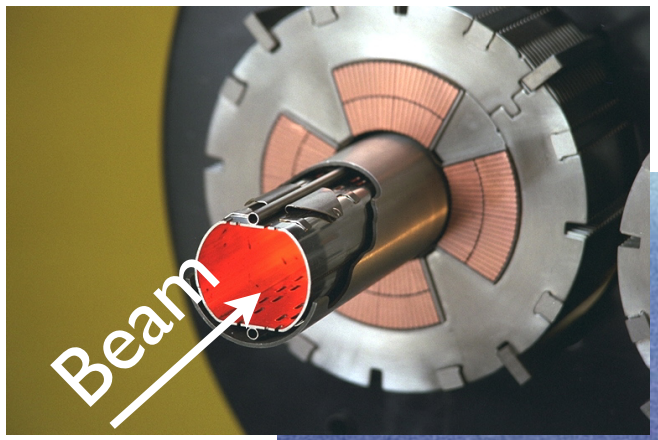
Injection optics and during acceleration IP5- CMS

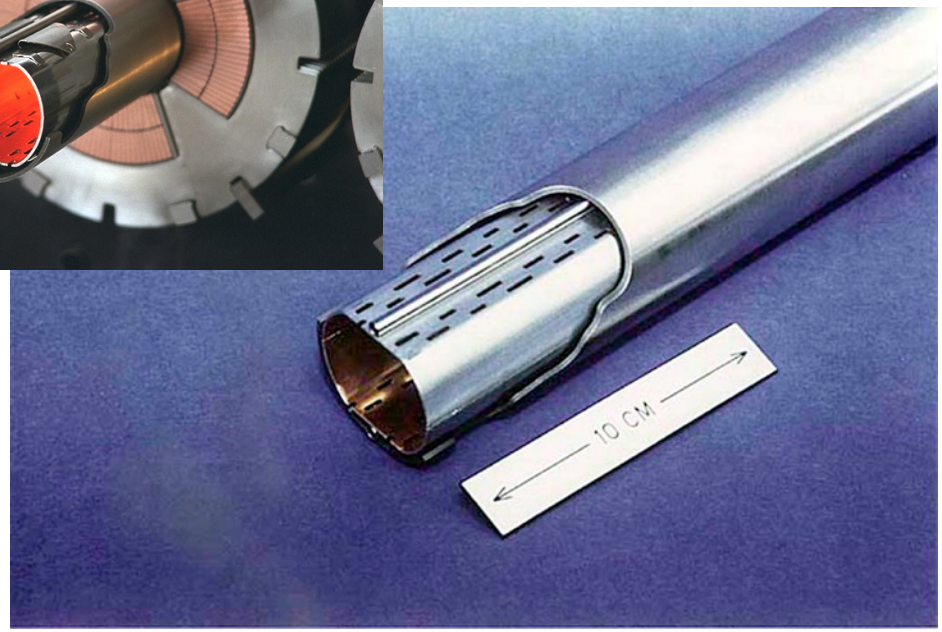


During acceleration the beams are separated and their dimensions is few mm



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.

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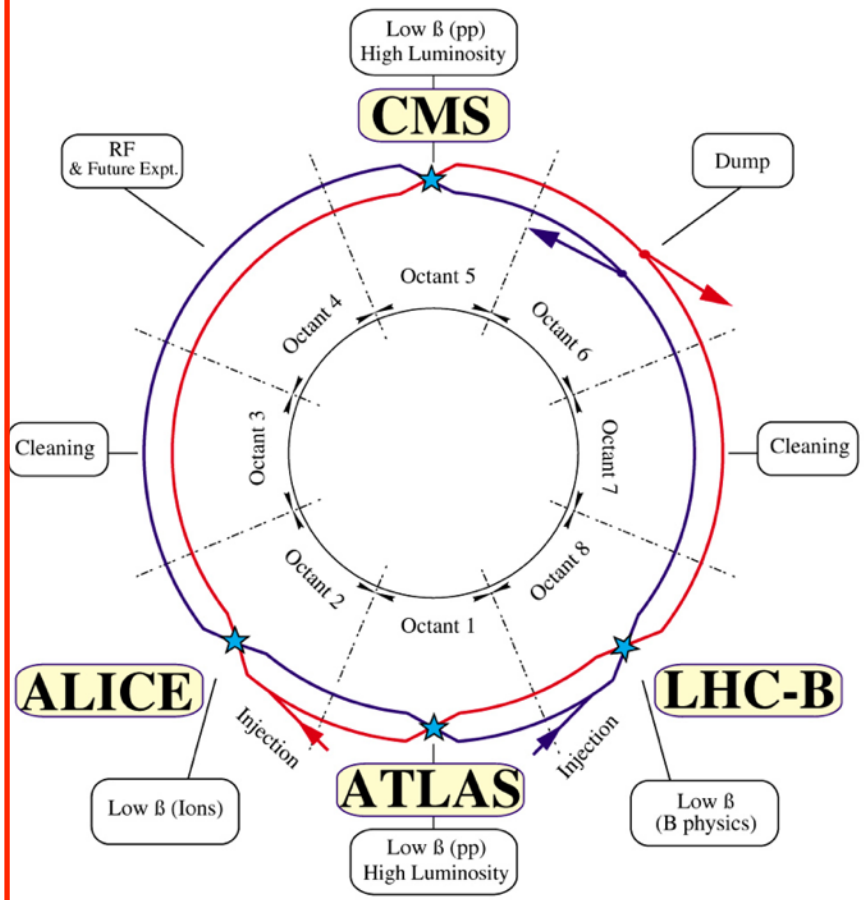
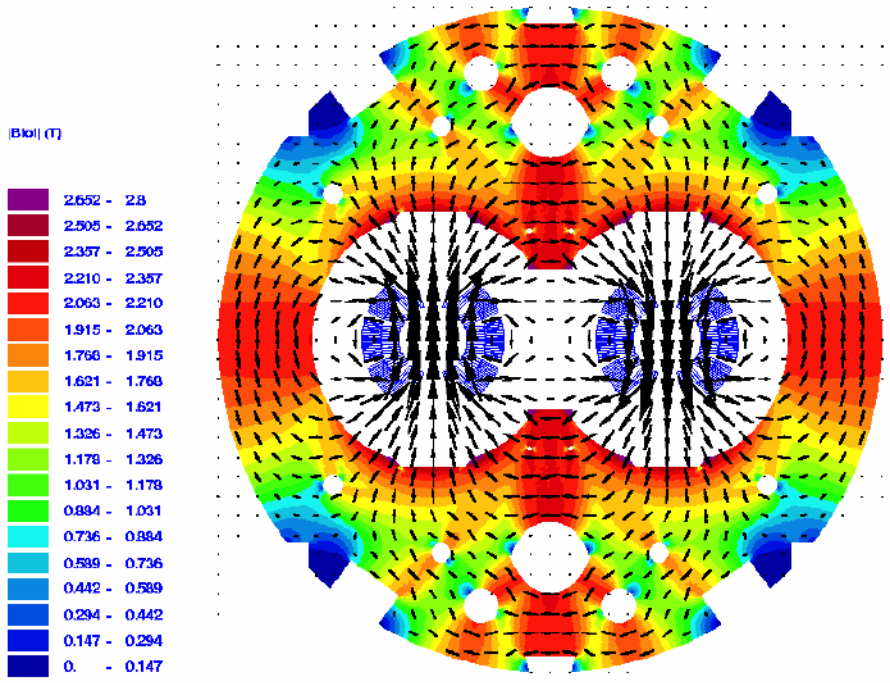
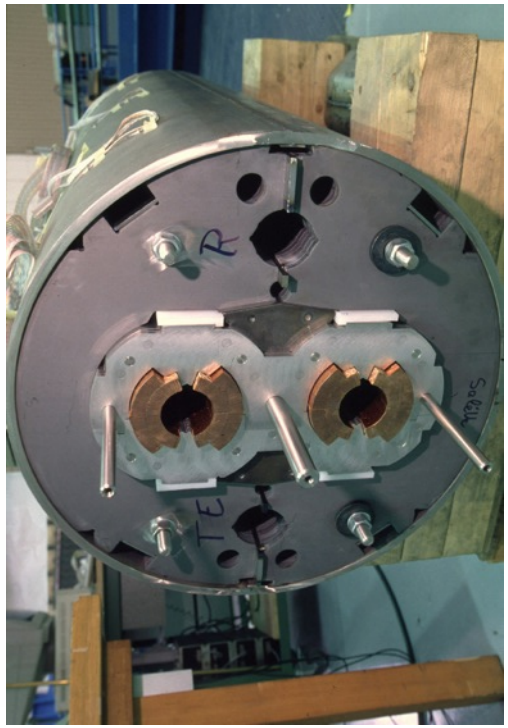
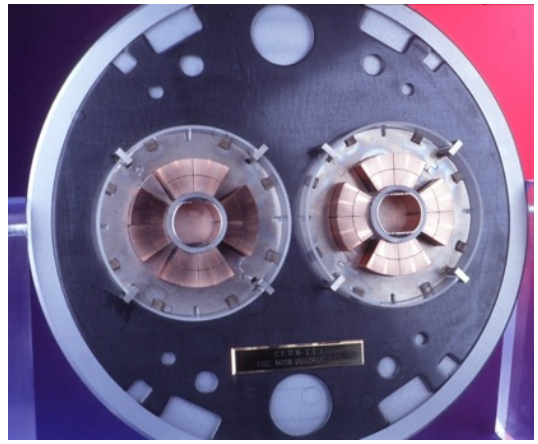


