DEPARTMENT OF EDUCATION
SCHOOLS DIVISION OF NEGROS ORIENTAL
REGION VII
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MAGNETIC POLES, MAGNETIC FORCE AND MAGNETIC FIELD

for GENERAL PHYSICS 2/ Grade 12/ Quarter 3/ Week 7

SELF-LEARNING KIT

NegOr_Q3_GenPhysics2_SLKWeek7_v2

FOREWORD

This Self-Learning Kit is designed to cater your needs as STEM students for Modular Distance Learning. It is carefully planned to holistically develop your life-long learning skills. This serves as a guide in understanding concepts about magnetic fields, Lorentz Force, magnetic flux and motion of charged particles.

This module enables you to determine the differences between electric interactions and magnetic interactions in terms of force, type of charge, and work. In addition, you will know how to evaluate the total magnetic flux in the solenoid. The application on the concepts of magnetic fields can be appreciated also such as but not limited to the use of Magnetic Resonance Imaging Machines (MRI) and refrigerator magnets.

Moreover, force due to both electric and magnetic forces will influence the motion of charged particles. The resulting change to the trajectory of the particles will differ qualitatively between these two forces. However, this kit only focuses on the motion of charged particles in a magnetic field. It also evaluates the magnetic force when a segment of wire is placed in a uniform magnetic field.

This Self-Learning Kit will provide a short and learner-friendly content that stirs your curiosity, develop understanding, and support critical thinking.

The writers hope that this Self-Learning Kit can serve its purpose to you, as the target learners. Mastery of the content is encouraged before proceeding to the next learning competency.

OBJECTIVES

At the end of this Self-Learning Kit, you should be able to:

K: differentiate electric interactions from magnetic interactions;
: describe the motion of charged particles in a magnetic field.

S: evaluate the total magnetic flux through an open surface;
: evaluate the magnetic force on an arbitrary wire segment placed in a uniform magnetic field; and

A: recognize the importance of magnetic fields in areas such as but not limited to health and medicine.

LEARNING COMPETENCIES

Differentiate electric interactions from magnetic interactions. **STEM_GP12EMIIIh-54).**

Evaluate the total magnetic flux through an open surface. **(STEM_GP12EMIIIh-55).**

Describe the motion of a charged particle in a magnetic field in terms of its speed, acceleration, cyclotron radius, cyclotron frequency and kinetic energy **(STEM _GP12EMIIIh_58)**

Evaluate the magnetic force on an arbitrary wire segment placed in a uniform magnetic field **(STEM _GP12EMIIIh_59)**

I. WHAT HAPPENED

PRE-ACTIVITY:

Quicklab: Using your refrigerator magnets, try sliding the back of one refrigerator magnet in a circular path across the back of another one. What do you feel? Why is this so? Write your answers in your notebook/Activity Sheet.

Adapted from https://www.pinterest.ph/pin/544091198703785307/

Figure 1. Refrigerator magnets attached to the door of a refrigerator

PRE-TEST:

TRUE OR FALSE: Write **TRUE** if the statement is correct and **FALSE** if otherwise. Write your answer on your notebook/Answer Sheet.

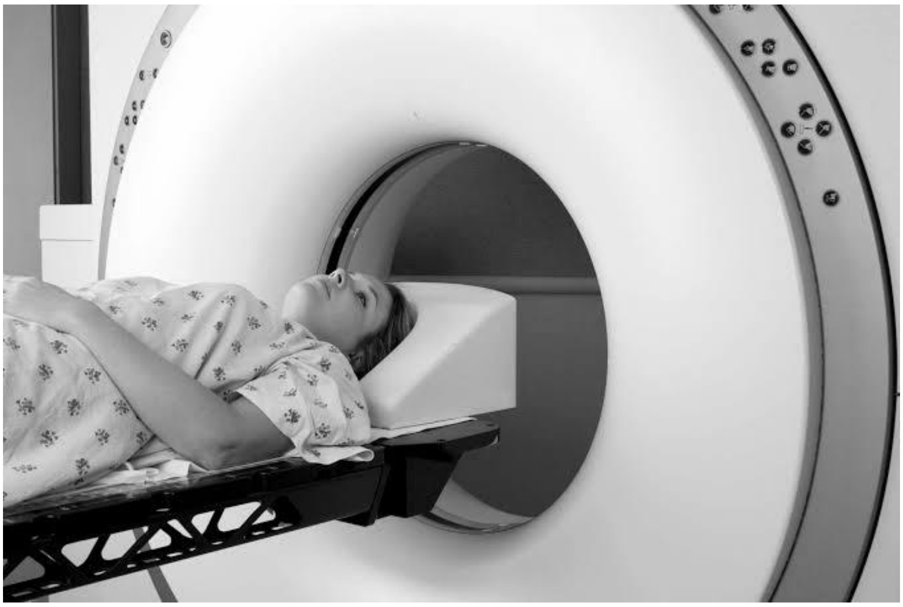
1. A north pole will always have a corresponding south pole in the same magnet.
2. The electric force acts on a charged particle regardless of whether the particle is moving.
3. Magnets are found in some commonly used medical equipment such as Magnetic Resonance Imaging Machines.
4. Magnetic poles exist in isolation like electric charges.
5. The magnetic force acts on a charged particle only when the particles are in motion.
6. The magnetic force changes the direction of the velocity and the magnitude of the velocity or speed.

7. Magnetic forces exert work on particles and change their kinetic energy.
8. The magnetron was invented by E. O. Lawrence and M. S. Livingston in 1934 to accelerate particles
9. The magnetic force on a charged particle moving through a region with a magnetic field is always parallel to the velocity of the particle.
10. Electric current is an ordered movement of charge.

II. WHAT I NEED TO KNOW

DISCUSSION:

Magnets are found in some commonly used medical equipment such as Magnetic Resonance Imaging Machines. MRIs use powerful magnetic fields to generate a radar-like radio signal from inside the body, using the signal to create a clear, detailed picture of bones, organs and other tissue. An MRI magnet is very strong – thousands of times more powerful than common kitchen magnets. Another medical use for magnets is for treating cancer. A doctor injects a magnetically-sensitive fluid into the cancer area and uses a powerful magnet to generate heat in the body. The heat kills the cancer cells without harming healthy organs.



