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Mechanical Phenomenon of Moving Charged Particles in Electromagnetic Field.

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Abstract

A charged particle can move in a number of ways when both electric and magnetic fields are present, including straight-line motion, cycloid motion, and other complicated motions. The charged particle is accelerated by magnetic and electric forces. However, there is a limitation to the magnetic field since acceleration caused by the magnetic field only applies to changes in motion direction. The particle is prone to move in a circular trajectory due to magnetic force, which is always normal to the particle's velocity. The electric force, on the other hand, runs parallel to the electric field and can modify the direction and amount of the force depending on the starting direction of motion of the charged particle with regard to the electric field. When the vectors of velocity and electricity are at an angle, the particle travels in a parabolic path. "cross fields" refers to one of the significant electric and magnetic field orientations. When magnetic and electric fields are present at right angles at the same time, this is referred to as having "crossing fields." In the study of electromagnetic measurement and application, the behavior of charged particles such as electrons under crossed fields is crucial. Here, the trajectory of the moving charged particles are observed at different positions with varying magnetic fields. Phase space of the charged particles are also observed in different orientations by using the Fortran codes which is found in accordance with the theoretical order.

Keywords: Electromagnetic fields, Phase space, Lorentz force, Trajectory.

1. Introduction

The study of electromagnetic forces, a form of physical interaction that happens between charged particles, is the focus of the branch of physics known as electromagnetism. Electric fields, magnetic fields, and light are examples of electromagnetic fields that are typically produced by electromagnetic force. One of the four basic interactions in nature is the electromagnetic force. The Lorentz force is the result of the combined action of the electric and magnetic forces of an electromagnetic field on a moving point-charged particle [1]. An electric field E and a magnetic field B exert a force on a charged particle traveling at speed v is given by

$$\boldsymbol{F} = q\boldsymbol{E} + q(\boldsymbol{v} \times \boldsymbol{B}) \qquad (1)$$

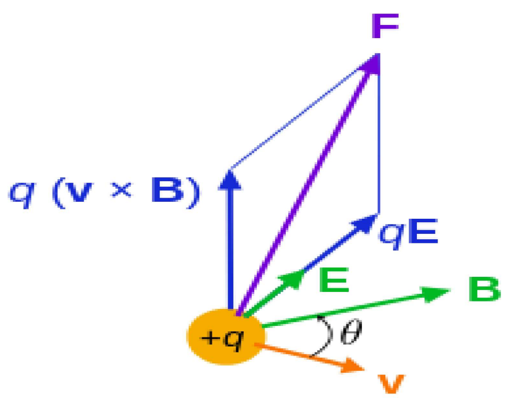

Figure 1: Lorentz force on a charged particle (of charge q) in motion. [2]

Electric fields and magnetic fields vary in space and time. It was found in a paper published by James Clerk

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Maxwell in 1865 and Hendrik Lorentz [3] arrived at a complete derivation in 1895[4], identifying the contribution of the electric force a few years after Oliver Heaviside correctly identified the contribution of the magnetic force [5]. It is valid even for particles moving with the speed of the light. (i.e.**v**≈c) [6]

$F_x = q(E_x + v_y B_z - v_z B_y)$ (2)

$F_y = q(E_y + v_z B_x - v_x B_z)$ (3)

$F_z = q(E_z + v_x B_y - v_y B_x)$ (4)

The component of the velocity parallel to the field is unaffected since the magnetic force is zero for motion parallel to the field. This produces helical motion (spiral motion) rather than circular motion. It shows how electrons not moving perpendicular to the magnetic field. In general, the electric and magnetic fields are functions of position and time. A particle moving in a magnetic field in the direction perpendicular to the magnetic field vector experiences a Lorentz force in the direction perpendicular to both the magnetic field and the velocity vector. This force imposes a gyration of the particle around the magnetic field, with a gyro-frequency is given by

$$\omega_c = \frac{qB}{m} \quad (5)$$

where q is the electric charge of the particle, B is the magnetic field magnitude, and m represents the mass of the particle. The radius of this gyration motion, known as the gyroradius,

$$r_c = \frac{v_\perp}{\omega_c} \quad (6)$$

where $v_\perp$ is the component of velocity perpendicular to the magnetic field. Note that the gyrofrequency is by convention never negative. However, the motion around the magnetic field is charge dependent, as ions will gyrate in such a way that the angular velocity vector is antiparallel with the magnetic field, and electrons will gyrate such as the angular velocity vector is parallel with the magnetic field. Fig. 2 shows a schematic representation of charge-dependent motion in a uniform magnetic field. If the particle's velocity has an arbitrary direction with respect to the magnetic field, it is convenient to decompose it into a perpendicular and parallel component with respect to the magnetic field, such that $v = v_\perp + v_\parallel$. Therefore, the equation of motion for a particle under the influence of an ambient uniform magnetic field, and in the absence of electric or gravitational fields,