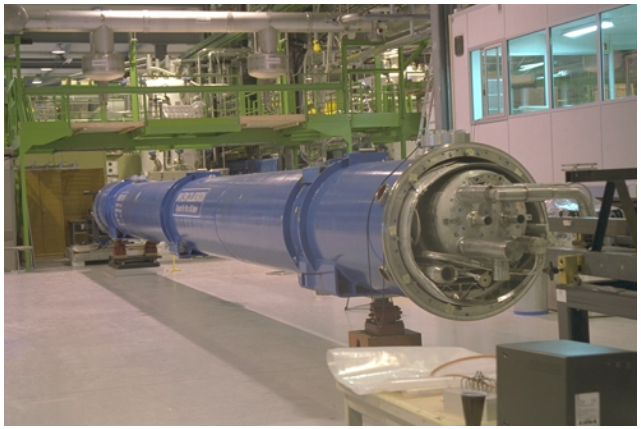
Two-in-one magnet design

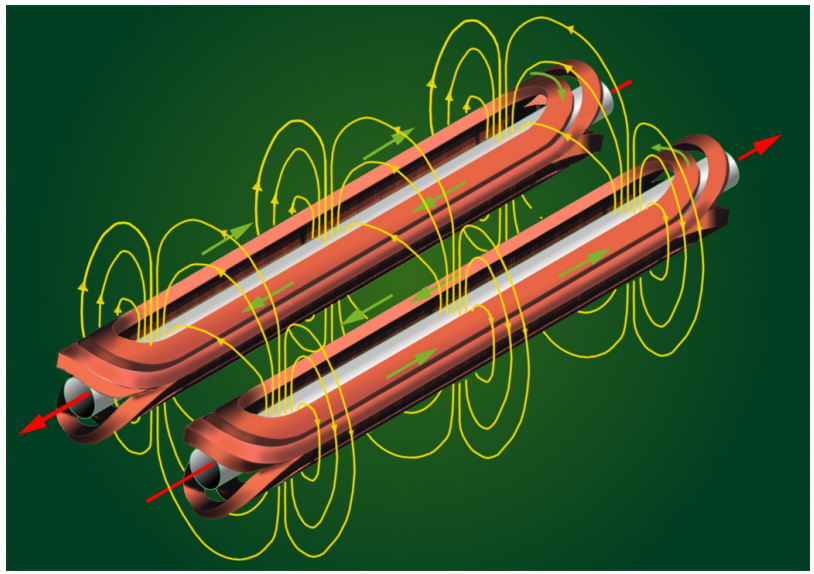




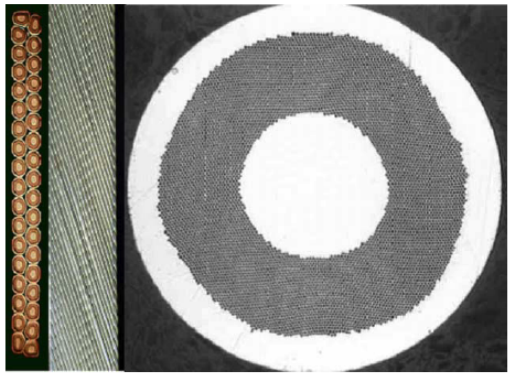


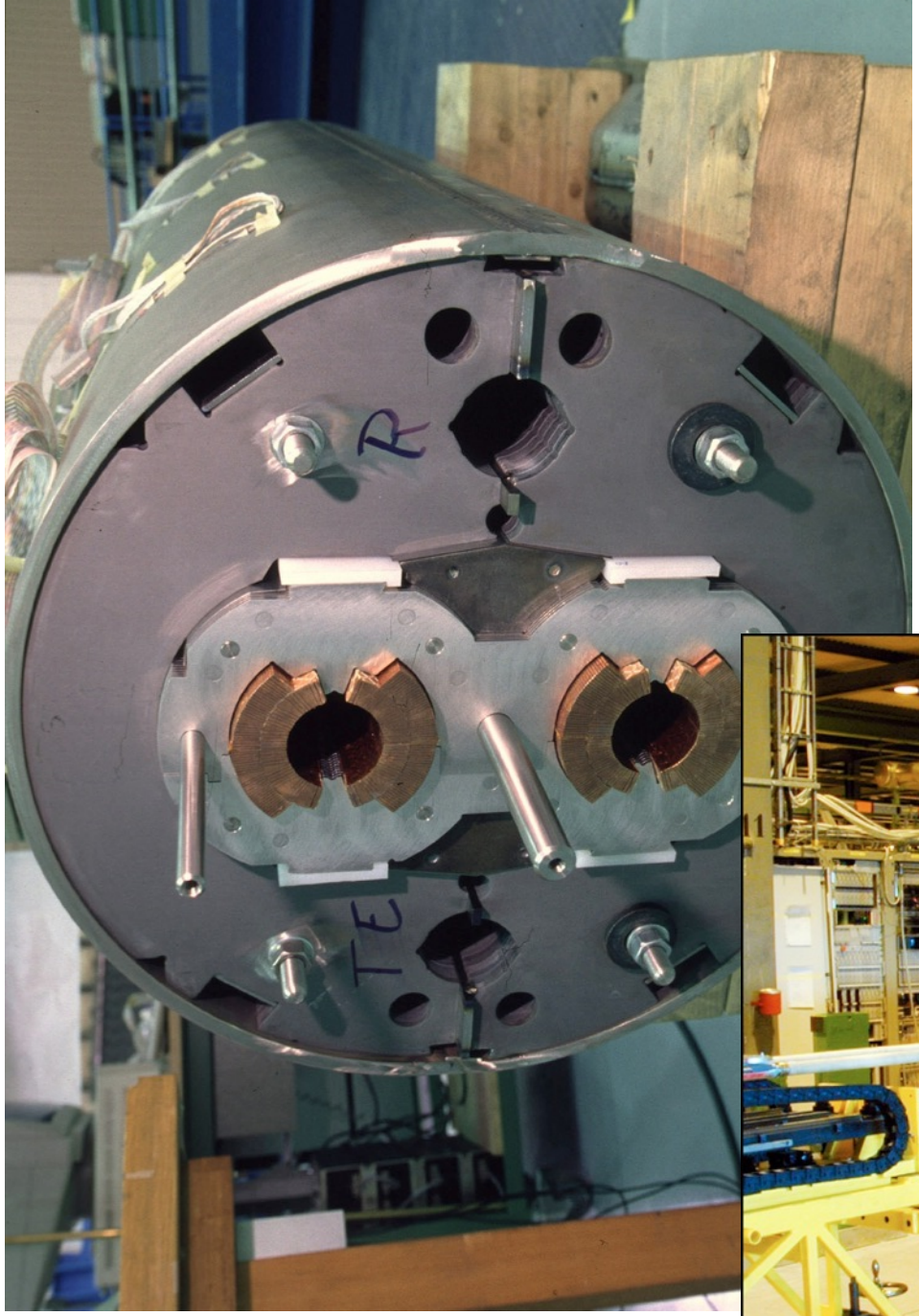
The LHC is one ring where two accelerators are coupled by the magnetic elements.





Nb -Ti superconducting cable in a Cu matrix





At 7 TeV:

I_{max} = 11850 A Field=8.33 T

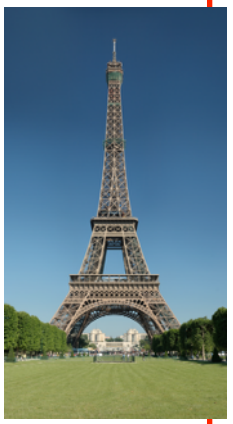
Stored energy= 6.93 MJ

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

Weight = 27.5 Tons

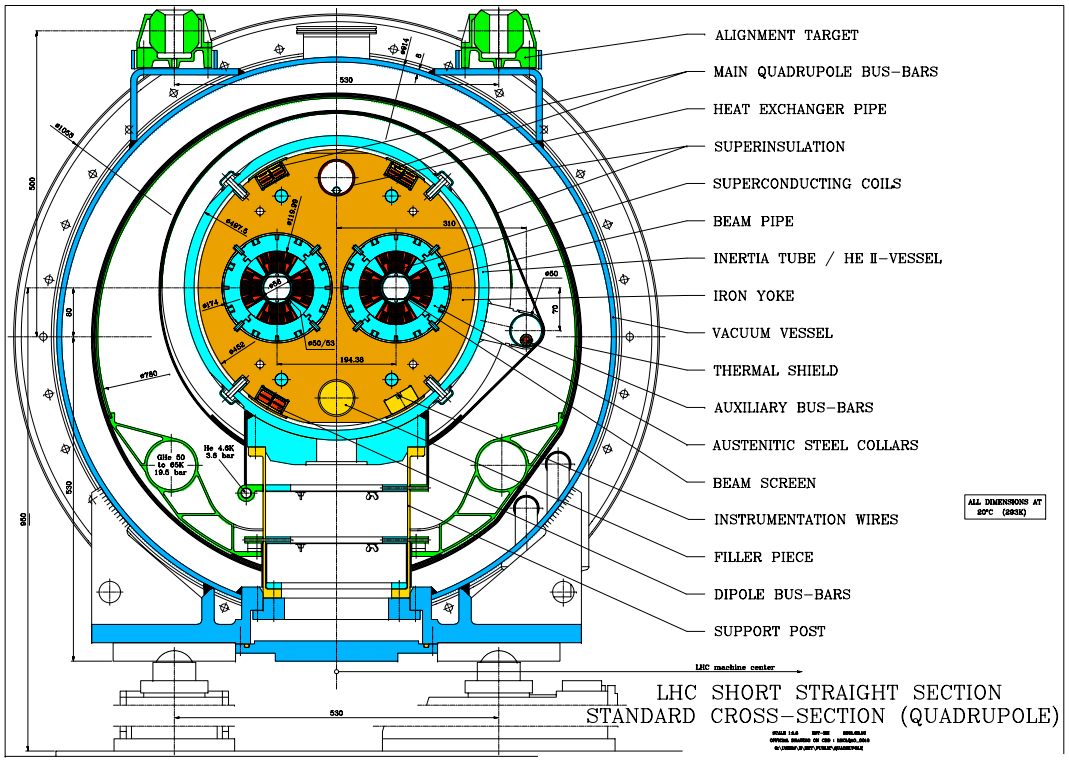
Length =15.18 m at room temp.

