Particle Accelerators

Introduction

Particle accelerators are a vital tool for research into matter at the atomic and nuclear scale. They are designed to generate beams of charged particles and anti-particles, which are accelerated to high energies before colliding with each other or with a target to release energy, to free particles from the nuclei of atoms or to create new particles.

At ISIS a particle accelerator is used to produce a high intensity beam of protons that is collided with a target to produce neutrons.

The ISIS Cockcroft-Walton Machine

Elsewhere particle accelerators are commonly used for accelerating electrons to produce X-rays and also for accelerating deuterons, alpha particles and heavy ions.

There are three main types of particle accelerator. These are:

- the linear accelerator (linac)
- the ring or circular accelerator (cyclotron)
- the circular synchrotron

History

Experiments such as Rutherford's scattering experiment of 1911 had to rely on the use of naturally occurring energetic particles to probe the structure of matter. The limits this placed on scientific investigation led to efforts to generate a greater supply of more energetic particles than those available from natural radioactive sources.

Early successes included the van de Graaff accelerator, which produces high voltages using a continuously recharged moving belt to deliver charge to a high-voltage terminal consisting of a hollow metal sphere; and the Cockcroft–Walton accelerator which achieves high voltages by charging a bank of capacitors in parallel and then connecting them in series.

Both types of accelerator are still in use today, most commonly for the injection of particles into larger, more powerful accelerators.

Linear Accelerators

The linac accelerates charged particles in a straight line by generating a high frequency alternating electric field along the common axis of a series of hollow ‘drift’ tubes.

During the first half of each alternating field cycle, the particles in the gaps between the drift tubes experience an accelerating field since they are repelled by the similarly charged tube they are leaving, and are attracted by the oppositely charged one they are approaching.

During the second half of the cycle, when the field is in the opposite direction and would decelerate them, the particles travel (or drift) through the centre of the tubes and are shielded from its effect. In this way the particles only ever experience accelerating electric fields.

As the particles travel down the linac, the drift tubes increase in length to directly compensate for the increase in speed as they must spend the same length of time drifting through each tube.

The main advantage of linear accelerators is that the particles are able to reach very high energies without the need for extremely high voltages.

The main disadvantage is that, because the particles travel in a straight line, each accelerating segment is used only once. This means that the only way of achieving particle beams with even higher energy is to undertake the expense of adding segments to the length of the linac.

At ISIS, a 50 metre linear accelerator is used to accelerate H– ions with an initial energy of 665 keV to an energy of 70 MeV.

Cyclotrons

The cyclotron can achieve higher energies (about a hundred MeV), in a smaller space than is possible with a linac by accelerating the particles in circular paths.

A source of charged particles is placed at the centre of two semi circular ‘D’ shaped electrodes called dees that have a gap between them. Above and below these are the poles of a powerful electromagnet.

A voltage applied to the dees creates an electric field that accelerates the particles as they cross the gap between them. In the dees, the particles follow a semi-circular path (because of the magnetic field) bending through 180° to emerge once again at the gap between them. The voltage between the dees is alternated in synchronisation with the particles motion so that as the particles reach the gap the electric field has reversed and can accelerate the particle once more.

As the particles become more energetic it becomes harder to bend them so as they are accelerated the diameter of their circular path in the dees becomes larger.

The particles therefore follow a spiral path from the source to emerge from a hole in one of the dees at high energies.

The maximum energy attainable depends on how many times the particles can cross the gap before leaving the cyclotron. This in turn depends on how tightly the particles can be bent in the dees which is governed by the strength of the magnetic field.

For protons, with a ordinary cyclotron, this would be about 10 million electron volts (10MeV).

Synchrotrons

The development of the synchrotron resulted from the need for energies at about the GeV range.

Particles are first injected from another accelerator into the synchrotron, which is essentially a doughnut shaped vacuum tank surrounded by a ring of magnets. Unlike the cyclotron a single large diameter magnet is not required, making it possible to build synchrotrons with diameters measured in tens or hundreds of metres.

At ISIS the 70MeV H– ions produced in the linac are converted to protons, and accelerated to 800MeV in a 52 m diameter synchrotron.

As with the cyclotron, the synchrotron employs magnetic fields to send the beams of charged particles in a circular path and electric fields to accelerate their speed. With the synchrotron, however, the magnetic field rises in step with the velocity of the particles. This keeps them moving in a circle of nearly constant radius, rather than the widening spiral experienced in the cyclotron.

The frequency of the electric field changes to match the increasing speed of the particles. However, at high energies the particles move so close to the speed of light that they make a circuit in constant time. Instead of increasing speed, they simply gain more momentum via an increase in mass.