Adapted from https://www.nhs.uk/conditions/mri-scan/

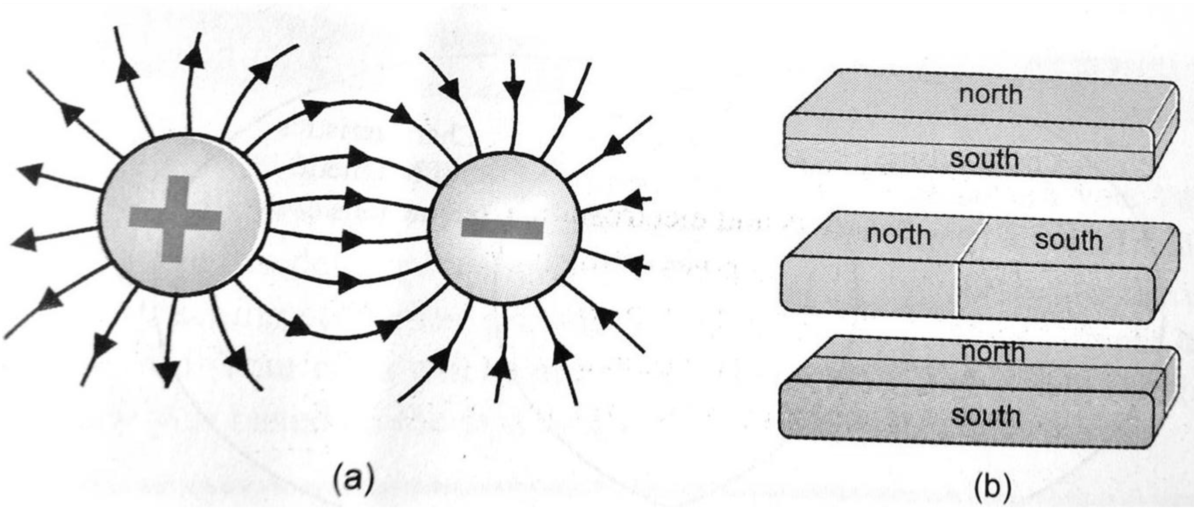
Figure 2. An MRI machine uses powerful magnetic fields to generate a radar-like radio signal from inside the body

The Magnetic Poles, Magnetic Force and Magnetic Field

Interactions of Magnetic Poles and Magnetic Force

Just like electric charges, a magnetic pole exists as either a north-seeking pole or a south-seeking pole. These poles are commonly known as the *north pole* and the *south pole* of a magnet. How they interact with one another is similar to how electric charges interact. Like poles repel, and unlike ones attract each other. The repulsion and attraction are caused by the **magnetic force** that exists between magnetic poles.

However, magnetic poles exist in isolation like electric charges. A negative charge can exist by itself as well as a positive charge. On the other hand, a north pole will always have a corresponding south pole in the same magnet. Breaking a magnet in half will only produce a smaller magnet with both a north pole and a south pole.



Adapted from DIWA Learning System, Inc.

Figure 3. (a) Electric charges may exist on their own; (b) the poles of a magnet cannot be separated even it is chopped into two

Electric and Magnetic Forces

There are several important differences between electric and magnetic forces:

- The electric force acts in the direction of the electric field, whereas the magnetic force acts perpendicular to the magnetic field.
- The electric force acts on a charged particle regardless of whether the particle is moving, whereas the magnetic force acts on a charged particle only when the particles is in motion.
- The electric force does work in displacing a charged particle, whereas the magnetic force associated with a steady magnetic field does no work when a particle is displaced.

From the last statement and on the basis of work – kinetic energy theorem, we conclude that the kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone. In other words,

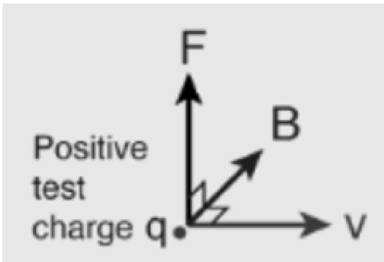
when a charged particle moves with a velocity ***v*** *through a magnetic field, the field can alter the direction of the velocity vector but cannot change the speed or kinetic energy of the particle.*

The Magnetic Field

In our study of electricity, we described the interactions between charged objects in terms of electric fields. Recall that an electric field surrounds any stationary or moving electric charge. In addition to an electric field, the region of space surrounding any moving electric charge also contains a *magnetic field*. A *magnetic field* also surrounds any magnetic substance.

Historically, the symbol $\boldsymbol{B}$ has been used to represent a magnetic field. The magnetic field $\boldsymbol{B}$ is defined from the *Lorentz Force Law (Lorentz's Forces are forces on electrically charged particles due to electromagnetic fields)*. The magnetic force on a moving charge is expressed as:

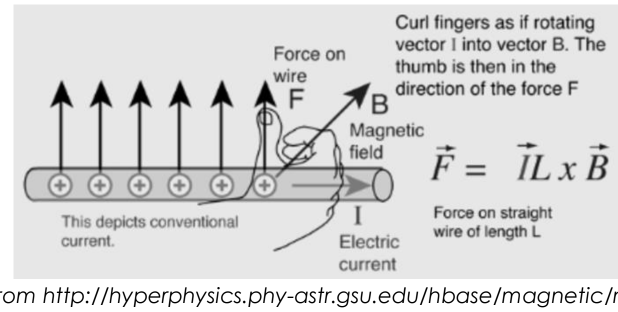
$$\boldsymbol{F = qv\,x\,B}$$



Adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html

The implications of this expression include:

- The force is perpendicular to both the velocity $\boldsymbol{v}$ of the charge $\boldsymbol{q}$ and the magnetic field $\boldsymbol{B}$.
- The magnitude of the force is $\boldsymbol{F = qvB}$ sin $\boldsymbol{\theta}$ is the angle $< \boldsymbol{180}$ degrees between the velocity and the magnetic field. This implies that the magnetic force on a stationary charge or a charge moving parallel to the magnetic field is zero.
- The direction of the force is given by the right-hand rule. The force relationship above is in the form of a vector product.



Adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html

When the magnetic force relationship is applied to a current-carrying wire, the right-hand rule may be used to determine the direction of force on the wire.

