Nuclear Physics

The following subject areas will be treated

- **Introduction, motivation** (mass-spectroscopy, accelerators, LHC)
- **Fundamental properties** of atomic nuclei (size, composition, mass, binding energy, angular momentum, parity)
- **Radioactivity** (fundamentals and introductory theories)
- **Nuclear models** (Liquid drop, Fermi-gas, Shell-model, Collective model)
- **Nuclear forces** (deuteron, Yukawa-force)
- **Nuclear reactions** (cross-sections, microscopic, macroscopic, partial waves approx., Born-approx., DWBA)
- **Nuclear fission** (fundamentals, chain reaction and safety)
- **Nuclear fusion** (stellar fusion, fusion devices, ITER)

Textbook: Kenneth Krane: Introductory Nuclear Physics
Lecturer: Prof. Dr. Csaba SÜKÖSD sukosd@reak.bme.hu
Practice: Máté HALÁSZ halasz.m@gmail.com

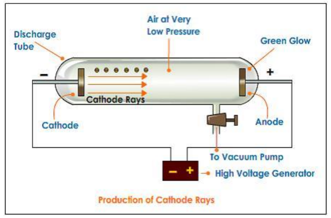
1

Lecture 01: Introduction, motivation

End of XIXth century: electricity and magnetism are known
Maxwell's equations
Forces on electrically charged objects: $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

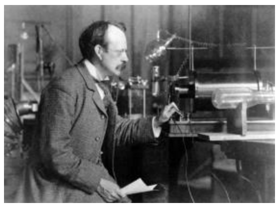
Electrical field: accelerates
Magnetic field: bends the path (force is $\perp$ to the velocity)

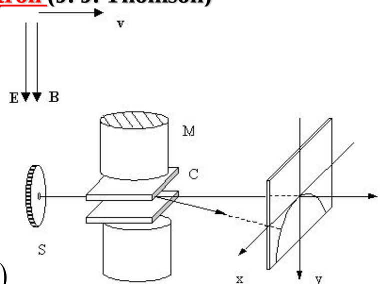
In the focus of studies: cathode rays in vacuum tubes



2

1897: Discovery of the electron (J. J. Thomson)





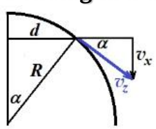
Initial velocity: $\mathbf{v} = (0, 0, v_z)$
Time of flight in the fields: $t = \frac{d}{v_z}$

Outgoing velocity in y direction: $v_y = a_y \cdot t = \left(q \cdot \frac{E}{m}\right) \cdot t = \left(q \cdot \frac{E}{m}\right) \cdot \frac{d}{v_z} = \frac{q \cdot E \cdot d}{m \cdot v_z}$

Centripetal acceleration in x direction: $\frac{v_z^2}{R} = \frac{q \cdot v_z \cdot B}{m}$, from this: $R = \frac{m \cdot v_z}{q \cdot B}$

3

Bending in x direction:



From this we have: $\frac{d}{R} = \frac{v_x}{v_z}$ and so

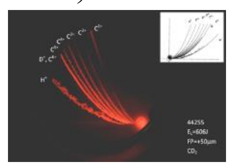
$$v_x = v_z \frac{d}{R} = v_z \frac{d \cdot q \cdot B}{m \cdot v_z} = \frac{q}{m} \cdot d \cdot B$$

If the screen is at L distance: $y = L \cdot \frac{v_y}{v_z}$ and $x = L \cdot \frac{v_x}{v_z}$

From this we get $y = L \cdot \frac{q \cdot E \cdot d}{m \cdot v_z^2}$, and $x = L \cdot \frac{q \cdot B \cdot d}{m \cdot v_z}$

Eliminating v_z we finally have: $y = \left(\frac{m}{q}\right) \cdot \left(\frac{E}{L \cdot B^2 \cdot d}\right) \cdot x^2$

The curve on the screen is a parabola!
From it the $\frac{m}{q}$ and the v_z of the object can be determined!
Knowing q (e.g. elementary charge) the mass can be measured: mass spectroscopy



4

Thomson experiment: the $\frac{q}{m}$ of the cathode rays are the same for every cathode material!! Discovery of electrons!

