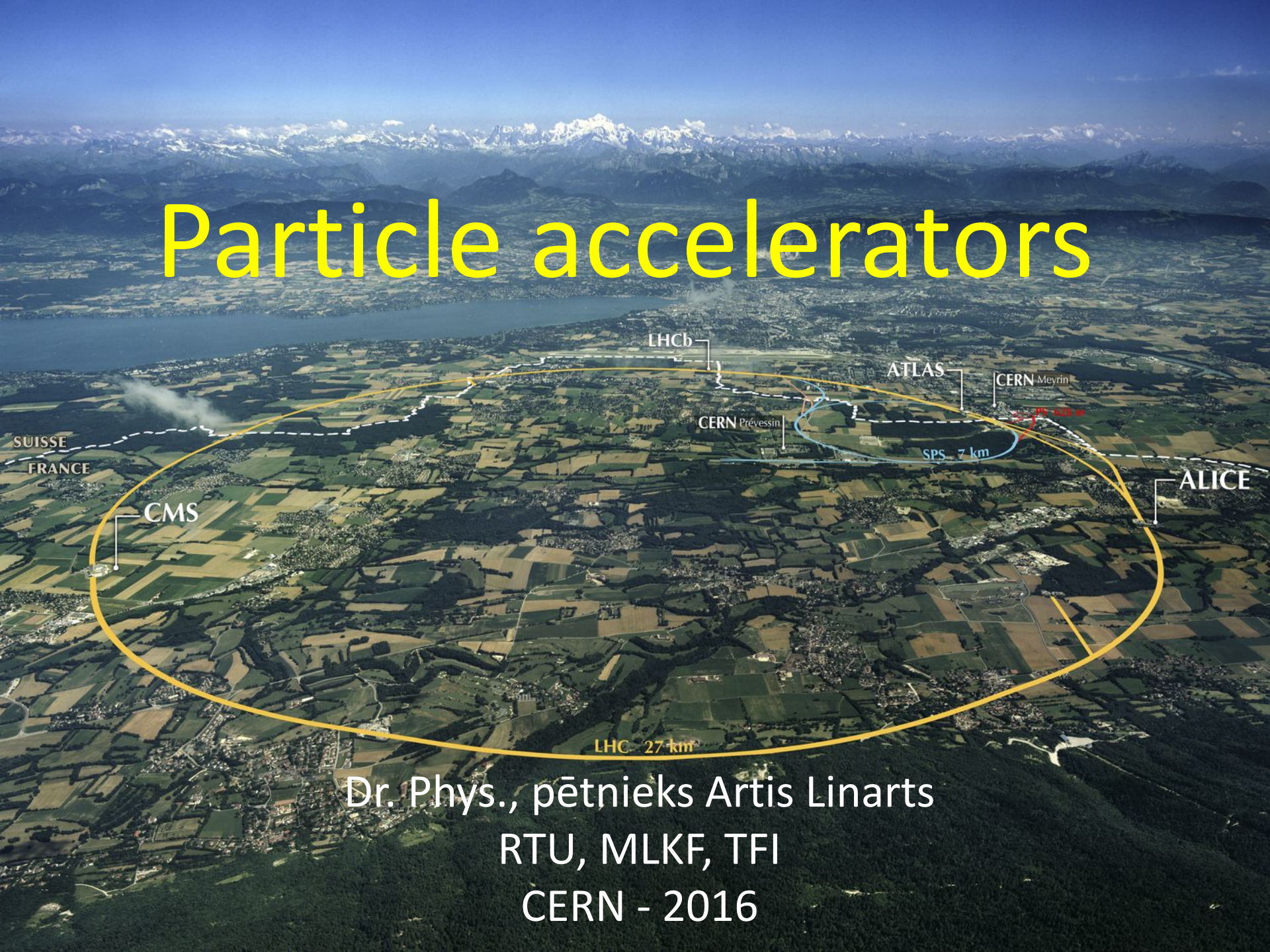
Particle accelerators



Dr. Phys., pētnieks Artis Linarts
RTU, MLKF, TFI
CERN - 2016

Why particle accelerators ?

- *Why accelerators?: need to produce under controlled conditions 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.

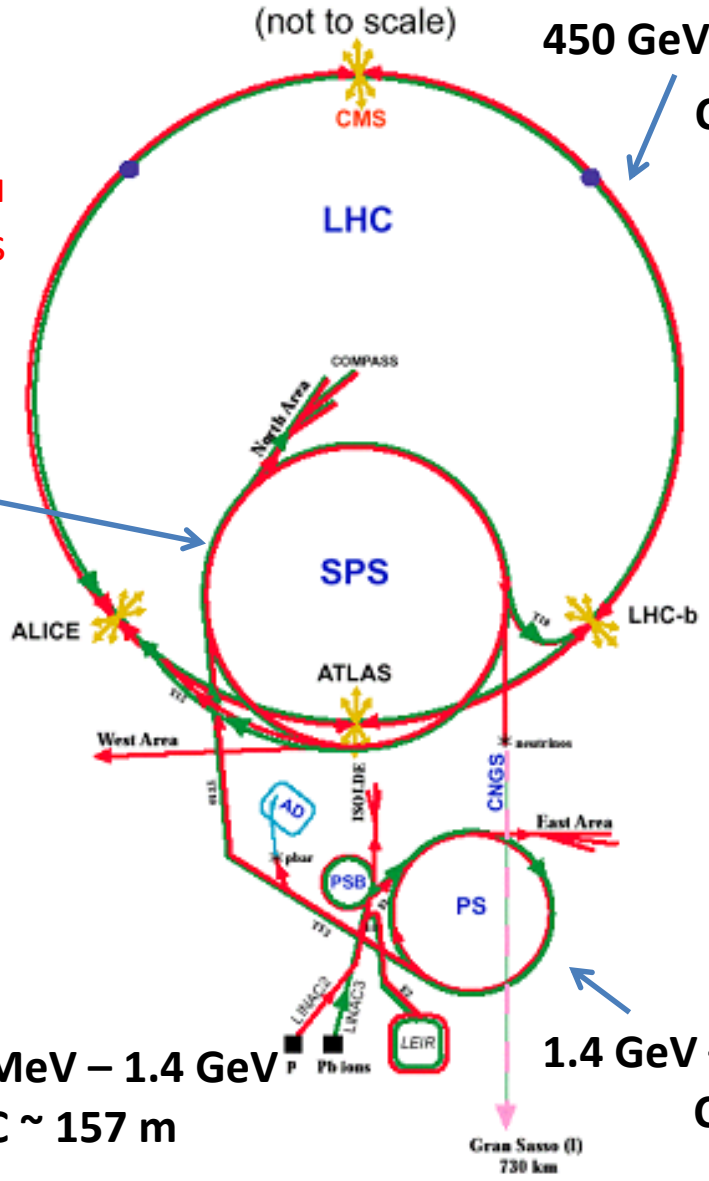
CERN paātrinātāju komplekss

Mērķis – LHC radīt lādētu daļiņu sadursmes ar lielām enerģijām, lai ar sensoru palīdzību izprastu vielas uzbūvi, visuma izcelšanos un atklātu jaunas daļiņas

Ultra high vacuum – 10^{-10} mbar

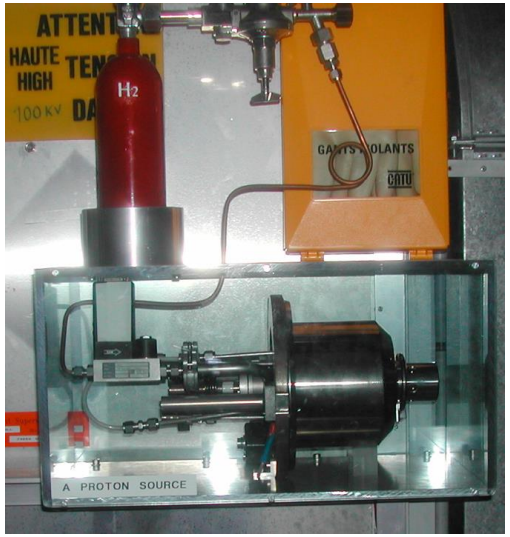
Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