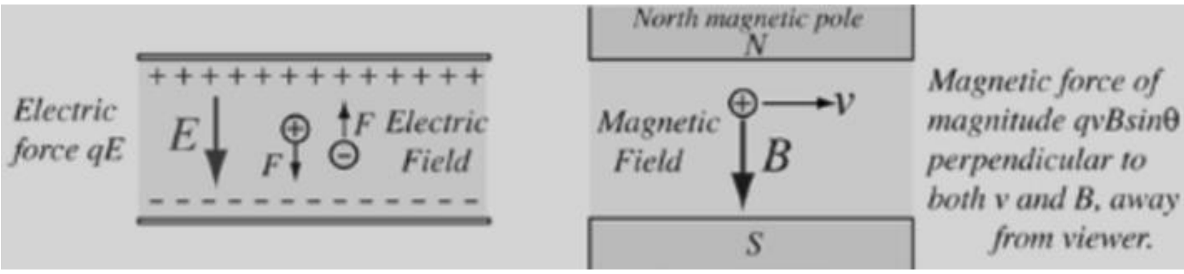
From the force relationship above, it can be deducted that the units of magnetic field are Newton seconds/ (Coulomb meter) or Newtons per Amper meter. This unit is named the Tesla. It is a large unit, and the smaller unit Gauss is used for small fields like the Earth's magnetic field. A Tesla is 10, 000 Gauss. The Earth's magnetic field at the surface is on the order of half a Gauss.

Lorentz Force Law

Both the electric field and magnetic field can be defined from the Lorentz force law:

$$\underbrace{F = qE}_{\text{Electric force}} + \underbrace{qv \times B}_{\text{Magnetic force}}$$

The electric force is straightforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnet part of the force is given by the right-hand rule.

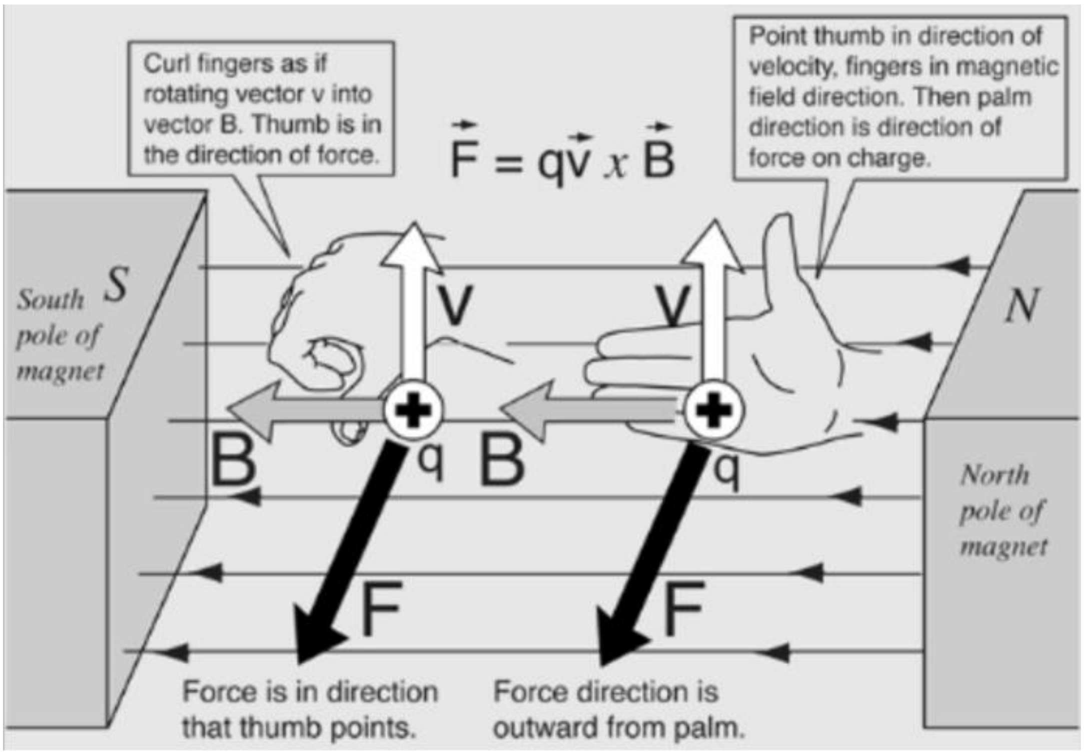


Adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html

Right-Hand Rule

The right-hand rule is a useful mnemonic for visualizing the direction of a magnetic force as given by the Lorentz force Law. The diagrams below are two of the forms used to visualize the force on a moving positive charge. The force is in the opposite direction for a negative charge moving in the direction shown. One fact to keep in mind is that the magnetic force is perpendicular to both the magnetic field and the charge velocity, but that leaves two possibilities. The right-hand rule just helps you pin down which of the two directions applies.

For applications to current-carrying wires, the conventional electric current direction can be substituted for the charge velocity v in the diagram below.



