LE ROLE DES AIMANTS DANS LES ACCELERATEURS DES PARTICULES

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CONTENTS

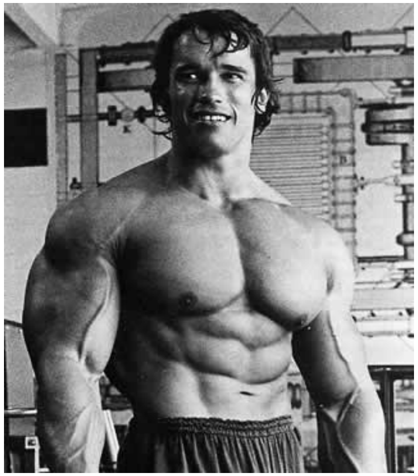
- Units for energy: TeV, J
- Lorentz force: two ways of accelerating
  - Linear
  - Circular
- Synchrotrons
- Stability and quadrupoles
  - Tune

Energy

- Different units to express the same idea: ability of making a work
- Physics: Joule = Force * displacement [N m]

  ex: at fitness rising 40 kg of 1 m

  $$L = m\ g\ h = 40 * 9.8 * 1 = 400\ \ J$$



- Power: Joule/s = Watt

  Ex: 1 series of 12 in half a minute

  $$P = L\ /\ t = 400 * 12\ /\ 30 = 160\ W$$

- Typical power of a normal human being ~150 W

ENERGY

- Different units to express the same idea: ability of making a work
- High energy physics: ElettronVolt = e charge * 1 volt [eV]

  the energy acquired by one electron (or proton) accelerated by a potential of 1 volt

$$L = q\,V \qquad 1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

- 1 KeV = 10^{3} eV = 1.6×10^{-16} J
- 1 MeV = 10^{6} eV = 1.6×10^{-13} J
- 1 GeV = 10^{9} eV = 1.6×10^{-10} J
- 1 TeV = 10^{12} eV = 1.6×10^{-7} J

Looks very small but we put all energy just in ONE particle

ENERGY

- 1 TeV = 10^{12} eV = 1.6×10^{-7} J
  - Looks very small but we put all energy just in ONE particle
  - 7 TeV = 7×10^{12} eV = 1.1×10^{-6} J
- We have about 110 billions of protons per bunch, with 2800 bunches per beam, so 310 000 billions of protons
  - Looks a lot, but 1 g of matter has about ~10^{23} protons
- Energy of one beam $310 \times 10^{12} \times 1.1 \times 10^{-6}$ J = 340 MJ
- Energy stored in the magnetic field
  - Energy density: $B^2/2\mu$
  - For a LHC dipole 7 T, 28 mm aperture radius
    - Area: 0.045 m^2 (two apertures)
    - Stored energy: 7 MJ for one dipole (both apertures), 8400 MJ all LHC
  - So energy of the magnetic field is much larger than energy of the beam

ENERGY

- Energy stored in the LHC
  - 8400 MJ in the LHC dipoles
  - 340 MJ per beam

- Assuming that the cycling time is one day, power is
  - 8800 / 24 / 3600 W = 100 kW

