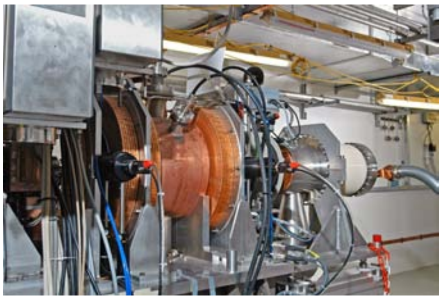
Electron Gun

Diamond uses high energy electromagnetic waves to study matter; these waves are produced by accelerating electrons. The electron gun is where the electrons begin their journey.



Electrons are released from a cathode (at Diamond this is made from Tungsten) using a process called thermionic emission. By applying a voltage between the tungsten cathode and the anode an electric field is generated and this accelerates the electrons.

Using the Simulator

1. Click on the button marked 'show instructions' and follow them.
2. Click on the button marked 'show theory' for help understanding what is happening

Can you Calculate?

Using the equation given in the theory for the (kinetic) energy of the electrons, can you calculate the energy (in Joules) of an electron if the voltage applied to the anode was 1kV?

The electronvolt (eV) is also a unit of energy, like the Joule. Find the conversion factor (does it look familiar?) and calculate the energy of the electron above in eV.

The electronvolt is defined as the energy gained by an electron when it is accelerated through a field of one volt. By using electronvolts as the standard unit of energy in particle physics it makes calculations much simpler. Electronvolts can also be used as a unit of mass, see if you can find out more.

Can You Explain

- The process of thermionic emission
- Why metals are used as the cathode
- The relationship between the electric field and the energy of the electron

Trivia

You may have a small particle accelerator in your house, as electron guns are also used in older-style (CRT) televisions and monitors.

Insertion Devices – The Undulator

Diamond uses high energy electromagnetic waves to study matter; these waves are produced by accelerating electrons. Some waves are produced by the dipole magnets, but even more are produced by insertion devices know as wigglers or undulators.

An Undulator

As electrons are accelerated around corners they will emit radiation, the frequency of which is determined by the energy of the electrons. If you wish to emit higher intensity radiation you can achieve this by steering the electrons around even more corners, using insertion devices such as undulators. The electrons pass between two rows of magnets. The magnets are aligned with opposing magnetic fields next to each other (North-South-North-South etc). When the electrons pass between the magnets they are forced in one direction and then the other, they undulate or wiggle. This motion increases the intensity of radiation that is emitted and can be used for experiments.

Using the Simulator

1. Click on the button marked 'show instructions' and follow them
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Can you Calculate?

A typical experiment at Diamond may use X-rays with a wavelength of 0.1nm (10^{-10}m). Can you calculate both the frequency and energy of these X-rays?

The X-rays produced by the insertion devices at Diamond are produced by moving electrons, so there is a Doppler effect. i.e. The frequency of the radiation observed by the Diamond scientists is different to the frequency at which the radiation is produced. You may have come across the Doppler Effect in your studies, an example is hearing a siren on a moving vehicle, the pitch (frequency) is different depending on the speed and direction of travel.

Due to the properties of light and relativistic effects a different equation is used for Doppler shift in electromagnetic waves:

$$f_R = \sqrt{\frac{c+v}{c-v}} f_S$$

Where f_R is the frequency seen by the receiver (our scientists), f_S is the frequency produced by the source (the electrons), c is the speed of light and v is the speed of the source. This equation assumes the source is coming towards the receiver.

If the electrons are travelling at 99.9999% of the speed of light what is the frequency of the radiation when it is produced by the electrons?

Constants
Speed of light (c) $\approx 3 \times 10^8$ ms^{-1}
h = 6.626×10^{-34} Js (Plank's constant)
1eV $\approx 1.6 \times 10^{-19}$ J

Can You Explain

- Why insertion devices are used
- What effect increasing the magnetic field strength has
- Why magnets are aligned North-South-North-South etc

Trivia
Insertion devices can be designed to give off a broad spectrum of frequencies (wigglers) or tuned to give off specific frequencies (undulators). Undulators are also used as the radiation producing element in free electron lasers.

The LINAC (Linear Accelerator)

Diamond uses high energy electromagnetic waves to study matter; these waves are produced by accelerating electrons. When the electrons leave the electron gun they are injected into the LINAC (LINear ACcelrator).