$$m\frac{dv}{dt} = q\boldsymbol{v} \times \boldsymbol{B} \quad (7)$$

becomes

$$\frac{d\boldsymbol{v}_\parallel}{dt} + \frac{d\boldsymbol{v}_\perp}{dt} = \frac{q}{m}\,\boldsymbol{v} \times \boldsymbol{B} \quad (8)$$

Since the cross product $\boldsymbol{v}_\parallel \times \boldsymbol{B} = 0$, the motion of charged particles will in turn generate a magnetic field, which will tend to oppose the background field, which acts to reduce the external magnetic field. This is the reason that gases made up of charged particles are diamagnetic. For simplicity, let us assume that the velocity vector is prescribed as $v_0 = v_\perp, 0, v_\parallel$, and the vector radius of the guiding center is given by $r_g = 0, \pm r_c, v_\parallel \boldsymbol{t}$. The concept of the guiding center is intrinsic to the concept of a uniform homogeneous magnetic field, and the guiding center approximation only holds in regions where the magnetic field is strong and if the performs many gyrations in the timescale it experiences gradients in the field.

Now, if in addition to the uniform field, there is a uniform and constant external field (that can be gravity, electric field, etc.), then the equation of motion becomes [7]

$$m\frac{dv}{dt} = \boldsymbol{F} + q\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} \quad (9)$$

The drift produced by the external force F, due to its normal component to the magnetic field is given by

$$\boldsymbol{v_F} = \frac{\boldsymbol{F} \times \boldsymbol{B}}{q \times \boldsymbol{B}^2} \quad (10)$$

Furthermore, if we consider the motion of the charged particle in a medium where an external uniform electric field is applied, the drift due to electric field becomes [8]

$$v_E = \frac{\boldsymbol{E} \times \boldsymbol{B}}{\boldsymbol{B}^2} \quad (11)$$

Interestingly enough, this drift is charge independent, meaning that positively and negatively charged particles drift with the same speed and in the same direction, therefore this drift does not produce a net electric current.

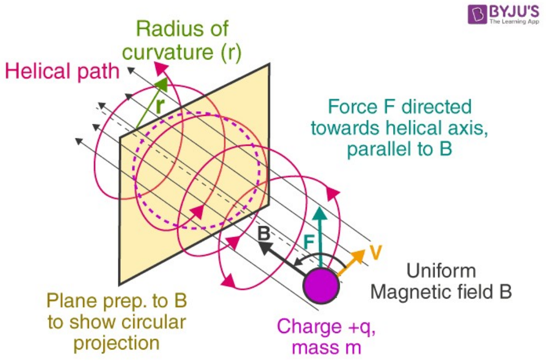

Fig 2: Helical motion of a moving charged particle in constant electromagnetic field.[9]

2. Materials and Method

It is research that combines a theoretical and computational approach. Here, different orientations of the applied electromagnetic fields have been used to examine the mechanical processes of moving charged particles in electromagnetic and simply magnetic fields. The trajectories and mechanical phenomena of moving charged particles in electromagnetic and magnetic fields have been studied using Fortran 90. Within the Fortran 90 environment, the trajectories are plotted using Xmgrace and gnuplot. [10]

3. Results and Discussion

Force due to both electric and magnetic forces will influence the motion of charged particles. However, the resulting change to the trajectory of the particles will differ qualitatively between the two forces. In a vacuum where collisions between particles are not very frequent a particle with charge q, mass m, and velocity v perpendicular to a uniform magnetic field B (no E) moves in a circular path with the specified radius. It can also deflect the trajectory of a charged particle with an electric field, although not into a circular path. If the electric force on the particle is both equal and opposite to the magnetic force, the net force on the particle will be zero. This work presents pedagogical overview of classical dynamics of charged particles in electromagnetic field.

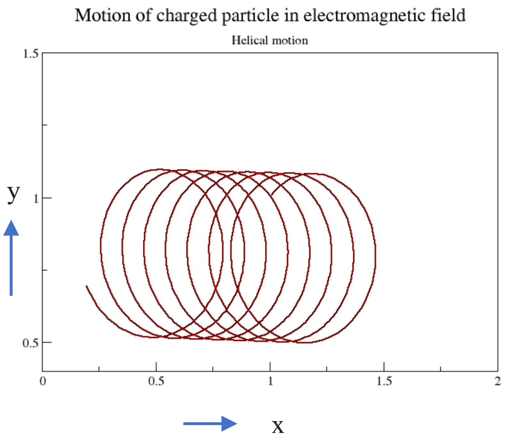

Figure 3 : Helical motion and magnetic mirror.