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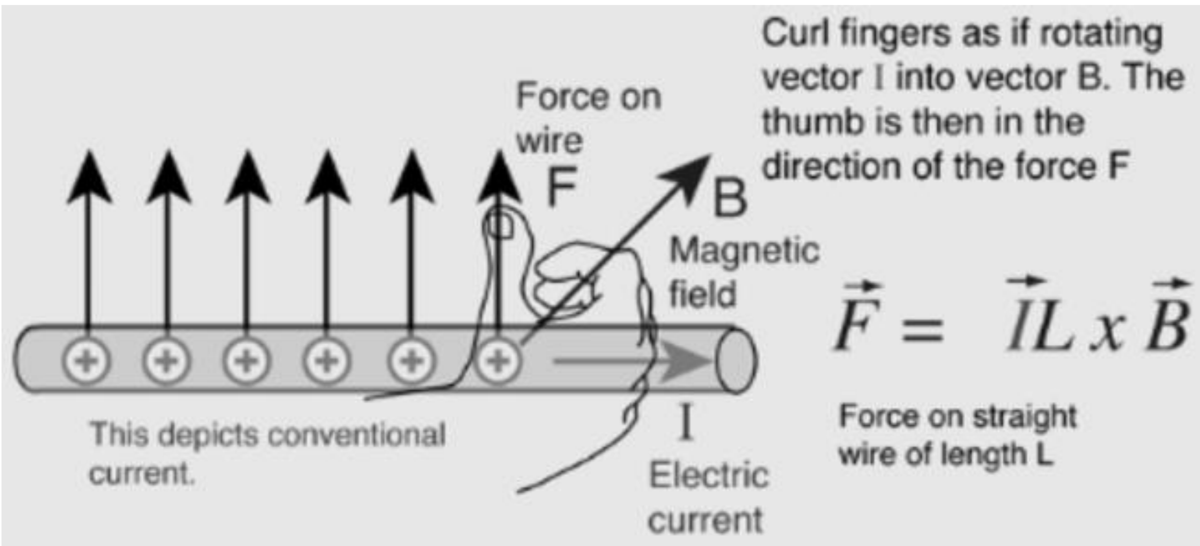
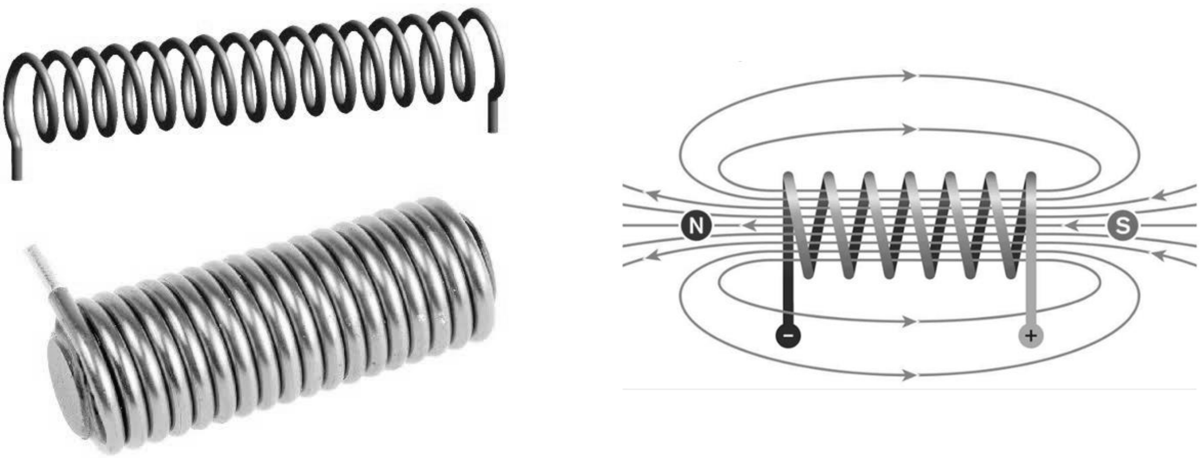


Adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html

Magnetic Effects of Different Materials

Suppose you have a long solenoid *(a long wire wound in the form of a helix)* placed in a vacuum, and a fixed current is supplied to the coil. An induced magnetic field *(B_{vacuum})* exists at a point in the solenoid. Filling the solenoid with a different material will yield a different magnetic field *(B).* Relating these two magnetic fields will produce a quantity referred to as the relative permeability of the material that was used to fill the solenoid.



Adapted from https://circuitdigest.com/article/what-is-solenoid-its-working-principle-and-types

Figure 4. A solenoid, a long wire wound in the form of a helix

Mathematically, this quantity is computed as follows:

$$k_m = \frac{B}{B_{vacuum}}$$

In this equation, the magnetic field is characterized by the letter $\boldsymbol{B}$, and $\boldsymbol{k_m}$ is a material's magnetic permeability.

Relating the relative permeability of a material to the permeability of free space or vacuum ($\mu_0 = 4\pi \; x \; 10^7 \; T - m/A$) yields the permeability of the material mathematically expressed as:

$$\mu = k_m \mu_0$$

The table below summarizes the various effects of the value of k_m on the magnetic field inside the solenoid as different materials fill it up instead of a mere vacuum.

Table 1. Effects of different values of k_m

Type of Material	k_m	**Effect on the Magnetic Field of the Solenoid**
Diamagnetic	Slightly lower than 1	Slightly decreases B
Paramagnetic	Slightly higher than 1	Slightly increases B
Ferromagnetic	50 or larger	Greatly increases B

Adapted from DIWA Learning Systems Inc.

Magnetic Flux

Every magnetic pole is surrounded by a magnetic field, wherein the magnetic force from the pole could affect other magnetic poles. The strength of this force wears out by moving farther from another pole. The measurement of the strength of the magnetic force from the pole is referred to as the **magnetic flux.** Mathematically, this is computed using the equation:

$$\Phi = BA\cos\varphi$$

In this expression, Φ is the magnetic flux, B is the calculated magnetic field of the pole, A is the surface from where magnetic flux is being measured, and φ is the angle between the magnetic field lines and the line normal to A. Magnetic flux is measured using the unit Weber *(Wb).*

Example1:

A 40-cm solenoid with a cross-sectional area of 8 cm^2 is wound with 300 turns of wire and made to carry a current of .2 A. Its core has a relative permeability of 600. Calculate the flux in the solenoid.

Solution: The 40-cm solenoid generates a magnetic field in vacuum computed as follows:

$$B_{vacuum} = \frac{\mu_0 NI}{L} = \frac{(4\pi\, x\, 10^{-7} T \cdot m/A)\,(300\, turns)\,(1.2\, A)}{0.40\, m} \approx 1.13\, mT$$

Consider that the core has K_m value of 600. Thus, you have:

$$B = k_m B_{vacuum} = (600)\,(1.13\, x\, 10^{-3}\, T) \approx \mathbf{0.68\, T}$$

Note that because the field lines are perpendicular to the cross section of the solenoid, the magnetic flux is thus computed as follows:

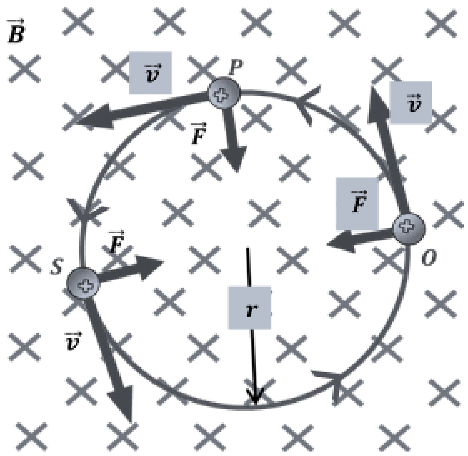
$$\Phi = BA \approx (0.68\, T)(8\, x 10^{4}\, m^2) \approx 54 \mu Wb$$

The flux in the solenoid is approximately $\mathbf{54\, \mu Wb.}$

> ***Big Idea:***
>
> *Magnetic poles have associated magnetic forces. Around each magnetic pole is a magnetic field. This field has a strength measured by the magnetic flux.*

Motion of Charged Particles in a Magnetic Field

The magnetic force on a charged particle moving through a region with a magnetic field is always perpendicular to the velocity of the particle. The magnetic force therefore changes the direction of the velocity but not the magnitude of the velocity or speed. The motion of a charged particle under the action of a magnetic field alone is always motion with constant speed. Therefore, magnetic forces do not exert work on particles and do not change their kinetic energy.



