Experimental techniques in high-energy nuclear and particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

LECTURE 2.

Accelerators - 1

Prof. Rino Castaldi
INFN-Pisa
rino.castaldi@pi.infn.it

Why do we need accelerators?

- Resolution of "Matter" Microscopes
  - → Wavelength of Particles (γ, e, p, ...) (de Broglie, 1923)

$$\lambda = h/p = 1.2\ \text{fm}/\boldsymbol{p}\ [\ \text{GeV}/c]$$

  - → Higher momentum => shorter wavelength => better the resolution

- Energy to Matter
  - → Higher energy produces heavier particles

$$E = mc^2 = \frac{m_o c^2}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma m_o c^2$$

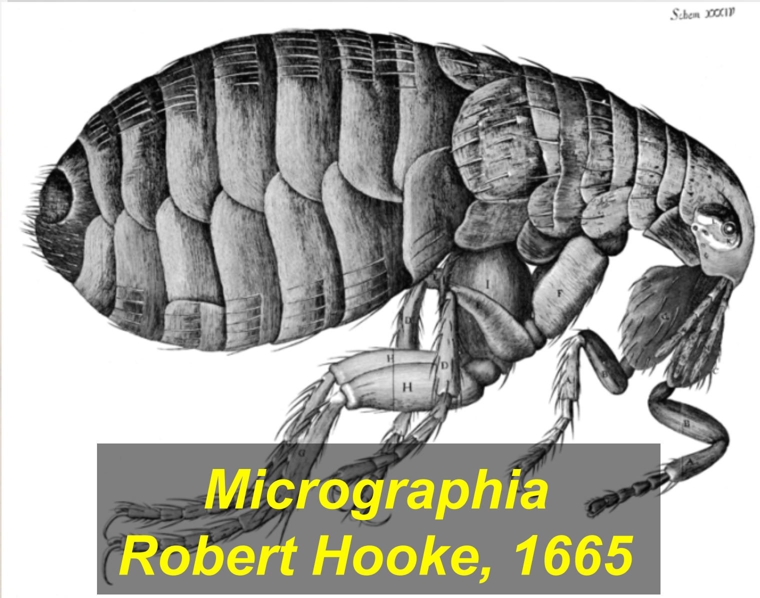
- Penetrate more deeply into matter

Microscopes & Telescopes ~ 400 Years Ago

Compound microscope
~1670, Glasgow
Magnification ~30

Galileo’s telescope, ~1609, Florence
Magnification ~30

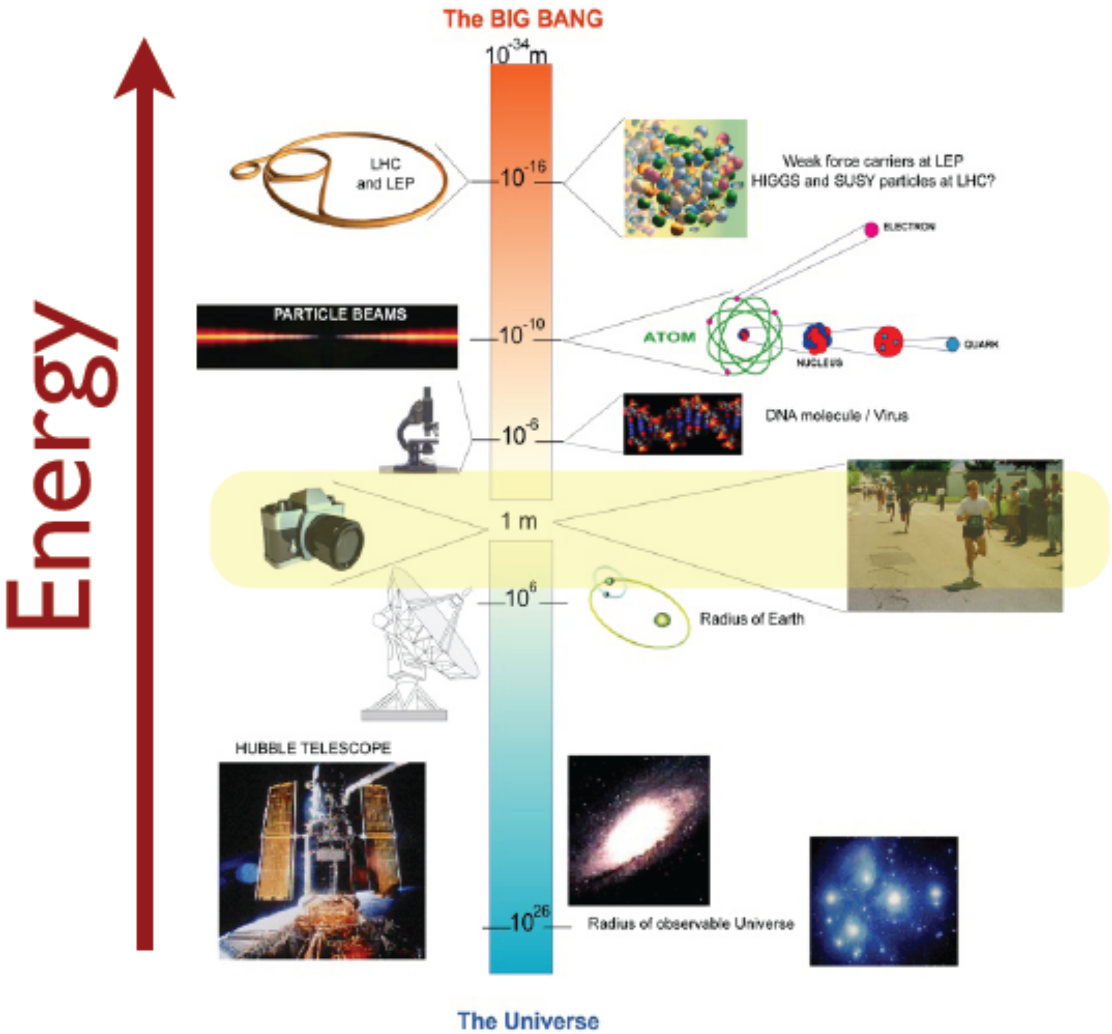
THE UNIVERSE
YOURS TO DISCOVER
INTERNATIONAL YEAR OF
ASTRONOMY
2009



Micrographia
Robert Hooke, 1665

Siderius Nuncius,
Galileo Galilei, 1610

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"

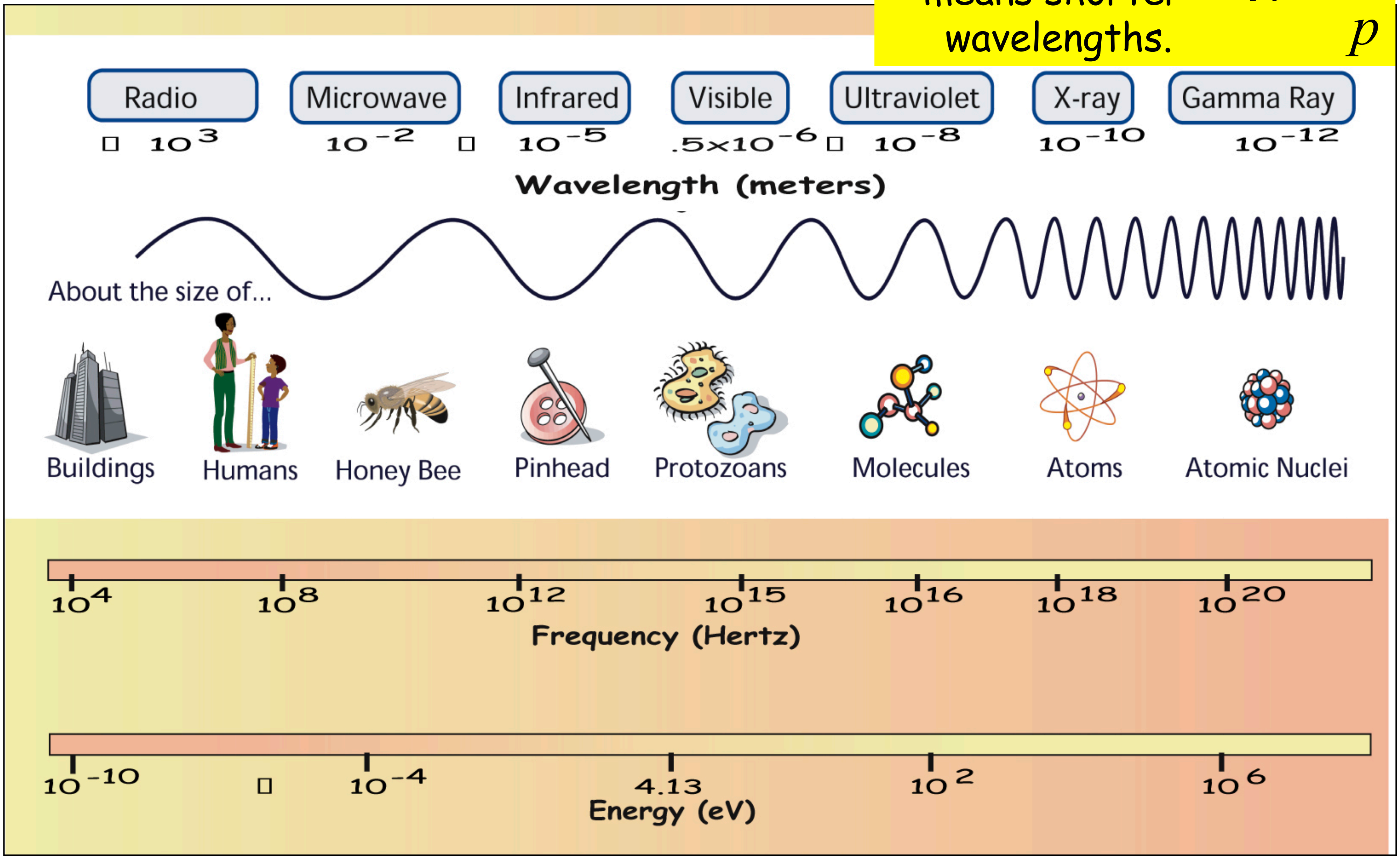
The typical energy of our life is eV

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

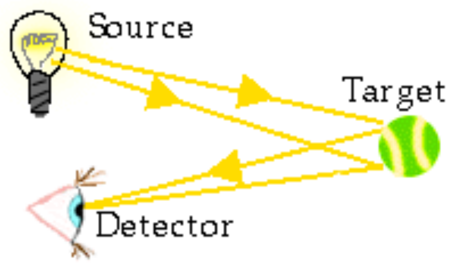
Probing Matter

Higher energies means shorter wavelengths.

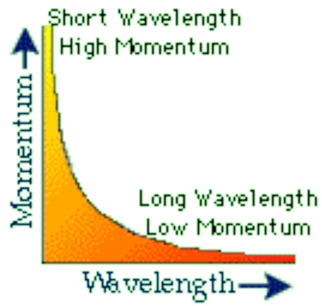
$$\lambda = \frac{h}{p}$$



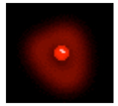
Why use higher and higher energies?

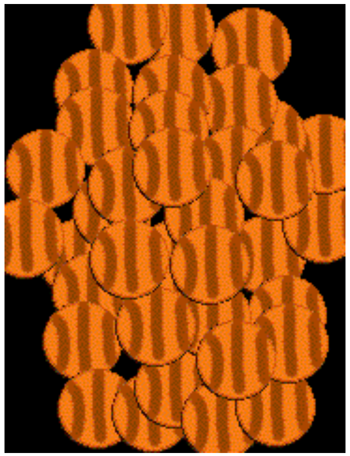
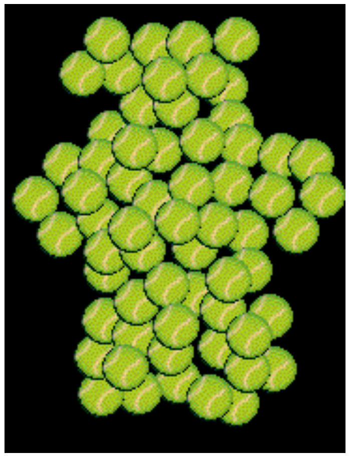
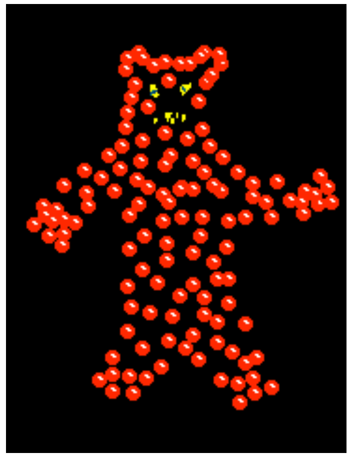


$$\lambda = h/p$$



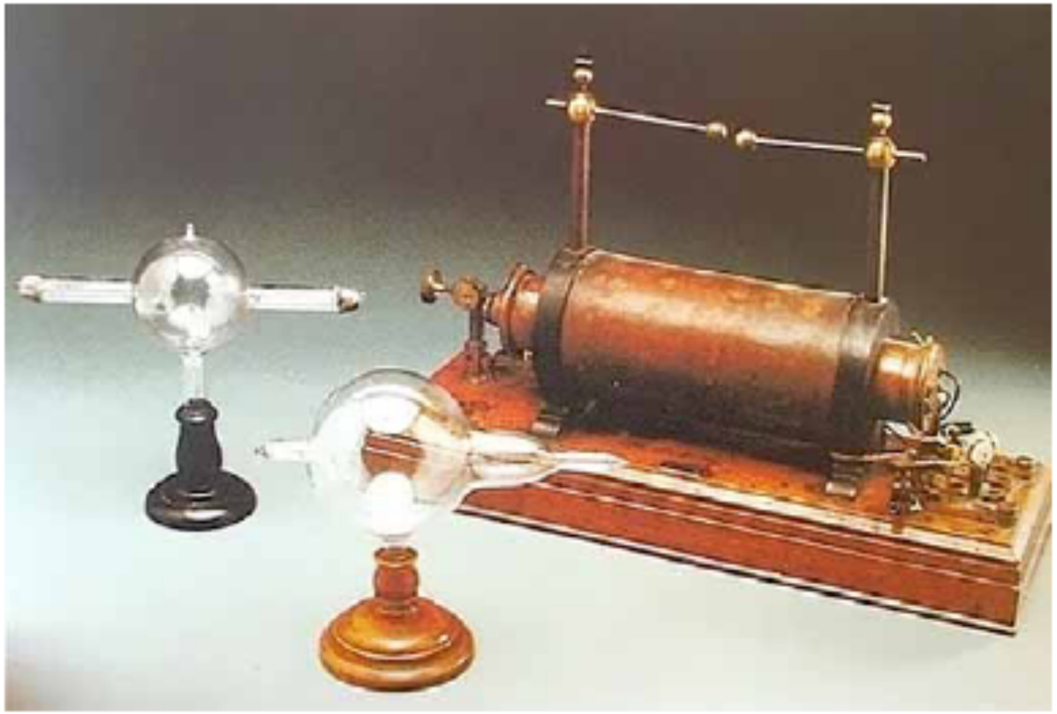




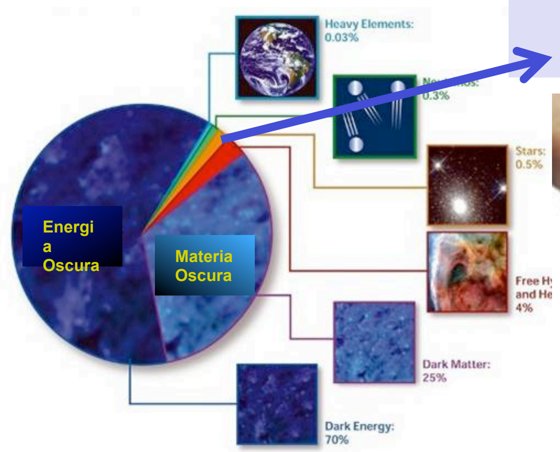




∴ The more energetic the probe, the finer the accessible detail

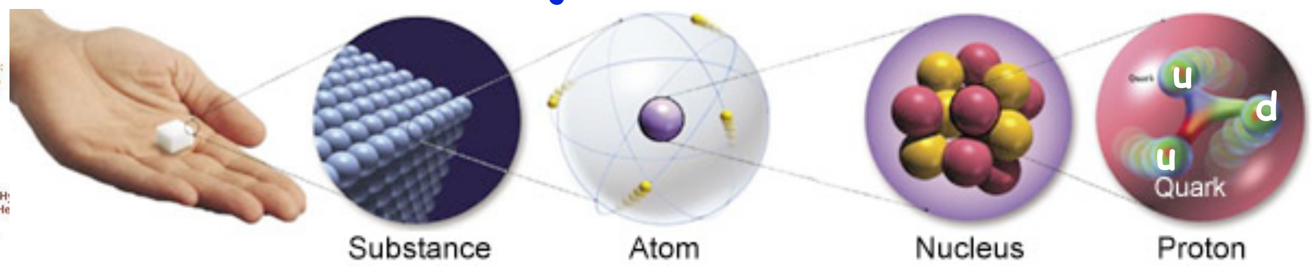
How can we understand the underlying structure of things?



