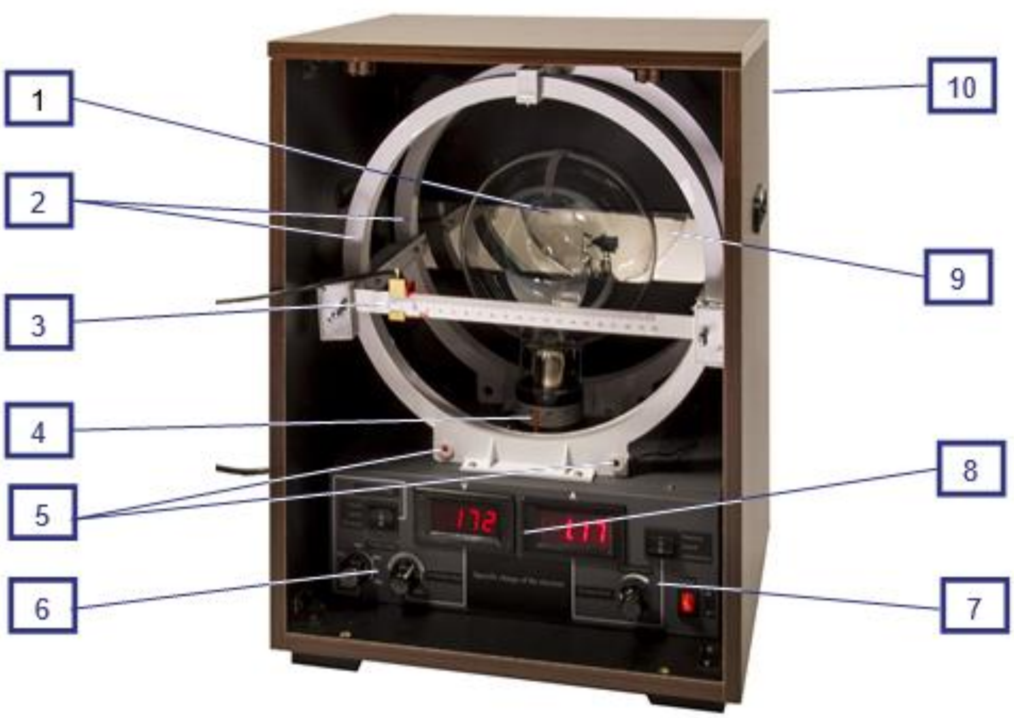
Digital e/m Apparatus

P6-3000

INSTRUCTIONAL GUIDE

Introduction

The LFD001 Lorentz Force Demonstrator is a “fine beam tube” device in which a sharply focused electron beam is projected into a vacuum containing a trace of inert gas. Ionization of the gas around the electron beam creates a glowing discharge marking the path of the electrons and helping to maintain the sharp focus of the beam. The demonstrator shows deflection of the beam by transverse electric fields and by magnetic fields of various orientations. The value of *e/m* can be found by bending the electron beam into a circular path with a homogeneous magnetic field and measuring the accelerating voltage of the electron gun, the strength of the magnetic field and the radius of the circular beam path.



1. “Fine beam” vacuum tube
2. Helmholtz coils
3. Metric ruler with LED sighting device
4. Angle scale and pointer for tube
5. Current direction indicators
6. Accelerating and deflection voltage controls
7. Power and coil current controls
8. Accelerating voltage and coil current meters
9. Mirror for parallax elimination
10. Case with black interior for better visibility

Background

The Lorentz fine beam tube is a vacuum tube containing small amount of inert gases, an electron gun, and a pair of deflection plates. When the appropriate voltages are applied to the tube, the electron gun emits a beam of electrons. Electron collisions with the gas molecules excite the gas molecules and produce light emission in a cylindrical sheath around the electron beam as the excited molecules relax, rendering the electron paths visible.