(PAUL A. TIPLER 2008)

Figure 5. The orbit of a charged particle in a uniform magnetic field.

Figure 5 shows that the magnitudes of both force $\vec{F}$ and velocity $\vec{v}$ are constant. The directions of the force and velocity changed but their magnitudes are the same. The particle therefore moves under the influence of a constant-magnitude force that is always at right angles to the velocity of the particle.

We can use Newton's second law to relate the radius of the circle to the magnetic field and the speed of the particle. If the velocity is $\vec{v}$ the magnetic force on a particle that has charge q is given by $\vec{F} = q\vec{v} \times \vec{B}$. The magnitude of the net force is equal to qvB, because $\vec{v}$ and $\vec{B}$ are perpendicular.

Newton's second law gives

$$F = ma$$

$$qvB = m\frac{v^2}{r}$$

or

$$r = \frac{mv}{qB}$$

Equation 6.c-1

Where:

$r = radius$

$m = mass\ of\ the\ particle$

$v = velocity$

$q = charge$

$B = magnetic\ field\ of\ strength$

The period of the circular motion is the time it takes the particle to travel once around the circumference of the circle. The period is related to the speed by

$$T = \frac{2\pi r}{v}$$

Substituting for (Equation 6.c-1), we obtain the period of the particle's circular orbit, which is called the ***cyclotron period***:

$$T = \frac{2\pi\left(\frac{mv}{qB}\right)}{v} = \frac{2\pi m}{qB}$$

or

$$T = \frac{2\pi m}{qB}$$

Equation 6.c-2. Cyclotron Period

Where:
$T = cyclotron\ period$
$\pi = value\ of\ pi$
$m = mass\ of\ the\ particle$
$q = charge$
$B = magnetic\ field\ of\ strength$

The frequency of the circular motion, called the ***cyclotron frequency***, is the reciprocal of the period:

$$f = \frac{1}{T} = \frac{qB}{2\pi m}$$

so,

$$\omega = 2\pi f = \frac{q}{m}B$$

Equation 6.c-3. Cyclotron Frequency

Where:
$\omega = angular\ speed$
$\pi = value\ of\ pi$
$m = mass\ of\ the\ particle$
$q = charge$
$B = magnetic\ field\ of\ strength$
$f = frequency$

Note that the period and the frequency given by Equations 6.c-2 and 6.c-3 depend on the charge-to-mass ratio q/m but the period and the frequency are independent of the velocity v or the radius r. Two important applications of the circular motion of charged particles in a uniform magnetic field are the mass spectrometer and the cyclotron.

In a particle accelerator called a ***cyclotron***, particles moving in nearly circular paths are given a boost twice each revolution, increasing their energy and their orbital radii but not their angular speed or frequency. Similarly, one type of ***magnetron***, a common source of microwave radiation for microwave ovens and radar systems, emits radiation with a frequency equal to the frequency of circular motion of electrons in a vacuum chamber between the poles of a magnet.

Example 2: Cyclotron Period

A proton has a mass equal to $\mathbf{1.67 \times 10^{-27} kg}$, has a charge equal to $\mathbf{1.60 \times 10^{-19} C}$, and moves in a circle of radius $\boldsymbol{r = 21.0cm}$ perpendicular to a magnetic field equal to $\mathbf{4000\ G}$. Find (a) the speed of the proton and (b) the period of the motion.

Strategy: Apply Newton's second law to find the speed and use distance equals speed multiplied by time to find the period.

Solution:

(a) 1. Apply Newton's second law ($\boldsymbol{F = ma}$):

$$\boldsymbol{F = ma} \quad \Longrightarrow \quad \boldsymbol{qvB = m\frac{v^2}{r}} \quad \Longrightarrow \quad \boldsymbol{r = \frac{mv}{qB}}$$

2. Solve for speed:

$$\boldsymbol{v = \frac{rqB}{m} = \frac{(0.210\ m)(1.60 \times 10^{-19} C)(0.400 T)}{1.67 \times 10^{-27} kg}}$$

$$= \boxed{\mathbf{8.05 \times 10^{6} m/s = 0.0268c}}$$

(b) Use distance equals speed multiplied by time and solve for the period:

$$\boldsymbol{2\pi r = vT}$$

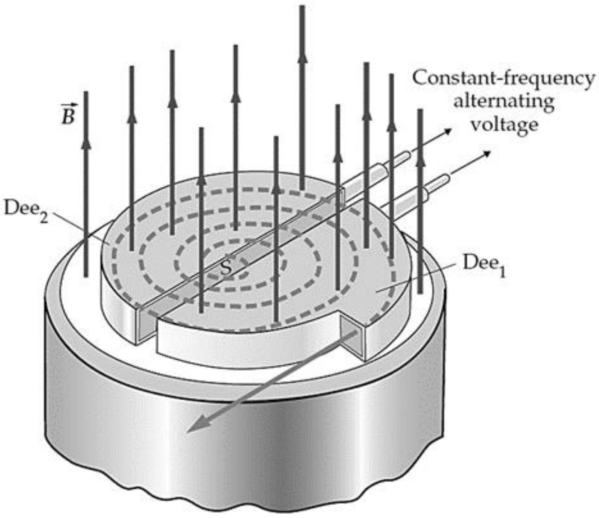
So,

$$\boldsymbol{T = \frac{2\pi r}{v} = \frac{2\pi(0.210m)}{(8.05 \times 10^{6} m/s)}} = \boxed{\mathbf{1.64 \times 10^{-7} s = 164\ ns}}$$

Discussion: The radius of the circular orbit is proportional to the speed, but the period of the orbit is independent of both the speed and radius.

