EP228 Particle Physics

Particle Accelerators

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Course web page
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Outline

1. **Introduction**
2. **Electrostatic (DC) Accelerators**
3. **Linear Accelerators**
4. **Circular Accelerators**
5. **Tevatron and LHC**
6. **The Future Accelerators**
7. **Exercises**

- ***See also*:**
  - **http://www.cern.ch**
  - **http://en.wikipedia.org/wiki/Tevatron**
  - **http://en.wikipedia.org/wiki/Particle_accelerator**
  - **http://en.wikipedia.org/wiki/Large_Hadron_Collider**
  - **http://en.wikipedia.org/wiki/Cockcroft-Walton_generator**

1. Introduction

In particle accelerators we use electric and magnetic fields.

- A **particle accelerator** is a device that uses electric fields to propel ions or charged subatomic particles to high speeds and to contain them in well-defined beams.

- An ordinary CRT television set is a simple form of accelerator.

- Accelerators are some of the remarkable tools of modern science.

- They have an important role in *Particle Physics* (PP) and *Nuclear Physics* (NP)

- Nowadays, they are in demand of variety of applications:
  - *Condensed matter Physics*
  - *Electronic industry*
  - *Biomedical areas*
  - *Geophysical areas*
  - *Food processing*
  - *Sewage treatment*

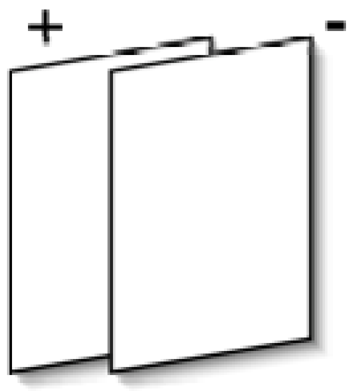
- **In PP and NP we have to consider**
  - the required energies of particles
  - the desired beam intensity
  - the economic constraints

- **Basically accelerators can be categorised in two types**
  - *Linear accelerators* (Linac)
  - *Circular accelerators*

- We will begin with Electrostatic accelerators…

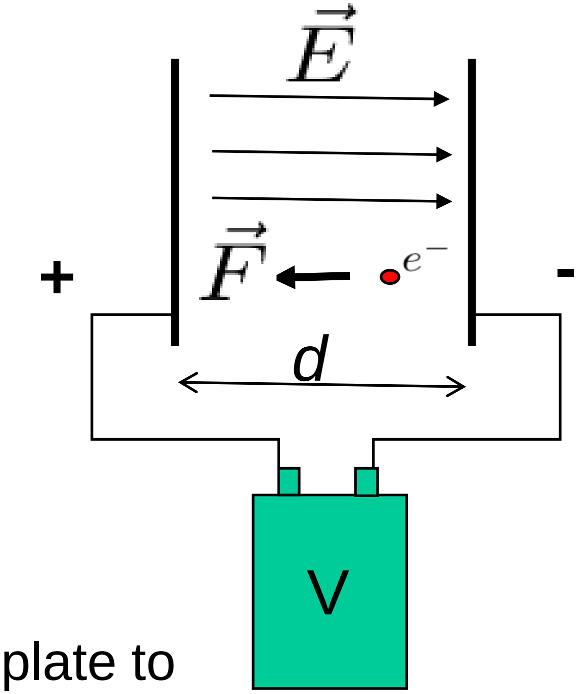
2. Electrostatic (DC) Accelerators

- **Parallel Plate Capacitor**



$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$

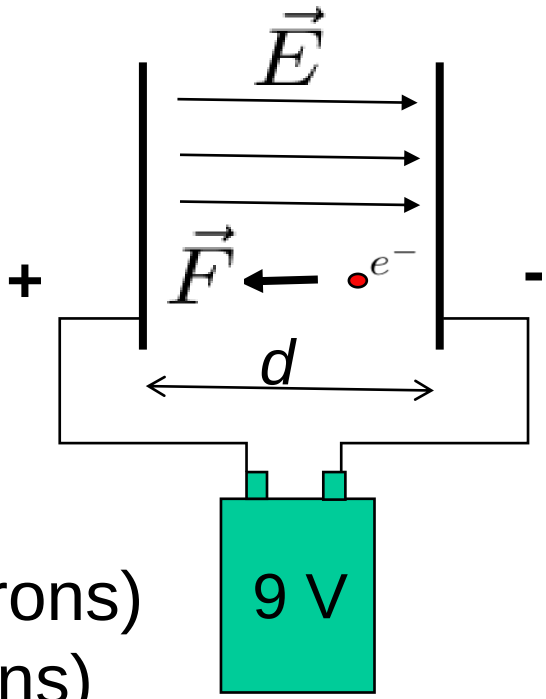


As the electron accelerates from the right hand plate to the left, the change in kinetic energy is the work done,

$$W = F * d = q*E$$
$$= q*(V/d)*d$$
$$= qV$$
$$= \Delta K = K_f - K_i$$

- If started from rest ($K_i = 0$):

$$K_f = \frac{1}{2} m v_f^2 = qV \longrightarrow v_f = \sqrt{2qV/m}$$

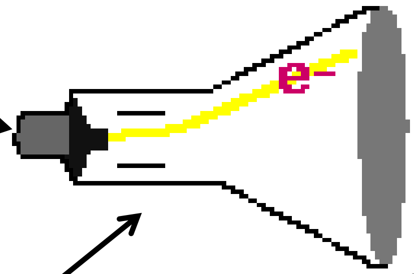


- For V = 9 Volts
  $v_f = 1.8 \times 10^6$ m/s = 0.006c (for electrons)
  $v_f = 4.2 \times 10^4$ m/s = 0.00014c (for protons)

- How much voltage can we deliver?
  Let's look at a TV set

Your (old) TV Set [CRT]

heated filament, electron source (cathode)



phosphorescent screen which lights up when struck by electrons

electromagentic fields to ***accelerate*** and steer the electron beam (*ray*)

evacuated glass container (tube)

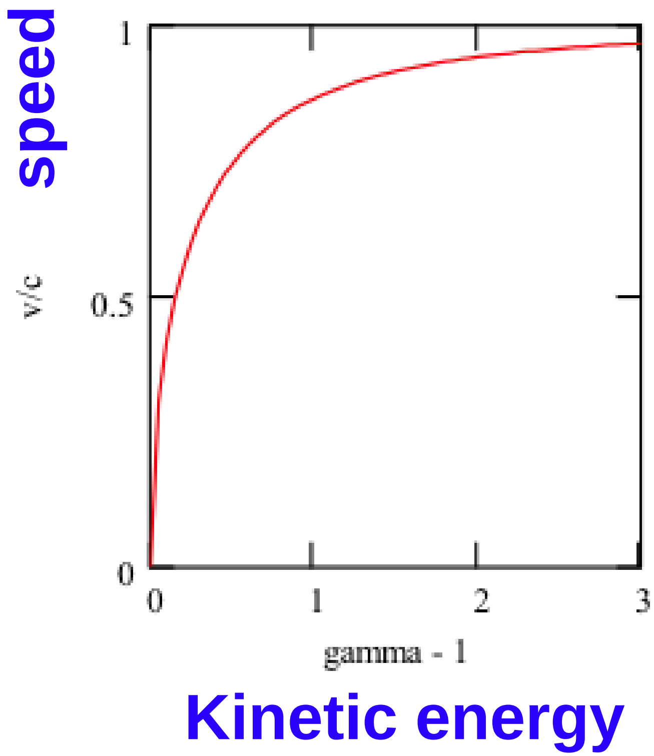
Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10,000 eV**!

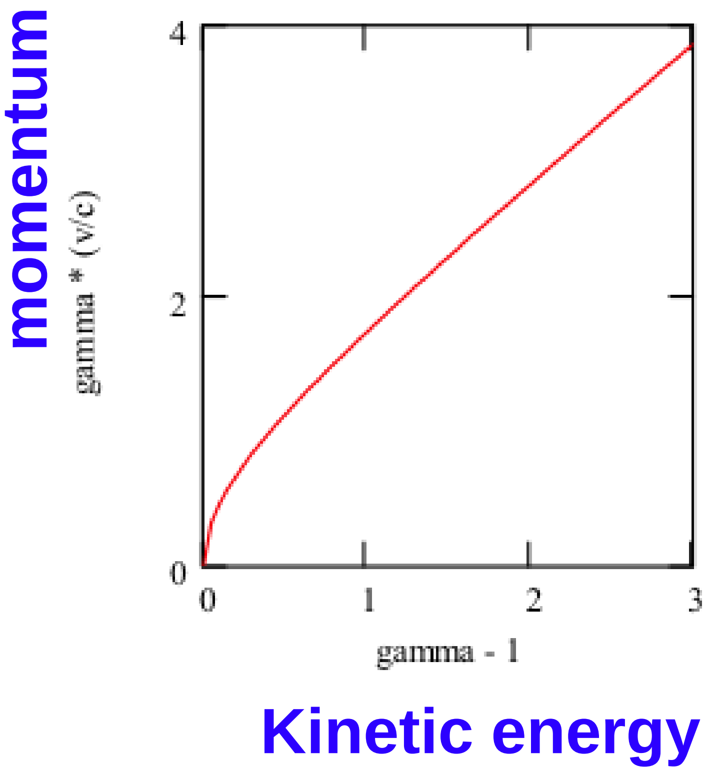
- An electron in a typical TV set, with **$T = 10$ keV** kinetic energy, say, would thus be moving about **$v = 0.2c$**

- What if
  $T = 50$ keV ==> $v = c$
  $T = 100$ keV ==> $v = 2c$

- **Does this means electron can move faster than speed of light?**

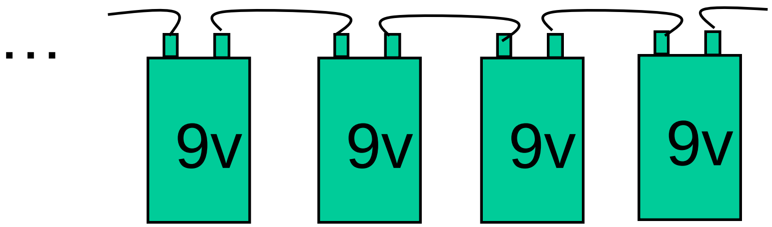
  No, we have to include relativistic effects which play an important role in high energy particle accelerators. Hence, we need to include the relativistic effects at high energies.