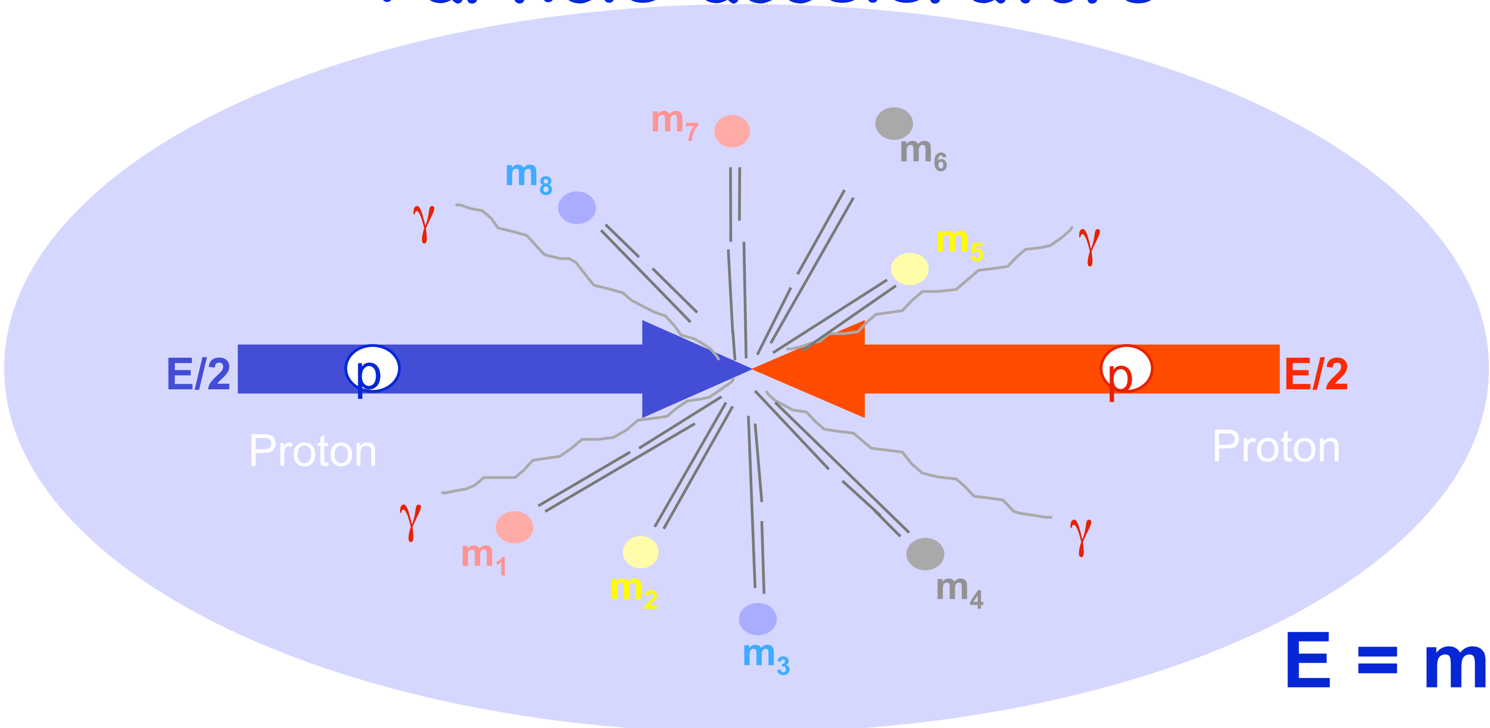
Wilhelm Röntgen Discovered X-rays in 1895



Ordinary Matter (~5%)

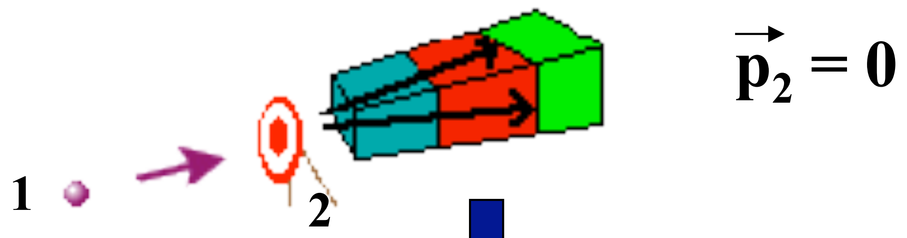


Particle accelerators

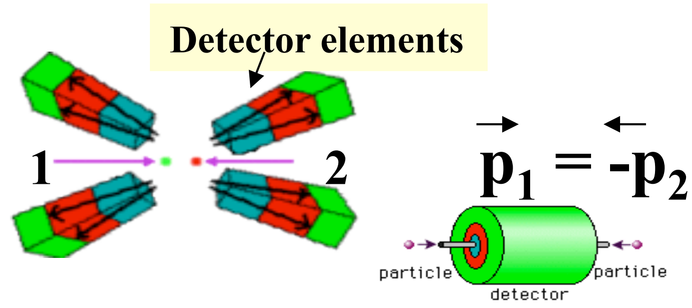


$$E = mc^2$$

In an high energy collision many particles can be produced both of matter and antimatter

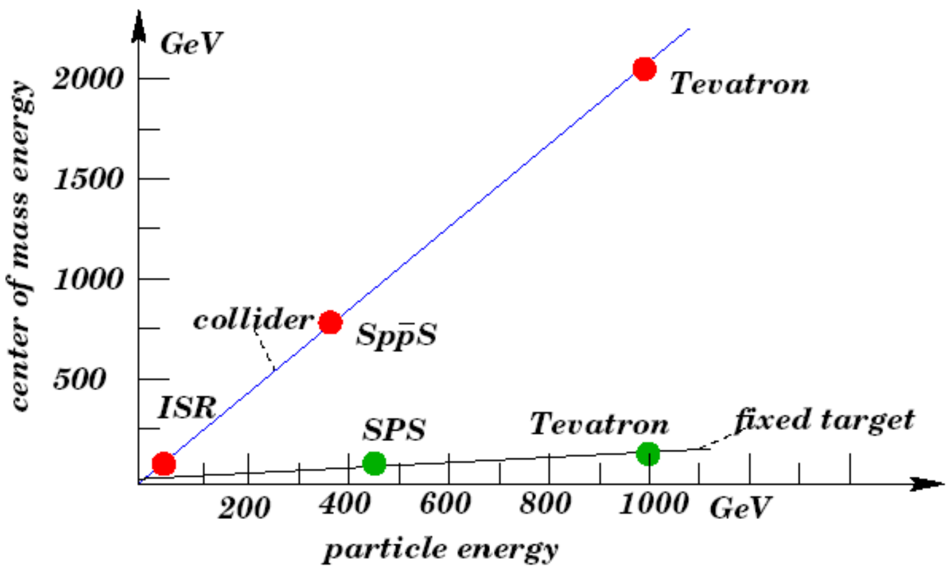


$$E_{CM} = \sqrt{2E_{beam}m_{target}}$$



$$E_{CM} = 2E_{beam}$$

if $E_{beam1} = E_{beam2}$

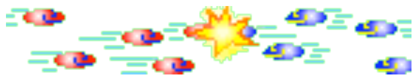


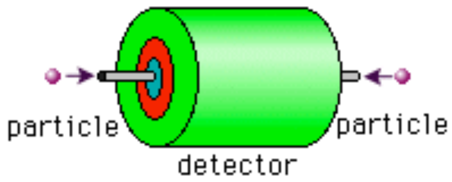
1960 ↗ : *e^+ / e^- collider*

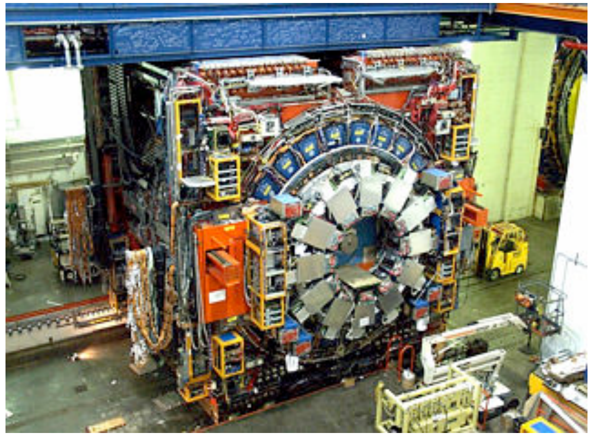
1970 ↗ : *p^+ / p^- collider*

Target Types

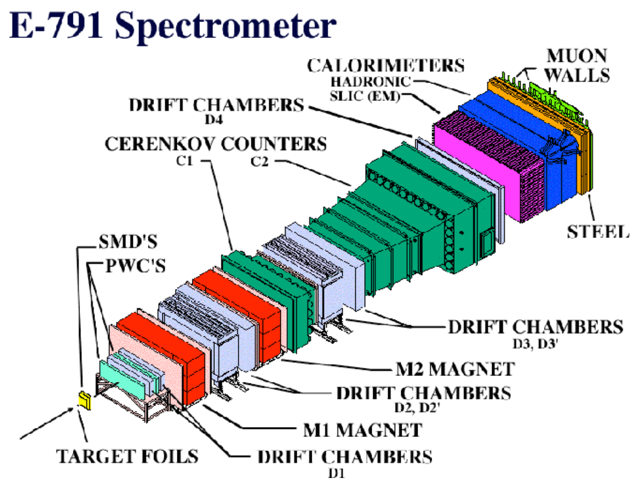
Colliding beam







Fixed target



Why do we need accelerators?

Accelerate and collide particles to high energies.

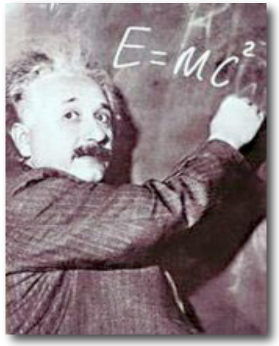
The higher energies allow us

i) To look deeper into matter (E α 1/size)
$\lambda = h/p$ ("powerful microscopes")

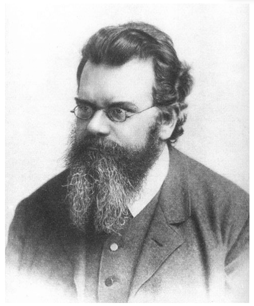
ii) To produce and study properties of new heavier particles ($E = mc^2$)

iii) To probe conditions of matter in the early universe ($E \approx kT$) $\Rightarrow$ Revisit the earlier moments of our "baby" universe ("powerful telescopes"), "looking back in time" to observe phenomena and particles normally no longer visible or existing in our time.

De Broglie

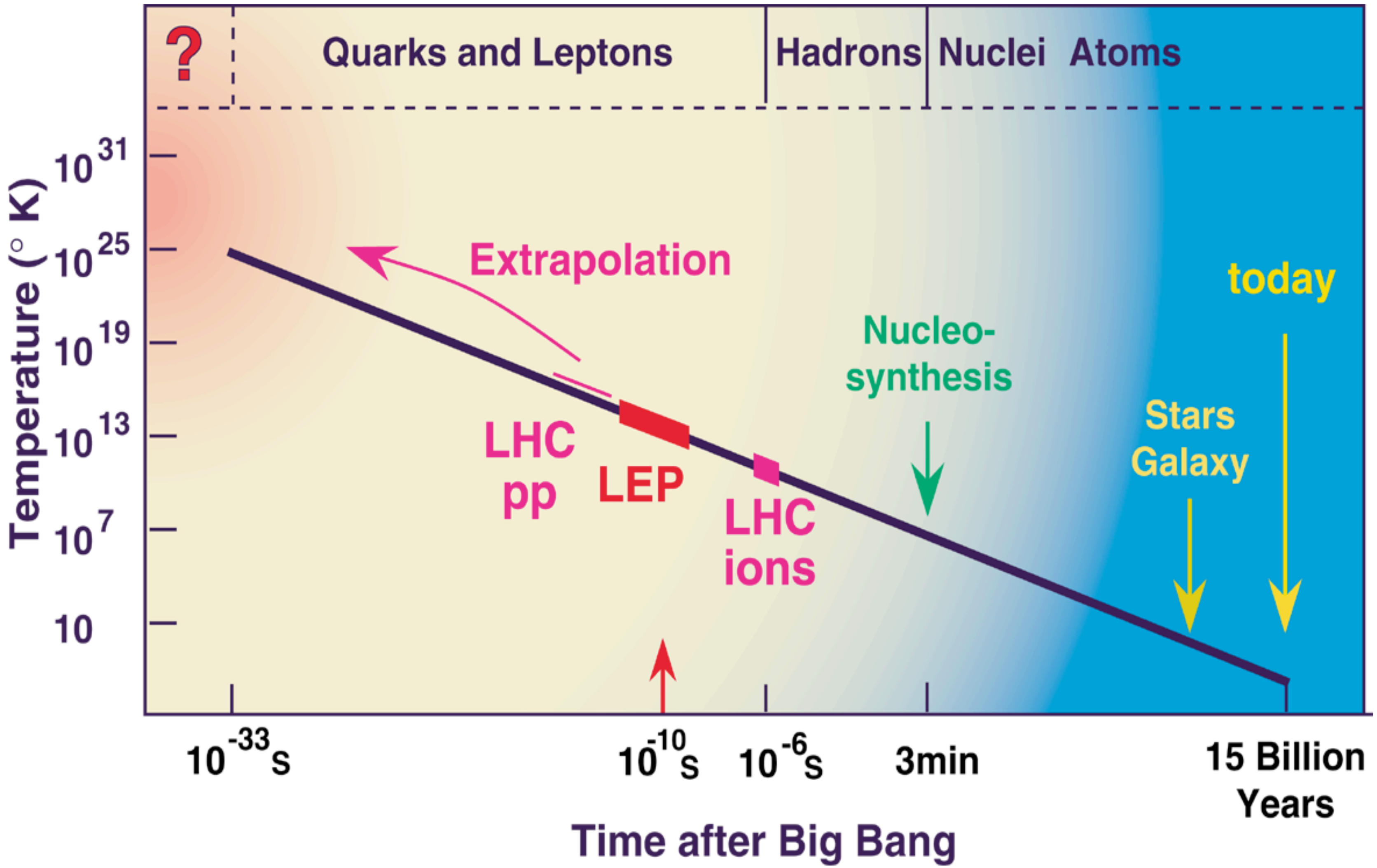


Einstein



Boltzmann

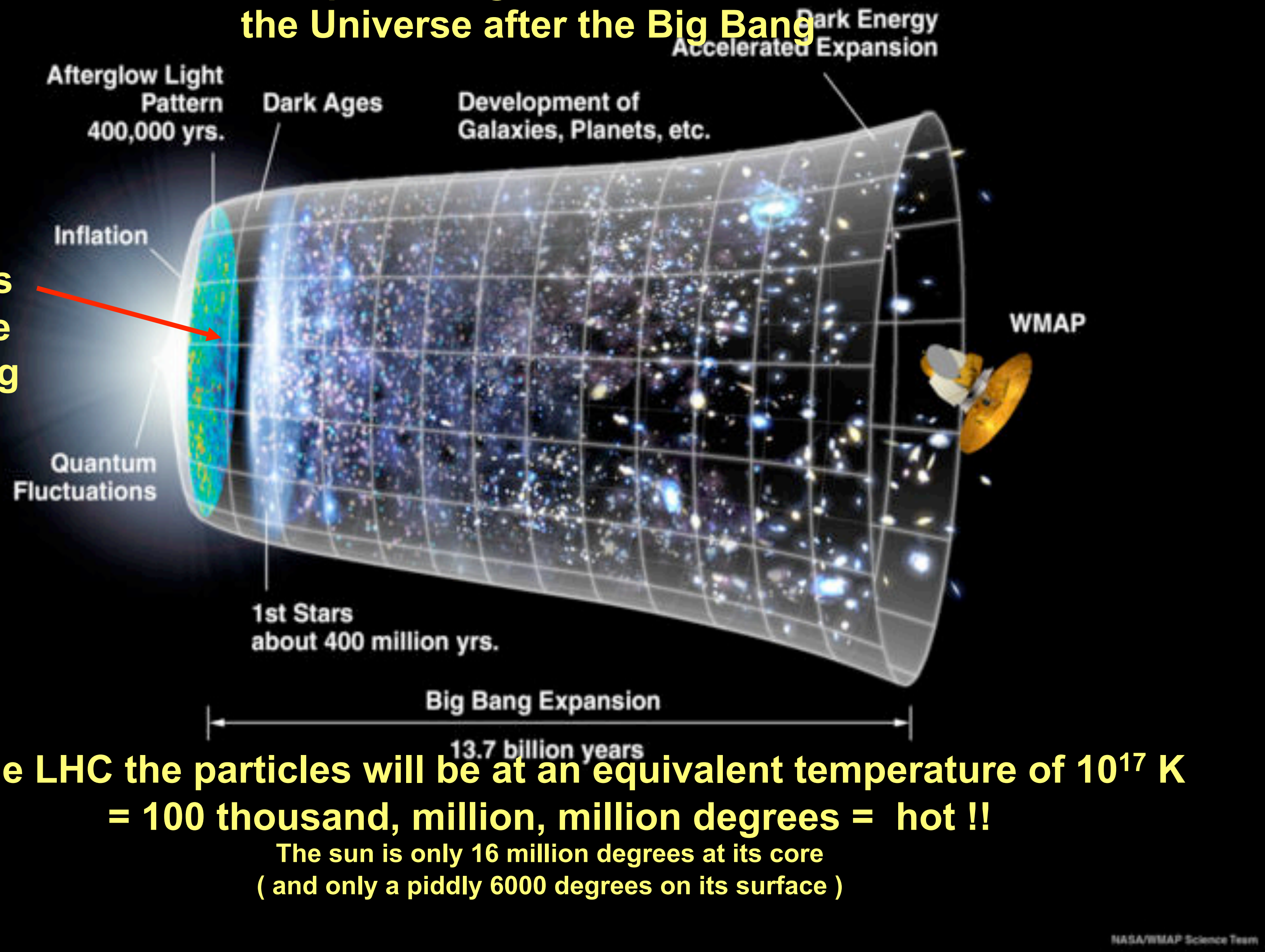
LHC: towards the origin of the Universe



The two frontiers of physics

Particle accelerators (like LHC) will recreate the conditions prevailing in the first moments of the Universe after the Big Bang

LHC ~10^{-15} seconds after the Big Bang



At the LHC the particles will be at an equivalent temperature of 10^{17} K = 100 thousand, million, million degrees = hot !!

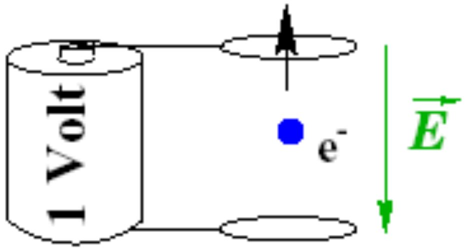
The sun is only 16 million degrees at its core
(and only a piddly 6000 degrees on its surface)

Units

- **Energy Gain:**

1 eV

→ *(1.6 * 10^{-19} J)*



- **Common Units:** *keV, MeV, GeV, TeV*

  (10^3, 10^6, 10^9, 10^{12})

- **Total Particle Energy:**

  - *Relativity:* $E = mc^2$; $m = \gamma * m_0$

    $\gamma = 1/\sqrt{1 - \beta^2}$; $\beta = v/c$

  - *Electron:* $m_0 = 9.11*10^{-31}$ kg; 0.51 MeV/c^2

  - *Proton:* $m_0 = 1.67*10^{-27}$ kg; 0.94 GeV/c^2

1 eV is a tiny portion of energy. 1 eV = $1.6 \cdot 10^{-19}$ J

m_{bee} = 1g = $5.8 \cdot 10^{32}$ eV/c^2
v_{bee} = 1m/s → E_{bee} = 10^{-3} J = $6.25 \cdot 10^{15}$ eV
E_{LHC} = $14 \cdot 10^{12}$ eV

To rehabilitate LHC…
Total stored beam energy:
10^{14} protons * $14 \cdot 10^{12}$ eV ≈ $1 \cdot 10^{8}$ J

this corresponds to a  m_{truck} = 100 T, v_{truck} = 120 km/h

1 eV/c^2 = 1.783 10^{-36} kg

Acceleration Concepts

- Lorentz Force:

$$\frac{dp}{dt} = q \cdot \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

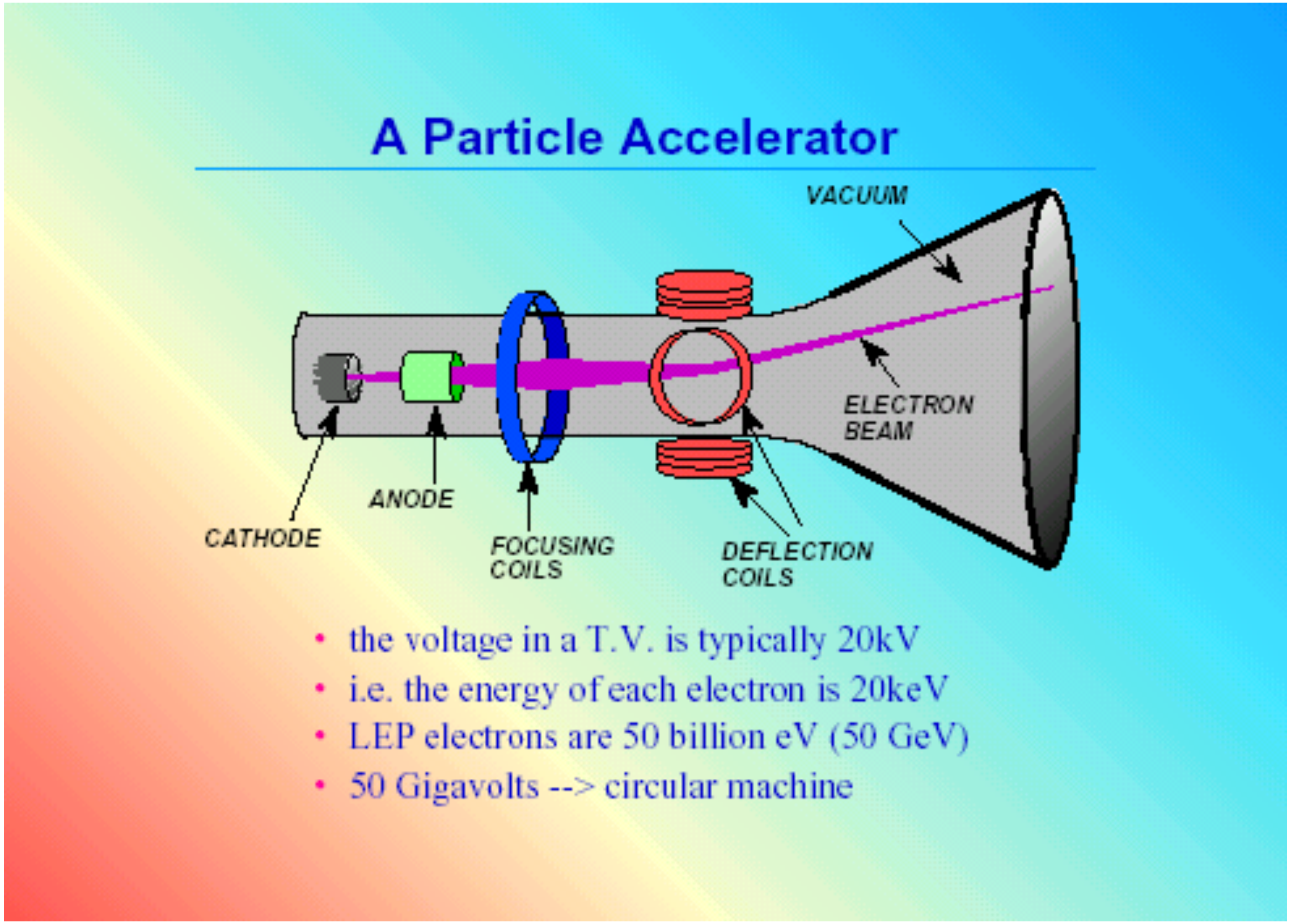
→ energy gain only due to electric fields!