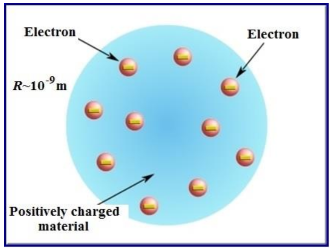
Moreover: for the negatively charged rays $\left(\frac{|q|}{m_-}\right) >> \left(\frac{|q|}{m_+}\right)$

from where we get $m_- << m_+$ (since matter is electrically neutral, therefore positive and negative charges must be the same)

For example for hydrogen: $m_+ \approx 1836 \cdot m_-$

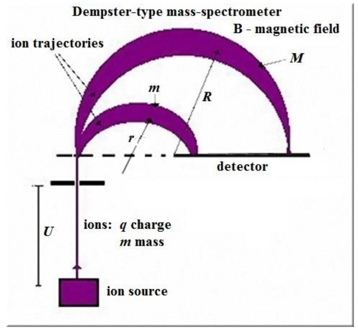
Thomson model of the atom:

Small, light electrons in heavy large positive material („pudding model”)



5

Mass spectroscopy



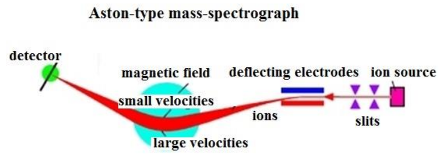
Particles having the same (q/m) arrive at the same place!

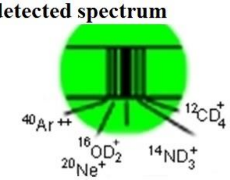
Small mass-differences Can be measured accurately!

For example (q/m)=1/20 „mixed” beam:

$^{40}Ar^{++}$, $^{20}Ne^{+}$, $^{16}OD_2^{+}$, $^{14}ND_3^{+}$, $^{12}CD_4^{+}$

detected spectrum





6

Atomic mass unit (u)

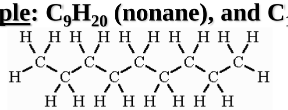
Definition: 1 u = $\frac{M(^{12}\mathrm{C})}{12}$, i.e. the 12th part of the mass of ^{12}C atom

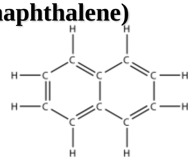
Why the carbon atom?

Because it can form compounds with many other atoms!

Mass-doublet method!

For example: C_9H_{20} (nonane), and $C_{10}H_8$ (naphthalene)





The mass of both is about 128

Precisely: $M(\text{nonane}) = 9\cdot M(\mathrm{C})+20\cdot M(\mathrm{H})$

$M(\text{napht.}) = 10\cdot M(\mathrm{C})+ 8\cdot M(\mathrm{H})$

$\Delta M = -M(\mathrm{C})+12\cdot M(\mathrm{H})$

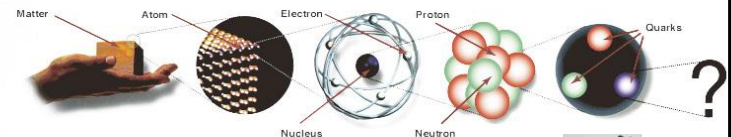
From this: $M(^1\mathrm{H}) = \frac{M(^{12}\mathrm{C})}{12} + \frac{\Delta M}{12} = 1{,}0000\ldots + \frac{\Delta M}{12}$

Measurement: ΔM = 0,09390032 ± 0,00000012 u, so

$M(^1\mathrm{H}) = 1{,}00782503 \pm 0{,}00000001\,\mathrm{u}$

7

How do we think about the structure of the matter now?



Like Russian dolls…

Where do we know it from? Using „microscopes”

However, the spatial resolution of a microscope is limited by the wavelength of the „light” used:

Dolphins and bats use ultrasound: $\lambda \approx 0{,}1\ldots1\,\mathrm{mm}$

Visible light: $\lambda \approx 0{,}4\ldots0{,}8\,\mu\mathrm{m}$

Ultraviolet light: $\lambda \approx 0{,}1\ldots0{,}4\,\mu\mathrm{m}$

EM waves with smaller wavelengths: no optical material (lens)!

How to resolve smaller objects?

