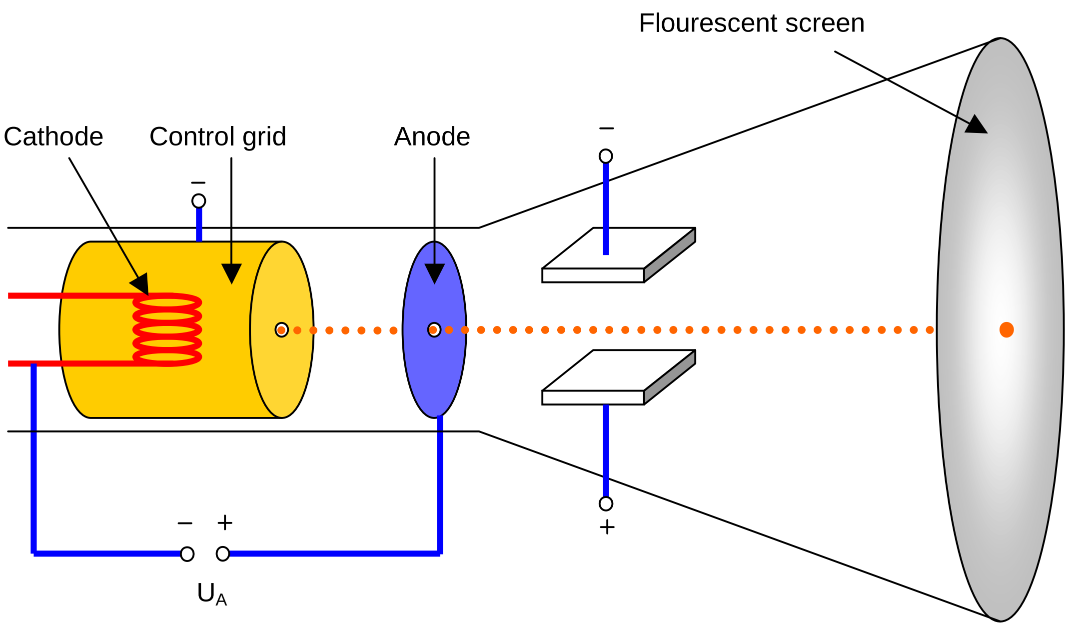
Introduction

The Cathode Ray Tube or Braun's Tube was invented by the German physicist Karl Ferdinand Braun in 1897 and is today used in computer monitors, TV sets and oscilloscope tubes. The path of the electrons in the tube filled with a low pressure rare gas can be observed in a darkened room as a trace of light. Electron beam deflection can be effected by means of either an electrical or a magnetic field.