The negatively charged electrons are accelerated through a series of charged electrode tubes. The polarity of the tubes switch as the electrons pass so they are always being accelerated in the same direction. By doing this the electrons at Diamond are accelerated to almost the speed of light.

Using the Simulator

1. Make sure the switch is flipped to manual
2. Click on the button marked 'show instructions' and follow them
3. Click on the button marked 'show theory' for help understanding what is happening

Can You Calculate?

The kinetic energy of a particle can be found using the equation:

$$E = \frac{mc^2}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

Where m is the rest mass of the particle, c is the speed of light and v is the speed of the particle.

When the electrons leave the LINAC they are travelling at 99.9987% of the speed of light can you calculate the energy of the electrons in electronvolts (eV)? There are some constants below that might help you (note that some values can be rounded up, but it is crucial you use the complete ratio noted above for the speed).

Electronvolts are a measure of energy, but as energy and mass are related ($E=mc^2$) they can also be used as a unit of mass. The mass of an electron can be given as

0.511 MeV/c^2. Try doing the calculation above but using this value for m (note that because of the units the c^2 on the top of the equation is cancelled out), does it make the calculation easier or harder?

Constants:
Speed of light (c) $\approx 3 \times 10^8$ ms^{-1}
Charge on an electron $\approx 1.6 \times 10^{-19}$ C
Mass of an electron $\approx 9.1 \times 10^{-31}$ kg

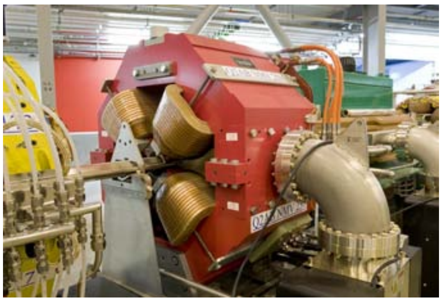
Can You Explain

- Why the polarity of the electrode changes
- Why there are lots of electrodes and not just one
- Why the size of the electrodes vary

Trivia
Diamond's LINAC is about 10m long; the longest in the worlds is at the SLAC National Accelerator Laboratory in the USA and it over 2 miles long!

Quadrupole Magnets

Diamond uses high energy electromagnetic waves to study matter; these waves are produced by accelerating electrons. The fast moving electrons are steered using magnets; to focus the electron beam quadrupole magnets are used.



The electrons move around the Diamond synchrotron in bunches which have a tendency to diverge (spread out). It is important to keep electron bunches that make up the beam focus on a tight path, this focusing is done using quadrupole magnets. Four magnets (one quadrupole) are used to produce a combined magnetic field which exerts a force on the electrons focusing them in one plane. A second quadrupole magnet is set up to focus the now 'flat' beam in the perpendicular plane. The combination of the two magnets squeezes the bunch of electrons together. This is easier to visualise by using the simulations.

Using the Simulator

1. Click on the button marked 'show instructions' and follow them
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Can you Calculate?

The main reason the electrons in a bunch diverge is due to their negative charge as they are all repelling each other. A typical bunch contains 10^{12} electrons, and at its smallest point (just after leaving the quadrupole) has a diameter of ~$10x10^{-6}$m. Can you calculate how much force the main bunch of electrons is exerting on an electron on the edge of the bunch? (You can use the approximation that all of the rest of the charge acts at a single point in the middle of the bunch.). Coulombs Law (given below) may help you.

Can you work out how fast it is accelerating?

Does that seem quick? In practise it is not quite as fast as this due to relativistic and other effects, but it is fast enough for the bunches to expand from $10x10^{-6}$m to $150x10^{-6}$m in diameter as they travel between quadrupoles. Getting fifteen times larger may not sound much, but this happens in approximately 0.000000016seconds. If you expanded at that rate, in less than a second, you would be bigger than the sun!

Coulombs Law (used to calculate the force between charged particles):

$$F = \frac{1}{4\pi\varepsilon_0} \times \frac{q_1 q_2}{r^2}$$

Where ε_0 is the permittivity of free space, r is the distance between the charges and q_1, q_2 are the charges on each of the particles.