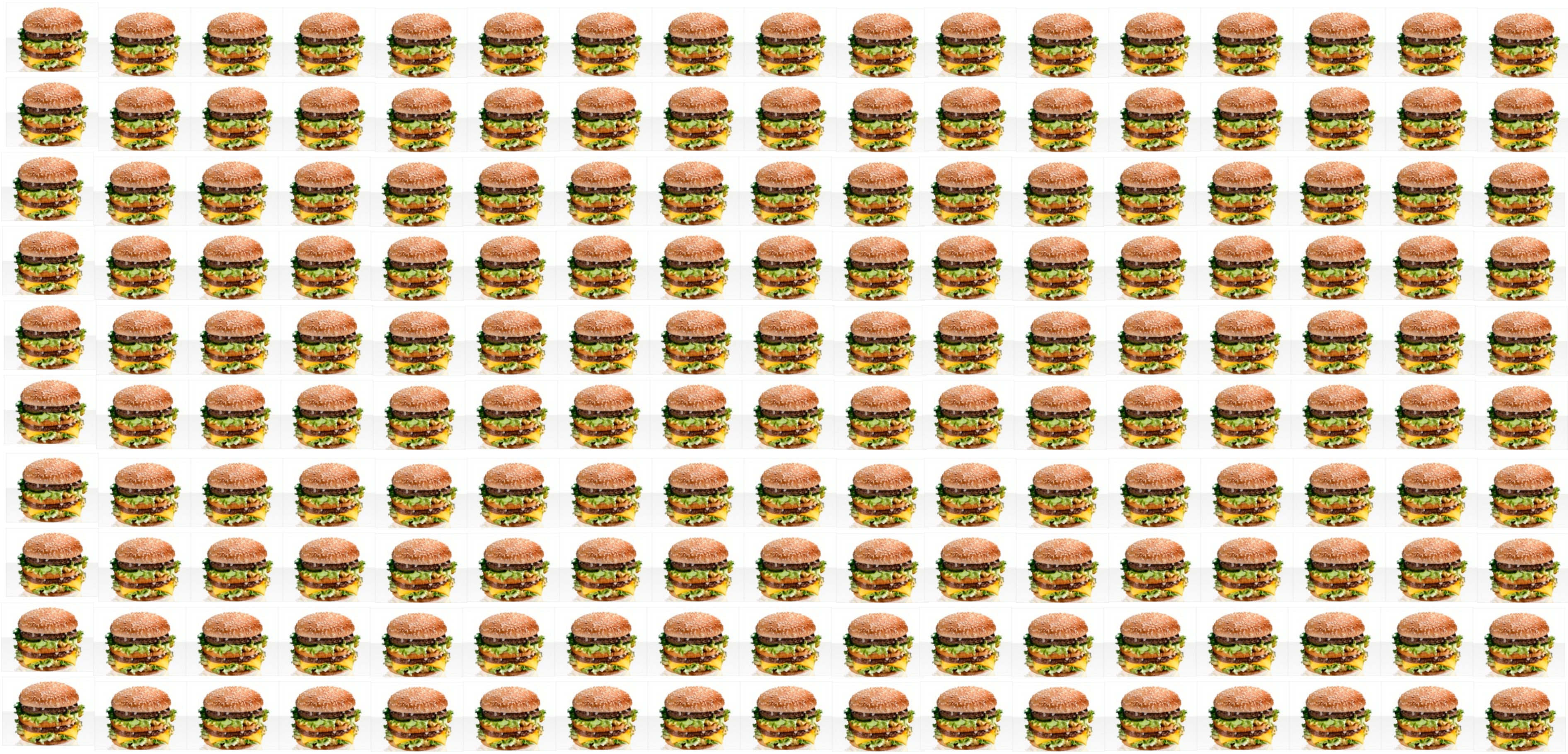
  - Consumption power with all accelerators on is about 200 MW - no surprise the machine is not at all effective

Energy

- Different units to express the same idea: ability of making a work
  - For food we use calories (in the communist era, they used kJ, it was much simpler …)
  - 1 cal = 4.18 J
    - Just to add confusion, what you see on food box is NOT calories but kcal!

      [thanks to Paolo for telling me, I was lost]
    - So a big Mac is not 500 cal but 500 kcal = 2 MJ
    - So LHC beam has the energy of 170 BigMac concentrated in a 300 000 billion of protons
  - Human need per day: 2000 kcal = 4 BigMac = 8 MJ
    - Power estimate: 8 106 / 24 / 3600 = 92 W (that fit with previous estimate)

ENERGY



LHC beam energy [A. Warhol, 1986]