speed
v/c
1
0.5
0
0
1
2
3
gamma - 1
Kinetic energy

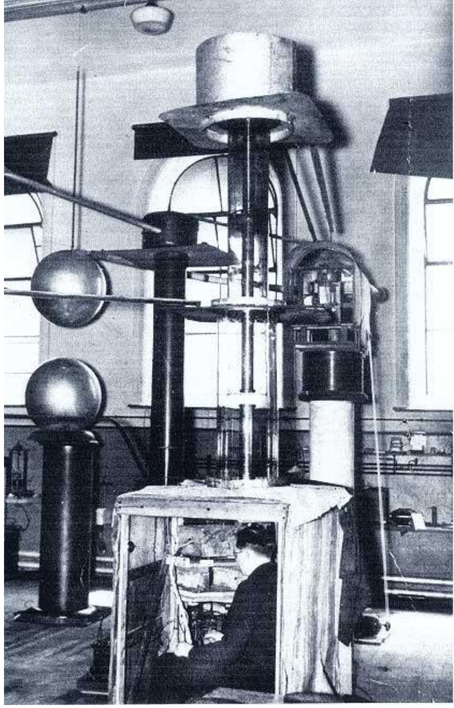

momentum
gamma * (v/c)
4
2
0
0
1
2
3
gamma - 1
Kinetic energy

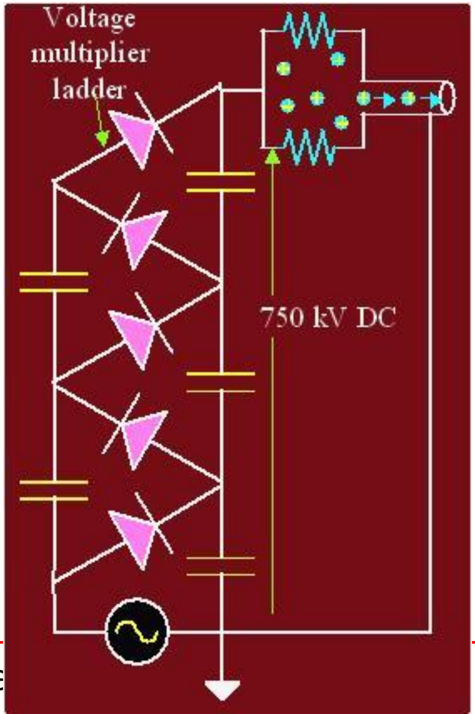
- How to get high voltage?
  How high can we go?

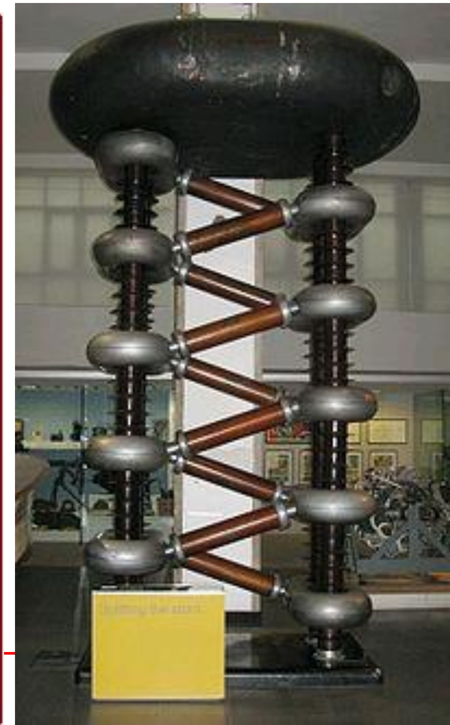
- String a bunch of batteries in series!
  Not very practical…



- ## Cookroft-Walton Machine
  - First high voltage particle acc. (developed 1930s)
  - Voltage-doubling circuits were used (~ 100 kV)
  - Based on passing ions through sets of aligned electrodes operated at successfully higher fixed potentials
  - They won Nobel prize for "*Transmutation of atomic nuclei by artificially accelerated atomic particles*"





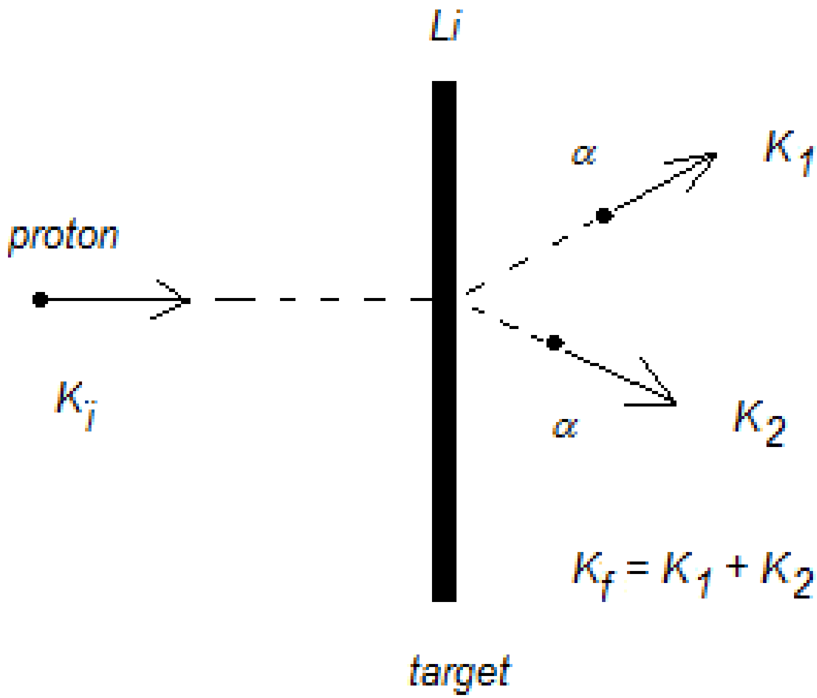


Experimental verification of S.R.

In 1932, using Cookroft-Walton Machine the following reaction produced:

$$^{1}H \;+\; ^{7}Li \rightarrow \; ^{4}He + \; ^{4}He$$

$$p \;+\; ^{7}Li \;\rightarrow\; \alpha \;+\; \alpha$$



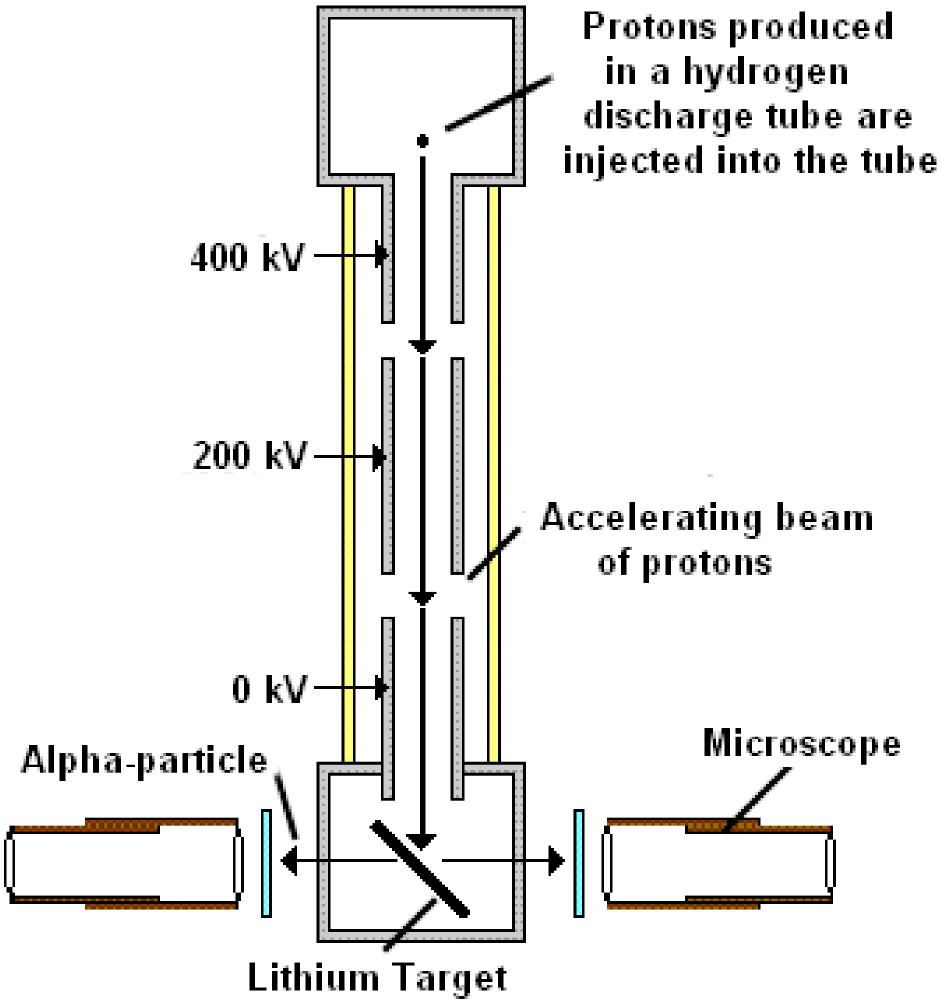
Kinetic energy of protons
was K_i = 600 keV.

Masses
m(^{7}Li)= 7.01600 a.m.u = 6534.5 MeV/c^2
m(^{4}He)= 4.0026 a.m.u = 3727.9 MeV/c^2
m(p) = 938.3 MeV/c^2

Protons were accelerated and slammed into lithium atoms producing alpha-particles and energy. Thus the mass (rest energy) of the proton and lithium was converted into the mass of two alpha-particles and kinetic energy.