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



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

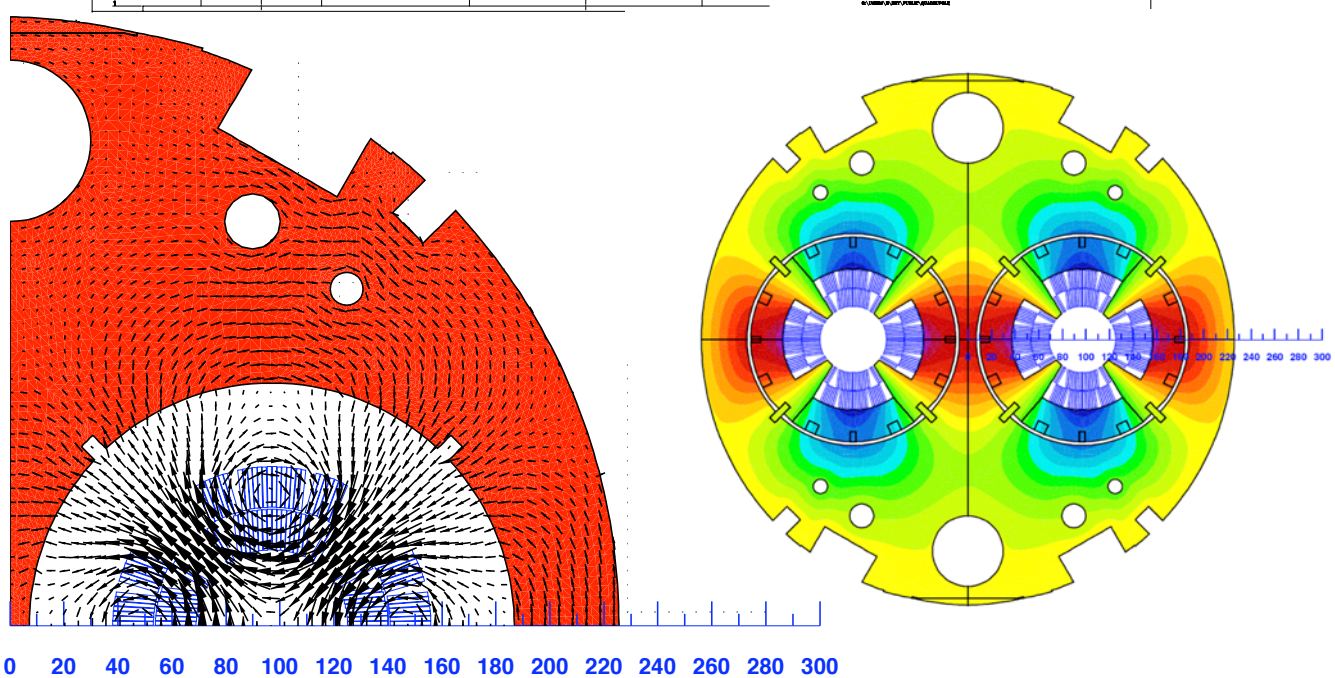
Quadrupoles are also two-in one

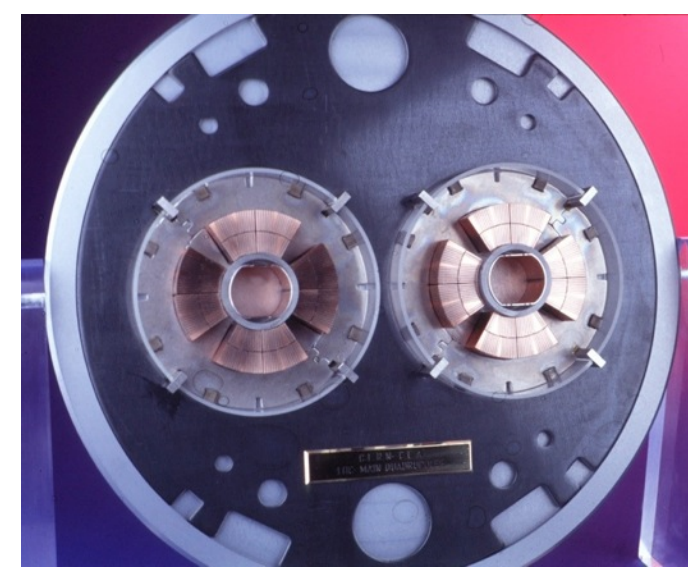


At 7 TeV:

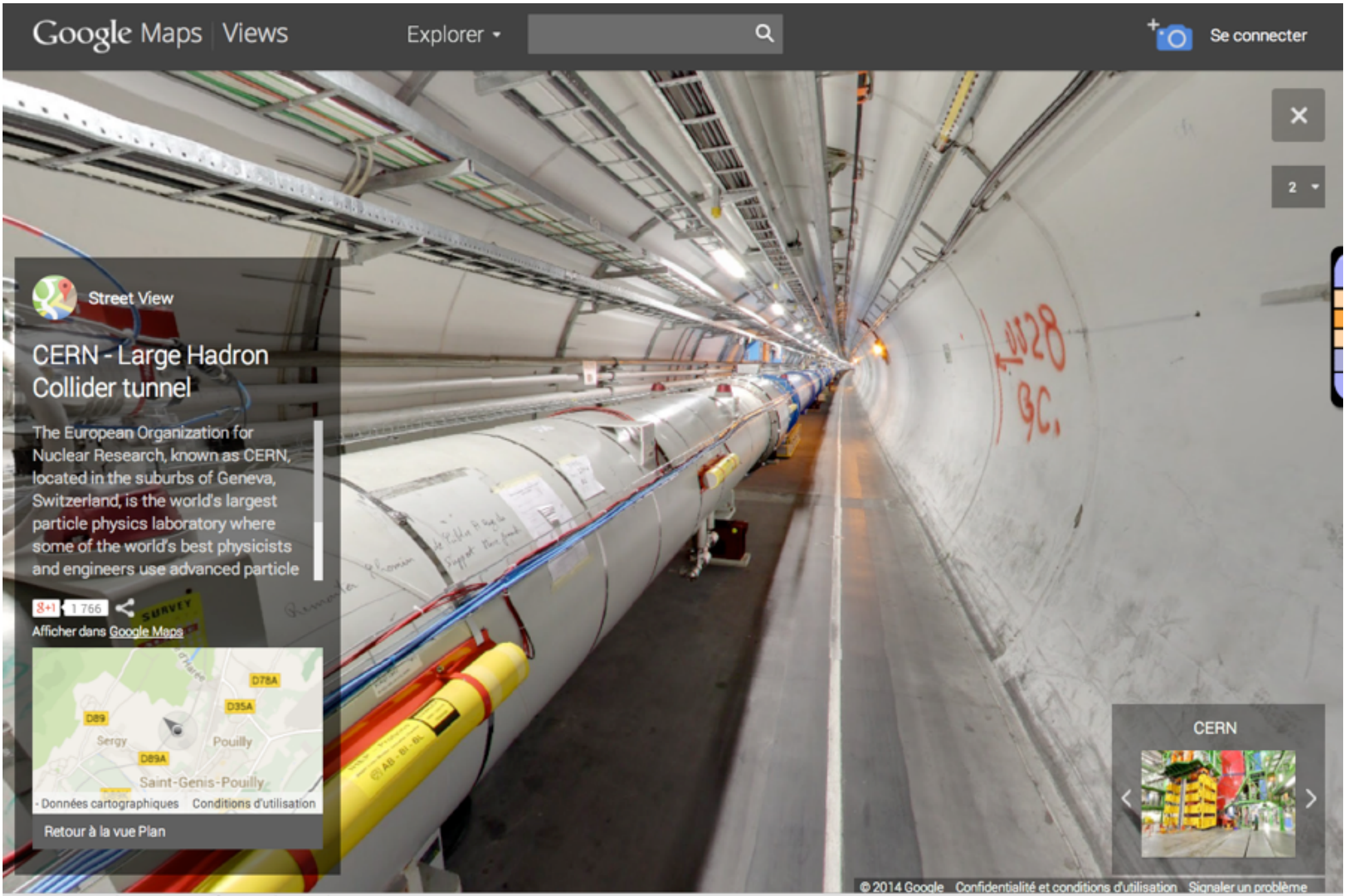
I_{max} = 11850 A
Field=225 T/m

Weight = 6.5 Tons
Length =3.1 m

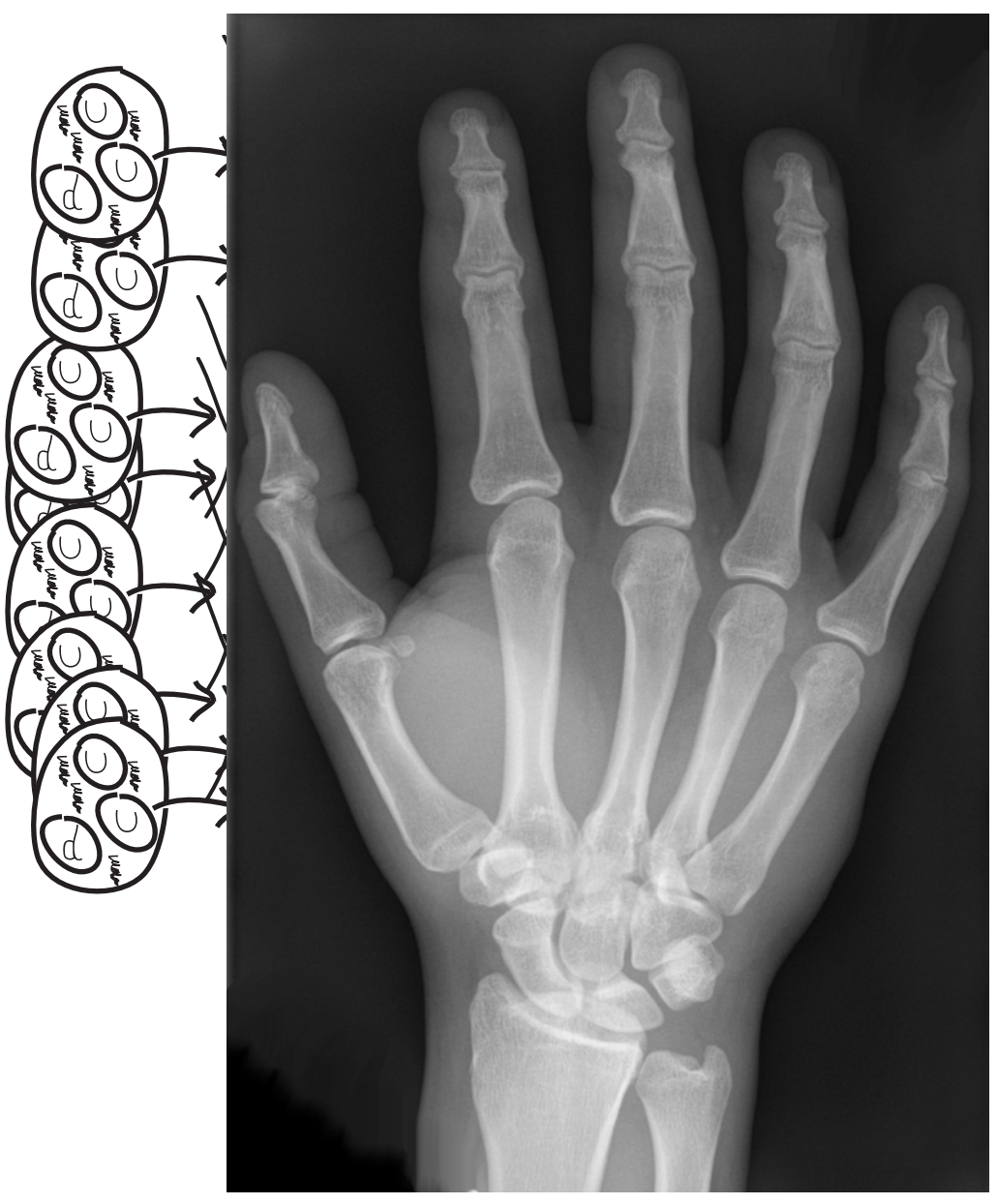




Where we are going to go ....



What happens if I put a hand in front of the beam?



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

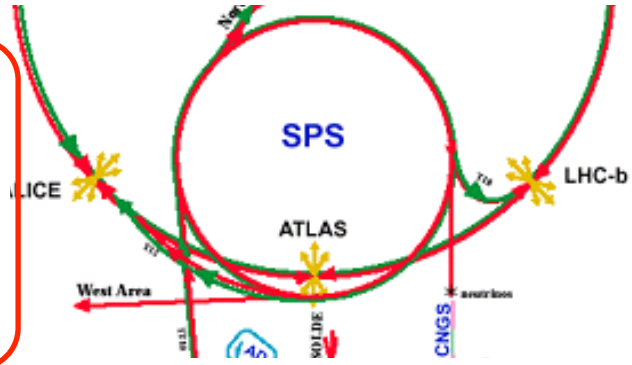
which corresponds to the aircraft carrier navigating
at v=5.8 m/s or 11.2 knots (or around 5.3 knots if you're an American aircraft carrier)

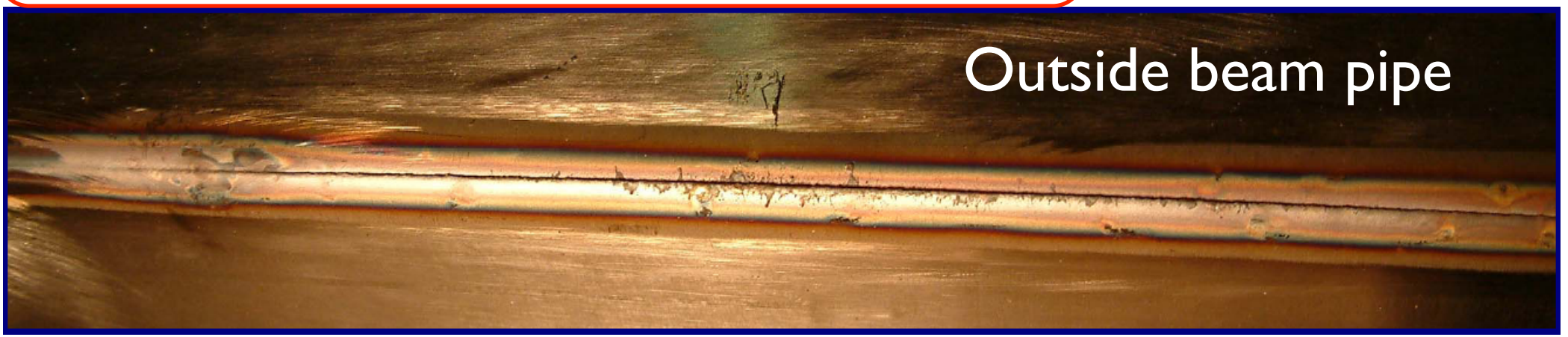
So, what if something goes wrong?

