Particle accelerators

Particles and Universe

Maria Krawczyk, Aleksander Filip Żarnecki

March 21, 2017

Introduction

Natural radioactivity

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Nobel prize for H.Becquerel,
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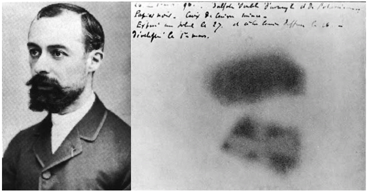

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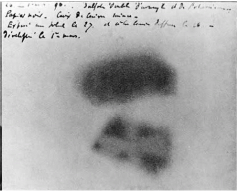

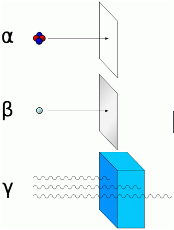

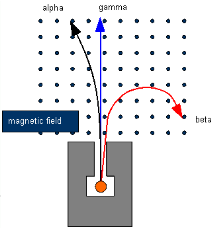

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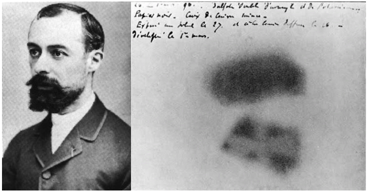

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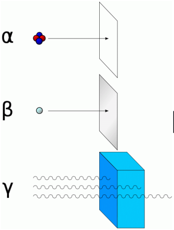

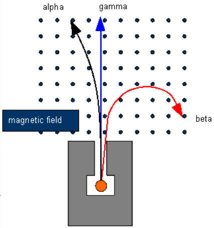

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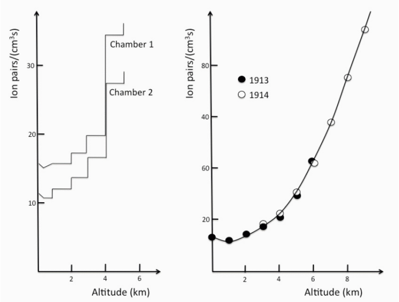
Strong radioactive sources became one of main tools in research.
Spectacular discoveries: nucleus, proton, neutron.
But energies up to about 50 MeV could only be obtained...

Cosmic rays Discovered by Victor Hess in 1912.



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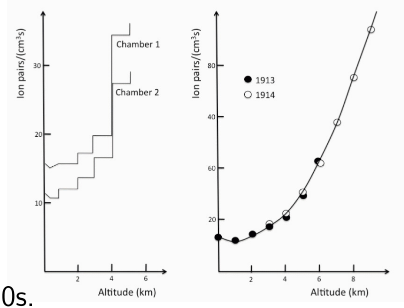
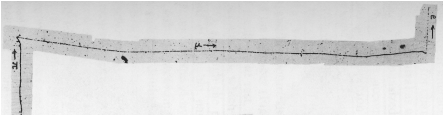


Main tool for discoveries in 1930s – 1950s.

Discoveries of positron, muon, pion, kaon.

Applications limited by small intensity, decreasing fast with energy...



Primary cosmic rays

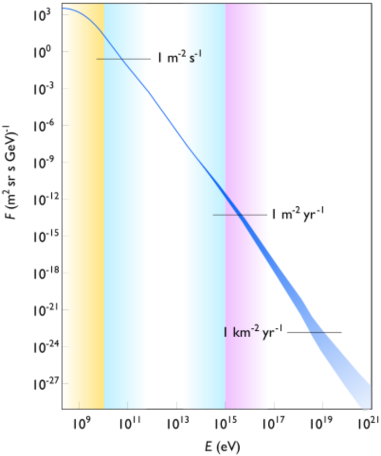
Observed in the cosmic space, outside Earth's atmosphere

Composition:

- protons (^1H) $\sim$ 86%
- α particles (^4He) $\sim$ 13%
- heavier nuclei $\sim$ 1%
- neutrons, electrons $\ll$ 1%

(neglecting neutrinos and photons)

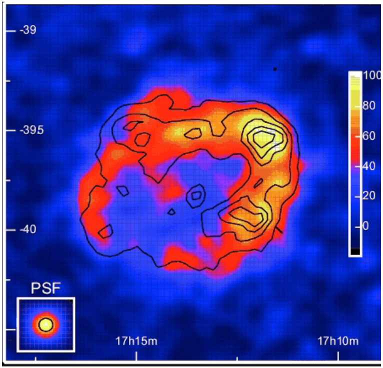
Same as the "composition of the Universe..."



Primary cosmic rays

Super-Nova Remnants (SNR) are good candidates for CR sources:

- observed galactic rate:
  one per 30 – 100 years.
- explosion releases $\sim 10^{44}$ J
  about 10% transferred to CRs
- shock-wave in the inter-stellar medium can explain the observed energy dependence
- can accelerate up to $\sim 5 \cdot 10^{15}$ eV



RXJ1713:
high energy gamma from HESS (contours) vs X-ray (color)

Secondary cosmic rays

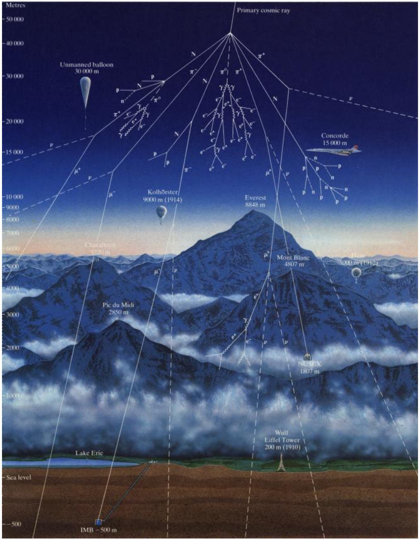
Result of the primary cosmic ray interactions in the Earth's atmosphere. Secondary particles, mainly pions and kaons, are copiously produced in these interactions. Both pions and kaons are unstable, produced in their decay chain are muons and electrons.