Experimental verification of S.R.

$$p + {}^{7}Li \rightarrow \alpha + \alpha$$



Experimental verification of S.R.

$$p + {}^{7}Li \rightarrow \alpha + \alpha$$

Using conservation of energy we have ($E_i = E_f$)

$$K_i + m_i c^2 = K_f + m_f c^2$$

or

$$\Delta K = K_f - K_i = m_i c^2 - m_f c^2$$
$$= m_p c^2 + m_{Li} c^2 - 2m_\alpha c^2$$
$$= 17\ \text{MeV}$$

Cookroft-Walton measured the K.E. of alpha particles and they found:

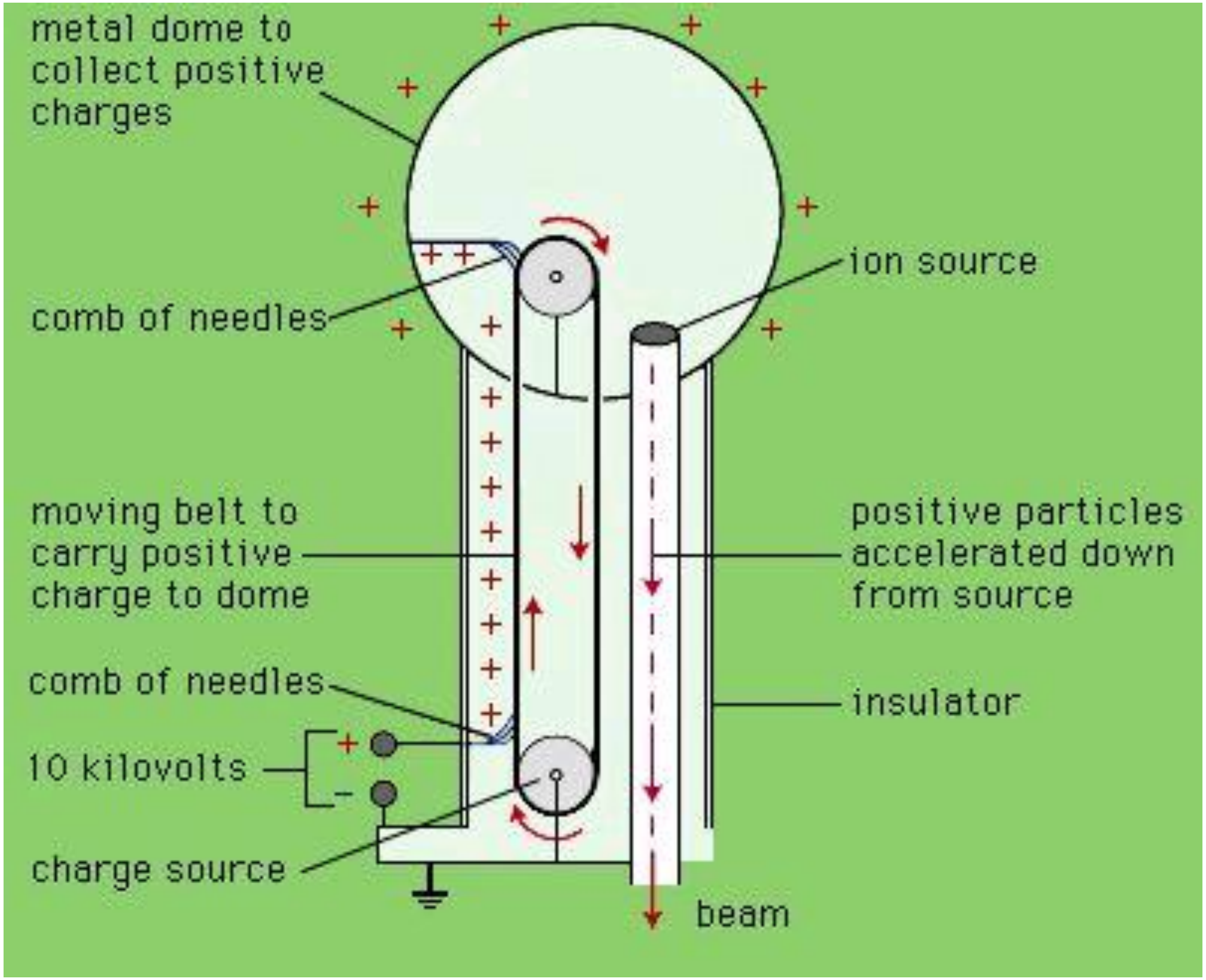
$$\Delta K = K_1 + K_2 - K_i = 17.2\ \text{MeV}$$

The result is consistent with the prediction of Special Relativity.

This reaction was the **first experimental proof of Einstein's $E = mc^2$**

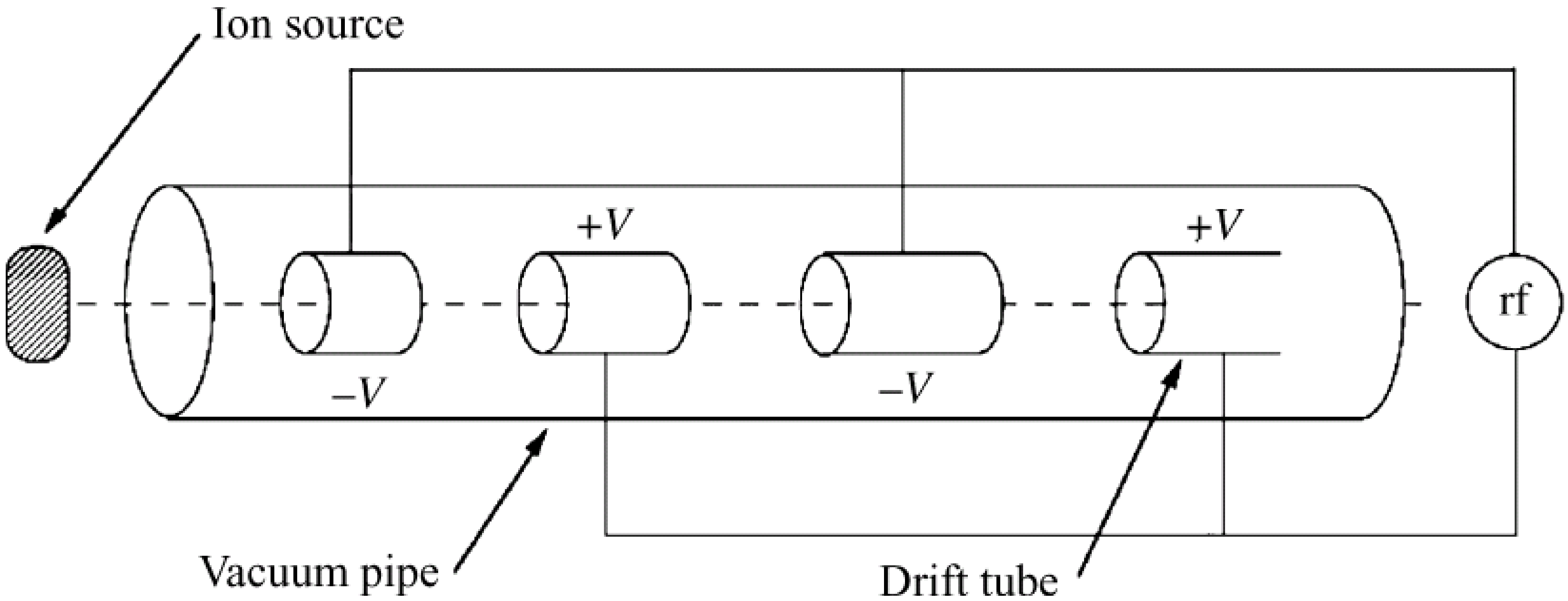
Van de Graaff Accelerators

- The most common potential-drop accelerator in use today is the *Van de Graaff Accelerator*.
- Several configurations exist and have achieved voltages < 25 MV.
- The basic principle relies on the fact that since the charge on any conductor resides on the outermost surface, if a conductor carrying charge touches another conductor that envelops it, then, irrespective of potential, it will transfer all its charge to the outer conductor.


metal dome to collect positive charges
ion source
comb of needles
moving belt to carry positive charge to dome
positive particles accelerated down from source
comb of needles
insulator
10 kilovolts
charge source
beam

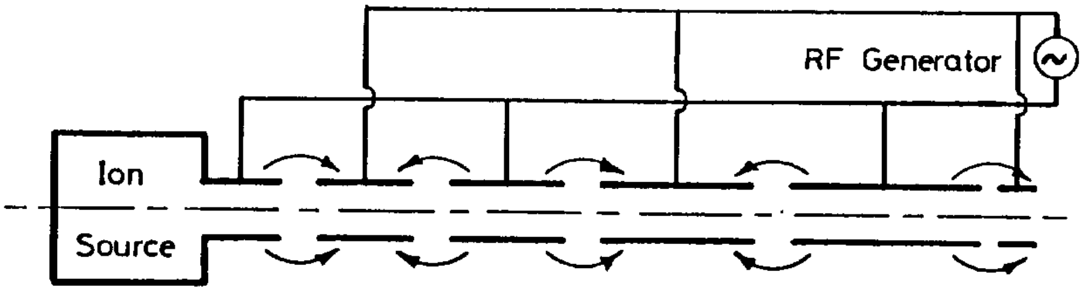
3. Linear Accelerators

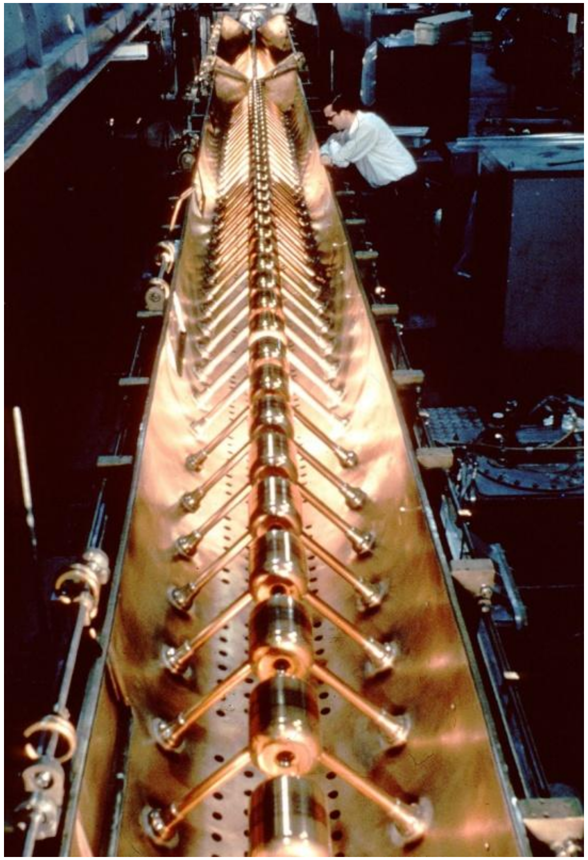
- In a linear accelerator (or linac) for acclerating ions, particles pass through a series of metal pipes called **drift tubes**, that are located in a vacuum vessel and connected successively to alternate terminals of an R.F. oscillator.



