Introduction to CERN/accelerators

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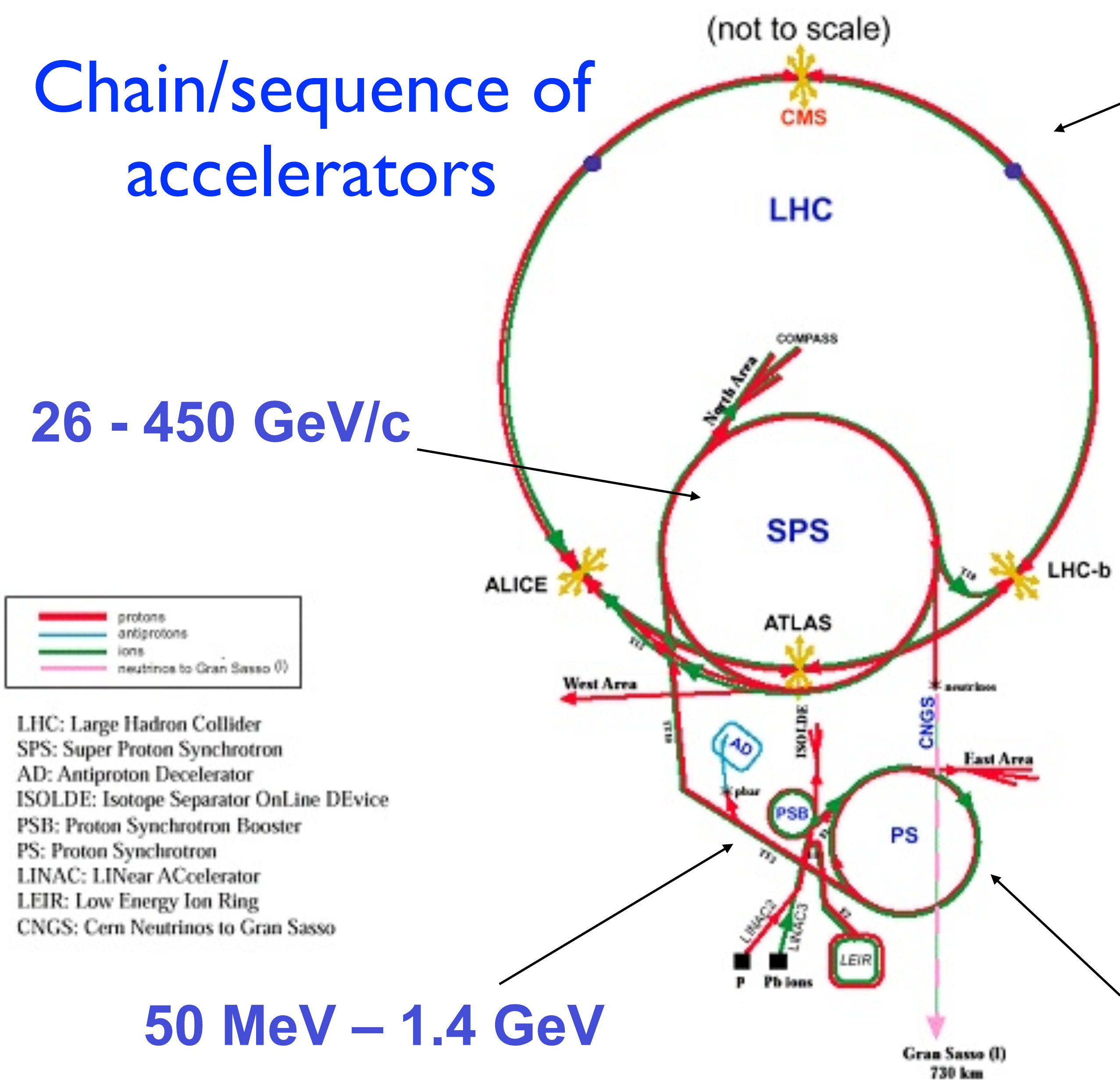
A Google view of high energy accelerators

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

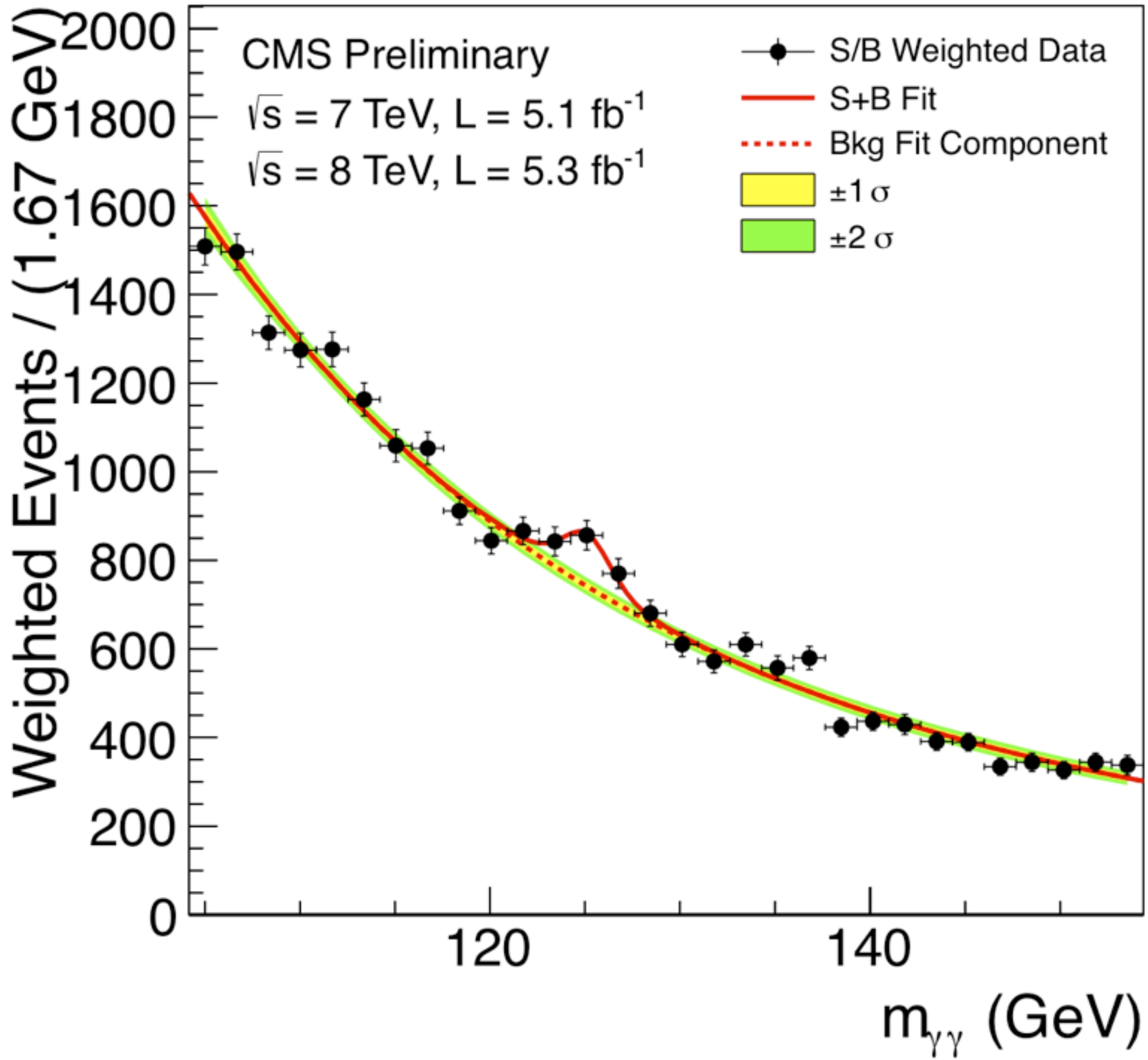


450 GeV /c – 7 TeV /c

26 - 450 GeV/c

50 MeV – 1.4 GeV

1.4 GeV – 26 GeV/c



CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
$\sqrt{s}$ = 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
$m_{\gamma\gamma}$ (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

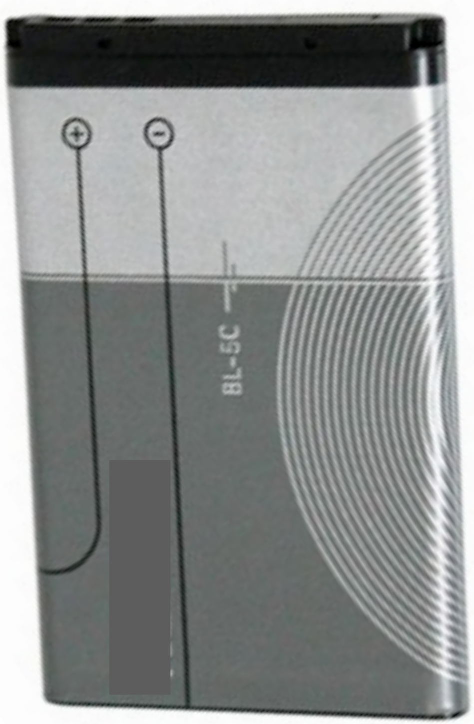
It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays 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

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.

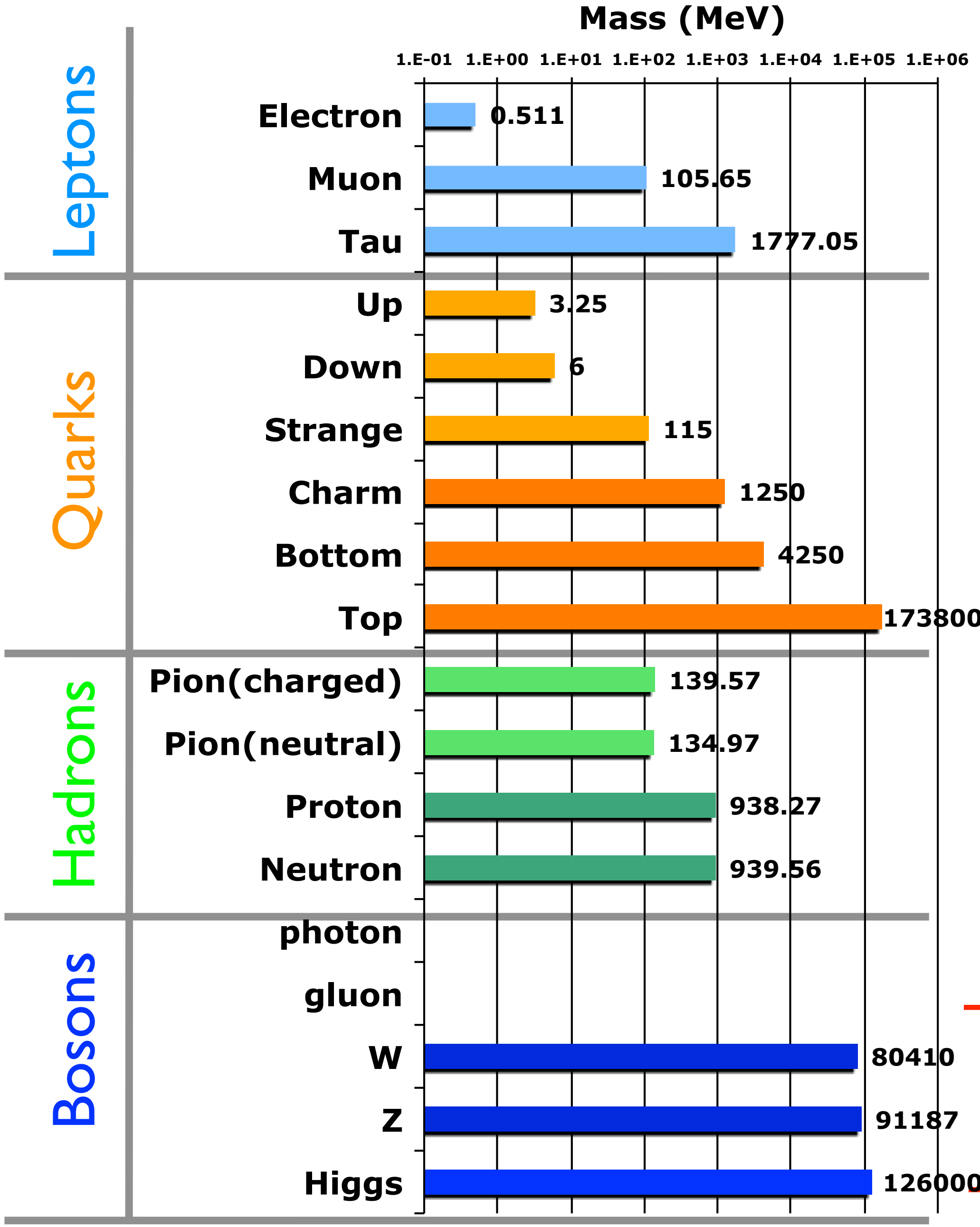
Voltage: 3.7 V
Height: 4.5 cm
proton mass ~ 1 GeV
To accelerate an electron to an energy equivalent to a proton mass:

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

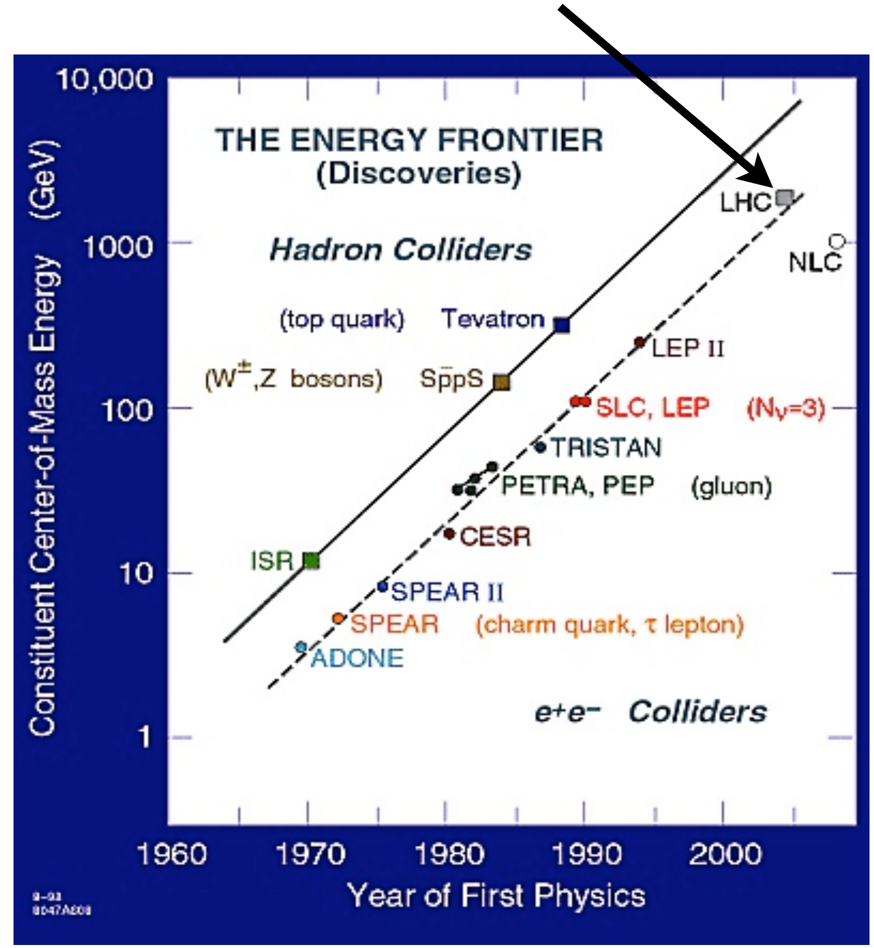
12 000 000 m ~ THE EARTH DIAMETER

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

History/Energy line vs discovery



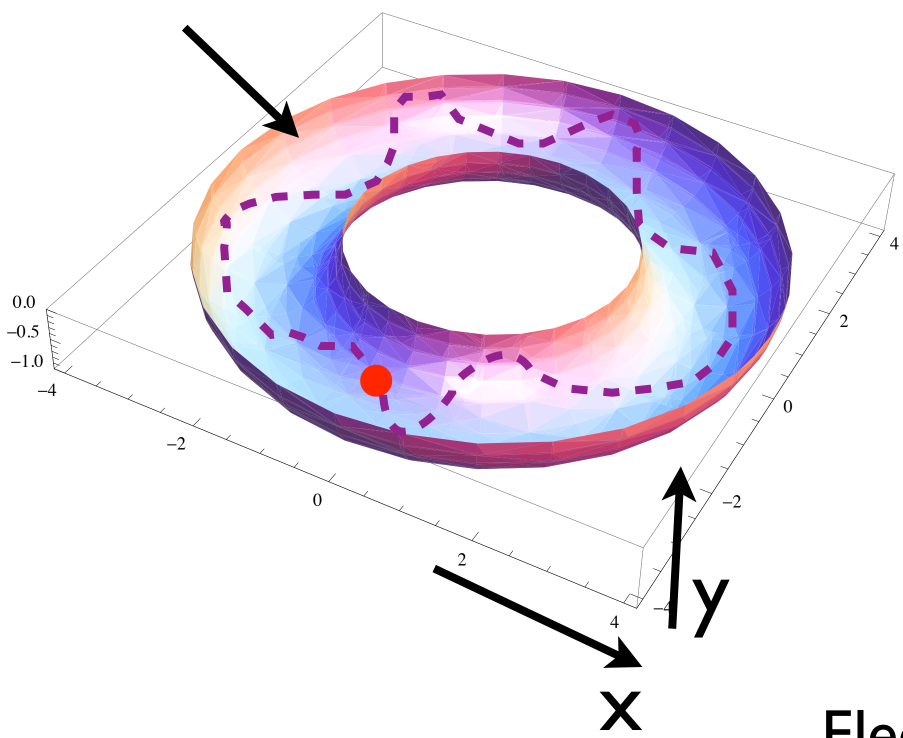
Higgs and super-symmetry ?
Or something else maybe



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)

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

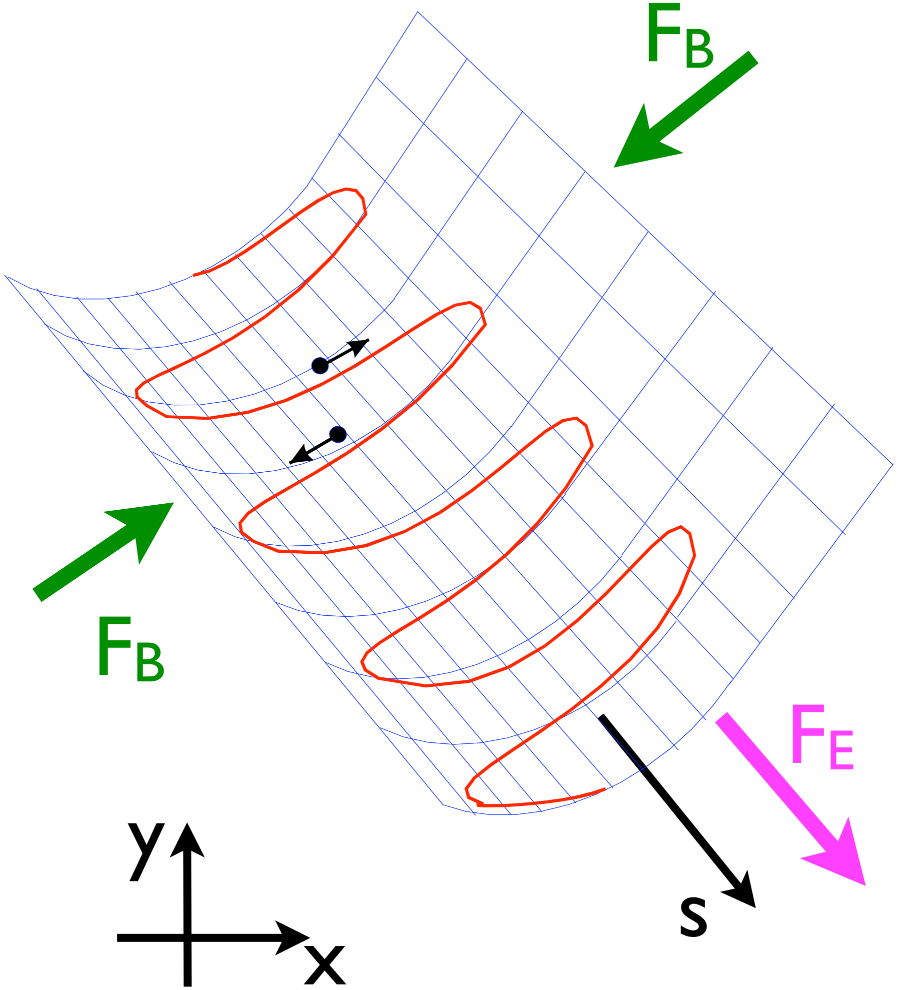
An ***accelerator*** *is formed by a sequence (called* ***lattice****) of:*

a) Magnets → Magnetic Field

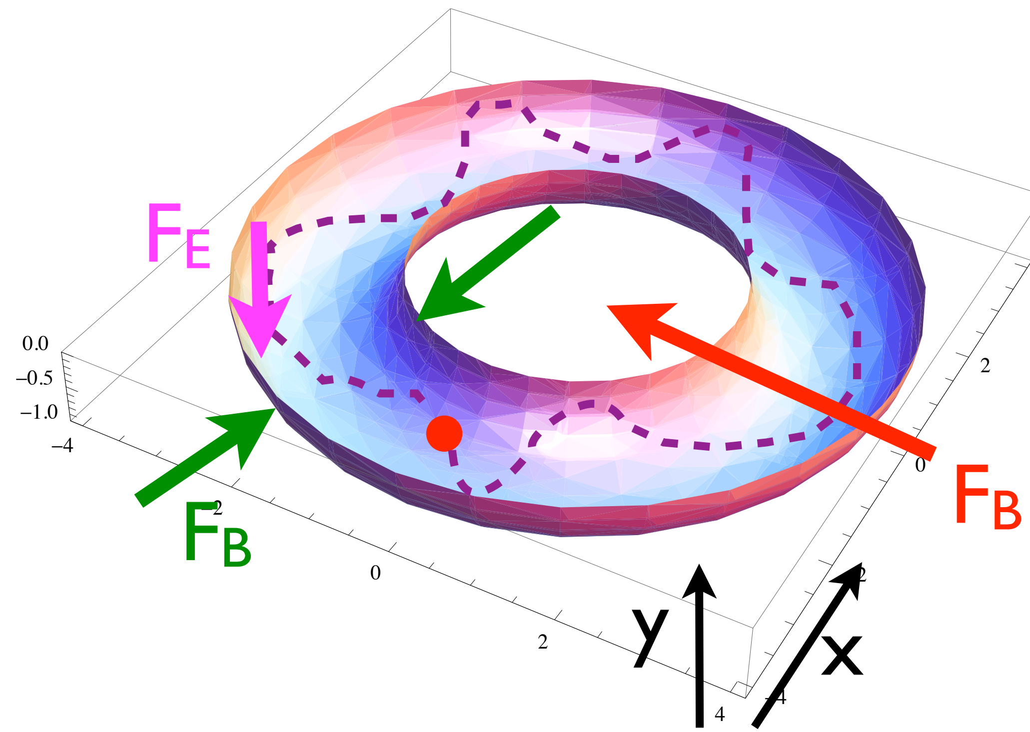
b) Accelerating Cavity → Electric Field

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

Linear Accelerator



Circular Accelerator



Building Blocks of an accelerator

1) A particle source

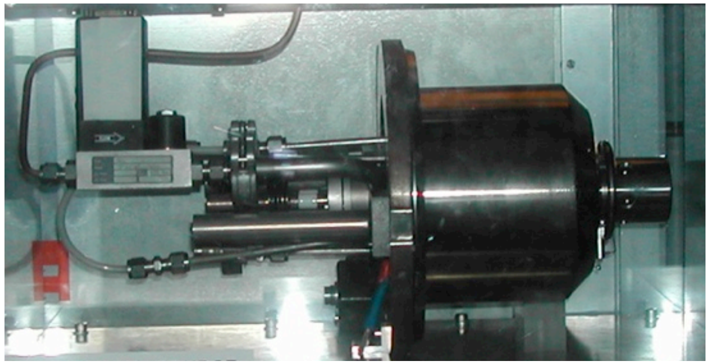
2) An accelerating system

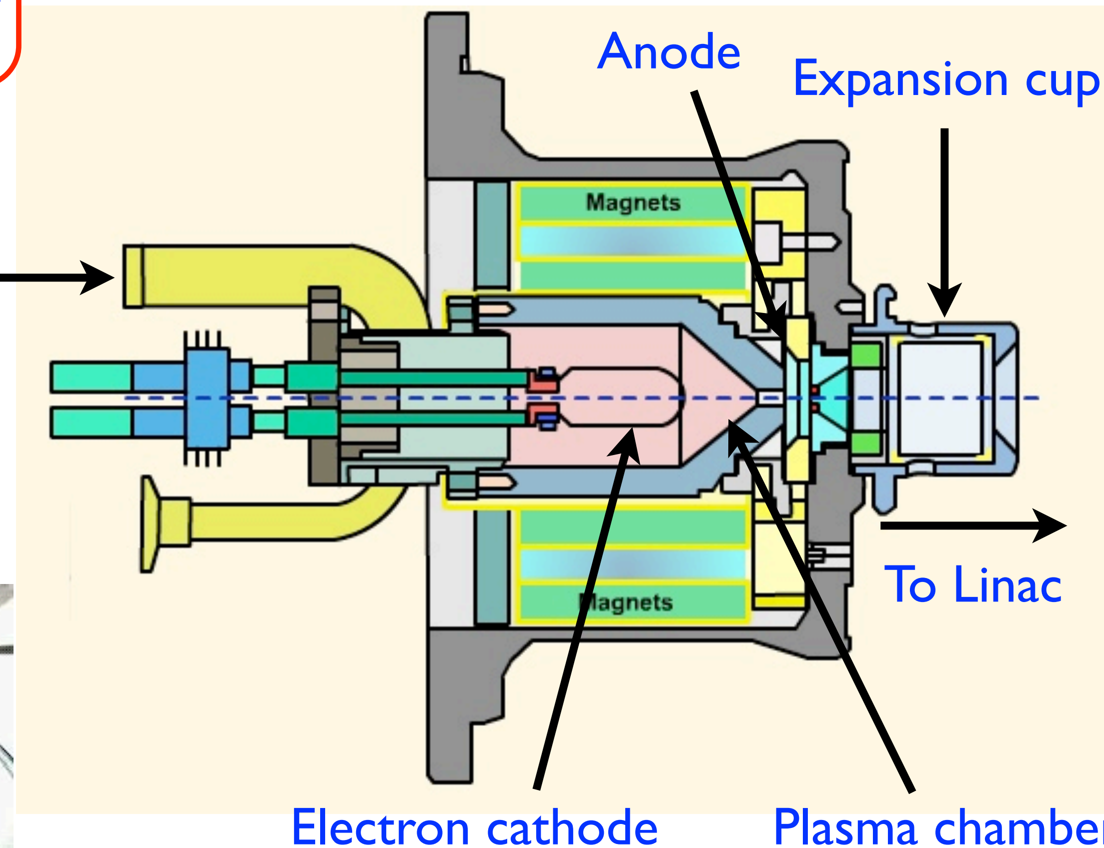
3) A series of guiding and storage devices

Everything under vacuum

How to get protons: duoplasmatron source

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





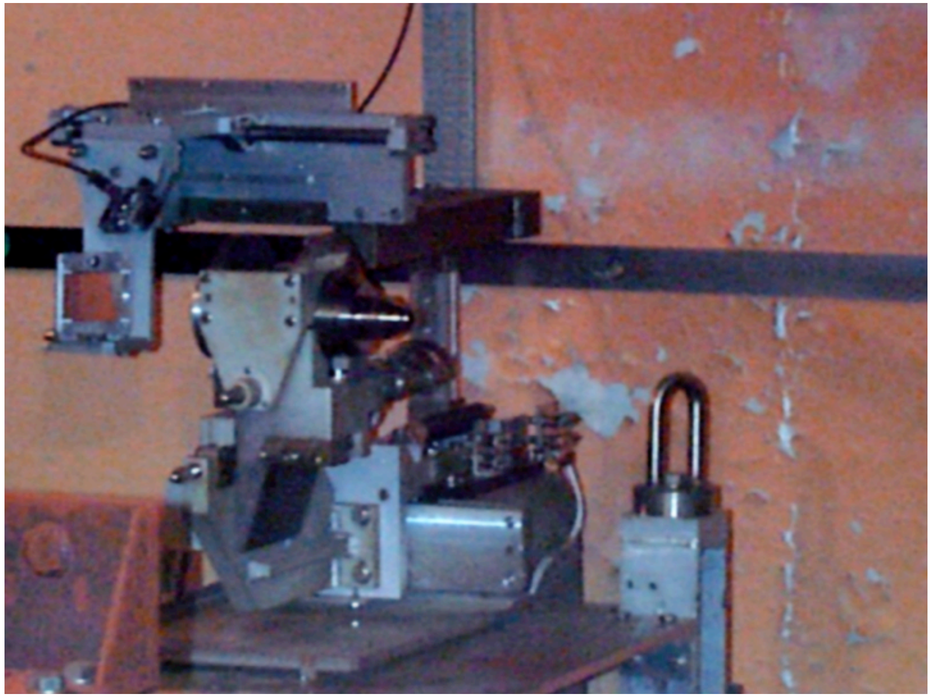
Hydrogen supply (one lasts for 6 months)

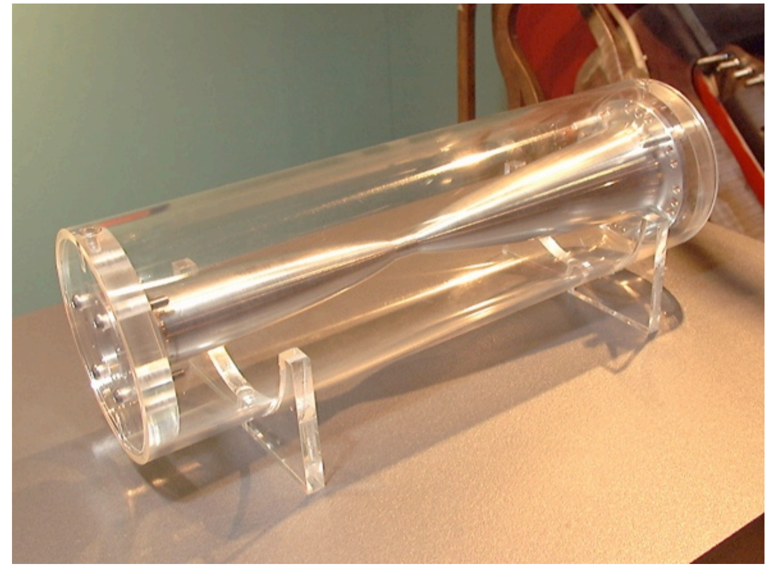
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, $v \approx 4000$ km/s

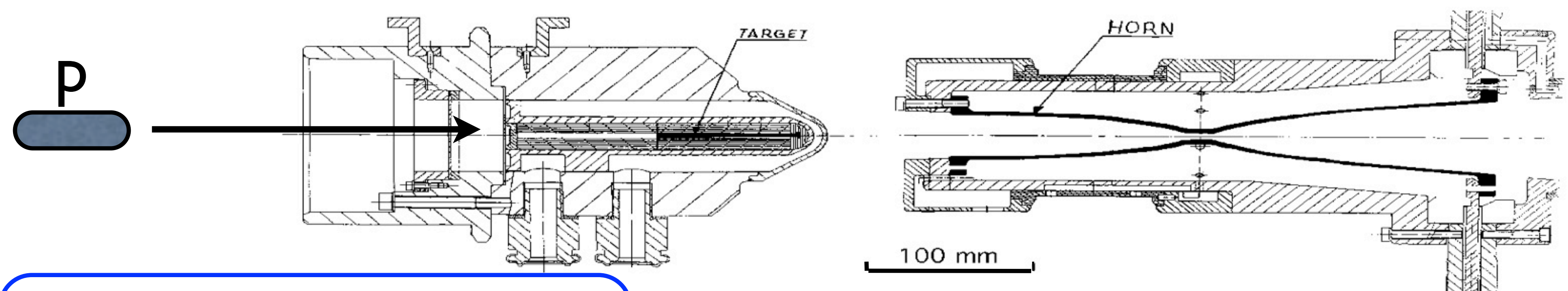
The SPACE SHUTTLE goes only up to 8 km/s

Cern Control Center: first LHC day

How to get antiprotons







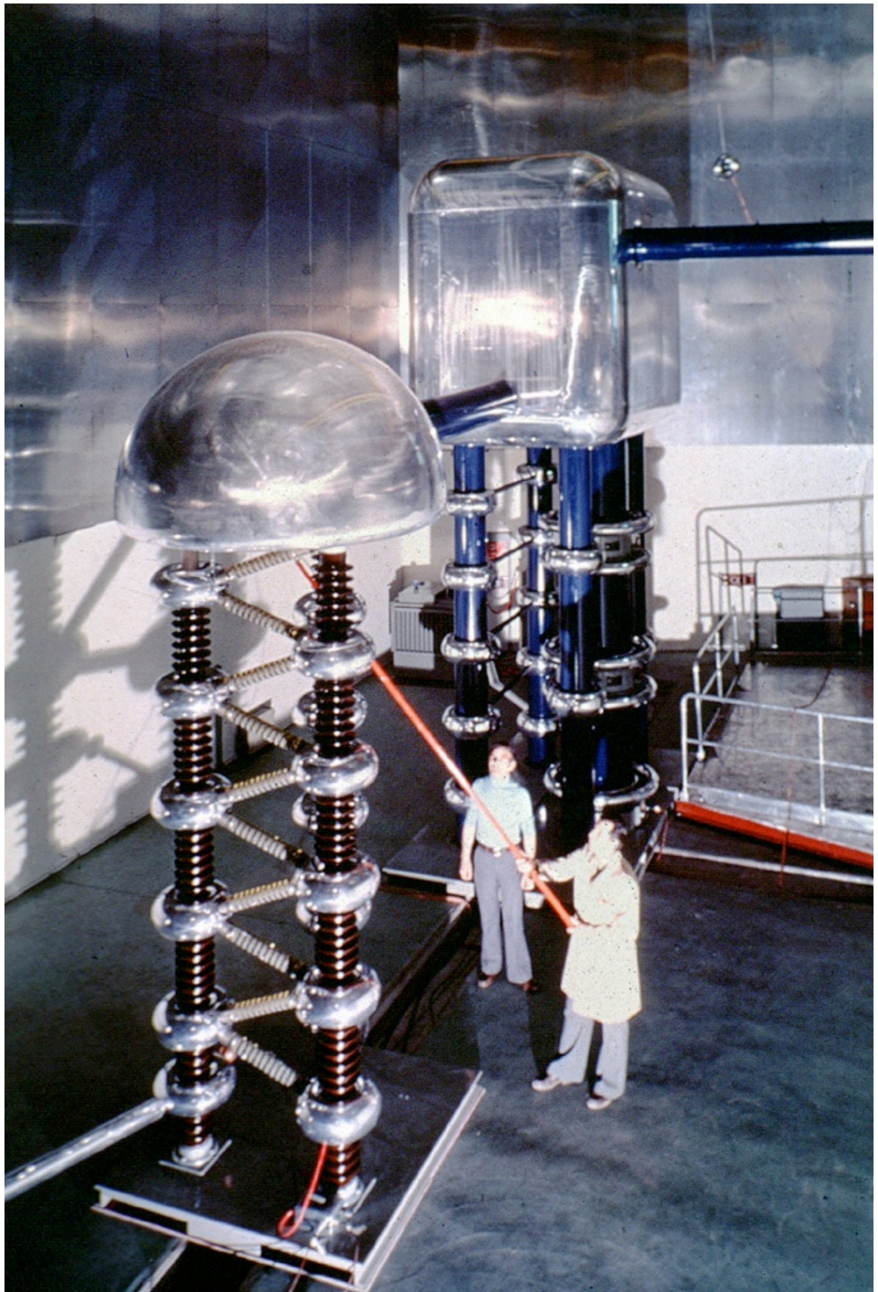
Starting from high energy p and with a very low efficiency

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

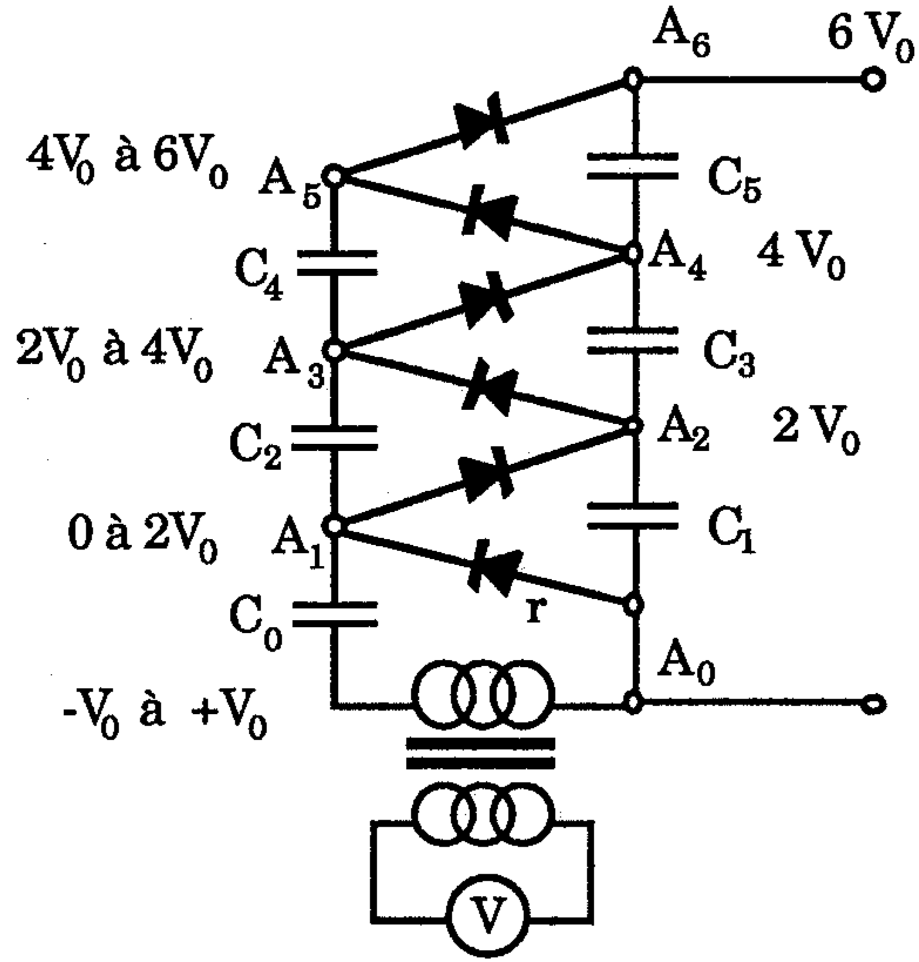
10^{13} p to have about 10^{7} antiprotons

E se volessimo neutrini da spedire al Gran-Sasso?