The Cyclotron

The cyclotron was invented by **E. O. Lawrence and M. S. Livingston in 1934** to accelerate particles, such as protons or deuterons, to large kinetic energies. The high energy particles are used to bombard atomic nuclei, causing nuclear reactions that are then studied to obtain information about nuclei. High-energy protons and deuterons are also used to produce radioactive materials and for medical purposes.



(PAUL A. TIPLER 2008)

Figure 6. Schematic drawing of a cyclotron. The upper-pole face of the magnet has been omitted. Charged particles, such as protons, are accelerated from a source S at the center by the potential difference across the gap between the dees. When the charged particles arrive at the gap again the potential difference has changed sign, so they are again accelerated across the gap and move in a larger circle. The potential difference across the gap alternates with the cyclotron frequency of the particle, which is independent of the radius of the circle.

The kinetic energy of a particle leaving a cyclotron can be calculated by setting $\boldsymbol{r}$ in Equation 6.c-1, to the equal maximum radius of the dees and solving the equation for $\boldsymbol{v}$:

$$\boldsymbol{r = \frac{mv}{qB}}$$

then

$$\boldsymbol{K = \frac{1}{2}mv^2 = \frac{1}{2}\left(\frac{q^2B^2}{m}\right)r^2}$$

Equation 6.c-4. Kinetic energy of a particle leaving a cyclotron

Example 3: ENERGY OF ACCELERATED PROTON

A cyclotron for accelerating protons has a magnetic field of 0.150 T and a maximum radius of 0.500 m. (a) What is the cyclotron frequency? (b) What is the kinetic energy of the protons when they emerge?

$\boldsymbol{Mass\ (m)\ proton\ = 1.67 \times 10^{-27} kg}$,
$\boldsymbol{Charge\ (q)\ proton = 1.60 \times 10^{-19} C}$.

Strategy:

Apply Newton's second law $\boldsymbol{F = ma}$ with $\boldsymbol{\vec{F} = q\vec{v} \times \vec{B}}$. Use $\boldsymbol{v = r\omega}$ and solve for the frequency and the speed.

Solution:

(a) 1. Apply $\boldsymbol{F = ma}$, where $\boldsymbol{F}$ is the magnetic force and $\boldsymbol{a}$ is the centripetal acceleration. Substitute $\boldsymbol{r\omega}$ for $\boldsymbol{v}$ and solve for $\boldsymbol{\omega}$**.**

$$\boldsymbol{F = ma}$$

$$\boldsymbol{qvB = m\frac{v^2}{r}}$$

$$\boldsymbol{qr\omega B = m\frac{r^2\omega^2}{r}}$$

$$\boldsymbol{\omega = \frac{qB}{m} = \frac{(1.60 \times 10^{-19}\ C)(0.150T)}{1.67 \times 10^{-27} kg}}$$

$$\boldsymbol{= 1.44 \times 10^{7}\ rad/s}$$

2. Use $\boldsymbol{2\pi f = \omega}$ to calculate the frequency in cycles per second (hertz):

$$\boldsymbol{f = \frac{\omega}{2\pi} = \frac{1.44 \times 10^{7}\ rad/s}{2\pi\ rad}}$$

$$\boldsymbol{= 2.29 \times 10^{6}\ Hz = 2.29\ MHz}$$

(See next page for the continuation)

Continuation: *Example 3:* ENERGY OF ACCELERATED PROTON

(b) 1. Calculate the kinetic energy:

$$\boldsymbol{K = \frac{1}{2}mv^2 = \frac{1}{2}mr^2\omega^2}$$

$$\boldsymbol{= \frac{1}{2}(1.67 \times 10^{-27}kg)(1.44 \times 10^7\ rad/s)^2(0.500m)^2}$$

$$\boldsymbol{= 4.33 \times 10^{-14}\ J}$$

2. The energies of protons and other elementary particles are usually expressed in electron volts. Use $\boldsymbol{1\ eV = 1.60 \times 10^{-19}\ J}$ to convert to eV:

$$\boldsymbol{K = 4.33 \times 10^{-14}\ J \times \frac{1\ eV}{1.60 \times 10^{-19}\ J} = 271\ keV}$$

Discussion:

The exit speed of the proton is $\boldsymbol{v = r\omega = (0.500\ m)(1.44 \times 10^7\ rad/s) = 7.20 \times 10^6\ m/s}$. The speed of light is $\boldsymbol{3.00 \times 10^8\ m/s}$. Our calculated value of $\boldsymbol{1.44 \times 10^7\ rad/s}$ for the angular frequency is plausible because it is a high speed that is less than ten percent of the speed of light.

SOLVE THIS! (Problem #1)

Now that we have learned about Motion of Charged Particles in a Magnetic Field and The Cyclotron, we can now apply what we have learned by answering the following problem.

Read the problem carefully and solve it on your notebook, don't forget to show your solution.

A cyclotron for accelerating protons has a maximum radius of 0.700 m and has a magnetic field of 0.200 T. (a) What is the cyclotron frequency? (b) What is the kinetic energy of the protons when they emerge? (10 points)

Magnetic Force on a Current-Carrying Conductor

Calculating the Magnetic Force

Electric current is an ordered movement of charge. A current carrying wire in a magnetic field must therefore experience a force due to the field. To investigate this force, let's consider the infinitesimal section of wire as shown in Figure 8. The length and cross-sectional area of the section are $\boldsymbol{dl}$ and $\boldsymbol{A}$, respectively, so its volume $\boldsymbol{V = A \cdot dl}$. The wire is formed from material that contains $\boldsymbol{n}$ charge carriers per unit volume, so the number of charge carriers in the section is $\boldsymbol{nA \cdot dl}$. If the charge carriers move with drift velocity $\vec{\boldsymbol{v}}_{\boldsymbol{d}}$ the current $\boldsymbol{I}$ in the wire is

$$\boldsymbol{I = neAv_d}$$

The magnetic force on any single charge carrier is $\boldsymbol{e\vec{v}_d \times \vec{B}}$, so the total magnetic field $\boldsymbol{d\vec{F}}$ on the $\boldsymbol{nA \cdot dl}$ charge carriers in the section of the wire is

$$\boldsymbol{d\vec{F} = (nA \cdot dl)e\vec{v}_d \times \vec{B}}$$

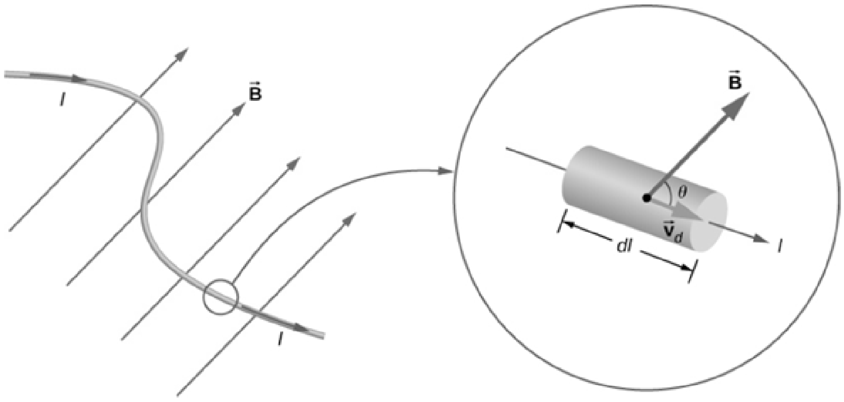
We can define $\boldsymbol{dl}$ to be a vector of length $\boldsymbol{dl}$ pointing along $\vec{\boldsymbol{v}}_{\boldsymbol{d}}$, which allows us to rewrite this equation

$$\boldsymbol{d\vec{F} = neAv_d d\vec{l} \times \vec{B}}$$

or

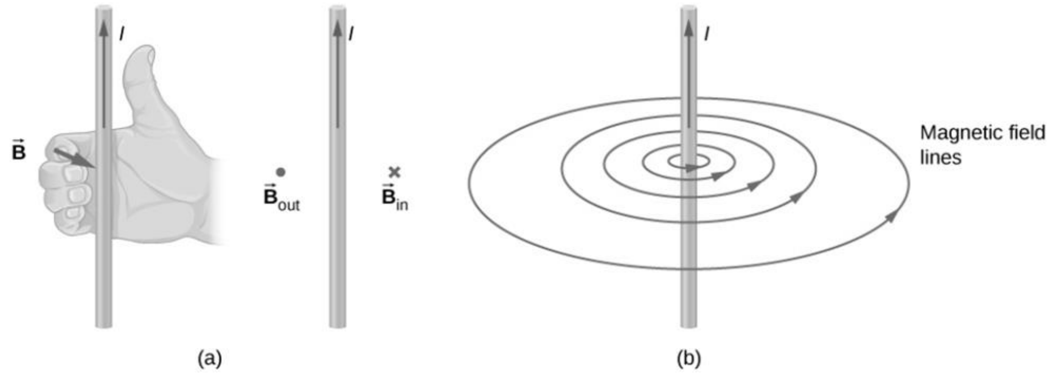
$$\boldsymbol{d\vec{F} = Id\vec{l} \times \vec{B}}$$

This is the magnetic force on the section of wire. Observe that it is actually the net or total force exerted by the field on the charge carriers themselves. The direction of this force is given by RHR-1, where you point your fingers in the direction of the current and curl them toward the field. Your thumb then points in the direction of the force.



(Ling, Loyola and Moebs 2016)

Figure 7. An infinitesimal section of current-carrying wire in a magnetic field**.**



(Ling, Loyola and Moebs 2016)

Figure 8. **(**a) When the wire is in the plane of the paper, the field is perpendicular to the paper. Note the symbols used for the field pointing inward (like the tail of an arrow) and the field pointing outward (like the tip of an arrow). (b) A long and straight wire creates a field with magnetic field lines forming circular loops.

To determine the magnetic force $\vec{F}$ on a wire of arbitrary length and shape. If the wire section happens to be straight and $\boldsymbol{B}$ is uniform, the equation differentials become absolute quantities, giving us

$$\vec{F} = I\vec{l} \times \vec{B}$$

This is the force on a straight, current-carrying wire in a uniform magnetic field.

Example 4: Calculating Magnetic Force on a Current-Carrying Wire

A long, rigid wire lying along the y-axis carries a $\mathbf{5.0}\ \boldsymbol{A}$ current flowing in the positive y-direction. (a) If a constant magnetic field of magnitude $\mathbf{0.30}\ \boldsymbol{T}$ is directed along the positive x-axis, what is the magnetic force per unit length on the wire? (b) If a constant magnetic field of $\mathbf{0.30}\ \boldsymbol{T}$ is directed 30 degrees from the +x-axis towards the +y-axis, what is the magnetic force per unit length on the wire?

Strategy:

The magnetic force on a current-carrying wire in a magnetic field is given by $\vec{F} = I\vec{l} \times \vec{B}$. For part a, since the current and magnetic field are perpendicular in this problem, we can simplify the formula to give us the magnitude and find the direction through the RHR-1. The angle $\boldsymbol{\theta}$ is 90 degrees, which means $\sin\theta = 1$. Also, the length can be divided over to the left-hand side to find the force per unit length. For part b, the current times length is written in unit vector notation, as well as the magnetic field. After the cross product is taken, the directionality is evident by the resulting unit vector.

Solution:

1. We start with the general formula for the magnetic force on a wire. We are looking for the force per unit length, so we divide by the length to bring it to the left-hand side. We also set $\boldsymbol{sin\ \theta}$. The solution therefore is

$$\boldsymbol{F = IlBsin\ \theta}$$

$$\boldsymbol{\frac{F}{l} = (5.0\ A)(0.30\ T)}$$

$$\boldsymbol{\frac{F}{l} = 1.5\ N/m}$$

Directionality: Point your fingers in the positive **y**-direction and curl your fingers in the positive **x**-direction. Your thumb will point in the $-\vec{\boldsymbol{k}}$ direction. Therefore, with directionality, the solution is

$$\boldsymbol{\frac{\vec{F}}{l} = -1.5\ \vec{k}\ N/m}$$

2. The current times length and the magnetic field are written in unit vector notation. Then, we take the cross product to find the force:

$$\boldsymbol{\vec{F} = I\vec{l} \times \vec{B} = (5.0\ A)l\hat{j} \times (0.30T\ cos(30°)\hat{\imath}}$$

$$\boldsymbol{\vec{F}/l = 1.30\hat{k}N/m}$$

Discussion:

This large magnetic field creates a significant force on a small length of wire. As the angle of the magnetic field becomes more closely aligned to the current in the wire, there is less of a force on it, as seen from comparing parts a and b.