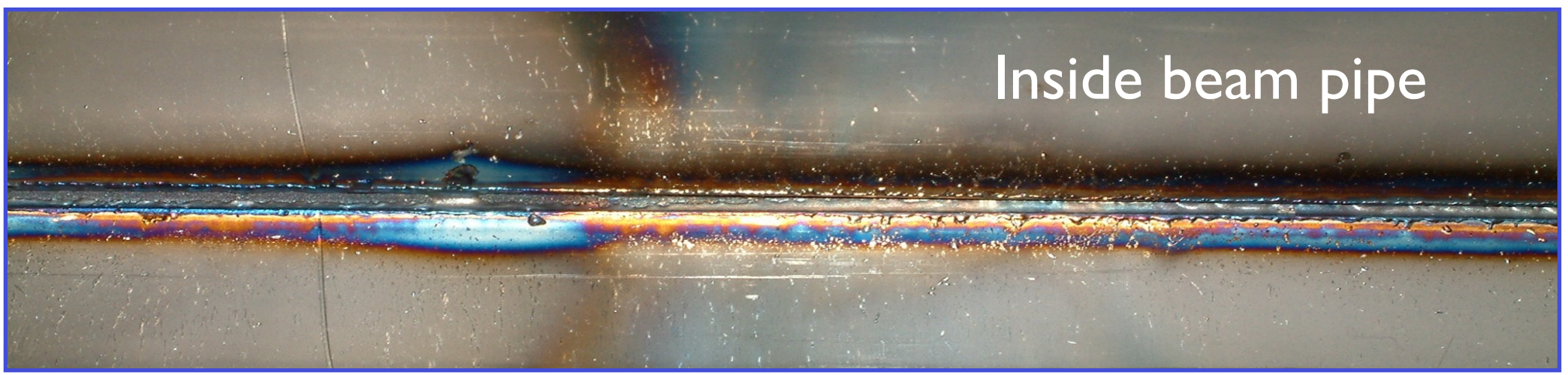
What is needed to intercept particles at large transverse amplitude or with the wrong energy to avoid quenching a magnet?

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)







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

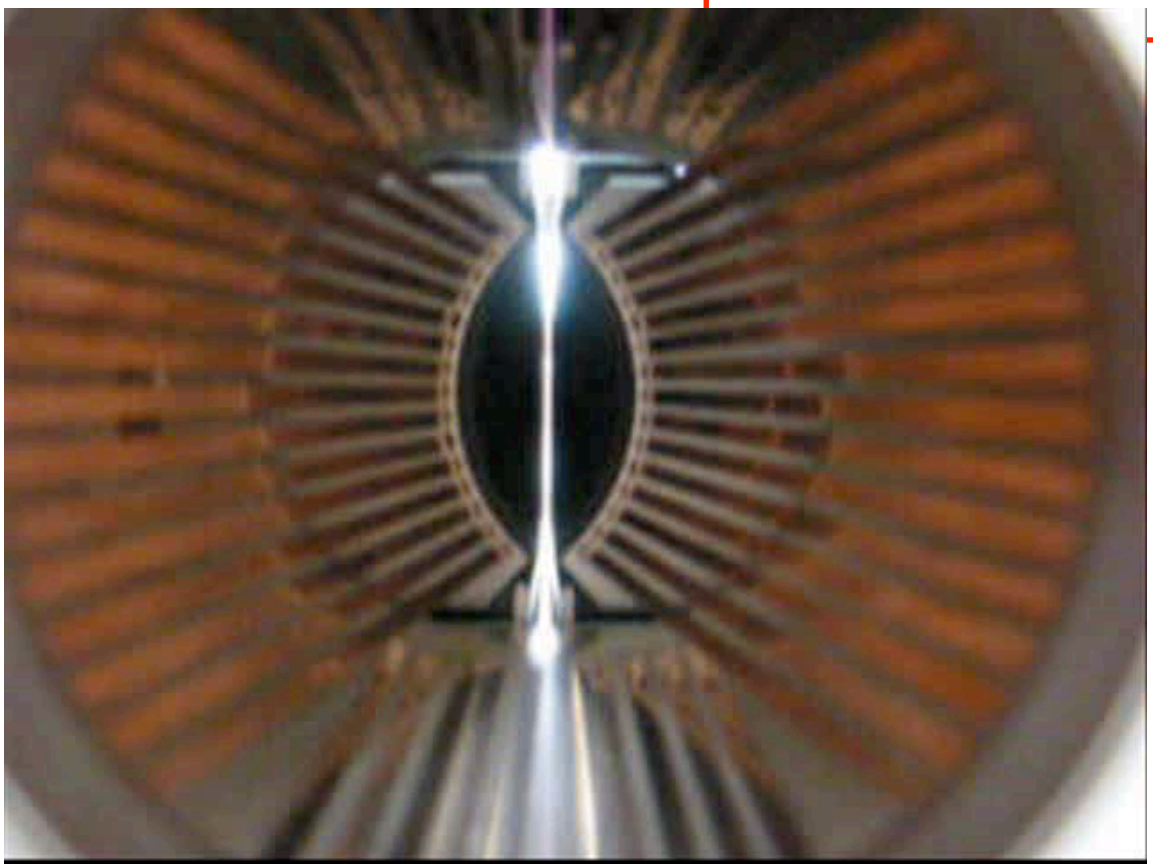
SPS experiment:

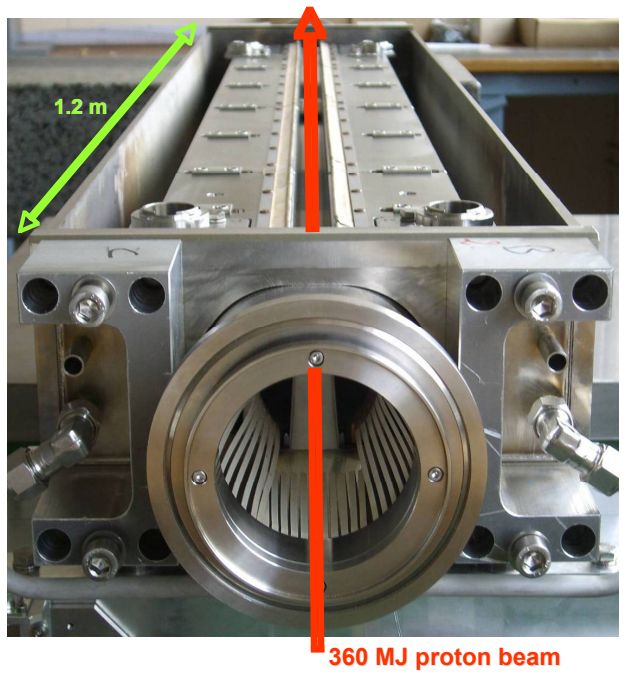
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