Cockroft-Walton. Old CERN proton pre-injector



High voltage unit composed by a multiple rectifier system



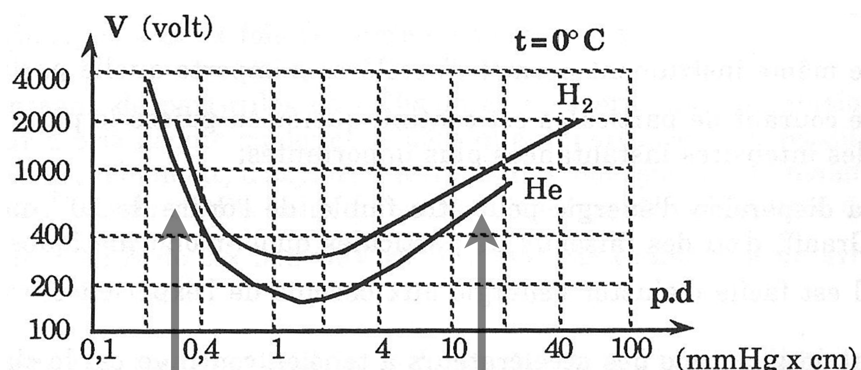
CERN: 750 kV, used until 1993

Bits an pieces are in the garden outside the Microcosm of the low energy part

Main limitation

Main limitation:
electric discharge due to too high Voltage.
Maximum limit: 1 MV

Limit set by Paschen law:
the breaking Voltage between two parallel electrodes depends only on the pressure of the gas between the electrodes and their distance



Low pressure: gas not too dense, long mean average path of electrons

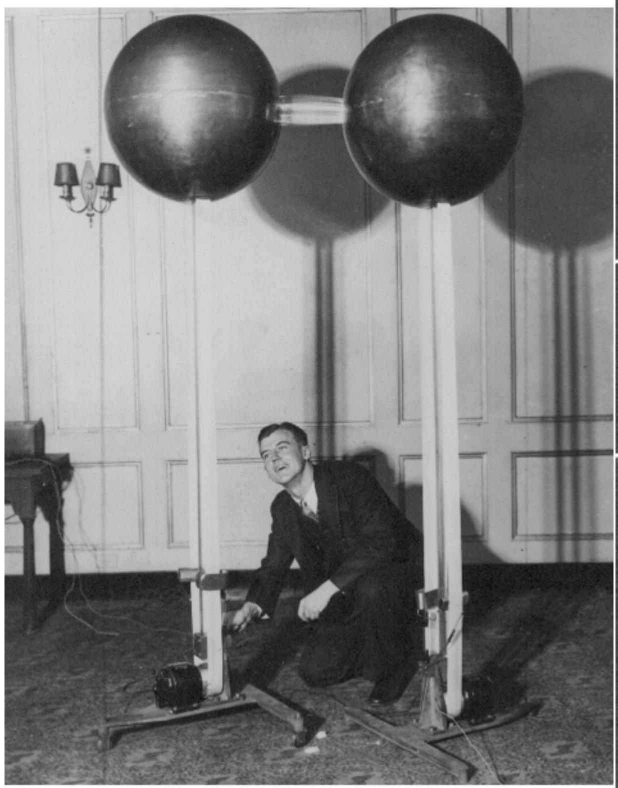
High pressure: dense gas, large Voltage needed for gas ionisation

Van De Graaf electrostatic generator (1928)

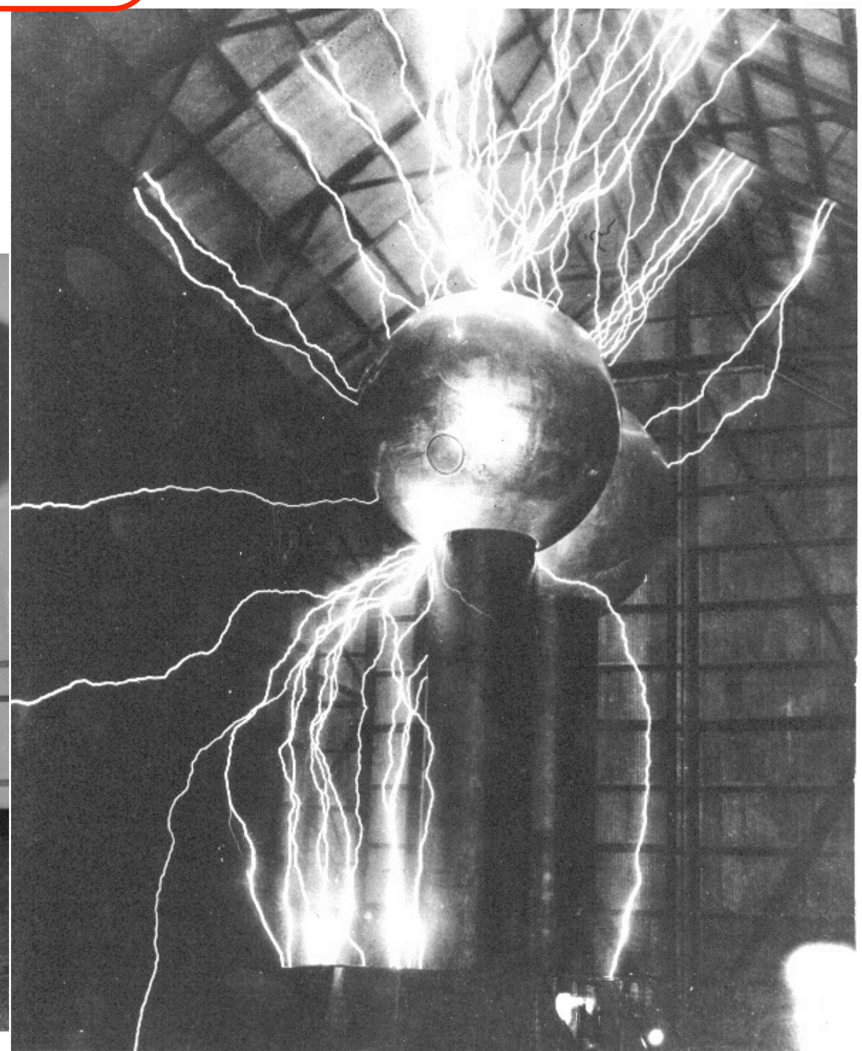
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: 10 MV

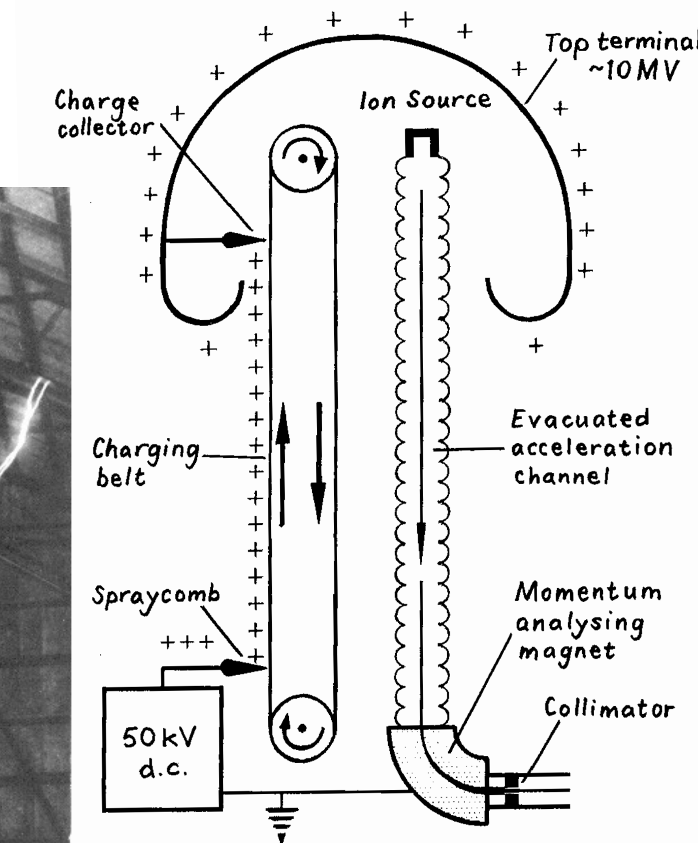
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



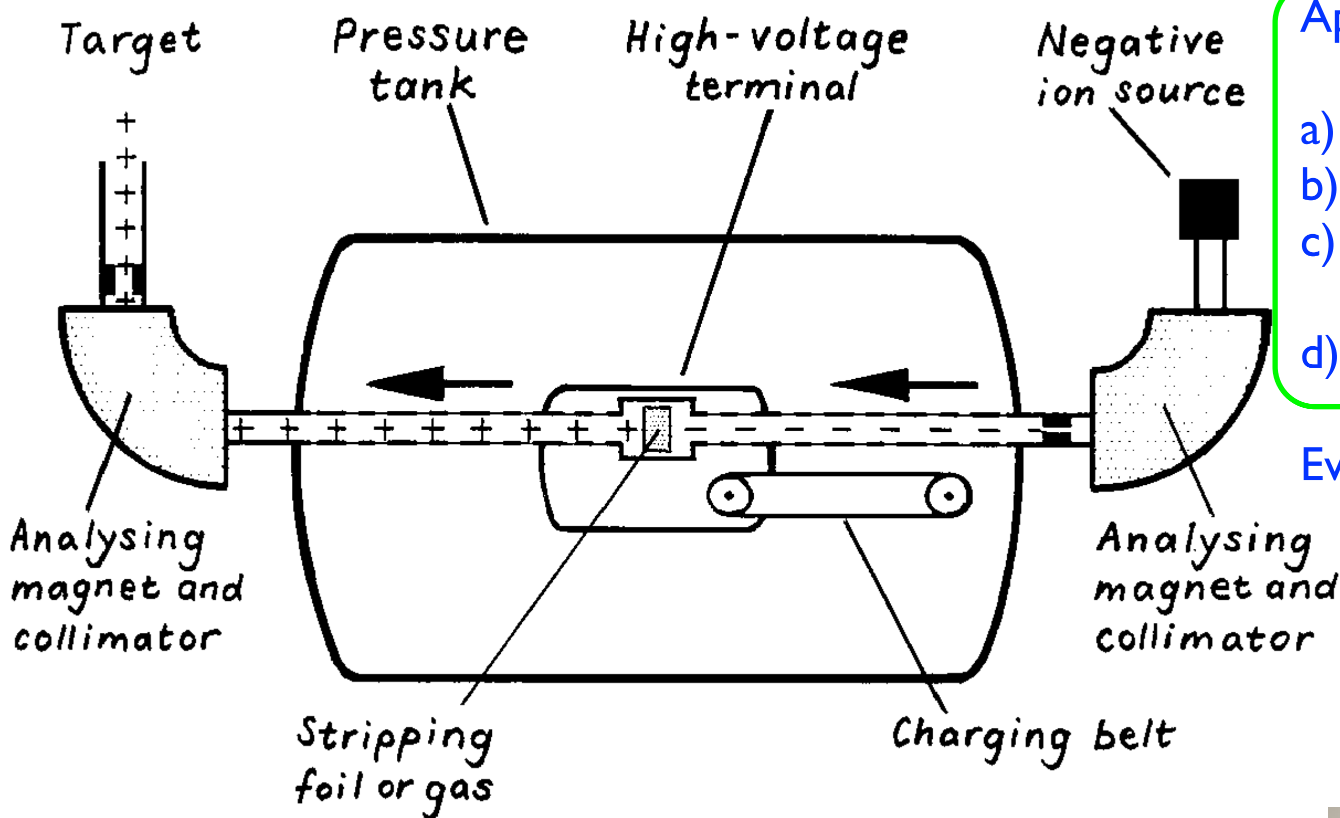
R. J. VAN DE GRAAFF WITH FIRST GENERATOR



AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)



Tandem



Application of Van der Graaf generator

a) Source of negative ions (150 keV)
b) Van Der Graff column (25 MV)
c) Stripping foil
change in charge
d) Further re-acceleration

Everything in a pressurized vacuum tank

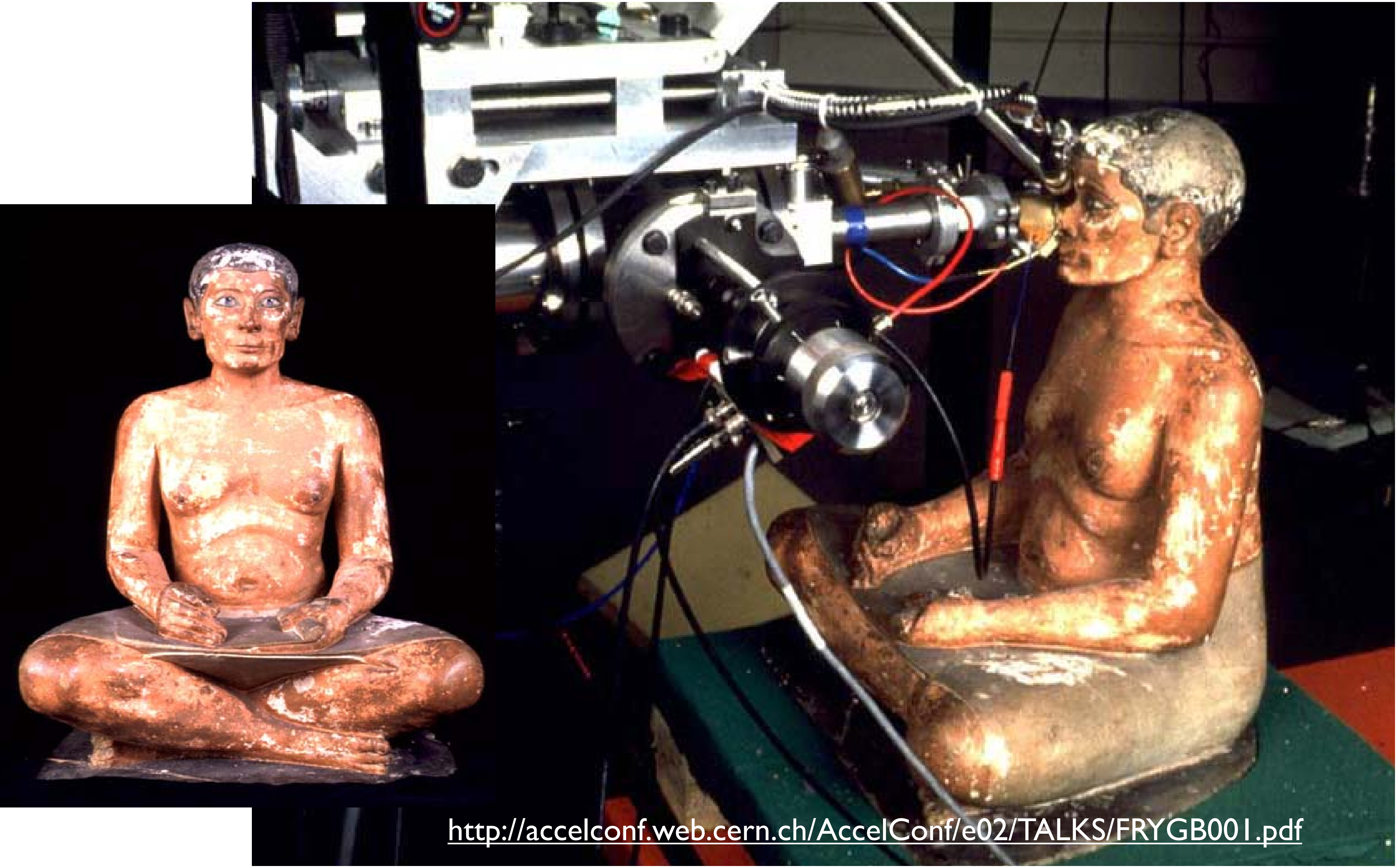
Since negative and positive multicharge states are used, different energies can be obtained

Current applications:

a) Low energy injector for Ions
Still in use at Brookeven (US) as injector for Cu and Au ions

b) Compact system for "other uses"
Dating of samples at Louvre.

Application of Louvre Tandem: composition of scribe eyes



http://accelconf.web.cern.ch/AccelConf/e02/TALKS/FRYGB001.pdf

Cyclotron

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

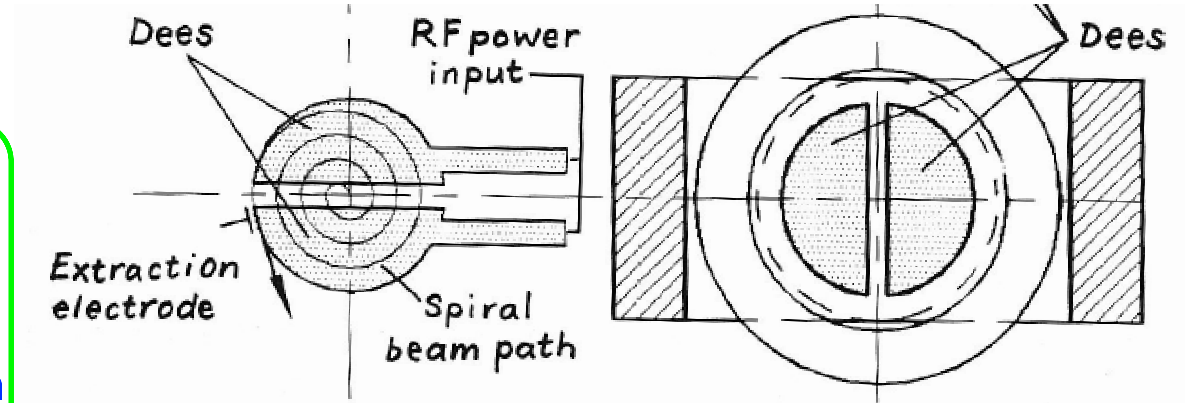
Electrical (E) RF field generated between two gaps with a fixed frequency

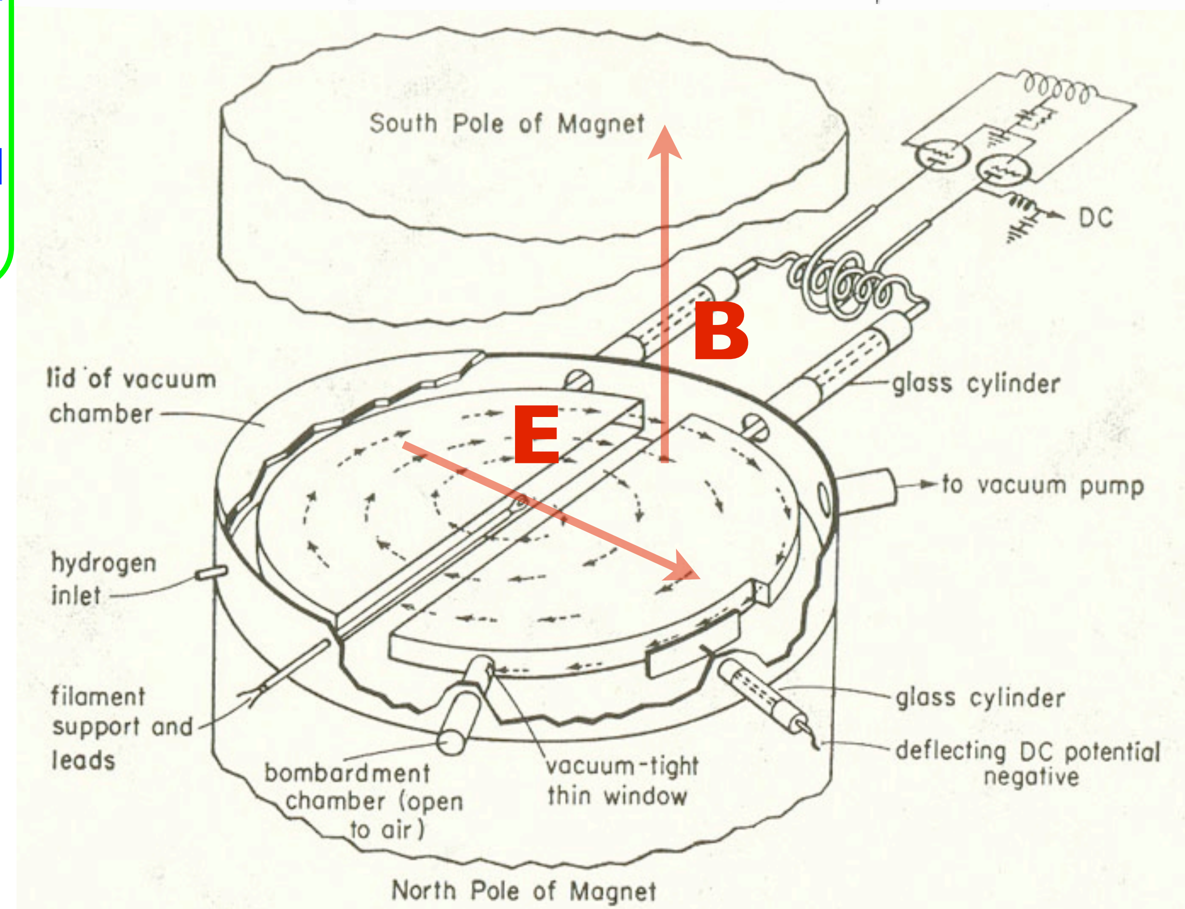
Particles spiral while accelerated by E field every time they go through the gap

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

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

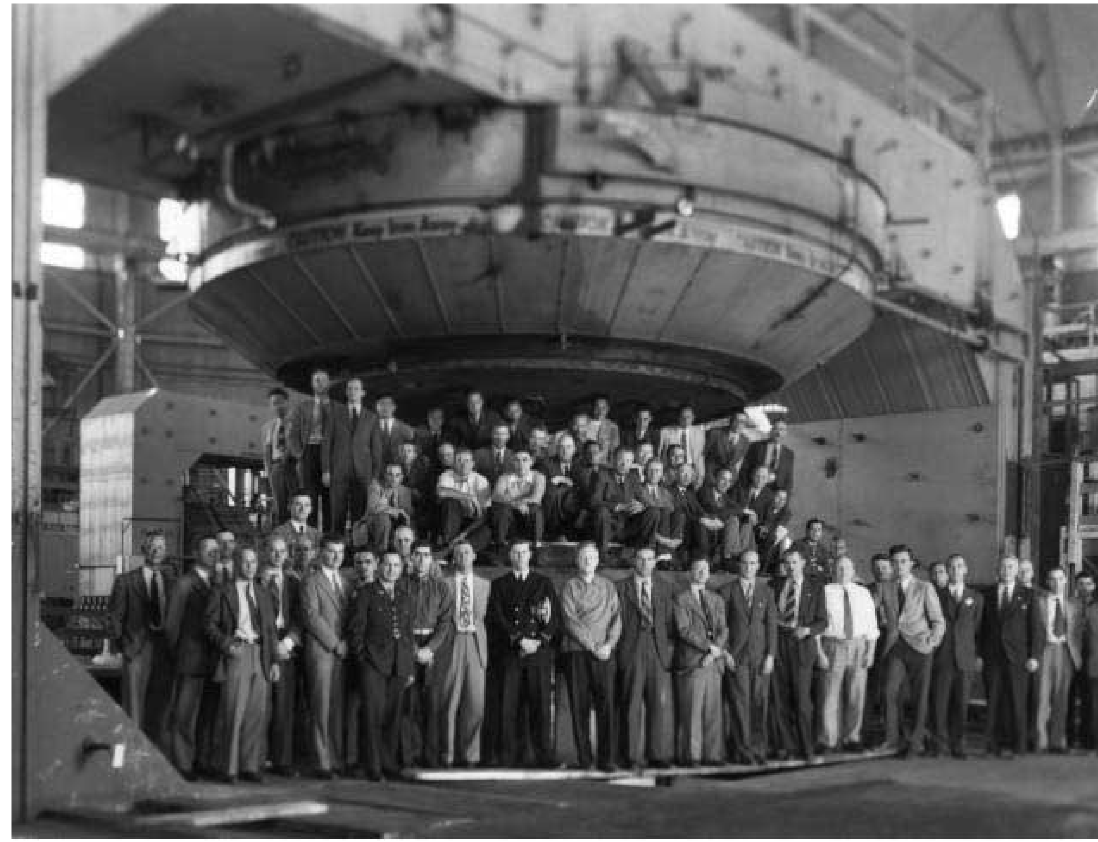


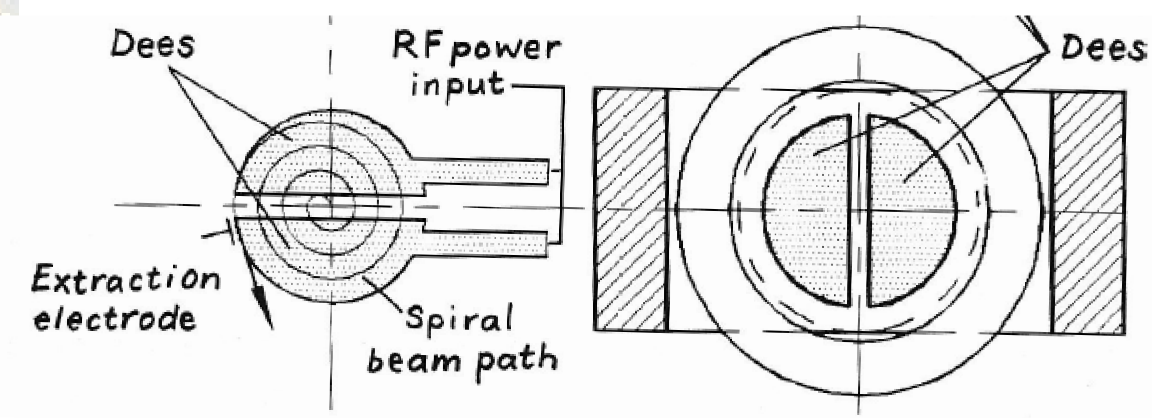


www.physics.rutgers.edu/ cyclotron/

Invented by Lawrence, got the Noble prize in 1939

The first cyclotron and the Berkeley one





Synchrotron (1952, 3 GeV, BNL)

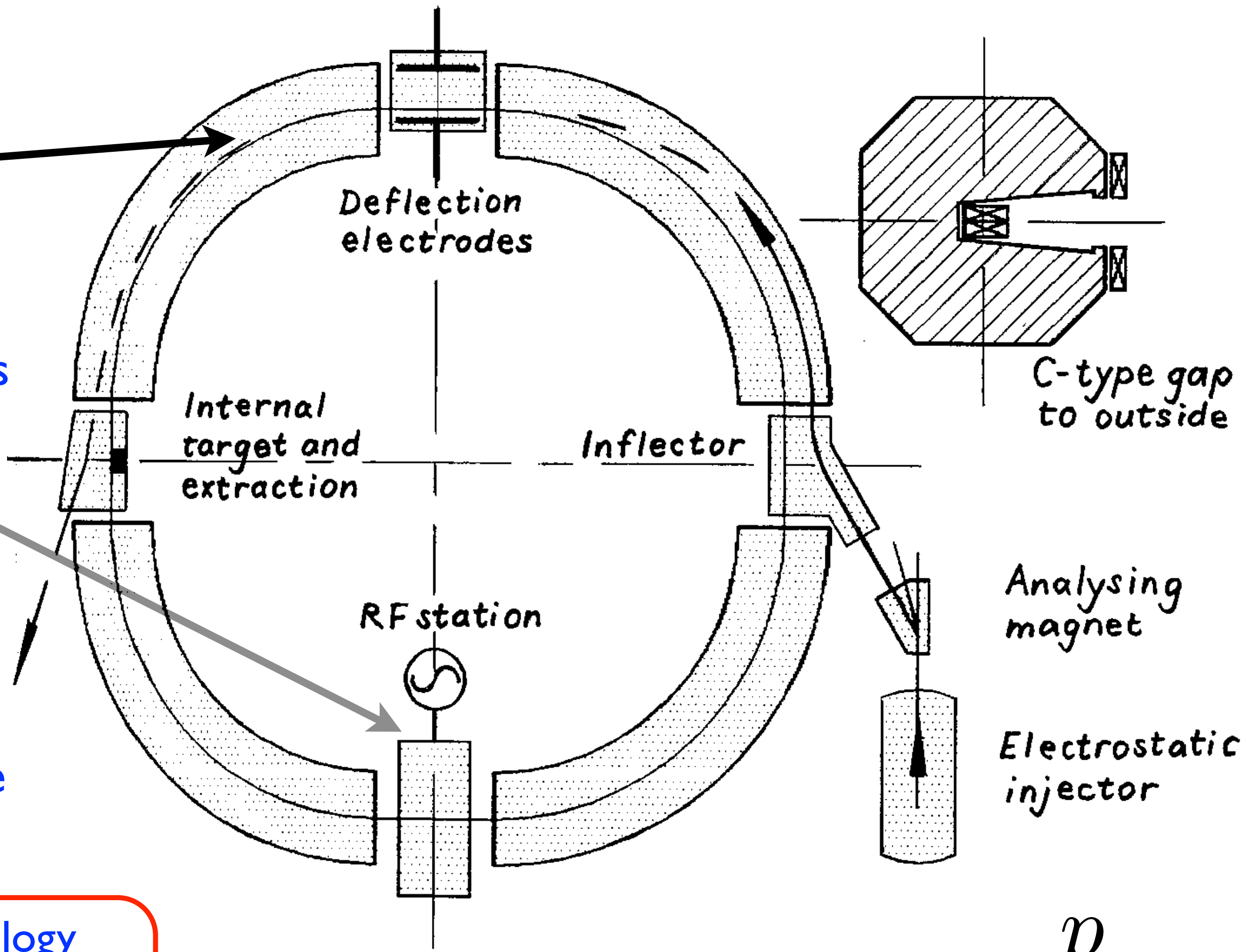
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

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

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

e electric charge

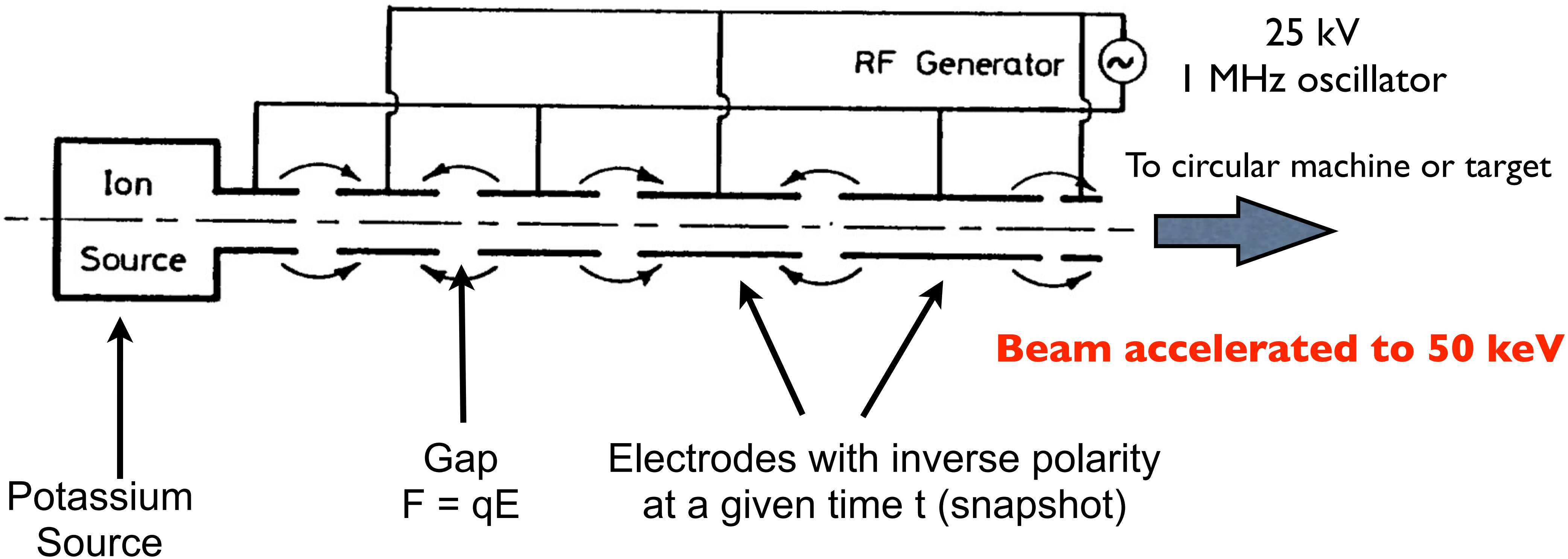
ρ constant radius of curvature



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

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

Wideroe linac: the first linear accelerating structure



First linac composed by drift tubes interleaved by acceleration gaps powered by an RF generator. (1928, Wideroe PhD)

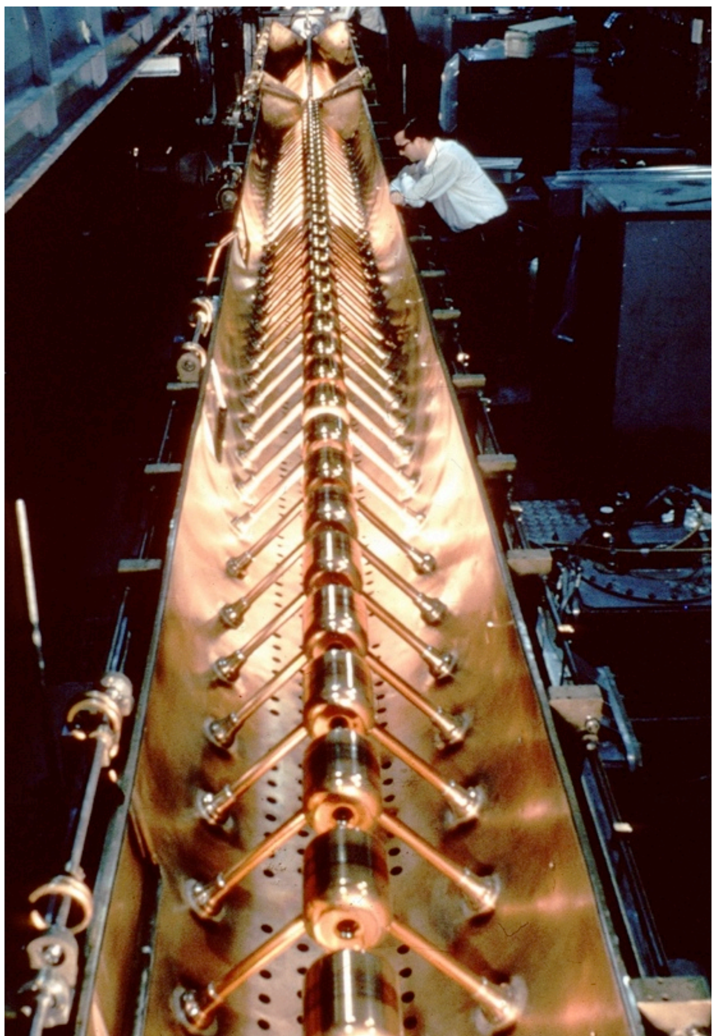
Obs: the drift tube length has to increase because particles are not yet relativistic. To an energy increase corresponds a speed increase, and the particle has to travel more in the shielded region to be in phase with the accelerating field.

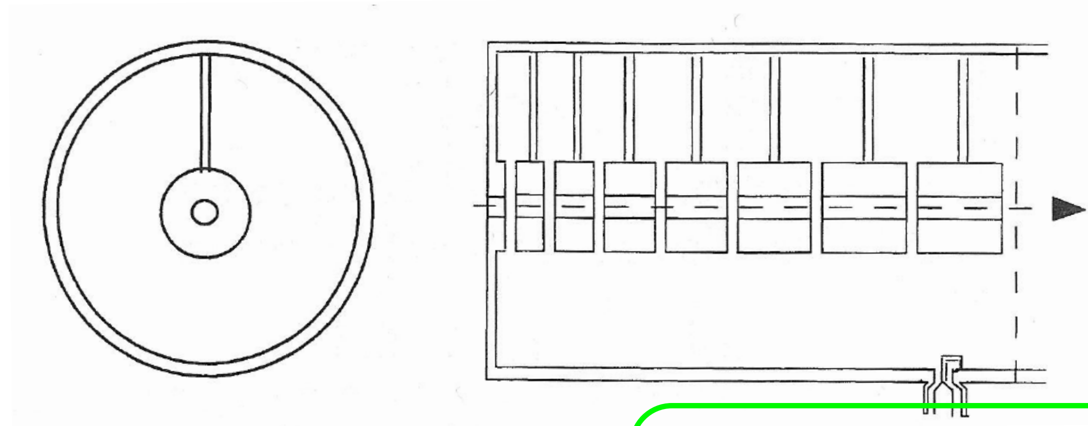
Main limitation: after a certain energy, the length of the drift tube is too long. The RF frequency has increase to some 10 MHz, need to enclose the structure in a resonator to avoid field losses.

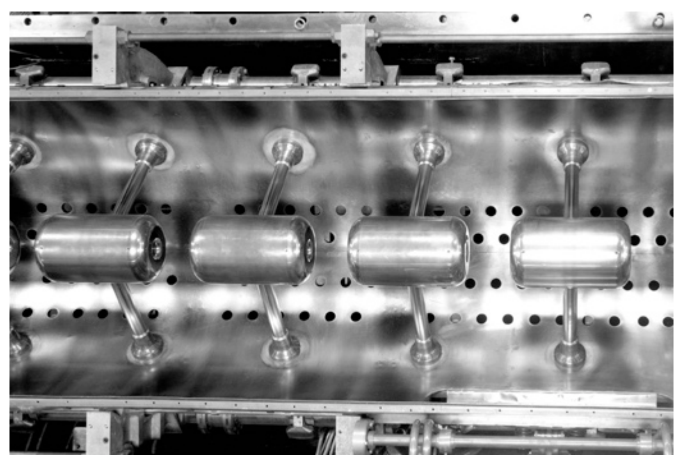
Alvarez drift tube linac

Linac composed by ***drift tubes*** interleaved by ***acceleration gaps*** as Wideroe linac, but field generated in a ***resonant cavity***. The frequency of the field can go up to 200 MHz.

Currently we have ***two Linacs at CERN*** with Alvaretz structure, ***for protons and ions***.







Inner structure of Linac 1 (Alvarez type). The drift tubes are supported on stems, through which the current for the quadrupole magnets (located inside the tubes) and the cooling water are supplied.
Linac 1 accelerated protons to 50 MeV.

CERN accelerator complex overview

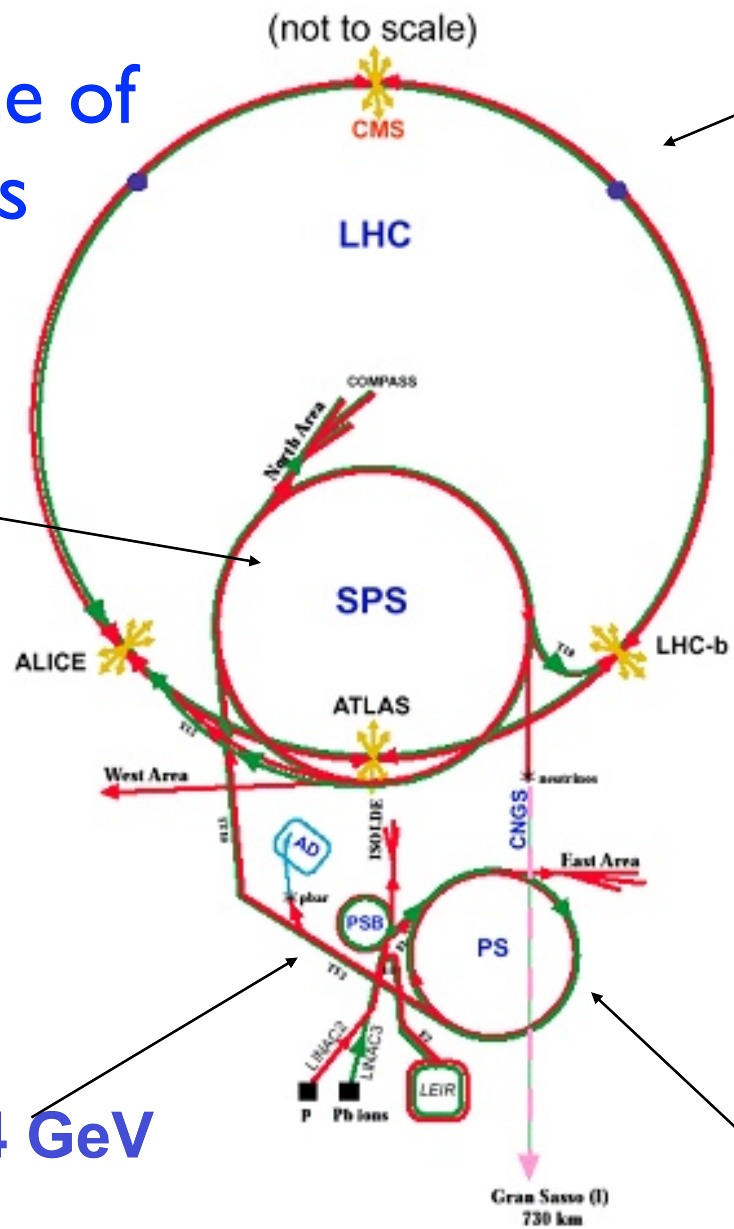
Chain/sequence of accelerators

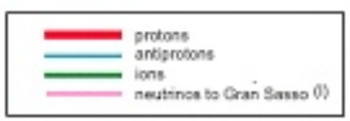
450 GeV/c – 7 TeV/c

C ~ 27 km

26 - 450 GeV/c

C ~ 6 km





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?

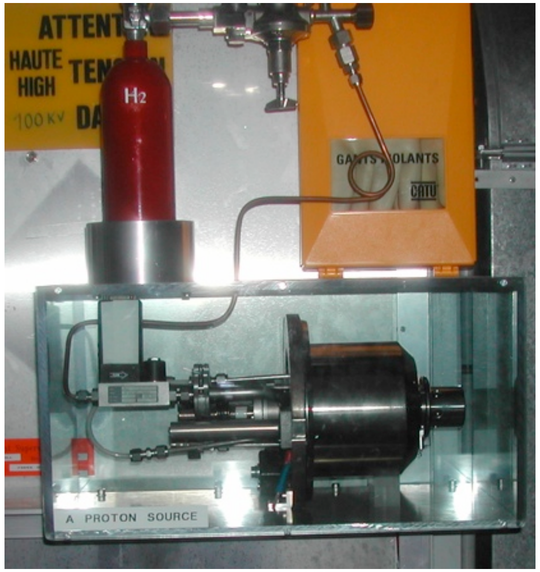
50 MeV – 1.4 GeV

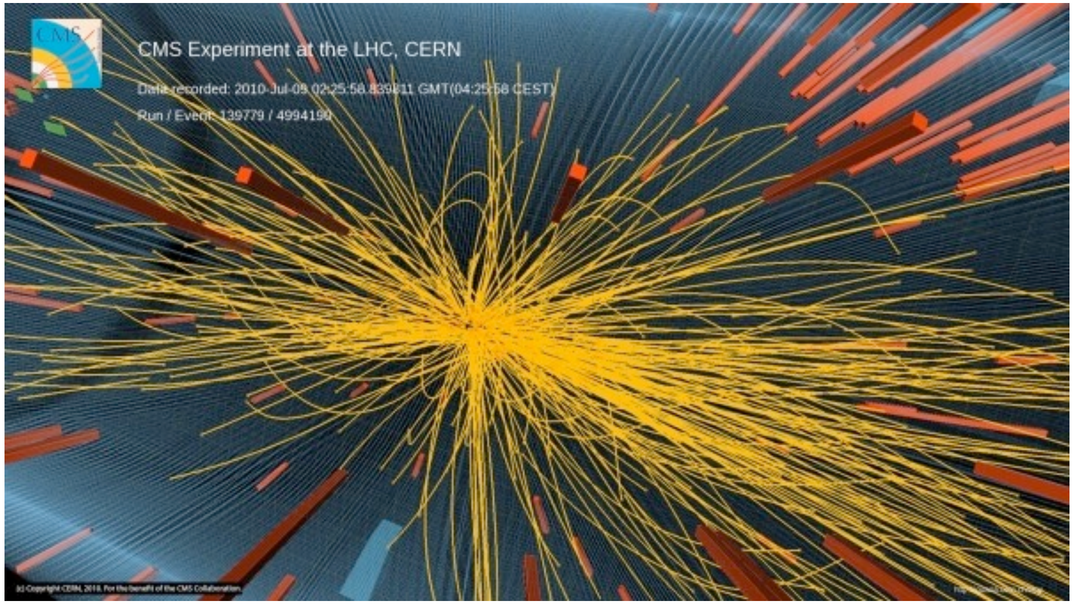
C ~ 157 m

1.4 GeV – 26 GeV/c

C ~ 630 m

Basically accelerators brings you ...