LORENTZ FORCE

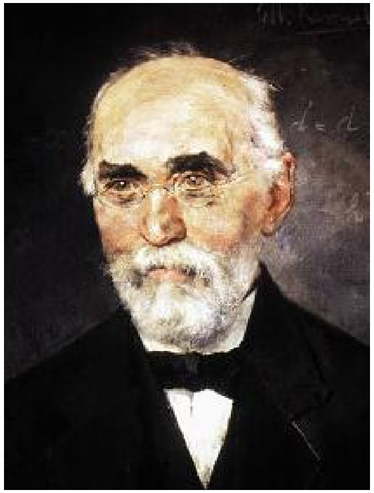
- How to accelerate particles?
- Lorentz force acts on charged particles
  - Protons, electrons, muons, … but not neutrons, neutrinos
- Electrical field accelerates particles

$$\vec{F} = e\vec{E}$$

- Magnetic field bends particles

$$\vec{F} = e\vec{v} \times \vec{B}$$

  - Very strange force: does not increase velocity but changes direction



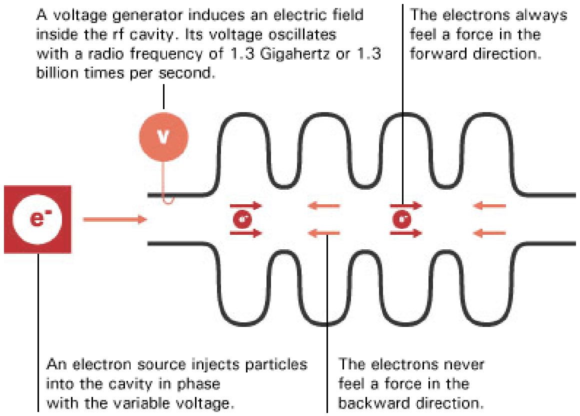
Hendrik Antoon Lorentz, Dutch

(18 July 1853 – 4 February 1928), painted by Menso Kamerlingh Onnes, brother of Heinke, Nobel proze for discovery in superconductivity

Linear and circular

- First idea: using electrical field to increase energy, like a gun

$$\vec{F} = e\vec{E}$$



- Energy proportional to length of the machine and to the electrical field
- Radiofrequency technology – present limit to ~35 MV/m (ILC)
    - So, 10 km of machine accelerates to ~350 GeV
- CLIC aims at factor 3 larger 100 MV/m

Linear and circular

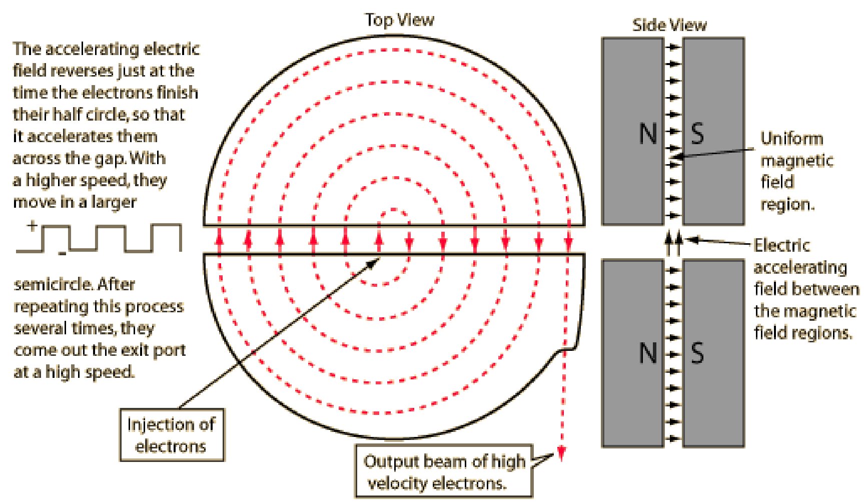
- Alternative idea: using magnetic field to bend particles, one small section accelerates and the beams goes back

$$\vec{F} = e\vec{E} \qquad \vec{F} = e\vec{v} \times \vec{B}$$

- Main relation

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

Constant

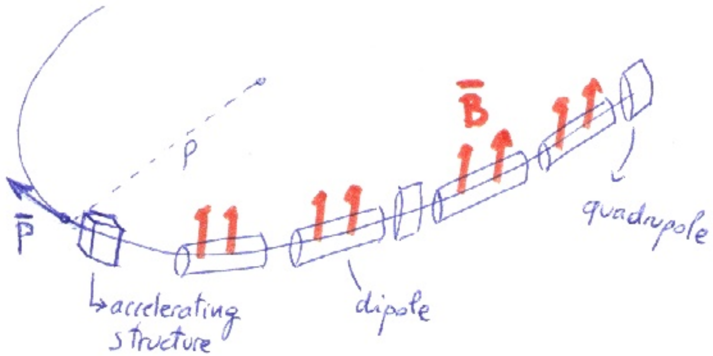


Cyclotron idea [1932, LBL]