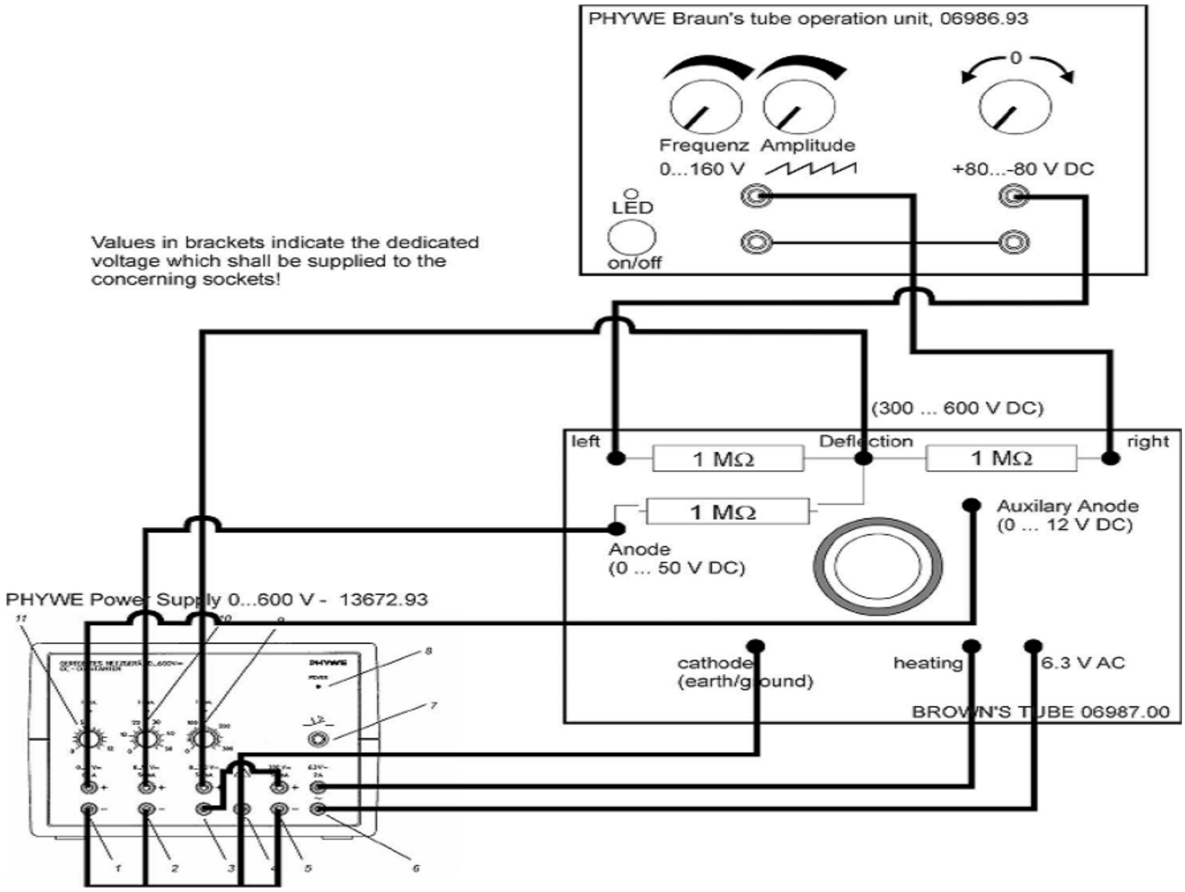
Functional principle

- The source of the electron beam is the electron gun, which produces a stream of electrons through thermionic emission at the heated cathode and focuses it into a thin beam by the control grid (or "Wehnelt cylinder").
- A strong electric field between cathode and anode accelerates the electrons, before they leave the electron gun through a small hole in the anode.
- The electron beam can be deflected by a capacitor or coils in a way which causes it to display an image on the screen. The image may represent electrical waveforms (oscilloscope), pictures (television, computer monitor), echoes of aircraft detected by radar etc.
- When electrons strike the fluorescent screen, light is emitted.
- The whole configuration is placed in a vacuum tube to avoid collisions between electrons and gas molecules of the air, which would attenuate the beam.