- Scalar and Vector Potential:

$$\vec{E} = -grad\phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t}$$

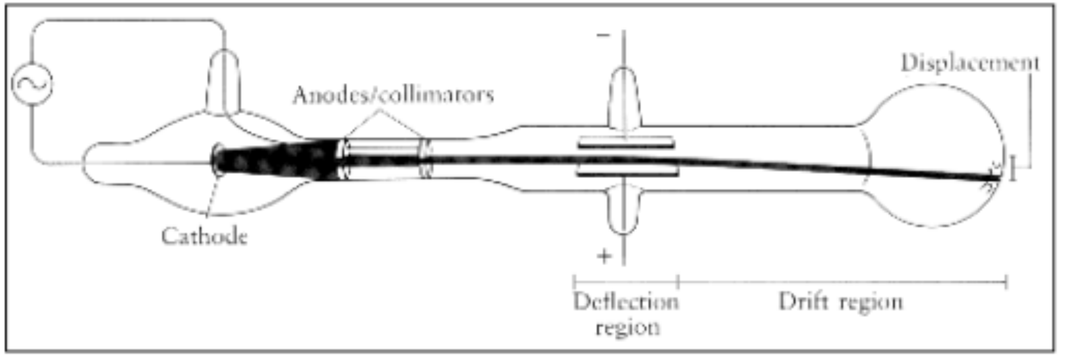
- Electrostatic acceleration → A = 0
- Acceleration with time varying fields → $\phi = 0$

Home old television

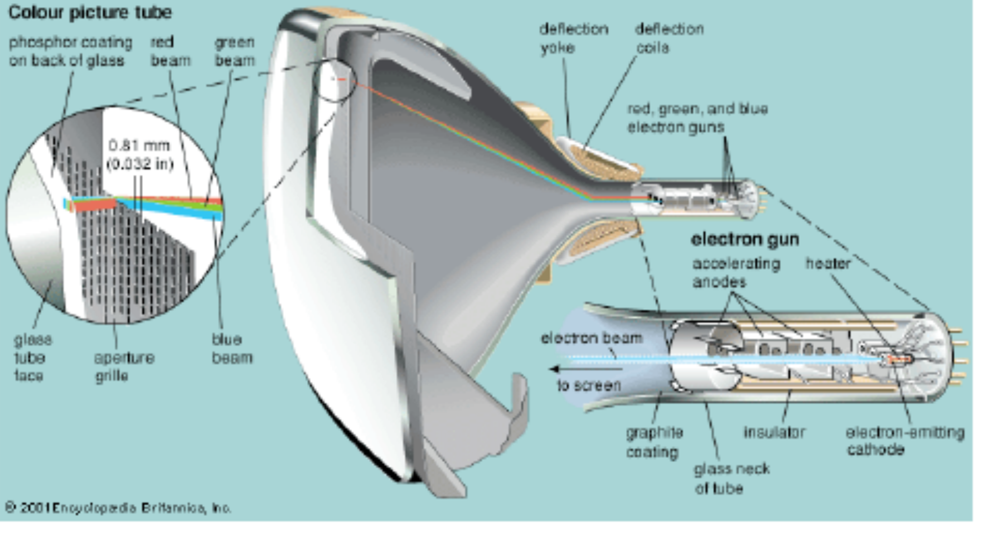


Particle Source: e⁻

- Electrons: Cathode Ray Tube (Thomson)



- Day to day application: Old television sets



elettron accelerated up to ~ 20 KeV

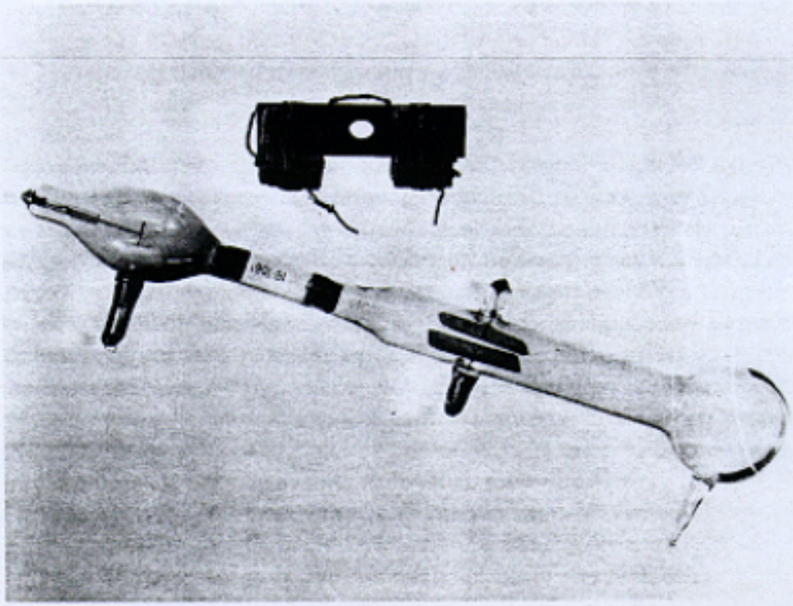
Cathode Ray Tube

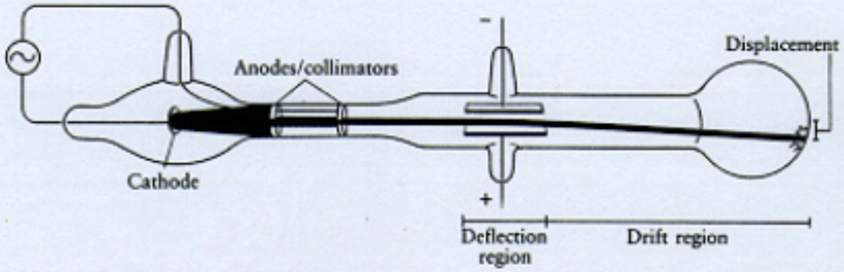
1986:

Thomson

experimental evidence for the electron

Nobel Price for Thomson in 1906

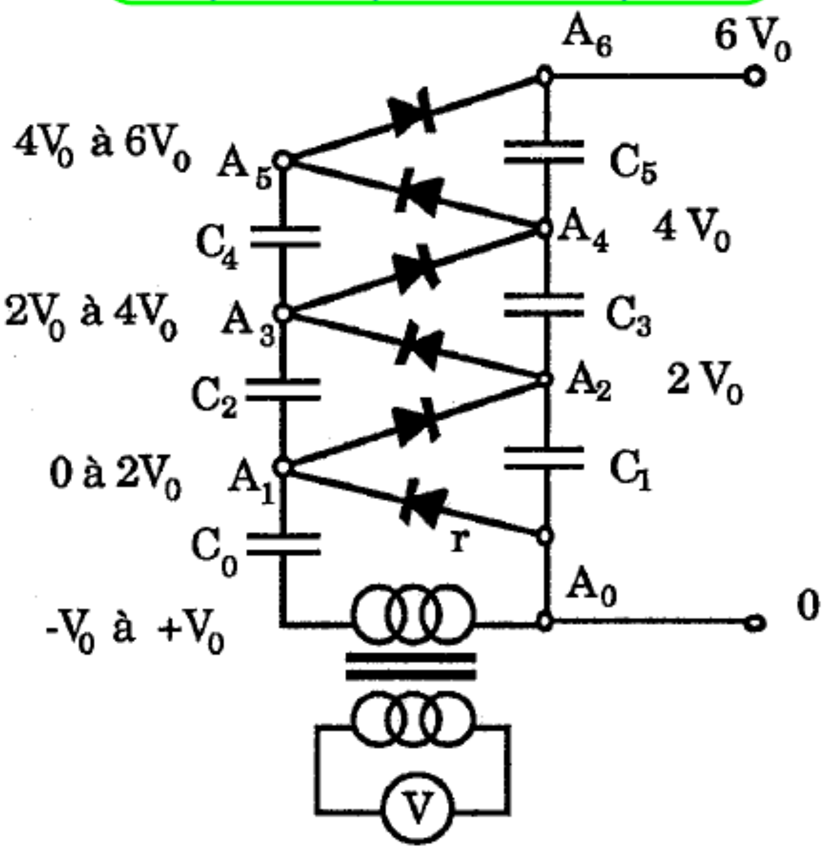


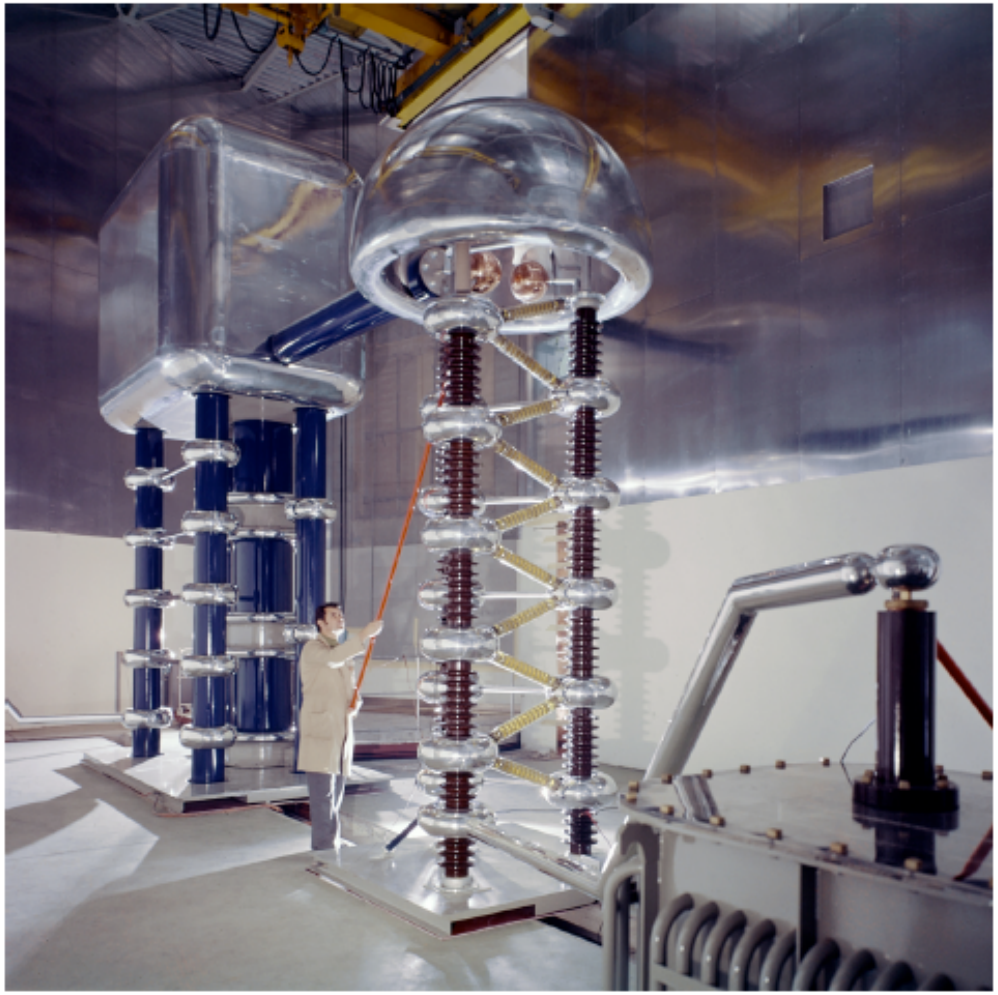


Above: One of the tubes with which J. J. Thomson measured the mass-to-charge ratio of the electron. Below: A schematic view of Thomson's apparatus. The cathode is connected by a wire through the glass tube to a generator that supplies it with negative electric charge; the anode and collimator are connected to the generator by another wire so that negative electric charge can flow back to the generator. The deflection plates are connected to the terminals of a powerful electric battery, and are thereby given strong negative and positive charges. The invisible cathode rays are repelled by the cathode; some of them pass through the slits in the anode and collimator, which only admit a narrow beam of rays. The rays are then deflected by electric forces as they pass between the plates; they then travel freely until they finally hit the glass wall of the tube, producing a spot of light. (This figure is based on a drawing of Thomson's cathode-ray tube in Figure 2 of his article "Cathode Rays," *Phil. Mag.* 44(1897), 293. For clarity, the magnets used to deflect the rays by magnetic forces are not shown here.)

Cockroft-Walton
(electrostatic acceleration)

High voltage unit composed by a multiple rectifier system



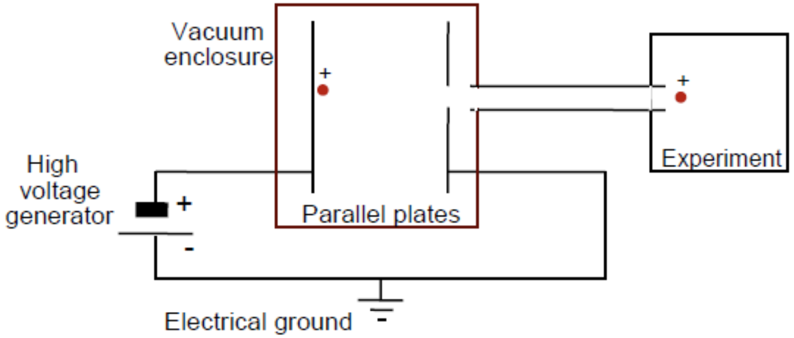


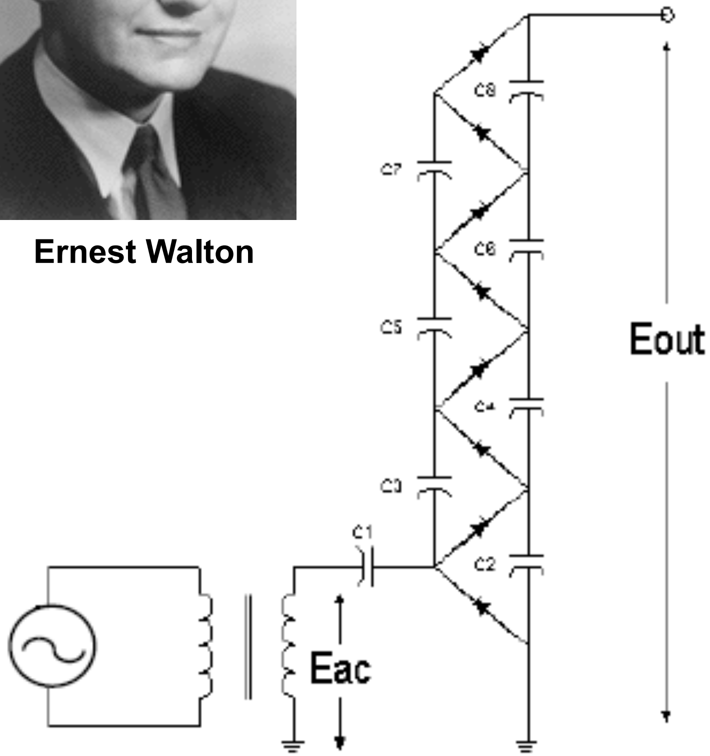
Electric discharge due to too high
Voltage: maximum limit 1 MV

CERN: 750 kV, used until 1993

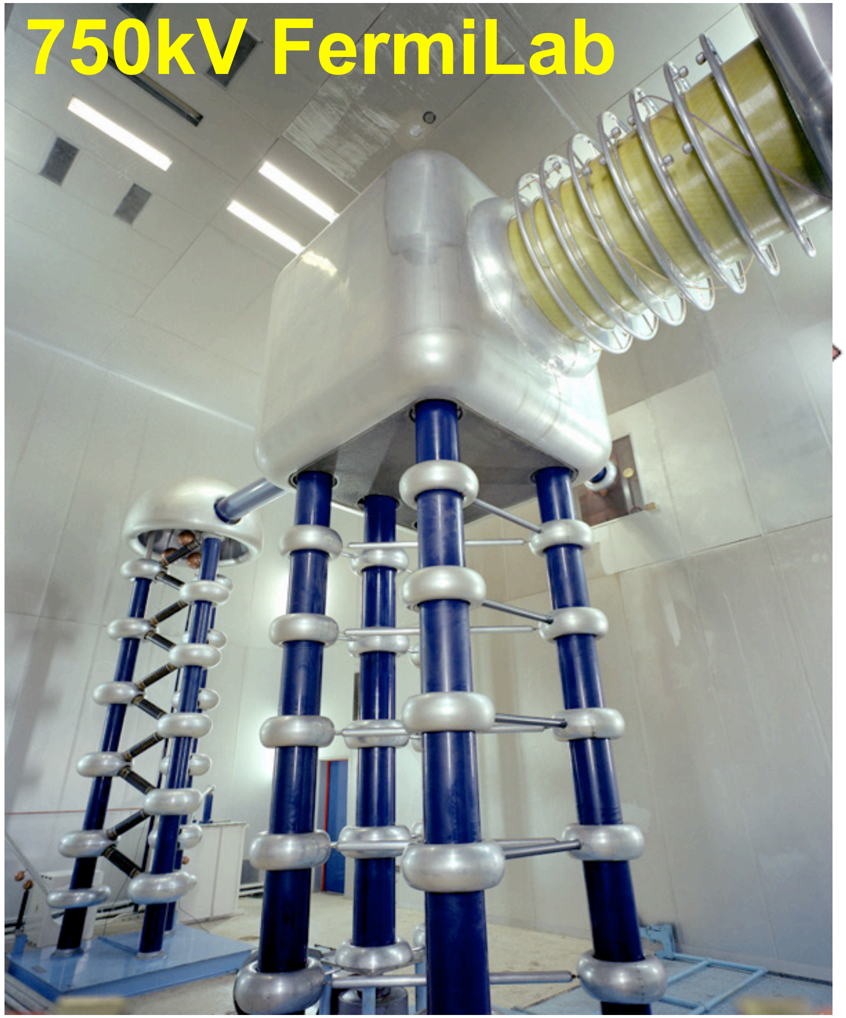
Cockroft-Walton
(electrostatic acceleration)