At the sea level:

- muons $\mu^{\pm}$ ~70%
- electrons $e^{\pm}$ ~25%
- protons and pions $\pi^{\pm}$ ~3%

Average flux: 180 particles per $m^2 \cdot s$

charged particles only...



Introduction

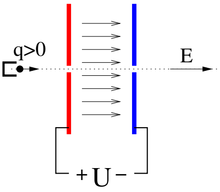
Scientific discoveries were possible thanks to new research tools...

1897 –	electron	
1911 –	atomic nucleus	cloud chamber
1919 –	protonu	
1929 –		Van der Graaff accelerator
1931 –	neutron	Lawrence cyclotron
1932 –	positron	Cockcroft-Walton generator
1937 –	muon $\mu^{\pm}$	
1947 –	pion $\pi^{\pm}$	
1949 –	kaon $K^{\pm}$	
1952 –		bubble chamber
1955 –		synchrotron

$\Rightarrow$ dawn of modern particle physics

Electrostatic accelerators

E.Rutherford was the first to point out the advantages of particle acceleration (1919). Charged particles (and nuclei) can be easily accelerated with strong electric field.



$E = E_\circ + U \cdot q$

Higher energies require higher voltages!

New devices developed to obtain high accelerating voltages:

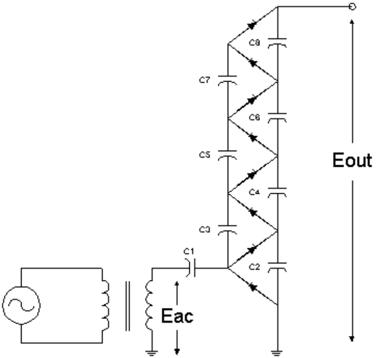
⇒ Van der Graaff generator (1929): 1.5 MV

⇒ Cockroft-Walton generator (1932): 750 kV

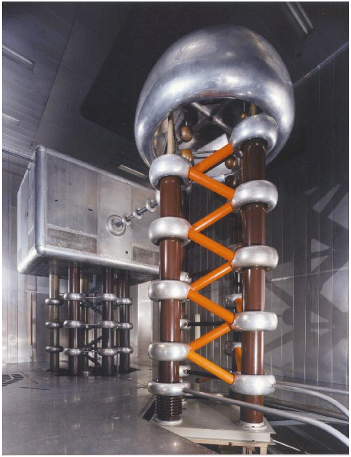
Still used in some specific applications...

Cockroft-Walton generator

Principle

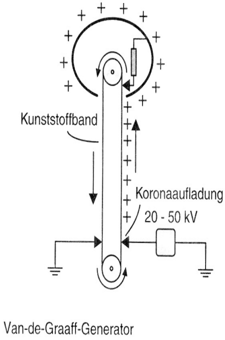


H^- source for CERN proton liniac

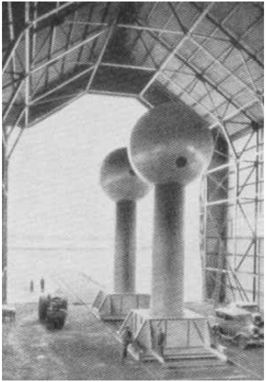


Van de Graaff generator

Principle



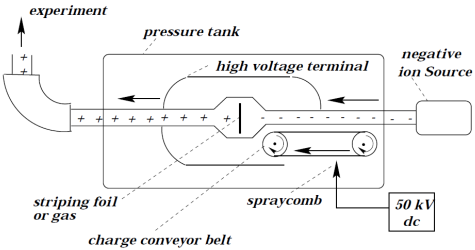
History



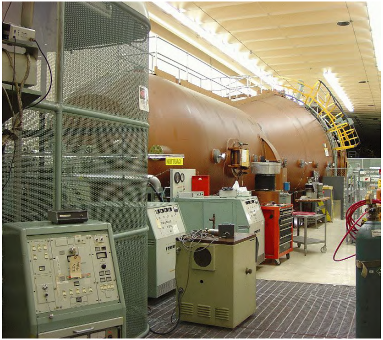
Modern devices

Van de Graaff generator

"Tandem"
generator for ion acceleration:



AGS Complex at BNL:

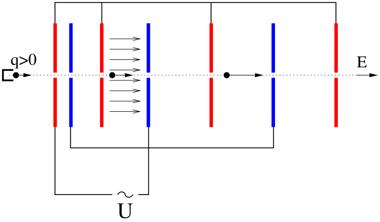


$E_{max} = 29$ MeV (p); 385 MeV (U)

Linear accelerator

First idea: Gustav Ising 1924.

Proof of concept: Rolf Wideroe 1927,
accelerated potassium ions to 50kV with 25kV oscillator



Use oscillating voltage source.

With proper frequency and gap widths setting particle passes same accelerating voltage many times.