- https://www.youtube.com/watch?v=3Bm60HdvI6s

- Energy is gained by RF cavities



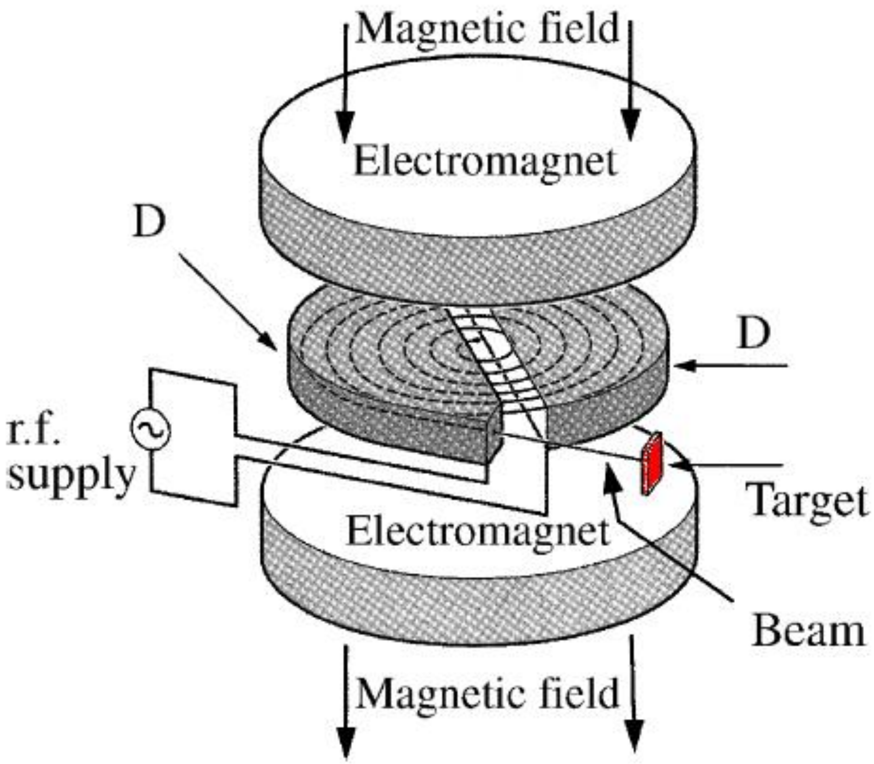


- **SLAC - Standford Linear Accelerator Center**
  - Total length = 3.2 km
  - 100,000 RF cavity
  - Ecm = 50 GeV (electron)

4. Circular Accelerators

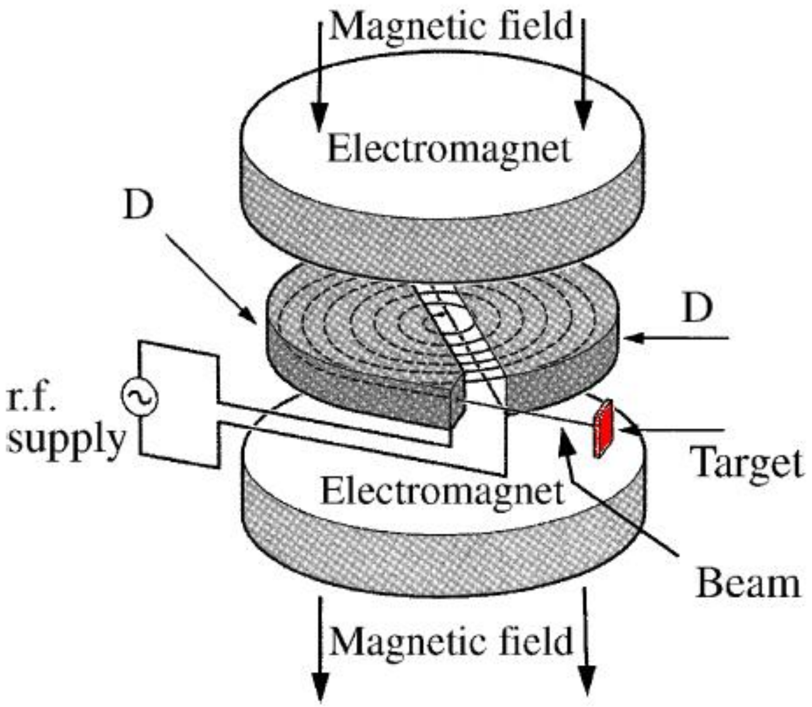
Cyclotrons

- Circular (or Cyclic) accelerators used for low-energy nuclear physics experiments are of a type called **cyclotrons**.
- They are also used to produce beams of particles for medical applications, including proton beams for radiation therapy.



Schematic diagram of a cyclotron

- The accelerator consists of two ‘D’-shaped sections across which an r.f. electric field is established.
- Charged ions are injected into the machine near its centre and are constrained to traverse outward in spiral trajectories by a magnetic field.
- The ions are accelerated each time they pass across the gap between the dees.
- At the maximum radius, which corresponds to
the maximum energy, the beam is extracted to hit a target



https://www.youtube.com/watch?v=VAqjyQC4zwk

Cyclotron Frequency

A moving charge in a cyclotron will move in a circular path under the influence of a constant magnetic field. For non-relativistic motion:

$$m\frac{v^2}{r} = Bqr \longrightarrow \frac{v}{r} = \frac{qB}{m}$$

Relation between anglar velocity and *v*:

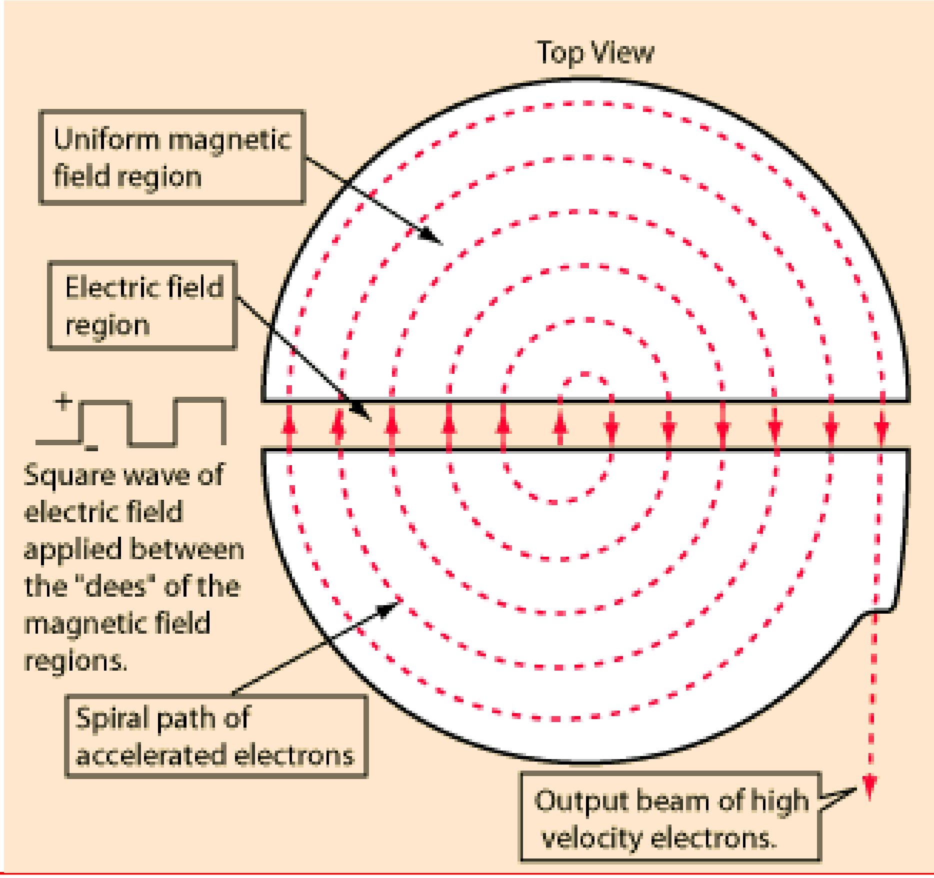
$$\omega = v / r$$

Therefore frequency of the motion:

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

To keep the acceleration in phase, cyclotron frequencey must satisfy:

$$f = f_{cyclotron} = \frac{qB}{2\pi m}$$



- The maximum kinetic energy that a charged particle has when it is extracted at radius R is given by

$$K_{\mathrm{max}} = \frac{1}{2} m v_{\mathrm{max}}^2 = \frac{1}{2} m \omega^2 R^2 = \frac{(qBR)^2}{2m}$$

- This is a basic relation between B and the size of magnet (R).

- **Example 1**:
  Let B = 1.5 T and R = 0.4 m. Find the frequency of the alternating source to accelerate protons, and the maximum kinetic energy gained by these protons:

$$f_{cyc} = 22.8\,\mathrm{MHz} \quad \text{and} \quad K_{\mathrm{max}} = 17\,\mathrm{MeV}$$

Synchronous Accelerators

For relativistic energies cyclotrons formulas can not be used.

For this case, one can use the relation:

$$f_{cyclotron} = \frac{qB}{2\pi m}\sqrt{1 - v^2 / c^2}$$

Consequently, to hold acceleration, either the *f* or *B* or both must be changed.

- Machines where B is held constant but f is varied are called **synchrocyclotrons**
- Machines where f is held constant but B is varied are called **synchrotrons.**

Gaziantep University Proton Accelerator Center

In our university, we have a Cyclotron for the production of radionuclides to be used in medicine.