8

Louis de Broglie

(1892-1987)
Discovery 1924
Nobel-prize 1929

The „wave-nature” of the particles

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

h ⟵ Planck's constant
p ⟵ momentum (=$m \cdot v$)

Improving the spatial resolution: particles with higher momenta

First application:
Electron microscope
Idea of Leo Szilárd (1928)
Prototype by Ernst Ruska and Max Knoll (1931)
Working principle: electrons accelerated by a few 100 kV $\longrightarrow \lambda \approx 0{,}1 \ldots 1 \cdot 10^{-11}$ m
„Optics” with electromagnetic lenses (Hans Busch 1926)

David J. Morgan: https://www.flickr.com/photos/tz1_1zt/112072422/

One of the main motivations for building accelerators: reducing λ and going deeper and deeper into the structure of matter

9

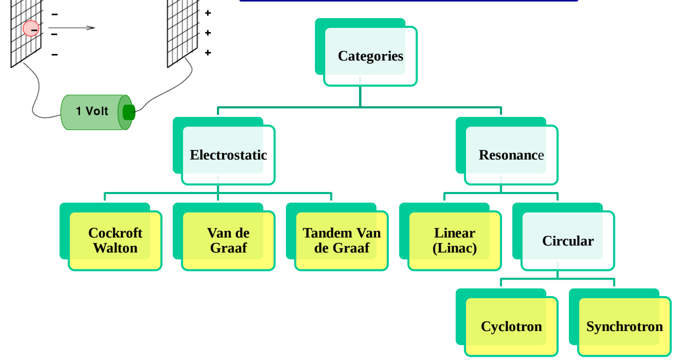
Particle accelerators

Charged particles can be accelerated by electric field

$$\mathbf{a} = \frac{\mathbf{F}}{m} = \frac{q}{m} \cdot \mathbf{E}$$

Common unit: electronvolt (eV)

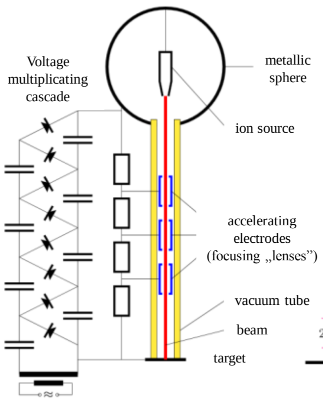
1 eV = 1,602176565(35)·10^{-19} J



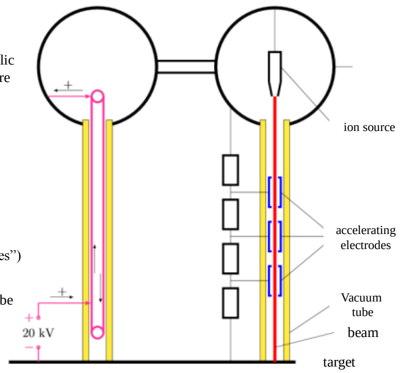
10

Electrostatic accelerators

Cockroft-Walton (cascade-generator)

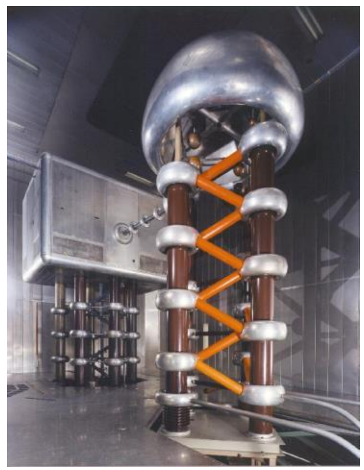


Van de Graaf generator



11

Cascade generator



http://www2.physics.umd.edu/~eno/teaching/751/f13/handouts/accelerators/Cockcroft-Walton.jpg

Van de Graaf generator

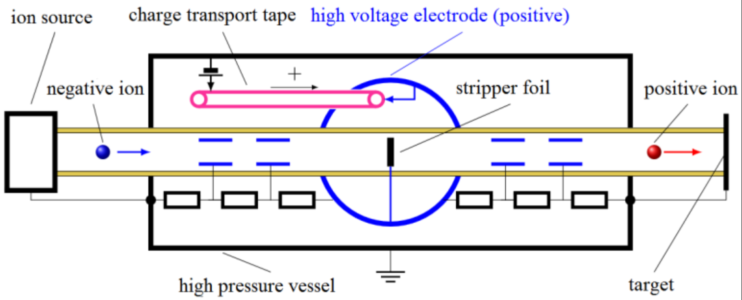
http://bama.ua.edu/hep/vandegraaff.htm

12

Problem with the Cascade and Van de Graaf generators:

The ion source needs power, but it is at high potential.
Difficult and cumbersome to power!