Energy multiplication.

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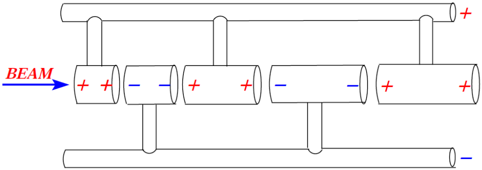

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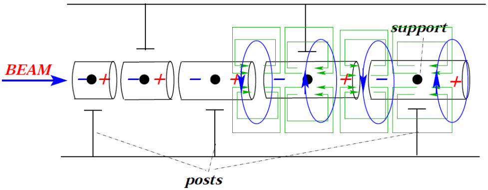

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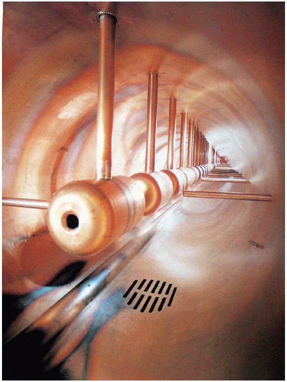
Energy multiplication.

In the modern design accelerating tubes act as high frequency resonators.
Pre-accelerators for most accelerators are build that way...

Accelerators

Linear proton (pre)accelerators:

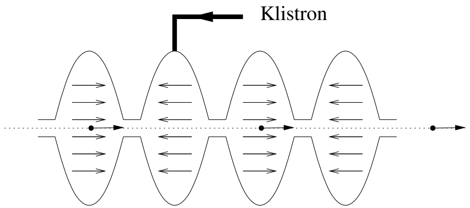
Tevatron @ Fermilab



SPS @ CERN

Accelerating cavity

In the high energy limit, when the particle travels with (approximately) speed of light, it is easier to generate standing electromagnetic wave in a dedicated cavity powered by a klystron.



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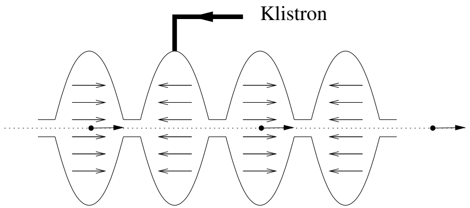
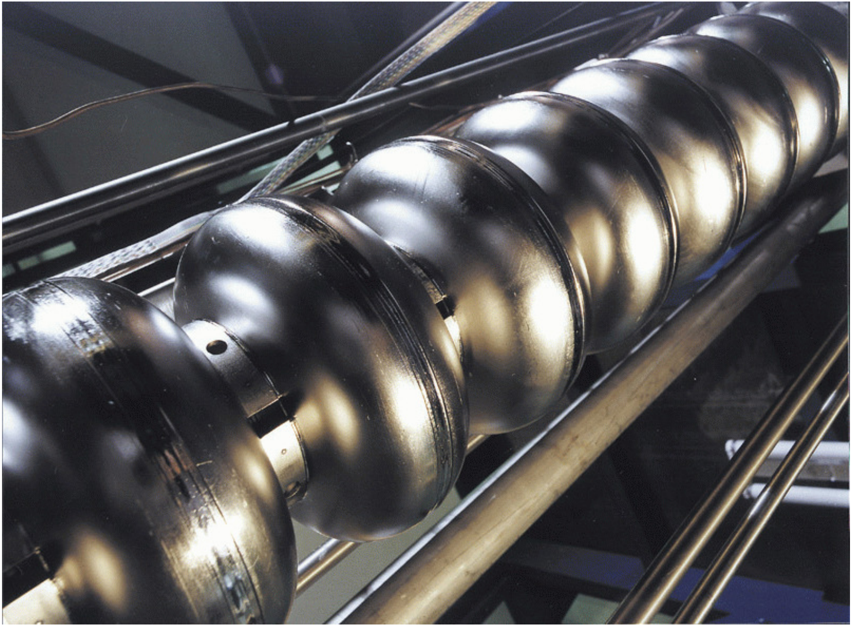


Frequencies used range from about 100 MHz to 10 GHz.
Superconducting cavities can give gradients up to about 30 MV/m.
Very efficient acceleration, but the total length increases with energy...

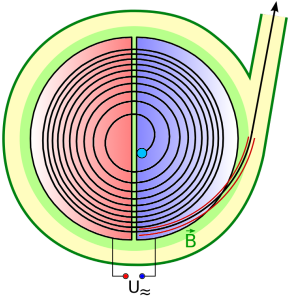
Accelerating cavity

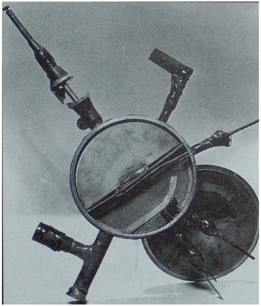


Cyclotron

To reduce the accelerator size we have to force the particle to pass the same accelerating gap many times. Magnetic field can be used for that...

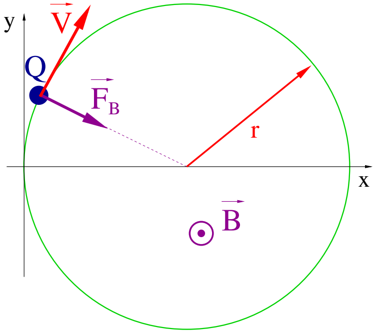
First device of this type was built by Ernest Lawrence in 1931:





Cyclotron

Maximum momentum (and energy) is limited by the magnetic field.