Model:

TR-19 Cyclotron

ADVANCED CYCLOTRON SYSTEMS, INC.

www.advancedcyclotron.com

- Specs of TR19:

BEAM ENERGY (Variable Energy)

Minimum:	14 MeV Proton operation, 7 MeV Deuteron operation
Maximum:	19 MeV Proton operation, 9 MeV Deuteron operation

EXTRACTED CURRENTS

Total extracted current: protons available to 300 μA

Total extracted current: deuterons available to 50 μA

MAGNET

Orientation:	Vertical
Geometry:	4 Sectors (closed)
Hill angle:	Variable 45º
Average induction:	1.2 Tesla
Opening for access:	1.0 m

- Specs of TR19:

RF SYSTEM

Number of dees:	2 (45º)
Dee voltage:	50 kV
RF frequency:	73 and 37 MHz
Power required:	18 kW
Energy per rev:	200 keV

ION SOURCE (External)

Type:	H- multicusp
Output current:	3 mA (nominal), 4 mA (maximum)
Bias voltage:	25 - 30 kV

VACUUM SYSTEM

Operating pressure:	< 2 x 10^{-6} Torr
Cryopumps:	one 4,000 l/s (H_2O) each

Production of Radiopharmaceutical in Gaziantep University

Radyofarmasötik ilaçlar:

- Florodeoksiglikoz (FDG)
- F-DOPA
- F-Choline
- FluoroThymidine (FLT)
- Fluoroestradiol (FES)
- Amonyum (13NH4)

Radyoniklid bileşikleri:

$^{64}CuCl_2$

$^{68}GaCl_3$

^{89}Zr-Oxalat

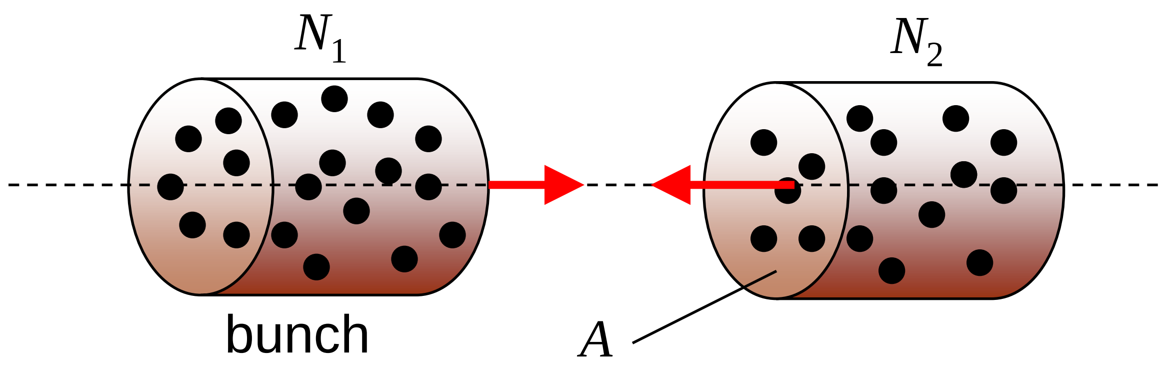
Big Accelerators

- **Luminosity (L)**
  Particles collides as the form bunches. Reaction rate (R) and the cross-section (sigma) is proportional to each other

$$R = L\sigma \qquad L = fn\frac{N_1 N_2}{A}$$

f: frequency

n: number of bunches



Example 2:

At LEP, there were 8 bunches of electrons and 8 bunches of positrons in circulation (circumference of 27 km). Each bunch contains $N_{e^-} = N_{e^+} = 1.7\times 10^{11}$ **particles. If the beams have the cross-sectional area of** $A = 4\times 10^{-3}\ \mathrm{mm}^2$

(a) calculate the velocity of the circulating electron if its energy is 45.6 GeV

$$\gamma = \frac{E_e}{m_e c^2} = \frac{45.6 GeV}{0.511\times 10^{-3} GeV} = 89236.8$$

$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} \to v = \frac{c}{\sqrt{1-\gamma^2}} = \frac{c}{\sqrt{1-1/(89236.8)^2}} \approx c = 3\times 10^8 m/s$$

(b) Calculate the frequency of the collision and the cross-over rate of the beams

$$\text{frequency}:\ f = \frac{v}{2\pi R} \approx \frac{c}{2\pi R} = \frac{3\times 10^8 m/s}{27\times 10^3 m} \approx 11\times 10^3\ \mathrm{Hz} = 11\ \mathrm{kHz}$$

$$\text{cross-over rate}(t):\ x = \frac{2\pi R}{n} = ct \to t = \frac{2\pi R}{nc} = \frac{1}{nf} = \frac{1}{8\times 11\times 10^3 s^{-1}} = 11\times 10^{-6} s = 11\mu s$$

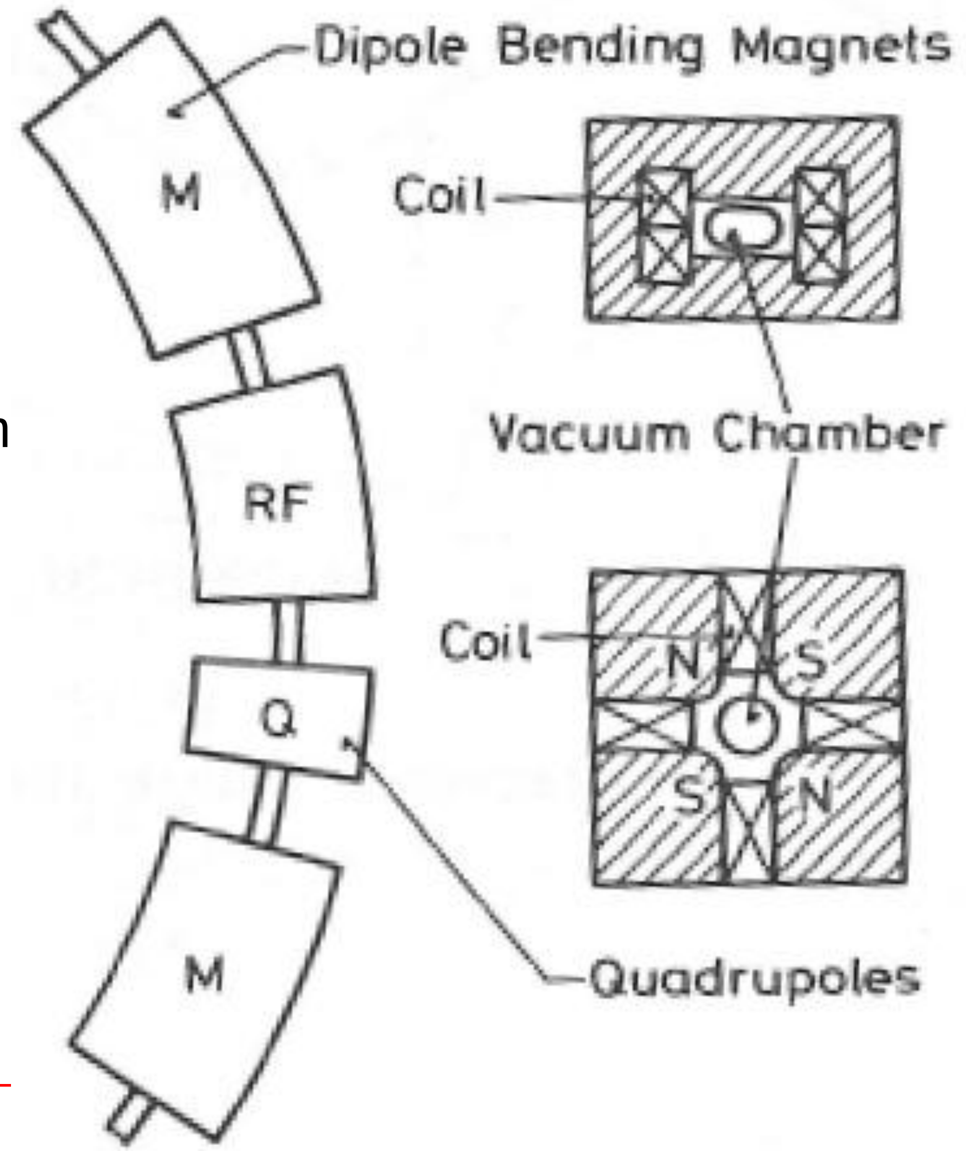
(c) Calculate the luminosity

$$L = fn\frac{N_{e^-}N_{e^+}}{A} = (11\times 10^3\ \mathrm{s}^{-1})(8)\frac{(1.7\times 10^{11})^2}{4\times 10^{-5}\ \mathrm{cm}^2} = 6.4\times 10^{31}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$$

(d) Calculate the production rate of the Z bosons if the cross section $\sigma = 30\ \mathrm{nb}$

$$R = L\sigma = (6.4\times 10^{31}/\mathrm{s}\cdot\mathrm{cm}^2)(30\times 10^{-9}\times 10^{-24}\ \mathrm{cm}^2) \approx 2/\mathrm{s}$$

- **In the big accelerators,**
  - particles are accelerated via **RF cavities,**
  - their directions are deflected by bending magnets known as **dipoles**
  - the **quadropols** are used to focus the beam, since the beam particles intent to spread out.



5. Tevatron and LHC

- **Tevatron** is a circular particle accelerator at the Fermi National Accelerator Laboratory in Batavia, USA.
- The Tevatron is a **synchrotron** that accelerates protons and antiprotons in a 6.28 km ring to energies of up to 1 TeV, hence the name.

- **Fermilab (Fermi National Accelerator Laboratory)**
  - E_{CM} = 1.96 TeV (Tevatron) proton-antiproton collider
  - Discover:
    1977: bottom quark
    1995: top quark

Fermilab Main Control Room

LEP (Large electron-positron Collider)

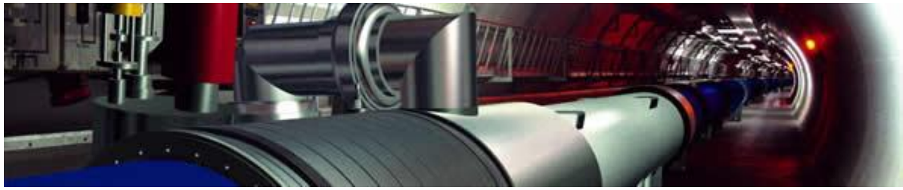
- LEP was one of the largest particle accelerators ever constructed.
- It was built at CERN.
- The results of the LEP experiments allowed precise values of many quantities of the Standard Model, such as W and Z bosons.