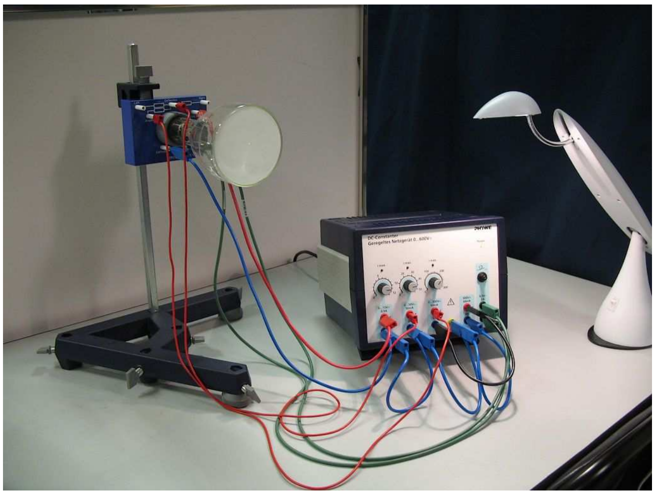
Setup

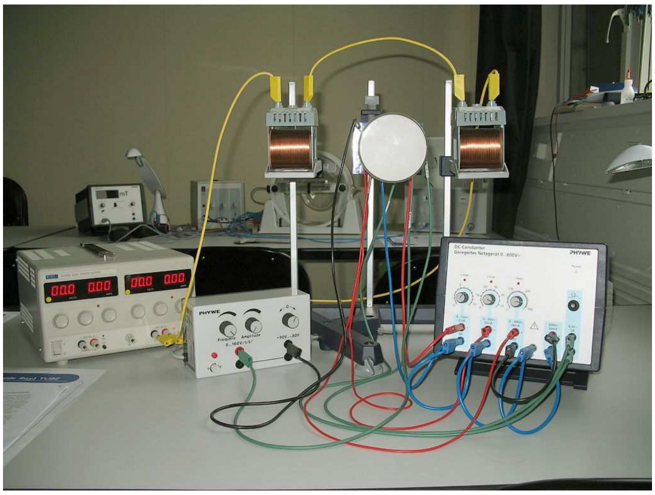
Equipment	Assembling the experiment
• Braun's tube • Power supply for Braun tube • Power supply, 0...600 VDC • Coil, 1200 turns (2x) • Coil holder (2x) • Support base „PASS" • Support rod „PASS", square, l = 400 mm (3x) • Right angle clamp „PASS" (3x) • Connecting cord, safety	1. Connect the sockets of the cathode ray tube to the power supply as shown in the circuit diagram below. 2. To achieve a magnetic deflection of the electron beam setting two series connected coils, 1200 winding, on a coil holder which (possibly with the aid of clamping columns) can be secured to retort stands; the common coil axis should intersect the cathode ray tube between anode and deflector plates.

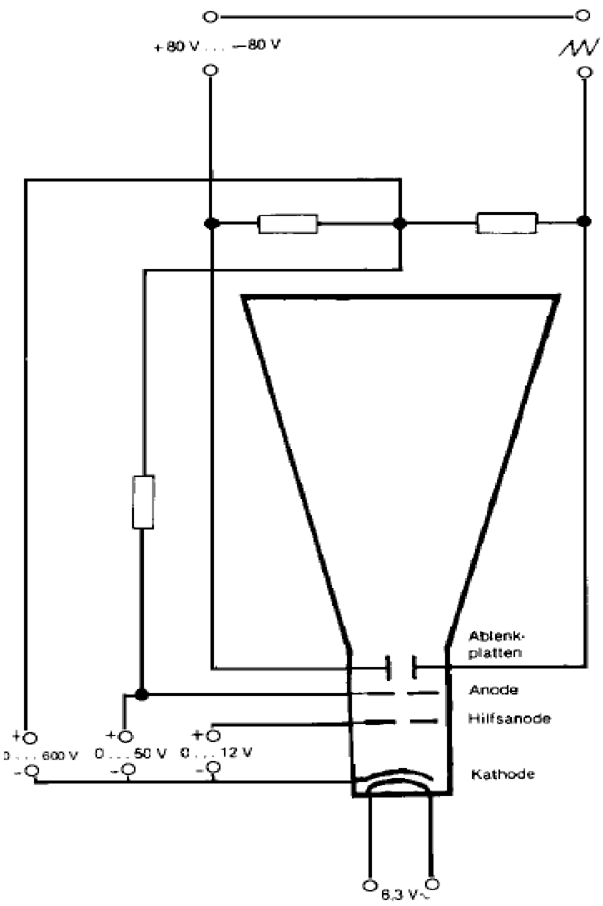


Experimental procedure

1. Set the voltage of the auxiliary anode to 10 V using the first knob on the dc power supply
2. Set the voltage of the anode to about 30…50 V using the second knob on the dc power supply
3. Use the third knob to intensify the beam (200…300 V)
4. Modulate the voltage of the anode and the auxiliary anode to get a sharp beam (knob 1+2)
5. Switch on the Braun's tube operation unit
6. Build up a time base by increasing frequency and amplitude





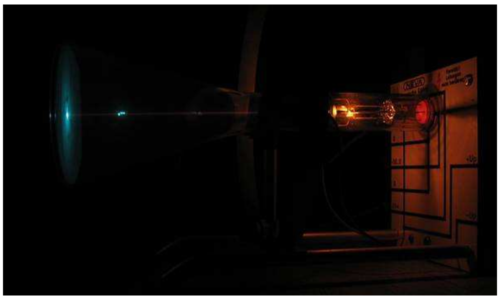


Safety precautions

- Don't touch cathode ray tube and cables during operation, voltages of 300 V are used in this experiment!
- Do not exert mechanical force on the tube, danger of implosions!

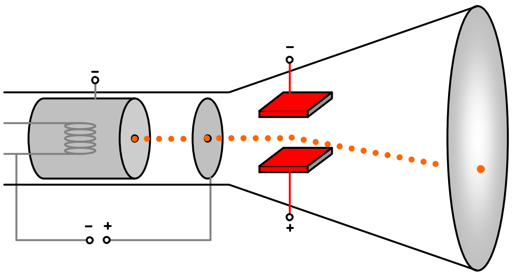
Classical experiments

1. Build up the experimental setup (see “setup”) and observe the spot at the screen and the beam inside the tube! The voltage at the auxiliary anode should be such as to give a clearly visible light spot (approx. 8-10 V).

