The magnetic field and its applications

FRONTIERS

Explaining the magnetic field

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Welcome!

It's time to meet the theory of the Magnetic field and all its mysterious properties and great applications. We've used compasses in navigation for centuries; now let's explore new physics by using the magnetic field!

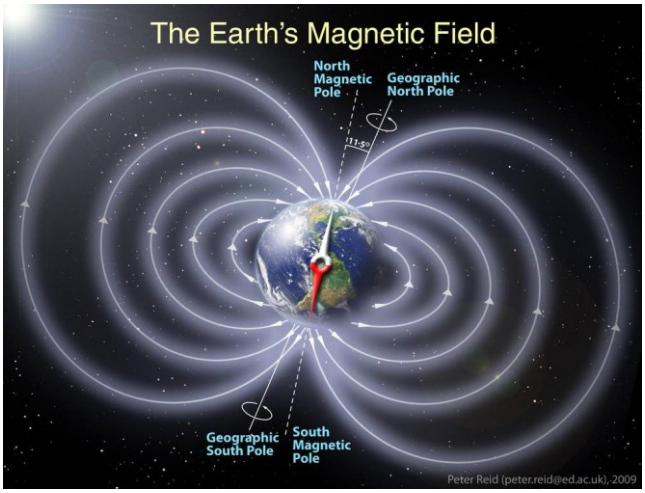
Magnets

Though, what is actually producing a magnetic field in the first place?

A magnet is a material or object that produces a magnetic field. A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. An everyday example is a refrigerator magnet used to hold notes on a refrigerator door. Materials that can be magnetized, which are also the ones that are strongly attracted to a magnet, are called ferromagnetic. These include iron, nickel and cobalt.

Ferromagnetic materials can be divided into magnetically "soft" materials, like annealed iron, which can be magnetized but do not tend to stay magnetized and magnetically "hard" materials, which do. Permanent magnets are made from "hard" ferromagnetic materials.

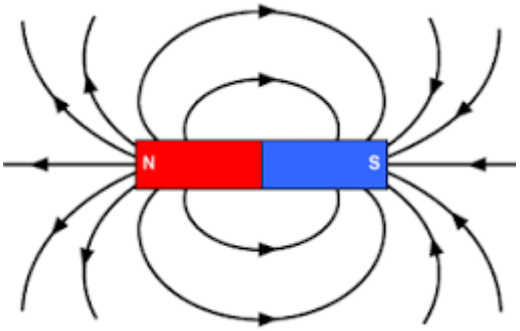
An electromagnet is made from a coil of wire that acts as a magnet when an electric current passes through it but stops being a magnet when the current stops. Often, the coil is wrapped around a core of "soft" ferromagnetic material such as steel, which greatly enhances the magnetic field produced by the coil.



Earth itself is a giant natural magnet. Earth's magnetic field protects life from the solar wind.

Magnetic Field Properties

Experimenting has shown that magnetic field's magnitude is stronger at the magnet's edges. So we call these high magnetic field spots, poles. The north pole of a magnet is defined as the pole that, when the magnet is freely suspended, points towards the Earth's North Magnetic Pole in the Arctic (the magnetic and geographic poles do not coincide). Opposite poles (north and south) attract and same poles repulse.



The magnetic field is denoted by the symbol B and measured in Teslas (1Tesla=1 N/mA) in the SI.

The magnetic field at any given point is specified by both a direction and a magnitude (or strength); as such it is represented by a vector field. It is represented by magnetic field lines, which show the direction of the field at different points.

The direction of the magnetic field at any point is parallel to the direction of nearby field lines, and the local density of field lines can be made proportional to its strength.

The magnetic field lines of a magnet are considered by convention to emerge from the magnet's North Pole and reenter at the South Pole.

Except from magnetic dipoles (as the red/blue shown on the figure above) there are some other types of magnets which are widely used like the tetrapole magnets, solenoids and toroids -the last two named after their shape.

Indicatively, the earth's magnetic field's strength is 60 micro Tesla while a Magnetic Resonance Imaging device uses a magnetic field of 1,5 Tesla!