John Cockroft   Ernest Walton





$$E_{out} = N_{stage}\, E_{ac}$$



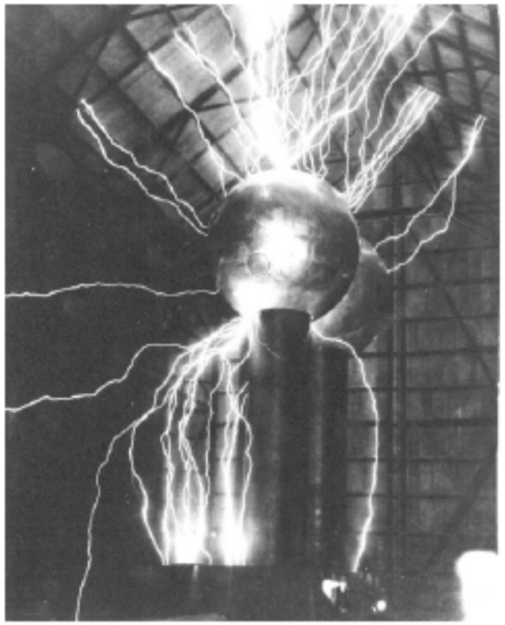
Van De Graaf electrostatic generator (1928)

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

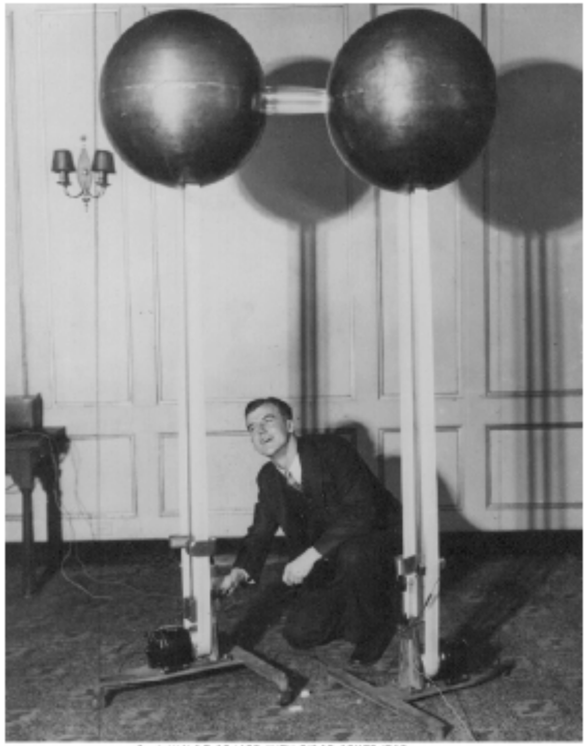
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: **10 MV**

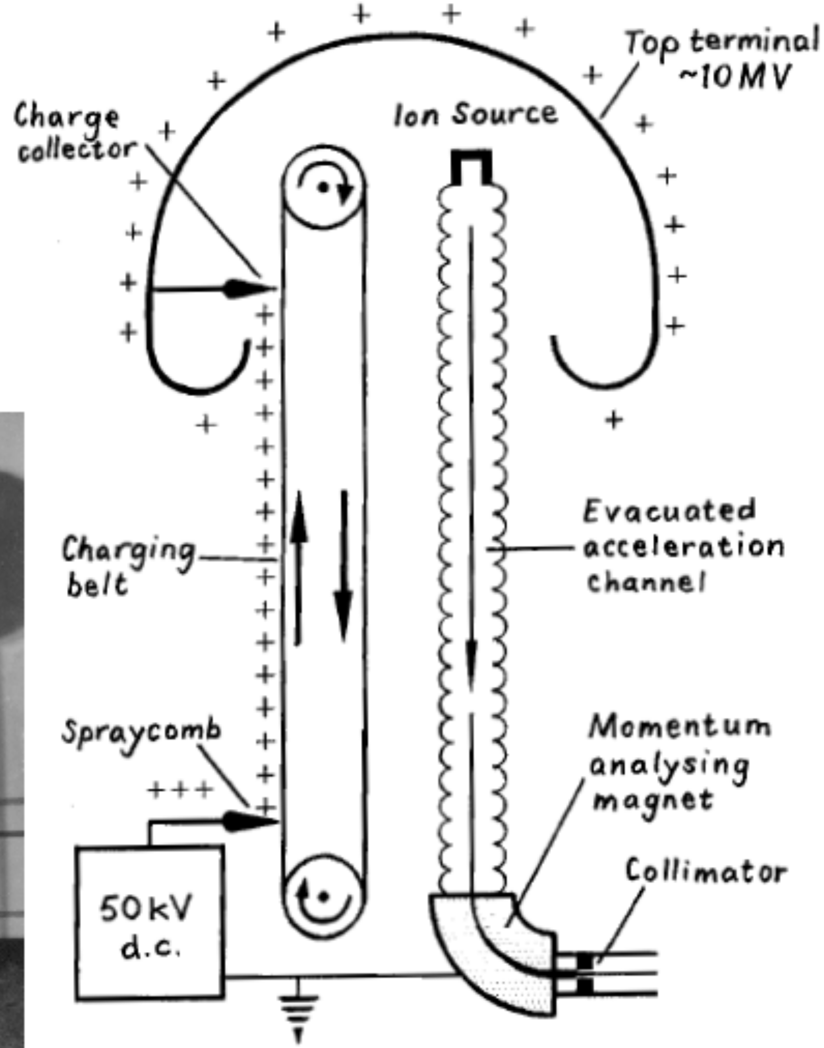
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



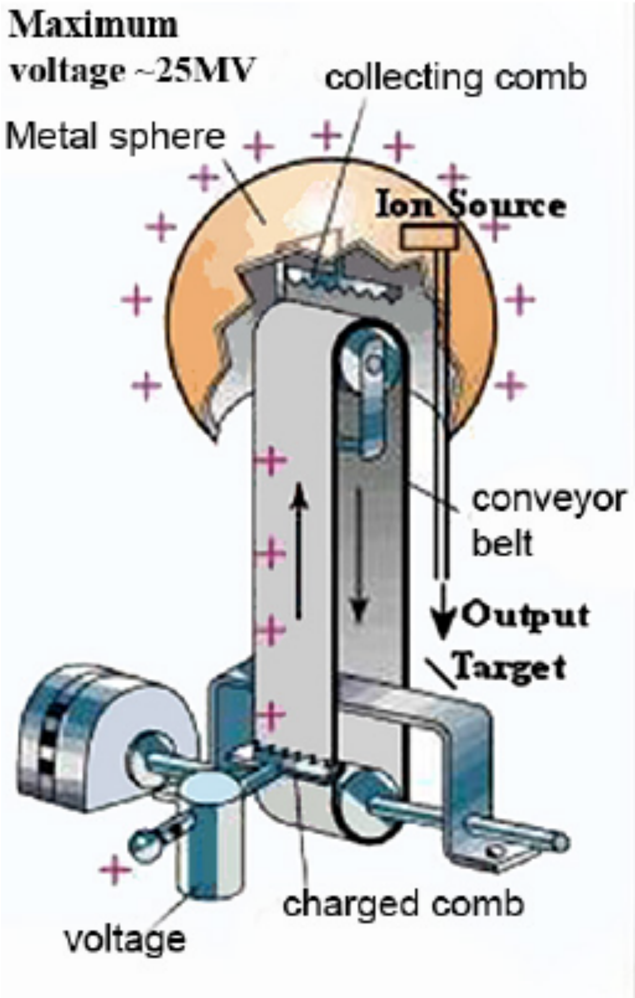
AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

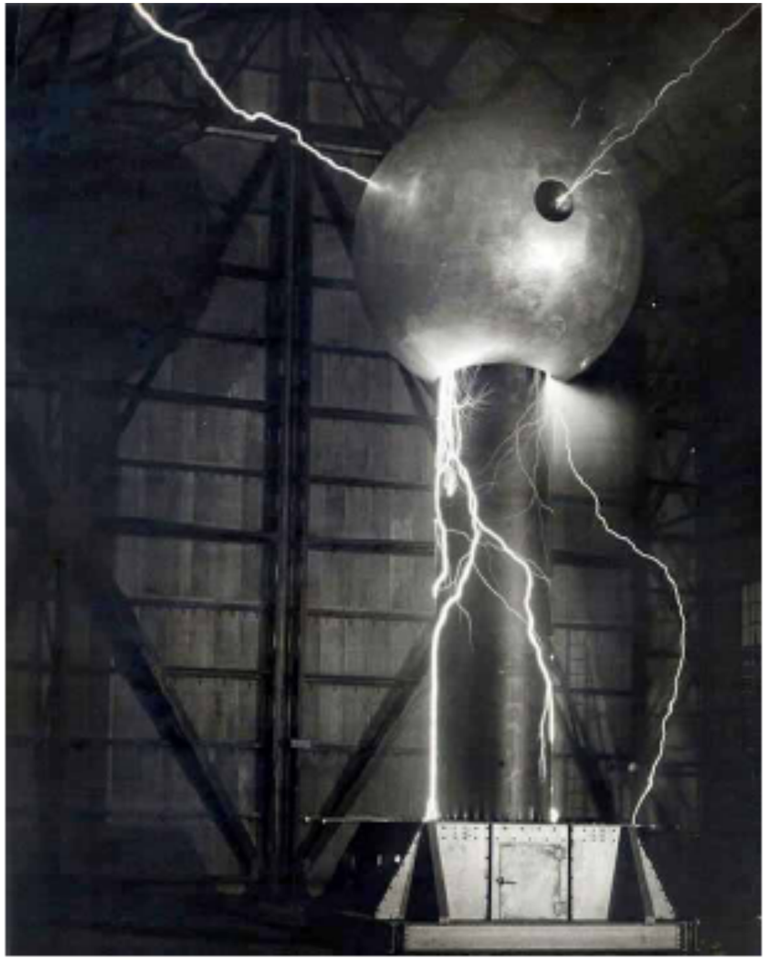


R. J. VAN DE GRAAFF WITH FIRST GENERATOR



Van De Graaf generators

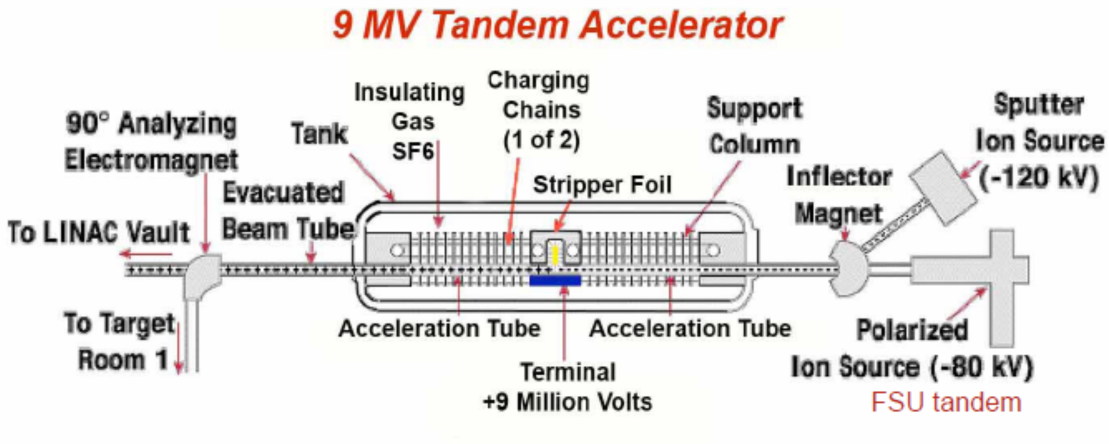




Van de Graaff's generator a Round Hill MA

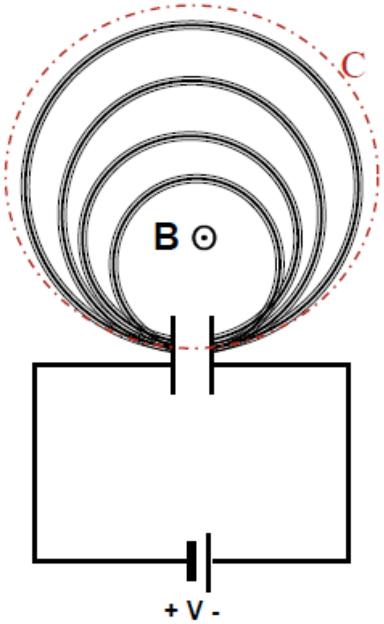
Tandem Van de Graaff

- Introduced in the 50's
  - accelerate negative ions, strip, and accelerate positive ions



Change the charge of the beam from - to + at the HV electrode

Possible DC accelerator?



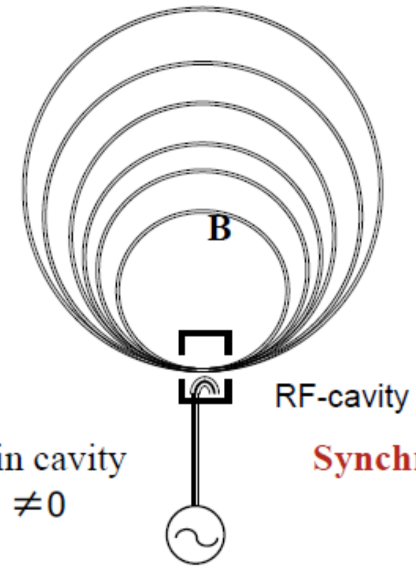
$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

or in integral form

$$\oint_C \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t}\int_S \mathbf{B} \cdot \mathbf{n}\, da$$

∴ There is no acceleration without time-varying magnetic flux

No! Maxwell forbids this!

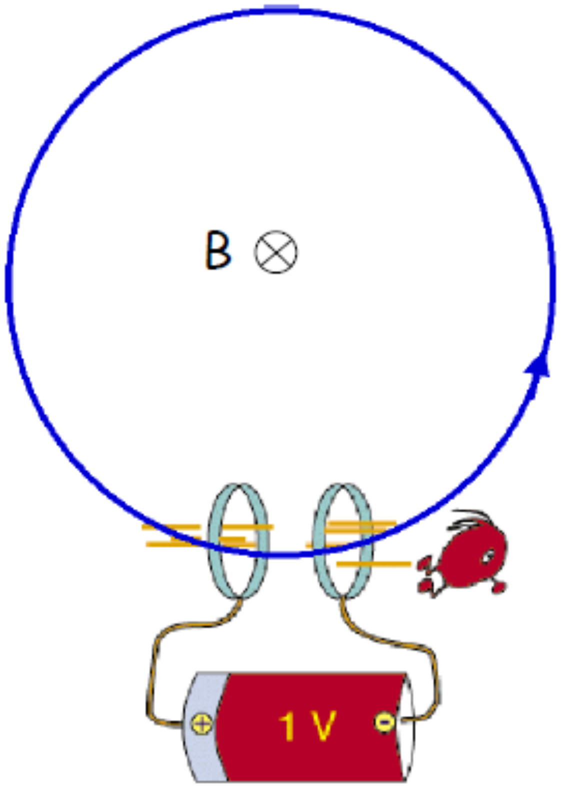


Note that in cavity $dB/dt \neq 0$

Synchronism condition: $\Delta\tau_{rev} = N/f_{rf}$

$\Rightarrow$ **Microtron**

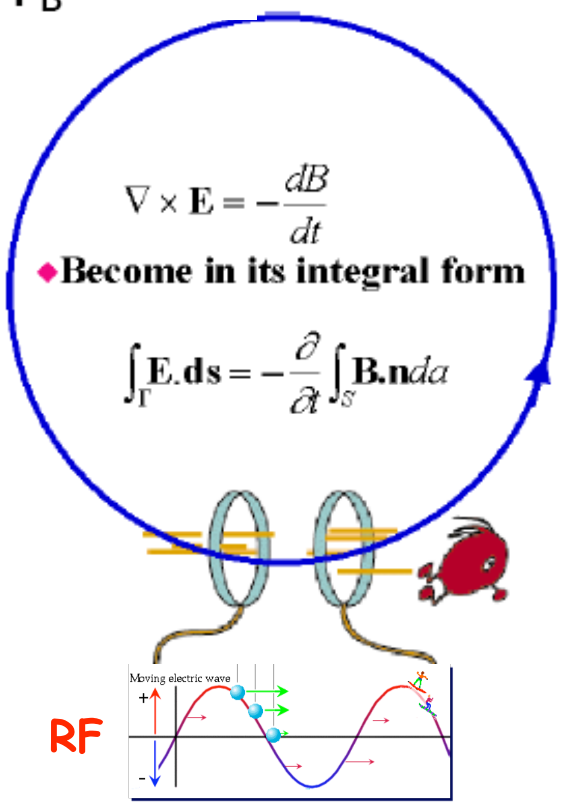
Simple Circular Accelerator



- Circular orbits determined by magnetic field
- Acceleration on each orbit
- Will this work?

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

No! Maxwell forbids this!



There is not acceleration
without time-varying magnetic flux

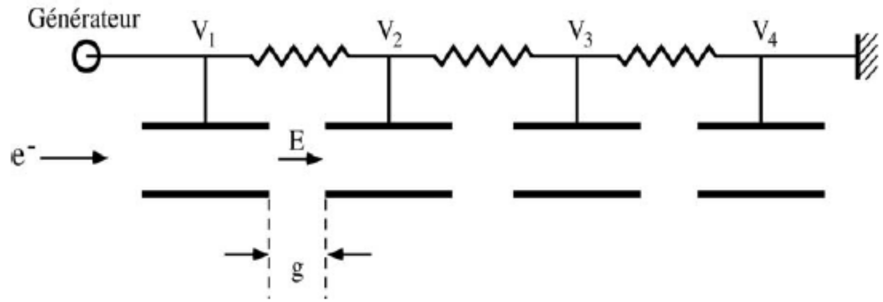
The accelerator has to provide kinetic energy to the charged particles, i.e. increase the momentum of the particles. To do this, we need an electric field E in the direction of the momentum of the particles:

Electrostatic accelerator

Gain: n.e.ΔV

Limit: $V_G = \Sigma V_i$

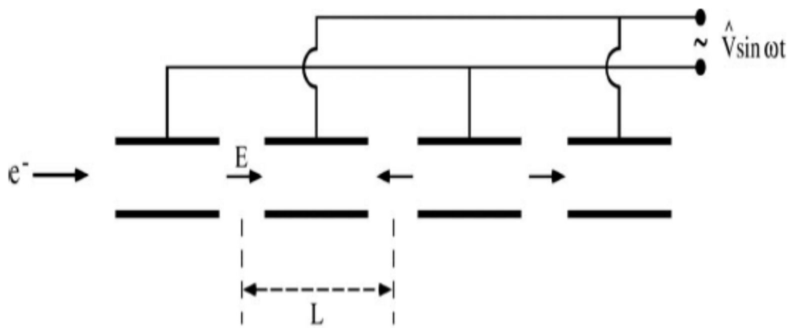
Sparks !