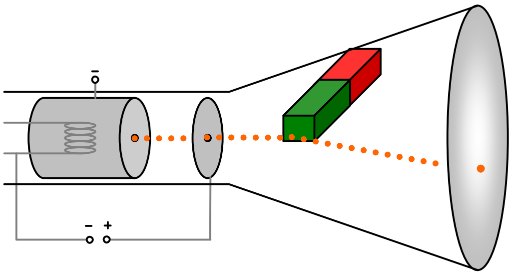


2. We can change the horizontal position of the light spot by adding a tension (-80V…+80V) to the left deflection plate.

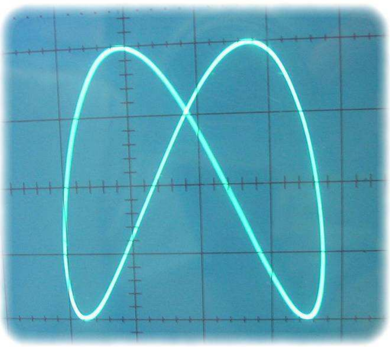
3. The electron beam will wander from the left to right when writing the time base if we add tension to the right plate. We can change the frequency and the width of this tension.

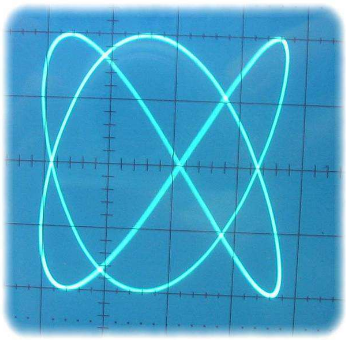


4. Magnetic deflection of the electron beam can be demonstrated by approaching the pole of a bar magnet to the cathode ray tube. As it is shown on the photograph we can provide magnetic field to the tube by using another power supply. The tension that this device provides is DC, so the deflection caused to the light spot is standing and **perpendicular**.



5. It is possible to produce a set-up for periodic deflection of the electron beam with the aid of an alternating magnetic field, setting two series connected coils, 1200 winding, on a coil holder which (possibly with the aid of clamping columns) can be secured to retort stands; the common coil axis should intersect the cathode ray tube between the anode and deflector plates.

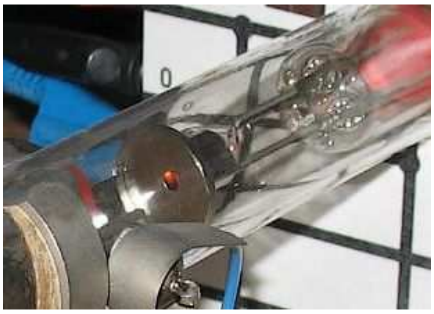




Production of free particles

Tasks:

1. Plug off the heating tension of the cathode and increase the accelerating voltage to 300 V. Do you see any electron beam?
2. Set the cathode heating voltage to 6,3 V and increase the accelerating voltage to 300 V. Do you see an electron beam?
3. Diversify the voltage at the Control grid. How does the spot at the screen change?



Results:

1. If there is no cathode heating, no beam can be observed.
2. With a hot cathode, there is an electron beam inside the tube.

> Explication:
> If the cathode is hot, electrons can leave the metal surface because their thermionic energy is higher then the emitting energy of the material (thermionic emission),

3. Higher voltage on the control grid cause a more sharpen spot on the screen.

> Explication:
> The potential of the control grid is negative compared to the cathode. The electrons (freed by thermionic emission) are rejected by the control grid all around the cathode, that's why they are focussed in the middle which results in a fine electron beam.

Particle physics: production of free particles

A particle source can be found at the beginning of every accelerator. Since acceleration is always caused by electromagnetic fields, only charged particles like electrons or protons (or ions) are used. Particle sources of **electron** accelerators use the same principle as the cathode ray tube:

- A hot cathode emits electrons (thermionic emission)
- A control grid focuses the electrons before they are accelerated by electric fields
- Other electrodes (inexistent at the cathode ray tube) allow a further acceleration and focusing of the electrons.

