CERN Summer school 2009
Introduction to accelerators

by

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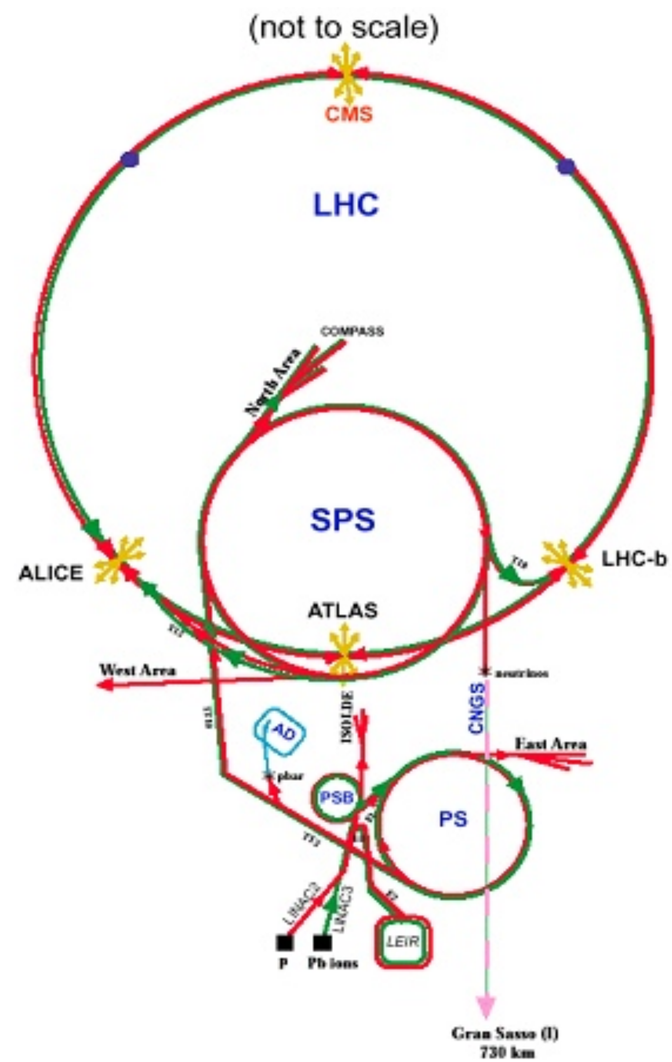
CERN BE-ABP

Lecture Summary

Lectures aim: provide a basics knowledge about accelerator physics, also on the technical point of view

Lecture Ia : Introduction, Motivations
Lecture Ib: History and Accelerator types
Lecture II: Transverse beam dynamics
Lecture IIIa: Longitudinal beam dynamics
Lecture IIIb: Beam Control
Lecture IV: Main limiting factors
Lecture V: Technical challenges



Blue: Simone
Red: Elias

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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 collinding in large accelerators to study the matter constituents and their interactions laws. **Does it look like the LHC ?**

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

PS will be 50 in November ...

High energy:

PS 26 10^9 eV (GeV)

LHC 7 10^{12} eV (TeV)

Large accelerators:

PS ~628 m (cir.)

LHC ~ 27 km (cir.)

Colliding:

PS fix target exp.

LHC real collider

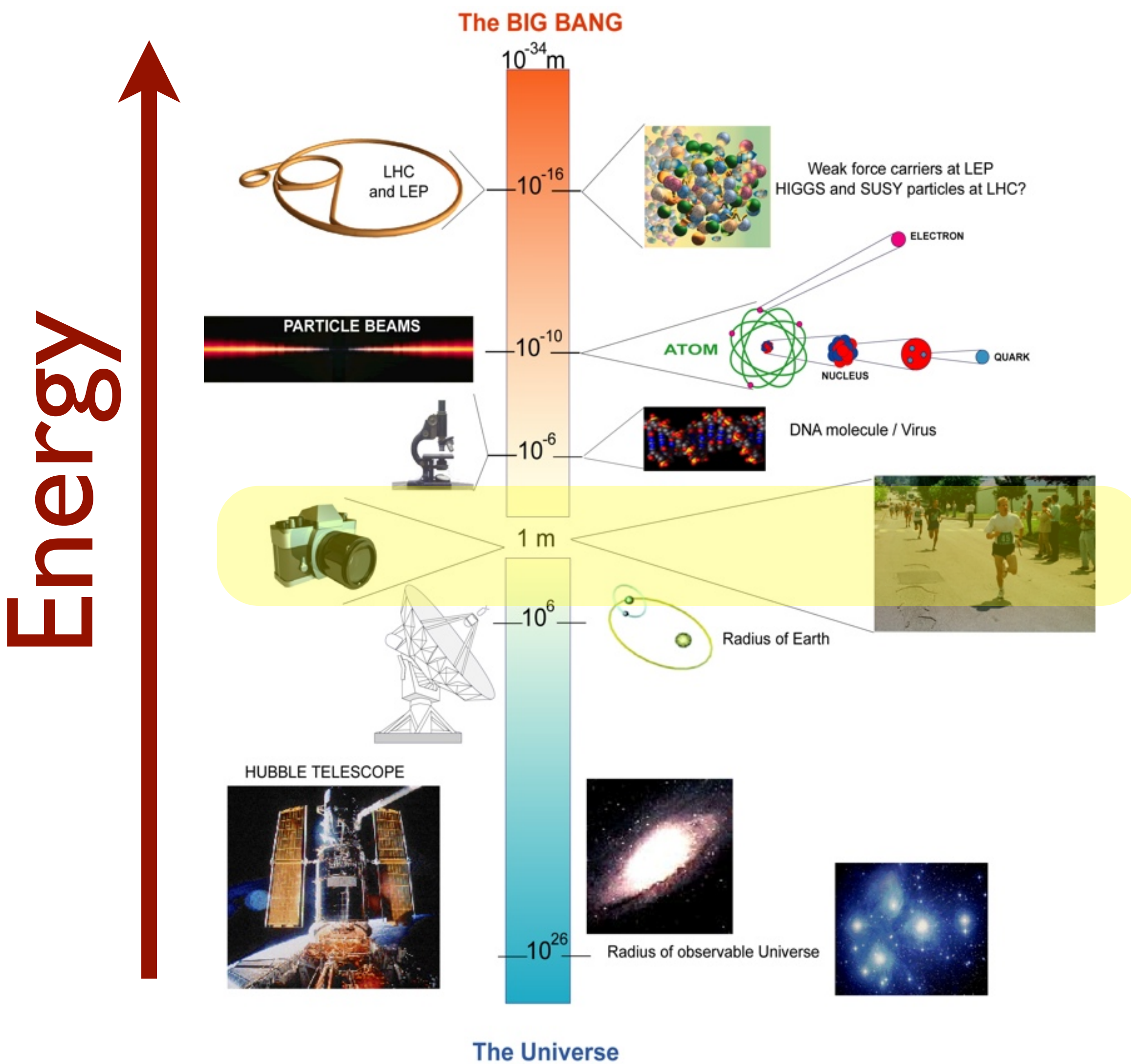
Interactions laws:

PS discovery neutral currents

LHC hopefully the Higgs (+)

Why high energies? Why large accelerators? Colliding means what?

The right instrument for a given dimension



Wavelength of probe radiation should be smaller than the object to be resolved

$$\lambda << \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy of Radiation
Atom	10^{-10} m	0.00001 GeV (electrons)
Nucleus	10^{-14} m	0.01 GeV (alphas)
Nucleon	10^{-15}m	0.1 GeV (electrons)
Quarks	?	> 1 GeV (electrons)

Radioactive sources give energies in the range of MeV

Need accelerators for higher energies.

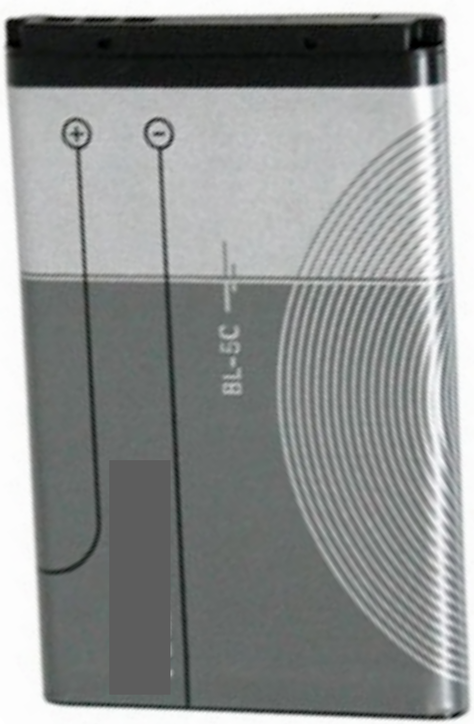
"electronic eyes"

The typical energy of our life is eV

So, how we can reach the energy/dimension of the big bang?

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 → 3.7 eV energy of e- from one electrode to the other

Height: 4.5 cm

proton mass ~ 1 10^9 eV

To accelerate an electron to an energy equivalent to a proton mass:

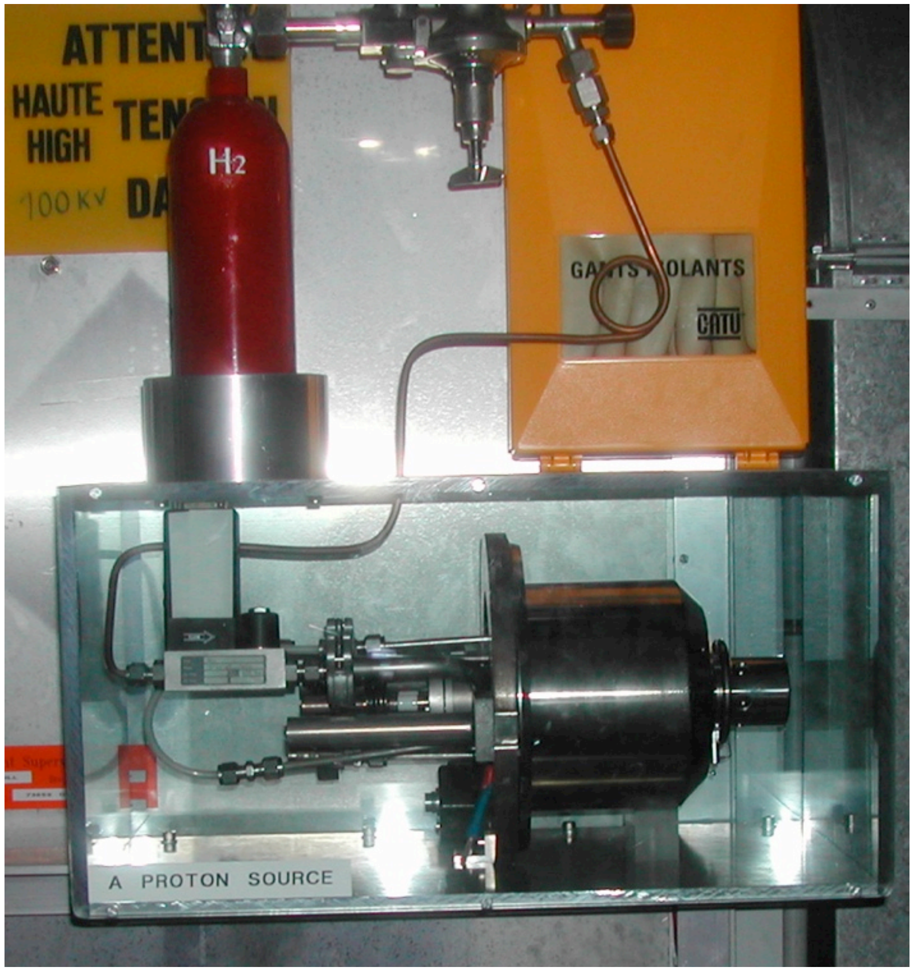
1 GeV/3.7 eV = 270 270 270 batteries

270 270 270 batteries * 0.045 m ~ 12 000 000 m

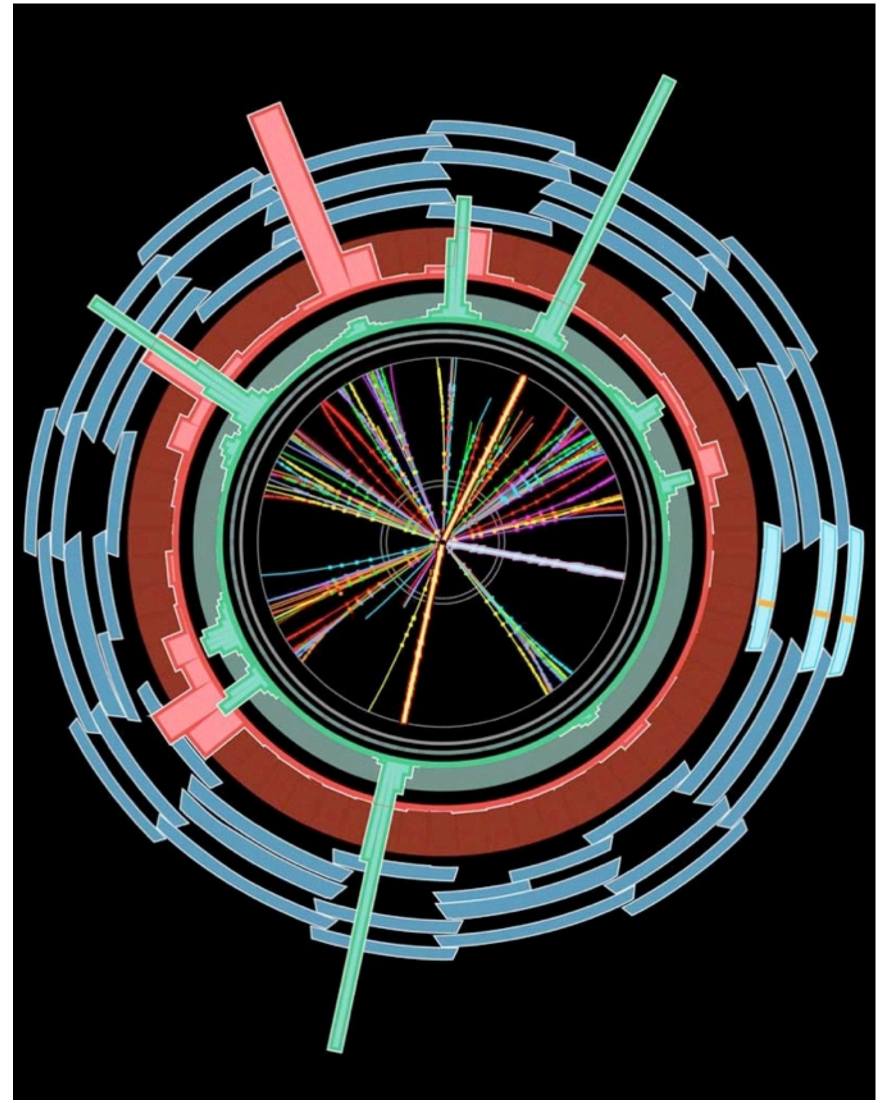
12 000 000 m ~ THE EARTH DIAMETER

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

Basically we want to bring you ...



from nearly a bottle of hydrogen

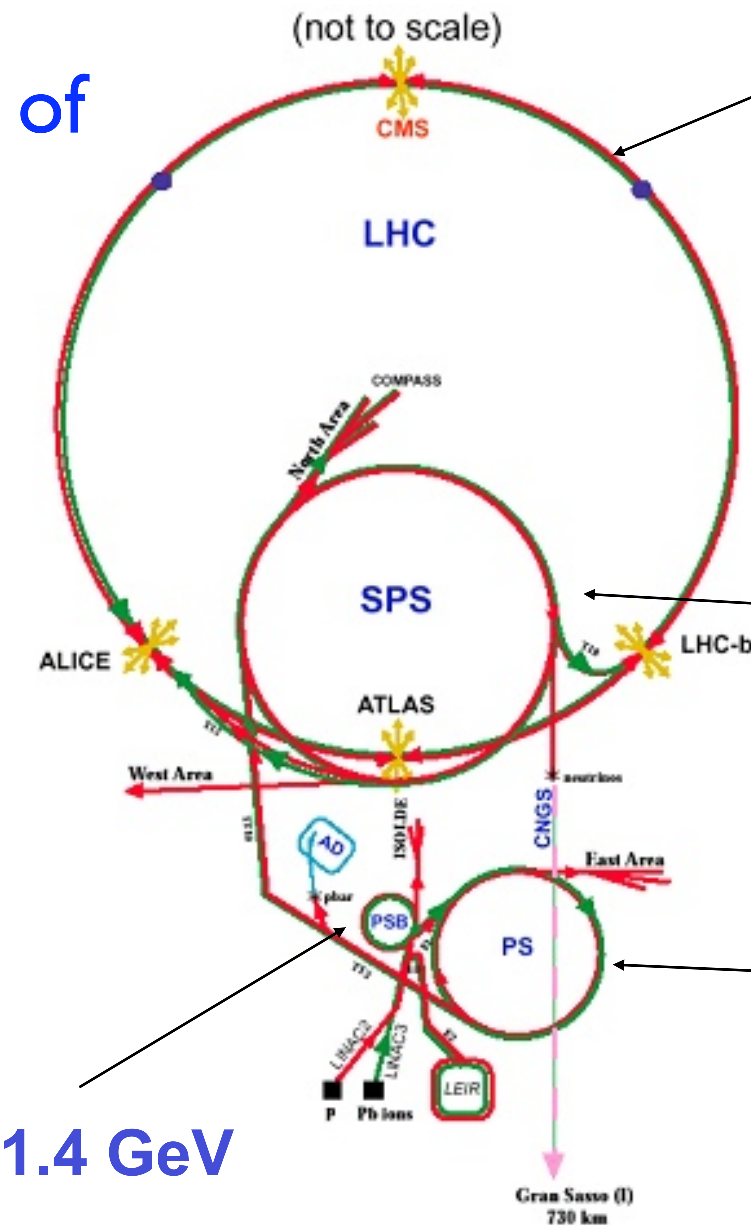


to a little bit before this

through the history of this science, the theory,
the technological challenges and the applications

