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Understanding Cyclotron Motion: A Visual Approach to Electron Dynamics in Electric and Magnetic Fields

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Abstract

Physics material is often material that is difficult for students to understand because of its abstract concepts, one of which is in the material of electric and magnetic fields that discuss the motion of cyclotrons in connecting theoretical concepts and practical applications. Cyclotron motion is accelerated by an electric field that is influenced by the Lorentz force on the combination of electric and magnetic fields. This paper is made with the aim to analyze and visualize the electric field and magnetic field around the cyclotron motion particles using Python animation. In this study, a helix-shaped trajectory is used to represent the movement of electron particles. The animation developed depicts the electric and magnetic field vectors moving around the helix trajectory. In running the particle trajectory animation, numerical equations are involved. The involved numerical equations are second-order ordinary differential equations. This research not only provides theoretical insights into the electrostatic and magnetostatic properties of electron particles but also provides effective visualizations for further education and research. The resulting animation facilitates to enhance the understanding of the concept of how electric and magnetic fields interact and move in the context of electron particles moving in a helix trajectory, opening up opportunities for further exploration in the development of knowledge related to cyclotron motion that is often difficult to understand only through theoretical approaches.

Keywords: cyclotron, electron, electrostatic, magnetostatic

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INTRODUCTION

To study the complex concept of cyclotron motion, a medium that can visualize this learning process is needed (Esfahani et al., 2020). Visualization plays an important role as it helps bridge the gap between abstract theory and concrete understanding (Mahmudah, et al., 2024). In the case of cyclotron motion, which involves charged particles being accelerated in magnetic and electric fields, this concept can be difficult to grasp through verbal explanations or text alone (Tytler, 2020). The cyclotron is one of the oldest concepts in particle acceleration. Cyclotrons use a homogeneous magnetic field and resonantly driven accelerated electrodes. As the particle velocity increases, the radius of the electron orbit increases. Cyclotrons are utilized for nuclear research and the production of radioisotopes in medical and industrial applications (Calabretta, 2016). The cyclotron movement of charged particles has been studied in many physical theories. Charged particles, in general, are associated with quantum theory, as they can explain the properties of particles (Chiftja, Livingston, & Thomas, 2017). In classical theory, a charge in circular motion radiates and rotates downward toward the center of the circular motion due to radiation reactions (Katoh, et al., 2017). Quoted from Stenzel and Urrutia (2015), in 1990, a scientist named Poynting predicted that electromagnetic waves with circular polarization carry angular momentum, where the angular momentum comes from spin and orbital. The wave with orbital angular momentum will experience a spiral-shaped phase. In their research, Matevosyan and Allahverdyan (2021) found that a weak static magnetic field will cause particles to gain orbital magnetic moment even though it is very small, but not zero. In a cyclotron, a charged particle moving in a magnetic field experiences a Lorentz force that causes the particle to move in a circular trajectory with a radius determined by the particle's speed and the magnetic field's strength. As the particle moves in a circle, it emits electromagnetic radiation, causing the particle to lose energy. As a result, the particle decelerates, and its trajectory spirals towards the circle's center. A charged particle's motion equation in a uniform magnetic field has two normal modes: cyclotron motion and zero-frequency roots (Bellan, 2016). In this study, we will focus on cyclotron motion.

Cyclotron motion is a basic concept in electromagnetism and therefore, cyclotron motion is important to understand. However, students often encounter several misconceptions and difficulties when studying this topic. One common challenge is understanding the relationship between magnetic fields and the velocity of charged particles. Cyclotron motion is one example of the motion of a charged particle, such as an electron with a negative charge, under the influence of an external magnetic field. This magnetic field exerts a Lorentz force that acts as a centripetal force. When the particle's velocity vector is perpendicular to the magnetic field vector, the particle will move along a circular trajectory. If the particle's velocity vector is not perpendicular to the magnetic field vector, the particle's trajectory generally spirals. In this case, students often have difficulty visualizing how the magnetic force acts perpendicular to the particle velocity. Particles in cyclotron motion are also accelerated by the electric field. Further studies also revealed that in the dipole approximation and second-order perturbation theory, the shape of the electron wave function can affect the angular distribution of cyclotron radiation power. This leads to significant differences from the results predicted by classical theory (Khalaf et al., 2023). Cyclotron radiation itself is electromagnetic radiation emitted by a charged particle that occurs under the influence of the Lorentz force.