Proton sources use this principle as well: the first step is to produce electrons in the same way as in the cathode ray tube. The targets of the electron gun are atoms like hydrogen which is ionised by the fast electrons, protons are left over.

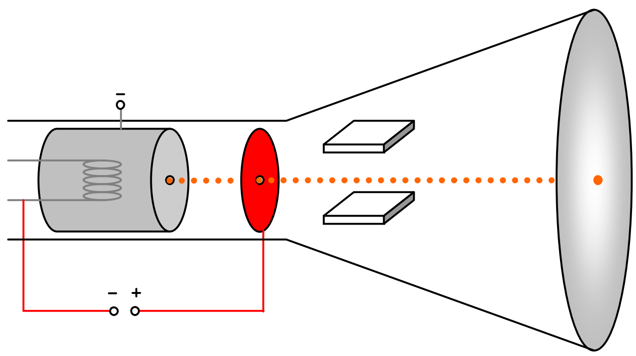
This procedure is also used in the proton source of the LHC, see picture below. The glass case in front of the proton source contains a 1:1-model of it.

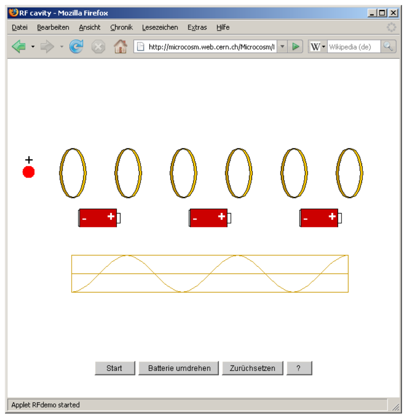
CERN proton source

LINACs

Tasks:

1. Add different accelerating tensions to the anode. How does the spot at the screen change?
2. What is the speed of electrons that have been accelerated with 250 V at the cathode ray tube?
3. What is the speed of electrons that have been accelerated with 90 kV at the first electrostatic accelerator of the LHC (located inside the proton source)?
4. Electrostatic acceleration is limited because high voltages cause flashovers between the capacitor plates. The solution is to put many accelerators in line, which is simulated at http://microcosm.web.cern.ch/microcosm/RF_cavity/ex.html. Try to accelerate a particle!





Results:

1. We differ to cases:
   a. Low acceleration voltage ➔ no beam. The electrons are not moved towards the screen.
   b. High acceleration voltage ➔ beam spot becomes visible. The electrons are accelerated towards the screen. The higher the acceleration voltage, the faster is the speed of the electrons which means a lighter beam spot.

2. Kinetic energy of the electrons: $E = 250\ eV = 4 \cdot 10^{-17}\ J$

   Speed of the electrons: $v = \sqrt{\frac{2 \cdot E}{m_e}} = 9{,}38 \cdot 10^6\ \frac{m}{s}$

3. Energy of the protons: $E = 90\ keV = 1{,}44 \cdot 10^{-14}\ J$

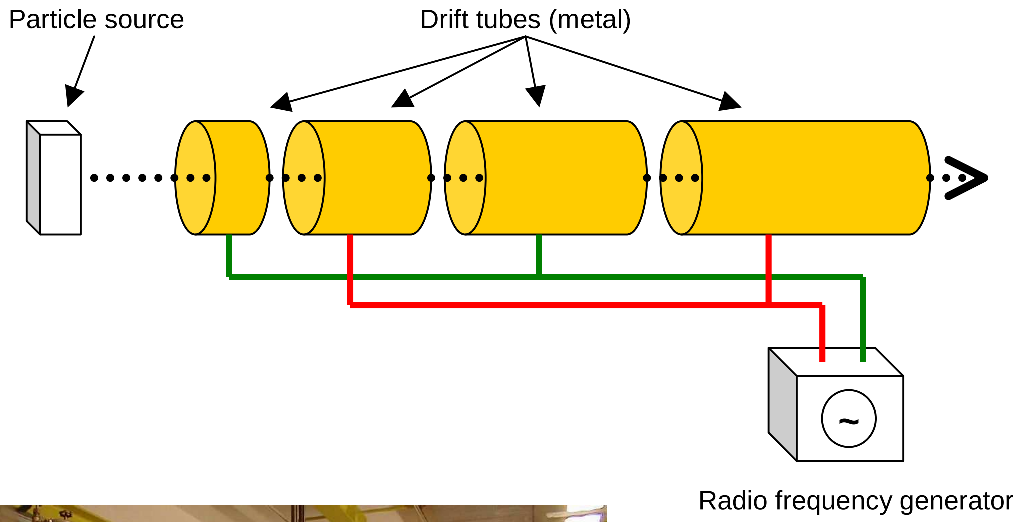
   Speed of the protons: $v = \sqrt{\frac{2 \cdot E}{m_p}} = 4{,}15 \cdot 10^6\ \frac{m}{s}$

