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Helical Glow Discharge Emission Trajectory Formed by Lorentz Force of an Axially Symmetric Electromagnetic Field

by

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Abstract

An experiment was conducted to visualize the phenomena corresponding to the Lorentz force acting on an axially symmetric electromagnetic field discharge system. The experimental setup comprised a hollow hemispherical cathode with a permanent magnet inside and a rod anode facing each other in a vacuum chamber. A 3 kV DC voltage was applied between the electrodes, and the light-emitting trajectory caused by the glow discharge was photographed. The trajectory exhibited a helical structure from the cathode toward the anode, and the direction of rotation differed depending on the magnet's polarity. In other words, the helical trajectory of the glow discharge matched the direction of the Lorentz force. The phenomenon is relatively simple but is rarely visualized. The experimental method is considered suitable for use in educational settings.

Keywords: Lorentz force, Helical light-emitting trajectory, Glow discharge, Axially Symmetric Electromagnetic Field

1. Introduction

As electromagnetism involves many invisible phenomena, various tools have been devised in educational settings [1-3]. The electromagnetic force acting on charged particles, the Lorentz force, is an important factor in learning electromagnetism. A representative visualization of the electromagnetic force is the behavior of cathode rays [4]. It continues to be widely used as a simple educational tool. Charged particles move in a circular motion (cyclotron) owing to the electric field $\boldsymbol{E}$ and magnetic flux density $\boldsymbol{B}$. The visible trajectory of the cathode rays using Crookes tubes was used for two-dimensional spiral deflection. However, the three-dimensional helical trajectory has rarely been observed. Alternatively, winding motions found in detached plasmas for laboratory applications [5,6] are unsuitable in educational settings. Therefore, graphical aids for visible electromagnetic fields in computer simulations are being incorporated into teaching materials as content [7,8].

This research aims to find a simple aid for visualizing the phenomenon corresponding to the Lorentz force using experimental equipment for educational use. A helical luminous trajectory appeared when demonstrating glow discharge in an axially symmetric electromagnetic field. In this phenomenon, a negative glow discharge from a hollow hemispherical cathode with a permanent magnet inside helically moves in low-pressure air toward the opposite rod-shaped anode. This phenomenon is consistent with the direction of the Lorentz force but was not observed earlier.

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2. Experiments and analyses

The experiment was conducted in an axially symmetric electromagnetic field discharge system, using a hollow hemispherical cathode (diameter:100 mm, thickness:2 mm, made of stainless steel) and a rod-shaped anode (diameter:2 mm, made of copper) oppositely placed, as shown in Fig. 1. A circular neodymium magnet (diameter:20 mm, thickness:5 mm, maximum magnetic flux density:261 mT) was placed inside the cathode, at a minimum gap of 1 mm from its inner surface. The magnet was held with acrylic block support. The anode, excluding the 5 mm tip, was coated with a 2 mm thick silicone rubber. The shortest distance between the cathode and anode tips was 70 mm. The electrode system was placed in a desktop vacuum chamber with a glass bell jar (inner diameter:150 mm, height:200 mm) and vacuum pump unit. The inside of the chamber was evacuated using an oil rotary vacuum pump (ULVAC G-20DA), and the pressure was measured using a Pirani vacuum gauge (ULVAC GP-2A). The anode was connected to a high-voltage DC power supply (MCP M10-HV5000A) through a current limiting resistor of 500 kΩ; the cathode was grounded through the power supply. The average discharge current was measured using an analog DC ammeter (Yokogawa Electric, Japan; 0–30 mA).