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

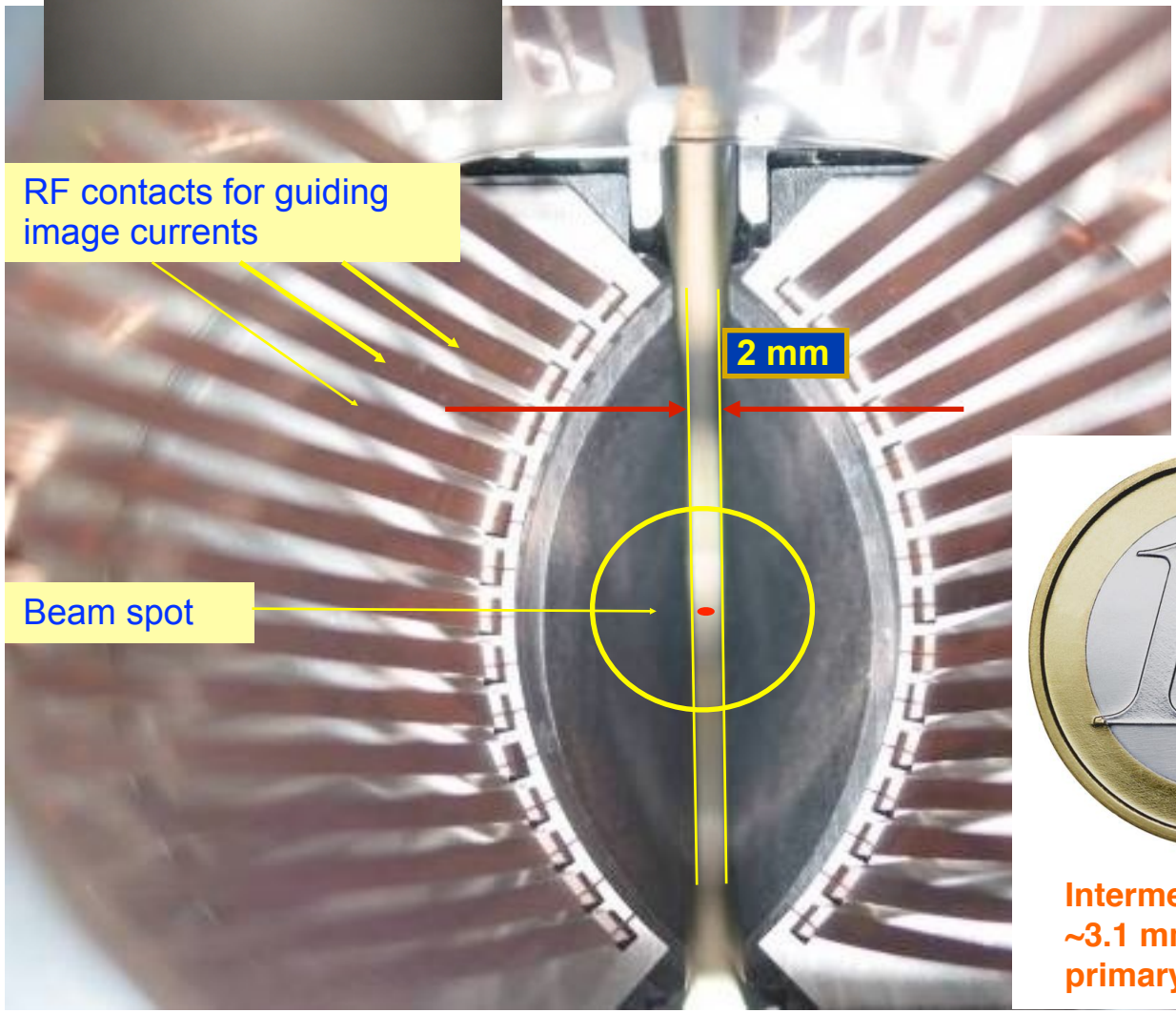
from S. Redaelli



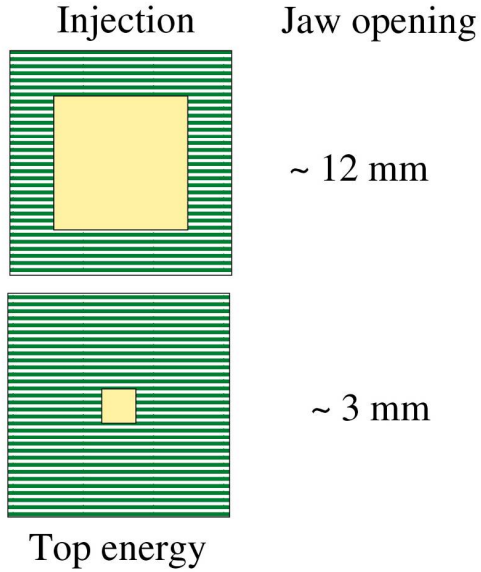


Collimator animation 2013

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



10 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

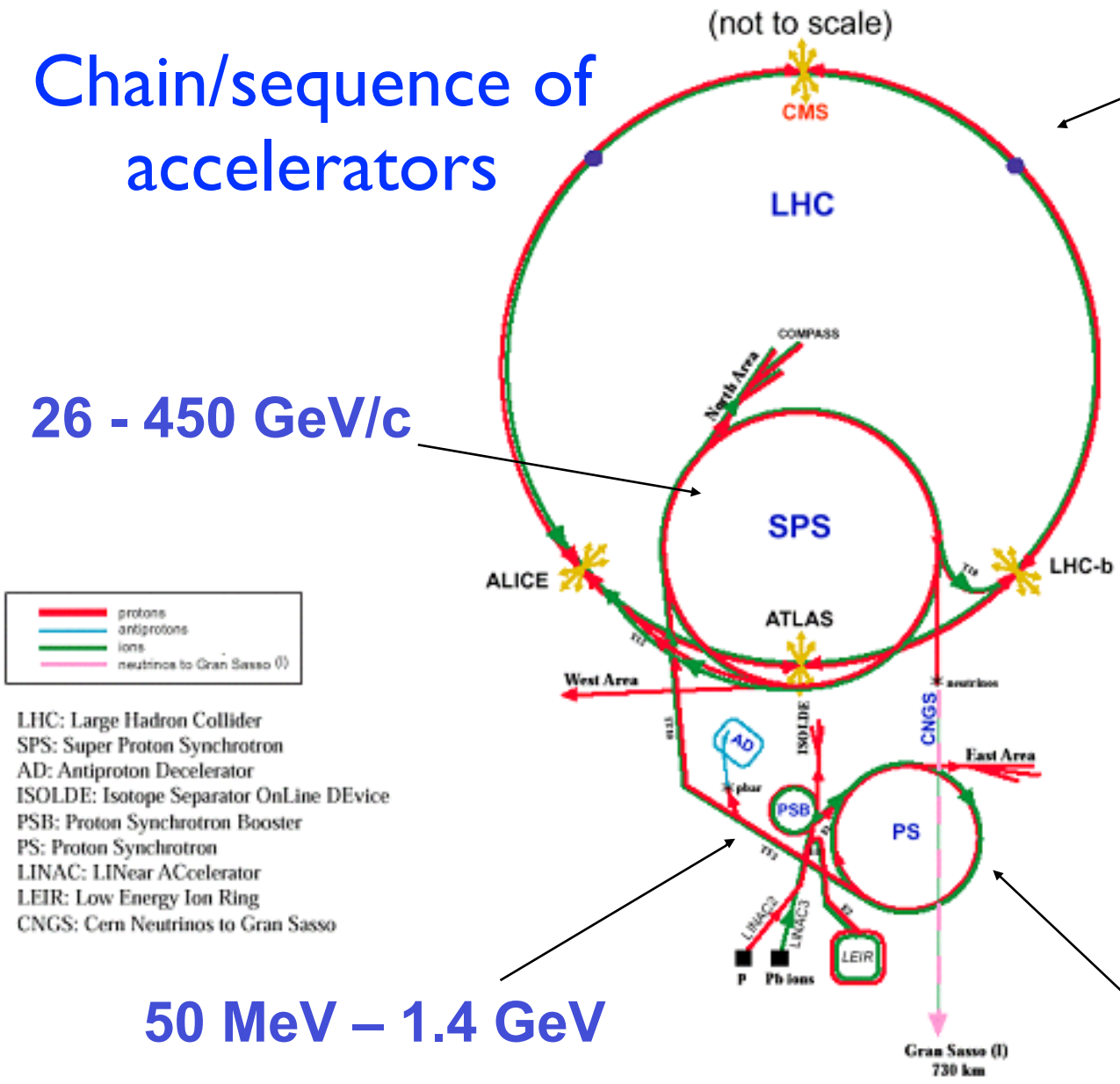
Chain/sequence of accelerators

450 GeV /c – 7 TeV /c

26 - 450 GeV/c

50 MeV – 1.4 GeV

1.4 GeV – 26 GeV/c

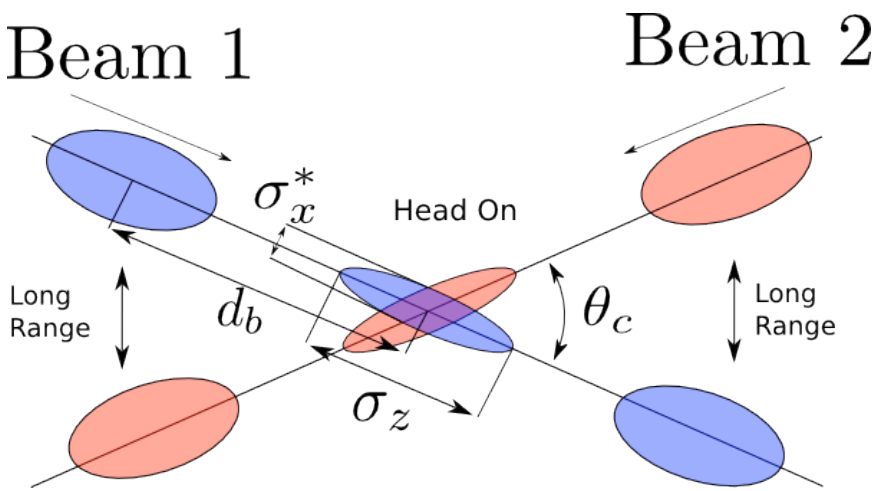


LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Few LHC numbers ...

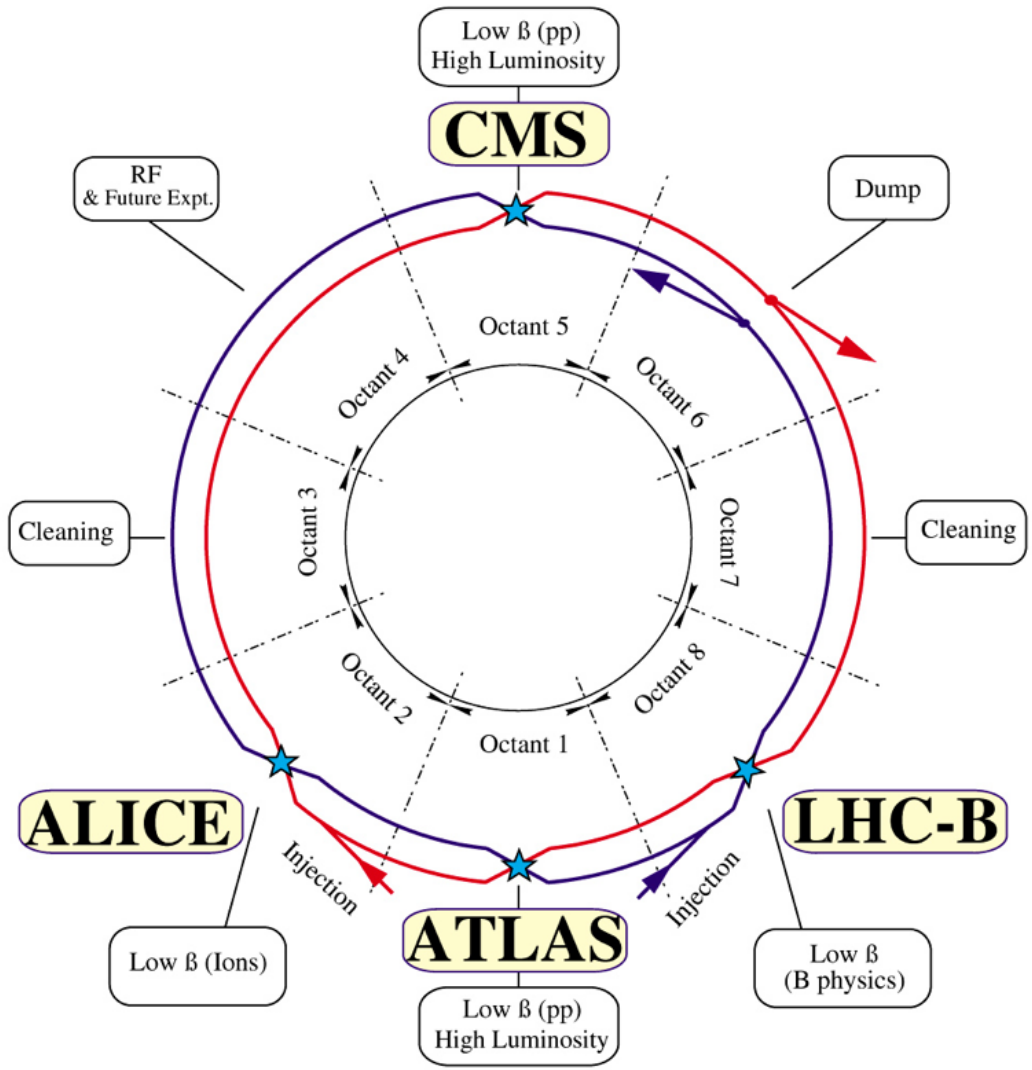
$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

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



Luminosity	1 10
Particle per bunch	1,15 10
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