Genial solution: **Tandem Van de Graaf generator**



Note: double gain in energy! For example: 10 MV ⟶ 20 MeV

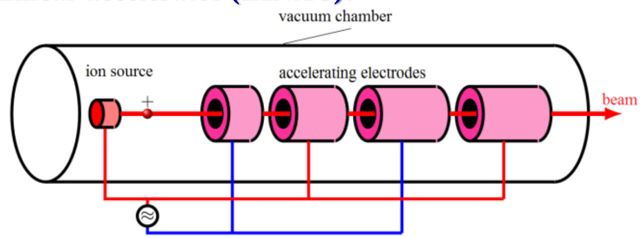
13

Resonance accelerators

Main idea:

Use the **same** accelerating field several times
to get higher and higher energy

Linear accelerator (LINAC):



Inside the electrodes: no field (Faraday cup)
Between the electrodes: accelerating field
(focusing) (alternates with good frequency ⟶ „resonance")

14

Linear accelerator (contd.):

Sample calculation:
Frequency: 2,5 GHz = $2{,}5\cdot10^9$ [1/s]
Accelerating voltage: 1 MV
Energy goal: 1 TeV = 10^{12} eV ⟶ velocity ~ speed of light (c)

Consequence:
Half period: $T/2 = 2\cdot10^{-10}$ s
Number of accelerations needed: $n = \frac{10^{12}}{10^6} = 10^6$
Needed length: $L = n \cdot c \cdot \frac{T}{2} = 10^6 \cdot 3 \cdot 10^8 \cdot 2 \cdot 10^{-10} = 6 \cdot 10^4\ [\mathrm{m}]$
Length = 60 km! VERY difficult to achieve (almost impossible)!

Solution: **curved trajectory ⟶ circular accelerators**

15

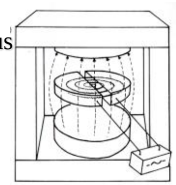
Circular accelerators

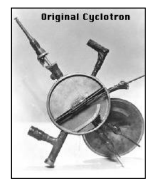
Cyclotron

First patent: **05.01.1929 Leo Szilárd**
First working device (1930):
Ernest Orlando Lawrence
(American patent 26.01.1932)
(Nobel Price: 1939)

Szilárd and Lawrence 27.04.1937

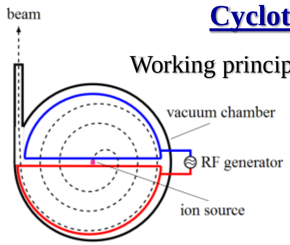
Working principle:
1) Particles are bent by homogeneous constant **magnetic** field
2) Particles are accelerated by periodical **electric** field





16

Cyclotron (contd.)



Working principle with calculation:

Centripetal force:

$$F = \frac{mv^2}{r} = q \cdot (v \cdot B)$$

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

Therefore the time of the revolution remains constant as well!

If the particle started „well", it arrives always in good phase into the accelerating slit ⟶ it will be accelerated again and again.

Consequences:

ω and *B* must be well adjusted ⟶ „resonance"

Only particles in good phase get accelerated ⟶ „bunch" of particles

Maximal velocity: $v_{max} = \frac{q}{m} \cdot B \cdot R$, where *R* is the max. radius

Maximal energy: $E_{max} = \frac{1}{2} m \cdot v_{max}^2 = \frac{q^2 B^2}{2m} \cdot R^2$

http://www.reak.bme.hu/fileadmin/user_upload/felhasznalok/sukosd/letoltesek/Ciklotron_en/Ciklotron.htm

Cyclotron (contd.)

Sample calculation:

Proton: $m = 1{,}67 \cdot 10^{-27}$ kg, $q = 1{,}6 \cdot 10^{-19}$ C

Magnetic field: 4 T (achievable only with superconducting magnets)

Energy goal: 1 TeV = 10^{12} eV

Consequence:

$R^2 = \frac{2mE_{max}}{q^2 B^2}$ Needed radius: $R = \sqrt{\frac{2mE_{max}}{q^2 B^2}} = 36{,}12$ m

Impossible to achieve!

Another problem: $\omega = \frac{v}{r} = \frac{q}{m} \cdot B$

It is constant only until *m* remains constant!

When entering in the relativistic region: $m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

so we get: $\omega(v) = \frac{q}{m_0} \cdot B \cdot \sqrt{1 - \frac{v^2}{c^2}}$ The particles get out of resonance!