Magnetic Field Force

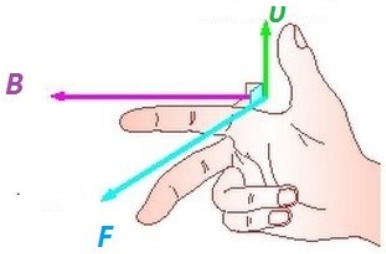
A particle of charge q moving with velocity v in the presence of a magnetic field B experiences a force that bends its track. This force is called Lorentz force (F_L) and it is given by the equation:

$$F_L = B\ q\ v \sin\alpha$$

α : the angle between the v and B vectors

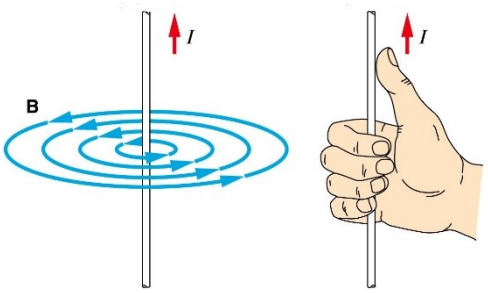
As we can derive from the equation, the Lorentz force is zero when the particle moves in the same linear orientation as the B field (sinα=0) . It maximizes when the particle moves perpendicularly to the magnetic field lines, so sinα=1.

The charged particle will curve perpendicularly to both the instantaneous velocity vector v and the B field according to the right-hand rule (in detail, if the fingers of the right hand are extended to point in the direction of v and are then curled to point in the direction of B, then the extended thumb will point in the direction of F).



Force on a current-carrying wire

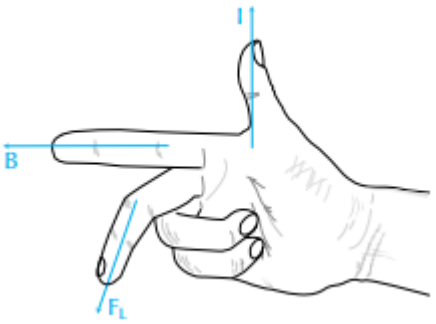
When a wire carrying an electric current is placed in a magnetic field, each of the moving charges, which comprise the current, experiences the Lorentz force, and together they can create a macroscopic force on the wire (sometimes called the Laplace force). By combining the Lorentz force law above, with the definition of the electric current, the following equation results, in the case of a straight, stationary wire:



$$F_L = B\ I\ \ell\ sin\alpha$$

where ℓ is the length of wire, I is electric current's intensity and α is the angle between I and B vectors.

We also use the right hand rule to determine Laplace force direction.



Superconductors

Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic flux fields occurring in certain materials, called superconductors, when cooled below a certain critical temperature. It was discovered by Dutch physicist Heike Kamerlingh Onnes. The electrical resistance of a metallic conductor decreases gradually as temperature is lowered. In common conductors, such as copper or silver, this decrease is limited by impurities and other defects. Even near absolute zero, a real sample of a normal conductor shows some resistance. In a superconductor; the resistance drops abruptly to zero when the material is cooled below its critical temperature. An electric current flowing through a loop

of superconducting wire can persist indefinitely with no power source.

Teacher Guidelines:

Have your students draw the magnetic field lines of a magnet (could be the earth) and have them construct a a compass as well.

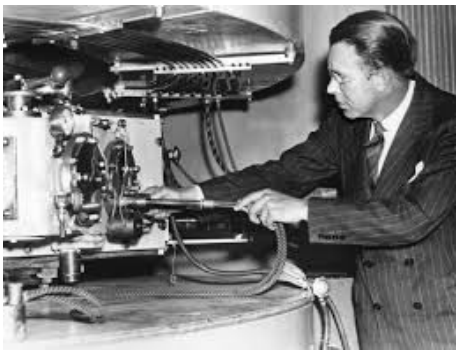
Exploratory Phase

Hypothesis generation and design

Define Goals and/or questions from current knowledge

How do we use magnets?

I Cyclotron

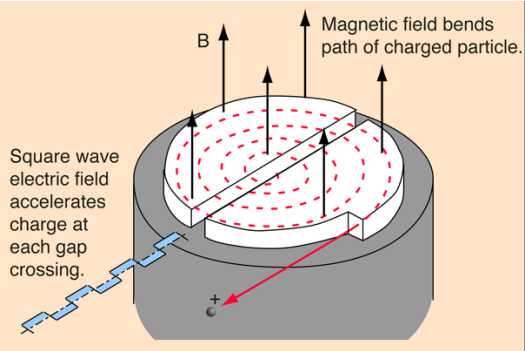


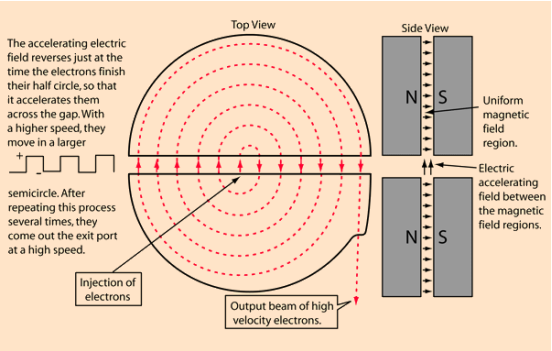
As we discussed earlier, the force of the magnetic field is always perpendicular to the charged particle's velocity vector. Thus, the Lorentz force functions as a centripetal force and the particle will follow a circular orbit. If we set the Lorentz force and the centripetal force of a circular motion of radius R, equal, for a particle of q charge, m mass and speed v:

$$m\,\frac{v^2}{R} = B\,q\,v$$

By simplifying the above equation and solving for the radius of the circular motion that the particle will follow inside the magnetic field:

$$R = \frac{m\,v}{B\,q}$$





This motion is called cyclotron motion and was first discovered and used by Ernest Lawrence.

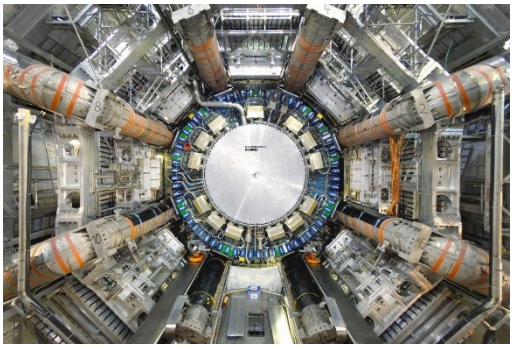
II At CERN

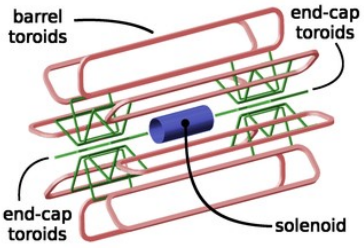
The cyclotron is the basic function of the modern giant accelerators used in large science research centers, like CERN - Conseil Européen pour la Recherche Nucléaire- the largest experimental center of nuclear research, specializing in particle physics, in the world. It is located west of Geneva, at the French-Swiss border.

In this giant laboratory, scientists have constructed the largest circular particle accelerator

ever built, the LHC (Large Hadron Collider). The twenty seven kilometer long circular LHC tunnel is mainly filled with superconducting dipole magnets, which are the most complex components of the machine. Their superconducting coils allow them to convey extremely high currents without any loss of energy and thus achieve very high magnetic fields. These very high magnetic fields are necesary in order to bend the trajectory of the protons that are accelerated at a speed close to the speed of light. Overall, there are 1232 15 meter long dipole magnets, weighing 35 tones each. Huge detectors have been placed at collision points so scientists can collect data about particles' momentum.

The larger detector is called ATLAS. The detector is in a strong magnetic field which bends the trajectories of charged particles. ATLAS uses two different kinds of magnets. The first is a system of three toroidal magnets (one large central and two smaller pieces in the front and back part of the main cylinder of ATLAS) with superconductive coils that form a cylinder whose axis is parallel to the direction of the particles moving in the accelerator (as shown in the next photo). The second is a solenoid magnet with 2m diameter whose axis is also parallel to the direction of the particles moving in the accelerator. Positively and negatively charged particles are curved in opposite directions from the same magnetic field. The radius of curvature and direction of the particles used to determine the momentum and the charge of particles.





Watch videos and meet LHC and ATLAS!

LHC Collider

ATLAS

III Magnetic Levitation

Another impressive magnetic field application is magnetic levitation, a method by which an object is suspended with no support other than magnetic fields. Magnetic force is used to counteract the effects of the gravitational acceleration and any other accelerations. Magnetic trains are based on this application. They hold the speed record for trains (400 to 500 km per hour) and move without making contact with the ground. This technology in no new in Japan, United States and Europe. Though, it is recently promoted for being an environment friendly mean of transport.

Teacher Guidelines:

Have your students search for other applications of the magnetic field

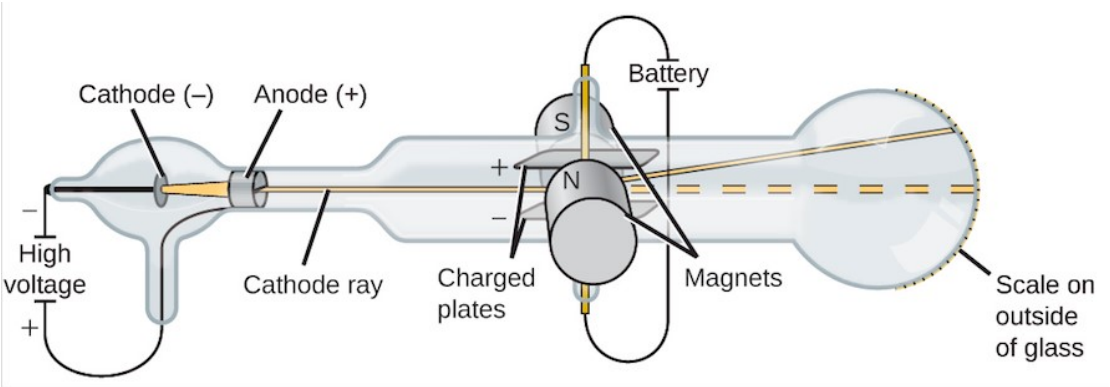
Generation of Hypotheses or Preliminary Explanations

e/m Experiment

As we discussed earlier, the cyclotron motion is the basic function of modern accelerators. Taking a closer look at the cyclotron equation, we can say that if we know the magnetic field's magnitude, the particle's charge and if we observe and measure the radius of the particle's circular motion then we can calculate the charge to mass ratio which is important for identifying a particle:

$$\frac{q}{m} = \frac{v}{B\,R}$$

It was the same process that Joseph John Thomson (1856-1940) followed, when he first calculated the e/q ratio (e: electron charge) at the University of Cambridge in 1897, using this experimental setup:



In this vacuum tube, electrons coming from the incandescent cathode, accelerate due to an electric potential V and form the cathode ray.

The electric field deflects the cathode ray.

According to the conservation principle of energy, the kinetic energy that the electrons will carry is equal to the electric field force's work:

$$\frac{1}{2}mv^2 = V\,e$$

Thus, the speed:

$$v = \sqrt{\frac{2eV}{m}}$$

The electron beam gets through a speed filter and then it ends up in a screen covered with fluorescent material which glows at the spots where electrons fall.

The electron pass the filter without being deflected only if their speed is v=E/B so:

$$\frac{E}{B} = \sqrt{\frac{2eV}{m}}$$

$$\frac{e}{m} = \frac{E^2}{2VB^2}$$

The magnitudes of B, V and E can be measured so the ratio e/m can be calculated.

Thomson found out that the e/m ratio did not differ despite the cathode material. This fact showed that the particles of the beam, which today are called electrons, are components of the common matter. This way, he actually discovered the electron!

Watch a ray of electrons that follow circular motion due to magnetic field force!

[Deflecting a Beam of Electrons with Helmholtz Coils]

Teacher Guidelines:

If you school lab has the e/m equipment have your students perform the experiment and watch how the radius of curvature of electrons change by changing the value of B.

Planning and experimenting

Plan Investigation

Accelerator Platform

It's time to visualize what we've learned so far! Let's get in the accelerator!

Task

Particle Tracks

In this platform we can simulate a particle's trajectory/orbit in a magnetic field and observe how this orbit depends on the factors we talked about.

We can select the particle, alter the speed, the magnetic field's magnitude and orientation and watch how the particles bend! We can also activate the vector representations. On the top of our screen we can see the speed-momentum and momentum-radius of the orbit graphs.

Teacher Guidelines:
The first time you open the platform it will probably ask you to register. Do it and next time your students will open it, it will go straight to the application.

Perform Investigation 1

Are you ready?

Open the platform Particle Tracks

1. Set

Speed	Magnetic Field Orientation	Magnetic Field
0,9c	Into the Page	0,5T

and run the simulation for electron, proton, neutrino and muon. Watch the orbit and observe the charts. What are your conclusions? Why do the orbits differ?

2. Repeat the first step but change the orientation of the magnetic field.

Speed	Magnetic Field Orientation	Magnetic Field
0,9c	Out of Page	0,5T

What changes did you notice? Can you explain these changes?

3. Set

Speed	Magnetic Field Orientation	Particle
0,9c	Out of Page	Electron

and run the simulations for the following magnetic field magnitudes:

Magnetic Field	0,5T	2T	4T	8T

What do you notice? How does the magnetic field's magnitude affect the orbit of the particle?

4. Set

Particle	Magnetic Field Orientation	Magnetic Field
neutrino	Into the Page	5T

and run the simulations for the following speed magnitudes:

Speed	0,9c	0,95c	0,99c	0,999c	0,9999c

Teacher Guidelines:

If you need help watch the "Tutorial" of the application

Perform Investigation 2 (More advanced)

Students can use the HYPATIA tool to study the motion of a charged particle in the ATLAS solenoid magnetic field, in order to determine the strength of the field which is used to measure the momentum of the particles produced by particle collisions at the CERN LHC accelerator. The momentum of the tracks, as measured by the detector, is provided (since the magnetic field is known-but not given for this purpose of this exercise).

For this purpose you can use the following demonstrator
https://www.golab.eu/ils/measurement-of-magnetic-field-with-the-giant-atlas-solenoid

Teacher Guidelines:

Investigation 2 is more advanced and the students should be familiar with the ATLAS event analysis tool HYPATIA which is described in detail in demonstrator Discover the Z and Higgs bosons.

Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

Make a graph of the radius of curvature versus momentum.

How does the momentum-speed graph change?

What do you notice going to velocities close to c?

Teacher Guidelines:
Talk to your students briefly about the relativistic momentum and how it increases with the speed

Explanation: Formulate an explanation based on the analysis of your evidence

We‘ve learned to calculate the force that charged particles experience in a magnetic field and the radius of their orbit.

We’ve learned how we use giant electromagnets to accelerate particles in the largest scientific center in the world.

There is something more to learn. Unlike the laws of electricity there are no magnetic monopoles. In a magnetic field there are always North and South Pole, and the field lines that connect them.

In conclusion, the notion of the field is also important in physics. Though it is not visible, we experience its presence through its interaction with the particles that enter it. Other examples of fields are the gravitational and electric field. You can find interesting similarities and differences, if you compare these three fields.

Teacher Guidelines:

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Let's try to answer some questions with what we've learned from this journey.

Using the equation for the circular motion of a charged particle in a magnetic field, can you estimate what will happen to the radius of its orbit if we double the magnetic field's magnitude?

What's the magnetic field magnitude needed for a proton to move with speed 0,99c in the 27km circumference of the Large Hadron Collider?

Compare what your results with the Earth's magnetic field magnitude. What do you notice?

Teacher Guidelines:

Try to trigger discussions on the application of the magnetic fields.

Communicate

Communicate and justify your explanation

We've completed an introduction to the mysterious world of magnetism.

Let's discuss about this journey.

What new stuff did we learn about the magnets?

Which was the most impressive thing you learned?

Which was the hardest one to understand?

Have we realized the greatness of the application of the magnetic field and its significance in our life?

Teacher Guidelines:

Have the students write a small summary of their measurements and present them to their fellow students.

Reflect

Reflect on what you have learned from the learning process

Without the presence of magnets in nature, and without the push for research, discovery, and invention by those that consistently occupied themselves with magnetism, maybe today we wouldn't enjoy many goods of our modern civilization.

- ✓ Industry

The function of electric motors is based on the magnetic properties that a wire acquires when it curries current.

A few years after Hans Christian Oersted's observations in 1820, which proved that a current carrying wire obtains magnetic characteristics, Michael Faraday and Joseph Herny, independently, proved that it can happen vice versa. They discovered that a rotating magnet inside a coil can cause current flow. The function of electric generators is based on this discovery.

Magnetic trains are based on magnetic levitation.

- ✓ Medicine

Magnetic resonance imaging (MRI) is a medical imaging technique used in radiology to form pictures of the anatomy and the physiological processes of the body in both health and disease. MRI scanners use strong magnetic fields, radio waves, and field gradients to generate images of the organs in the body. MRI does not involve x-rays, which distinguishes it from computed tomography (CT or CAT). While the hazards of x-rays are now well-controlled in most medical contexts, MRI still may be seen as superior to CT in this regard.

- ✓ Modern Science Experiment

Cyclotrons are still used mainly for nuclear physics research or in hospitals for cancer therapy. When the particles acquire large velocities, their relativistic mass increases and modifications have to be made to the above principle, leading to different accelerating technologies. Modern accelerators use a large number of magnets to keep the particles

bending and also keep them within a vacuum pipe of many kilometers length. Each revolution of the beam of particles increases their momentum, thus requiring a stronger bending force. This is achieved by using strong electromagnets, namely sending more current through the magnet's winding. In order to achieve such high currents (and magnetic fields) the wire used in these electromagnets is made from superconductive material.

The major accelerator facilities make use of several types of devices to build up the energy of the particles. Some of the types of apparatus used are:

- ✓ Cyclotrons: An oscillating electric field repeatedly accelerates charged particles across the gap between semicircular magnetic field regions.
- ✓ Synchrocyclotrons: cyclotrons with variable-frequency accelerating voltages to track relativistic effects.
- ✓ Betatrons: electron accelerators in a circular geometry with acceleration achieved by magnetic flux increase.
- ✓ Synchrotrons: large ring accelerators where the particles move in an evacuated tube of constant radius, accelerated by radio frequency applications with synchronous magnetic field increases to maintain the constant radius.