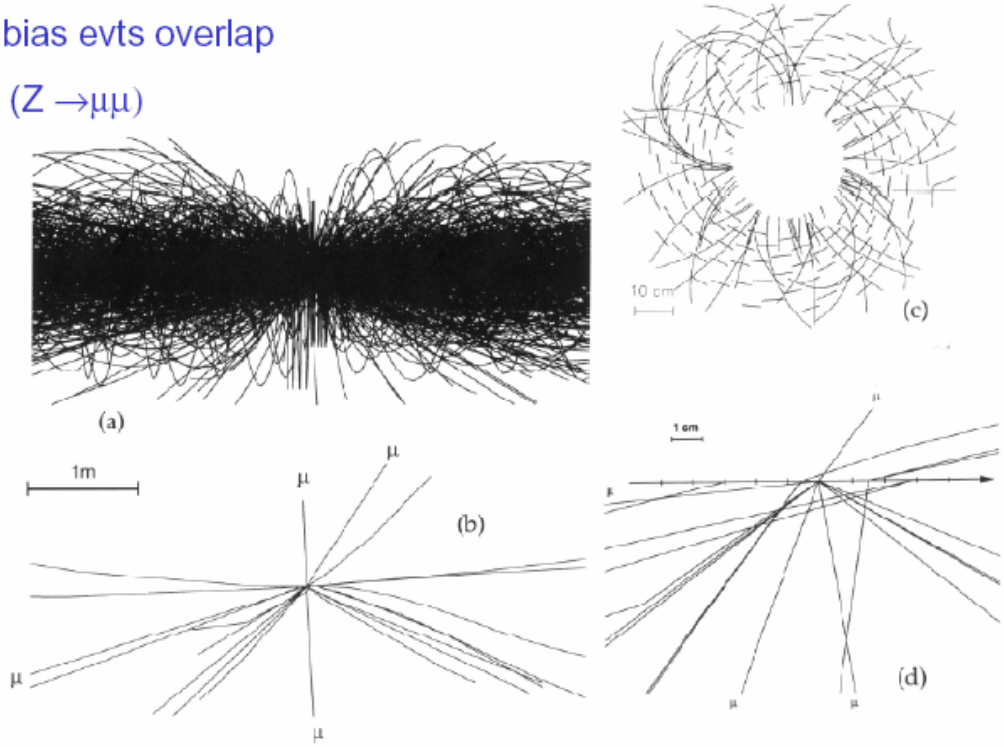


Particle type	protons (heavy ions, Pb82+)
Energy	450 GeV (injection) 7 TeV (collision energy) 2,75 TeV/u (ions collision)
Circumference	26658 m
Revolution frequency	**11,245 kHz** **1 turn= 89 mus**
Number of rings	1 (two-in-one magnet design)
Number of accelerators	2 (2 independent RF system)
Interaction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

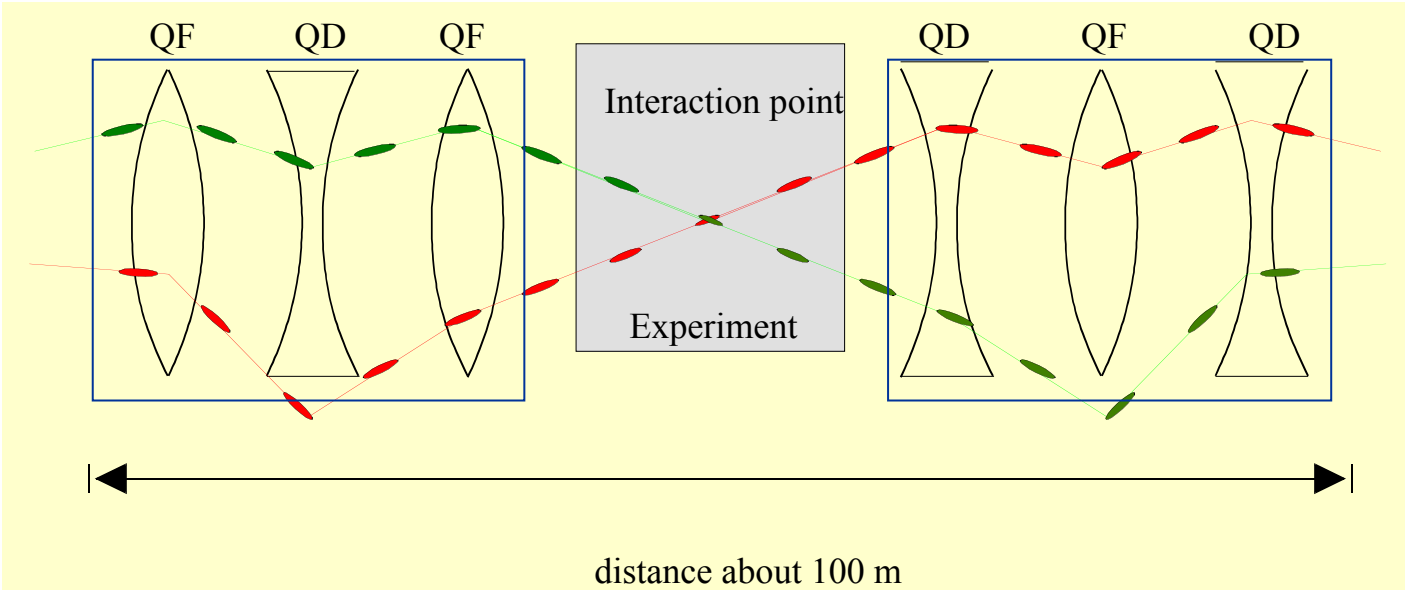
H→ZZ (Z →μμ)



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

~ 30 unwanted collision per crossing

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



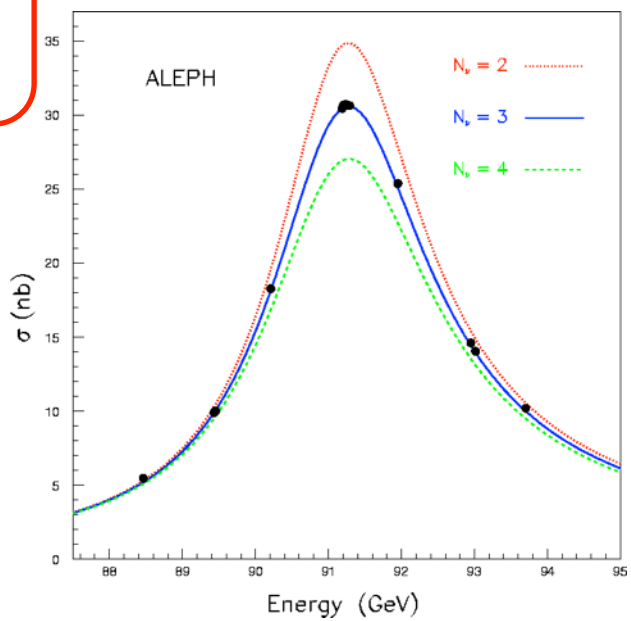
Θ	crossing angle	285 μrad
σ	RMS bunch length	7.55 cm
σ*	RMS beam size (ATLAS-CMS)	16.7 μm
F	L reduc. Factor	0.836

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

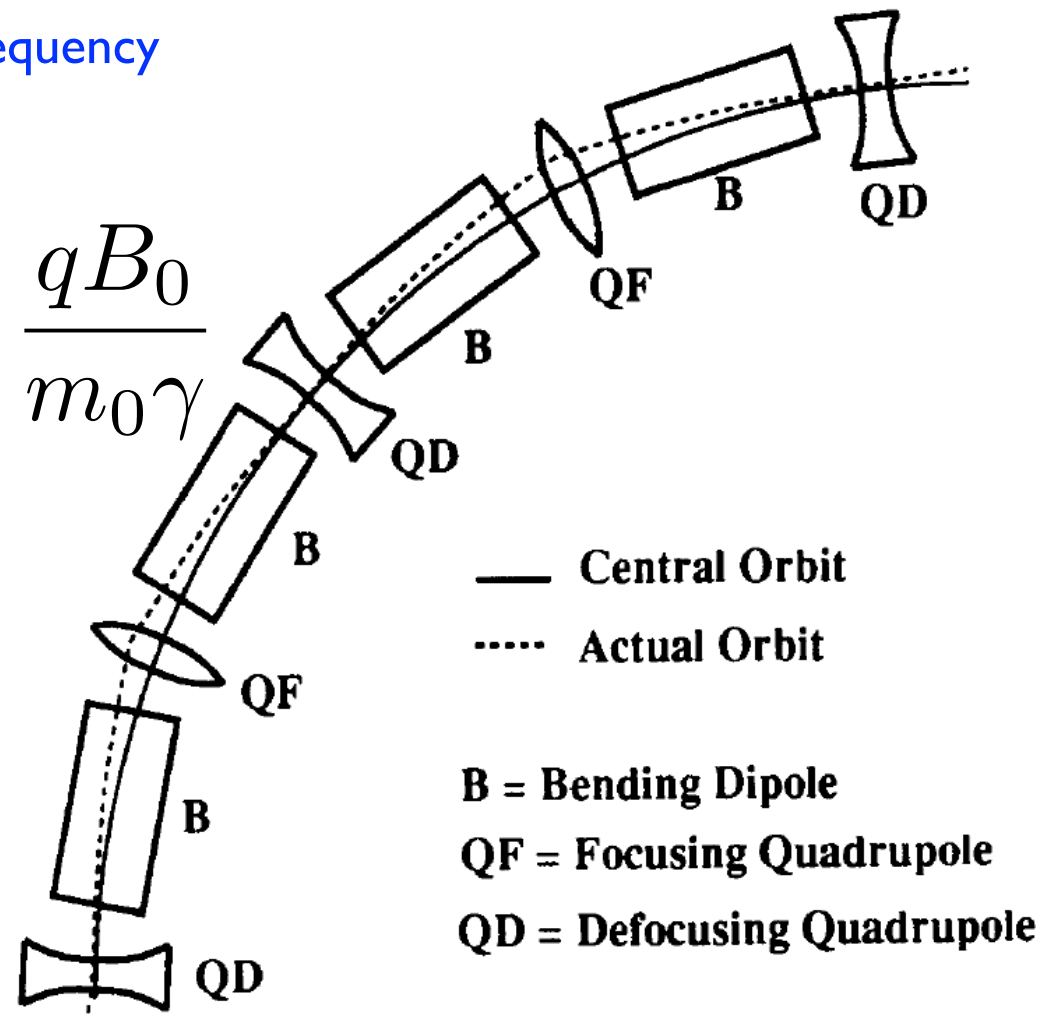
Energy fixed by bending strength and cavity frequency

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

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

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

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



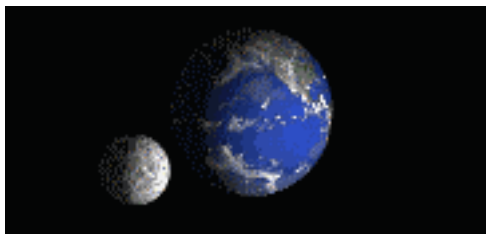
In LEP $\alpha = 1.86\ 10^{-4}$ a small variation the circumference induces a large variation in energy