- **Some properties**
  - Circumference = 27 km
  - About ~100 m underground
  - 1989-1995: Z boson precision measurement at $E_{CM} = m_Z c^2 = 91.2$ GeV
  - 1995-2000: $W^{\pm}$ boson precision measurement at $E_{CM} = 2m_W c^2 = 160$ GeV

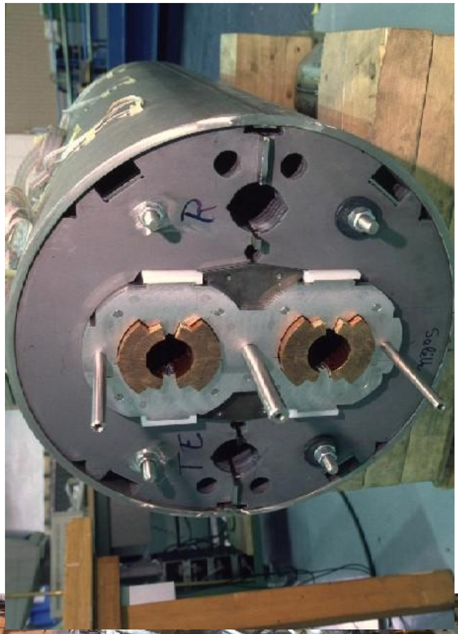
LHC: Large Hadron Collider

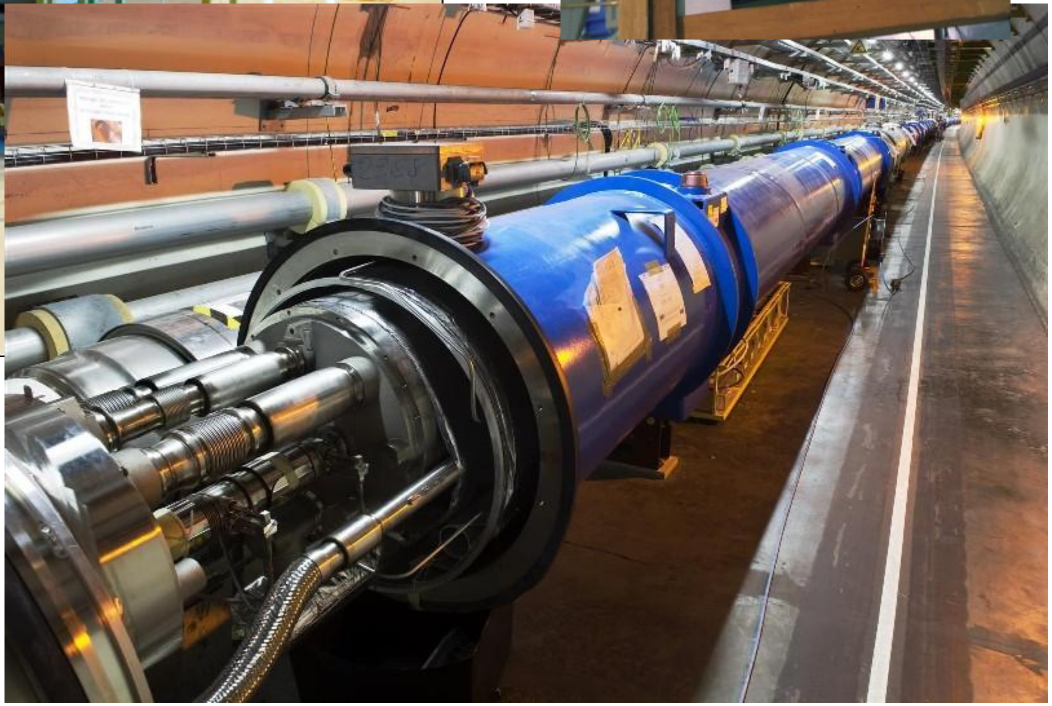
- **Large :** circumference = 27 km
  Hadron: accelerated particles
  - protons with Ecm = 14 TeV
  - Pb ions with Ecm = 1150 TeV (82 p ve 125 n)

- LHC project:
  - Idea: December 1994
  - LEP is converted to LHC
  - Started at September 2008
  - Cost: 3 billon €
  - Web: **lhc.web.cern.ch**

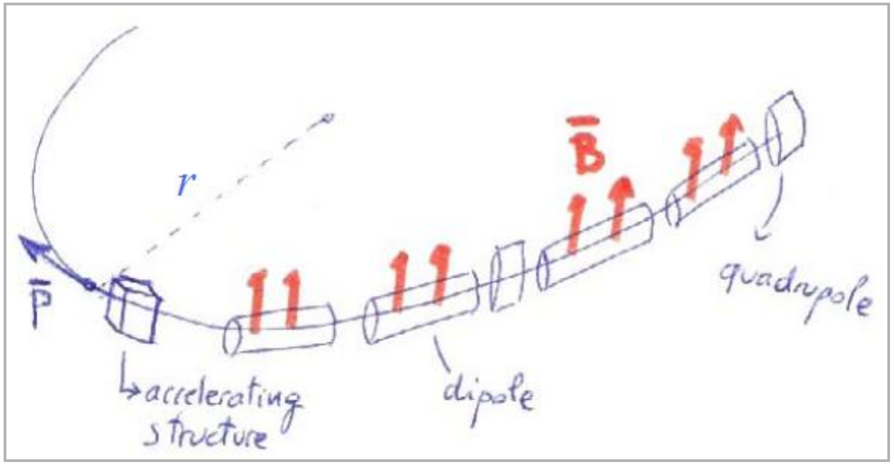



ALSTOM
JEUMONT INDUSTRIE





Why Large?



Centripedal Force: $F = mv^2 / r$

Lorentz Force: $F = evB$

Relativistic Dynamics:

$$p = \gamma m v \qquad \gamma = (1 - v^2/c^2)^{-1/2}$$

$$F = \frac{dp}{dt} = \gamma m \frac{dv}{dt} = \gamma m \frac{v^2}{r} = evB$$

Momentum: $p = eBr$

Total Energy: $E = \sqrt{p^2c^2 + m^2c^4}$

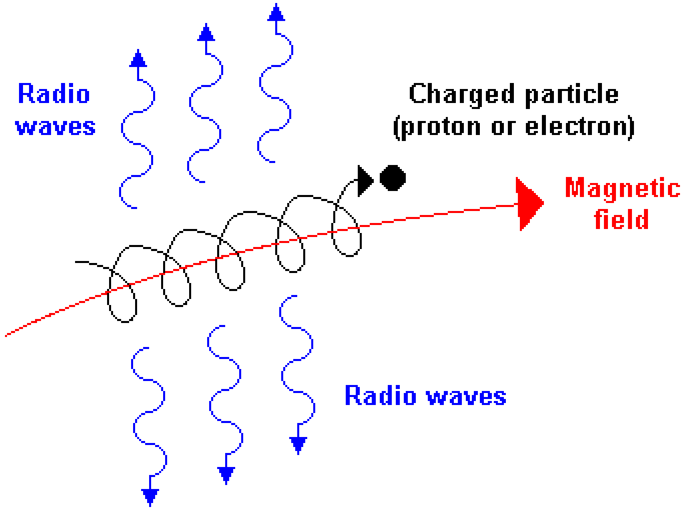
Ultra-relativistic limit: $E \approx pc = ecBr$

$$\boxed{E(\mathrm{GeV}) = 0.3Br}$$

Therefore, energy gained by the particle is proportional to radius of curvature

Why Large?

- *Synchrotron radiation* is the name given to the radiation which occurs when charged particles are accelerated in a curved path or orbit.
- Classically, any charged particle which moves in a curved path **or** is accelerated in a straight-line path will emit electromagnetic radiation.
- Particularly in the application to circular particle accelerators like synchrotrons, the radiation is referred to as **synchrotron radiation**.
- See also:
http://hyperphysics.phy-astr.gsu.edu/HBASE/Particles/synchrotron.html



Why Large?

- The large circumference is prefered to keep the synchrotron radiation to a practical level.
- The rate of energy loss being inversely proportional to the radius of curvature. Under the circular acceleration, an electron emits synchrotron radiation, the energy radiated (power lost) per particle per turn being

$$P = \frac{2ke^2\gamma^4 v^4}{3c^3 r^2}$$

- The loss of energy per orbit (turn) can be calculated from:

$$\Delta E = PT = P\left(\frac{2\pi r}{v}\right) = \frac{4\pi k e^2 \gamma^4 \beta^3}{3r}$$

Example 3:

The LEP electron synchrotron has a rated energy about *E* = 50 GeV and a radius of *r* = 4.3 km. Calculate the radiated power and energy loss per turn for the electrons.

$\gamma = E / m_e c^2 = 98000$ and v ~ c (beta~1)

$$P = \frac{2ke^2\gamma^4 v^4}{3c^3 r^2} = \frac{2(9\times10^9)(98000)^4(3\times10^8)^4}{3(3\times10^8)^3(4300)^2} = 2.3\times10^{-7}\ \text{W/electron}$$

$$\Delta E = (2.3\times10^{-7}\ \text{W})\left(\frac{2\pi(4300)}{3\times10^{-8}}\right) = 2.1\times10^{-12}\ \text{J} \approx 0.13\,\text{GeV}$$

