

Particle Accelerators

Uses: Hadron Therapy

- Ionising particles such as protons are fired into the body. They are aimed at cancerous tissue.
- Most methods like this irradiate the surrounding tissue too, but protons release most of their energy at the end of their travel. (see graphs)
- This allows the cancer cells to be targeted more precisely, with less damage to surrounding tissue.

Graphs:

- Dose vs Depth:** Shows Dose (y-axis, 0-10000) vs Depth (x-axis, 0-15 cm). Curves for X-rays (20 MeV), X-rays (4 MeV), Electrons (4 MeV), and Protons (150 MeV) are shown. The proton curve shows a sharp peak at approximately 13 cm depth.
- Graph of Systems Built:** Shows the number of systems built for various applications. Ion Implantation: 10280, E-Beam Material Processing: 7000, Electron Beam Irradiation: 2800, Nondestructive Inspection: 1500, Neutron Generators: 1500, Radioisotope Production: 1500, Ion Beam Analysis: 250, Synchrotron Radiation: 70.

Uses Overview

Systems Built

Application	Count
Ion Implantation	10280
E-Beam Material Processing	7000
Electron Beam Irradiation	2800
Nondestructive Inspection	1500
Neutron Generators	1500
Radioisotope Production	1500
Ion Beam Analysis	250
Synchrotron Radiation	70

Uses: Mass Spectrometry

- This is a technique in analytical chemistry.
- It allows the identification of chemicals by ionising them and measuring the mass to charge ratio of each ion type against relative abundance.
- It also allows the relative atomic mass of different elements to be measured by comparing the relative abundance of the ions of different isotopes of the element.
- An example mass spectrum is shown below:

Mass Spectrum:

Mass Spectrum showing Relative Abundance (%) vs m/z. Peaks are labeled at 121, 149, 179, and 207.

Diagram of a mass spectrometer. An ion beam enters a region with a 70-V cathode. It passes through a region with a negatively charged plate and then a region with a magnet. The path is deflected by the magnet, and ions are detected by a detector. Labels include: Negatively charged plate, 70-V cathode, Ion beam, Magnet, Ion detector, Sample M+, Anode, and Beam.

Electrostatic Particle Accelerators

- An **electrostatic voltage** is provided at one end of a vacuum tube.
- This is like the charge on a magnet.
- At the other end of the tube, there are **particles** with the opposite charge.
- Like north and south poles on a magnet, the opposite charges attract and the particle is pulled towards the voltage.
- The **electrostatic attraction** creates a **force** which causes the particle to **accelerate** towards the other end of the tube.
- In this way the particle accelerator causes particles to accelerate!

Diagram showing a particle (negative charge) moving from a region with a positive voltage to a region with a negative voltage. Arrows indicate the particle feels an electrostatic attraction and accelerates forward. A second diagram shows particles moving in a circular path around a central positive charge, with arrows indicating they are pulled towards the center.

Linear Particle Accelerators

- These are still in a straight line, but now the voltage is no longer static - it is **oscillating**.
- This means the voltage is changing - so if it were a magnet, it would be first positive, then negative.
- Like the electrostatic accelerator, a charged particle is attracted to it as the charges are opposite, but just as the particle goes past the voltage changes, and the charge of the plate swaps (so it is now the same charge as the particle).
- Again like magnets - the same charges **repel** (eg north repels north).
- This means the particle receives a force away from the voltage too, so at first it is accelerating towards the voltage, then as it goes past it continues to accelerate away!
- This allows the particle to be accelerated for longer - so it can get to higher speeds.
- There may be many such voltages in a row, with each causing more acceleration, making linacs much more powerful than electrostatic accelerators.

Diagram showing a particle moving through a series of alternating electric fields. Stage 1: Positive voltage, particle moves forward. Stage 2: Negative voltage, particle moves away from the field. This pattern repeats, allowing the particle to continue accelerating.