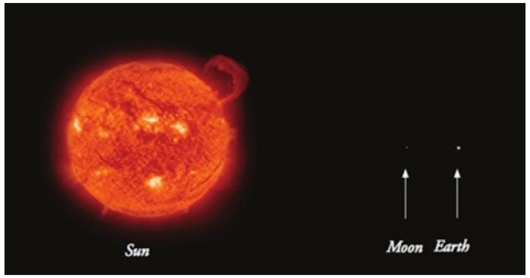




from nearly a bottle of hydrogen

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)

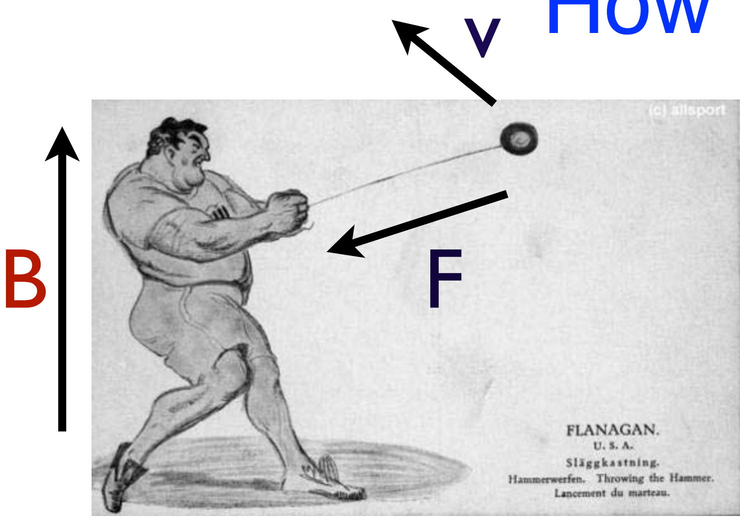


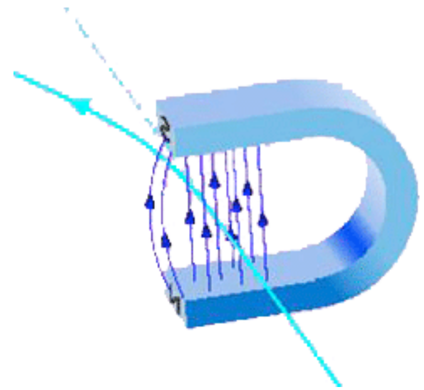
In the Linac 2, basically nothing.
In the **PSB,** a bit less than than 1.2 s.
In the **PS**, a bit less than 3.6 s
In the **SPS**, a bit less than 16.8 s
In the **LHC**, minimum 30 minutes

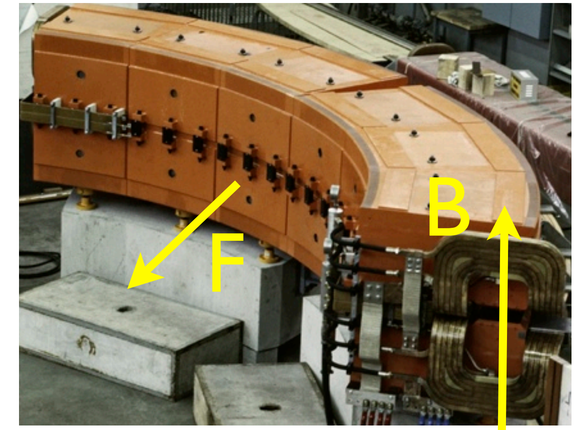
1 821.6 s → 546 480 000 km

about 3.7 time the distance Sun-Earth

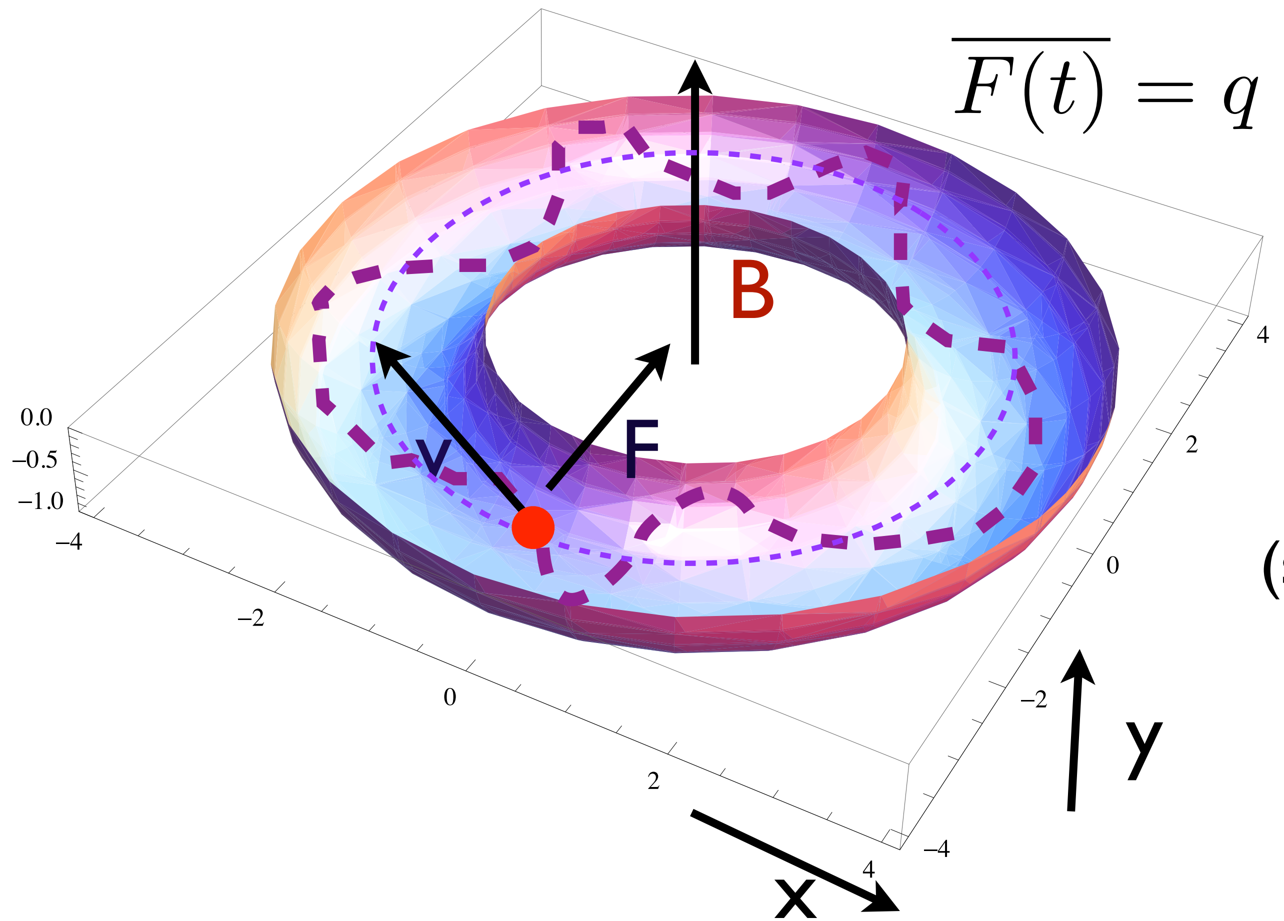
How an accelerator works ? A dipole







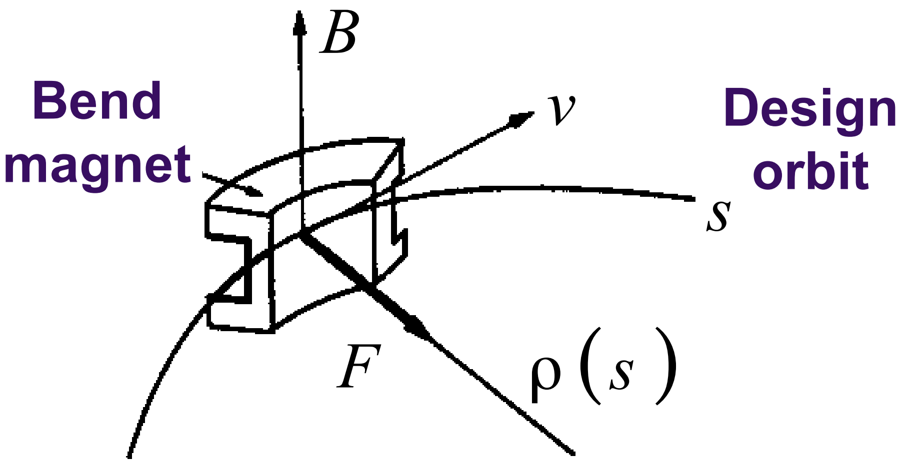
$$\overline{F(t)} = q\left(\cancel{\overline{E(t)}} + \overline{v(t)} \otimes \overline{B(t)}\right)$$



Particles of
different energy
(speed) behave differently

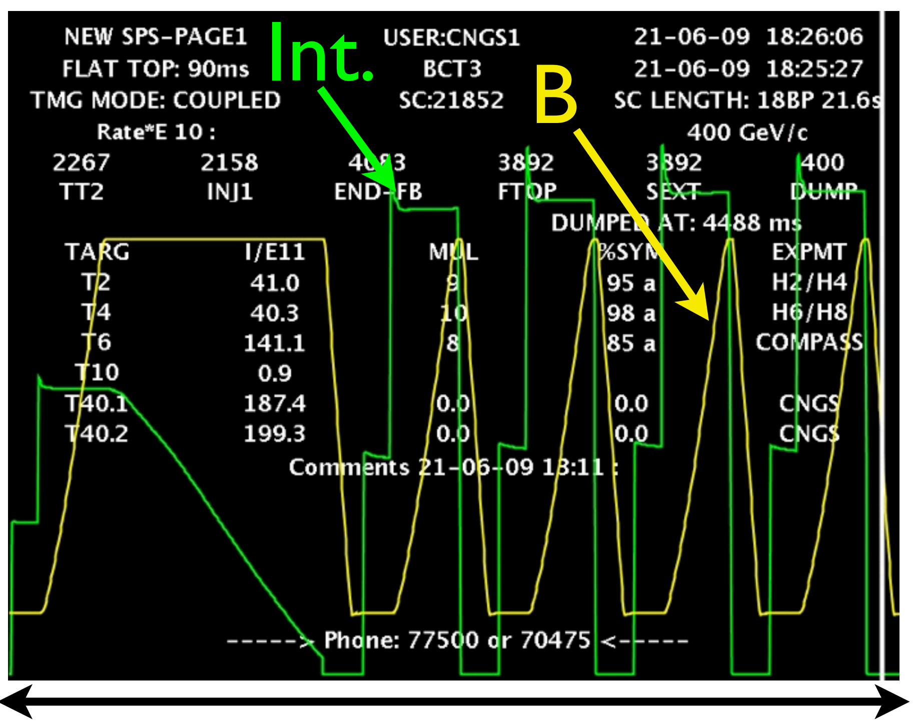
Magnetic field confines
particles
on a given trajectory

Dipoles



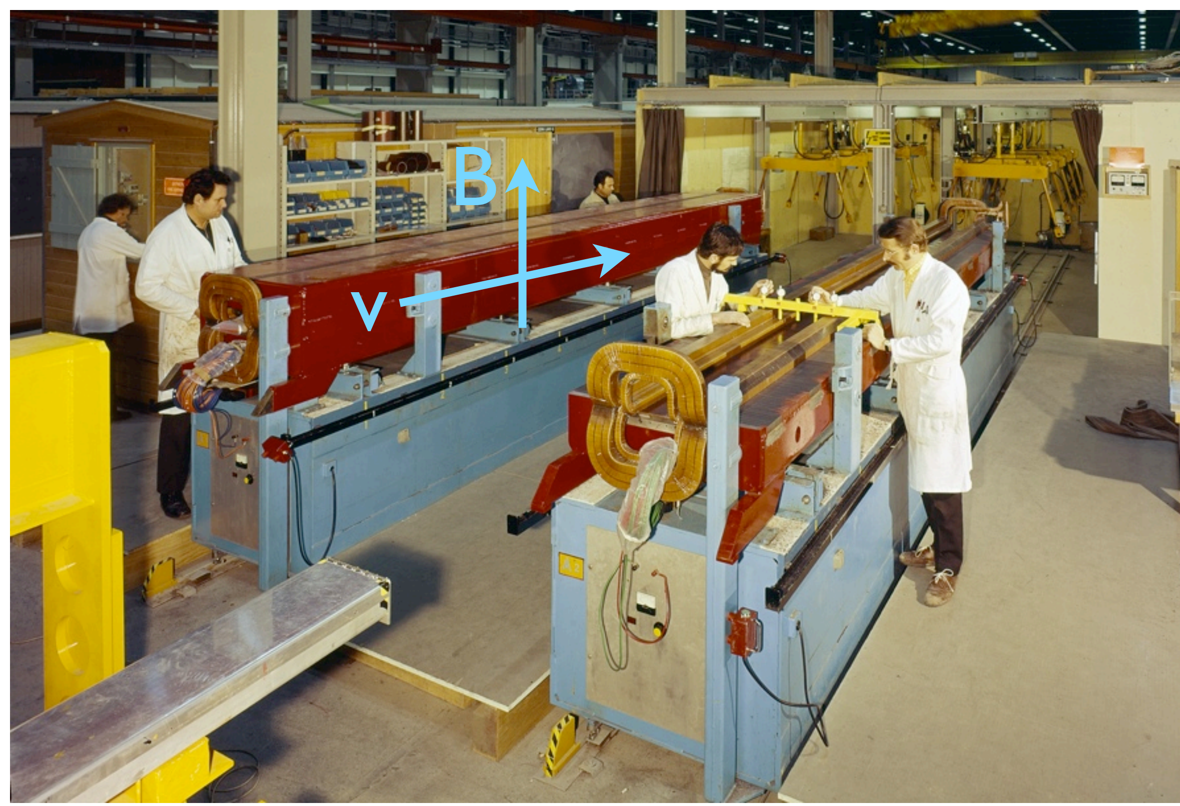
Force given by the vertical magnetic field compensates the centrifugal force to keep the particles on the central trajectory, i.e. in the center of the beam pipe.

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.

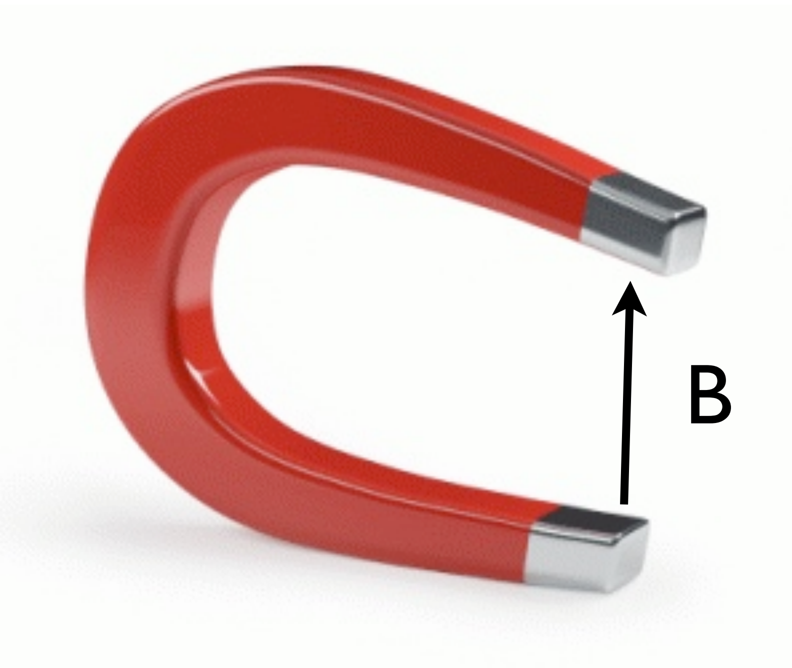


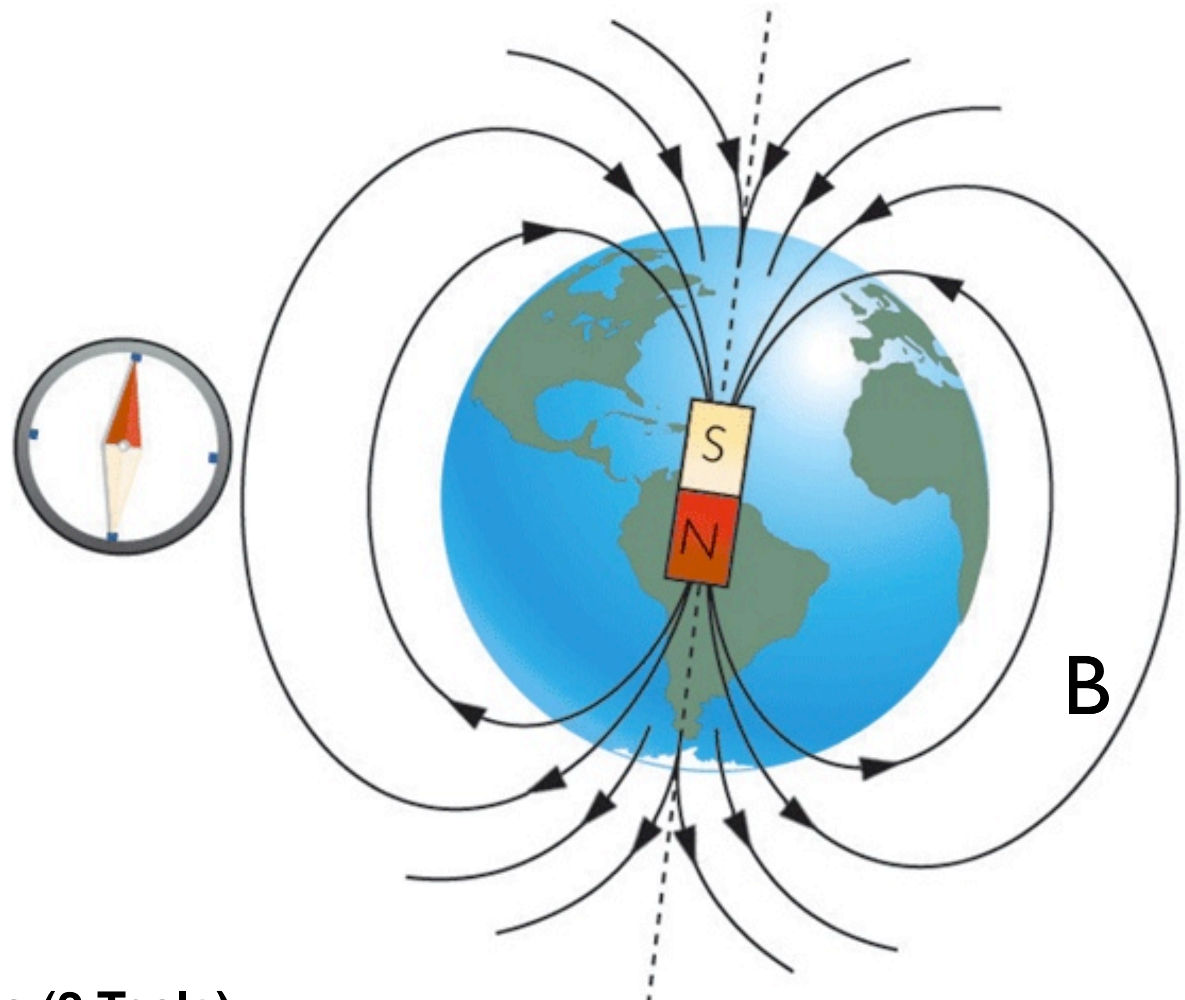
time (s) [21.6 s]

CERN-SPS dipoles, in total about 500



Two dipoles you should know we well

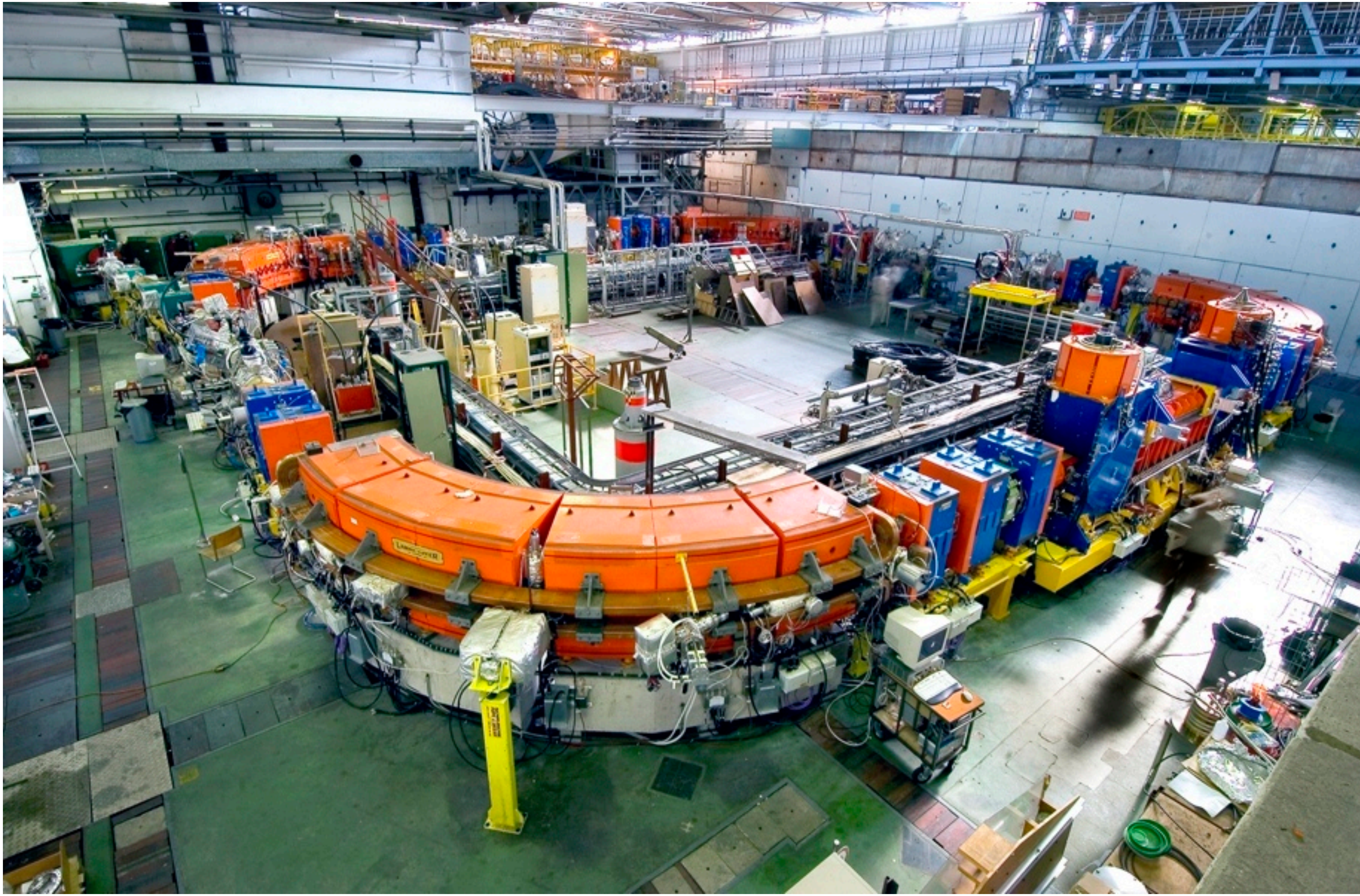




Earth Magnetic Field : ~ 0.6 Gauss

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

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



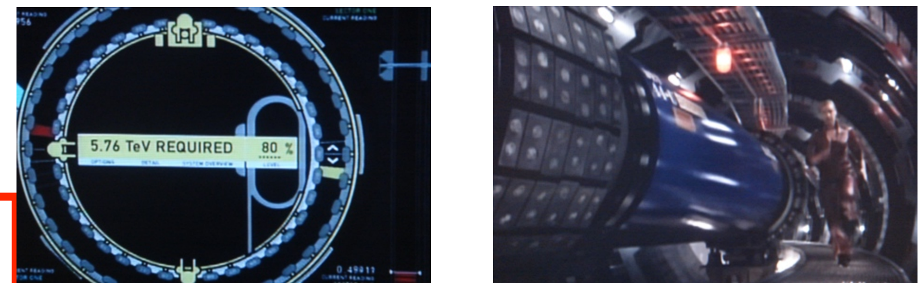
INTERLUDE:
THE TERMINATOR-3 ACCELERATOR

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 !)



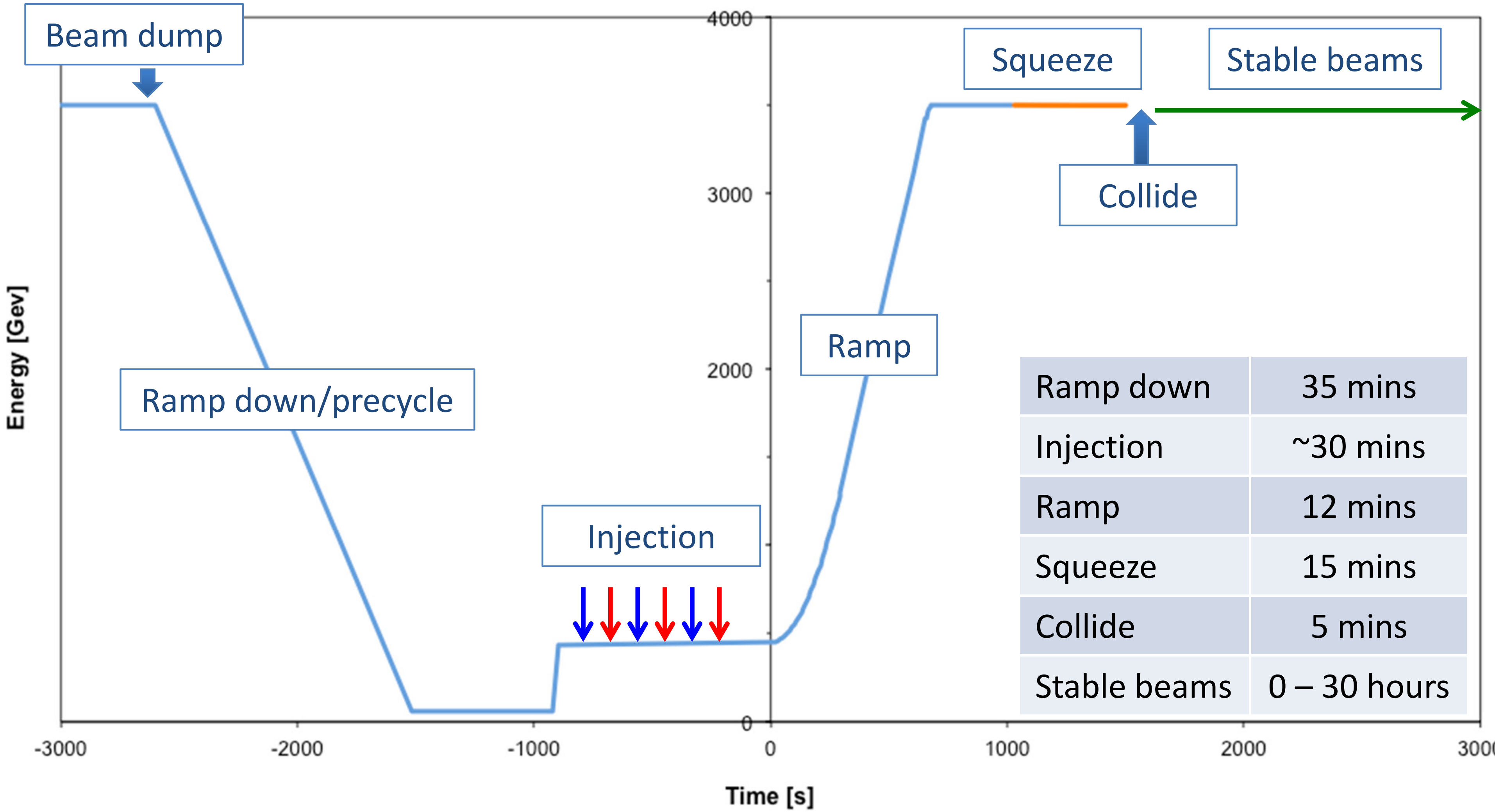
Energy of the machine (left) and size of the accelerator (right)

- 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

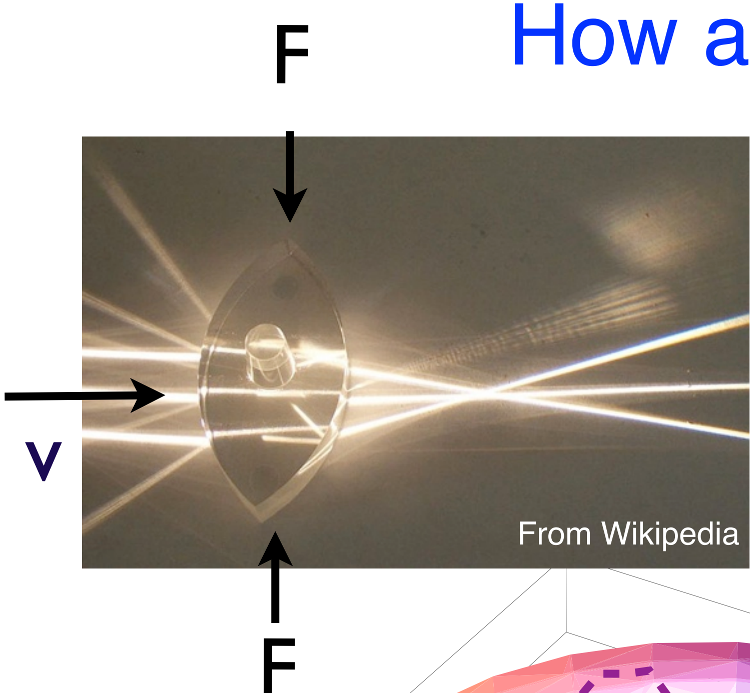
From E. Todesco CERN Summer student lecture

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 ?



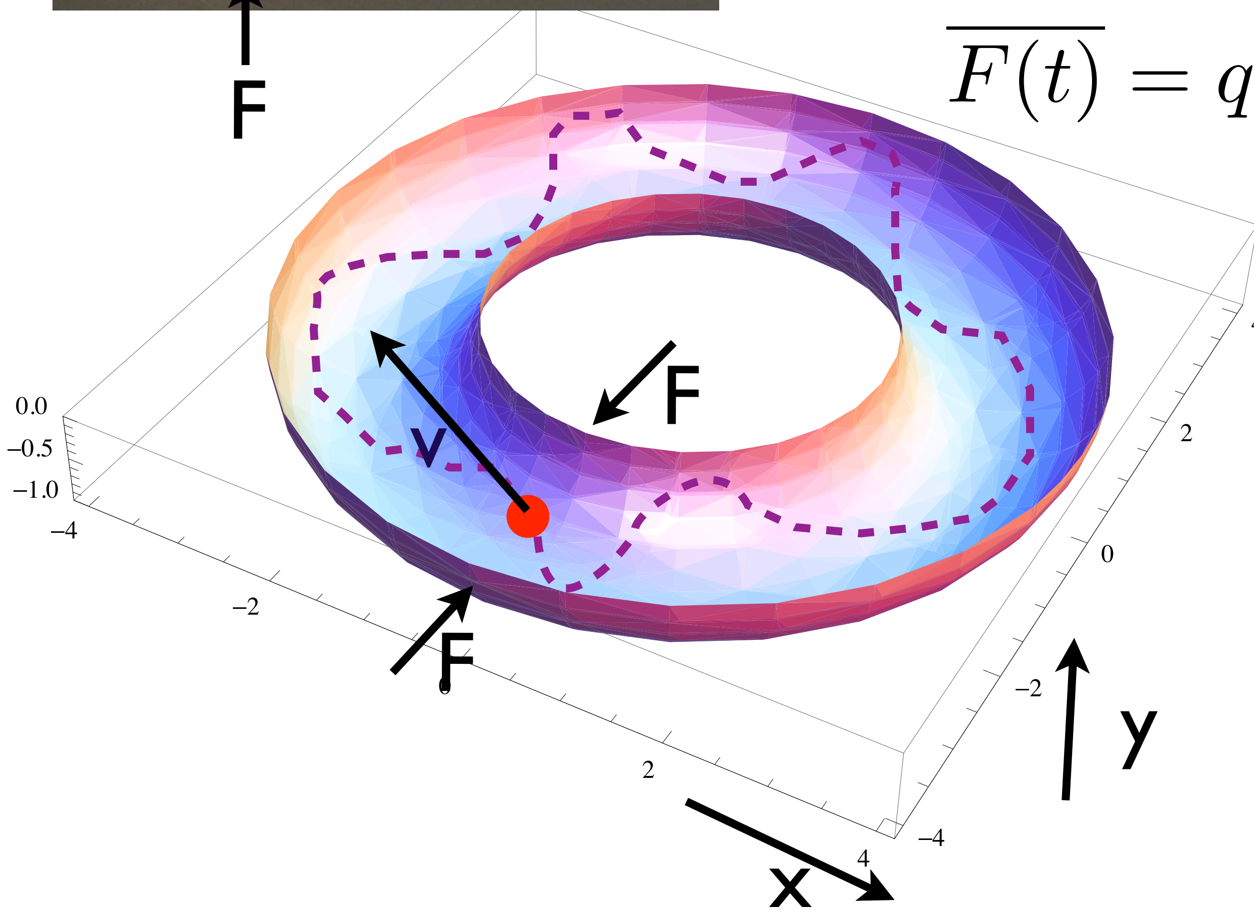
Goal: keep enough particles confined in
a well defined volume *to accelerate them.*

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

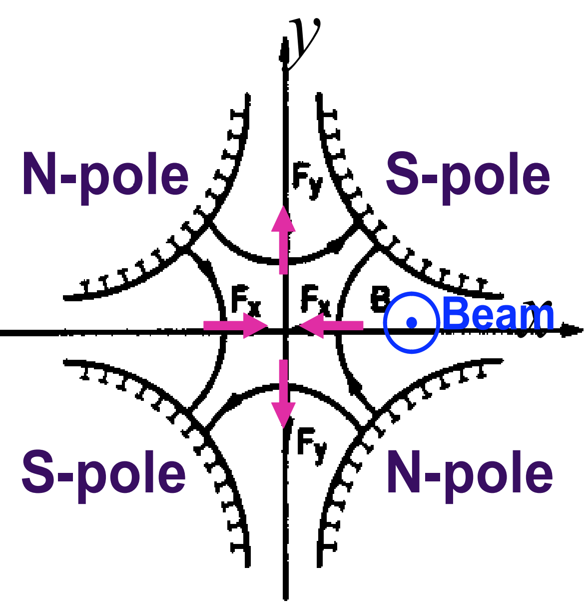
Magnetic field confines
particles
on a given trajectory

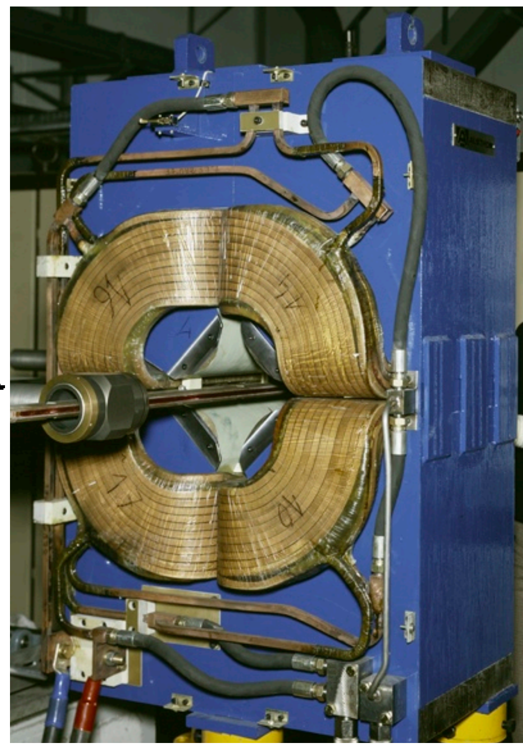


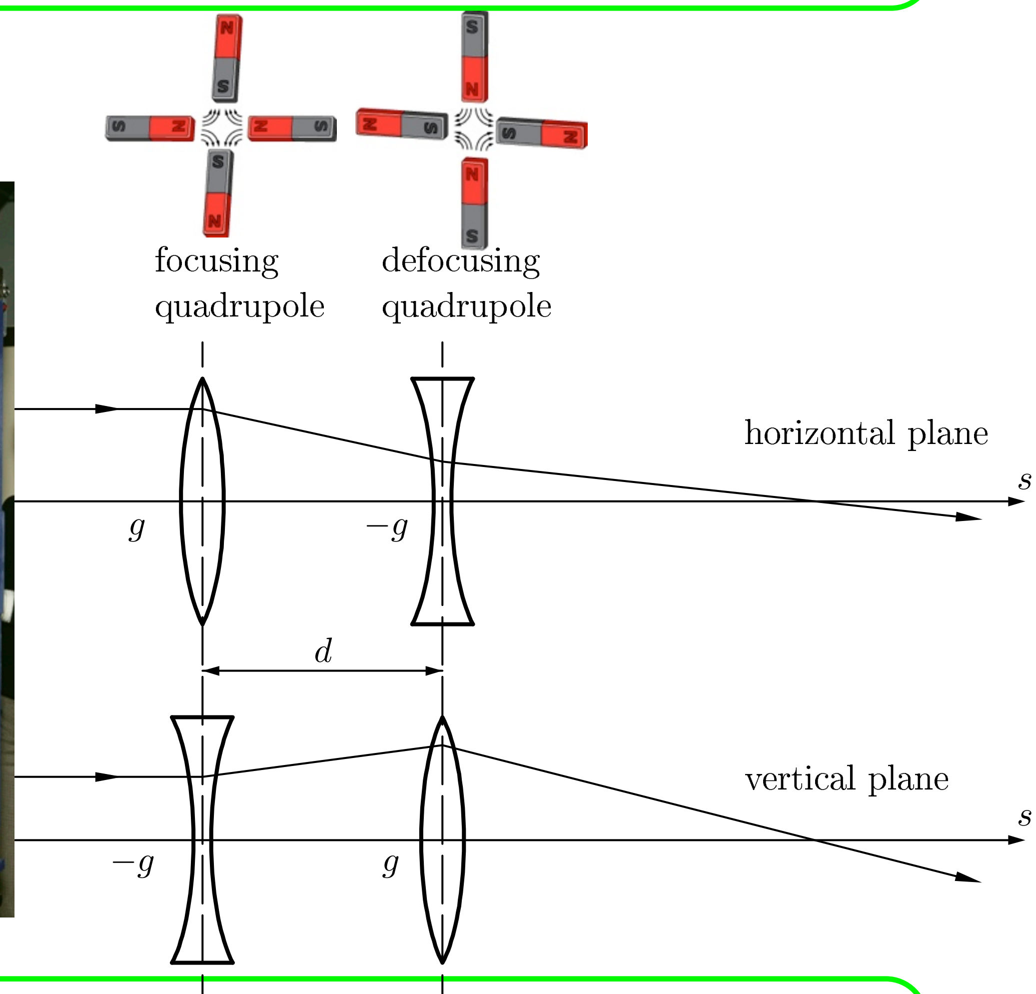
Synchrotrons: strong focusing machine

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



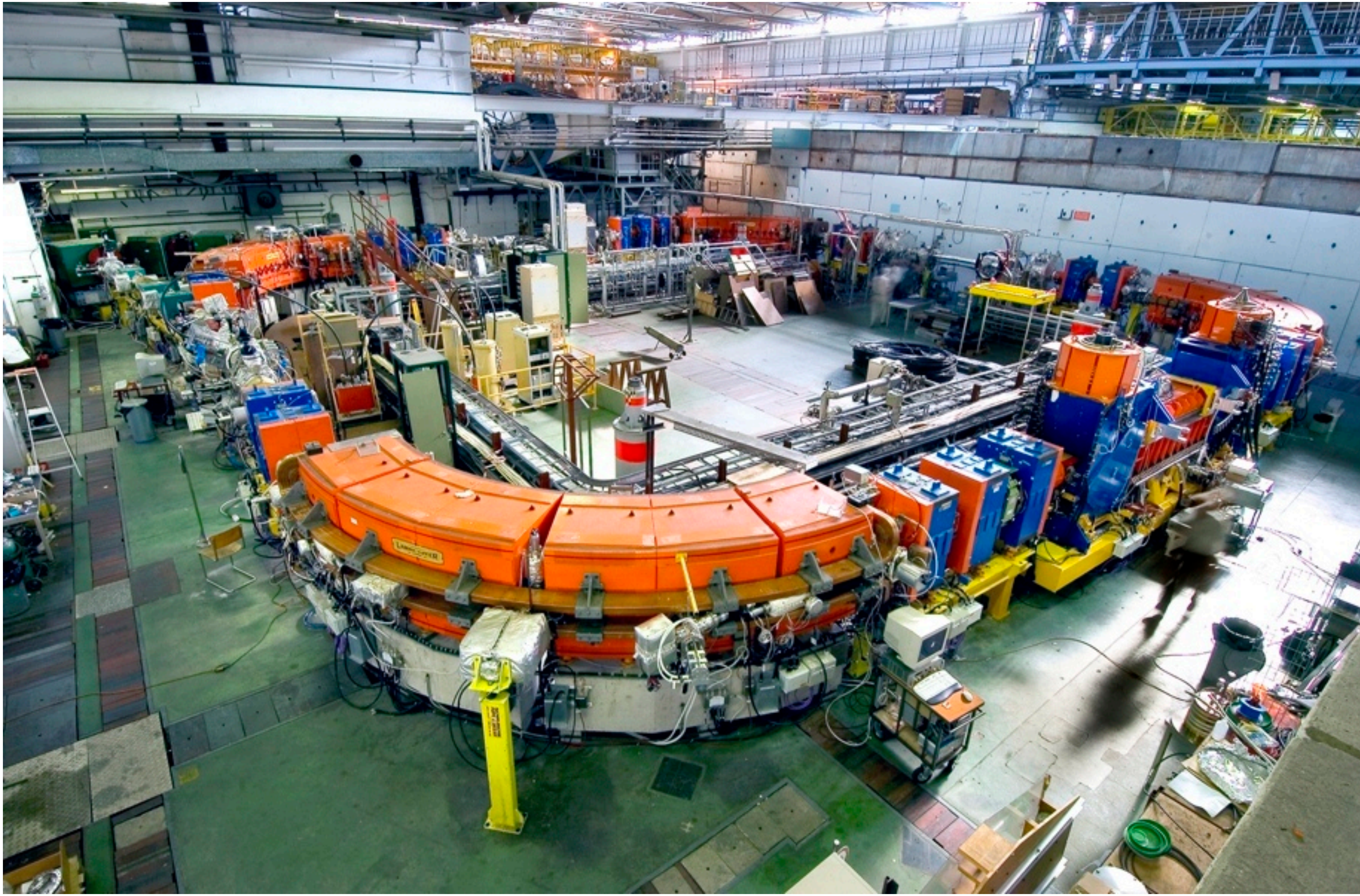




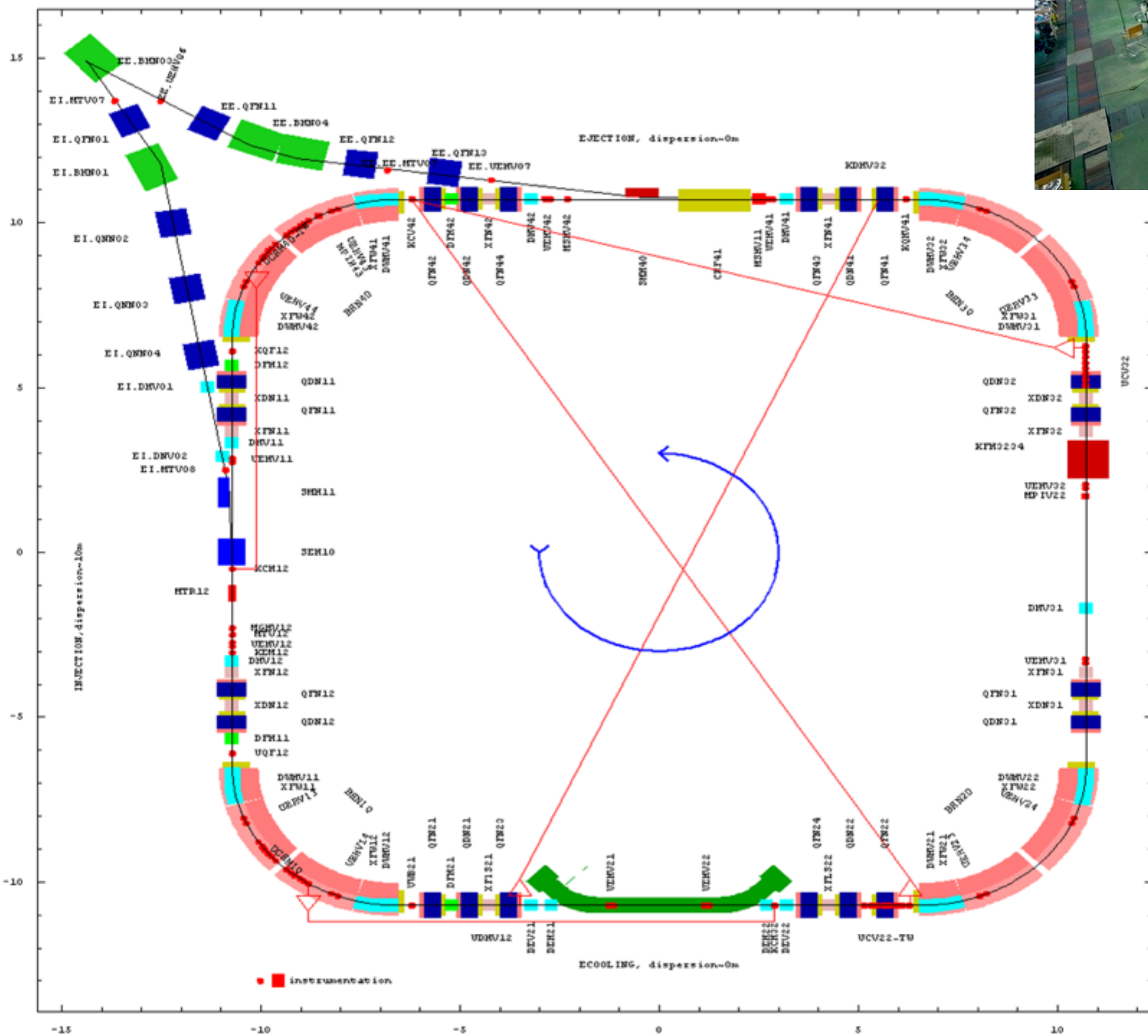
B field is focusing in one plane but defocusing in the other.