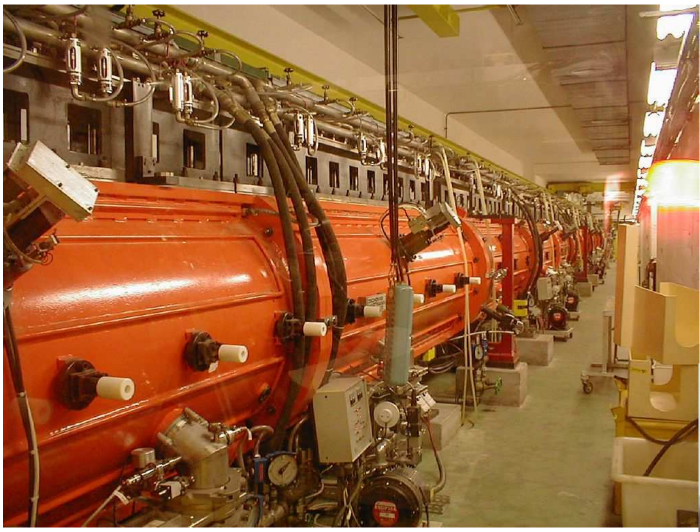
Consequences for particle physics:
Though protons are accelerated with 90 kV at the CERN proton source, they do not even reach the speed of the electrons accelerated with only 250 V at the Braun's tube. The reason is the high mass of the protons. In fact, proton accelerators like the LHC need much more energy to accelerate particles to high speed.

4. Getting into the second electric field, the particle slows down because the field is in the "wrong way". It is necessary to reverse the polarity at the right time to avoid this.

Particle physics: electrostatic and linear accelerators

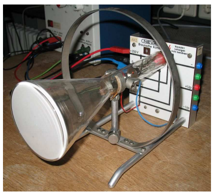
Inside the proton source of the LHC the particles are accelerated by 90 kV in an electrostatic way. Afterwards there is a linear accelerator, LINAC2, which uses the principle shown in the microcosm simulation. The pole change is realised in a tricky way: a constant radio frequency at so-called drift tubes ensures that the direction of the electric fields is in the right way to increase the speed of the electrons. The energy reached by the 30 m long LINAC2 is about 50 MeV, there is a frequency of 200 MHz on the drift tubes.





LINAC2 (top) and LINAC2 drift tubes (right)

Vacuum

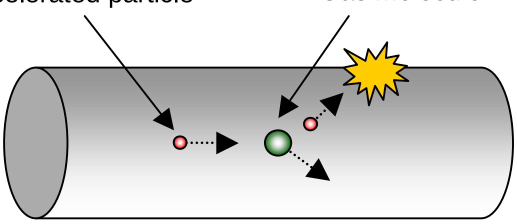


Task:
The cathode ray tube consists of a vacuum tube. Why?

Vacuum quality:

Vacuum	Pressure [bar]	Molecules / cm^3	Mean free path	Examples
Low vacuum	$1...10^{-3}$	$10^{19}...10^{16}$	0,1...100 µm	Vacuum cleaner
Medium vacuum	$10^{-3}...10^{-6}$	$10^{16}...10^{13}$	0,1...100 mm	Gas discharge lamp
High vacuum	$10^{-6}...10^{-10}$	$10^{13}...10^{9}$	10 cm...1 km	Electron tube
Ultra high vacuum	$10^{-10}...10^{-15}$	$10^{9}...10^{4}$	1 km ... 10^{5} km	Particle accelerator
Extremely high vacuum	$< 10^{-15}$	$< 10^{4}$	$> 10^{5}$ km	Outer space