- Energy (momentum p) proportional to curvature radius ρ and magnetic field B
  - If the field is fixed (permanent magnets), energy increases, radius of the orbit increases and finally particles escape the cyclotron

PRINCIPLES OF A SYNCHROTRON

- Idea: use electromagnet, increase field with energy to keep the same orbit
  - First for electrons McMillan, 1945
  - First for protons E. Oliphant, 1952



$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

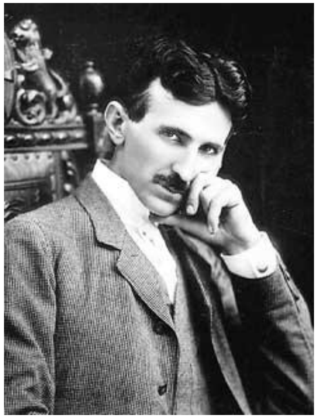
Constant

- Limits to the increase in energy
  - The maximum field of the dipoles (proton machines)
    - This is why high field magnets are important to get high energies!
    - This is a strange accelerator since most of it does not increase energy, but only bends …

TESLA INTERLUDE

Nikolai Tesla (10 July 1856 - 7 January 1943)

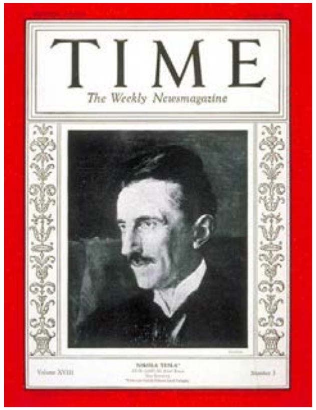
- Born at midnight during an electrical storm in Smiljan near Gospić (now Croatia)
- Son of an orthodox priest
- A national hero in Serbia – but also in the other republics of ex-Yugoslavia



Career

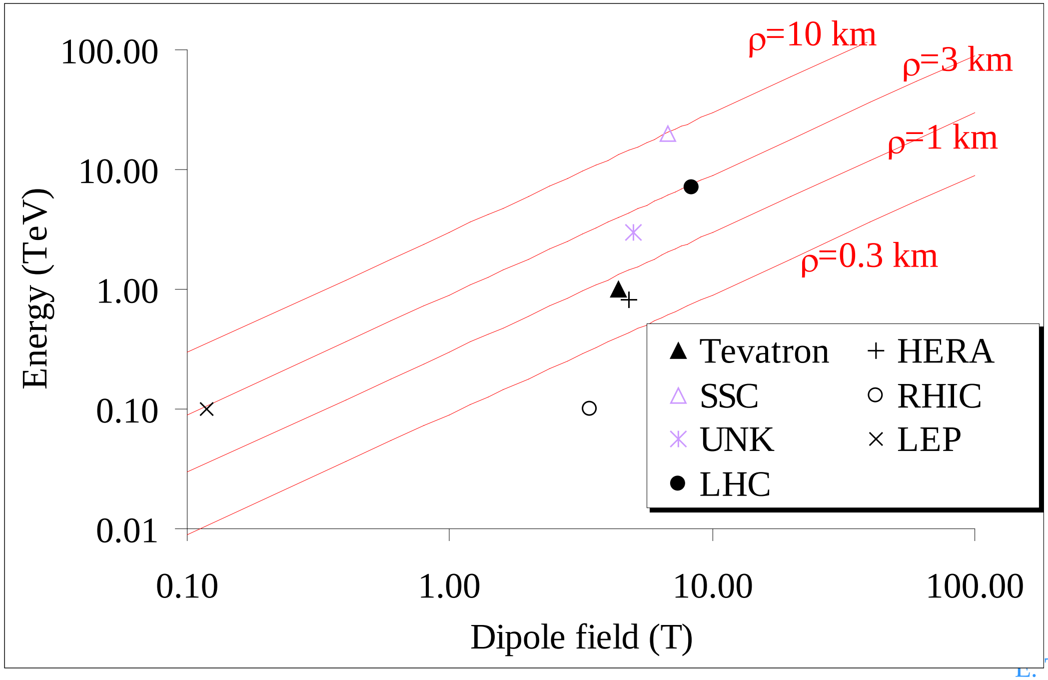
- Polytechnic in Gratz (Austria) and Prague
- Emigrated in the States in 1884
- Electrical engineer
- Inventor of the alternating current induction motor (1887)
- Author of 250 patents