In the uniform field perpendicular to the initial velocity, the Lorentz force acting on the particle is given by:

$$\vec{F}_B = Q\vec{V} \times \vec{B}$$

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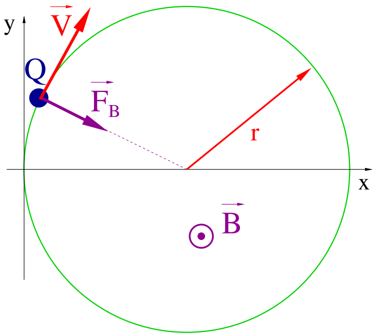

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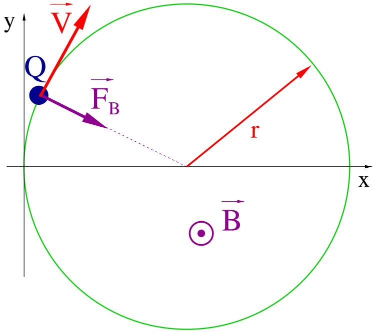

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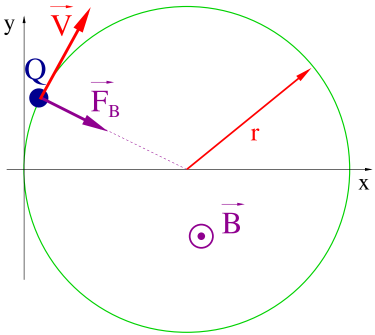

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Radius of track curvature in magnetic field is given by: $r = \frac{mV}{|Q|B} = \frac{p}{|Q|B}$

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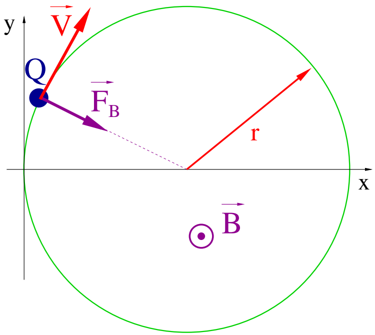

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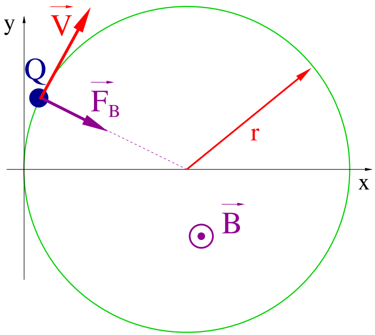

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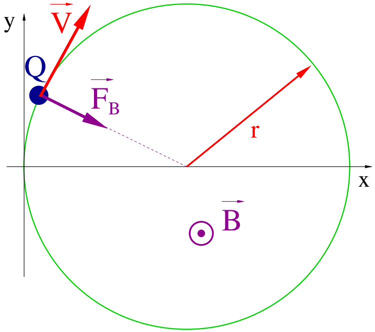

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$$p = 1e \cdot 1m \cdot 1\frac{V \cdot s}{m^2} = 1 \, \frac{eV}{m/s}$$

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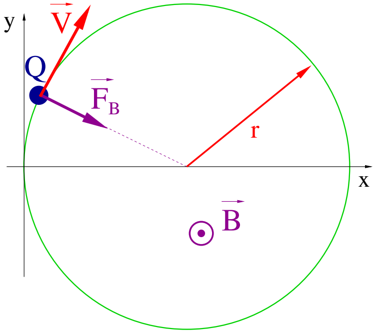

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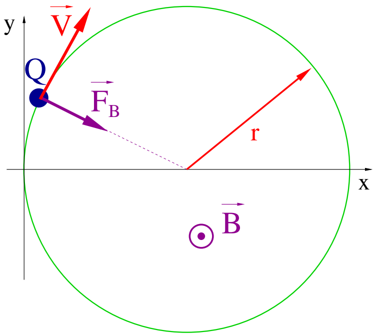

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First cyclotron: $r = 12cm$, $B = 1.3T \Rightarrow p = 45MeV/c \Rightarrow E_{kin} \approx 1MeV$

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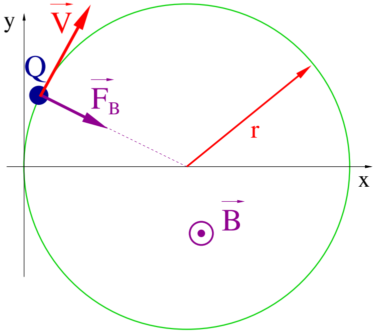

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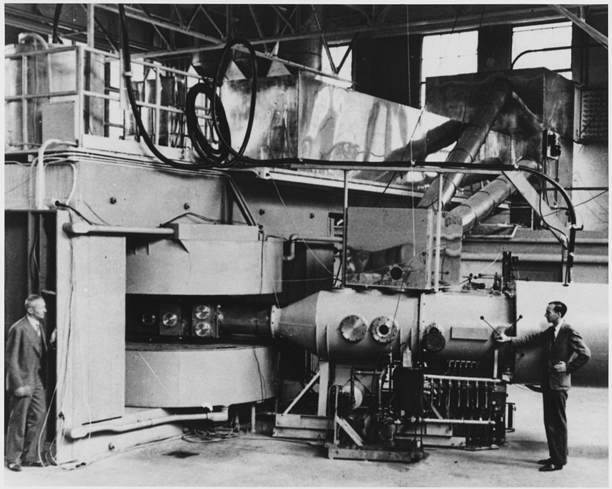
LHC: $r = 3000m$, $B = 8T \Rightarrow p_{max} = 0.3 \cdot 3000 \cdot 8\ GeV/c = 7.2\ TeV/c$

Cyclotron

In few years cyclotrons became a very powerful tool in particle research.