PERFORMANCE TASK:

Congratulations young scientist for reaching this far! Let us test your understanding about the previous topic by answering the following problem.

Read the problem carefully and solve it on your notebook, don't forget to show your solution.

Lying along the y-axis is a long, rigid wire which carries an **8.0 A** current flowing in the positive direction. (a) A **0.20 T** constant magnetic field is directed along the positive x-axis, find the magnetic force per unit length on the wire. (b) If a **0.20** T constant magnetic force is directed **45 degrees** from the +x-axis towards the +y-axis, solve for the magnetic force per unit length of the wire. (10 points)

III. WHAT I HAVE LEARNED

EVALUATION/POST-TEST:

I. **TRUE OR FALSE:** Write **TRUE** if the statement is correct and **FALSE** if otherwise. Write your answer on your notebook/Answer Sheet.

1. Magnetic poles exist in isolation like electric charges.
2. A north pole will always have a corresponding south pole in the same magnet.
3. The magnetic force acts in the direction of the electric field.
4. The magnetic force acts on a charged particle only when the particles are in motion.
5. The electric force acts on a charged particle regardless of whether the particle is moving.
6. The magnetic force associated with a steady magnetic field does work when a particle is displaced.
7. When a charged particle moves with a velocity ***v*** through a magnetic field, the field cannot alter the direction of the velocity vector but cannot change the speed or kinetic energy of the particle.
8. Magnets are found in some commonly used medical equipment such as Magnetic Resonance Imaging Machines.
9. Another medical use for magnets is for treating cancer.
10. Magnetic flux is the measurement of the strength of the magnetic force from the pole.
11. Electric current is an ordered movement of charge.
12. Magnetic forces exert work on particles and change their kinetic energy.
13. In a cyclotron, particles moving in nearly circular paths are given a boost twice each revolution.
14. The magnetic force on a charged particle moving through a region with a magnetic field is always parallel to the velocity of the particle.
15. The magnetic force changes the direction of the velocity and the magnitude of the velocity or speed.
16. A current carrying wire in a magnetic field must therefore experience a force due to the field.
17. The magnetron was invented by E. O. Lawrence and M. S. Livingston in 1934 to accelerate particles
18. Newton’s second law to relate the radius of the circle to the magnetic field and the speed of the particle.
19. The period of the particle’s circular orbit is called the cyclotron frequency.
20. Cyclotron frequency is the reciprocal of the cyclotron period.

II. **PROBLEM SOLVING**: Answer the given problems below. Show your solutions in your notebook/Activity Sheet.

1. A circular antenna of area $3m^2$ is installed at a particular place. The plane of the area of antenna is inclined at 47^0 with the direction of Earth's magnetic field. If the magnitude of Earth's field at that place is 40773.9 nT, find the magnetic flux linked with the antenna.

2. A cyclotron for accelerating protons has a maximum radius of 0.600 m and has a magnetic field of 0.150 T. (a) What is the cyclotron frequency? (b) What is the kinetic energy of the protons when they emerge? $\boldsymbol{Mass\ (m)\ proton\ = 1.67 \times 10^{-27} kg}$, $\boldsymbol{Charge\ (q)\ proton = 1.60 \times 10^{-19} C}$.

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SYNOPSIS AND ABOUT THE AUTHORS

This Self-Learning Kit gives emphasis on the differences between electric and magnetic interactions. Magnetic poles exist in isolation like electric charges. A negative charge can exist by itself as well as a positive charge. On the other hand, a north pole will always have a corresponding south pole in the same magnet. Breaking a magnet in half will only produce a smaller magnet with both a north pole and a south pole.

Moreover, Lorentz's Forces are forces on electrically charged particles due to electromagnetic fields. Both the electric field and magnetic field can be defined from the Lorentz force law:

$$\underbrace{F = qE}_{\text{Electric force}} + \underbrace{qv\,x\,B}_{\text{Magnetic force}}$$

Magnetic flux on the other hand, is the measurement of the strength of the magnetic force from the pole. Mathematically, this is computed using the equation $\Phi = BA\cos\varphi$ and is measured using the unit Weber *(Wb).*

In terms of motion of charged particles in a magnetic field, the magnetic force on a charged particle moving through a region with a magnetic field is always perpendicular to the velocity of the particle. The magnetic force therefore changes the direction of the velocity but not the magnitude of the velocity or speed. The motion of a charged particle under the action of a magnetic field alone is always motion with constant speed. Therefore, magnetic forces do not exert work on particles and do not change their kinetic energy.

ANSWER KEY

Pre-Activity:

- Answers of students may vary depending on their observations.

Pre-Test:

1. TRUE	6. FALSE
2. TRUE	7. FALSE
3. TRUE	8. FALSE
4. TRUE	9. FALSE
5. TRUE	10. TRUE

Solve This! Problem #1:

a.1. $\omega = 1.92 \, x \, 10^7 \, rad/s$
a.2. $f = 3.06 \, x \, 10^6 Hz = 3.06 \, MHz$
b.1. $K = 1.51 \, X \, 10^{-13} J$
b.2. $K = 944 \, keV$

Evaluation/Post-Test

I. True or False:

1. TRUE	11. TRUE
2. TRUE	12. FALSE
3. FALSE	13. TRUE
4. TRUE	14. FALSE
5. TRUE	15. FALSE
6. FALSE	16. TRUE
7. FALSE	17. FALSE
8. TRUE	18. TRUE
9. TRUE	19. FALSE
10. TRUE	20. TRUE

II. Problem Solving:

1. $89.47 \, \mu Wb$
2. (a.1) $\omega = 1.44 \, x \, 10^7 rad/s$
(a.2) $f = 2.29 \, x10^6 Hz = 2.29 \, MHz$
(b.1) $K = 6.33 \, x10^{-14} J$
(b.2) $K = 389 \, keV$

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