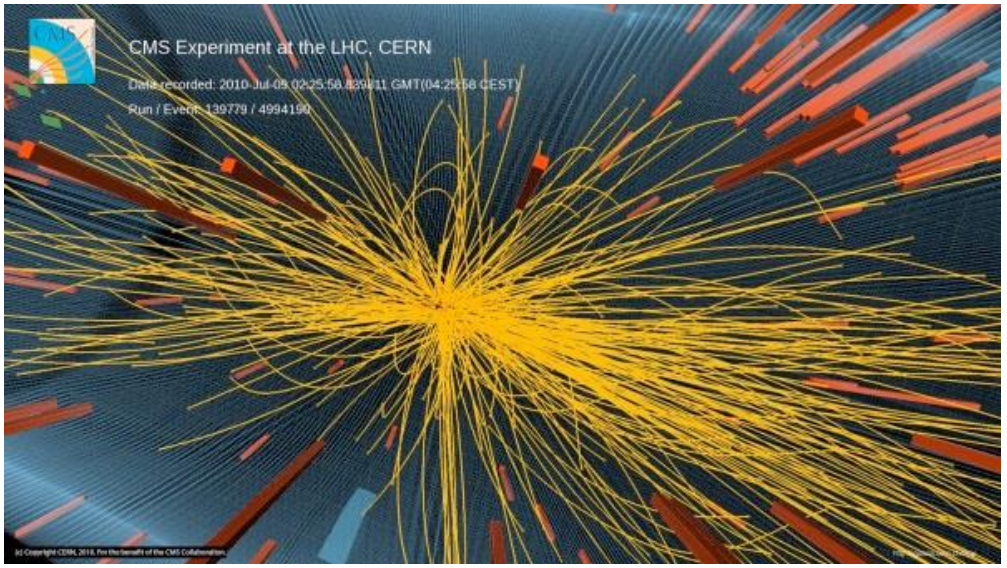
Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2



CERN paātrinātāju komplekss

Cik liels ceļš jāveic protonam no sākuma līdz sadursmes brīdim LHC?





No H_2 tvertnes

Linac 2, praktiski necik.

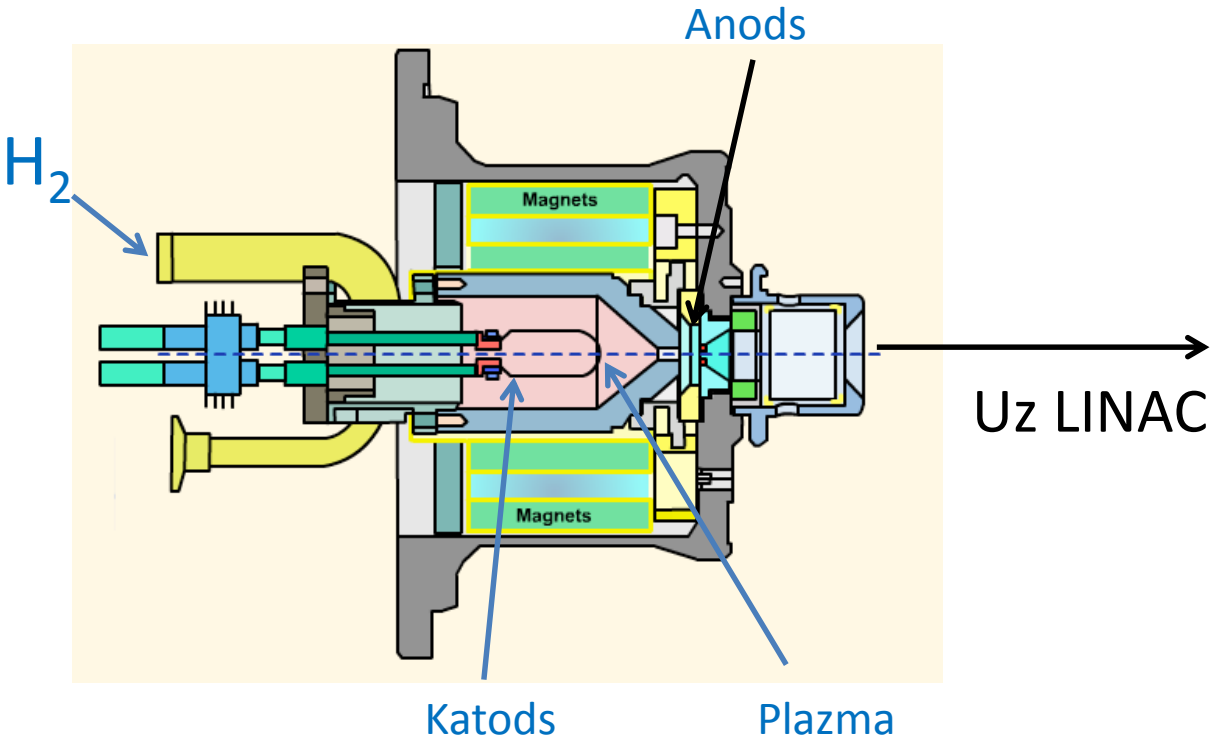
PSB, mazāk par 1,2 s.
PS, mazāk par 3.6 s
SPS mazāk par 16.8 s
LHC, vismaz 30 minūtes

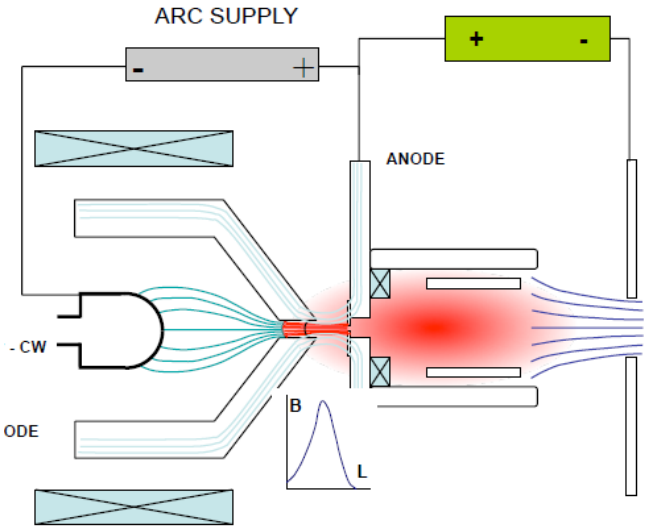
1 821.6 s → 546 480 000 km

3,7 reizes lielāks attālums nekā no Zemes līdz Saulei

Protonu iegūšana

Protonus iegūst ar elektronu starojumu jonizējot ūdeņradi





Protoniem izejot caur ~ 1mm^2 spraugu tiek paātrināti līdz 1.4 % c, v ≈4000 km/s

Paātrinātāju darbības princips

- Goal: keep enough CHARGED particles confined in a well defined volume to accelerate them for a sufficiently long time (ms - hours)