Berkeley 1939
1.5 m diameter



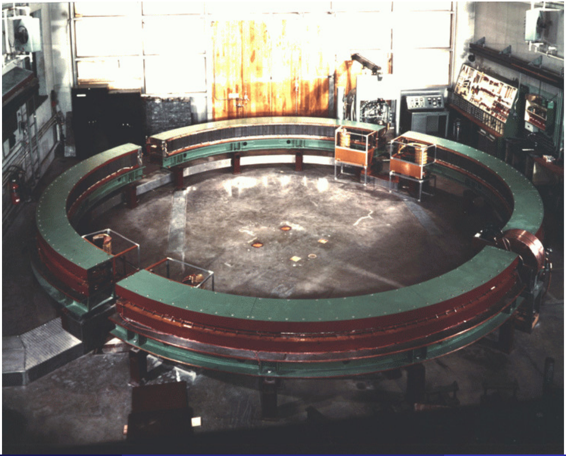
The largest single magnet cyclotron: 4.6 m in diameter $\Rightarrow$ 730 MeV/c (p).

Synchrotron

Invention of synchrotron (1945) was the next major breakthrough.

Large magnets and vacuum chambers not needed any more.

Dipol magnet field changing with energy keeps particles on the fixed orbit.



Focusing

Dipol magnets allow to keep accelerated particles on the “circular” orbit. However, the due to the increasing beam spread (both in space and momentum) efficiency of acceleration was low.

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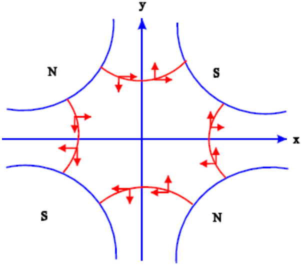
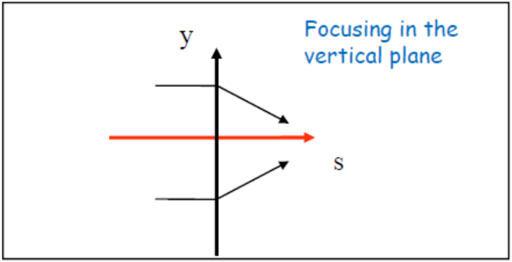
Quadrupol magnets focus particle beam, buy only in one direction.





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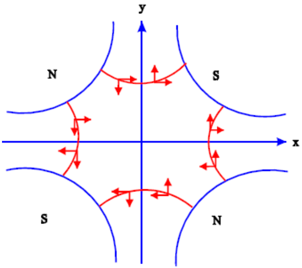

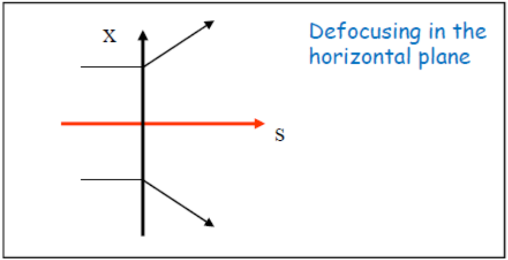

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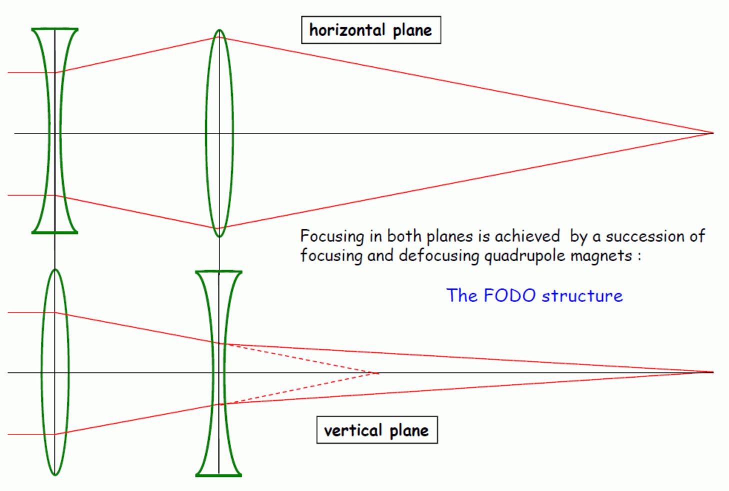
Strong focusing Developed at BNL in 1952

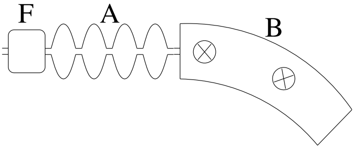


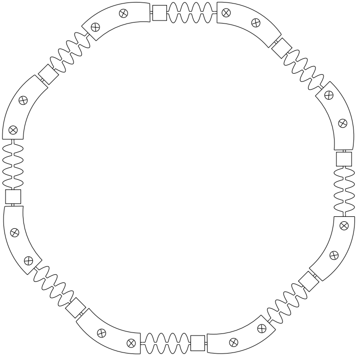
New accelerators: 1959 PS @ CERN (25 GeV), 1960 AGS @ BNL (33 GeV)