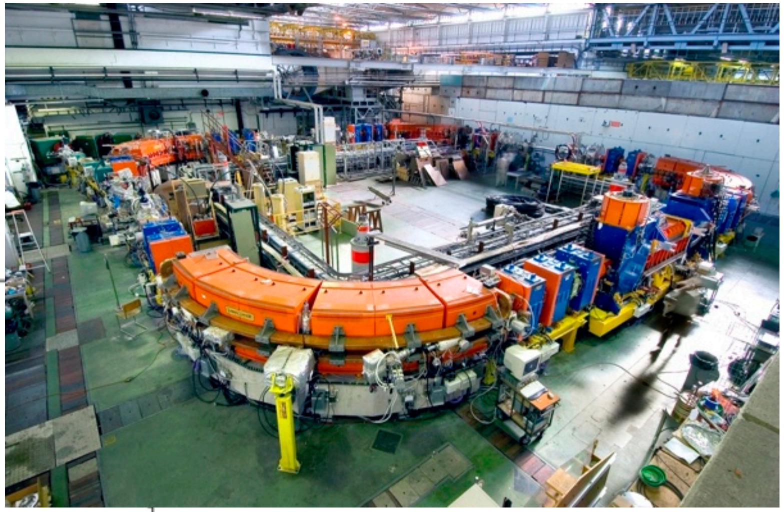
Typical lattice is FODO, focusing-drift-defocusing

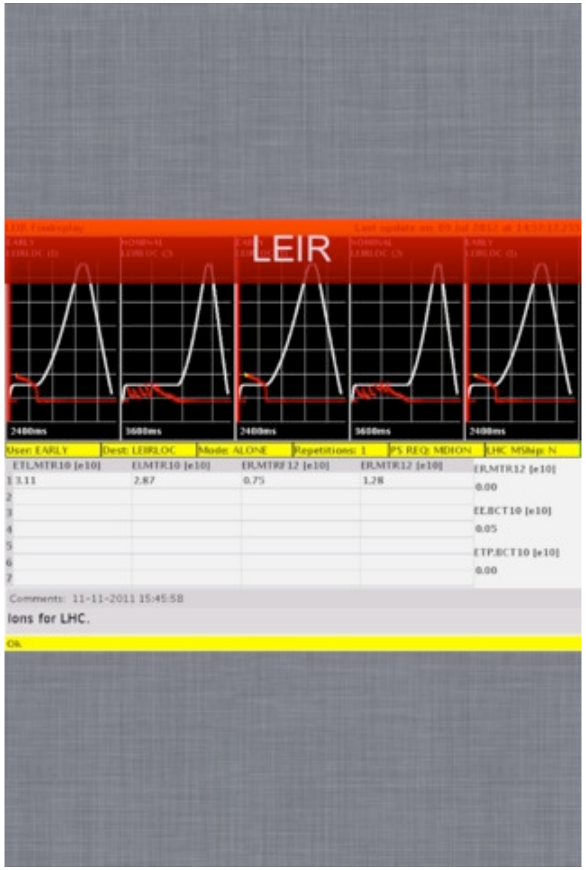
A synchrotron in a view: LEIR (Low Energy Ion Ring)



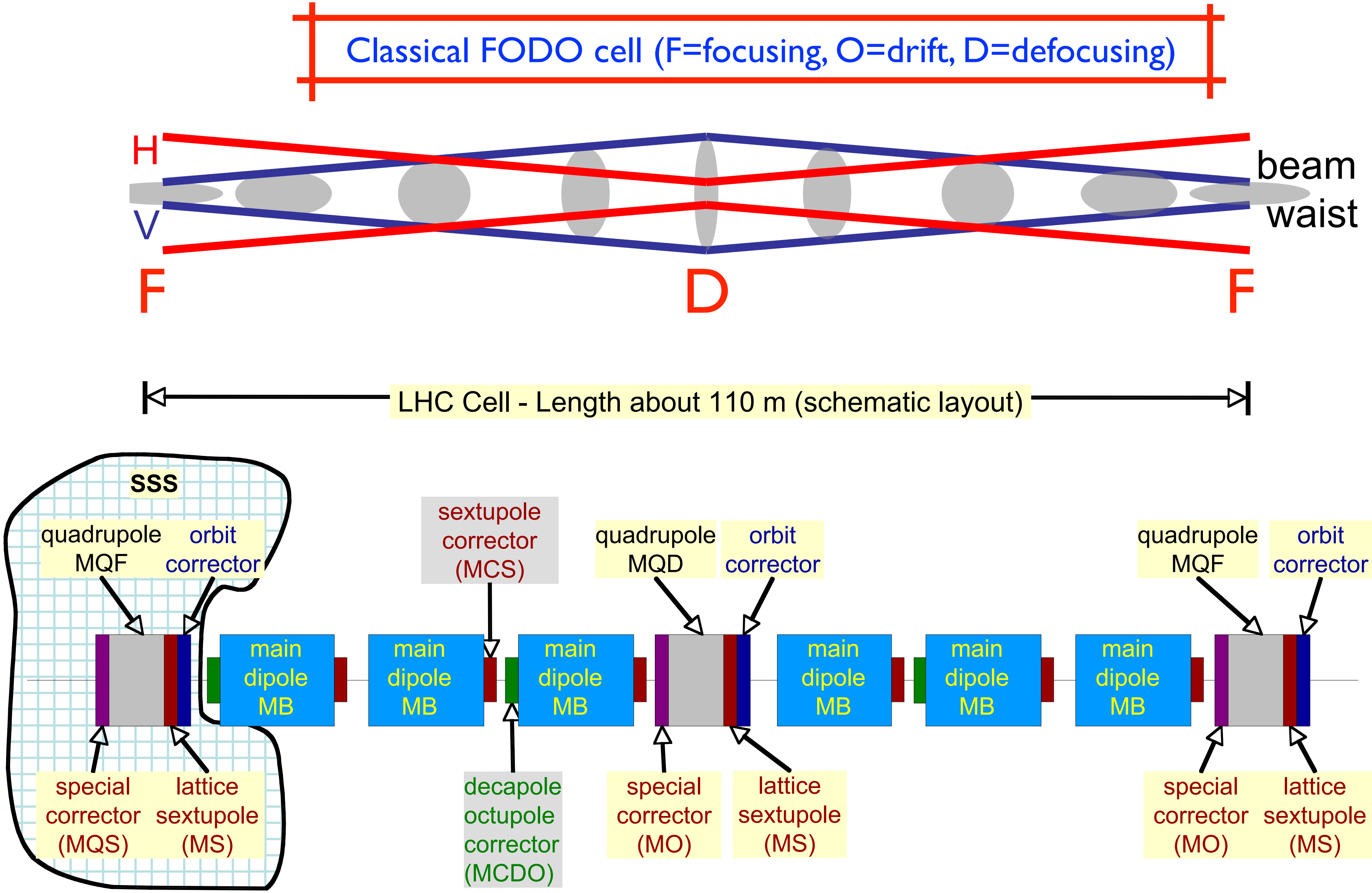
LEIR lattice







An example of a lattice: LHC cell

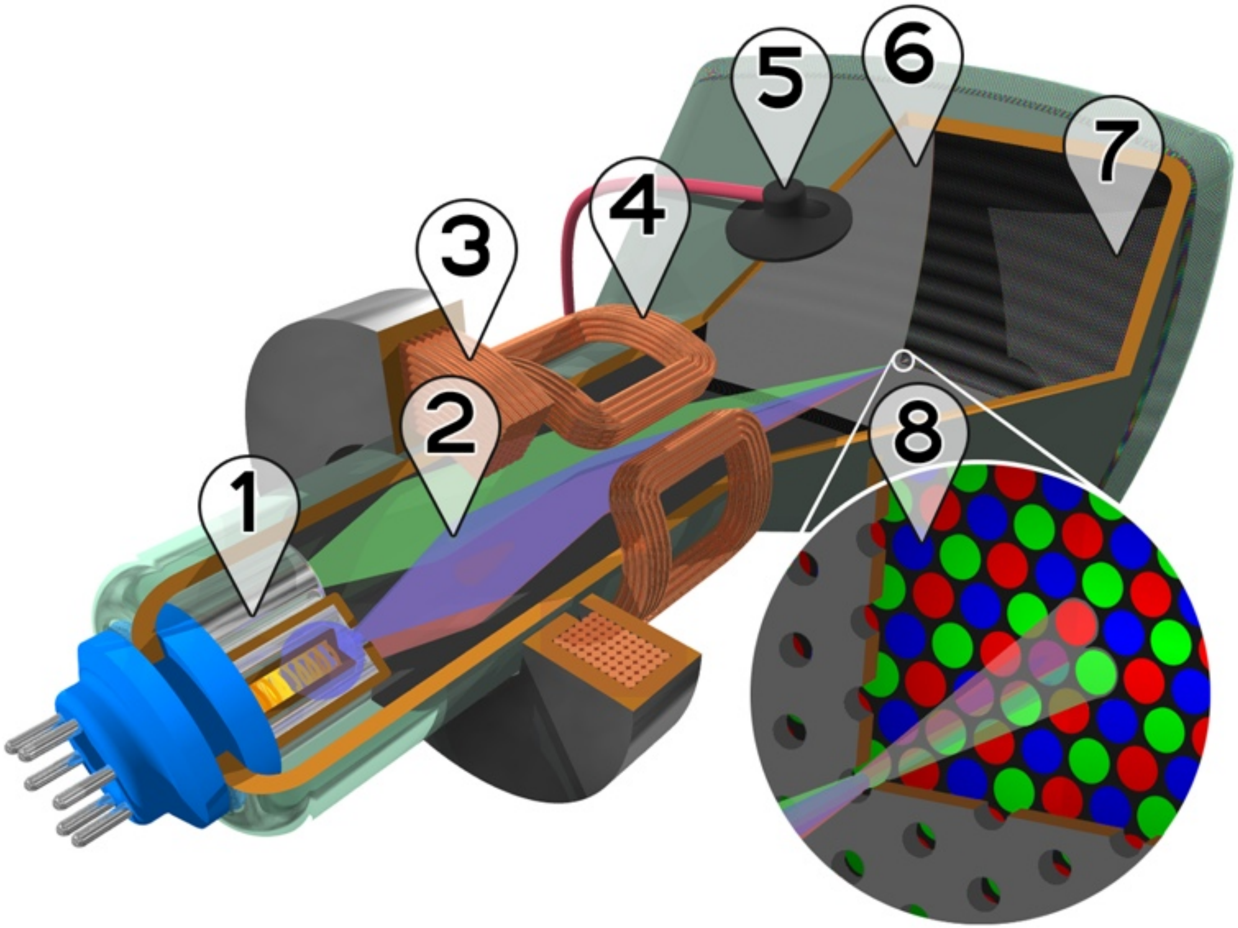


Apples vs Antiapples: protons vs antiprotons

Do protons fall in an accelerator?

And what about antiprotons?

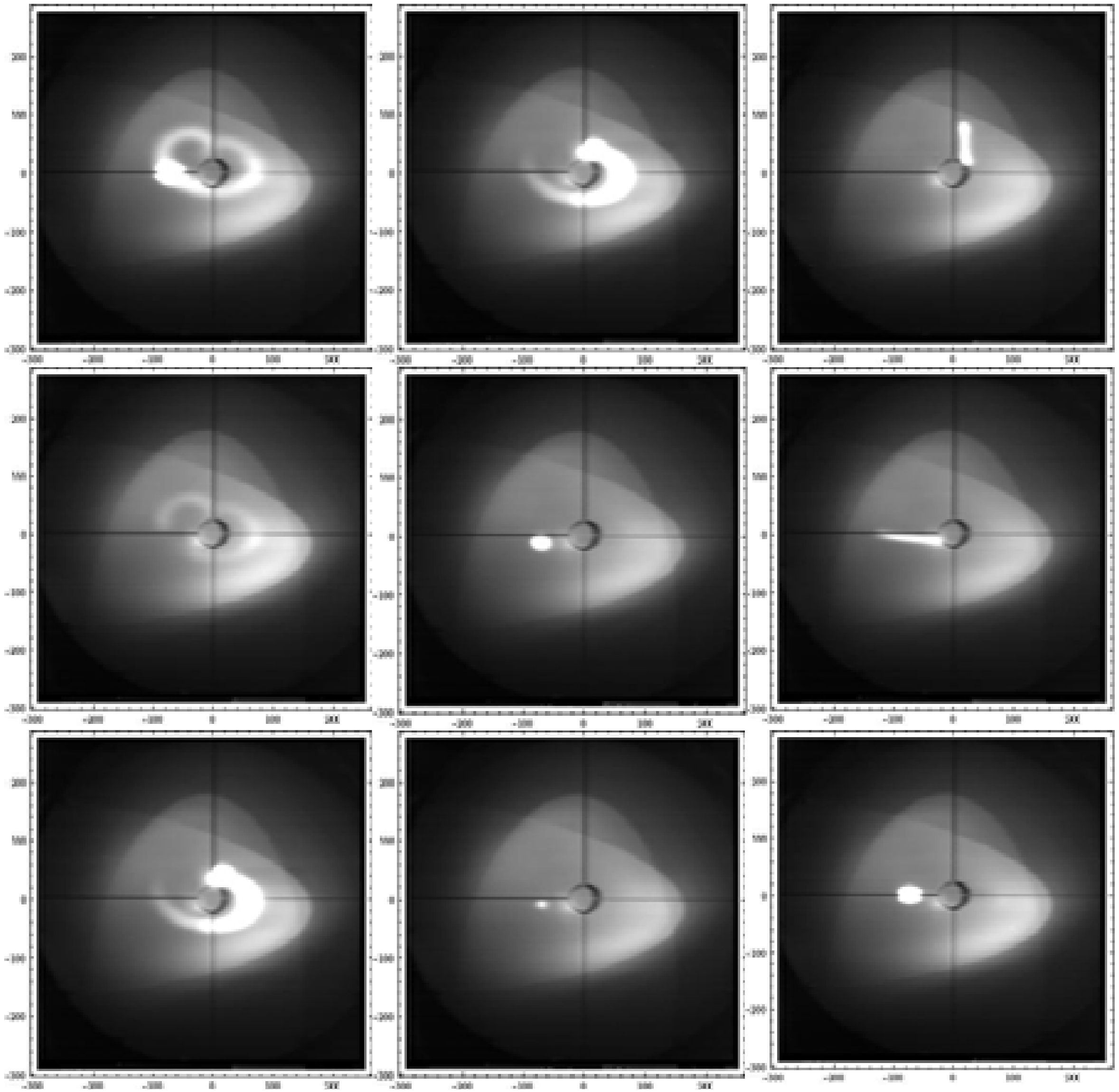
An accelerator that you know very well

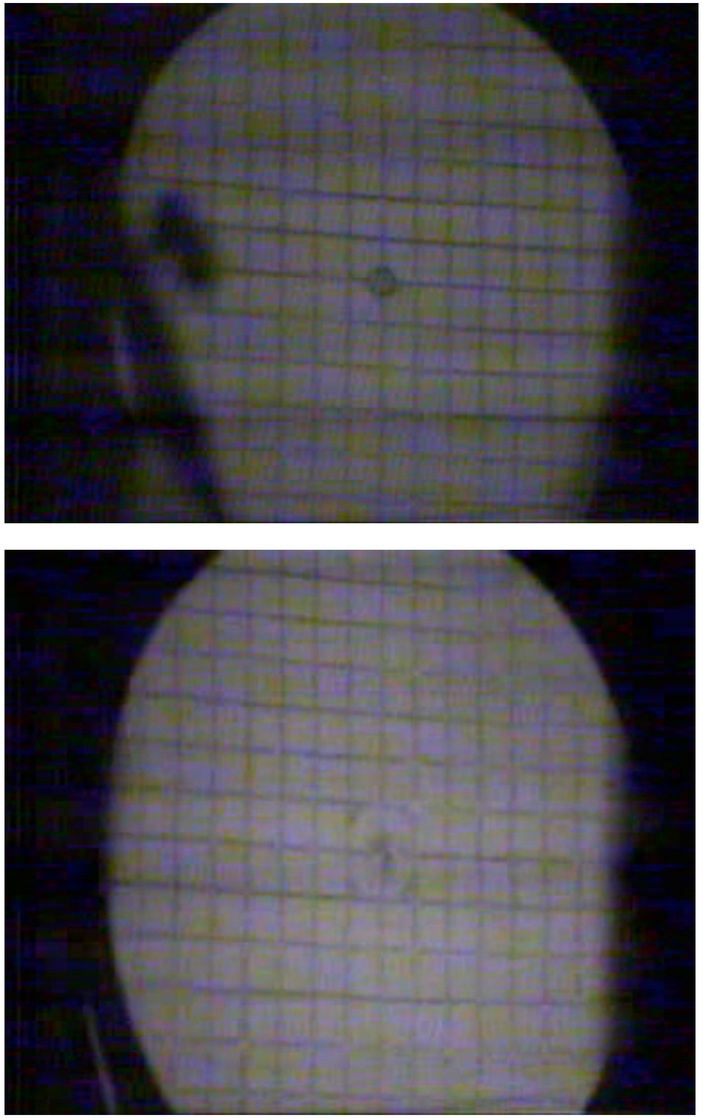


1. **Three Electron guns** (for red, green, and blue phosphor dots)
2. **Electron beams**
3. **Focusing coils**
4. **Deflection coils**
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the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

From Wikipedia

Real beam images



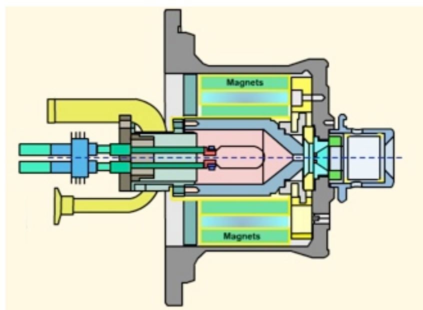


Courtesy of B. Goddard

[redacted]

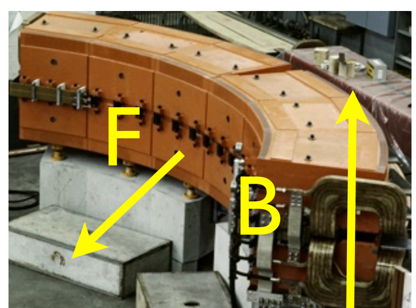
Summary: Building Blocks of an accelerator

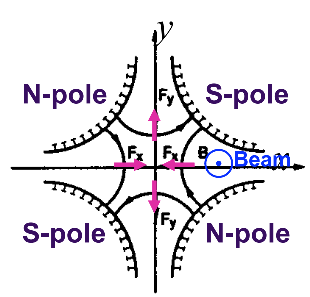
1) A particle source

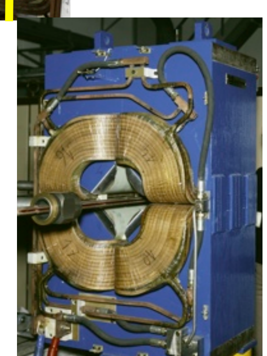


2) An accelerating system

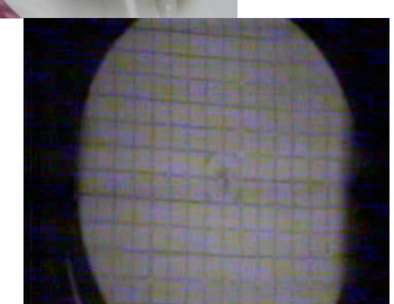
3) A series of guiding and focusing devices







Everything under vacuum



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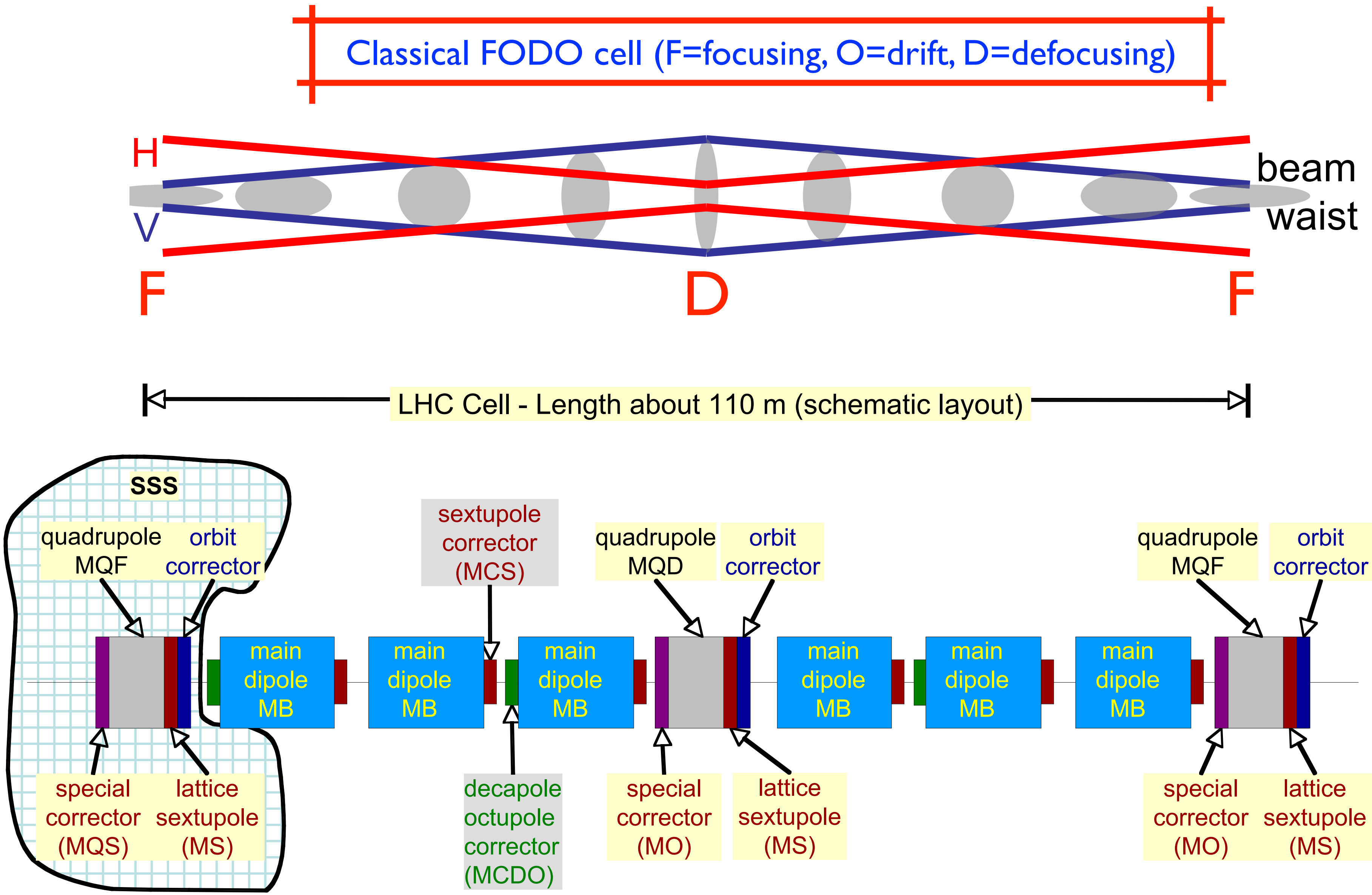
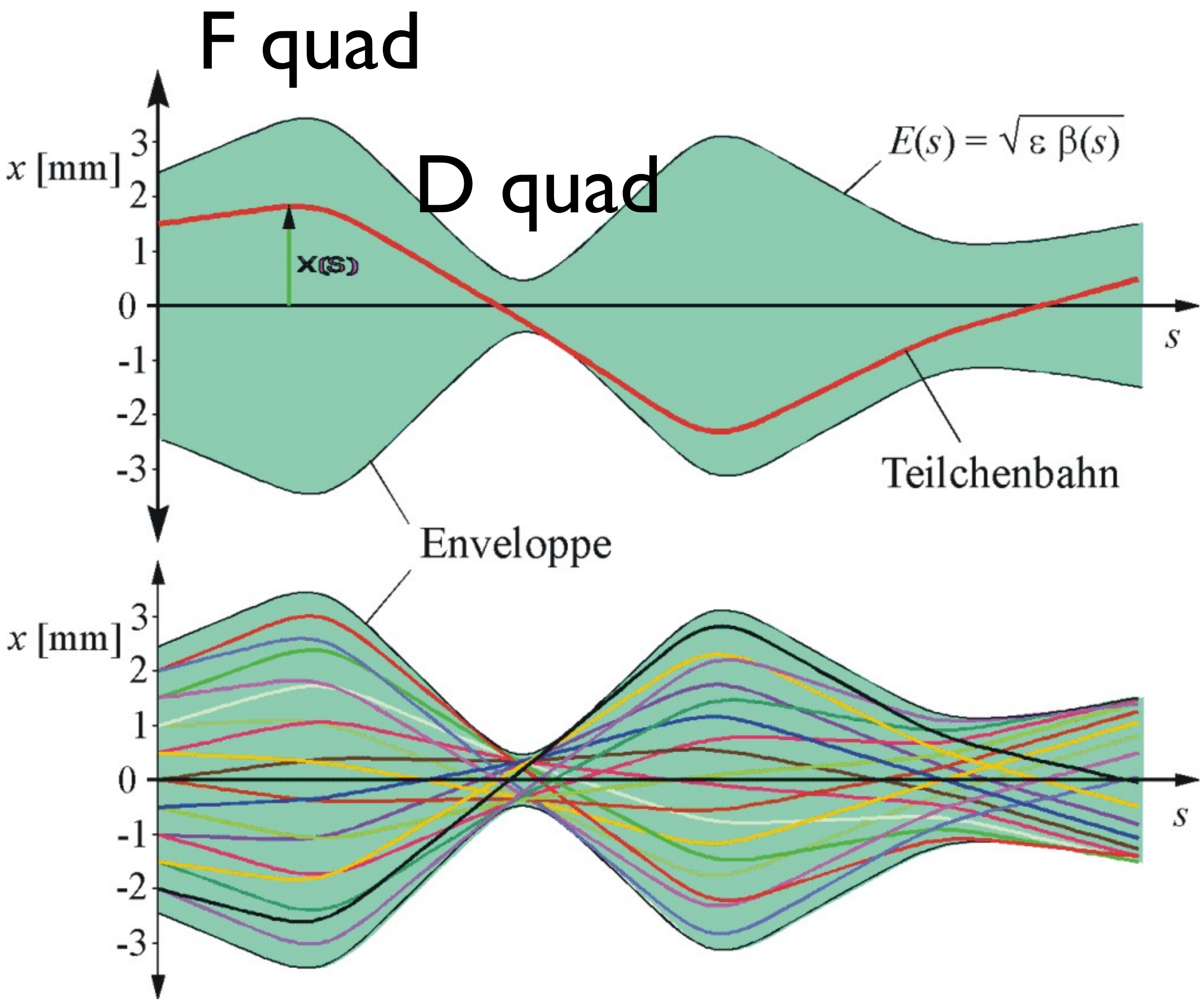


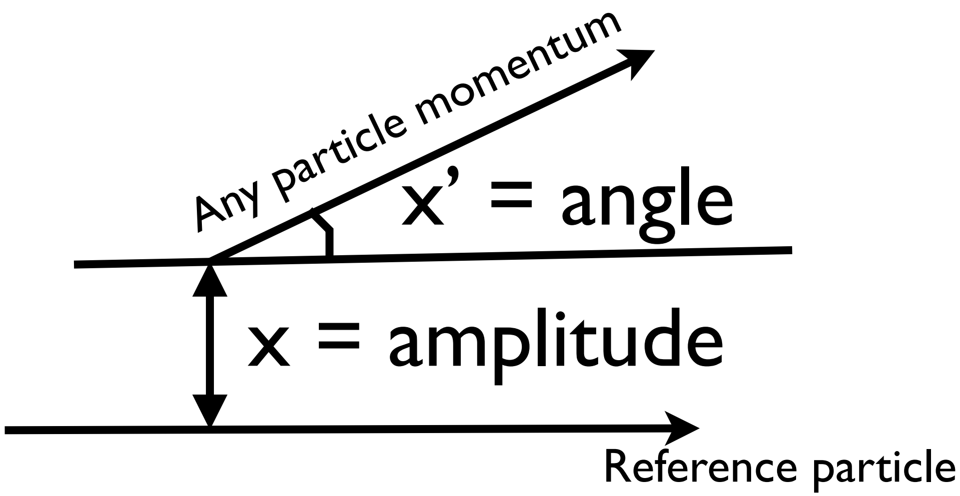
Definition of envelope

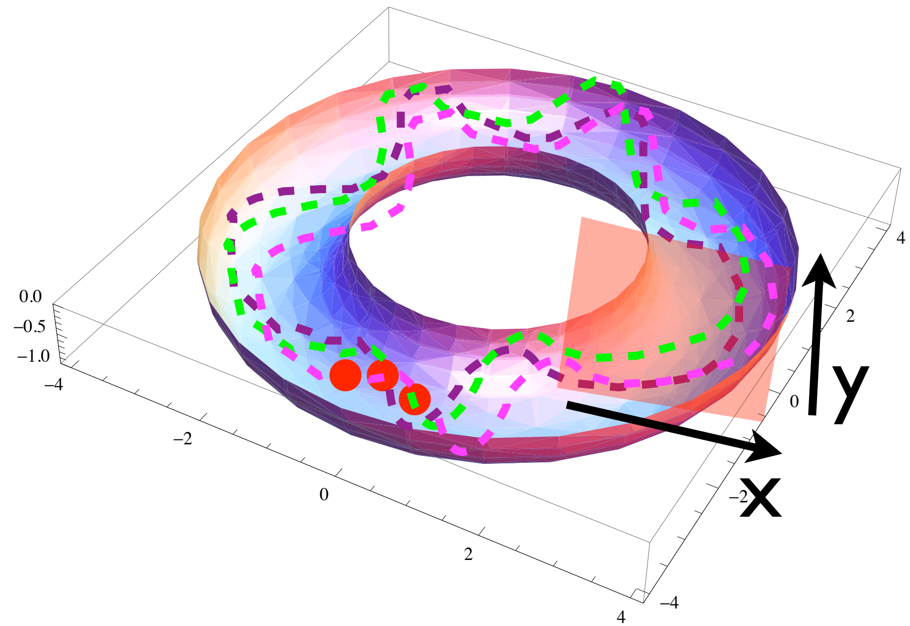
Beam physical dimension

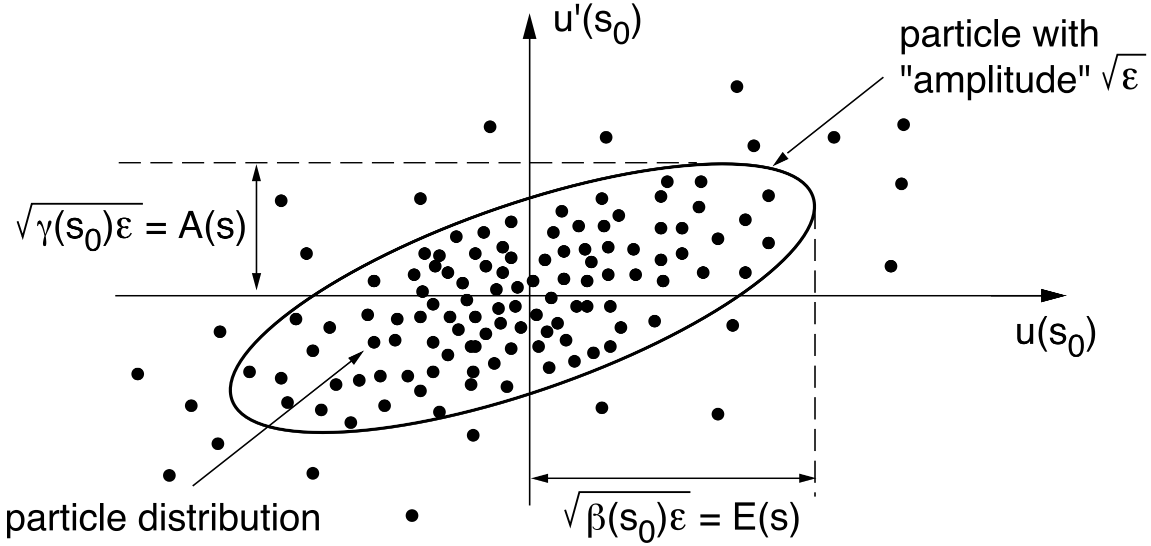


The envelope is defined as the maximum amplitude for which the particle remains in the machine vacuum chamber.

Our reference frame: xx', the phase space

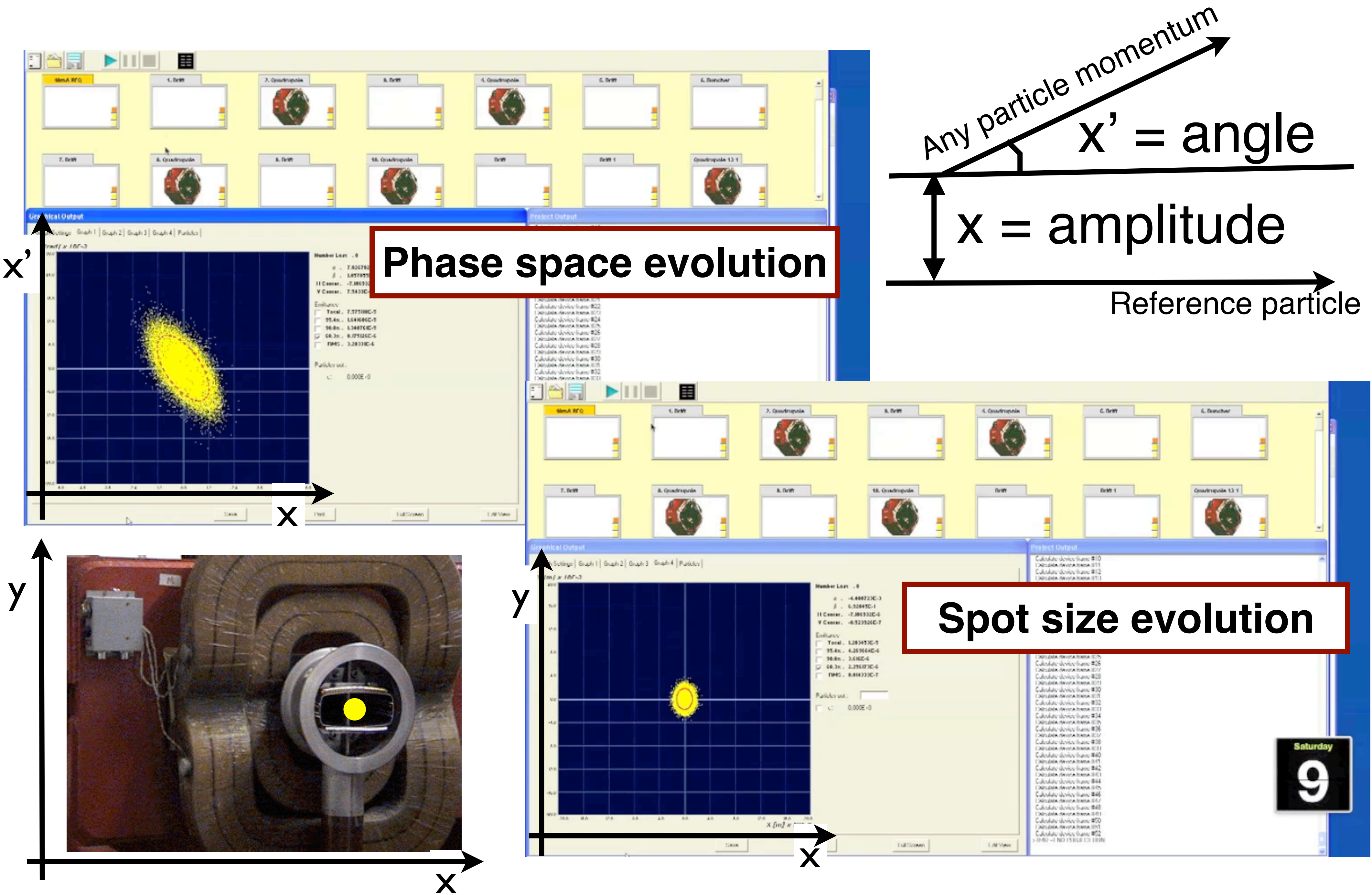






The space occupied in the xx' (or yy') plane by the beam at a given position in the machine is defined as Emittance

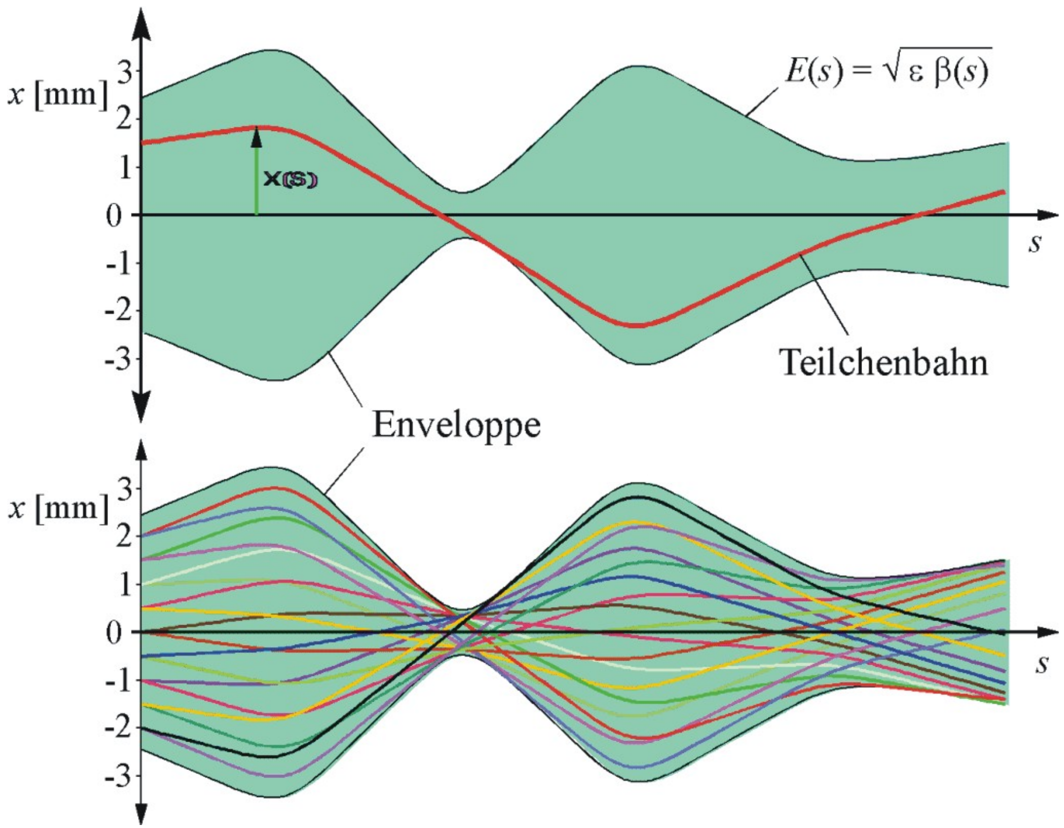
Particle transport in a lattice

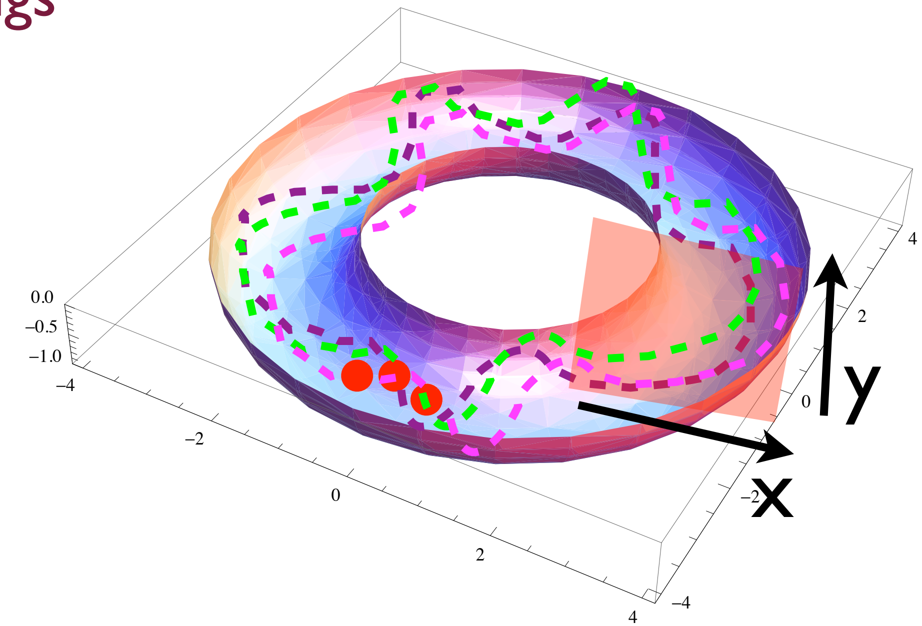


Tune

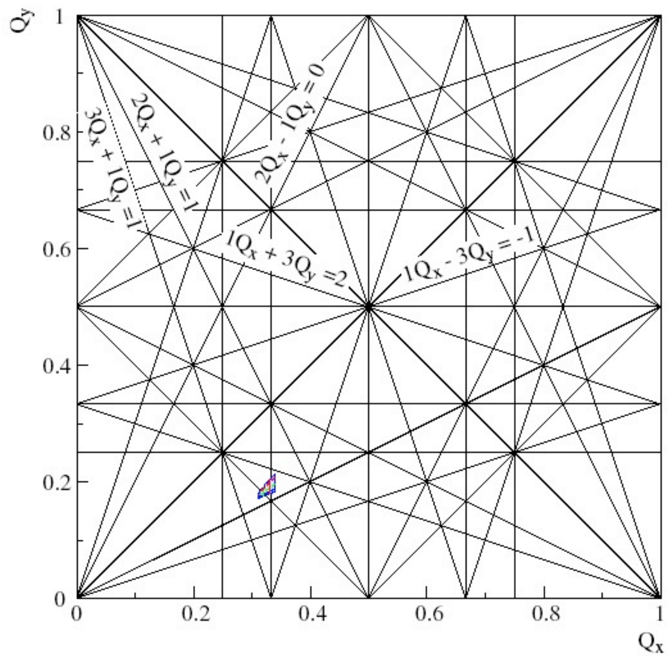
Tune: number of oscillations (called betatronic) in the xx' plane a particle does in one machine turn.

