Linac & collider

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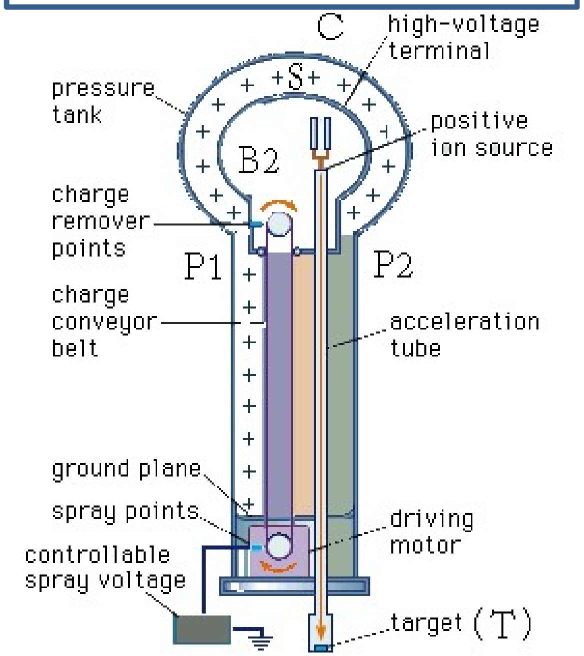
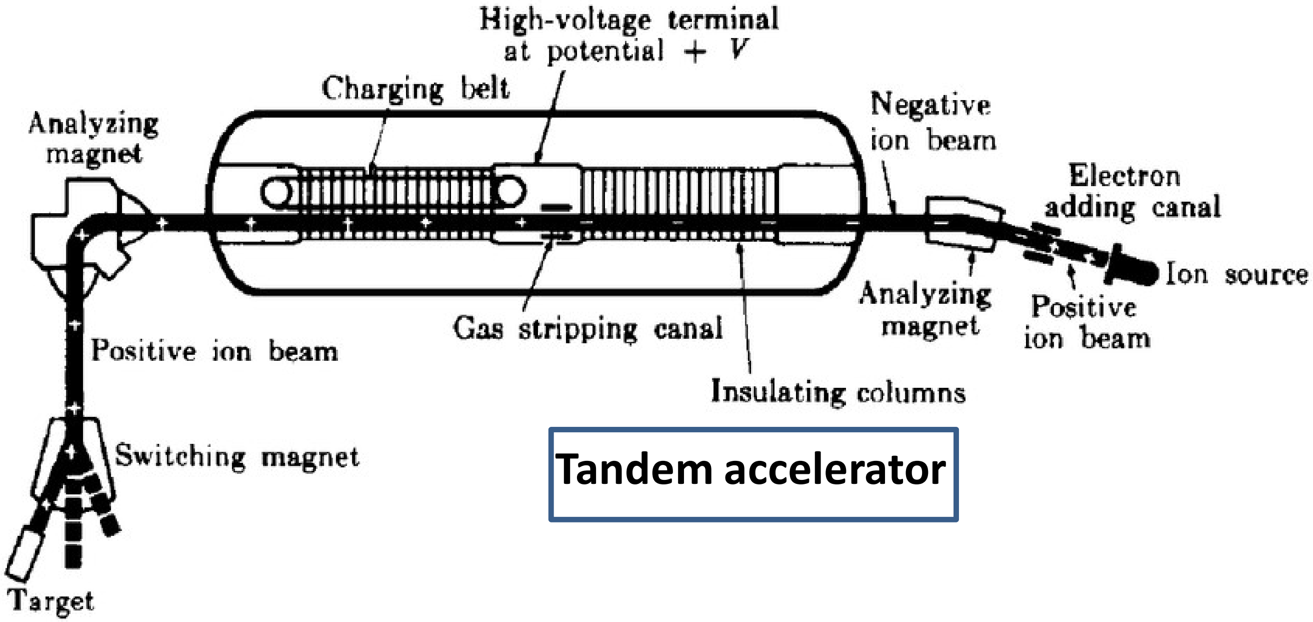
DC accelerators

Van de Graaf at Princeton and then MIT developed the static voltage generator named after him beginning in 1929. This was done by transferring charge from one electrode to another on a silk belt running between two pulleys.