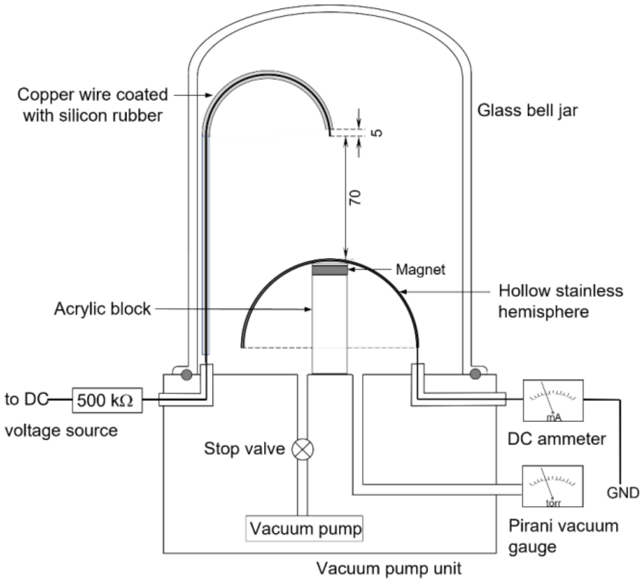
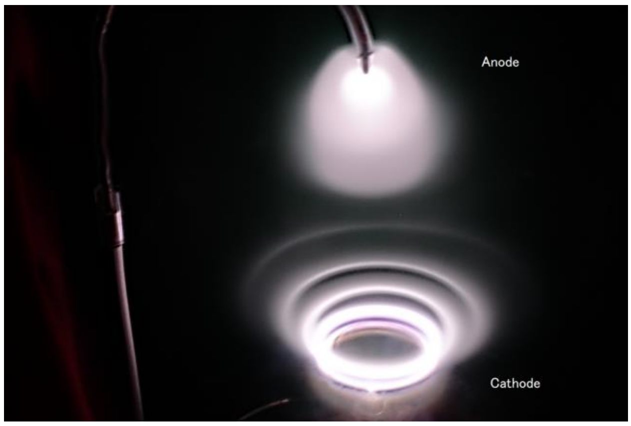


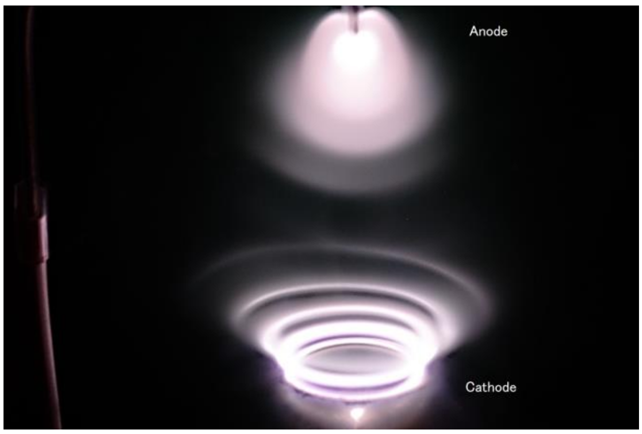
Fig.1 Schematic of the experimental setup.

The light emission behavior of the glow discharge depends on the air pressure. The mean free path lengthens when the pressure is relatively low, resulting in diffuse emissions. As the air pressure increases, diffusion is suppressed, and a contoured emission trajectory is observed. In the experiment, the pressure inside the chamber was reduced to 0.1 Torr (13.3 Pa), a voltage of 3 kV was applied between the electrodes, and the stop valve to the vacuum pump was closed. The pressure gradually increased as the glow discharge released the adsorbed gas. The photographs were taken at 0.7 Torr (93.3 Pa). The mean free path was approximately 0.51 and 0.07 mm at the beginning of the discharge and at the time of photographing, respectively. The discharge current is 5.1 mA. Since the current limiting resistor of 500 kΩ is placed in series, the potential difference between the cathode and anode electrodes is 450 V. The luminescence behavior remained stable for tens of seconds. The discharge luminous trajectory was photographed using a digital camera (Fujifilm X-E2) and lens (XF35 mm F1.4 R) with manual focus, automatic shutter speed, exposure ±0, ISO 800, and F5.6. The captured images were saved in jpeg format.

Fig. 2 shows the captured top surface of the magnet ((a) S pole and (b) N pole) when the camera is placed obliquely above the electrode. We observe a negative glow on the cathode side and a brighter positive column on the anode side. Because the discharge's luminous color is whitish (pale pink), we infer that the discharge releases water vapor, which is the gas adsorbed on the surfaces inside the chamber. For reference, when the stop valve was opened and the chamber was evacuated, the color changed to light reddish purple. As shown in Fig. 2, the whitish color is better in terms of visibility of the light-emission trajectory. Because the magnetic field prevents the charged particles from moving in the direction of the electric field, a contracted negative glow-emission region appears at the cathode. Such a contraction of the negative glow discharge is observed upon the application of a magnetic field [9]. In addition, because the charged particles move in a cyclotron, a ring-shaped light-emitting region is formed on the cathode's surface. The annular light emission progressed three-dimensionally and helically toward the anode. Furthermore, the winding direction is opposite to that of the N pole when the S pole is the magnet's upper surface.



(a) S pole as top magnet surface.



(b) N pole as top magnet surface.

Fig. 2 Photographed images taken diagonally from above between electrodes.

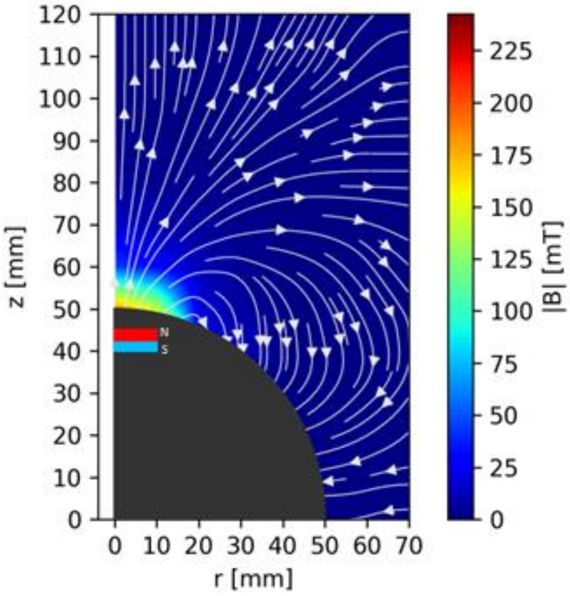
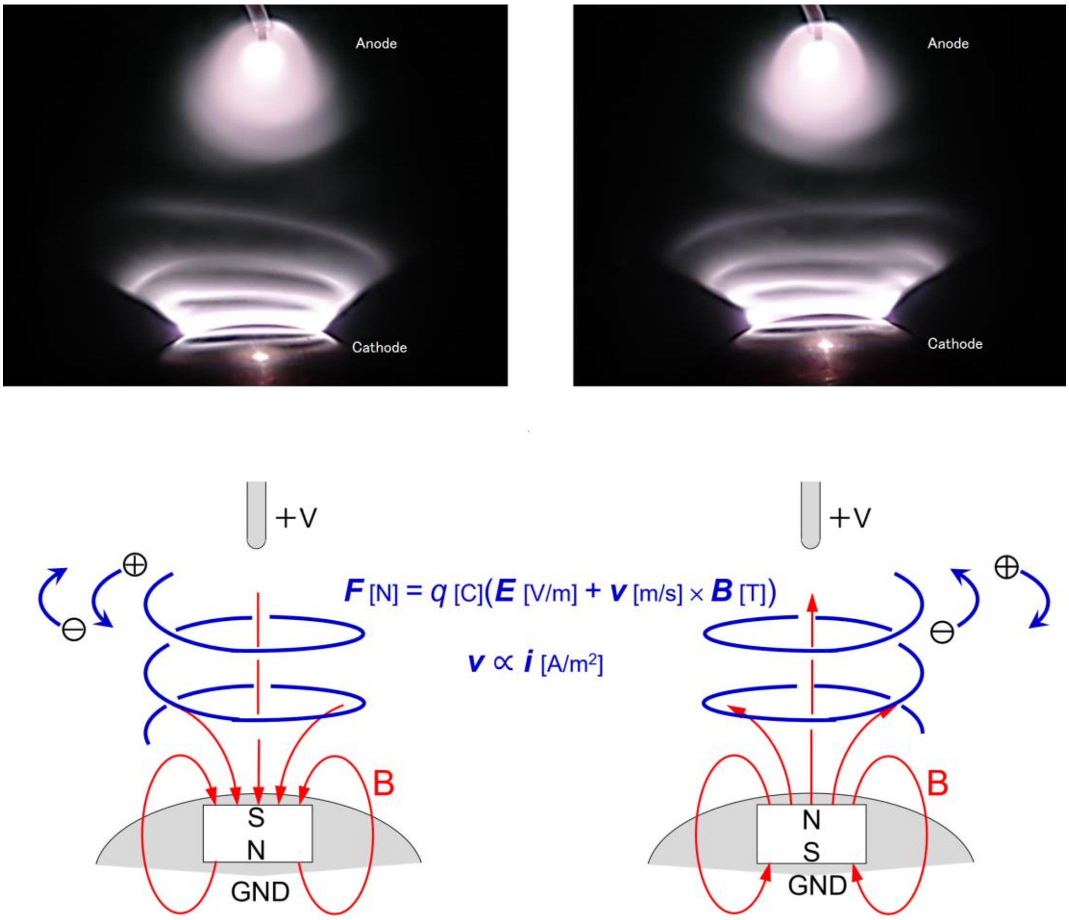