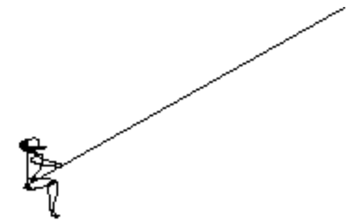
The tune depends on the quadrupole settings

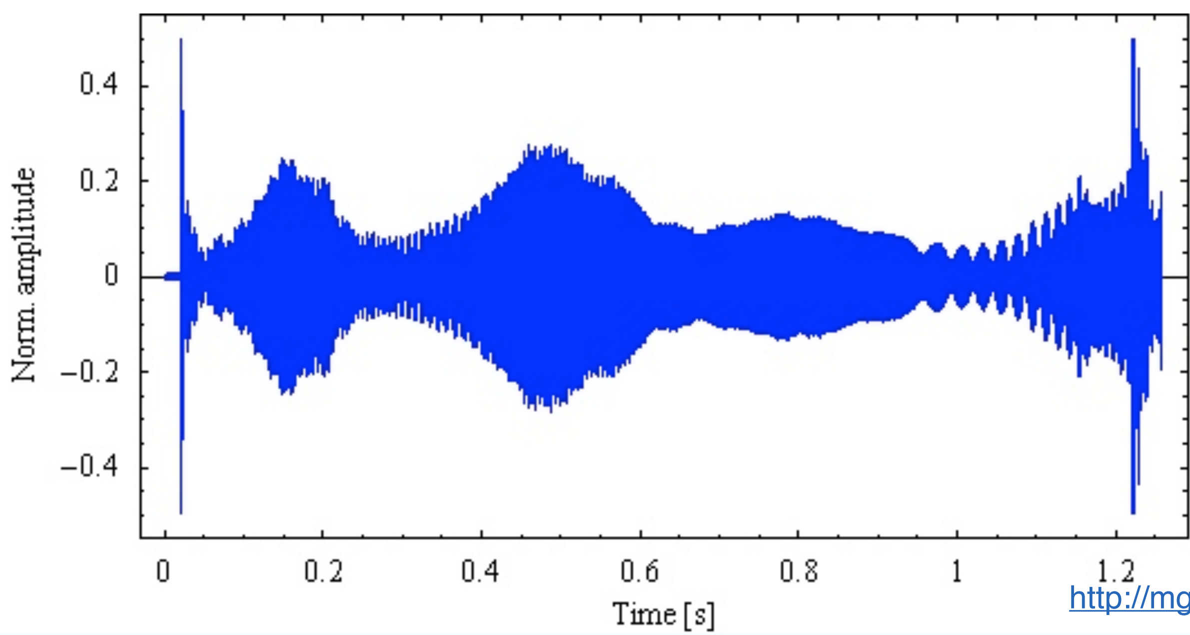


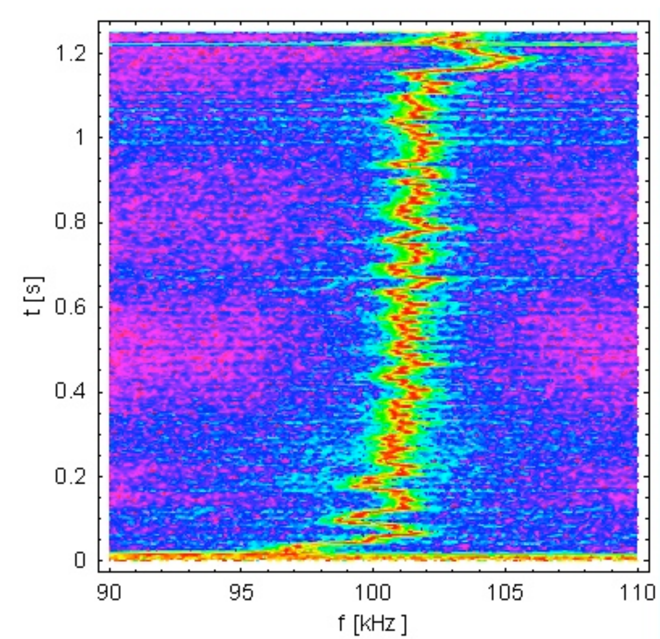


Tune: number of betatron oscillation in the transverse plane







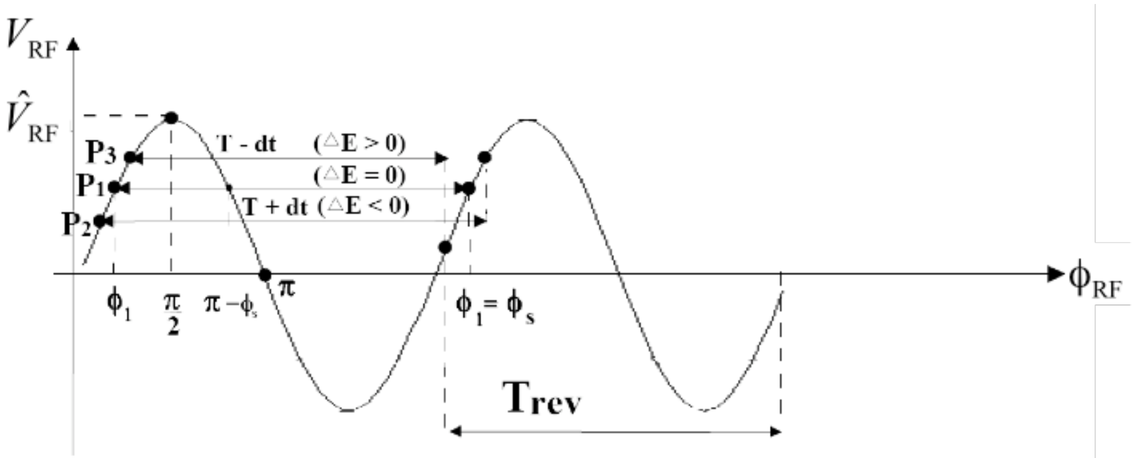


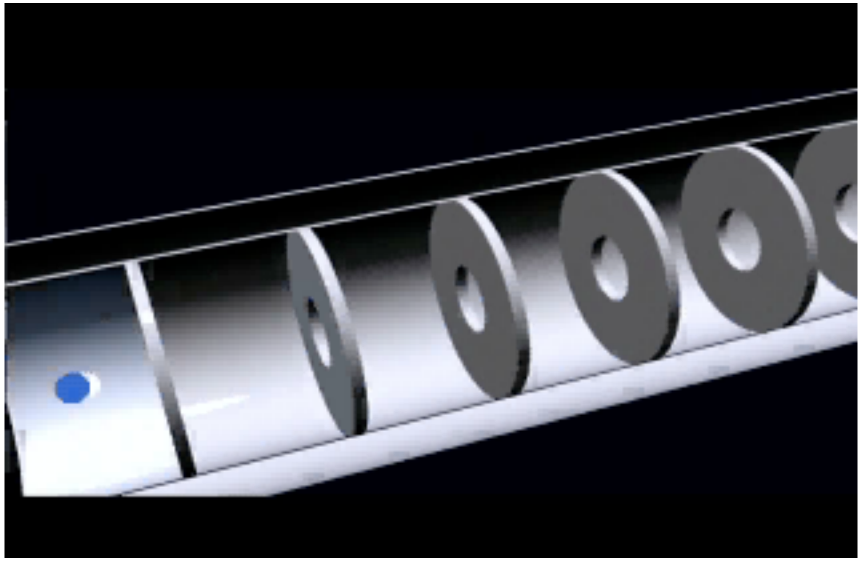
http://mgasior.web.cern.ch/mgasior/pro/3D-BBQ/ps.html

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.**

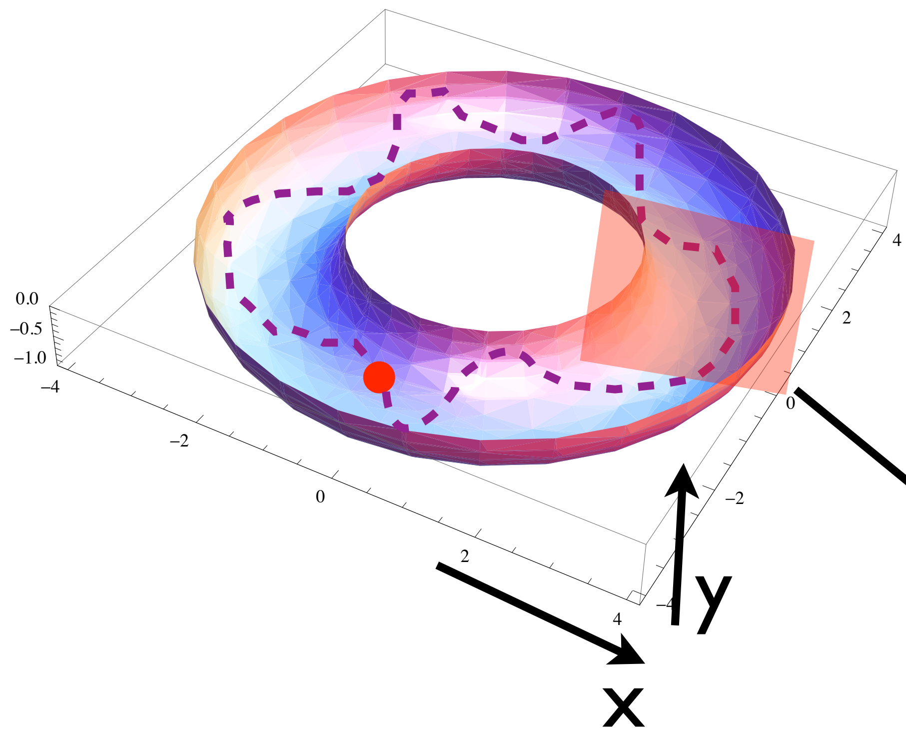
$$\Rightarrow \Delta E_1 = e\,\hat{V}_{RF}\,\sin\phi_1$$

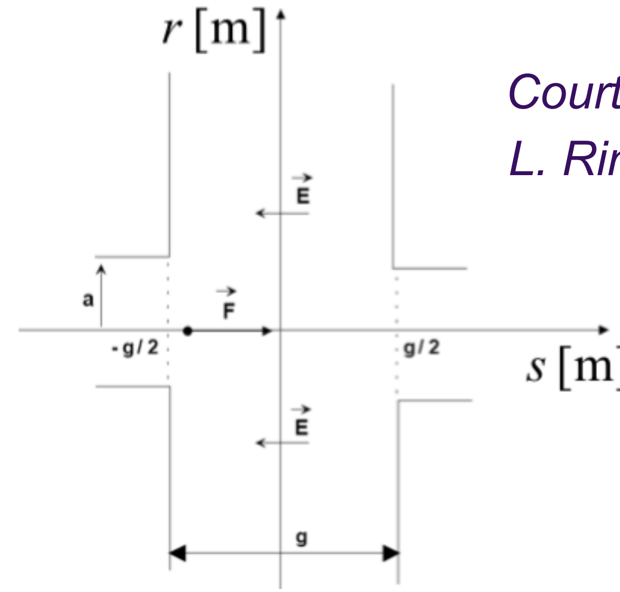




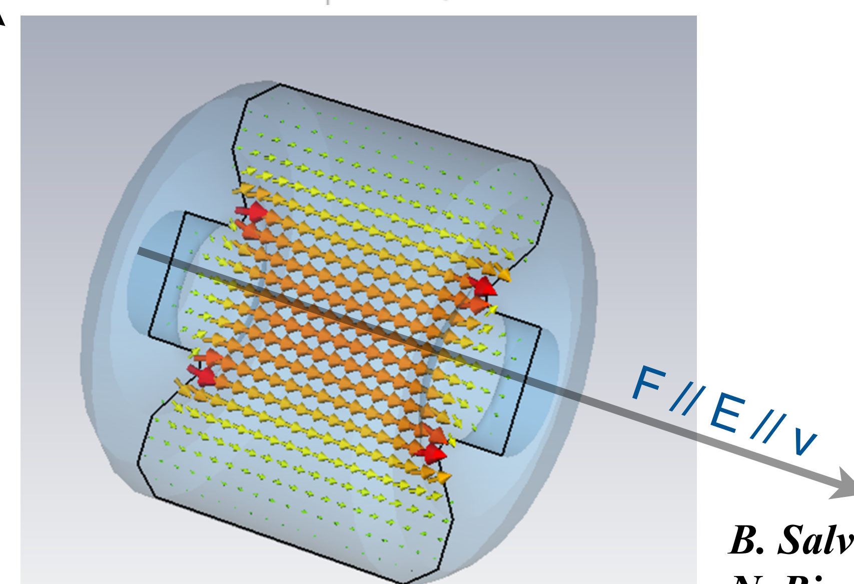
Acceleration I

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



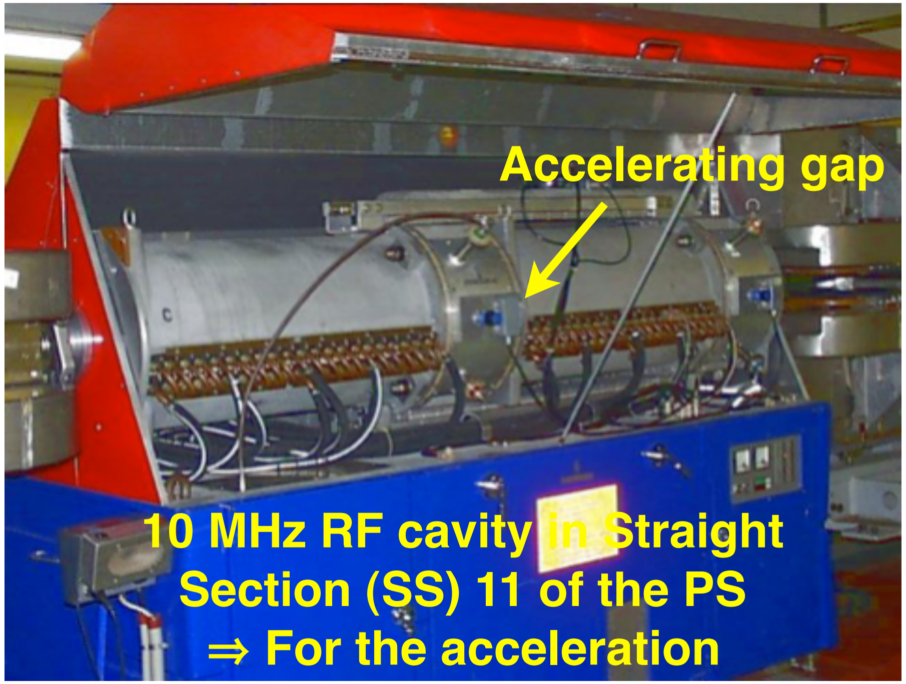
B. Salvant N. Biancacci

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

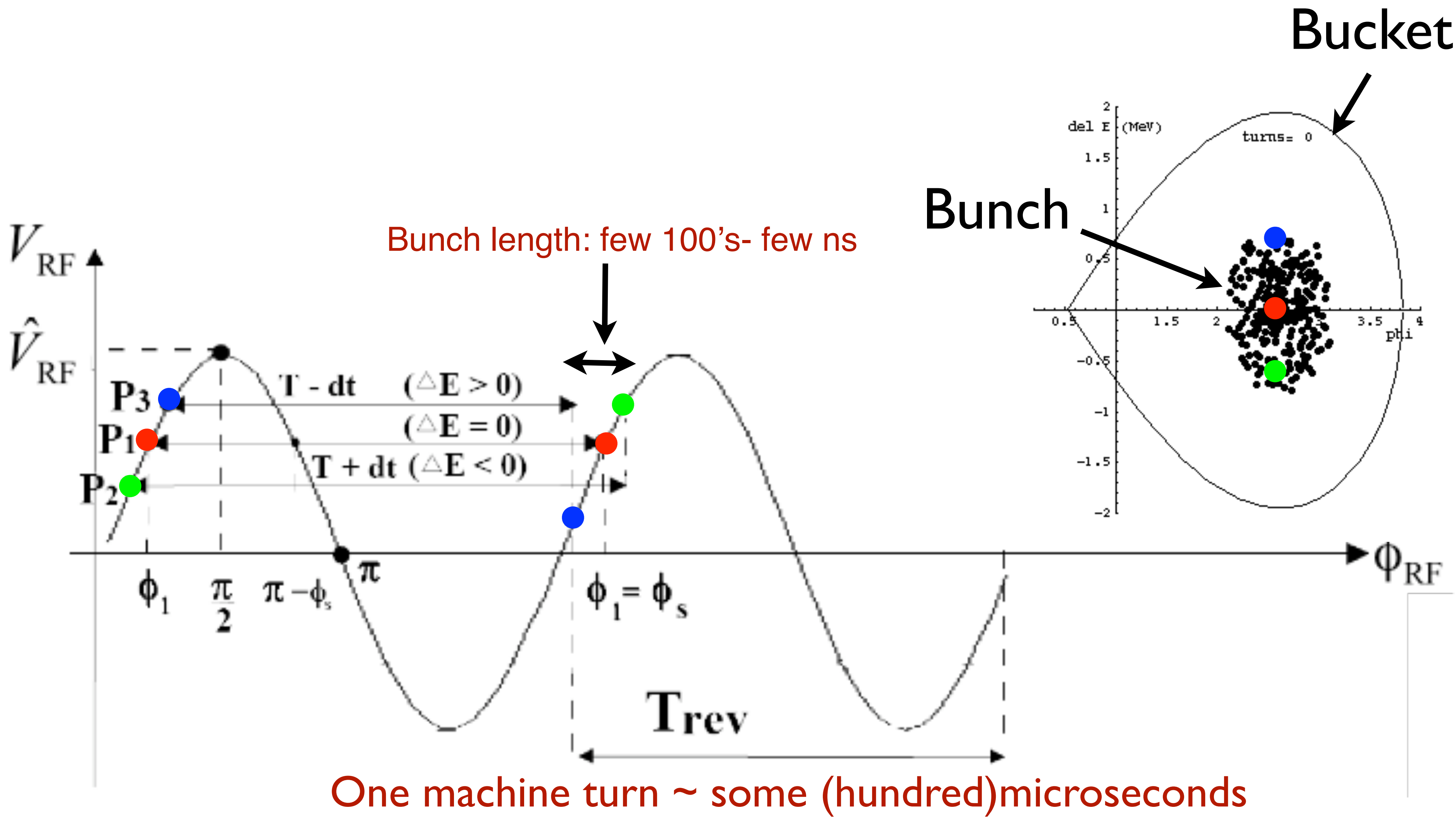
The dimension of the cavity changes with the RF wave length



World Radio Switzerland: 88.4 MHz

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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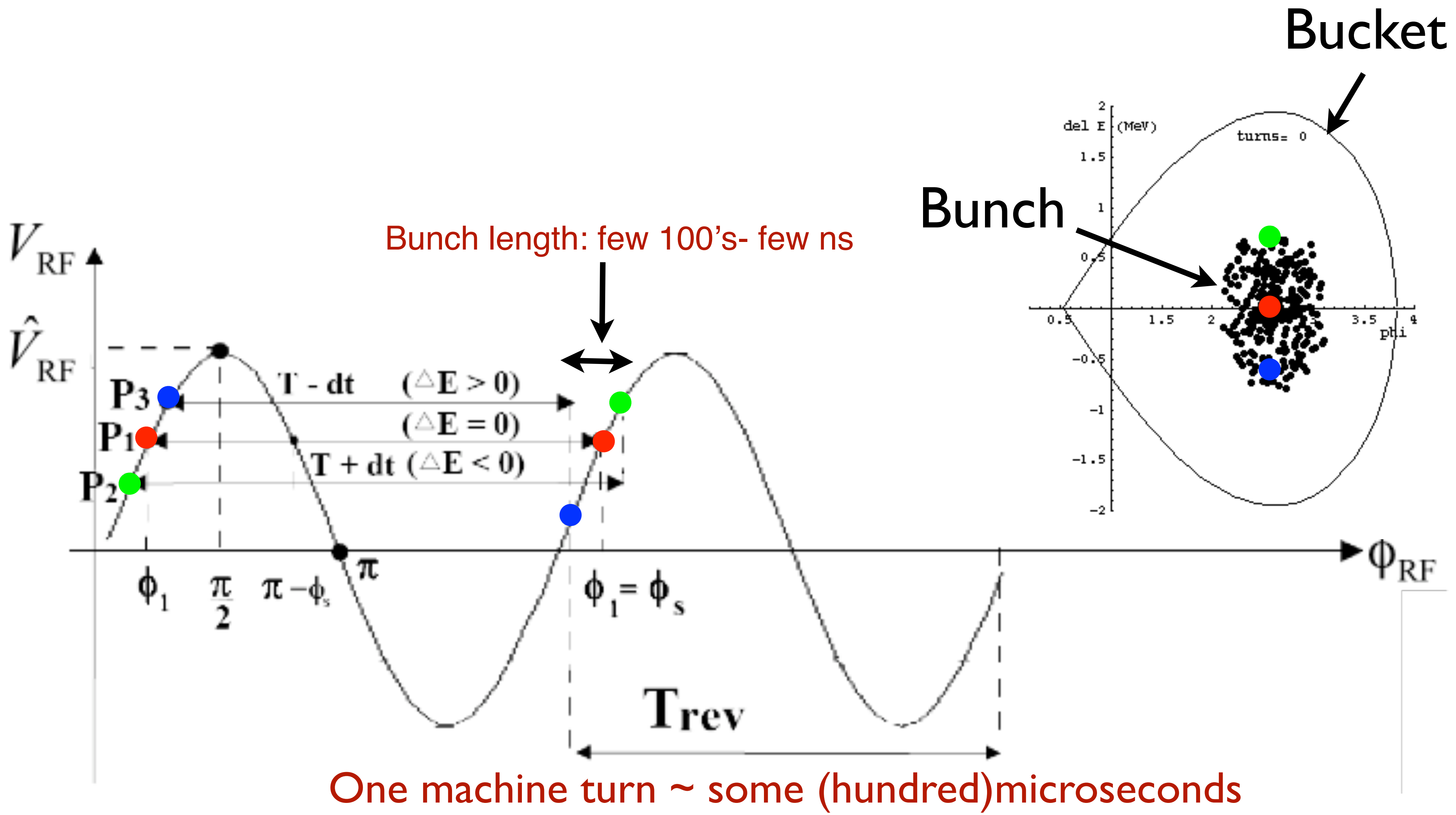
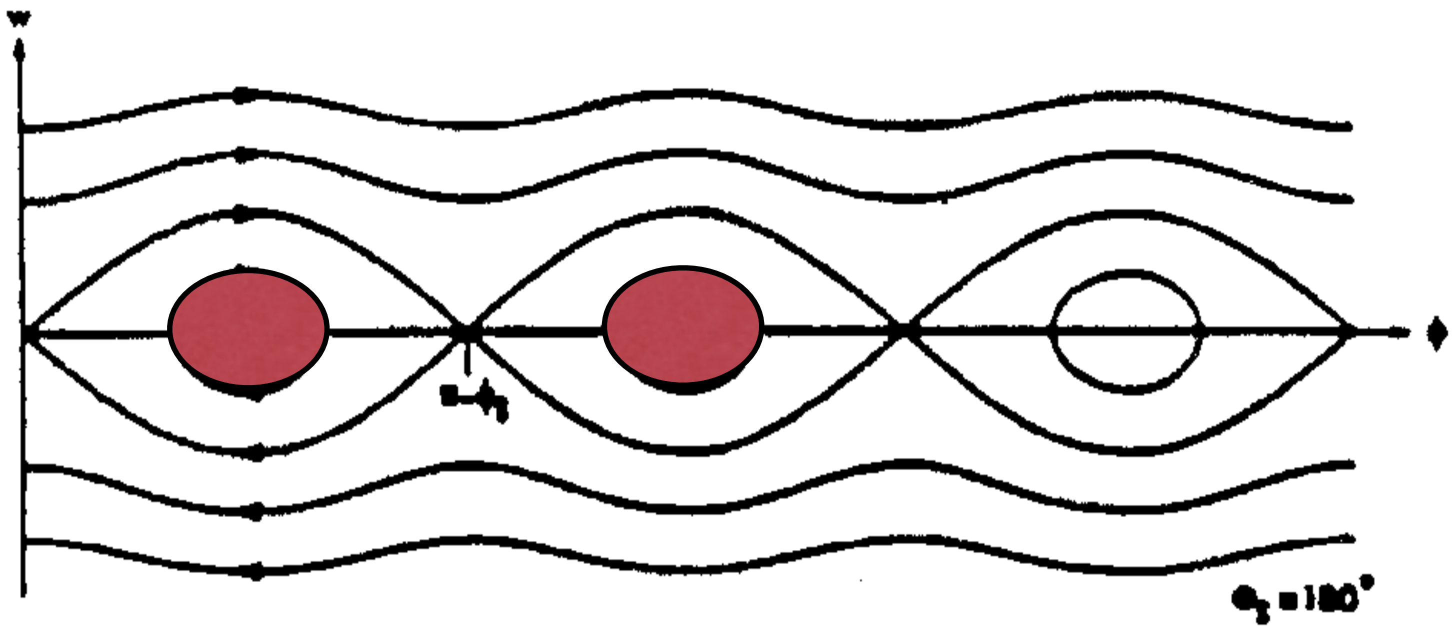


A chain of buckets



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 ?

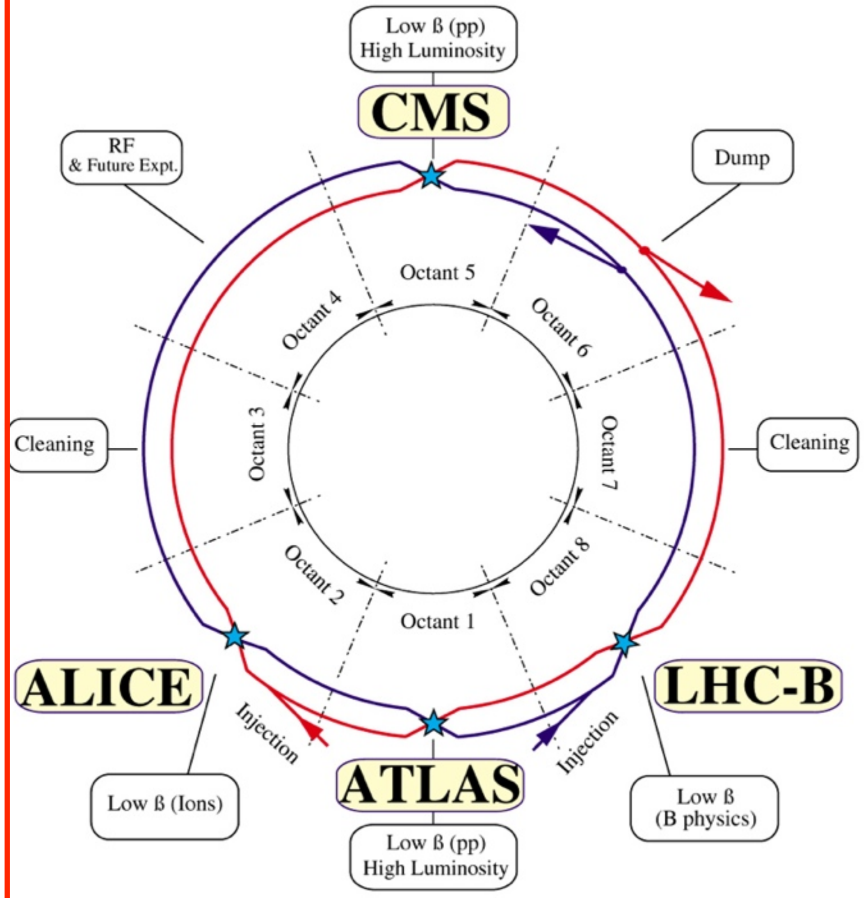
LHC: Large Hadron Collider

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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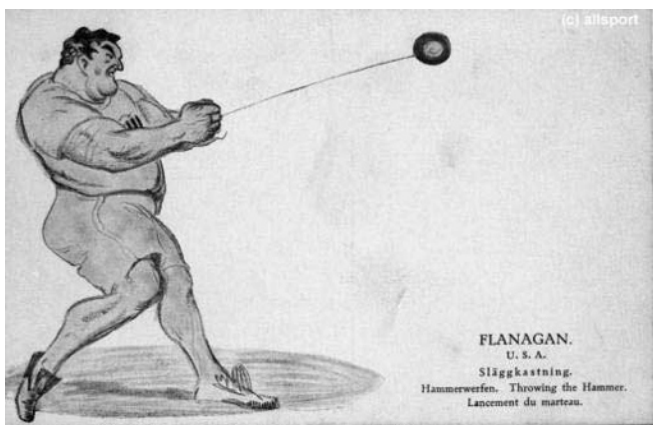
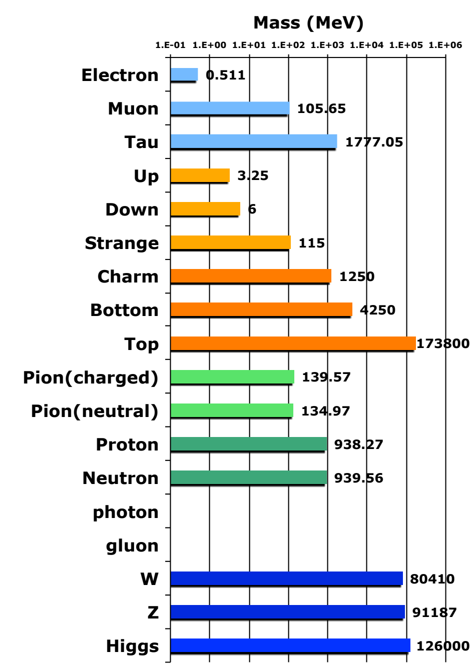
Limited by technology

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

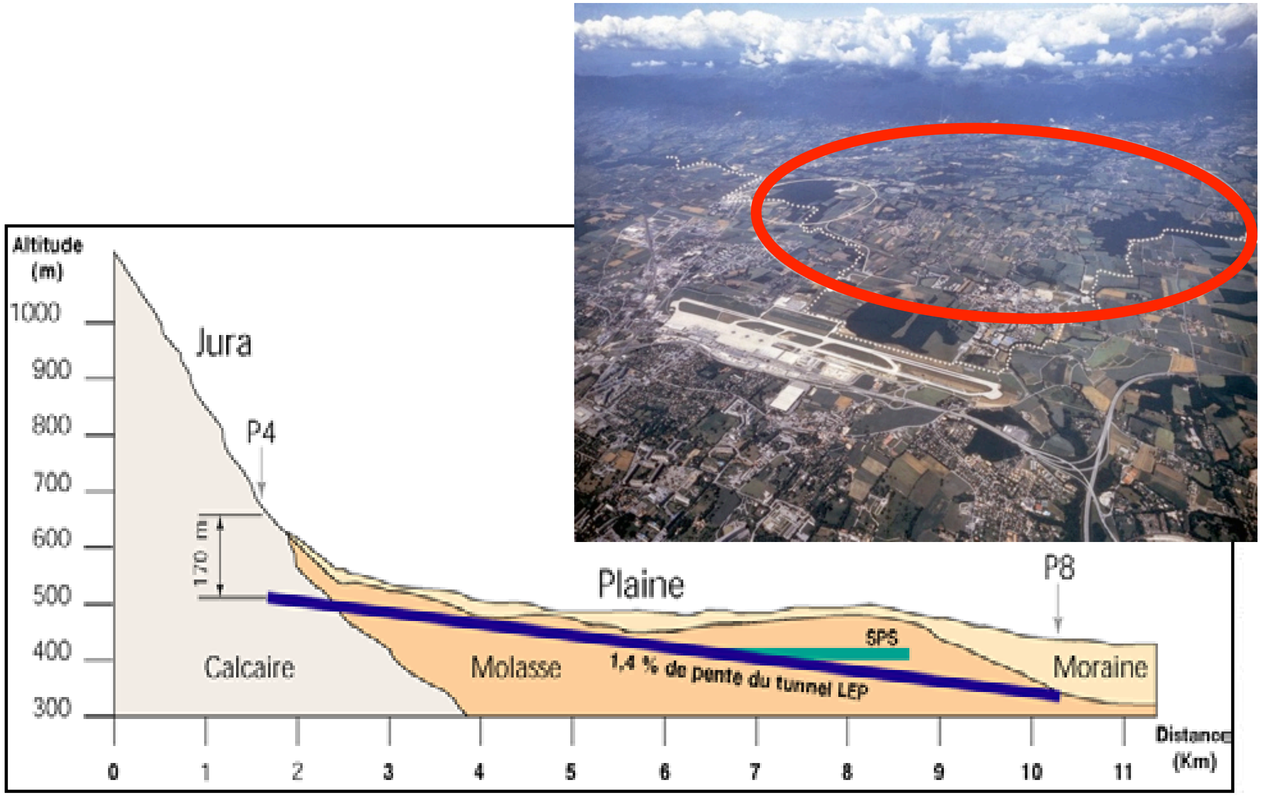


Radius: limited by cost,
and by the radius of the earth...



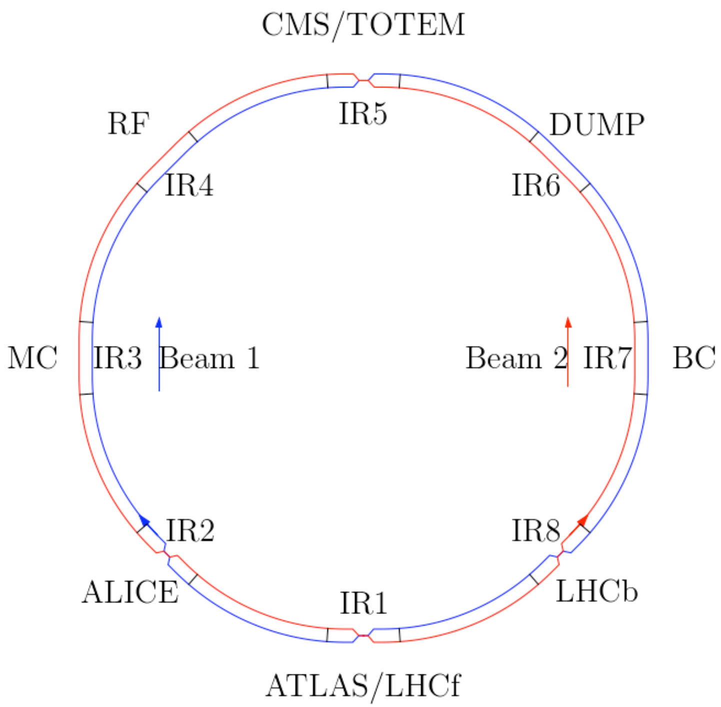
Given by the physics
This will depend on the mass of the particles we want to discover

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%



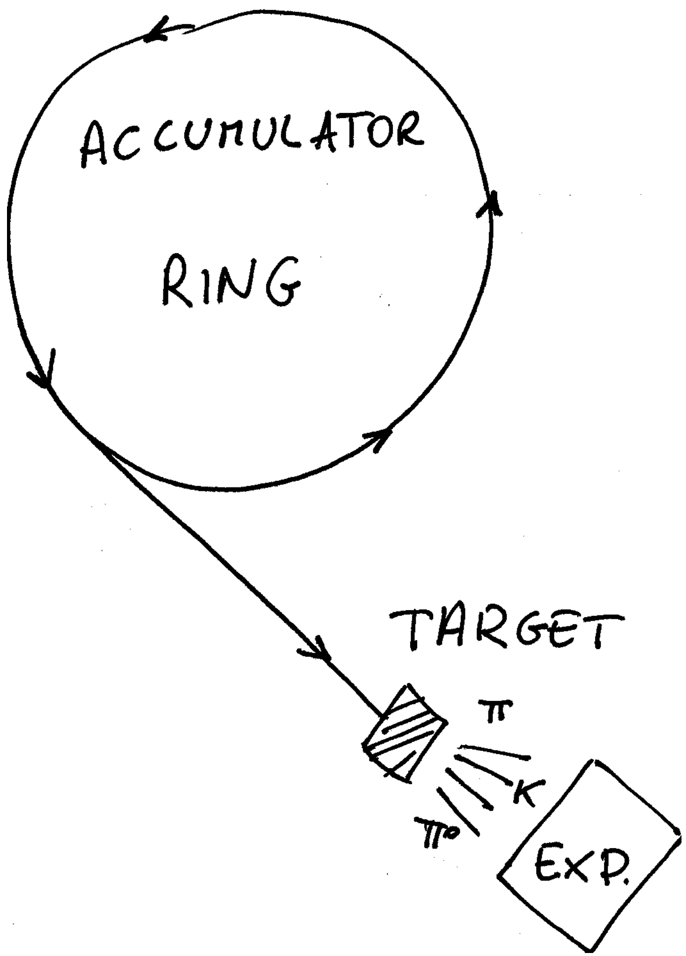
LHC: 8 independent sectors

8 straight sections

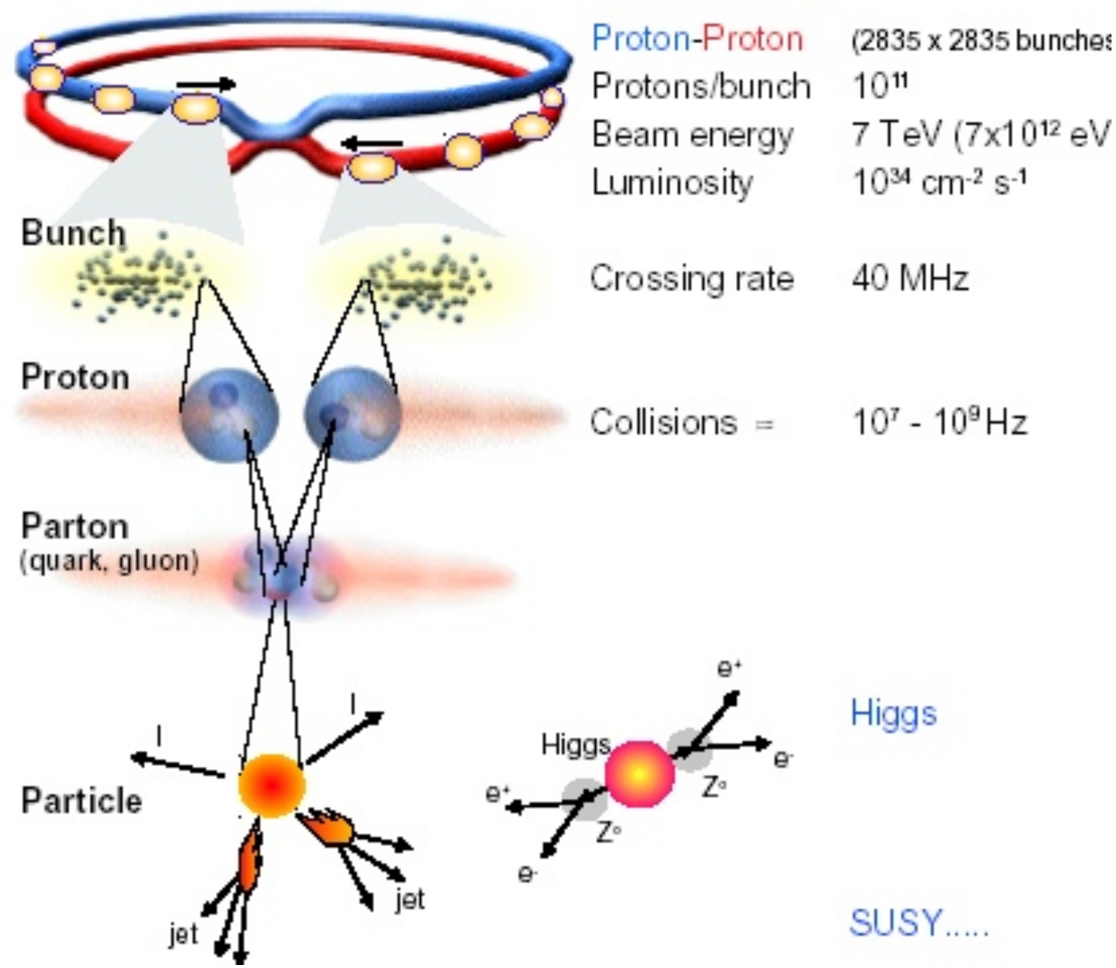
8 arcs

Different approaches: fixed target vs collider

Fixed target



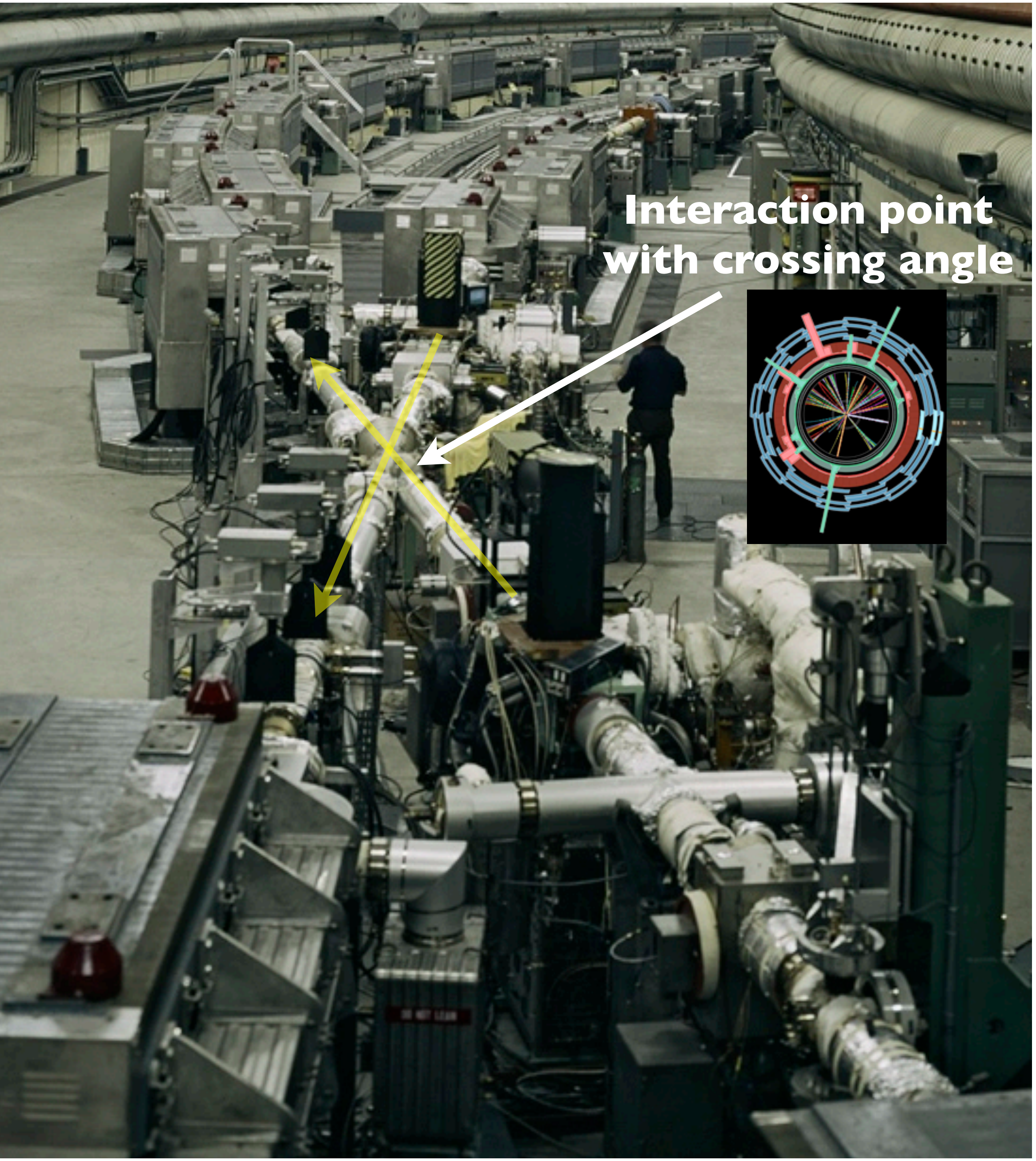
Storage ring/collider

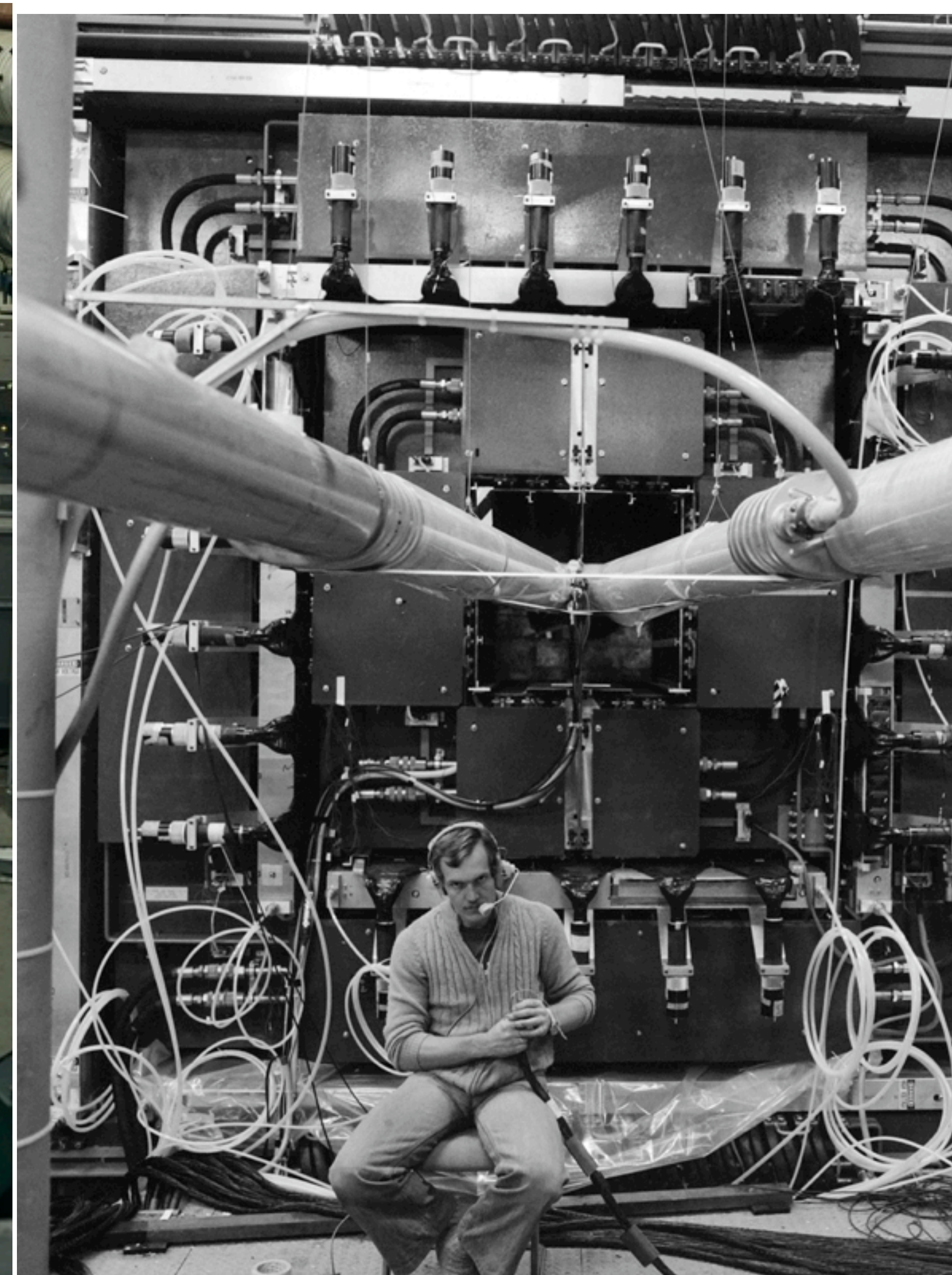


$$E_{CM} = \sqrt{2\left(E_{beam} mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