The highest energy van de Graaff accelerator can achieve a potential of about 30–40MeV for singly-charged ions and greater if more than one electron is removed by the stripper

Van de Graaff accelerator



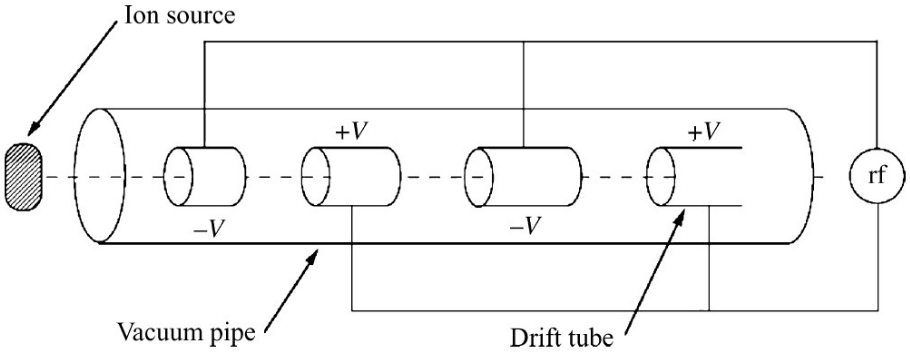


Tandem accelerator

AC accelerators

- Accelerators using radio frequency (r.f.) electric fields

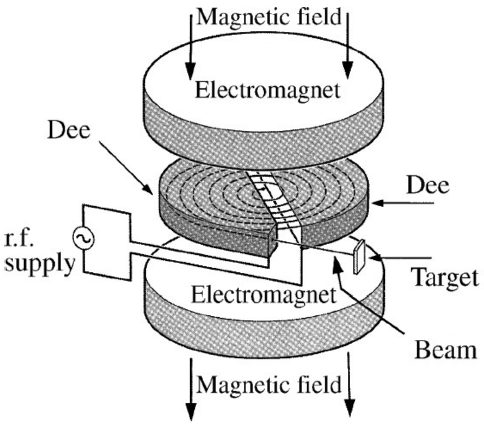
- Linear accelerator



- 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, as shown in Figure

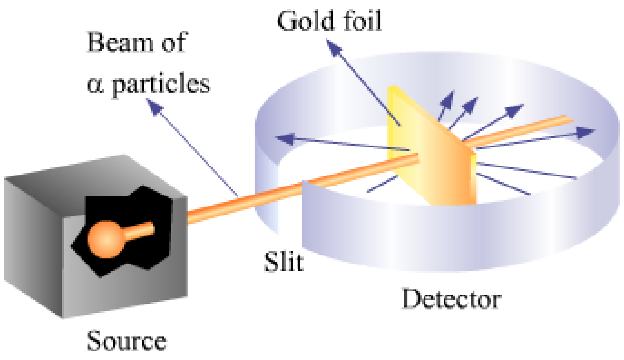
- Cyclic accelerator

cyclotron



Fixed-target experiments

- In a fixed-target experiment the target is stationary in the laboratory. Nuclear physics experiments are almost of this type



- Relatively easy to manage: Shoot a beam at a target

- In the laboratory frame at least some of the final-state particles must be in motion to conserve momentum. Consequently, at least some of the initial beam energy must reappear as kinetic energy of the final-state particles.

- The centre-of-mass energy is important because it is a measure of the energy available, to excited nuclei or to create new particles.

Beam

Target , fixed

E_{Beam} , P_{Beam} , m_b

Rest , m_T

$m_b \equiv m_T \equiv m$
$E_{LAB} \equiv E_{Beam} + m_T c^2$
$PLAB \equiv P_{Beam} + 0$

Let us construct the quantity (s), the square of the total incoming energy in the centre of mass frame, therefore, $\sqrt{s}$ referred to as the CM energy

$$s = \left(\sum_{i=1,2} E_i\right)^2 - \left(\sum_{i=1,2} \mathrm{p}_i\right)^2 c^2$$