Rather use RF fields !

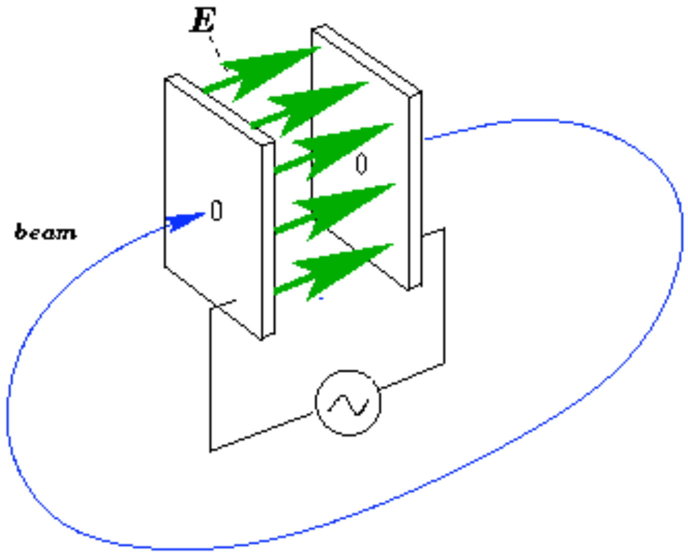
Wideroe structure

Synchronism: $L = vT/2$



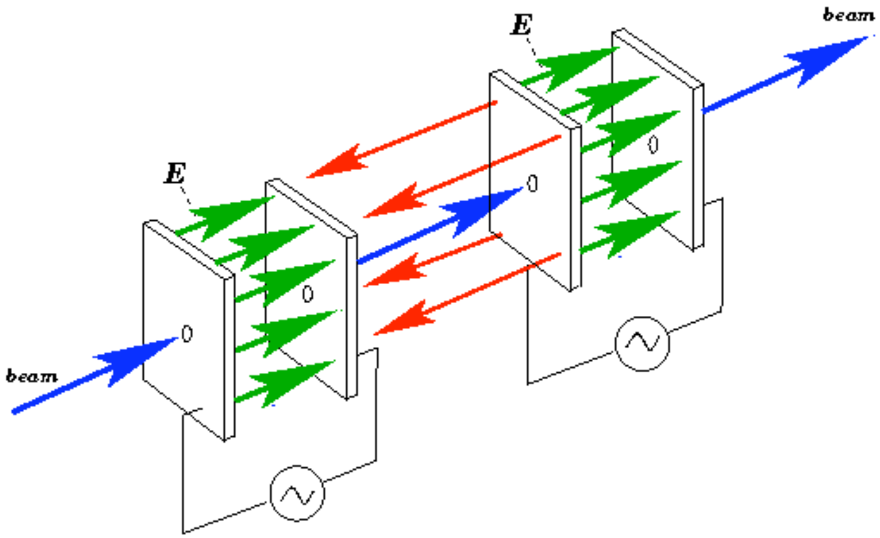
Time Varying Electrical Fields

Circular Accelerator



- Requires magnetic fields for trajectory guidance
- 'efficient' use of acceleration voltage
- beam energy limited by magnetic bending field

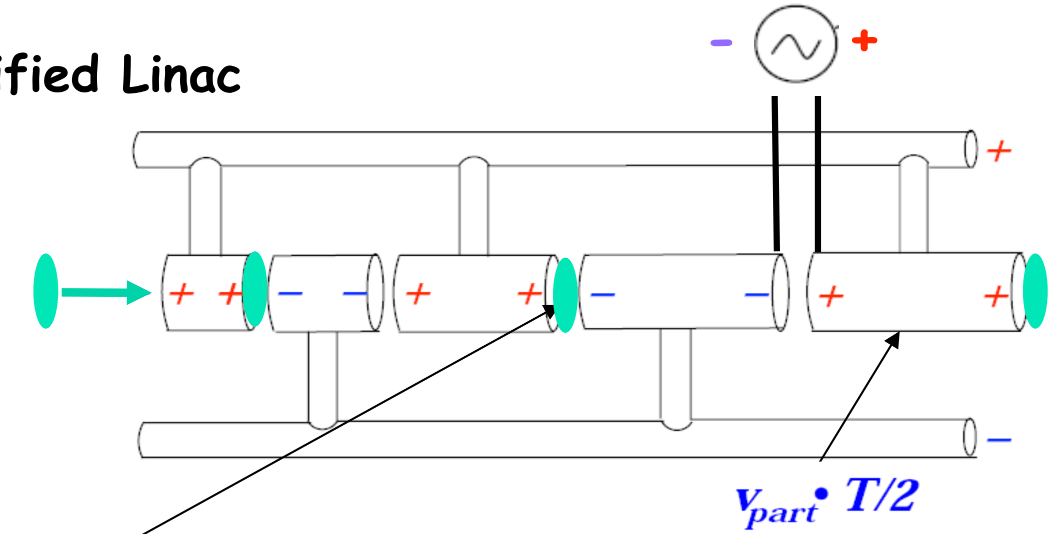
Linear Accelerator



Total acceleration voltage 'only' limited by accelerator length

Linear accelerators

Simplified Linac



Wideroe
1928

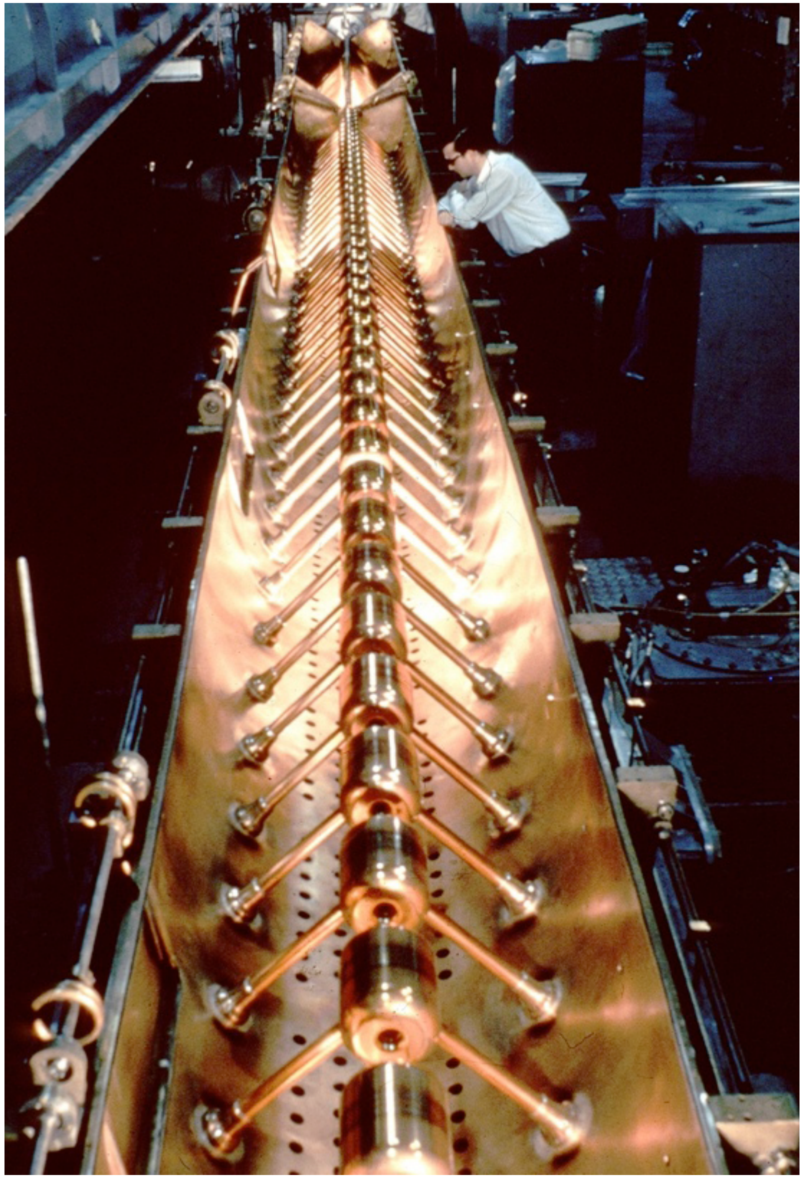
The particles are grouped together to make sure that the field has the correct direction at the time the particle group passes the gap.

The speed of the particles increases and the length of the modules change so that the particle's arrival in the gap is synchronized with the field direction in the gap

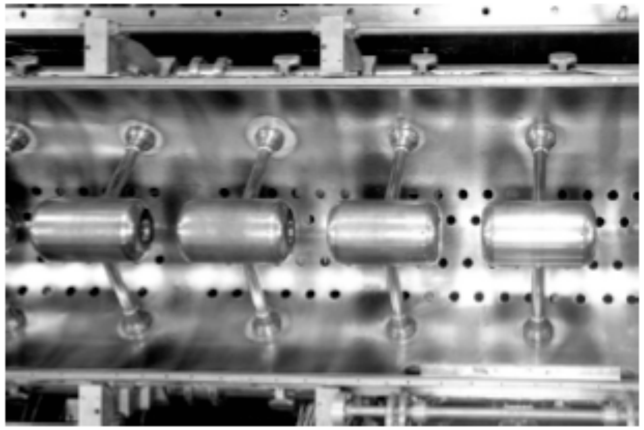
First Linac composed by drift tubes interleaved by acceleration gaps powered by an RF generator. (1928)

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

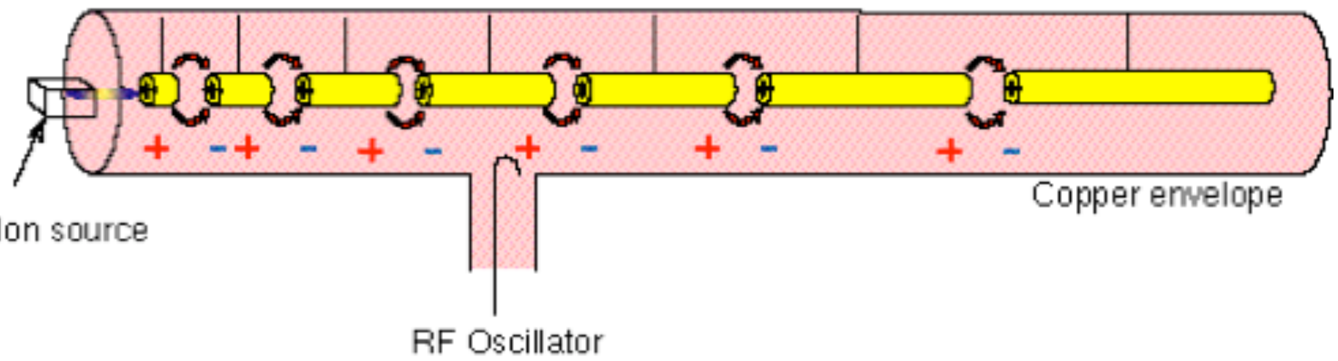


Linac composed by drift tubes interleaved by acceleration gaps as Wideroe linac, but field generated in a resonant cavity. The frequency of the field can go up to 200 MHz.

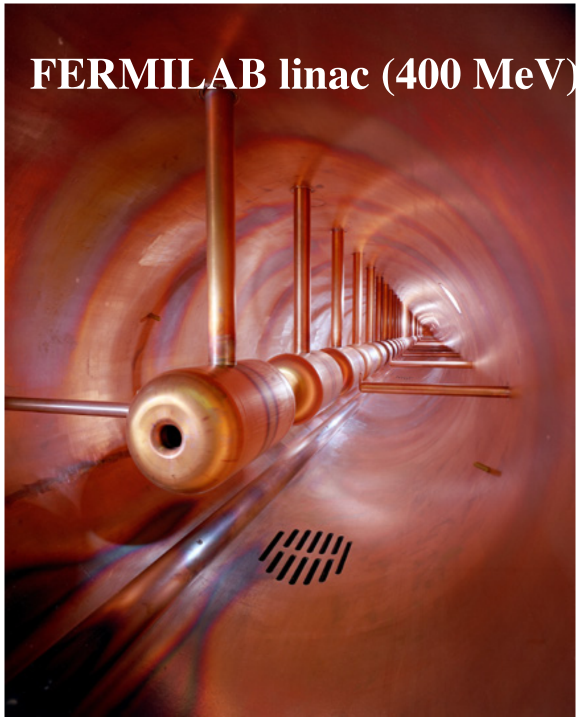


CERN Linac 1 :
accelerated protons to 50 MeV.

Linear accelerator



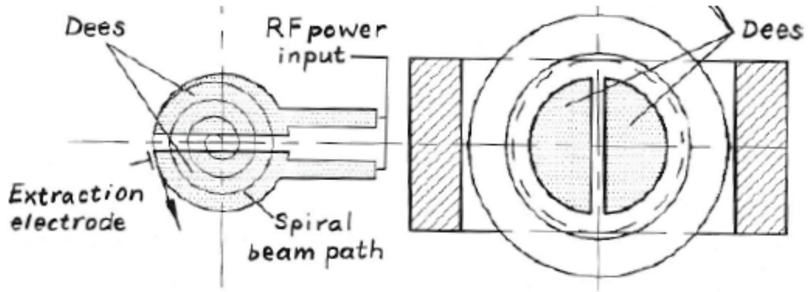
- Particle gains energy at each gap
- Lengths of drift tubes follow increasing velocity
- Spacing becomes regular as v approaches c

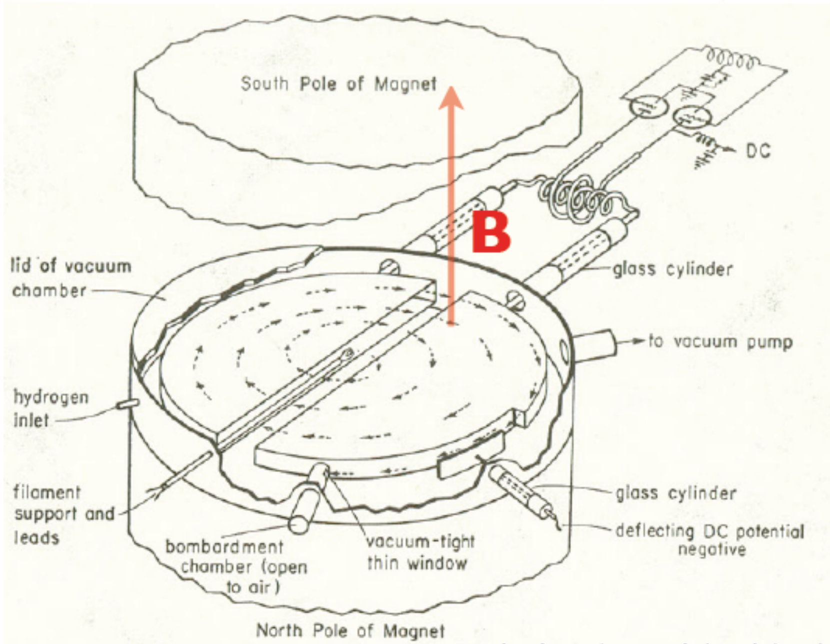



2 mile Linear Accelerator, SLAC, Stanford
World's straightest building
World's longest building