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

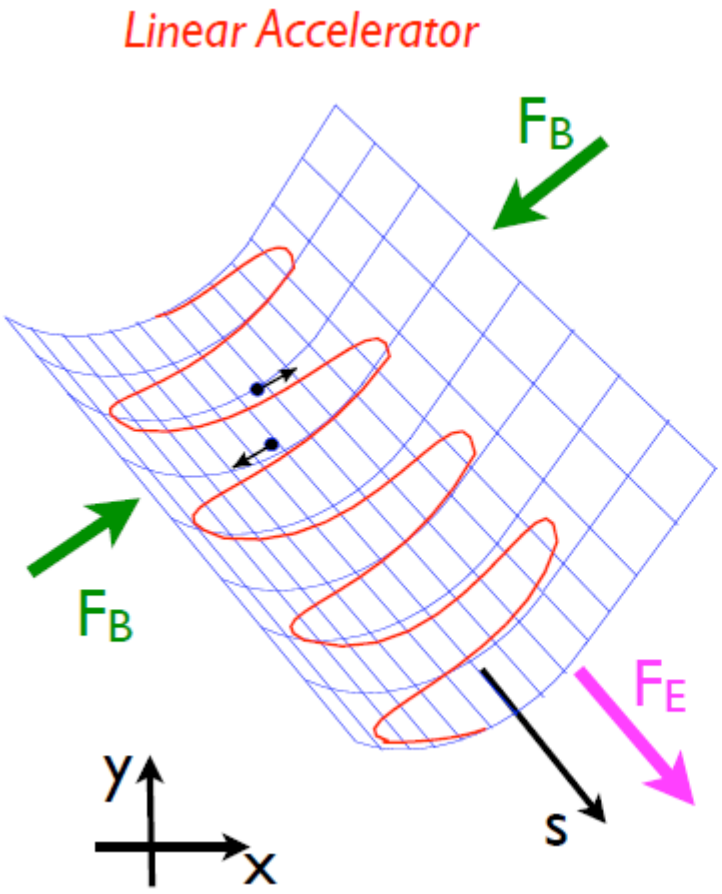
Magnetic field confines particles on a given trajectory

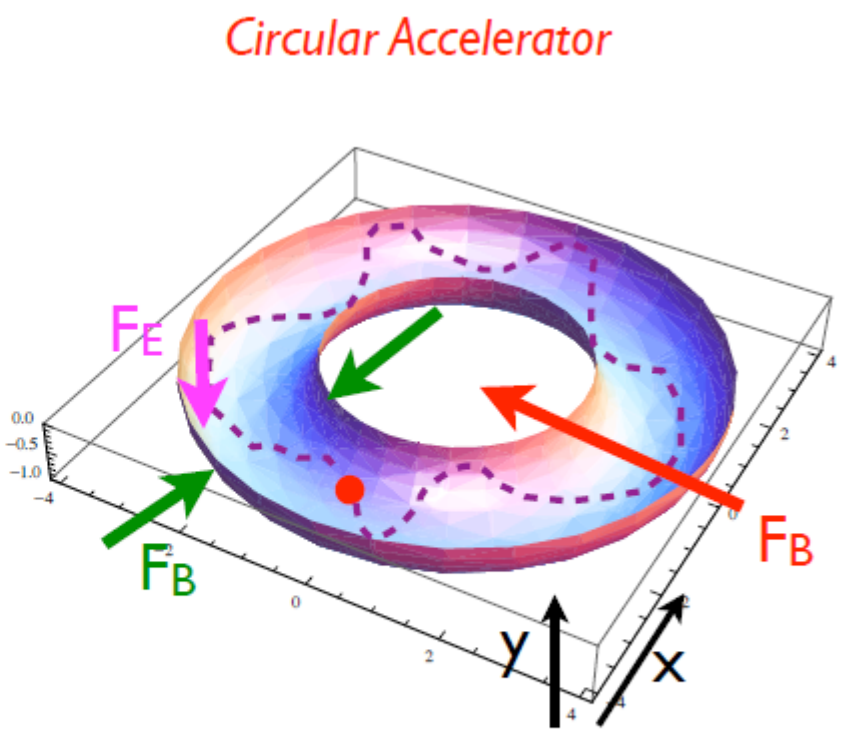
An accelerator is formed by a sequence (called lattice) of:

a) Magnets → Magnetic Field F_b

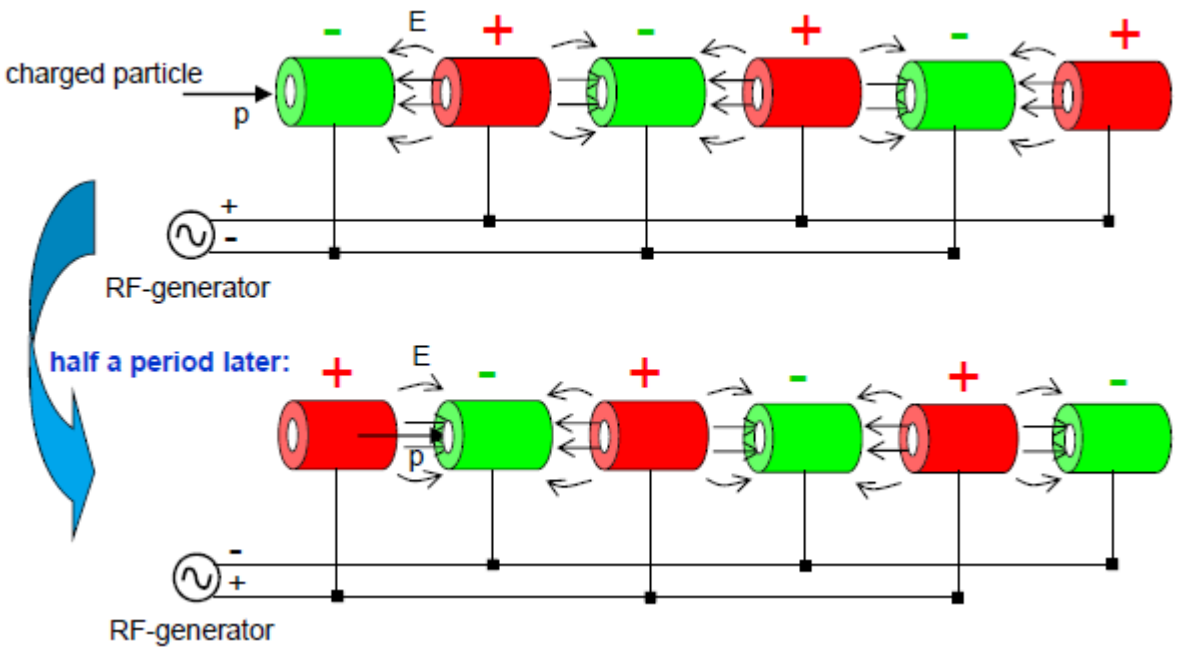
b) Accelerating Cavity → Electric Field F_E

Paātrinātāju darbības princips





Linac 2



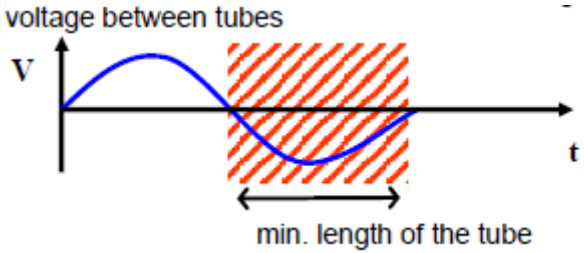
1928 Rolf Widerøe

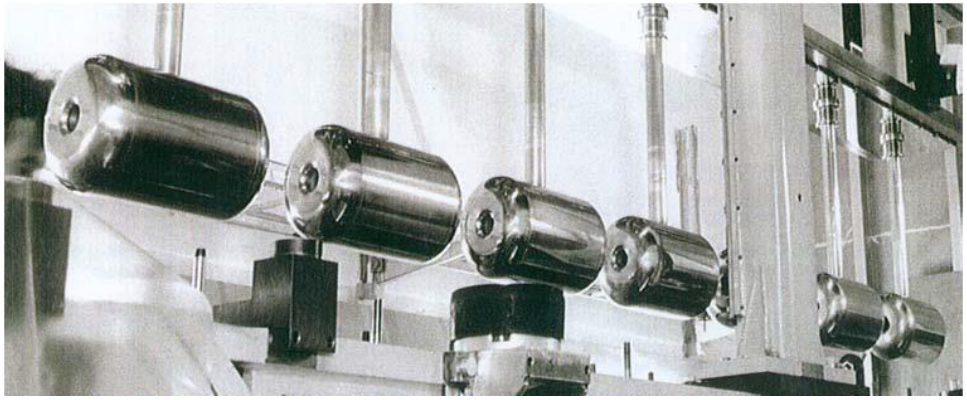
Protons pass through the conductors, which are alternately charged positive or negative. The conductors behind them push the particles and the conductors ahead of them pull, causing the particles to accelerate. Small quadrupole magnets ensure that the protons remain in a tight beam.