Structure

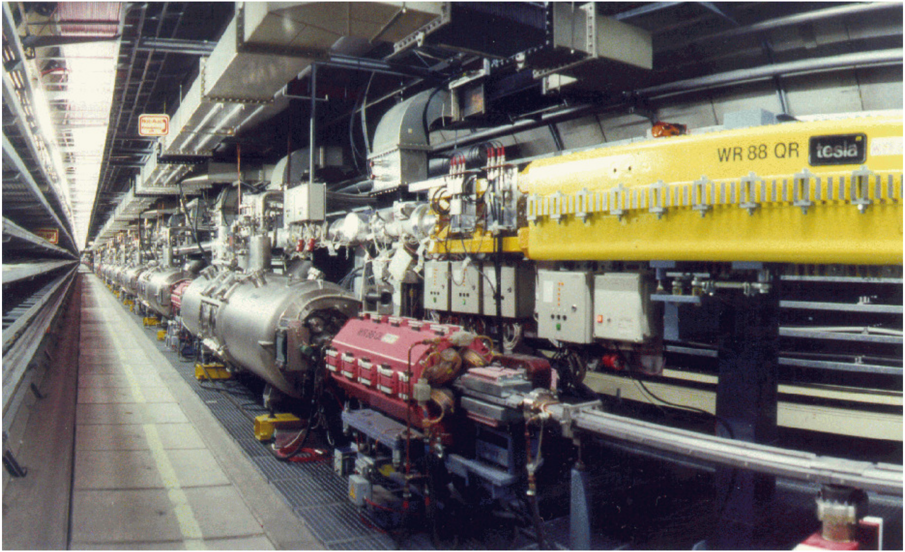
Modern circular accelerators are built from many (almost) identical segments.
Each segment includes three types of structures:

- bending magnets (B)
- focusing magnets (F)
- accelerating cavities (A)

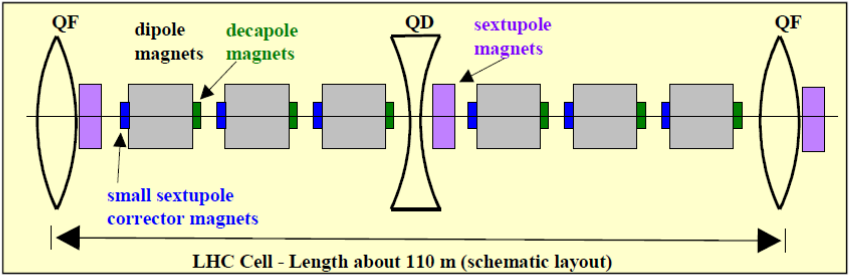




HERA (1992-2007) tunnel

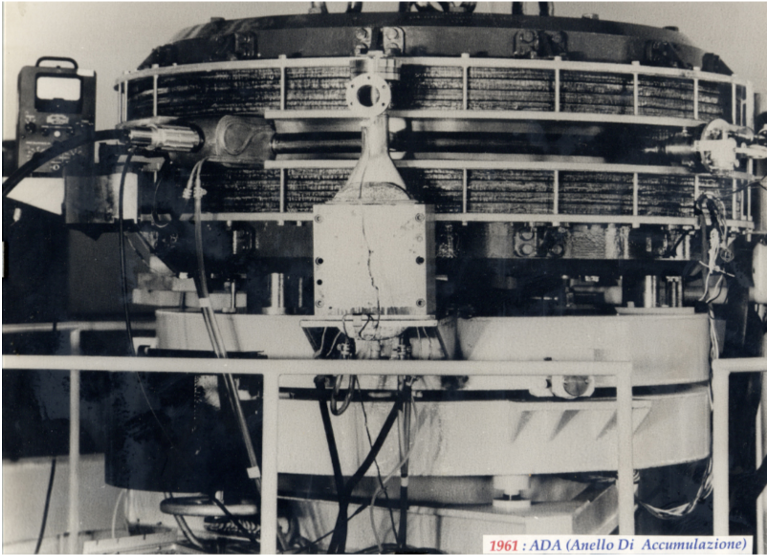


LHC arc lattice



- Dipole- und Quadrupol magnets
  - Provide a stable trajectory for particles with nominal momentum.
- Sextupole magnets
  - Correct the trajectories for off momentum particles (‚chromatic' errors).
- Multipole-corrector magnets
  - Sextupole - and decapole corrector magnets at end of dipoles
  - Used to compensate field imperfections if the dipole magnets. To stabilize trajectories for particles at larger amplitudes – beam lifetime !

First e^+e^- collider AdA @ Frascati (1961)



Most of the high energy frontier accelerators work in the "collider mode". Two beams are accelerated and stored in the ring, circulating in opposite directions. They can collide (almost) head-on in few crossing points.

The primary advantage is the increase of the center of mass energy:

$$E^\star = 2 \cdot E_{beam} \quad \text{for beam-beam collisions}$$

$$E^\star = \sqrt{2 \cdot E_{beam} \cdot m} \quad \text{for beam-target collisions}$$

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The price is the collision rate.

Probability of particle collision per beam crossing is very low ($\sim 10^{-10}$ at LHC), we need high beam intensities.