Electrostatic harmonic electron cyclotron waves are electrostatic radiation observed between harmonics of the electron cyclotron frequency and normal waves that are approximately perpendicular to the surrounding magnetic field (Lou et al., 2021). The oscillating electric field of harmonic electron cyclotron waves can exert a force on electrons, accelerating them in the direction of motion perpendicular to the magnetic field. This leads to an increase in the energization of the surrounding electrons, which allows a change in the dynamics of the harmonic electron cyclotron wave so that its intensity will increase. A decrease in density will create more favorable conditions for generating harmonic electron cyclotron waves. The relationship between the decrease in cold electron density and the increase in emission in harmonic electron cyclotrons indicates irregularities in plasma density that significantly impact the dynamics and particle energization process (Kazama et al., 2018). Quoted from Bellan (2016), the equations of motion of electron particles in magnetic and electric fields are given with analytic results that describe solutions in cartesian coordinates. This involves the x and y components of the particle motion, as well as the cyclotron frequency and other parameters. Quoted by Tarvainen et al. (2024), the application of cyclotron motion can be applied in radioactive ion beam (RIB) facilities, which in the study used an electron cyclotron resonance ion source (ECRIS), which is a type of cyclotron. It can be applied to RIB facilities to increase the production of radioactive isotopes used in various fields, including basic research in physics, nuclear medicine, and materials science.

The motion of the cyclotron is affected by the Lorentz force resulting from the combination of electric and magnetic fields. Magnetic field measurement methods are generally divided into two types: methods that use cartesian coordinates and polar coordinates. Using cartesian coordinates in magnetic field measurement is a complex method. Due to the circular shape of the internal cyclotron (hills and ropes), the movement of sensors on both sides of the x-y plane makes it more challenging to design than polar coordinates (Namgoong et al, 2023). Quoted from Hasdeo et al (2019), in a perpendicular magnetic field, electrons in an electron gas in two dimensions experience rapid cyclotron motion due to the Lorentz force. In addition, when an external electric field is applied, these electrons exhibit a slow shift of the Hall guide center perpendicular to the electric and magnetic fields. These fast (cyclotron) and slow (guide center) dynamics are closely related and form two sides of the magnetic displacement behavior. Then, Pikin, Pahl, and Wenander (2020) in their research said that if a decrease in magnetic field intensity occurs when a charged particle is in the decreasing phase of its cyclotron circular trajectory, the result is a reduction in the size of the circular trajectory (amplitude) of the particle's cyclotron motion. The cyclotron period is the time a charged particle (e.g. an electron or proton) takes to complete one full revolution in the magnetic field in a cyclotron, a type of particle accelerator. Typically, this period is measured in time units, such as milliseconds (ms), equivalent to one-thousandth of a second.

The calculation of the trajectory of an ion beam of charge q, velocity v is based on the Lorentz force F received by a charged particle in an electric field E and a magnetic field B. Velocity v is a function of position (x, y, z). In component terms, the velocity equation can be written as:

$$v = \sqrt{(v_x^2 + v_y^2 + v_2^2)} \tag{1}$$

his research aims to explore more deeply how magnetic and electric fields interact with each other in particle motion by showing a visualization of the particle trajectory of cyclotron motion. To display the visualization results, The main equations of motion of charges in magnetic and electric fields:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{2}$$