Note that, for the proton with the same energy ($\gamma = E / m_p c^2 = 54$ and beta ~ 1)

$$P = 2.3\times10^{-7}/10^{13} = 2.3\times10^{-20}\,\text{W/proton}$$

$$\Delta E = 2.1\times10^{-25}\,\text{J} \approx 1.3\times10^{-6}\ \text{eV}$$

LHC Complex

Protons are taken from H_2

$E_p \approx 0$, t=0

↓

LINAC2

E_p = 50 MeV

↓

PSB:
Proton Synchroton
Booster

E_p = 1.4 GeV

↓

PS

E_p = 25 GeV

↓

SPS: Super PS

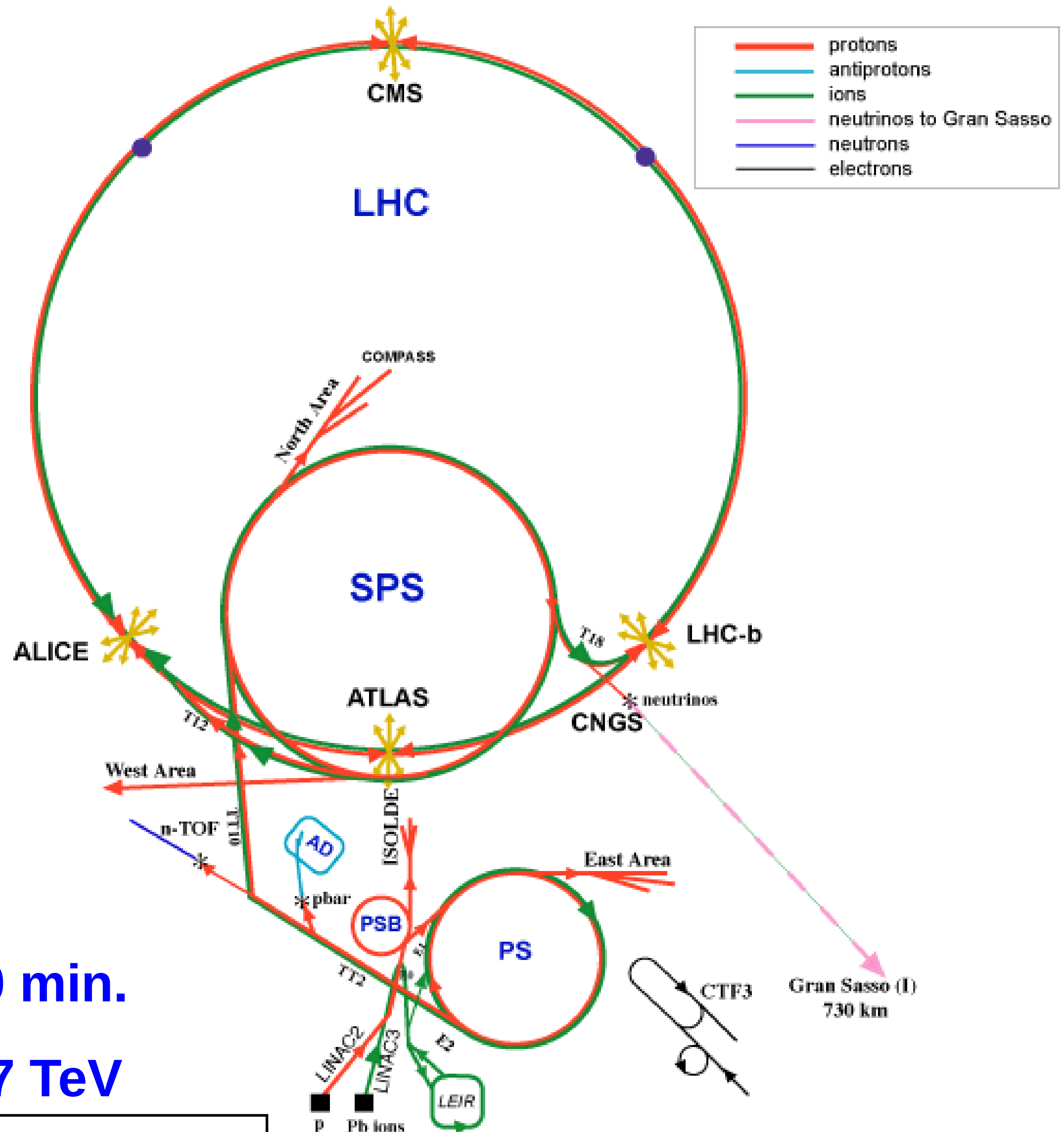
t = 20 min.

E_p = 450 GeV

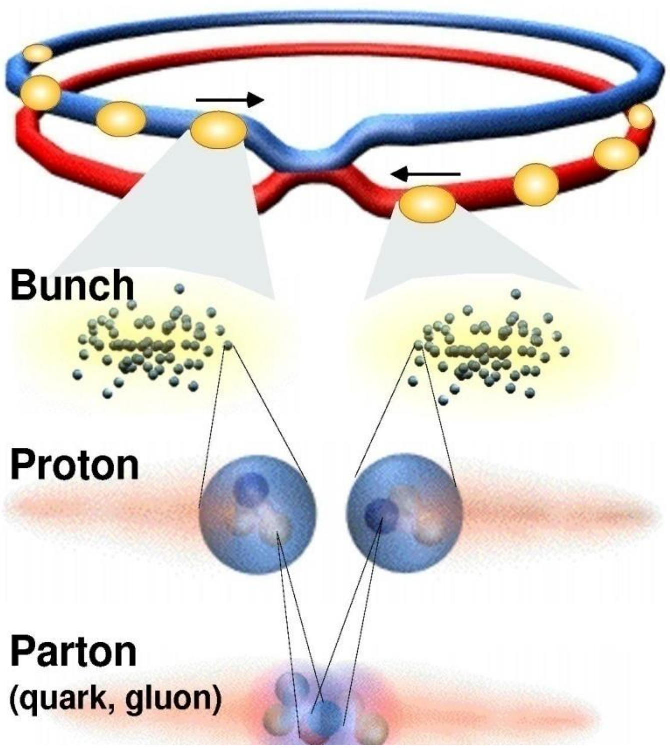
↓

E_p = 7 TeV

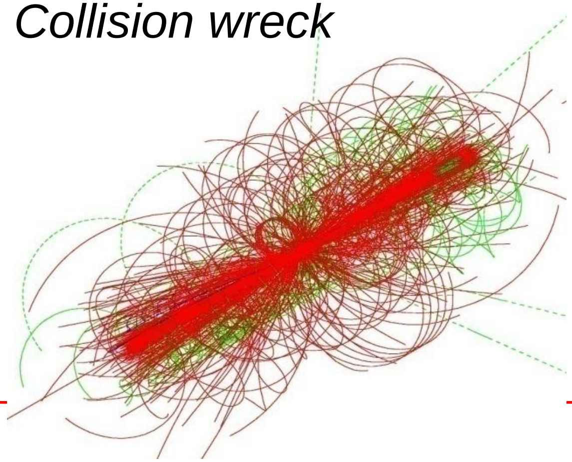
LHC → *Detectors*



About p-p collision at LHC



Collision wreck



- Maximum CM collision energy: E_{cm} = 14 TeV
- Total number of bunch: 2808 x 2808
- Bunch diameter: D = 16 μm (hair 50 μm)
- Number of particles per bunch: $N = 10^{11}$
- Luminosity: $L = 10^{34}$ cm^{-2}s^{-1}
- Distance between two bunches: d = 7.5 m
- Cross-over rate: t = 25 ns
- Collision frequency
  f = 1/25 ns = 40,000,000 Hz = 40 MHz
- Number of head on collision per bunch is 20

LHC News

- **23 November 2009**
  LHC circulated two beams simultaneously for the first time, allowing the operators to test the synchronization of the beams and giving the experiments their first chance to look for proton-proton collisions …

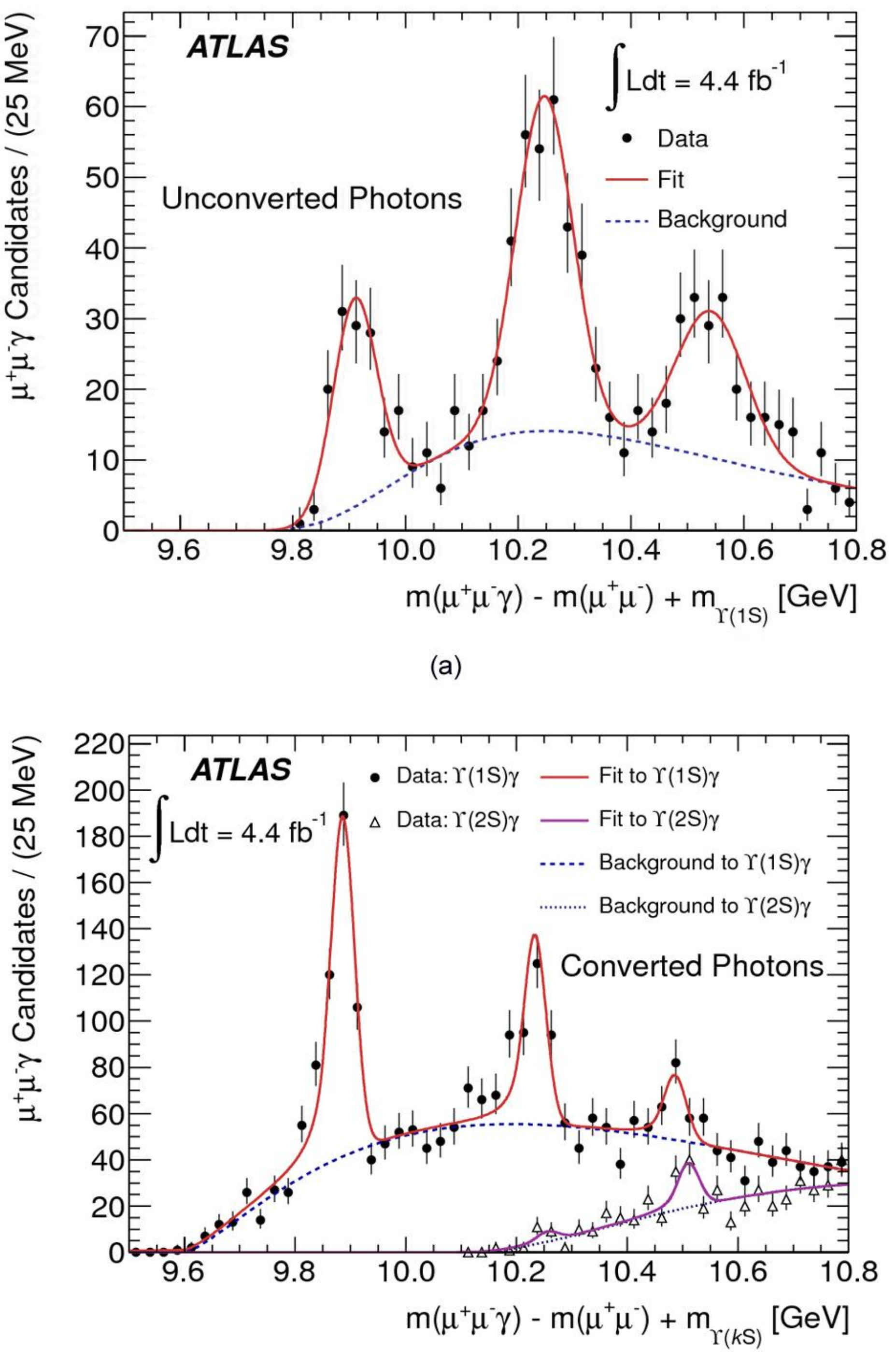
- See for more details:
  `http://lhc.web.cern.ch/lhc/`

  `http://lhc.web.cern.ch/lhc/News.htm`

LHC Discoveries

Discovery of the X_b?
December 2011

The *ATLAS* collaboration has announced the discovery of the X_b(3P), which is a bound state of a bottom quark and bottom antiquark (b b-bar).