The Helmholtz magnetic field arrangement consists of a pair of identical ring coils connected in series and placed parallel to each other at a separation of one coil radius.
When a current I flows in the coils, it produces a fairly homogeneous magnetic field in the central region between the coils, with a magnetic induction B given by:

$B = 9 \times 10^{-7}\, n\, I / R = 9 \times 10^{-4}\, I$ for this apparatus **(1)**

where n is the number of turns on the coil, I is the magnetizing current in amps, R is the radius of the coil in meters, and B is given in Tesla.

In the magnetic field produced by Helmholtz coil, the electron beam will be subject to a force **F** known as Lorentz force:

$$\mathbf{F} = e.\mathbf{V} \times \mathbf{B} \quad \textbf{(2)}$$

its magnitude is

$$F = e.v.B.\sin\alpha \quad \textbf{(3)}$$

Where F is the Lorentz force on an electron, e is the charge of the electron, v is the velocity of the electron, B is the strength of the magnetic field, and α is the angle between the direction of the electron's velocity vector and that of the magnetic field.

When Lorentz tube is rotated so that the electrons and the magnetic field are in the same direction ($\alpha = 0$) or opposite directions ($\alpha = 180°$), the electrons are not subject to any force. Their path will be a straight line.

When the direction of the electrons is perpendicular to that of the magnetic field, the Lorentz force will take its maximum value and will be directed perpendicular to both the direction of the electrons' velocity and the magnetic field. In equation (3), when both v and B are constant, F will be constant and the Lorentz force will serve as a centripetal force, producing a circular motion of the electrons (see *Figure 5*). The radius of the circle depends on the magnitude of the force, which is in turn determined by the magnetic field and hence by the magnetizing current.

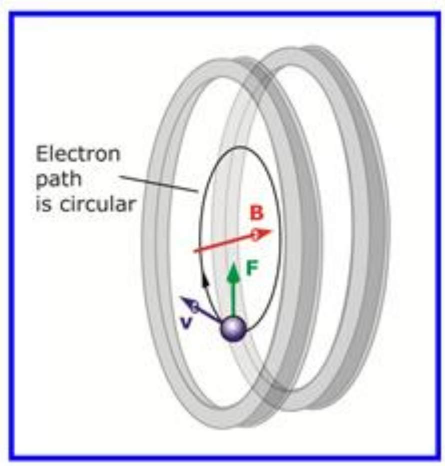


Figure 5

When α assumes a value other than 0 or 180°, the motion of the electrons can be decomposed into to two parts: a motion parallel to the magnetic field and one perpendicular to it. The parallel component, which is not subject to the Lorentz force, will be a straight line, while the perpendicular component will result in a circular motion under the Lorentz force. The resultant of these two motions will be a spiral.

The centripetal force on electrons in a uniform circular motion can be expressed as $m.v^2/r$, where m is the mass of the electron and r is the radius of the circular trajectory. As discussed above, the centripetal force is provided by the Lorentz force, so:

$$m.v^2/r = e.v.B \qquad (4)$$

Therefore, the charge-to-mass ratio of the electron, e/m, is determined by:

$$e/m = v/(r.B) \qquad (5)$$

The kinetic energy an electron gains in the accelerating electric field is equal to the work done on it by the field:

$$m.v^2/2 = e.V_a \quad (6)$$

where V_a is the accelerating voltage.

The velocity v of the electrons can therefore be found from equation (6):

$$v = \sqrt{(2e.V_a/m)} \qquad (7)$$

Substituting equations (1) and (7) into (5), we have the expression for the charge-to- mass ratio of an electron:

$$e/m = 2.47 \times 10^6\ V_a/r^2.I^2\ (C/kg) \qquad (8)$$

Therefore, the charge-to-mass ratio of the electron can be calculated if the accelerating voltage V_a, the magnetizing current I and the corresponding radius of the electron path, r, are measured.

The pair of deflection plates in the Lorentz tube is used for observing the motion of electrons in an electric field. When a voltage is applied so that the upper plate carries a positive charge, electrons will be deflect upwards at an angle α as shown in *Figure 6*.