Fixed-target experiment frame in which the target particle is at rest, its energy is mc^2 and its momentum is zero, whereas the projectile has energy E_{LAB} and momentum P_{LAB} so that we have

$$s = (E_{LAB} + mc^2)^2 - \mathrm{p}_{LAB}^2 c^2 = E_{LAB}^2 + m^2c^4 + 2mc^2 E_{LAB} - \mathrm{p}_{LAB}^2 c^2$$

in the last step we can use the relativity relation

$$E_{LAB}^2 - \mathrm{p}_{LAB}^2 c^2 = m^2 c^4$$

$$\boxed{S = 2m^2c^4 + 2mc^2E_{Lab}}$$

$$\sqrt{s} = \sqrt{2m^2c^4 + 2mc^2 E_{LAB}}$$

Dealing with relativistic particles, $E_{Beam} \gg mc^2$

Fixed-target collision We have CM energy as

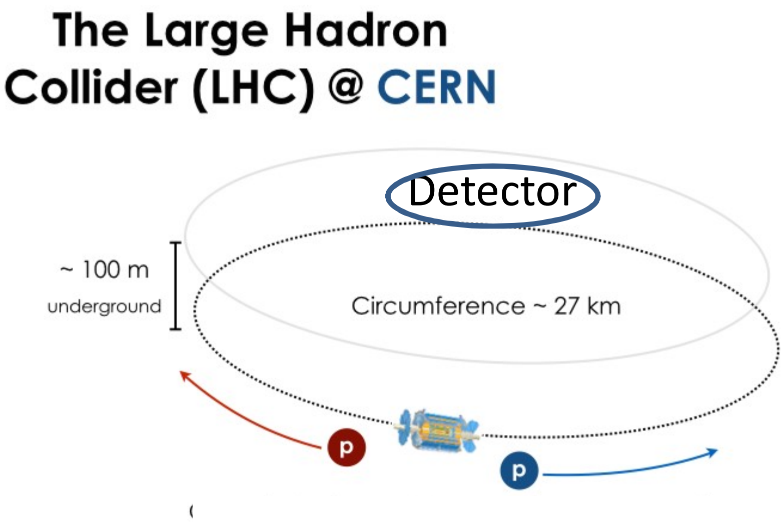
$$\boxed{E_{CM} \propto \sqrt{E_{Lab}} \simeq \sqrt{E_{Beam}}}$$

Collider

- In particle physics, high energies are required to produce new Particles.

- In the centre-of-mass frame (collider) the total momentum is zero and, in principle, all the energy is available for excitation /or particle production.

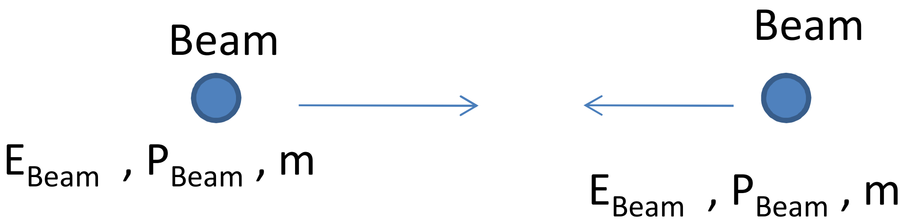
- A high centre-of-mass energy in fixed-target experiment is not possible that required very high beam energy which is not possible from the available accelerator. This is a disadvantage of fixed-target experiments.



- For use a slightly asymmetric collider (such as LHCb).

- Fully symmetric collider (like ATLAS)

- Depends primarily on your intention and what you're interested in.



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$$s = \left(\sum_{i=1,2} E_i\right)^2 - \left(\sum_{i=1,2} \mathbf{p}_i\right)^2 c^2$$

- In collider frame, where the momenta are equal and opposite the second term vanishes and we have