Linac 2

At the end of Linac 2, the proton bunches have reached the energy of 50 MeV and speed 31,4 % c

Low frequency RF generator (<10MHz)

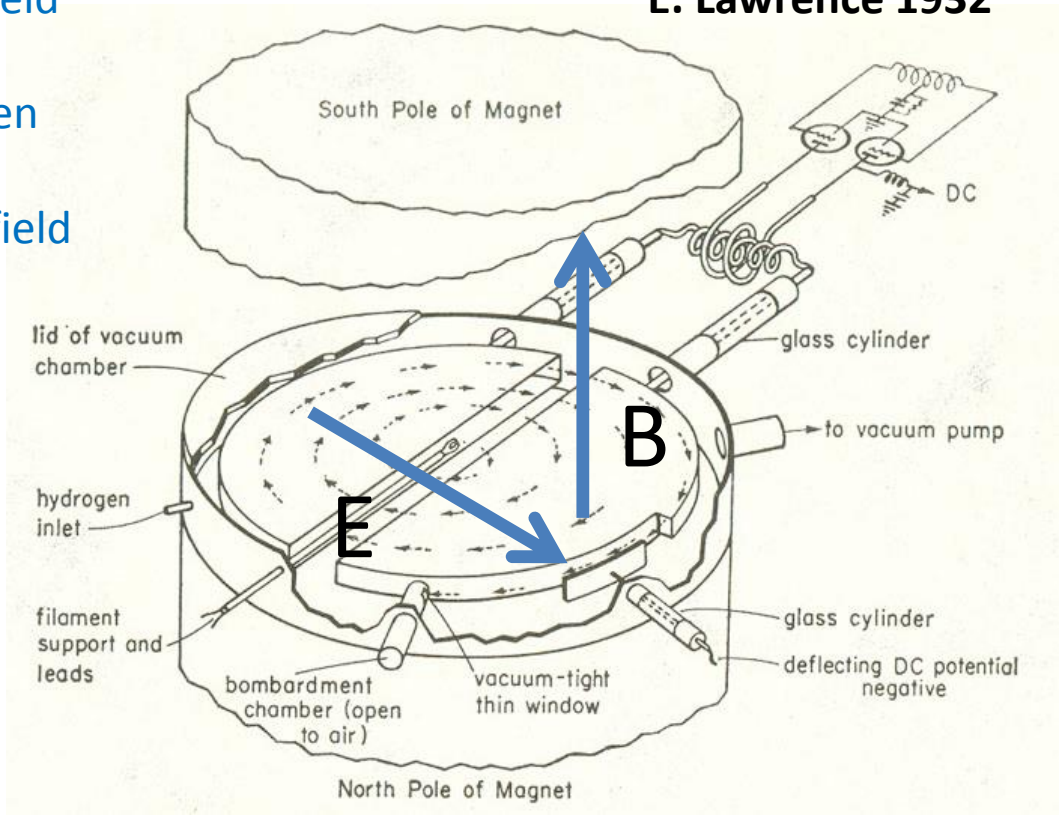




Ciklotrons

1)Particle source located in a vertical B field near the center of the ring
2)Electrical (E) RF field generated between two gaps with a fixed frequency
3)Particles spiral while accelerated by E field every time they go through the gap

E. Lawrence 1932

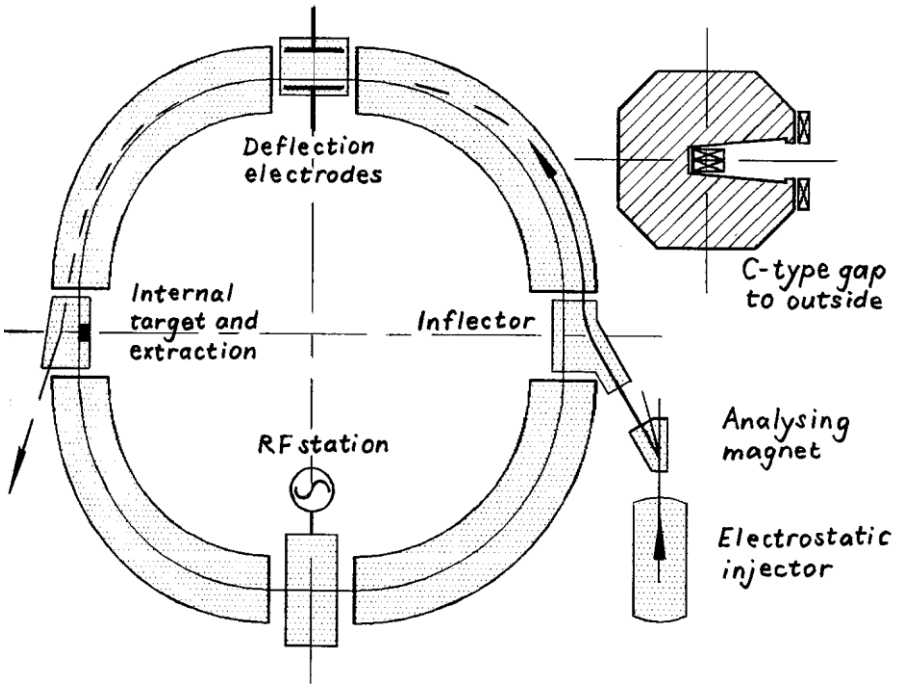


Main limitations:
1) not working for relativistic particles, either high energy or electrons
2) B field at large radius not vertical

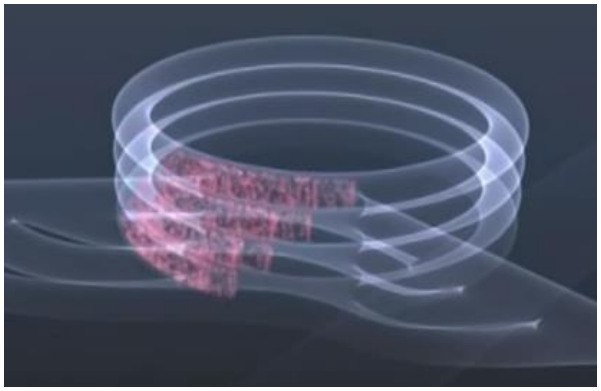
Sinhrotrons

New concept of circular accelerator (1952). 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 to also change.

$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = q\,v\,B = m\frac{v^2}{R} \quad \Rightarrow \quad R = \frac{m\,v}{q\,B}$$