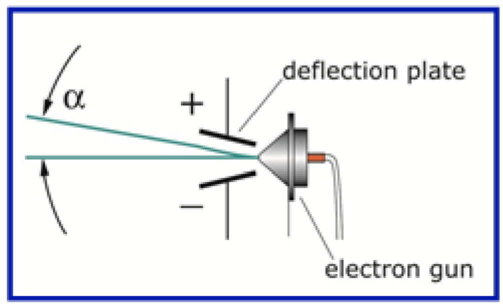


Figure 6

This angle can be determined from:

$$\tan \alpha = e.V_d / (l.s.v^2) \qquad (9)$$

where V_d is the voltage on the upper deflection plate, l is the length of the plate, s the mean distance between plates, and v the velocity of the electron in question.

Equation (9) shows that the deflection angle is directly proportional to the voltage on the deflection plates, and inversely proportional to the square of the electron's velocity, and thus inversely proportional to the accelerating voltage. When the polarity of the deflecting voltage is reversed, the electrons will be deflected downwards.

Controls

Figure 2

Figure 2 shows the front panel of the power supply unit:

1. Power on/off switch
2. Accelerating voltage adjustment knob
3. Accelerating voltage meter
4. Deflection voltage on/off/reverse switch
5. Deflection voltage adjustment knob
6. Coil current on/off/reverse switch
7. Coil current adjustment knob
8. Coil current meter
9. Coil current direction indicator – clockwise
10. Coil current direction indicator – counter clockwise
11. Angle scale for vacuum tube
12. Pointer for angle scale

Set-Up

First time Set-up

- Remove the cardboard box from inside the coils.
- Carefully take the vacuum tube out of the cardboard box.
- Holding the tube by its base (not the glass bulb), align the key on the tube base with the slot in the tube socket and carefully insert the tube into the socket.
- Loosen the knurled screw on the socket to allow the tube to rotate.

Starting Up

- Set accelerating voltage to 0.
- Set direction of magnetizing current to off.
- Set magnetizing current adjustment knob to minimum.
- Set switch for the direction of the deflecting voltage to off.
- Set deflecting voltage adjustment knob to 50V.
- Turn on the power switch and let the unit warm up for 5 minutes before applying an accelerating voltage.

Operation

Motion of Electrons in a Magnetic Field

- Turn the accelerating voltage control clockwise to increase the voltage until the electron beam trace shows up as a straight line. The voltage should be somewhere between 100V and 200V.
- Rotate the Lorentz tube until the pointer reads 90° on the scale. The trace should be a straight line to the left, perpendicular to the axis of the magnetizing coils.
- Turn the magnetic current switch to “counterclockwise”. The counterclockwise indicator will turn on, and the trace will deflect downwards due to the Lorentz force on the electrons. Turn the magnetizing current control clockwise to increase the magnetizing current. The angle of deflection will increase accordingly.
- Turn the magnetizing current control counterclockwise all the way, and set the magnetizing current switch to “clockwise”. The clockwise indicator will turn on, and the trace will deflect upwards.
- Turn the magnetizing current control clockwise to increase the current. The trace will become a circle, as shown in *Figure 5*. From equation (4), the diameter of the circle $d = 2r = m.V/(e.B)$. The diameter of the circle will increase when the accelerating voltage increases, or when the magnetizing current decreases.
- Rotate the Lorentz tube clockwise until the pointer reads 180°. The trace will become a straight line, because the electrons are not subject to any force in the magnetic field. Set the angle between 130° and 150°. The trace will become a spiral.

Motion of Electrons in an Electric Field

- Turn the magnetizing current control counterclockwise to minimum, and set the magnetizing current switch to “off”. Rotate the Lorentz tube until the pointer points to 90°. Set the deflecting voltage switch to “positive” to apply a positive voltage on the upper deflection plate. The trace will deflect upwards.
- Turn the deflecting voltage control clockwise to increase the deflecting voltage. The angle of deflection will increase.
- Increase the accelerating voltage while keeping the deflecting voltage un- changed. The angle of deflection will decrease, which verifies the relations in equation (9).
- Turn the deflecting voltage switch to “negative” to apply a voltage on the lower deflection plate. The trace will deflect downwards.