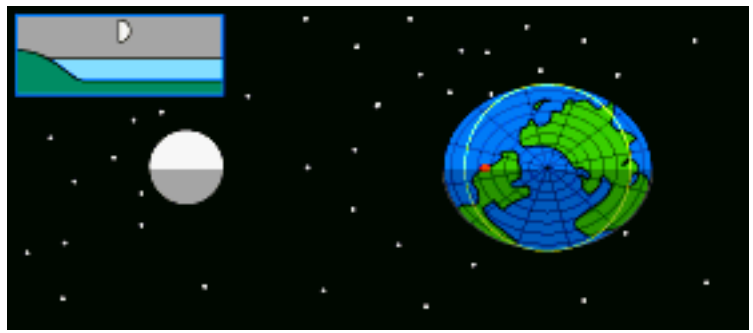
Moon tides can change earth geometry

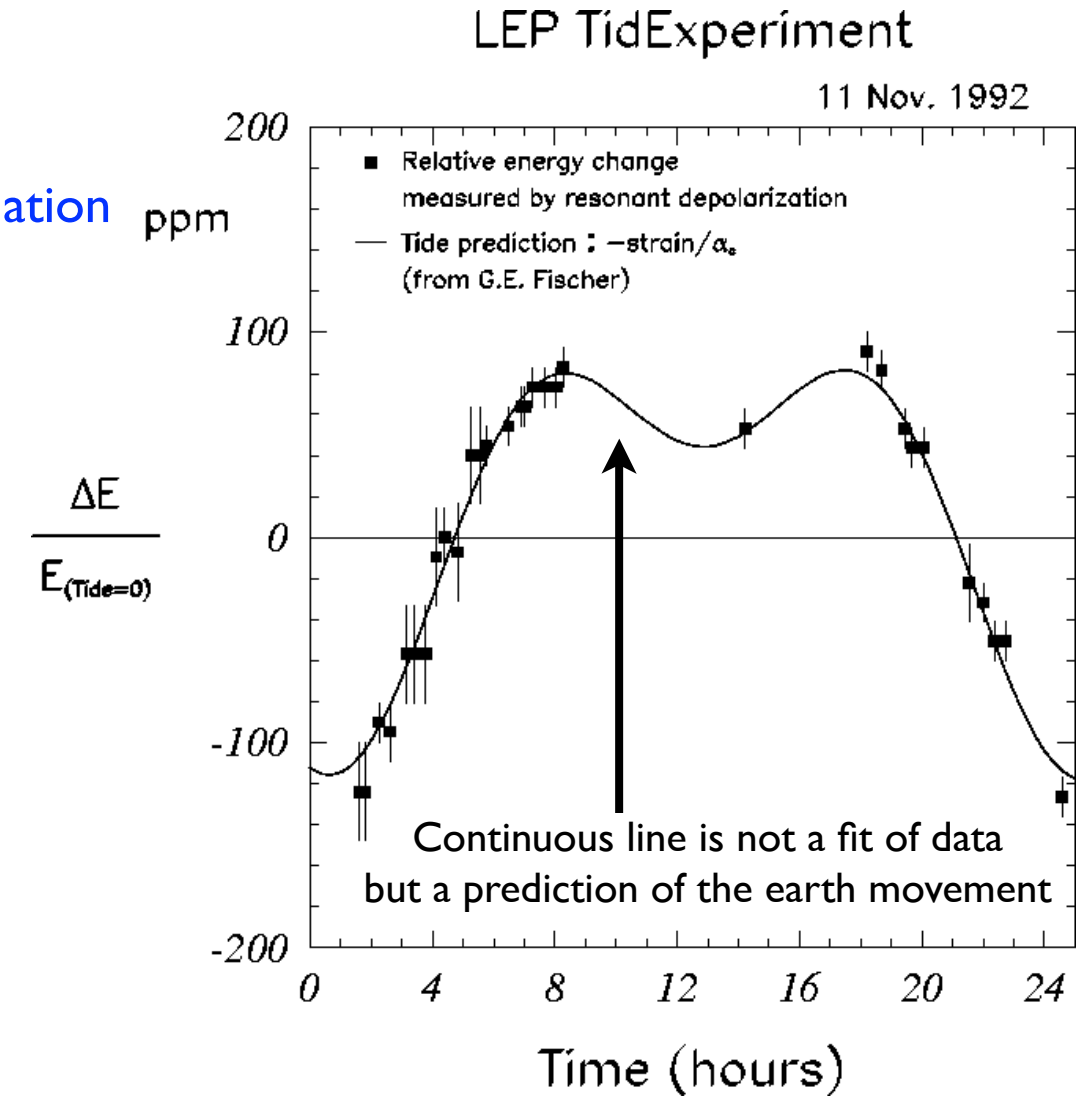
Moon induces a earth deformation similar to water tide.

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

The 12 h cycle is due to the earth deformation



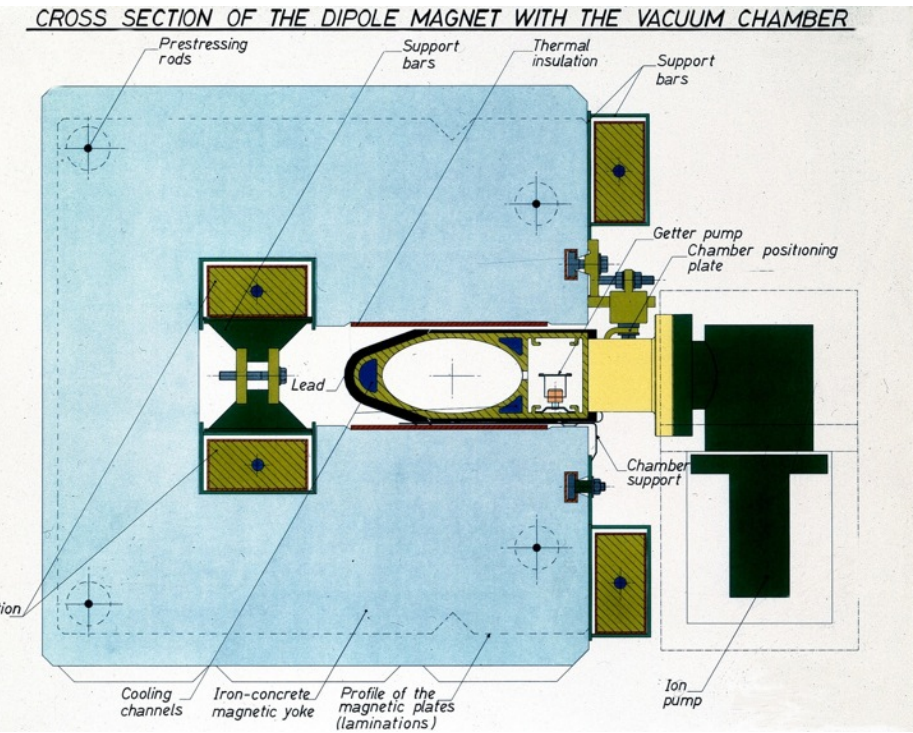


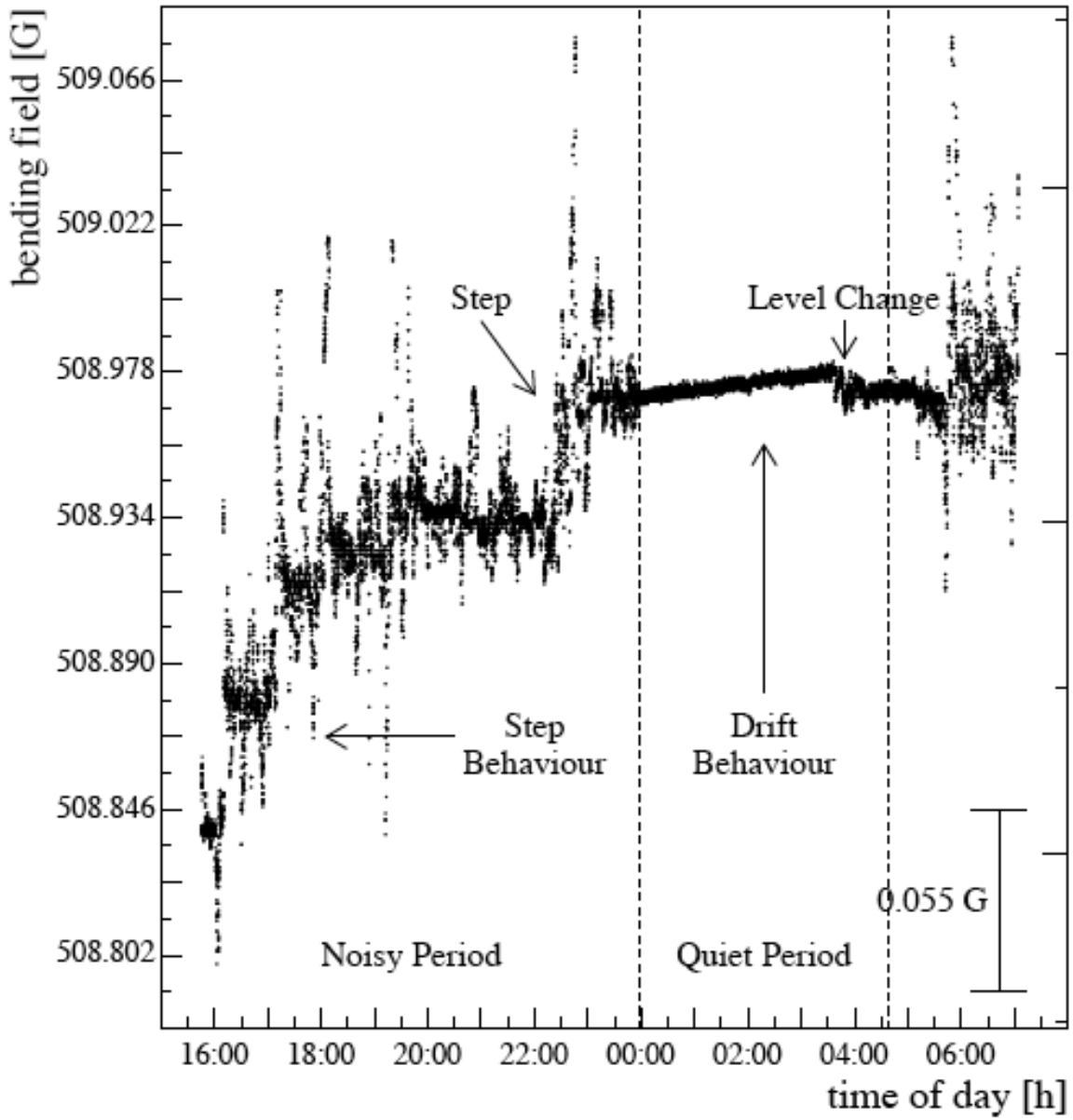


The effect is modulated by the different tide intensities and by the SUN tides

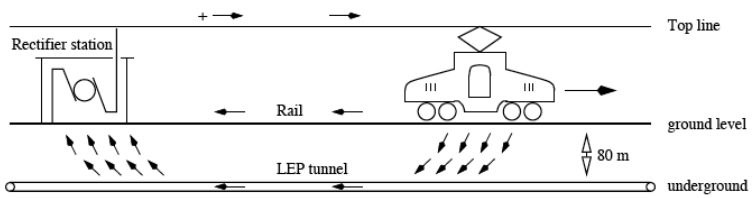
The problem: an accelerator is not in the middle of nothing

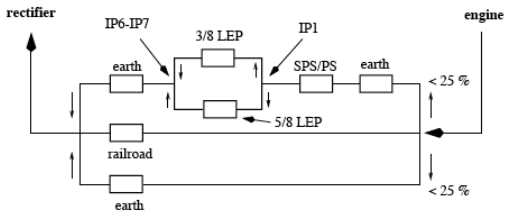
Observed variation of the bending strength of the LEP dipoles during the day