CERN accelerator complex overview

Chain/sequence of accelerators

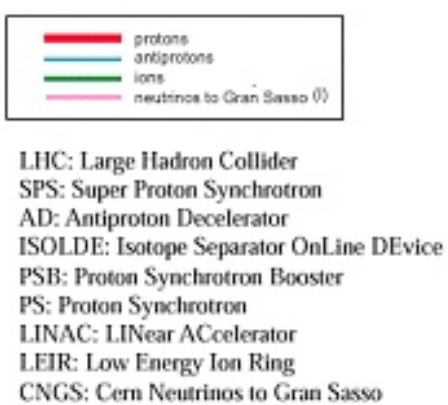


450 GeV /c – 7 TeV /c

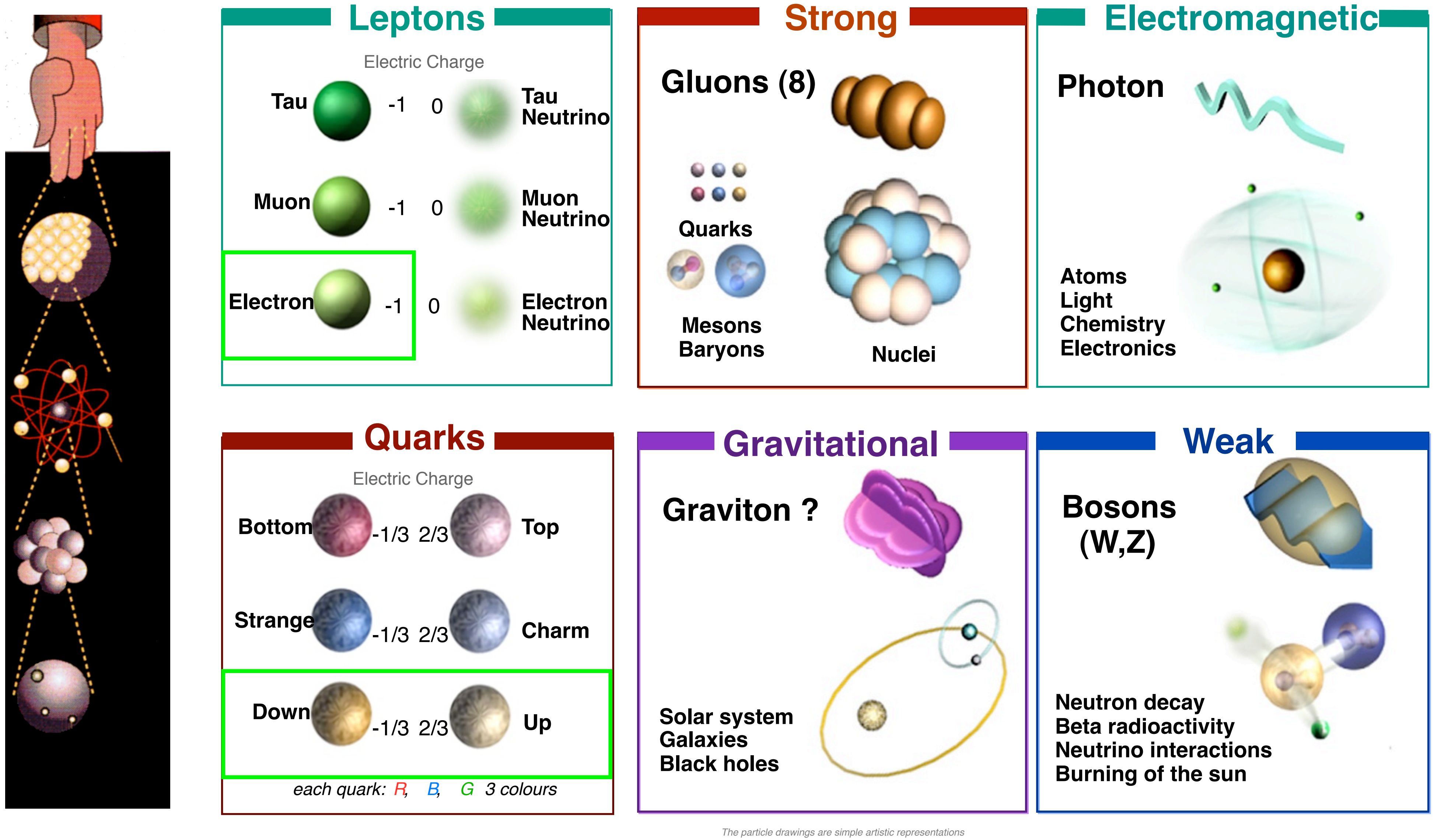
26 - 450 GeV/c

1.4 GeV – 26 GeV/c

50 MeV – 1.4 GeV



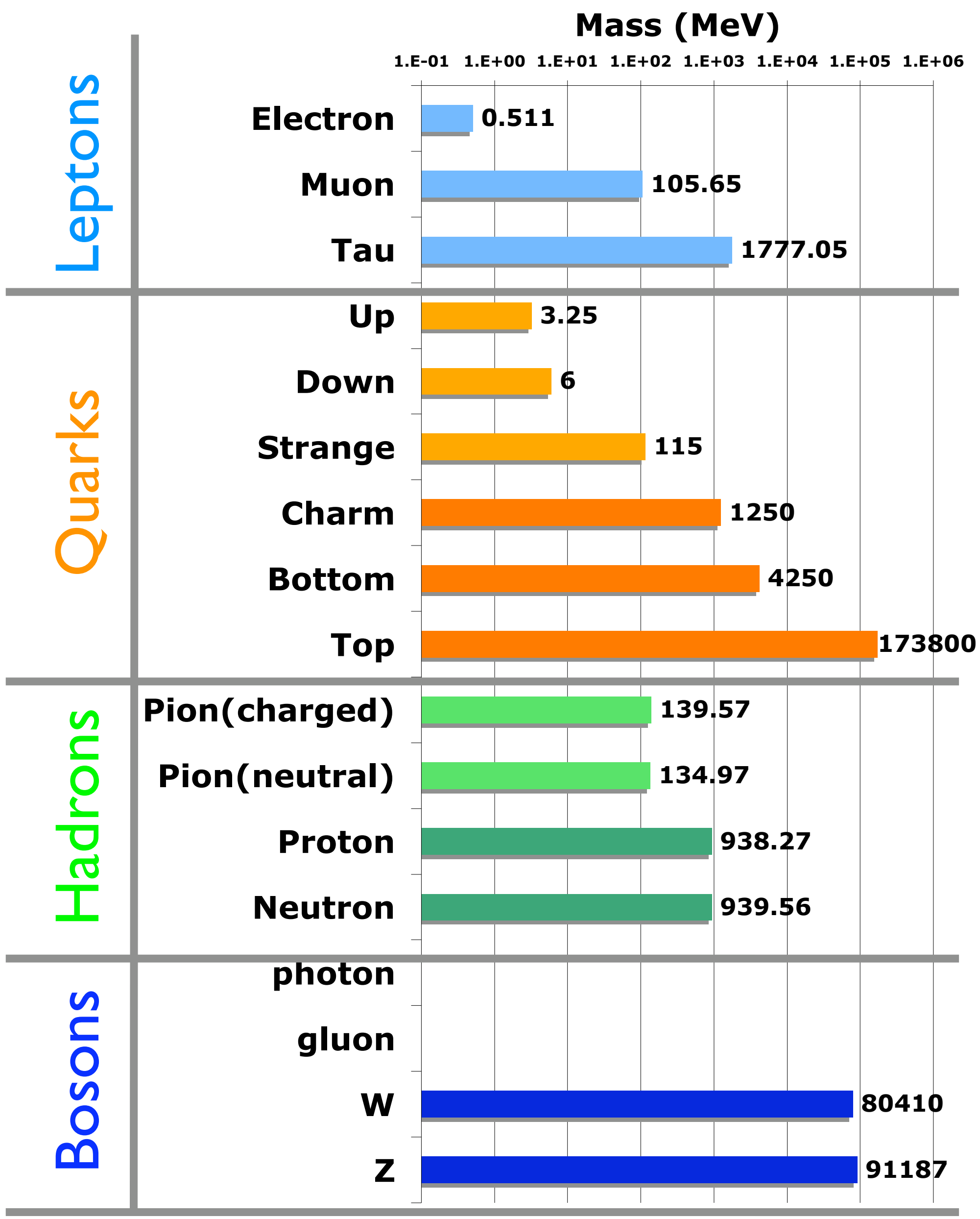
Matter constituents and interaction laws, the actors of our play



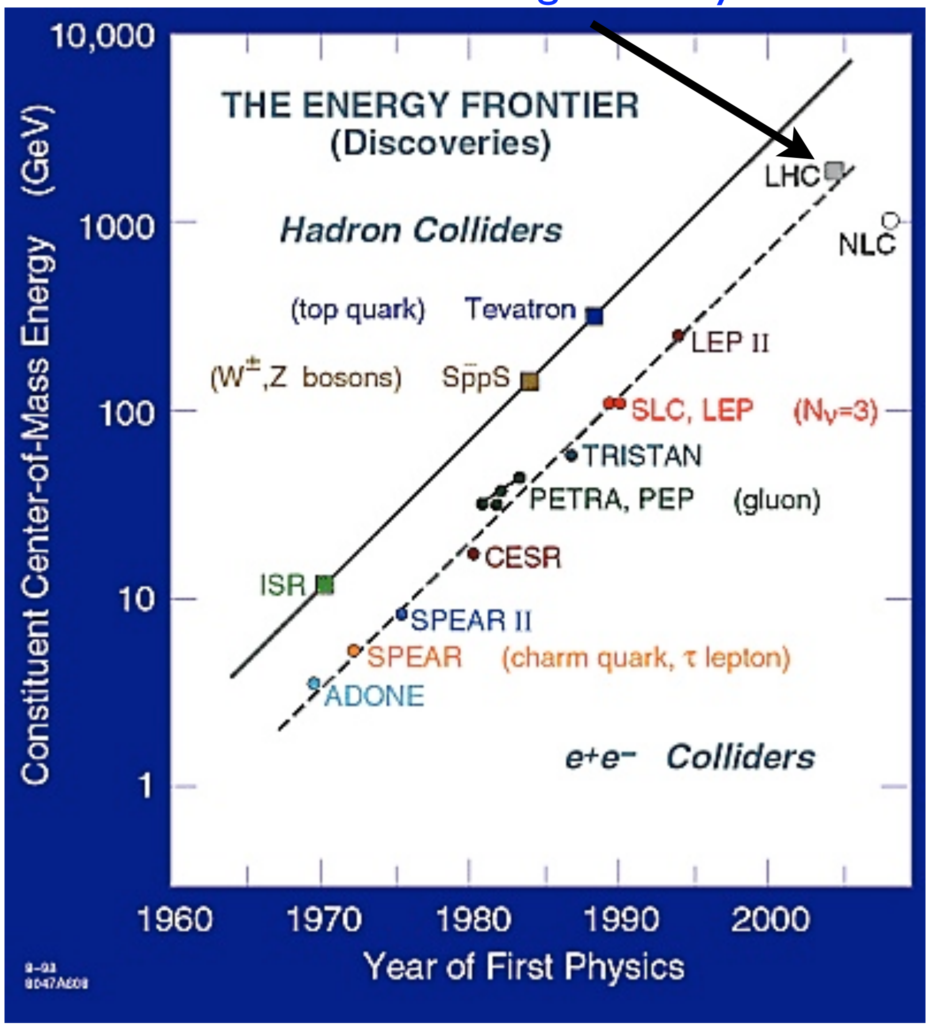
We need **enough energy** to produce directly the different particles, **at least their mass**

We need **enough intensity** (i.e. particle interactions) **to produce enough particles**

History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe

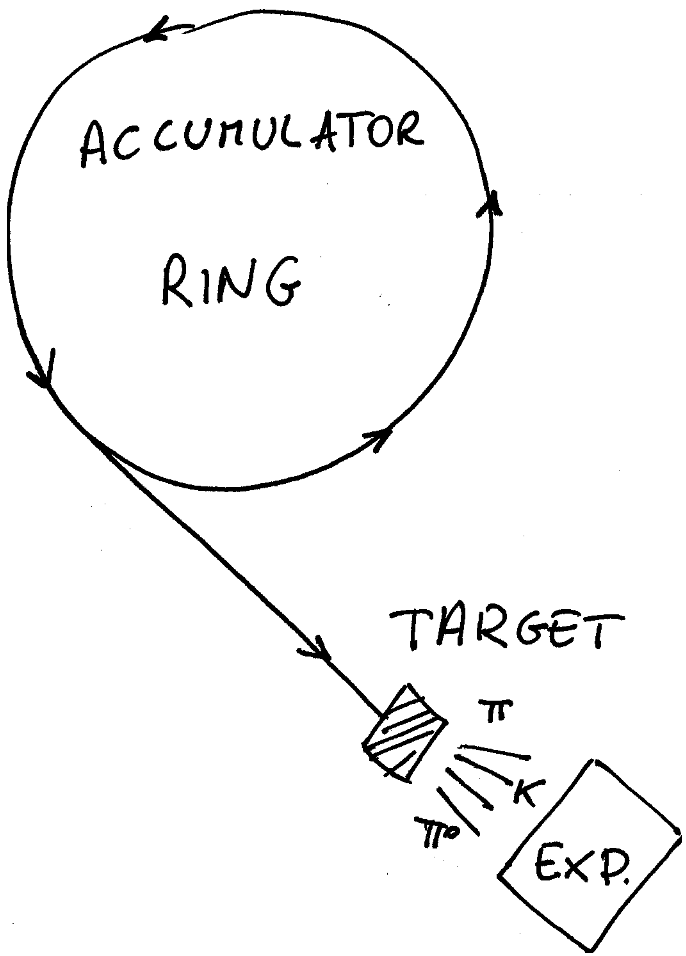


Behind the history plot is hidden the technological development required for each step

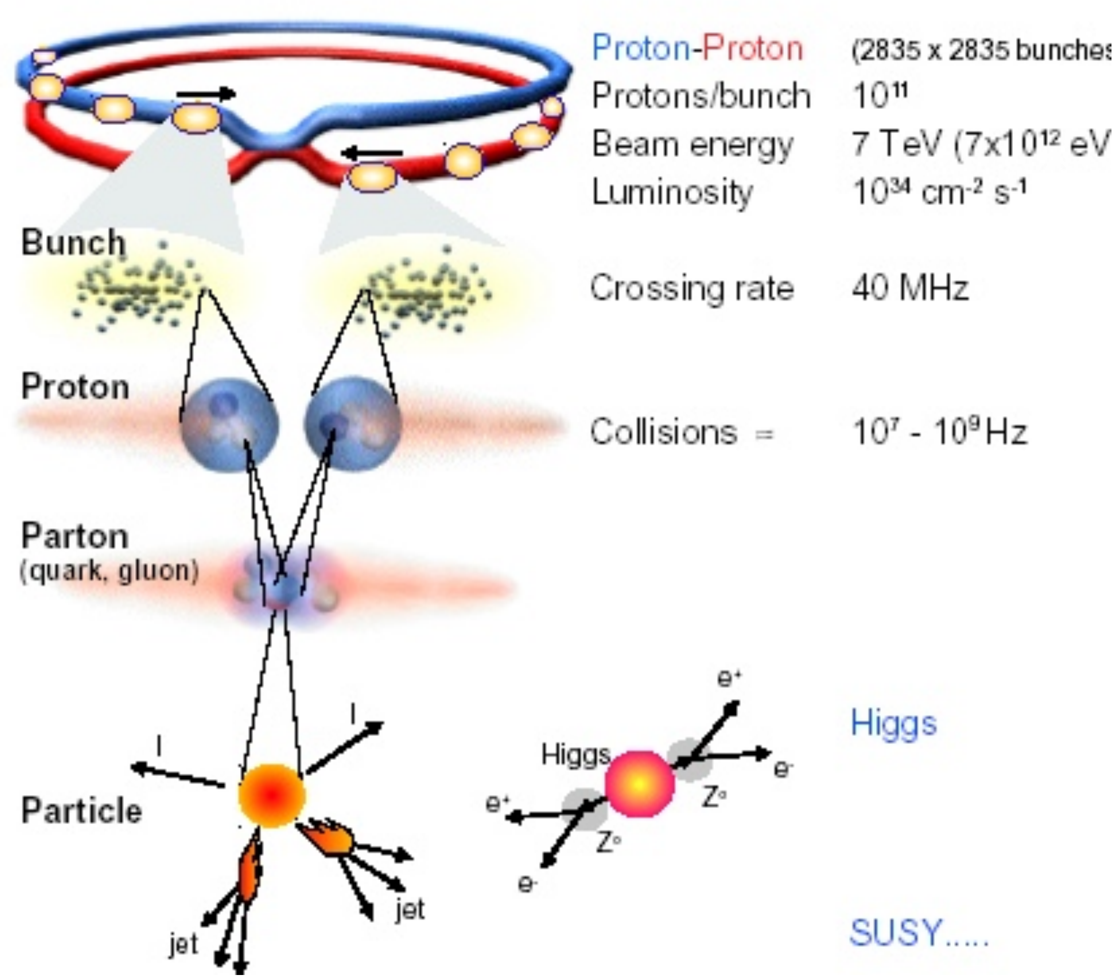
Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either p-$\bar{p}$ as Tevratron, p-p as LHC)