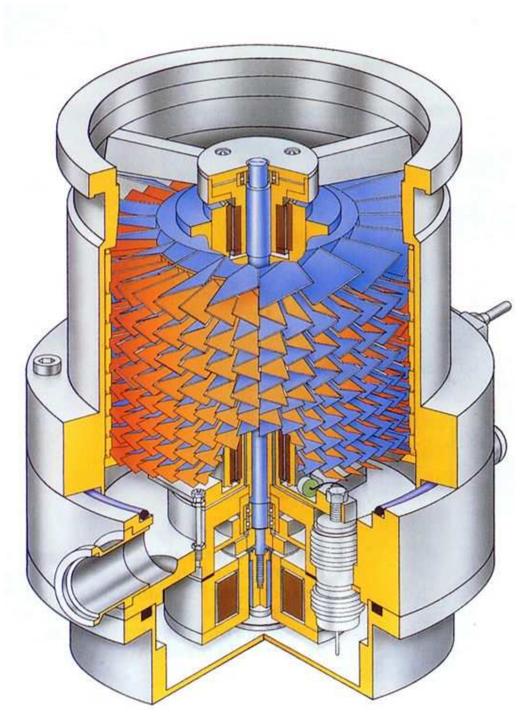
Result:
The Braun's tube is a vacuum tube to avoid collisions between electrons and gas molecules of the air. Collisions would slow down and leak the electrons, without vacuum the image on the screen would be less bright.



Particle physics: vacuum

Collisions between particles and gas molecules are undesired in particle accelerators as well. The leaked particle will be lost when it hits the metal of the beam pipe.

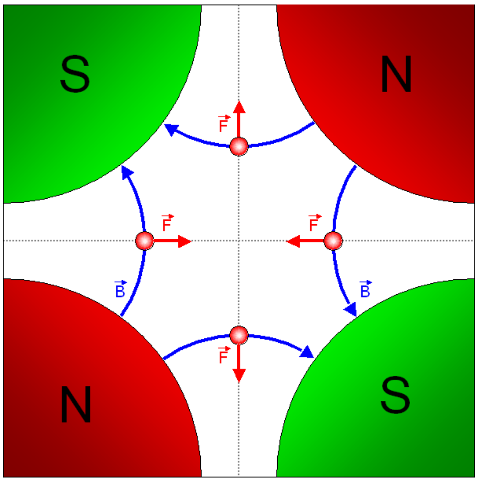
The solution is the same as in the cathode ray tube: the creation of a ultra high vacuum to increase the mean free path (the average distance a particle can fly without hitting a gas molecule). There is 9000 m^3 of pumped volume in the LHC, like pumping down a cathedral. Instead of 10^{19} molecules / cm^3 there are only 3 million molecules per cm^3 left.



Turbomolecular pump

Strong focusing

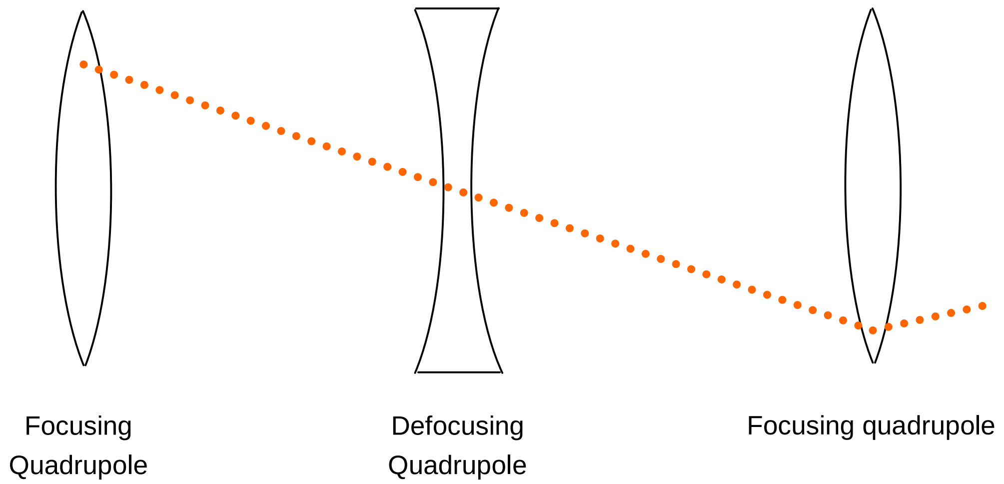
In spite of the ultra high vacuum there are still some gas molecules left in the beam pipe of a particle accelerator. Particles colliding with gas molecules will get lost when they are deflected and hit the beam pipe (see "vacuum"). Errors in the deflection magnets can also cause particles leaving the nominal way. Therefore it is indispensable to focus the beam. Modern accelerators (the LHC as well) use the so called "strong focusing" with quadrupole magnets. How does a quadrupole work?