The Cyclotron

- This was the first type of **circular particle accelerator**.
- The particles move around in a **spiral shaped path**. The **force** which keeps them moving this way is provided by a **static magnetic field**. This is the **Centripetal Force** (a force that causes circular motion).
- As they **orbit** (move around the centre) they pass through an **alternating electric field** which speeds them up in the same way as in the **linac**.
- But as the particles are moving circularly, they can pass through the same field many times, and thus can be accelerated more, by fewer magnets than a linac (there are normally two - called "dees").
- As the magnetic field does not change (it's **static**) the particles have to take the same time to complete one orbit (see the maths below). As they are speeding up, this means they have to travel further each time, and so move out in a **spiral trajectory**.
- The circular motion and fewer required magnets mean that cyclotrons are much smaller, more cost effective, and more powerful than linacs.

Diagram of a cyclotron showing particles moving in a spiral path. The magnetic field is provided by a static magnet. The electric field is provided by two "dees" (semicircular electrodes) that are connected to an alternating voltage source. The particles are shown moving from the center outwards, passing through the electric field region and being deflected by the magnetic field.

The Synchrotron

- The problem with cyclotrons is Einstein's relativity. As a particle speeds up, its mass increases. This limits the energy of the particles in a cyclotron. The equation for this is:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where
 m = relativistic mass
 m_0 = rest mass
 v = velocity
 c = speed of light in a vacuum $\approx 3 \times 10^8 \text{ ms}^{-1}$

- To get around this, the strength of the magnetic field that keeps the particles in a circle can be varied. As the particles go faster, the magnetic field strength (B) can be changed, so even as they change in mass the accelerator can work. This is a synchrotron.
- The magnetic field can be adjusted so precisely, that the particles no longer spiral, but instead are held within a large thin torus (ring doughnut shape).
- This allows much larger, cheaper and more powerful accelerators (such as the LHC at CERN) as you only need the edge of a circle, you don't need to clear the inside (like you would for a cyclotron - where the particles spiral from the centre).
- However the synchrotron is a closed circle so there is nowhere for a particle emitter, therefore the synchrotron cannot accelerate particles from rest, and instead needs a linac or cyclotron to fire particles into it.
- These are the most complex, but the largest and most powerful particle accelerators there are.

Diagram of a synchrotron showing particles moving in a circular path. The magnetic field is provided by a large electromagnet (M). The particles pass through an accelerating cavity (radio frequency quadrupole) to gain energy. The magnetic field strength increases as the particles move faster. The diagram shows the particle path, the magnetic field, and the accelerating cavity.

How a Synchrotron Works

4. **Storage Ring:** The booster ring feeds electrons into the storage ring, a many-sided donut-shaped tube. The tube is maintained under vacuum, as free as possible of air or other stray atoms that could deflect the electron beam. Computer controlled magnets keep the beam absolutely true. Synchrotron light is produced when the bending magnets deflect the electron beam; each set of bending magnets is connected to an experiment station or beamline. Machines filter, intensify, or otherwise manipulate the light at each beamline to get the right characteristics for experiments.

5. **Focusing the Beam:** Keeping the electron beam absolutely true is vital when a material you're studying is measured in billions of a metre. This precise control is accomplished with computer-controlled quadrupole and sextupole (six pole) magnets. Small adjustments with these magnets act to focus the electron beam.

3. **An Energy Boost:** The linear accelerator uses magnetic fields to force the electrons to travel in a circle. Radio waves are used to add even more speed. The booster ring ramps up the energy in the electron stream to between 1.5 and 2.9 gigaelectron volts (GeV). This is enough energy to produce synchrotron light in the infrared to hard X-ray range.

2. **Catch the Wave:** The electron stream is fed into a linear accelerator or linac. High energy microwaves and radio waves chop the stream into bunches, or pulses. The electrons also gain speed by "catching" the microwaves and radio waves. When they exit the linac, the electrons are traveling at 99.9998% of the speed of light and carry about 300 million electron volt energy.

1. **Ready, Aim...** Synchrotron light starts with an electron gun. A heated element, or cathode, produces free electrons, which are pulled through a hole in the end of the gun by a powerful electric field. This produces an electron stream about the width of a human hair.

Source: University of Saskatchewan / Paradigm Media Group Inc.