Measurement of the Charge-to-Mass Ratio of the Electron

- The electron beam itself is inaccessible inside the tube, so the diameter of the circle it traces must be measured remotely. This is done using the metric ruler, the mirror mounted on the back wall of the case, and the LED sighting device (see *Figure 7*).

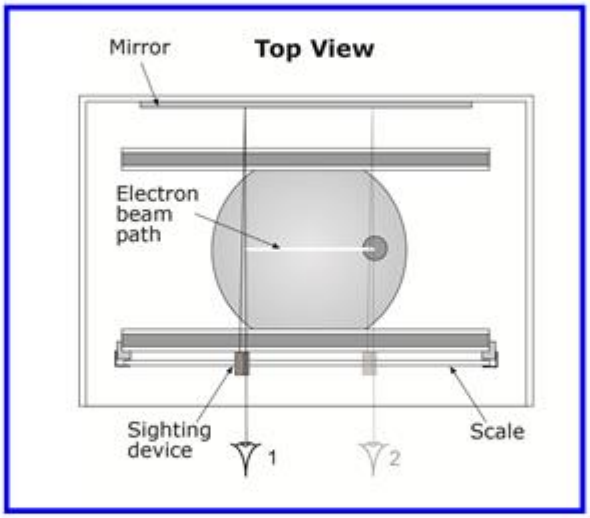
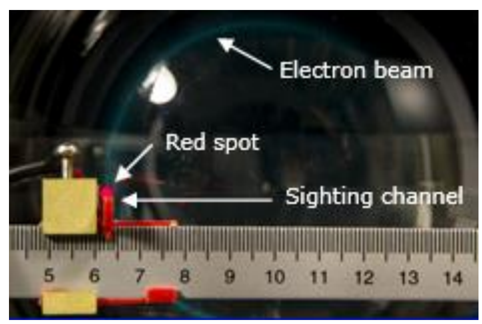


Figure 7

- Set the position of the Lorentz tube to 0°. Set the accelerating voltage to 150V. Set the magnetizing current switch to “clockwise”. Turn the magnetizing current control clockwise until the trace becomes a circle.
- Mount the ruler with the sighting device onto its support and adjust its height until it lines up with the diameter of the circle. Plug in the sighting device.
- The sighting device slides along the metric ruler and an LED projects a red spot onto the mirror. The reflection of the LED spot is viewed through a channel alongside the LED. Move the device along the ruler until the red spot appears to be aligned with one end of the diameter of the electron beam. Read the position of the device on the metric ruler, and then move the device to align the red spot with the other end of the electron beam diameter.



- The difference in the ruler readings is the beam diameter.
- Record the magnetizing current and the accelerating voltage. Calculate the charge-to-mass ratio from equation (8).
- Repeat the procedure with different accelerating voltages and magnetizing currents. Take the average value of the result

Maintenance/Tips

- Store the unit in a cool, dry, clean place.
- Do not place the unit upside down either in transportation or in storage.
- Handle the unit carefully. Do not subject it to excessive forces.
- After each use, tighten the knurled screw on the socket for the tube.
- Make sure the accelerating voltage is set to zero before turning on the unit.
- Wait 5 minutes after the unit is turned on before applying the accelerating voltage.
- Apply the accelerating voltage before each observation and turn it to zero immediately after the observation is finished. Turn the accelerating voltage to zero before turning off the unit.
- Do not use the unit for more than 1 hour continuously.
- Before switching the direction of the magnetizing current, turn the magnetizing current to minimum to avoid possible damage to the switch by arcing.
- Hold the base of the Lorentz tube when rotating the tube. Do not hold the glass bulb. Do not exceed the range of 0° – 180°.
- When observing Lorentz force, make sure to turn the electrostatic deflecting voltage control to minimum and set the deflecting voltage switch to “off’.
- When observing the force of the electric field, make sure to turn the magnetizing control to minimum and set the magnetizing current switch to “off’.