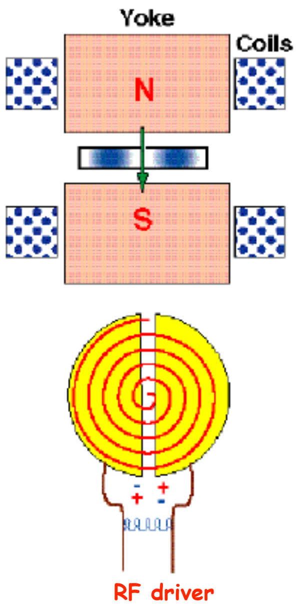
Cyclotron

- 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



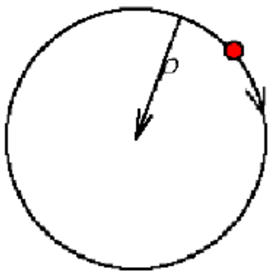


www.physics.rutgers.edu/ cyclotron/



$$e\mathbf{v} \times \mathbf{B} = \frac{mv^2}{\rho}$$

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



Invented by Lawrence, got the Noble prize in 1939

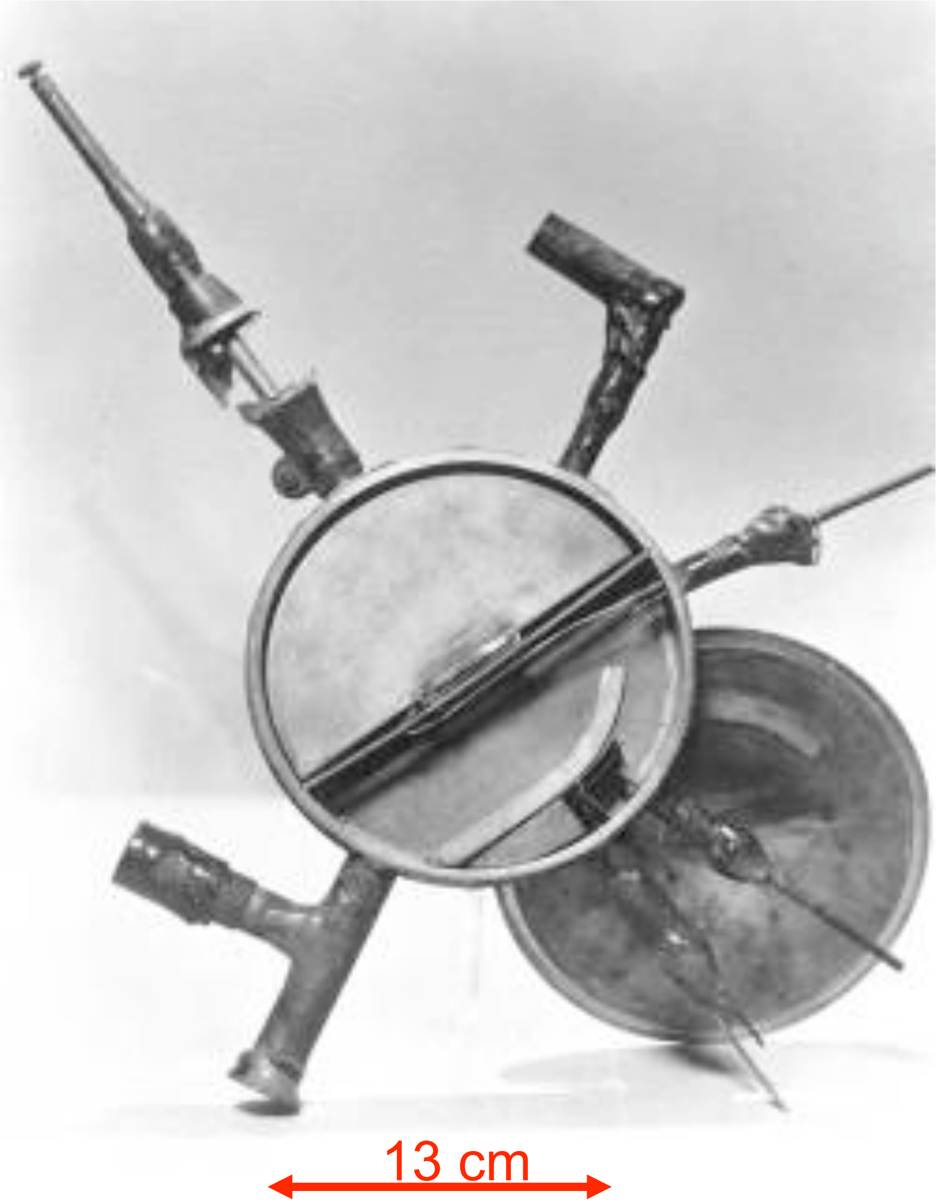
$$\omega = \frac{q}{m} \cdot B$$

$$r = \frac{m}{q} \cdot \frac{v}{B}$$

Ref: E. Wilson, CERN

m = const $\Rightarrow$ f_{rev} = const for B = const

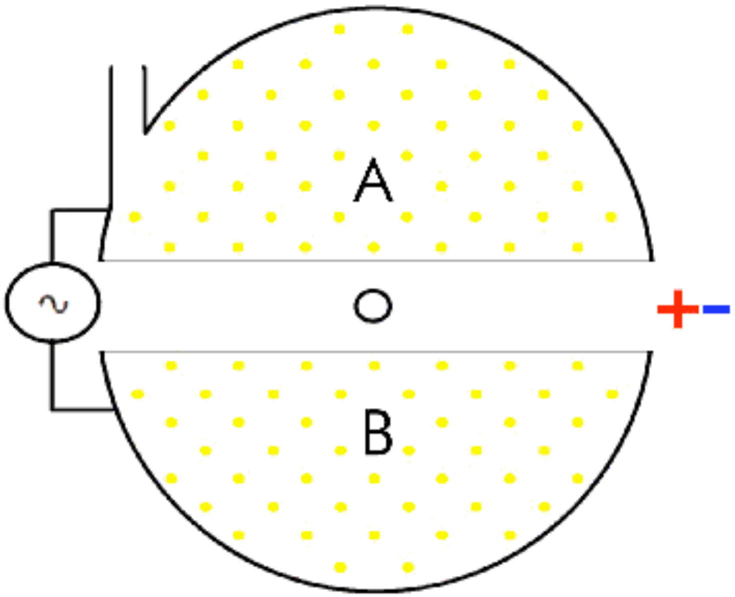
Circular Accelerators



Cyclotron

First circular particle accelerator built by Ernest O. Lawrence & Stanley Livingston at Berkeley in 1930.

Energy = 80 keV, Diameter = 13cm



The first cyclotron and the Berkeley one

The first cyclotron with a
diameter of 5 inches

The Cyclotron

Centripetal force=-Centrifugal force:

Continuous particle flux

$$\frac{mv^2}{r} = Bqv$$

Reorganizing:

$$\frac{v}{r} = \frac{Bq}{m}$$

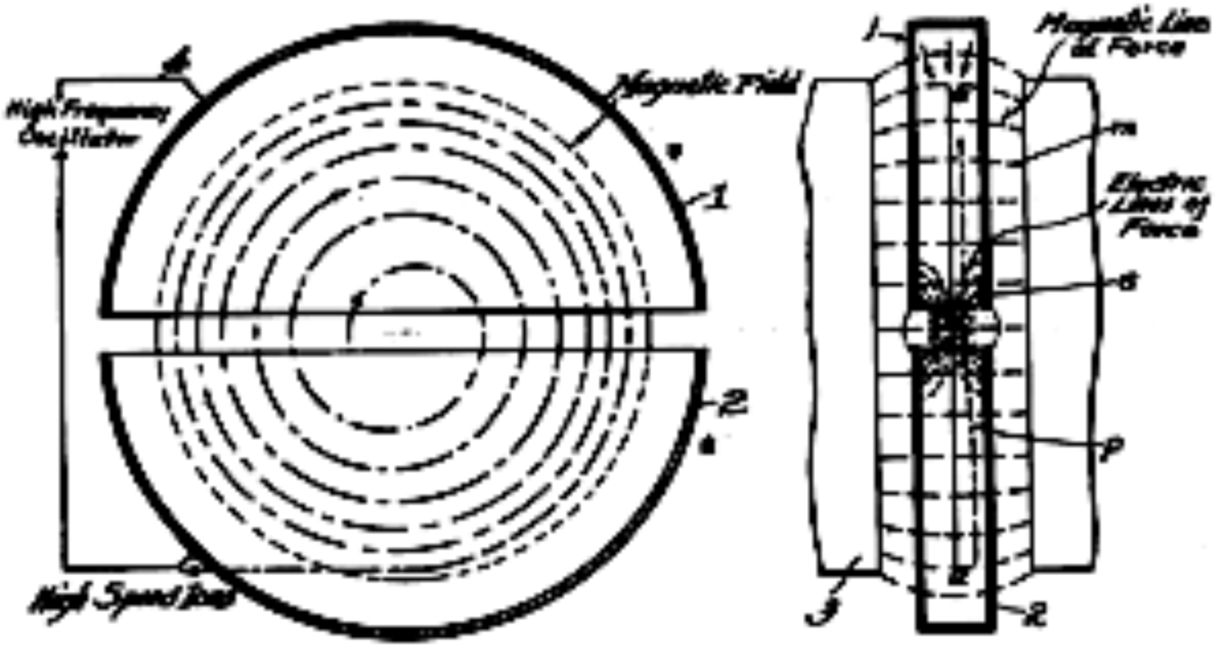
/r is equal to angular sp

$$\omega = \frac{Bq}{m}$$

$$f = \frac{\omega}{2\pi}$$

Therefore,

$$f = \frac{Bq}{2m\pi}$$



The frequency does not depend on the radius, if the mass is contant. When the particles become relativistic this is not valid any more. The frequency must change with the particle velocity: synchrcyclotron. The field can also change with the radius: isochronous cyclotron

Synchrotron (1952, 3 GeV, BNL)

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

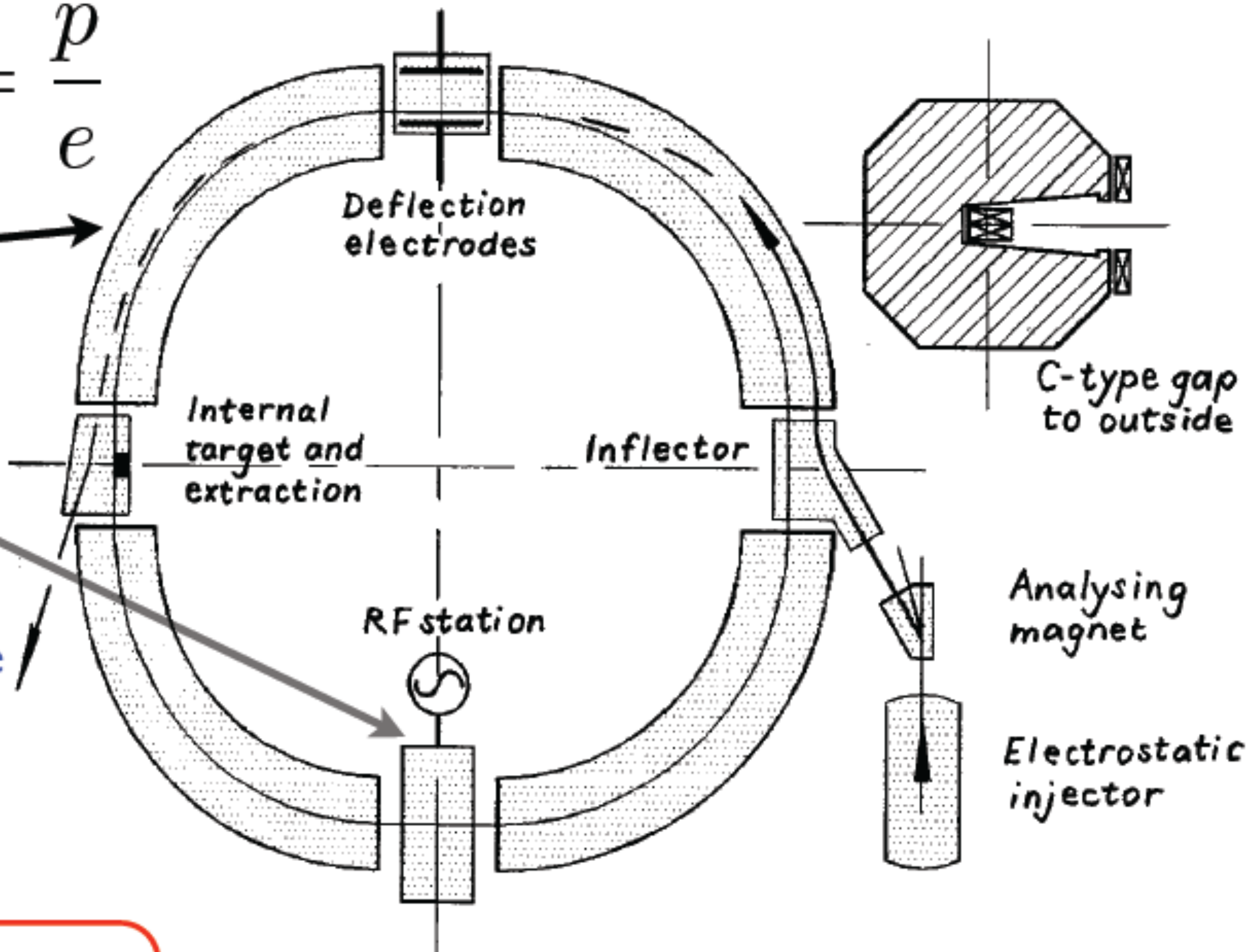
Particle rigidity: $B\rho = \frac{p}{e}$

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

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

e electric charge

ρ constant radius of curvature



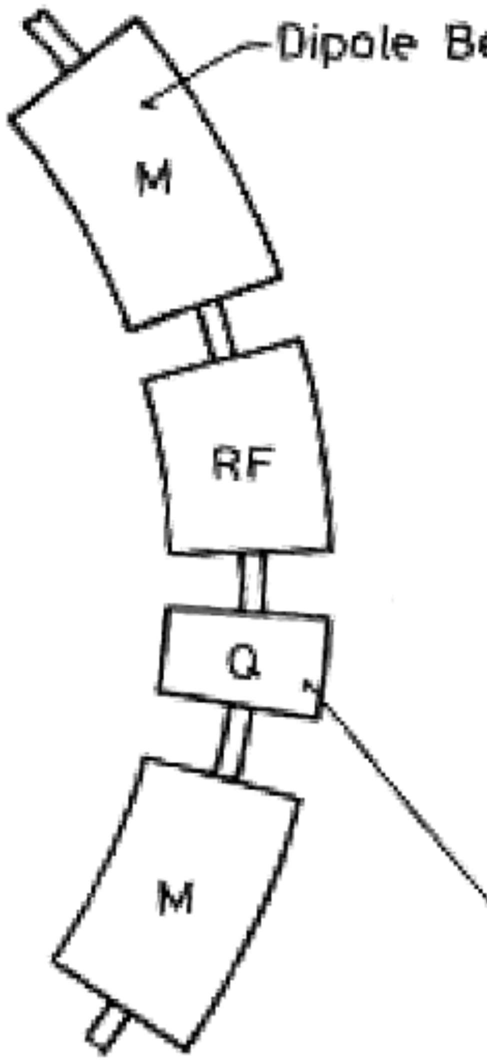
New magnetic elements for injection and extraction.

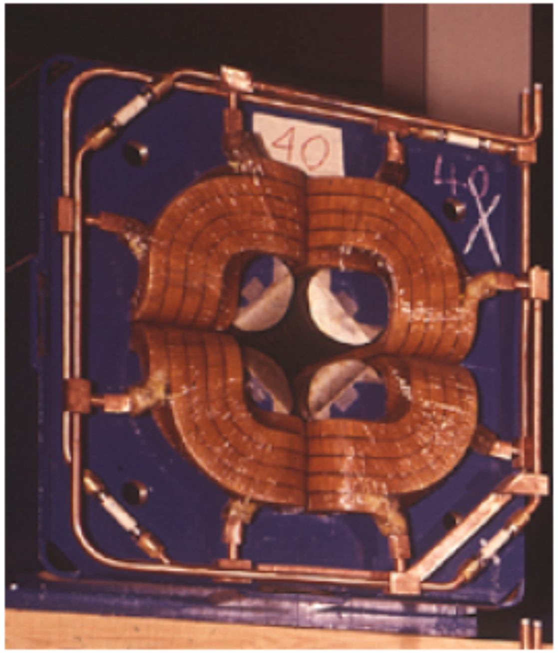
Bending strength limited by used technology to max ~ 1 T for room temperature conductors

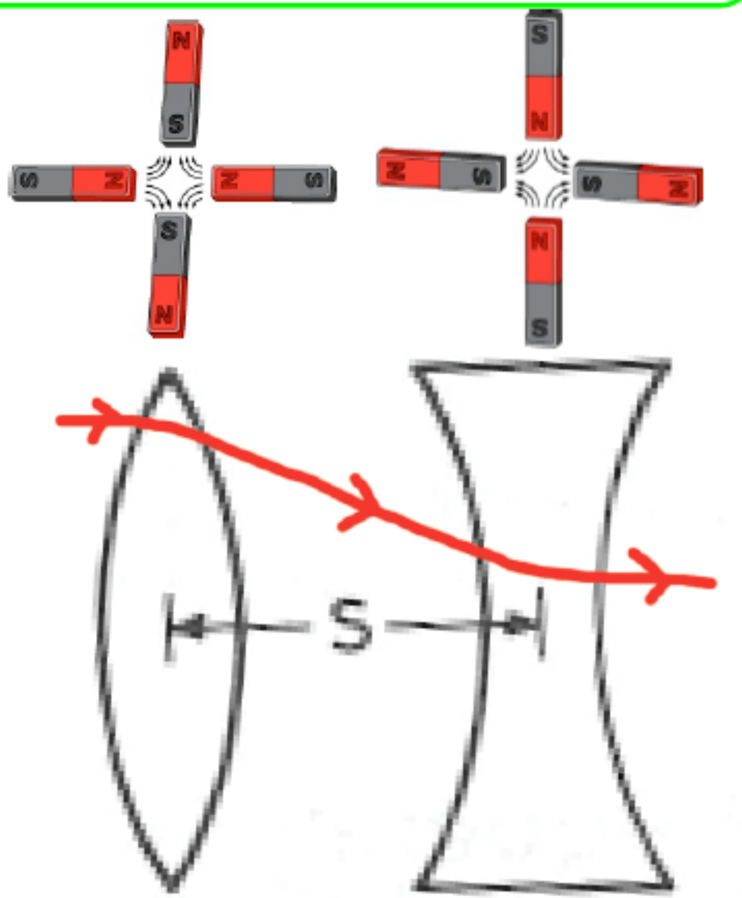
Weak focusing machine: no quadrupoles yet
Strong focusing machine, using quadrupoles, were proposed in 1952

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).

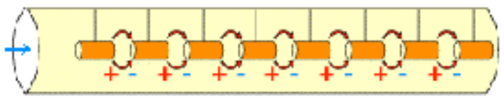


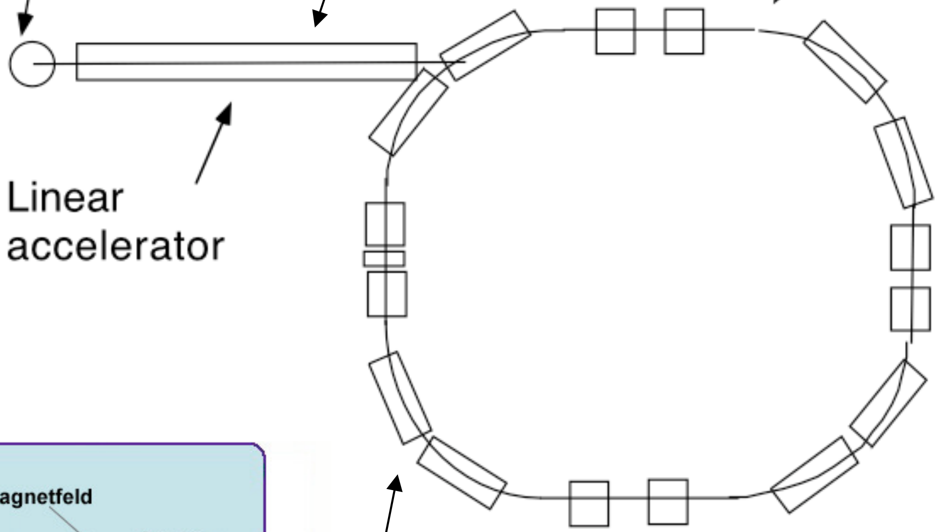


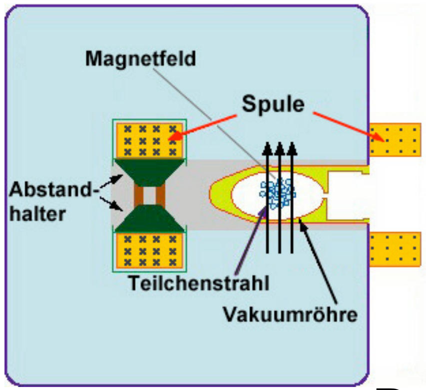


Modern particles accelerators for high energy up to LHC energy (7 TeV) work in this way.