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

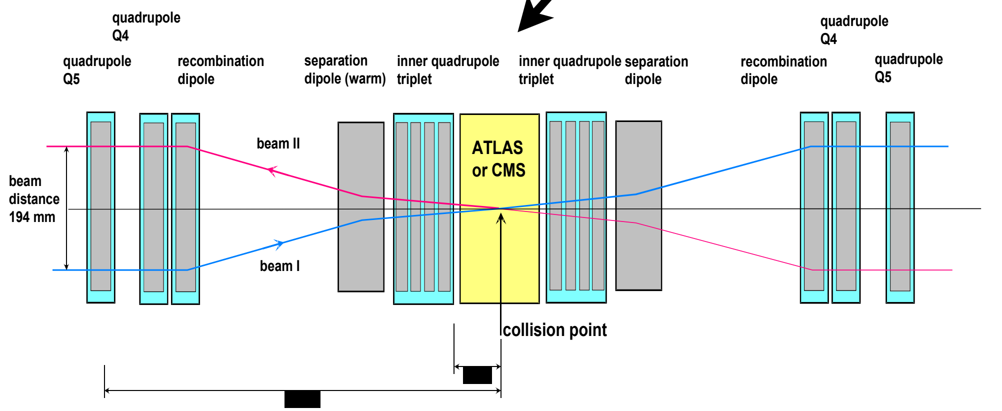
ISR: first proton-proton collider



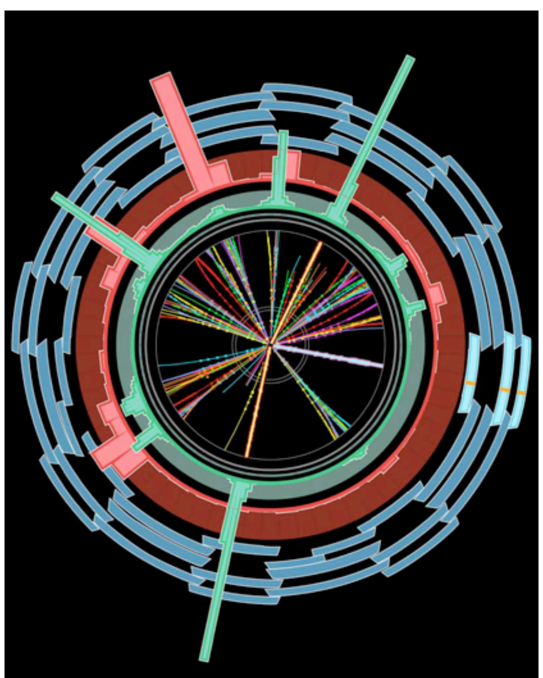


Luminosity

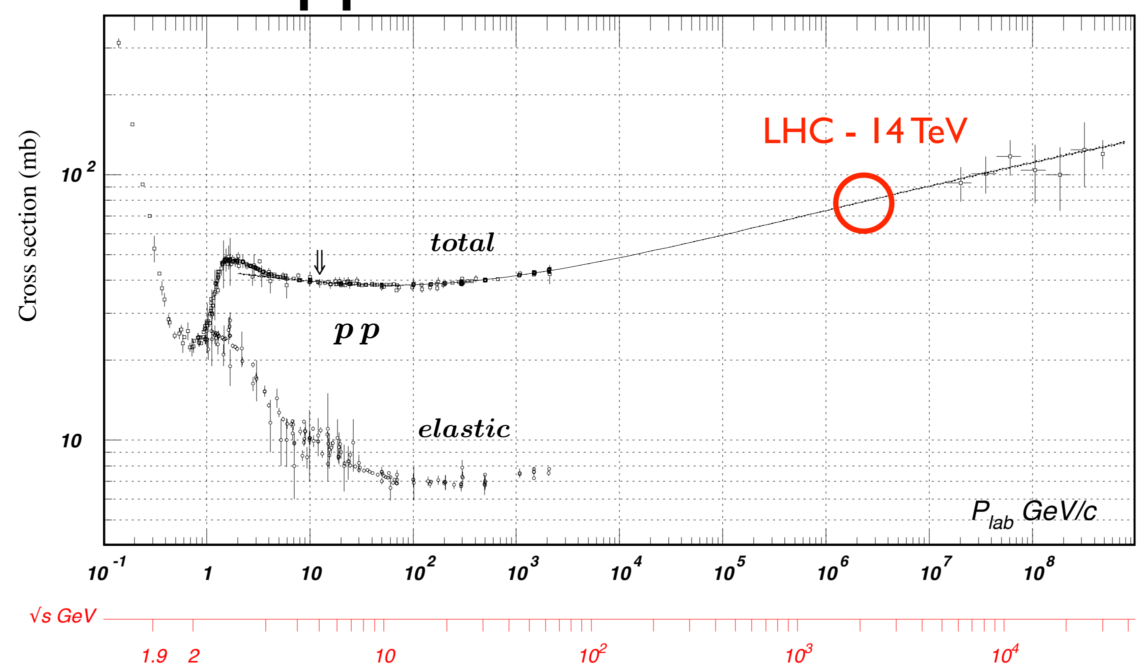
$$N_{event} = L\sigma_{event}$$



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

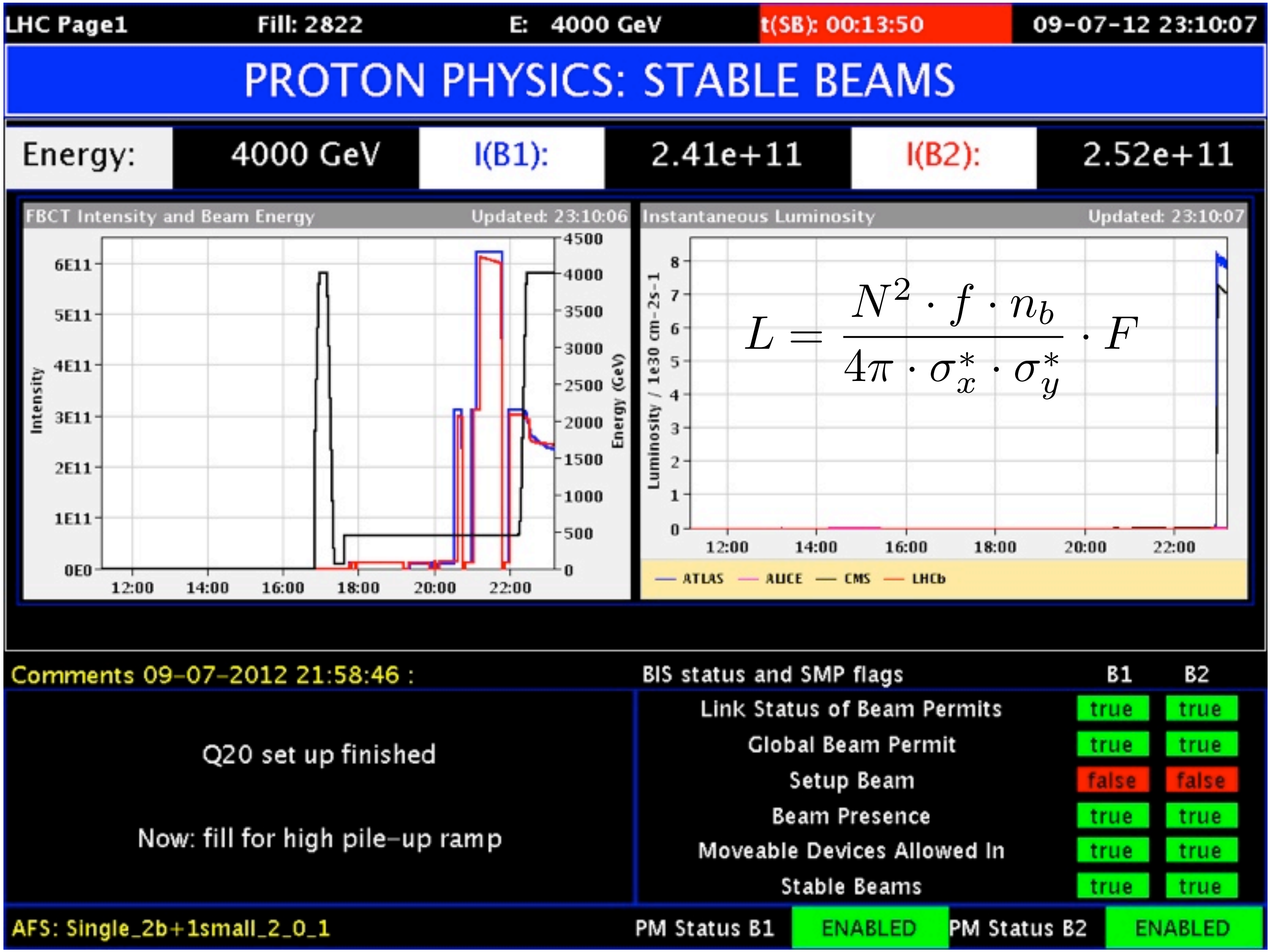
Beam dimension at the IP

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

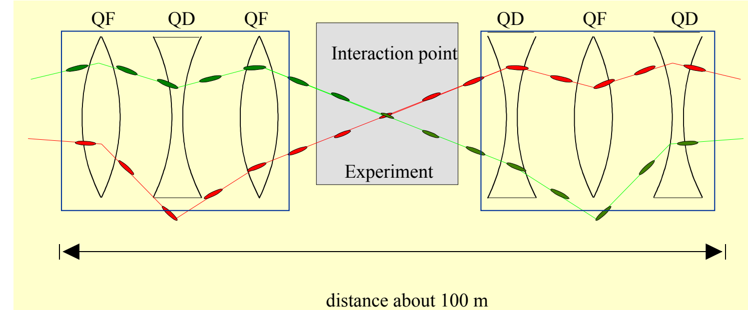
At first look, the smaller the better

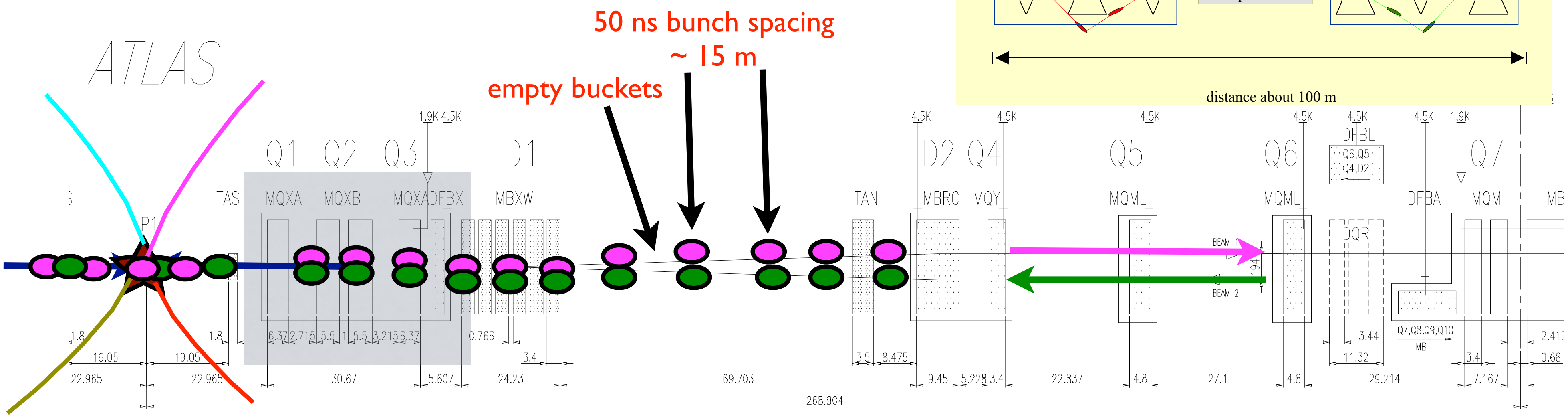
$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}$$

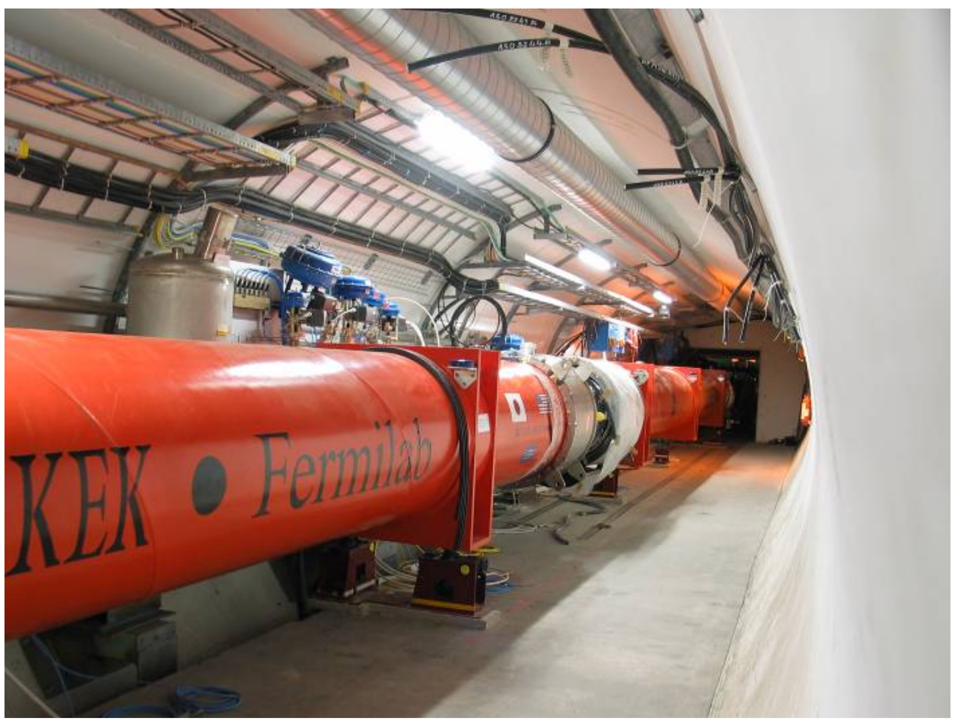
LHC Operational page



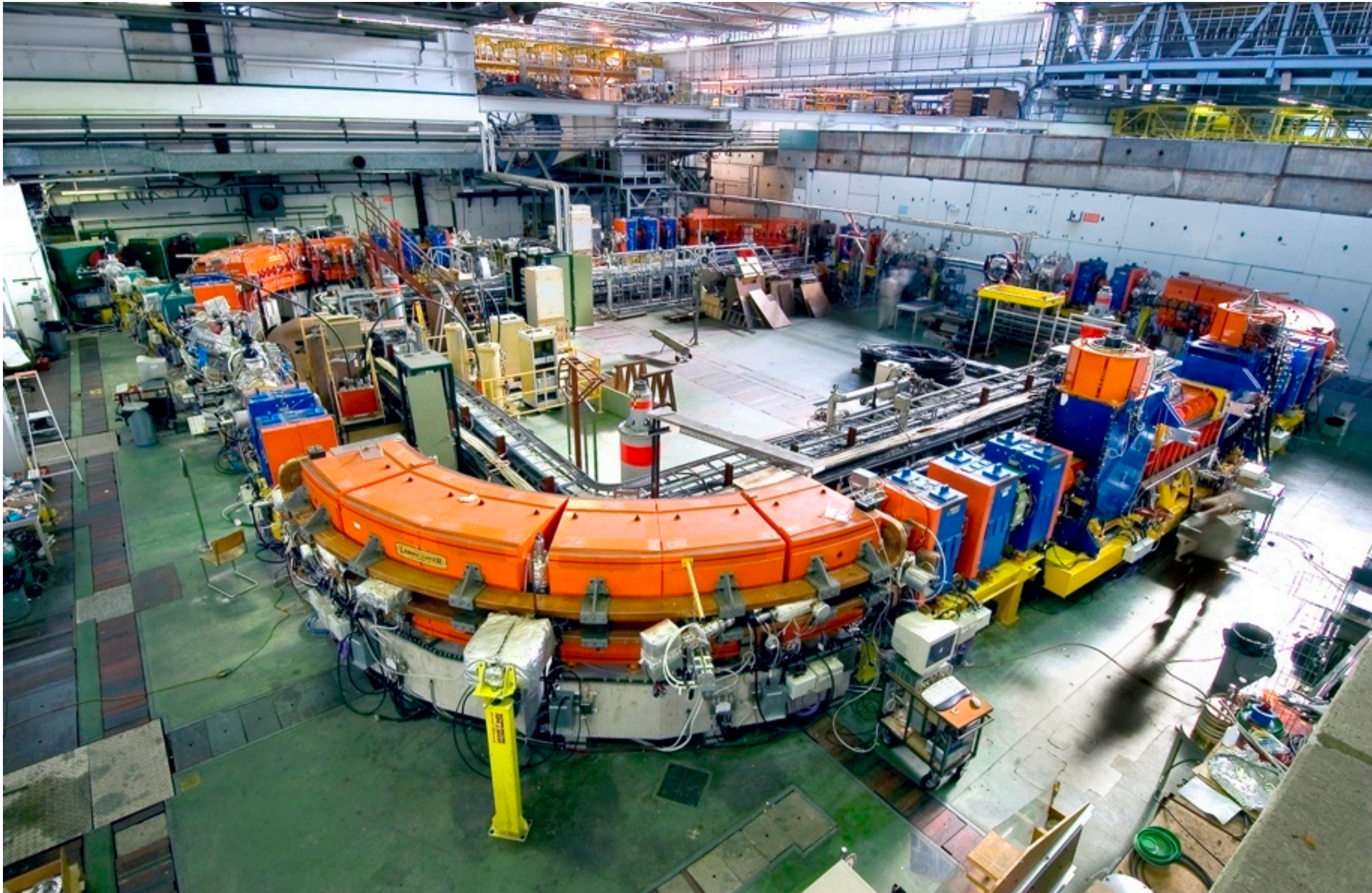
Inner triplet: final focusing
⇒ how to make the beam small at the IP



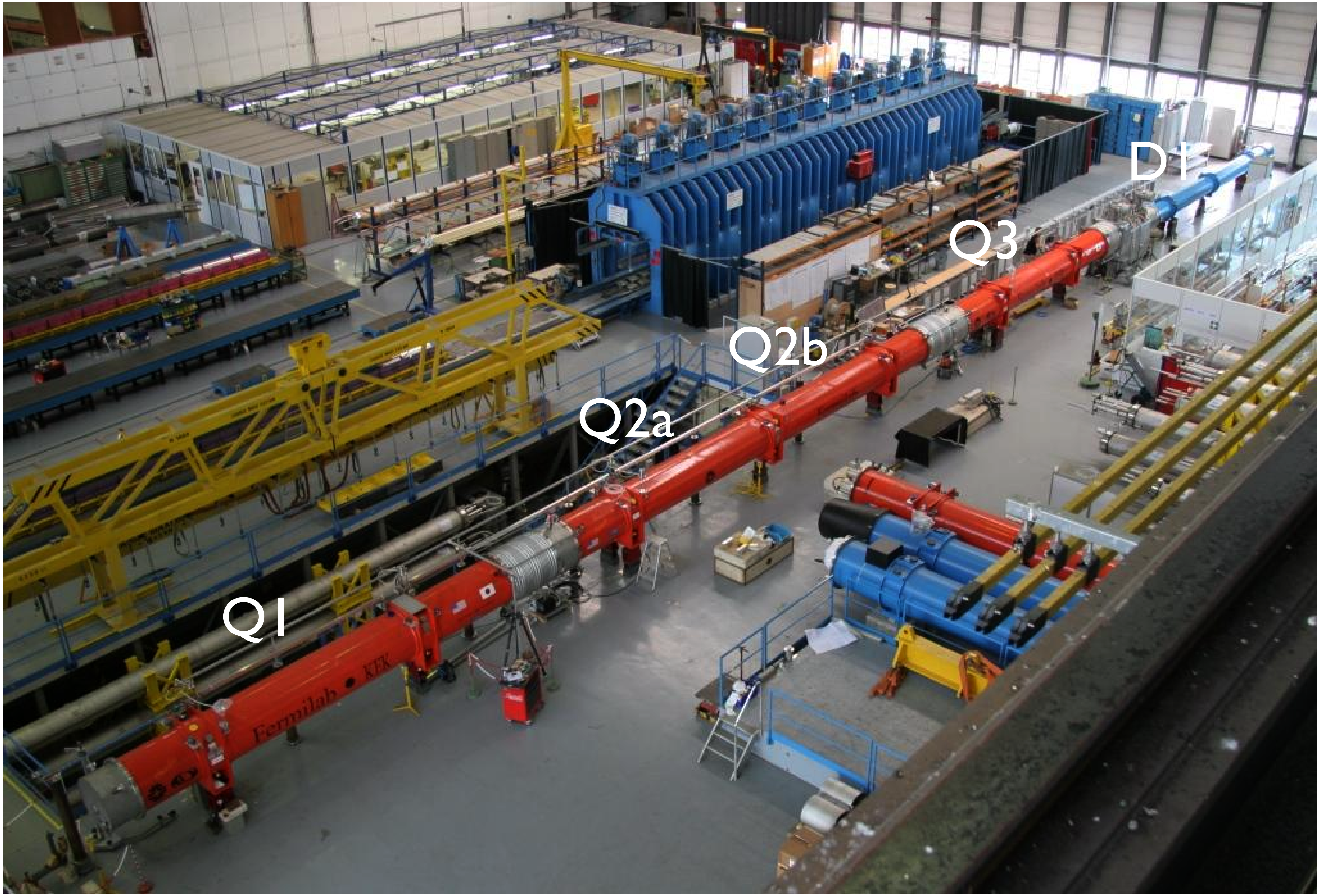




A synchrotron in a view: LEIR (Low Energy Ion Ring)



Triplets before lowering in the tunnel



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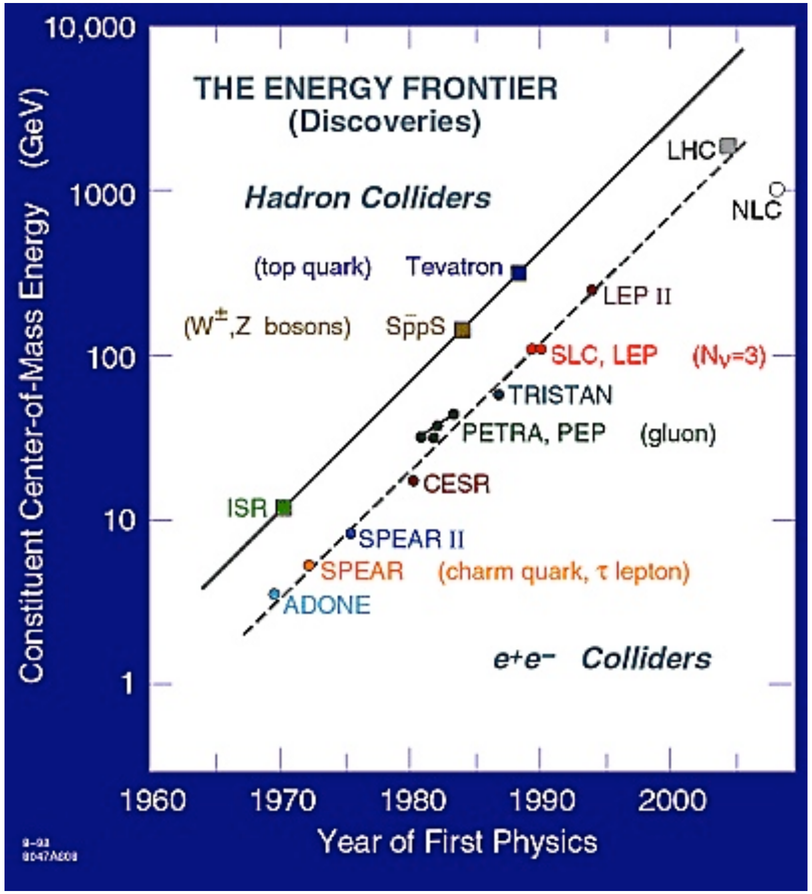
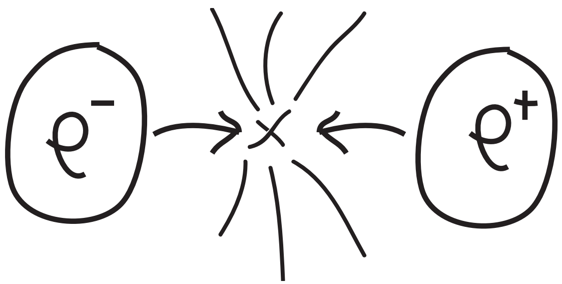
The beams are stored at 7 TeV for few 10 h to produce collisions. When the intensity is too low, the two rings are emptied and the process of injecting, accelerating, storing and colliding is restarted, until one finds the higgs or supersymmetry... then one needs a bottle of Champaign and a nobel price ...



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

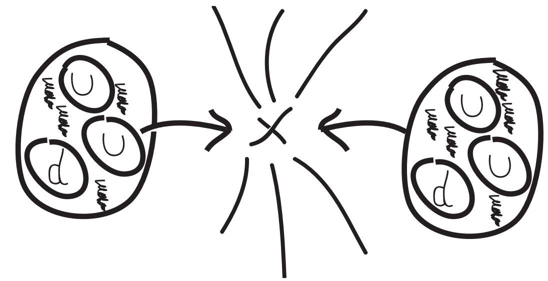
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

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

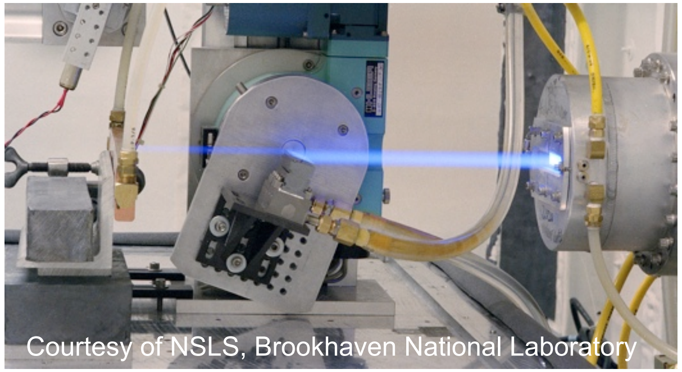
$r_0 = \frac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

ρ particle bending radius

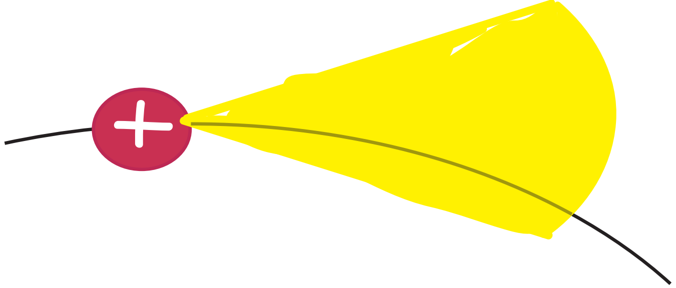
Energy lost per turn per particle due to synchrotron radiation:

e- ≈ some GeV (LEP)

p ≈ some keV (LHC)

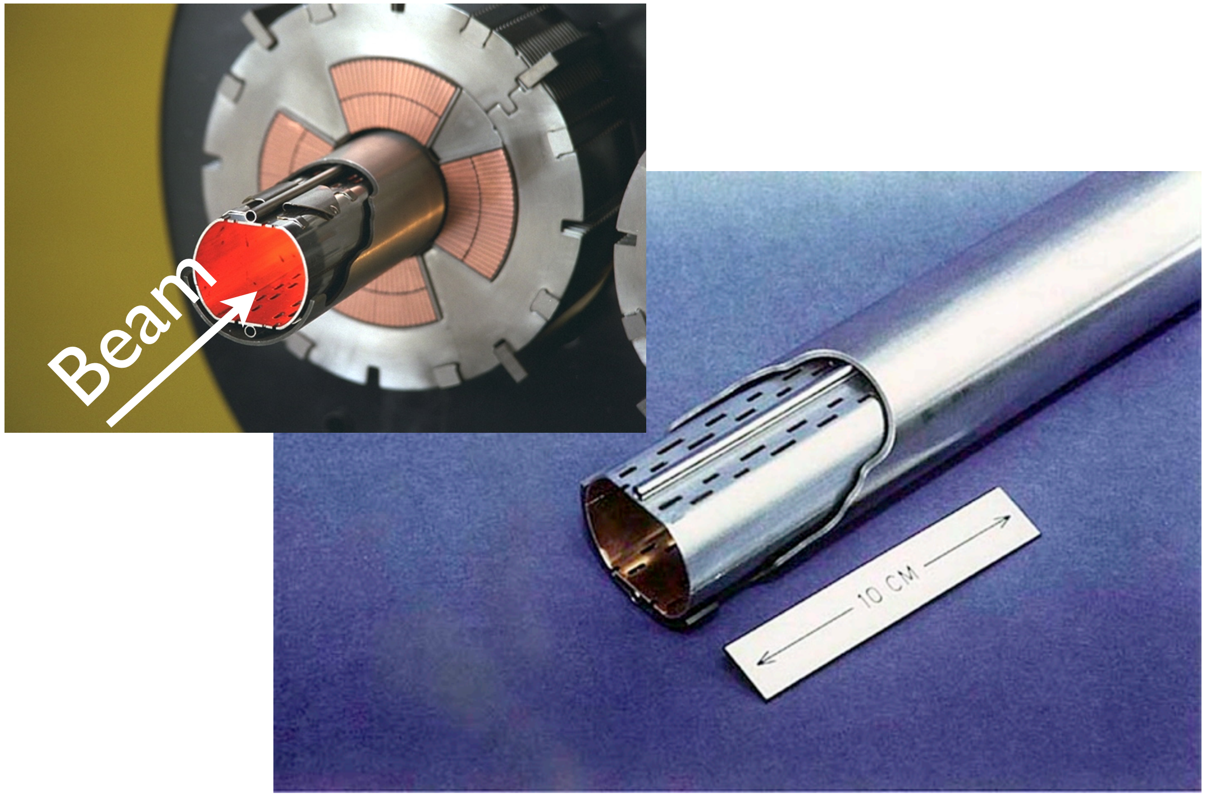

Courtesy of NSLS, Brookhaven National Laboratory

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



Power lost per m in dipole: <u>some W</u>
Total radiated power per ring: <u>some kW</u>

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 ?

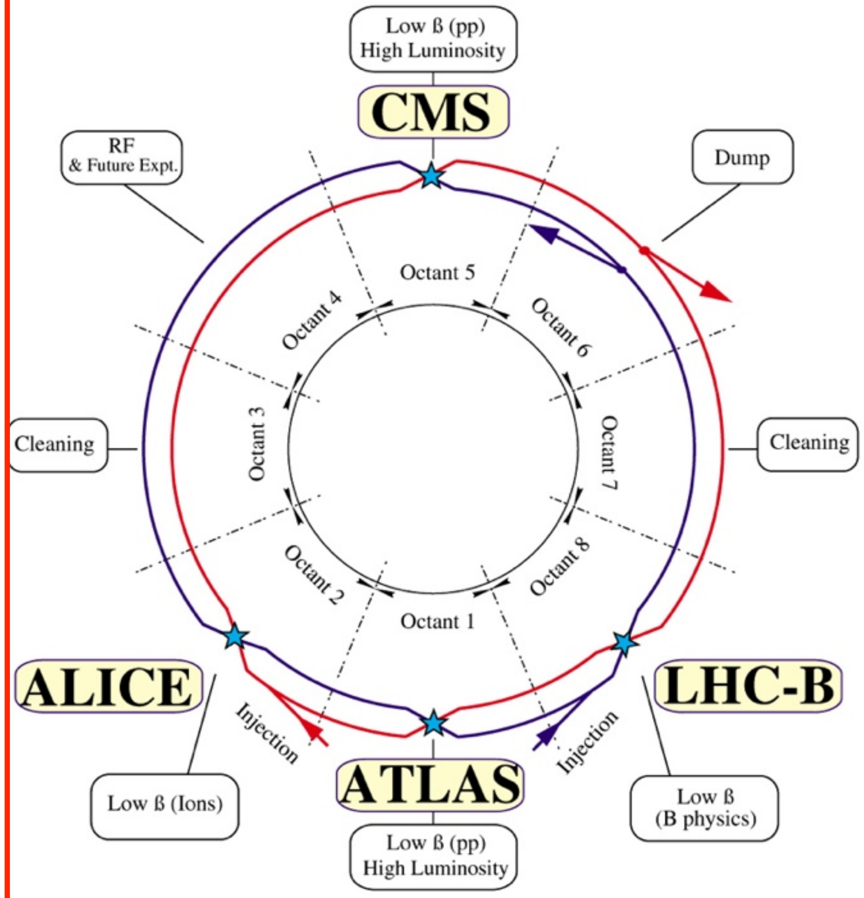
LHC: Large Hadron Collider

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

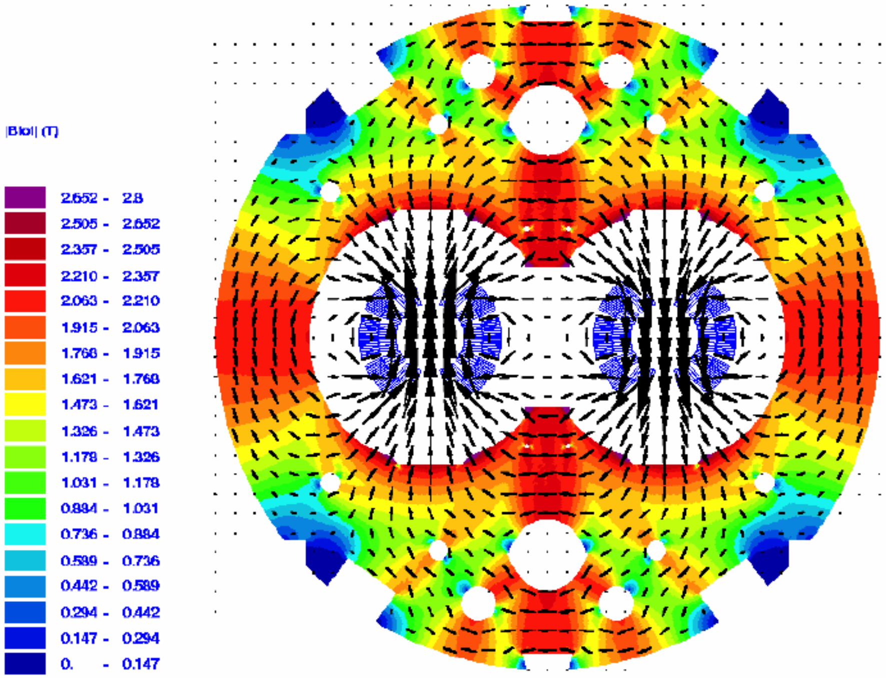
Large: high energy needs large bending radius *due to the maximum magnetic field existing technology can produce*
26.7 km circumference

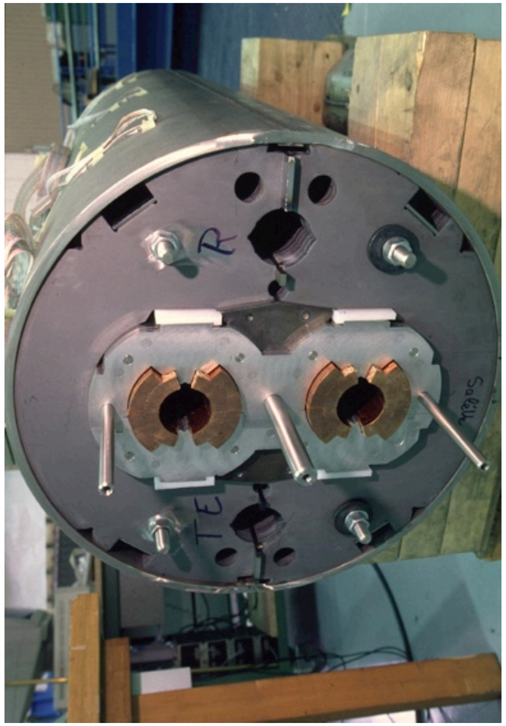
Hadrons: p p collision ⇒ synchrotron radiation and discovery machine.

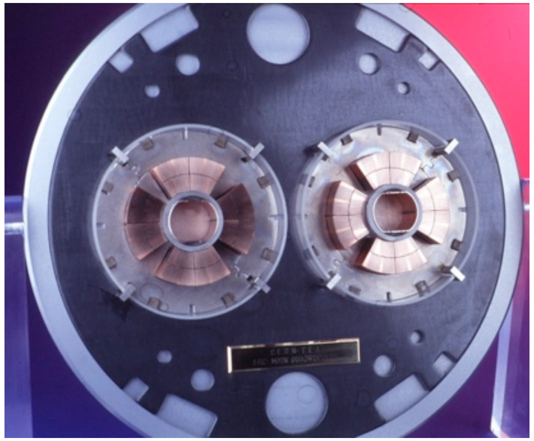
Collider: particles are stored in two separated rings which are synchrotrons, and accelerated from injection energy (450 GeV) to 7 TeV.
At 7 TeV the two beams are forced to cross in collision points to interact.
The beams are stored at 7 TeV for few 10 h to produce collisions. When the intensity is too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



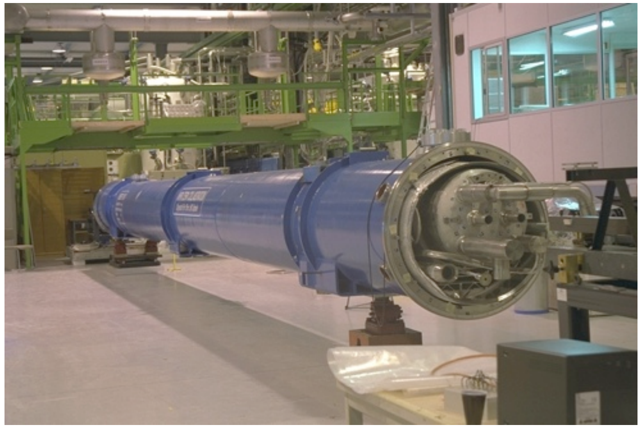
Two-in-one magnet design

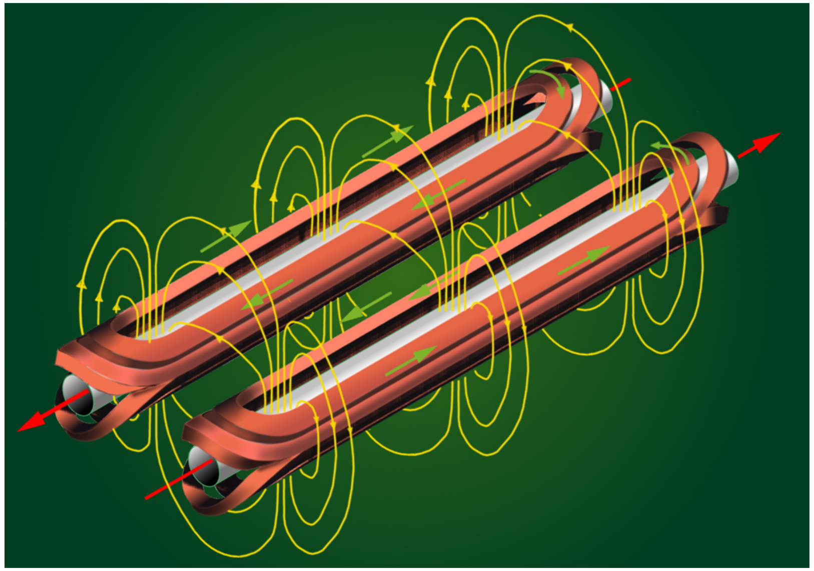




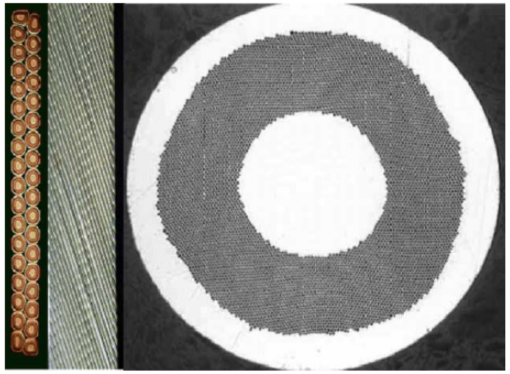


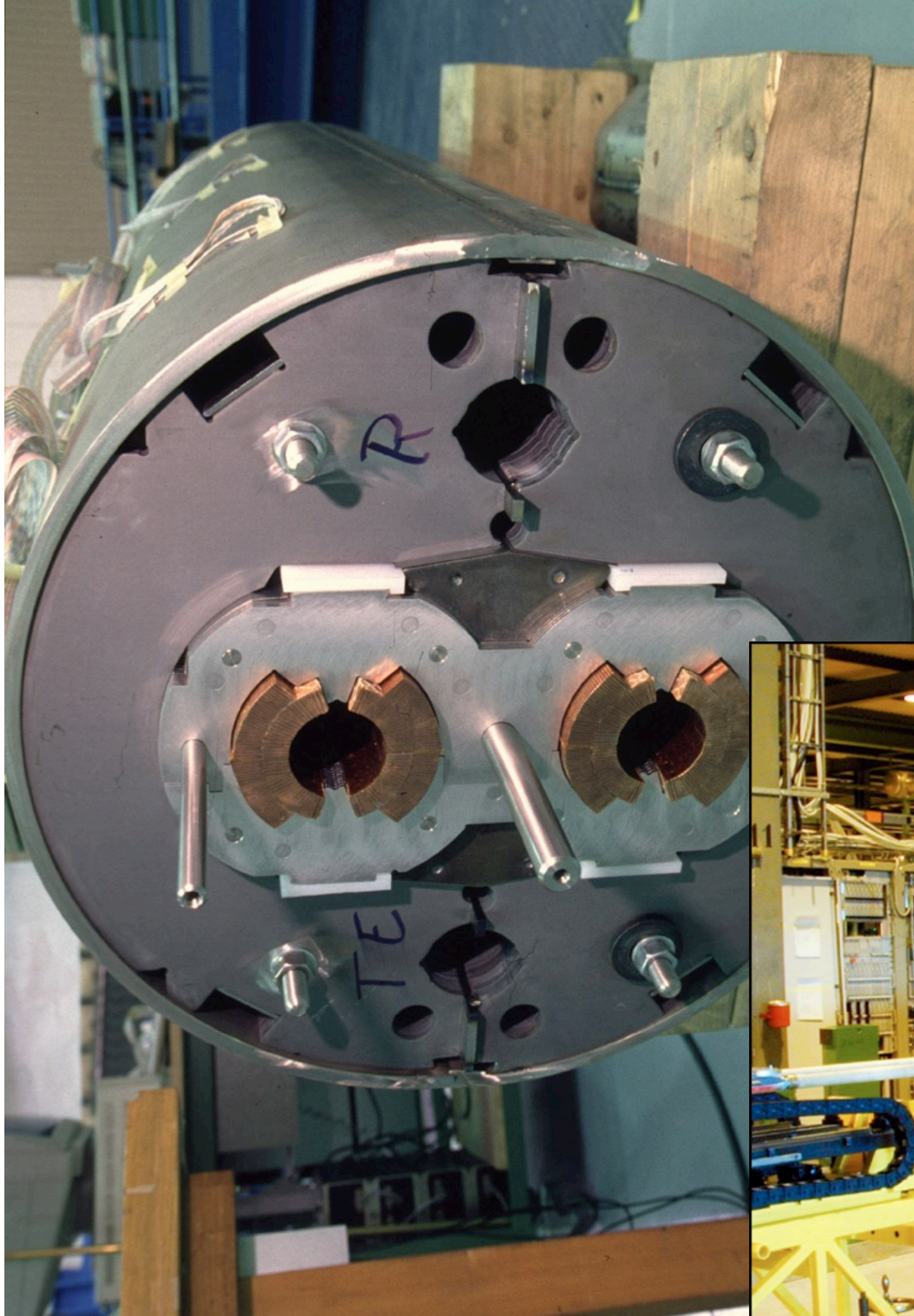
The LHC is <u>one ring</u> where <u>two accelerators</u> are coupled by the magnetic elements.





Nb -Ti superconducting cable in a Cu matrix





At 7 TeV:

I_{max} = 11850 A Field=8.33 T

Stored energy= 6.93 MJ

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

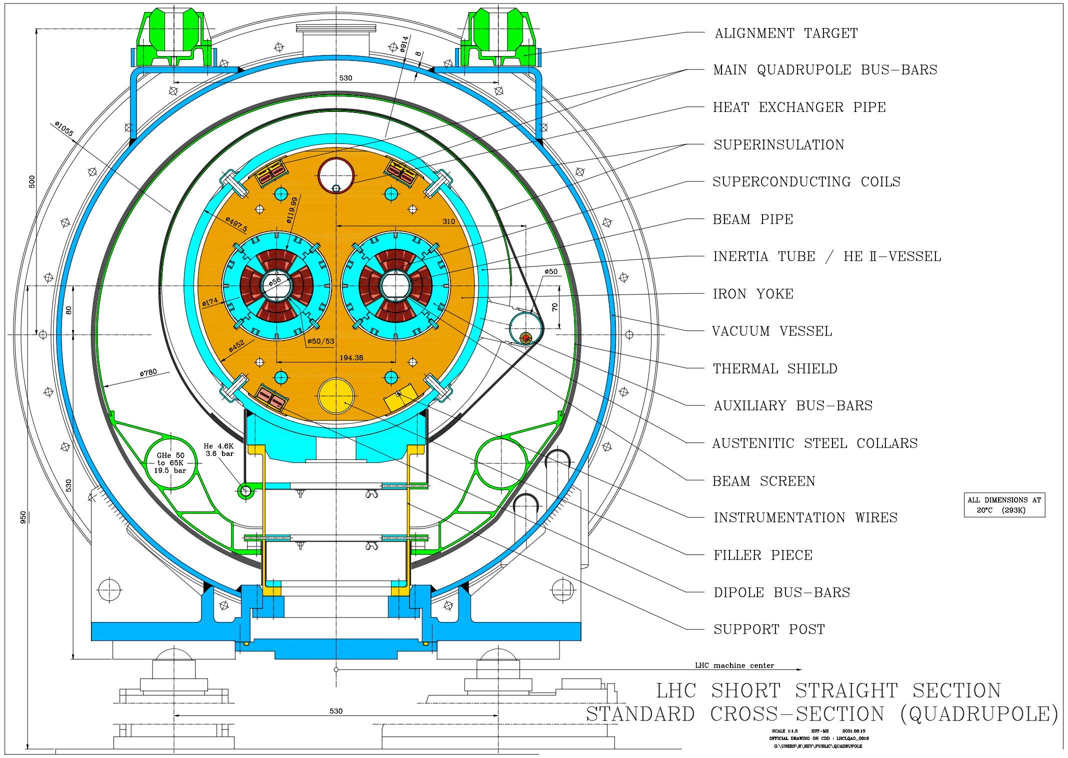
Weight = 27.5 Tons

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

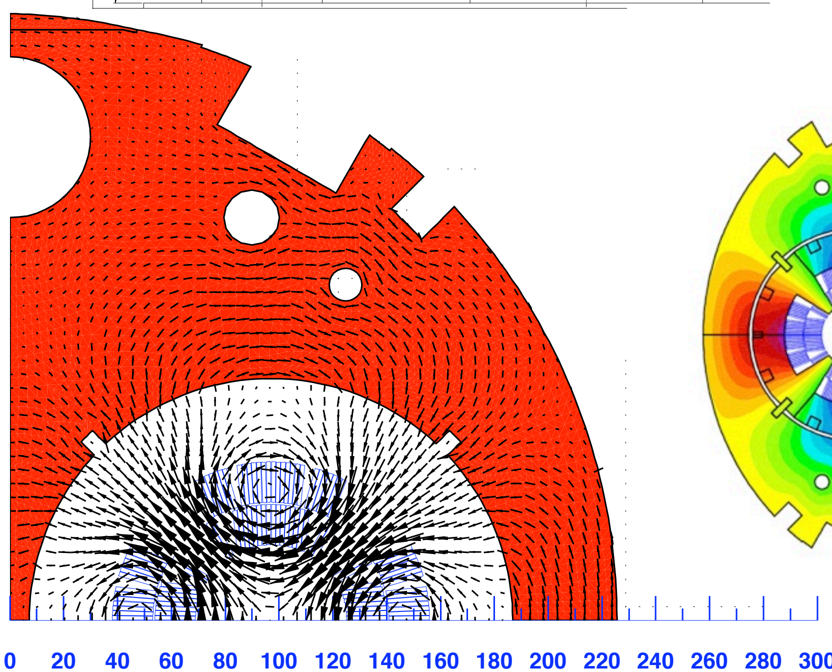
Quadrupoles are also two-in one

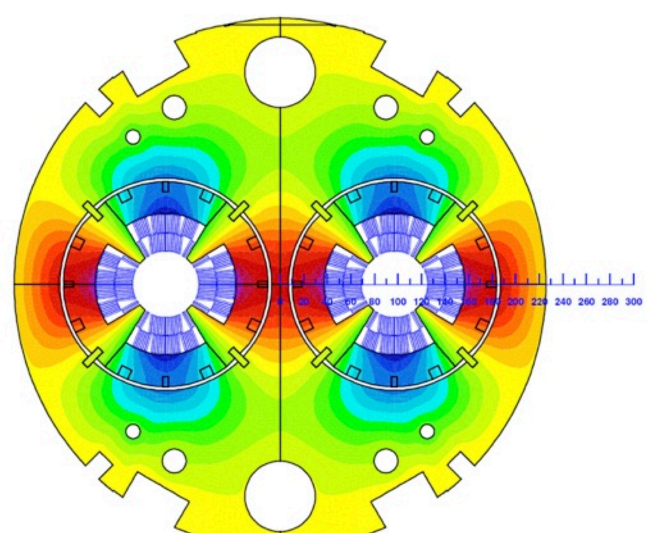


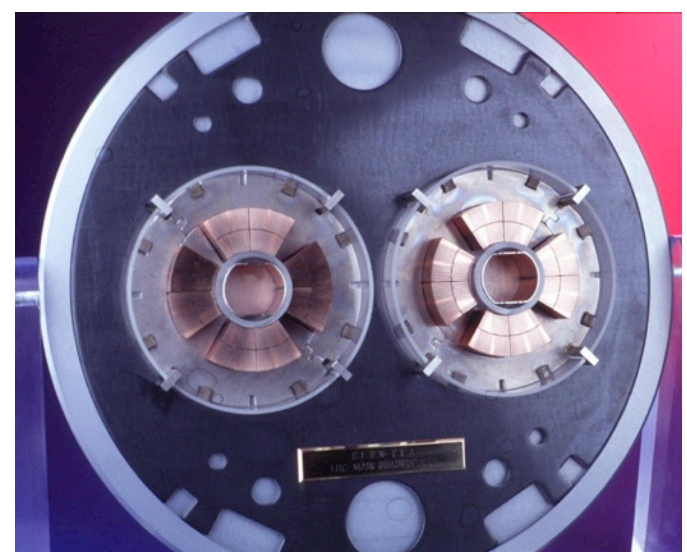
At 7 TeV:

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 2×10^7 kg.
Or the USS Harry S. Truman (Nimitz-class) - 88,000 tons.

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

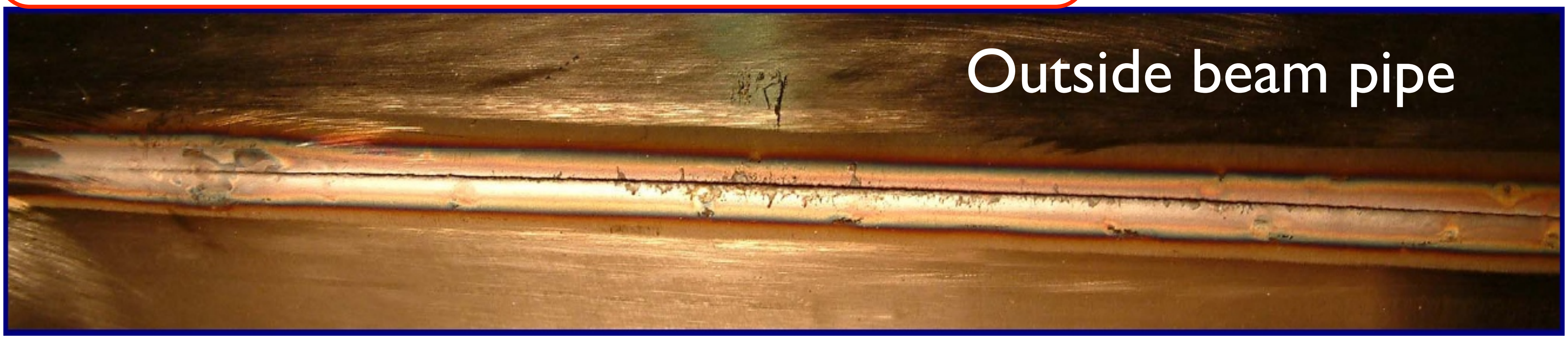
which corresponds to the aircraft carrier navigating
at v=5.8 m/s or 11.2 knots (or around 5.3 knots if you're an American aircraft carrier)

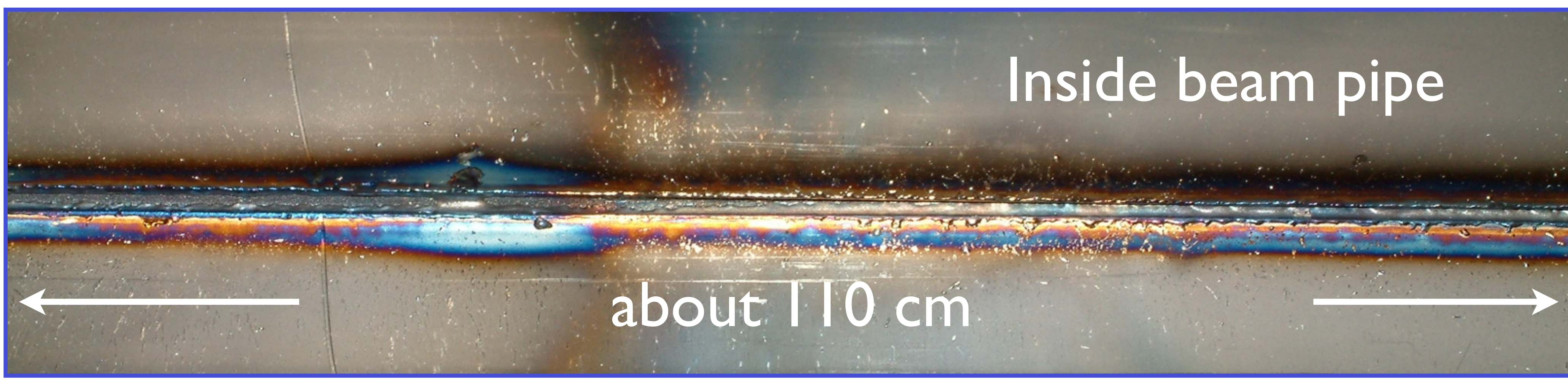
So, what if something goes wrong?

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)
1.15×10^{11} p+ per bunch, for total intensity of 3.3×10^{13} p+
<u>Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)</u>





B.Goddard CERN AB/BT

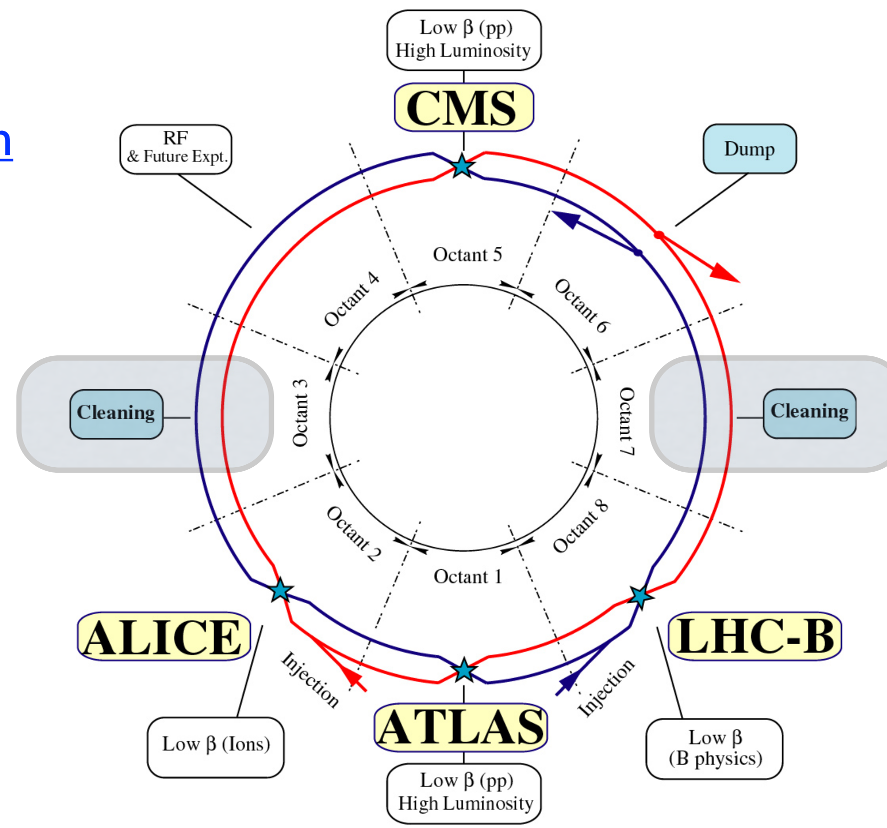
Collimation system for machine protection

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

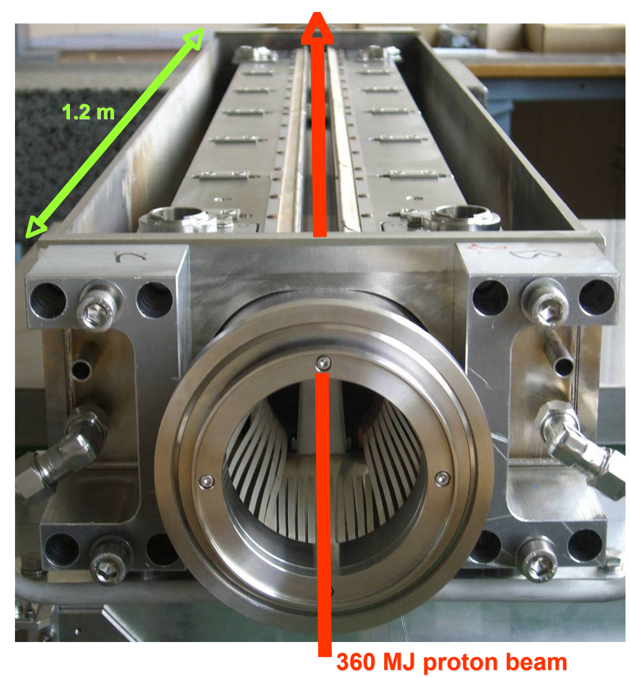
SPS experiment:

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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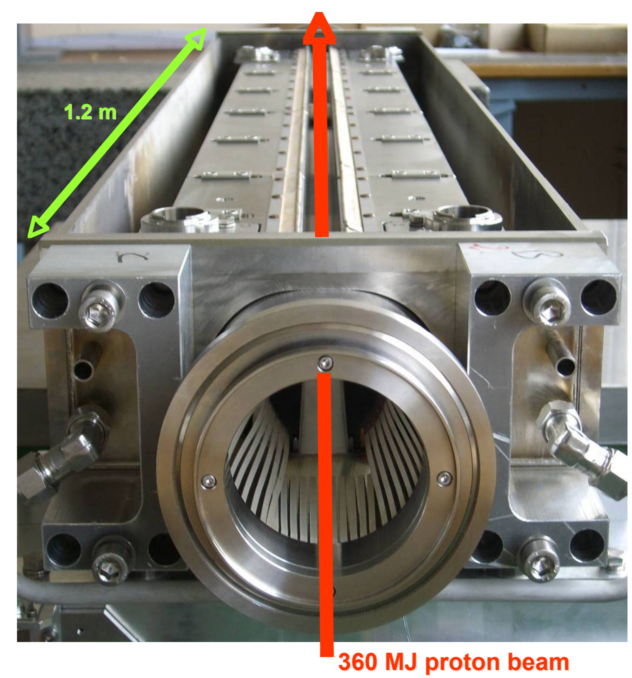

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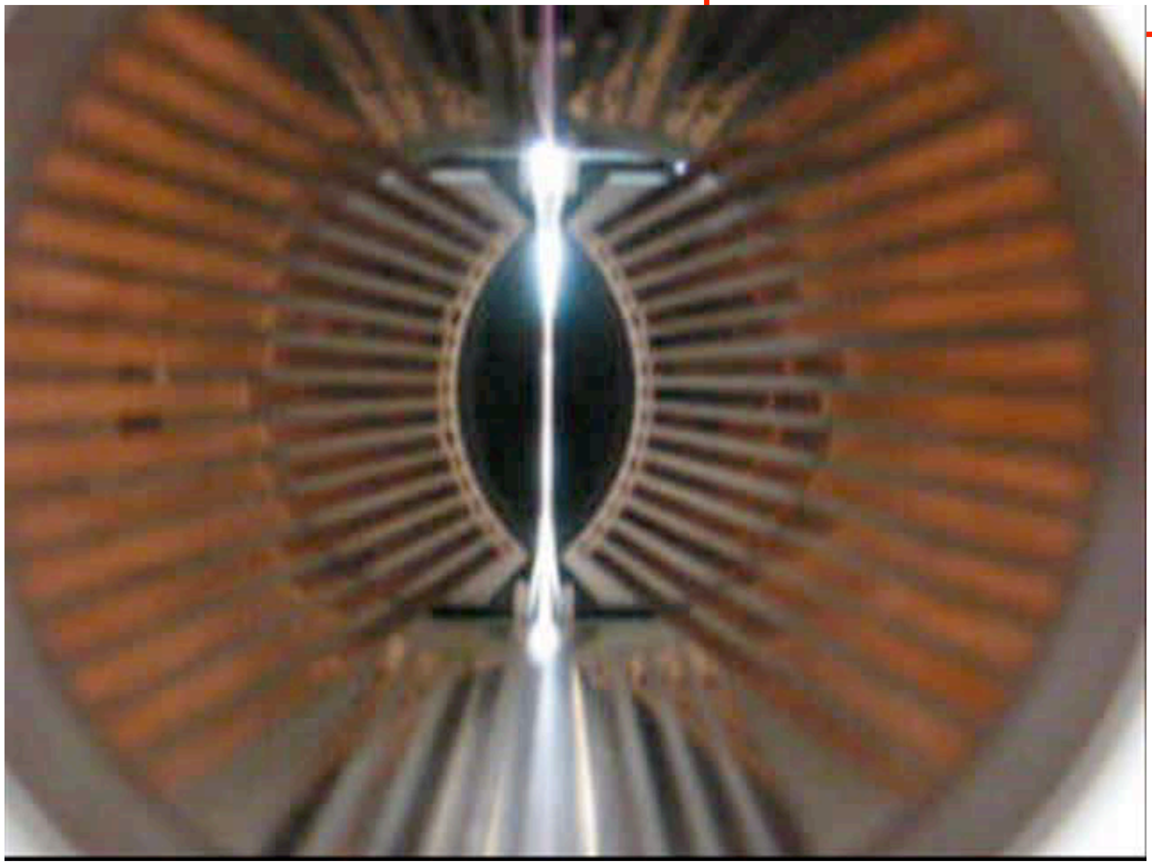
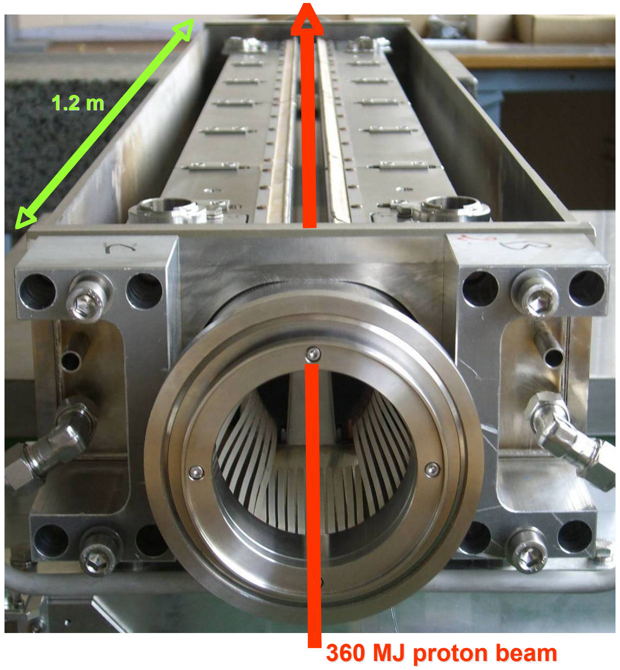
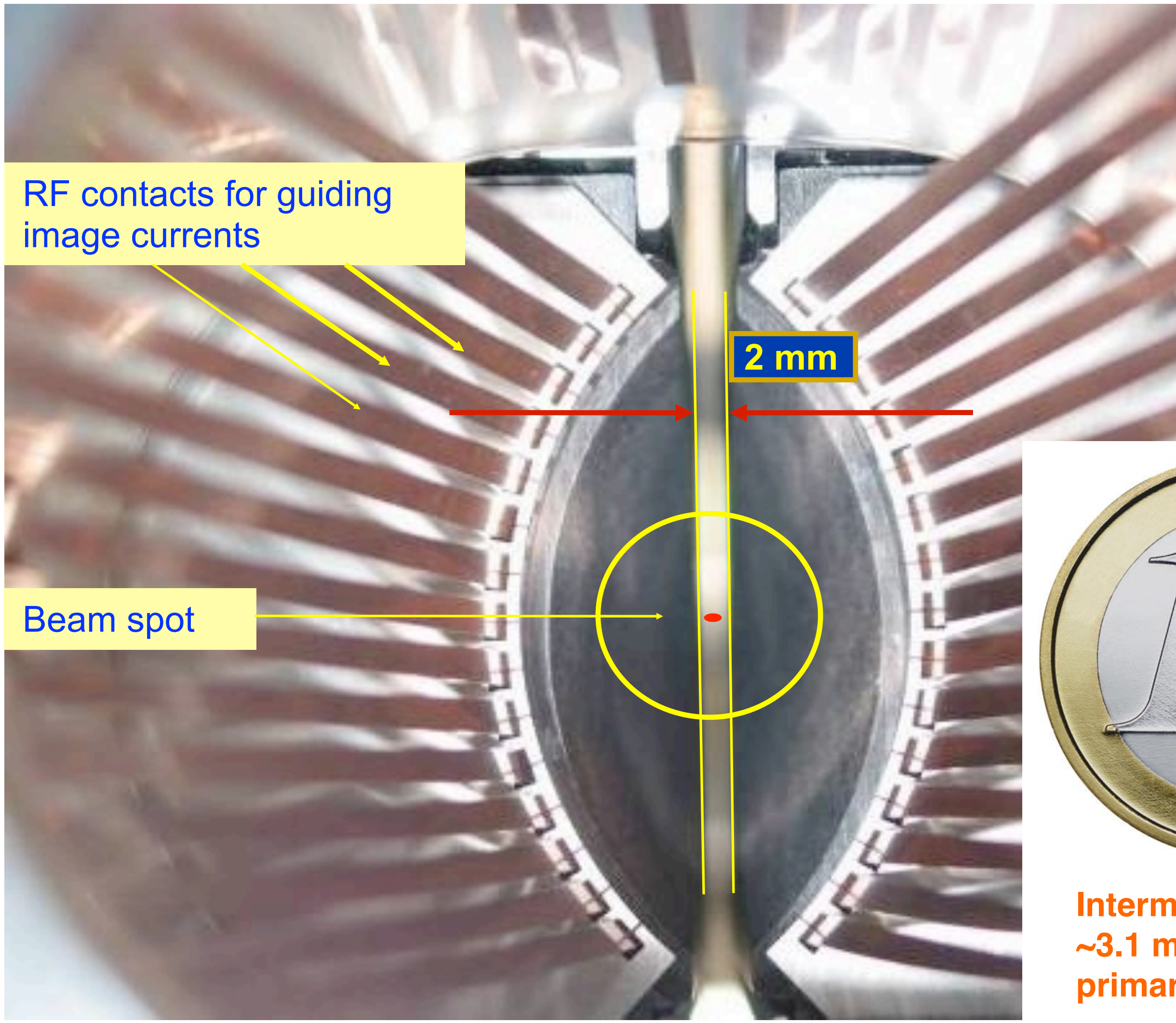
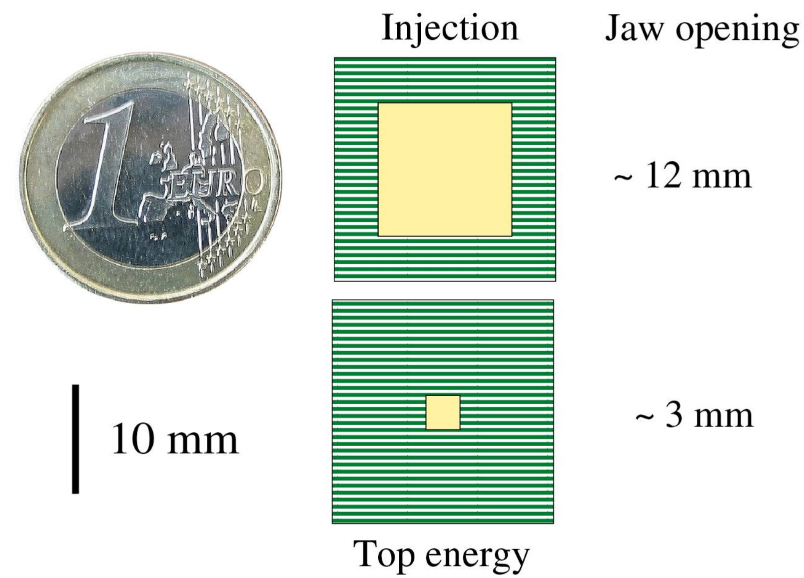
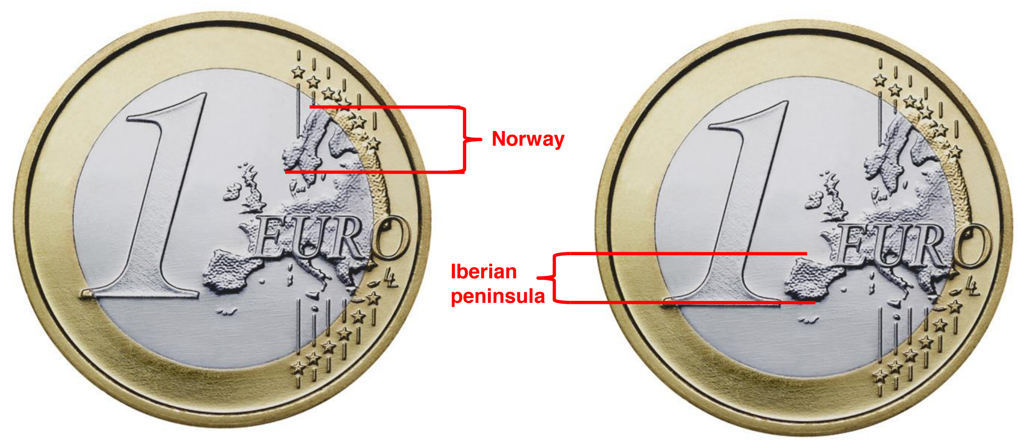




At 7 TeV, beam really small, 3σ diam. ~ 1.2 mm







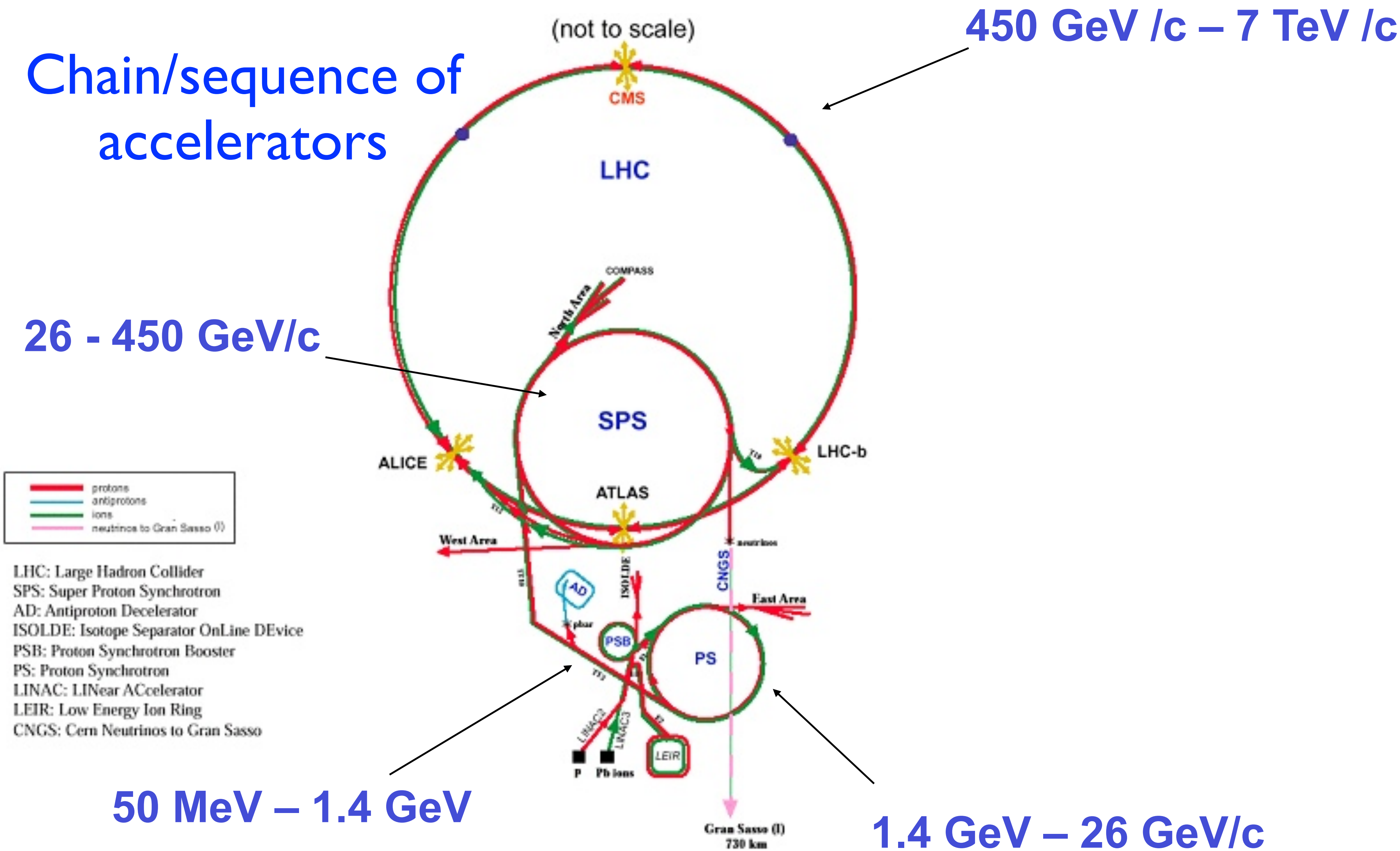
Intermediate settings (2011): ~3.1 mm gap of primary collimator

Tight settings: ~2.2 mm gap of primary collimator

Precision required for collimator movements about 25 μm

CERN accelerator complex overview

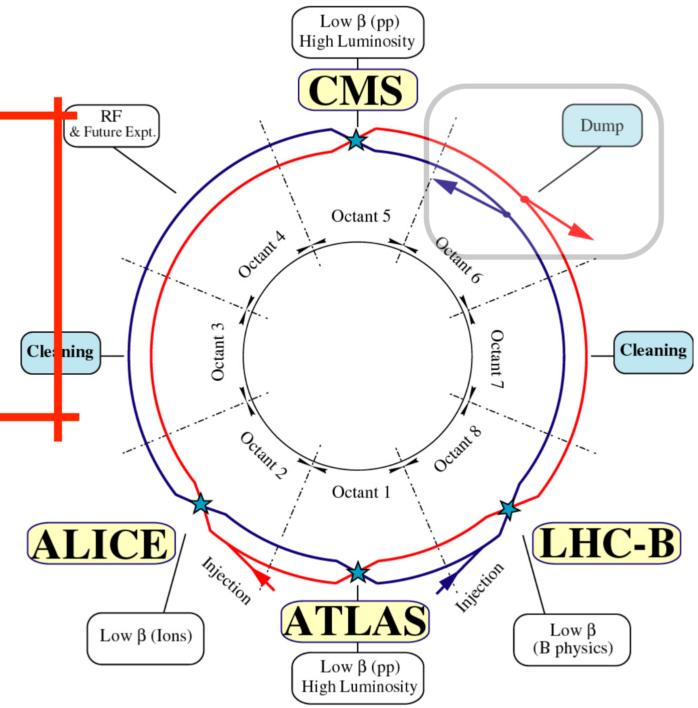
Chain/sequence of accelerators

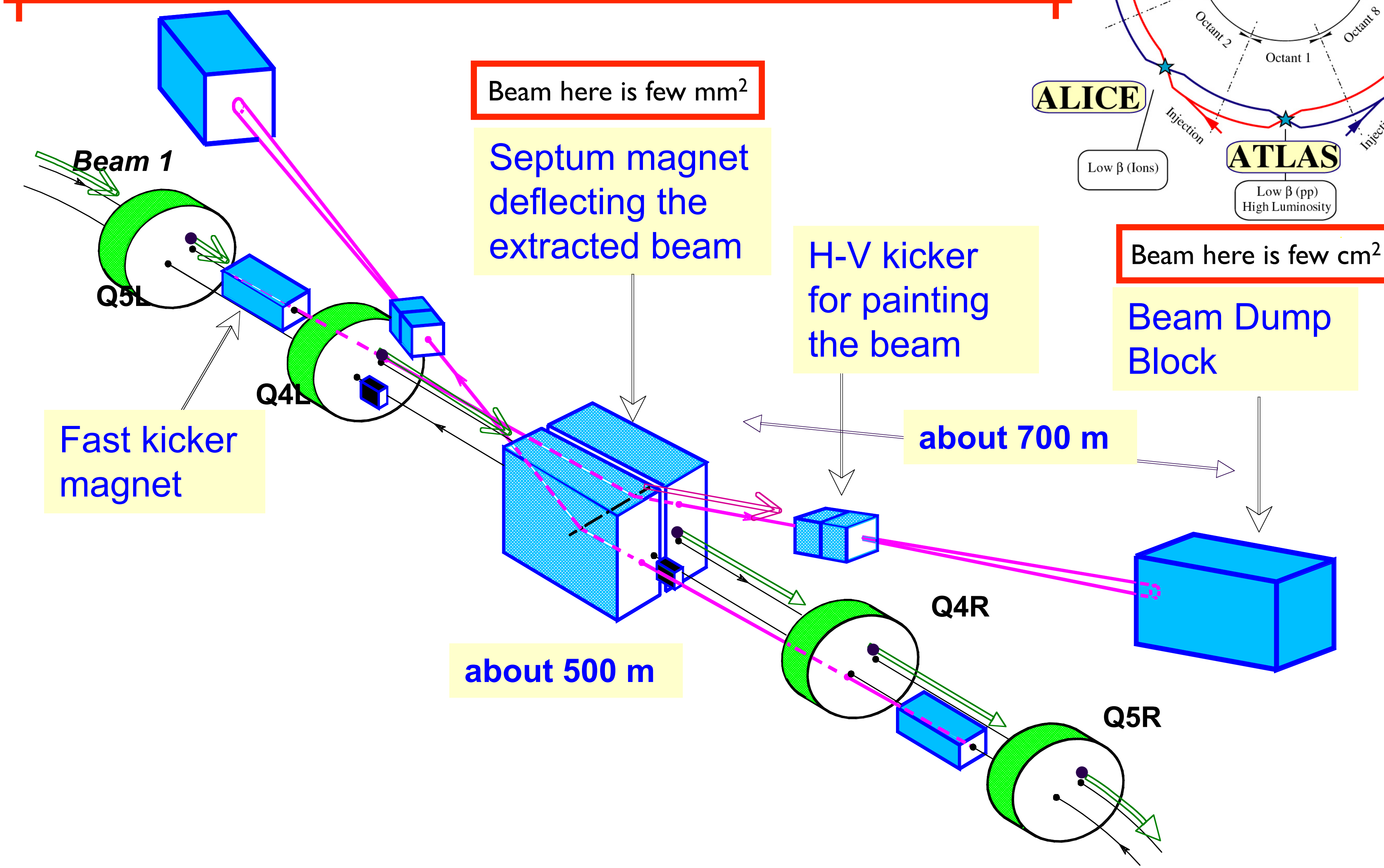


LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

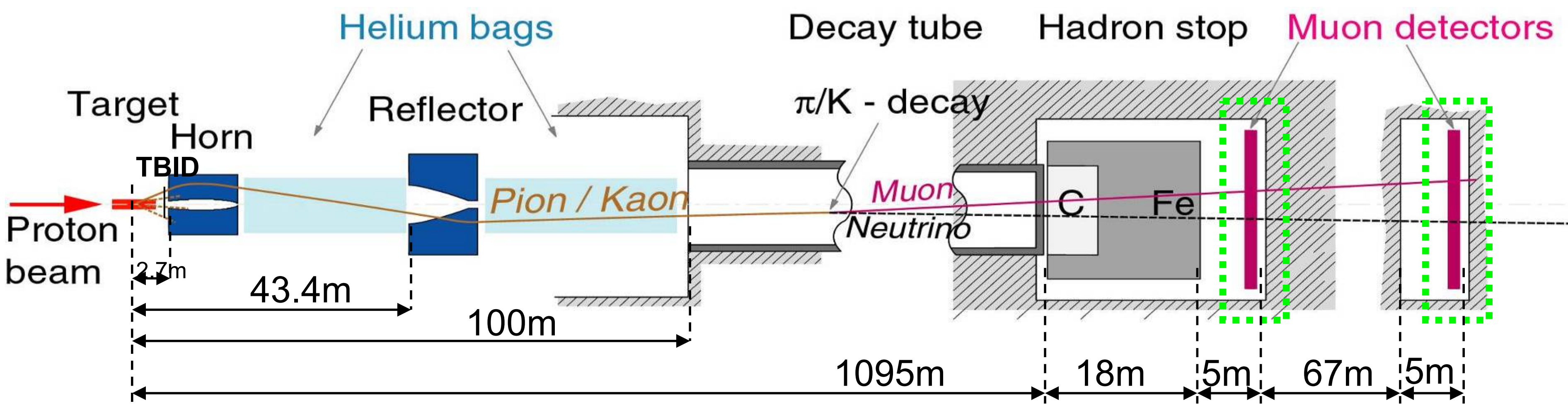
Beam extraction, LHC as example

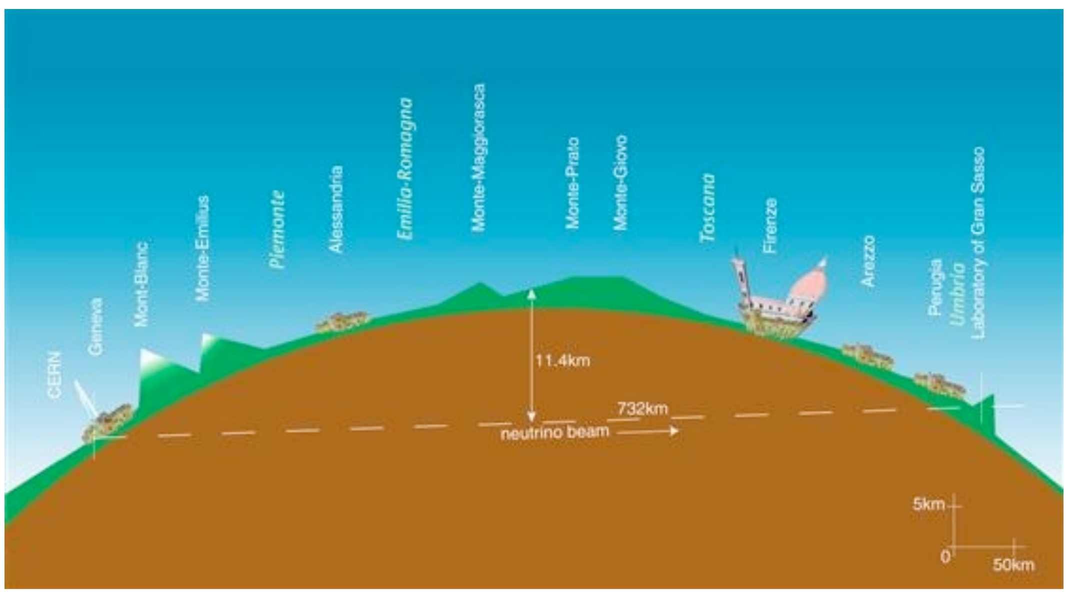
At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn. Beam dump built to absorb full power at full energy.