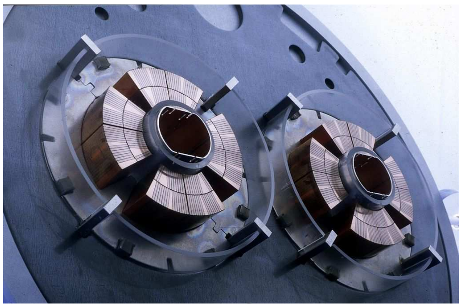
An electron which flies towards the observer into the field of a quadrupole magnet experiences a Lorentz force, if it is not exactly in the middle of the magnet (see left figure).

- If the deviation is left or right of the centre, the Lorentz force points at the middle of the magnet, which can easily be verified with the left-hand-rule. That means the beam is focussed horizontally.
- If the deviation is up or down of the centre, the Lorentz force points outwards. That means that there is a vertical defocusion caused by the quadrupole magnet.

But why can we use quadrupoles for focusing if they are defocusing in the vertical direction? The idea is to put many quadrupole lenses (since they cause focusing, the magnets act like optical lenses) in a row, but every 2nd is turned by an angle of 90°. For each plane, the beam is alternating focused and defocused



The beam focusing at LHC is done by 500 quadrupole magnets, each 3m long.



Tasks:

1. Show mathematically that the combination of two lenses (1x focusing, 1x defocusing, same focal length) does not merge, but focuses alltogether.

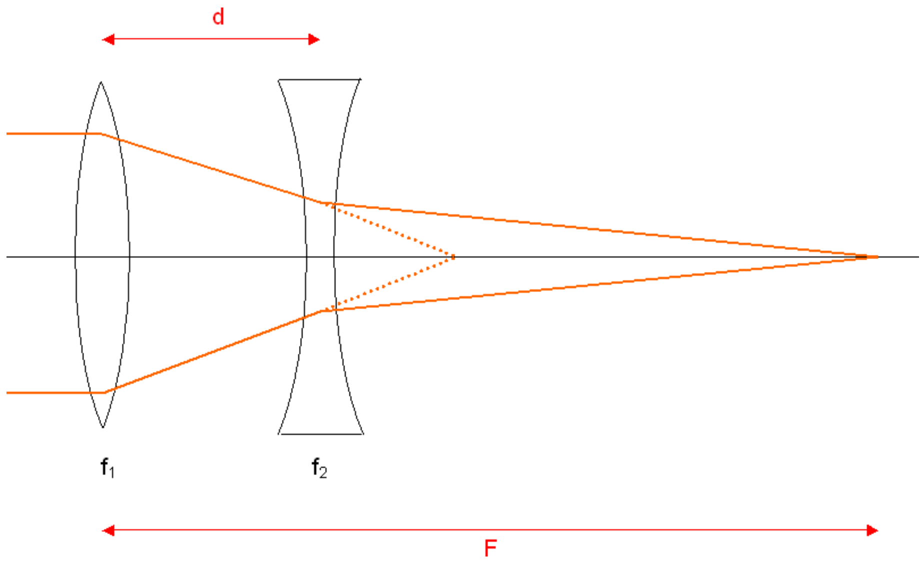
   Tip: the total focal length F of a system of two lenses with focal lengths f_1 and f_2 at the distance d is:

   $$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \cdot f_2}$$

2. Use four bar structurally identical coils or bar magnets to build up a quadrupole magnet! Add an alternating voltage to the deflection plates of the cathode ray tube to fan out the beam. Demonstrate the focusing and defocususing effect of a quadrupole magnet!

Results:

1. The first quadrupole lense is focusing, the second defocusing. Since their focal length is the same, we can write f_2=-f_1. After setting this in the formula for the total focal length of the lense system we get $\frac{1}{F} = \frac{d}{f_1^{\,2}}$. The total focal length is therefore positively, which means that the combination of two quadrupole lenses under an angle of 90° is focusing in all.



2. see picture: