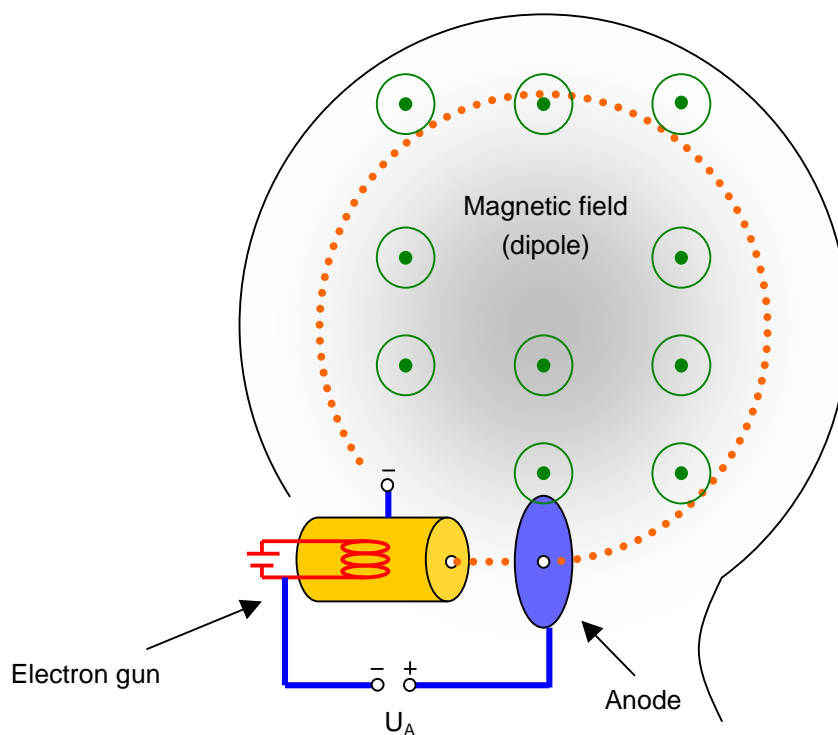


Introduction

A fine beam tube consists of a spherical glass plunger filled with noble gas under low pressure. An electron gun inside the tube (cathode, control grid and anode) generates a beam of electrons. The beam stimulates gas molecules to the emission of light, whereby the beam becomes visible within the tube. The magnetic field of two Helmholtz coils forces the electrons onto a circular path that allows us to determine the specific charge e/m .

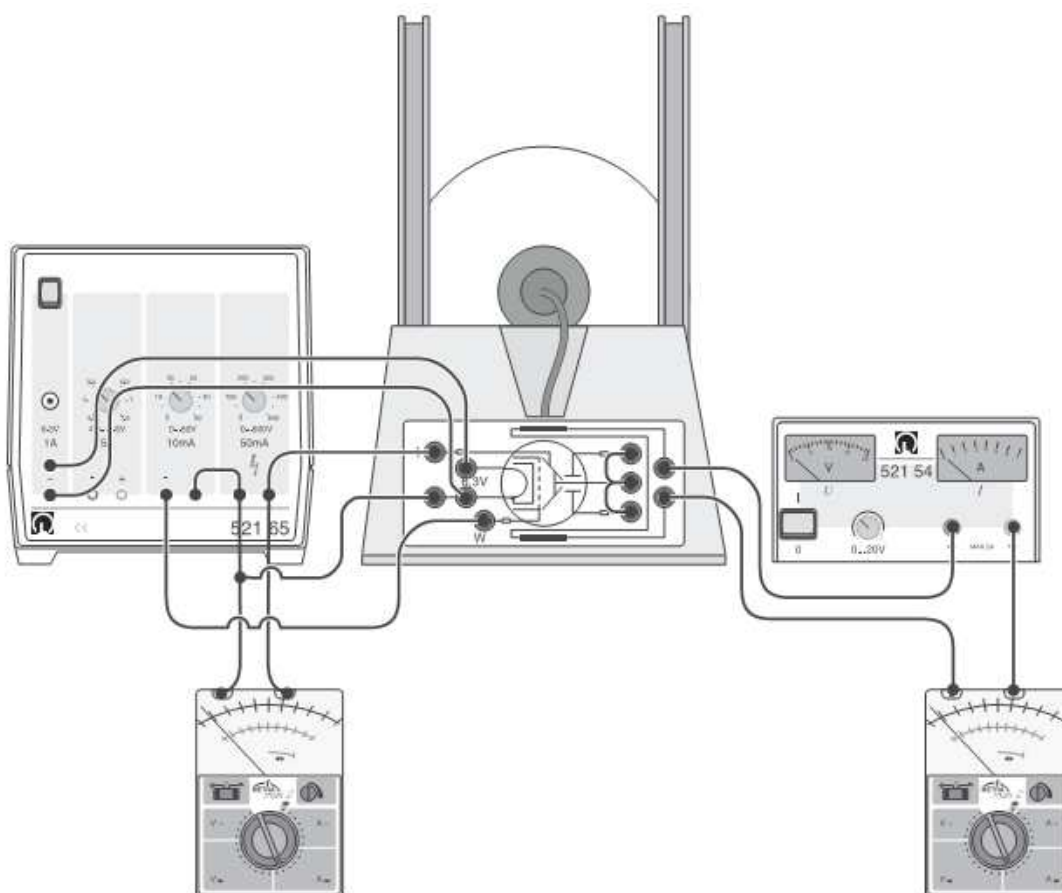
Functional principle

- 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 fine beam tube contains hydrogen molecules at low pressure, which through collisions with electrons are caused to emit light. This makes the orbit of the electrons indirectly visible
- To demonstrate deflection in magnetic fields and calculate the specific charge e/m the fine beam tube is placed in a magnetic field of two Helmholtz coils.



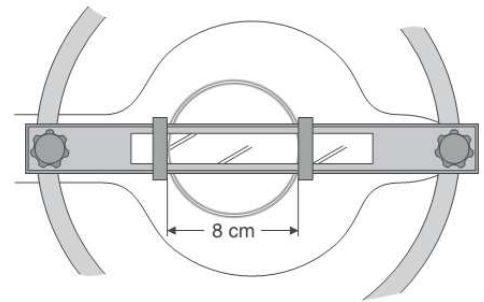
Setup

Equipment	Assembling the experiment
1 Fine beam tube 1 Helmholtz coils with holder and measuring device 1 DC power supply 0 ... 500 V 1 DC power supply 0 ... 20 V 1 Voltmeter, DC, ≤ 300 V 1 Ammeter, DC, ≤ 3 A 1 Steel tape measure, 2 m 3 Safety connecting leads, 25 cm 3 Safety connecting leads, 50 cm 7 Safety connecting leads, 100 cm additionally recommended: 1 Teslameter, 1 Axial B-probe (Fig. 4), 1 Multicore cable, 6-pole, 1,5 m long	<ol style="list-style-type: none"> 1. Connect the 6.3-V input end of the fine beam tube to the 6.3-V outlet of the DC power supply. 2. Short-circuit the positive pole of the 50-V outlet of the DC power supply with the negative pole of the 500-V outlet and connect with the socket “-” of the fine beam tube (cathode). 3. Connect the socket “+” of the fine beam tube (anode) with the positive pole of the 500-V outlet, the socket W (Wehnelt-cylinder) with the negative pole of the 50-V outlet. 4. In order to measure the acceleration potential U connect the voltmeter (measuring range 300 V-) to the 500-V outlet. 5. Short the deflection plates of the fine beam tube to the anode. 6. Connect the DC power supply and ammeter (measuring range 3 A-) in series with the Helmholtz coils.



Experimental procedure

1. Power up the DC power supply and set acceleration potential $U = 300 \text{ V}$. Thermionic emission starts after warming up for a few minutes.
2. Optimize focusing of the electron beam by varying the voltage at the Wehnelt-cylinder from 0 ... 10 V until it leads to a narrow, well defined beam with clear edge definition.
3. Connect the DC power supply of the Helmholtz coils and look for current I , at which the electron beam is deflected into a closed orbit.
4. Move the **left slide** of the measuring device so that its inner edge, mirror image and escape aperture of the electron beam come to lay on one line of sight.
5. Set the **right slide** for both inside edges to have a distance of 8 cm.
6. Sight the inside edge of the right slide, align it with its mirror image and adjust the coil current I until the electron beam runs tangentially along the slide edge covering the mirror image

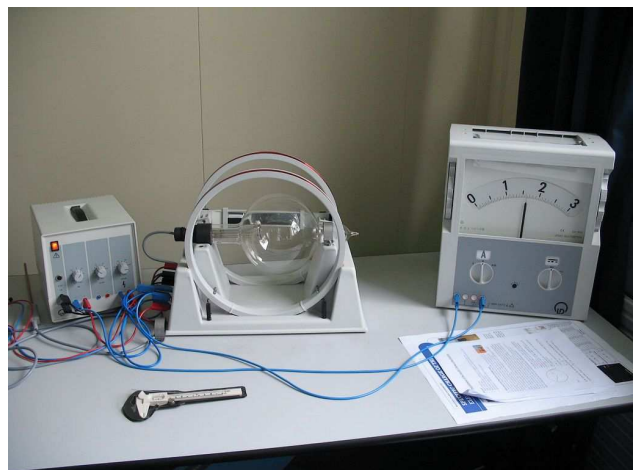


If the electron beams after leaving the anode is deflected to the wrong (left) side:

1. disconnect both power supplies.
2. exchange the connections at the DC power supply in order to change the polarization of the magnetic field.

If the electrons do not move on a closed orbit but on a helical curve line:

1. Loosen the mounting bolts of both holding brackets (read the information manual for the fine beam tube).
2. Carefully rotate the fine beam tube around its longitudinal axis, until the electron beam runs on a closed circular orbit.
3. Fasten mounting bolts.



Safety precautions

- Don't touch fine beam 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!

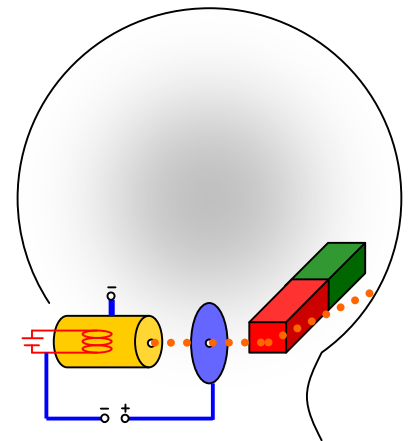


Classical experiments

1. Build up the experimental setup (see "setup"), first without Helmholtz coils and observe the beam inside the tube!



2. Magnetic deflection of the electron beam can be demonstrated by approaching the pole of a bar magnet to the cathode ray tube.
3. Now add the Helmholtz coils to the experimental setup and repeat 2. with the magnetic field of the coils! Adjust the magnetic field so that the orbit of the electron beam is completely inside the tube!
4. Determine the specific charge e/m of electrons!



To determine the specific charge e/m you measure the radius of the circular electron beam in a magnetic field B . The centripetal force at the orbit is equal to the Lorentz force:

$$e \cdot v \cdot B = \frac{m \cdot v^2}{r} \Rightarrow r = \frac{m_e \cdot v}{e \cdot B}$$

The electrons were accelerated by the voltage U_A between anode and cathode. That's why we can calculate the speed of the electrons via the kinetic energy:

$$E_{kin} = \frac{1}{2} \cdot m_e \cdot v^2 = e \cdot U_A \Rightarrow v = \sqrt{2 \cdot \frac{e}{m_e} \cdot U_A}$$

Applying this in the first equation you get an expression for e/m that only contains the parameters U_A , B and r that can easily be measured at the fine beam tube.

$$r = \frac{m_e}{e \cdot B} \cdot \sqrt{2 \cdot \frac{e}{m_e} \cdot U_A}$$

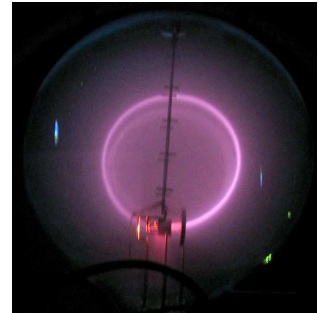
$$\Rightarrow r^2 = \frac{m_e^2}{e^2 \cdot B^2} \cdot 2 \cdot \frac{e}{m_e} \cdot U_A = \frac{m_e}{e} \cdot \frac{2 \cdot U_A}{B^2}$$

$$\Rightarrow \frac{e}{m_e} = \frac{2 \cdot U_A}{B^2 \cdot r^2}$$

Cyclotron

Tasks:

1. Generate an electron beam in the fine beam tube and adjust the magnetic field so that the orbit is completely inside the tube!
2. In which way does the radius of the orbit change if you increase the acceleration voltage U_A (constant magnetic field)?
3. Measure the radius of the orbit at a magnetic field of $B=0,0015\text{T}$ for several acceleration voltages U_A !
4. Compare to theoretical values!



Results:

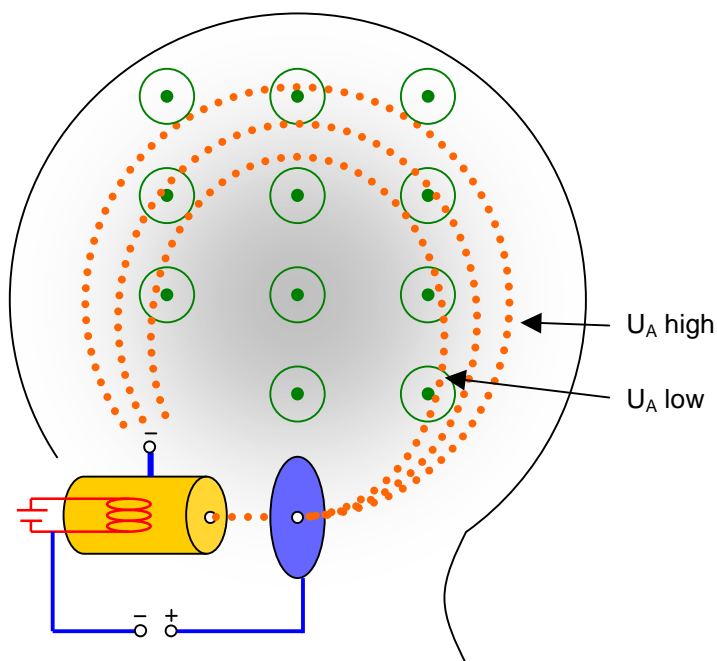
1. Since Lorentz force always act vertical to the moving direction, the electrons go on a circular path. That means it is possible to force particle to fly an orbit with electric fields which is used at circular accelerations, see below.
2. The centripetal force at the orbit is equal to the Lorentz force:

$$\Rightarrow \frac{m \cdot v^2}{r} = q \cdot v \cdot B$$

$$\Rightarrow r = \frac{m \cdot v}{q \cdot B}$$

If the acceleration voltage U_A increases, the electrons get more kinetic energy, their speed v increases as well. Because of the proportionality of r and v the radius r raises, too.

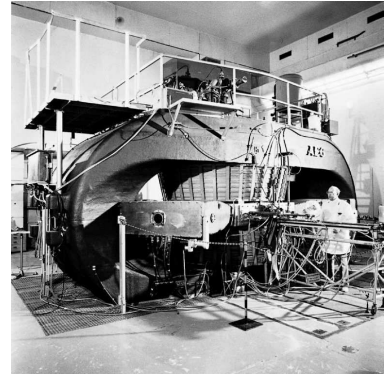
3. The higher the acceleration voltage, the bigger is the radius of the orbit (see 2.).
4. Calculation of the theoretical values with $r = \frac{m \cdot v}{q \cdot B}$



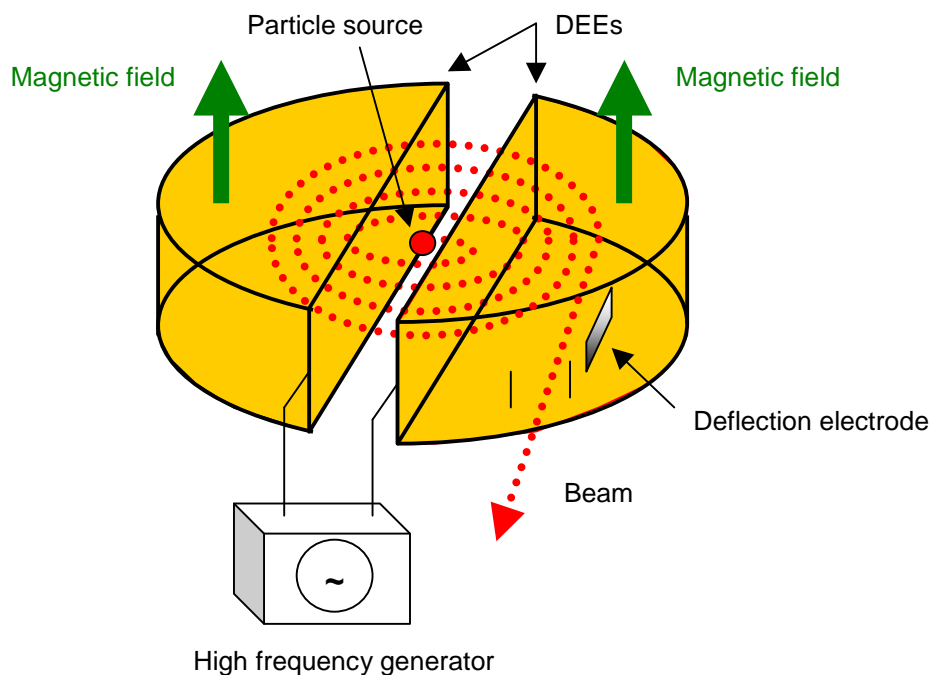
Particle physics: circular accelerators

With rising energy of the accelerated particles LINACs (linear accelerators, see experiment “cathode ray tube”) get very long and expensive. That’s why the idea of circular accelerators was born: by using magnetic fields to force particles into an orbit, the *same* accelerating unit can be used multiple times.

The first type of circular accelerators ever built was the cyclotron. The acceleration takes place between two D-shaped electrodes (so-called Dees) by a high frequency AC voltage. A strong magnetic field all over the Dees forces the particles onto an orbit so that the acceleration between the Dees can take place multiple times. After each semicircle particles are accelerated by the electric field between the Dees.



Like we saw in task 2, the radius of the orbit increases with higher particle speed. Since particles were accelerated in the cyclotron each semicircle, the orbit they go is a helix – that’s why high energy cyclotrons get very large.



Synchrotron

Tasks:

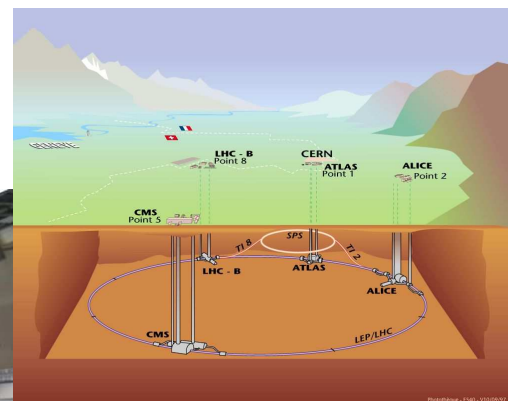
1. Set the acceleration voltage to $U_A=200V$. Regularize the magnetic field thus the radius of the circular path is $r=4\text{ cm}$!
2. Gradually increase the acceleration voltage U_A in steps of 25 V . Regularize the magnetic field always that the radius is constant $r=4\text{ cm}$! Which field strength is needed every time?
3. Compare to calculated values!

Results:

1. see "setup"
2. To balance the bigger radius, the magnetic field has to be increased.
3. Since Lorentz force equals centripetal force, we can dissolve:

$$\frac{m \cdot v^2}{r} = q \cdot v \cdot B \Rightarrow B = \frac{m \cdot v}{r \cdot q} = \frac{m \cdot \sqrt{2 \cdot \frac{e}{m} \cdot U}}{r \cdot e}$$

This experiment with the fine beam tube showed us: it is possible to keep the radius of the orbit constant by increasing the magnetic field synchronously to the energy of the particles. This is used in circular accelerators called "synchrotrons" to keep the particles on a stationary circle (oppositional to the helix path inside a cyclotron). The advantage of a synchrotron is that the magnetic field needs only be at the path and not the whole surface of the accelerator – that's why you can build up very big experiments, till the 27 km long Large Hadron Collider at CERN.



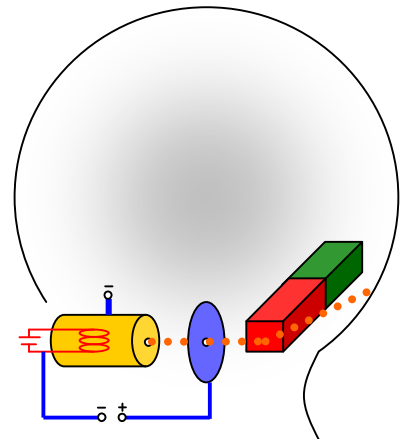
Particle detectors: determination of impulse and charge

Tasks:

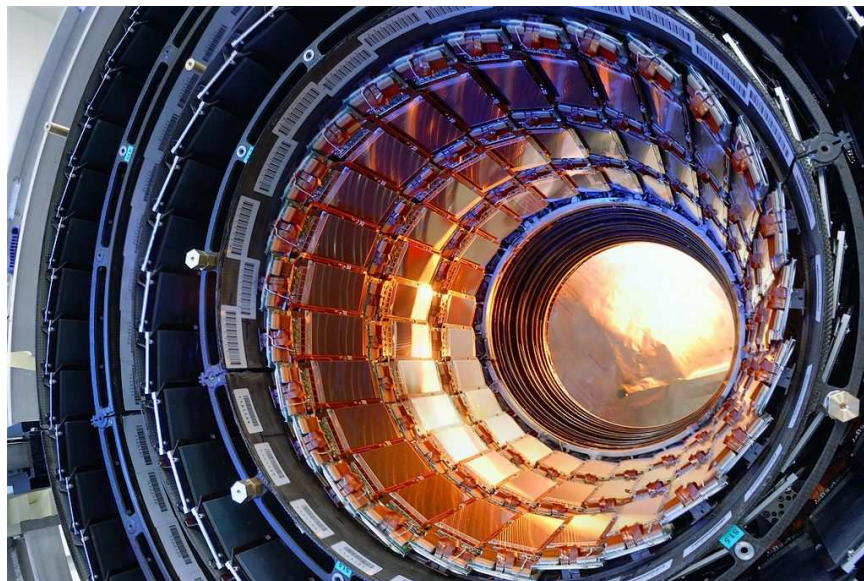
1. Use a bar magnet to show that the beam in the fine beam tube consists of negative charged particles!
2. Choose any desired acceleration voltage between $U_A=200\ldots300\text{V}$ and regularize the magnetic field thus the electron beam is inside the glass tube. Measure the radius of the electron orbit and use this to calculate the impulse of the particles!
3. Compare your result to the value of the impulse which can be calculated of the acceleration voltage!

Results:

1. Approaching the north pole of a bar magnet from behind to the fine beam, the field goes forwards to the observer. Since particles fly to the right, the “left-hand-rule” (valid for negative charged particles) says that there is a Lorentz force on top. Because particles in the fine beam tube are deflected to the top, they are charged negatively which doesn't wonder because they are electrons.



This principle is used in particle detectors as well: for deciding if the charge of a particle is negative or positive, you observe the trajectory within a magnetic field. At CMS detector, the trajectory is measured by the tracker, made of semiconductor materials.