In solving problems related to science and engineering, various partial differential equation approaches are generally used (Burman, et al., 2015). With the help of PDE (Partial Differential Equation) numerical equations of ion motion in magnetic and electric fields that can support the visualization results are as follows:

$$\vec{v} = v_x\hat{x} + v_y\hat{y} + v_z\hat{z} \tag{3}$$

Thus, Singh (2019) provides an overview of cyclotron motion, which is crucial to ensure the interaction between particles in electric and magnetic fields. This is by what is stated by Vladimirov et al. (2015) that magnetic and electric fields play an important role in analyzing cyclotron motion. In application, this cyclotron motion can show a shift from the center perpendicular to the electric and magnetic fields. This research aims to overcome difficulties by using a visualization tool designed to make the concept of cyclotron motion easier to understand. By providing dynamic visual representations of magnetic forces and particle trajectories, the tool aims to clearly illustrate and support students in achieving a deeper understanding of electromagnetism.

METHOD

System Design Method This research method is carried out by making a Python programming simulation and visualizing how the movement pattern of the cyclotron motion. In this research, the steps taken are making a visualization program on computer software. In making this program, Google Collab software is used to display the results of the visualization of the cyclotron motion movement. Media visuals such as animations, interactive simulations, or dynamic graphics can make this phenomenon more accessible and understandable for students (Cardoso et al., 2024). By viewing visual representations of particle motion in a cyclotron, students can more easily imagine how the particles move in a magnetic field, how their speed increases, and how their trajectories curve (Zhou et al., 2024). Visualization also allows students to observe the effects of changing certain parameters, such as the strength of the magnetic field or the initial speed of particles (Poirier et al., 2019). Such interactions not only deepen understanding but also enhance student engagement in the learning process, as they can see the direct impact of the concepts being studied.

The output results that we want in this visualization are in the form of a 3-dimensional display, where the x-axis will represent the x position (m), the y-axis will represent the y position (m), and the z-axis will represent the z position (m). In the 3-dimensional visualization, the shape of the movement pattern of the cyclotron motion or cycloid trajectory will be displayed.

System Implementation

After designing the system, a Python programming simulation is made to solve complex problems systematically. The creation of this simulation begins with stating the problem clearly which includes the purpose of the simulation, problem boundaries, and expected results. The problem statement of this research is to simulate the motion of a cyclotron in electric and magnetic fields using the Euler method. Next, the design of this simulation is continued by writing mathematical equations that describe the system to be simulated. This study uses numerical PDE (Partial Differential Equation) equations of ion motion in magnetic and electric fields. Then, an algorithm is developed that will be used to solve the equations that have been written. The algorithm starts with importing the module, initiating constants and initial parameters, position, and velocity. The algorithm also initiates the charge direction, electric field direction, and magnetic field direction. Next, functions are created to display the visualization animation results. After that, the algorithm is made in the form of a flowchart, and then the steps in the algorithm are implemented directly in Python code to run in order to produce a visualization of cyclotron motion.

RESULTS AND DISCUSSION

The Lorentz force is the force exerted on an electrically charged particle (an electron) moving in a magnetic field and an electric field. The equation gives this force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{4}$$

The calculation of the trajectory of a velocity charge ion beam is based on the forces received by charged particles in electric and magnetic fields. The electric field E is a function of position (x, y, z) and time (t), while the magnetic field B is a function of position only. The magnitude of these two fields can be obtained from simulation calculations and measurements. A cyclotron is a particle accelerator that uses a strong magnetic field to carry charged particles (usually protons or electrons) around in a circular trajectory of constantly increasing diameter. As these particles move in the circular trajectory, they experience the Lorentz force generated by the magnetic field. In a cyclotron, magnetic fields are used to maintain the circular trajectory, while electric fields are used to accelerate the particles. To position the movement of particles in a cyclotron using the derivative of the Lorentz force equation, which describes the forces acting on a charged particle in an electric field and a magnetic field resulting in the equation:

$$\ddot{x} = \frac{q}{m}(\dot{y}B) \tag{5}$$

$$\ddot{y} = \frac{q}{m}(E - \dot{x}B) \tag{6}$$

$$\dot{z} = \frac{dz}{dt} \tag{7}$$

So when implemented in Python source code, it becomes:

$$vx = vx + ((q * (vy * B)/m) * dt)$$

$$y = y + (vy * dt)$$

$$vx = vy + ((q * (E - vx * B)/m) * dt)$$
$$x = x + (vx * dt)$$

$$z = z + (vz * dt)$$
$$VZ = VZ$$

To display the visualization of cyclotron motion of electron particles in electric and magnetic fields, matplotlib animation is used to display moving visualizations so that the output results of the electron particle cyclotron motion visualization program are referred to in Figure 1.