Fig. 3 Magnetic flux density distribution and magnetic lines of force between electrodes.



(a) S pole as top magnet surface.

(b) N pole as top magnet surface.

Fig. 4 Explanation of luminous trajectory of helical glow discharge.

Generally, important parameters for this discharge phenomena include discharge voltage and atmospheric pressure. In the environment of this experimental equipment, the discharge starting voltage was approximately 1 kV at an atmospheric pressure of 0.1 torr (13.3 Pa). The helical glow discharge emission trajectory was observed at applied voltages of 2 kV to 5 kV (5 kV is the upper limit of the power supply) and atmospheric pressures in the range of approximately 0.2 torr (26.7 Pa) to 2.5 torr (333.3 Pa). It was found that in this pressure range, the emission trajectory toward the anode becomes clearer as the pressure increases, and that when the pressure exceeds 2.0 torr, the spacing between the light emitting paths narrows and becomes unclear.

Fig. 3 shows the magnetic flux density distribution and lines of force between the electrodes; the upper surface of the magnet is the N pole. This is obtained through the linear interpolation of magnetic flux densities ($\boldsymbol{B}_r$ and $\boldsymbol{B}_z$) measured at 5–10 mm intervals between the electrodes in the radial direction r and axial direction z using a magnetic probe (Mother Tool, MT-801). Rendering of these measured values was performed using Matplotlib with Python on the Google Colaboratory execution environment. The maximum magnetic flux intensity $|\boldsymbol{B}|$ is 230 mT at the top edge (0, 50 mm) of the hemispherical electrode surface. The annular light trajectory closest to the hemispherical electrode, in Fig. 2, appears at a position of approximately 20 mm in the radial direction, approximately at (20, 50 mm), which is slightly outside the side edge of the magnet. This position corresponds to the area where the magnetic lines of force surround the cathode. Because electrons in these areas are enclosed in the magnetic field, a high electron density area is formed near the cathode's surface [10-12]. The glow discharge often assumes a filamentary structure under the influence of magnetic lines of force [5]. The magnetic field distribution in Fig. 3 is the static magnetic field formed by the magnet and excludes that created by the moving charged particles. However, the annular light emission position (20, 50 mm) closest to the cathode appears where the magnetic lines of force enclosed the cathode at the shortest distance. The electron density near this position is expected to be relatively high.

Fig. 4 describes the luminous trajectory of the helical glow discharge. Photographs were taken of areas immediately adjacent to the electrode's axis of symmetry. As described above, the light emission exhibited a helical structure from the cathode toward the anode, and the direction of the rotating trajectory depended on the magnet's polarity. The directions correspond to the Lorentz force; i.e., $\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B})$ [N], where q [C]: amount of charge, $\boldsymbol{E}$ [V/m]: electric field, $\boldsymbol{v}$ [m/s]: drift velocity of charged particles proportional to current density, $\boldsymbol{B}$ [T]: magnetic flux density. As a theoretical analysis was not performed here, the phenomenon needs to be investigated while measuring the physical parameters, such as the drift velocity of charged particles, to quantitatively understand the details.

3. Conclusions

The helical light-emitting phenomenon of glow discharge in an axially symmetric electromagnetic field was demonstrated to visualize the emission trajectory corresponding to the Lorentz force in an electromagnetic discharge system. A helical light-emitting trajectory, coinciding with the direction of the Lorentz force, was observed even with a relatively simple device. Although the physical details of this phenomenon need to be based on plasma diagnostics, this method finds applications in educational settings.

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