A rather strange character, a lot of legends on him …

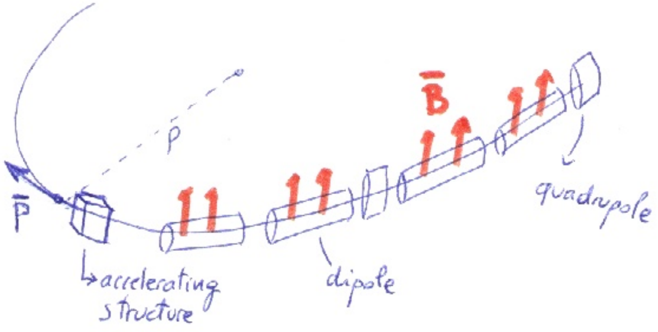


Principles of a synchrotron

- Relation momentum-magnetic field-orbit radius
  - Having 8 T magnets, we need 3 Km curvature radius to have 7 TeV
  - Present limit of technology 8 T (LHC after LS1)
  - Future: to 11-12 T (11 T and QXF for Hi Lumi 2016-2022)
  - Future: to 15-20 T (~2030)

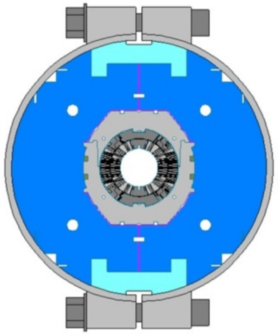


$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

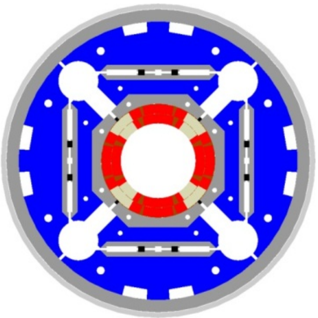


PRINCIPLES OF A SYNCHROTRON

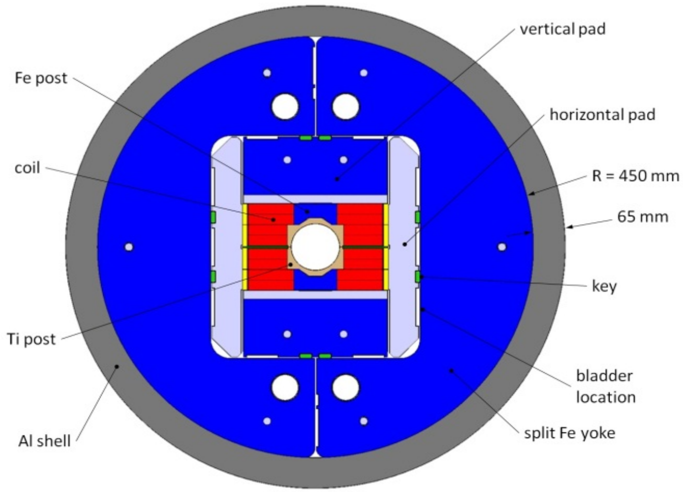
- The path towards high fields
  - Present limit of technology 8 T (LHC after LS1)
  - World record in accelerator magnet 13.8 T (LBL HD2)
  - Near future: towards 11-13 T with Nb_3Sn
    - 11 T dipole
    - 12 T peak field in QXF insertion quadrupole
    - 13 T Fresca2 (large aperture dipole for test station)
  - Mid-term future: 15-20 T with Nb_3Sn and HTS



11 T [M. Karppinen et al.]



QXF [P. Ferracin et al.]