General setup:





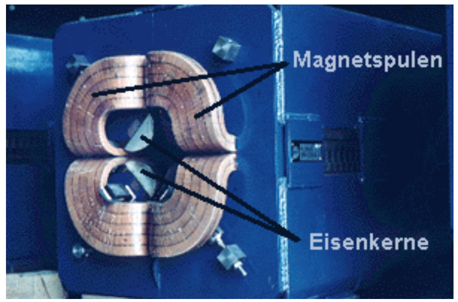


$p=0.3\ B\ R$

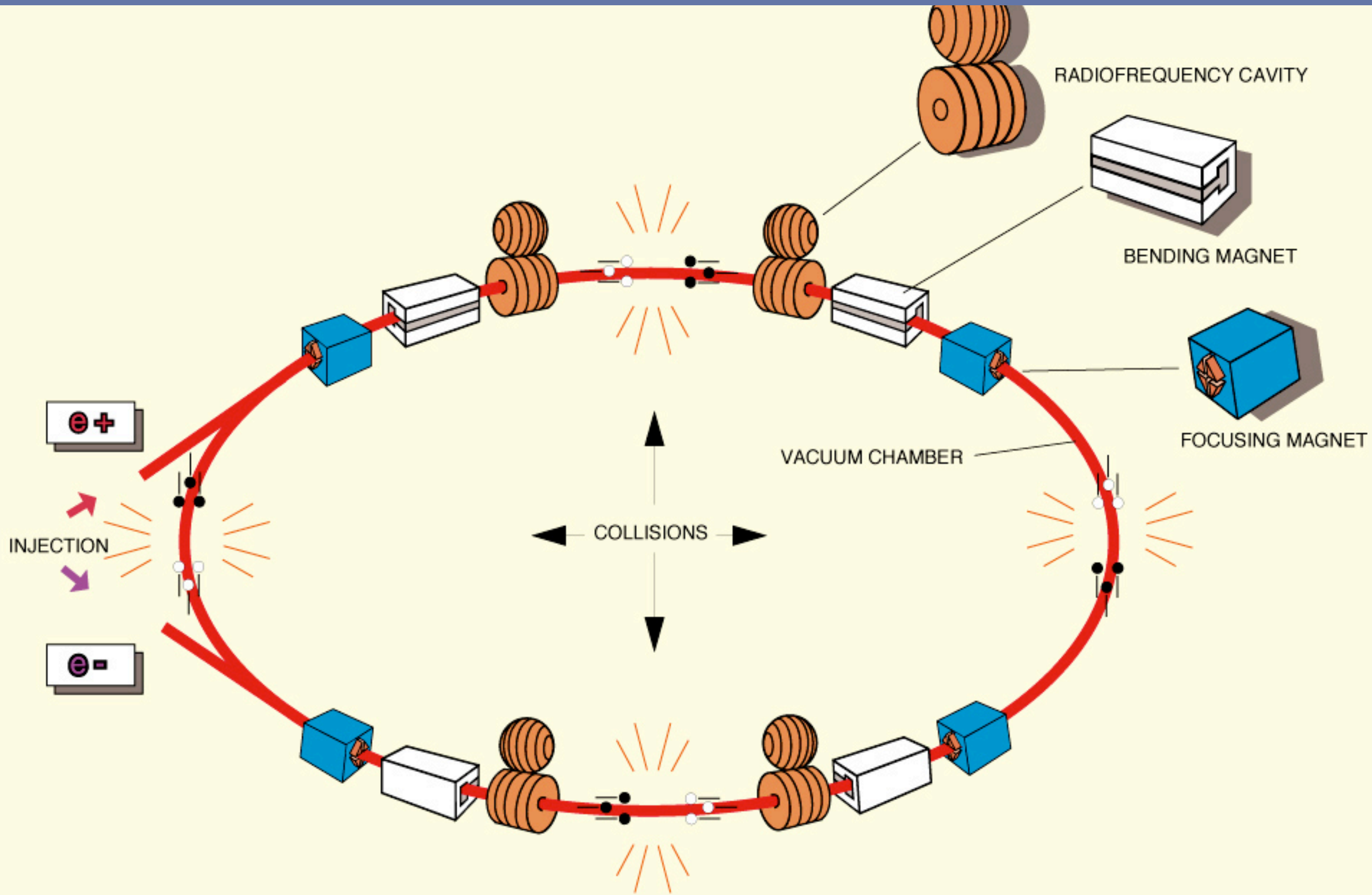
p [GeV/c]

B [T]

R [m]

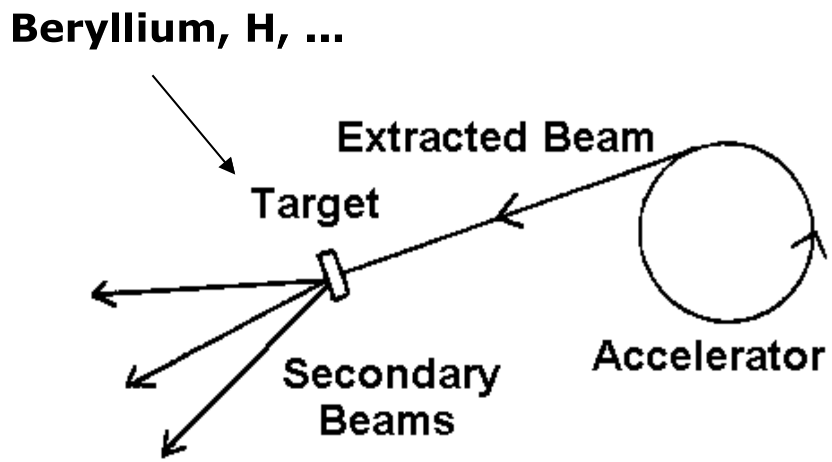


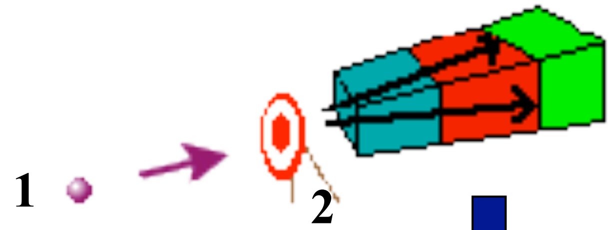
Principal Components of a Synchrotron



In a **Collider**, bunches of particles/antiparticles circulate in opposite directions.

To the experiment...

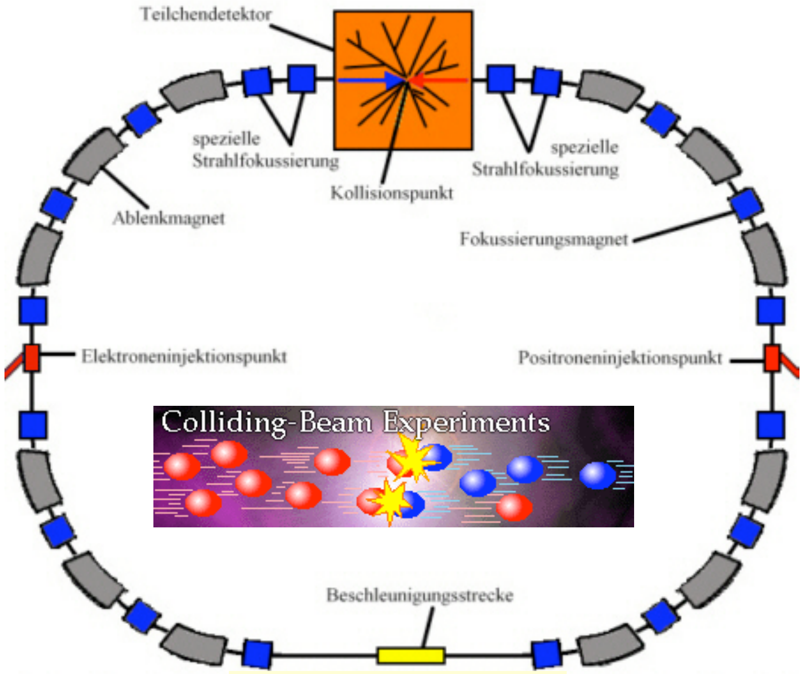


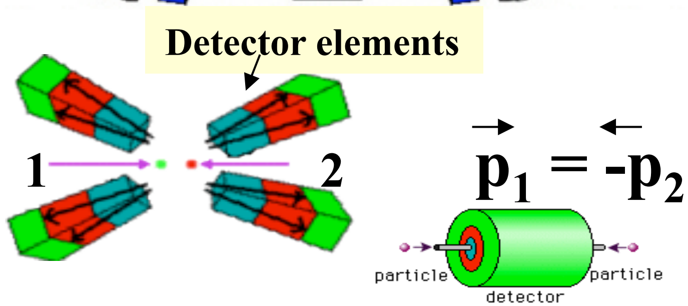


$$\vec{p}_2 = 0$$

$$E_{CM} = \sqrt{2 E_{beam} m_{target}}$$

example: 450 GeV proton beam on Hydrogen target : E_{CM} = 30 GeV, available for production of new particles





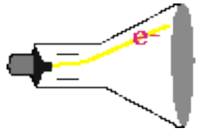
$$\vec{p}_1 = -\overleftarrow{p}_2$$

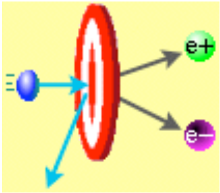
$$E_{CM} = 2 E_{beam}$$

if $E_{beam1} = E_{beam2}$

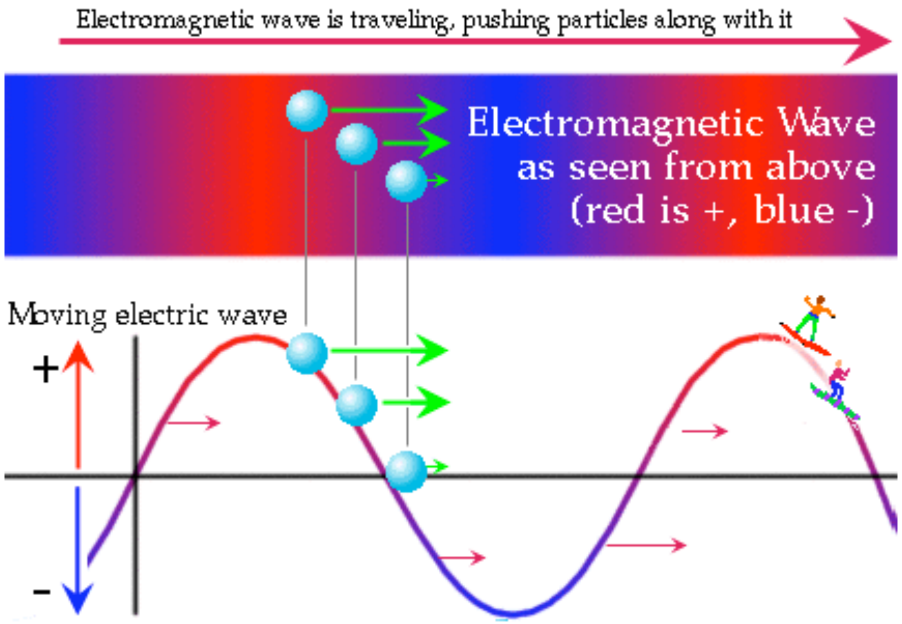
How do we "shoot" probe particles?

☛ Acquire some probe particles

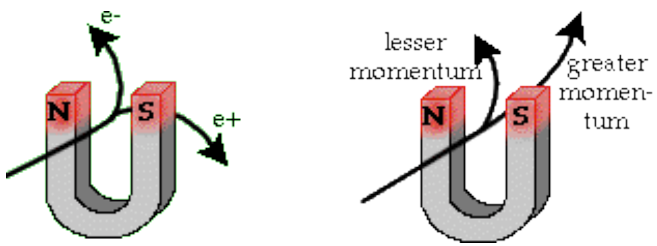




☛ Accelerate the probe particles
Final speed ~ c



☛ Steer and aim the probe particles



What type of particle to accelerate?

- Particles must be
  - **charged**
    - accelerated by electric fields (Energy = charge * Voltage-difference)
    - steered and focused using magnetic fields (p = q 0.3 R B)
  - **long lived**
    - best : infinite life-time
    - but : due to Lorentz factor $\gamma\tau$, the life-time in the accelerator can be reasonably long
    - example :
      - **Pions**, τ=2.6x10^{-8} sec, E=200 GeV, γ = E/m = 200/0.140 = 1428.6, $\gamma\tau$ =0.04 msec, v ≅ c, ⇒ average distance travelled = c γ τ = 11 km, good enough for fixed target experiments (**CERN, PSI,...**)
      - **Muons**, τ=2.2x10^{-6} sec, E=200 GeV, m = 0.1 GeV/c^2 ⇒ $\gamma\tau$ =4.4 msec !, average distance travelled = **1320 km!** (there are ideas for a **muon collider!**)

- In practice for colliders up to now:
  - **electrons, anti-electrons, protons, anti-protons**

Beam Energy

- For high-energy beams, one has to
  - pass the particles through very large electric fields (voltage differences)
    - ⇨ technological limitations
  - pass them through many smaller fields in a line
    - ⇨ need many cavities, on a long line
  - pass them through the same electric field many times
    - ⇨ circular path via dipole magnets

- However: for last option there is to consider:

a) if particle energy constantly increasing, must increase magnetic field synchronously ('synchrotron')

b) accelerated charged particles emit radiation :

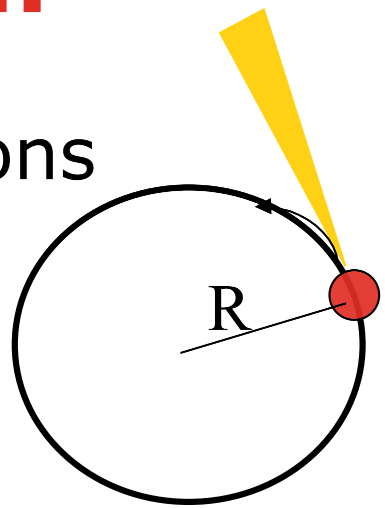
synchrotron radiation!

Synchrotron Radiation

- energy loss per revolution for electrons

$$\Delta E = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{2\pi R} \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{E}{m} \qquad R = \text{orbit radius}$$

$$\Delta E[GeV] = 5.7\times 10^{-7}\,\frac{E^4[GeV]}{R[km]}$$



- Example : LEP, $2\pi R$=27km, E=100 GeV (in 2000)
  - **ΔE = 2 GeV!!**
  - LEP at limit, need more and more energy just to compensate energy loss

- Note : for ultrarelativistic protons/electrons ($\beta \cong 1$)

$$\Delta E[p]/\,\Delta E[e] = (m_e/m_p)^4 = \mathbf{10^{-13}\ !!}$$

What are accelerators used for?

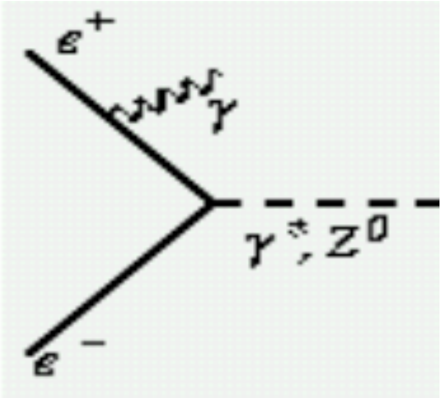
Basic and Applied Research		Medicine	
High-energy phys.	120	Radiotherapy	7500
S.R. sources	50	Isotope Product.	200
Non-nuclear Res.	1000	Hadron Therapy	20
Industry			
Ion Implanters	7000		
Industrial e- Accel.	1500	Total:	17390

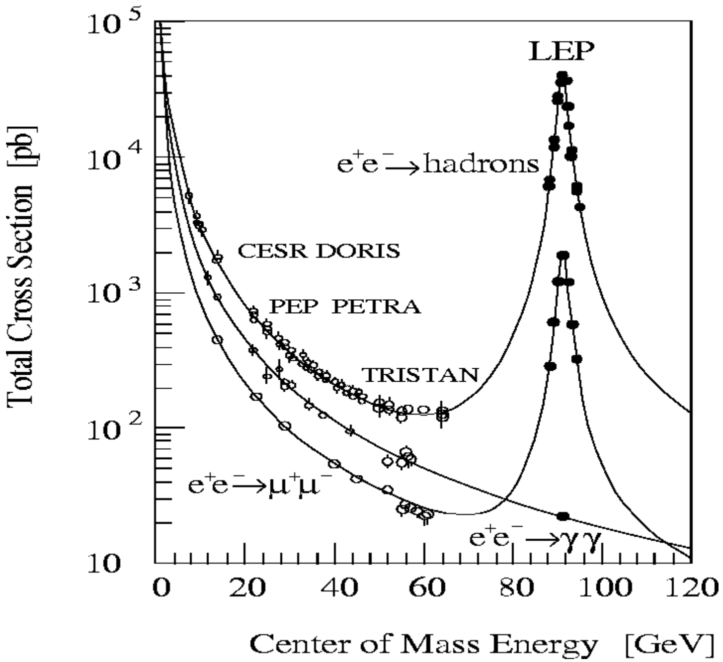
Courtesy: W. Mondelaers JUAS 2004

MORE SLIDES

How much beam energy is really available for producing new particles?

- In an e^+e^- collider :
  - practically all of it
  - However: Photon radiation in the initial state can reduce the effective E_{CM}
  - particularly important when close (in energy) to a resonance

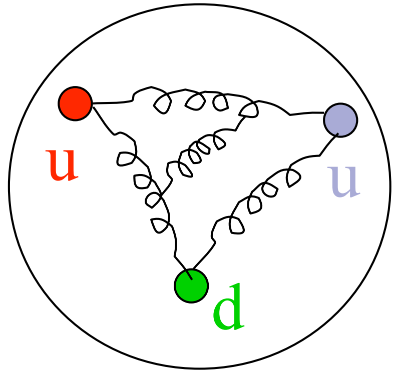




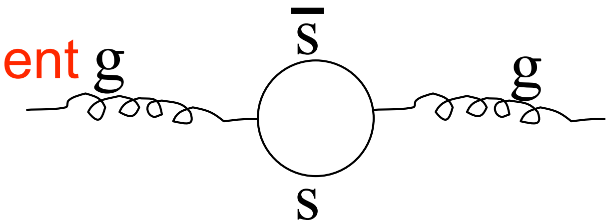
- Advantages:
  - energy very precisely adjustable, for example, to be at a resonance (e.g. Z: 91 GeV, Upsilon: 9.46 GeV) where the cross section is large
- Disadvantages:
  - When looking for new particles with unknown mass: Have to scan "manually" the beam energy

Proton structure

- (Anti-) Protons are a quark-gluon soup
  - 3 valence quarks bound by exchange of gluons
  - Gluons are colored and interact with other gluons
  - Virtual quark pair loops can pop-up generating additional quark content (sea-quarks)
  - Proton momentum is shared among all constituent partons (quarks& gluons)