Silicon tracker in the middle of the CMS detector

2. At the circular path, centripetal and Lorentz force are equal:

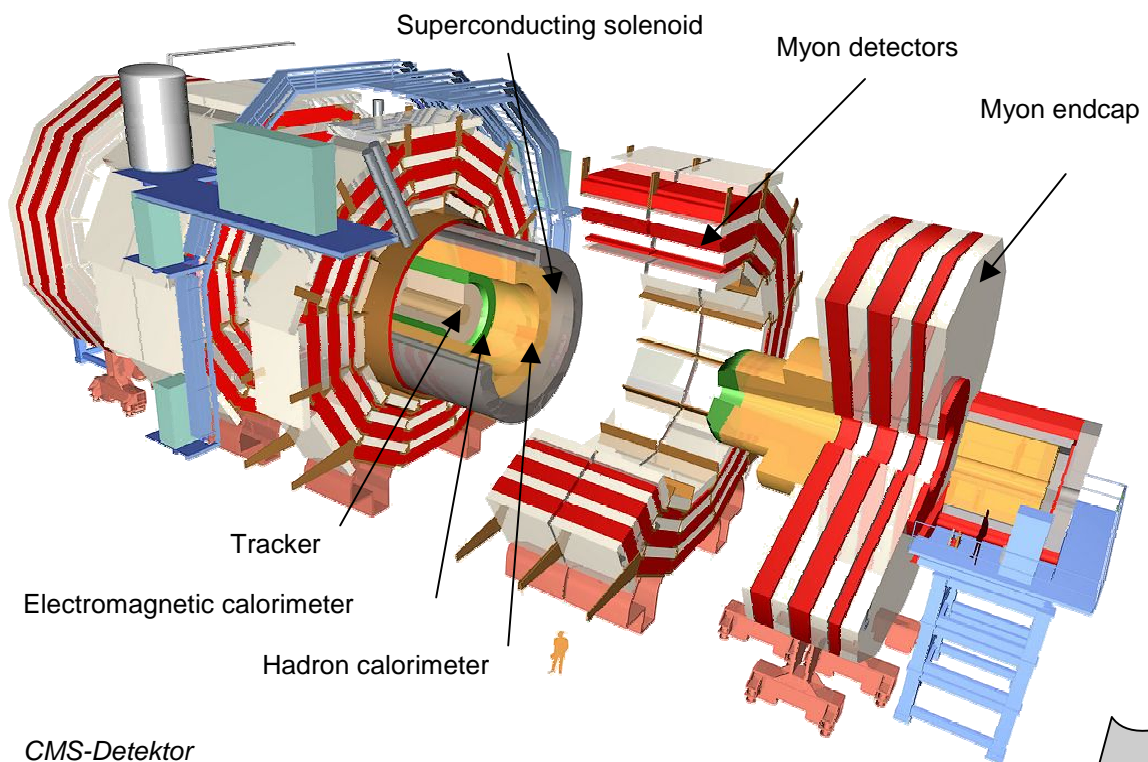
$$\Rightarrow q \cdot v \cdot B = \frac{m \cdot v^2}{r}$$

$$\Rightarrow q \cdot B \cdot r = m \cdot v = |\vec{p}|$$

Because the charge of the electron $q=e$ is known and magnetic field B and radius r can be measured, we can calculate the impulse of the electrons.



In particle detectors the deflection within magnetic fields is used to determine the impulse of particles in the same way as in the fine beam tube. That's why particle detectors need strong magnetic fields – at the CMS detectors this is a 13m long superconducting solenoid with a diameter of 13 m. The magnetic field at the maximum current of 20.000 A is about 4 T.



3. Passing the acceleration voltage U_A in the fine beam tube, the electrons get the kinetic energy

$$E_{kin} = e \cdot U = \frac{1}{2} m \cdot v^2. \text{ That's why the impulse is: } p = m \cdot v = \sqrt{2 \cdot e \cdot m \cdot U}.$$

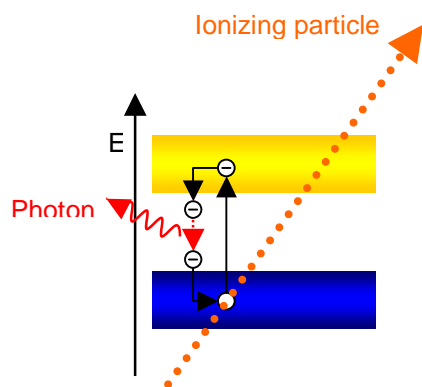
Particle detectors: determination of energy with calorimeters

Tasks:

1. In which way do the electrons become visible at the fine beam tube?
2. Why do you need to darken the room when you use the fine beam tube?