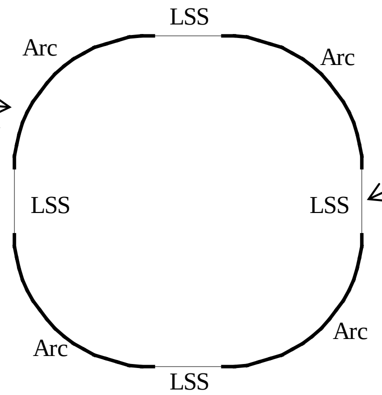


Fresca2 [G. De Rijk et al.]

Principles of a Synchrotron

$$\vec{F} = e\vec{v} \times \vec{B}$$

$$p = eB\rho$$

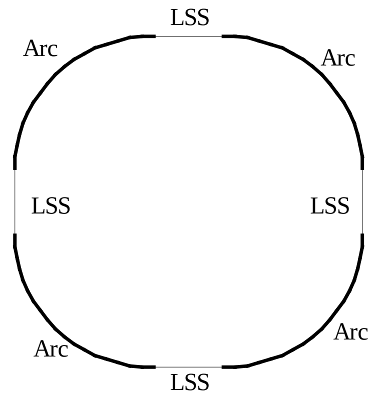


$$\vec{F} = e\vec{E}$$

- Colliders: two beams with opposite momentum collide
  - This doubles the energy !
  - One pipe if particles collide their antiparticles (LEP, Tevatron)
  - Otherwise, two pipes (ISR, RHIC, HERA, LHC)

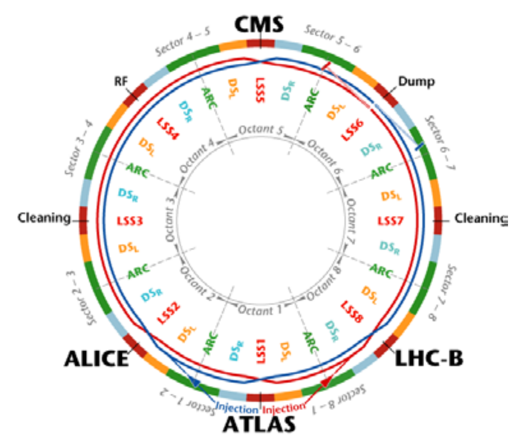
Principles of a synchrotron

- The arcs: region where the beam is bent
  - Dipoles for bending
  - Quadrupoles for focusing
  - Correctors



A schematic view of a synchrotron

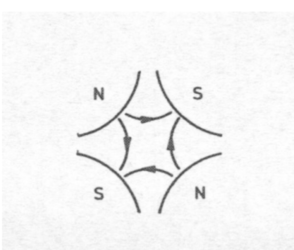
- Long straight sections (LSS)
  - Interaction regions (IR) where the experiments are housed
    - Quadrupoles for strong focusing in interaction point
    - Dipoles for beam crossing in two-ring machines
  - Regions for other services
    - Beam injection (dipole kickers)
    - Accelerating structure (RF cavities)
    - Beam dump (dipole kickers)
    - Beam cleaning (collimators)