Sinhrotronu paātrinātāju komplekss



PSB – from 50 MeV to 1,4 GeV

↓

PS – from 1,4 GeV to 25 GeV

↓

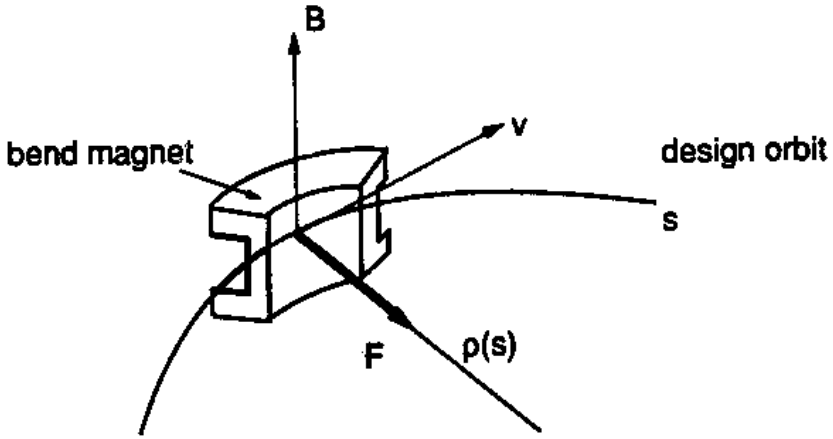
SPS – from 25 GeV to 450 GeV

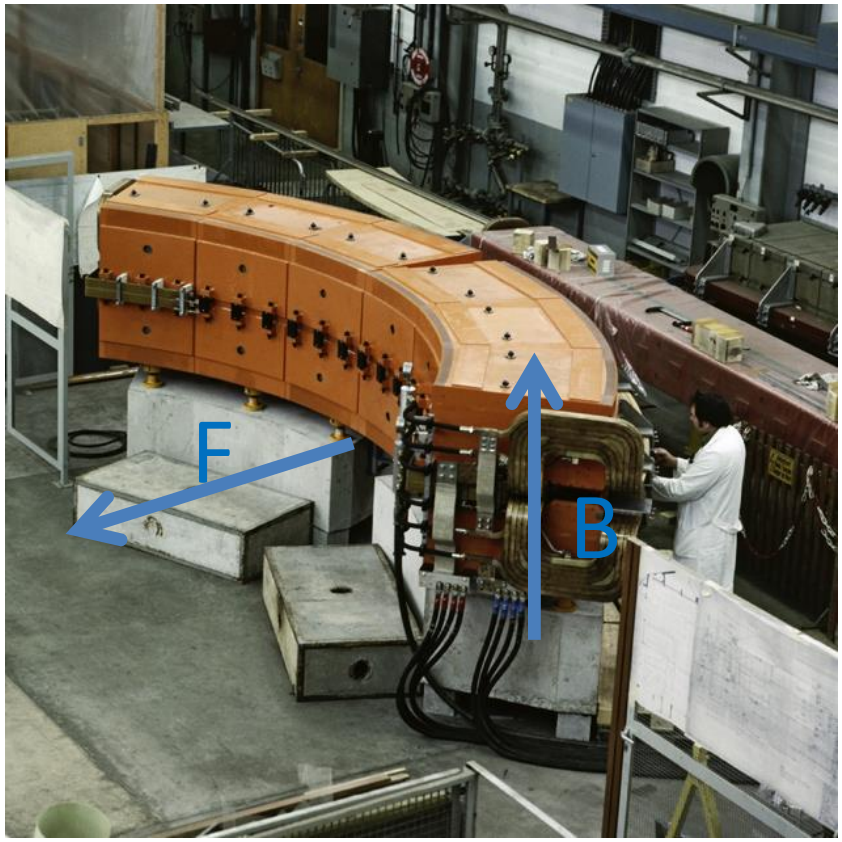
↓

LHC – from 450 GeV to 7 TeV

Dipolu magnēts

Force given by the vertical magnetic field compensates the centrifugal force to keep the particles on the central trajectory

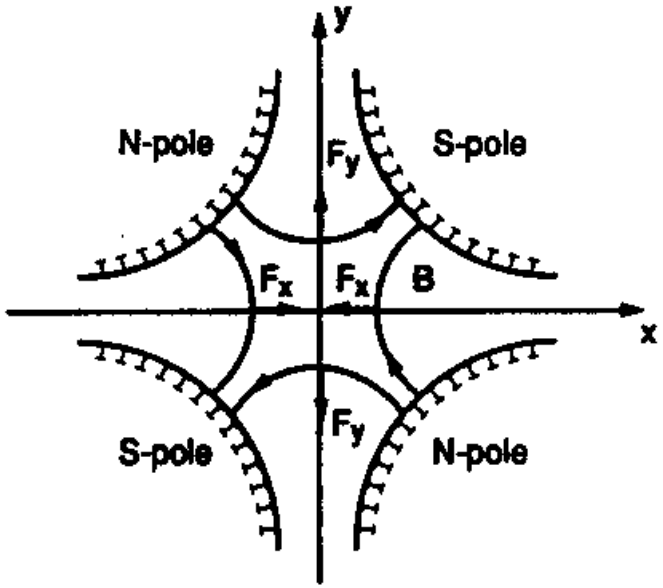


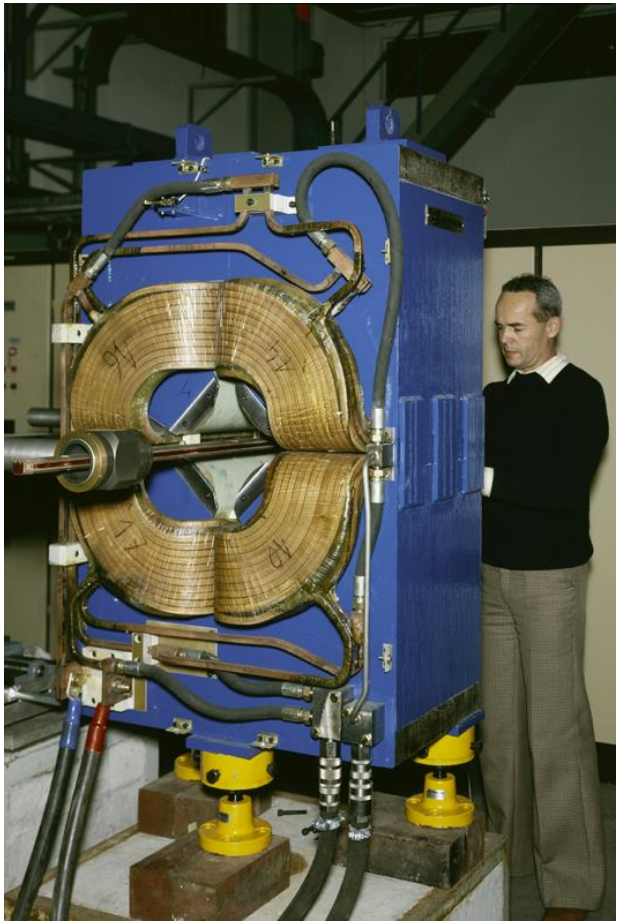


A fast dipole, able to deflect the beam in few μs is called kicker. A kicker is used to extract the beam from the machine.!

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

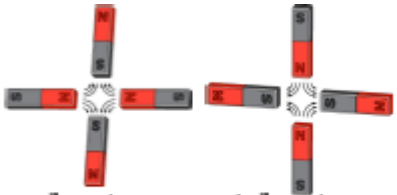
Kvadrupolu magnēts

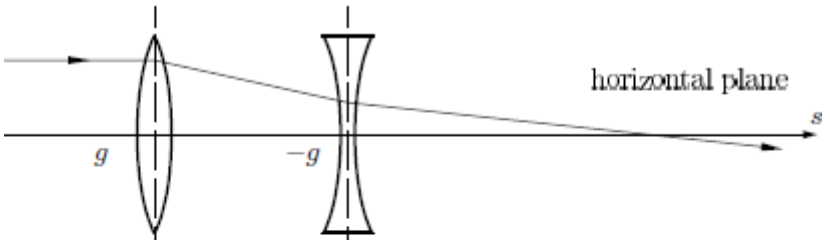




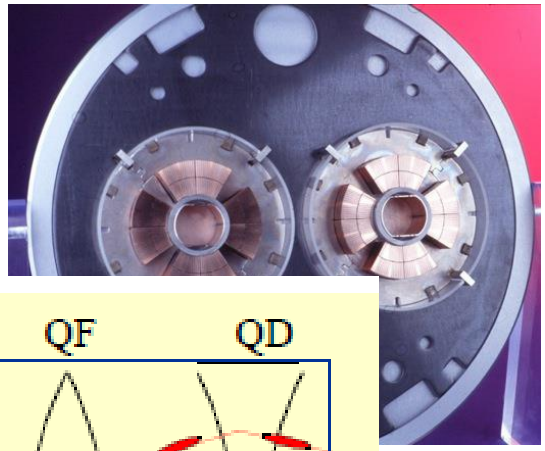
Dipoles are interleaved with quadrupoles to focus the beam.
Quadrupoles act on charged particles as lens for light. By alternating focusing and defocusing lens the beam dimension is kept small

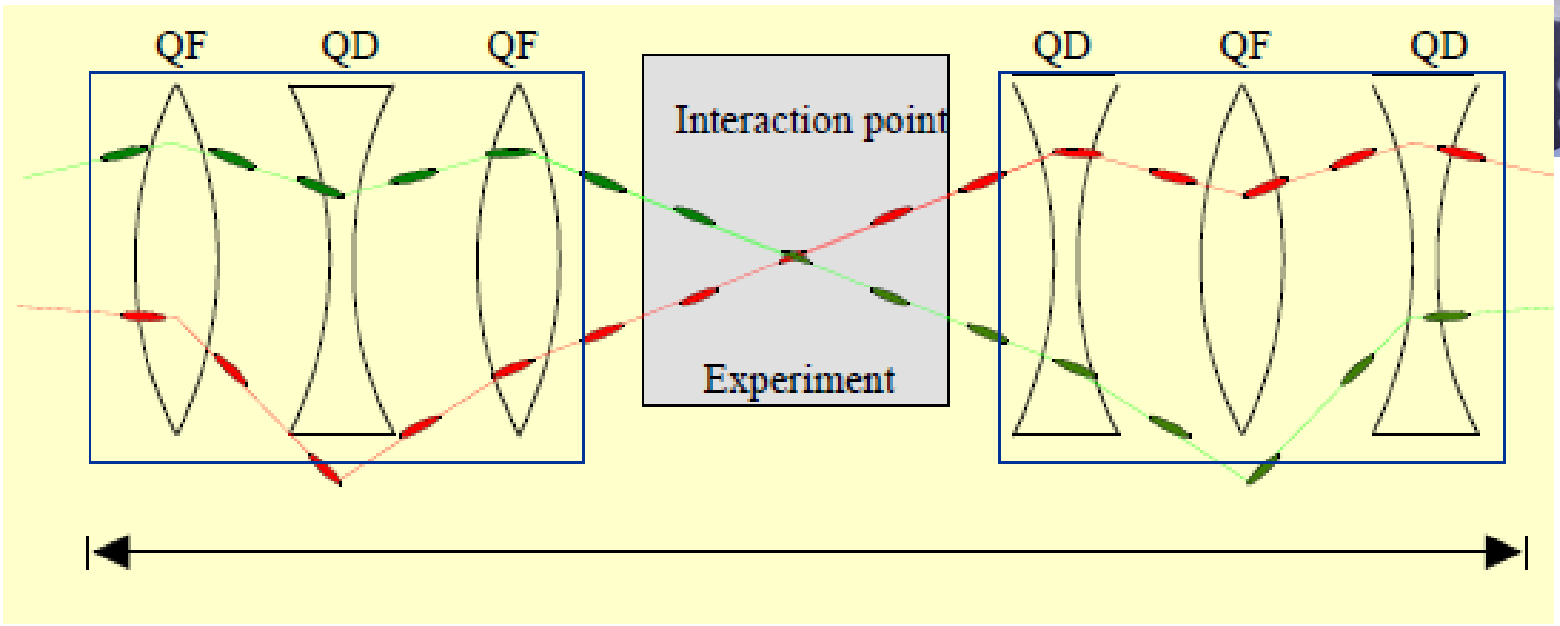
Magnētiskās lēcas





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





LHC

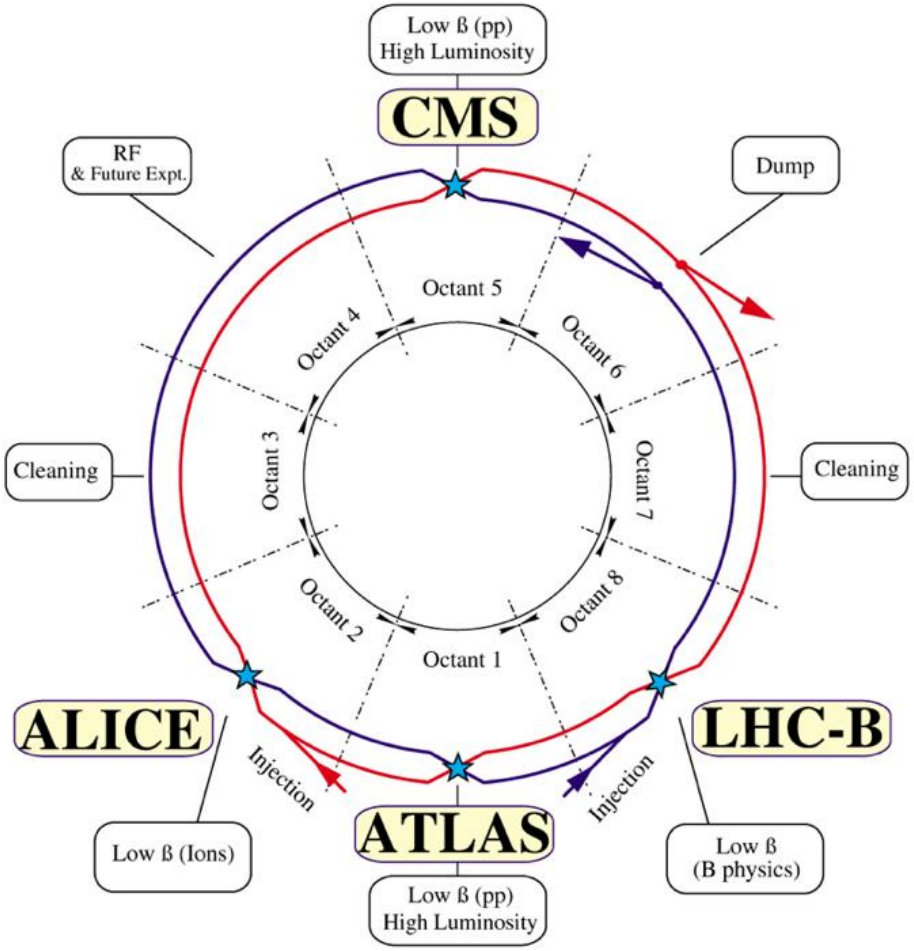
LHC is a collider and synchrotron storage ring:

Large: high energy needs large bending radius 26.7 km circumference

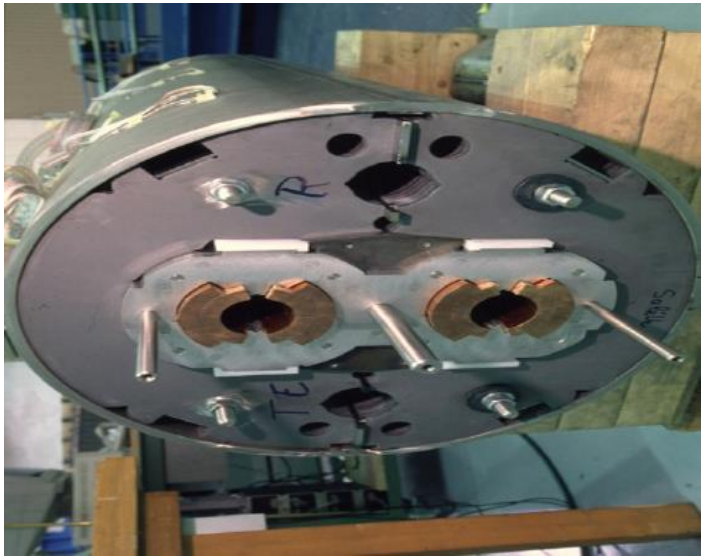
Collider: particles are stored in two separated rings which are synchrotrons, and accelerated

from injection energy (450 GeV) to 7 TeV.

At 7 TeV the two beams are forced to cross in collision points to interact.

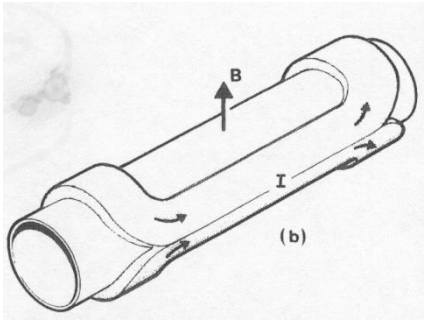


LHC fakti



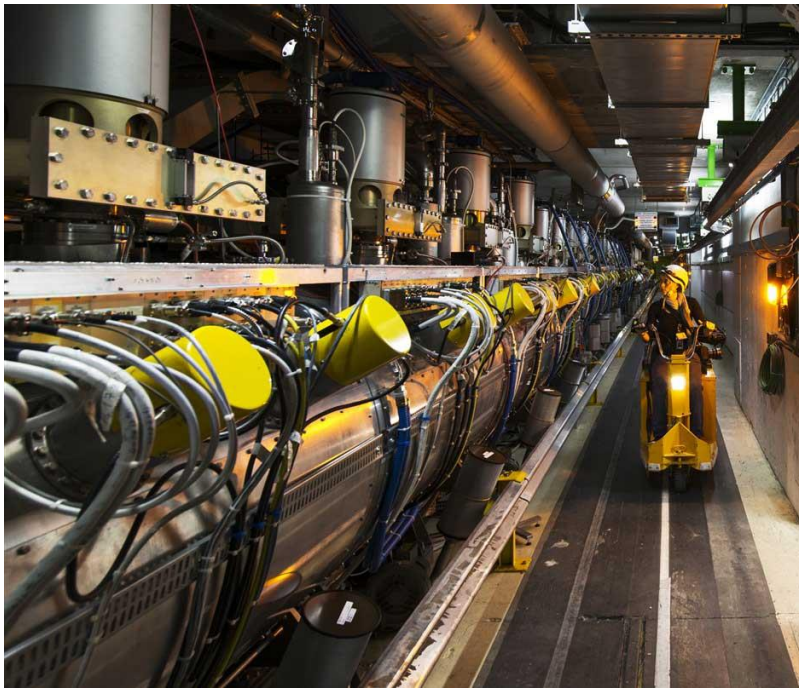
Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

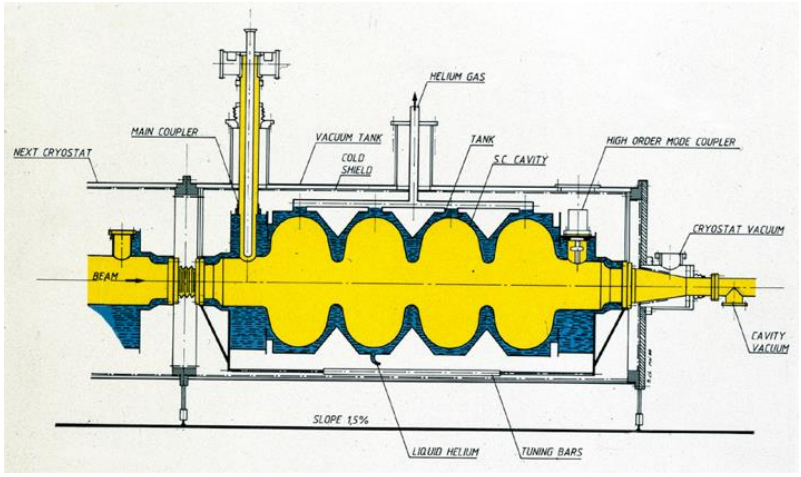
Nb –Ti superconducting cable – operational temperature 1,9 K



LHC paātrinātājs

The field in an RF cavity is made to oscillate at a given frequency, so timing the arrival of particles is important. On LHC, each RF cavity is tuned to oscillate at 400 MHz. The ideally timed proton, with exactly the right energy, will see zero accelerating voltage when the LHC is at full energy. Protons with slightly different energies arriving earlier or later will be accelerated or decelerated so that they stay close to the energy of the ideal particle.



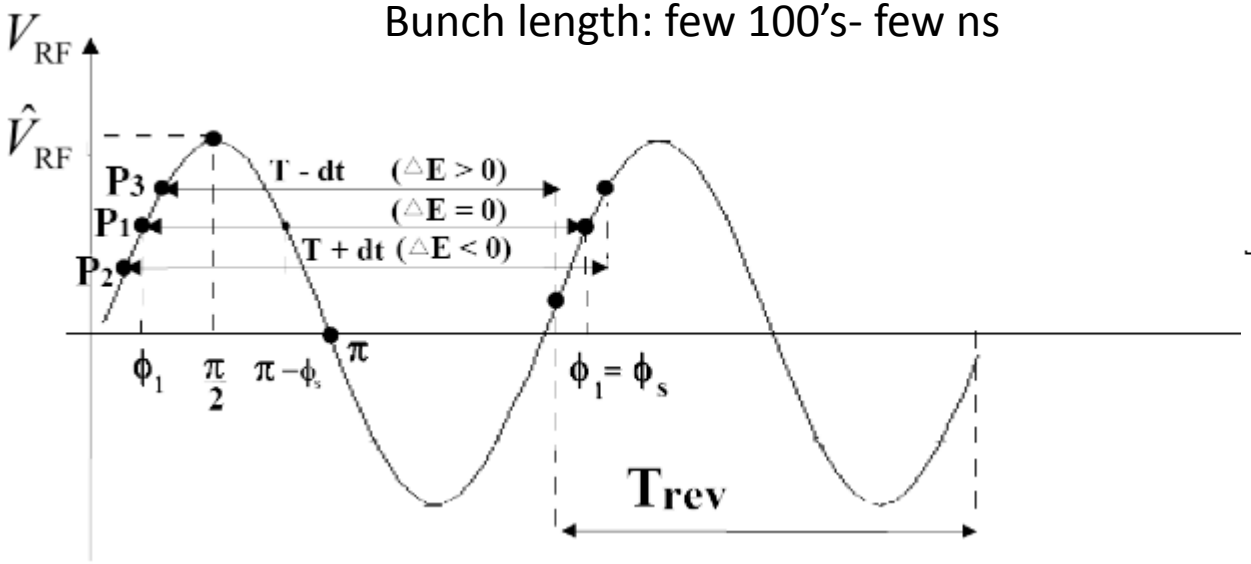


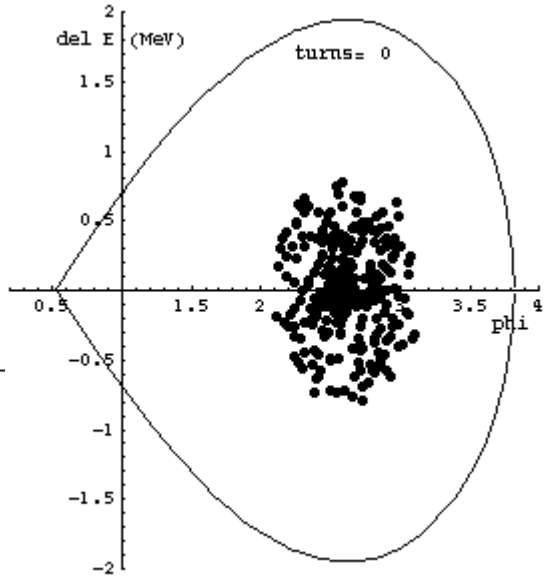
Each lap around LHC protons gain ~ 485 keV =>
About 10^6 laps to reach full energy