Results:

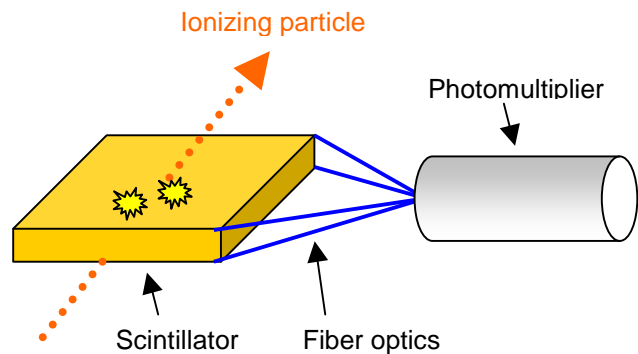
1. At the fine beam tube, the accelerated electrons hit atoms of the filling gas and stimulate them to emit light.



The same principle is used in detectors: particles which fly through special scintillating material (e.g. zinc sulfide) give away their kinetic energy to the scintillator, whose atoms get on a higher energy level. Dropping down to the initial condition, the energy difference is emitted as a photon. This light can be transformed into an electrical signal by the photoelectric effect.

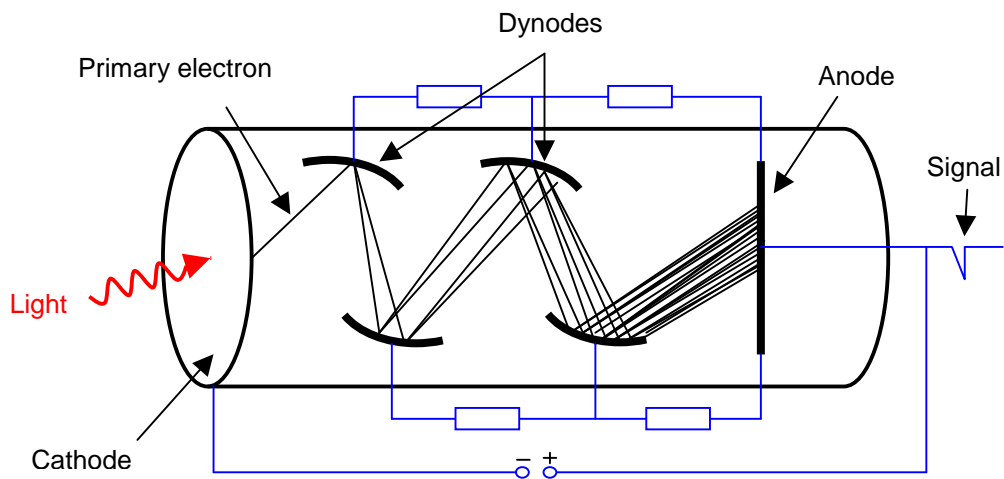


Scintillators made of PbWO_4 (transparent crystal) for the EM calorimeter of the CMS detector



2. The brightness of the beam inside the fine beam tube is very low and not visible by daylight.

The brightness of the light flash inside the scintillator is very low as well. The flashes have to be amplified by a so called photomultiplier. The photons emitted at the cathode are accelerated in an electric field between several electrodes ("dynodes"). At every dynode the initial photon causes the release of many secondary electrons, so the photo current is amplified by factor 10^7 . That is sufficient to be registered with electric measurement amplifiers.



Particle physics: calorimeter

Calorimeters are used to measure the energy of particles. They are built up in layers: dense material such as iron or lead alternate to scintillators. Through interactions with the dense material the primary particles (whose energy has to be measured) decay in many secondary particles which decay further until the primary energy is gone. The energy is proportional to the emitted light in the scintillators and the depth of penetration.