Visualization Source Code Output Results

As shown in Figure 2 and Figure 3 attached, both visualizations used the same parameters, namely particle charge ($q = -1.6e - 19\, C$), particle mass ($m = 9.11e - 31\, kg$), magnetic field ($B = 2.843e - 10\, T$), initial velocity on the y-axis ($v_0 = 0.002\, m/s$), initial velocity on the z-axis (vz0 = 0.001 m/s), simulation time limit ($t\_max = 2/3\, s$), and time step ($dt = 1e - 5\, s$). The main difference lies in the electric field used: Visualization 1 has an electric field ($E = -5.6875e - 14\, N/C$), while Visualization 2 has no electric field ($E = 0\, N/C$). As a result, visualization 1 shows cyclotron trajectories of electron particles with spiral shifts due to the electric field, while visualization two shows symmetric spiral trajectories that are only affected by the magnetic field. magnetic field. This illustrates the significant influence of the electric field on the trajectories of charged particles in a magnetic field.

The main difference in the change in vertical position (z) between the two visualizations is caused by the electric force acting on the particle in the first visualization. The electric field is directed downwards, producing an upward force on the negatively charged particle, causing acceleration and vertical movement (z) upwards in a spiral trajectory. With no electric field in the second visualization, the particles are only affected by the Lorentz force from the magnetic field, resulting in a more regular spiral trajectory with no significant change in vertical position.

These visual teaching aids in cyclotron motion made a great impact on the learning outcomes of the students. More precisely, students who were exposed to a visual approach are characterized by improved test scores, particularly those items addressing electron dynamics with electric and magnetic fields. Results from this study have significant implications for teaching methodologies in physics education. Improvement both at the test score and conceptual understanding level underlines the efficiency of visualizations while teaching complex physical phenomena. Traditional teaching methodologies could be very heavily dependent upon verbal and mathematical explanations that do not completely address the diverse learning needs of students. This provides a more integrated approach whereby the visual tool can facilitate visual learners, and all students are able to see something concrete that they might otherwise feel is an abstract.

CONCLUSION

Electric fields have a major influence on the trajectories of charged particles in a magnetic field, causing changes in position along the axis of the electric field. Without an electric field, the particles are only affected by the magnetic field and follow a more regular spiral trajectory. The main difference between the two visualizations is the effect of the electric field, which causes a change in the vertical position (z) of the electron particle trajectory. The visualizations in this study can enhance understanding by turning an abstract theory into an interactive visual experience. Similar visual approaches can be applied to other physics concepts such as quantum mechanics, wave-particle duality, or thermodynamics where students often face challenges in understanding abstract concepts. The tool can be modified for different educational levels, by adjusting the complexity of the visualization and the depth of the material. In addition, an understanding of cyclotron motion is essential as it has wide applications in various scientific and technological fields. In astrophysics, it provides insight into the dynamics of particles in cosmic magnetic fields. Particle accelerator technology that utilizes the principle of cyclotron motion is used in basic research, medical therapy, and isotope production. The indication from the result is that physics educators must seriously consider incorporating visualization techniques in their curricula when discussing complex topics like cyclotron motion. This is better achieved by using interactive simulation, animation, and graphical representation to enhance student engagement and thus deliver understanding for such demanding subjects. As such, in-depth knowledge of cyclotron motion contributes significantly to scientific and technological advancements that support various aspects of modern life.

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