Different approaches: fixed target vs collider

Fixed target

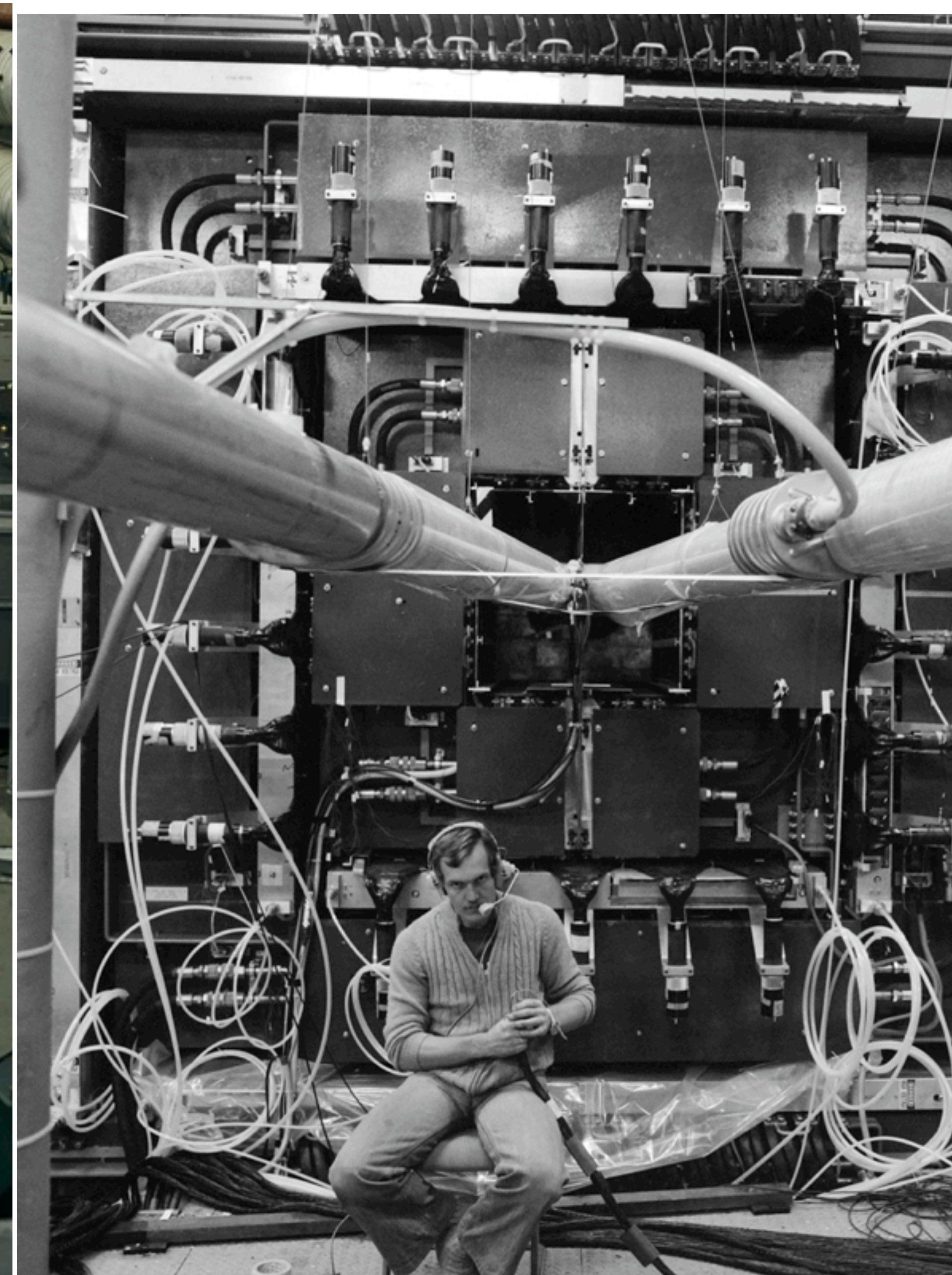


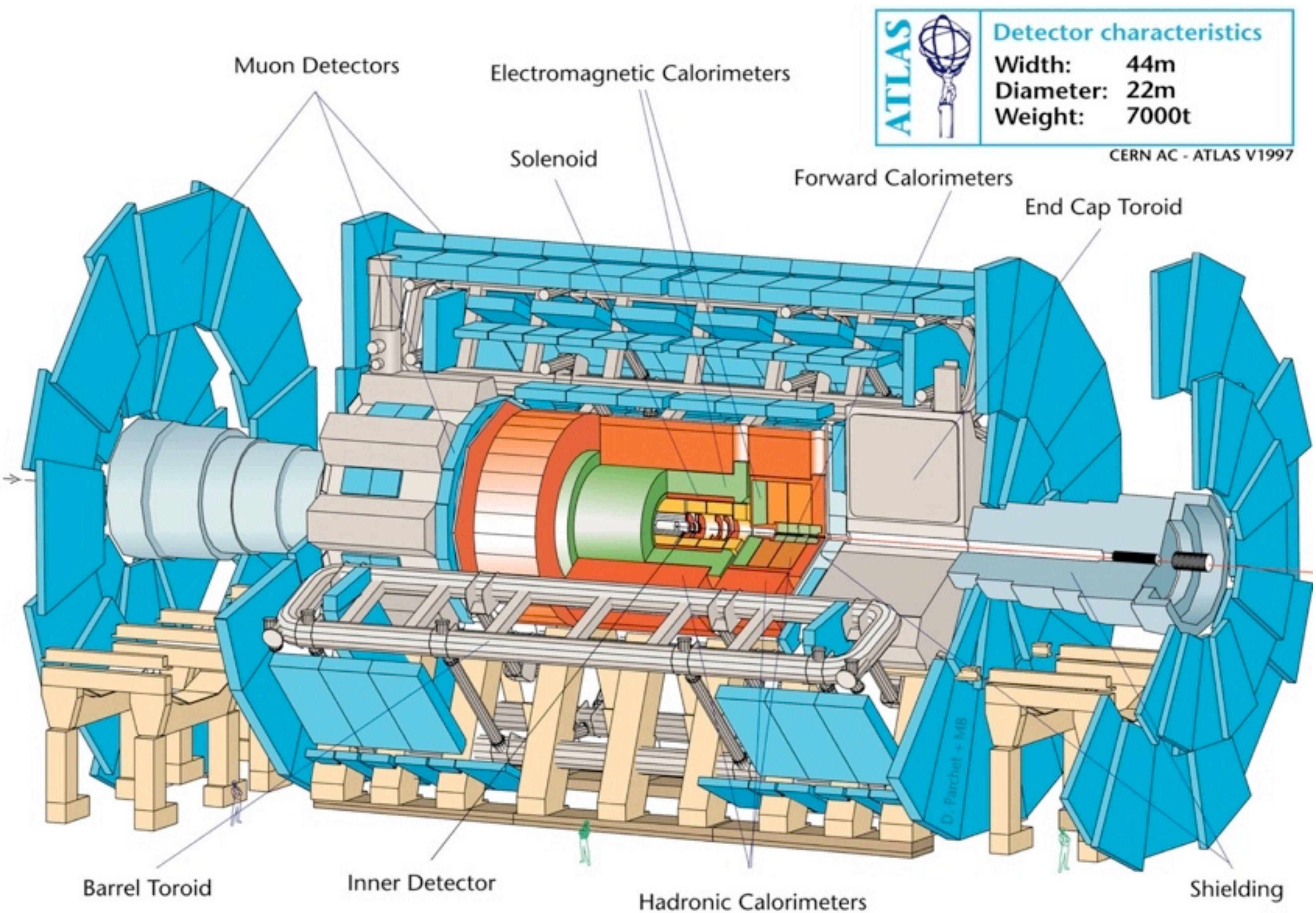
Storage ring/collider



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

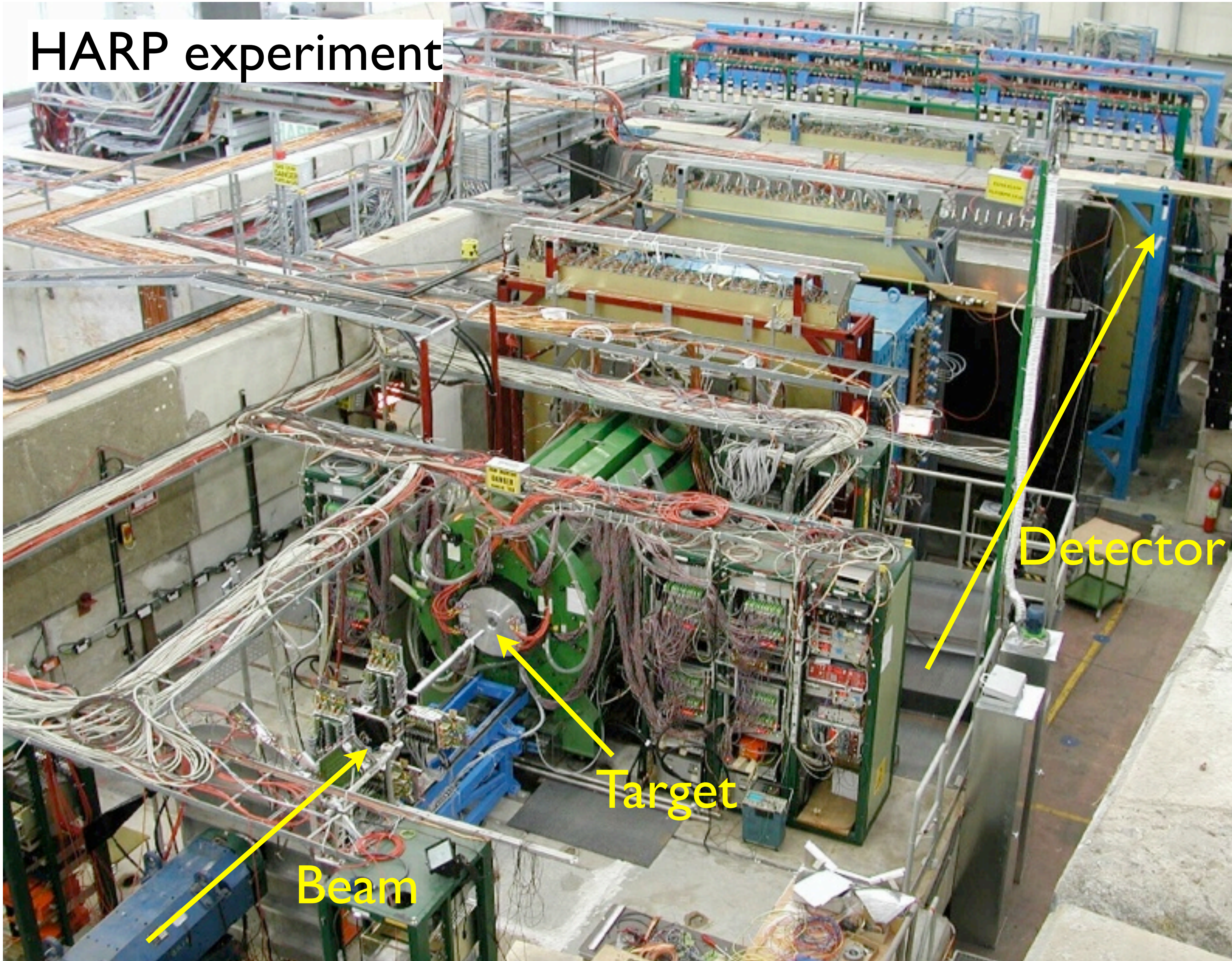
ISR: first proton-proton collider



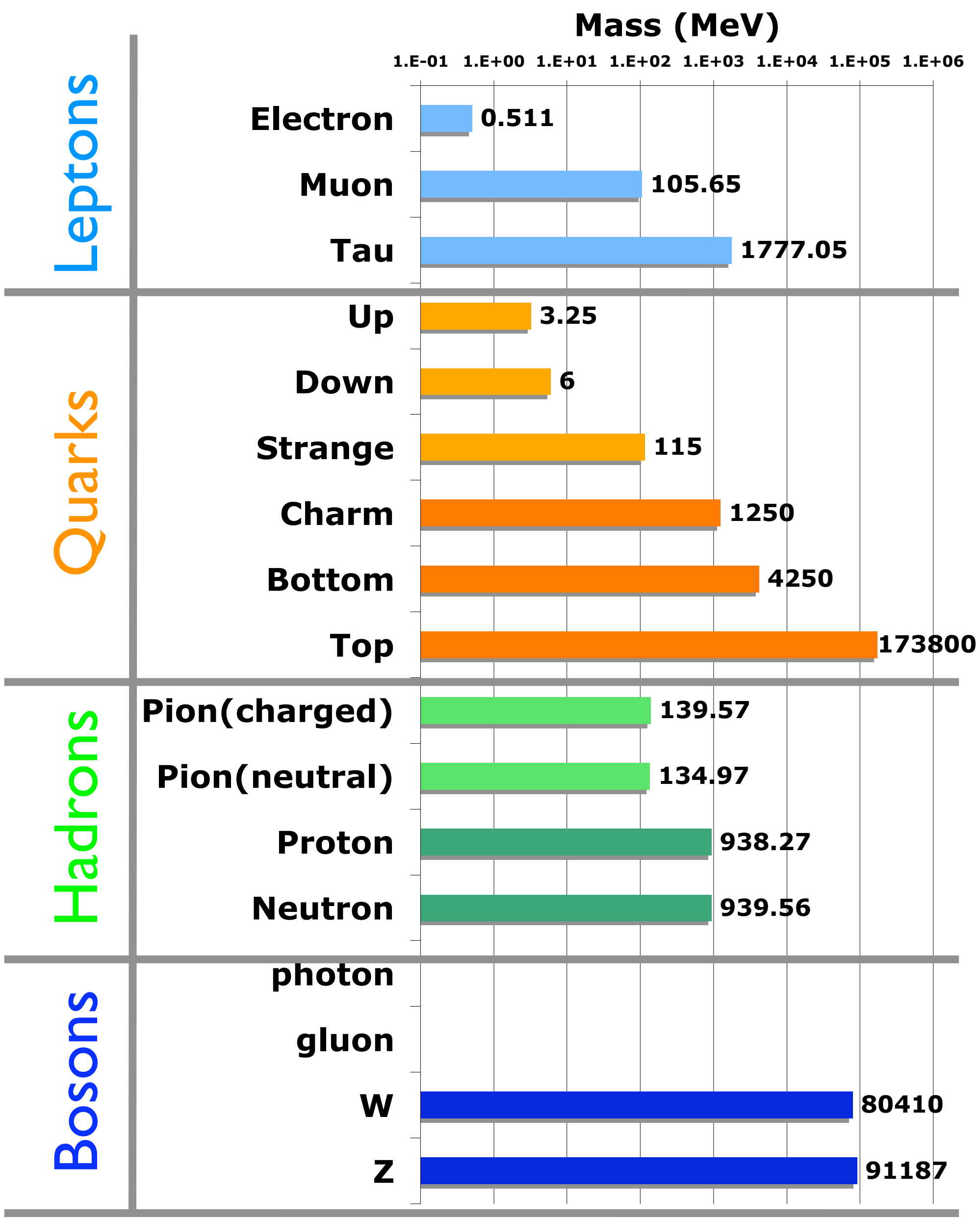


Detector characteristics
ATLAS
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

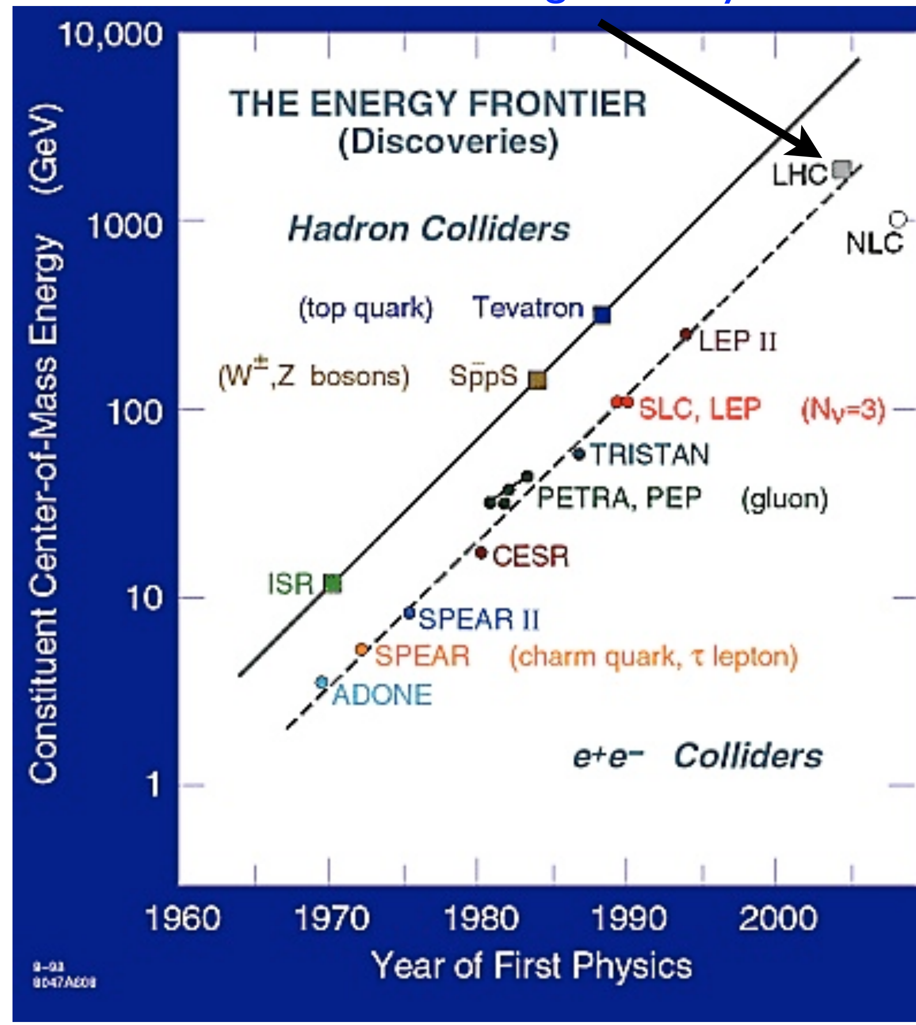
HARP experiment



History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe

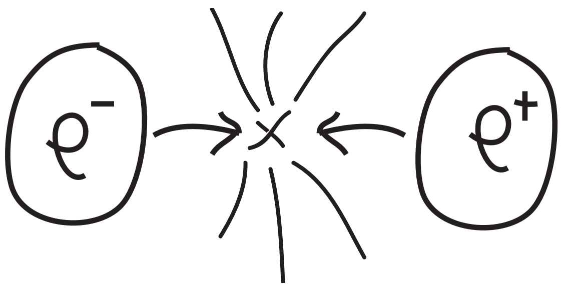


Behind the history plot is hidden the technological development required for each step

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

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

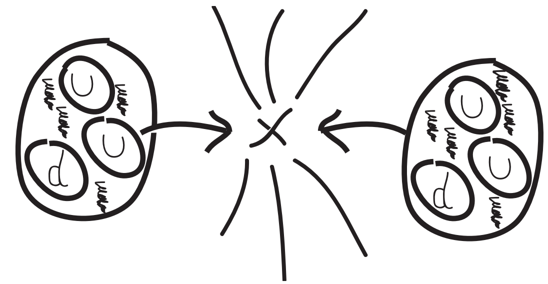
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

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

Precision measurement (LEP)

<u>Cons:</u> above a certain energy is no more convenient to use electron because of too high <u>syncrotron radiation</u> (last lecture)

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 < 2Eb

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

Discovery machine (LHC)

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

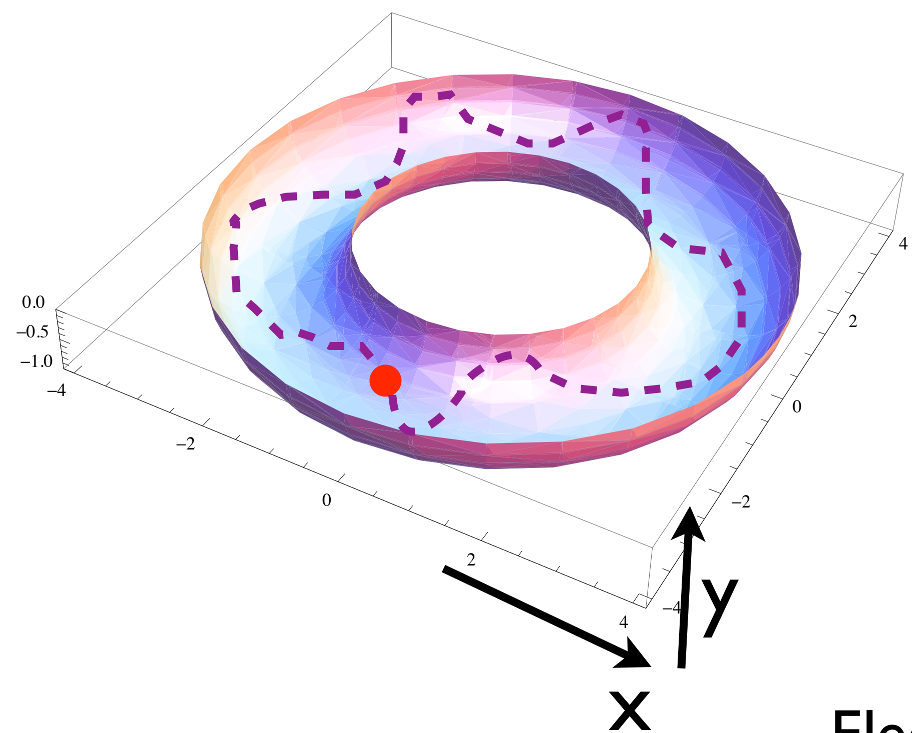
Synergy between accelerators and particle physics

- First prove that the ***antiproton life time has to be comparable to the one of the protons*** (from CPT theorem) came from the ICE storage ring in 1978 (ICE does not exists anymore...)
  - Antiproton lifetime before ICE experiment: 1.2 10^-4 s
  - About 240 antiprotons stored for 85 h, the final intensity of about 80 antiprotons due to Coulomb scatting on residual gas.
    - Estimated final lifetime: about 32 h in the rest frame.

- This experiment also opened the era of the p-$\overline{\text{p}}$ collider which required storage time of about 24 h.

See Phys. Lett. 78B, 1 pag.174, you will find 2 nobel prices in the author list

How an accelerator works ?



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

How ? Lorentz Force!

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

Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

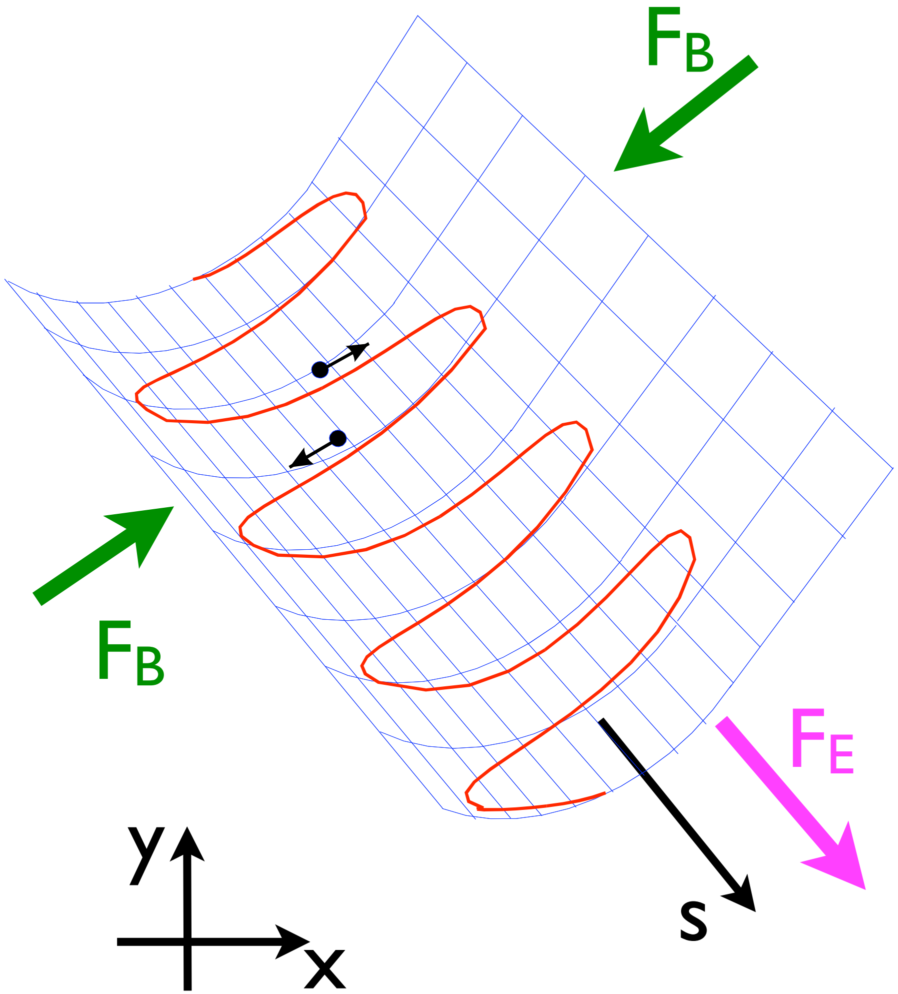
*An **accelerator** is formed by a sequence (called **lattice**) of:*

a) Magnets

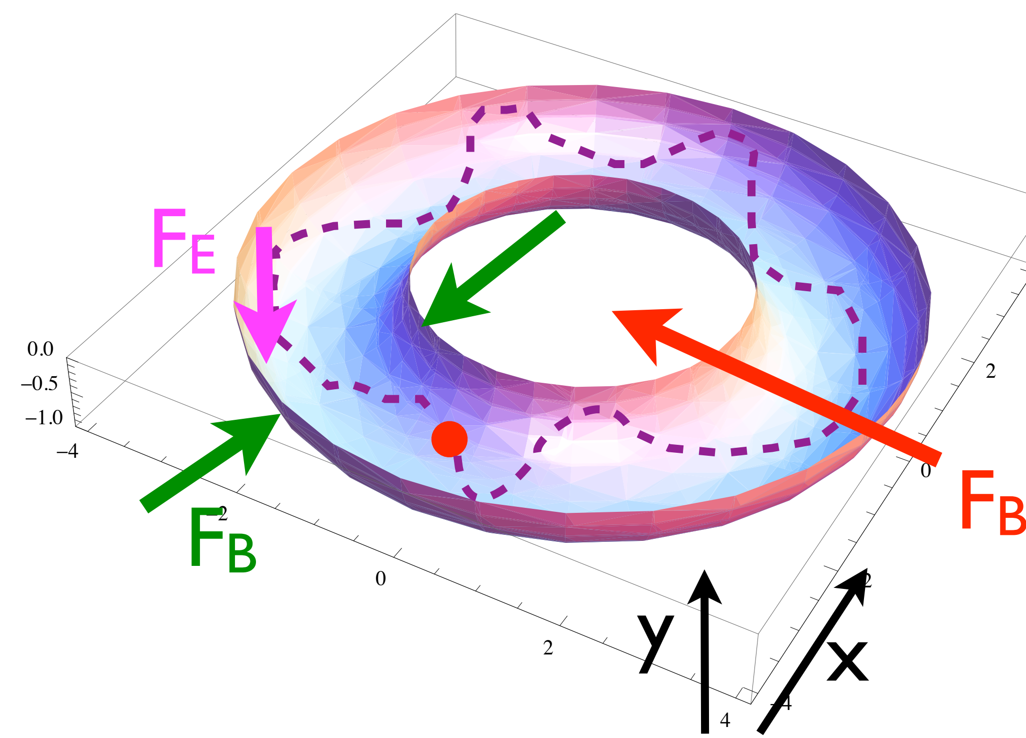
b) Accelerating Cavity

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

Linear Accelerator

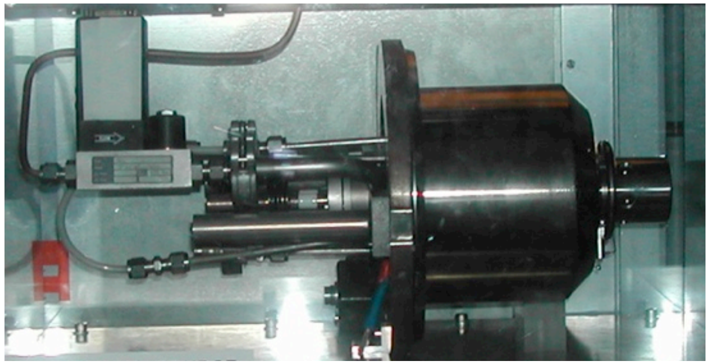


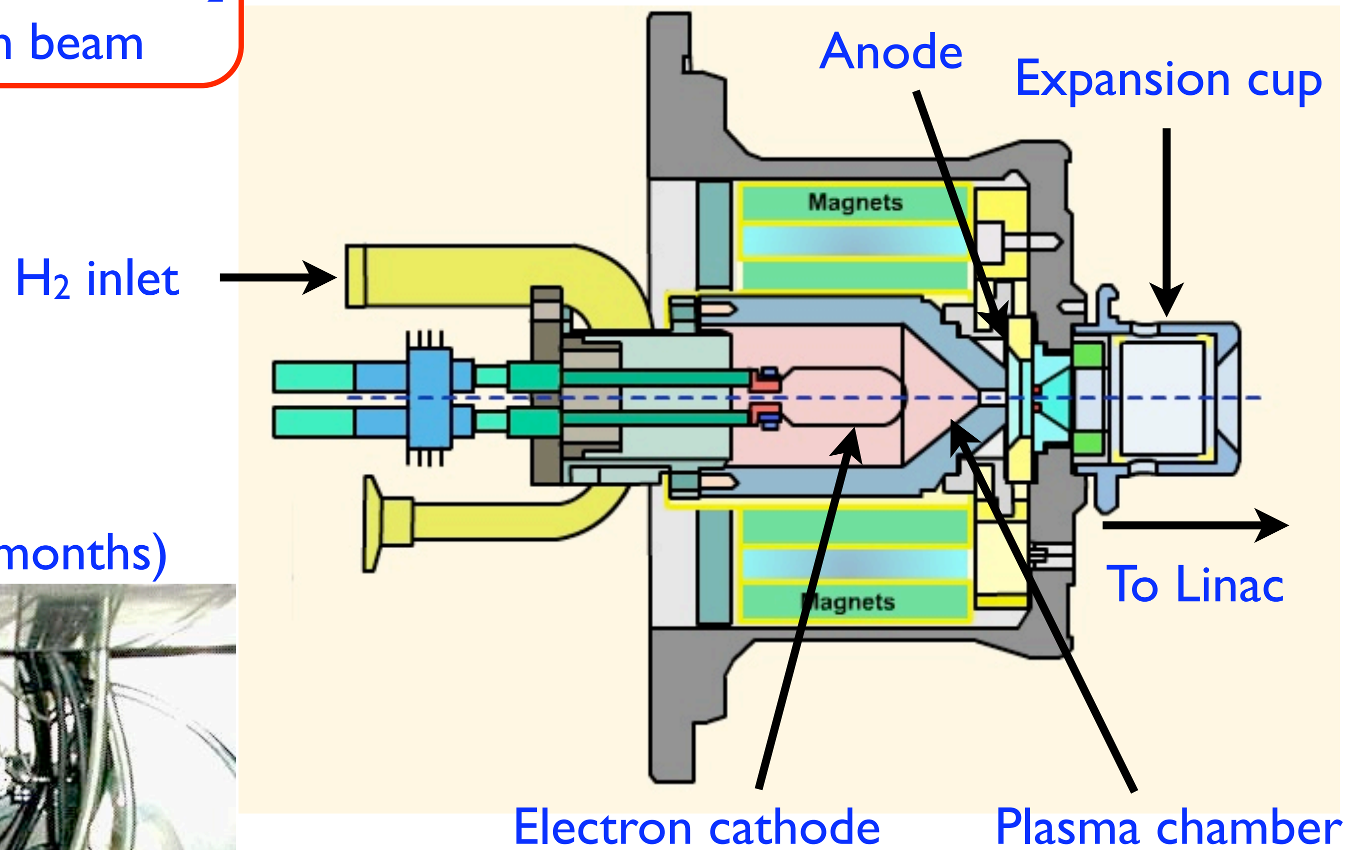
Circular Accelerator



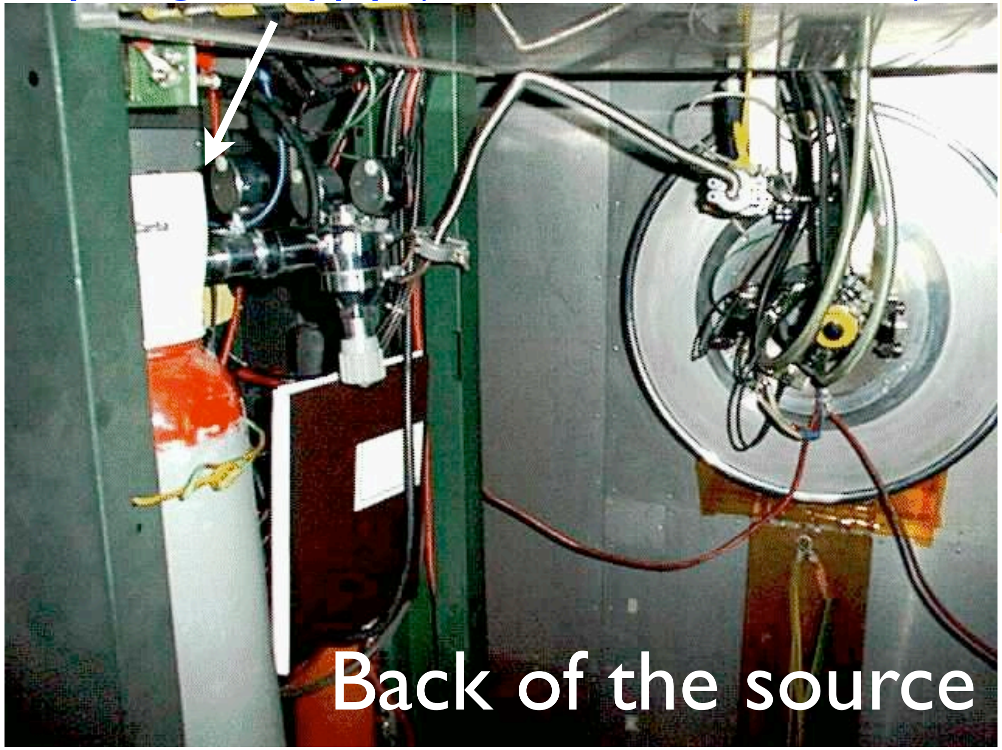
How to get protons: duoplasmatron source

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





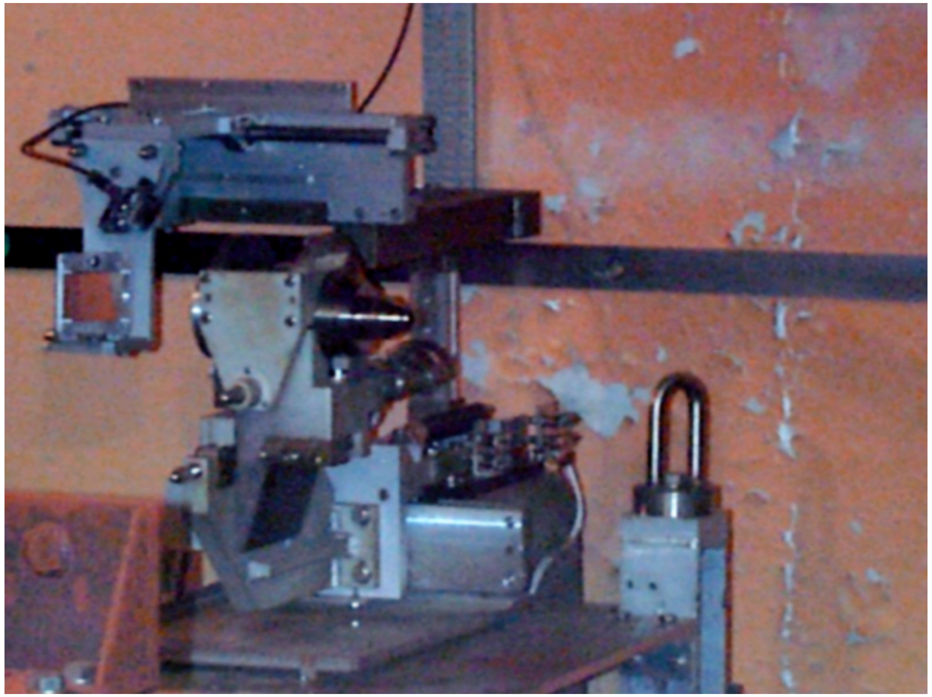
Hydrogen supply (one lasts for 6 months)

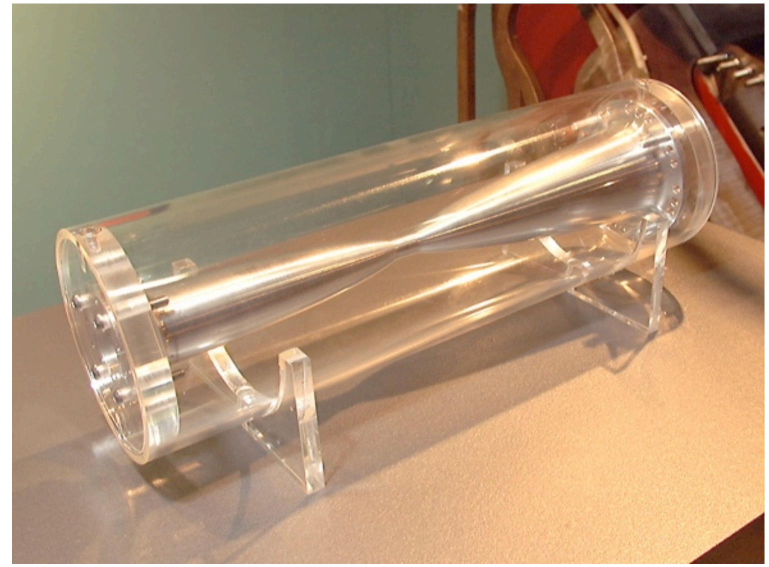


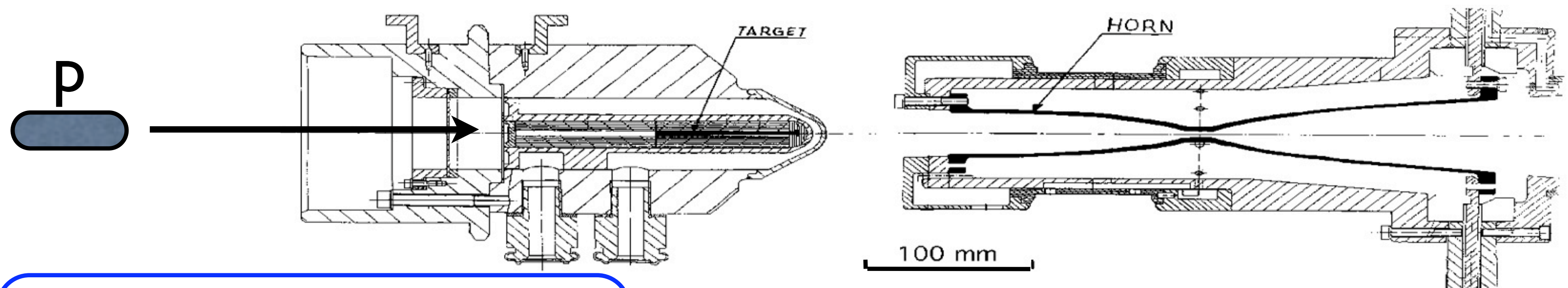
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, $v \approx 4000$ km/s

The SPACE SHUTTLE goes only up to 8 km/s

How to get antiprotons





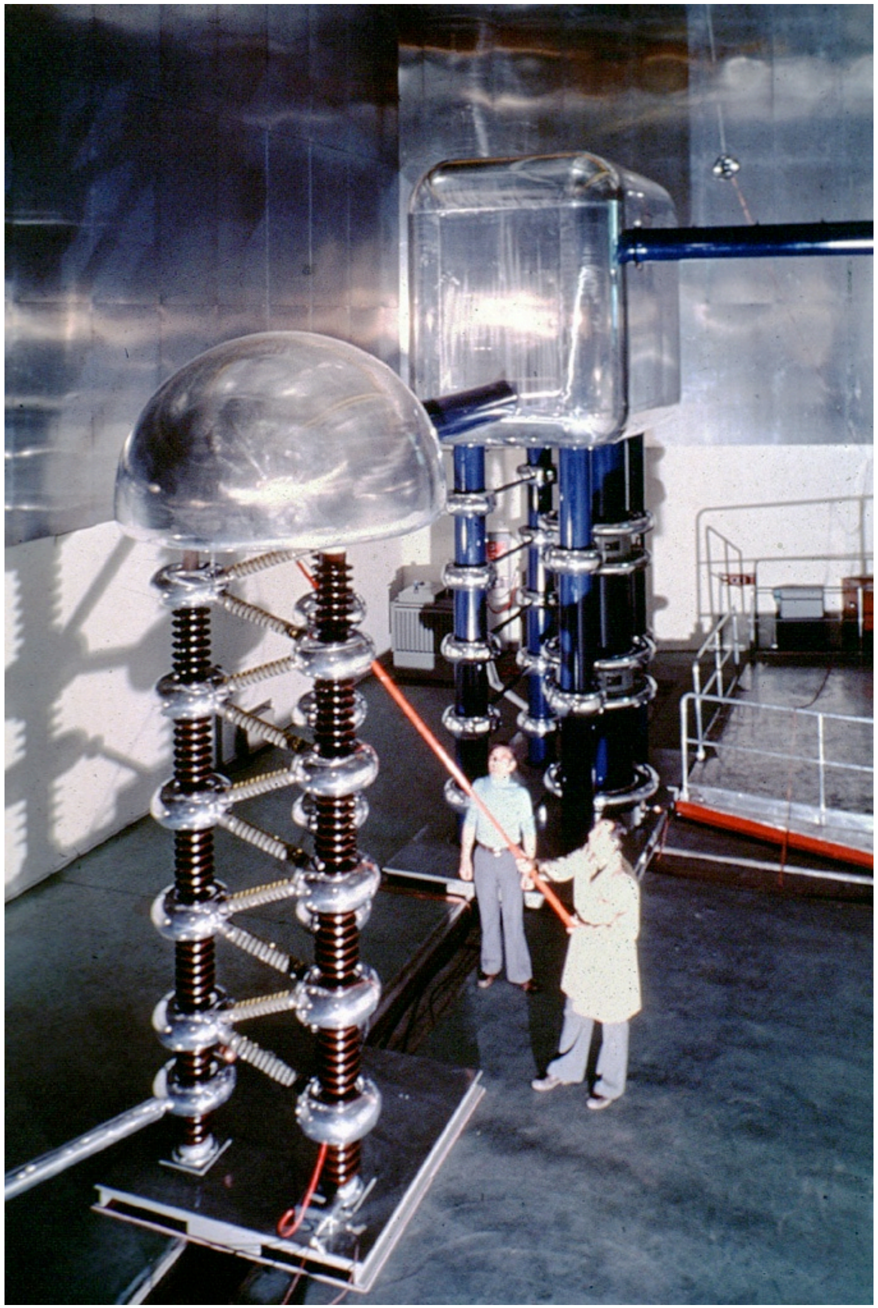


Starting from high energy p and with a very low efficiency

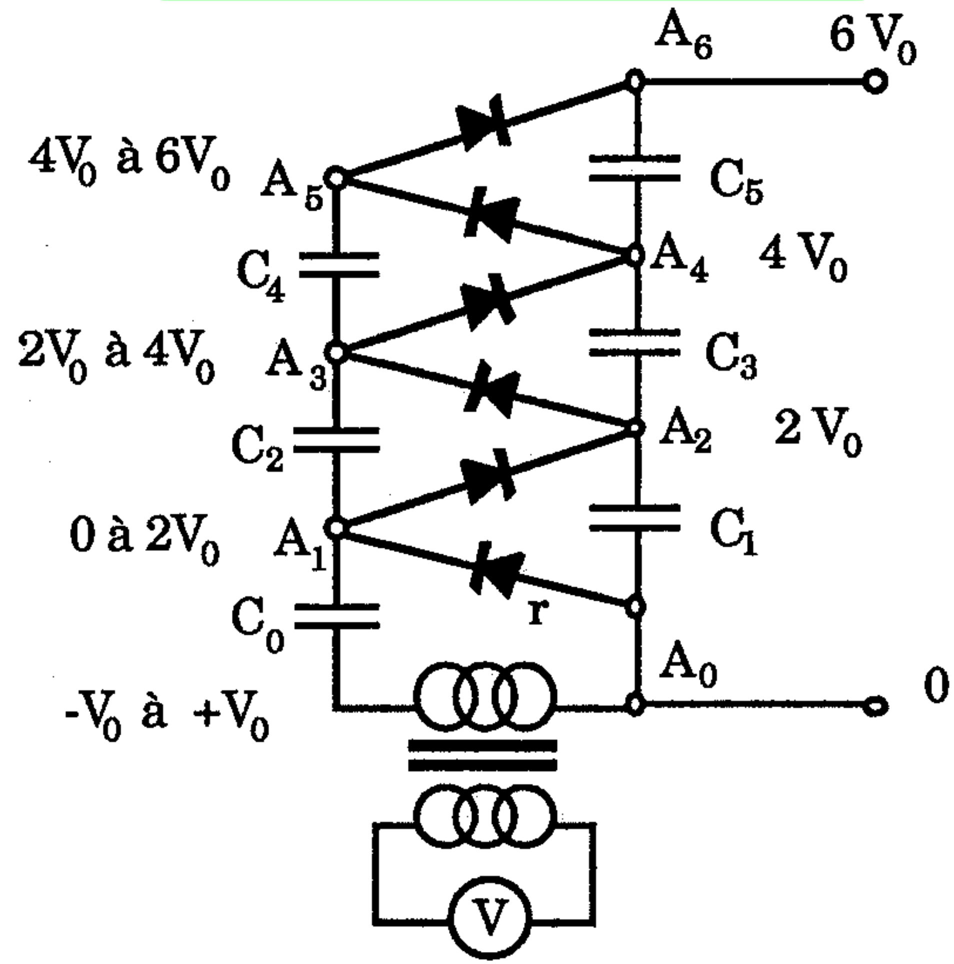
$$p + p \rightarrow p + p + p + \bar{p}$$

See lecture on Antimatter

Cockroft-Walton. Old CERN proton pre-injector



High voltage unit composed by a multiple rectifier system



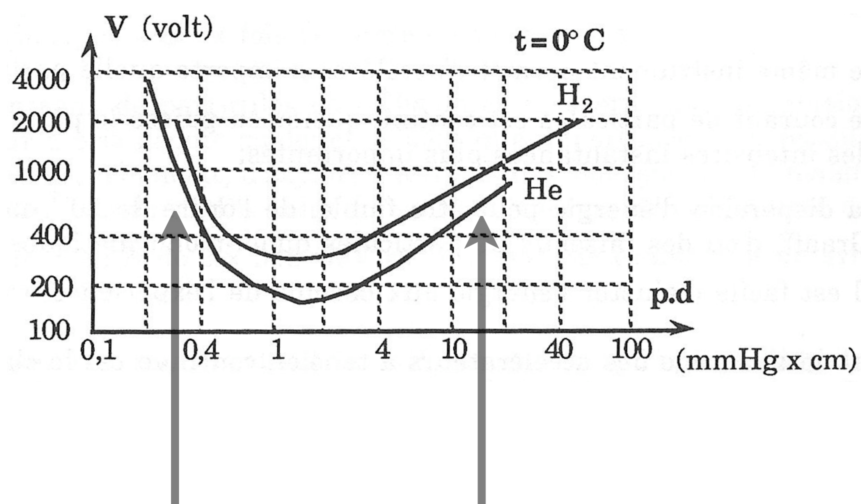
CERN: 750 kV, used until 1993

Bits an pieces are in the garden outside the Microcosm

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

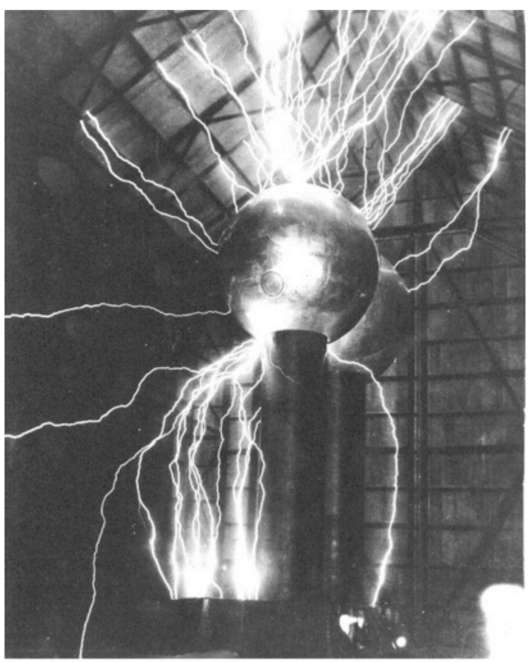
Van De Graaf electrostatic generator (1928)

Limit of Cockroft-Walton bypassed by placing the high voltage parts under high pressure gas.

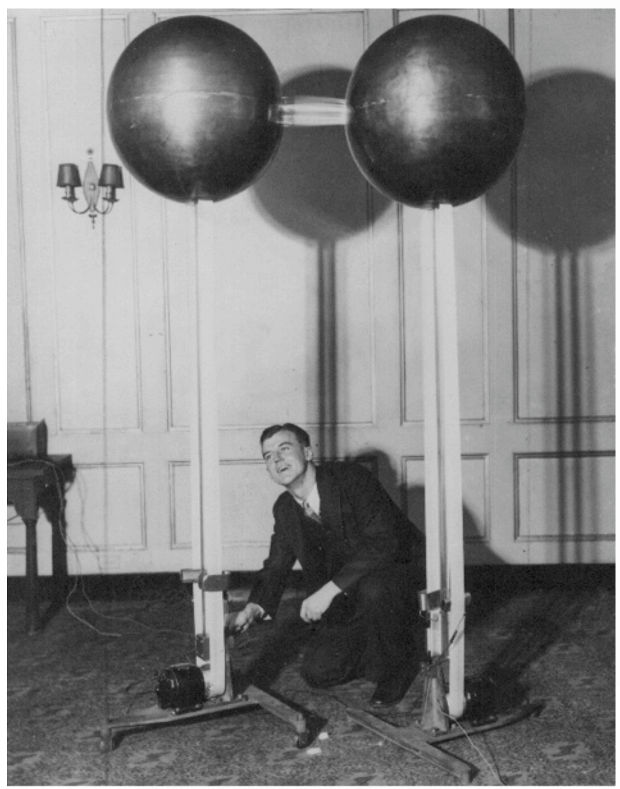
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: **10 MV**

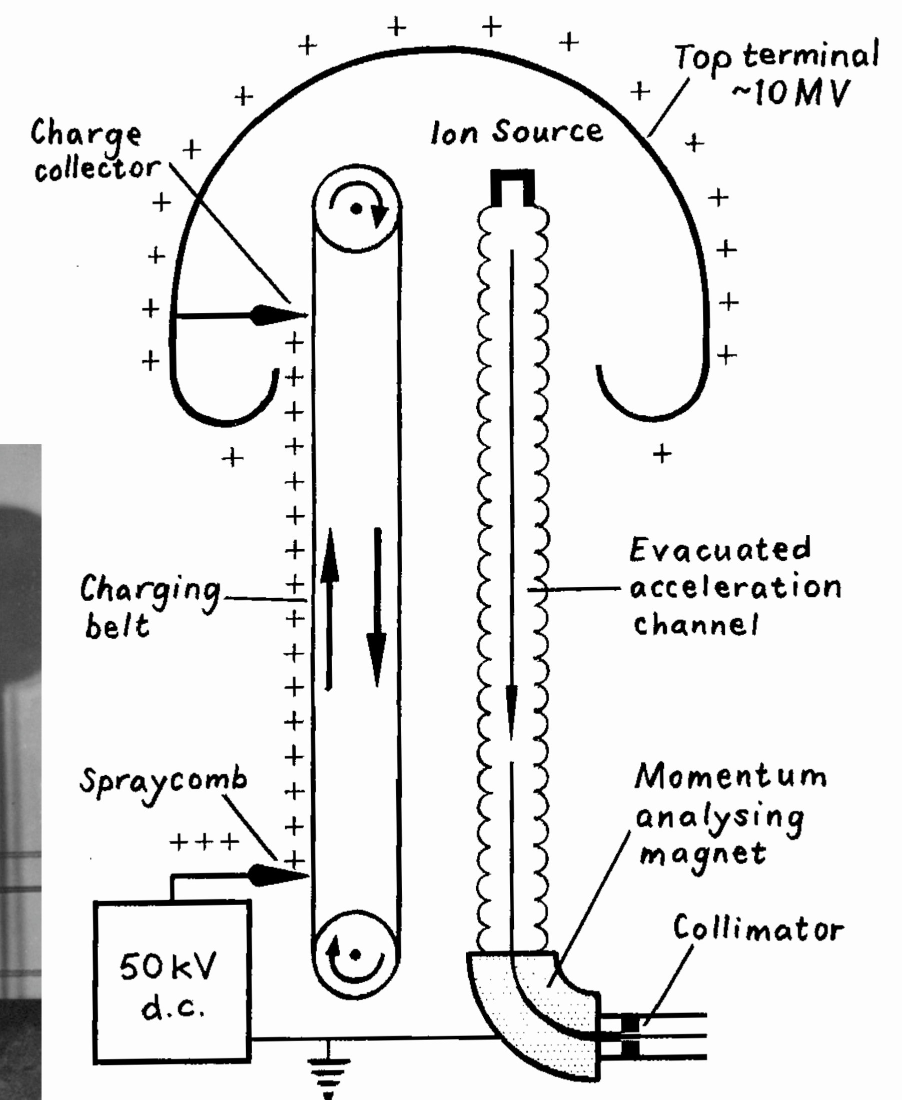
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



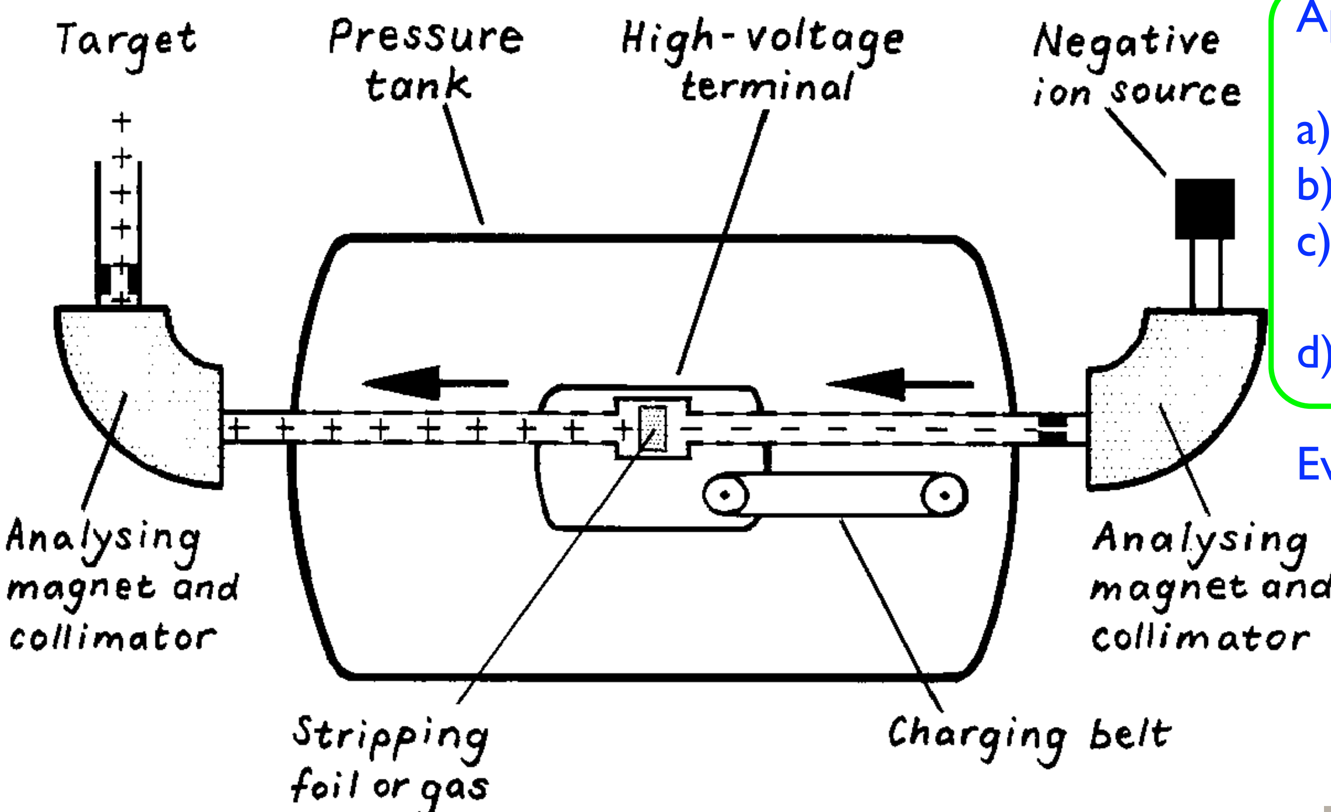
AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)



R. J. VAN DE GRAAFF WITH FIRST GENERATOR



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

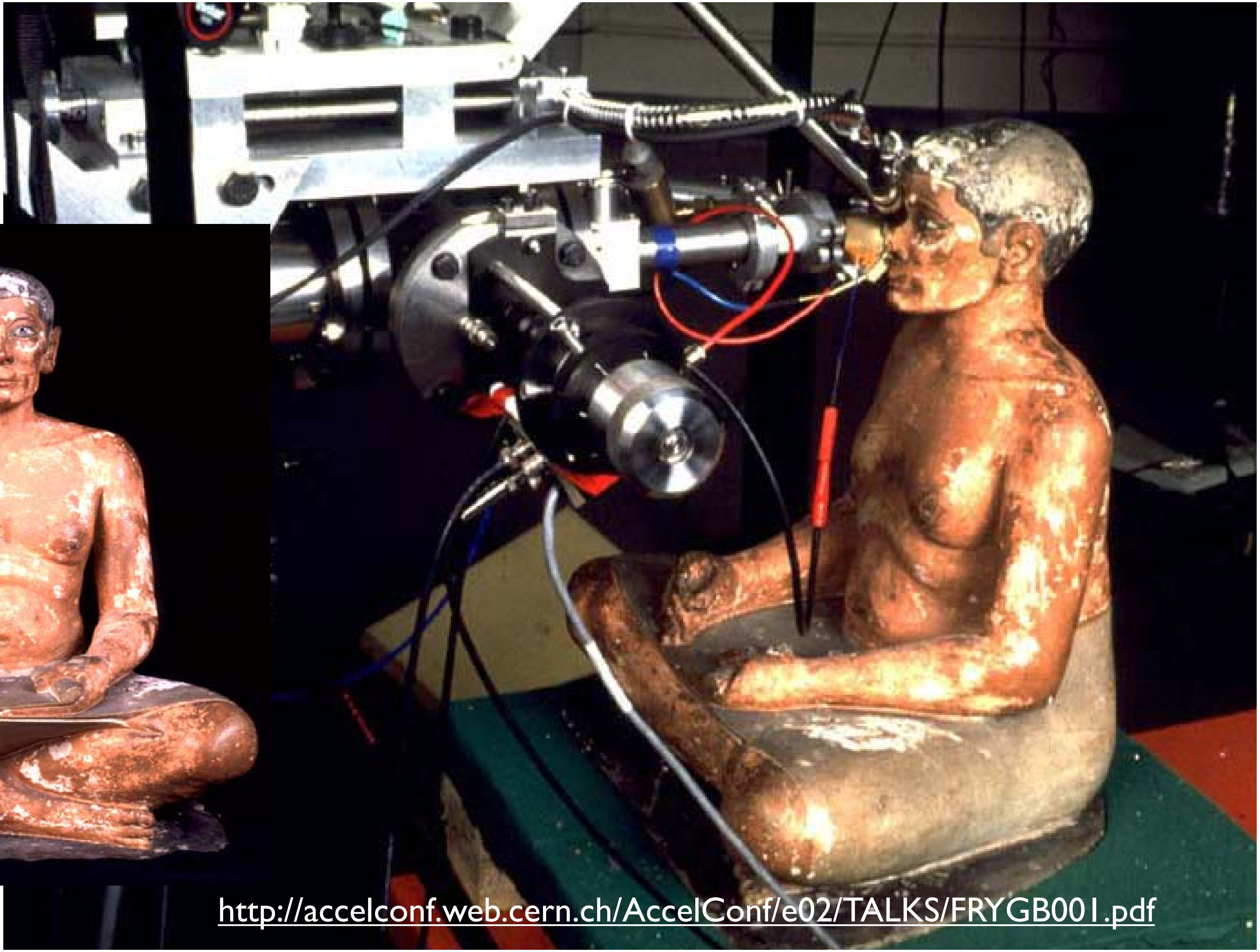
Since negative and positive multicharge states are used, different energies can be obtained

Current applications:

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

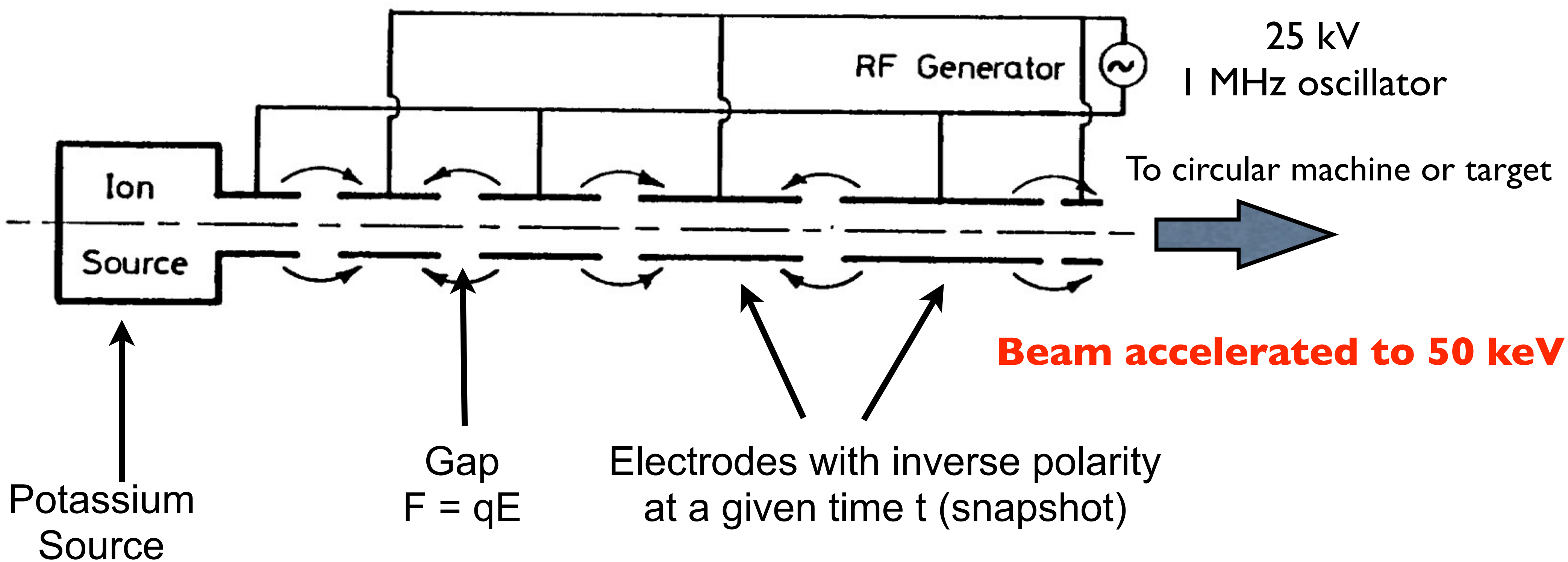
b) Compact system for "other uses"
Dating of samples at Louvre.

Application of Louvre Tandem: composition of scribe eyes



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

Wideroe linac: the first linear accelerating structure



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

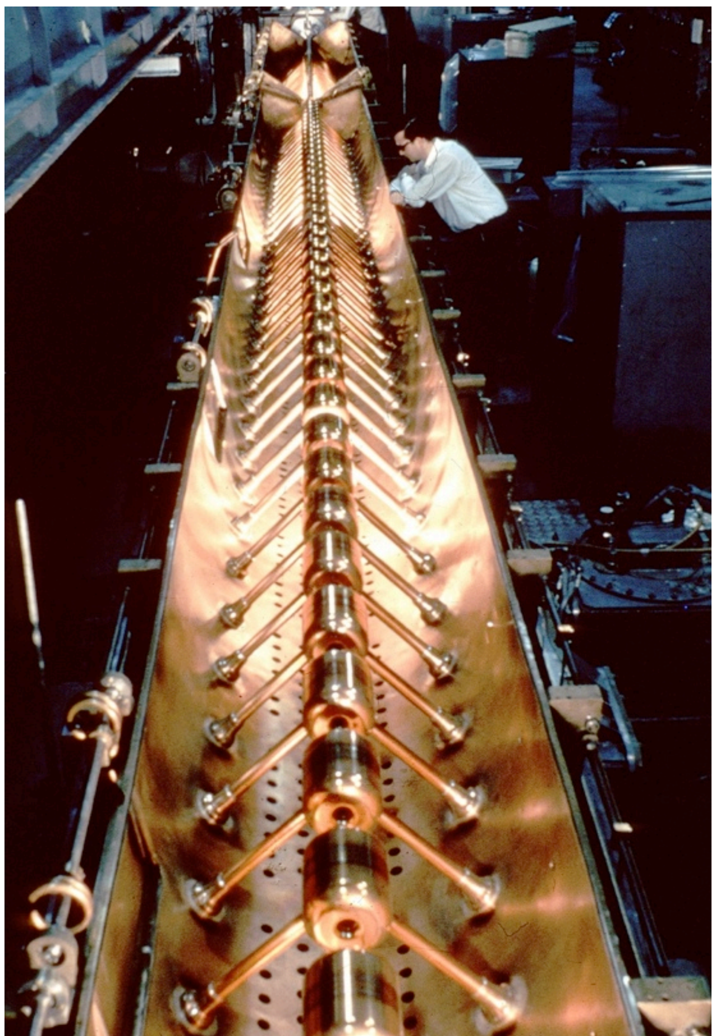
Obs: the drift tube length has to increase because particles are not yet relativistic.
To an energy increase corresponds a speed increase, and the particle has to travel more in the shielded region to be in phase with the accelerating field.

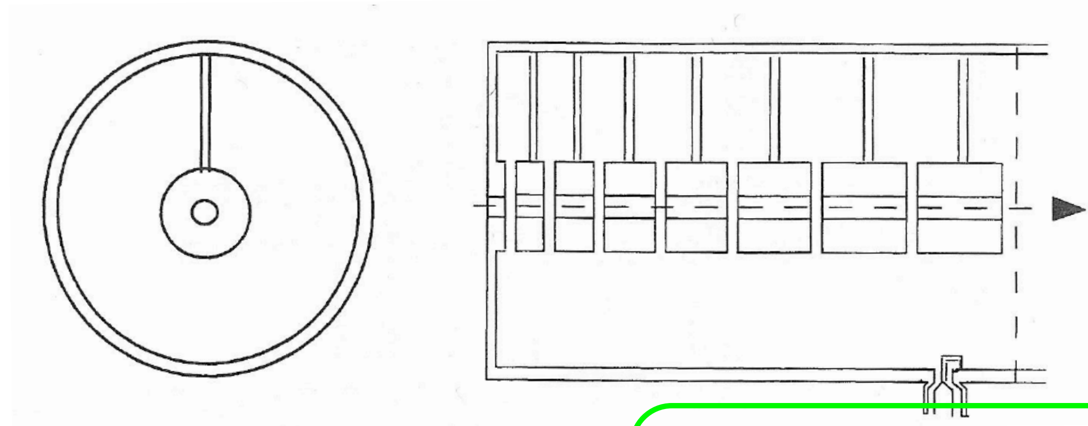
Main limitation: after a certain energy, the length of the drift tube is too long.
The RF frequency has increase to some 10 MHz, need to enclose the structure in a resonator to avoid field losses.

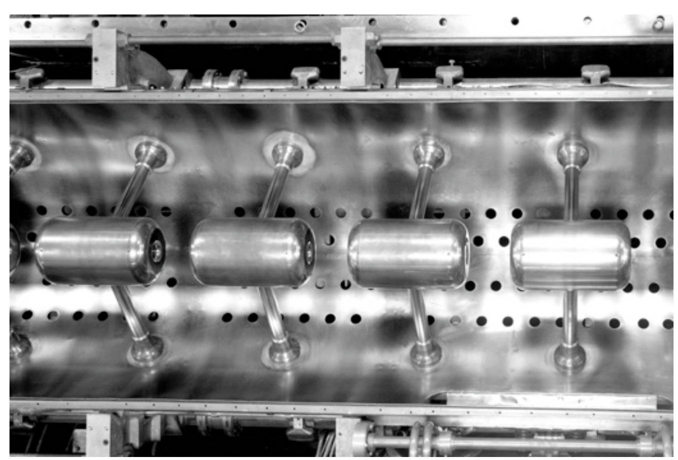
Alvarez drift tube linac

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.

See lecture for linear collider

Cyclotron

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

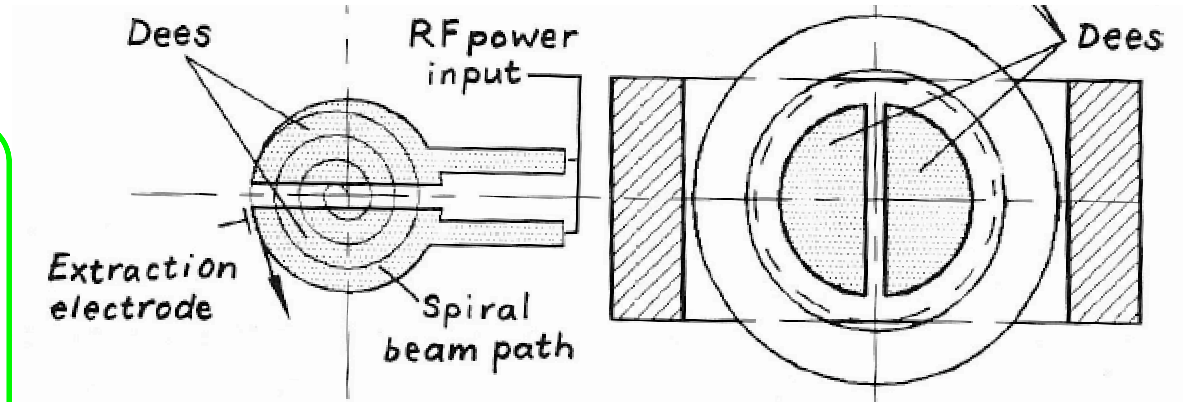
Electrical (E) RF field generated between two gaps with a fixed frequency