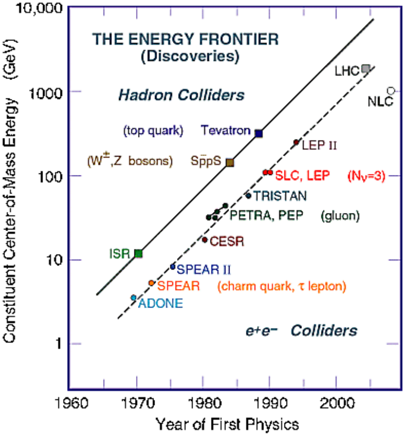
For fixed target experiments it is 0(1), we can get much higher rates...

History

Rapid development of the particle physics was thanks to many new accelerators built in 1970s – 1990s.

Energies increased by almost 3 orders of magnitude.

Unfortunately, sizes and costs of new machines increased rapidly as well...



Colliders

LEP

LEP was the largest accelerator built so far, its circumference was 27 km. Collided e^+e^- at CMS energies up to 209 GeV.

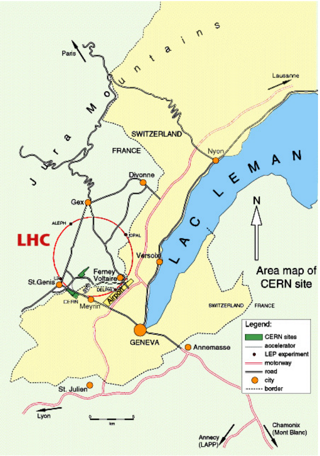
LHC

Installed in the same tunnel after LEP.

Two beams with 2800 bunches each, 10^{11} protons per bunch.

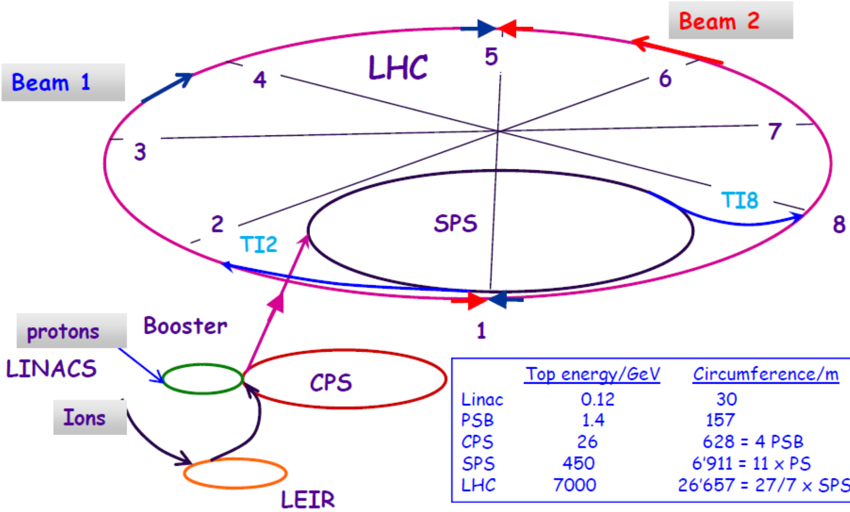
Nominal beam energy: 7 TeV.
Bunch crossing every 25 ns.

Single bunch energy: $\sim 10^5$ J
Total energy: $\sim 6 \cdot 10^8$ J



LHC @ CERN, Geneva

LHC tunnel



	Top energy/GeV	Circumference/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

Limitations

To get higher beam energies we need to built bigger and bigger ($\Rightarrow$ more expensive) accelerators

Why?

What limits the energy, which can be achieved?

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Magnetic field has to rise with increasing beam energy to keep protons inside the accelerator pipe. $p = |Q|\ r\ B$

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But we face the fundamental limit: critical magnetic field of superconductors.

We can only build (on industrial level) magnets up to 10 T.
$\Rightarrow$ we have to increase bending radius to increase energy...

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What limits the energy, which can be achieved?

For circular e^+e^- colliders ⇒ synchrotron radiation.

Circulating electrons loose energy due to synchrotron radiation. Power of energy losses increases as $\sim E^4/R^2$

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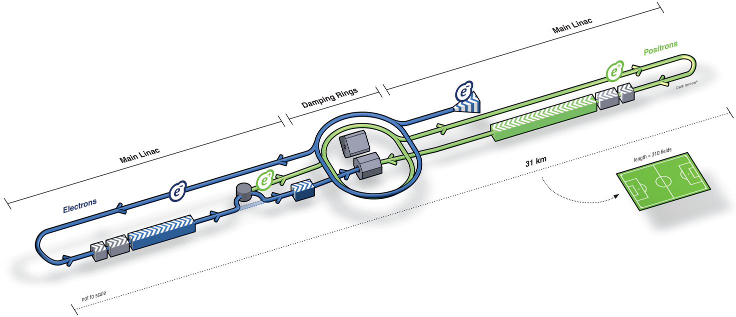
We have to compensate the losses with accelerating cavities.
Accelerating gradient limited $\Rightarrow$ need larger accelerator to add more cavities.

For larger bending radius we also reduce synchrotron radiation.