LHC paātrinātājs

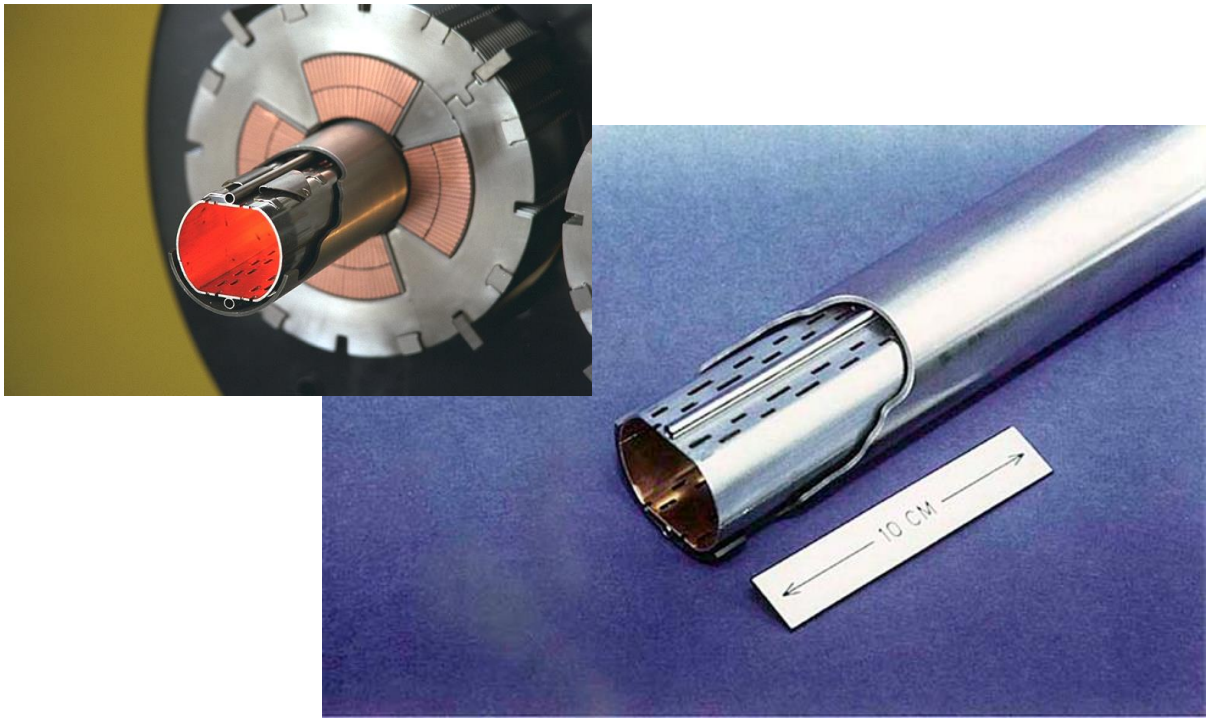
Particles are confined within a range in phase and energy called **BUCKET and are grouped into bunches by the electric field**

Bunch length: few 100's- few ns





LHC turpinājums



Beam screen to protect Superconducting magnets from Synchrotron radiation.

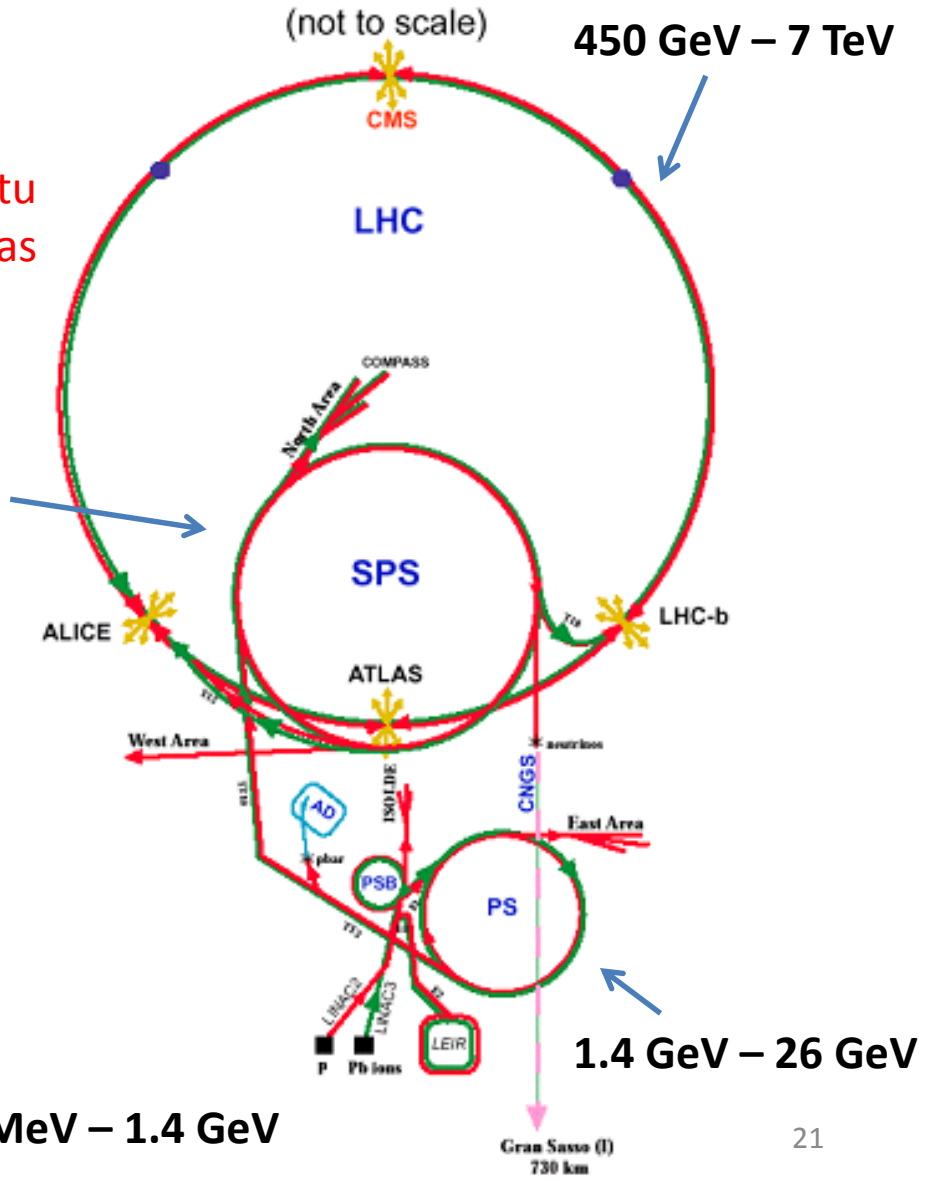
Vacuum required to avoid unwanted collision far from the IPs and decrease the Luminosity
Typical vacuum: 10^{-13} Torr
There is ~6500 m3 of total pumped volume in the LHC, like pumping down a cathedral.

Power lost per m in dipole: some W
Total radiated power per ring: some kW

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Vēlreiz CERN paātrinātāju komplekss

Mērķis – LHC radīt lādētu daļiņu sadursmes ar lielām enerģijām, lai ar sensoru palīdzību izprastu vielas uzbūvi, visuma izcelšanos un atklātu jaunas daļiņas



Ultra high vacuum – 10^{-10} mbar

protons
antiprotons
ions
neutrinos to Gran Sasso (I)

Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2

LHC enerģijas apjomi

Total stored beam energy at top energy (7 TeV), nominal beam, 334 MJ

Nominal LHC parameters: 1.15 10^{11} protons per bunch

2808 bunches

British aircraft carrier:

HMS Illustrious and Invincible weigh 20,000 tons all-up and fighting which corresponds to the aircraft carrier navigating v=5.8 m/s

At 7 TeV:

Imax = 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

Paldies par uzmanību!

Atsauces

- http://phys.org/news/2015-05-us-cern-agreement-paves-era-scientific.html
- http://home.cern/about/accelerators/linear-accelerator-2
- http://home.cern/about/accelerators/proton-synchrotron-booster
- http://home.cern/about/accelerators/proton-synchrotron
- http://home.cern/about/accelerators/super-proton-synchrotron
- Introduction to accelerators by Simone Gilardoni CERN-BE/ABP
- Introduction to Accelerator Physics by Pedro Castro / Accelerator Physics Group (MPY)
- G J Wiener et al Phys. Educ. 51 (2016) 035001