Synchrotron

Early history:

Vladimir Veksler (Russian, 1944, published in a Soviet journal)

Edwin McMillan (American, 1945, first electron synchrotron, Nobel Prize in Chemistry 1951)

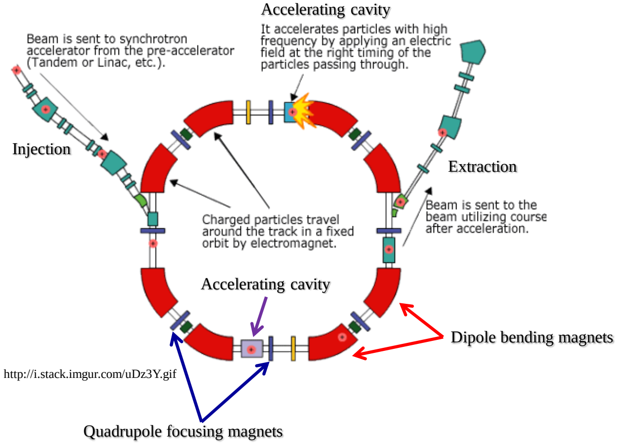
Sir Marcus Oliphant (Australian, 1954, first proton synchrotron)

Imagine a linac bent to closed shape (circle or polygon consisting of different sectors)!

Working principle:

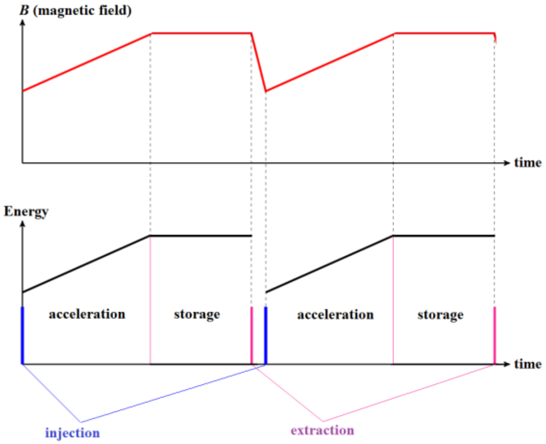
1) Particles are bent by **magnetic** field sectors, where the field is adjusted to the actual energy of the particles
2) Particles are accelerated by sectors with **electric** field cavities
3) Cannot start from zero kinetic energy ⟶ injection of already accelerated particles
4) Use of quadrupole magnets to focus and to handle the beam

Synchrotron (contd.)



http://i.stack.imgur.com/uDz3Y.gif

Synchrotron (contd.)



Working cycles of a synchrotron (accelerator + storage ring)

CERN and LHC

Conseil Européen des Recherches Nucléaires (Council of European Nuclear Research)

<u>Founded:</u> in 1954
12 founding member countries (Germany among them)
<u>Objective:</u> internationalisation of the nuclear research.
At the beginning really nuclear research was carried out, but soon the particle and high energy physics became the main research area.

Today there are 21 member countries of CERN.
Beside the members there are „observer” countries too (USA, Canada, India, etc.)

Hungary is also member of CERN since 1992

CERN and LHC (contd.)

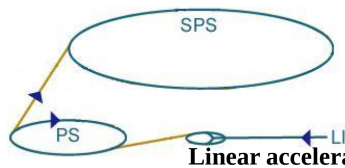
History of the big accelerators of CERN

1959: **Proton synchrotron** (PS)
28 GeV protons (1 GeV = 10^9 eV)
underground location
circumference: 628 m

CERN and LHC (contd.)

History of the big accelerators of CERN

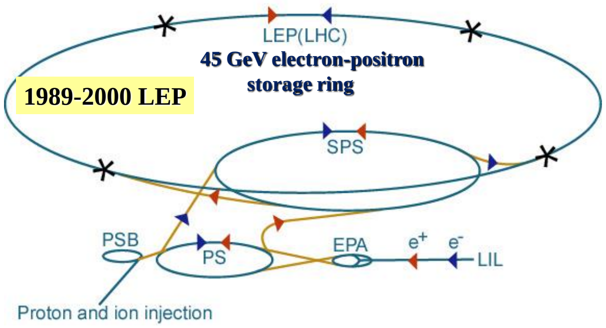
1976: **Super Proton Synchrotron** (SPS)
400 GeV protons
underground location
circumferences: 6 km



Linear accelerator and „preinjector”

CERN and LHC (contd.)

History of the big accelerators of CERN



25

CERN and LHC (contd.)

The accelerators of CERN on an aerial photograph

26

CERN and LHC (contd.)