ILC

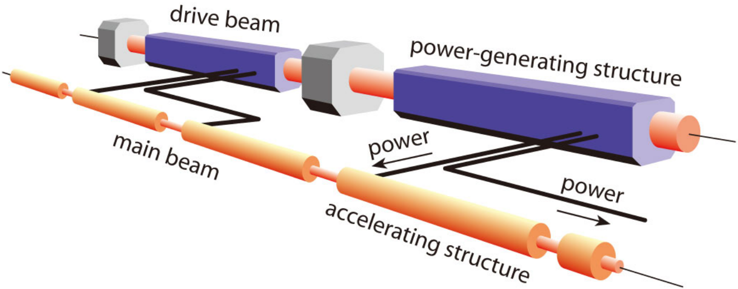
Synchrotoron radiation is no longer a problem for linear accelerators.
Detailed design of the International Linear Collider is ready.



Decision expected in 2017. Could be built in Japan before 2030...

CLIC

Energy available at linear colliders is limited by accelerating gradient.
Superconducting cavities powered by klystrons can give up to 30 MV/m.
Higher gradients (for accelerating "main" beam) expected in cavities powered with radiation emitted by high intensity "drive" beam



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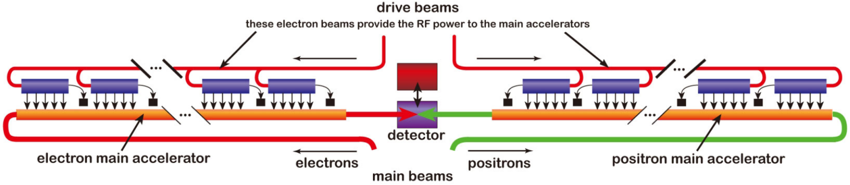

"transformer": high current @ low energy ⇒ low current @ high energy

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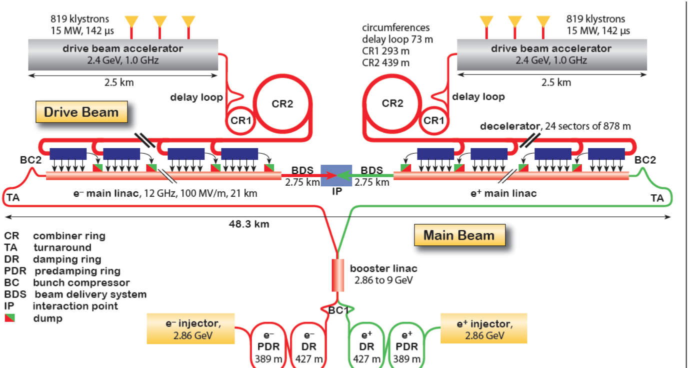
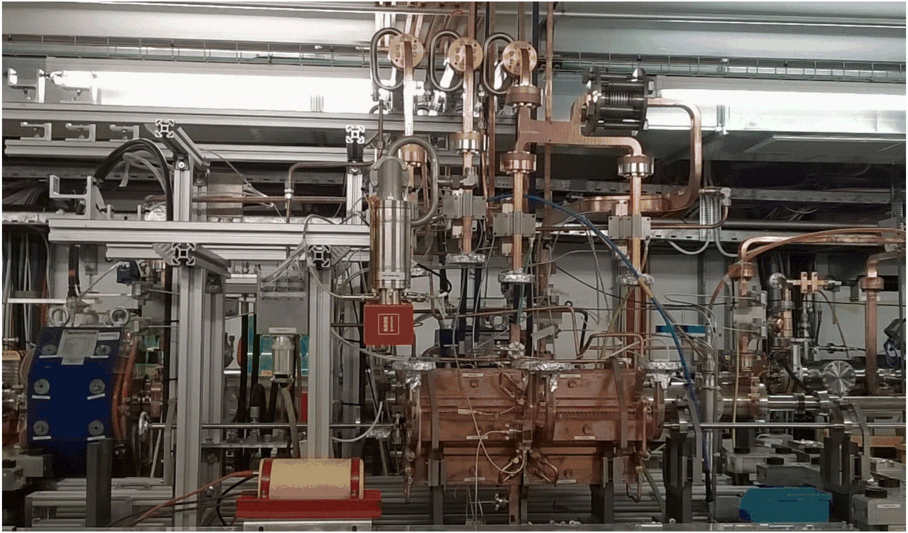


Being developed at CERN. Decision: ∼2020 (European Strategy Update)?

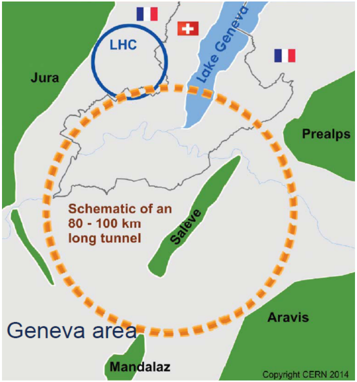
Future projects

CLIC Test beam at CERN



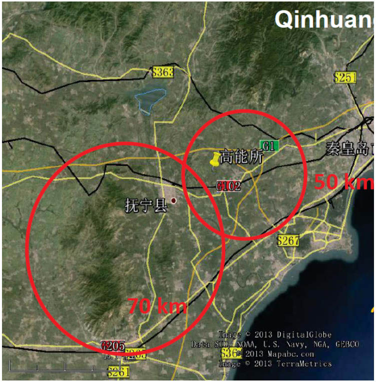
Considered options for building the next circular proton collider after LHC.

FCC (CERN)



$\sim$2040 ?...

CCC (China)



$\sim$2025 (e^+e^-), 2035 (pp)

In the first phase, e^+e^- machine could be installed $\Rightarrow$ Higgs factory