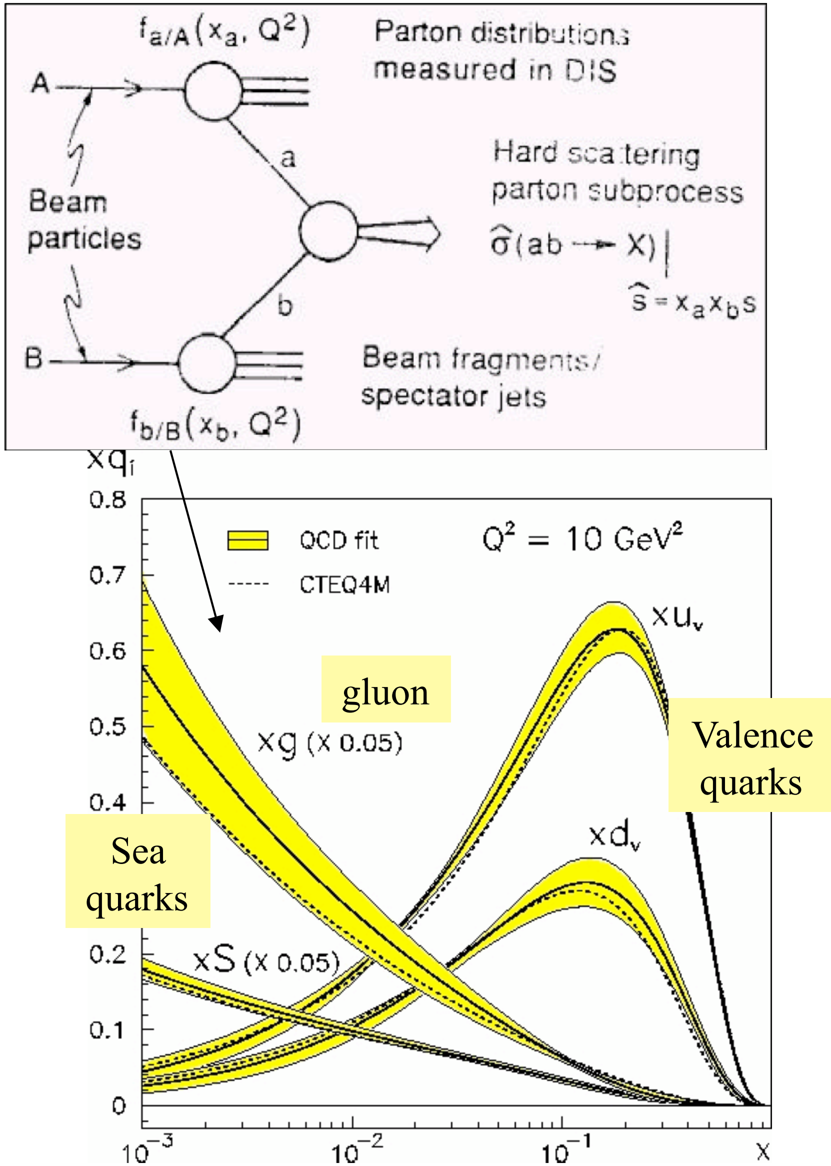
Proton



Virtual quark loop

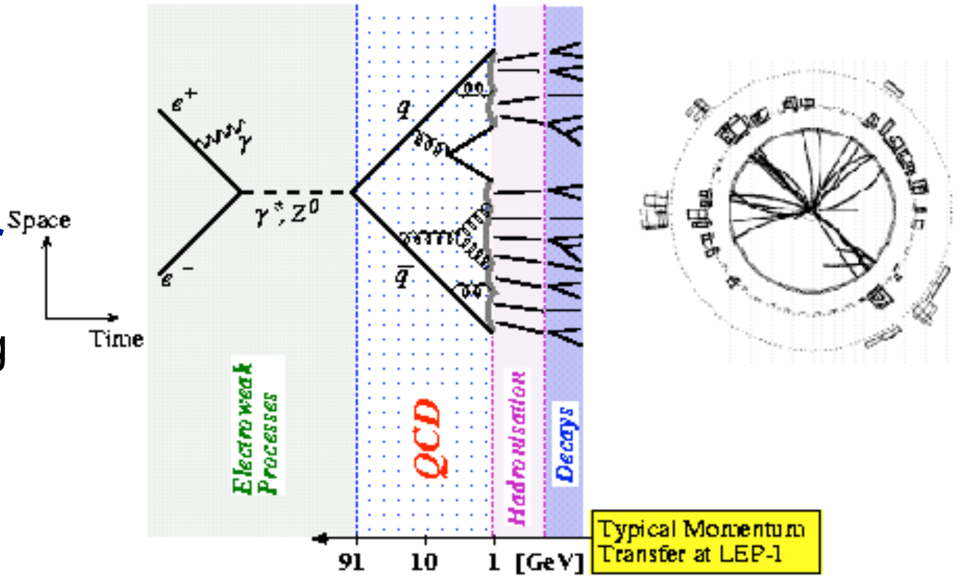
How much beam energy is really available for producing new particles?

- In an proton collider :
  - hard interaction due to partons
  - **Effective $E_{CM}^2 = x_a\, x_b\, E_{CM}^2$**
  - x_a, x_b << 1
- Advantages:
  - because in every collision the x_i are chosen "at random", there is a natural scan of effective E_{CM} : good for exploration of new energy regime (for new particles)
- Disadvantages:
  - effective E_{CM} not adjustable by operator
  - since in general $x_a \neq x_b$: centre-of-mass system boosted w.r.t. to lab system

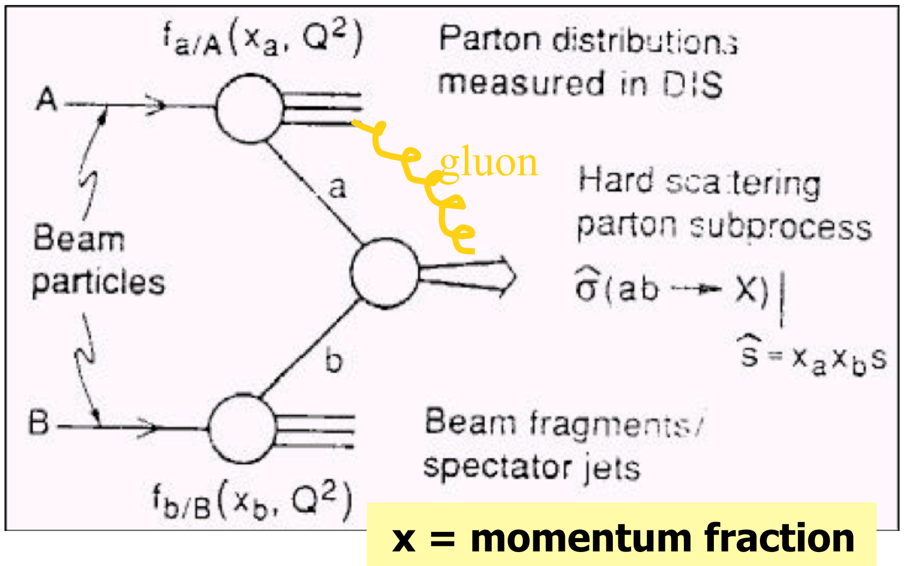


Further arguments for particle type

- take e^+e^- annihilation to quarks
  - e^+, e^- are **point-like** particles (to our present knowledge)
  - colliding particles do **not carry colour** charge ⇒ no interference between initial and final state because of strong interaction (gluon emission)
  - ⇒ theoretical calculations are **"easy" and precise**



- take proton-proton collisions:
  - protons are **made out of quarks and gluons**, actual interaction is between these partons
  - parton distributions cannot be computed from first principles, only determined from experiments
  - colliding particles carry **colour charge** ⇒ interference
  - ⇒ theoretical calculations are very **"difficult", and not very precise**



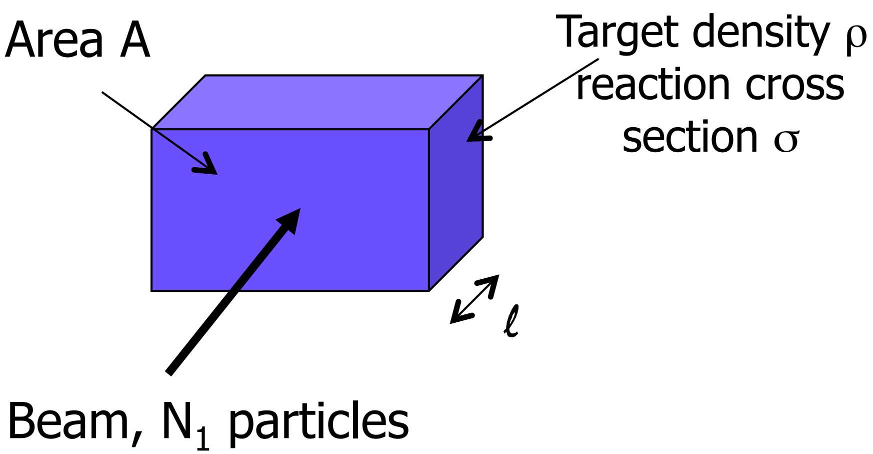
Key Properties of Accelerators

- The type of particle accelerated
- The energy to which the particles will be accelerated
- the fraction of the beam energy which is actually available for producing new particles
- Luminosity

Luminosity

- Luminosity(L) = reaction rate per unit cross section

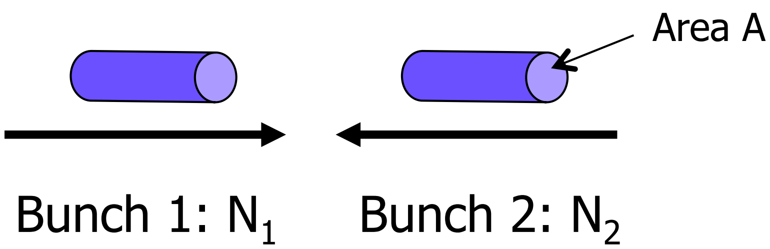
  N=number of events : **$dN/dt = \sigma L$**



Luminosity L =

$$\frac{1}{\sigma}\frac{dN}{dt} = \frac{dN_1}{dt}\rho l = \frac{dN_1}{dt}\frac{N_2}{A}$$

Colliding beams:



Luminosity L =

$$f\frac{N_1 N_2}{A} = \omega \ n \ \frac{N_1 N_2}{A}$$

f = collision frequency
ω = turns per second
n = number of bunches

Luminosity...

- Typical values
  - LEP : $L = 10^{31} - 10^{32}\ cm^{-2}\ sec^{-1}$
  - LHC : $L = 10^{34}\ cm^{-2}\ sec^{-1}$

- Amount of recorded data often expressed in $[pb^{-1}]$, namely integrated luminosity:

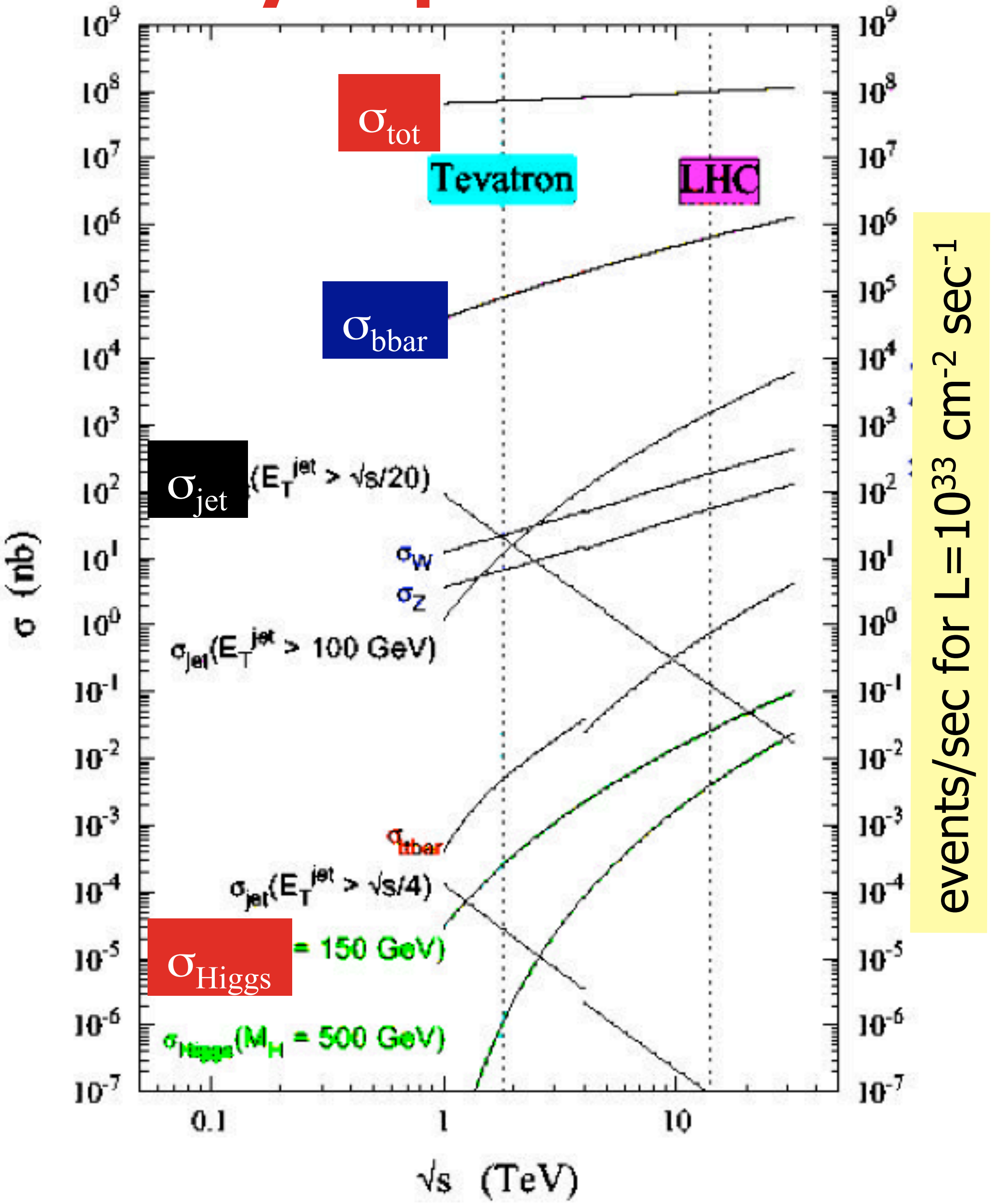
$$L_{int} = \int dt\, L$$

$\Rightarrow$ Number of events recorded over some period T : $N = \sigma L_{int} = \sigma L T$

- *units* : 1 barn = $10^{-28}\ m^2$,

- eg. on an excellent day, LEP could produce $3\ pb^{-1}$ of data
  $\sigma(e^+e^- \rightarrow hadrons) = 30\ nb \Rightarrow$ 90000 *hadronic* events/day

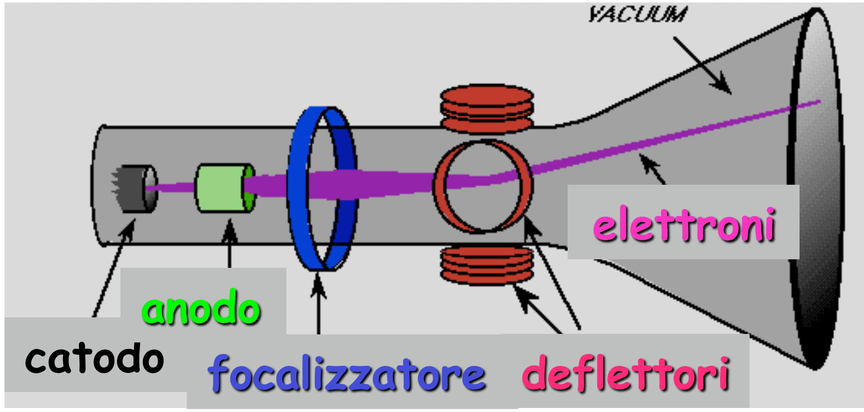
Why important to have high luminosity?



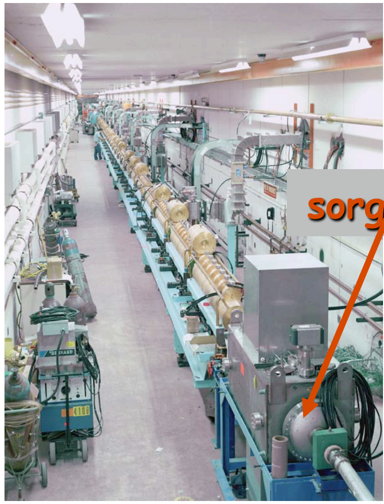
- of course, more data means smaller statistical errors
- because the interesting events are rare (i.e. have small cross sections)

Come si accelerano le particelle

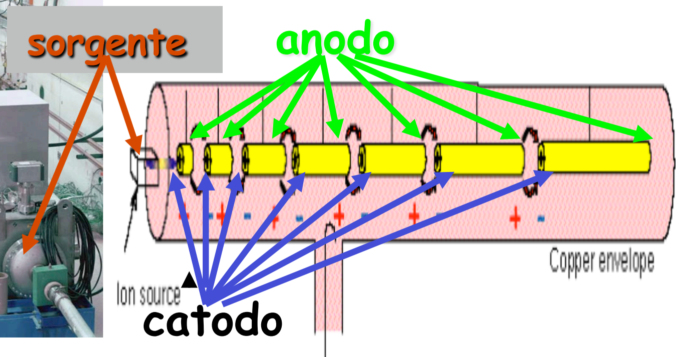
l'acceleratore di casa: il televisore



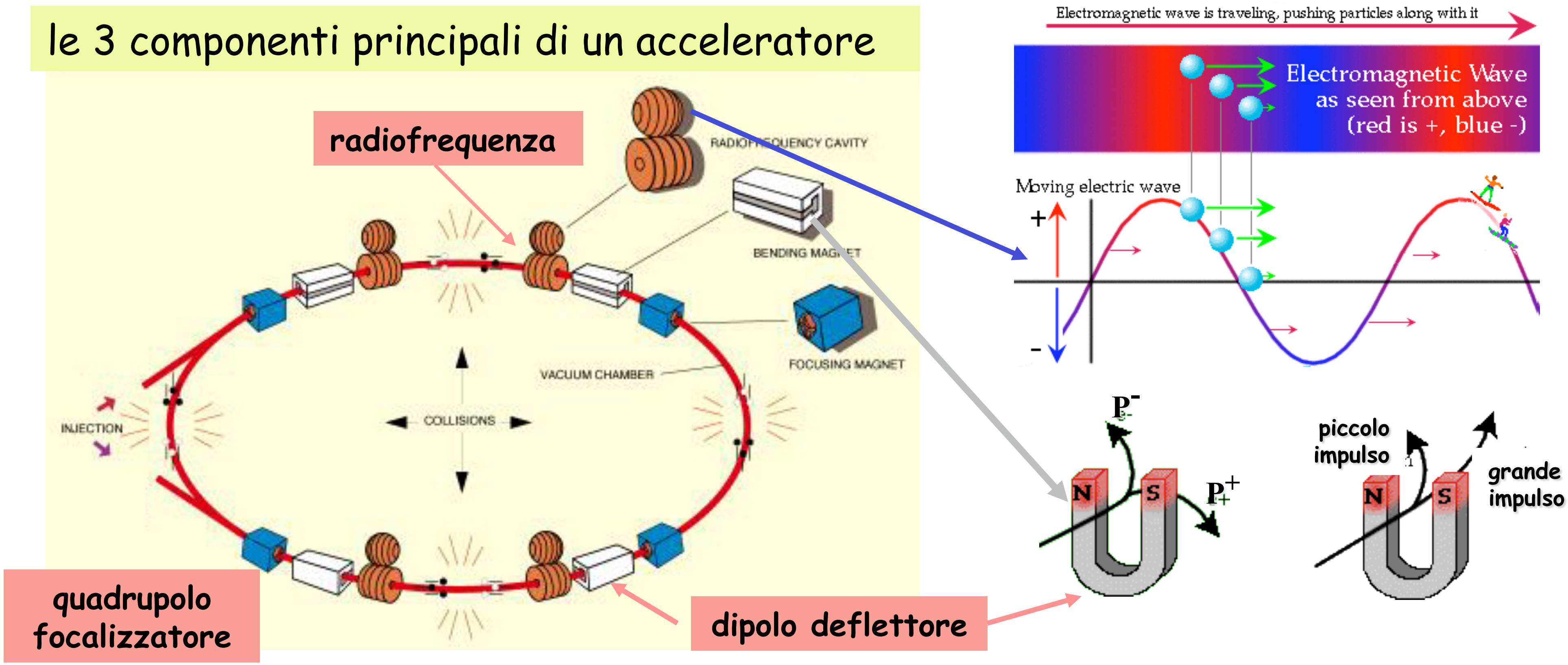
l'energia degli elettroni è ~ 20 KeV



(FERMILAB-Chicago)
acceleratore lineare
energia 400 MeV



le 3 componenti principali di un acceleratore



General Idea of Colliding Particle Experiments

- Collide probe particles with target
- Detect particles from collision
- Interpret results