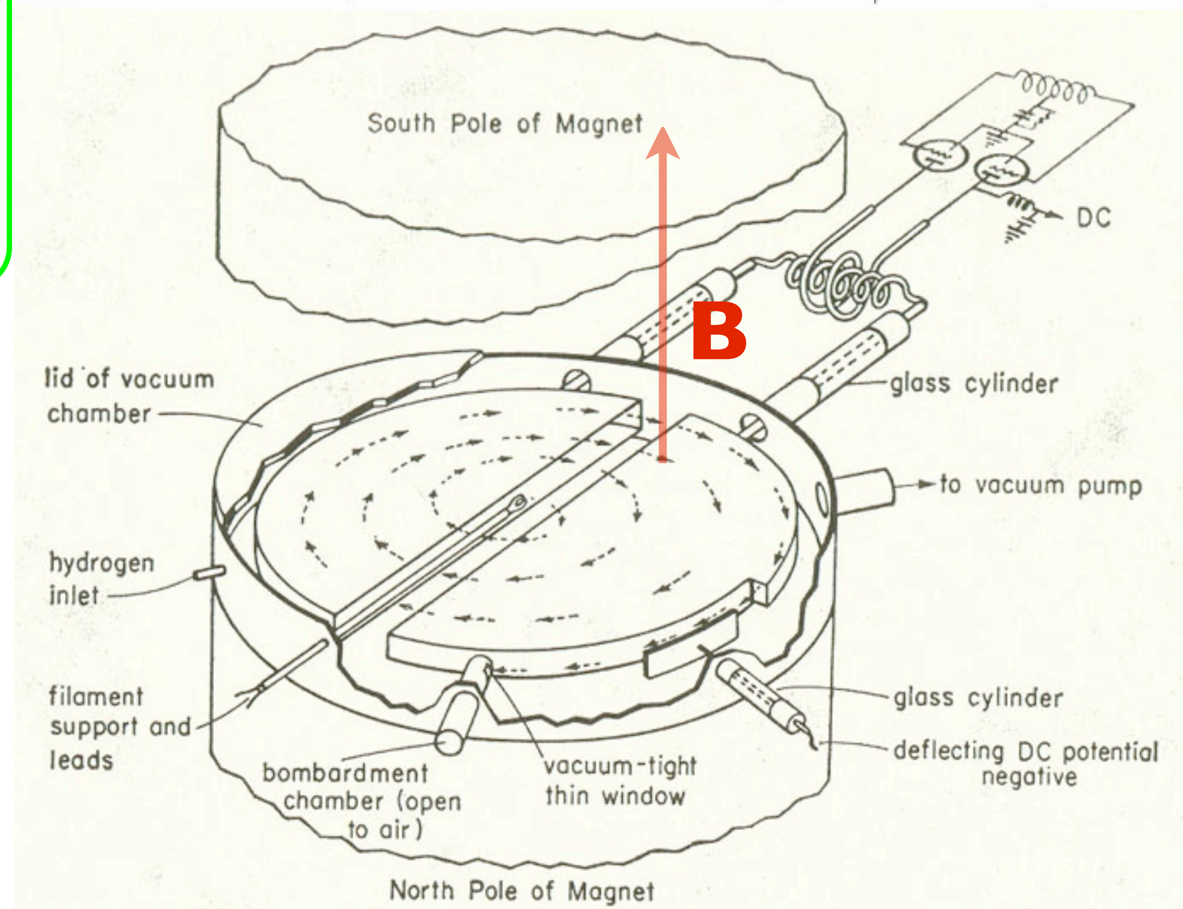
Particles spiral while accelerated by E field every time they go through the gap

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

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

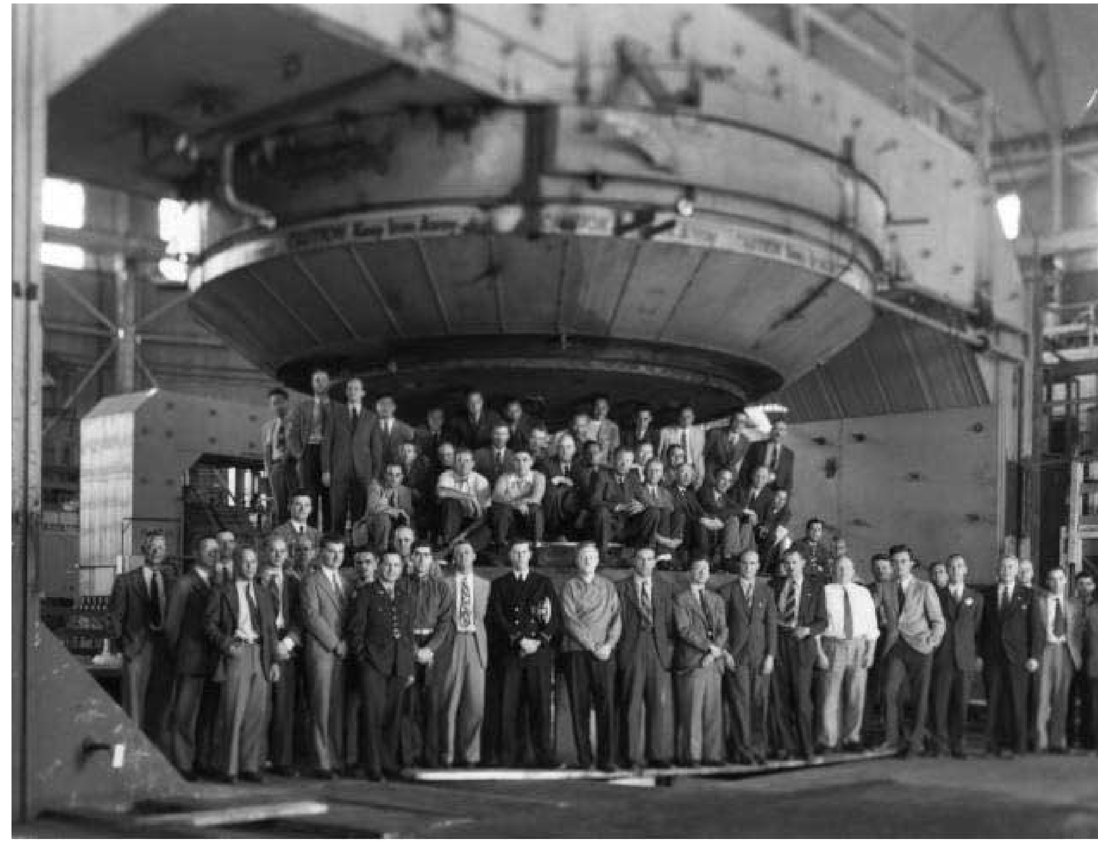


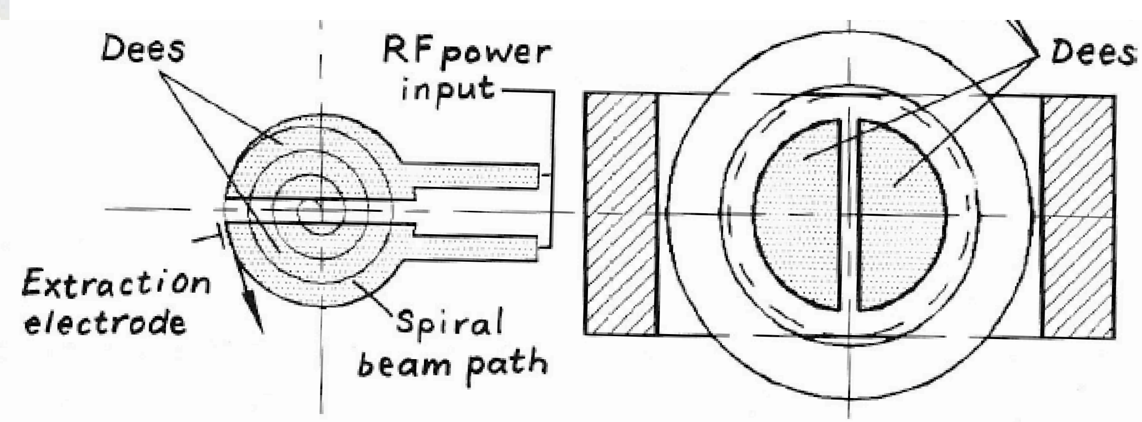


www.physics.rutgers.edu/ cyclotron/

Invented by Lawrence, got the Noble prize in 1939

The first cyclotron and the Berkeley one

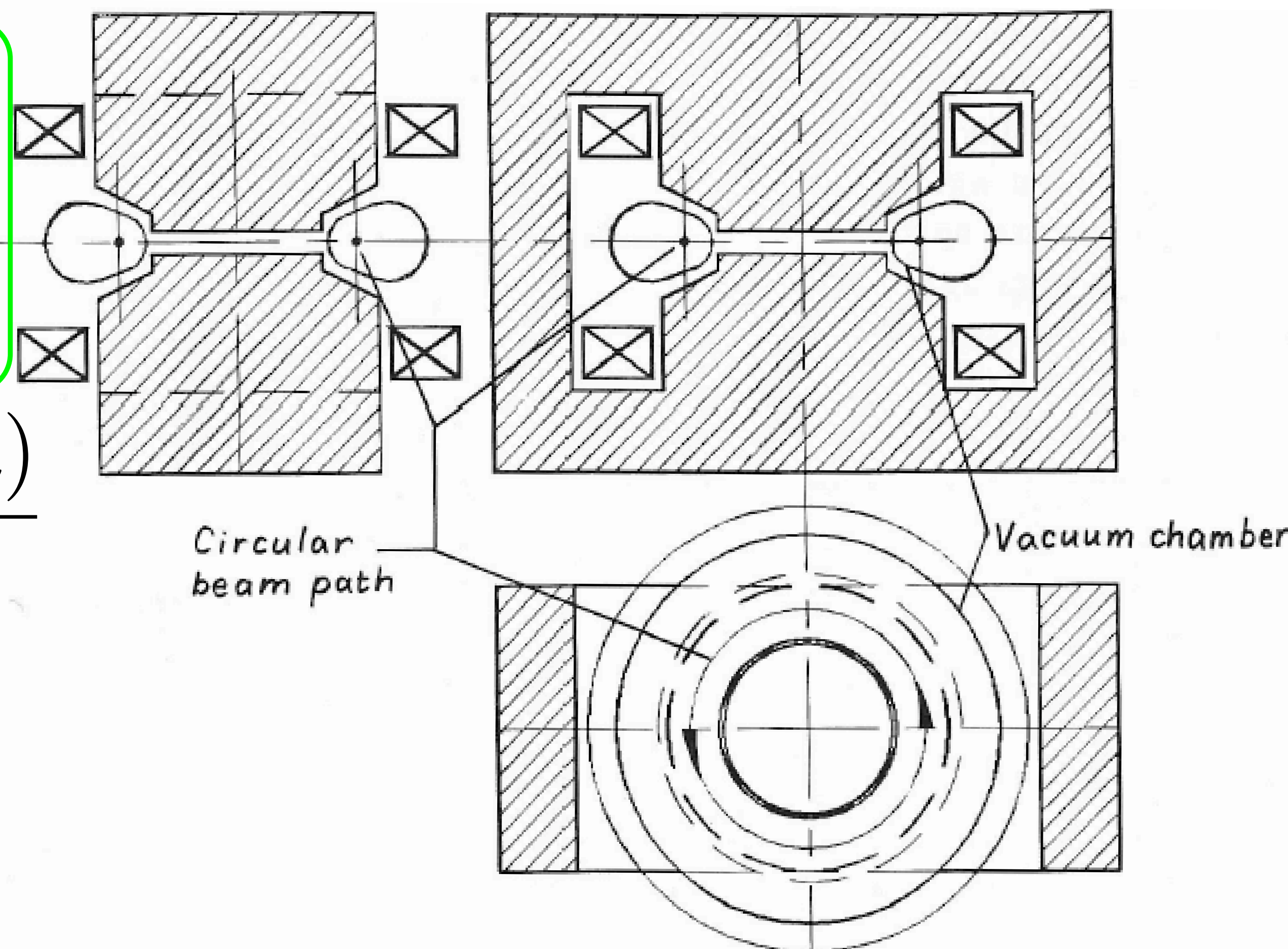




Betatron (invented by Wideroe in 1923)

Accelerating field generated by the variation in time of the magnetic flux which couples with the “current” flowing in the vacuum chamber, the beam to accelerate.

$$eE_{\varphi} = \frac{e}{c} R \frac{dB(R)}{dt}$$



Large betatron built:

R = 1.23 m

Bmax= 8.1 kG

pmax= 300 MeV/c

Main limitation:
1) iron saturation

Kerst built the first one in 1940 for electrons up to 2.3 MeV
Betatron transverse oscillations first introduced in 1941
Betatron named for beta rays, namely electrons

Betatron

Betatron from wikipedia

Betatron used for xray generation

Synchrotron (1952, 3 GeV, BNL)

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

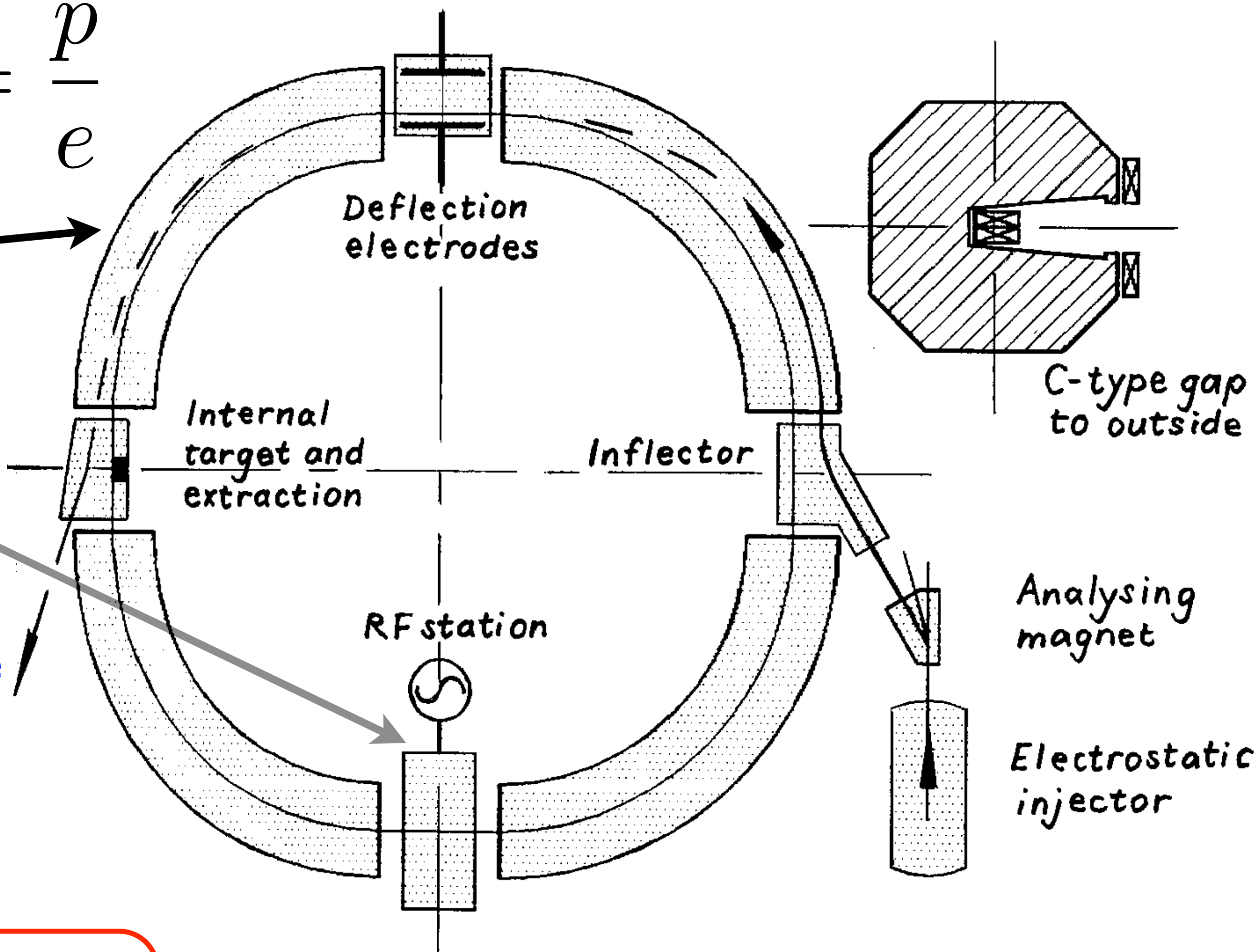
Particle rigidity: $B\rho = \dfrac{p}{e}$

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

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

e electric charge

ρ constant radius of curvature



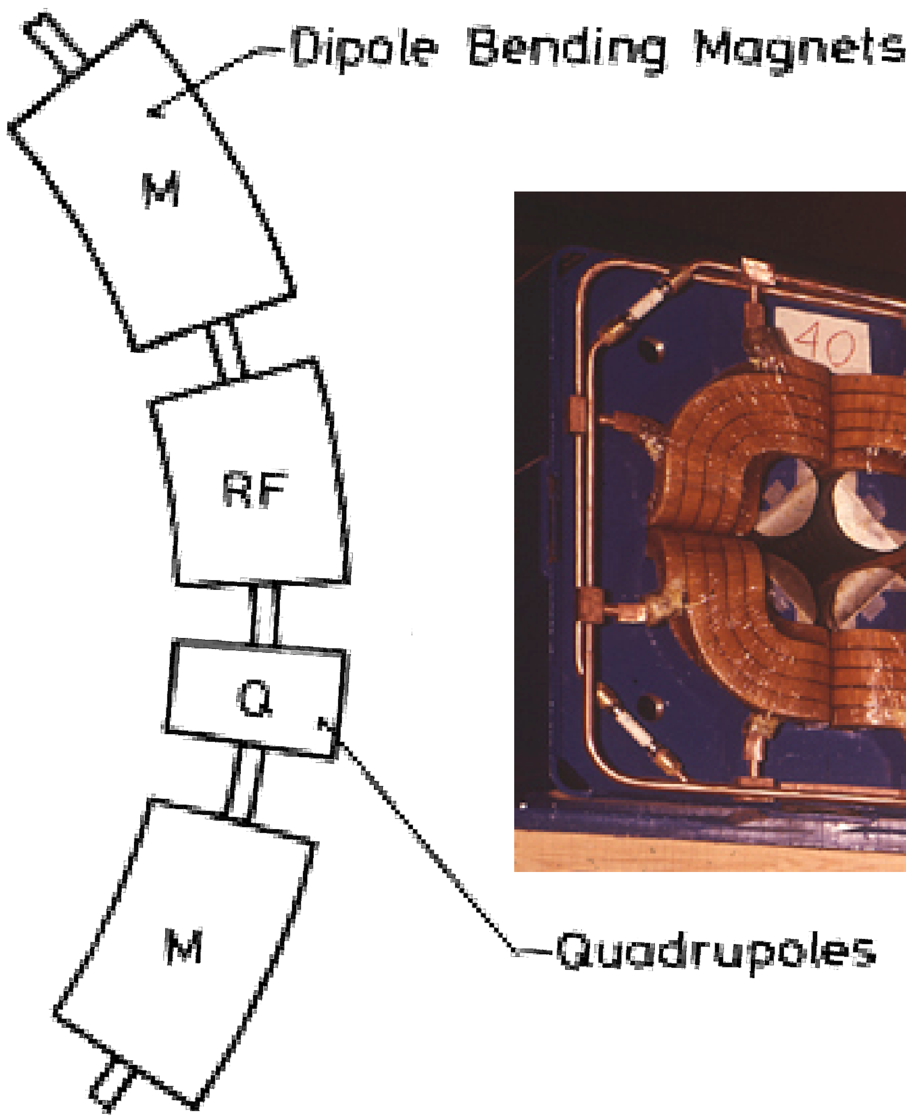
New magnetic elements for injection and extraction.