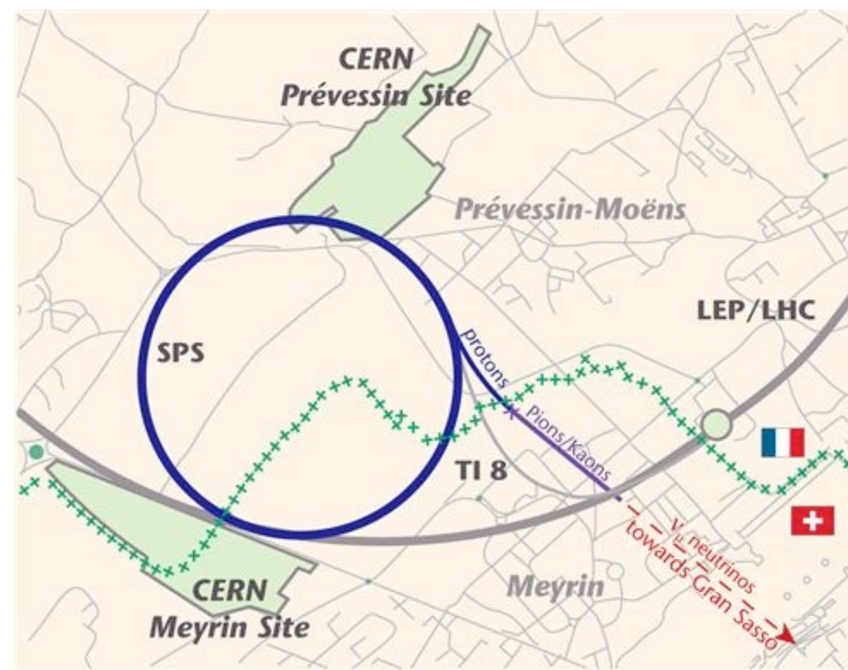




CNGS, conventional neutrino beam



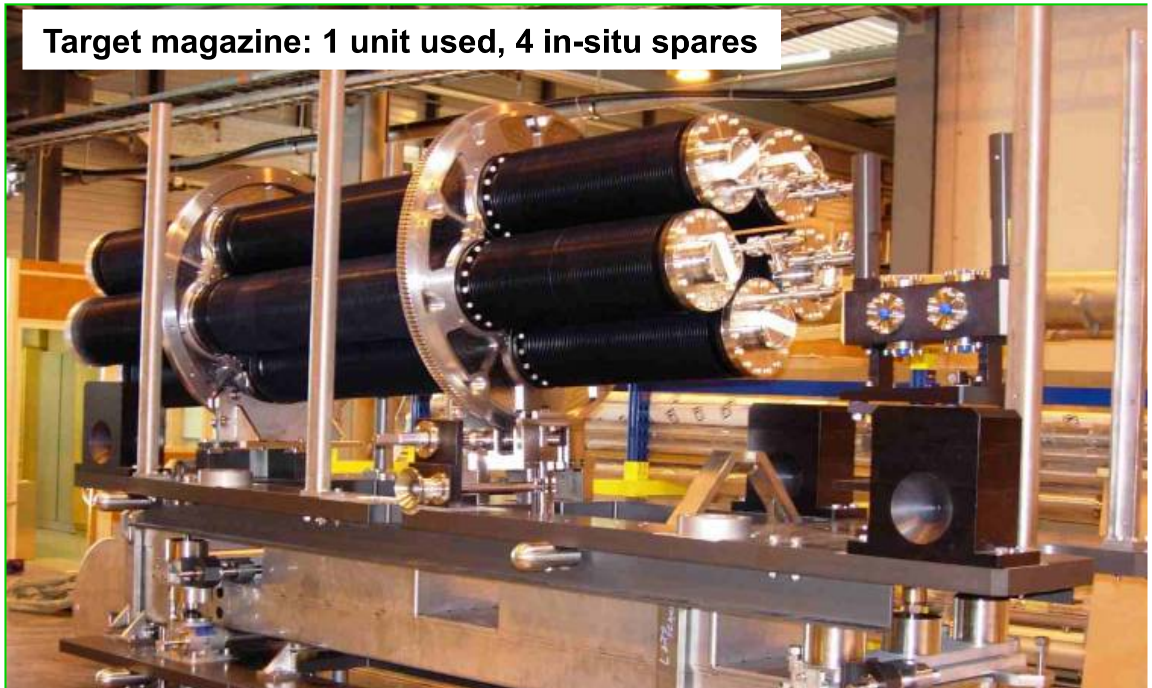


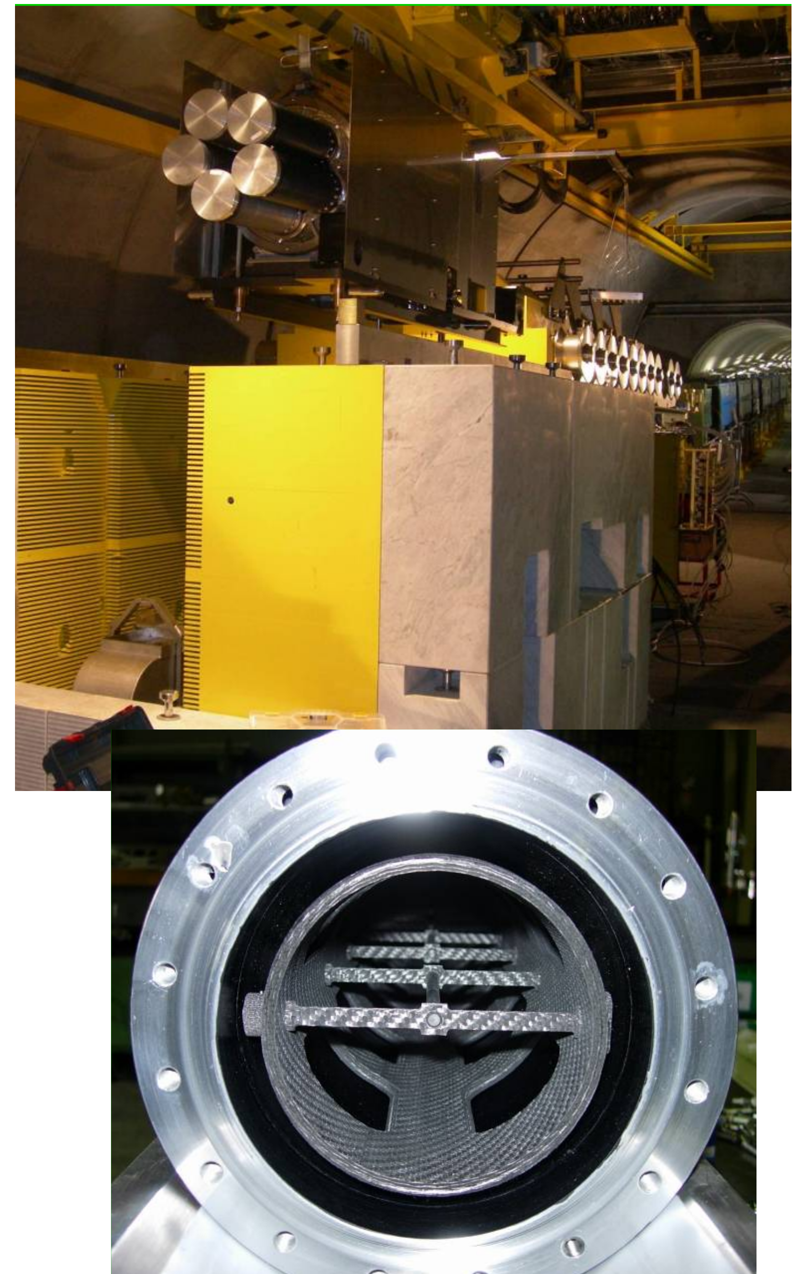


CNGS looks for ν_τ appearance in a beam of ν_μ

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



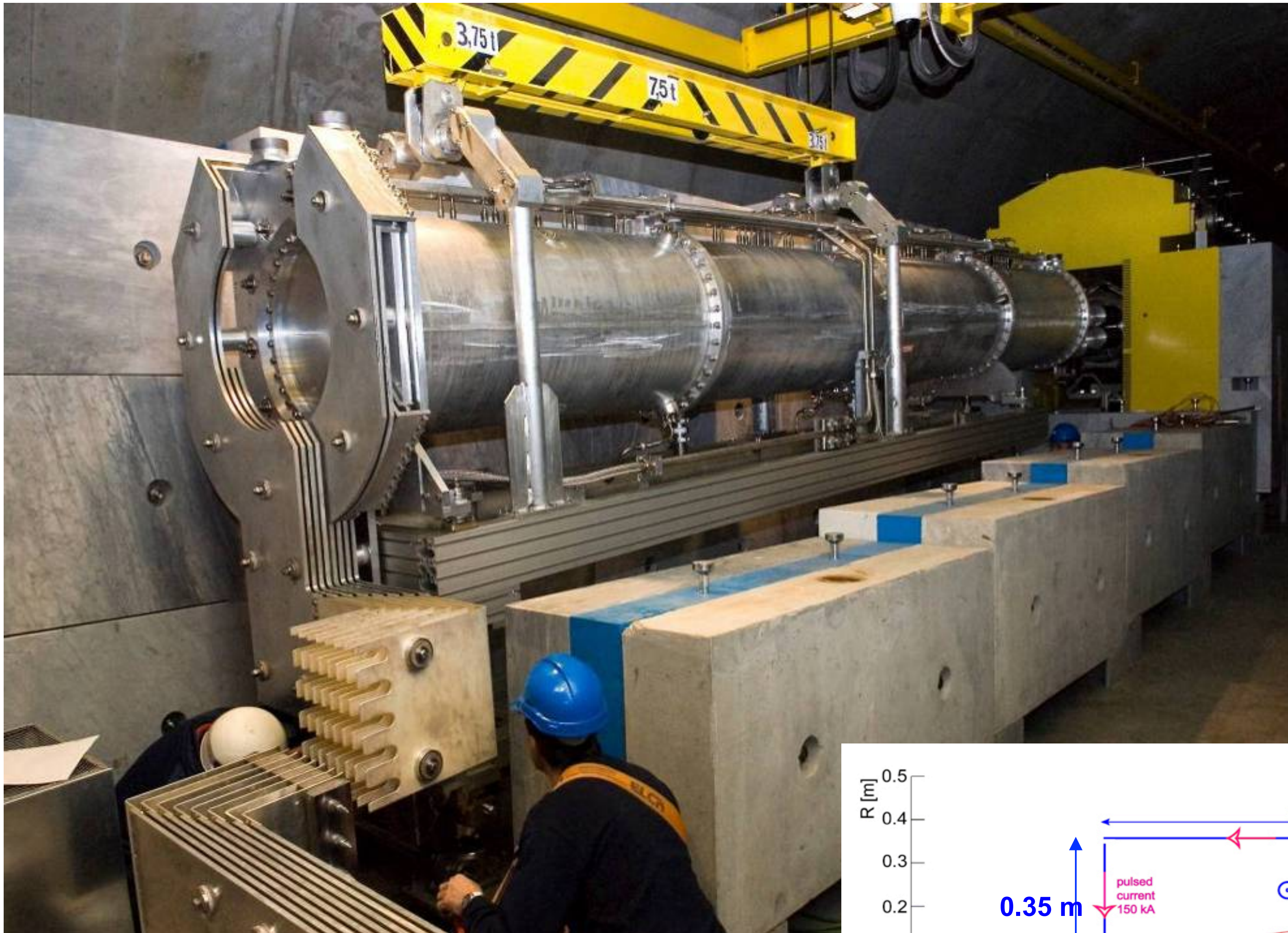


Highly radioactive area.

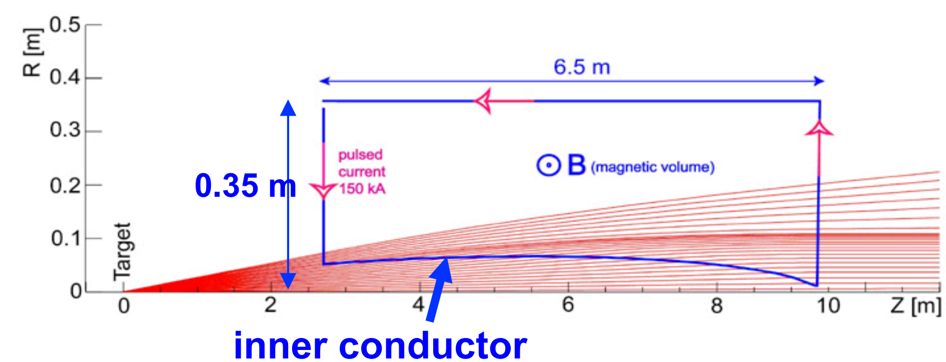
Everything has to be built to be remotely handled

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

CNGS horn



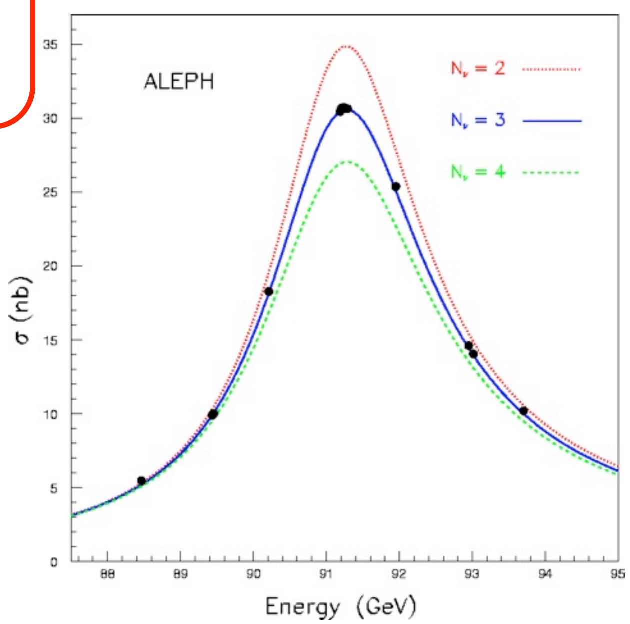
3,75 t
7,5 t



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

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?

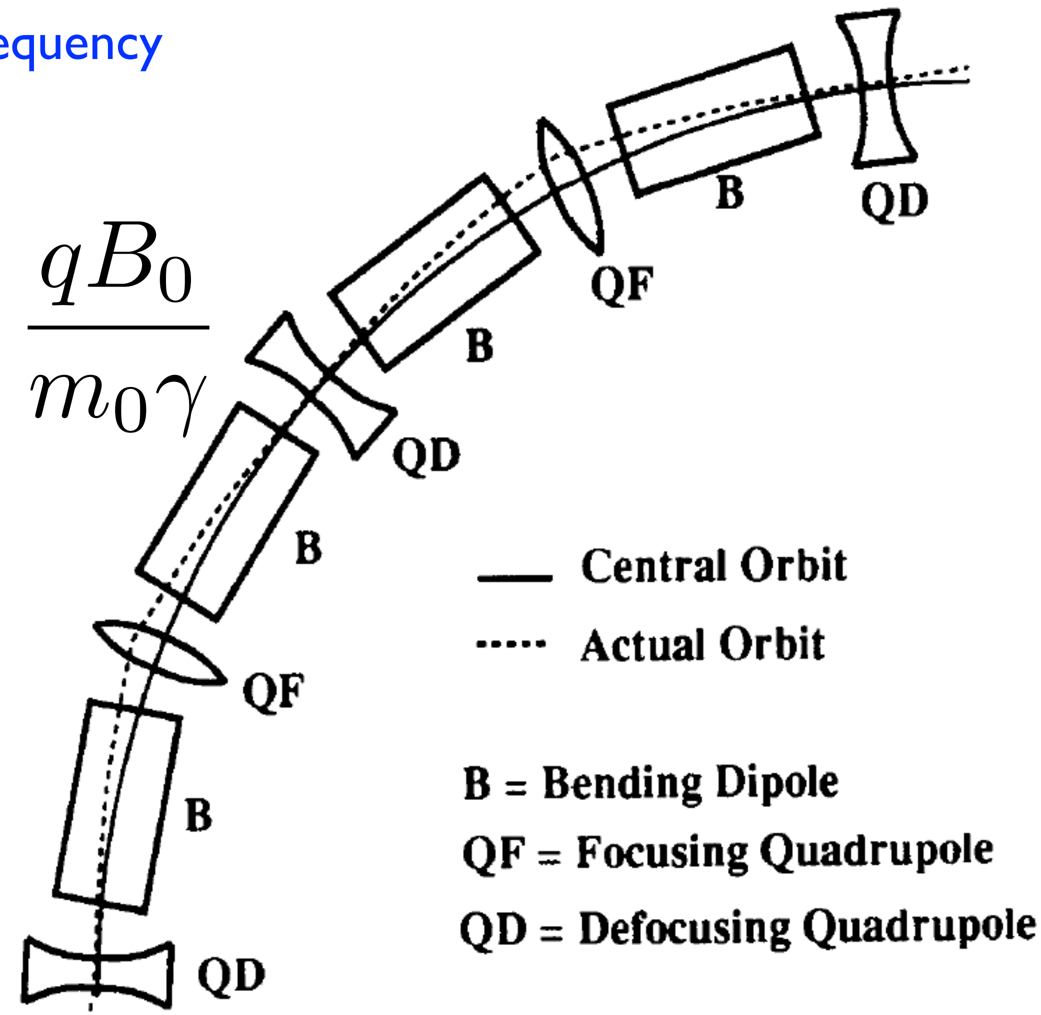
“Rappel”of strong focusing synchrotron optics

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.

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

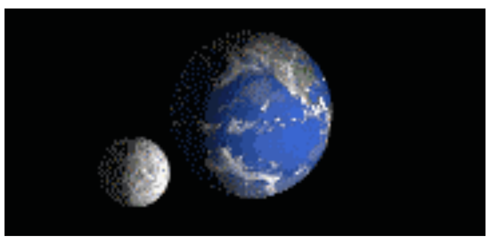
In LEP $\alpha = 1.86\ 10^{-4}$ a small variation the circumference induces a large variation in energy

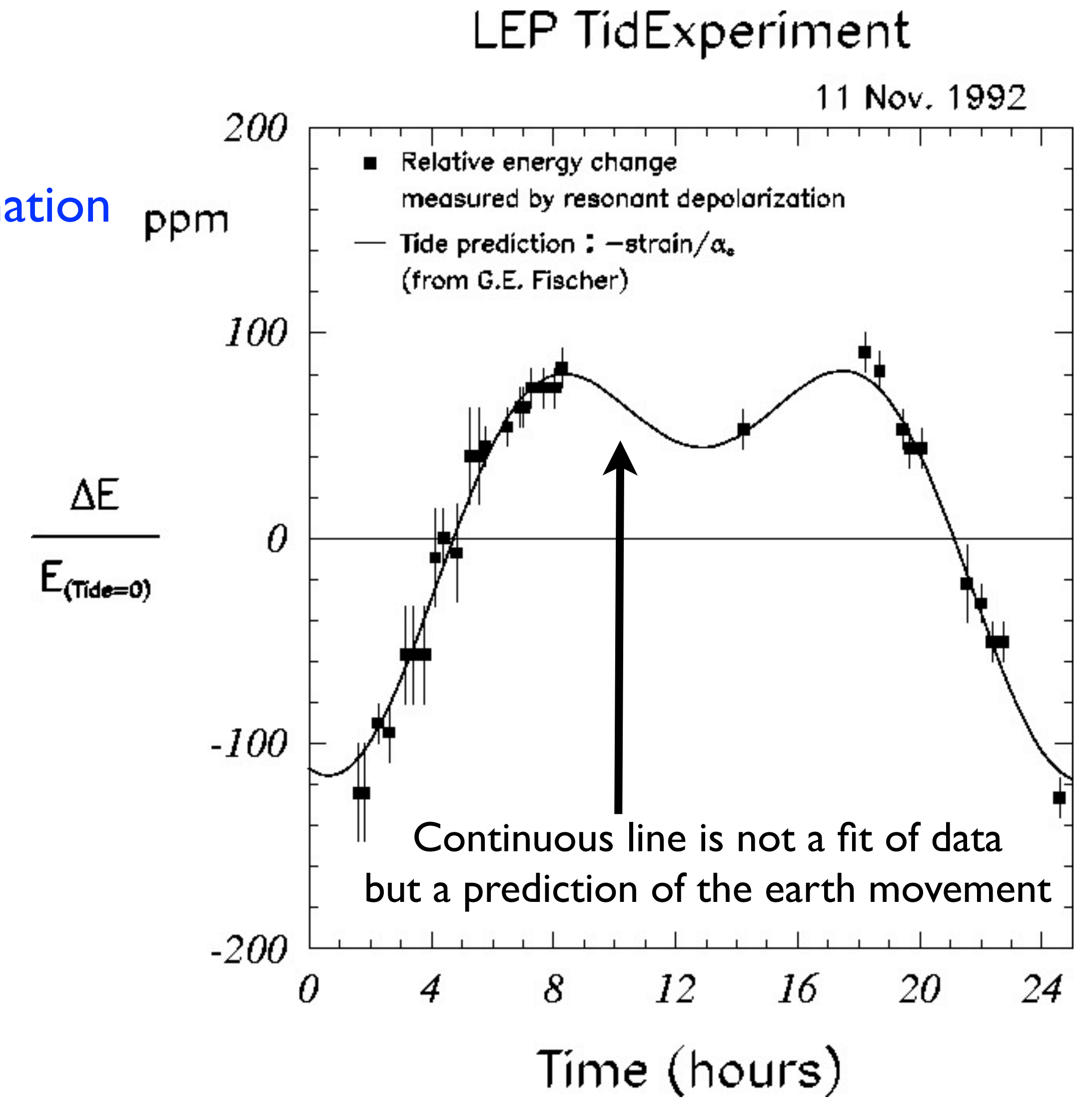
Moon tides can change earth geometry

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

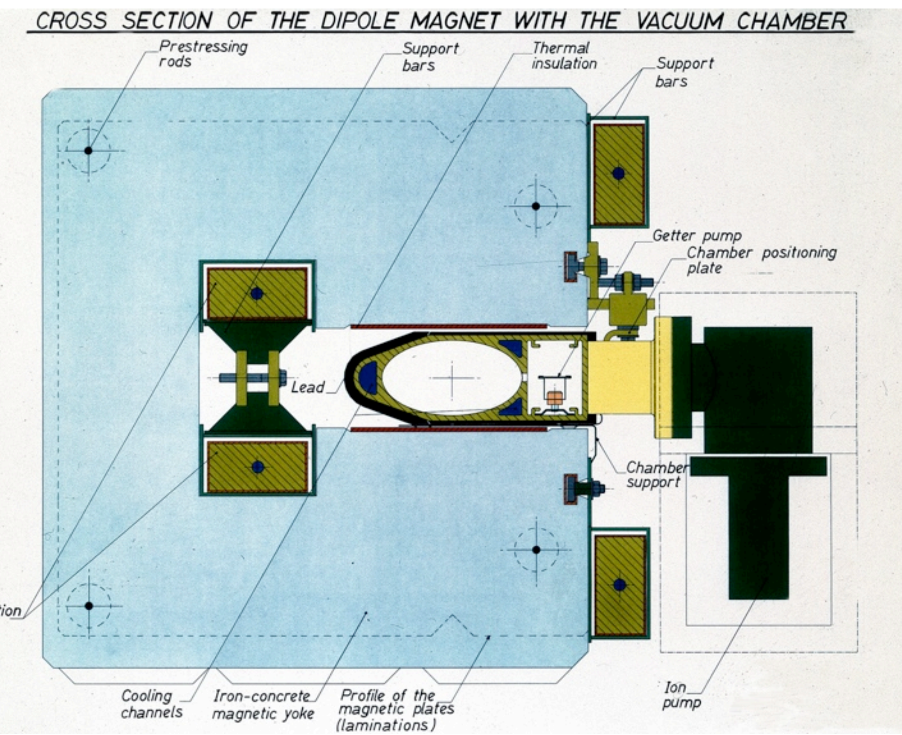


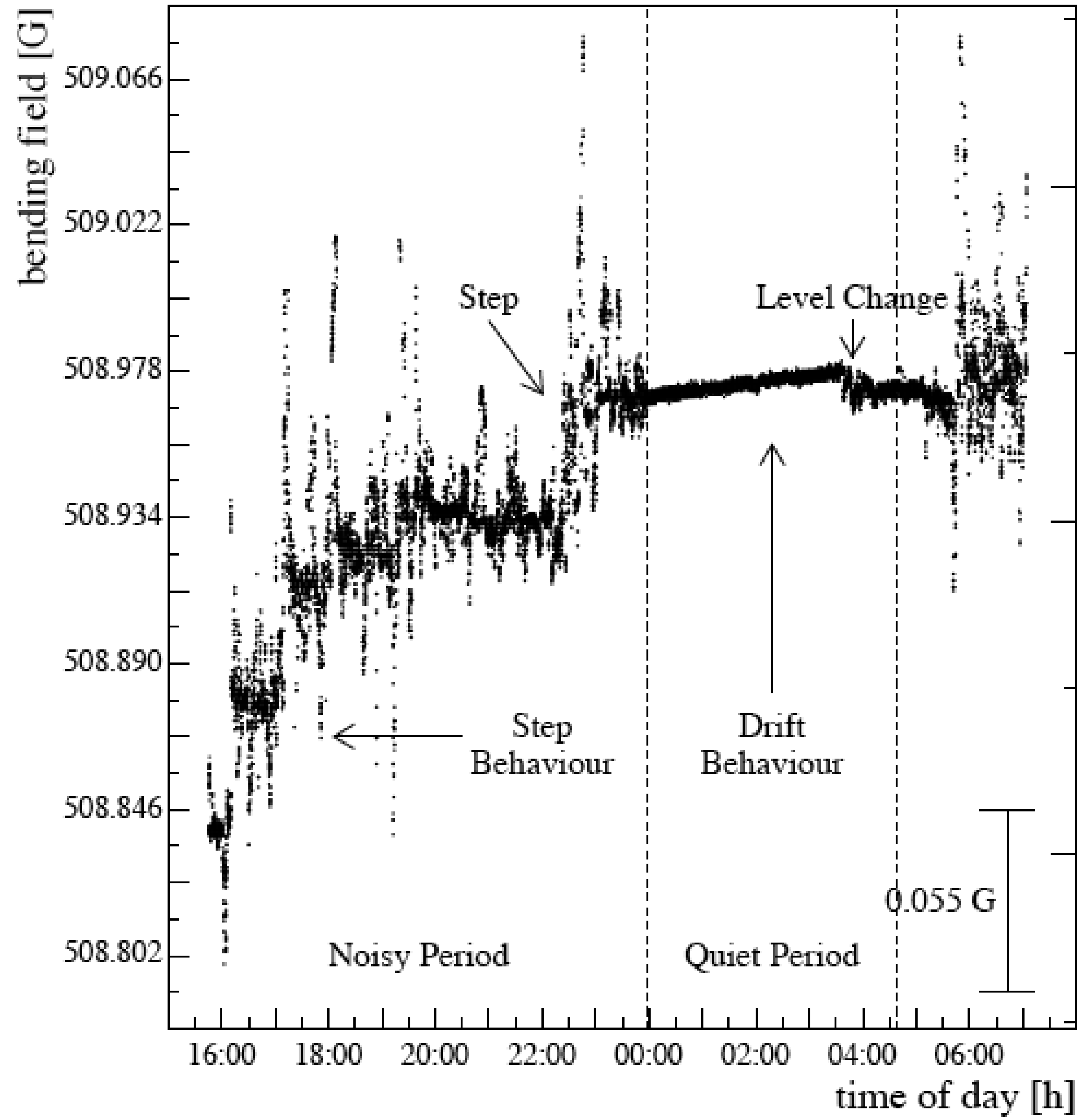


The effect is modulated by the different tide intensities and by the SUN tides

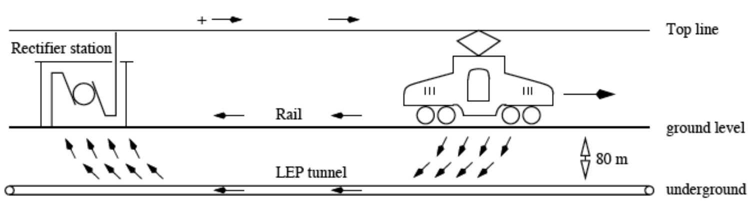
The problem: an accelerator is not in the middle of nothing

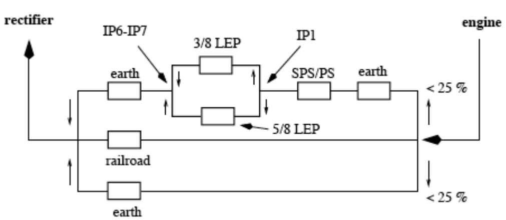
Observed variation of the bending strength of the LEP dipoles during the day

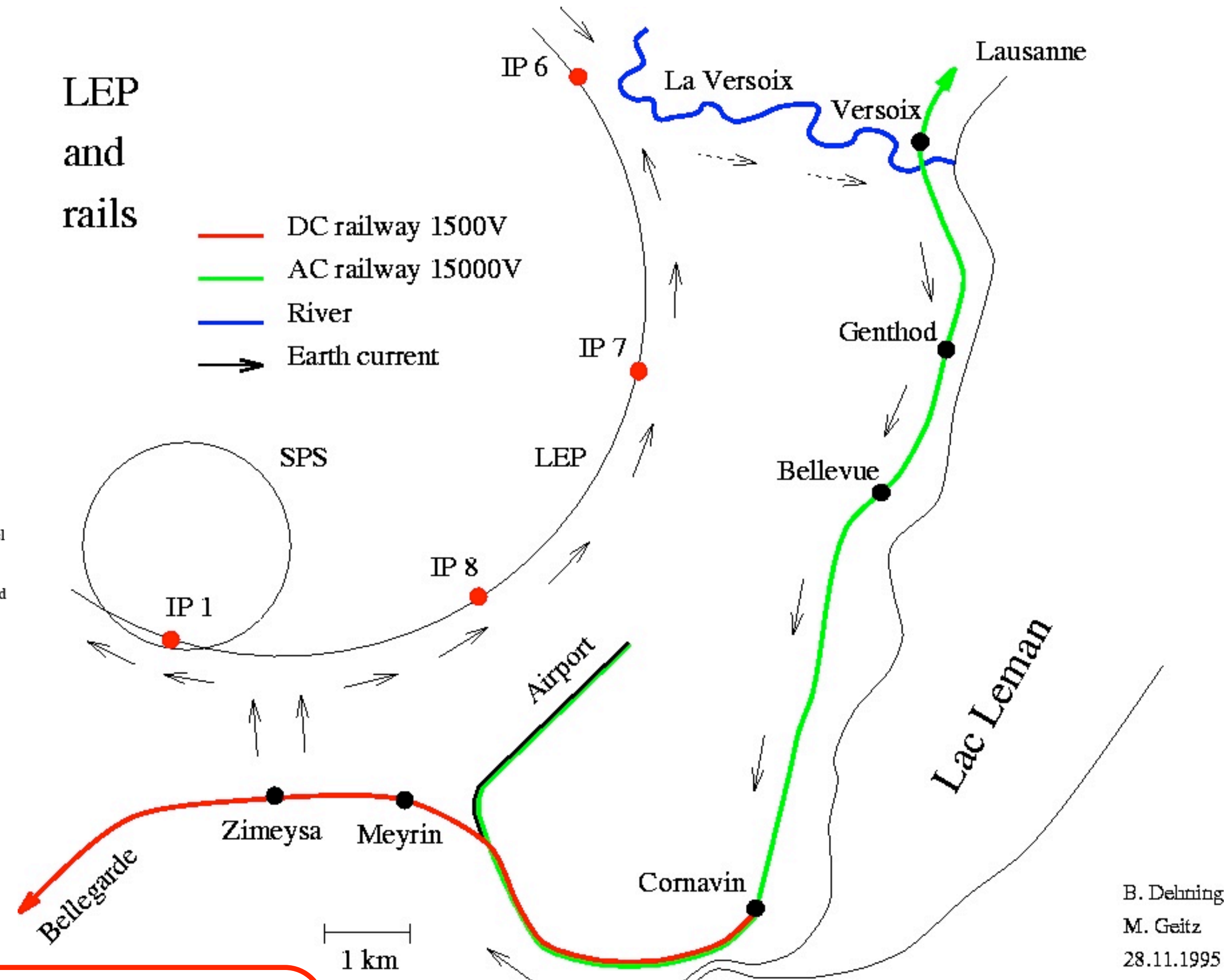




Influence of train leakage current

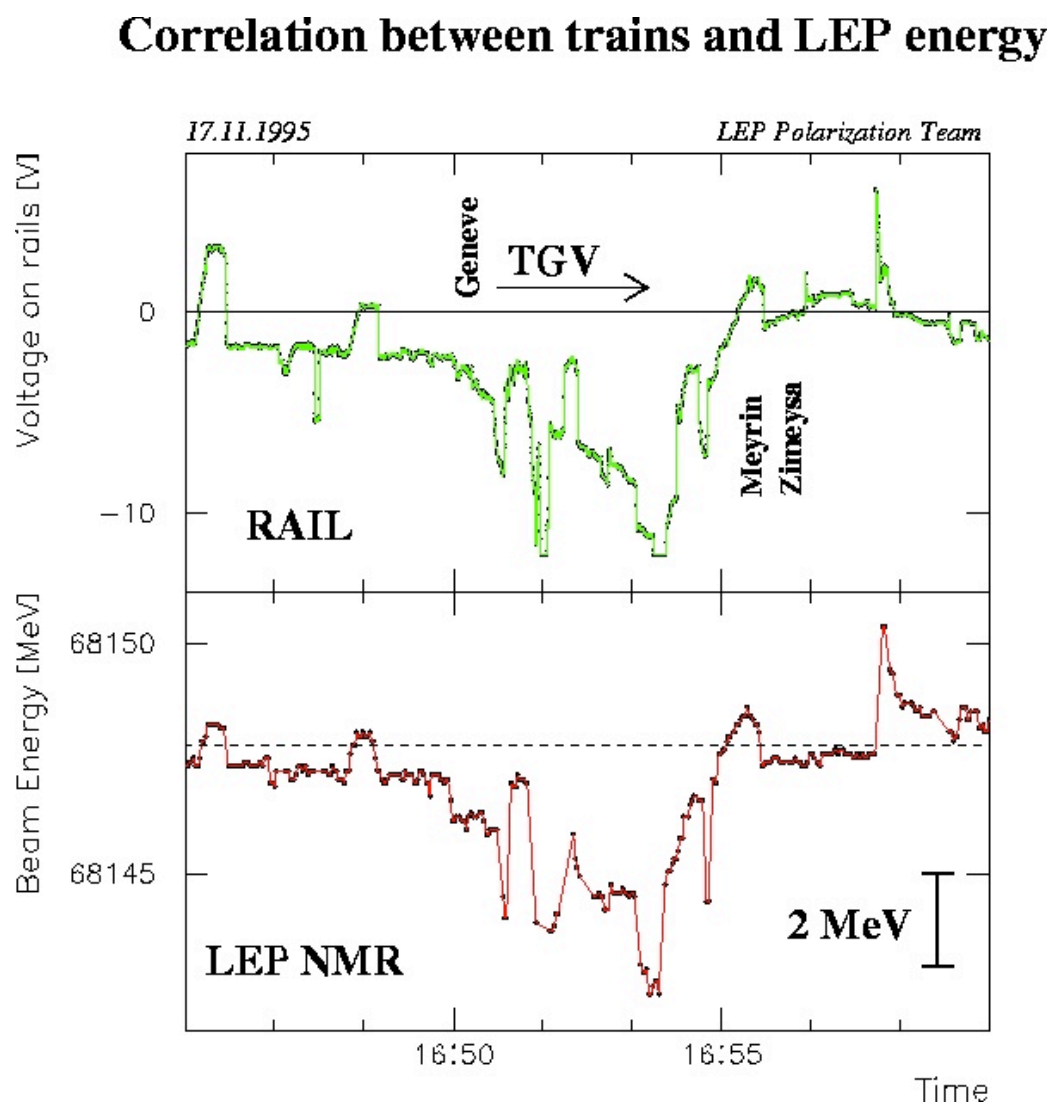






LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

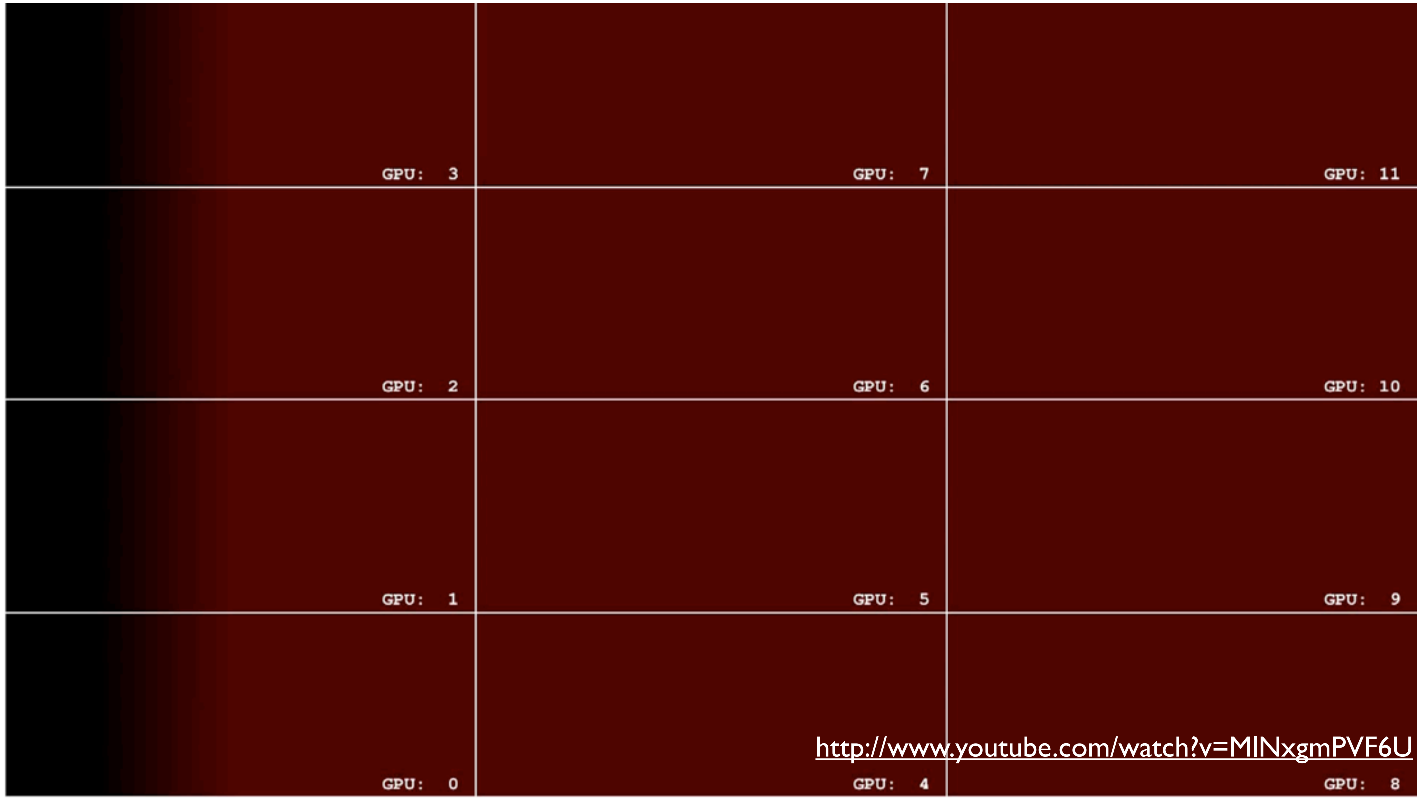
The evidence, TGV to Paris at 16:50 ...



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

- See Lucio's lecture plus ....

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



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

Thanks for your attention!!!