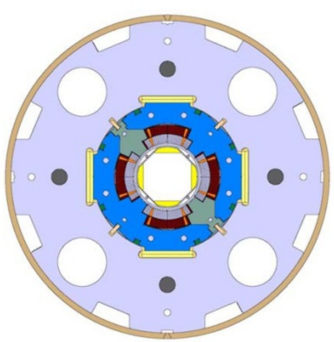


The lay-out of the LHC

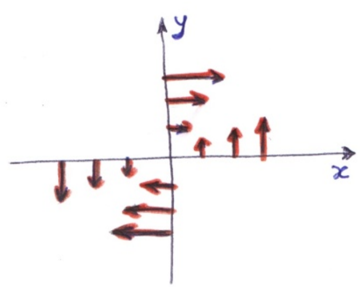
LINEAR STABILITY AND QUADRUPOLES

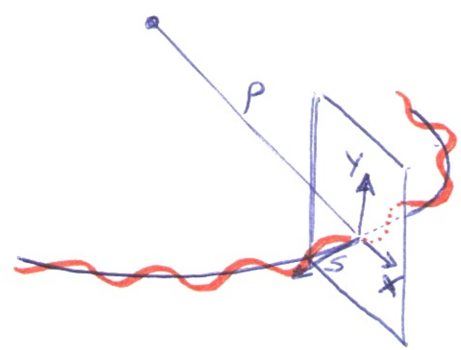
- LHC case:
  - Bending radius is 2.8 km
  - Error of 1% in the magnetic field changes the orbit of 2.8 m, but the beam tube is 100 times smaller (28 mm radius !)
    - We would need a huge precision in our magnets to have the particles in the beam tube
- You need a force to bring back the particle to the center of the tube: given by the quadrupole
  - If the particle is in the center, no field – otherwise the quadrupolar field brings it back





MQXC [G. Kirby, et al.]

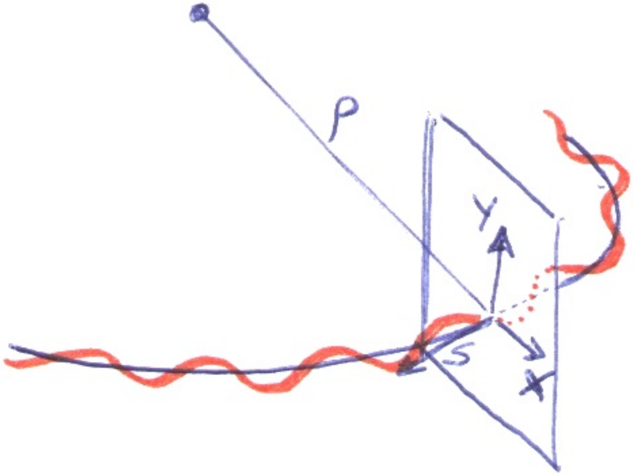




LINEAR STABILITY AND QUADRUPOLES

- The oscillations of the beam around the central orbit are called betatron oscillations
  - The number of oscillations in one turn of the machine is called tune
  - For the LHC tune is 59.28, 63.31
    - Please note these numbers are not integers
    - Resonances !! Any imperfection can cause instability if the effect is resonant – this is why we need correctors

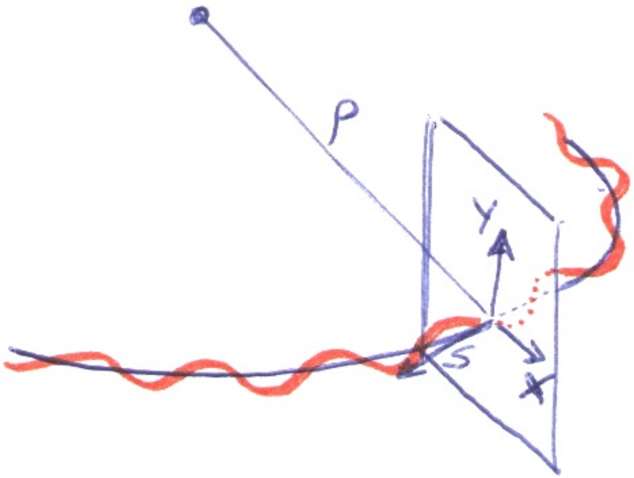
Resonant forcing of harmonic oscillator



Betatronic oscillations

CHRMOATICITY AND SEXTUPOLES

- The tune of the machine should not cross resonances
  - Little variation of energy produce variations of tune (chromaticity) – analogy with optics
    - Typically in the LHC protons have different energy by 1 per mil
  - A sextupole can correct and minimize this effect
  - And so on … we have up to dodecapole in the LHC !!



SUMMARY

- One can accelerate charged particle thanks to Lorentz force
- Synchrotrons are compact machines to get very large energies
  - A lot of energy in a few particles
  - The accelerating part is a small fraction, most of the work is the magnetic field to bring the beam back
- Limits to circular machines: magnets 8 T
  - Higher energies can be obtained by larger machines or higher fields
- We push towards 11-12 T to break the Nb-Ti barrier
- We aim at 15-20 T in 10 years from now

- Quadrupoles are needed to focus the beam
  - High order correctors to stabilize it