The Large Hadron Collider (LHC)

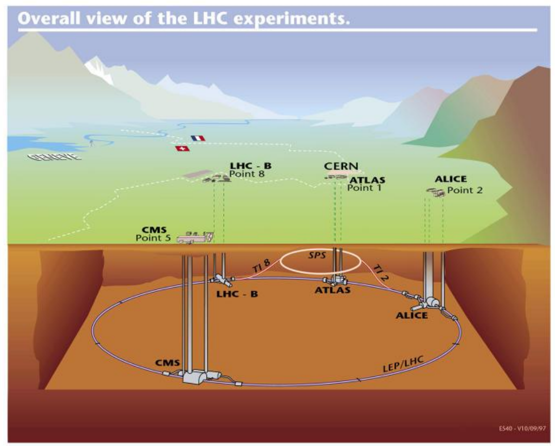
- Opened on the 10th Sept. 2008.
- Underground tunnel (50- 100 m deep)
- Superconducting magnets
- Mainly proton-proton collision,
- Sometimes even lead-lead collision (!!)
- Energy: 7000 GeV/proton,
  in collision 14000 GeV(!!!)
- 10^{11} particles in a bunch

- Four big detectors:
  ALICE, ATLAS, CMS, LHC-B

CMS detector
under construction

27

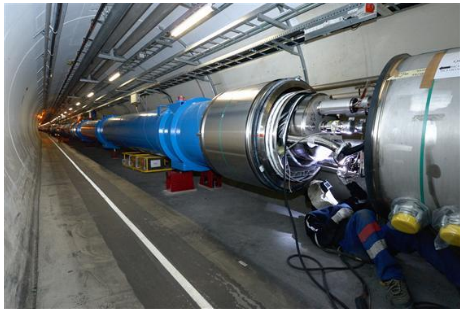
CERN and LHC (contd.)



28

Dipole magnets

- The biggest ones in the World: 8.4 T field, 11700 A current
- Length: 14.3 m, weight: 35 t, Energy stored: 1.29 GJ
- 1232 pieces along the ring, 0.5 MChF/unit
- Superconducting coils are made of niobium-titan
- Huge magnetic forces ($4 \cdot 10^6$ N/m) (400 t/m)



29

Cooling

- Superconducting magnets in 1.9 K superfluid helium,
- 31000 t material should be cooled through 27 km
- Several step compressors, 40000 leakage free junctions
- 12 million litre liquid N_2 will be evaporated at the start of cooling down
- 700000 litre helium are used

Vacuum

- Ultrahigh vacuum 10^{-10} torr (3 million molecules / cm^3)
- See level 760 torr, 90 km 10^{-3} torr, 1000 km 10^{-10} torr

30

Beam parameters

Linear accelerator
250 MeV protons

Hydrogen bottle proton ion source

31

Beam parameters

– Linear accelerator	0.25 GeV (250 MeV)
– PS Booster (PSB)	1.4 GeV
– Proton Synchrotron (PS)	25.0 GeV
– Super Proton Synchrotron (SPS)	450.0 GeV
– LHC fills up in both directions during 4 min 20 s	
– Acceleration during 20 min	7000 GeV (7 TeV)
– Storage during several hours	

- The proton packets fly nearly with speed of light (7 TeV)
- 2808 packets in the ring in one direction
- 10^{11} protons in a packet
- Protons revolve 11246 times in a second
- Beam diameter in the collision point is about 16 μm
- packet length is a few cm (like human hairbreadth)
- About 20 collisions of protons at packet crossings, every 25 ns
- 800 million collisions in a second (!!) Energy: 14 TeV!

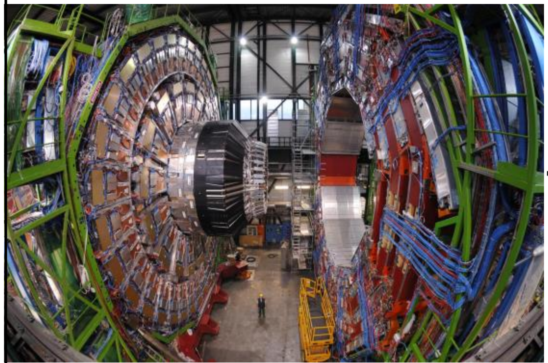
32

CERN and LHC (contd.)

In the tunnel of the LHC (2007)

33

CERN and LHC (contd.)



The CMS detector (2008)

34

CERN and LHC (contd.)

„Houston" The Control Room of the LHC just before start (2008)

35