Constants:

Permittivity of Free Space (ε_0) = 8.85×10^{-12} F/m
Charge on an electron ≈ 1.6×10^{-19} C
Mass of an electron ≈ 9.1×10^{-31} kg

Can You Explain

- What a quadrupole magnet is
- Why Diamond uses quadrupole magnets in pairs
- What forces act on the electrons and in what direction
- What effect increasing the current has on the system

Trivia

The current flowing in Diamond's quadrupole magnets heats them up and they are cooled down using water. The Large Hadron Collider (LHC), a particle accelerator built by the CERN laboratory in Geneva, also has quadrupole magnets that need cooling. However, the LHC doesn't use water, but approximately 96 tonnes of liquid helium, as it is cooled to a very chilly 1.9 K (-271.25 °C)

The RF (Radio Frequency) System

Diamond uses high energy electromagnetic waves to study matter; these waves are produced by accelerating electrons. As the electrons emit the electromagnetic waves they lose energy, which needs to be topped up. This is done using the radio frequency (RF) system.

A radio frequency cavity

As the electrons travel around the storage ring they emit radiation (X-rays) and therefore lose energy. This energy is replaced in a set of three cavities called RF (Radio Frequency) cavities. Inside the cavity is a varying electric field. As a bunch of electrons moves through the cavity the electric field changes so that there is always a negative field behind the bunch and a positive field in front of it. By doing this the energy of the electrons is increased all the way across the cavity. The electric field is on a cycle that repeats every time a bunch goes through the cavity.

Using the Simulator

1. Click on the button marked 'show instructions' and follow them
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Can you Calculate?

Can you calculate the frequency of the cycling electric field in the RF cavities (i.e. how many times a second does an electron bunch pass through the cavity)?

There are 900 electron bunches in the storage ring and each one is travelling at virtually the speed of light (assume they are for this calculation). The storage ring is 562m long.

What is the frequency of radio waves? (You could try looking on the electromagnetic spectrum). Can you see now why they are called radio frequency cavities?

Constants:
Speed of Light (c) $\approx 3 \times 10^8$

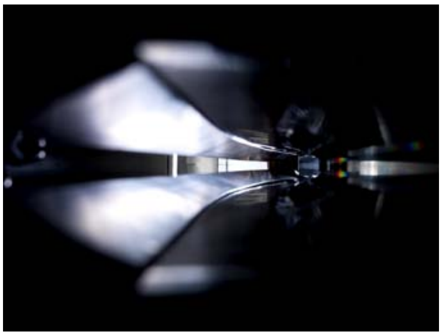
Can You Explain

- Why we need to top up the energy of the electrons.
- Why the electric field inside the cavity is varied (look at the simulator with the RF wave shown, and imagine what would happen if it was static).
- Why the varying field has to be in phase with the electrons (i.e. changing at the same speed as the electrons are moving).

Trivia
The standing wave that boosts electrons in one direction it can simultaneously be used to do exactly the same to positrons (anti-electrons) in the other direction. This feature can be very useful and was used in the LEP (Large Electron-Positron) collider at CERN, Geneva.

The Vacuum System

Diamond uses high energy electromagnetic waves to study matter; these waves are produced by accelerating electrons. The fast moving electrons travel along pipes and it is important that these pipes are under vacuum.



A view along the vacuum pipe

Although the electrons moving around the Diamond synchrotron have lots of energy they would lose it very quickly if they collided with air molecules. A collision would also be likely to change the direction of travel of the electron and send it out of the beam. To prevent this from happening the beam of electrons is contained within a beam pipe that is under vacuum, i.e. the air and other gasses have been removed from it. It is impossible to remove everything, but for every molecule left in the machine approximately 1,000,000,000,000 have been removed.

Using the Simulator

1. Click on the button marked 'show instructions' and follow them
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Can you calculate?

Pressure is defined by the equation:

$$P = \frac{F}{A}$$

Where F is the force exerted over an area of A.

The storage ring vacuum pipe at Diamond is approximately 10cm in diameter and 562m long (you can ignore the thickness of the pipe walls). The pressure within the pipe is 1×10^{-7} Pa.

Can you calculate the net force being exerted on the pipe simply by the pressure of the Earths atmosphere?

Does this seem a lot? In comparison the force exerted by gravity (the weight) on a 1kg mass is only 10N.

Constants:
Air pressure on surface of Earth $\approx$ 101325 Pa

Can You Explain

- Why particle accelerators are held under a vacuum
- What effect decreasing the pressure has on the path of an electron

Trivia
Although there is no perfect vacuum, intergalactic space is pretty close and has only about 1000 hydrogen atoms per m^3. In comparison on earth there are about 3 x 10^{25} (10,000,000,000,000,000,000,000,000) molecules per m^3.

The lowest vacuum created on Earth was at the CERN laboratory, but this still had a billion (1,000,000,000) molecules per m^3.