$$\boxed{S = (2E_{Beam})^2}$$

$$\sqrt{s} = 2E_{Beam}$$

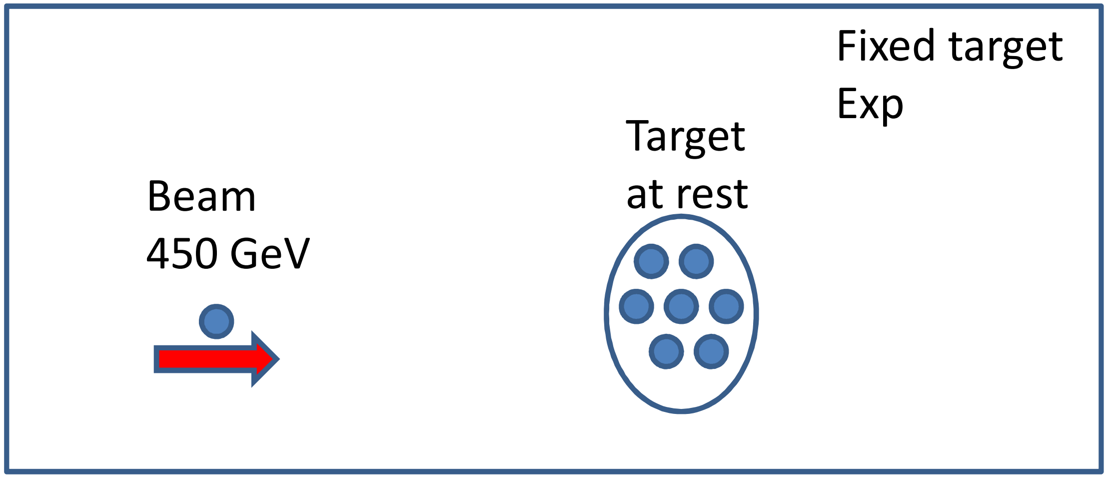
- In Collider collision We have CM energy as $E_{CM} = 2E_{Beam}$

fixed target collisions we have $E_{CM} \propto \sqrt{E_{beam}}$

colliding beams we have $E_{CM} \propto E_{beam}$

Example

Protons beam



Fixed target
Exp

Target
at rest

Beam
450 GeV

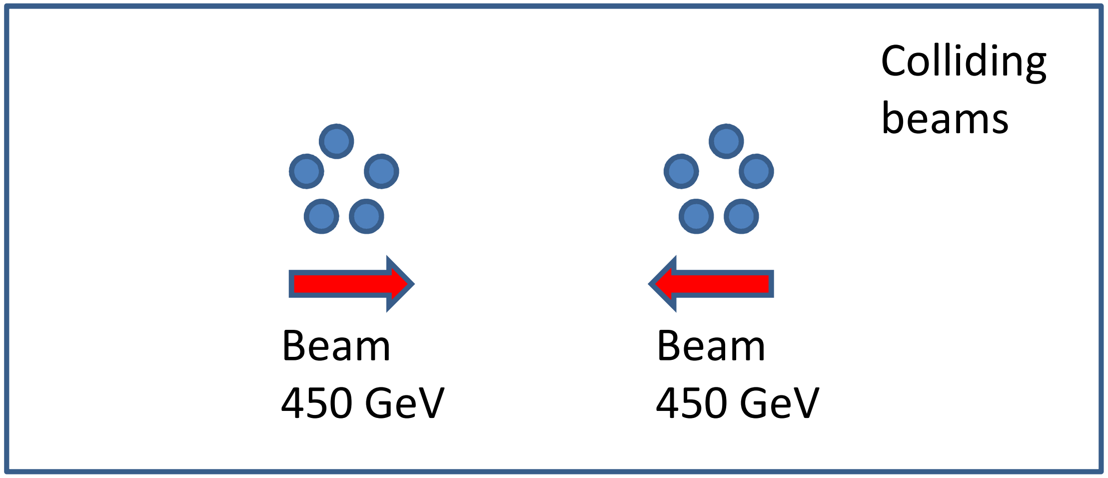
Rough estimate

$E_{Beam} >> m_p c^2$

$$E_{CM} = \sqrt{2 m_p c^2 E_{Beam}}$$

$$= \sqrt{(2 \times 0.938 \times 450)}$$

$$= 29.05 \text{ GeV}$$



Colliding
beams

Beam
450 GeV

Beam
450 GeV

$$E_{CM} = 2E_{Beam}$$

$$= 450+450$$

$$= 900 \text{ GeV}$$

1. If a 1000 GeV proton hits a resting proton, what is the free energy to produce mass?

Ans: The free energy to produce mass in fixed target exp is equivalent to the E_{CM}

$E_{Beam} = 1000$ GeV

E_{CM} have to measure

Here $E_{Beam} >> m_p c^2$

$$E_{CM} \cong \sqrt{2 m_p c^2 E_{Beam}}$$

$$= \sqrt{(2 \times 0.938 \times 1000)}$$

$$\boxed{\sim 43.3 \text{ GeV}}$$

2. In the colliding-beam storage ring, protons at energy of 50 GeV collide head-on. What energy must a single proton have to give the same center-of-mass energy when colliding with a stationary proton?