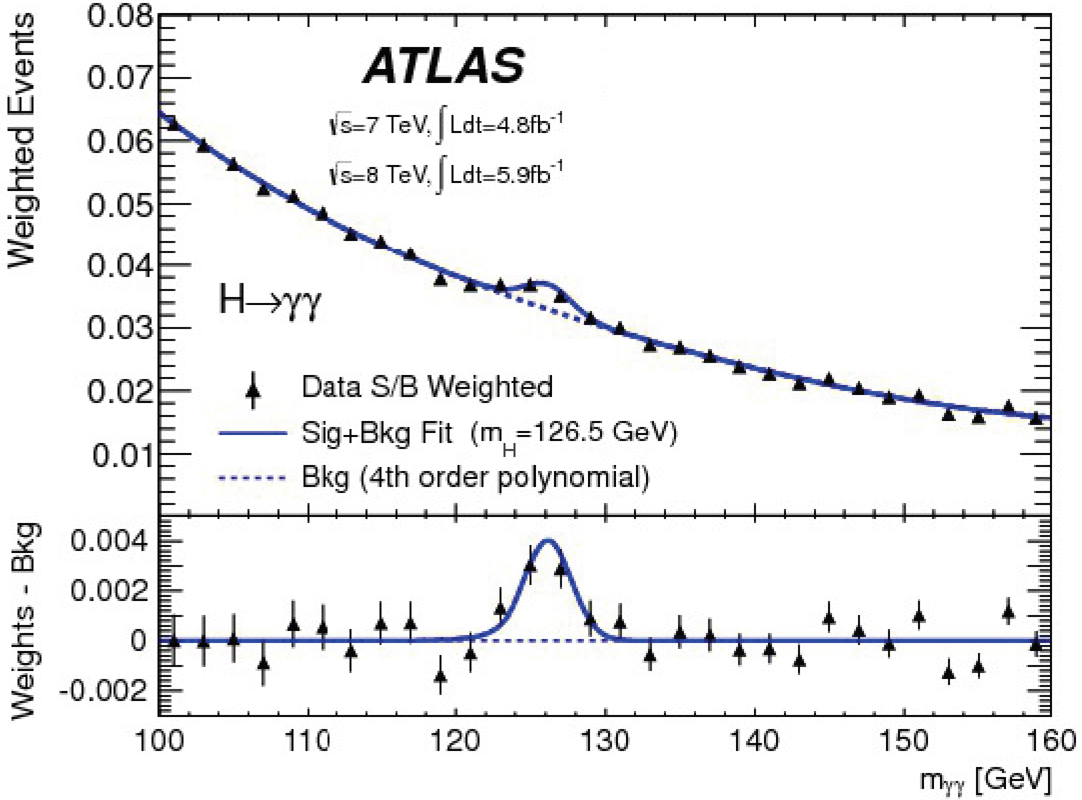
LHC Discoveries

Discovery of the Higgs Boson?

July 2012

ATLAS data

($H \to \gamma\gamma$)



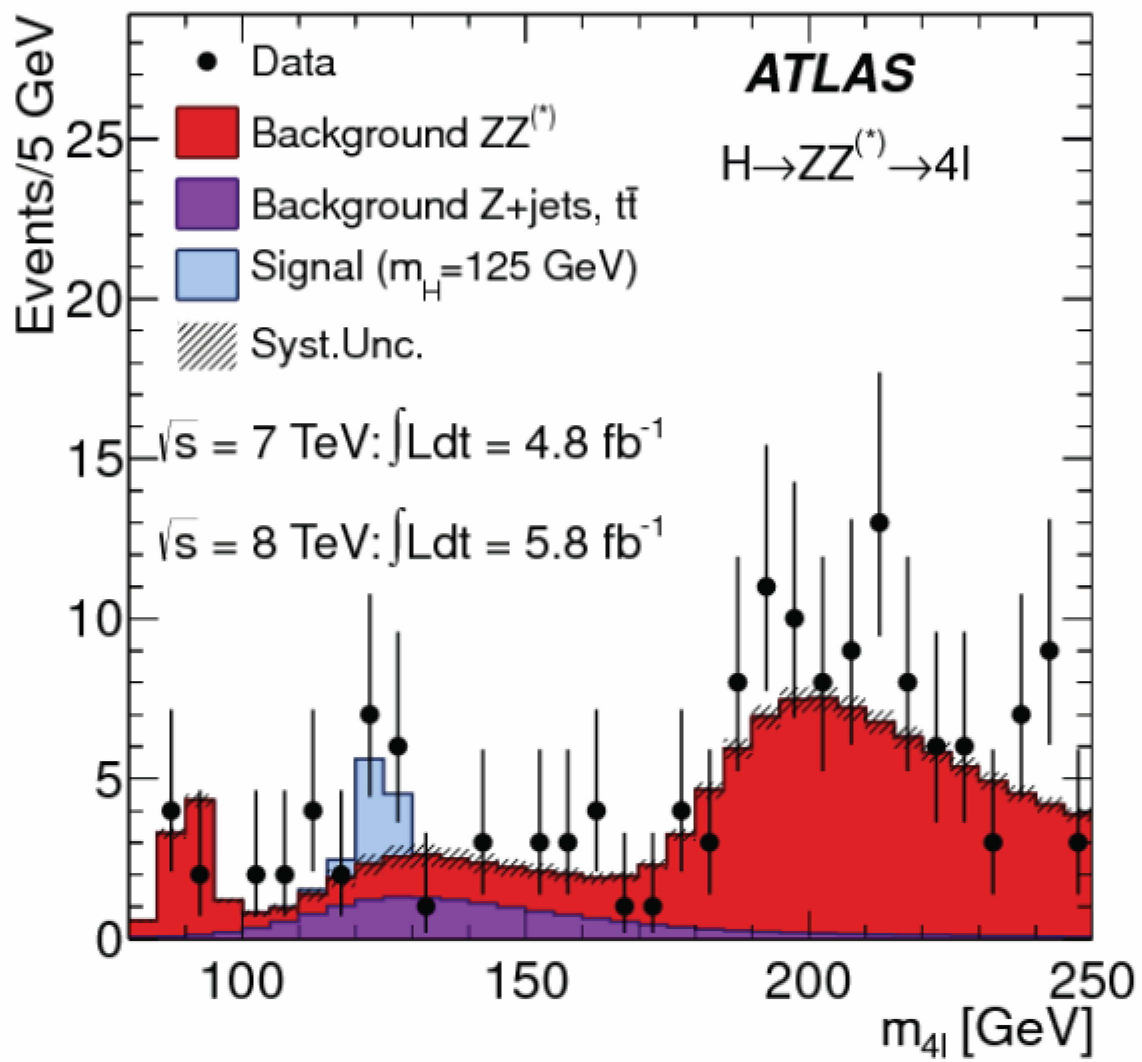
LHC Discoveries

Discovery of the Higgs Boson?

July 2012

ATLAS data

($H \rightarrow$ 4 leptons)



7. The Future Accelerators

- **The Compact Linear Collider (CLIC)**
  is a proposed linear particle accelerator under design at CERN. It would be built after the LHC. It will be 40 km long and will allow electrons to gain energy of 3 TeV.

- **The International Linear Collider (ILC)**
  is a proposed linear particle accelerator. It is planned to have a collision energy of 500 GeV initially, and, could be completed in the late 2010s. The ILC would collide electrons with positrons. It will be between 30 km and 50 km.

Exercises

1. Explain the operating principle of the van de Graaff accelerator.
2. Explain the operating principle of linacs.
3. What is the importance of the beam focusing?
4. Explain the importance of the radius of curvature of a accelerator? Why it must be large?

5. (a) Find the non-relativistic and relativistic kinetic energy, momentum, velocity of an electron accelerated by means of the potential difference V = 100 kV. (b) Repeat your calculation for a proton.

6. A cyclotron accelerates protons to 10 MeV with a maximum orbital radius of 40 cm. (a) Find the velocity of the protons (b) Find the strength of the required magnetic field B (c) What must be frequency of the RF supply? (d) If the amplitude of the accelerating voltage is 50 kV, how many orbits are required to reach full energy?

7. (a) Show that the energy gained by the ultrarelativistic particle of charge *e* in a circular orbit of radius *r* in a magnetic field B is given by $E(\mathrm{GeV}) = 0.3Br$ (b) Estimate the required magnetic field for the electrons in the LEP (E = 45.6 GeV).

8. Protons are injected into a linear accelerator so that they have *K* = 20 keV as they coast through the first drift tube. The frequency of the ac voltage supply is 50 MHz and the peak potential difference across each gap is 200 kV. Consider the proton that passes from the first to the second tube properly synchronized at the peak potential drop. (a) How long must the second tube to be if the proton is to arrive at the next gap in proper synchronization with the accelerating voltage? (b) How long must the tenth to be?

9. In the Tevatron, protons are injected from a ring that uses a conventional magnets into final, superconducting ring with about 150 GeV. Then they gain roughly 1 MeV per orbit as the move around the final ring. (a) How many orbits does a proton have to make to gain the full energy of 1 TeV? (b) Given that the ring has radius 1 km, how far does the proton travel inside the ring and how long does this final acceleration take?

10. At the Tevatron, protons and and antiprotons, ortiting in opposite directions around a circle of radius of 1 km, are used for the collision at the E_{CM} = 1.96 TeV. Calculate the radiated power and energy loss per turn for the antiprotons.

11. For the Tevatron operation, given that

$N_{protons} = 2\text{x}10^{11}$, $N_{antiprotons} = 4\text{x}10^{10}$ and n = 36 bunches

$f = 36 \text{ x } (3\text{x}10^{5}\ \text{km/s})/6 \text{ km} = 18 \text{ x } 10^{5}$ Hz

$A = \pi\ (60\ \mu\text{m})^{2}$

Calculate (a) luminosity and (b) the number of collisions per second (i.e. the rate) of protons and antiprotons if the proton/antiproton cross-section is 60 mb.