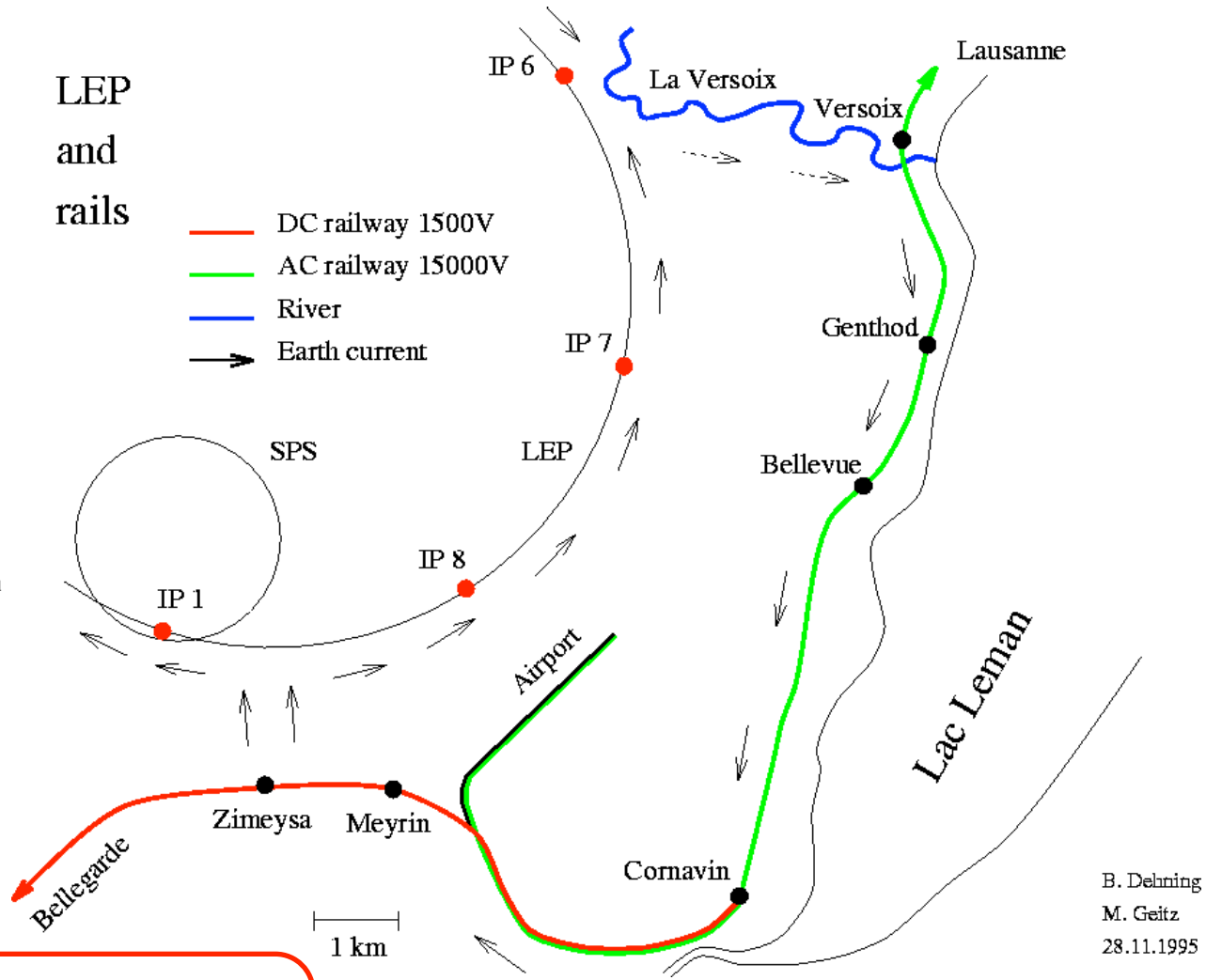




Influence of train leakage current

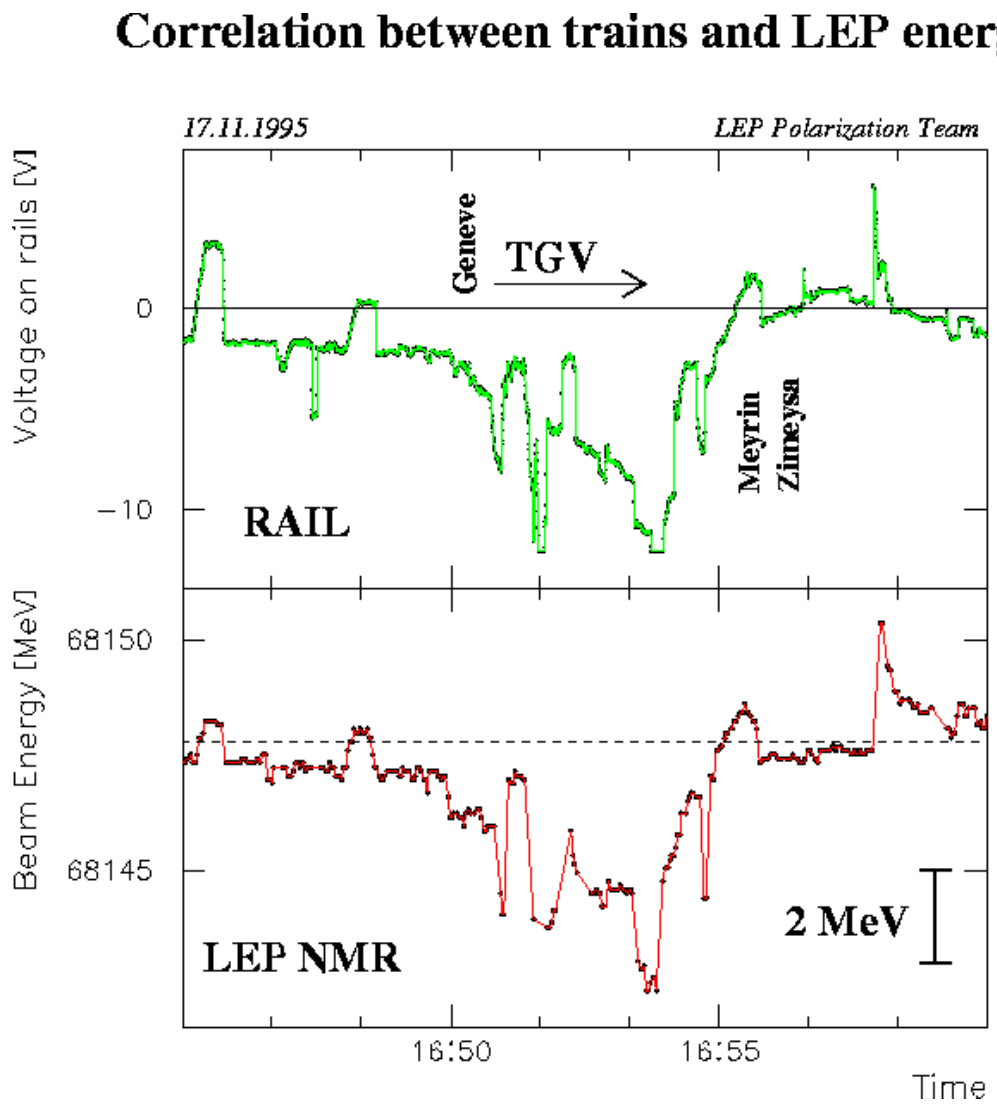






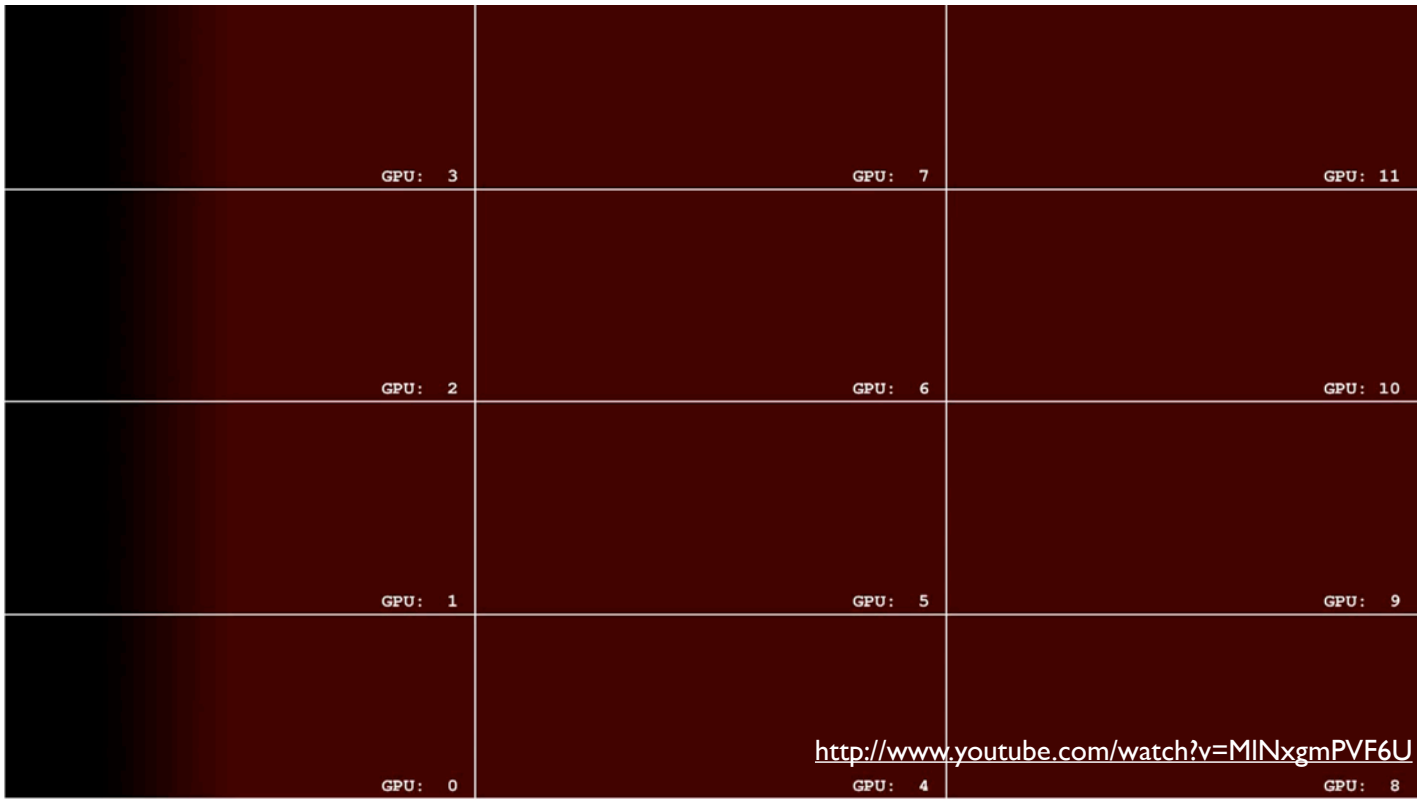
LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

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...

Thanks for your attention!!!