Ans.

Proton energy beam, $E_{Beam} = 50$ GeV

Center mass energy in head on collision $E_{CM} = 2E_{Beam}$

$E_{CM} = 100$ GeV

Beam energy required in fixed target exp. to achieve 100 GeV as E_{CM}

$$E_{Beam} >> m_p c^2$$

$$E_{CM} \cong \sqrt{2 m_p c^2 E_{Beam}}$$

$$E_{Beam} \cong (E_{CM})^2 / m_p c^2 = (100 \times 100) / (2 \times 0.938)$$

$\boxed{5.33 \times 10^3 \text{ GeV}}$ Required beam energy

The available centre-of-mass energy to create new particles is not only sufficient but other conservation parameters are required

Conservation Laws

- Energy and Momentum, Angular Momentum conserved in all interactions
- Charge conservation
  Well established
- Lepton and Baryon number
- Quark Flavours, Isospin,
- Parity
  Conserved in strong and electromagnetic processes Violated in weak interactions

Some steps in high energy experiments

Collisions

The production of very massive particles is a rare event and happens typically less than once per billion collisions. Therefore, the LHC was designed to produce more than 1 billion collisions per second. The total number of collisions is often expressed in units of “inverse femtobarns” (1 fb^{-1} represents ~ 80,000 billion collisions).

Detection

A collision creates thousands of particles that pass through a detector, which surrounds the collision point. Detectors are like huge 3-dimensional digital cameras consisting of about 100 million sensors, which are organised in several layers and contribute information about the position or the energy of a particle. Charged particles traversing a sensor in a “tracker” produce a small electrical signal, which is then amplified and recorded together with the position of the sensor. A strong magnetic field bends the trajectories of charged particles, allowing their ‘momentum’ (the product of mass and velocity) to be measured. The energy of neutral and charged particles is measured in calorimeters, which are arranged in several layers outside the tracker.

Event selection

Interesting events from millions of collisions, typically 1000 “raw” events per second (equivalent to about 1 GB) are then transferred to the CERN data centre and written to mass storage, resulting in a data volume of several 10,000 TB per year per detector.

Reconstruction

Each “raw” event contains all the information recorded in the different detector layers. In the event reconstruction, these raw data are transformed into physical quantities. Charged particle tracks are identified and their parameters (direction, curvature) are determined; energy deposits in the calorimeters are summed up; the information from the different layers is combined to reconstruct physics objects. By adding the energy of all measured particles together and comparing it with the collision energy, the ‘missing energy’ of a particle that has escaped detection (e.g. a neutrino) can be inferred.

Calibration

The measurement of the position and energy of detector layers must be precisely calibrated before their output can be interpreted as physics signals. The energy scales of the calorimeters are calibrated by using the decay products of well-known particles. The calibration data are used in the reconstruction programmes to transform the measured signals into physical quantities.

Data analysis and search

The physics analysis starts with the event summary data, which contains complete information about the reconstructed event. The analysis programmes consist of a set of selection criteria, and their goal is to search for specific patterns among the detected particles by calculating a set of derived physical quantities for each event.

Comparison with simulated data

It is important to understand the differences between simulated and experimental data when looking for signs of new particles. For each analysis, the number of simulated events must be comparable with (or even larger than) the number of analysed events, to ensure that statistical fluctuations are not dominated by uncertainties in the background distributions.

Statistics

Before the discovery of a new particle can be claimed, scientists must make sure that the excess of events on top of the background distribution has a sufficiently high statistical significance.

Discovery

- If a new particle is discovered, many other questions arise.
- What are the properties of the particle, such as its mass, lifetime, spin charge?
- Is the particle produced alone or in association with another particle?
- Which theoretical model fits the observations best?
- All this analysis work will eventually lead to greater knowledge, new models, new predictions – and new experiments.

Assignment

1. Write the advantage and disadvantage of fixed target experiments and collider experiments.
2. Discuss the symmetric and anti-symmetric mass colliders.
3. Assume we accelerate protons and make them collide with protons at rest. What should be the energy of the proton beam to produce the same centre of mass energy as is achieved in collisions at the LHC collider, dealing with relativistic case.
4. What is beam current in colliders?
5. What is the role of magnetic field in measuring the particle?
6. Discuss the Lepton colliders and the hadron colliders.