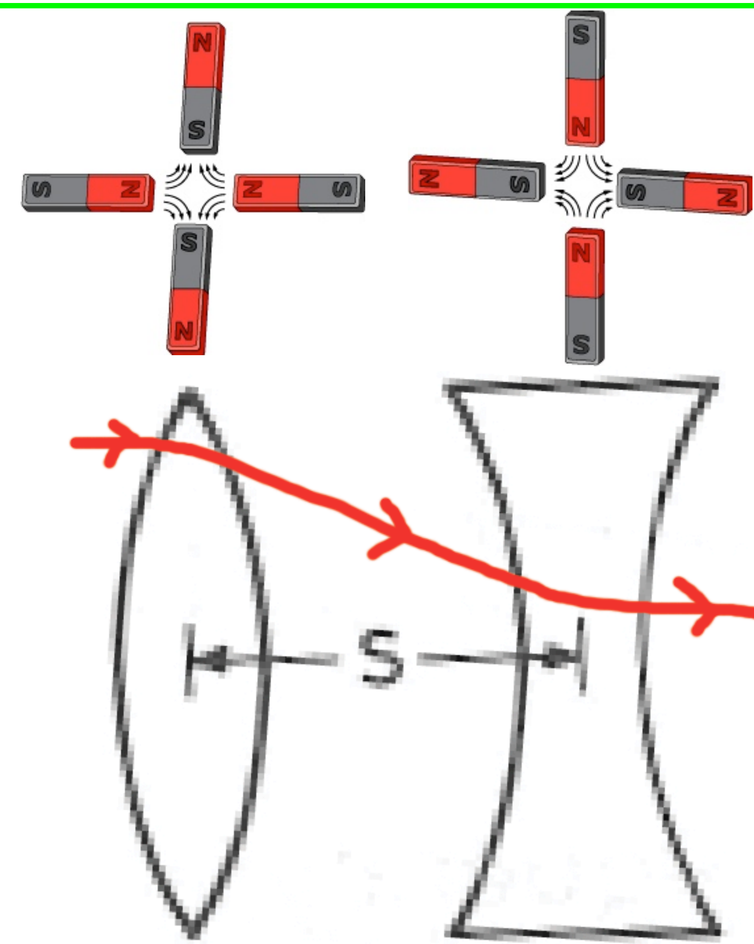
Bending strength limited by used technology to max ~ 1 T for room temperature conductors

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

The last generation of synchrotrons: strong focusing machine

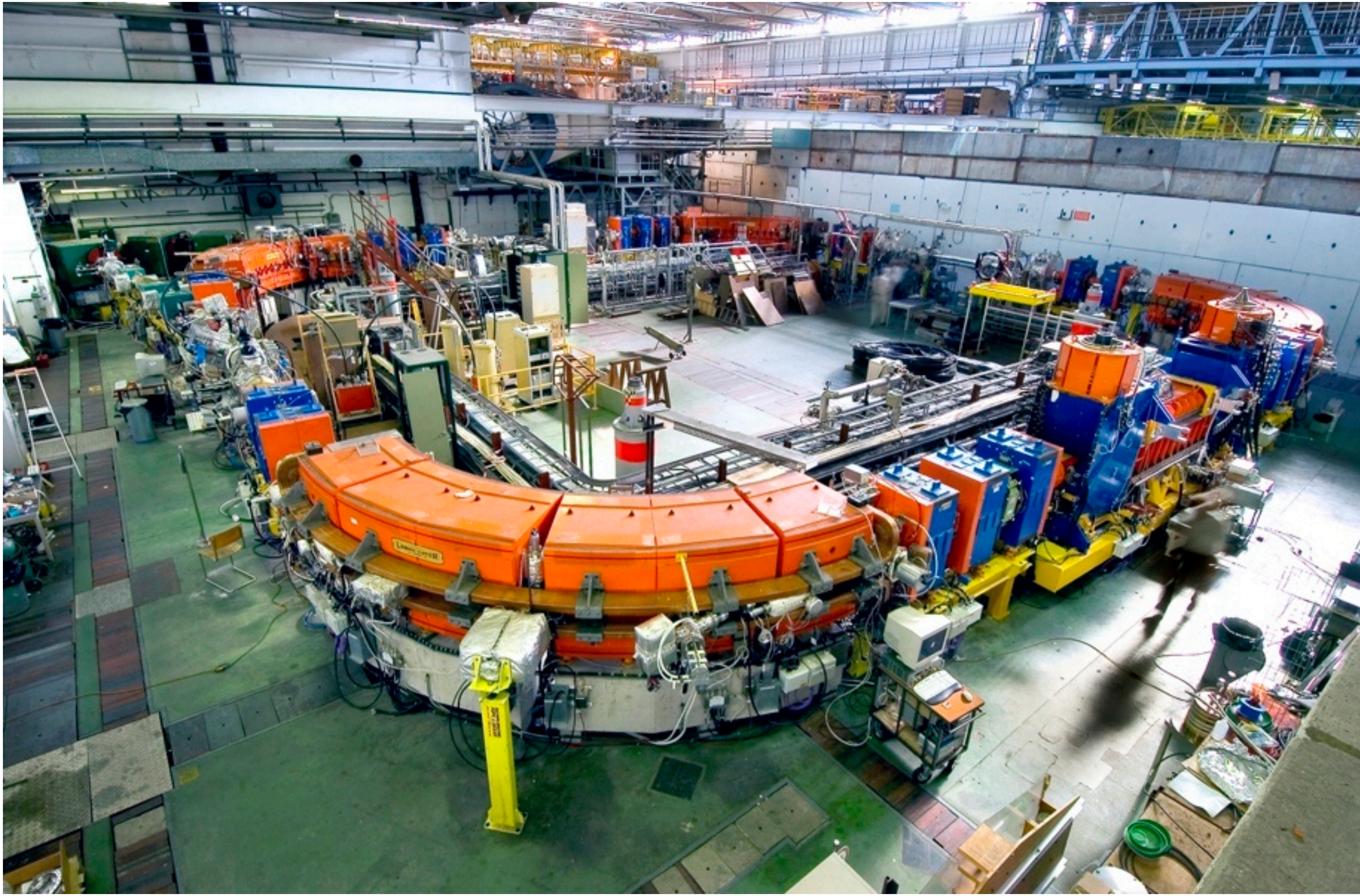
Dipoles are interleaved with quadrupoles to focus the beam. Quadrupoles act on charged particles as lens for light. By alternating focusing and defocusing lens (Alternating Grandient quadrupoles) the beam dimension is kept small (even few mum^2).





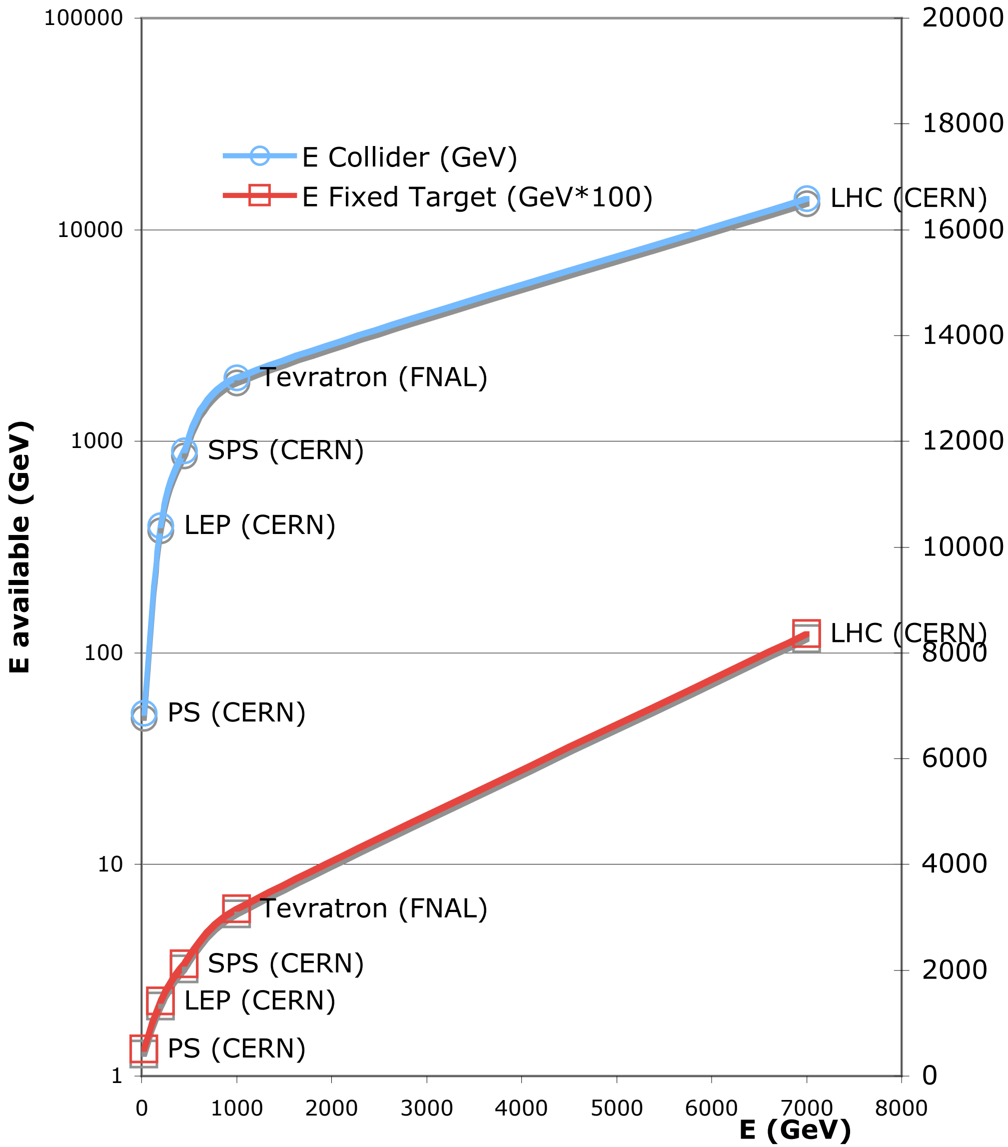
Modern particles accelerators for high energy up to LHC energy (7 TeV) work in this way.

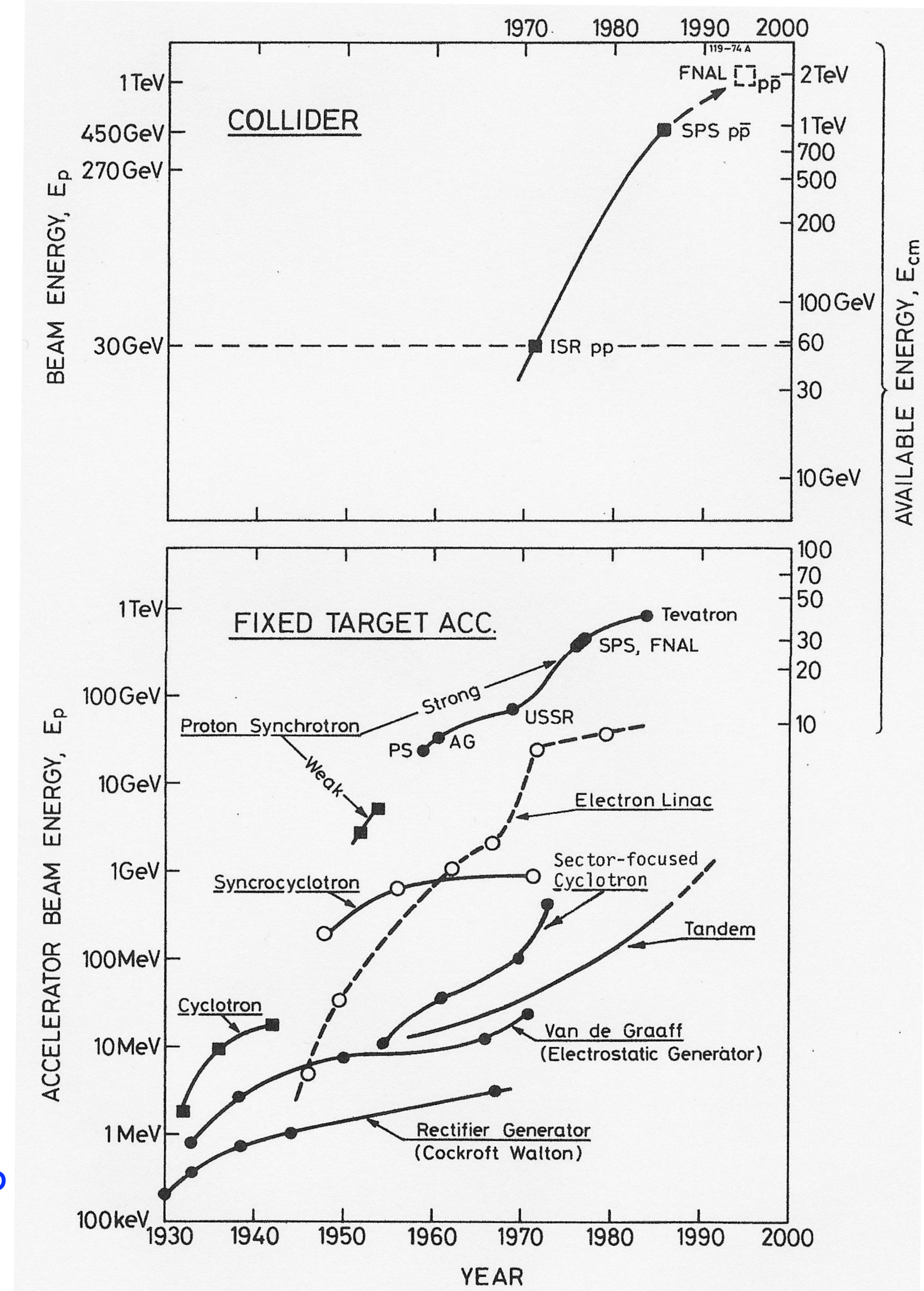
A synchrotron in a view: LEIR (Low Energy Ion Ring)



More in tomorrow lecture ...

The story of accelerator vs energy





Early days only fixed target: easier conception of the accelerator, lower energy, simpler experimental setup

Interlude: a brief recall of energy scales and kinematic relationships

$$m = \sqrt{E^2 - p^2} \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

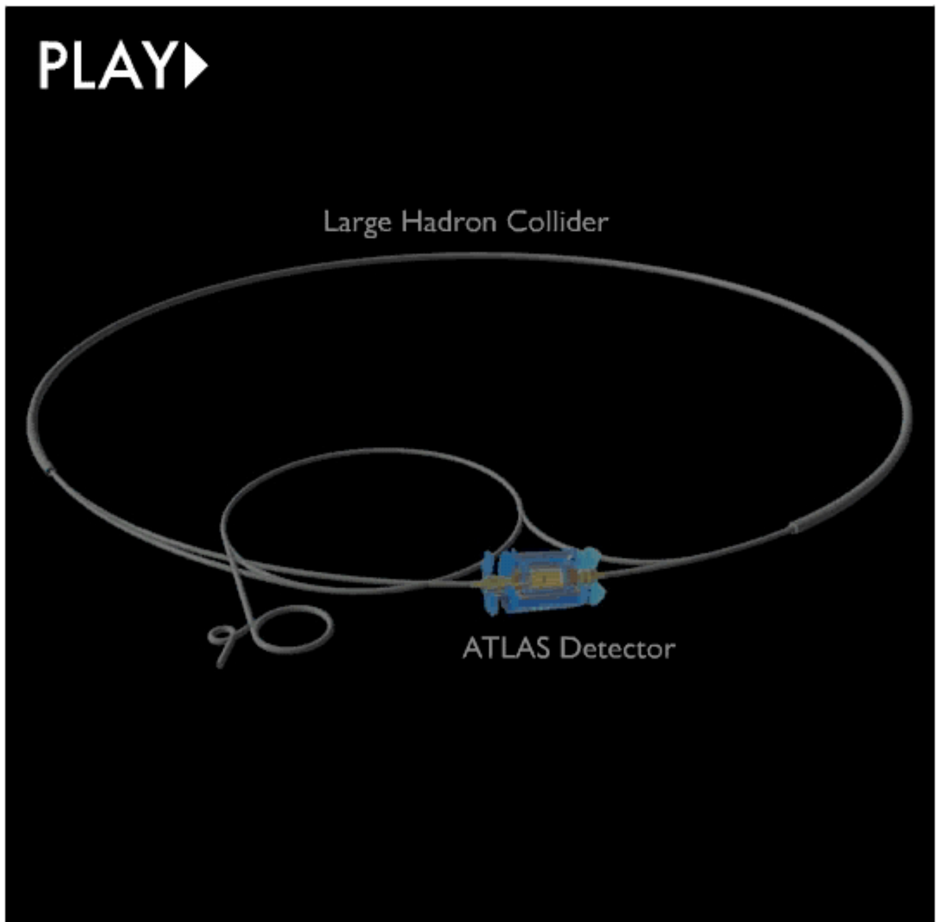
- WARNING: for purists or non-experts: Energy, Masses and Momentum have different units, which turn to be the same since c (speed of light) is considered equal to one.
  - Energy [GeV], Momentum [GeV/c], Masses [GeV/c^2] (Remember golden rule, $E=mc^2$ has to be true also for units...)
- Just an as a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

WARNING: the letters β γ will be used later with a different meaning, as TWISS or OPTICS parameters which have nothing to do with relativistic kinematics.

Why particle accelerators ?

- *Why accelerators:* need to produce under <u>controlled conditions</u> HIGH INTENSITY, at a CHOSEN ENERGY particle beams of GIVEN PARTICLE SPECIES to do an EXPERIMENT

- An experiment consists of studying the results of colliding particles either onto a fixed target or with another particle beam.



The cosmo is already doing collisions with different mechanisms:

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

The universe is able to accelerate particles up to 10^6 MeV protons (See cosmology lectures)