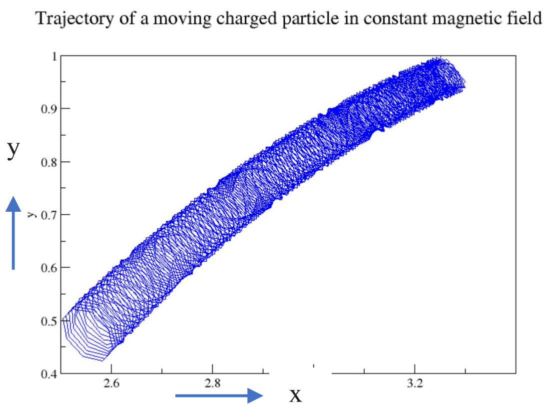

Figure 4: Trajectory of a moving charged particle in constant magnetic field.

Figure 3 shows the helical motion of a moving charged particle in uniform electromagnetic field whereas the figure 4 shows the trajectory of motion of a moving charged partilc in inclined magnetic field.

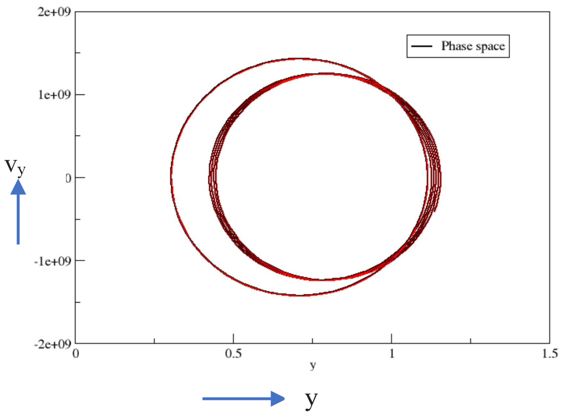

Fig 5: Phase space of moving charged particle in electromagnetic field

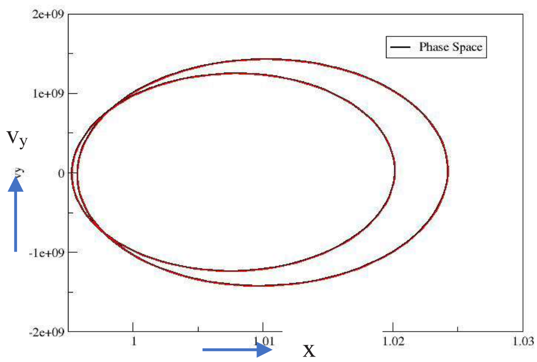

Fig 6: Phase space of moving charged particle in electromagnetic field

Figure 5 and 6 represent the phase space of the moving charged particle whereas figure 7 represents the resultant velocity in plane in the presence of external electromagnetic field.

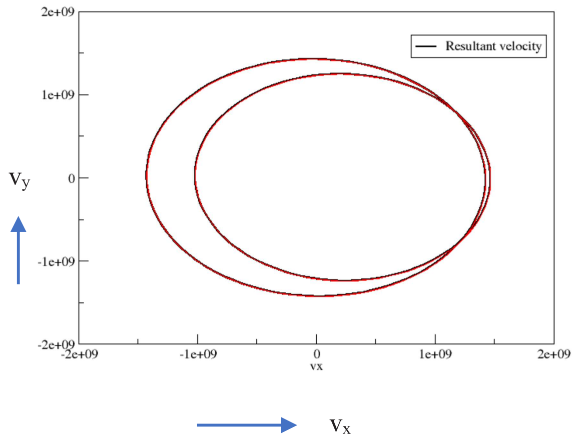

Fig 7: Resultant velocity of charged particle in electromagnetic field

4. Conclusions

Motion of charged particle in external electric and magnetic fields *i.e.* mechanical phenomena of Lorentz force is studied by using computational approach: by using Fortran codes. Investigation is carried out for three approaches on moving charged particle in combined electric and magnetic field, in constant magnetic field in plane and space. The interactions of the external electromagnetic field with the electromagnetic field of the moving charged particle are studied at different orientations which determine the trajectory of the charged particles. The trajectories of the particles resembled the circular motions and helical motions within the theoretical aspect.

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